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(Positive) Ion and proton sources

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Big Facilities all over the world (FAIR-GSI, LHC, RIKEN RIBF, MSU FRIB) require intense beams of multiply charged ions

Intense proton beams are needed for the world's leading facility for research using neutrons, the European Spallation Source

Muon colliders and neutrino factories will be boosted by the availability of intense proton/H_2^+ beams

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Ion and proton sources

Covering the needs of scientific facilities

Since end of 80's continuously increasing performances

major technological challenges motivating the current R&D in the field

What they need

Components
Maintainance

Interesting current opportunities for industry

What they can provide

Interesting future opportunities in Europe for industry

possible involvement in R&D collaborations

procurement contracts in the next 5 years

ION SOURCES MOTIVATIONS

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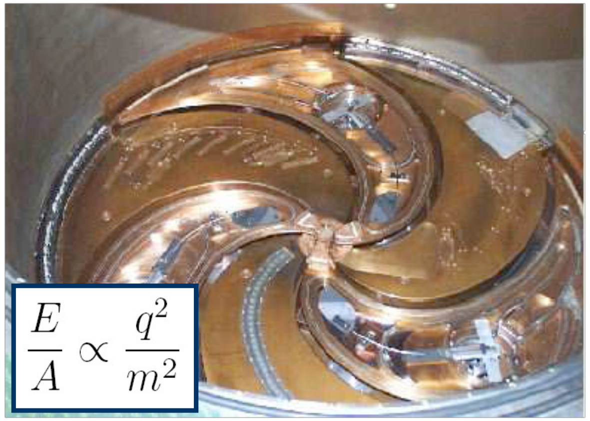

$$\frac{E}{A} \propto \frac{q^2}{m^2}$$

INFN-LNS Cyclotron

Increase of Ion Charge States → Higher energies attainable by Accelerators

Increase of Ion Current → Decrease of acquisition times for rare events

- **Low emittance.**
- **High stability and long-time operations without maintenance**

Increase of Ion Sources performances enhances the Accelerators ones without main hardware modifications

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Relevant ion sources

1) High current Proton sources (100 to 200 mA and norm. emittance 0.2-0.3 π mm.mrad)

2) High charge states ion sources (sub-mA or emA range, high versatility required for NP, high stability for medical or industrial applications

3) Multiply charged ion sources (multi-mA) for consumer market and microelectronics

Microwave discharge sources (MDIS) are suitable for 1), Electron Cyclotron Resonance ion sources (ECRIS) for 2), some new design is to be prepared for 3)

Other interesting types

- Laser ion sources (duty cycle, stability, reproducibility, emittance)
- RF negative sources for Spallation Sources etc (maintainance)
- Large area H- sources for Neutral Beam Injection (stability, maintainance)

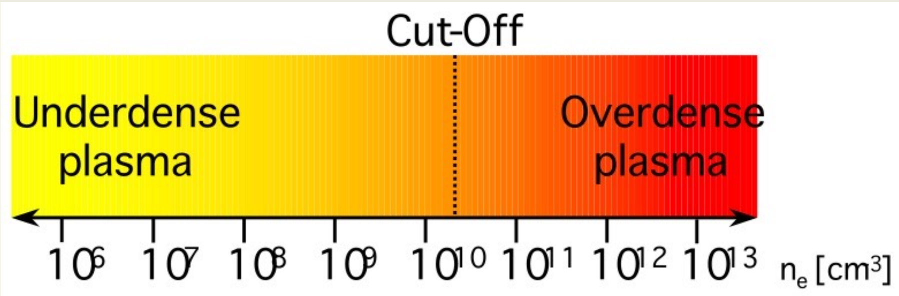
Overcoming the current limits

Current ~ 100 mA for protons and other monocharged species will be required in the next years by different projects, mA for multiply charged ion beams

$$I \sim n_e / \tau_i$$

⇓

Larger plasma density is required in ion sources' chamber



Strategy

High charge states (ECRIS):
high electron density, high plasma confinement time
→ high frequency, high magnetic field

High current (MDIS):
high electron density (overdense plasmas), low plasma confinement time → 2.45 GHz frequency, low magnetic field

$$I_{ext} \propto \frac{n_e}{\tau_i} \;; \qquad < q > \propto n_e{}^{*}\tau_i$$

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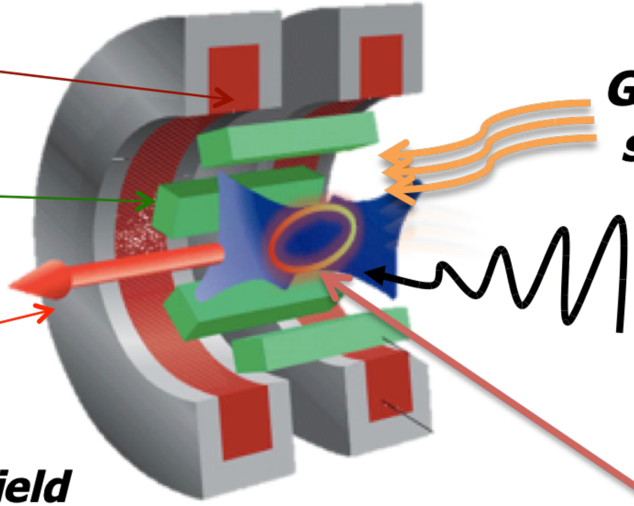
ECR Ion Sources Setup

***Solenoids** for*
Axial confinement

***Hexapole** for*
radial confinement

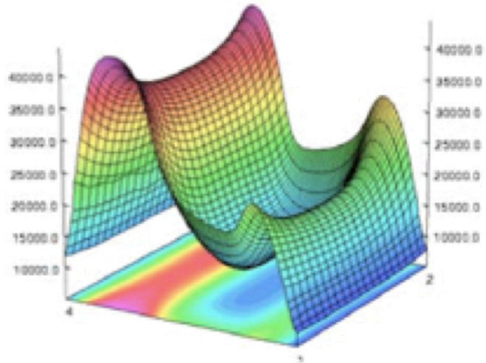
Extraction system



Gas injection system

Incident microwaves
*few **kW** at **tens GHz***

"B_minimum" Magnetic Field
structure



el. dens. 10^{12}-10^{14} cm^{-3}
el. temperature 0.01-10 keV

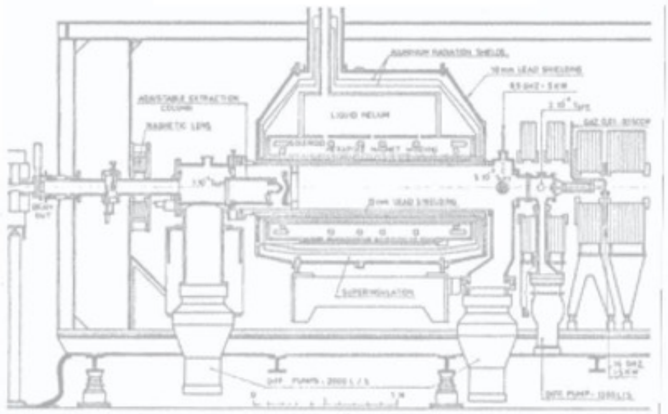
ECR Surface
$B_{ECR} = \omega_{RF} m_e / e$

The 70's&80's: First Generation ECRIS

- MINIMAFIOS – ECREVIS– LBL ECR …

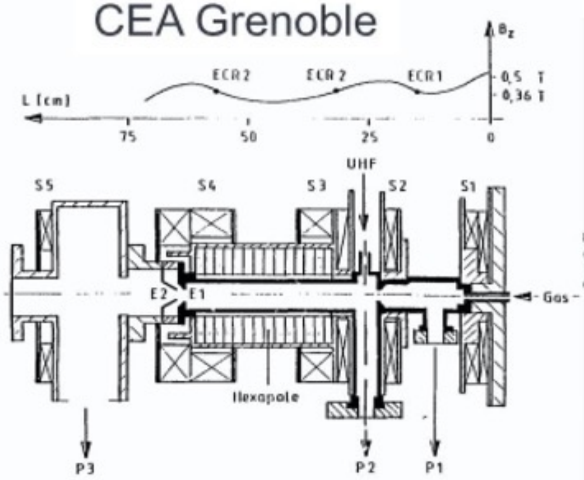
ECREVIS

Louvain la Neuve

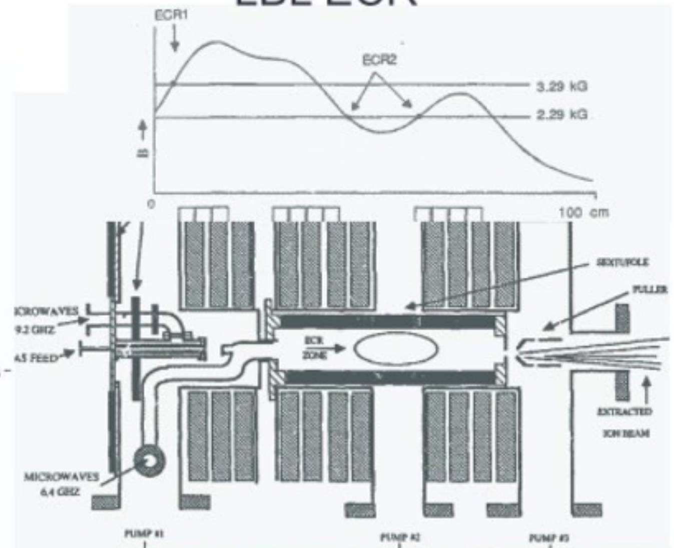


MINIMAFIOS

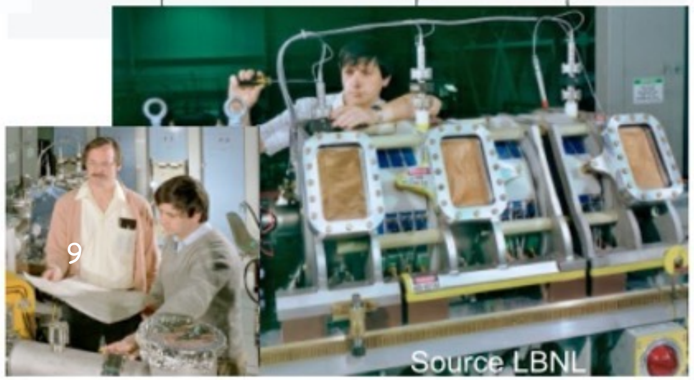
CEA Grenoble



LBL ECR

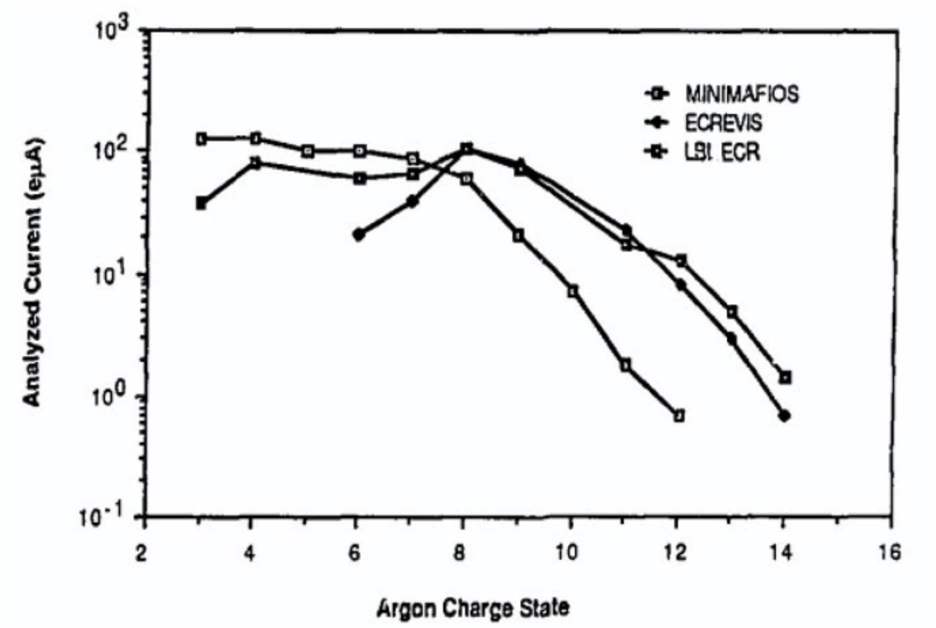


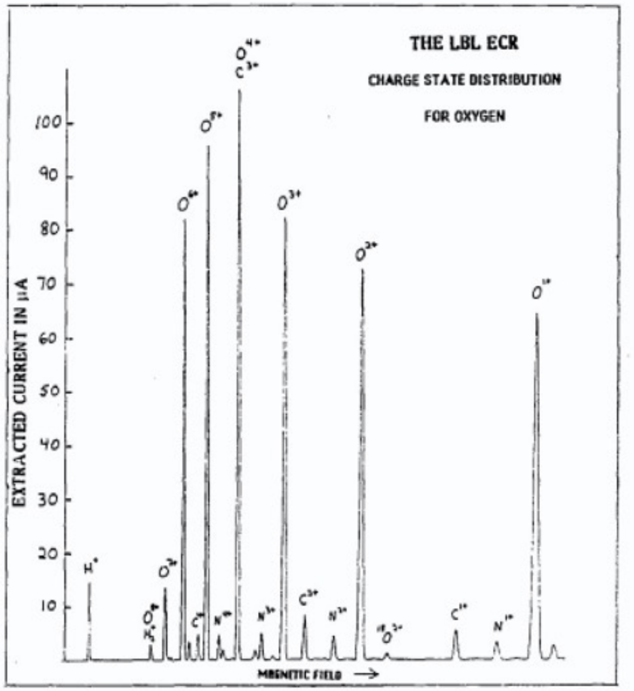
The First ECR beam in A cyclotron was achieved at Louvain La Neuve (B)



First generation ECRIS performances

- International competition for results was already there!
- First International Workshop on Ion sources in Berkeley





Typical beam performance of G1:
~100 μA Ar^{8+}
~100 μA O^{6+}

SERSE ion source

Beam	I(eμA)	Beam	I(eμA)	Beam	I(eμA)
O^{6+}	540	Kr^{22+}	66	Au^{30+}	20
O^{7+}	208	Kr^{25+}	35	Au^{31+}	17
O^{8+}	62	Kr^{27+}	7.8	Au^{32+}	14
Ar^{12+}	200	Kr^{29+}	1.4	Au^{33+}	12
Ar^{14+}	84	Kr^{31+}	0.2	Au^{34+}	8
Ar^{16+}	21	Xe^{27+}	78	Au^{35+}	5.5
Ar^{17+}	2.6	Xe^{30+}	38.5	Au^{36+}	2.5
Ar^{18+}	0.4	Xe^{31+}	23.5	Au^{38+}	1.1
Kr^{17+}	160	Xe^{33+}	9.1	Au^{39+}	0.7
Kr^{18+}	137	Xe^{34+}	5.2	Au^{40+}	0.5
Kr^{19+}	107	Xe^{36+}	2	Au^{41+}	0.35
Kr^{20+}	74	Xe^{38+}	0.9	Au^{42+}	0.03

Ref.: S. Gammino, G. Ciavola, L. Celona et al., Rev. Sci. Instr. 70(9), (1999) 3577

