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

E Sartori[1,2], R. Agnello[1,3], M. Agostini[1], M. Barbisan[1], M. Bigi[1], M. Boldrin[1], M. Brombin[1], V. Candeloro[1,2], R. Casagrande[1], S. Dal Bello[1], M. Dan[1], B.P. Duteil[1,3], M. Fadone[1], L. Grando[1], P. Jain[1], A. Maistrello[1], I. Mario[1,6], R. Pasqualotto[1], M. Pavei[1], A. Pimazzoni[1], C. Poggi[1], A. Rizzolo[1], A. Shepherd[1,4], M. Ugoletti[1], P. Veltri[5], B. Zaniol[1], P. Agostinetti[1], D. Aprile[1], G. Berton[1], C. Cavallini[1], M. Cavenago[6], G. Chitarin[1,2], G. Croci[7], R. Delogu[1], M. De Muri[1], M. De Nardi[1,2], S. Denizeau[1], F. Fellin[1], A. Ferro[1], E. Gaio[1], C. Gasparrini[1], A. Luchetta[1], F. Lunardon[1,2], G. Manduchi[1], N. Marconato[1,2], D. Marcuzzi[1], O. McCormack[7], R. Milazzo[1], A. Muraro[8], T. Patton[1], N. Pilan[1], M. Recchia[1], A. Rigoni-Garola[1], F. Santoro[1,2], B. Segalini[1,2], M. Siragusa[1], M. Spolaore[1], C. Taliercio[1], V. Toigo[1], P. Veltri[5], P. Zaccaria[1], R. Zagorski[1,9], L. Zanotto[1], M. Zaupa[1], M. Zuin[1], G. Serianni[1]

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[2)] Department of Management and Engineering, Università degli Studi di Padova, Strad. S. Nicola 3, 36100 Vicenza, Italy
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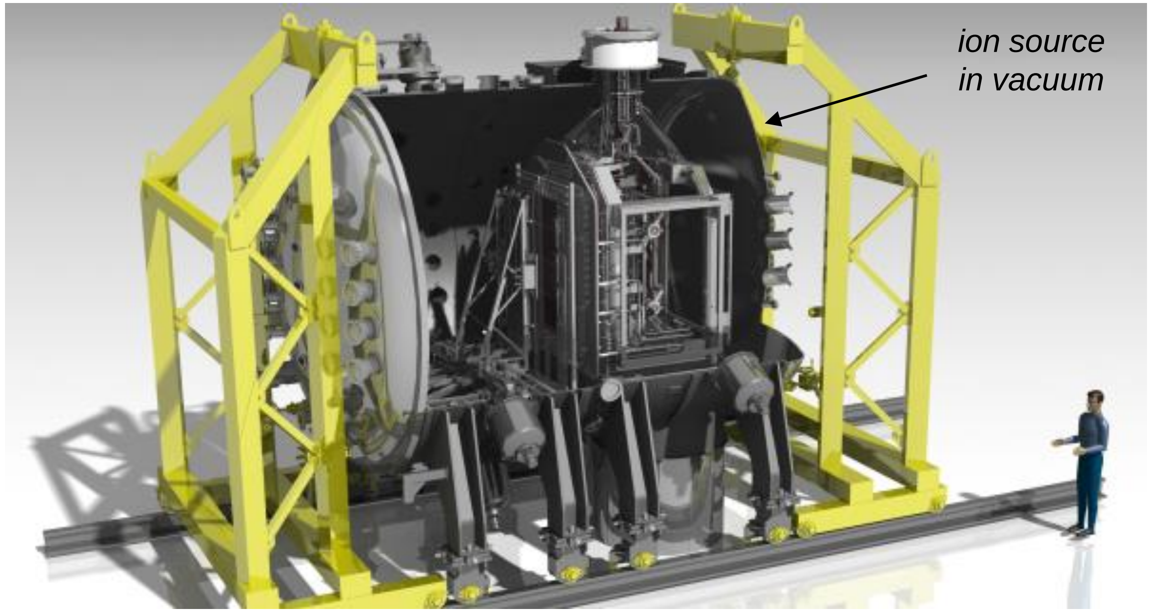
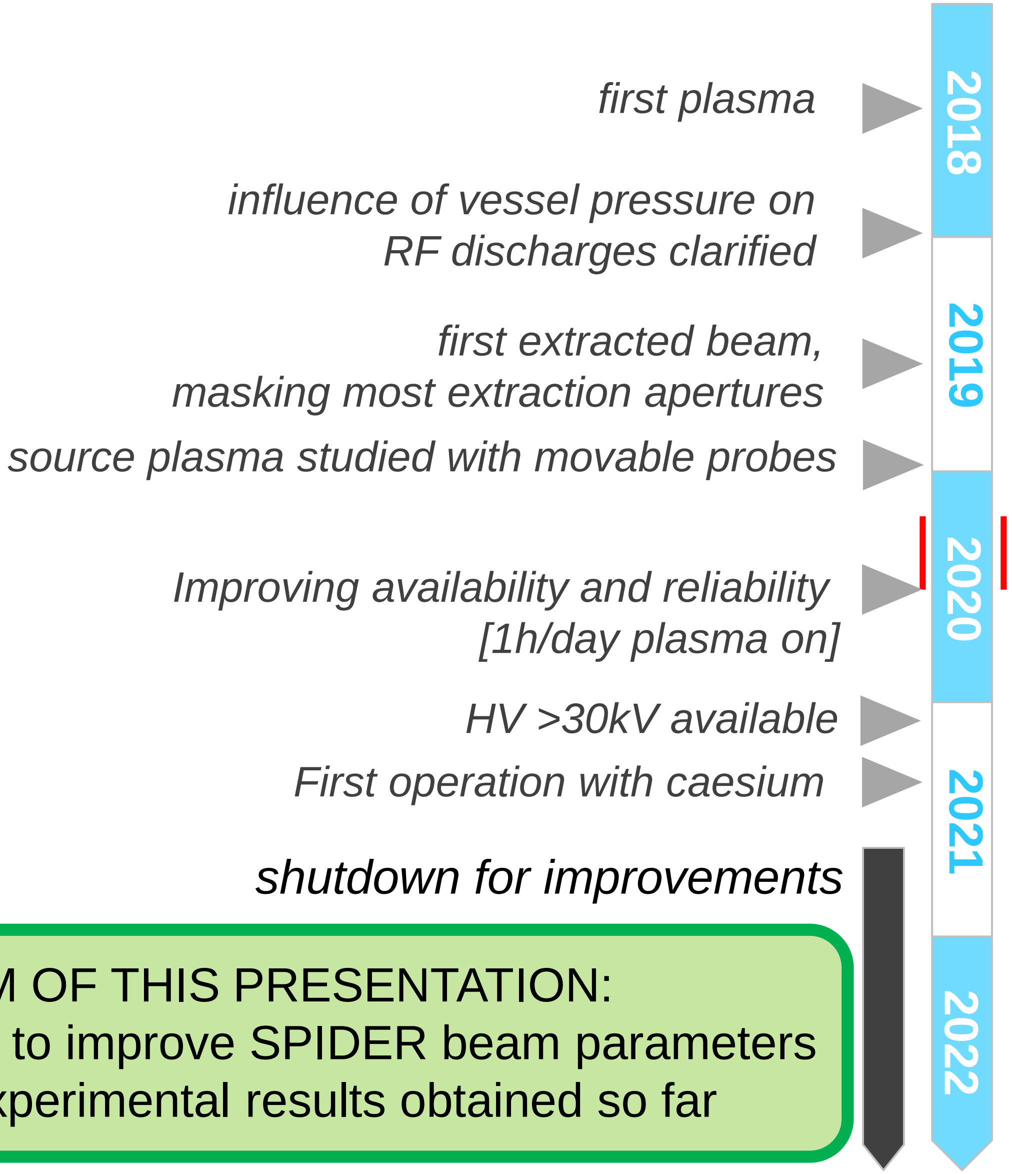
SPIDER full-size prototype source for ITER HNB



Full scale **plasma source** of ITER Heating Neutral Beams;
RF plasma source based on IPP design, 2x ELISE

Targets: optimisation of

- Extracted current density (355 A/m^2 H^-, 285 A/m^2 D^-)
- Uniformity over 1280 apertures (within 10%)
- Stability (1 h beam)
- Co-extracted electron fraction (<0.5 H^-, <1 D^-)

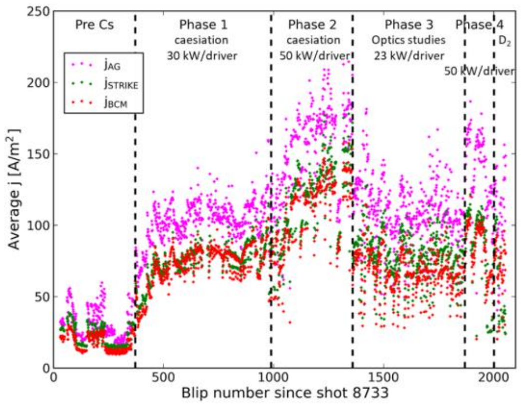


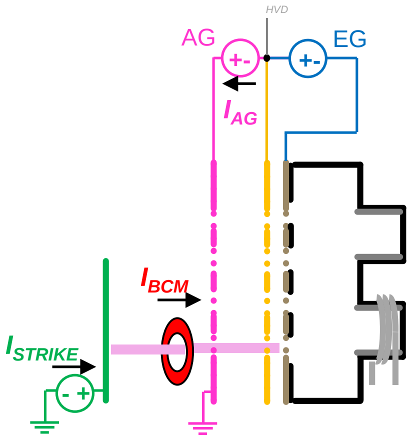
AIM OF THIS PRESENTATION:
Discuss how to improve SPIDER beam parameters using experimental results obtained so far

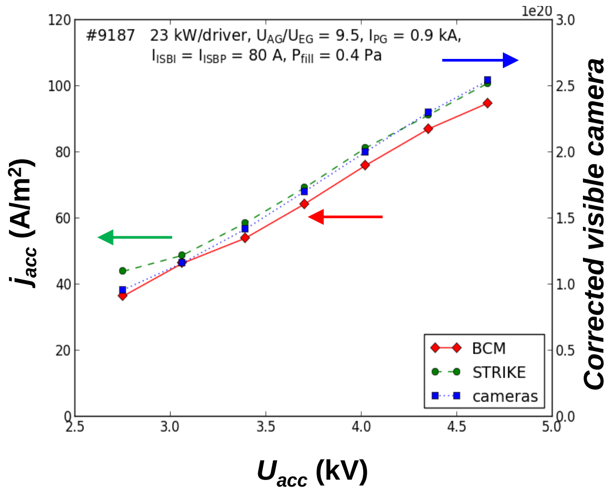
Outline

- Measuring beam current and improvements
- Vertical profile of beam current
- Vertical profile of plasma parameters
- Operation of caesium ovens
- Non-homogeneity among RF drivers: vertical and horizontal
- Transverse field inside drivers and RF coupling
- New needs for plasma source diagnostics
- Reducing beamlet core divergence
- Operating full-size ITER HNB prototype source with 1280 apertures

