8th International symposium on Negative Ions, Beams and Sources - NIBS'22

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Book of Abstracts

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An H- Surface Plasma Source for the ESS Storage Ring

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H- charge exchange (stripping) injection into the European Spallation Neutron Source (ESS) Storage Ring requires a 90 mA H- ion source that delivers 2.9 ms pulses at 14 Hz repetition rate (duty factor ˜4%) that can be extended to 28 Hz (df 8%). This can be achieved with a magnetron surface plasma H- source (SPS) with active cathode and anode cooling. The Brookhaven National Laboratory (BNL) magnetron SPS can produce an H- beam current of 100 mA with about 2 kW discharge power and can operate up to 0.7 % duty factor (average power 14 W) without active cooling. We describe how active cathode and anode cooling can be applied to the magnetron SPS to increase the average discharge power up to 140 W (df 8%) to satisfy the needs of the ESS. We also describe the use of a short electrostatic LEBT as is used at the Oak Ridge National Laboratory Spallation Neutron Source to improve the beam delivery to the RFQ.

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Photo-assisted Cl-, Br- and I- production in cesium sputter ion source

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The negative ion formation in the cesium sputter ion sources occurs on the surface of a cathode containing the ionized material. The cathode is covered by a thin layer of cesium (Cs), which lowers the work function of the surface enhancing the negative ion formation. Vogel [1] recently introduced a hypothesis that the negative ion current can be enhanced by exposing the cathode to a laser beam resonantly exciting neutral cesium atoms to 7p electronic states, which acts as a catalyst for negative ion production via so-called ion pair production. We have recently demonstrated that the photo-assisted production of negative ions can be provoked by lasers at various wavelengths with the photon energy exceeding a certain threshold, which questioned the resonant ion pair production hypothesis [2]. Furthermore, the laser-assisted production of negative ions of oxygen (O-) as well as aluminium (Al-) was observed with the off-resonance diode lasers [3]. This observation opens the door for practical applications of photo-assisted negative ion production for all negative ion species, not just those with their electron affinity level in resonance with the excited states of neutral Cs. In this paper we present new results for Cl-, Br- and I- ions, obtained with a higher power, better focused and controlled laser setup. Finally, we explain the laser enhancement with a qualitative model.

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Numerical study of RF power coupling in fusion-relevant single- and multi-driver Hˆ- ion sources

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ITER's large and powerful neutral beam injection system is based on a modular concept, where eight cylindrical 'drivers'are attached to one common expansion and extraction region. In each driver, a plasma is sustained via inductive coupling with powers of up to 100 kW at a driving radio-frequency (RF) of 1 MHz to produce fusion-relevant hydrogen beams. These high powers impose great stress on the electric system and hence the ion source's reliability is decreased. Recent measurements at the single-driver test bed BATMAN Upgrade showed that the RF power transfer efficiency η, which measures the ratio of power absorbed by plasma to total RF power, is only around 50%, leaving room for optimization. In multi-driver test beds such as ELISE η is found to be even further decreased to around 40%. To explain this difference, a previously validated self-consistent 2D RF power coupling fluid model is applied. At the same absorbed power per driver the model shows virtually the same spatial distributions of plasma parameters and power absorption in single- and multi-driver sources. However, the coil current is increased in multi-driver ion sources due to a changed spatial distribution of the magnetic RF field in the region surrounding the drivers. In the exemplary case of the ELISE ion source this results in a slight decrease of η compared to the single-driver setup. Typically, in multi-driver sources conductive shields are applied to cancel the electrostatic interference between drivers. These shields are found to affect the spatial distribution of the RF fields even more severely. In the case of the ELISE ion source, the model calculates a further decrease of η, being in good agreement with experimental measurements. The effect is shown to be highly nonlinear with distance between shield and RF coil, wherefore it is advisable in future multi-driver ion sources to maximize this distance.

Oral session 3 / 4

Ultra-low work function of caesiated surfaces and impact of specific hydrogen plasma species

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Negative hydrogen ion sources for fusion and accelerators predominantly rely on the surface production mechanism. For that, a low work function surface is required to convert incoming hydrogen atoms and ions into negative ions. Due to the so far unsurpassed performance of caesium in this context [1-2], research on caesiated surfaces is unabated. During ion source operation the caesiated surface is affected by residual gases from the background pressure during vacuum phases (between 10^{-10} mbar for accelerators and up to 10^{-5} mbar for fusion), as well as by reactive hydrogen species during plasma phases comprising the atomic hydrogen radical, hydrogen ions and UV/VUV photons with energies of up to 15 eV. The combined influence can reach from cleaning the caesiated surface [3] to caesium removal from the surface [4]. The complex dynamics during ion source operation necessitates dedicated investigations on specific scenarios, which are performed at a flexible laboratory setup.

The experiment ACCesS is equipped with an in-situ work function diagnostic based on the photoelectric effect and was lately upgraded w.r.t. the threshold sensitivity. The detection limit for photocurrents was lowered by several orders of magnitude which now reveals ultra-low work function values of caesiated surfaces under moderate vacuum conditions [5]. The work function of significantly below that of bulk Cs is attributed to the formation of Cs oxide layers upon reaction of Cs with

residual water inevitably present due to the base pressure of 10^{-6}–10^{-5} mbar. The second modification of the experimental setup is an external ICP source with which the surface under investigation can be exposed to fluxes of specific hydrogen plasma species, where magnets and a MgF_2 window are used to select the species (H, H_x^+, VUV). It is revealed that each species can affect the surface separately and that their combined influence leads to a work function after repetitive short plasma pulses that is slightly higher than the ultra-low work function reached under vacuum conditions, but still lower than bulk Cs.

Due to this multitude of influences, a transfer of quantitative work function values to ion source operation is not straightforward. Therefore, a work function measurement system for ion sources was developed and recently installed at the Batman Upgrade ion source; first preliminary results will be shown.

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Caesium Balance of the ISIS H^- Penning Ion Source in Long Pulse Operation

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We have developed a semi-empirical model predicting the equilibrium caesium coverage (in monolayers) and the resulting work function of the ISIS Penning ion source cathode (in eV) in long pulse operation. We use the caesium balance model to predict the temporal structure of the extracted H^- beam current pulses and compare the model predictions to experimental data with 60 mA, 2 ms beam pulses at 50 Hz. The experimentally observed droop of the beam current is reproduced by the model. The results imply that extracting square beam pulses in the long pulse operation mode requires more efficient cathode cooling. We apply the model for 70 mA, 3 ms beam pulses at 14 Hz, relevant for ESSνSB project. We conclude that achieving these parameters requires reducing the cathode temperature by 200 °C, and ramping the discharge current to cancel the discharge voltage droop.

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First H- Beam Extracted from the Non-Caesiated External RF-Coil Ion Source at ISIS

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A high power, high duty-cycle, negative hydrogen ion source is in development at ISIS. Stable operation of an inductively-coupled plasma pulsing at 50 Hz, 1 ms, 70 kW has been perfected with no apparent lifetime issues. Novel features of the ion source include an external RF-coil, a very low power ignition gun, an adjustable permanent magnet filter field, a water cooling jacket and multiple large 3D-printed components. First beam has been extracted from the ion source and the commissioning efforts required to achieve it are presented herein.

Oral session 5 / 7

SImplified fluid models of radiofrequency and plasma density for NIO1 and design

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Inductive coupling of radiofrequency power to plasma is a complicate process, since it depends from the density of plasma itself for two major reason: (1) ionization is a chain reaction process; (2) with no Faraday screen (as in many sources and until now NIO1), a capacitative coupling may mix with inductive coupling. Several empirical 2D model can be developed, depending on collisional effect, which usually include stoschatic heating and filter action. Typical implementation with nonlinear partial differenstial equation (PDE) systems is reviewed. Together with a gallery of selected result for NIO1 original design (5 turn coil) and as built (7 turn coil), paper addresses some theoretical points. It can be recognized that (1) implies that PDEs have singularities, which fully justifies guided convergences of the solver; in particular lower bounds for field variables shoulb enforced. Comparison with hydrodymical models is attempted. Typical convergence is slow. Filter strength in the order of 8 mT (or line integrals of 7×10^{-4} T m) seems needed to achieve electron temperature lower than 2 eV (for negative ion production) at extraction.

Oral session 11 / 8

Study of plasma meniscus including the surface produced negative ions by using PIC-MCC simulation

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It is essential to generate the negative ion beams with good beam optics for the negative ion sources. Negative ion beam optics is determined by the shape of the plasma meniscus, which is an ion emitting surface. However, for the electronegative plasma including the surface produced H- ions in the negative ion sources, the key parameters to control the plasma meniscus and the dependence on these parameters are unclear.
In this study, the plasma meniscus and relevant physical structure such as the sheath in the electronegative plasma including the surface produced H- ions is investigated by using PIC-MCC simulation. The region from the source plasma up to the accelerator is modeled for a single aperture, and thus, the plasma meniscus can be solved self-consistently. Electrons, H+ ions, volume produced H- ions are assumed to be launched as Maxwellian distributions with the temperatures of 0.8 eV, 0.3 eV, 0.1 eV, respectively. After the plasma contained the electrons, the H+ ions, and the volume produced

H- ions reaches the steady state, the surface produced H- ions are launched uniformly from the PG surface. The surface produced H- ions are assumed to be the half-Maxwellian distribution with the temperature of 1 eV.
It is shown that the distance deff, between the plasma meniscus and the extraction grid depends on the ratio of the negative ion density to the electron density as well as the plasma density. Especially, the distance deff, decrease with the increase of the ratio under the constant plasma density, which means that the shape of the plasma meniscus becomes flat or convex rather than concave. This is due to the larger space charge effect of the H- ions than that of electrons. The electric field produced by the space charge of the H- ions prevents penetration of the electric field for H- extraction into the source plasma.

Poster session 1 / 9

Continuous pulse advances in the negative ion source NIO1

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Consorzio RFX and INFN-LNL have designed, built and operated the compact radiofrequency negative ion source NIO1 (Negative Ion Optimization phase 1) with the aim of studying the production and acceleration of H- ions. In particular, NIO1 was designed to keep plasma generation and beam extraction continuously active for several hours. Since 2020 the production of negative ions at the plasma grid (the first grid of the acceleration system) is enhanced by a Cs layer, deposited on its surface by means of active Cs evaporation in the source volume. For the negative ion sources applied to neutral beam injectors for fusion, keeping the beam current and the fraction of co-extracted electrons stable for times of at least 1 h is essential. Optimal conditions must also take into account the redistribution of caesium among the plasma box surfaces due to the action of the plasma.
The paper presents the latest results of the NIO1 source, in terms of beam performances during continuous (6÷7 h) plasma pulses. The effect of the plasma grid temperature on the production of negative ions is studied. Moreover, the conditions of the source are discussed also in terms of Cs density circulating in the volume as measured by the laser absorption spectroscopy diagnostic, and of basic plasma properties thanks to the measurements of emission spectroscopy.

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Repercussions of the magnetic filter field and the extraction aperture configurations on the negative ion beam properties: insights from a Particle-In-Cell model.

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In this talk, we will describe in detail the consequences on the negative ion kinetics of the asymmetry in the plasma parameters perpendicular to the magnetic field direction (due to the plasma polarization induced by the Hall current intercepted by the ion source wall). This work is relevant to negative ion sources with a magnetic filter field producing an electron drift directed toward one of the walls. We will show using a 2.5D Particle-In-Cell model [1] (2.5D meaning the numerical mesh is 2D but particle losses parallel to the magnetic field lines are also considered) that the transverse plasma asymmetry results in an extracted negative ion beam current density profile which is asymmetric as well. In addition, we will discuss how the geometry of the extraction aperture affect the total ion current and phase-space properties of beam which is extracted from the ion source.

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Oral session 6 / 11

Key parameters for the ion velocity distribution at the plasma meniscus of a caesiated negative ion source

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Neutral beams are a valuable option to provide heat and current drive to a magnetically confined plasma. In addition they can be used as a diagnostics for the positive ion temperature and, in case of nuclear fusion reactions, for the amount of helium ash. In the case of ITER, stringent requirements are set on the acceptable beam divergence and aiming in order to propagate such beams up to the tokamak itself. Besides the well-known dependence of the beamlet optics on the beam energy and perveance, other important features affecting the optics are the ion spatial and velocity distribution at the plasma boundary facing the extractor, the so-called plasma meniscus. In a caesiated negative ion source, such distribution is influenced both by the birth energy of the negative ions and by the ion transport in the plasma itself.
In this work, the effect of different plasma parameters on the ion velocity distribution at the meniscus is simulated by means of a particle tracing code with Monte Carlo collisions. Among them, the key role of the positive ion energy in the source is highlighted, as well as the consequences on the optics of the accelerated negative ion beams.

Oral session 3 / 12

Mach probe diagnostic for determining positive ion fluxes in H^- ion sources

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In NNBI ion sources neutral hydrogen atoms and positive ions impact on low work function grid surfaces, where they are converted to negative ions and subsequently extracted. Knowledge and control of the positive ions flux is hence crucial for optimizing the negative ion yield and also for benchmarking numerical models. To this end a Mach probe diagnostic can be used, which determines the direction and magnitude of the positive ion flux. The plasma in ion sources is typically weakly magnetized, rendering the interpretation of Mach probe data difficult. For this reason a two step approach was chosen, where at first a previously used Mach probe was re-commissioned and applied in a well diagnosed and versatile laboratory scale experiment. From these experiments important insights regarding the design of a new combined Langmuir- and Mach probe, its calibration procedure and data interpretation were obtained. As a second step the newly designed probe is applied in the ITER prototype RF negative ion source, where the fluxes of positive ions are obtained in the vicinity of the extraction system. This contribution covers the results from the small laboratory scale experiment as well as first measurements of the positive ion flux in the ITER prototype ion source.

Poster session 1 / 13

Creating negative ion beams from neutral gases using a negative Hydrogen ion source

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Negative ion beams are valuable for applications where tandem accelerators are used for ion injection [1], such as university research centers in the area of surface analysis using RBS (Rutherford Backscattering Spectrometry) and PIXE (Particle Induced X ray Emission) [2] and for high energy, light ion implantation in semiconductor devices [3]. A typical method for negative ion production uses a charge exchange method where positive (1+) ions are incident upon a vacuum region of alkali or other metallic vapour at an energy of a few tens of keV [1], such that a double charge exchange occurs to produce negative (1−) ions. This technique results in alkali or other metal contamination of vacuum surfaces and is difficult to maintain, and, with regards to ion implantation, the metallic vapour can contaminate the silicon wafers being processed. In this paper, we will be following Doupé and Litherland [4] where a negative ion beam (Y^-) is incident on a neutral vapour (X0) for a single step charge exchange: Y^- + X0 ⟶ Y0 + X^-, where the newly created X^- along with any remaining Y^- are accelerated with an electrostatic accelerator in order to avoid issues with alkali materials and general metallic contamination. We will describe our experimental setup which leverages D-Pace's H^- ion source [5], and a charge exchange vacuum box with an in-vacuo electrostatic accelerator followed by a 1:500 resolution mass spectrometer system. Neutral non-metallic vapours shall be bombarded with up to 15 mA (DC) H^- beams over the energy range 10-30 keV to create negative ion species to be accelerated by the 10-20 kV electrostatic accelerator. The neutral gases to be studied are He, CO2, H2, CH4 and the resulting conversion rates to He^-, C^-, CO^-, $C2^-$, $CO2^-$, $H2^-$, H^-, O^-, $O2^-$ etc. shall be reported as measured by the spectrometer system. Determination of the cross-sections to form the excitation function of this charge exchange process for the listed gases in the energy range 10 –20 keV is the ultimate purpose of this work.

