First year of operation of SPIDER, prototype source of ITER neutral beam injectors

G. Serianni on behalf of NBTF team and

contributing staff of ITER-IO, F4E, INDA, QST, NIFS, IPP and other European institutions

Consorzio RFX, Padova, Italy

Outline

- Few physics issues of neutral beams
- Main SPIDER components
- First operations of SPIDER, ion source of ITER Neutral Beam Injectors
  - First characterisation of beam

SPIDER: full scale prototype of HNB/DNB source

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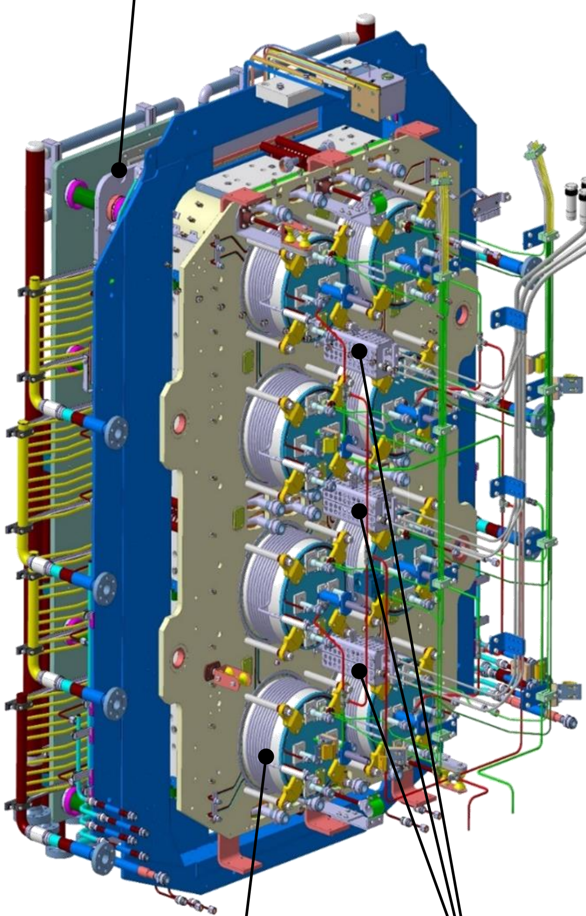
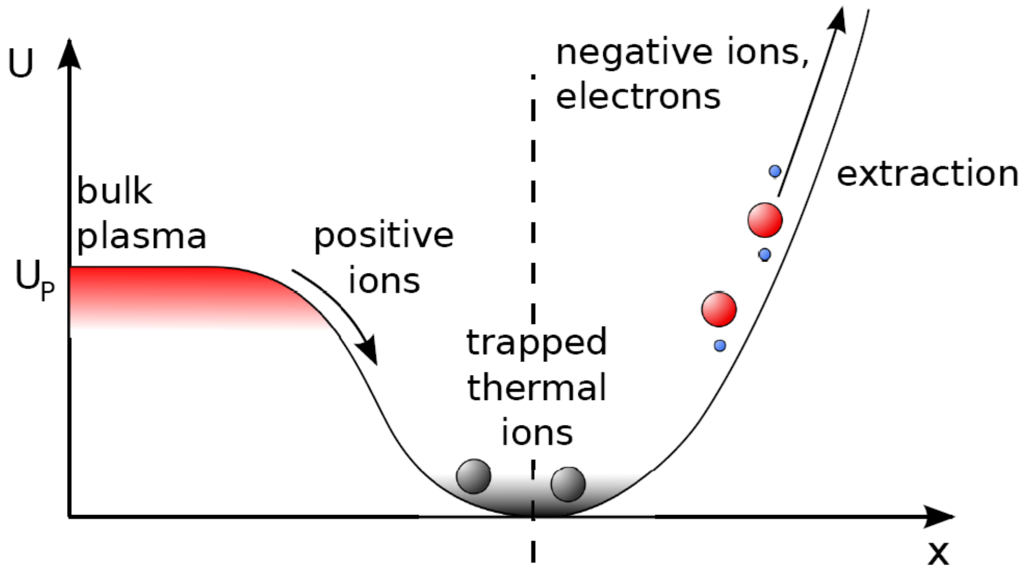


- Optimisation of production of negative ions in terms of:
  - Density
  - Uniformity
  - Stability
  - Co-extracted electrons

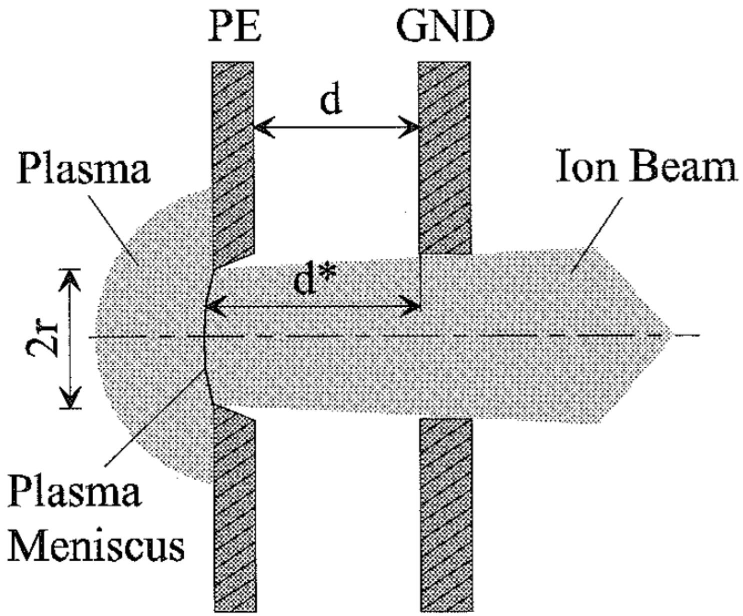
	Unit	H	D
Beam energy	keV	100	100
Maximum Beam Source pressure	Pa	<0.3	<0.3
Uniformity	%	±10	±10
Extracted current density	A/m^2	>355	>285
Beam on time	s	3600	3600
Co-extracted electron fraction (e^-/H^-) and (e^-/D^-)		<0.5	<1

Beam extraction: meniscus

- Boundary/interface between (source) plasma & beam (accelerator)
  - Debye sheath, trapping positive ions, allowing extraction of electrons and H^-
- Co-extracted electrons
- Meniscus curvature helps beam focussing



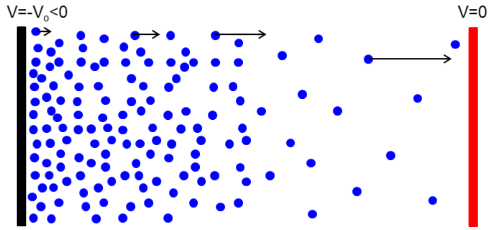
T. Kalvas, CERN Accelerator School 2012



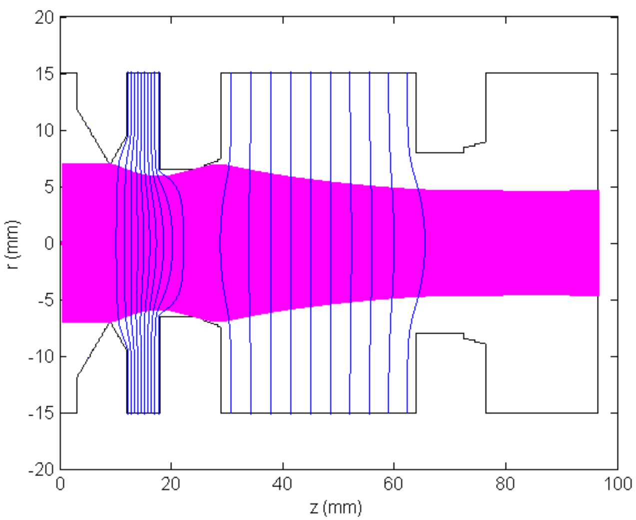
I. G. Brown, The Physics and Technology of Ion Sources, Wiley

Perveance

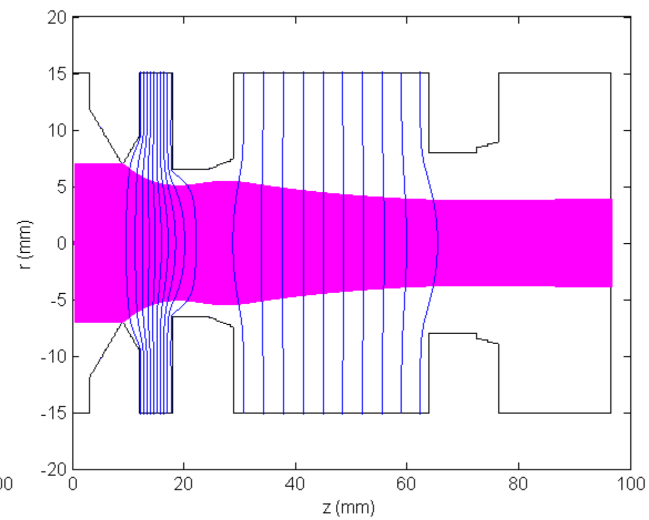
- From Child-Langmuir law: $P = \frac{I}{V_o^{3/2}} = \frac{4}{9}\varepsilon_o\sqrt{\frac{2Ze}{m}}\frac{\pi r_a^2}{d^2}$



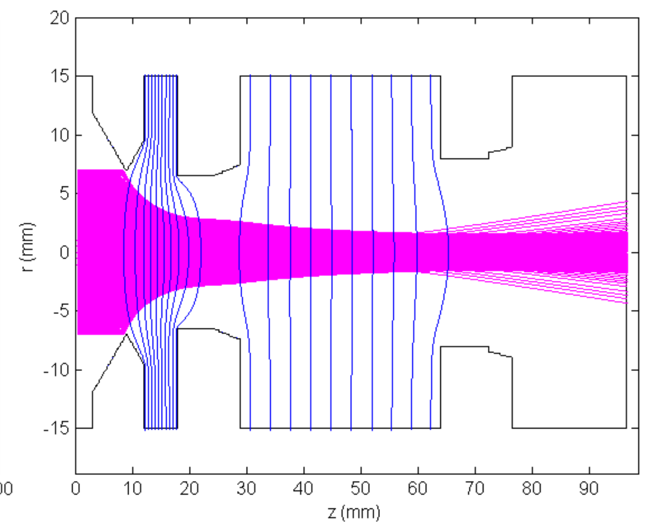
461A/m²



355A/m²



177A/m²



Over-perveant beam:
increased divergence!
If too large current density,
particles repel each other

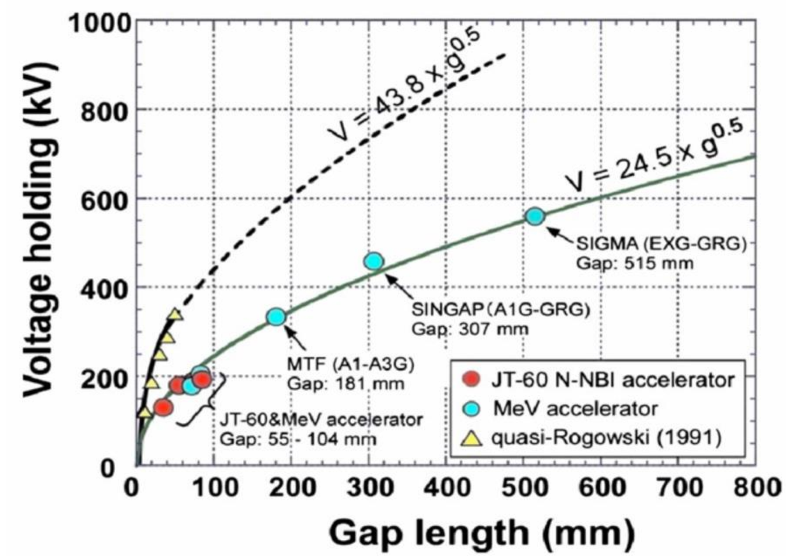
Optimal perveance

Under-perveant beam:
increased divergence!
If too few particles, trajectories
are squeezed by electric field

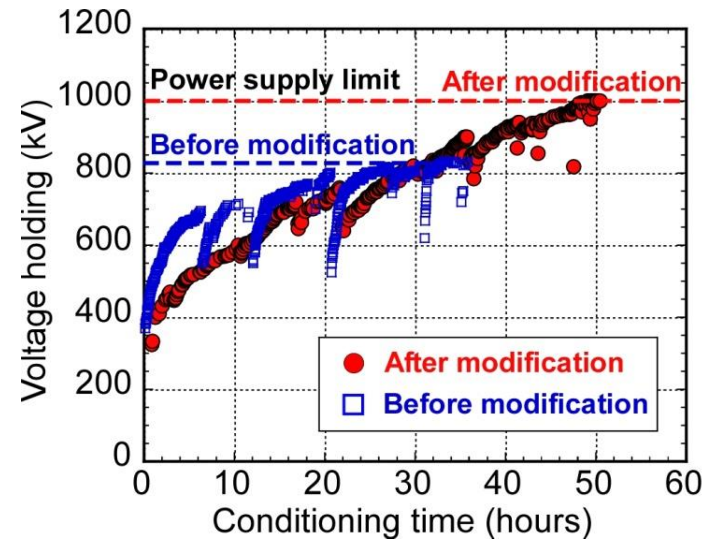
High voltage: issue

- Acceleration to 1MeV
  - Voltage holding can be an issue in multi-aperture accelerators
    (dashed line: parallel planar electrodes)
- Breakdown voltage ~(gap length)$^{1/2}$

Brown, The Physics and Technology
of Ion Sources, Wiley



- Accelerator conditioning required

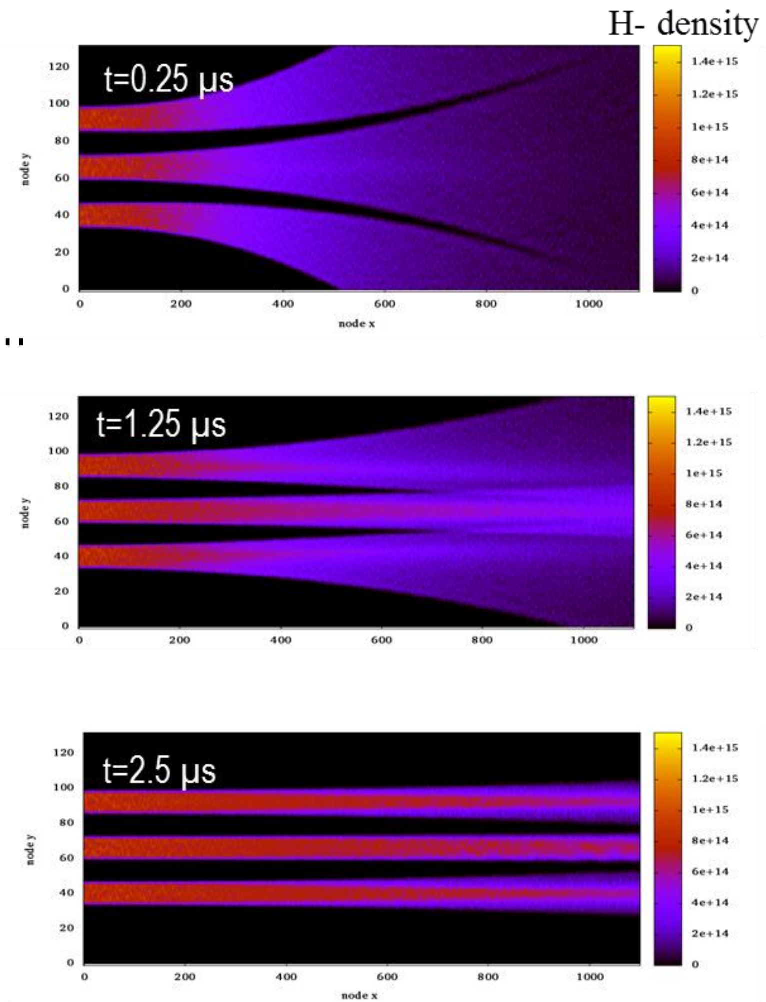


E. Spada et al., IEEE Trans. Plasma Sci. **47**, 2019 (2759)

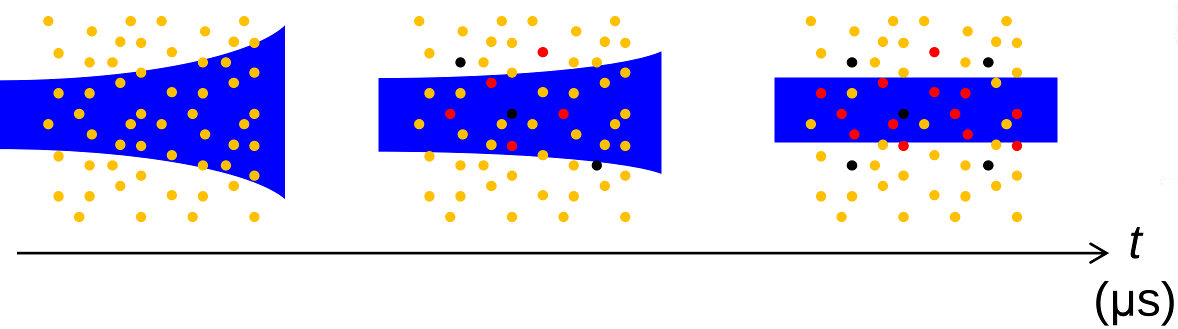
Drift region: space charge compensation

CONSORZIO RFX
Ricerca Formazione Innovazione

- Ionisation of background gas:
  - $\underline{H}^0 + H_2 \rightarrow \underline{H}^0 + H_2^+ + e$
  - Positive particle trapped in beam potential
  - Negative particles (electrons) ejected from bear.. region



- Stationary equilibrium reached:
  - Negative ion beams usually slightly overcompensated (unlike positive ion beams)



E. Sartori et al., Rev. Sci. Instrum. **87** (2016) 02B917

On-going activities: inductively-coupled RF plasmas, operation and modelling

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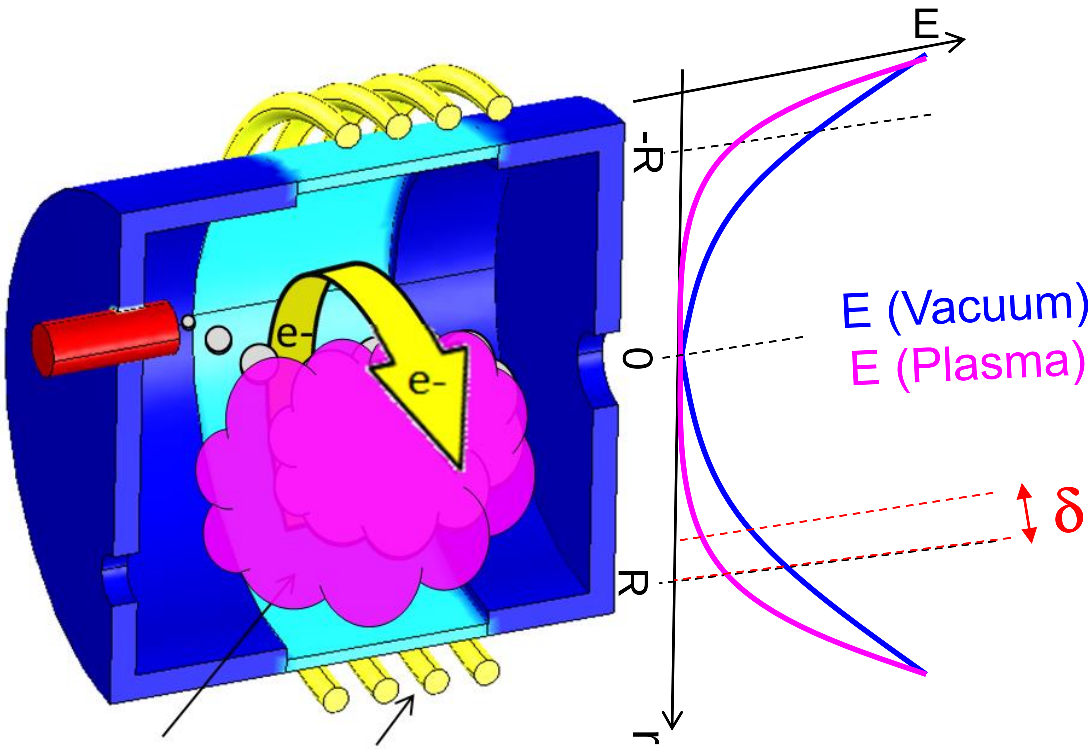
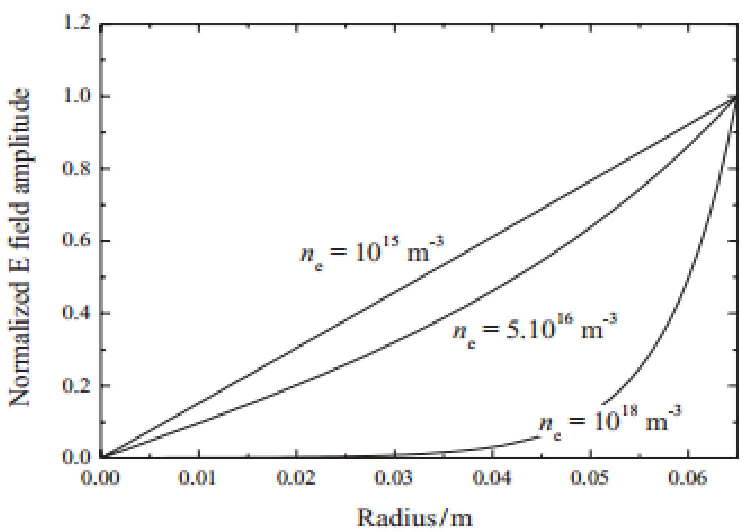
- Particle regime
  - electric field forces electrons to oscillate
  - when plasma is created it shields E field: i.e. wave is attenuated
  - E field drops with typical length scale (skin depth)