Measurement of negative ion beam current



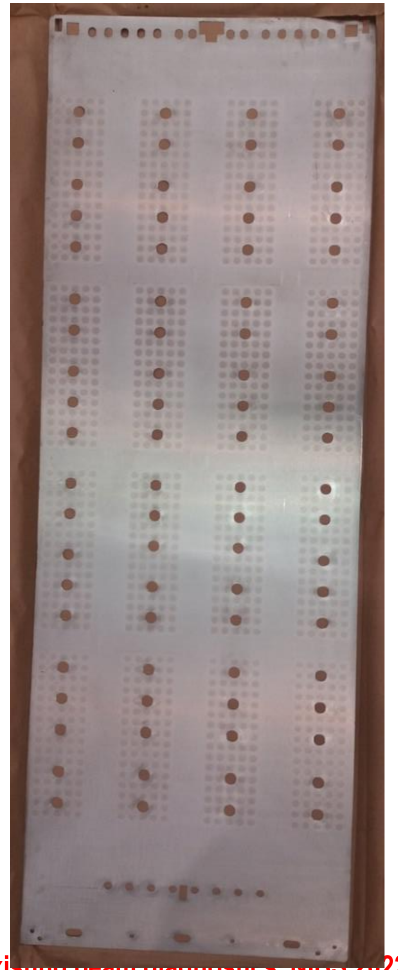




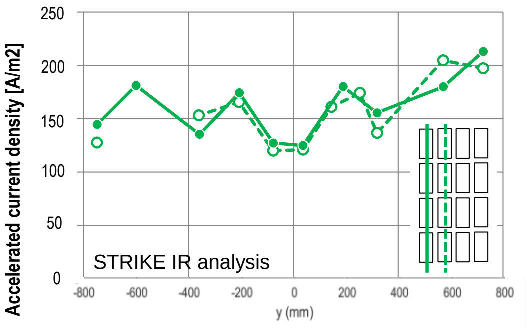
- Measurement of negative-ion beam current not straightforward: experience with single-beamlets [1] extremely useful as «training» in view of next op. without PG mask
- beam current <80% acceleration current from HV power supply
- Indications for future operation from frequency analysis of accelerated current:

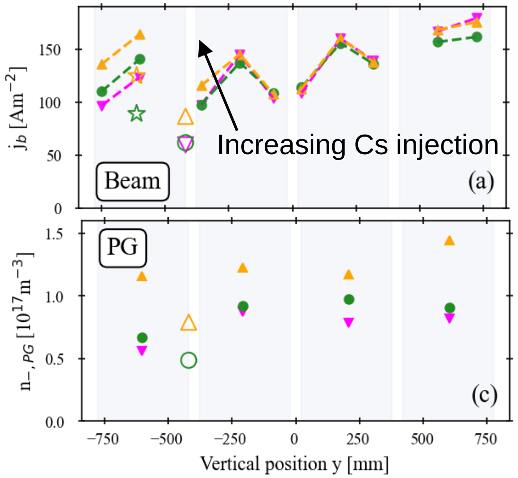
FREQUENCY ANALYSIS OF ACCELERATED BEAM CURRENT[2]

Frequency range	Cause	I_R [%] (M & Bz)	I_R [%] (F)
0.9 - 1.1 MHz	Driver oscillators	1 – 5%	5 – 15%
0.8 - 2 kHz	Driver beatings	< 2%	< 2%
N×50 Hz	Power supplies	1 – 7%	1 – 10%
~ 140 kHz	EG power supply	0.5 – 6%	0.5 – 10%



[1] S Alastair, Direct current measurements of the SPIDER beam: a comparison to existing beam diagnostics, NIBS 2022
[2] B. Pouradier-Duteil, First characterization of the SPIDER beam AC component with the BeamletCurrent Monitor, SOFT 2022

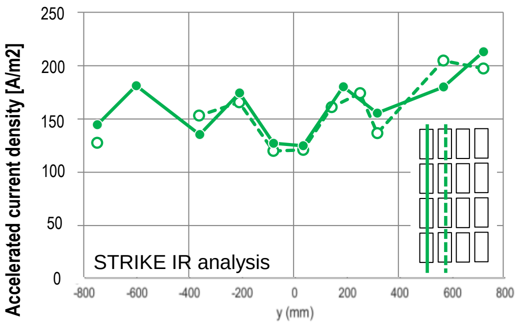


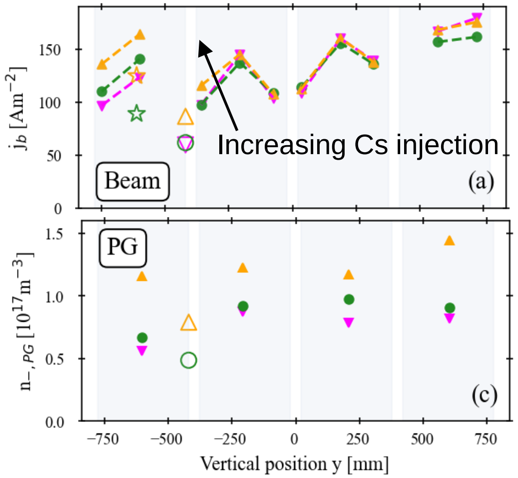


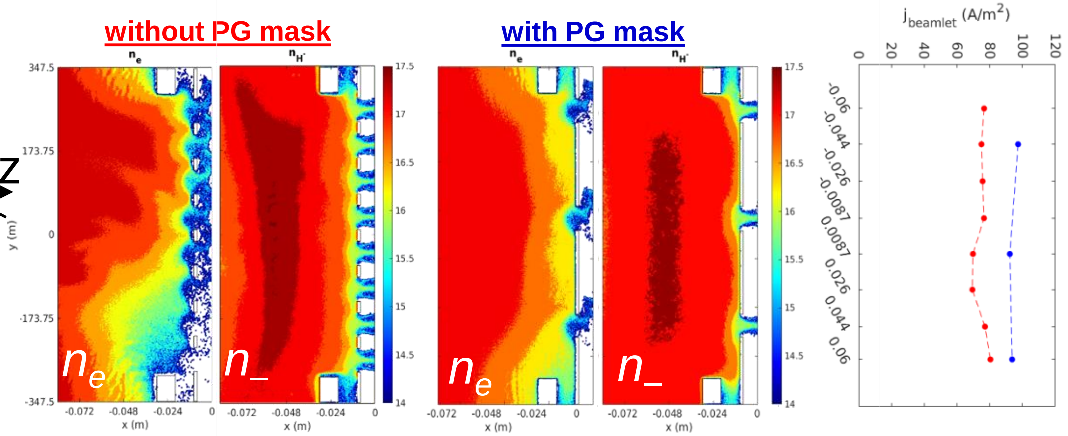
- Not-so-uniform vertical profile, even within each beamlet group[1,2]: possible to measure only thanks to PG mask covering most apertures (individual beamlets)

[1] E Sartori, First operations with caesium of the negative ion source SPIDER, Nucl. Fusion 62 086022 (2022)
[2] G. Serianni, Spatially resolved diagnostics for optimization of large ion beam sources, RSI 93 (8), 081101 (2022)

Measurement of negative ion beam current profile



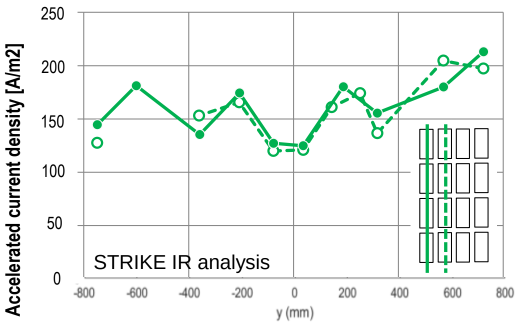


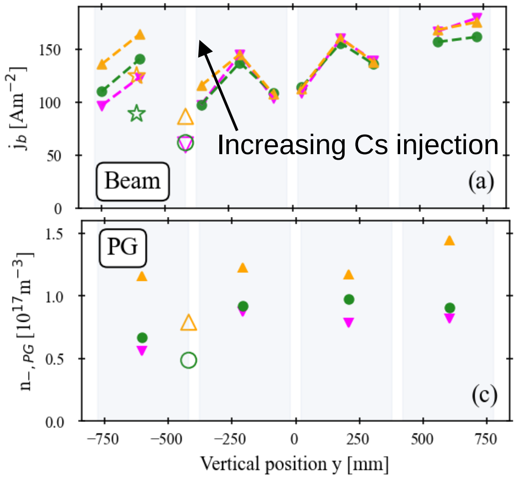


- Not-so-uniform vertical profile, even within each beamlet group[1,2]: possible to measure only thanks to PG mask covering most apertures (individual beamlets)
- Study of extraction region 2D PIC: uniform flux from plasma side, rather uniform H^- beamlets extracted. Masking does not modify spatial distribution of n_- , only increases absolute value[3]

[1] E Sartori, First operations with caesium of the negative ion source SPIDER, Nucl. Fusion 62 086022 (2022)
[2] G. Serianni, Spatially resolved diagnostics for optimization of large ion beam sources, RSI 93 (8), 081101 (2022)
[3] E Sartori, Influence of plasma grid-masking on the results of early SPIDER operation, SOFT 2022

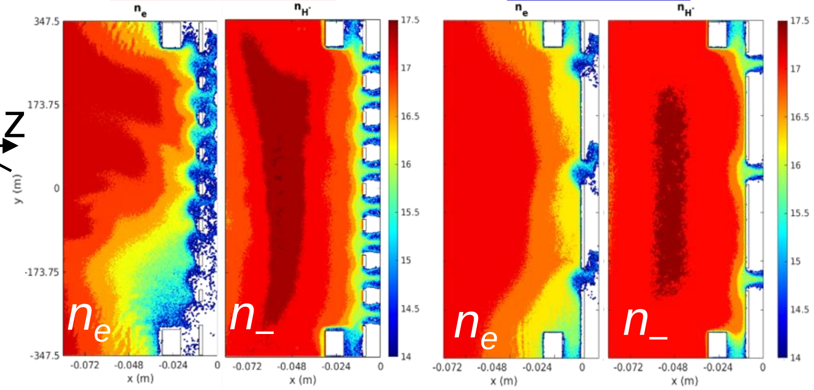
Measurement of negative ion beam current profile