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Oral session 11 / 14

Dynamic responses of negative ion meniscus to externally applied RF field

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Dynamic responses of negative ion meniscus to externally applied RF field with 2% arc discharge power were investigated experimentally. Three types of responses were identified. First is the beamlet width oscillation with the same frequency as the applied RF field. The second is the oscillation of the beamlet axis. The third is the response of the time-averaged beamlet width. These responses are different properties observed for the positive ion beamlet, indicating that the meniscus formation mechanism for negative ion beam extraction differs from that for positive ion beam extraction, which is well explained by the Bohm sheath model. The empirical scaling for the amplitude of the beamlet width oscillation was obtained. The beamlet width oscillation is proportional to the externally applied RF field and the slope of the perveance curve. The beamlet Oscillation is recognized to be a linear response of the meniscus. On the other hand, the response of the time-averaged beamlet width is nonlinear, and the higher order of the perturbation should be considered in the beamlet focus model.
Strong frequency dependence of the response of the beamlet width is identified, suggesting that the beamlet response can be mitigated when the RF frequency becomes low.

Oral session 8 / 15

120 mA Operation of J-PARC Cesiated RF-Driven H^- Ion Source

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In NIBS2020, the stable operation of the J-PARC cesiated RF-driven H^- ion source (IS) in a test-stand with a 65 keV 110 mA beam and a beam duty factor of 4.5 % (1 ms x 45 Hz), whose transverse emittances were measured to be suitable for the J-PARC radio-frequency quadrupole LINAC, was reported. In the operation, the beam intensity was limited only by the maximum IS terminal voltage of about 66 kV due to the withstand voltage of the 2 MHz RF matching circuit to deliver the 2 MHz maximum 50 kW RF power from the ground level to the plasma. The terminal voltage available for the stable operation was increased to about 70 kV by improving the withstand voltage of the matching circuit. The J-PARC IS operation with a 68.6 keV 120 mA and a beam duty factor of 4 % (1 ms x 40 Hz) is reported in this paper. The measured transverse emittances of the beam are also presented.

Poster session 1 / 16

Numerical study of the plasma meniscus shape and beam optics in RF negative ion sources

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In order to extract intense ion beams with good beam optics from hydrogen negative ion sources, it is important to control the shape of the plasma meniscus (i.e. beam emission surface). In our previous study [1], it is shown that the plasma meniscus in the negative ion source depends on the H--electron density ratio as well as the bulk plasma density. Recently, it is pointed out experimentally that the poor beam optics in the RF negative ion sources may be due to the fluctuation of the shape of the plasma meniscus resulted from the fluctuation of the plasma density[2].
The purpose of this study is to clarify the physical mechanism for the poor beam optics in the RF discharge numerically. Especially the dependence of the shape of the plasma meniscus on bulk plasma density is investigated. For this purpose, 3D-PIC (three-dimensional Particle-in-Cell) simulation was conducted for a model geometry of the extraction region for the Linac4 H- ion source in CERN. The preliminary results show that the shape of the plasma meniscus depends on the bulk plasma density: In the case of the optimum plasma density, the plasma meniscus shape is flat, and the resultant beam optics is good. If the plasma density is slightly higher (12 %) than the optimum density, the plasma meniscus shape is convex while if the plasma density is slightly lower (20 %) than the optimum density, the plasma meniscus shape is concave. In these plasma densities, the beam optics is poor. This result qualitatively agrees with the typical experimental result, and supports the above hypothesis for the poor beam optics in the RF negative ion sources.

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Poster session 1 / 17

Influence of different magnetic configurations on plasma parameters in SPIDER device

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The ITER fusion reactor will be heated by fast neutral beams generated by accelerating and neutralizing negative ions, produced in a RF inductively-coupled plasma and expanding through a region featuring a magnetic filter. Since the beginning of SPIDER operation in 2018, many issues have been solved, lessons learned and objectives reached, but fixing several major problems requires a long shutdown, started at the end of 2021, in which the whole plasma source and accelerator will be dismounted. In this phase additional modifications with respect to the original design will be introduced in order to improve the system performance, driven by the experience acquired in the

last years. These include the addition of further sets of permanent magnets in the plasma source expansion chamber and around the RF drivers, with the aim of improving the plasma confinement and consequently its density and possibly its uniformity.
The present paper reports the results of numerical studies of the plasma parameters in SPIDER source with different types of modifications of SPIDER device including new permanent magnets configurations. Analysis are done by means of the numerical code FSFS2D in which a self-consistent two-dimensional fluid description of the source, including neutral gas flow, plasma chemistry, RF-plasma coupling in the driver and plasma transport through the magnetic filter has been implemented. The different particle species (electrons, H^+, H_2^+, H_3^+, H^-, atoms and molecules) are described by continuity equations; the electron temperature is governed by the electron energy balance equation. Particle fluxes are found from momentum equations neglecting inertia (drift-diffusion approximation). Electrons and ions are coupled by the Poisson equation.
In order to partially account for the 3D flow pattern within our 2D model, simulations are done in two geometrical situation, in the vertical plane with the magnetic filter being perpendicular to the integration domain and in the horizontal plane with the filter field in the integration surface. Preliminary results indicate, that the permanent magnets around the RF driver tends to increase the plasma density in the driver. The influence of the magnetic fields on the negative ion currents in the expansion zone is also investigated.

Poster Session 2 / 18

Characterization of the Plasma in SPIDER using a Cs-H Collisional Radiative model

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SPIDER (Source for the Production of Ions of Deuterium Extracted from a Radio frequency plasma), hosted at the Neutral Beam Test Facility (NBTF) in Padova, Italy, is the full scale prototype for the ITER Heating Neutral Beam (HNB) source.
A collisional radiative model for caesium-hydrogen plasmas was recently developed. When used in conjunction with measurements from Optical Emission Spectroscopy, Laser Absorption Spectroscopy and electrostatic probes, the model can provide estimates of the plasma parameters with a good spatial resolution thanks to the many lines of sight available.
This work presents a characterization of the plasma in SPIDER with this method during the first experimental campaign with caesium. In particular, we investigate the influence of the source biases and the direction of the magnetic filter field on the plasma properties, and compare the results with those of other source and beam diagnostics.

Poster session 1 / 19

Direct current measurements of the SPIDER beam: a comparison to existing beam diagnostics

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For negative ion beam sources there are several methods of measuring the accelerated beam current, namely electrical measurements at the power supply and calorimetric measurements. On SPIDER, the ITER Heating Neutral Beam full-scale beam source, electrical measurements at the acceleration grid power supply (AGPS) are complemented by polarizing the diagnostic calorimeter STRIKE to provide an additional electrical measurement of the accelerated current. This is in addition to the calorimetric measurements provided by STRIKE. These diagnostics give differing measurements of the beam current. Exploiting the reduced number of open apertures on SPIDER a new beam diagnostic has been installed to measure the individual beamlet currents directly. The so called Beamlet Current Monitor (BCM) has been used to measure the current of five beamlets during the most recent SPIDER campaign.
This work compares the BCM current to the electrical measurements at the Acceleration Grid Power Supply (AGPS) and STRIKE calorimeter. The average BCM current agrees well with the STRIKE measurements, indicating that the AGPS overestimates the beam current. The individual beamlets are compared to the STRIKE calorimetric measurements, showing similar current trends with the source parameters.

Oral session 12 / 20

Simple beam energy recovery as alternative to Residual Ion dump in Neutral Ion Beam Injections

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The Neutral Ion Beam Injection will be used to further heat the plasma temperature to reach the ignition of the fusion reaction to producing energy in ITER project and some energy efficiency is required. Recently a very simple beam energy recovery based on space charge effect has been proposed as an alternative to the Electrostatic Ion Dump since had some advantages in removing the residual ion after the negative beam neutralization [V. Variale et al, Rev. Sci. Instrum. 91, 013516 (2020)]. Preliminary simulation results showed that the proposed device was able to remove all the residual ions by collecting them at very low energy on proper electrodes. Further simulations with more accurate space charge calculations were needed to confirm the high residual ion collection efficiency obtained in the preliminary simulations of ref. [V. Variale et al, AIP Conference Proceedings 2052, 070006 (2018)]. In this contribution, new simulation results with a code that perform more accurate space charge calculations will be presented. The more accurate space charge calculations presented here suggest some modification on the previous collector model to increase the ion collection efficiency. Further ion recovery simulations with the modified collectors have been also presented and discussed. The proposal of the experimental test foreseen for that device on a scaled ion beam source will be also updated.

Poster session 1 / 21

Drift and non-uniformity mitigation in H- source with Plasma Ion Funnels

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The H- multiaperture ion sources requested by NBI for fusion researches need fair plasma uniformity on those apertures placed on in the so called Plasma Grid, both to facilitate perveance matching of all beamlet and to balance erosion of caesium layer in long pulses. The flow of particle drifts due to both the magnetic filter (Bf), needed in the extraction region to reduce electron density temperature, and to the extraction electric field, forms a pileup with resulting top/bottom plasma asymmetry. The plasma density, however, can be controlled by funnel electrodes and bias plate (BP) with proper polarization. Assuming that filter current flows vertically, as in SIPDER, and in designs for MITICA and DTT (Divertor Test Tokamak), we have Bf horizontally directed and vd vertically directed, say in toward bottom to fix ideas. In smaller sources, pile up is less important, but non-uniformity of plasma near walls is proportionally more important. The variety of experimental results and conditions suggest a long and careful discussion. Several remedies were proposed, based on modification of the E x B pattern, to reduce plasma flow accumulation at specific points (source bottom). In the funnel concept, the BP is supplemented by many electrodes inside the extraction region. Voltages among PG, BP, funnel and wider plasma chamber walls, as well Bf, are key parameters. Due to the large computation size of the full problem, several approximate simulation methods were used. 3D simulations with no space charge have shown good ion extraction condition for preventing direct electron co-extraction [V. Variale, M. Cavenago, on Proceedings IPAC 2022, Bangkok (Thailand)]. In this contribution an empirical model for plasma sheath and space charge is also solved in 2D (using nonlinear multiphysics solvers) and a discussion on drift trajectories that mostly confirm similar 3D results is introduced. Comparisons with other fluid models in the literature are considered. Effects of wall condition are also critically discussed.

Oral session10 / 23

Recent H– ion source research and development at the Oak Ridge National Laboratory

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Abstract. The U.S. Spallation Neutron Source (SNS) is a state-of-the-art neutron scattering facility delivering the world's most intense pulsed neutron beams to a wide array of instruments which are used to conduct investigations in many fields of science and engineering. Neutrons are produced by spallation of liquid Hg by bombardment of short (˜1�s), intense (˜40A) pulses of protons delivered at 60 Hz by a storage ring which is fed by a high-intensity, 1 GeV H- LINAC. This facility has operated almost continuously since 2006, with ion source performance increasing over those years, and now currently providing 50-60 mA of H- ions with a duty-factor of 6% for maintenance-free runs of several months with near 100% availability. Ion source research and development at ORNL has played a key role in enabling and supporting this success: this report provides an update on ongoing ion source research and development efforts which have been undertaken since the previous NIBs conference in 2020. These include improvements to the plasma ignition gun and dual frequency excitation of the external antenna ion source; upgrades to the ion source RF and electrical systems; incremental improvements to the ion source extraction system and Low Energy Beam Transport (LEBT) as well as upgrades to the LEBT and beam diagnostic systems.

Oral session 8 / 24

Discoloration of RF antenna coil surface after long-term operation of J-PARC ion source

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In J-PARC (Japan Proton Accelerator Research Complex) center, continuous operation duration of the Radio Frequency (RF) negative hydrogen (H^-) ion source equipped with the internal RF antenna coil is extended step by step in these 6 –7 years for the goal to supply stable beam during the entire period of J-PARC user operation each year. From Nov. 2020 to Apr. 2021, the continuous ion source operation for 3,651 hours (5 months) was achieved with 60 mA H- beam current at the ion source exit, 0.825 % duty factor (25 Hz repetition) and 25 kW RF power injection. As the lifetime of the RF ion source is mainly limited by failure on the enamel coating of the RF antenna, detailed evaluation of the antenna surface is required to ensure feasibility of the further extension of the operation time.
In the present study, surface discoloration on the RF antenna coil observed after the 5 months operation [1] is investigated by application of digital microscope and SEM/EDS analyses. The material mapping and the line spectrum obtained by the EDS analysis show that depositions of the sputtered source chamber wall materials and the injected cesium on to the enamel coating are the most possible candidate for the discoloration. The dimension measurements of the RF antenna thickness before and after the long-term operation support the idea that the discoloration is due to the deposited materials and hence insulation of the RF antenna coil by enamel coating is maintained. The emittance measurement after the operation also shows that the RF plasma and the beam formations are not affected by the deposition on the antenna.
On the other hand, possible mechanisms leading to antenna catastrophic failure starting from material depositions on the antenna coating will be discussed in the presentation with the present status of the J-PARC RF ion source.

[1] T. Shibata, *et al.*, J. Phys. Conf. Ser. **2244** 012041 (2022).

Oral session 3 / 25

Photoelectric current measurement of plasma grid materials for a compact H- ion source

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Low work-function materials have been being studied for the use of plasma grids (PG) of negative hydrogen (H-) ion sources to avoid Cs injection to the sources. In the surface H- ion production process, the low work-function of the surface enlarges the survival probability of H- ions leaving from the surface. The work function of the PG can be measured by photoelectric effect, but small quantum efficiencies of photoelectric effect make detection of electron emission under noisy plasma

environment impossible. Semiconductor light sources can generate large photon fluxes; they have the small photon emission area, and the narrow band width of the wavelength spectrum. Thus, we have designed a compact system which exposes the surface of a test PG material with the light from a high-power semi-conductor light source.
The system is composed of a small (60mm diameter, 80mm long) multi-line-cusp ion source and a 3 W light emitting diode (LED) optical system. Light from LEDs of different wavelengths (365nm, 405nm, 470nm, 525nm, 625nm) is focused onto the PG surface using an optical lens. An extraction electrode system behind the PG forms a beam of H- ions produced by in the source. In the first stage, the correlation between the photoelectric current and the H- ion current will be studied for various PG materials, such as Mo, C12A7 electride, and so on. The absolute value of the work function can be also derived by using multiple wavelengths light sources.

Oral session 9 / **27**

Development and Commissioning of a Hydrogen Ion Source for the CERN ALPHA Experiment

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The CERN ALPHA experiment makes precision measurements of antihydrogen atoms held in a superconducting magnetic minimum trap. Recent studies of the antihydrogen spectrum have provided unique tests of fundamental physics, and to improve on these studies ALPHA is now proposing upgrades to directly compare hydrogen and antihydrogen within their existing atom trap. One route towards producing cold, neutral hydrogen atoms is the integration of a hydrogen ion source into the experiment. Ideally, this should provide both positive (H+, H2+, H3+) and negative (H-) ions to facilitate different schemes for producing and trapping hydrogen atoms. For compatibility with ALPHA's existing beamlines, the source must produce modest (˜10 µA) beam currents at very low final energies (<100 eV). PELLIS, previously developed at JYFL, is a filament-driven ion source that generates 5-10 keV H- beams with small emittances and microamps of beam current. Here, we present a modified PELLIS design to provide both positive and negative hydrogen ions for ALPHA. The use of an electromagnet filter field in PELLIS allows for the optimisation of H- volume production, and also tuning of the positive ion species fraction. We present simulations of H+ and H- transport through the initial extraction optics, which have been reconfigured for matching into a previously proposed transport beamline at 5 keV. We detail vacuum simulations that were used to guide the optics design, allowing the source (at 10-2 mbar) to interface with a transport beamline ˜0.5 m downstream that has strict vacuum requirements of < 10-9 mbar. We present experimental results from commissioning of the source to show that it achieves similar beam currents for both H- and positive ions, and to infer the species fraction of positive ions.