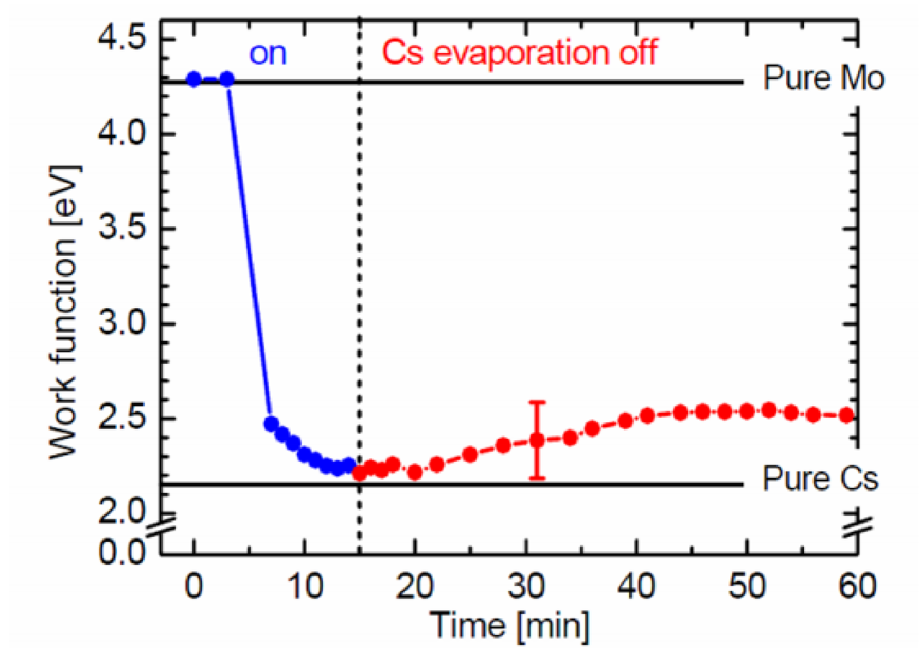


P. Chabert, Physics of RF Plasmas, Cambridge Univ. Press

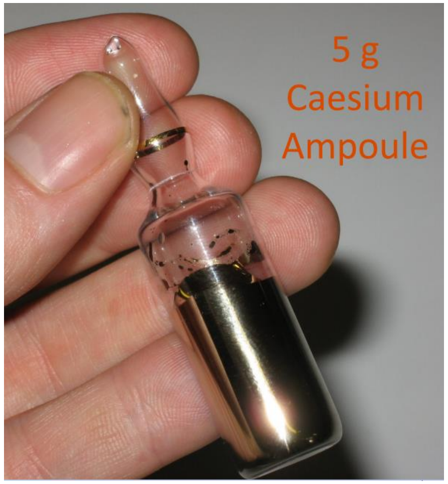
On-going activities: caesium management and modelling

- Small quantity of caesium vapor increases negative ion yield

- The work function is reduced (≈pure Cs)
- Source Conditioning needed
- Plasma grid temperature >140°
- Source body temperature 35°C to avoid trapping of Cs on the walls
- Many plasma pulses to distribute Cs



W. Kraus, CERN Accelerator School



D. Faircloth, CERN Accelerator School

Surface Production:
- Need for Caesium
- Poor reproducibility
- Negative ion flux limited by space charge: plasma is needed

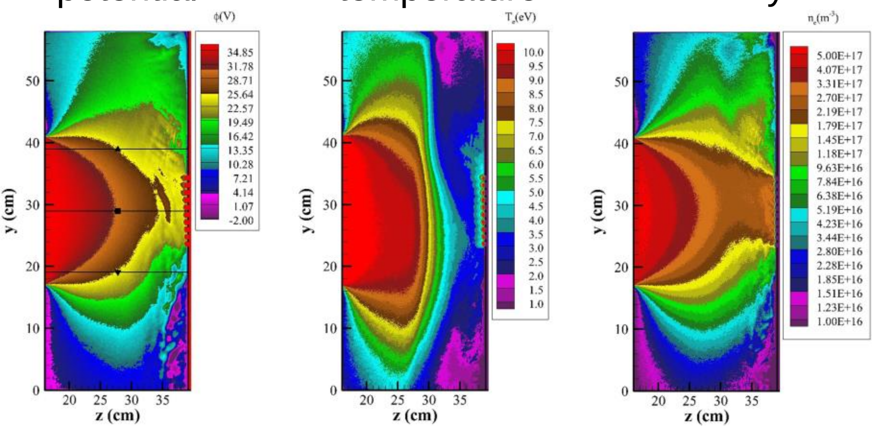
Vs.

Volume Production:
- ion currents < 30 A/m^2
- High co-extracted electron current

On-going activities: modelling of source and extraction

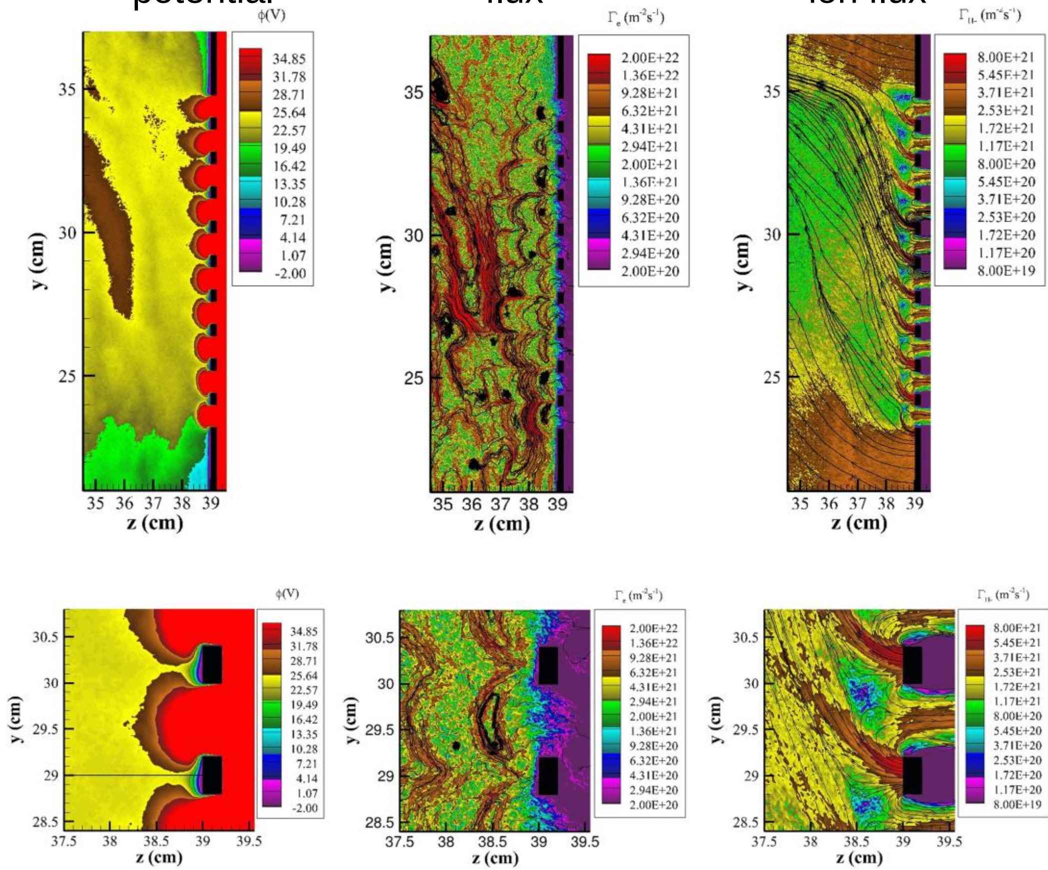
Plasma modelling

Electric potential | Electron temperature | Electron density



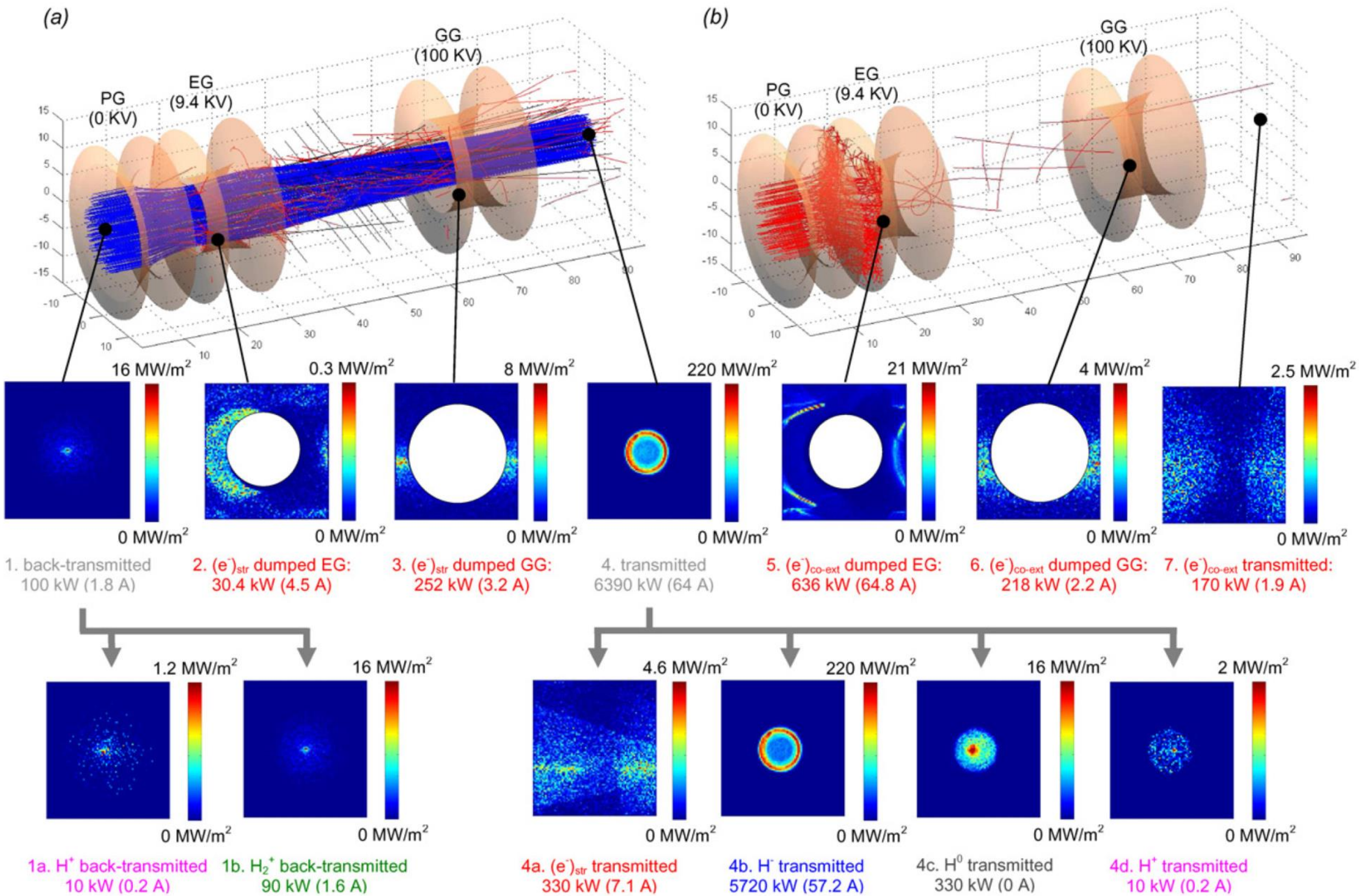
Beam extraction modelling

Electric potential | Electron flux | Negative ion flux



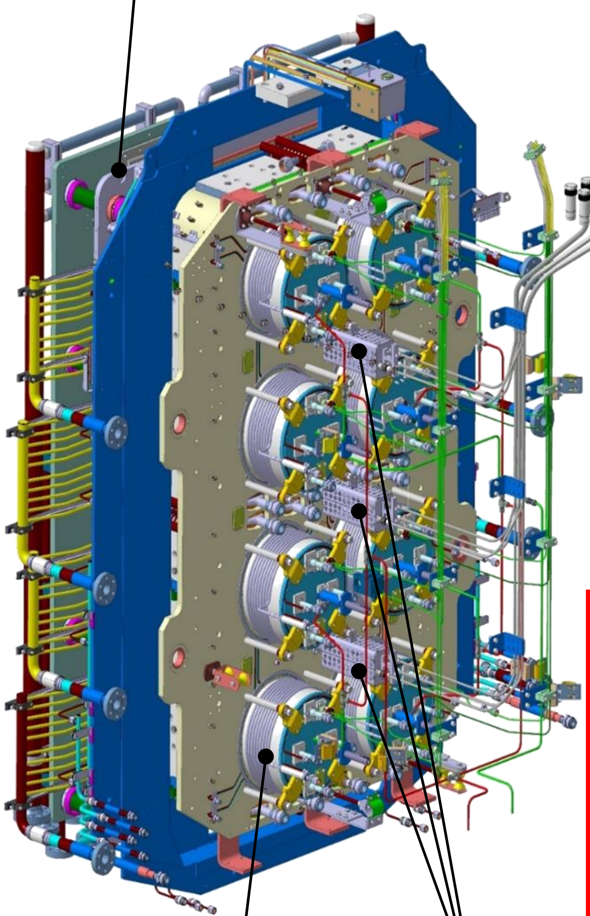
F. Taccogna, P. Minelli, New J. Phys. **19** (2017) 015012

On-going activities: beam transport modelling



P. Agostinetti et al., Nucl. Fusion **51** (2011) 063004

SPIDER: full scale prototype of HNB/DNB source



- Optimisation of production of negative ions in terms of:
  - Density
  - Uniformity
  - Stability
  - Co-extracted electrons

	Unit	H	D
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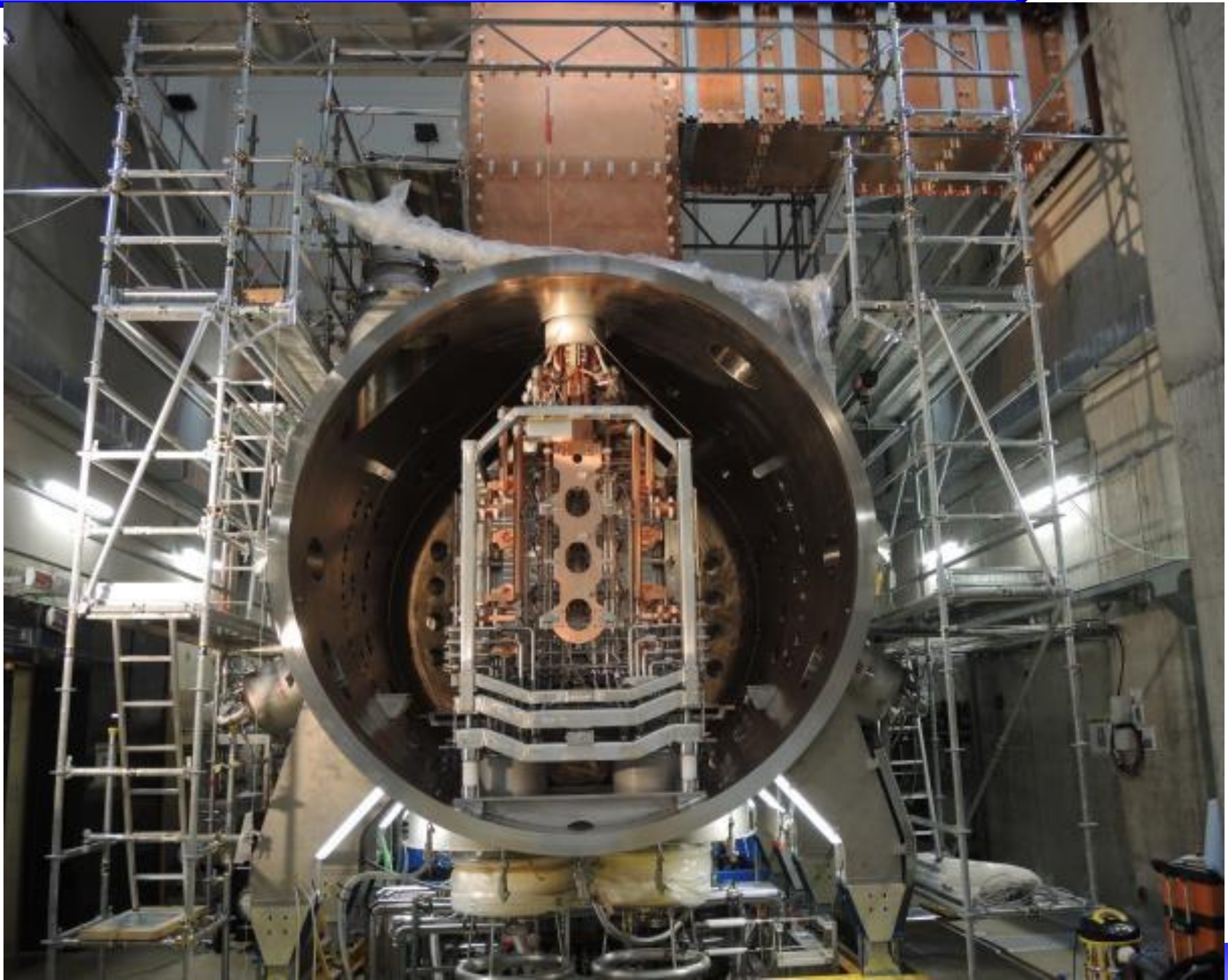
SPIDER beam source inside vacuum vessel