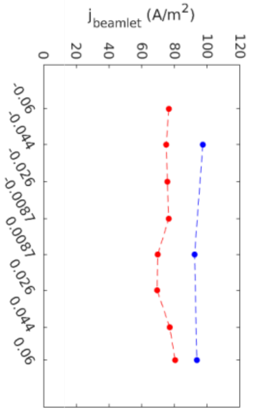


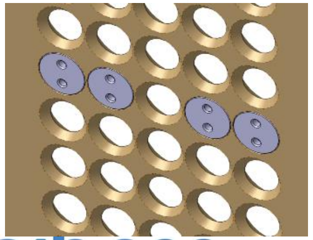


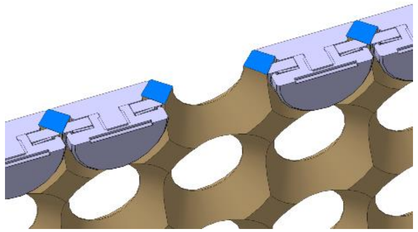
without PG mask

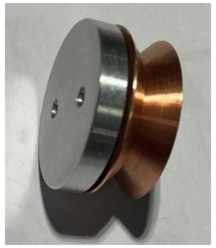
with PG mask







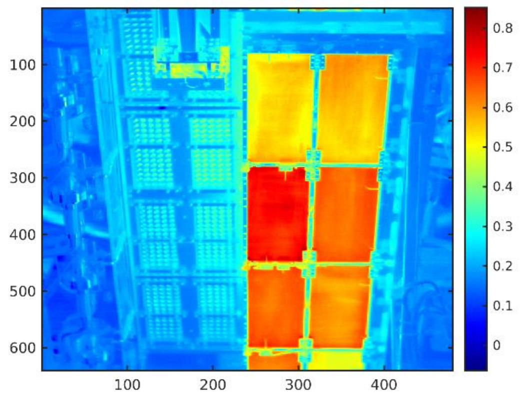


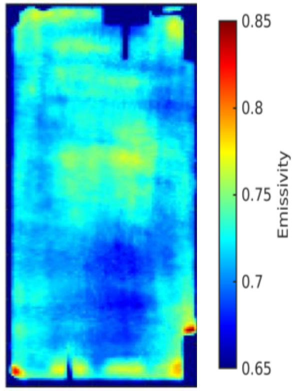


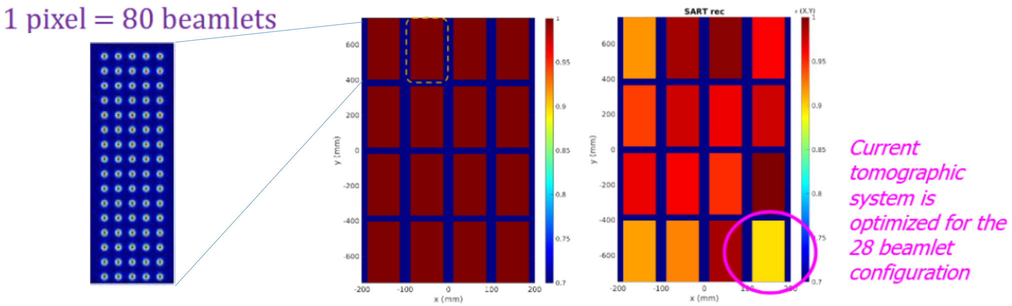
- Not-so-uniform vertical profile, even within each beamlet group[1,2]: possible to measure only thanks to PG mask covering most apertures (individual beamlets)
- Study of extraction region 2D PIC: uniform flux from plasma side, rather uniform H$^-$ beamlets extracted. Masking does not modify spatial distribution of n_- , only increases absolute value[3]
- Single beamlet studies proposed also for future operation: uniformity within the beamlet group, operation of Allison Emittance Scanner[4]

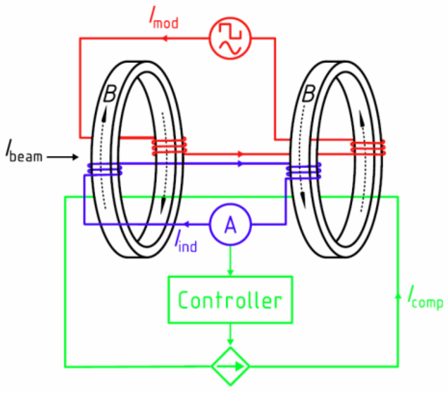
[1] E Sartori, First operations with caesium of the negative ion source SPIDER, Nucl. Fusion 62 086022 (2022)
[2] G. Serianni, Spatially resolved diagnostics for optimization of large ion beam sources, RSI 93 (8), 081101 (2022)
[3] E Sartori, Influence of plasma grid-masking on the results of early SPIDER operation, SOFT 2022
[4] C Poggi, First tests and commissioning of the emittance scanner for SPIDER, FED 168, 112659 2021

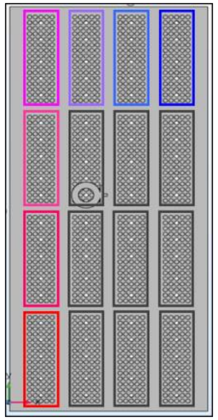
Measurement of negative ion beam current profiles



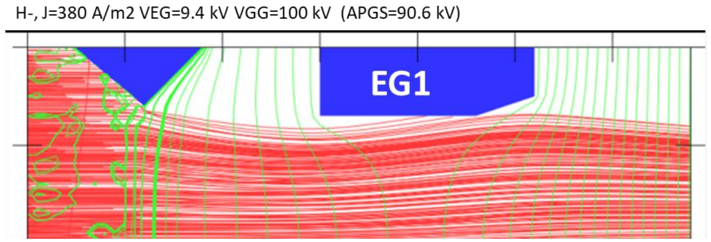


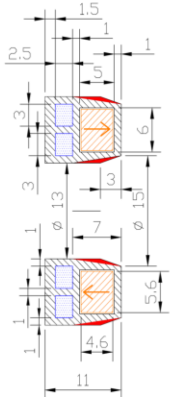






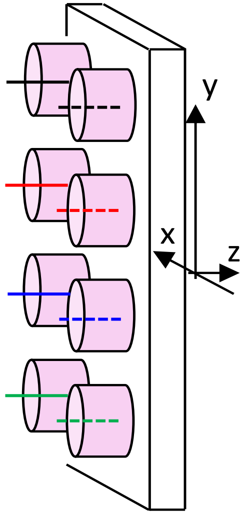
- Preparation of 2D correction maps of CFC emissivity to improve accuracy of STRIKE diagnostic calorimeter
- Prepration of beam tomography from visible cameras [1]
- Feasibility study to develop «beamlet group current monitors» [2] based on fluxgate concept
  (Direct Current Current Transformer)
- Machining tapering of EG aperture to reduce beamlet intercetion: maximise the esperimental window with full beam transmission is important to correctly measure the non uniformities

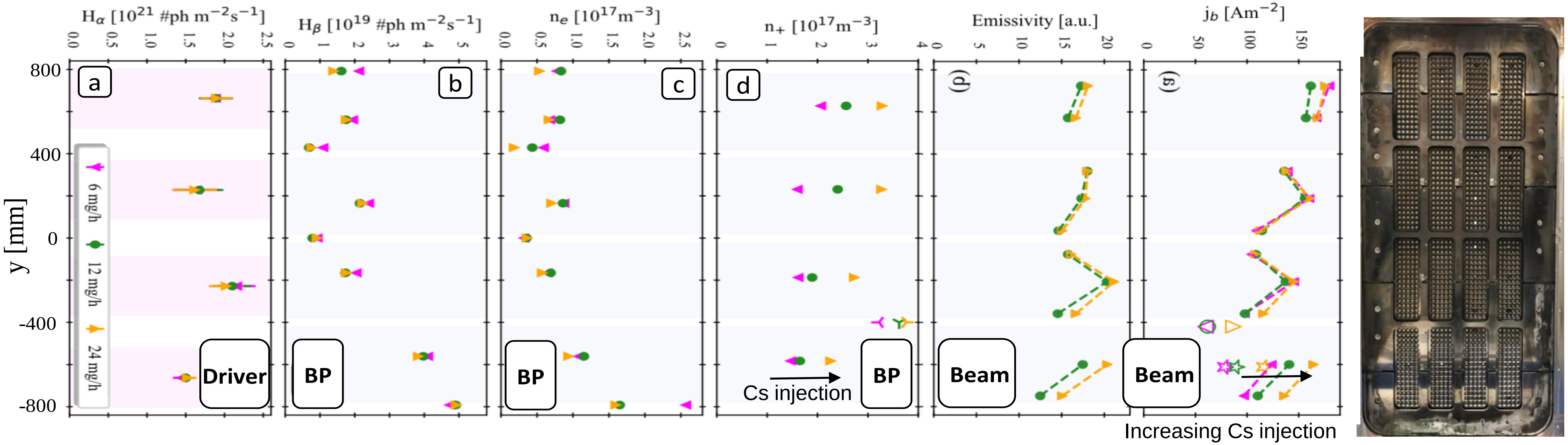




[1] M Ugoletti, Development of the tomographic reconstruction technique of SPIDER negative ion beam, SOFT 2022
[2] R Pasqualotto, Improvement of SPIDER diagnostic systems, SOFT 2022