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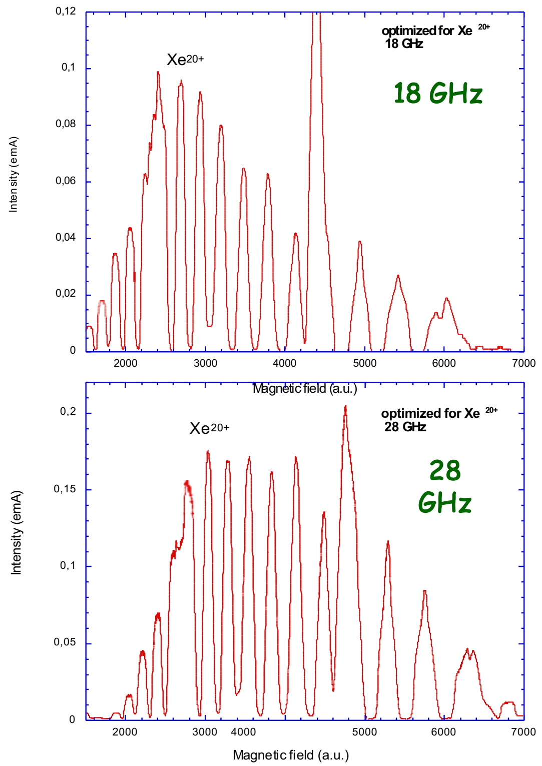
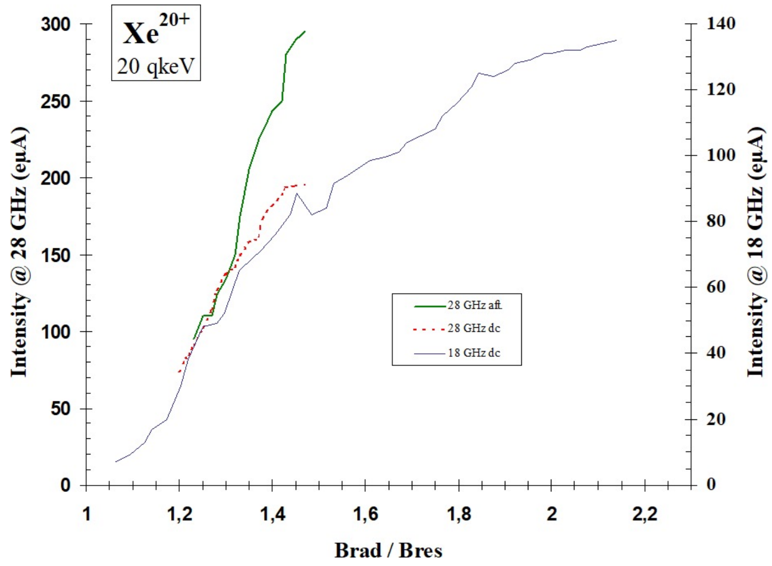
SERSE 28 GHz





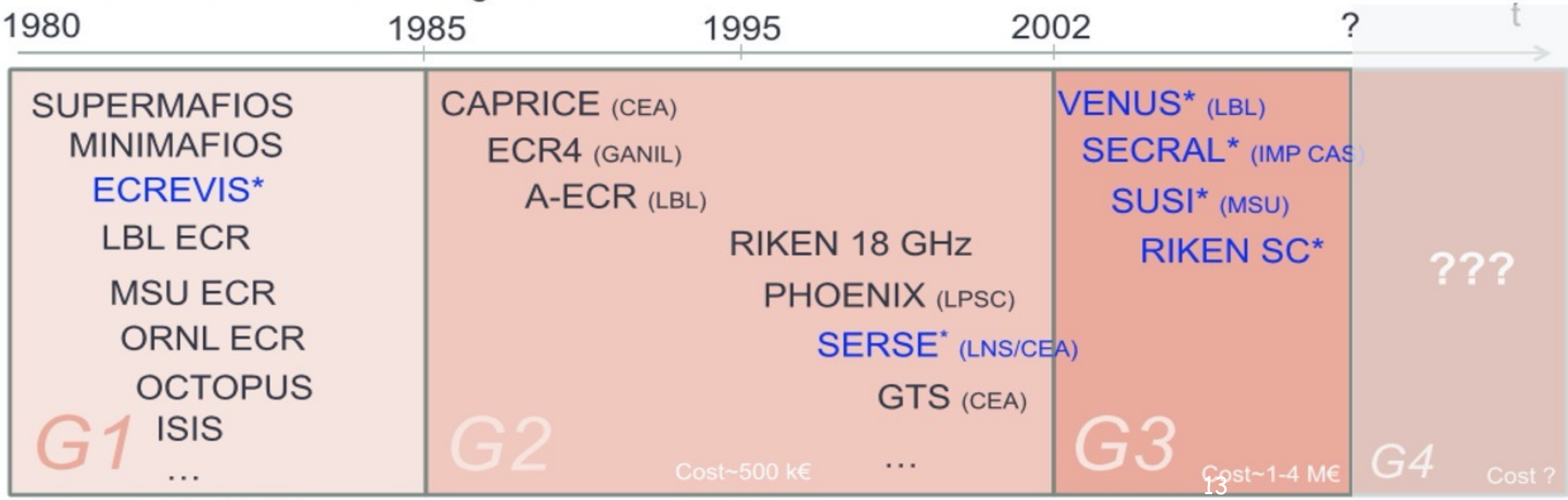
Ref.: S. Gammino, G. Ciavola, L. Celona, D.Hitz, A. Girard,G. Melin, Rev. Sci. Instr. 72(11), (2001) 4090

MAIN Issues:

- Beam Transport losses
- Plasma chamber cooling
- Increase of X-ray heat load in the cryostat

Third generation ECRIS

- The new high performance ECR ion sources are optimized for ECR frequency $18 < f < 28$ GHz
- The high magnetic field intensity required to confine the plasma ($\sim 2\text{-}4 \times B_{ECR} \sim 2\text{-}4$) makes the use of copper coil technology unreasonable in term of electrical power consumption (2T hexapole in Cu technology=> 3-4 MW electrical power).
- New ECRIS are preferably fully superconducting, with a large plasma volume to produce very high charge states for Cyclotrons or High intensity LINAC
- The beam current dramatically increases when the source is operated at higher frequency, and new technical challenges have arisen….



*Superconducting ECRIS

VENUS: The first 3rd Generation ECRIS

	≤2015	> 2015
$^{16}O^{6+}$	2850	**4750**
O^{7+}	850	**1900**
$^{40}Ar^{12+}$	860	**1060**
Ar^{16+}	270	**525**
Ar^{17+}	37	**120**
Ar^{18+}	1	**4**
$^{78}Kr^{18+}$		^{84}Kr **770**
Kr^{23+}	88	**420**
Kr^{28+}	25	**100**
Kr^{32+}		**7**
$^{129}Xe^{27+}$	400	**705**
Xe^{38+}	7	**26**
Xe^{45+}		**0.8**
$^{197}Au^{47+}$	4	$^{197}Au^{51+}$ **5**
Au^{52+}	0.8	**4.7**
Au^{58+}		**0.6**
$^{209}Bi^{45+}$	18	**63**
Bi^{50+}	5.3	**27**
Bi^{55+}		**7.2**
Bi^{59+}		**0.7**
$^{238}U^{33+}$	450	
U^{36+}	220	

VENUS

B_{max} on axis: 4 T, B_r radial: 2.2 T, operating at 28+18 GHz

First plasma in 2002

Time evolution of the beam intensity

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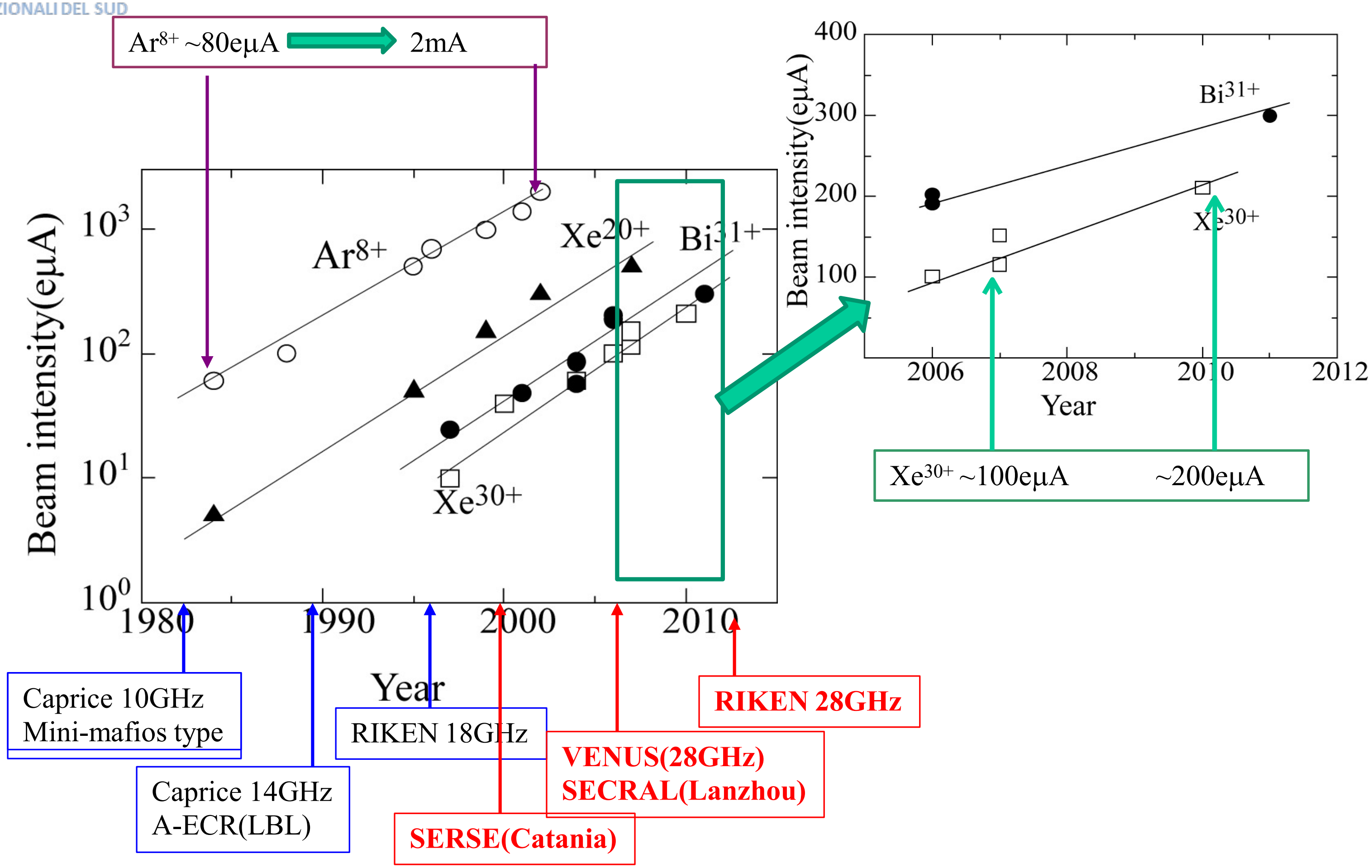


$$I_i^q \sim \frac{1}{2}\frac{n_i^q q e V_p}{\tau_i^q} \longrightarrow I_i^q \propto n_e V_p$$

$$\frac{n_e^2 \langle q \rangle}{\sqrt{T_e}} \sim \frac{5.2 \times 10^3}{e} \cdot \frac{P_{rf}}{V_p} \longrightarrow n_e \propto k_q \sqrt{P_{rf} \mathrm{T} V_p}$$

$$\Longrightarrow I_i^q \propto k_q \sqrt{P_{rf} \cdot V_p}$$

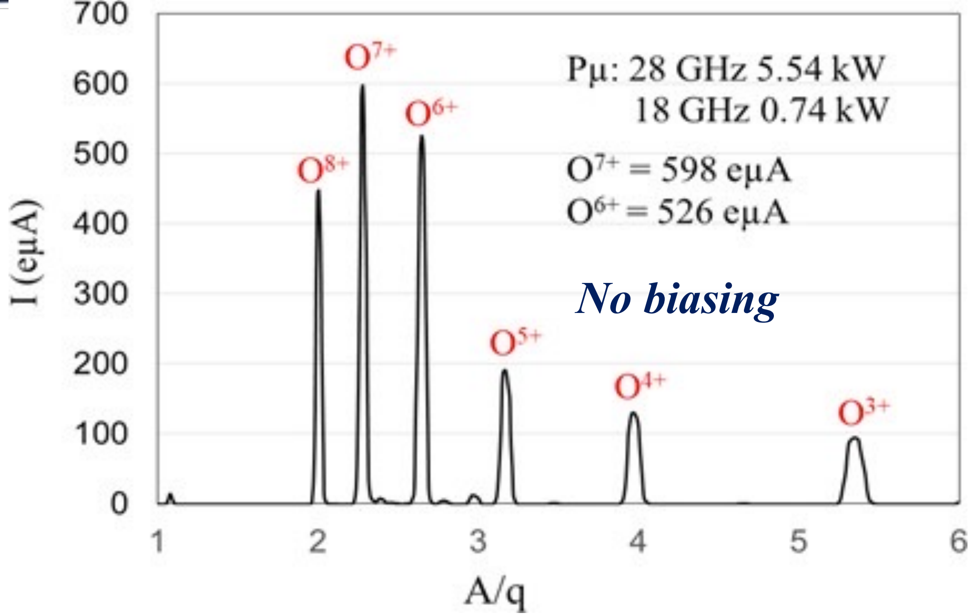
G. Melin, et al., *Journal of Applied Physics* **86**, 4772 (1999)

$$\langle q \rangle \sim \frac{P_{rf}}{V_p n_e^2} \propto \frac{P_{rf}}{V_p} \cdot \frac{1}{n_e^2}$$

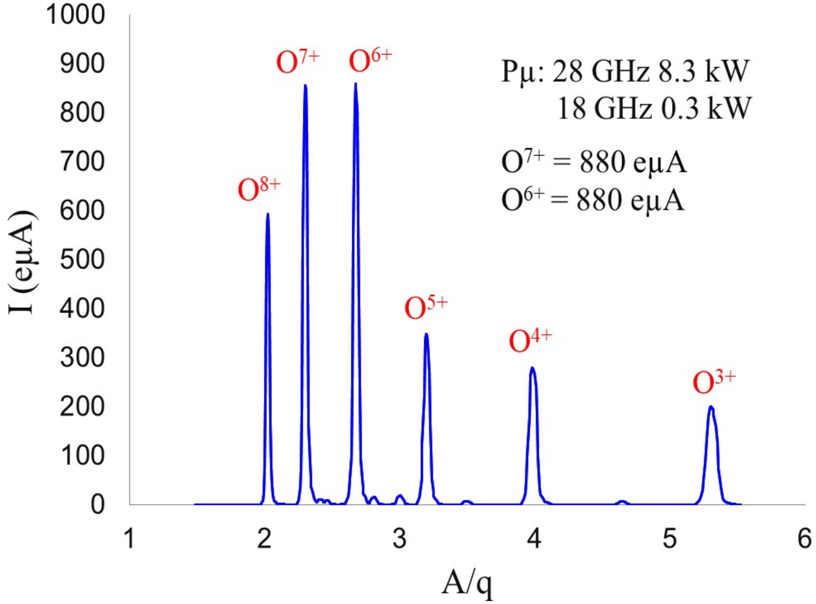
High performance ECR ion source:

- **High intensity= high power + big plasma volume**
- **Higher charge state= high power density + bigger volume (confinement)**