SPIDER beam source inside vacuum vessel

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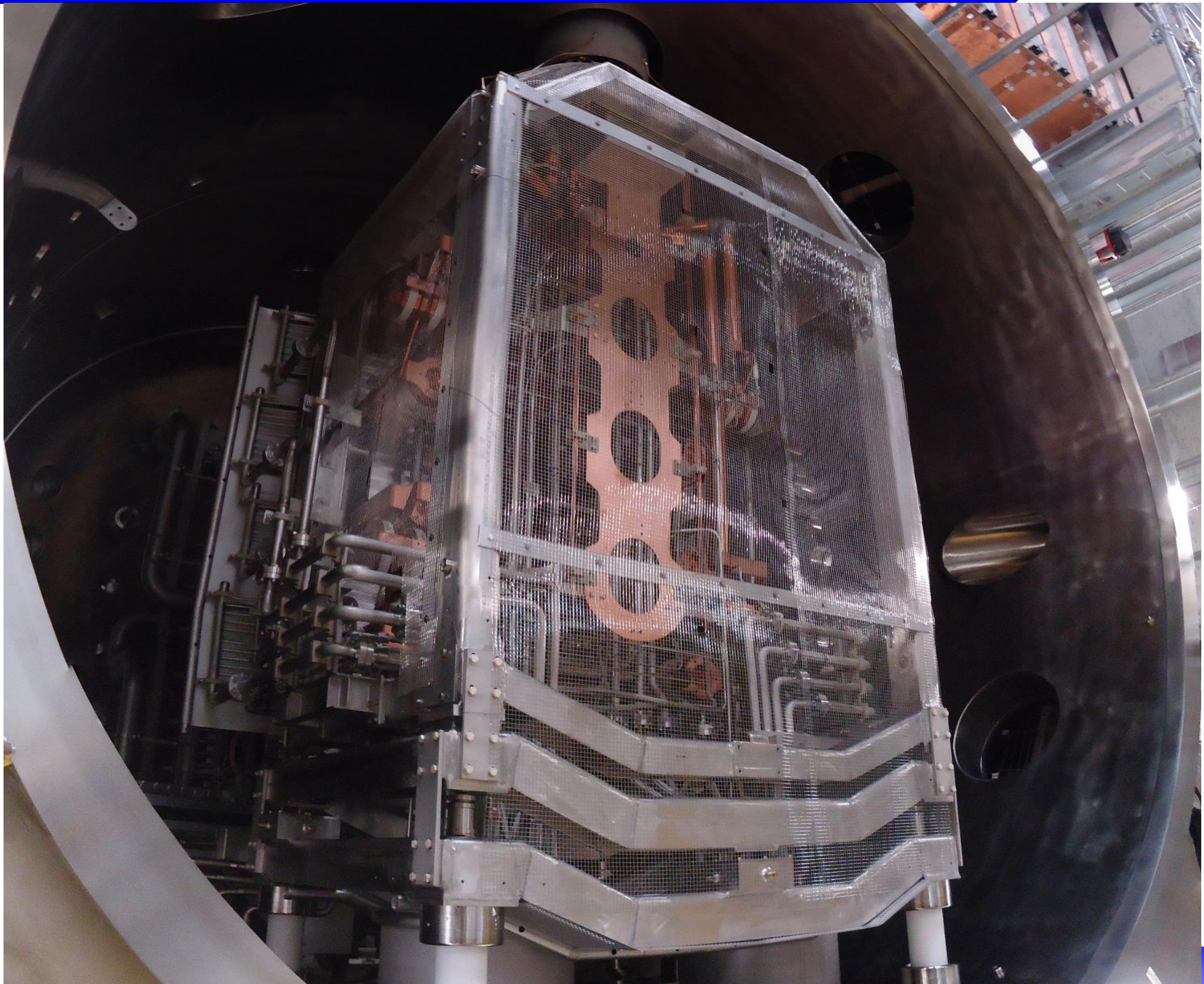
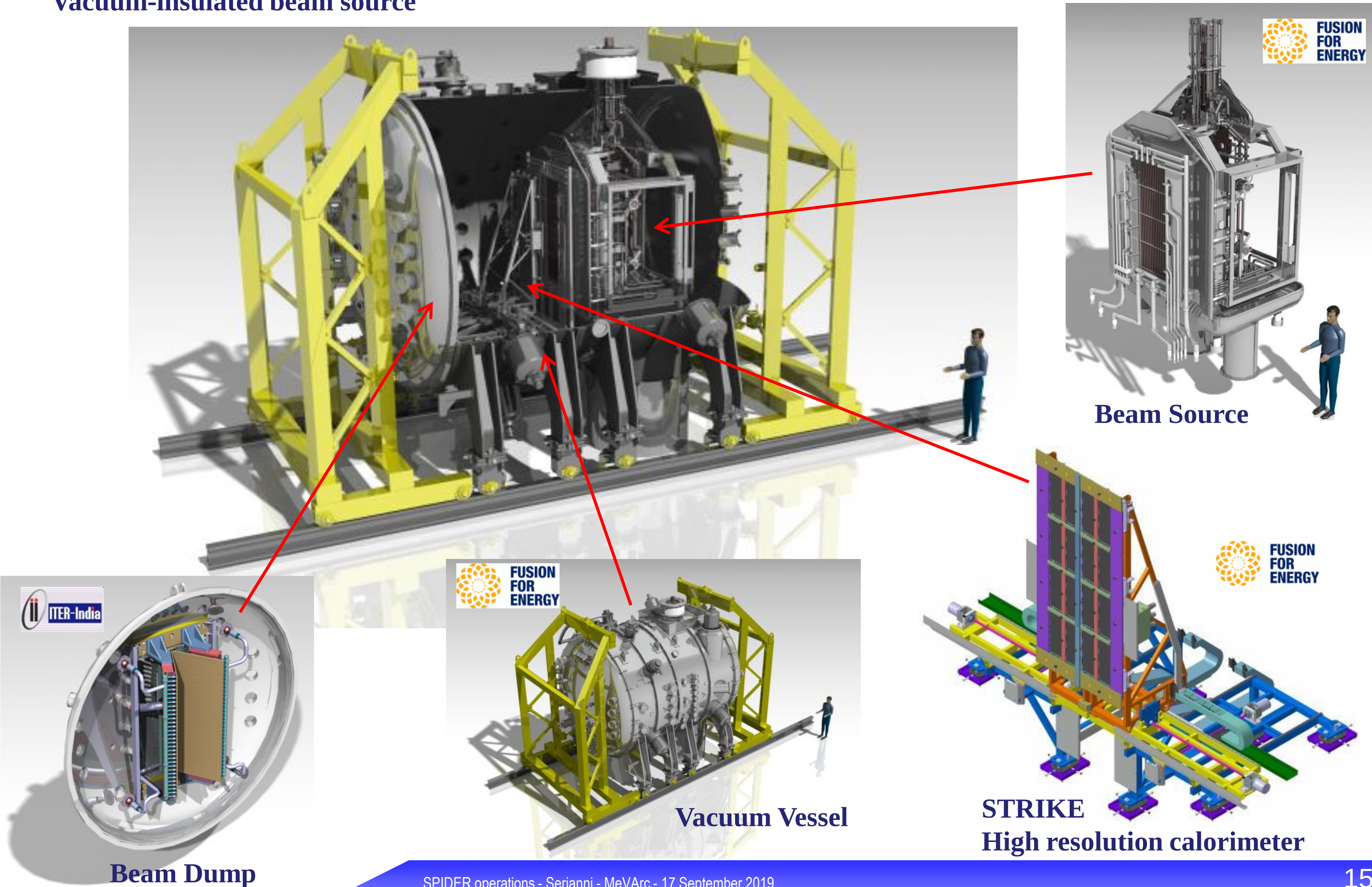


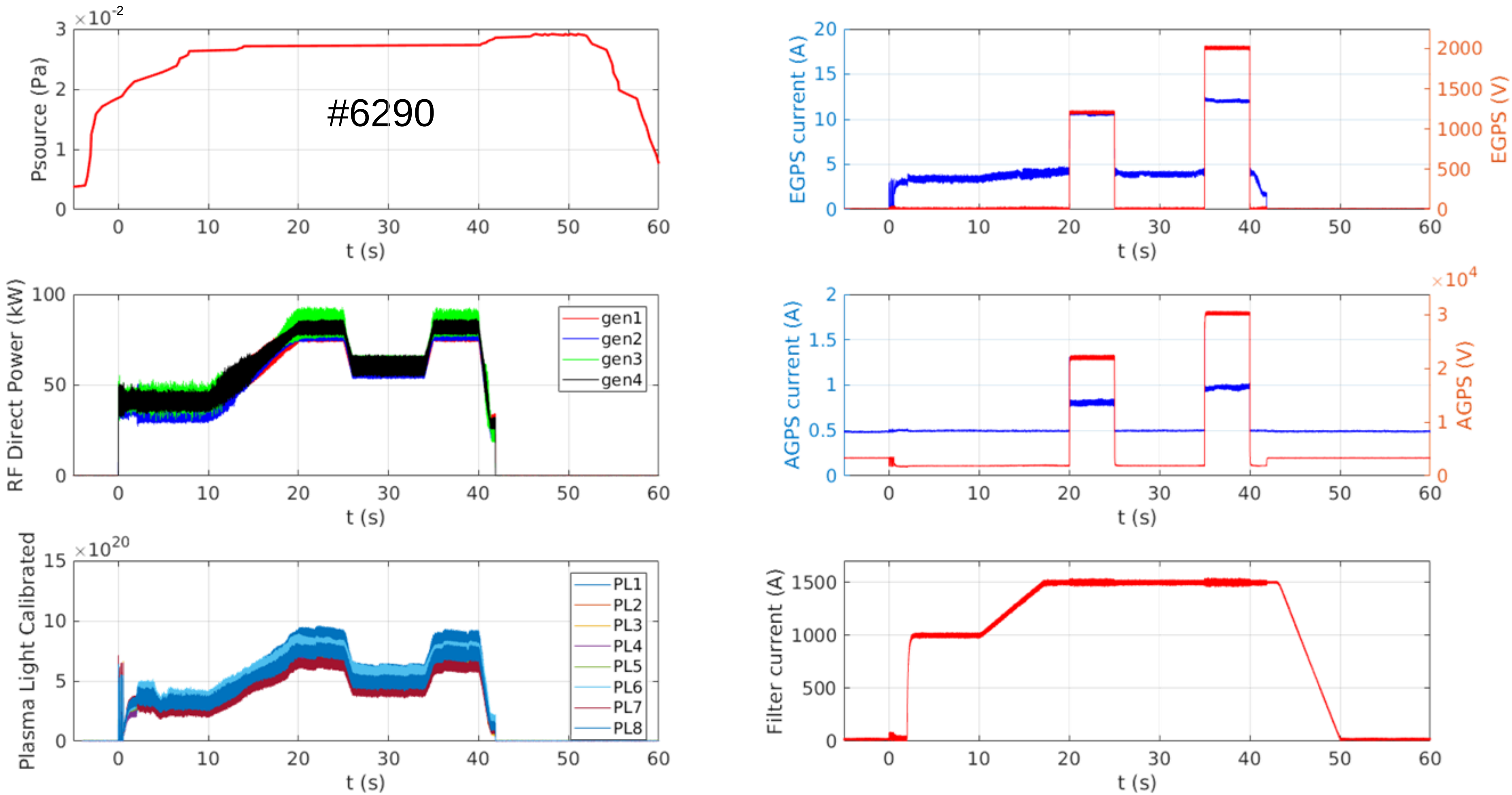
SPIDER Components

Vacuum-insulated beam source



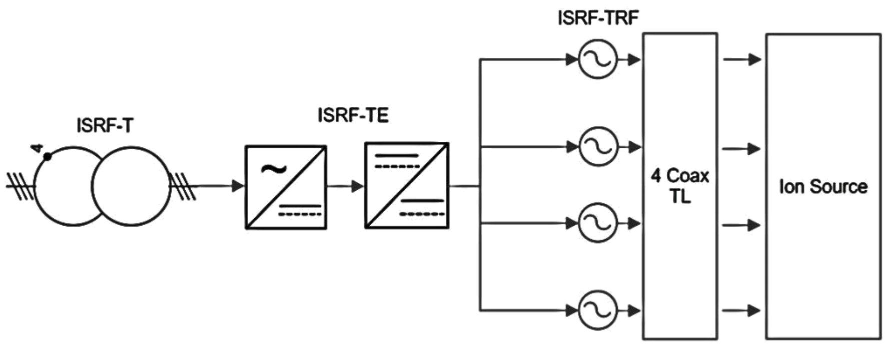
Example of beam pulse

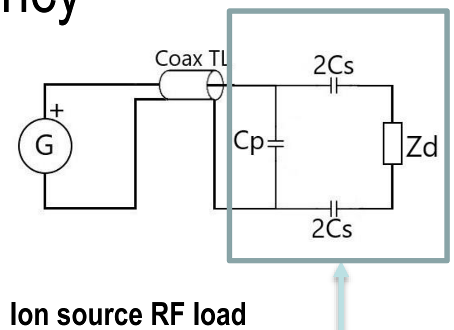
- Large flexibility of SPIDER control system



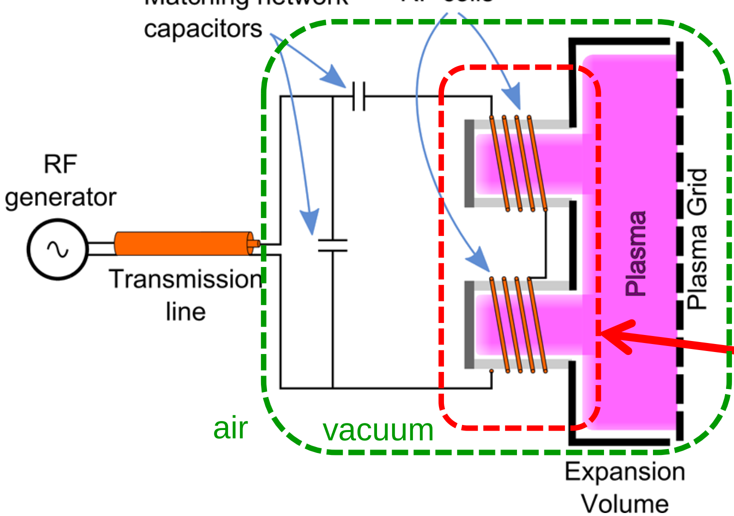
The SPIDER RF system

- **4 RF generators** (ISRF-TRF), transmission line (TL), ion source RF load
- Each RF generator: pair of **power tetrodes** in push-pull connection; **variable capacitor C_v** to tune operating frequency





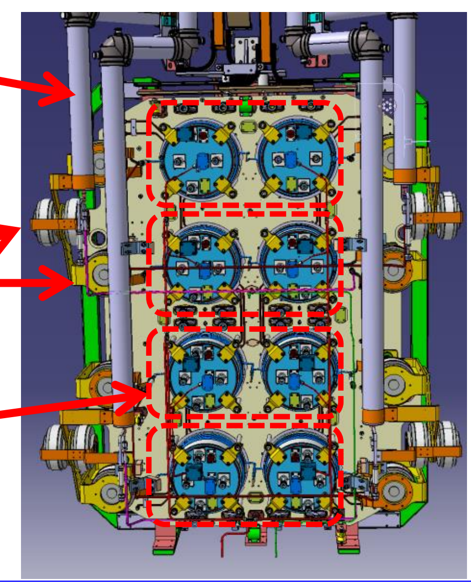
Ion source RF load



RF transmission lines connected to RF oscillators

Matching network capacitors

Driver pairs



ISRF1

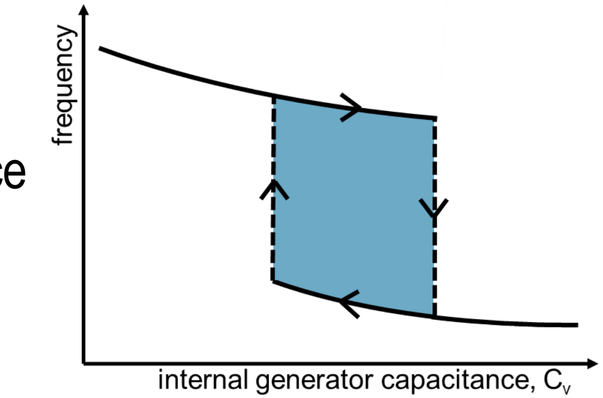
ISRF3

ISRF4

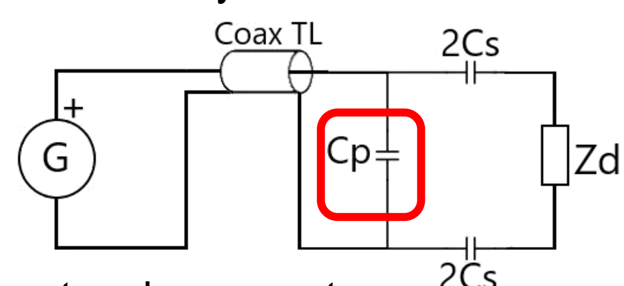
ISRF2

Improvement in RF power management

- **RF power limit** identified (80kW out of 200kW):
  - power transfer **depending** on equivalent load impedance
  - sudden **frequency flips** near impedance matching
    - RF power constrained, as observed in other facilities

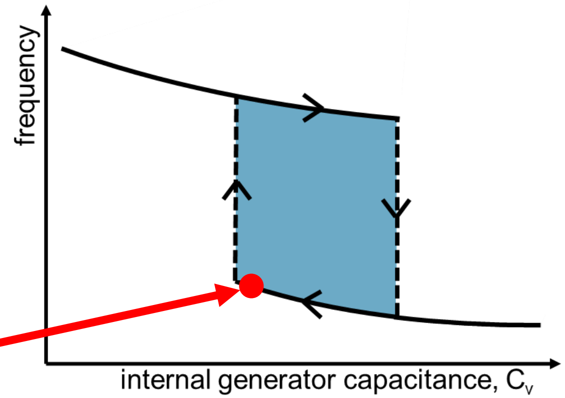


- Strategy:
  - implementation of **feedforward control** of capacitor of RF generators (C_v)
  - development of **model** reproducing different behaviours of ISRF system to:
    - support SPIDER operation
    - analyse its performances
    - help in achieving nominal performances
  - **experimental campaign** to analyse different matching network parameters
    - different parallel capacitors in different circuits: C_p = 5 nF; 6.5 nF; 10 nF (design value); 15 nF



Operation of single RF generators

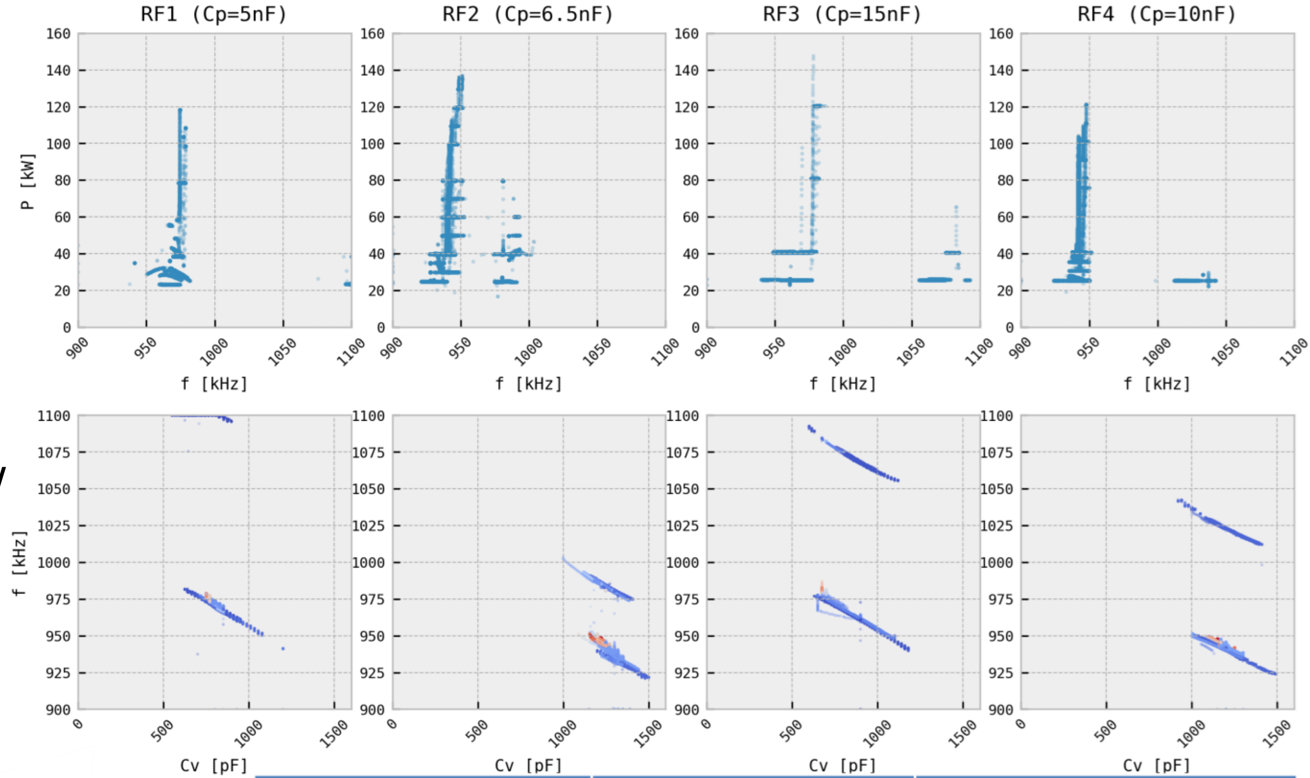
- Hysteresis depending on C_v observed and modelled
  - best C_v value near lower flip frequency

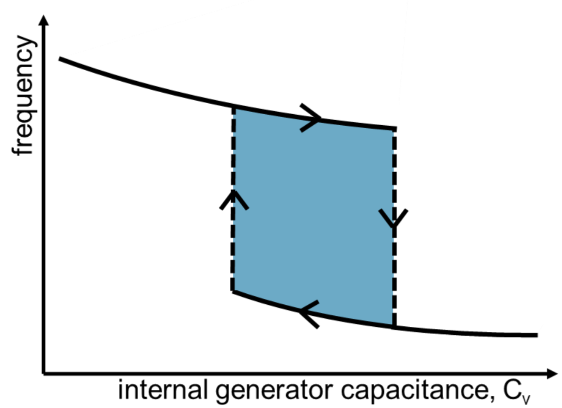


C_p [nF]	C_v [nF] limit
5 (RF #1)	0.76 ± 0.05
6.5 (RF #3)	0.88 ± 0.05
10 (RF #4)	1.22 ± 0.05
15 (RF #2)	1.3 ± 0.05

Operation of single RF generators

- Hysteresis depending on C_v observed and modelled
  - best C_v value near lower flip frequency
- RF power limit depending on C_p value