Poster session 1 / **29**

Numerical and experimental investigations of a microwave interferometer for the negative ion source SPIDER

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The electron density close to the extraction grids and the co-extracted electrons represent a crucial issue when operating negative ion sources for fusion. An excessive electron density in the plasma expansion region can indeed inhibit the negative ion production and introduce potentially harmful electrons in the accelerator. When entering the accelerator, electrons risk overheating the accelerator grids, representing a major problem especially for MITICA, designed to accelerate negative ions up to 1 MeV.
Among the set of plasma and beam diagnostics proposed for SPIDER upgrade, a heterodyne microwave (mw) interferometer at 100 GHz is currently being explored as a possibility to measure electron density in the plasma extraction region. The major issue in applying this technique in SPIDER is the poor accessibility of the probing microwave beam through the source metal walls and the long distance of 4 m at which mw modules are located outside the vacuum vessel. Numerical investigations in a full-scale geometry showed that the power transmitted through the plasma source apertures was above the signal-to-noise ratio threshold for the microwave module sensitivity, so, an experimental proof-of-principle of the setup to assess the possibility of signal phase detection was performed. The microwave system was tested on an experimental full-scale test-bench mimicking SPIDER viewports accessibility constraints, including the presence of a SPIDER-like plasma. The outcome of first tests revealed that, despite the geometrical constraints, in certain conditions, the phase detection, and, therefore, the electron density measurement is possible. The main issue arises from decoupling the one-pass signal component from spurious multipaths generated by mw beam reflections, requiring dedicated signal cross correlation analysis. These preliminary tests demonstrated that despite the 4 m distance between the mw modules and the presence of metal walls, phase signal detection in different conditions of plasma densities is possible when full 8 cm diameter viewports are available.
In this contribution, we discuss the numerical simulations, the outcome of the preliminary experimental tests and suggest design upgrades of the interferometric setup to enhance signal transmission. This includes a new design of the emitting horn to improve its directivity and the addition of focusing elements to enhance mw beam transport along the propagation path. Moreover, it is envisaged to perform next tests in frequency sweep mode; by measuring the phase shift over a frequency range, it is expected to reduce the error on phase shift at a given frequency.

Poster session 1 / 30

Observation of beamlet displacement and parallelism in NIO1

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The compact radiofrequency negative ion source NIO1 (Negative Ion Optimization phase 1) has many available CF40 ports for side views of beamlet matrix. Two kinds of deflecting magnetic systems are

present, namely the fringe field of the source filter Bs (mostly directed in vertical direction, x, where z is beam extraction direction) and the electron deflection filter Bd (due to magnets inserted in the extraction grid EG and the post-acceleration grid PA) mostly directed in the horizontal direction (y). Their effect can be separated by visible cameras looking from different directions, namely CAM1 (looking from −x axis) is sensitive to Bs while CAM2 (looking from −y axis) verifies Bd effect; both cameras are also sensitive to beam optics, dependent on extracted beamlet currents, their uniformity and applied voltage. Optional algorithms for noise rejection and pre-smoothing can improve automatic recognizing of beamlet peaks, while a good fraction of images can be simply fitted by Gaussian shapes. This analysis allows to estimate beamlet displacement and deflection. Furthermore, alignment and scaling of images is discussed also with reference to background objects, to validate the analysis performed. At the optimum of beam optics, the two dimensional analysis of the beam shape is carried out, to verify the Gaussian shape of the beamlets in both dimensions. The position of the beamlet peaks is studied along beam propagation direction when the beam optics is optimized, to estimate the residual vertical deflection as a function of the beamlet current and source parameters. Experimental data are exploited to perform systematic analysis of correlation between images, other source measurements and simple beam simulation is also attempted. Moreover, beamlet convergence was sometimes observed, and corresponding datasets were tagged for optics correction. Finally beam size information useful for Faraday cup design is obtained.

Poster Session 2 / 31

Study of the relationship between the source complexity and the beam divergence and homogeneity in SPIDER

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The large size and complexity of ITER negative ion source prototype play a key role in determining the homogeneity of the multi-beamlet negative ion beam current and divergence.
Visible tomography, which has already proved capable of characterizing the isolated beamlet properties with high temporal and spatial resolutions, can be exploited to study the beam dependence on source parameters along the entire beam profile.
In SPIDER, the plasma is generated by four pairs of radio-frequency drivers operating simultaneously and then it expands in the expansion region, where a dedicated magnetic filter field reduces the destruction probability of negative ions. To increase the production of negative ions, cesium is evaporated in the plasma source and distributed over the Plasma Grid (i.e. the first grid of the three-grid accelerator which faces the plasma) by the plasma itself. The plasma properties are studied from the drivers to the expansion region by spectroscopic measurements and they are correlated with the beam behavior. The non-homogeneous plasma density profile is related to the non-homogeneous distribution of cesium on the Plasma Grid, and thus to the uneven availability of negative ions along the beam vertical profile. This is accentuated by the 3D dynamics of the plasma drift due to the combined effects of the electrical and magnetic filter fields, which are critical in reducing respectively the co-extracted electron current and the electron temperature close to the extraction region.
The performances of SPIDER large-size negative ion beam are presented and explained in terms of plasma source behavior, also suggesting some possible improvements to ameliorate the beam properties for future Heating Neutral Beams.

Poster session 1 / 33

Study and development of diagnostic systems to characterise the extraction region in SPIDER

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SPIDER is a radio frequency (RF) driven negative ion source part of the Neutral Beam Test Facility (NBTF), prototype of the negative ion source of ITER's neutral beam injector. It is composed of 8 cylindrical drivers, capable of igniting the plasma through the inductive coupling with 4 radio frequency generators, each delivering up to 200kW. Its goal is to accelerate 50A of negative hydrogen ions up to 100keV, with beam uniformity within 10% over the entire beam cross section of approximately 2m^2.

The experiment started its operations in 2018, and recently its capability of negative ion production in caesium operation has been tested. Results achieved until now are aligned with the ones obtained in similar test facilities, however, SPIDER presents some further challenges due to its dimensions, to the presence of more than one driver, and to the non-uniform plasma expansion. All these physical problems affect the uniformity of the extracted beam, hence, the machine has yet to reach the expected nominal performances and to improve it, at the end of 2021, SPIDER entered a major shutdown.

One the most important aspects studied during the first experimental campaign is uniformity, addressed both in terms of plasma and of caesium distribution. The latter is particularly relevant since its quality is directly related to the beam uniformity and divergence. To have more insight about these issues, monitoring the plasma properties in the extraction region is crucial, hence in the present contribution, the design and development of two new diagnostic systems is displayed: a movable Langmuir probe and a Retarding Field Energy Analyser (RFEA), both installed close to the plasma grid.

The first can provide a scan along the vertical direction of the main plasma parameters with better spatial resolution with respect to the existing set of fixed Langmuir probes embedded in the grid system, possibly interacting with other sensors to produce complementary measures.
The latter, instead, allows the monitoring of the positive ion energy distribution: positive ions, in fact, can be precursors of the negative ones produced at the caesiated surface, but also contributes the energy of negative ions and their extraction probability and thus collecting information about their energy distribution allows inferring details about the extracted negative ion beam.

The two diagnostics are designed focusing on the experimental constraint of integrating the diagnostics in a harsh and complex environment such as SPIDER plasma: a preliminary study of the placement inside the source is carried out, then the electrode of the movable probe and the RFEA sensor are dimensioned according to the spatial and energy resolution requested of the system.

Poster session 1 / 34

Investigations on Cs dispersion and Mo coating on SPIDER components

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SPIDER is the 100 keV full-size Negative Ion Source prototype of the ITER Neutral Beam Injectors and it is operating at Consorzio RFX in Padova, Italy. It represents the most powerful Negative Ion Source in the world. SPIDER works with RF plasma from which Deuterium and/or Hydrogen ions

are produced and extracted.
At the end of 2021, a scheduled long-term shutdown started to perform major modification and improvements aiming to solve issues and drawbacks identified during first years operation. First action of the shutdown period was, the disassembly and characterisation of SPIDER beam source after removal from vacuum vessel and its positioning inside the clean room,. Each component was carefully observed, catalogued and the whole procedure has been documented.
Some source components, i.e. Plasma Grid, Extraction Grid, Bias Plate, revealed the presence of different and non-uniform red, white and green coatings that might be correlated to back-streaming positive ions impinging on grid surfaces, electrical discharges and caesium evaporation. Thus, several analyses have been carried out to understand the nature of such coatings and the study is still ongoing. The evidence of caesium evaporation and deposition, such as the formation of oxides and hydroxides, on molybdenum coated SPIDER components is presented by means of surface characterisation analyses like Scanning Electron Microscope (SEM), X-Ray Diffraction (XRD) and X-Ray Photoelectron Spectroscopy (XPS).

Poster session 1 / 35

Design and test of a module of a breathable Electrostatic Shield for the MITICA 1 MV negative Ion Beam Source

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The electrical insulation of the Negative Ion Beam Source at 1 MV is one of the challenging issues of MITICA, the prototype of the Heating Neutral Beam Injector for ITER. A collaborative effort between QST and Consorzio RFX is presently under way for assessing and optimizing this insulation [1]. According to extrapolation models based on recent reduced-scale experiments, the voltage holding capability of the single-gap vacuum insulation between the Beam Source (at -1 MV) and the Vessel (at ground potential) appears to be critical. However, the same models also show that the installation of intermediate Electrostatic Shields could effectively separate the single-gap insulation into 2 (or more) independent gaps, subjected to a fraction of the total voltage, and thus improve substantially the effectiveness of the Beam Source insulation [2]. A HV test campaign is already planned using full-scale mock-up electrodes, reproducing in detail the geometry of the Beam Source and Accelerator, under realistic operating conditions. In this campaign, the possibility of introducing an intermediate Electrostatic Shields (ES) surrounding the Beam Source (BS) is considered, so as to improve voltage holding by dividing the 1 MV vacuum gap in two independent insulating gaps of 400 kV and 600 kV respectively. However, the negative ion source in the BS shall operate with H2 or D2 gas at a pressure of ˜ 0.3 Pa (for optimal negative ion production), whereas in the surrounding vacuum insulation gas pressure shall not exceed about 0.04 Pa, to avoid Paschen- type discharges. Therefore, an ES having sufficient gas conductivity (breathability) is necessary to allow efficient pumping of background gas all around the BS. In order to avoid any reduction of the voltage holding capability due to direct shine-through effect and, at the same time, guarantee sufficient gas conductance, a modular structure with double-walls and staggered holes has been envisaged for the ES. The paper will present the criteria adopted for the design of a prototype ES module, with double-walls and optimized hole geometry (diameter and pitch of the holes, distance between walls) for maximum gas conductance. The results of voltage holding tests performed using the "breathable" ES module as intermediate electrode will also be presented and compared to those obtained in comparable reference configurations, with a flat intermediate electrode (no apertures) and also without intermediate electrode.
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[2] N. Pilan et al. Fusion Engineering and Design 88 (2013) 1038–1041, http://dx.doi.org/10.1016/j.fusengdes.2013.02.071

Oral session 3 / 36

Effect due to Cs injection upon the beam current oscillation extracted from the J-PARC negative hydrogen ion source

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A negative hydrogen (H^-) ion source with the plasma excited by 2 MHz radio frequency (RF) power serves as the beam source for the Japan Proton Accelerator Research Complex (J-PARC). We have been studying the H- ion beam intensity modulation at the frequency of plasma excitation RF power since we have found the beam carried the fluctuation at 2 MHz after the RFQ linac [1]. Higher frequency components were found present in the peripheral region of the plasma [2], and the high-speed emittance measurement system developed to clarify the change of the beam in phase space revealed the existence of diverging halo component oscillating at 2 MHz [3]. The fluctuation amplitude at the beam center was less than about 20%, while there was observed the component oscillating at 4 MHz.
The 4 MHz component seems related to the production of high energy electrons by the RF antenna as the intensity of the RF induction electric field takes the maximum twice in each cycle. On the other hand, the direction of RF magnetic field and the direction of electron flow change at 2 MHz frequency. Thus, H- ion formation mechanisms in the ion source can be estimated through precisely characterizing the extracted H^- ion beam. The H^- ion beam fluctuation can be observed in the H^- ion current measured with a Faraday cup. Before introducing Cs, the measured beam current showed the fluctuation at 4 MHz frequency when the axial magnetic field correction (AMFC) coil was turned off. The main fluctuation frequency changed to 2 MHz as the voltage to excite the coil to induce AMFC was increased. Injection of Cs into the ion source increased the H- ion current, while the 4 MHz component nearly disappeared for both cases of AMFC on and AMFC off. Possible mechanisms responsible for diminishing 4 MHz fluctuation component by Cs injections are discussed.

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[2] M. Wada et al. Rev. Sci. Instrum. 91, 013330 (2020).
[3] T. Shibata et al. AIP Conf. Proc. 2373, 05002 (2021).

Oral session 9 / 37

Rotational and vibrational temperatures of Hydrogen nonequilibrium plasmas from Fulcher band emission spectra

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A roto-vibrational specific corona model is discussed for the simulation of the Fulcher spectrum in low pressure Hydrogen discharges. The model takes into account the processes of electron-impact excitation, spontaneous emission and predissociation and allows to simulate the molecular Fulcher spectrum in the [600:640] nm range.
The model is applied to the analysis of emission spectra collected at the SPIDER negative ion source.

It will be shown that the model can reproduce measured spectra with good accuracy and thus provide an estimation of the vibrational and rotational temperatures of the molecular component in discharge; the latter can also be taken as a good estimation of the gas temperature. Knowledge of these quantities is important for the accurate modelling of the plasma kinetics.
Results are presented for different values of the discharge applied power and source pressure and for the driver and expansion regions of the discharge, thus providing a characterization of the rotational and vibrational temperatures of H_2 as a function of these machine parameters.

Poster Session 2 / 38

Spider plasma emission between 300 nm and 900 nm in different operative conditions

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SPIDER is the prototype source for ITER negative ion beams in operation at Padova PRIMA test facility since 2018. SPIDER mission is to produce an extracted negative ion beam of section 1.5x0.6 m2 and a current density of 355 A/m2 (H-) or 285 A/m2 (D-) while keeping the fraction of co-extracted electrons below 0.5 (H)/1 (D). During the experimental campaigns in SPIDER, the operating conditions and many hardware components underwent several modifications. The former includes change of gas (hydrogen or deuterium), cesium injection, and variation of the main discharge parameters: pressure, RF power, source and grid bias, extraction and acceleration voltages, etc. Other modifications arose from the need to better understand the experimental findings: introduction of gas dopants, changes in the oscillator electric circuits (capacitance, connections), functioning with a reduced set of RF generators, reversal of the magnetic filter field, etc. In some cases these changes were the only way to make the plasma operation possible, such as the masking of the plasma-facing grid, or the redesign of the electric circuit for the generation of the magnetic filter field in the plasma. In a situation of continuously changing the experimental conditions it is fundamental to trace them out and to compare the experimental results with the previous ones. In SPIDER the optical emission spectroscopy diagnostic, providing real time measurements of plasma emission, demonstrated to be a reliable non invasive tool to monitor the plasma conditions in the source. This work shows the dependence of plasma optical emissions on the modifications of SPIDER experimental conditions and offers possible interpretations of their influence on plasma emission.