Plasma parameters and beamlet current profile

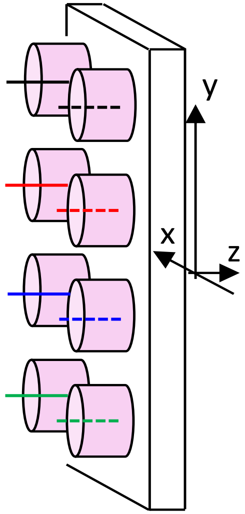


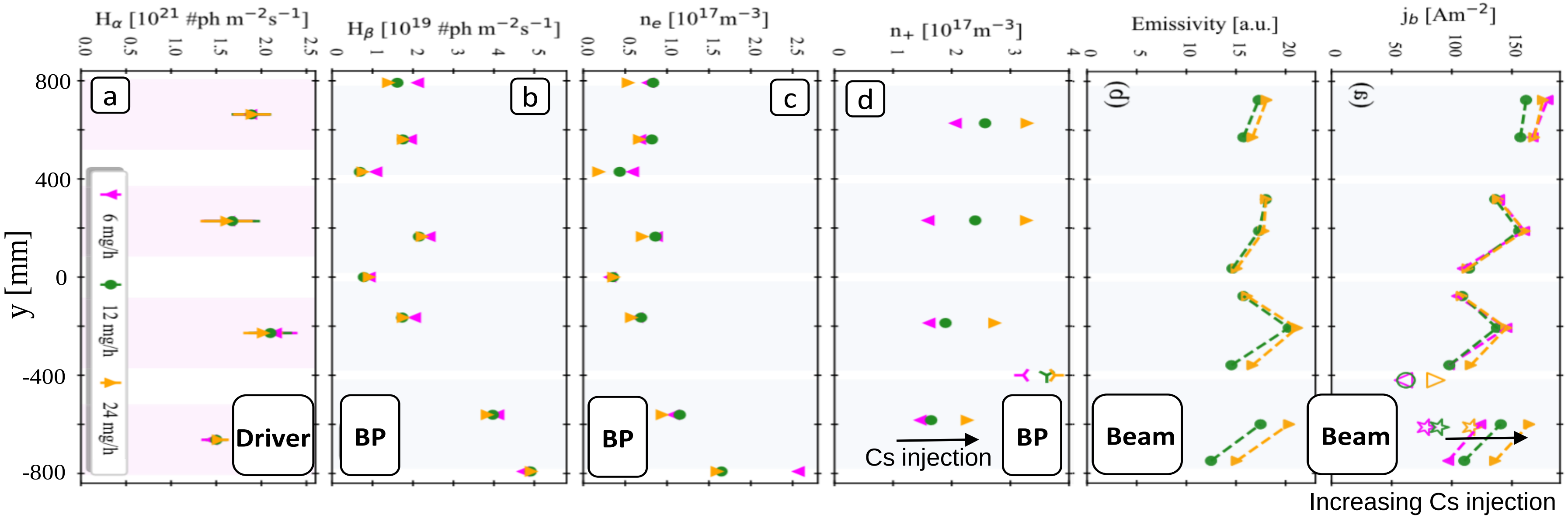


- Plasma parameters inside drivers appear to be uneven

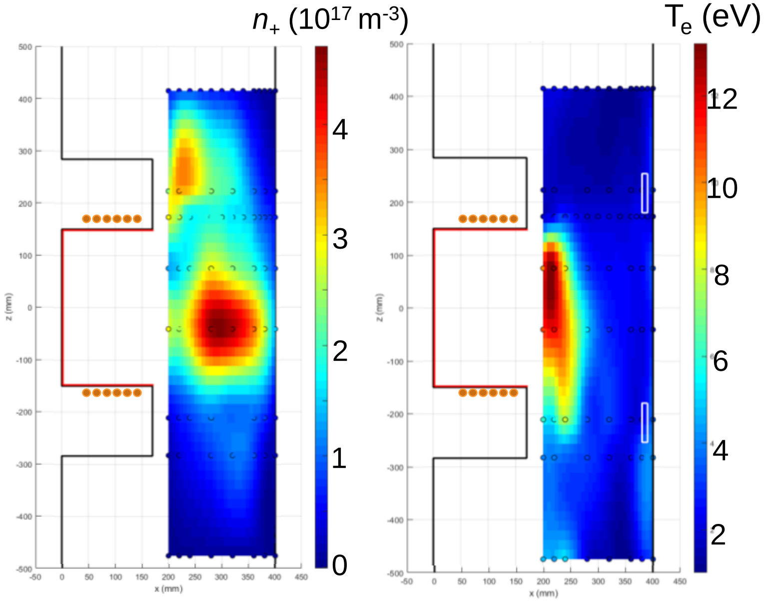
[1] G Serianni, Spatially resolved diagnostics for optimization of large ion beam sources, RSI 93 (8), 081101 (2022)

Plasma parameters and beamlet current profile





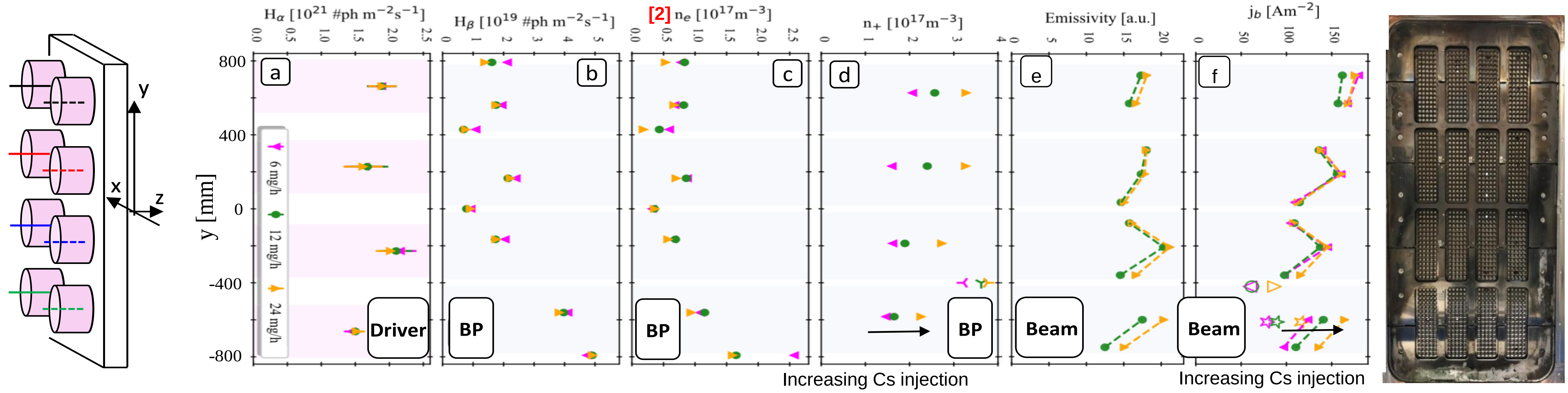
PREVIOUS MEASUREMENT WITH MOVABLE ELECTROSTATIC PROBES



- Plasma parameters inside drivers appear to be uneven
- At the bottom of the source, electrons reach the extraction region; flow of hot electrons from drivers; caesium does not affect this drift

[1] G Serianni, Spatially resolved diagnostics for optimization of large ion beam sources, RSI 93 (8), 081101 (2022)

Plasma parameters and beamlet current profile

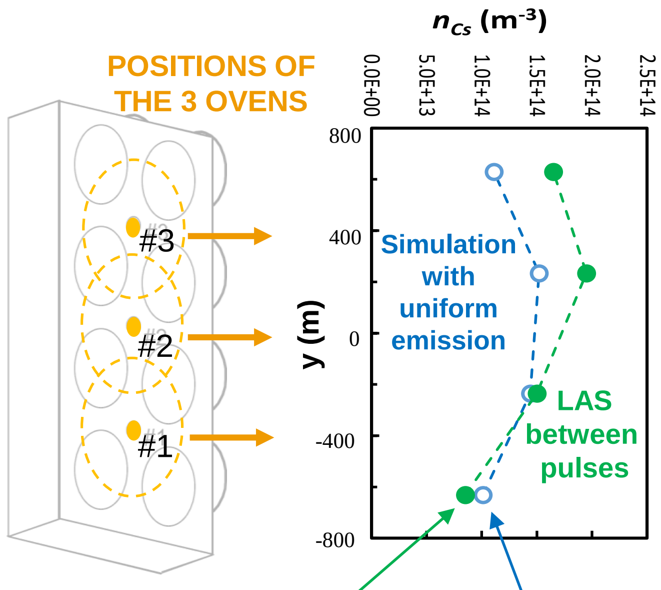


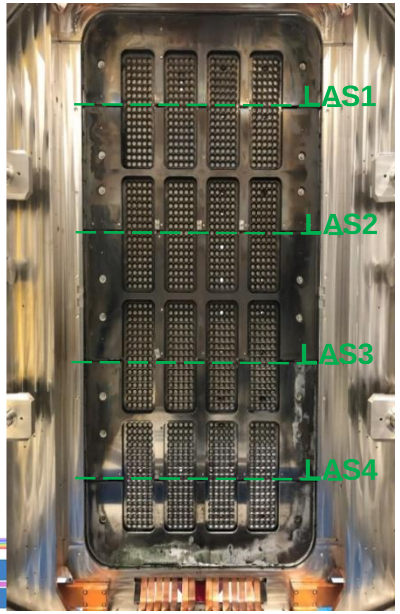
- Plasma parameters inside drivers appear to be uneven
- At the bottom of the source, electrons reach the extraction region; flow of hot electrons from drivers; caesium does not affect this drift
- At the bottom, less positive ions; less beamlet current; caesium evaporation improves both
- Visual inspection: PG/BP surface clean at the bottom

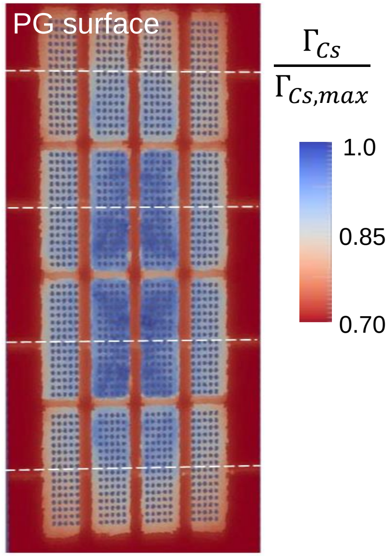
[1] G Serianni, Spatially resolved diagnostics for optimization of large ion beam sources, RSI 93 (8), 081101 (2022)

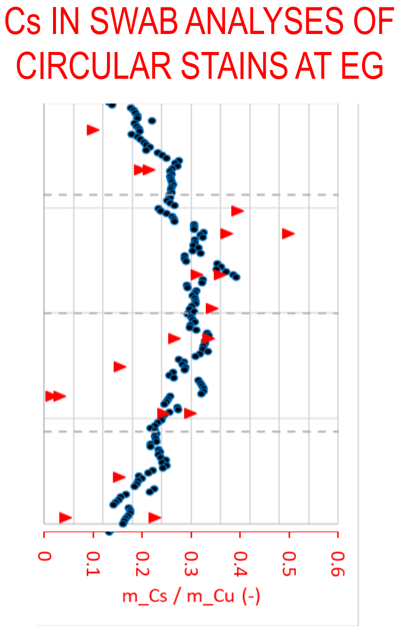
[2] B Pouradier Duteil, Characterization of the Plasma in SPIDER using a Cs-H Collisional Radiative model , NIBS 2022