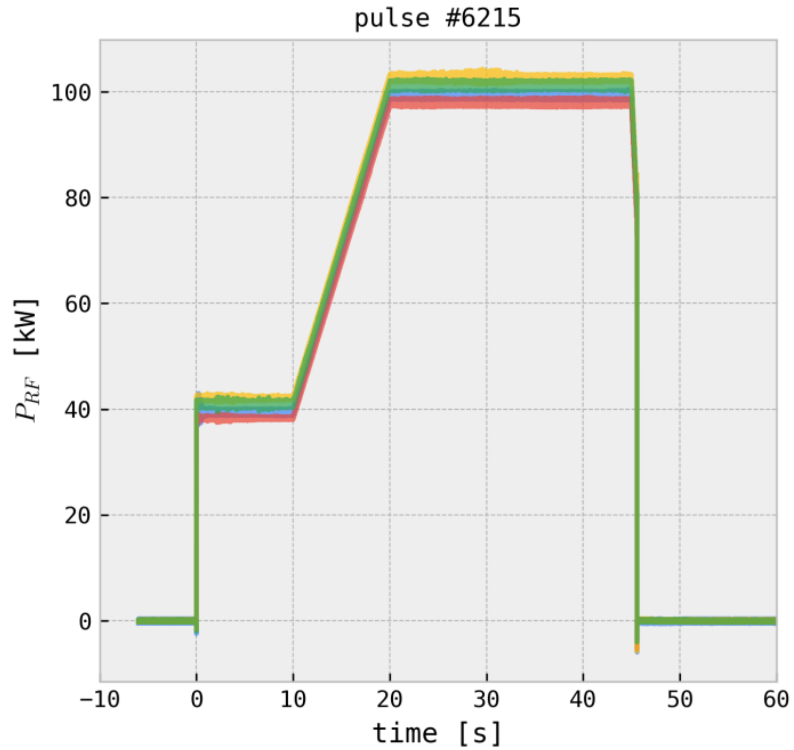




C_p [nF]	C_v [nF] limit	Maximum reached P_{RF} [kW]
5 (RF #1)	0.76 ± 0.05	120
6.5 (RF #3)	0.88 ± 0.05	150
10 (RF #4)	1.22 ± 0.05	125
15 (RF #2)	1.3 ± 0.05	135

Operation of single RF generators

- Hysteresis depending on C_v observed and modelled
  - best C_v value near lower flip frequency
- RF power limit depending on C_p value
- Simultaneous operation of 4 RF generators:
  - max RF power 100kW so far



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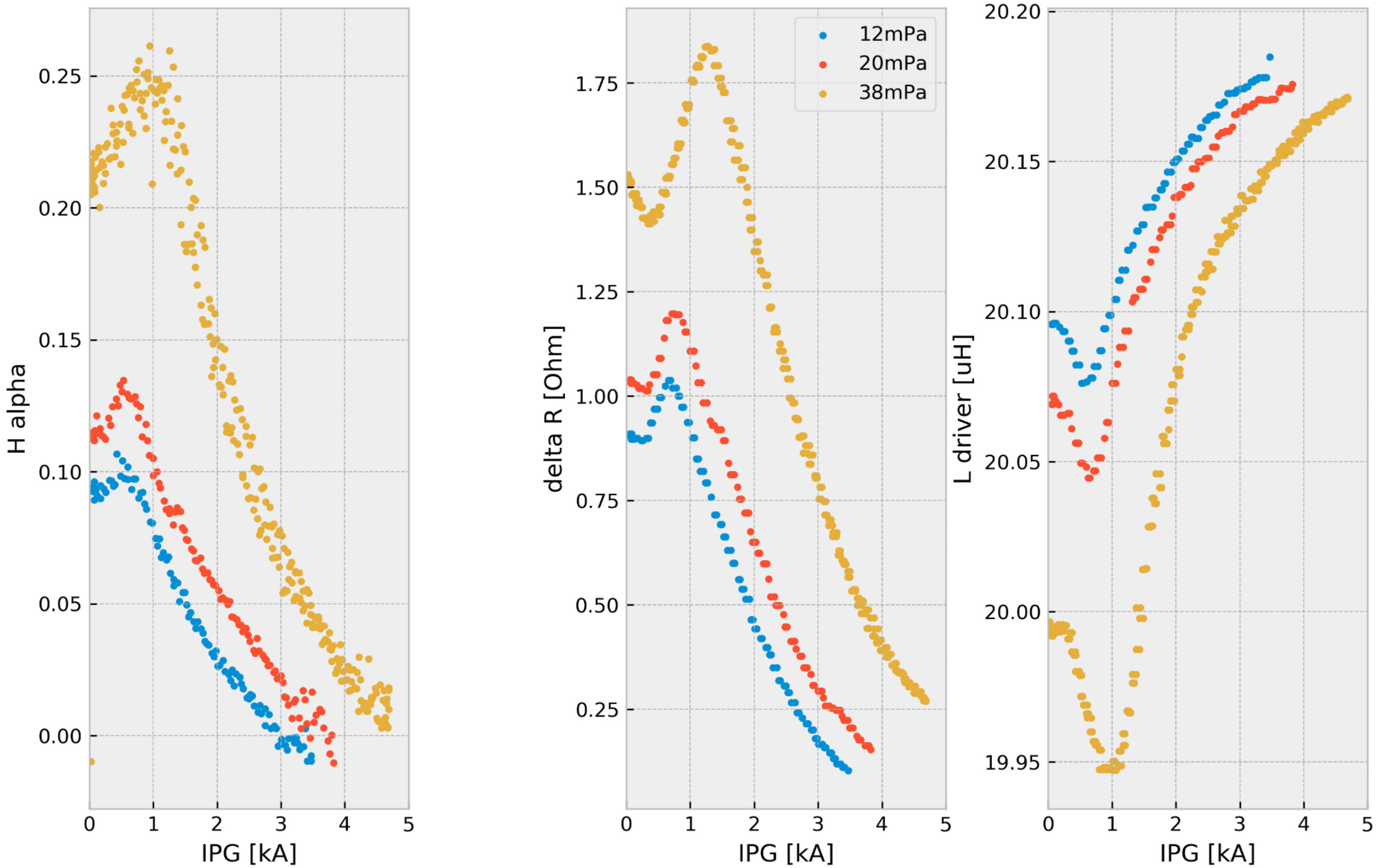
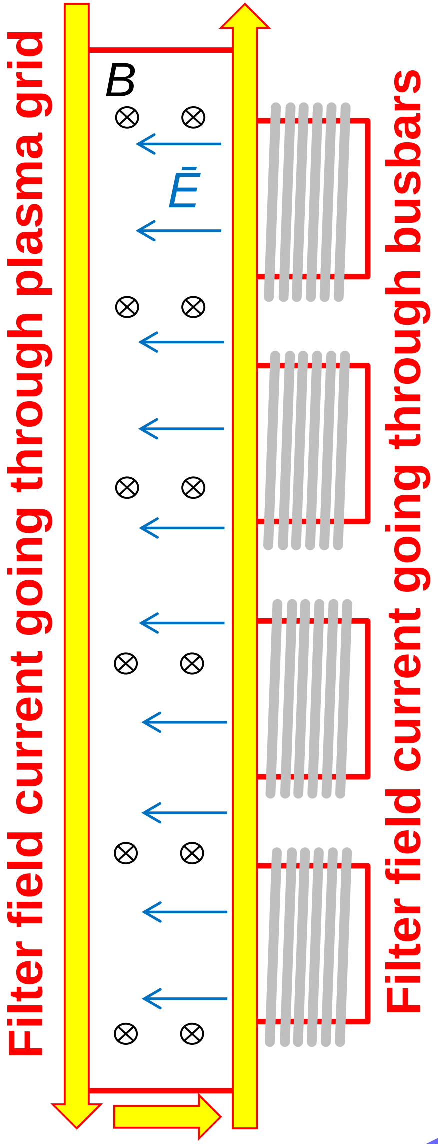
Experimentation with SPIDER filter field

- Effect of filter field on driver plasma



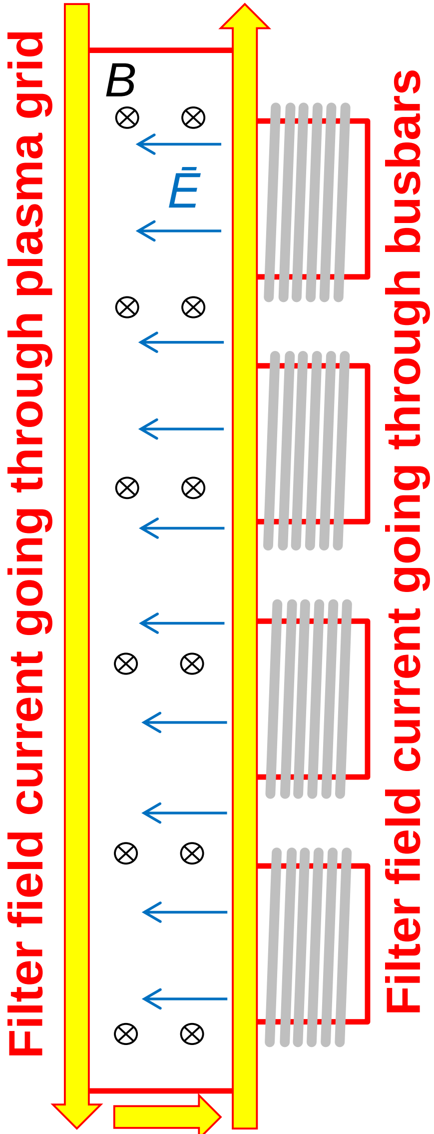
SPIDER filter field configuration

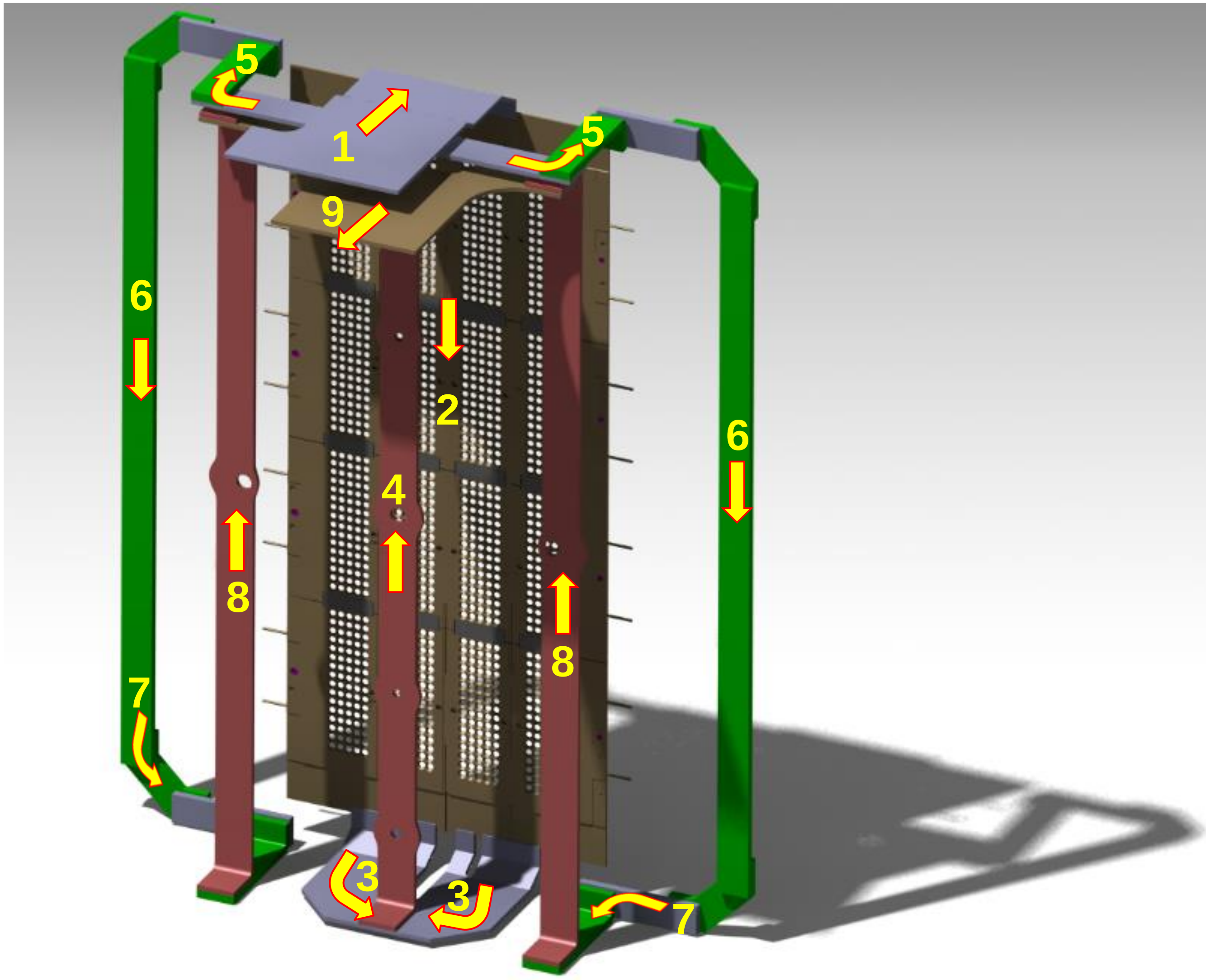
- Schematic path of filter field current



SPIDER filter field configuration

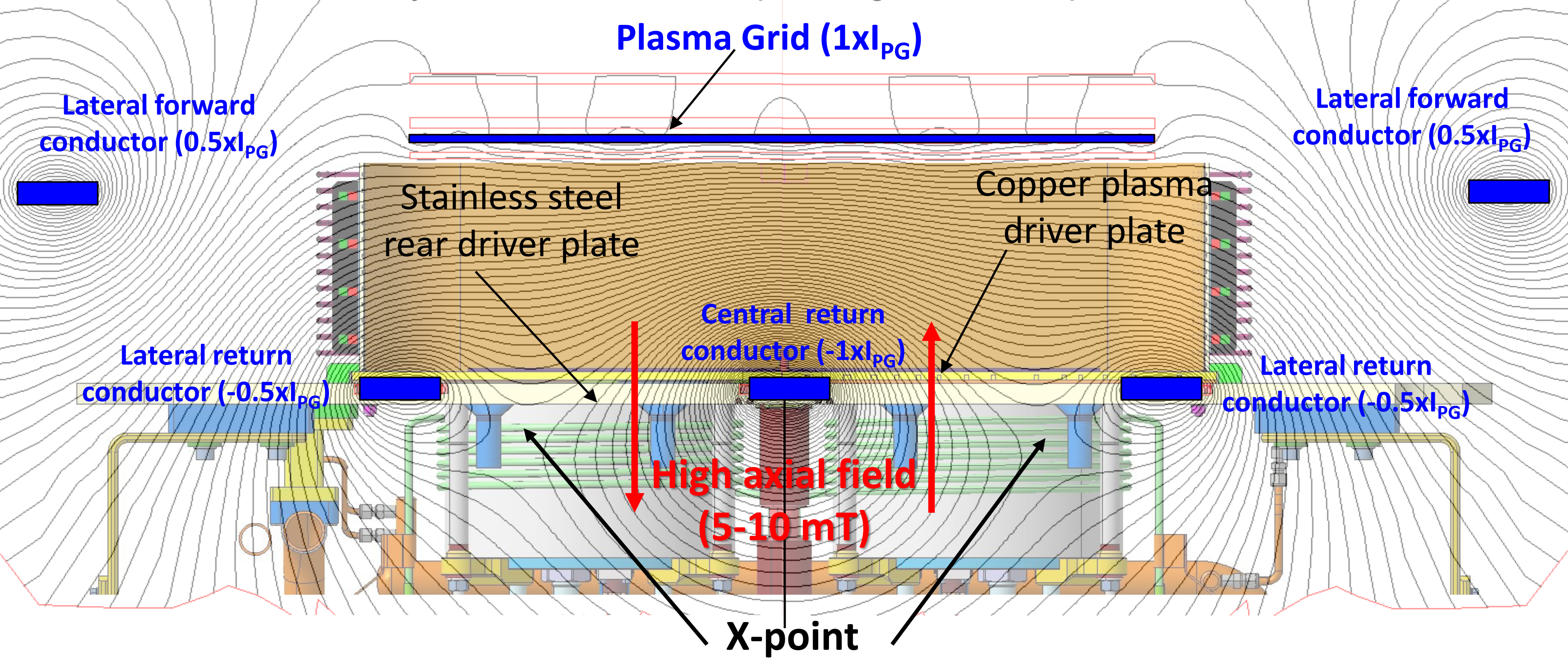
- Detailed path of filter field current





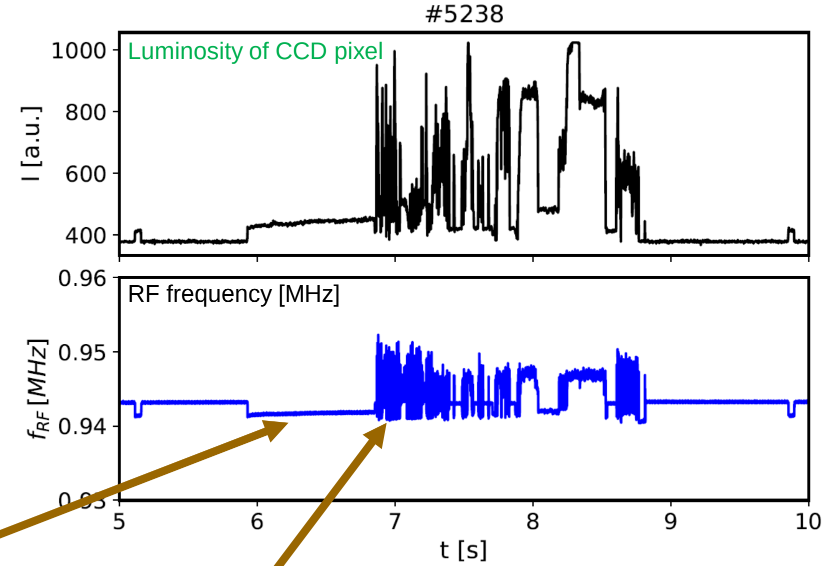
SPIDER filter field configuration

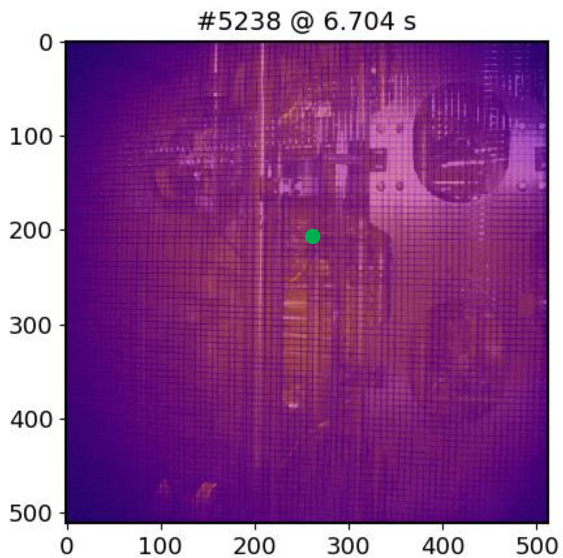
- Present filter field configuration:
  - PG busbar layout designed for: max B field strength and **uniformity** in plasma source (upstream of PG), B field **parallel** to PG, low B field in drivers
  - Non-uniformity of return currents implies high axial component of B field in drivers

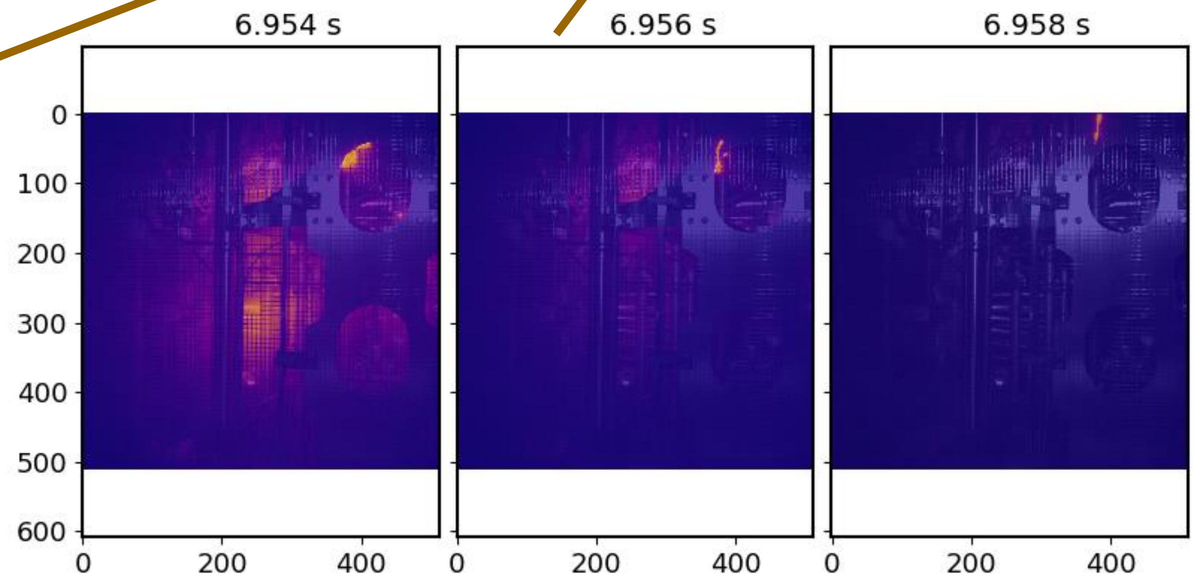


RF breakdown outside plasma chamber

- Beam source in vacuum
- Breakdown on source rear side due to RF:
  - analysis by fast cameras
  - investigation of pressure effect