Poster Session 2 / 39

Influence of plasma parameters on the effectiveness of multi-cusp magnetic field confinement in negative ion sources

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Cusp-shaped magnetic fields are widely used to confine plasmas in various applications. This kind of field topology is obtained by placing a set of permanent magnets with alternate orientation and regular step on the plasma chamber surfaces.
Within this magnetic field configuration, plasma loss is localised in correspondence of the permanent magnets, where the field lines are perpendicular to the walls. The width of such loss cone, usually called leak width, was found to be proportional to the geometric mean of the ion and electron Larmor radii, so that it becomes smaller for increasing magnetic field intensity.
At the same time, plasma diffusion towards the walls is reduced in the regions where the field lines are parallel to the surfaces: this leads to the formation of a Plasma Exclusion Zone (PEZ), whose characteristic dimension depends on the distance between the magnets.
Besides field intensity and geometry, plasma interaction with the cusp-shaped magnetic field –which determines the confinement effectiveness –might also be affected by plasma properties such as electron temperature, plasma potential across the sheath and collisionality. The estimation of both the leak width and the PEZ, while considering also these dependencies, is still difficult as a comprehensive tool is currently not available. On this basis, the present contribution describes a numerical analysis of the dependence of both the PEZ size and the leak width on the main plasma parameters, performed by means of a 2D-3V Particle-In-Cell code. In negative ion sources, multi-cusp configuration is commonly applied at the source walls, but also in the beamlet extraction region, due to the presence of electron deflection magnets embedded in the extraction grid. The obtained results are finally compared with theoretical and numerical estimations from previous works.

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Utilization of Compact ECR plasma source for large area H- ion production

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One of the most significant applications of plasma-based hydrogen negative ion (H-) sources is the production of high current, large area H-beams, which are used for the neural beam injection (NBI) system of a fusion plasma reactor like ITER. Such beams demand high density, uniform plasma (˜10ˆ12/cmˆ3 with variation limited to 10%) with low electron temperature (≤ 1 eV) generated over a large area. Presently, to meet such requirement, RF-ICP discharges are used, that however utilizes high powers (Prf˜800 kW). In the present work, an alternate novel plasma source, namely Compact Electron Cyclotron Resonance (ECR) Plasma Source (CEPS, patentee: Plasma Lab, IIT Delhi) is described that aims to produce similar plasma in a large expansion chamber with low input power to improve the energy efficiency. The CEPS (dia: 0.09 m, length: 0.11 m) is coaxially attached to the top dome (marked z = 0) of the chamber (dia ˜ 1.0 m, height ˜ 1.0 m). It is a compact and portable source that uses axially poled NdFeB permanent ring magnets encapsulating CEPS's source section. The magnetic field structure is fairly complex inside CEPS with an ECR surface lying within it. In the expansion chamber, the magnets produce a diverging field that decays exponentially along the axis. Experiments were conducted with minimum μ-wave power ≈ 400W and at hydrogen gas pressure of 1-5 mTorr. The large volume plasma was characterized with cylindrical Langmuir probes, placed at different positions, in both axial as well as radial direction. Axial direction measurements revealed high plasma density of ˜2×10ˆ11/cmˆ3 near to the source (z = 5 - 10 cm), reducing to ˜ 6 × 10ˆ10/cmˆ3 over the axial span of 60 cm towards the downstream. On axis electron temperature (Te) near the source was recorded to be ˜ 55 eV which drops to ˜ 5 eV within 5 cm span towards the downstream and further reduced to ˜ 2eV at z = 60 cm. Radial profiles at different planes of the expansion chamber indicated the presence of moderately dense and uniform plasma with a low Te ˜ 0.5 - 3 eV in the downstream over 80 cm dia. Noticeable improvement in radial uniformity is also observed, as one moves from up-stream region (˜ 30 %) i.e., near to the CEPS source to downstream regions (˜15

%) but at the expense of a fall in the plasma density. The low Te and the uniformity are in favor of large area surface production of H- which is prone to destruction in a high Te environment due to its low electron affinity (0.75 eV). Moreover, the pertaining condition is also encouraging for volumetric production of H-via the 2-step dissociative attachment (DA) process, where one needs high Te (˜20 eV like in upstream) for excited H2 formation and low temperature (1 eV in downstream) for H-production. Work is now underway to estimate the H-density at the downstream plane using a particle balance model.

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Experimental Characterization and Theoretical Studies of ECR Produced Hydrogen Plasma Ion Beams

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Hydrogen plasma with its multiple constituent species (H, H2 at ground and excited vibrational levels, H+, H2+, H3+, H-) offers a rich array of applications in diverse fields of science and technology such as in materials processing, production of ion beams for fusion plasma heating etc. In the present work, a combination of a solenoid and a set of five permanent ring magnets were used to produce ECR hydrogen plasma within a source section (ID=9.1 cm, length=11.6 cm) and allowed to expand into a larger cylindrical chamber (ID=48.2 cm, length=75 cm) in the pressure range 1-8 mTorr and 650W, CW microwave power. The experiments were undertaken to explore suitable regions of negative hydrogen ion production within the expansion chamber. The plasma has been characterized using a specially designed Langmuir probe (LP), with an on-axis Retarding Field Energy Analyzer (RFEA) being used for beam measurements.
LP measurements revealed, for most cases, that the plasma within the source region has a single electron population, which subsequently splits into two electron populations downstream. Suitable regions of H- production (Te ˜ 1 eV at p = 8 mTorr) were found in the downstream regions and at higher pressures. The point at which splitting occurs can vary from well inside the source to outside the source. At lower pressures, it is noted that there is a significant drop in the plasma potential from within the source into the expansion chamber. This ambipolar field would be ideal for ion acceleration. Hence, an axial RFEA [1, 2] was used to measure ion energies close to the mouth of the plasma source section. The RFEA shows ions having energy ≈ 62 eV and ≈ 36 eV (5 cm and 10 cm away from the source respectively) at 1 mTorr pressure. Hence, the source region not only pumps plasma into the expansion chamber, it also gives rise to high energy ion beams within the expansion chamber as the interconnecting opening provides both electrical and diffusive contact between the two systems, which helps generate flows and ion beams.
In order to corroborate the experimental observations of ion beams in the expansion chamber and the contribution of the different ionic/molecular hydrogen species, a 2-zone global model was developed with separate particle and power balance equations being setup for the two zones (the source section and the expansion chamber) taking into account particle and power flow across the two zones, wall losses, current balance across the interconnecting opening, etc. The two zone global model results obtained were compared with the experimental results both inside and outside the plasma source section and it was found that there is a reasonable match between the model and experimental results. The detailed results would be presented in this paper.

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Operation and Research Activities on the Three H- Injector Systems at the Spallation Neutron Source

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The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory is an accelerator-based, short-pulse (sub-µs) neutron production facility for a broad range of scientific applications. A 65-keV H- injector consisting of an rf-driven H- ion source and an electrostatic low energy beam transport section delivers high-current (>50 mA), time-structured (60 Hz, 1.0 ms macro-pulse divided into ˜1000 mini-pulses of < 1 µs in length) H- beam to the SNS accelerator complex. In the recent five production run cycles of SNS, a single H- ion source was operated for 3-4 months as scheduled for each run cycle with excellent availability of ˜99.9%. For the ongoing run started in early May 2022, the ion source is also on track to finish a 95-day operational cycle with high availability. Besides the H- injector on the main accelerator complex, the SNS campus also hosts two similar test injector systems: one is for providing beam for a 2.5-MeV RFQ Beam Test Facility and the other is dedicated for ion source, low energy beam transport, and beam chopper development. The recent R&D activities on these test injector systems, including an optimization study of the ion source electron dumping circuit and improvement in performance consistency among ion sources, will also be presented.

Poster session 1 / 43

Study on the stitching method of beam target infrared image based on local transformation

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As a beam diagnostic tool with the highest resolution, the 1D-CFC (one-dimensional carbon fiber composite) calorimeter can obtain the key beam parameters such as beam divergence, beam uniformity. According to the design of accelerating system of ion source for CRAFT NNBI (Comprehensive Research Facility for Fusion Technology Negative Ion based Neural Beam Injection system), the CFC calorimeter is designed as a narrow and long structure with the size of 1800mm×680mm. In order to obtain a clear beam profile, two infrared cameras are used to photograph the temperature distribution of CFC surface. Considering the field of view in horizontal and vertical direction, incomplete diagnostic calorimeter infrared images with partially overlapping contents are obtained. In order to analyze conveniently and obtain a complete and accurate image data, the two images acquired from the different infrared camera need to be stitched. In this paper, the global geometric structure of the image is preserved, the overlapping regions are matched using straight line and point features, and for the non-overlapping regions, constraints based on global similar transformation are introduced to reduce perspective and projection distortion, and show the single-view stitching results finally. The experimental results show that this method can obtain pixel-level stitching results in the non-fixed viewpoint, which has stronger robustness and generality compared with the traditional method and can provide effective data for the next step of beam parameter analysis.

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Preliminary design of tungsten wire calorimeter for CRAFT NNBI

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As one of effective means for plasma heating and current driving, neutral beam injector have been installed in most of nuclear fusion experimental devices in the world. High power neutral beam long pulses are required for continuous heating was required according to the development and research of magnetic controlled fusion energy. Large area high current ion source is the key equipment of neutral beam implantation system, in order realize efficient plasma heating, it is necessary to tune and optimize the ion source. As a common ion source diagnostic technology, tungsten wire calorimeter has been widely used in foreign neutral beam test platforms. In this paper, a tungsten wire calorimeter for beam source diagnosis is preliminarily designed. The relationship between temperature distribution of tungsten wire and heat conduction and radiation is explored by heating tungsten wire in vacuum environment, the diameter of tungsten wire and the time to reach thermal equilibrium, the temperature distribution of tungsten wire under different beam energy and influence of beam current with different divergence angle on the temperature distribution of tungsten wire are simulated and analyzed by finite element method. It also designs the frame of tungsten wire calorimeter, analyzes the fixing mode of tungsten wire and frame, the insulation isolation between tungsten wire and frame, tests the spring tension used for fixing tungsten wire, and determines the connection mode between spring and tungsten wire. Finally, the preliminary design of the tungsten wire calorimeter is completed. The operation of the calorimeter will provide a method for studying the spatial and temporal resolution of the beam, and provide a powerful technical means for the exercise and test of the exercise and test of the ion source.

Poster session 1 / 45

Optimization of a negative oxygen ion beam

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Negative ion beams are of interest to a wide range of applications. Many previous studies investigated properties of H- or D- with beam diameters on the centimeter scale or larger due to their relevant applications in fusion or accelerators. However, less work has been done with other ion species and beam sizes in the millimeter range or smaller. Such beam properties are particularly important in the application of Secondary Ion Mass Spectroscopy (SIMS). SIMS analysis relies on measurements of secondary ions generated by the sputtering of a sample with primary ion beams (i.e. O-, O2-, etc). Radio frequency plasmas have been shown to be a successful primary stage to generate ion beams for SIMS instruments. High spatial resolution on the target requires a highly collimated beam with high current density. In addition, such a plasma source needs to deliver a very stable current, which improves precision and reproducibility of the resulting measurements.

In this context, we are developing a negative oxygen ion source capable of long-term (days) steady state operation. The source generates inductively coupled plasmas using a novel antenna, and can produce positive or negative ion beams. A filter magnetic field is applied at the beam exit to deflect

electrons. The ion beam current is measured using a Faraday cup with a secondary-electron suppressor plate. An optical spectrometer in the visible range is used to monitor the neutral composition inside the plasma.
Preliminary results showed that the extracted positive ion beam has a beam current ten times higher than that of negative ions. In both extraction polarities, a linear relationship between beam current with RF power, and non-linear relationship with filter magnetic field strength, chamber pressure, and voltage on the beam extraction grids are found. Changes in chamber size and wall temperature are also found to affect the beam quality, indicating the significance of surface effects in the creation/destruction of negative oxygen ions. To enhance plasma density, an additional DC magnetic field is installed along the axis of the chamber. Results will be presented in comparison with a traditional solenoid coil antenna.

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THE 1MV MITICA POWER SUPPLY BEYOND THE MODERN TECHNOLOGICAL LIMITS: FIRST EXPERIENCE DURING INTEGRATION PHASE

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MITICA, the full scale prototype of ITER Heating Neutral Beam (HNB), is under realization at the Neutral Beam Test Facility (Padova, Italy). MITICA Power Supply is a very complex system, composed of several non-standard equipment, beyond the present industrial standard for insulation voltage level (-1MVdc) and dimensions. Procured by European and Japanese Domestic Agencies, it consists of five DC generators, rated for -200kVdc each and series connected to produce -1MVdc acceleration voltage, linked via a SF6 insulated Transmission Line to the beam source, installed inside the vacuum vessel. The Ion Source and Extraction Power Supply system is installed inside a large air insulated Faraday cage and fed by 1MV Insulating Transformer.
Individual components were tested in factory, then voltage withstand tests (up to 1.265MVdc) have been performed at site in five subsequent steps (from 2018 to 2019), according to the installation progress, after connecting equipment belonging to different procurements.
Nevertheless during integrated commissioning up to 1MV, started in 2021, a breakdown occurred somewhere in the HV plant, either in air or in SF6, causing the fault of one diode bridge arm inside 1MV DCG. By means of a fast transient model developed ad hoc, it was possible to explain the failure with the uneven diodes voltage distribution determined by parasitic elements contribution in transient conditions. Moreover, the model allowed verifying the effectiveness of the additional protections presently under detail design phase.
To identify the locations of possible weak insulation points, a new insulation test was performed with enhanced diagnostic on air insulated parts, mainly adding cameras on the visible field. While testing at 1MV, the Insulating Transformer was damaged by an arc suddenly generated at the top of its bushing. Dedicated refined analyses showed that a breakdown in the HV system can generate an impulse overvoltage exceeding the transformer insulation design capability. A way to reduce the stress to the admissible value (interposing an additional RCL passive component) has been identified and is presently under conceptual design.
To identify the possible source of the breakdowns, the detection system has been further enhanced:
- by adding various current and voltage sensors along the plant and recording the typical breakdown patterns via a reduced voltage benchmark campaign;
- identifying with the support of HV experts suitable instruments for DC partial discharge detection, as a first step on the air-insulated part;

- installing a number of cameras at normal and high acquisition frame rate and realizing a microphone network to identify the possible source and propagation of any abnormal acoustic signal.
If such diagnostic system has proven to be effective during the test campaign presently still ongoing, it can be optimized and adopted definitively both in MITICA and in the future HNBs as early breakdown detection system.
Unavoidable schedule delays have been introduced but MITICA has demonstrated its usefulness in identifying and addressing unpredictable problems deriving from the integration of high voltage non-standard components, allowing the definition of corrective actions and tests in due time for the ITER HNBs installations.