Control of caesium evaporation and improvement of emission nozzle





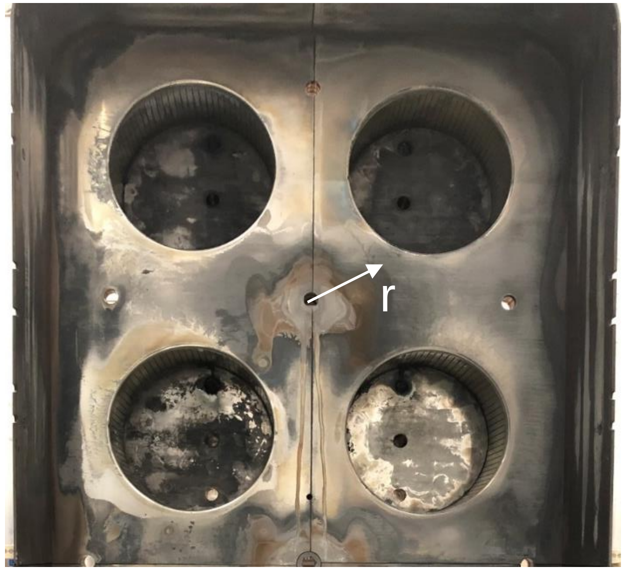


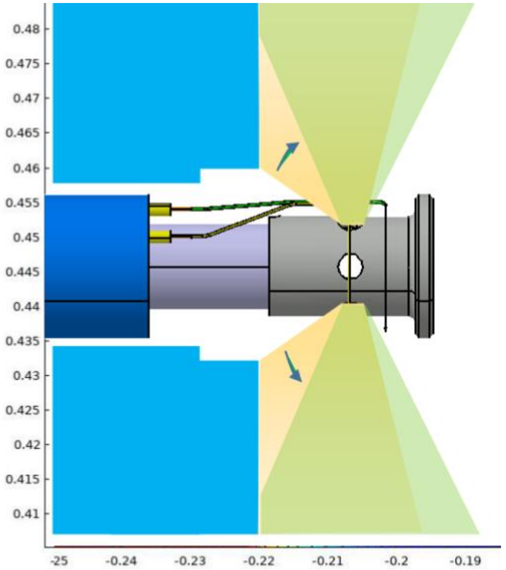


- In SPIDER short-pulse operation with caesium, vacuum phase was key for Cs dynamics: focus on this phase to maximise uniformity
- Comparison of simulations against Laser Absorption Spectroscopy, to verify equal emission from each oven[1]
- Comparison against sampling of stains at extraction grid, direct projection through PG apertures of first emission from nozzle[1],[2] (not much affected by plasma, nor by stray particles in the accelerator since they are far from the apertures)
- Role of plasma in Cs dynamics: evidence of quite large amount of Cs^{+} in the plasma is found at the lateral walls (i.e. maximum amount found at cusps)

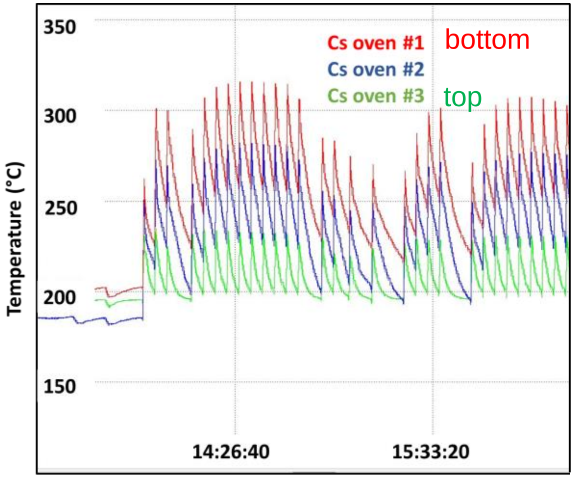
[1] M Fadone, Summary of caesium evaporation and deposition during SPIDER's first campaign, NIBS 2022
[2] M Pavei, Status of SPIDER beam source after the first 3.5 years of operation, SOFT 2022

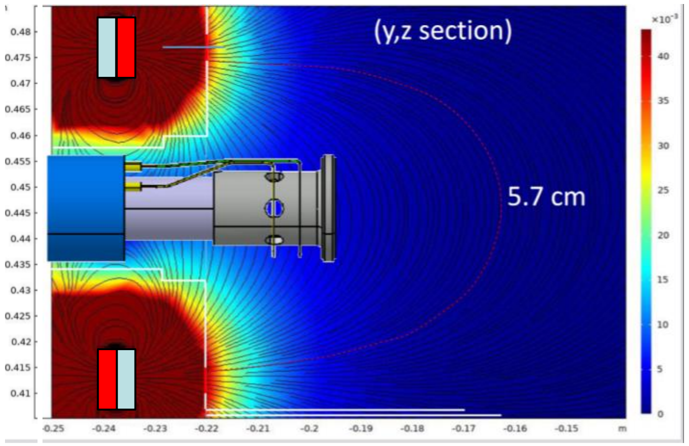
Control of caesium evaporation and improvement of emission nozzle





- Oven nozzle geometry shall be improved to avoid evaporating directly around the nozzle

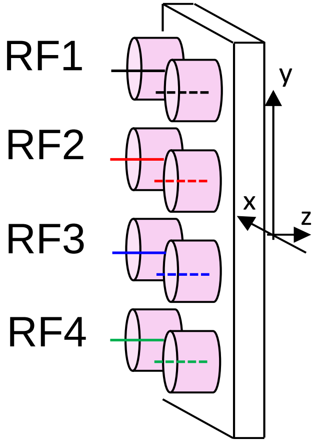


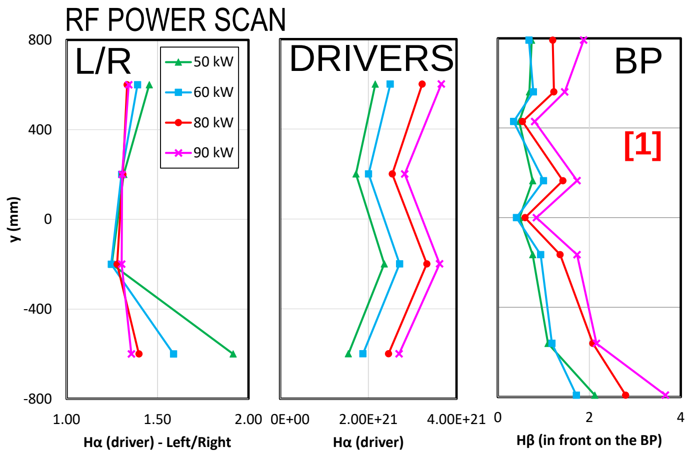


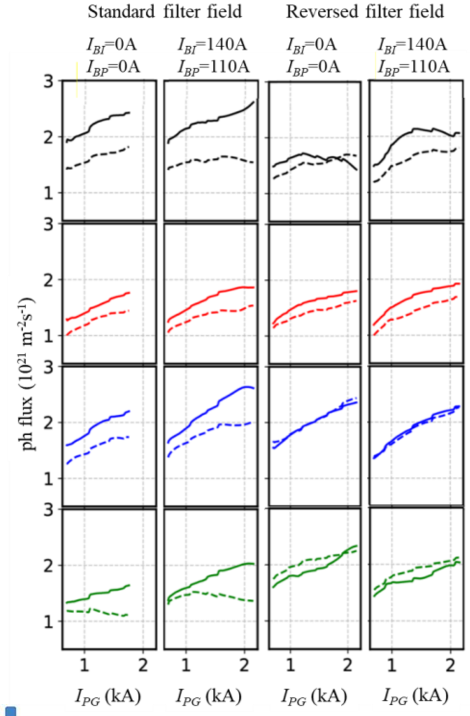
- By interaction with the plasma, the oven nozzles are overheated, each one differently: might result in uncontrolled Cs release (i.e. not in steady-state)

[1] M Fadone, Summary of caesium evaporation and deposition during SPIDER's first campaign, NIBS 2022
[2] M Pavei, Status of SPIDER beam source after the first 3.5 years of operation, SOFT 2022

Vertical uniformity and non-homogeneities among RF generators



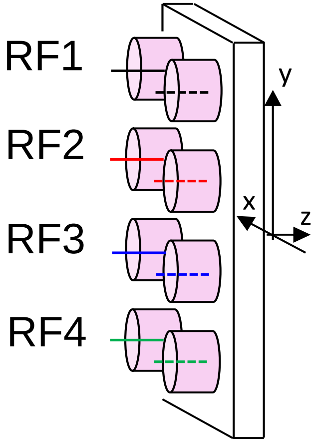


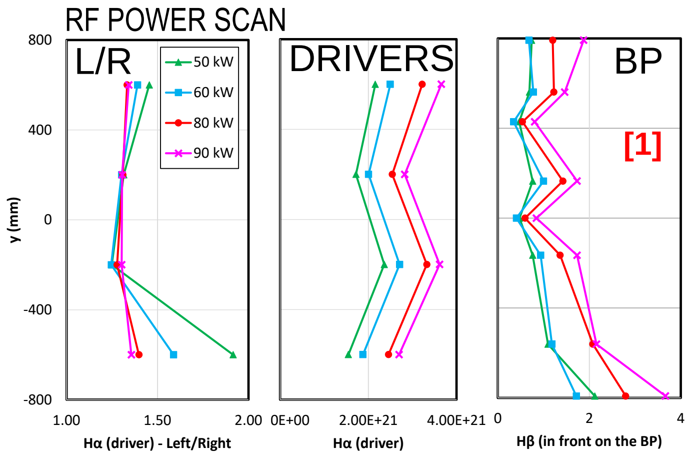


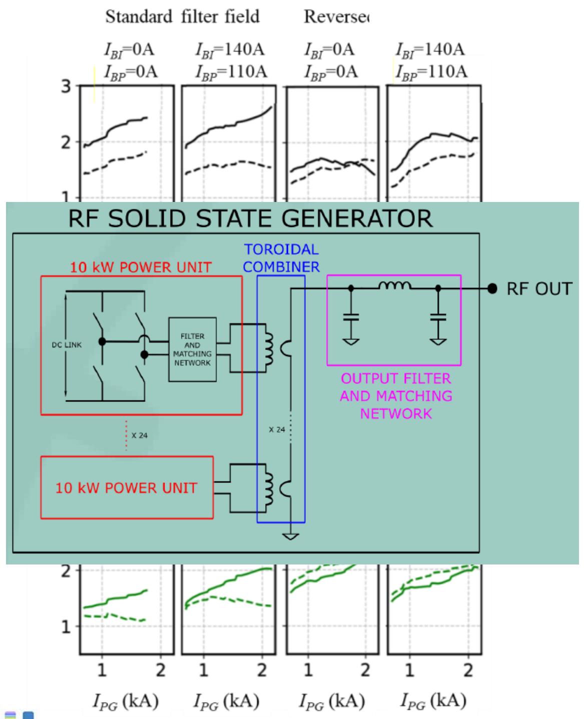
- Beam and plasma parameters along vertical direction depends on RF power, filter field, pressure, bias: difficult to understand link to plasma and source parameters[1],[2]
- Plasma drifts in expansion region mixes with uneven RF power coupled to each driver