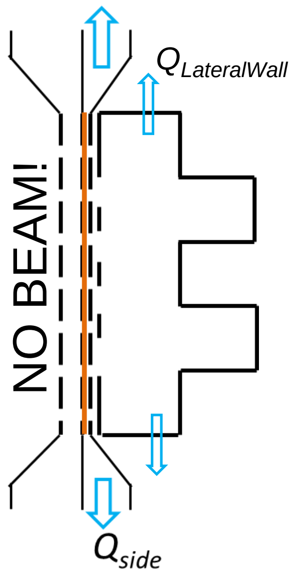




A. Zamengo, M. Agostini, RF Breakdowns in the SPIDER experiment during its first operational phase, MeVArc 2019

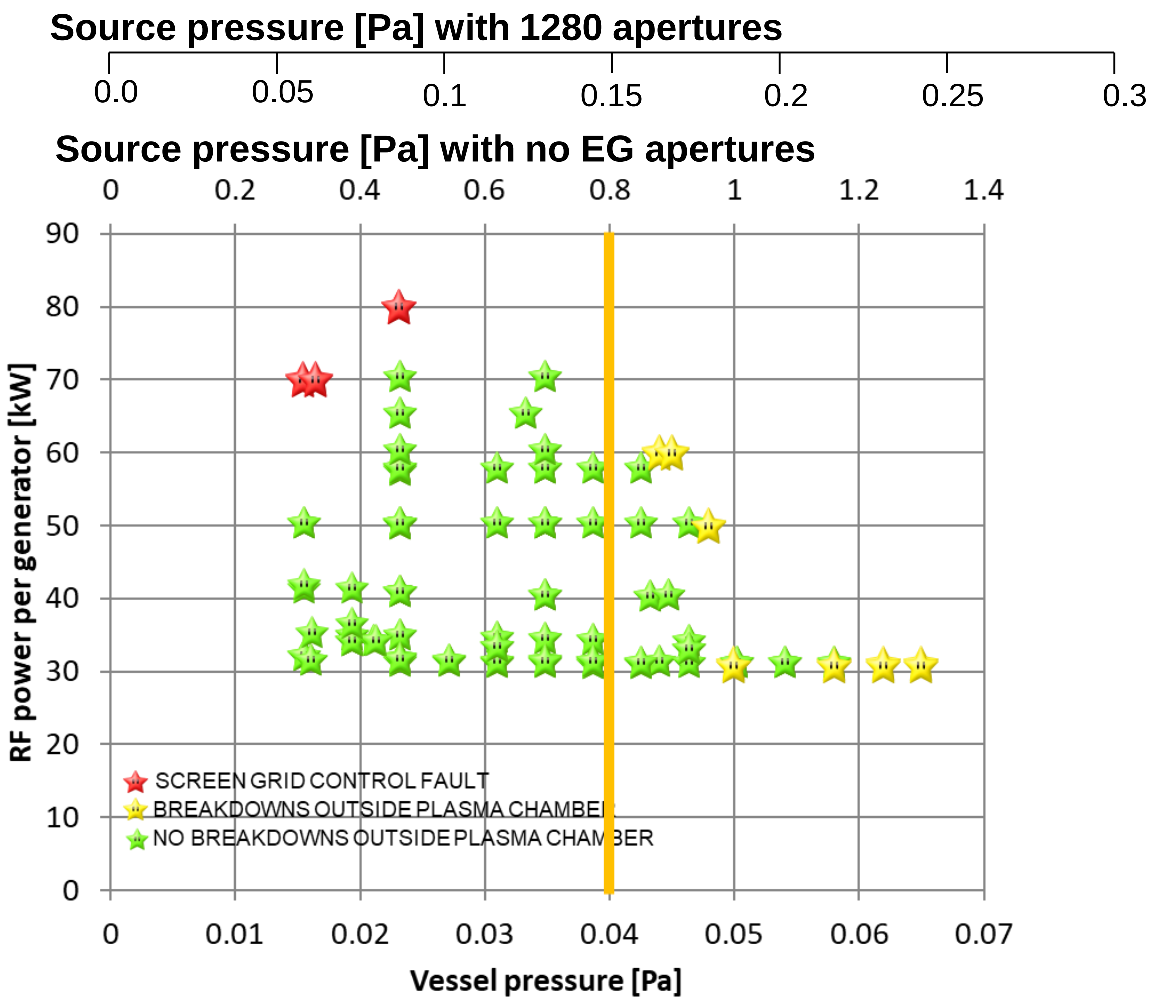
RF breakdown outside plasma chamber

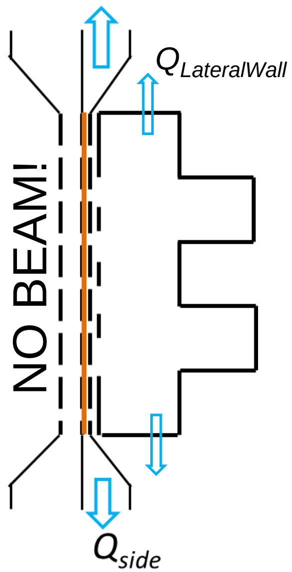
- Hypothesis: RF breakdowns induced by large background gas pressure
- Installation of mask on upstream side of EG
  - all EG apertures blinded



RF breakdown outside plasma chamber

- Identification of discharge conditions vs background gas pressure





RF breakdown outside plasma chamber

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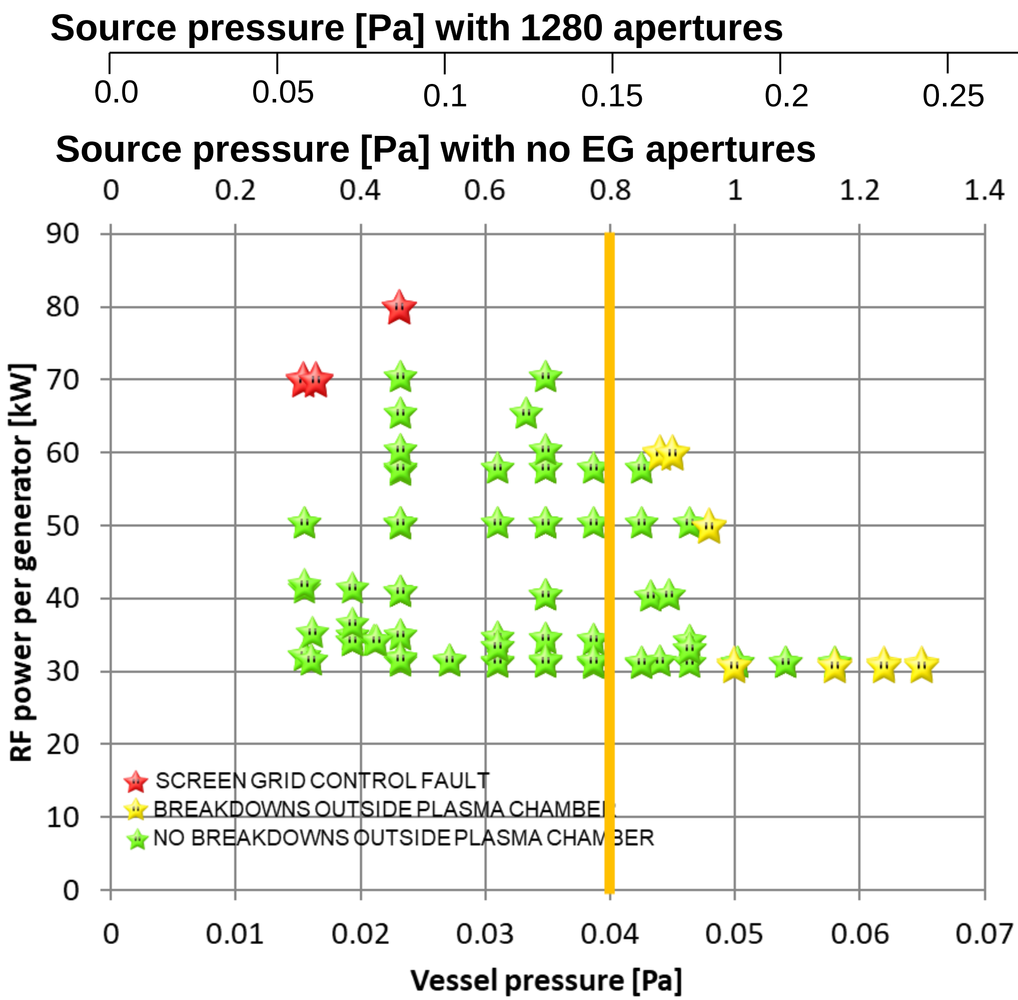
- Identification of discharge conditions vs background gas pressure



$p_{vessel} \approx 40$ mPa seems threshold for RF discharges

- More powerful pumping system required
- Long time scale

M. Siragusa et al., Numerical simulation of experimental tests performed on ZAO® Non-EvaporableGetter pump designed for NBI applications, ICIS2019, poster WedP50
M. Siragusa et al., Simulation of the gas density distribution in the accelerator of the ELISE test facility, ICIS2019, poster WedP15

RF breakdown outside plasma chamber

CONSORZIO RFX
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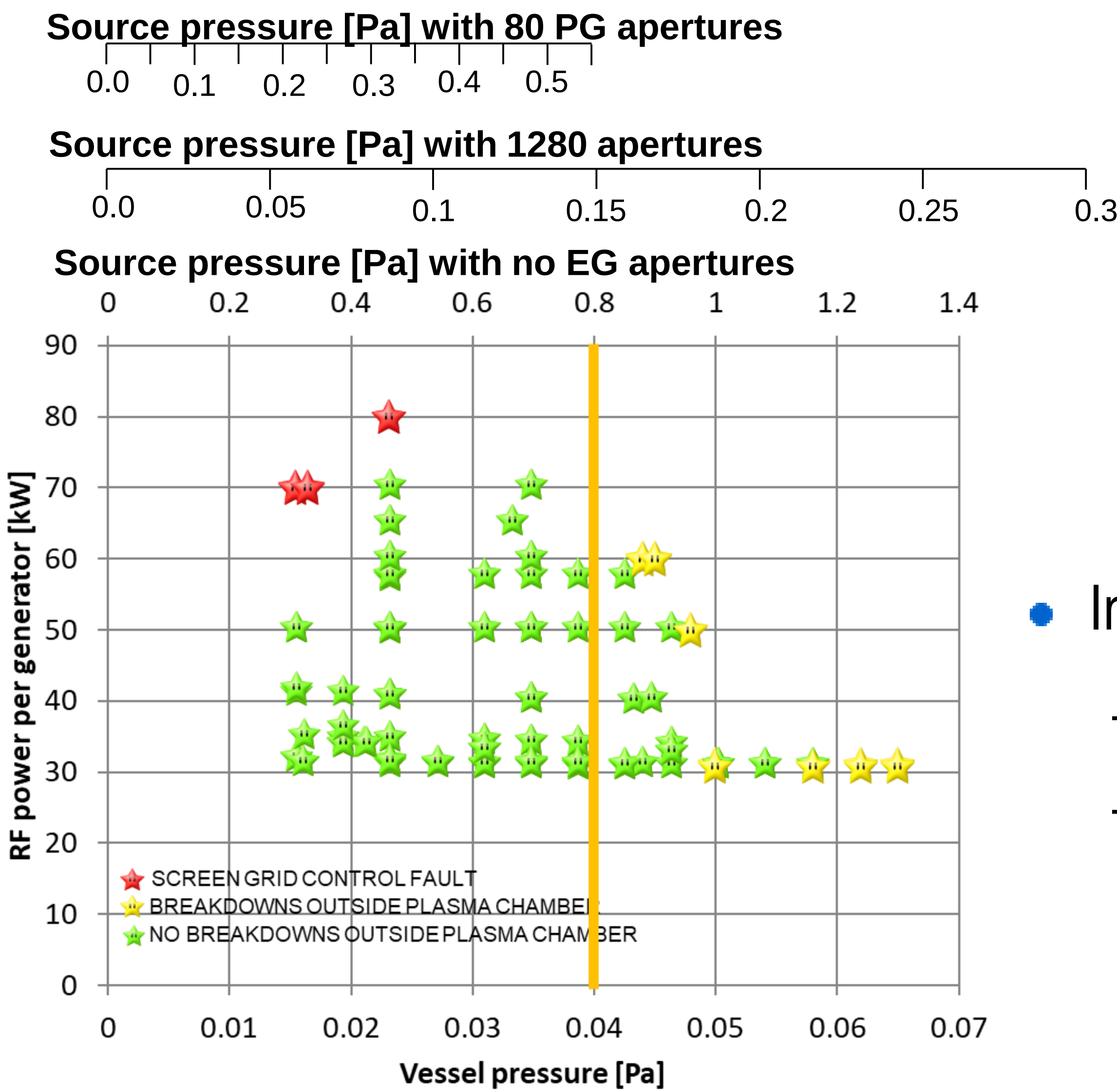
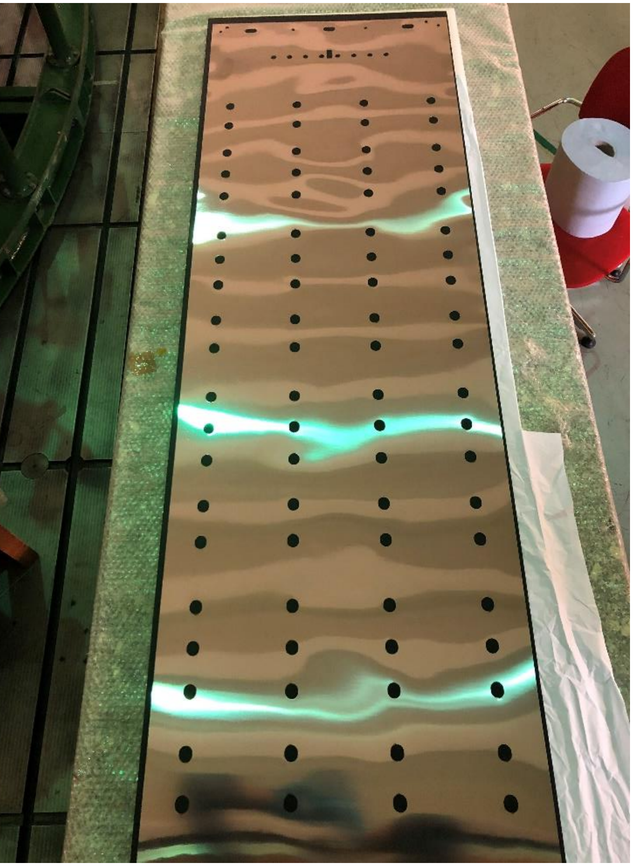


- In the meantime:
  - installation of plasma grid mask
  - number of beamlet determined by numerical simulations

Installation of plasma grid mask

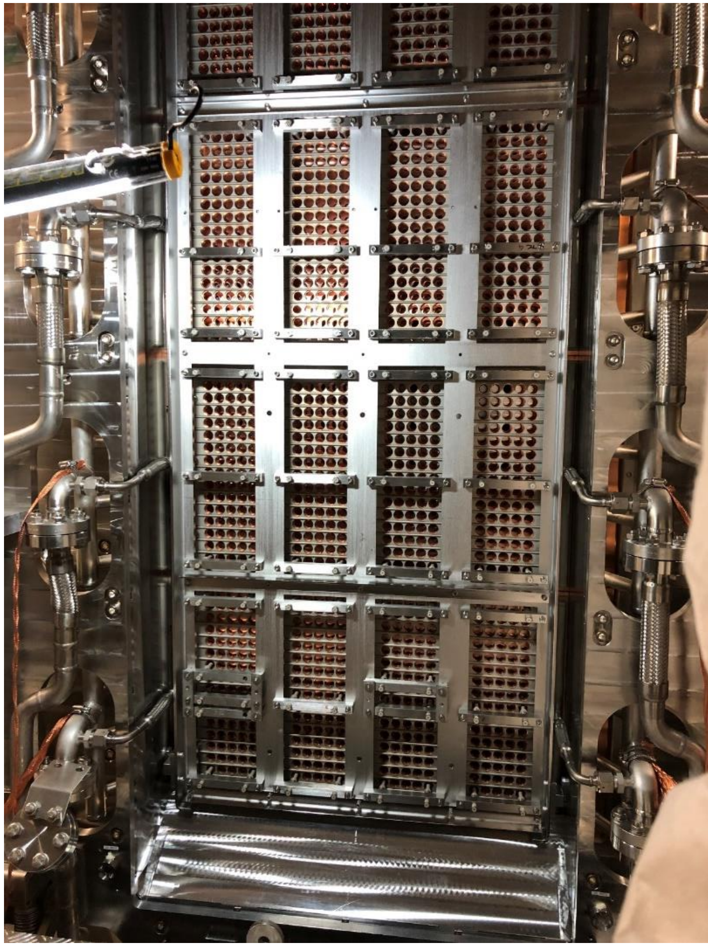
- No access from plasma side
- Installation between PG and EG

Molybdenum plate 0.25mm thick



Pushers press mask against PG, acting from GG
Pyrex pushers to be installed in view of Cs operation

View from downstream



A. Maistrello et al., Voltage Hold Off Test of the Insulating Supports for the Plasma Grid Mask of SPIDER, ISFNT2019, subm. Fusion Eng. Des.
M. Pavei et al., SPIDER Plasma Grid masking for reducing gas conductance and pressure in the Vacuum Vessel, ISFNT2019, subm. Fusion Eng. Des.