Best VENUS Oxygen Charge state Distributions (CSDs) on <q>



ECR Oxygen CSDs peaked at O^{7+} for the first time
Average charge <q> ~ 6.5



VENUS Oxygen CSDs peaked at O^{7+} and O^{6+}
Average charge <q> ~ 5.8

A full exploration will be carried out in the future

- ***Peaking at O^{7+} in oxygen CSD is a good step forward for VENUS and ECRIS technology***
- ***A complexly-shaped aluminum insert could benefit the production of higher ion charge states***
- ***A symmetric plasma chamber is not a necessity for the 3rd and future generation of ECRIS***

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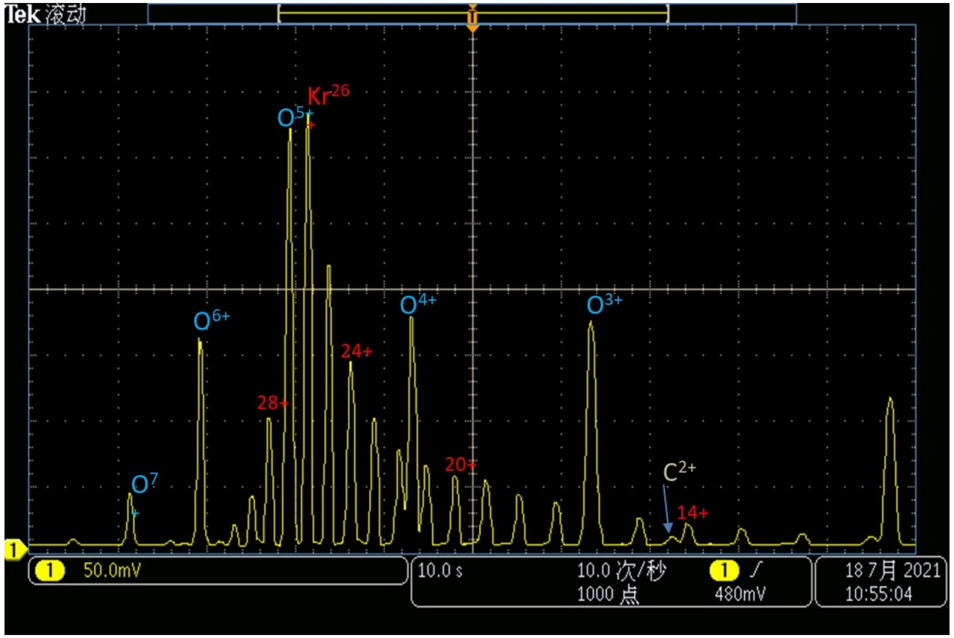
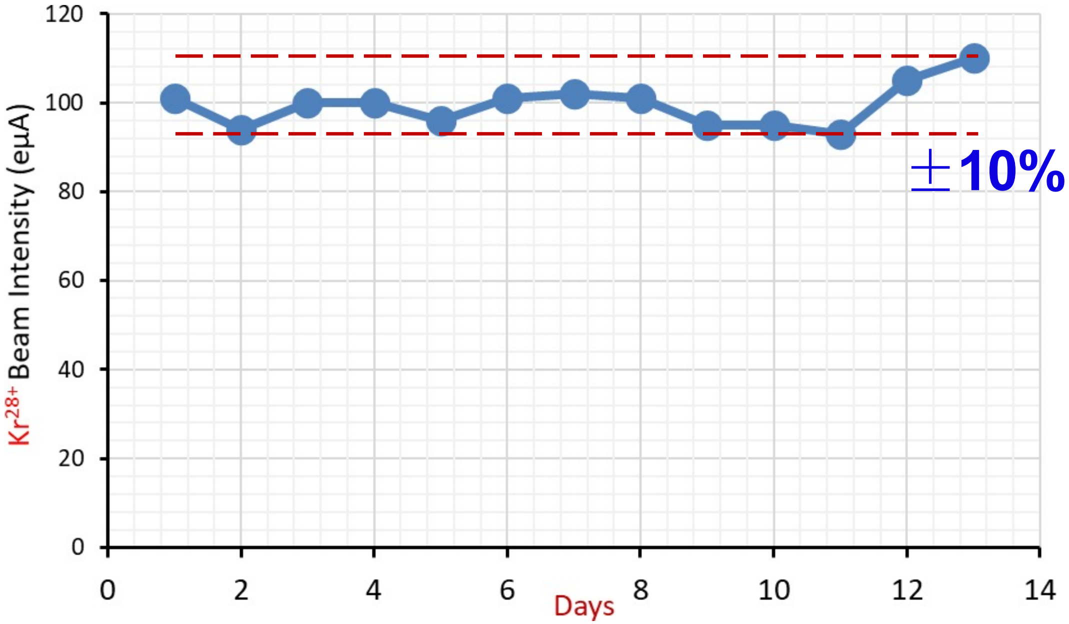
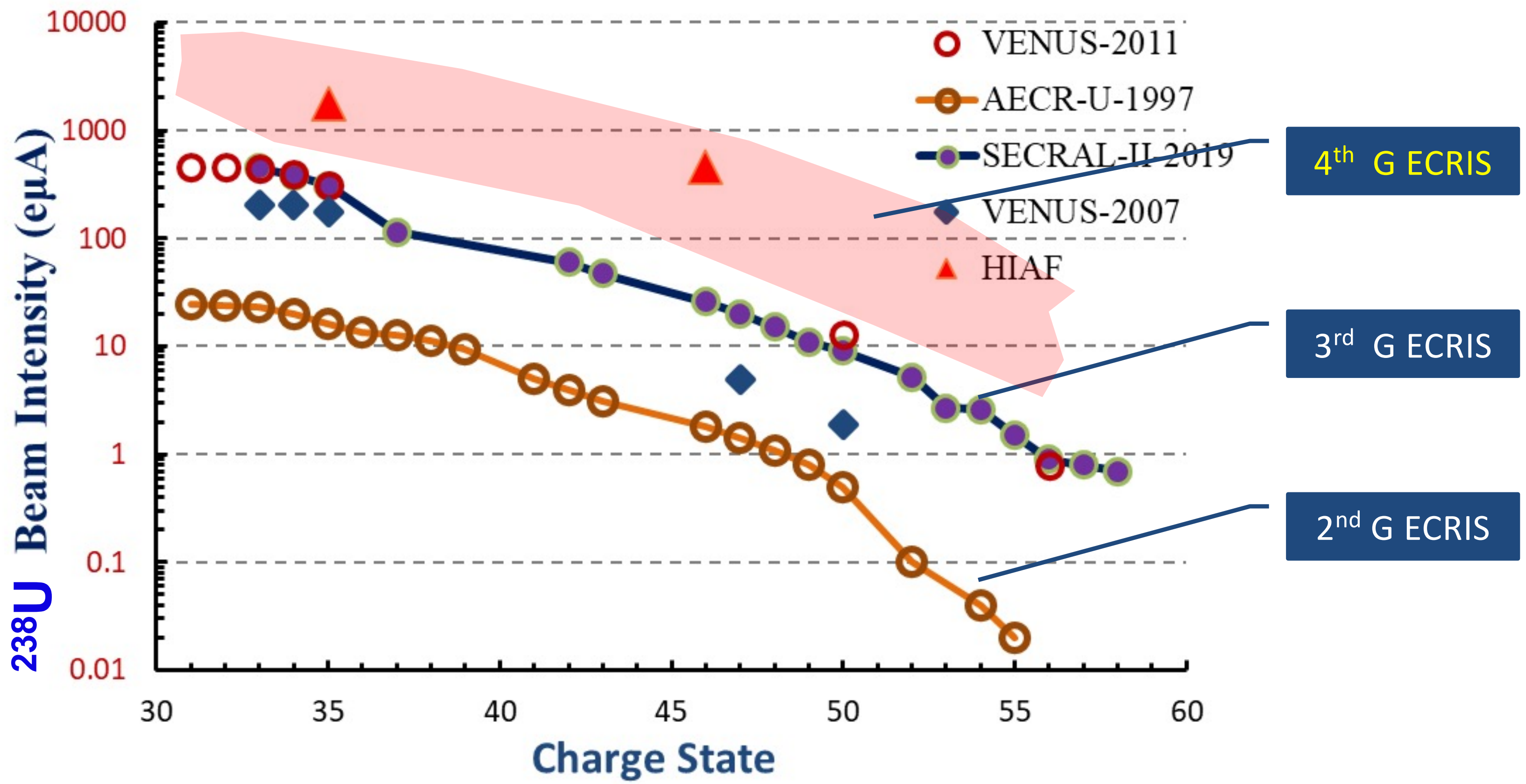
$^{86}Kr^{28+}$= 100 eμA, P_{rf}= 6.0 kW, Power density=1.16 kW/l





L. Sun, ICIS'21, TRIUMF

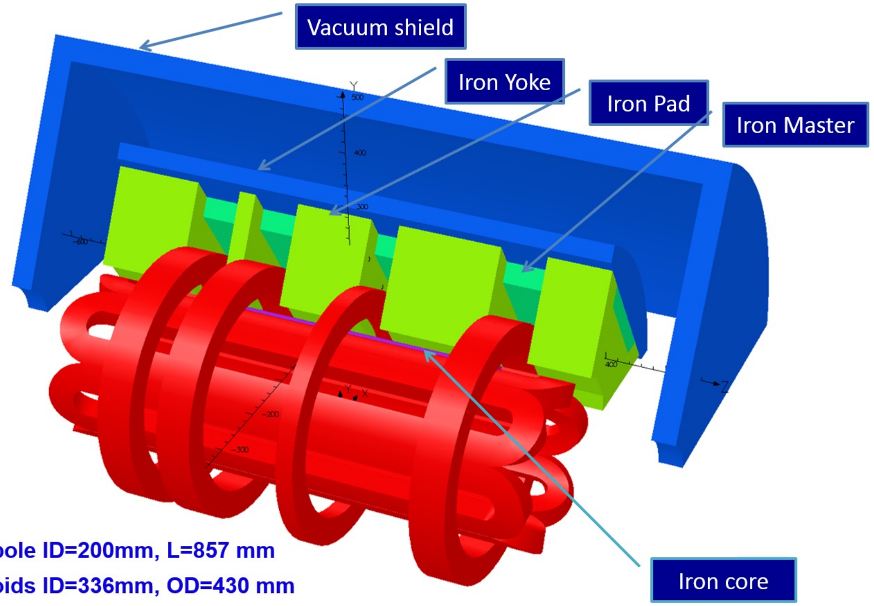
High Intensity HCI Beam Needs: Production



FECR: a 4th G ECRIS

Specs.	Unit	3rd G ECRIS	4th G ECRIS	FECR
frequency	GHz	24-28	40~56	45
Operational RF Power	kW	4~10	10~40	20
B_{ECR}	T	0.86~1.0	1.4~2.0	1.6
B_{rad}	T	1.8~2.2	2.8~4.0	≥3.2
B_{inj}	T	3.4~4.0	5.6~8.0	≥6.4
B_{min}	T	0.5~0.7	/	0.5~1.1
B_{ext}	T	1.8~2.2	3.0~4.5	≥3.4
Plasma Chamber ID	mm	100~150	>100	≥140
Mirror Length	mm	420~500	≥500	500
Cooling Capacity@4.2 K	W	0~6.0	>10.0	≥10.0