Poster Session 2 / 47

Highly electronegative plasma conditions in the SPIDER negative ion source

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Neutral Beam Injectors (NBIs) based on negative ions will be the workhorses of the ITER experiment, where they are expected to provide up to 33MW of power to heat the fusion plasma. The negative hydrogen ions are extracted from a RF plasma, in which a magnetic filter field cools down the electrons reaching the so-called expansion region allowing the formation of negative ions near the apertures in the plasma grid. To further improve the production of negative ions, cesium is usually evaporated inside the source and deposited onto the plasma walls, reducing the work function of the surfaces. This dramatically increases the density of negative hydrogen ions near the surfaces, causing the transition to a highly electronegative plasma in the vicinity of the plasma grid.
In this paper, the emergence of this condition in SPIDER, the prototype ion source of ITER NBIs, is assessed starting from the results of the Langmuir probes embedded in the plasma grid and bias plate electrodes in the expansion region, whence negative ions are extracted. These sensors were extensively used during the last SPIDER campaigns with the injection of cesium, and a reduction of the electron saturation current was observed, indicating that the plasma is moving towards an ion-ion plasma. We present here the characterization of the occurrence of this condition, its dependence on machine parameters such as the RF power, the polarization of the plasma grid and bias plate electrodes with respect to the source walls, and its dependence on the cesiation procedure effectiveness as evaluated in terms of negative ions density measured by the cavity ring-down and laser absorption diagnostics, and in terms of the beam and coextracted electrons currents.

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Plasma Electrode Materials for Cs-free Negative hydrogen ion Sources

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Cesium additives are currently used in negative hydrogen(H-/D-) ion sources, which are key components in nuclear fusion plasma heating systems and high energy proton accelerators. Here, a thin cesium layer on a Molybdenum plasma electrode (or plasma grid), PE, lowers the surface work function, and results in high H-/D- production rates. However, in future systems, alternative ion source schemes and/or alternative new PE materials realizing high negative ion yields are demanded from the maintenance aspect, and for the stable operation. In this paper, we focus the discussion on some new PE materials from viewpoints of production mechanism and ion source applications.

Generally, negative hydrogen(H-/D-) ion sources are operated at the positive PE bias, for higher extracted H- current and reduction of the co-extracted electron current. The plasma potential profiles are affected by the positive PE bias, and hence, H- transport towards the extraction is enhanced. We will discuss the bias effect in an ion source with a C12A7 electride PE.

When the PE is positively biased, the production surface is mostly bombarded by energetic neutrals, but the basic H-/D- production processes can be simulated by ion injection. An ion energy analysis mass spectrometry is used to detect the negative ions produced on the surface negatively biased in a H2 or D2 plasma. The photoemission yield spectroscopy is used as well to measure the surface work function. Some results obtained with alternative materials such as diamond-like carbon or C12A7 electrides will be shown.

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Source Performance Optimization in Cesiated Mode in ROBIN

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ITER reference design, inductively coupled single driver RF-source ROBIN is operational at IPR, Gandhinagar. The first phase of the operation yielded H- ion current density of 22-25 mA/cm2 and with electron to-ion ratios >1. The Cesium (Cs) consumption was very high compared to a similar source operated at IPP, Garching. The lessons learned from the operational experience showed the operational limitations in presence of impurities and excessive evaporation of Cs into the source. Since then the source was disassembled, cleaned, and reassembled to enable the restart of operations under improved and controlled conditions. Recent experiments assisted by relevant diagnosis on the cleaned ROBIN source under controlled cesiated conditions and improvements based on the lessons learned have resulted in achieving H- ion current densities >30 mA/cm2 and electron to ion ratios < 1 and with Cs consumption reduced to ˜12 mg/hr. Systematic studies related to parametric dependence on the source filling pressure and power have been performed with powers up to 80 kW coupled to the source at an RF frequency of 937 kHz. The role of plasma grid bias on the H- ion current densities, electron to ion ratios, beam transmission, plasma, and negative ion densities, and electron temperatures have been studied in detail. The observations and results related to Cs conditioning, source performance optimization, source parametric dependence on the beam, and related observations and findings related to the effects of the bias voltage on the source performance shall be presented and discussed.

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Correlation H- beam properties to Cs-coverage

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A cesiated RF driven source delivers H- ion that, after stripping at the end of the 160 MeV H- linear injector, provides protons to CERN's accelerator complex including LHC, where the protons reached a record energy of 6.8 TeV. During initial caesiation, the dual production mechanism of H- ions, via dissociative attachment of electron onto roto-vibrationally excited H2-molecules (volume) and re-emission as negative ions of protons or hydrogen atoms colliding on a low work function caesiated molybdenum plasma electrode (surface), exhibits a stunning reduction of co-extracted electrons correlated to an increase of the H- ion current to RF-power yield. This paper describes the evolution of the beam-profile and -emittance at today's operational beam intensities of 35 mA for various ratios of volume and surface ion-origin. The presence of surface produced ions occurring on a conical plane is characterized by the electron to ion ratio and by measurement of the Cs-coverage of the molybdenum plasma electrode down to a fraction of a monolayer. Angular distributions are extracted from Beam Emission Spectroscopy (BES) measurements for specific volume and surface production modes. These experimental results provide an initial comparison to beam formation simulation software packages (ONIX [1]) coupled to Beam transport codes (IBSimu [2]) presented in ref. [3].

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Poster session 1 / 51

Effect of plasma grid and bias plate biasing on the SPIDER negative ion beam

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Biased plasma electrodes in negative ion sources can be used for reducing the amount of co-extracted electrons, together with the magnetic filter field. In SPIDER, both the plasma grid (PG) and the bias plate can be independently polarized with respect to the source body, and this work characterises their effect on the plasma in the expansion region and on the accelerated beam. By increasing the polarization voltages, the extracted electron current decreases, but the spatial non-uniformities of the plasma in front of the PG are enhanced. This non-uniformity in the plasma reflects also upon the accelerated ion beam: at large polarization voltages, the bottom region of the beam exhibits a lower accelerated current with respect to the top region, which may also result in increasing the local divergence.
The characterization of both the beam and the plasma is carried out with different diagnostics that allow spectroscopic, calorimetric and electrical measurements, in order to clarify the different effects of biased electrodes in SPIDER.

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Investigation of spatially resolved plasma parameter and potential distributions at the BATMAN Upgrade ion source

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In H^- ion sources for neutral beam heating applications, the creation of negative ions relies on the surface conversion of H atoms and positive ions at the plasma grid surface. The yield of this process is strongly influenced by the energy of the impacting particles. In general, a higher energy or velocity of H or H_x^+ results in a higher conversion rate. However, the velocity of the created H^- ions does also increase which can lead to a higher beam divergence. In a simple picture, the velocity of the positive ions is largely determined by the spatial distribution of the plasma potential between the driver region, where the ions are created, and the plasma grid. Spatially resolved experimental investigations of the plasma potential are scarce. Therefore, a detailed investigation is carried out exemplarily at the geometry of the BATMAN Upgrade ion source setup using a 2D fluid code with a self-consistent consideration of the RF power coupling [1, 2]. The code does not only yield the spatial distribution of plasma parameters and potentials, but also of the particle fluxes (which are compared to results of Mach probe measurements in another contribution to this conference [3]). Therefore, the fluid code allows for a detailed investigation of the particle fluxes and of the positive ion velocity impinging on the plasma grid. Calculations are performed for a variation of pressure, RF power and for different strengths and topologies of the magnetostatic filter field. Where available, the results are compared to experimental measurements. Furthermore, a variation of the both the driver and expansion region geometry is investigated in order to study the impact of source design changes especially on the plasma potential in axial direction.

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Poster session 1 / 53

Comparison among possible design solutions for the Stray Field Shielding System of the DTT Neutral Beam Injector

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The main purpose of the Divertor Tokamak Test facility (DTT) is to study alternative solutions to mitigate the issue of power exhaust under integrated physics and technical conditions relevant for ITER and DEMO [1]. The proposed system features a Neutral Beam Injector (NBI) heating system, providing deuterium neutrals (D^0) with an energy of 510 keV and an injected power of 10 MW to the tokamak chamber.
In this framework, the conceptual design of the Stray Field Shielding System (SFSS) for the DTT NBI is under development in order to suppress the potentially harmful effects of the stray poloidal field from the tokamak on the accelerated charged beam. Various possible design solutions to solve this problem are here presented and compared, with a particular focus on the time-dependent field minimization procedure and particle tracing simulations, used during the design validation phase with the objective of maximizing beamline performances.

[1] R. Ambrosino, DTT - Divertor Tokamak Test facility: A testbed for DEMO, Fus. Eng. Des. 167 (2021) 112330

Oral session 3 / 54

Exploring Cesium and H- beam properties internal to the LANSCE H- Ion Source using Resonant Absorption Spectroscopy and Cavity Ring Down Spectroscopy

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The Los Alamos Neutron Science Center (LANSCE) H- ion source has provided stable output for decades of LANL mission needs, but its maximum beam output has remained the same at ˜15 mA. A roadblock to improving beam output has been a lack of thorough understanding of the internal mechanisms of LANSCE H- ion source. The LANSCE H- Ion Source Laser Diagnostic Stand (HLDS) was recently built and commissioned to explore these internal mechanisms using laser absorption techniques, in particular to measure and diagnose dynamic H- and Cesium (Cs) properties. The Cs density probe is based on resonant absorption of a continuous wave diode laser tuned though the D2 line of cesium (˜852 nm). The H- measurement relies on a much weaker photo-ionization process, and therefore relies on a cavity ring down spectroscopy measurement. The design, construction and commissioning of HLDS will be reviewed, the measurements and capabilities using the Cs laser diagnostic will be presented, and the status of the H- laser diagnostic will be discussed.

Oral session 11 / 56

BATMAN Upgrade: general results from beam optics studies

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The BATMAN Upgrade (BUG) test facility at IPP is contributing to the development of RF-driven H^- sources towards the ITER neutral beam injection and beyond. BUG is equipped with an 1/8 size of the ITER NBI ion source and thus is highly flexible for setup changes or diagnostic access. The extraction and acceleration system consists of three grids (plasma grid PG, extraction grid EG and grounded grid GG, up to 45 kV total high voltage) with one beamlet group of 14x5 apertures. To cancel out the row-wise horizontal zig-zag deflection of the extracted beam caused by the alternating vertical polarity of the co-extracted electron suppression magnets installed in the EG, additional asymmetric deflection compensation magnets have been installed in the upper half of the EG.

One target of BUG are studies of whole beam and beamlet optics; for the latter, an individual beamlet is isolated in the upper half of the beamlet group. BUG is well equipped with beam diagnostics, among them is a CFC tile calorimeter, which is used to determine the divergence of the isolated, single beamlet and Beam Emission Spectroscopy, which is installed at a total of 16 lines of sight at two different axial positions. A robust compensation of the zig-zag compensation for the design parameters could be verified by these diagnostics. General results from beam optics investigations – in particular the dependence of the source filling pressure, the magnetic filter field and the influence of the PG bias –are summarized in this contribution and its impact on full-size sources for NBI is discussed.

Poster Session 2 / 57

USE OF ELECTRICAL MEASUREMENTS FOR NON-INVASIVE ESTIMATION OF PLASMA ELECTRON DENSITY INSIDE THE DRIVER OF SPIDER

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SPIDER is a full-scale prototype of ITER HNBI radio frequency (RF) negative ion-source equipped with a 100 keV particle accelerator system. It has 4 RF circuits, each composed of an RF generator operating at a frequency of 1 MHz, rated power of 200 kW on 50 Ω load whose RF load is composed of a transmission line feeding a capacitor-based impedance matching network connected to two driver coils in series. The plasma in the source is initiated in the drivers through a filament and is heated via inductive coupling with the 8 driver coils. The plasma then expands into an expansion region towards the extraction and acceleration grid system.

To improve the performance of the SPIDER ion source, the characterization of plasma behavior in the driver region is necessary during experiments. In this regard, one of the key input parameter is plasma electron density. Its knowledge is also important for the methodology developed (in another work) for the estimation of power transfer efficiency to the plasma.

Experimental measurement of the electron density inside the driver of SPIDER is however a challenging task. The present main tool for its estimation is based on non-invasive optical emission spectroscopic measurements but the associated collisional radiative loss model is still under development. A more direct approach for the electron density estimation is via Langmuir probes measurements but permanent probes are not present in SPIDER. In this regard, some work was done in 2020, where Langmuir probes were temporarily inserted inside the drivers. This campaign provided some information about the electron density in SPIDER in several experimental conditions.

The paper discusses the performances of complementary non-invasive diagnostic tools for the estimation of electron density applied to SPIDER. This alternative diagnostic tool could be beneficial for ITER HNBI too, where a stringent criterion has to be maintained and no diagnostics inside the driver are foreseen due to high neutron flux and possible material damage from its radiation. In this work, two methods are considered, both are based on a plasma model, an electrical model of the RF circuit, and electrical measurements (like the voltage, current, etc) available at the output of the RF generators. The first one uses the modified power balance model on a driver (considering the losses in the passive structures), while the second one is an alternative method proposed by M. Bandyopadhyay et al and is based on the classical plasma conductivity and skin depth models. The stochastic heating collision frequency is also considered in this approach and its effect is discussed. The first results obtained from the two methods in terms of electron density for different drivers in SPIDER are presented and discussed in this work under a wide set of experimental conditions like RF power, gas pressure, PG current, type of gas, etc. The results obtained are also compared with preliminary estimations of plasma density obtained from temporary Langmuir probe measurements performed in 2020.

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Increasing the H- output current and Reducing Performance Variations of the SNS H- Source

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The SNS H- ion sources deliver the required ˜50 mA with practically perfect availability for the entire ˜4-months production cycles. The source performance varies from cycle to cycle but the required output current can be easily reached by adjusting the 2 MHz power. However, in about 10 years the SNS H- source is required to deliver routinely ˜60 mA for the second target station. While this has been demonstrated several years ago, the routine production of 60 mA needs more margins to deal with occasional deficiencies. The plans and the current status of those efforts will be presented.

Oral session 4 / 59

Paving the road towards ITER relevant long deuterium pulses at ELISE by investigating improved operational scenarios

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The ELISE test facility with its half ITER-size ion source is an essential part of the European Roadmap towards the ITER NBI system. One aim of ELISE is to demonstrate the ITER target values for the extracted current density, the ratio of co-extracted electrons to extracted ions and the uniformity of the extracted beam during long pulses, i.e. 1000 s in hydrogen and 3600 s in deuterium and at a filling pressure of 0.3 Pa.

Previously demonstrated in pulsed extraction mode, i.e. short beam extraction phases of ≈10 s each ≈150 s were 1000 s hydrogen plasma pulses with an extracted current density of over 90 % of the ITER target value, while also fulfilling the requirements for the electron-ion ratio and the beam homogeneity. In deuterium roughly 67 % of the ITER target for the extracted current density has been achieved for pulses longer than 45 minutes, limited by a pronounced vertical asymmetry and increase with time of the co-extracted electron current.

The temporal behaviour during such pulses, in particular of the co-extracted electrons, demonstrates a significant impact of the beam extraction on the caesium dynamics. Thus, CW extraction is mandatory for developing fully ITER relevant operational scenarios. After an extensive upgrade, ELISE is now capable of performing CW pulses, i.e. long-pulse beam extraction. The upgrade consists of a CW high voltage power supply and a CW beam calorimeter. The presentation introduces first results of long pulses in hydrogen.

In order to stabilize the co-extracted electron current during long pulses, particularly in deuterium, improved operational scenarios have to be developed. Investigated at ELISE was the effect of modifying electrostatic potentials close to the extraction system by means of setting the bias plate to a positive voltage with respect to the source vessel. In this operational scenario short pulses in deuterium can be achieved with an extracted negative ion current density of up to 90 % of the ITER target value.