Main SPIDER diagnostic systems

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Source diagnostics:

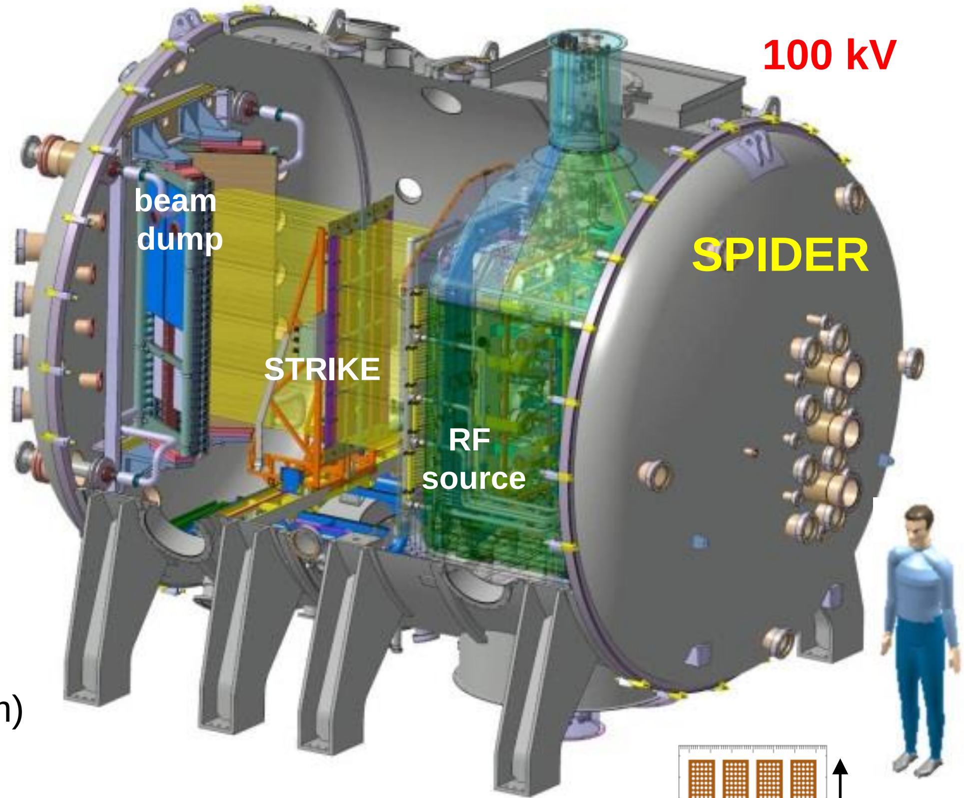
Electrical currents

Calorimetry and surface thermocouples M HNB
(dissipated power & local load on components)

Electrostatic probes
(plasma uniformity, T_e, n_e)

Source optical emission spectroscopy M
(source plasma T_e, n_e, n_{H^-}, n_{Cs}, n_H, impurities),

CRDS (n_{H^-}), **Laser absorption** (n_{Cs}) **M**



Beam diagnostics:

Calorimetry and surface thermocouples M HNB
(beam uniformity, diverg., aiming, vert. resol. 70 mm)

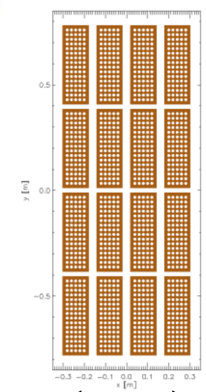
Instrumented calorimeter STRIKE
(beam uniformity over 2D profile & divergence, resolution 2mm, < 10 s beam pulse, SPIDER only)

Beam emission spectroscopy M
(beam divergence, stripping losses, uniformity)

Beam tomography M
(beam uniformity over 2D profile, resolution 1/4 beamlet group)

Neutron imaging M
(beam uniformity profile, resolution 3-4 cm, D only)

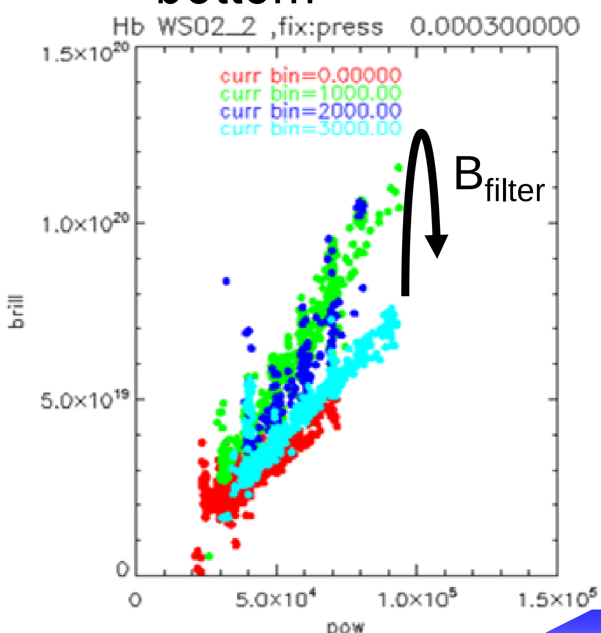
Also available in:
M – MITICA
HNB – ITER injector

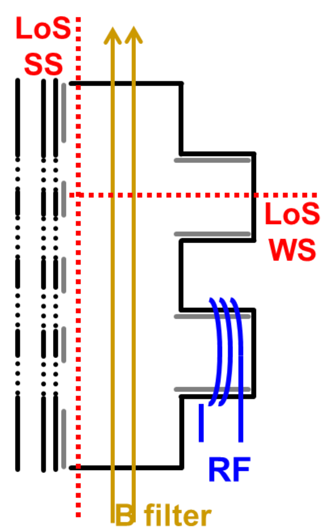


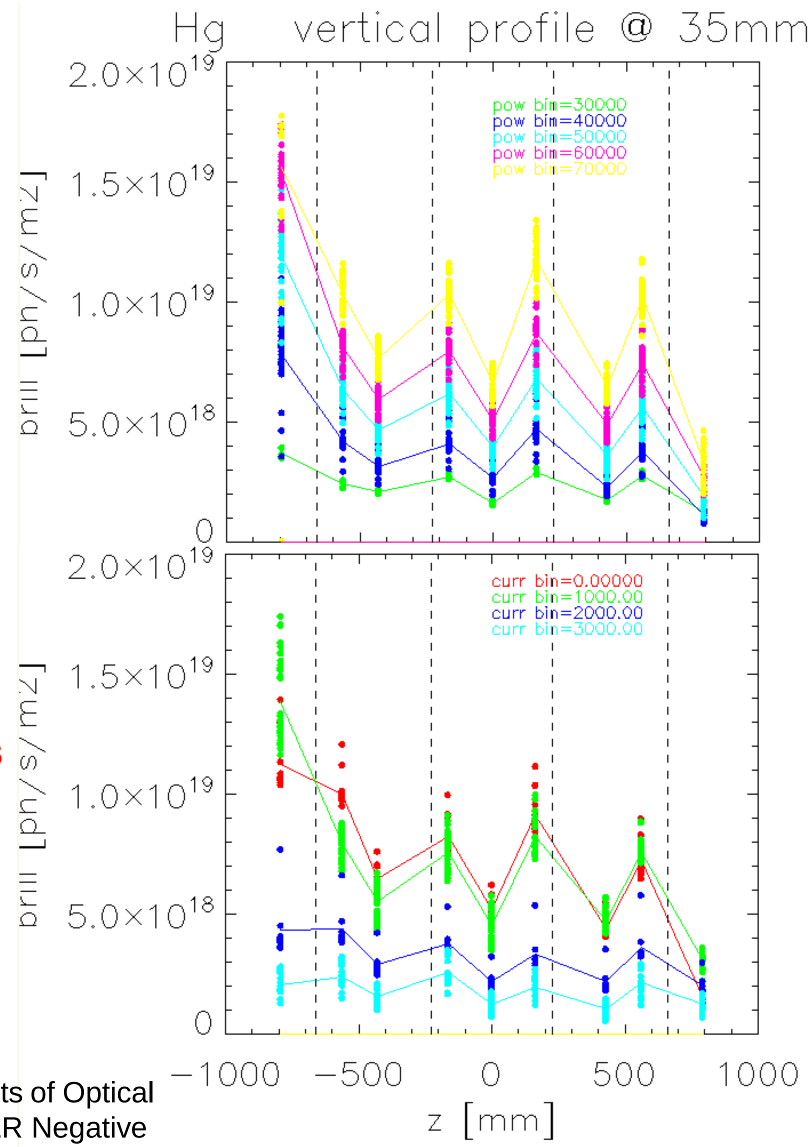
R. Pasqualotto et al.,
JINST **12** (2017) C10009

Preliminary characterisation of ion source

- Both in driver and close to PG, emission increases with RF power and decreases with magnetic filter field
  - Emission dependence on magnetic filter inside drivers due to return currents
- Plasma emission increases towards bottom







B. Zaniol et al., First measurements of Optical Emission Spectroscopy on SPIDER Negative Ion Source, ICIS2019, poster WedP13

Preliminary characterisation of ion source

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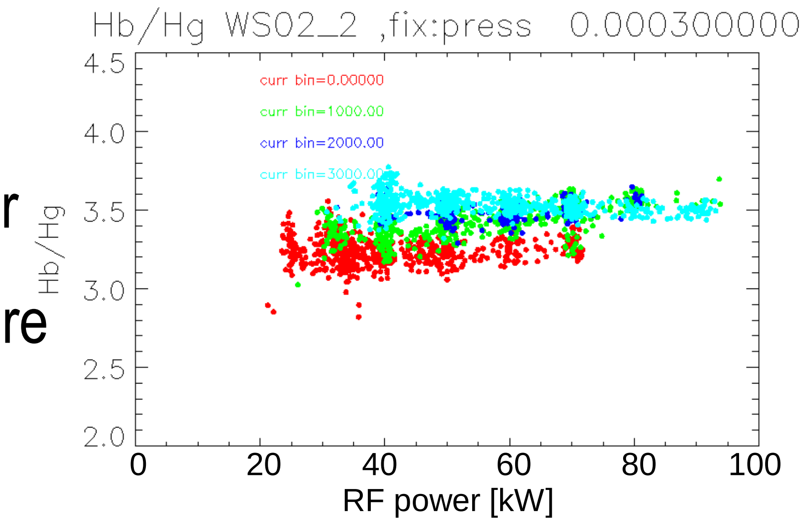
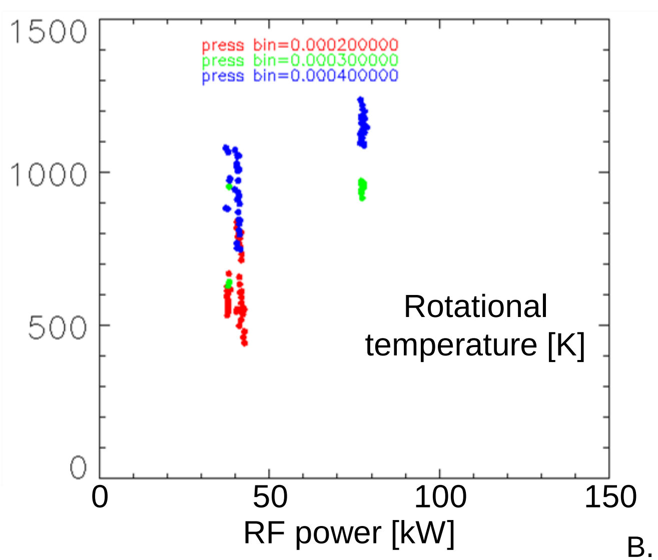
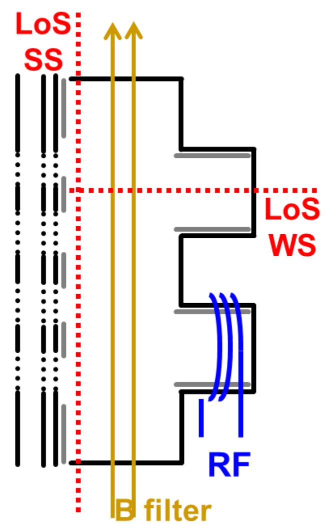
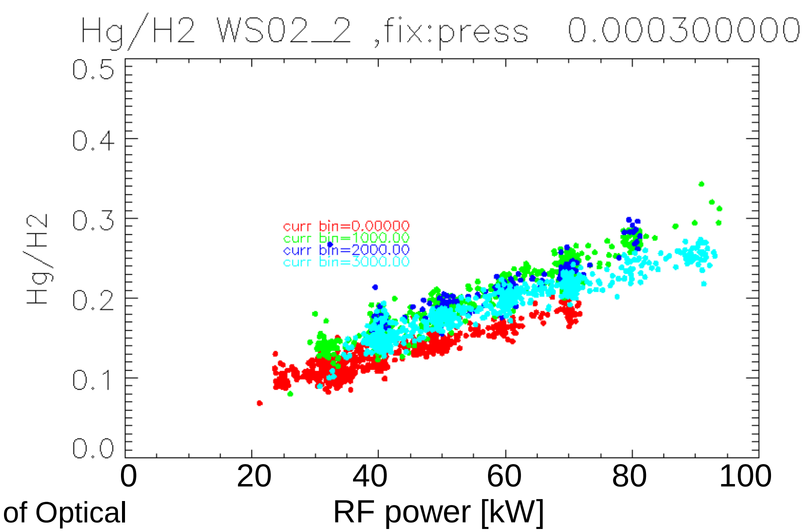
- No clear dependence of H_{beta}/H_{gamma} on RF power
- Increase of H_{gamma}/Fulcher with RF power
- T_{rot} increasing with RF power and pressure
- No effect of extraction on spectroscopy





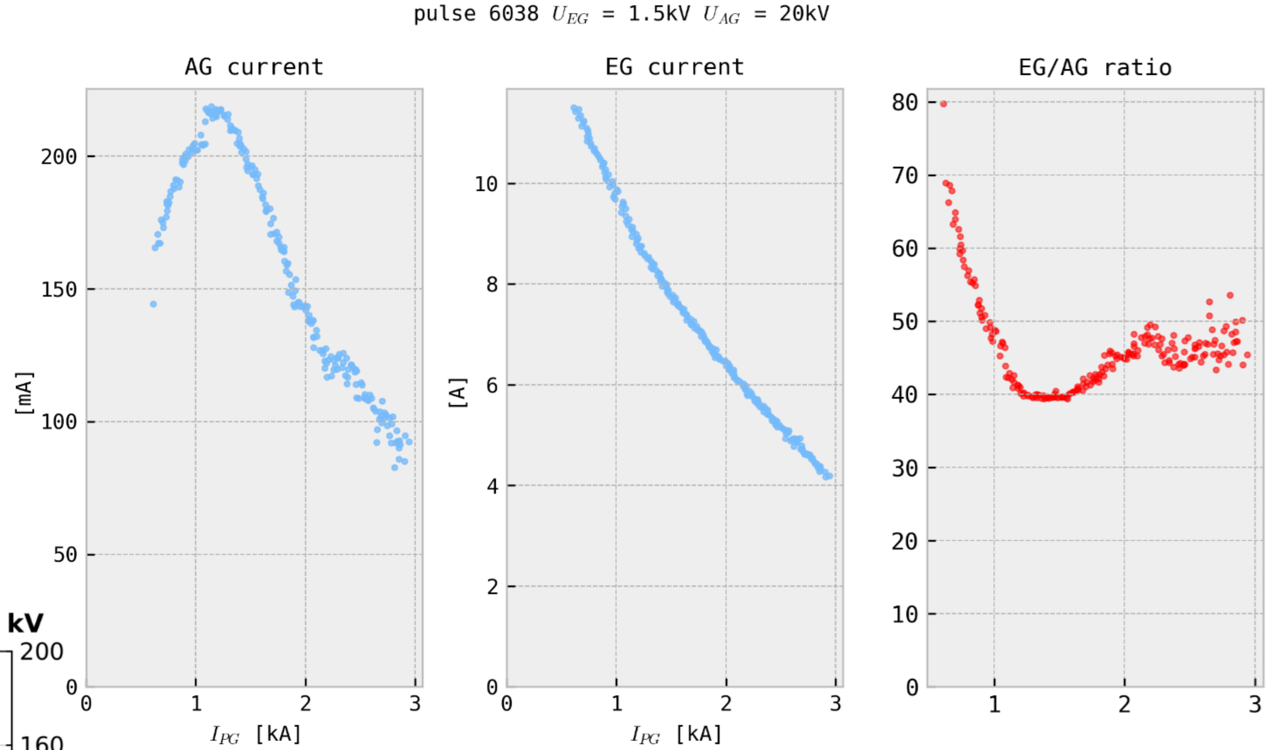


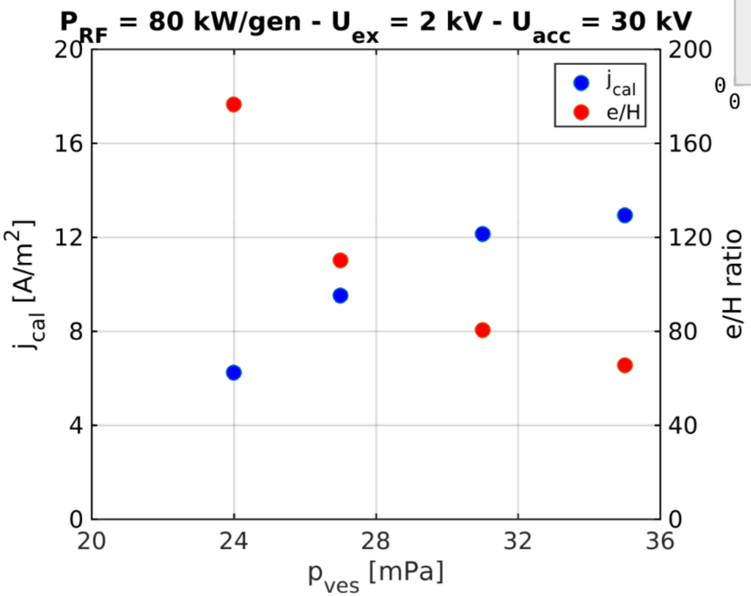


B. Zaniol et al., First measurements of Optical Emission Spectroscopy on SPIDER Negative Ion Source, ICIS2019, poster WedP13

Characterisation of co-extracted electrons

- Optimal B field for minimum current ratio

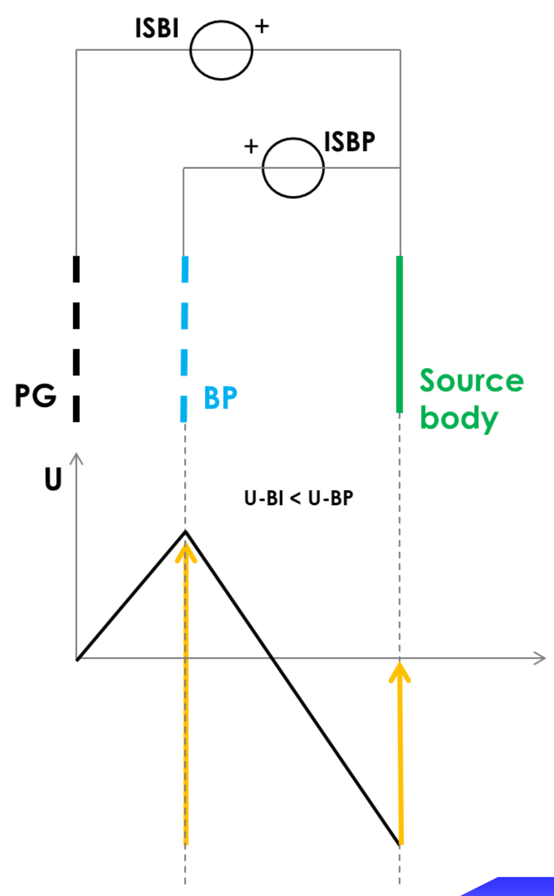


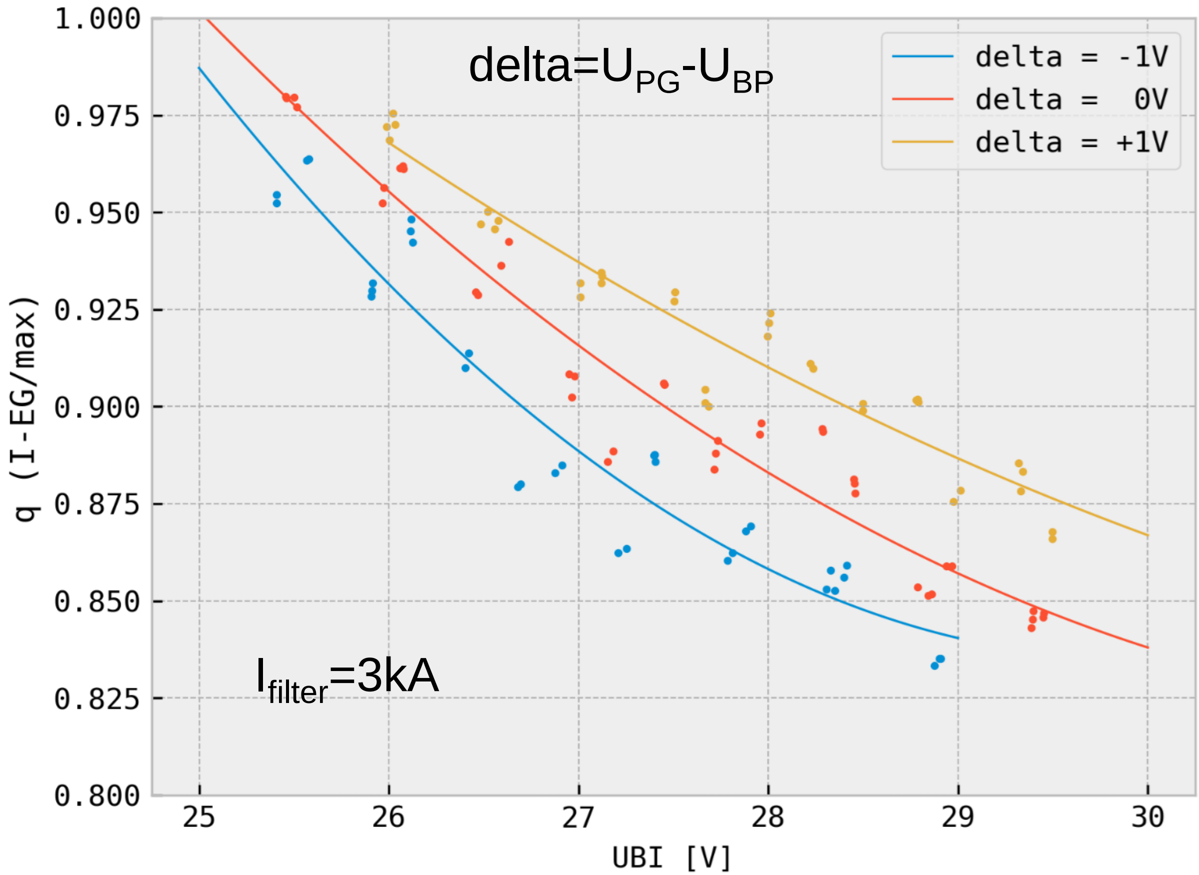


- Decay of co-extracted electron current wrt pressure

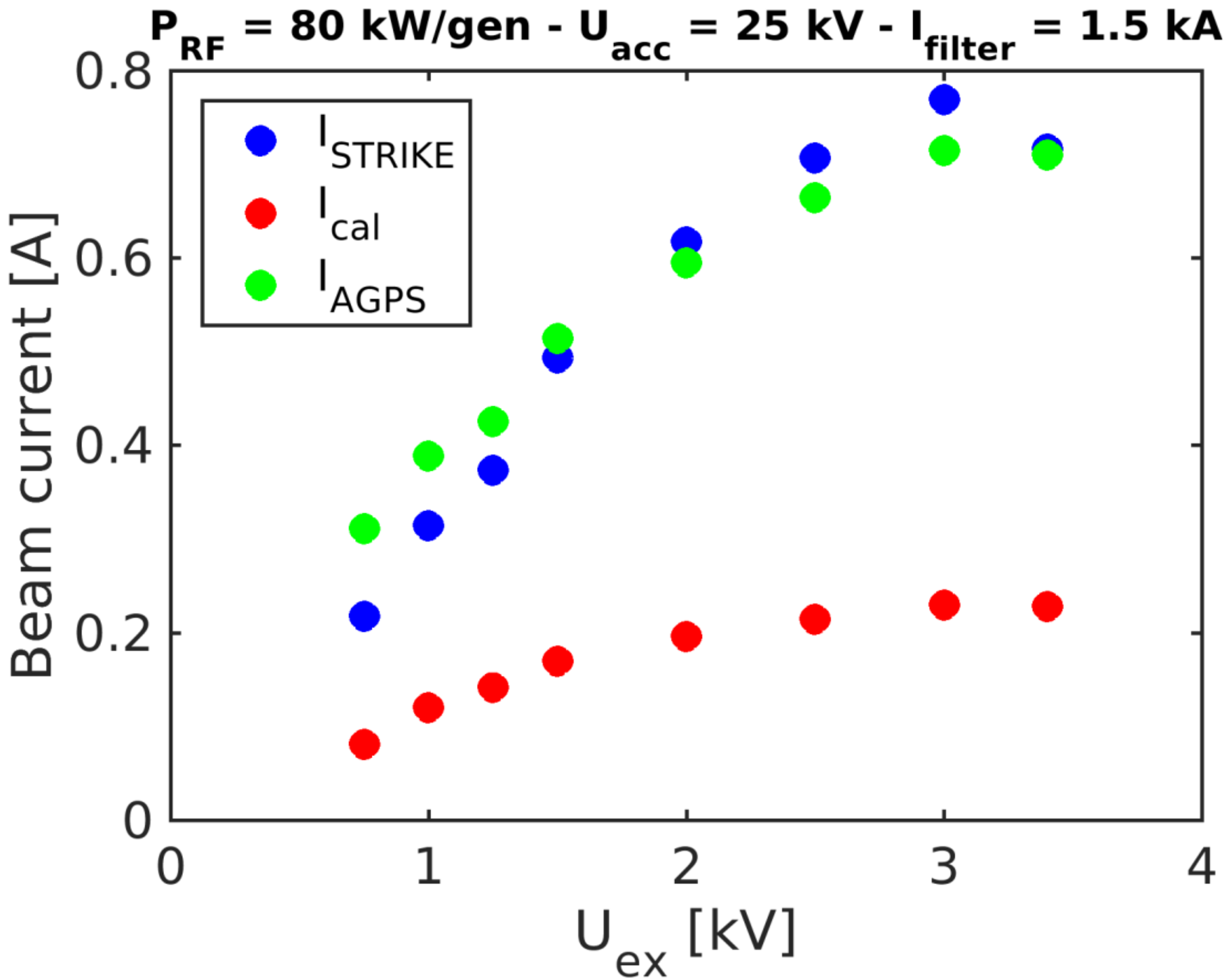
Indications from SPIDER operation w/o caesium