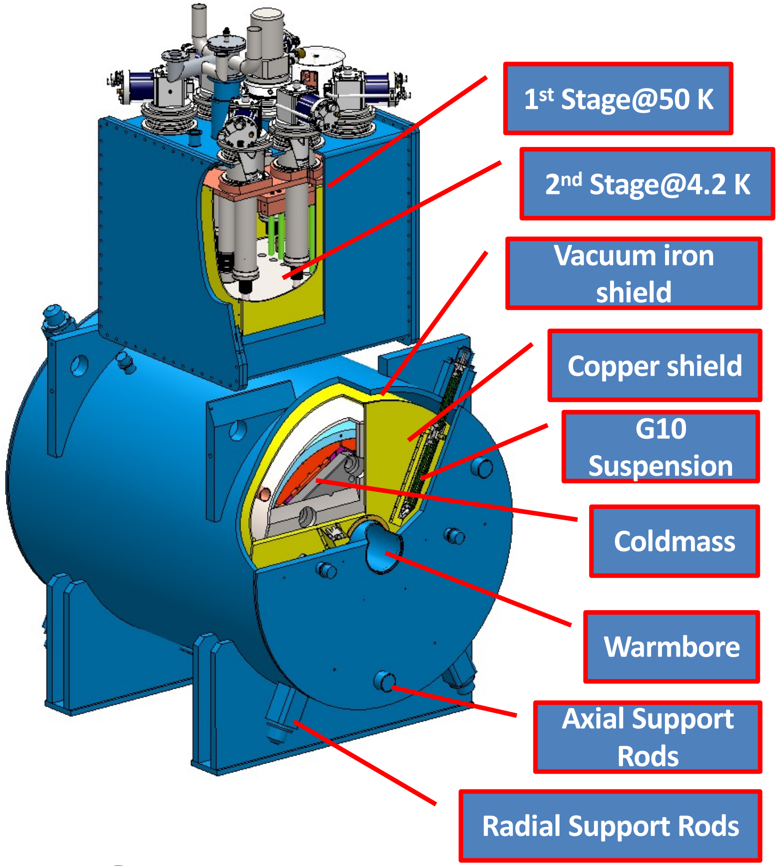
FECR Progresses: Magnet



Sextupole ID=200mm, L=857 mm

Solenoids ID=336mm, OD=430 mm

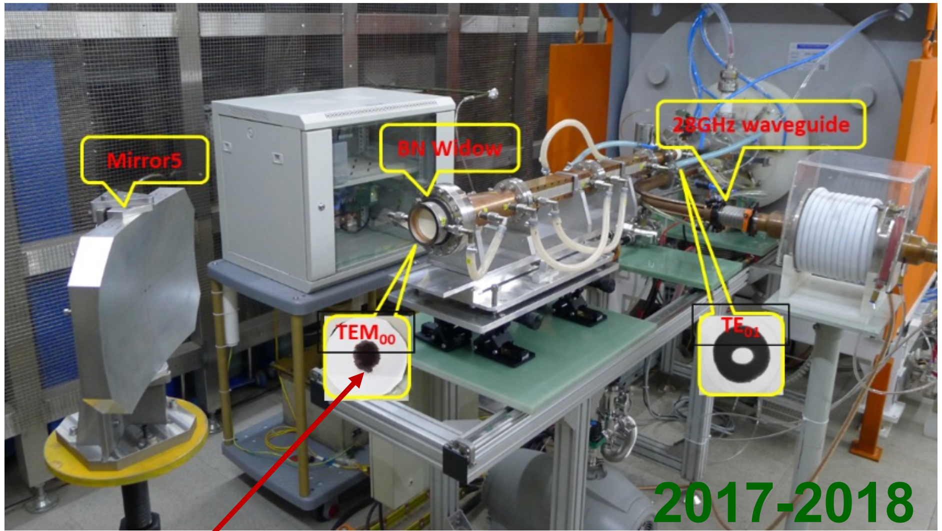
Coldmass Structure

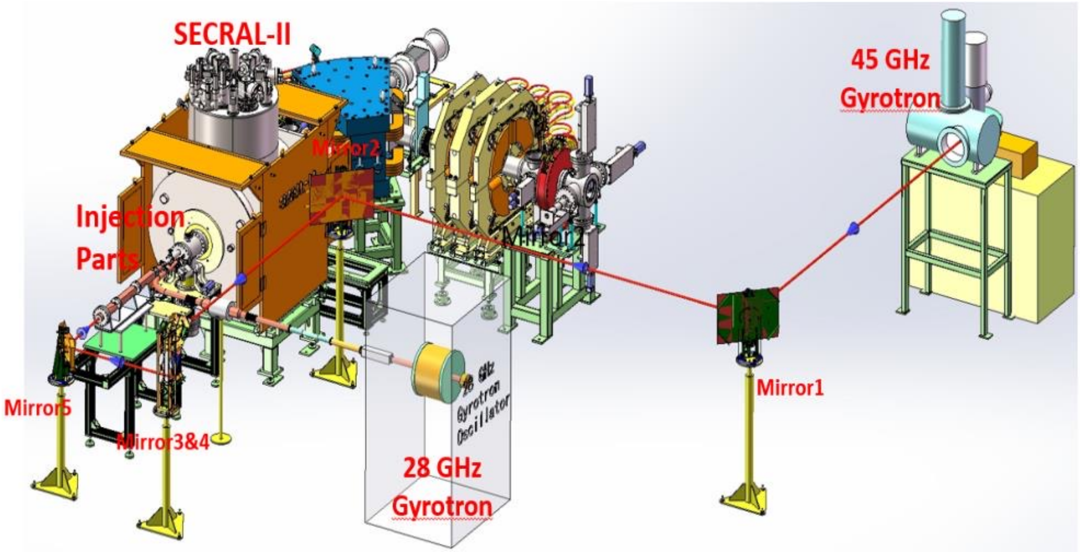


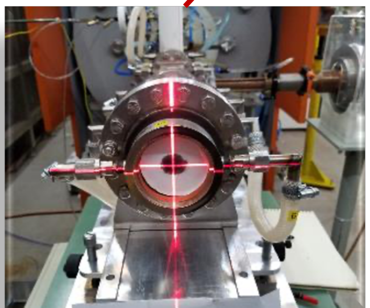
Magnet Structure

FECR Progresses: Microwave System test with SECRAL-II

45 GHz Microwave System for FECR





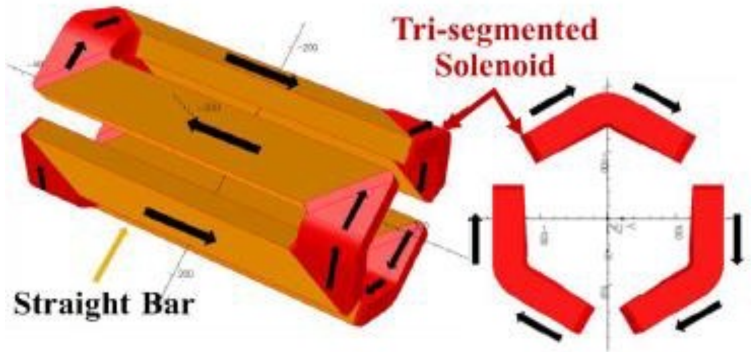


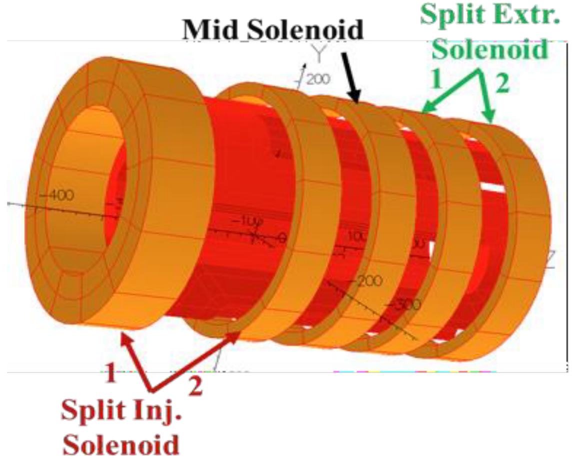
- **45 GHz/20 kW microwave transmission system based on Quasi-optical design**
- **First 45 GHz ECR plasma with SECRAL-II ion source**
- **Efficient transmission and coupling demonstrated**

J. W. Guo, et al., AIP Conference Proceedings **2011**, 090001 (2018)

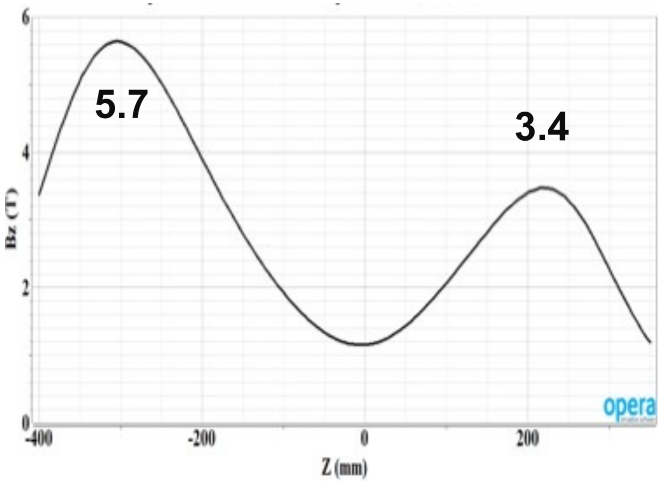
Status of MARS-D ECR Ion Source

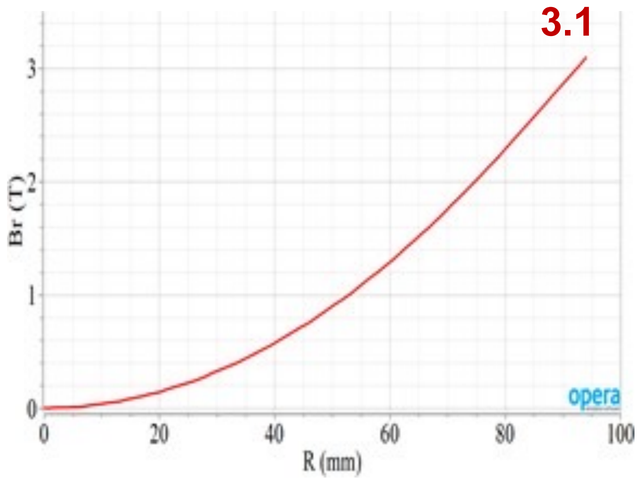
Mixed Axial and Radial field System



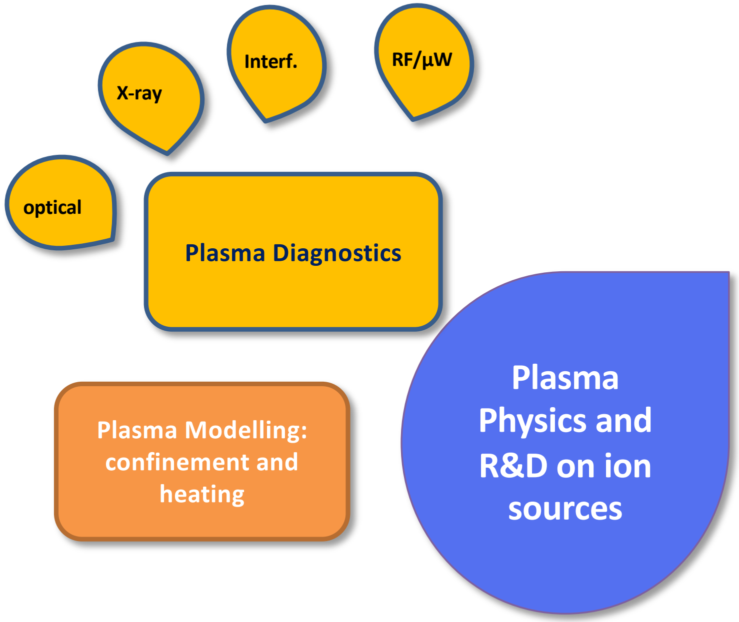


Combining a set of smaller solenoids with the closed-loop-coil allows for maximum fields of 5.7 T (axis) and 3.1 T (hexagonal chamber) to extend the NbTi conductor into 45 GHz ECR operations





These fields are good for a 45 GHz ECR ion source



C4) Improving Ion Beam services (ERIBS)

Participants: **JYU (coordination), ATOMKI, CNRS (IPHC, LPSC), GANIL, GSI, INFN (LNL-LNS), UMCG.**

ERIBS (European Research Infrastructure - Beam Services) aims at providing high-level ion beam services for the EURO-LABS research infrastructures by focusing on improvements in two key categories:

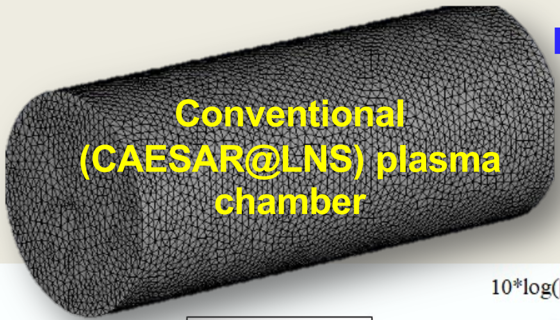
a) ion beam variety and production efficiency;

b) short and long-term ion beam stability.

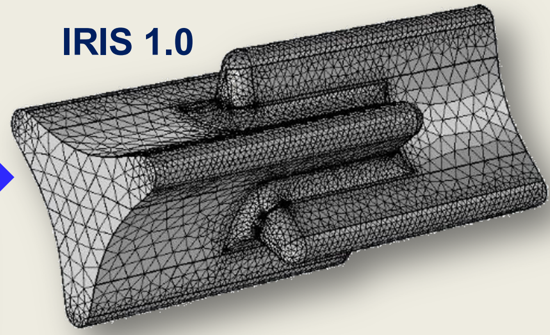
New µ-waves resonators: IRIS

IRIS 2.0

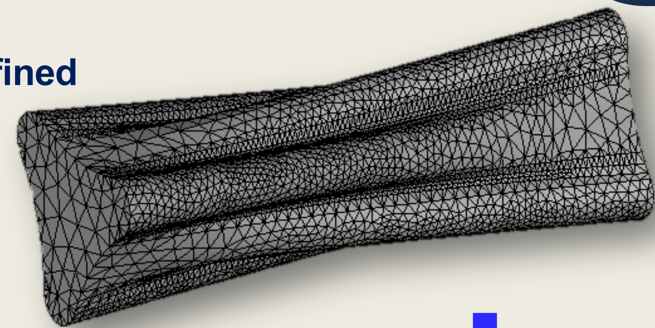
Innovative
Resonator
Ion
Source

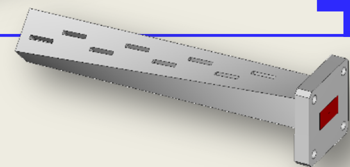


IRIS 1.0

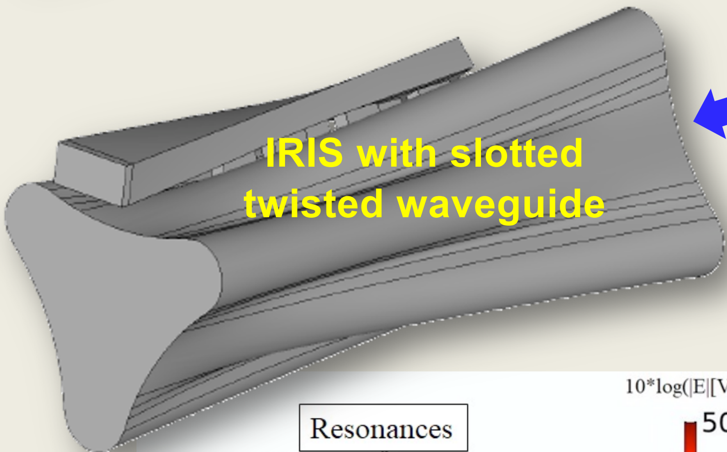


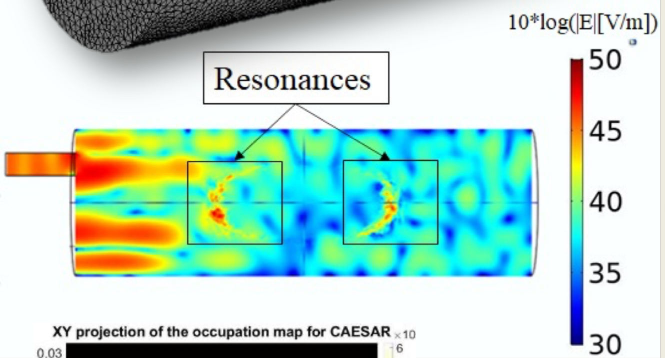
IRIS refined

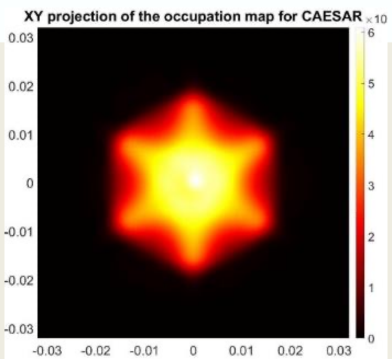


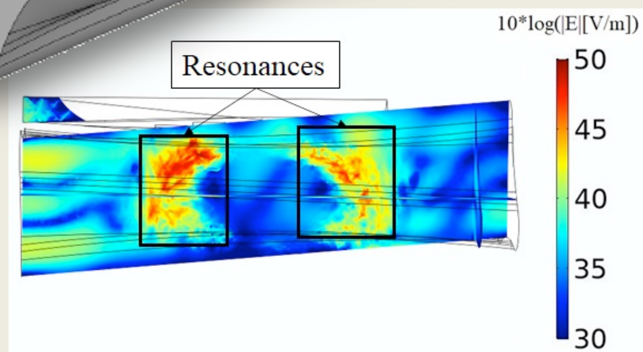


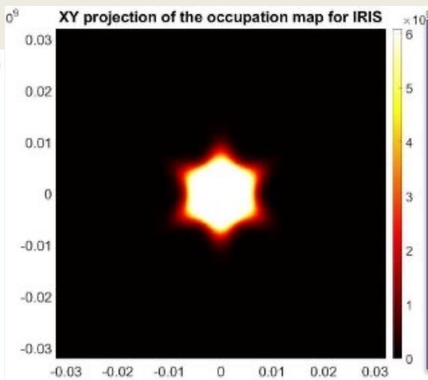
New microwave launching system with slotted/twisted waveguides











IRIS: italian patent pending n. 102020000001756

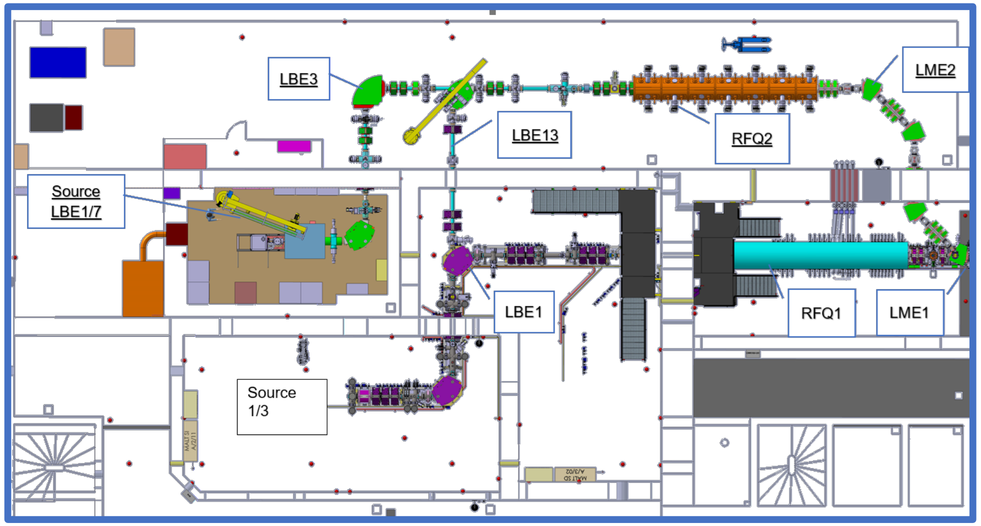
International patent pending N. PCT/IB2021/050696 // (E0130645) BRE-sz