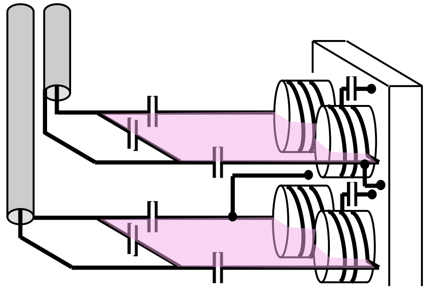
[1] M Ugoletti, Study of the relationship between the source complexity and the beam divergence and homogeneity in SPIDER, NIBS 2022
[2] M Agostini, Effect of plasma grid and bias plate biasing in SPIDER negative ion beam, NIBS 2022

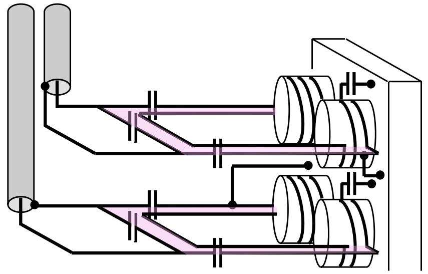
Vertical uniformity and non-homogeneities among RF generators







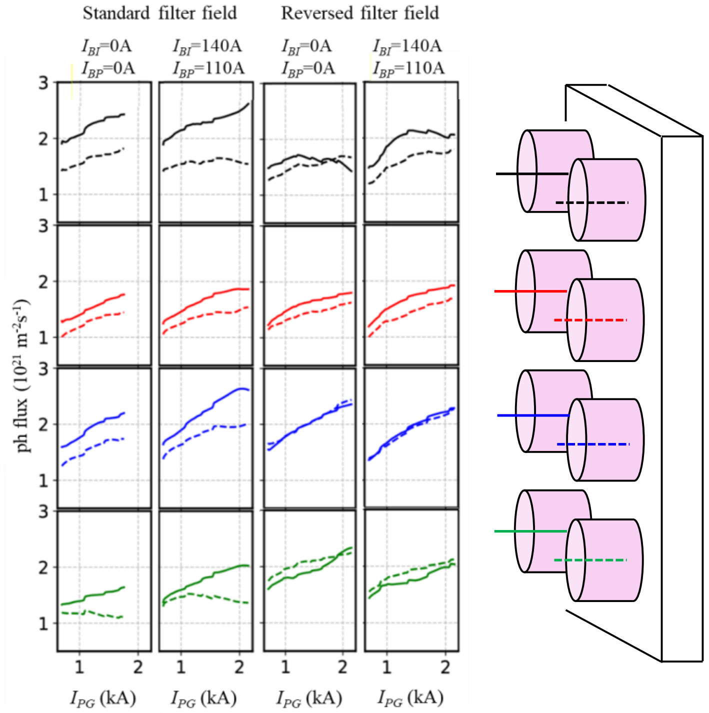




- Beam and plasma parameters along vertical direction depends on RF power, filter field, pressure, bias: difficult to understand link to plasma and source parameters[1],[2]
- Plasma drifts in expansion region mixes with uneven RF power coupled to each driver
- Replacement of oscillators with solid-state RF generators[3],[4],[5]
  - No internal resonance to set the frequency (avoidance frequency instability), direct control of the frequency allows to reach the best matching → **no output power limitation**
  - Avoidance of cross talk, if driven at the same frequency → **no modulation of RF power** among pairs of drivers
- Optimization of RF circuit geometry to minimise mutual inductance among RF circuits of different generators

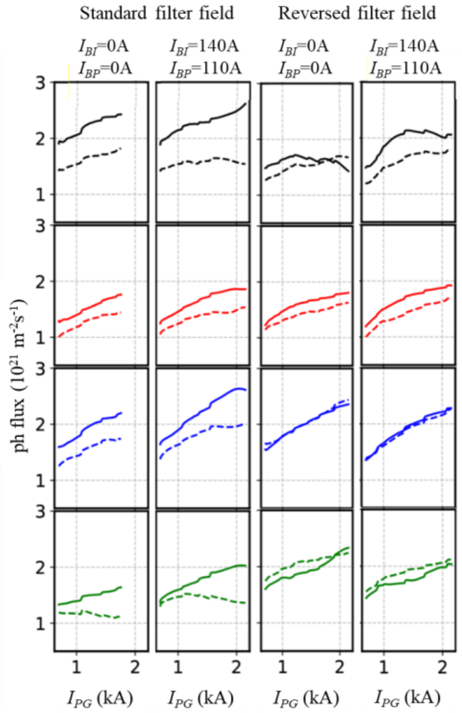
[1] M Ugoletti, Study of the relationship between the source complexity and the beam divergence and homogeneity in SPIDER, NIBS 2022
[2] M Agostini, Effect of plasma grid and bias plate biasing in SPIDER negative ion beam, NIBS 2022
[3] A Maistrello, Overview on Electrical Issues Faced During the SPIDER Experimental Campaigns, SOFT 2022
[4] V Toigo, The ITER Neutral Beam Test Facility: status and perspectives , NIBS2022
[5] R Casagrande, Guidelines for the integration of RF solid state generators for the high power ion sources of NBTF experiments and ITER HNB, SOFT 2022

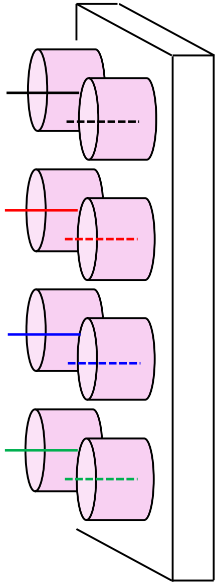
Left/right symmetry of RF drivers

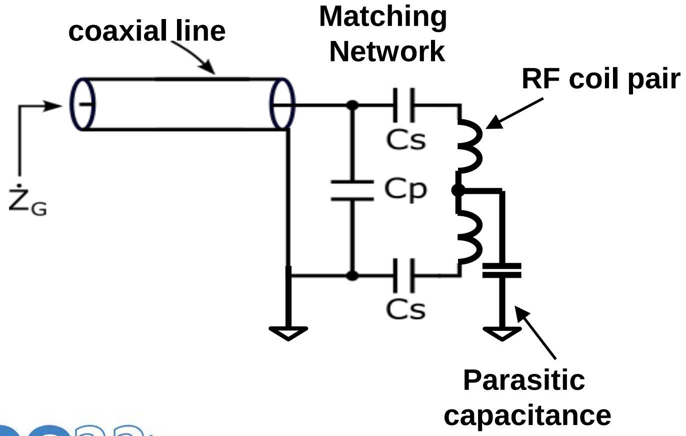


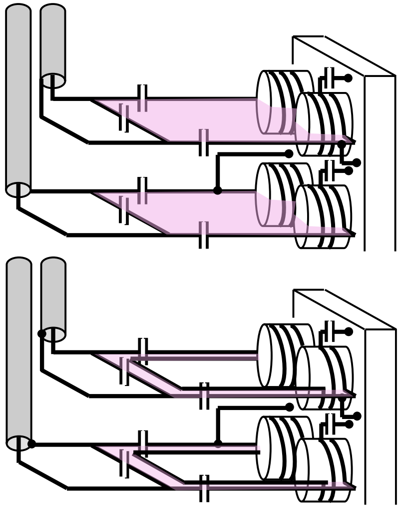
- Left/right asymmetry depends on filter field and bias. Not easy to justify.

Left/right symmetry of RF drivers





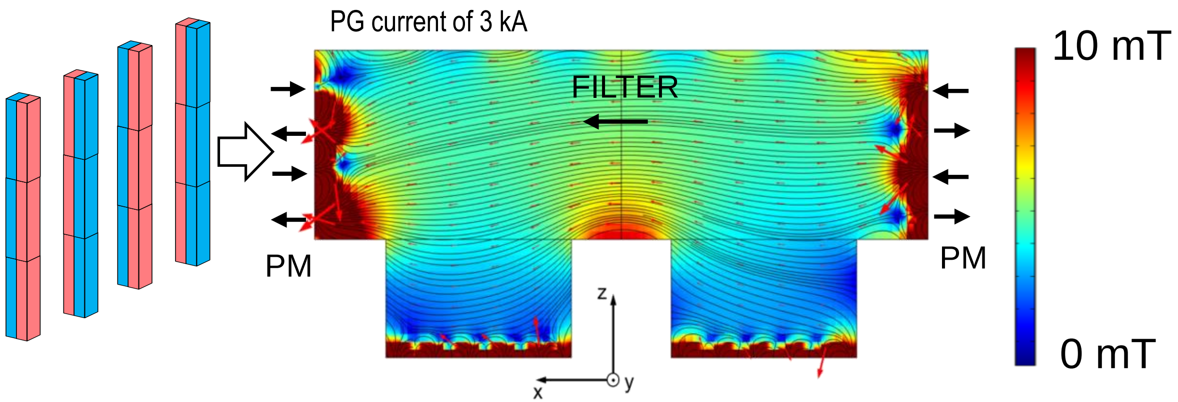


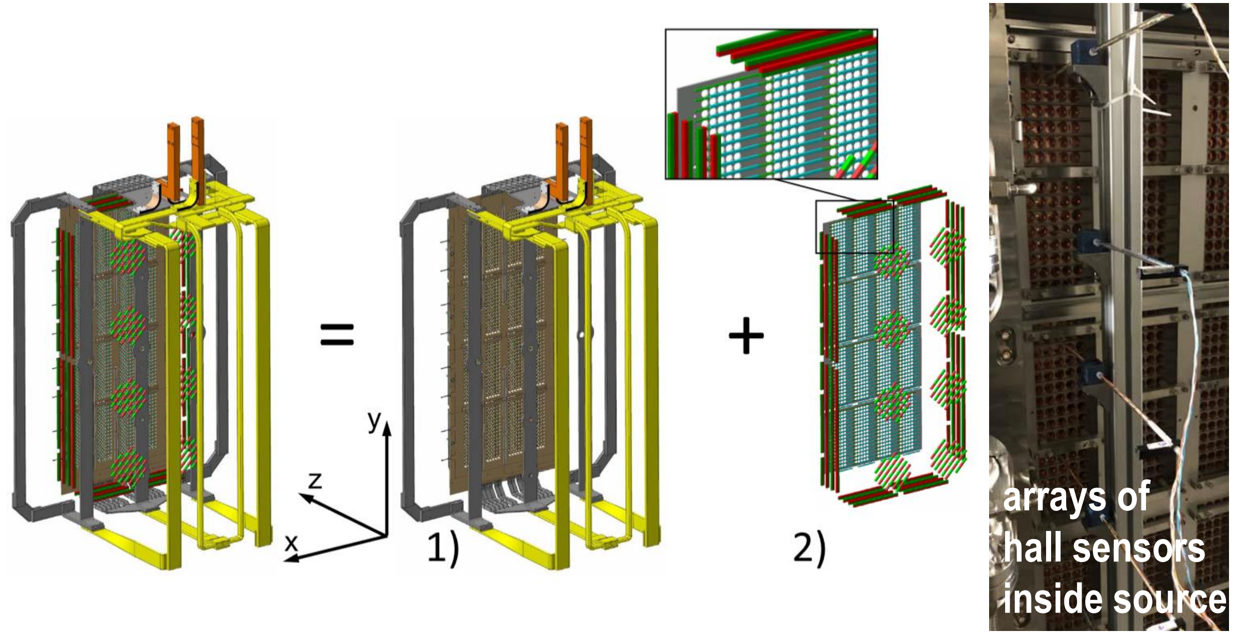


- Left/right asymmetry depends on filter field and bias. Not easy to justify.
- Can be related to RF circuit:
  - asymmetric parasitic capacitance? Difference of the current among RF coil pairs estimated between 2% and 4% (i.e. RF power within 10% difference)
  - Mutual inductance (adding constructively or destructively to its self-induced flux) → minimize mutual inductance, use of solid-state generators will mitigate

  Ongoing analyses to determine plasma parameters from electrical parameters[1]
- Can be related to asymmetry of magnetic filter field? Plasma drifts?