- Bias of plasma grid and bias plate:
  - With no caesium plasma potential can exceed limit of power supplies (30V)
  - Verification of influence on co-extracted electrons (low RF power, large filter field)

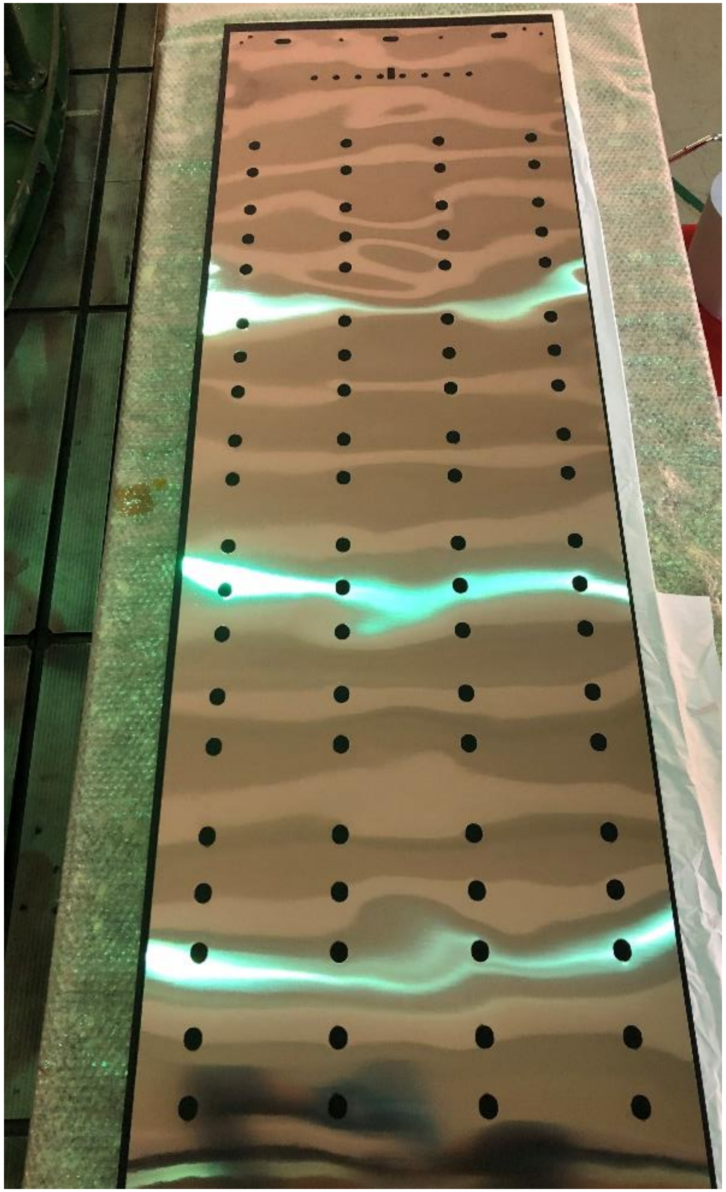


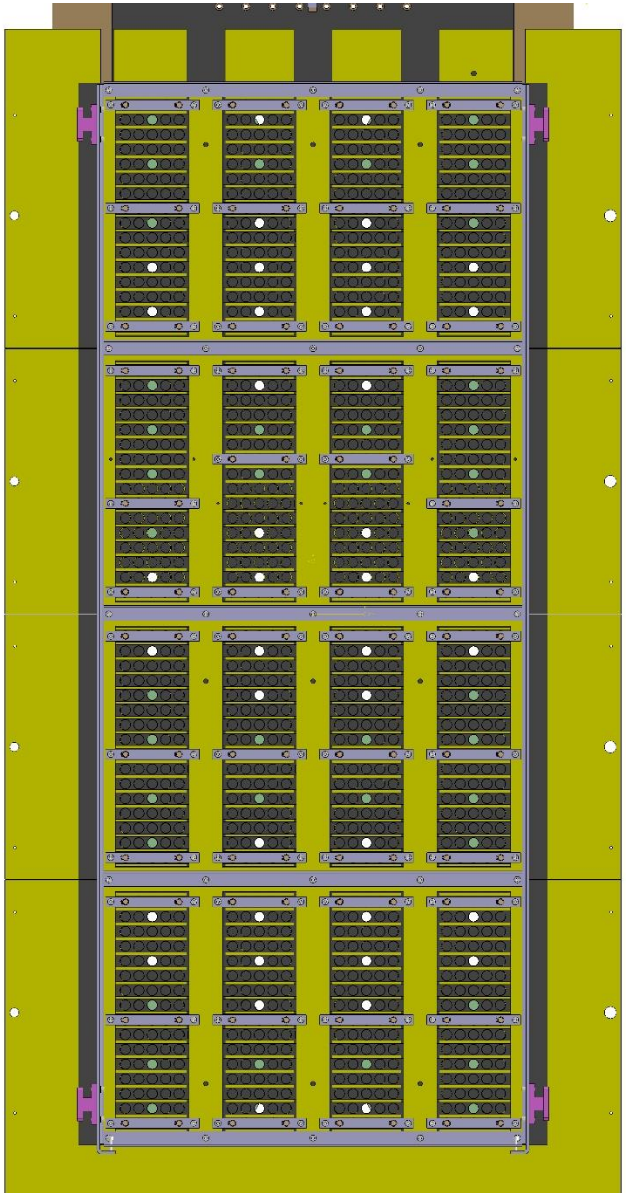


Characterisation of beam by AGPS current

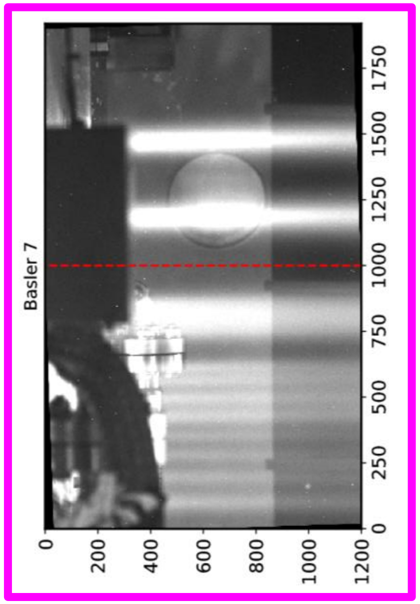


Operating beamlets

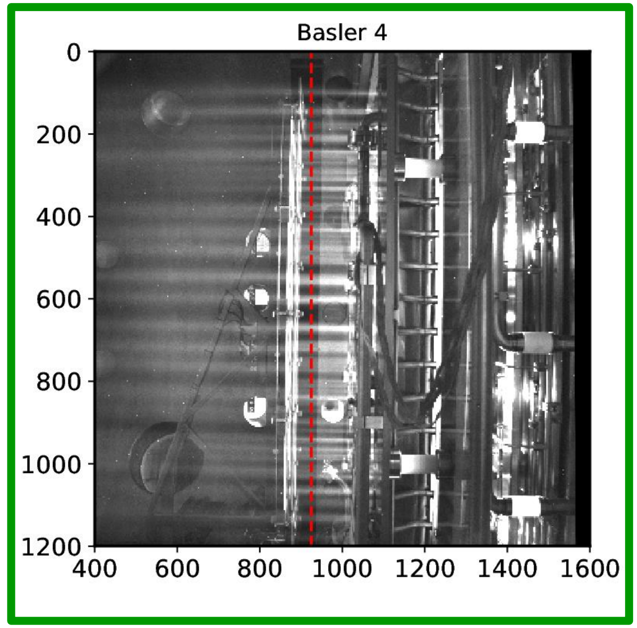


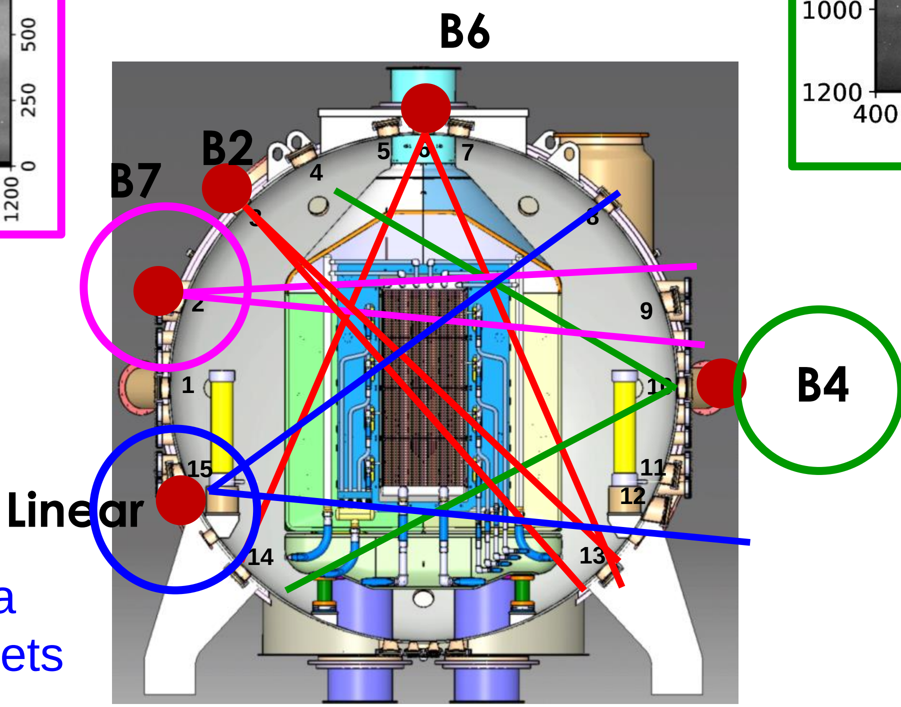


Characterisation of beam by visible imaging



B2 observes first beamlets of segment 1



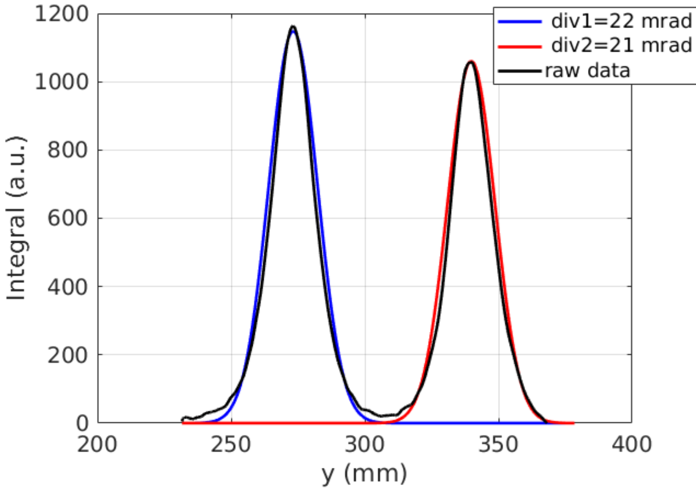


B4 observes: last beamlets of segment 2 and first beamlets of segment 3

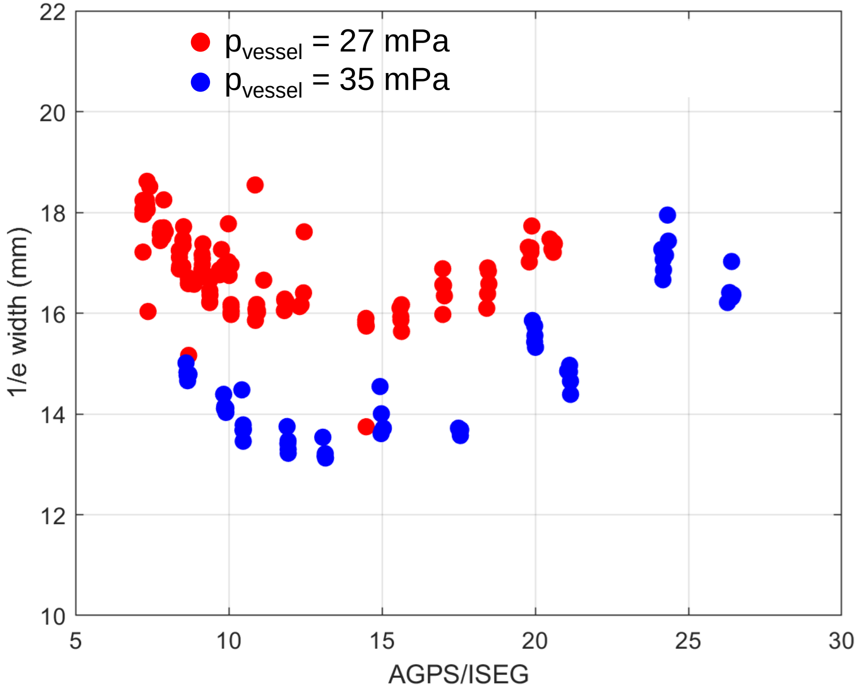
Linear camera observes beamlets of segment 4

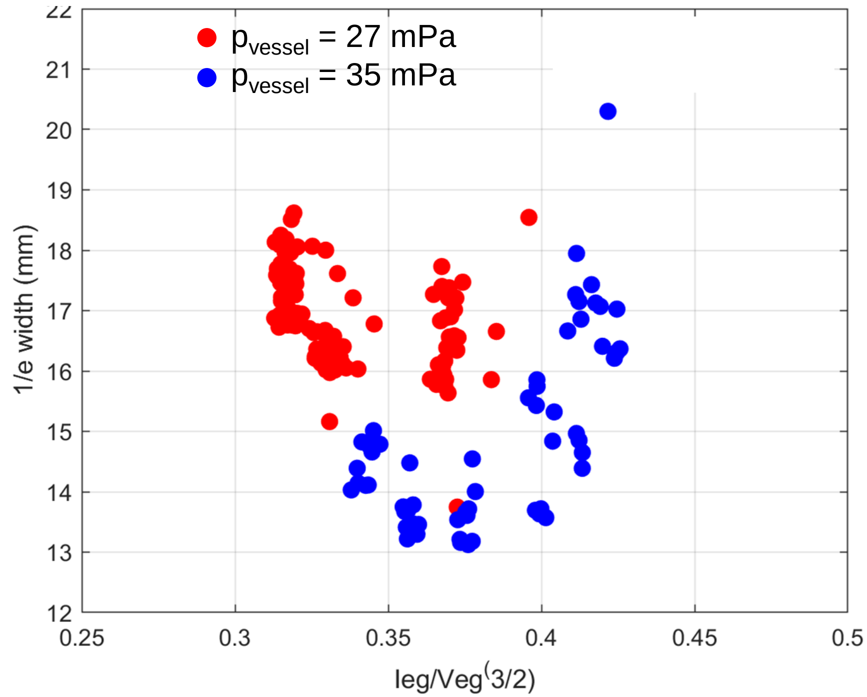
Characterisation of beam by 2D visible imaging

- Example of experimental data and corresponding fit

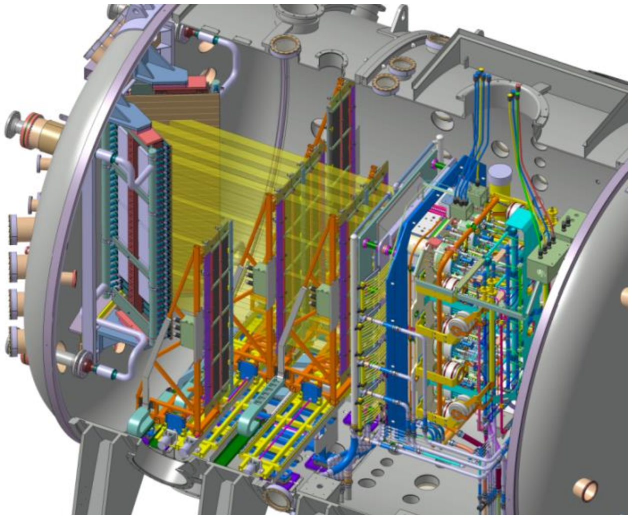


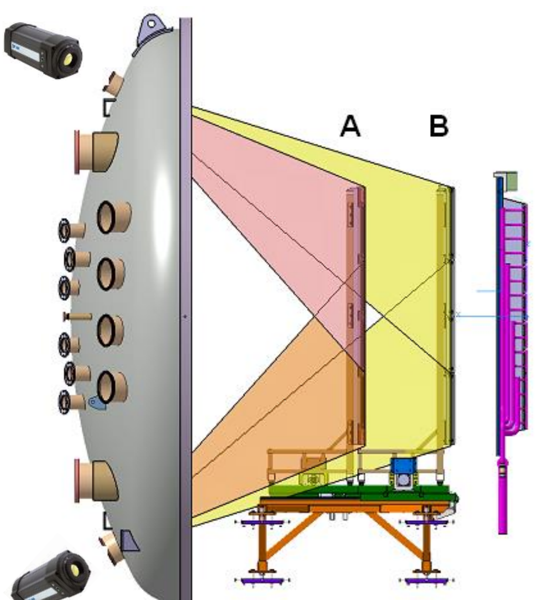
- Divergence vs ratio of acceleration and extraction voltages ; divergence vs normalised perveance