Project to design and build a second injector at SPIRAL2 with A/Q=7

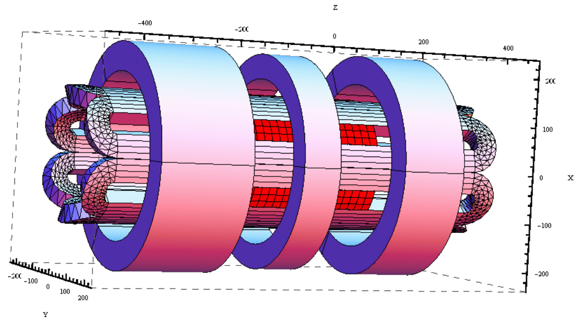
Budget obtained by ANR/France in 2021 - Planning : 2021-2028

Element	A/q	Operational Beam Current (μA)	Particle Current (pμA)	1 σ RMS normalized (π.mm.mrad)
$^{48}Ca^{11+}$	4.36	150	15	0.25
$^{238}U^{34+}$	7	170	5	0.10

Beams of reference for ions source and plateform design



- 28 GHz + 18GHz ion source on a HV platform ~70 kV
  - **Preliminary design study under progress**
  - Project team completed : LPSC, GANIL, CEA/DACM

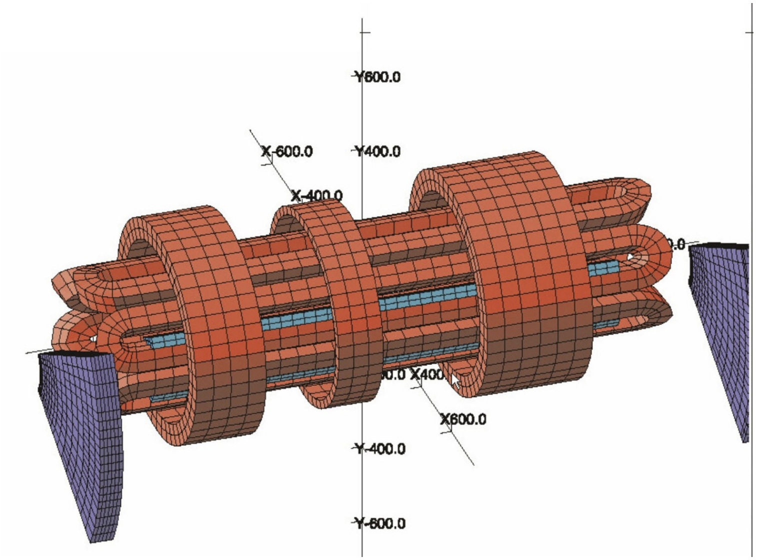


New ECRIS for the upgraded CS- SC-AISHa

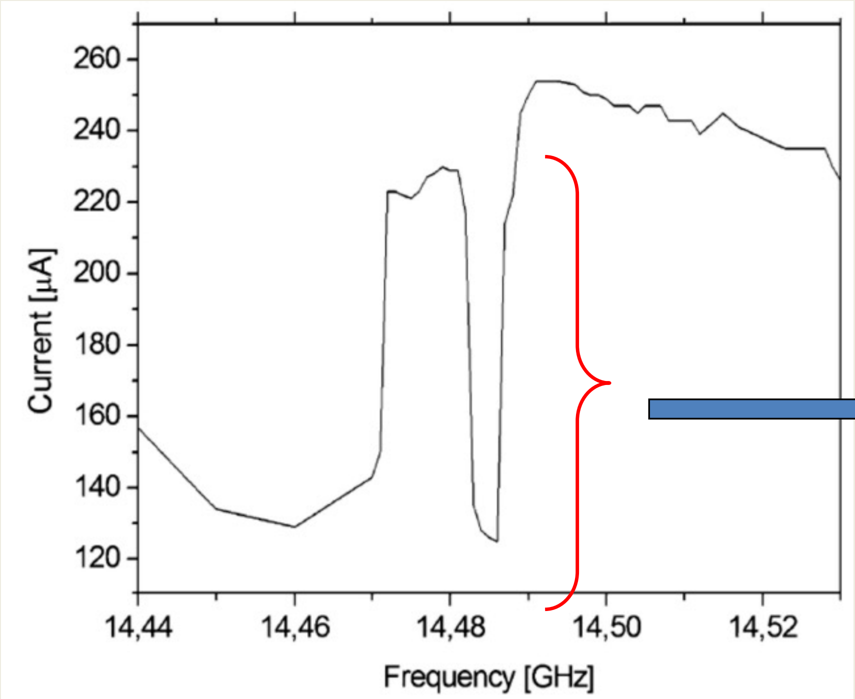
The AISHa ion source has been expressly conceived and realized for actual and future hadrontherapy facility (e.g.:HITRI+). It has a strong limitation on a radial field (1.28T instead of 1.55T of SERSE) affecting HCI production.

However the permanent magnet hexapole may be replaced by a superconducting structure with a minor changes on the solenoid coils for axial confinement (may be decreased to 3). Increase of extraction voltage is also mandatory.

Radial field	1.9 T
Axial field	3.5 T - 0.5 T – 2.2 T
Operating frequencies	24 GHz – 18 GHz
Operating power	5 + 5 kW (max)
Extraction voltage	60 kV (max)
Chamber diameter / length	Ø 130 mm / 600 mm
LHe	Free
Warm bore diameter	140 mm
Source weight	2100 kg



Evidence of Frequency Tuning Effect (FTE) on the SUPERNANOGAN source



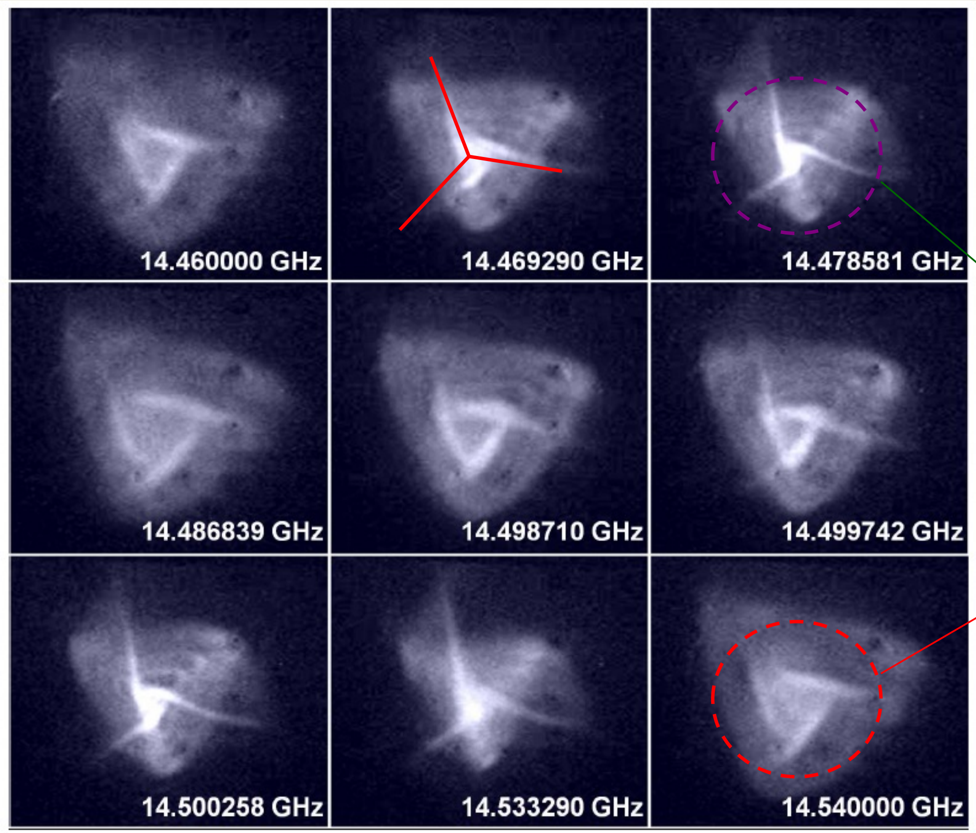
Trend of the analyzed C^{4+} current versus the RF frequency.

The extracted current is doubled after a frequency shift of 5 MHz

Transmission of a cyclotron or a RFQ changes significantly when the frequency of the source is slightly changed.

Frequency tuning on the CAPRICE source at GSI

[L. Celona, et al. Observations of the frequency tuning effect in the 14 GHz CAPRICE ion source. *Rev. Sci. Instrum.*, Feb. 2008. vol. 79, no. 2, p. 023 305.]



Frames of the extracted beam for different frequencies

"three cusp" shape of the extracted beam according to the magnetic structure

Well focused and high brightness beam

Broadened, low brightness beam

The Frequency Tuning strongly affects also the beam shape and brightness

Fluctuations of electron energy during the frequency tuning

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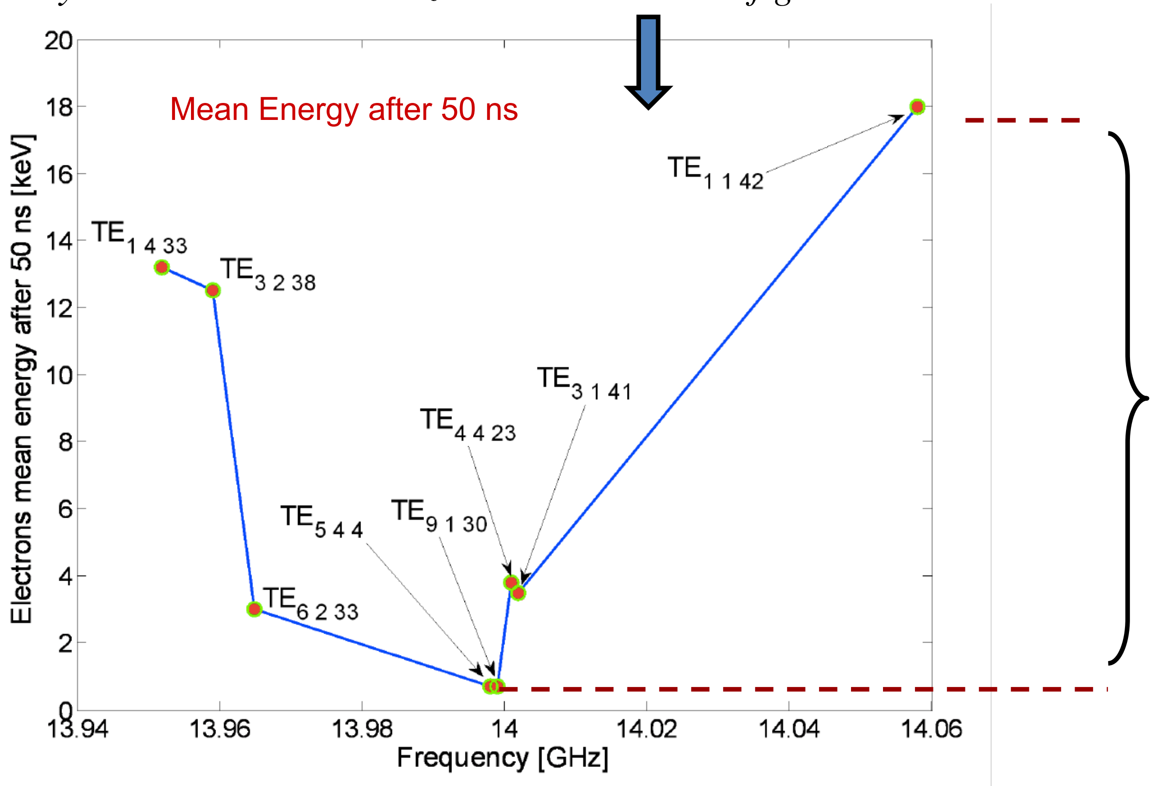
[S. Gammino et al, IEEE Trans. Plasma Sci., 2008]

3D collisionless Monte Carlo simulations about ECR-heating of electrons crossing many times the resonance zone in a min-B configuration.



Strong fluctuations of heating rapidity for different excited modes inside the plasma chamber

Exciting a mode is not enough: standing wave structure is dominant!

In some conditions slight variations of L are critical for hard-X rays generation (exp. with CAESAR)

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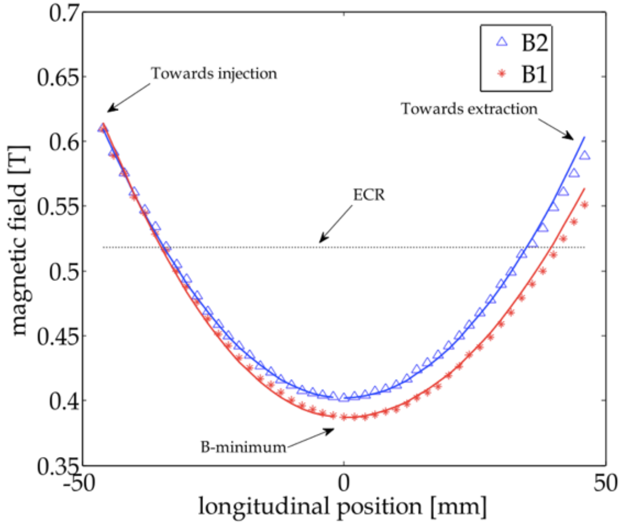
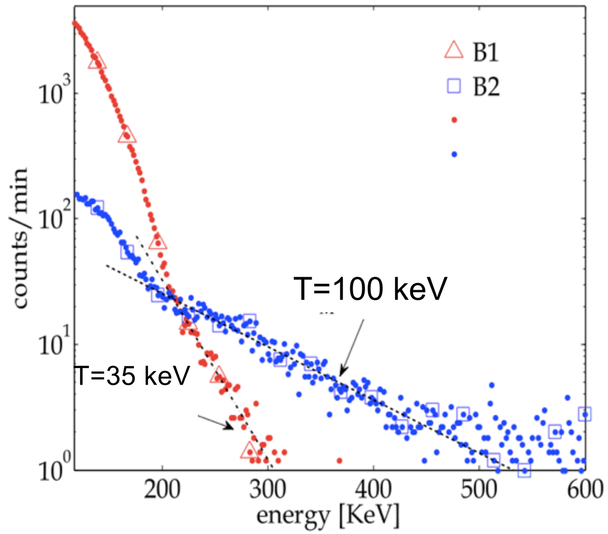
Comparison of the X-ray spectra obtained with slightly different B profiles