[1] P Jain, Use of electrical measurements for non-invasive estimation of plasma electron density inside the driver of spider, NIBS 2022

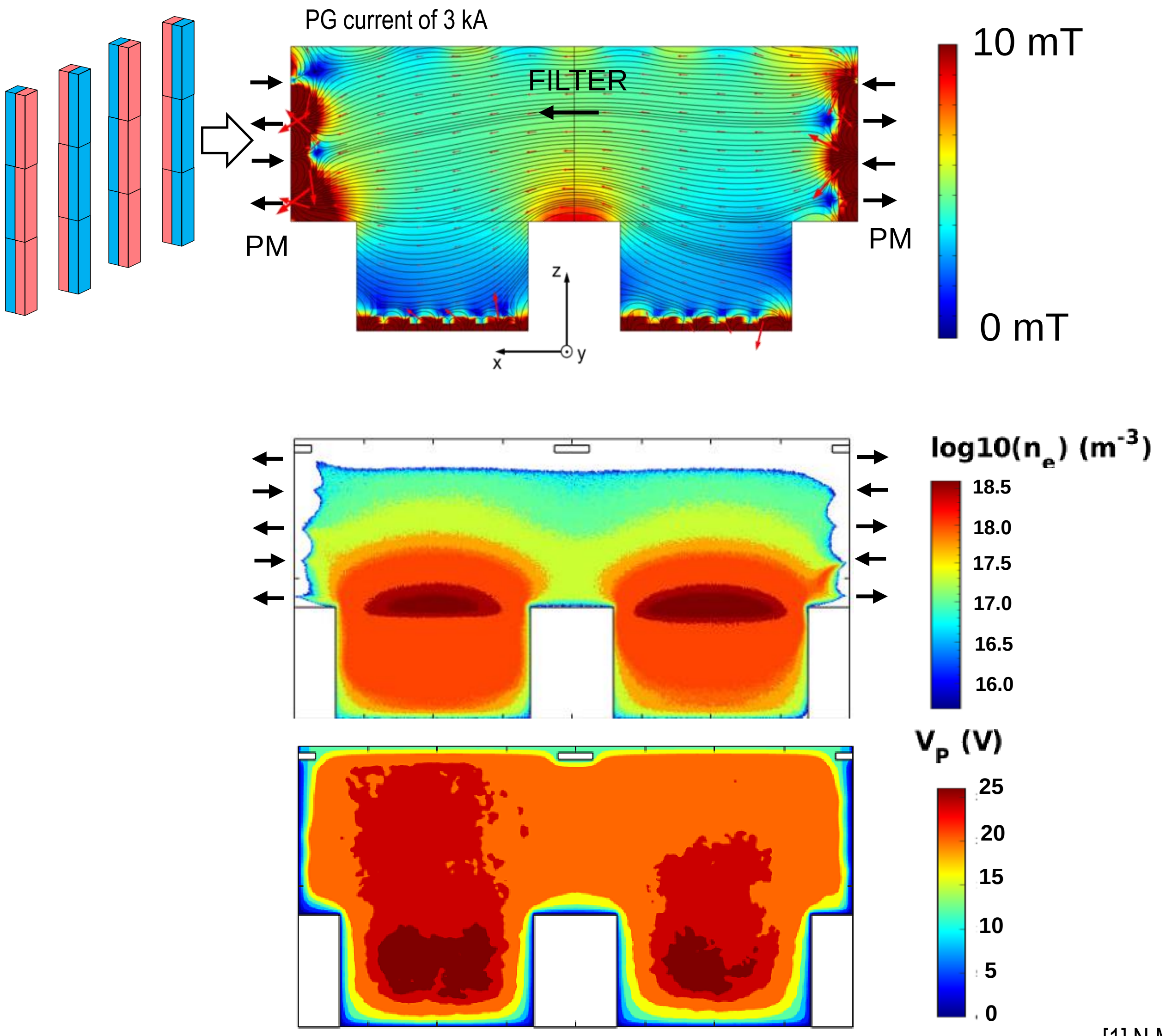




- Experimental verification of left/right symmetric contribution from filter field (e.g. unbalanced current on return busbars of PG current) was verified experimentally[1] (about 10% variation of B strength along vertical direction)
- PM in cusp configuration on lateral walls: left/right asymmetry of B field strength[1] (even reaching driver exit plane)

[1] N Marconato, Numerical and experimental assessment of the new magnetic field configuration in SPIDER, IEEE TPS 2022

Influence of magnetic field structure on asymmetries: FF in expansion region



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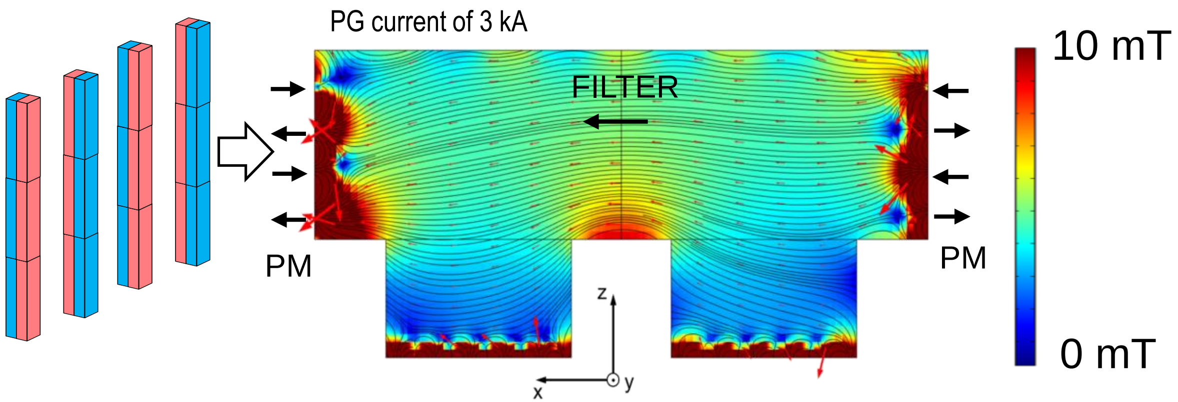
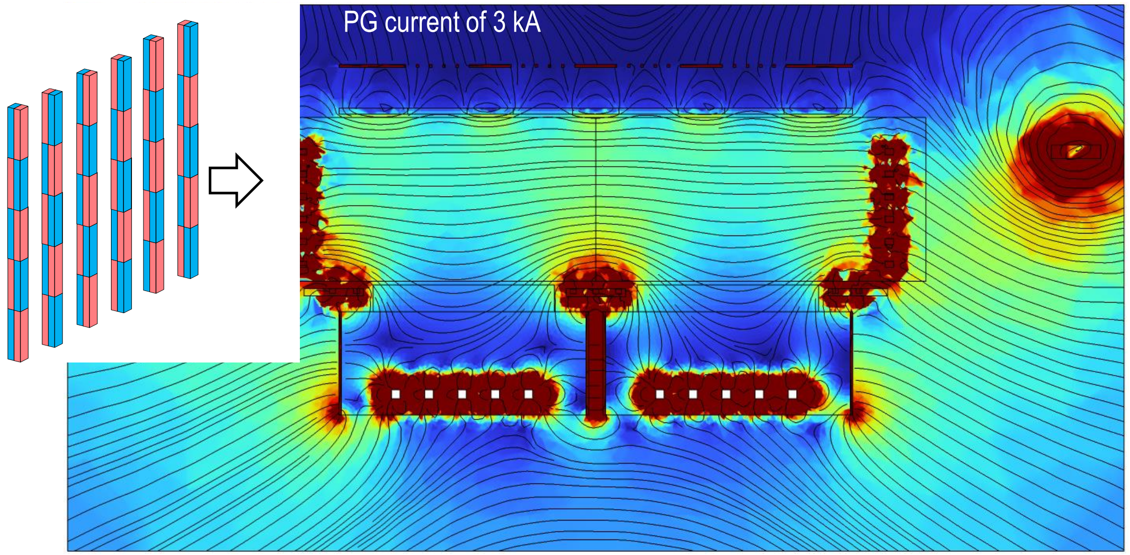
- PM in cusp configuration on lateral walls: left/right asymmetry of B field strength[1]
  (even reaching driver exit plane)
- 2D PIC simulations show the influence of LW magnets on plasma expansion and peak densities
  (ongoing: simplified filter field for the moment)

[1] N Marconato, Numerical and experimental assessment of the new magnetic field configuration in SPIDER, IEEE TPS 2022