In order to improve the physics insight, the experiments were supported by plasma diagnostics,with focus on Langmuir probes for determining electrostatic potentials as well as particle densities. Additionally, a 2D fluid code gives the general insight that the modified potentials of surface close to the extraction system strongly affect the fluxes of charged particles towards different surfaces and consequently can result in a reduction of the co-extracted electron current.

Oral session 6 / 60

Langmuir-probe measurement in the vicinity of plasma grid aperture of hydrogen negative ion source

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Hydrogen negative-ion source is widely used in the field of high energy particle physics and nuclear fusion science, but the extraction mechanism of hydrogen negative-ion, which is produced at the surface of Plasma Grid (PG) of the source, is not clear. Recent experimental analysis on beam phase-space structure suggests that the non-uniform negative-ion density distribution was formed near the extraction hole and this non-uniformity causes three components of negative-ion beam in the phase-space [1].

In order to evaluate the behavior of negative-ion in the vicinity of the extraction hole at PG, a Langmuir-probe measurement was performed using NIFS Research and development Negative Ion Source (NIFS-RNIS). From the probe measurement scanning the position of the tip along the aperture

axis going across source plasma area to beam area, we found a region where I-V curve characteristics significantly changes when the extraction voltage is applied. This suggests the probe passes through the plasma-beam interface (meniscus). The initial experimental results of measuring the meniscus will be introduced in the presentation.

Poster session 1 / 61

Summary of caesium evaporation and deposition during SPIDER' s first campaign

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SPIDER (Source for the Production of Ions
of Deuterium Extracted from a Radio frequency plasma)
is currently in a major shutdown period dedicated to
the upgrade of several components in order to enhance
its performances and guarantee their agreement with
the ITER requirements. During this phase, an indepth inspection of beam source components has been
fundamental to understand SPIDER's behaviour during
the previous experimental campaigns, and in particular
caesium evaporation inside the source by means of Cs
ovens. Caesium evaporation and its deposition on the
plasma grid (PG) is fundamental to minimize the work
function of PG surface and to optimize the generation
and extraction of negative ions. This work presents the
analysis of the caesium ovens'performances and their
status after removal. The experimental data obtained
via chemical analysis using environmental sampling with
Inductively Coupled Plasma Mass Spectrometry (ICPMS) are compared to previously developed numerical
models for the caesium evaporation and deposition, to
the results of a chemical surface analysis performed in
strategical locations of the source walls and extraction
grid, and to the Laser Absorption Spectroscopy (LAS)
measurements. This study helps understanding the nonuniformity of the negative ion beam extraction observed
during SPIDER experimental campaigns. In addition,
the future implementation of permanent magnets in the
back plate of the source is analysed in terms of caesium
deposition efficiency on the source walls.

Poster Session 2 / 62

H- Beam formation simulation in negative ion source for CERN' s Linac4 accelerator

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The caesiated surface negative ion (H⊠) source is the first element of CERN's LINAC4 a linear injector designed to accelerate negative hydrogen ions to 160MeV. The IS03 ion source, used during Run 3, is operated at 35 mA beam intensity, H^- ions are generated via plasma volume and caesiated molybdenum (Cs-Mo) plasma electrode surface mechanisms. The 3D PIC-Monte Carlo ONIX (Orsay Negative Ion eXtraction [1]) code has been written to study H⊠ beam formation processes in neutral injectors for fusion and adapted to single aperture accelerator H^- sources. The code was modified to match the conditions of the beam formation and extraction regions of the Linac4 H⊠ source [2]. A set of plasma parameters was chosen to characterize the plasma and to match the specific volume and surface production modes. New type of boundary conditions corresponding to single aperture sources are described in this contribution. Simulated results of the extraction regions are presented and benchmarked with experimental results obtained at the Linac4 test stand [3].

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Poster Session 2 / 63

Work Function Measurements in BATMAN Upgrade using LEDs Revealing Remarkably Low Values

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The work function of a surface can be determined by measuring the nA-photocurrents arising from the irradiation by light of different wavelengths. When the chosen photon energies are close to the work function, this energy threshold can be calculated using the Fowler method. As a novelty using fiber coupled LEDs as a light source of sufficient power, the work function inside a negative ion source was determined following this approach.
State of the art negative hydrogen ion sources for neutral beam injectors, as developed for ITER, rely on the surface conversion process of H and H_x^+ from a low temperature plasma at a cesiated surface with low work function. In order to reach longer pulse durations at high extraction currents, a stable work function, which is governed by cesium dynamics, impurities, and the interaction with the plasma, is crucial. Taking on the challenges of measuring small nA-photocurrents in a corresponding environment, a method was developed to investigate the work function for the first time ever directly inside a high-performance negative ion source, namely BATMAN Upgrade, which measures an eighth of the size of the ITER sources. As the chosen method relies on the observation of photocurrents inside the plasma chamber, its applicability is limited to the vacuum phase between plasma pulses. Besides gaining first experience with the new approach, an analysis of the work function's absolute value is of great interest for a verification of the previous assumption that cesium adlayers cause the work function to be the one of bulk cesium, i.e., $\chi = 2.14$ eV. Additionally, monitoring the temporal stability was a major aim for the conducted experiments, as work function variations are expected to impact the source performance.

The contribution shows the results for the first campaign of work function measurements during operation of BATMAN Upgrade. By conditioning the source with continuous cesium evaporation and accordingly increasing source performance, the work function's correlation with the extracted ion and electron current densities was investigated. It was thereby demonstrated that the work function in a well-conditioned source is regularly well below the minimum value of thick cesium layers and hence significantly below the assumed value. Comparably low results have recently been achieved in a dedicated laboratory experiment [1].

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Poster session 1 / 64

Development of a Negative Helium Ion Source with Non-Metallic Charge Exchange

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Negative Helium ion beams are required for tandem accelerators used at research centers and at implanter facilities. The common production method of such He^- beams involve the interaction of a positive Helium ion beam with a low pressure alkali metal vapour. This results in a small portion of He^+ undergoing two charge exchanges to create the desired He^-, on the order of a few [ref]. However, utilizing alkali metal vapour is problematic: leaving interior surfaces prone to flammability, contributing to sparking near electrostatic devices, and, for implanter facilities, negatively impacting silicon wafer production due to metallic contamination [1, 2]. Additionally, the use of a vapour for charge exchange requires a specialized vacuum system and considerable expense to limit the dispersion of the vapour. In efforts to address or remove these issues, a possible alternative creation method for He^- is here investigated, which uses a non-metallic foil as the charge exchange medium. To date reports of using graphite with this technique to convert (30 keV) He^+ to He^- yield a conversion rate on the order of 0.01% [3].
In this paper we shall describe using the He^+ beam generated by SFU's helium ion microscope (HIM), the conversion rate to He^- is measured using non-metallic foils. The He^+ beam collides with a non-metallic foil and the transmitted particles (anticipated to be He^{2+}, He^+, He^0, and He^-) are separated electrostatically into discrete beam spots and detected using a radiation camera (AdvaCam MiniPIX). The current of each beam is measured with the camera and compared with each other, and the incident beam current, to deduce relative intensities and conversion rates. The He^+ incident beam energies shall be varied through the range of 15 to 30 keV (at ˜10 pA) and shall be incident on foils of carbon, and silicon, in thickness range 25 to 100 nm. The corresponding charge exchange conversion rates (excitation functions) will be reported.

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Poster Session 2 / 65

Volume and surface effects in Cs-free regimes in NIO1

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NIO1 (Negative Ion Optimization phase 1) is a compact multi-aperture radiofrequency H^- ion source whose design was optimized for sustainable prolonged beam on target (BOT) operation; installation economy implied a drastic scaling as respect to fusion device D^- sources. The latter in a consistent view for energy production request a beam on tokamak (BOT) span of 20 years, that is 6 10^8 s. Even if Cesium improves H^- production as well known, Cs-free regimes (and intermediate regimes) deserve development effort, in view of avoiding long term contamination of the accelerator and for testing cleaning procedures. Data collected by NIO1 in a true Cs-free regime (before 2020) are thus very important, and need a thorough statistical analysis, with special attention to the technique of gas conditioning that was discovered in NIO1 and to some issues concerned with long term operation. Gas conditioning macroscopically proves the importance of surface effects, even when the final production of H- happens in the source volume. Exchange of ideas with the Electron Cyclotron Resonance Ion Sources (ECRIS) and concepts, such as 'electron starvation', biased disks, liners and wall coatings, are discussed. A classification of H^- ion sources in terms of surface to volume ratio (over 10^2 m^{-1} in matrix ion sources), practically achievable BOT (from 10^4 s to 10^6 s, per year) and working frequency (from few GHz in the ECRIS case down to 1 MHz) is reviewed. Gas mixing, conditioning and surface material perspectives are envisioned.

Oral session 8 / 66

Over 7200 hours commissioning of RF-driven negative hydrogen ion source developed at CSNS

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The China spallation neutron source project Phase-II (CSNS-II) aims to deliver proton beam of 500 kW on the target. To accomplish this goal, an RF-driven negative hydrogen ion source was developed to replace the penning ion source used in CSNS-I. The RF-driven ion source has been put into commissioning on CSNS accelerator since Sept. 8th of 2021. And it was shut down on July 26th of 2022, together with the whole accelerator for the annual maintenance in summer. In this run cycle it has accumulated service time of over 7200 hours without major maintenance and it shows no obvious decay. The availability of the ion source is above 99.99%, except for one or two sparks per day of the 50 kV high voltage platform, each spark causes 1 second trip of the accelerator. The RF-driven ion source has an external antenna winding around a silicon nitride plasma chamber, which shows quite robust in high duty-factor operation. In this report, we present the structure of the ion source, the improvements over other ion sources, and the issues met in the commissioning.

Poster session 1 / 67

Three-dimensional calculations of the inductive coupling between radio-frequency waves and plasma in the drivers of the SPIDER device

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This work documents the initial 3D calculations to simulate the coupling between RF waves and plasma in the plasma sources of the SPIDER device. Axisymmetric 3D calculations in the plasma domain alone compare well against equivalent 2D cases, yielding the expected axi-symmetry with coincident fields and Joule power coupled to the plasma. A model of SPIDER driver, the cylindrical chamber where the plasma is heated by the RF drive, is then defined including the metallic parts of the Faraday shield, insulator and vacuum layer up to the RF winding (not included in the calculation domain). First estimates of the power share in the different parts are shown based on experimental conditions. The results are sensitive to the particular geometry of the driver and the temperature of the Faraday shield

Oral session 4 / 68

The negative beam source with single driver for CRAFT NNBI: design and conditioning results

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The Comprehensive Research Facility for Fusion Technology (CRAFT) is a large scientific device that is preferentially deployed for the construction of major national science and technology infrastructures. A negative beam source based neutral beam injector (NNBI) with beam energy of 200-400 keV, beam power of 2 MW and beam duration of 100 s is one of the device. A giant radio frequency (RF) based negative beam source was designed for the CRAFT NNBI system. In order to understand the physics and pre-study the engineering problems for RF negative beam source, several beam sources with different scale will be design and tested. According to the R&D schedule, a negative beam source with single driver was designed, developed and tested firstly. The single driver beam source is a quarter of the size of full size negative beam source. It contains a RF driver, an expansion chamber and a negative ion accelerator with three electrodes, which is plasma grid (PG), extraction grid (EG) and ground grid (GG). In order to enhance the negative ion production, Cs is injected into the plasma chamber and a magnetic filter filed is produced by current flow through the PG to decrease the electron temperature. The negative beam source was tested on the test facility after assemble, including RF plasma generation, negative ion production, extraction and acceleration. The characteristic of plasma discharge, beam extraction and acceleration was studied without and with Cs injection. The long pulse of 105 seconds negative ion beam was achieved successfully. The extracted ion current is 160 A/m2 and the ratio of electron and negative ion is around 0.8. It lays good foundation for the R&D of negative ion source with multi-driver for CRAFT NNBI system. The details of design and experimental results of beam source was shown in this paper.

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A Method of Confirming the Operation of Active Magnetic Compensation Coils on the ITER HNBs

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As with all Neutral Beam injection into tokamaks, the ITER Heating Neutral Beam (HNB) beamline must ensure that the effect of the magnetic field is minimised in order for the pre-neutralised beam to avoid significant deflection which, when later neutralised, will enable it to pass through into the tokamak plasma without damaging the beamline. Due to the strength and range of the ITER magnetic field and the length of the HNB beamline, the system required here is significantly more complicated.
The Active Compensation and Correction Coils (ACCC) system is comprised of 9 coils in total for each HNB, each independently powered using a feedback system, based on the vertical field measurements made at several locations in the beamline. The locations of the measurements are not yet confirmed, but they will be situated in safe locations to avoid damage from the beam. If they have to be located some distance from the beam, this may mean that the exact field along the beam axis can only be loosely inferred, rather than directly measured.
Due to access limitations, initial calibration of the ACCC may require some other method to fine tune and confirm the baseline level. This paper will explore the possible use of the beamline thermocouples to optimise the level of the ACCC.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

Oral session 2 / 70

Towards low divergence beams for the ITER neutral beam injection system

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The beam divergence is the figure of merit applied to quantify the width of the particle angular distribution as they travel along the beamlines of neutral beam injection (NBI) systems. In the case of the high power neutral beam planned for the ITER experiment, a divergence of less than 7 mrad is mandatory to assure the power level needed for plasma heating in ITER.
In the last decades, the R&D around radiofrequency driven (RF) negative ions sources for fusion

focused mainly on solving the fundamental challenges related to increasing the negative ion current density while keeping the co-extracted electron current low, and on increasing the pulse length from few seconds to hundreds of seconds. Only recently, it was pointed out that the divergence of beams produces by this type of sources were higher than the above requirements (more than 20 mrad). Since then several activities were started to tackle this issue, involving several laboratories and including upgrades to the existing ion sources, dedicated investigation of the particle properties inside the plasma, modelling and improvements in the diagnostics systems.
This contribution reviews the recent developments on this topics in the last years, and includes the result of a benchmark activity carried out recently, aimed at comparing the divergence measured on 5 different ion sources, arc- and RF-driven. As a results of this coordinated effort several hypotheses about the root cause of the divergence increase could be tested. The common analysis of results from different diagnostic methods and input parameter studies gave insights into the sensitivity to input parameters with the conclusion that the RF source is characterized by about 12 mrad.
The more recent results seem to link the elevated divergence measured with the presence of high energy positive ions inside the RF plasma.