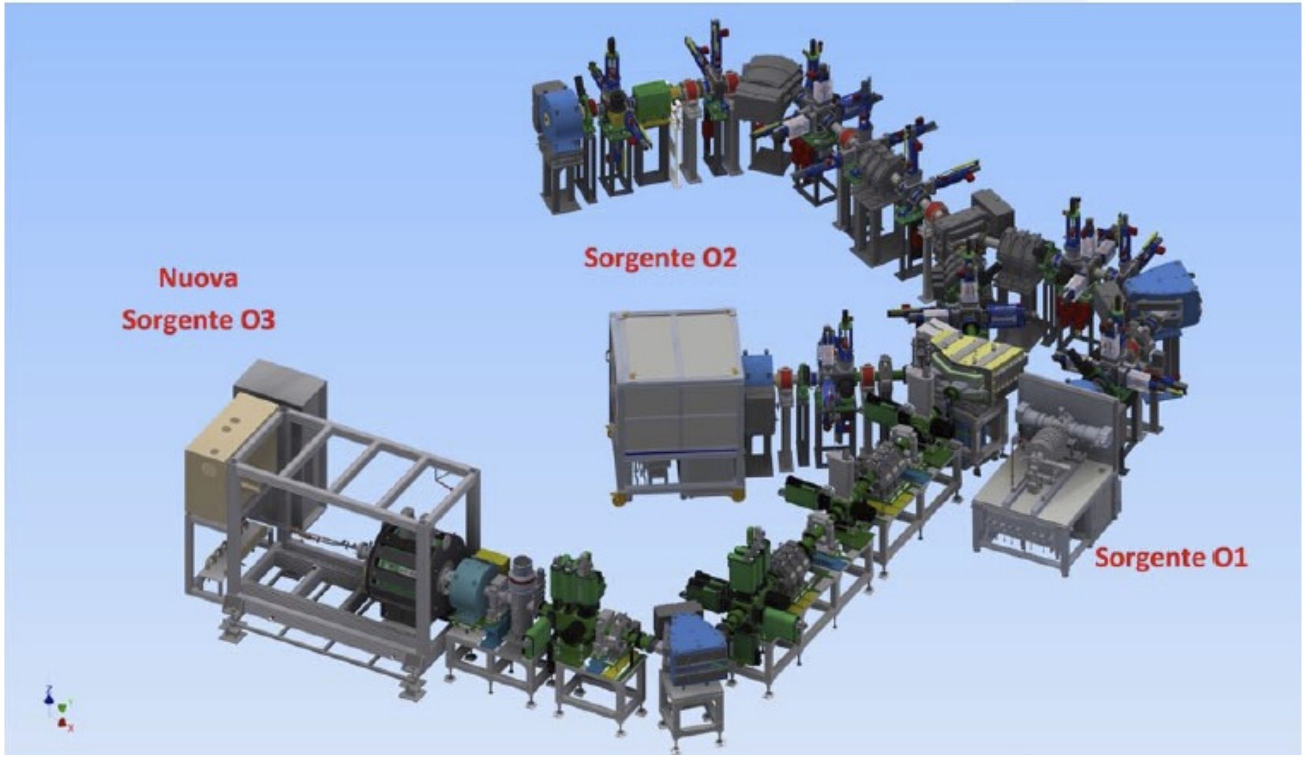




By changing the characteristic length of the mirror trap, L, of just 4mm, we obtained a completely different X-ray spectrum.

	L [mm]	l [mm]	W_b [keV]	$D_{\nu\nu}$ [a.u.]	T^{spec}[keV]	E_f [keV]
B1	60	30	300	100	35	300
B2	64	34	350	105	100	530

INSpIRIT



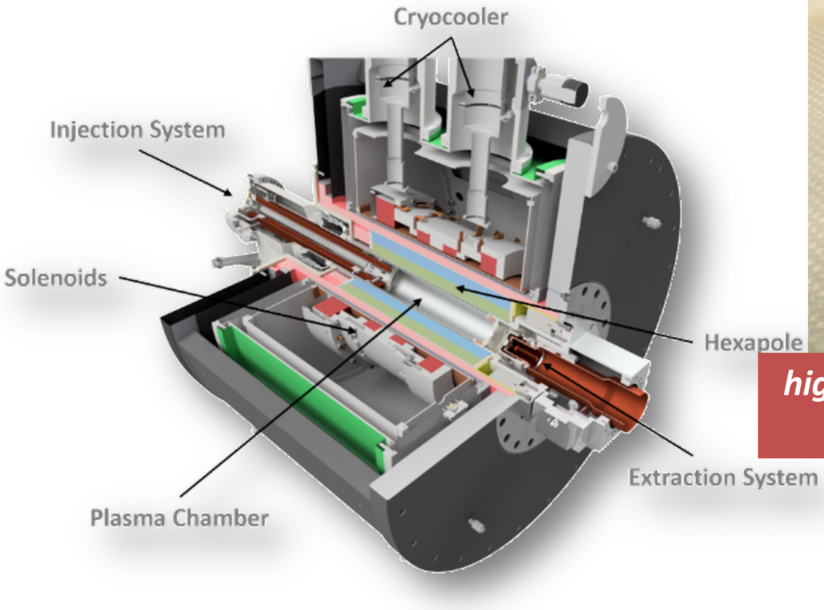
Revamping of critical components in order to speed some normal machine operations:

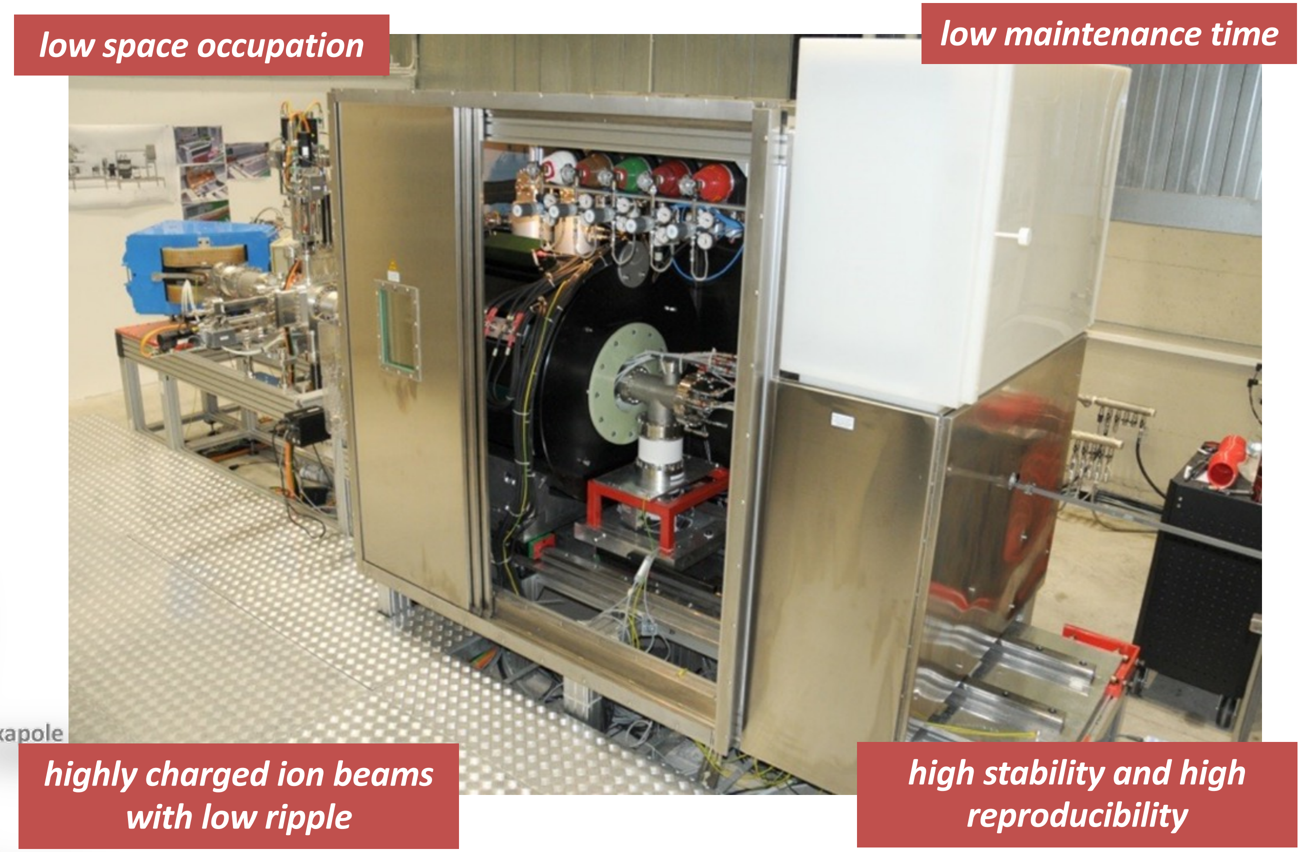
- Revamping of critical components to increase machine reliability
- Upgrade of the radiobiology laboratory
- **AISHa source** for **Helium, Lithium, Oxygen and Iron** for new clinical protocols (He, O, Li) and biological/material experiments for space radiation research.

UNIONE EUROPEA
Fondo europeo di sviluppo regionale
Regione Lombardia
fesr
POR FESR 2014-2020 / INNOVAZIONE E COMPETITIVITÀ

AISHa@LNS

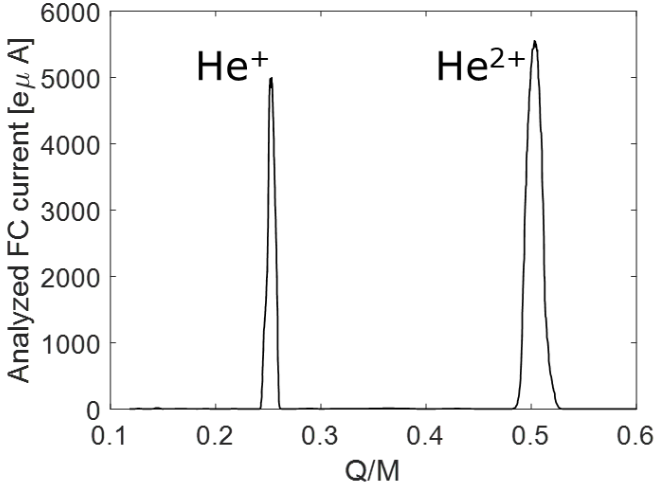
Radial field	1.3 T
Axial field	2.7 T - 0.4 T - 1.6 T
Operating frequencies	18 GHz – 21 GHz
Operating power	1.5 + 1.5 kW (max)
Extraction voltage	40 kV (max)
Chamber diameter / length	Ø 92 mm / 360 mm
LHe	Free
Warm bore diameter	274 mm
Source weight	1400 kg



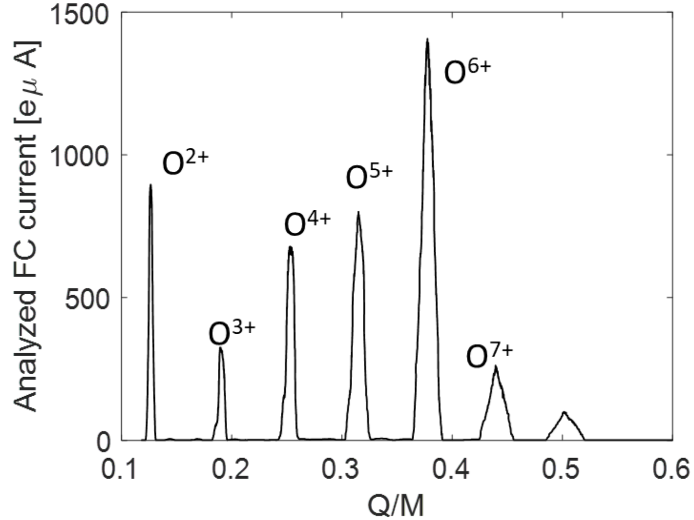


AISHa Performances

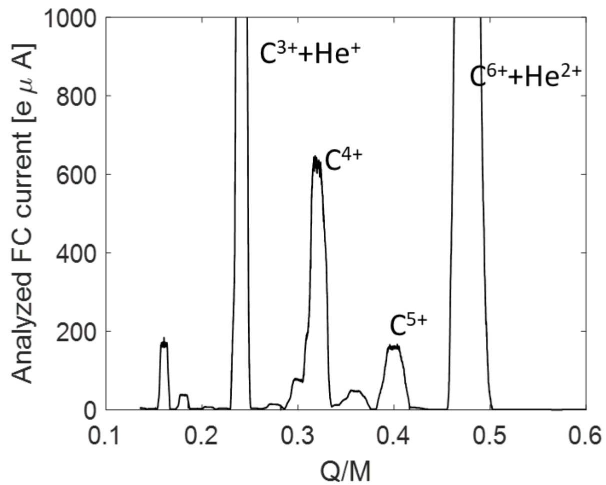
Charge state	Beam intensity [eμA]	$\varepsilon_{rms.norm}$ $[\pi \cdot mm \cdot mrad]$
$^{16}O^{6+}$	1400	0.2198
$^{16}O^{6+}$	225	0.115
$^{16}O^{7+}$	350	0.247
$^{12}C^{4+}$	650	0.272
$^{12}C^{4+}$	150	0.222
$^{12}C^{5+}$	165	---
$^{40}Ar^{11+}$	155	0.201
$^{40}Ar^{12+}$	140	0.201
He^{2+}	5400	0.418
He^{2+}	700	0.245

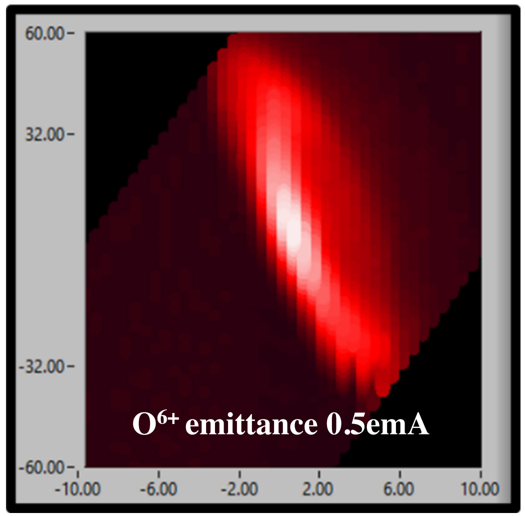


O2 + He (4:1)

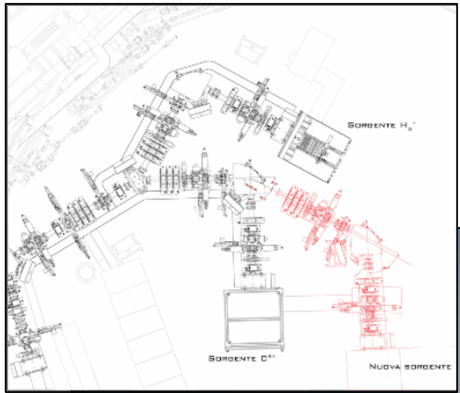


CH4+He (~10: 1)