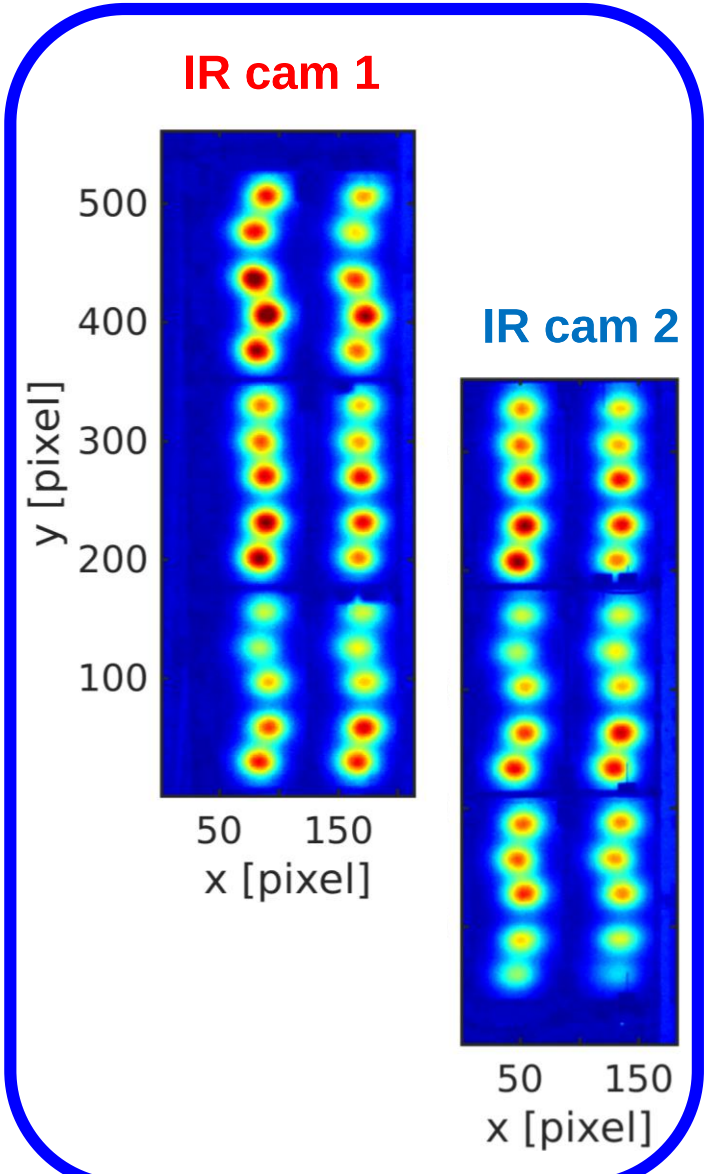


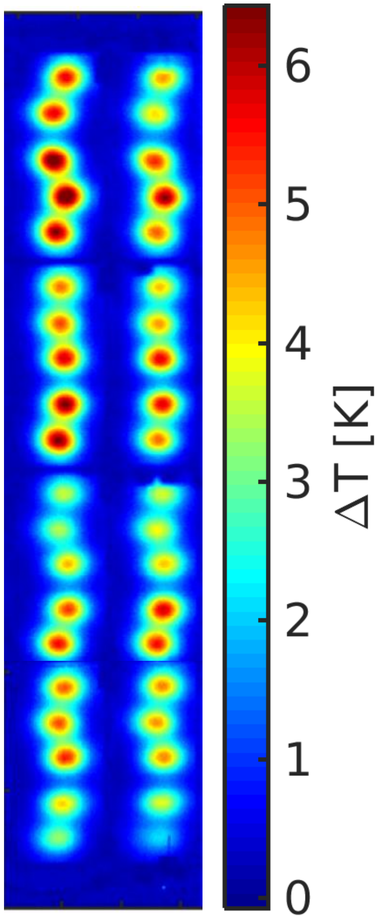


Characterisation of beam by STRIKE thermography





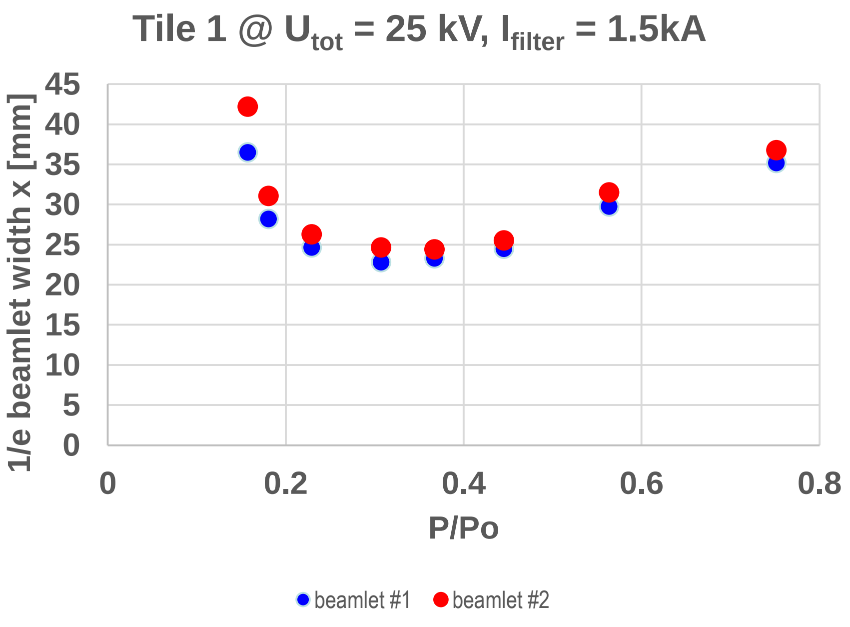




Characterisation of beam by STRIKE thermography

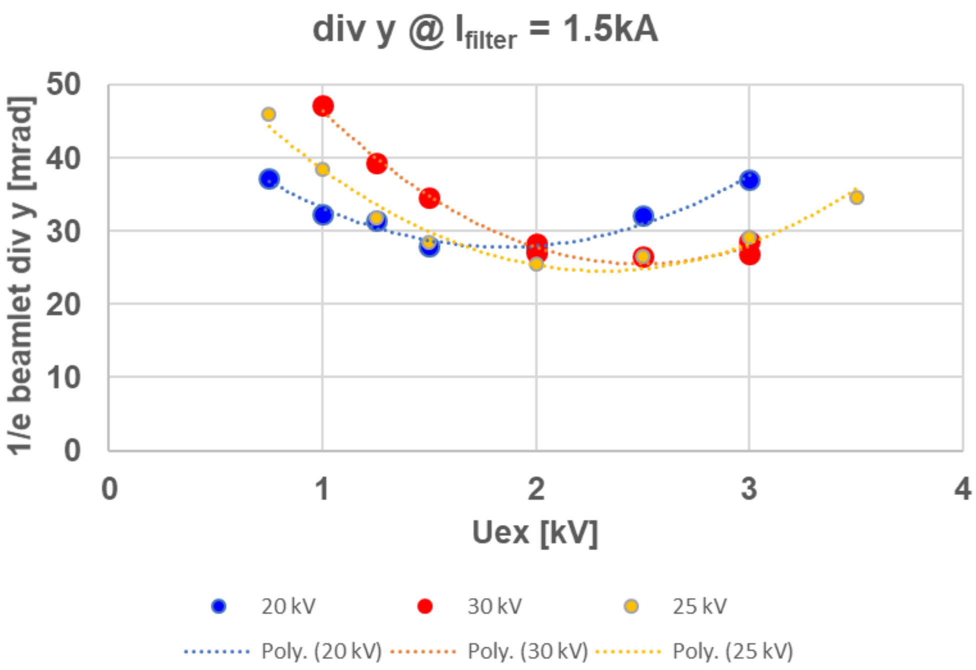
Pulse: #6246-#6250

X width of first two beamlets on Tile 1



Y DIVERGENCE at different U_tot

Pulses: #6229-#6243 and #6246-#6250



A Pimazzoni et al., Assessment of the SPIDER beam features by diagnostic calorimetry and thermography, ICIS2019, poster WedP32

Characterisation by Beam Emission Spectroscopy

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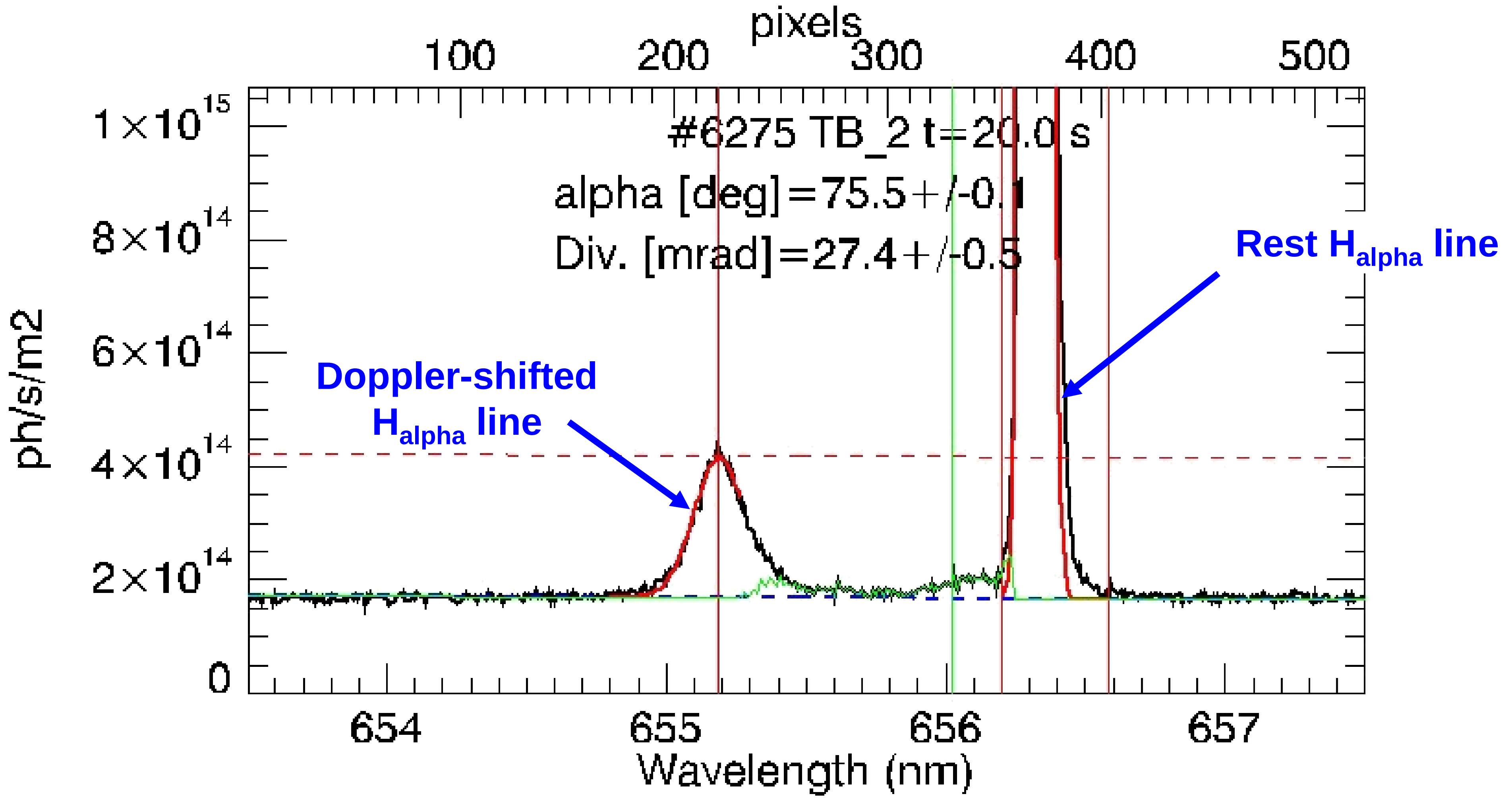
- 6275 20s 1.5/20kV



Beam physics: comparison of divergence measurements

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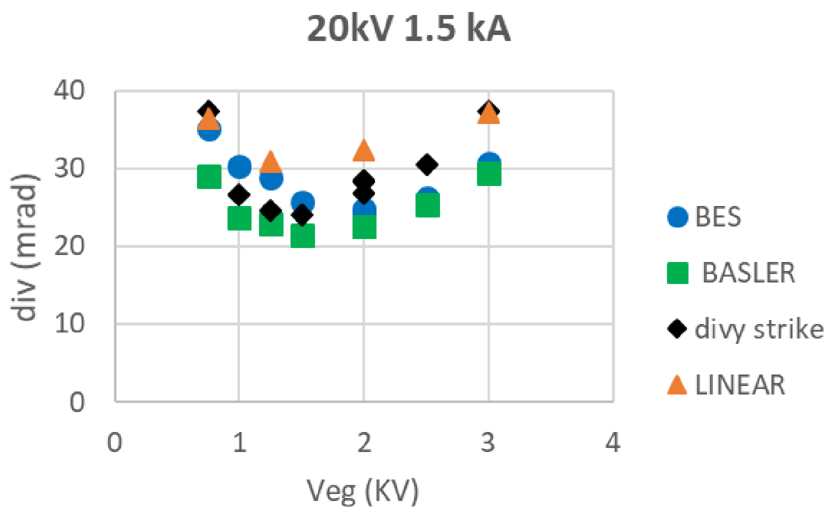
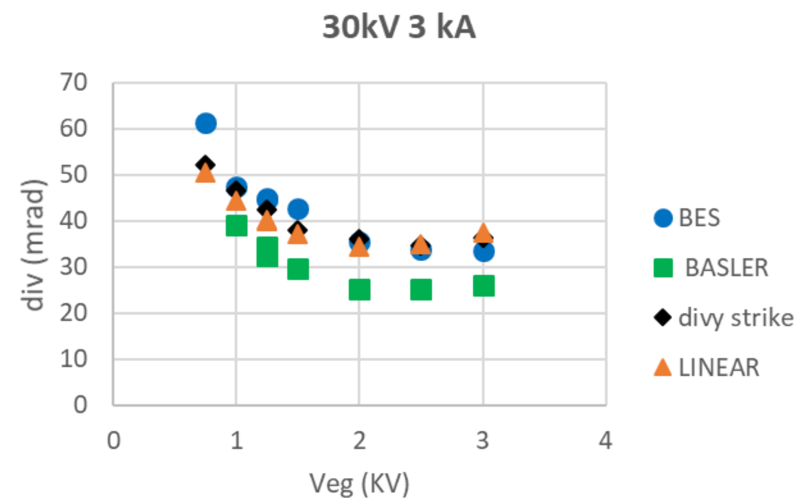
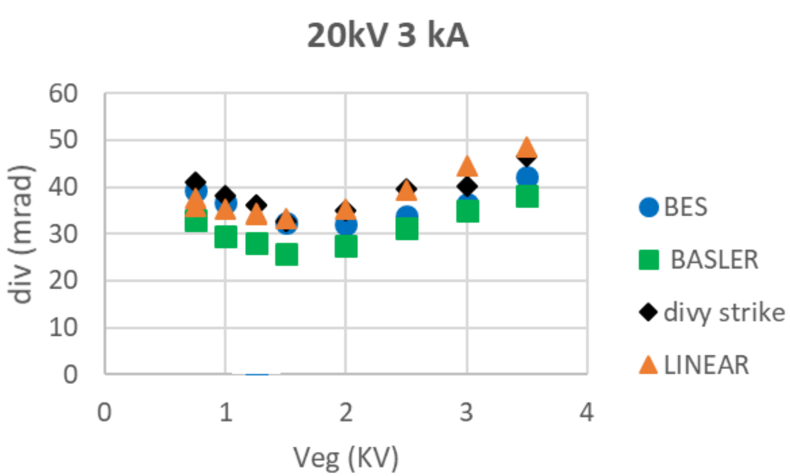
- Values and trends are similar despite different principles of operation

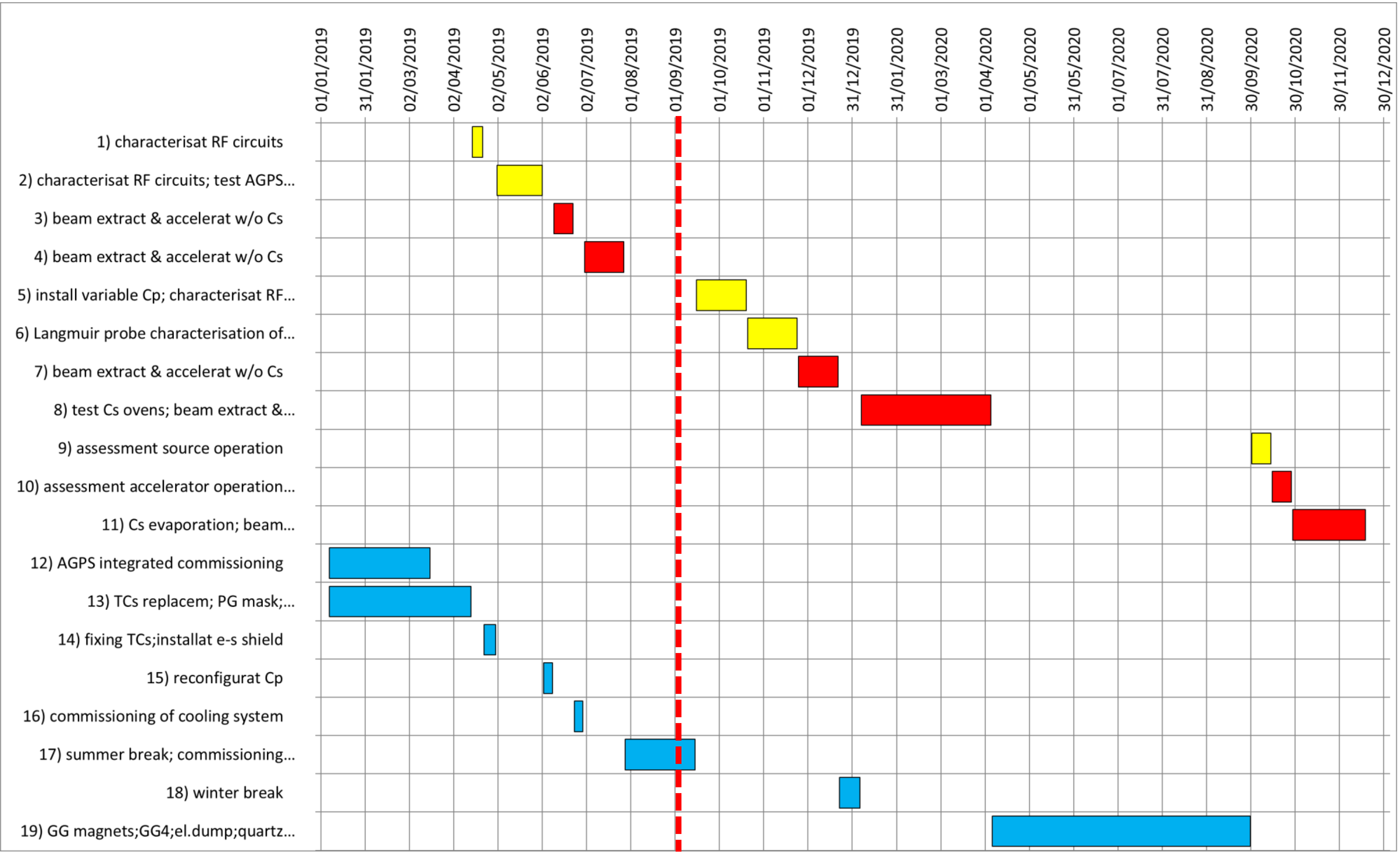






C. Poggi et al., Design and development of an Allison type emittance scanner for the SPIDER ion source, ICIS2019, oral ThuM01
C. Wimmer et al., Novel comparative measurement of H− beam divergences at the BATMAN Upgrade test facility: single beamlet and a group of beamlets, ICIS 2019, poster WedP11

SPIDER timeline

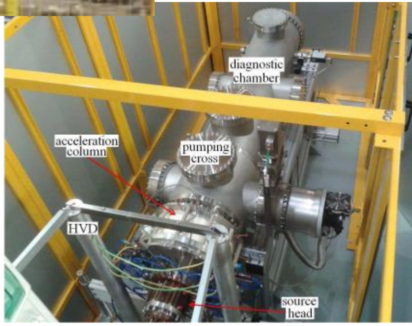


Other activities

- High voltage:
  - HVPTF: investigation of voltage holding in vacuum also with B field
  - HVSGTF: High Voltage Short Gap Test Facility

- HVRFTF: investigation of RF voltage holding and of RF circuit developments

- CATS: caesium test stand for investigation of caesium behaviour
- NIO1: small, modular and flexible test facility for test of magnetic and electrostatic configurations of source and accelerator



M. Cavenago et al., Improvements of the NIO1 Installation for Negative Ion Sources, ICIS2019, oral WedA04
E. Sartori et al., Analysis of current voltage characteristics for Langmuir probes immersed in an ion beam, ICIS2019, poster MonP23
V. Variale et al., Beam Energy Recovery for Fusion: Collector design for the test on NIO1 source, ICIS2019, poster WedP01
M. Fadone et al., Interpreting the dynamic equilibrium during evaporation in a Caesium environment, ICIS2019, poster MonP22
C. Poggi et al., CRISP: a Compact RF Ion Source Prototype for emittance scanner testing, ICIS2019, poster WedP22

Conclusions

- MITICA progressing
  - High voltage insulation tests on-going; breakdown tests due soon
- SPIDER operation without caesium:
  - Negative ion current density up to $25A/m^2$
  - Ratio of electron to negative ion current down to 40
  - Beamlet divergence in 20-30mrad range
- From SPIDER to MITICA
  - Improved RF circuits
  - Different configuration of magnetic filter field with no x-point
  - Pumping system expected to be ok
  - Other minor changes to be implemented

Thank you for your attention