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The impact of neutral beam parameters on current drive and neutron yield in DEMO-FNS

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DEMO-FNS facility (R = 3.2m, a = 1m, k = 2, B = 5T) will be a hybrid reactor designed to combine fusion and fission technologies. In a hybrid reactor the power is mainly produced by a fission blanket which is exposed to the neutron flux coming from confined plasma, or a fusion neutron source (FNS). Plasma parameters required for FNS steady-state operation are essentially lower as compared against "pure"fusion reactors, and FNS dimensions can be small. DEMO-FNS fusion power will be 40 MW.
DEMO-FNS neutral beam injectors (NBI) are designed to provide a steady state plasma heating, rotation, fueling, current drive and neutron generation. Four injector units will deliver 30MW power in deuterium, E = 500 keV, in a steady-state scenario. NBI concept and main components are almost copied from ITER HNBI, implementing acceleration of negative ions and their neutralization on gas.
The high density of injected power in DEMO-FNS implies a particular operation scenario with high fraction of fast particles, when the main part of neutron flux will result from fusion between hot ions and relatively cold background.
The current drive and neutron yield produced by the tangentially injected beam in a steady-state operation is to be tightly coupled with plasma magnetic geometry and kinetic profiles. The fast ions deposition and performance are limited by the losses associated with the neutral beam shape and aiming. The main channels of incident ("direct") beam losses include shine-through neutral power, fast ion drop-out and capture to banana orbits (orbital losses). The detailed evaluation of NB direct losses is a necessary step for NB energy, shaping and steering selection during the reactor design.
BTR (Beam TRansmission) conventional beam model is extended to a detailed analysis of beam losses and performance in plasma. The beam current drive and neutral yield can be efficiently enhanced for any beam-plasma configuration. The beam tracing workflow is implemented in BTOR (Beam in TORoid) suite, designed as a Python pipeline. The examples of BTOR comparison against "traditional"beam tracing suites, performed for other beam-driven tokamaks (T-15MD and EAST), justify the "light"beam model application to fast beam-plasma tuning. The results obtained for DEMO-FNS are compared with NBI performance in ITER, as both tokamaks are beam-driven and their NBI systems are quite similar.

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Plasma emission monitored via optical emission spectroscopy during the Cs conditioning at SPIDER

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The SPIDER test facility is the full-size ITER neutral beam injector (NBI) ion source, required to provide 355 $\mathrm{A/m^2}$ extracted negative ion current density in hydrogen (285 $\mathrm{A/m^2}$ in deuterium) with an electron-to-ion ratio lower than 0.5 (1 in deuterium). The negative ion source is integrated with a system of three grids, which allows the extraction and acceleration of ions. In the cases studied in this work, the source was operated with short plasma pulses, with a duration of about 30s, and repeated with an adjustable duty cycle of approximately 5 or 6 minutes. The maximum duration of the sequence was of about 1000 s. To fulfil the requirement on the extracted negative ion current with reduced amount of co-extracted electrons, the evaporation of caesium (Cs) into the ion source through Cs ovens (3 in SPIDER) and the optimisation of Cs conditioning techniques are mandatory.
At SPIDER, the plasma is monitored via optical emission spectroscopy techniques measuring the plasma emission in a line-of-sight (LOS) integrated manner in several positions inside the ion source. In particular, close to the extraction region, two sets (centred at 5 mm and at 35mm distance from the first grid) of 8 horizontal LOS are used to retrieve the vertical profile of the plasma emission.
During the Cs conditioning campaign performed at SPIDER, although the extraction capabilities were reduced due to technical problems, the RF power applied to the plasma reached 400kW with all four RF generators working simultaneously.
It is found that the surface emission originated from the first grid, the so-called plasma grid one, affects both the plasma radiation due the presence of negative ions, and the electrical measurements performed on biased components inside the ion source.
Aim of this work is to study the evolution of the plasma emission over the entire Cs conditioning campaign. The effect of Cs conditioning on electrical measurements is also presented and discussed.

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Progress in the development of negative ion beam source in Korea

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In Korea, as part of the ITER non-procurement core technology development project, the development of a negative ion beam source is in progress.
The overall period can be divided into 3 phases corresponding to 3 prototype negative ion beam sources. In the first phase, a Cs-free ion source using 2 MHz RF up to 10 kW was developed. A 4 mm thick water-cooled Faraday shield was inserted inside an Al_2O_3 cylinder with a diameter of 200

mm for CW operation. Beam extraction experiments were performed with a 3-grid system designed for a beam energy of 50 keV. In the second phase, the Al_2O_3 cylinder was replaced with a smaller 150 mm diameter aluminum nitride (AlN) cylinder and a thin copper Faraday shield was inserted without water cooling to improve RF power coupling. Evaporated Cs was injected by a Cs dispenser and the beam current enhancement was achieved. However, kW-level RF power was insufficient for the high-current negative ion beam extraction. The plasma grid (PG) temperature was also not controlled and the surface conditions for efficient negative ion surface production were not met. In the third phase, the whole system was newly developed. The 2 MHz RF power supply was replaced by a 400 kHz RF power supply up to 50 kW. In addition, a 3-grid system for 200 keV beam energy was developed. Our approach is first to generate higher density plasmas by increasing the input RF power and removing the Faraday shield. To protect the AlN cylinder, it adopts a pulsed operating system that generates a pulsed plasma discharge and minimizes the heat load of the plasma. Once high density plasma generation is achieved, beam extraction experiments using Cs injection and PG temperature control is planned. %are carried out.
Research on system upgrades for long pulse or steady state operation is also in progress. Plasma diagnostics using an RF-compensated Langmuir probe was performed as the first step in the approach to the new system. As the RF power was increased from about 4 kW to 30 kW, measured plasma densities were increased from on the order of 10^{17} m^{-3} to 10^{18} m^{-3} and (effective) electron temperatures were about 7 eV, indicating slightly decreasing behavior. Detailed experimental results are presented and discussed.

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Negative and positive ion density in front of negative ion production surface in large-scaled negative ion source for fusion

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A higher density of the negative ion in front of the plasma beam boundary is important to extract a higher beam current density in the negative hydrogen ion source. Negative ions are mainly produced on the surface of the plasma-facing grid electrode (PG) in cesium seeded negative ion source for fusion. The negative ions are produced from positive ions and atoms impinging to the PG surface by electron capture from the PG surface. Positive ion density in front of the PG is one of the key parameters to evaluate negative ion density. Relation between measured negative and positive ion density in Research and development Negative Ion Source at National Institute for Fusion Science (NIFS-RNIS) were investigated in hydrogen and deuterium operation with variations of various parameters. The negative hydrogen and deuterium ion density increased linearly with positive ion density when positive ion density was low, and gradually saturated in the higher positive ion density region. This relation in hydrogen operation was almost identical to that in deuterium operation at not only central higher positive ion density but also peripheral lower density regions. A Mutual Neutralization reaction (MN) is a dominant negative ion loss process in the present study. Taking into account parameter estimations of the MN frequency and fitting factors of the relation between negative and positive ion density, the negative ion density saturation and the the identical relation between hydrogen and deuterium operations can be explained by the loss process by the MN. Considering the variation of the positive ion flux and the constant atomic flux to the PG surface, dominant parent particle species will be discussed.

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The Effect of Beam Chopping on the Emittance Growth of Negative Hydrogen Ion Beam

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A fast electrostatic chopper is installed in the low-energy beam transport (LEBT) of China Spallation Neutron Source (CSNS) accelerator. It is used to chop the beam into pulses before RFQ accelerator. The chopped beam pulses synchronize with the period of Rapid Cycling synchrotron (RCS). But the electric field induced by this chopper will destroy the space charge compensation (SCC) in LEBT, which causes the rapid growth of H- beam emittance due to the space charge effect. This will lower down the beam transmission rate in RFQ and downstream accelerator. However, there is no quantified result of the effect of chopper electric field on the beam emittance for CSNS accelerator. In this paper, this effect is studied experimentally and the result will be used to guide the redesign of beam chopper at high beam current.

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Effects of different particle injection models on the results of PIC simulation

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Abstract: In particle-in-cell (PIC)simulation, different particle injection method is used to maintain the plasma source term. Common particle injection methods include a) constant flux injection in which a fixed number of ion-electron pairs are injected each time step and b) pair re-injection in which the number of ion-electron pairs injected is according to the number of positive ions removed. With different particle injection methods, there will be different results in particle simulation. For example, with the condition of negative ion surface strong production, there will be differences between the simulation results with conditions of pair re-injection and constant flux re-injection.
In this paper, a 1D3v PIC model is used to analyze the evolution of plasma state and parameters in the formation of SCL sheath and reverse sheath, and the differences in the formation of plasma sheath with different particle injection methods are compared. According to the simulation result, with the condition of surface production, the simulation result with pair re-injection does not match experiment result. In this paper, the advantages and disadvantages of different injection methods are analyzed. And a new conditional re-injection method, in which the number of injected ion-electron pair is changed according to the density of plasma, is proposed, and the applicable scene will be analyzed, so as to provide guidance for future PIC simulation and plasma research work.

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Laser Powder Bed Fusion: an innovative production method for creating components and devices for Nuclear Physics

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When we speak about Additive Manufacturing (AM), we think of a rather new manufacturing approach that allows to create objects layer-by-layer and without limits of shape. AM covers a wide range of techniques, that differ from each other by the class of material used for the process, the appearance of the raw material (powder, wire, sheet, etc.) and the way it is added and joined to the previous layer. Laser Powder Bed Fusion (LPBF) is probably the most important Metal Additive Manufacturing method, in which the energy source is a focused and powerful laser beam, whereas the feedstock material is a metallic powder. The process may look simple, but a deep knowledge of the thermodynamical and solidification behavior of each metal and the role that each process parameter plays in the final quality of the part must be held to properly manage this kind of process. Nonetheless, a great technical experience must be gained by the users.
The work here exposed intends to evaluate the applicability of LPBF for Nuclear Physics purposes. In particular, the studies made for the realization of ion sources and accelerators components are presented, starting from the process parameters tuning and material characterization initial stages, to the development of the final design and components production and test. LPBF of pure copper and copper alloys was investigated with the aim of producing the acceleration grids for nuclear fusion devices, while refractory metals were successfully processed for creating topologically optimized parts of a plasma ion source for Isotope-Separation-On-Line (ISOL) facilities. Also, the production via AM of pure copper and pure niobium superconducting radiofrequency cavities is examined.

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Development of Cs-injection System for KFE RF hydrogen Negative Ion Beam Source

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A prototype radio frequency (RF) negative hydrogen ion beam source is developed in Korea Institute of Fusion Energy (KFE). The target is to extract negative ion beam with 200 keV, 0.5 A for 100 ms. The RF power supply of 400 kHz delivers over 40 kW to the ICP without the Faraday shield. The plasma is generated and turned off within 120 us, and the RF power supply is stabilized within tens of milliseconds. The negative ion beam is successfully extracted, and the negative ion beam and the co-extracted electron current are separately measured. Since the beam current is limited to only about 30 mA, Cs assist is needed for the beam current enhancement. The Cs vapor injector and the plasma grid heating system are prepared to Cs assisted negative ion beam extraction. The Cs dispenser and SID are installed for Cs injection and its amount measurement. The Galden oil heater and the circulation system are installed to heat the plasma grid over 200 Celsius degree to optimize the surface interaction. The plasma grid temperature is assumed by the supply and return oil temperature. The plasma grid is successfully heated, and the weaknesses such as vacuum sealing o-ring are protected by water cooling. The enhancement of the ion beam current and suppression of co-extracted electron current by Cs vapor injection will be presented.

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Characteristics of extracted negative ion beam using electron emitters on the Cs-free negative ion source TPDsheet-U

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The cesium (Cs)-free negative-ion neutral-beam injection (NNBI) system is technical issue on the development of magnetic fusion reactors. The progress toward realizing a high-performance Cs-free negative-ion source based on volume production in a magnetized sheet plasma device (TPDsheet-U) is reported [1,2]. The volume production of negative hydrogen ions in the produced magnetized sheet plasma is proposed to be developed as a negative-ion source using Test Plasma produced by Direct current for Sheet plasma Upgrade (TPDsheet-U). High-density magnetized sheet plasmas are suitable for producing H- ions in dissociative attachment processes because of the narrow space (e.g., 10–30 mm) between high-energy (10–15 eV) and low-energy (˜1 eV) electron regions. Therefore, H- is formed by the dissociative attachment (DA) of low-energy electrons e (slow) (Te ˜1 eV) to highly excited molecules H2 (v”> 5), which are vibrated by the impact of high-energy electrons e (fast) (Te > 15 eV) in the plasma.
In the previous work, the results for the single-aperture grid are described as follows. (i) The negative-ion current density JC(H-) was ˜7.5 mA/cm2 at an extraction voltage of 10 kV, a discharge current Id of 90 A, and a gas pressure of 0.3 Pa. The performance of JC(H-) without Cs on TPDsheet-U is approximately one-fourth that of the negative-ion source on ITER-NNBI with Cs. To achieve the current value required by ITER-NNBI, the current density of negative ions, i.e. the negative ion density, should be increased by a factor of four [1].
In the present work, we have demonstrated to control cold electrons and increase negative ion density by increasing the cold electron density with setting electron emitters in the plasma periphery region. The JC(H-) is increased from 0.64 to 0.87 mA (36% increase) at a draw voltage of 10 kV, discharge current of 50 A and gas pressure of 0.3 Pa by increasing the filament temperature of the electron emitter from 800 K to 1400 K. In addition, JC(H-) increased from 0.32 to 0.67 mA (109% increase) by applying a negative bias voltage from 0 to -30 V against the electron emitter. These results indicate that this can facilitate the negative ion generation process, which is expected to further improve the performance of the Cs-free negative-ion source using this electron emitter.

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Construction of a Filament-RF driven hybrid negative ion source at NIFS

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Reduction of beamlet divergence angle is one of the most important targets of negative ion sources driven with Radio-Frequency (RF) to decrease the damages on the accelerator grid and improve the beam injection efficiency. Minimum beamlet divergence of RF driven source is ˜12 mrad and is much wider than the divergence accelerated from Filament-Arc (FA) drive sources; required beam divergences for ITER HNB and DNB are less than 7 mrad. The NIFS-NBI group started the commissioned

research on the difference of the beamlet divergence between FA and RF ion sources with the ITER Organization (IO) and the ITER-Technology & -Diagnostic / N-NBI division of IPP Garching (IPP). Comparison of the beam divergence in FA and RF sources can be realized by adding RF system to the NBTS designed for FA operation. The RF oscillator and components of the RF driver at ion source have been exported from IPP. The ion source installed at NIFS NBTS is modified to FA-RF hybrid source by replacing the backplate available to attach the RF driver on it. The NIFS NBI test stand (NIFS NBTS) equips several diagnostic devices to measure the source plasmas and accelerated beams. It is expected to investigate the difference of the plasma characteristics, particularly, the difference of time-dependent plasma potential in the vicinity of the meniscus, in the FA and RF driven modes. So far, the maximum RF power of ˜64 kW was obtained by connecting the RF cable to a dummy load and the infrastructures of the RF system has been almost installed.
Characteristics of the RF oscillator, matching box, and design of the RF backplate will be discussed.

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Energy distribution of fragments in H2 dissociation by electron impact for the use in numerical models

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In negative hydrogen ion sources, the kinetic energy of the atoms is directly related to the negative ion yield at the caesiated converter, with a larger contribution from hot atoms. The H0 energy distribution is related to the formation process: either the kinetic energy release resulting from dissociation of the hydrogen molecules or molecular ions, or the proton neutralization during reflection at walls. The interpretation of recent experimental measurements related to the translational energy distribution of atoms could profit from accurate inclusion of the initial energy distribution in numerical models. In this work, the inverse cumulative distribution functions related to the main dissociation processes are given, for simple implementation in Monte Carlo numerical simulations. As in negative ion sources non-equilibrium vibrational distributions of H2 are found, the energy distribution of fragments is calculated for all vibrational levels in the Franck-Condon and delta approximation. Finally, the application of the method to a simple testcase is discussed.