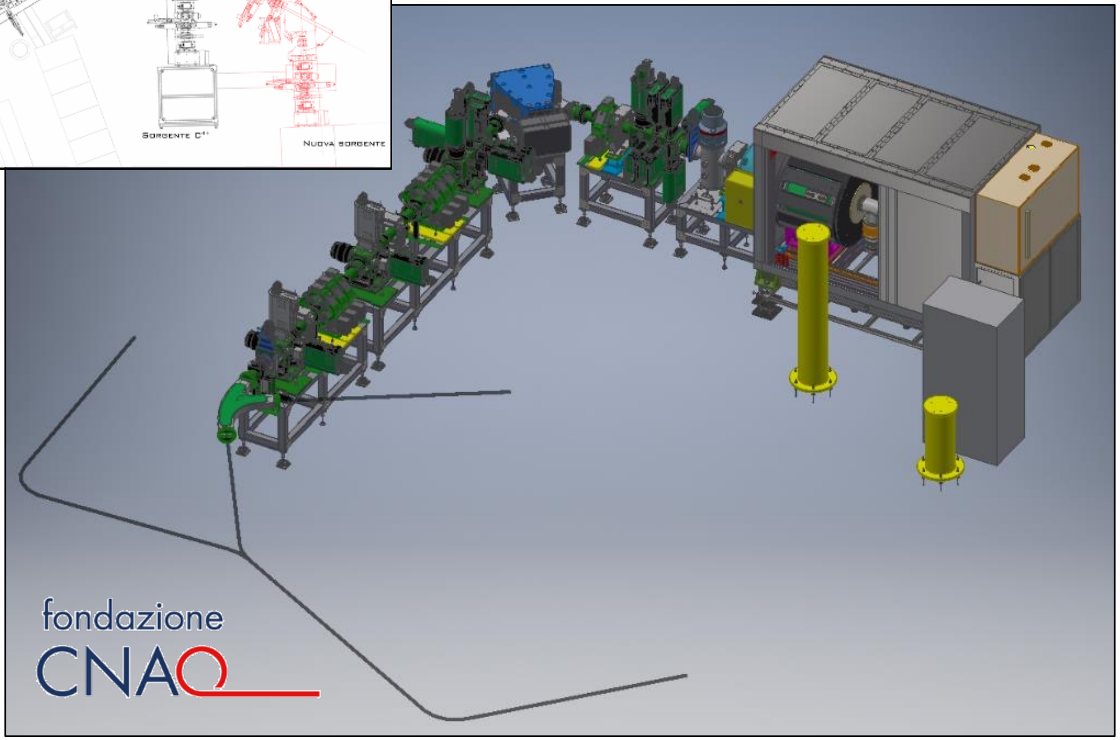


AISHa @ CNAO



INSpiRIT

INnovative accelerator facility with **S**ources **I**ons for
Research and radiation hardness studies
with **I**ndus**T**rial and clinical applications

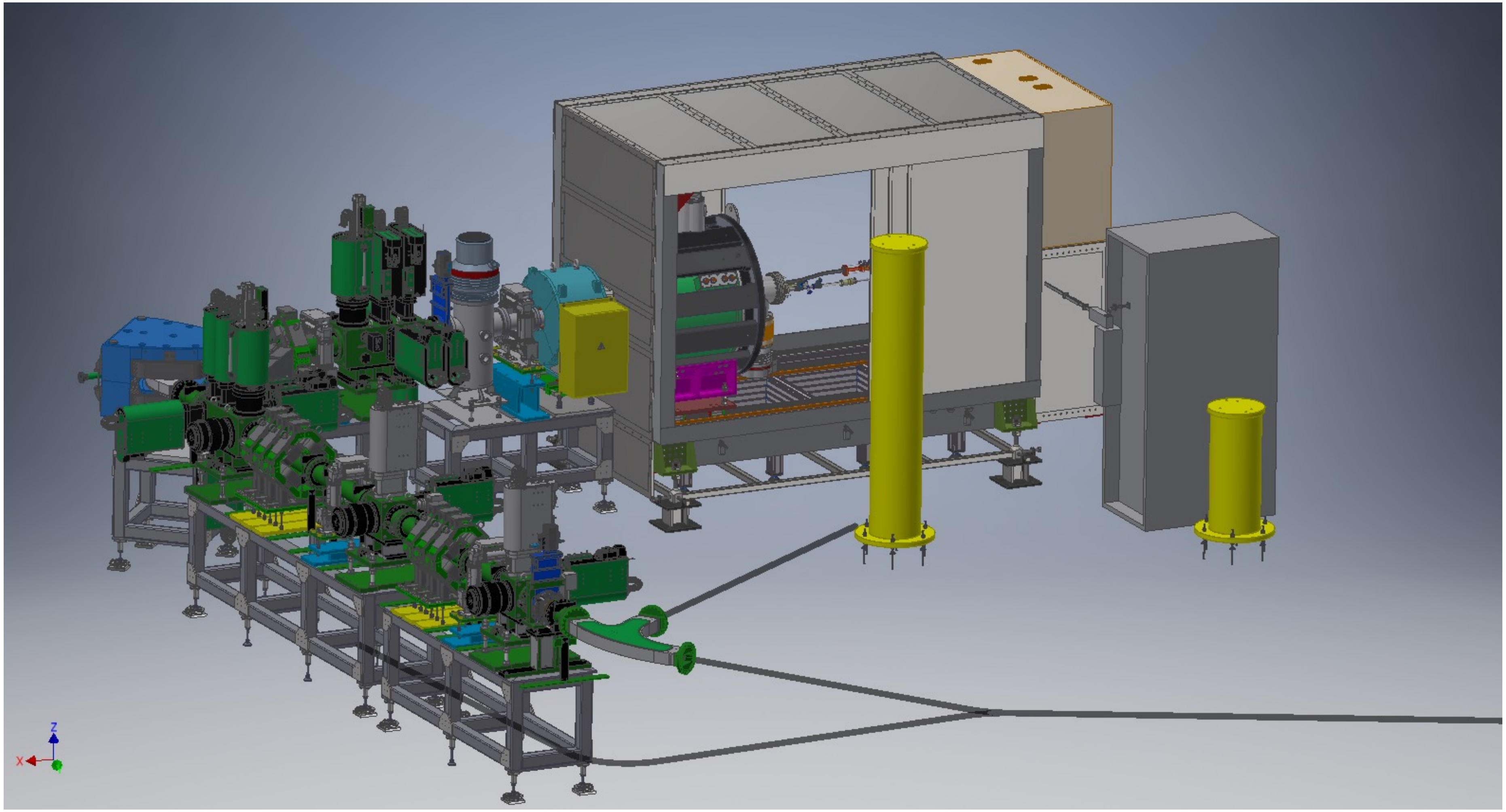


Helium, Lithium, Oxygen and Iron for new clinical protocols and biological/material experiments for space radiation research

Source and ancillary equipment are being preassembled in INFN-PV.

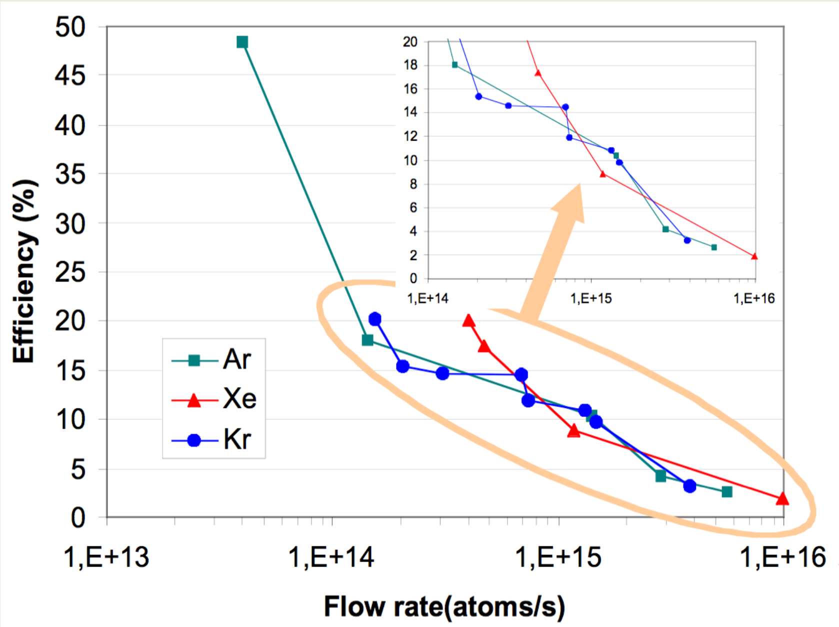
Commissioning is planned to start in Q4-2022 and will envisage night shifts

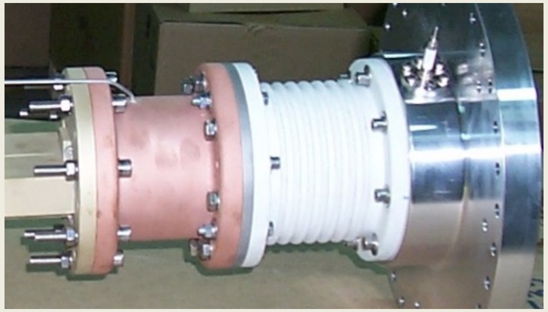
AISHa integration@CNAO

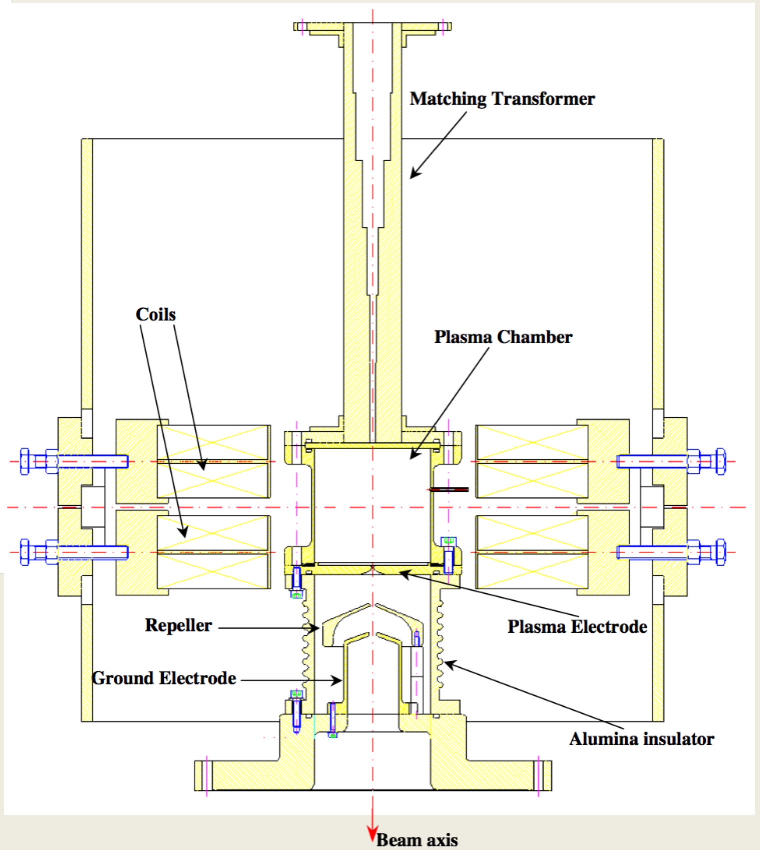


AISHa integration@CNAO

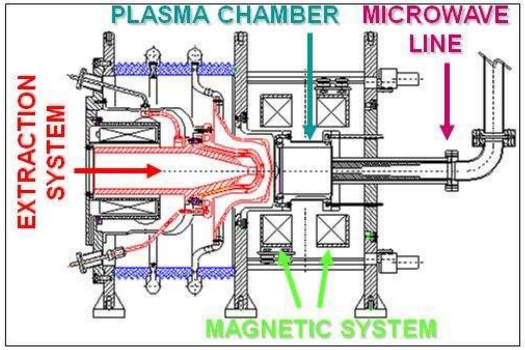
Microwave Discharge Ion Sources MIDAS 1 and 2 (1993-97)





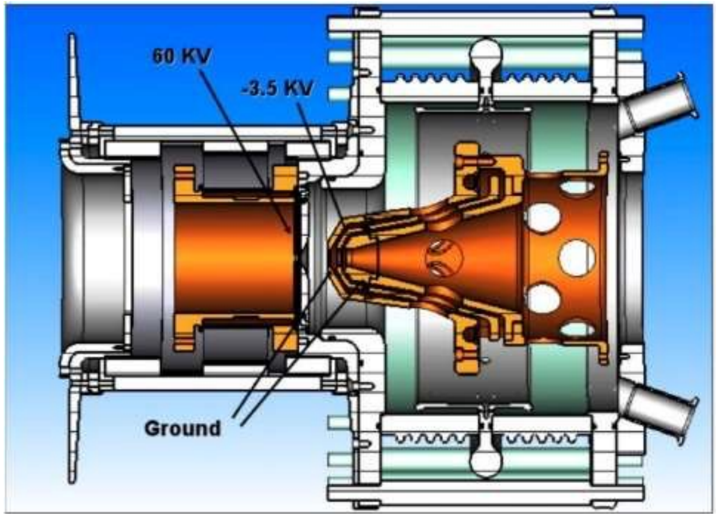


TRIPS - VIS



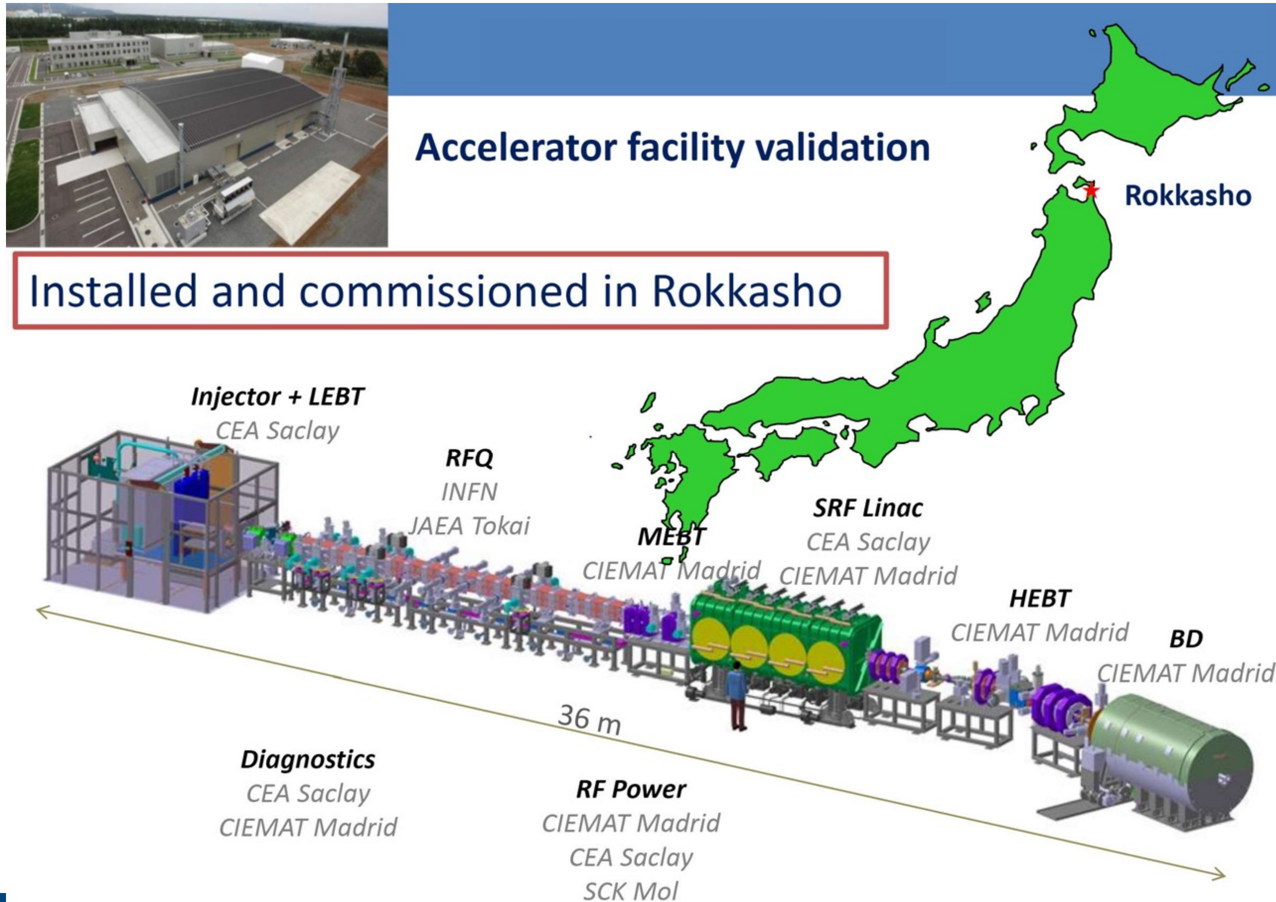
TRIPS

VIS



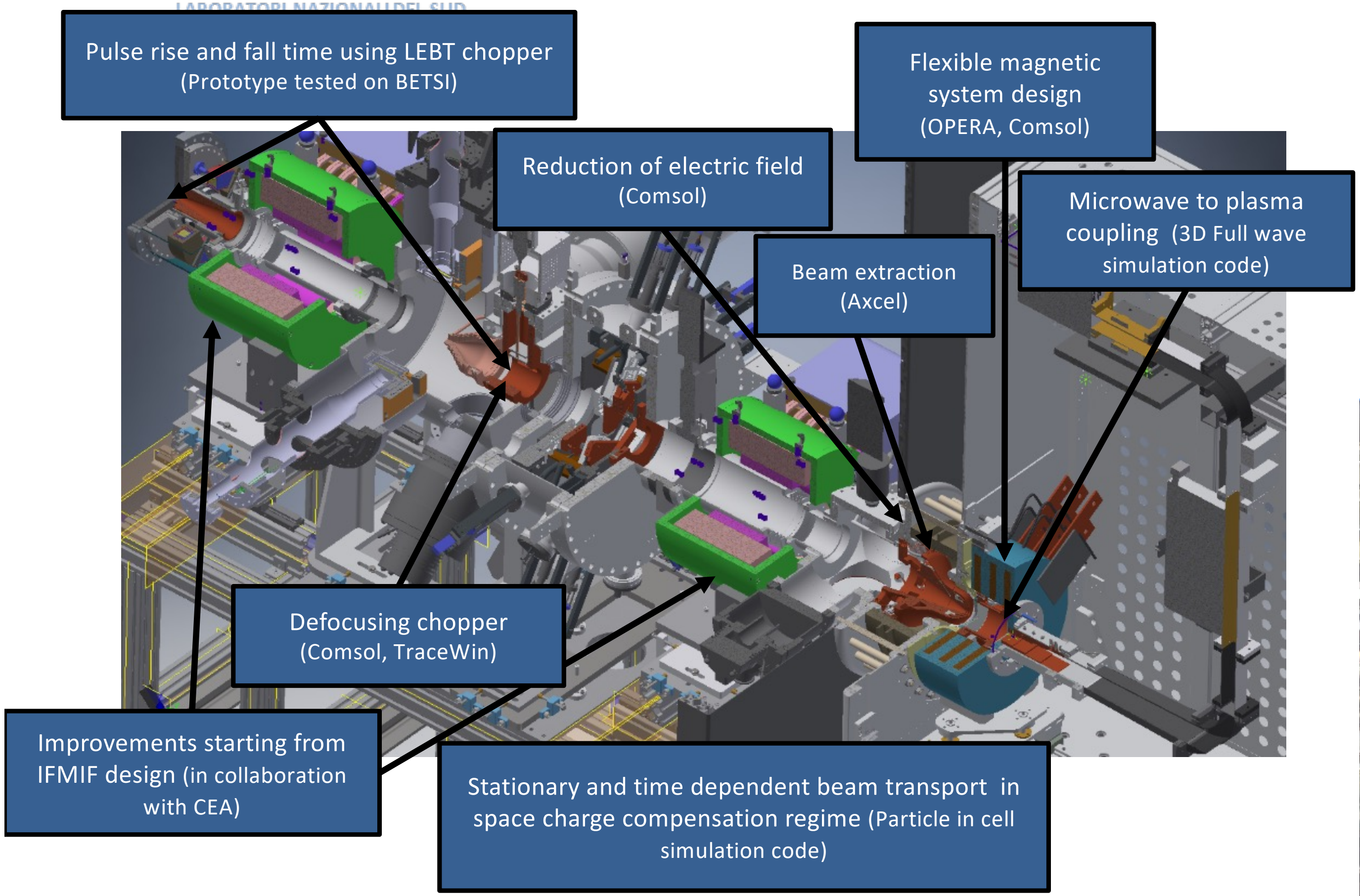
Performance	Value
Beam energy	80 Kev
Proton beam current	55 mA
Proton fraction	≈80%
RF frequency	2.45 GHz
RF power	Up to 1 kW
Axial magnetic field	875-1000 G
Duty factor	100 % (DC)
Extraction aperture	6 mm
Reliability	99.8% @ 35 mA
Transverse emittance (σ)	0.07 pi.mm.mrad @ 35 mA
Start-up after maintenance	32 hours

IFMIF-EVEDA



Accelerator facility validation
Rokkasho
Installed and commissioned in Rokkasho
Injector + LEBT
CEA Saclay
RFQ
INFN
JAEA Tokai
MEBT
CIEMAT Madrid
SRF Linac
CEA Saclay
CIEMAT Madrid
HEBT
CIEMAT Madrid
BD
CIEMAT Madrid
36 m
Diagnostics
CEA Saclay
CIEMAT Madrid
RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

ESS high intensity proton source



2011 Start of the design at LNS
2015 Start of the construction at LNS
12/09/2017 ESS visit for requirement verification
17/11/2017 End of the commissioning at LNS
01/02/2018 Delivered and assembled in Lund

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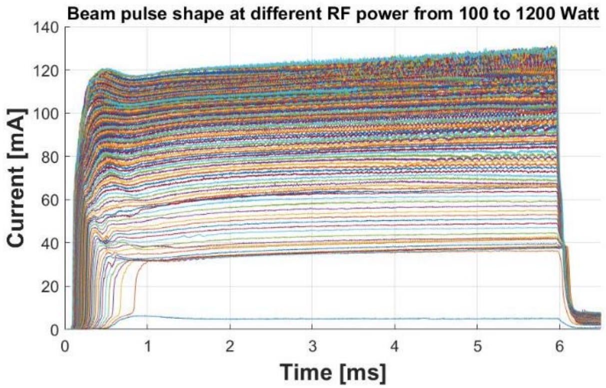
ESS high intensity proton source

PS-ESS was fully commissioned at LNS
and performance were validated by ESS personnel

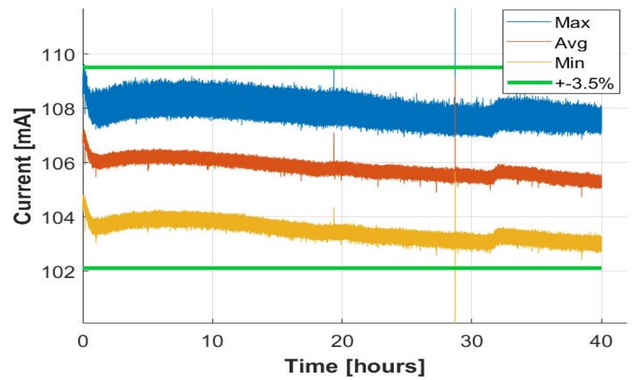
Requirement	Value	**Measurement done for configurations that satisfy the ESS stability requirements**	**Comments**
Total beam current	>90 mA	40 - 140 mA	✓
Nominal proton beam current	74 mA	40 - 105 mA	✓
Proton beam current range	67-74 mA	40 - 105 mA	✓
Proton fraction	>75%	Up to 85%	✓
Pulse length	6 ms	6 ms	✓
Pulse flat top	3 ms	3 ms	✓
Flat top stability	±2 %	< ±2 % up to 1.5%	✓
Pulse to pulse stability	±3.5 %	< ±3.5 % up to 3%	✓
Repetition rate	14 Hz	14 Hz	✓
Beam energy	75±5 keV	75 keV	✓
Energy adjustment	±0.01 keV	±0.01 keV	✓
Transverse emittance (99%)	1.8 pi.mm.mrad	1.06 pi.mm.mrad @ 82 mA	✓
Beam divergence (99%)	<80 mrad	50 mrad @ 82 mA	✓
Start-up after source maintenance	32 hours	32 hours	✓

Second source with second part of the commissioning was not needed

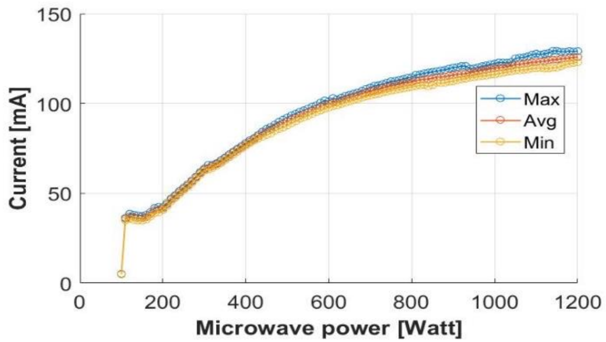
Intra-pulse stability < ±2%

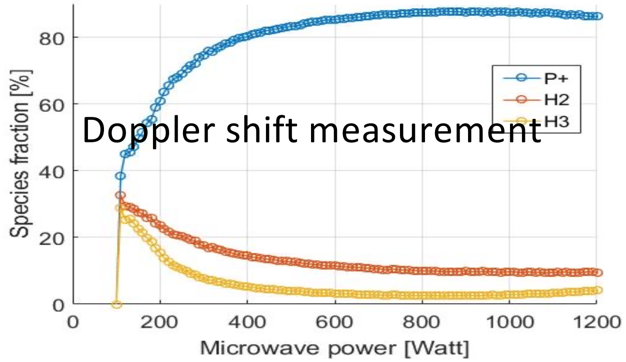


Pulse to pulse stability < ± 3.5%



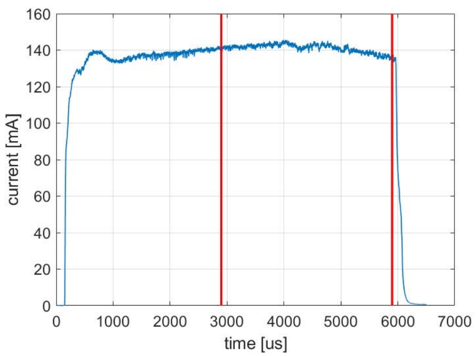
Minimum proton current range 67-74 mA

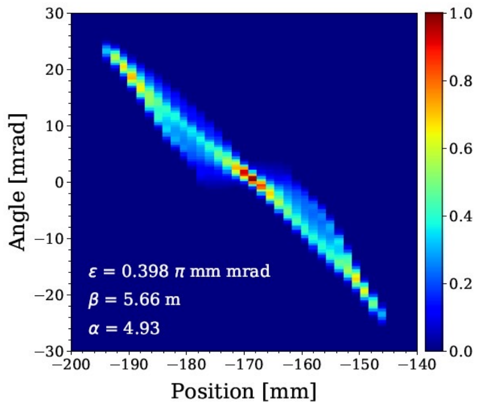


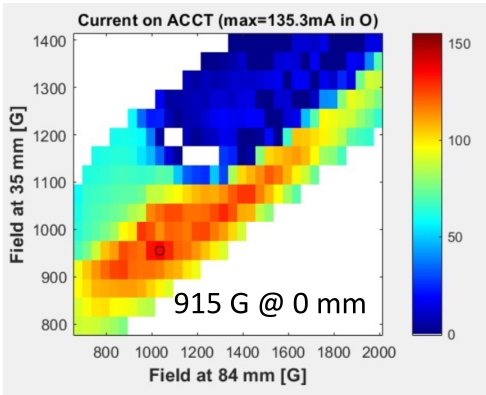


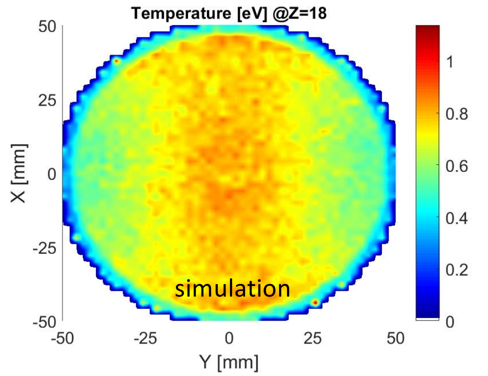
High Stability Microwave Discharge Ion Source

MDIS





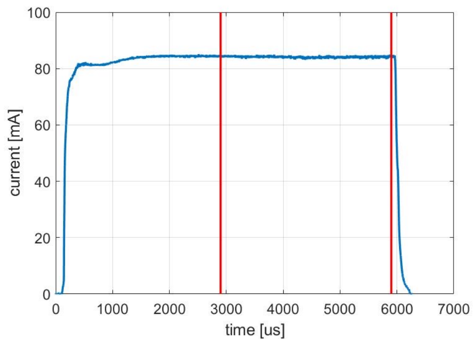


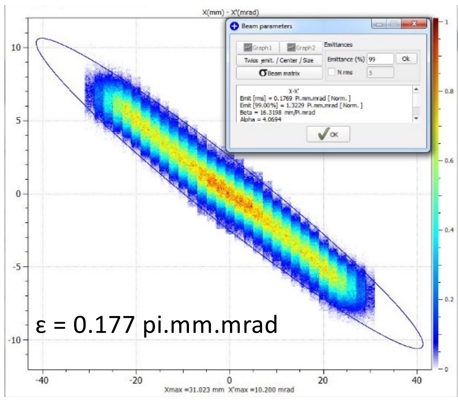


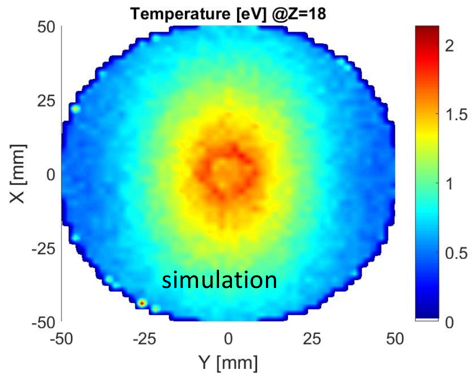
Goal 1: In-depth study of the largest dataset ever collected on this type of source (55000 source configurations)

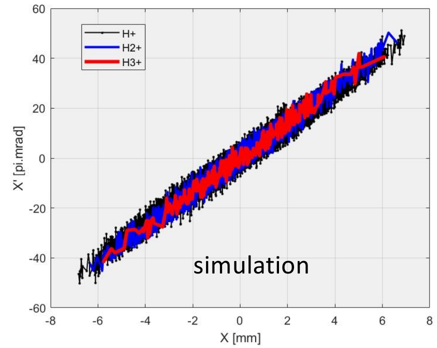
Goal 2: Ion source simulation tool development (from plasma formation to beam extract)

HSMDIS









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The future challenges

- Higher charge states required for heavy ions;
- Higher intensities are required for q/m > 0.3;
- Better brightness;
- Improved stability (1% or better);
- Metallic species reproducibility;
- High absolute ionization efficiency for rare elements;
- Improvements on magnets and generator technology;
- New heating schemes?

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Co-innovation

- Partnerships will be mandatory for high quality mechanical manufacturing;
- Specific procurements will be more and more demanding, i.e. microwaves generators and couplers, high voltage power supply, cryogenics, magnets production, vacuum setups, computer control (unmanned operation is yet available for many sources);
- Developments of specific projects according to the industrial needs is welcome (e.g. for microelectronics and for surface treatments);
- Stability and reproducibility are still to be improved and an industrial management may be helpful, especially for metallic species;
- Medical facilities are expected to need more ion sources and higher performances
- High current proton beams and light ion beams will be more and more useful for applications and the issue of minimization of construction costs needs coinnovation