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Experimental results of the SPIDER negative ion accelerator in view of the next operations

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Three years of experiments on SPIDER allowed characterizing the main features of the source plasma and of the negative ion beam, in the original design configuration. For the large dimensions of the source chamber, and of the extraction area, the investigation of the single-beamlet currents and of the source plasma uniformity had to be carried out to extend the knowledge gained in smaller prototype sources. The design based on multi-RF driver configuration, and the filter field topology were found to determine a peculiar behavior of the plasma confinement in the drivers favouring left-right asymmetries [also reflected on the available negative ion current], even after the early implementation of a new scheme of plasma-grid current and return busbars that greatly improved the performance at high filter field. The plasma properties in the driver and expansion region as well as the positive ion energy at the extraction region were studied in different experimental conditions, and interpreted also with the support of numerical models, suggesting that an improved plasma confinement could contribute to the increase of the plasma density, and –to a certain extent –tailoring the profile of the space potential; this is essential in order to maximize the presence of cold negative ions for the formation of low-divergence beamlets. Early results related to RF discharges on the

back of the plasma source and the gas conductance of the beam source suggested the reduction of the vessel pressure as mitigation, leading to the definition of a new pumping system. The difficulties related to the simultaneous operation, stable control and high-power operation of multiple RF self-oscillators were an unambiguous obstruction to the experimentation, calling for the implementation of RF solid-state amplifiers. The initial tests related to caesium management, the non-uniform plasma properties at different location across the plasma grid, and the challenges in the measurement of the current and divergence of the accelerated beamlet, unambiguously resulted in the need of new diagnostic systems to investigate with better resolution the spatial uniformities. This contribution summarises how the main experimental findings in the previous experimental campaigns are driving modifications to the SPIDER experiment, during this year shut down, in view of the future operation.

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Overview of MITICA diagnostics design and procurement

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MITICA, the full-size ITER heating neutral beam (HNB) injector prototype, is under construction in the ITER Neutral Beam Test Facility (NBTF) at Consorzio RFX. MITICA is based on an RF negative ion source, producing a 40A deuterium beam accelerated to 1 MeV; the beam is then gas neutralized with 60% efficiency, the residual ions are electrostatically removed, and it is finally dumped on a water cooled calorimeter. MITICA is required to validate the design and demonstrate the performance of ITER injectors: operate in stationary conditions for up to one hour, with low divergence, 3-7 mrad, intensity uniformity better than 10%, and low co-extracted electron fraction e^- /D^-<1.
On SPIDER, the 100 kV full size prototype of the HNB RF source in NBTF, a complete set of diagnostics is proving to be essential to characterise the plasma in the source and the beam, also to understand the complex behaviour of the system especially in the first years of operations when different kind of anomalies were affecting the performance and required deep investigation. Similarly on MITICA we are expecting the need to have a comprehensive range of measurements, especially for the key parameters like beam uniformity and divergence, but in general to assist in the operation. Most of these diagnostics will not be available on the ITER HNB, equipped mainly with thermocouples, because of the restricting ITER requirements and the reduced accessibility. MITICA will then represent the best bench test for the solutions considered for HNB thermocouples and their layout, e.g. fixation methods, cabling, connectors and feedthroughs.
This contribution, starting with a summary of diagnostics impact on operation understanding in SPIDER, will provide an overview of MITICA diagnostics (thermo-mechanical sensors, electrostatic probes, source and beam spectroscopy, beam imaging and tomography), a description of their current design, the status of procurements and some solutions that can be reproduced also in the ITER HNBs.

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The ITER Neutral Beam Test Facility: status and perspectives

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Efficient and reliable operation of the Heating Neutral Beam Injectors (HNB) is required to achieve thermonuclear-relevant plasma parameters in ITER, a fundamental step on the path towards unlimited sources of clean fusion energy. ITER will be provided with two HNBs, expandable to three, each one expected to inject into the plasma a beam composed of deuterium atoms accelerated up to 1 MeV energy, delivering a power of up to 16.5 MW for a beam pulse length up to 3600s.
These operating conditions have never been simultaneously reached before, and require the realization of a complex system far beyond the performance and technologies adopted in the existing neutral beam injectors.
Many issues need to be addressed, eg production of a high negative ion beam current (40A of D-, 46A of H-), using a caesiated source and a large number of beamlets (1280); reliable operation of the source, fully immersed in a low-pressure gas; holding of the 1MV voltage in vacuum; reliable operation of the 1MVdc power supply components, etc.
All these aspects led to recognizing that a dedicated Neutral Beam Test Facility (NBTF) is needed to carry out an international R&D programme aimed at constructing, testing and optimizing the full-scale prototype of the HNBs and at assisting ITER during its operation.
A fast track strategic plan was developed which is based on the implementation of two experiments operating simultaneously: MITICA, the full-scale prototype of the ITER HNB injector, and SPIDER, the full-size radio frequency (RF) negative-ion source.
SPIDER aims at testing and fine-tuning the ion source, in terms of ion current density, uniformity, co-extracted electron current and beam stability over time.
MITICA, using the ion source optimised in SPIDER, has the purpose of verifying the full performance of the accelerator and of the beam line components for the production of the focused neutral beam with the same characteristics as the HNB.
The present contribution gives a description of SPIDER, which went into operation in mid-2018. It operated for about 3.5 years and is now in a long shut down phase for the implementation of important changes, identified on the basis of previous experience, necessary to achieve full performance.
MITICA is still under construction and commissioning. During the integrated tests of 1 MV power supplies, issues occurred which resulted in failures and a delay in the overall plan. The problems encountered are now understood and are being addressed.
It will be shown that the experience acquired so far has fully confirmed the soundness of the choice of developing the ITER neutral beam test facility, with both its experiments, so that the HNBs will be realized on the basis of a reliable project, guaranteeing the performances required by the ITER operation.

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Characteristics of co-extracted electrons reduction for the Cs-free negative ion source using TPDsheet-U

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In fusion devices such as ITER, negative ion based neutral beam injection (NNBI) system is used for plasma heating. Cs-seeded RF driven negative ion source is typical for high-density negative ion production with surface production. However, Cs vapor seeding derived frequent maintenance and it makes long-term operation difficult. Therefore, it is necessary to develop the Cs-free negative ion source.
We are developing a Cs-free negative ion source based on TPDsheet-U[1].Generally, in all the negative ion sources using the volume production, a large amount of co-extracted electrons with the negative ion beam is observed. A large heat load on the extraction grid is occurred by co-extracted electron. In order to solve this issue, we devised a mechanism to reduce electron co-extraction with a Soft Magnetic plate for Filter (SMF) for TPDsheet-U. SMF on plasma facing grid (PG) curves magnetic field lines locally and traps the electrons. Actually, the maximum measured electrons current decreased from 15 mA/cm2 to 1.3 mA/cm2 at discharge current of 50 A in previous study[2].
In this experiment, we changed the distance between SMF and PG by using spacer to investigate the effect of the magnetic field distribution vicinity of PG on extracted current density. At the discharge current of 80 A and gas pressure of 0.3 Pa, the co-extracted electrons current density was

most reduced by using the 0.5 mm thick spacer, resulting in 6.7 mA/cm2 to 2.3 mA/cm2 and extracted negative ion current density was lower. (i.e., 5.2 mA/cm2 to 3.5 mA/cm2) In this case, the current ratio Ie/IH- was 0.67. From these results, it was obtained that changing the magnetic field distribution vicinity of PG is effective to reduce the co-extracted electrons.

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The effect of oxygen impurities on a caesium-covered Mo(001) surface: insights from Molecular Dynamics simulations for negative ion sources.

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Caesium-covered molybdenum surfaces are considered for negative ion production [1] [2]. Surface chemical-physics can help to understand the surface process influencing and determining device performances.
Molecular Dynamics simulations based on *ab initio* calculations in the framework of DFT(Density Functional Theory) have been used to simulate the interactions occurring at the gas-surface interface [[3] [4] [5]. In recent years, we have employed this computational tool to study the surface processes of interest in negative ion sources. The simulated processes occur on a short space/time scale but influence the complete process. Instead, the determined collisional data can be useful in the kinetic modelling of negative ion production [6] [7].
A few years ago, we started by simulating the process of the negative hydrogen ion formation [8] on a caesiated surface model [9]. Thus, we investigated and understood which formation mechanism (surface or volume) is the leading one [10]. The same investigation has been then conducted for deuterium [11].
Lately, given the non-optimal vacuum conditions in which these sources operate, we have started characterizing the interaction of oxygen (atomic and molecular) with the same surface model [12] [13].
In this contribution, after a quick overview of the previously obtained results, we will focus on those obtained for atomic and molecular oxygen interaction with the considered caesium-covered molybdenum surface. A detailed analysis of the occurring surface processes will be provided by foreseeing a possible way to attenuate the influence of the presence of oxygen on the negative ions production.

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Fundamental processes related to negative ion production of different ion species

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Fundamental processes related to negative ion formation by
volume production, surface production, and
double charge exchange production
of different ion species, such as hydrogen, helium, alkali metals, and halogens will be presented, together with their application.

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Stockli: RF (Light) Negative Ion Sources for Non-Fusion Applications, a tutorial

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Twenty years ago, there was no ion source that could provide high-currents (>20 mA) of H- beams at high duty factors (»1%). In addition, the lifetime of H- sources was limited to ˜2 Amp-hours. Therefore high-duty-factor H- sources had to be replaced every few weeks! The H- ion sources limited the power of the accelerators!
The development of RF H- sources has reversed the situation: Now accelerators limit the applicable performance of RF H- sources. RF H- sources yield >100 mA of H- with duty factors up to 10% and lifetimes up to 10 Amp-hours.
Without Cesium, RF H- ion sources deliver more than 20 mA, which is almost exclusively produced in the volume of the plasma as shown with the Rasser approximation. When Cesium is added, surface produced H- ions increase the H- output currents up to ˜60 mA. The Cs consumptions is less than 0.3 g per year. Nowadays RF H- ion sources do not have to be replaced for up to one year and their performances show no sign of old age!
This tutorial briefly reviews the basic processes of the H- formation and then describes the four RF H- ion sources that successfully feed advanced high-power H- accelerators.

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RF-driven negative ion sources for fusion

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The tutorial gives insights in the need, challenges and ongoing R&D of powerful and large RF-driven ion sources for extracting the required current of negative hydrogen ions (H- and D-) for fusion:

The neutral beam injection systems for the international fusion experiment ITER (www.iter.org) are based on large negative hydrogen ion sources that have to operate at very ambitious parameters. The large RF-driven negative ion sources (1 MHz, 800 kW, to illuminate a source area of 1.9 x 1 m2) have to deliver an accelerated current up to 46 A negative hydrogen ions (40 A for D- ,46 A for H-) extracted from 1280 apertures stable for one hour. The co-extracted electron current has to be kept below the extracted ion current to avoid damages of the grid system. At the source pressure of 0.3 Pa or below the negative ions have to be produced at a low work function surface for which cesium is evaporated into the source. In order to fulfill all these requirements an R&D program has been launched several years ago. The challenges, however, are enormous; among them the control of the cesium dynamics in the source that determines the reliability of the source performance, the amount of co-extracted electrons which limits the extractable negative ion current, and the size scaling of the source towards the ITER source size.

Poster Session 2 / 93

Laser-assisted negative ion production in caesium sputter ion source

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The negative ion formation in the caesium sputter ion sources occurs on the surface of a cathode containing the ionized material. The cathode is covered by a thin layer of caesium (Cs), which lowers the work function of the surface enhancing the negative ion formation. Vogel [1] recently introduced a hypothesis that the negative ion current can be enhanced by exposing the cathode to a laser beam. According to [1] this should resonantly excite neutral caesium atoms to electronic states, acting as a catalyst for negative ion production via so-called ion pair production. Recently JYFL-ACCLAB have revealed that the photo-assisted production of negative ions can be provoked by lasers at various wavelengths with the photon energy exceeding a certain threshold, which questioned the resonant ion pair production hypothesis [2]. Furthermore, the laser-assisted production of negative ions of oxygen (O-) as well as aluminium (Al-) was observed with the off-resonance diode lasers [3]. This observation opens the door for practical applications of photo-assisted negative ion production also for other negative ion species, not just those with their electron affinity states in resonance with the excited states of neutral Cs. In this presentation we present that the beam current enhancement does not depend on the resonant ion pair production, it depends on the applied laser power, ion source conditions, and the extracted beam current can be enhanced by a factor >2 [4].

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The BO2022 project. For a history of students and graduates of the University of Padova (1222- 20th century)

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The tutorial presents the Bo2022 database, a tool that collects - and will continue to collect in the future - Padua's academic population over the eight centuries of its history. The research project

BO2022,from which this database was born, began in 2019 and ended in February 2021, and one of its aims was to map the academic population from the foundation of the University of Padua, in 1222, to the second half of the twentieth century. And this is to give us new quantitative data, with which to read the history of our university, casting a glance at complex phenomena - mobility, freedom of study and research, religious pluralism, gender - outside the celebratory cameos of "illustrious students".

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A review of the NIFS negative-ion based NBI driven with Filament-Arc (FA) discharge

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Negative ion based NBI (n-NBI) system for the Large Helical Device (LHD) had developed at NIFS since 1987 and started the injection since 1998. Filament-Arc (FA) discharge was applied for the n-NBI system as the first-generation negative ion source. Three beamlines (BL) of the n-NBI system are installed to the LHD and the design values of injection power, beam energy, pulse duration, injection interval and beamlet divergence are 5 MW/BL, 180 keV, 10 sec, 3 min. and less than 5 mrad, respectively.
Long-pulse injection was carried out using one of the n-NBI BL and the pulse-duration of 128 sec. was achieved. In the high-power injection, the maximum injection power of 16 MW was obtained in simultaneous injection with three n-NBI BLs. To obtain more stable beam injection and to prepare the deuterium beam injection, physics based diagnostic experiments has been established at the NIFS NB Test Stand (NIFS NBTS). The diagnostic system is available to measure with some diagnostic devices at the same time and some of the phenomena of the caesium (Cs)-seeded hydrogen and deuterium plasmas and beamlet characteristics were revealed.
In this tutorial, characteristics of the plasmas in the FA negative ion sources and those of beams accelerated from the sources are presented based on the results of development, injection and diagnostic experiments.

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Computationally studying H- extraction and beamlet formation: the impact of the plasma model

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The ITER NBI requires H-/D-beamlets with a low divergence, in view of the beamline transmission. Ion extraction and beamlet formation are typically studied with gun-type codes such as IBSimu, which do not treat the plasma explicitly. The beamlet particles are tracked through the full grid system; the compensating charge density in the plasma region is given by an analytical function. As a result, many physical processes are neglected, such as the surface production of negative ions, particle drifts in the plasma as result of magnetic fields, and sheath formation at surfaces. The 3D PIC MCC code ONIX does include these processes, but the computational domain ends after the extraction region to limit the computational cost. ONIX was coupled with IBSimu to extend the computational domain so that the accelerated beamlet properties could be studied and compared to standalone IBSimu simulations. As already known from standalone ONIX simulations, the surface produced particles are very divergent. Since the IBSimu simulations do not include surface production, only the volume produced particles are studied. The angular distribution of the accelerated particles was fitted with a double Gaussian to evaluate the core and halo components. The core divergence and the average angle are very similar for both simulation approaches. The ONIX-IBSimu calculations have a less pronounced halo component compared to the IBSimu standalone calculations. This is a consequence of the Debye sheath, which forms between the plasma and the grid, and is included in ONIX but not in IBSimu. Particles coming from the plasma are repelled by the sheath and thus the extracted current density profile decreases near the edge of the aperture. Particles that are extracted near the edge tend to have a large angle in the accelerated beamlet, and thus fewer of these particles leads to a less pronounced halo. An attempt is made to include this effect ad-hoc in the IBSimu plasma model, so that the impact can be assessed over a wide range of parameter variations.