Influence of magnetic field structure on asymmetries: FF in expansion region





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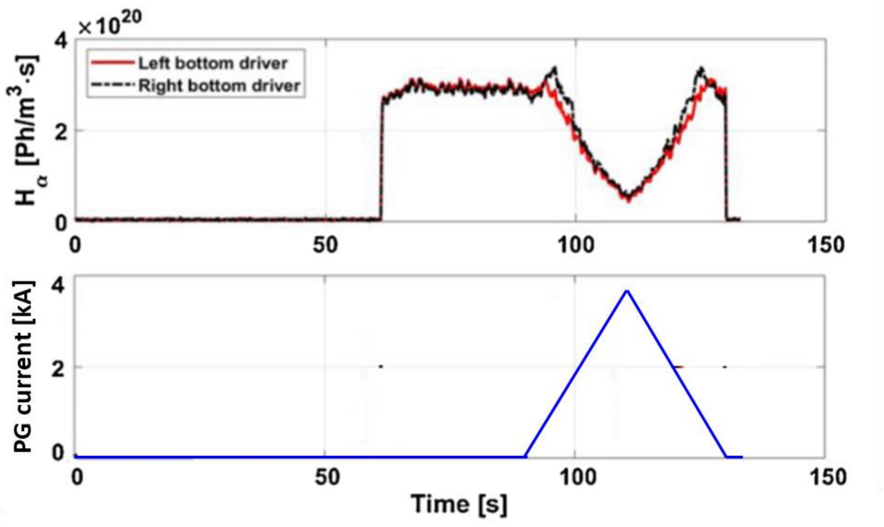
  (about 10% variation of B strength along vertical direction)
- PM in cusp configuration on lateral walls: left/right asymmetry of B field strength[1]
  (even reaching driver exit plane)
- 2D PIC simulations show the influence of LW magnets on plasma expansion and peak densities
- Change PM volume and cusp configuration at LW to minimise long-range effect[2]

[1] N Marconato, Numerical and experimental assessment of the new magnetic field configuration in SPIDER, IEEE TPS 2022
[2] N Marconato, Integration of new sets of magnets for improved plasma confinement in the SPIDER experiment, SOFT 2022

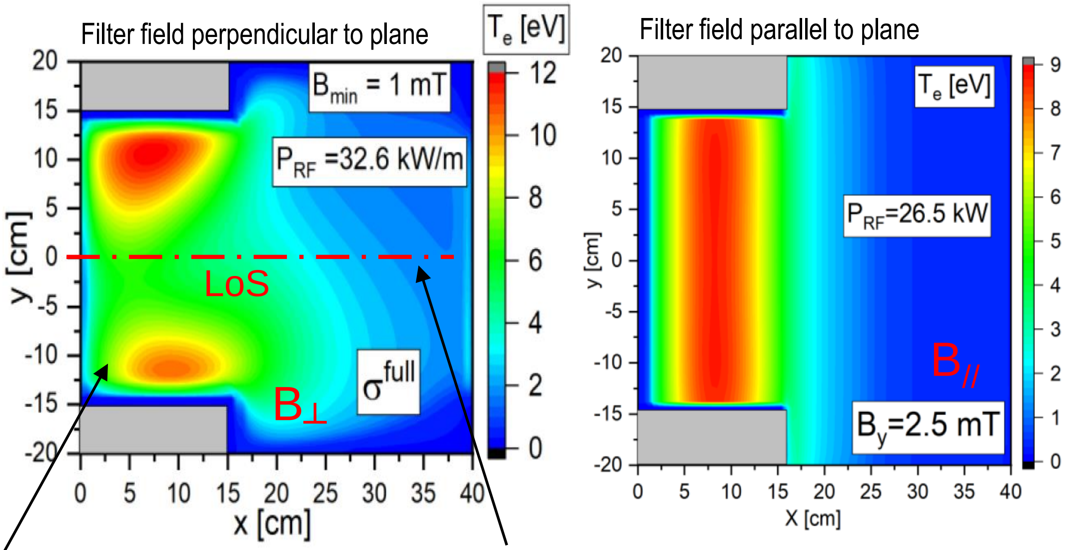
Effect of filter field inside drivers



- In the original configuration, strong transverse filter field strength inside the driver[1]. Increasing the filter field turned off the plasma.

[1] N Marconato, An optimized and flexible configuration for the magnetic filter in the SPIDER experiment, FED 166 112281 (2021)

Effect of filter field inside drivers



without B field, Te always peaks next to the RF coils, whatever the conductivity model;
with B⊥, the conductivity model determines the radial profile of absorbed power

Note that for different field strength, the plasma might move transversally wrt the LoS of the Hα signal

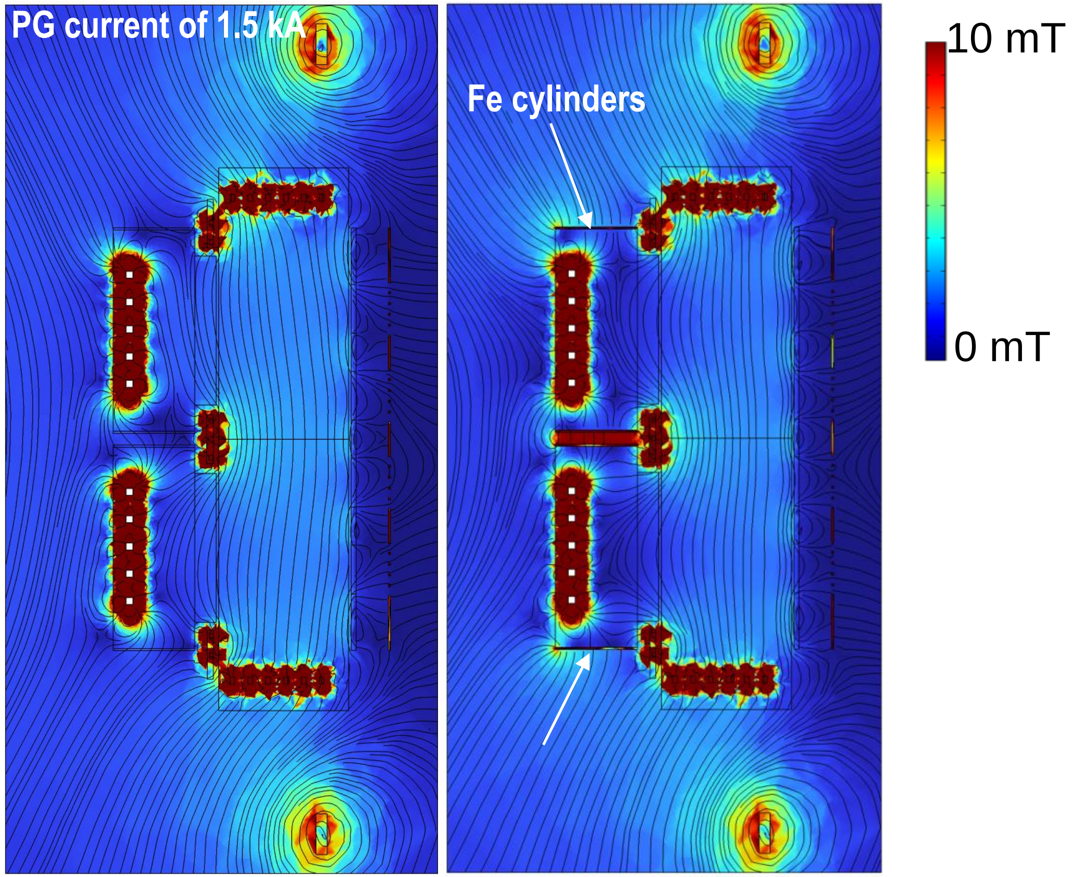
- In the original configuration, strong transverse filter field strength inside the driver[1]. Increasing the filter field turned off the plasma
- 2D steady-state fluid model FSFS2D (Fluid Solver For SPIDER in 2D)[2]. Fluid equations weakly coupled (P_{RF} and conductivity σ) to complex E_{Θ} induced field[3] (cylindrical symmetry, harmonic current, no displacement current)

$$\partial_r(r\partial_r E_\theta^p) + r\partial_{xx}E_\theta^p - \frac{E_\theta^p}{r} - i\omega r\mu_0\sigma E_\theta^p = i\omega r\mu_0\sigma E_\theta^V$$

- In B⊥ simulation, filter field strength is beneficial for confinement; $B_{//}$ simulation however provides possible explanation for experimental behavior
(note that cylindrical approximation is not valid, intrinsically 3D)
- Experimental measurements showed lower T_e next to the faraday shield, higher at center → $B_{//}$ simulation might provide (partial) explanation

[1] N Marconato, An optimized and flexible configuration for the magnetic filter in the SPIDER experiment, FED 166 112281 (2021)
[2] R Zagórski, 2-D Fluid Model for Discharge Analysis of the RF-Driven Prototype Ion Source for ITER NBI (SPIDER), IEEE TPS 2022
[3] R Zagórski, 2D simulations of inductive RF heating in the drivers of the SPIDER device, SOFT 2022

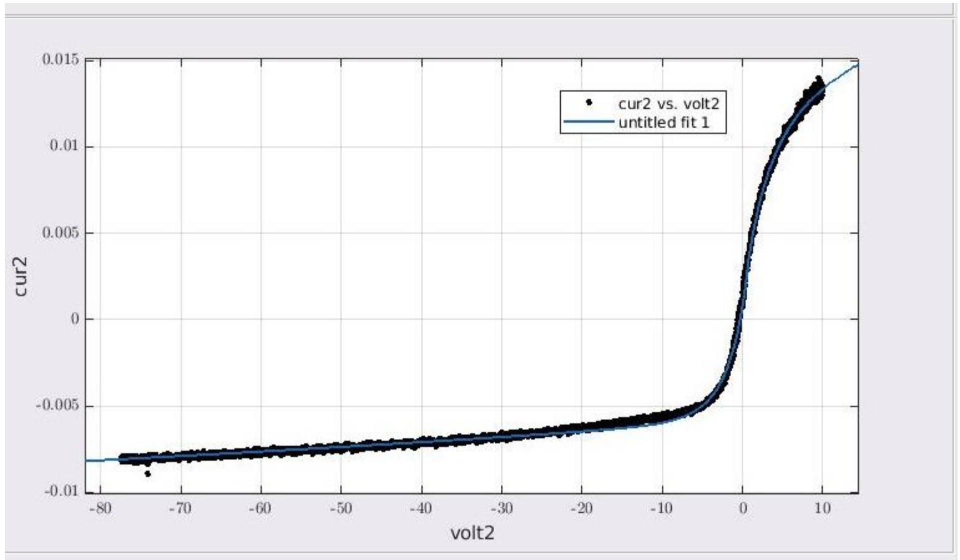
Effect of filter field inside drivers: Fe cylinders



- In the original configuration, strong transverse filter field strength inside the driver[1]. Increasing the filter field turned off the plasma
- Use of ferromagnetic cylinders (e.g. outside the electromagnetic shields of RF drivers) is one option to minimise the filter field inside drivers[4]
  (up to driver's exit, about ½ of the original value)
  Inside the drivers it now is reduced to about 30% of the value in the expansion region (it is about 65% without Fe).

[4] N Marconato, Integration of new sets of magnets for improved plasma confinement in the SPIDER experiment, SOFT 2022

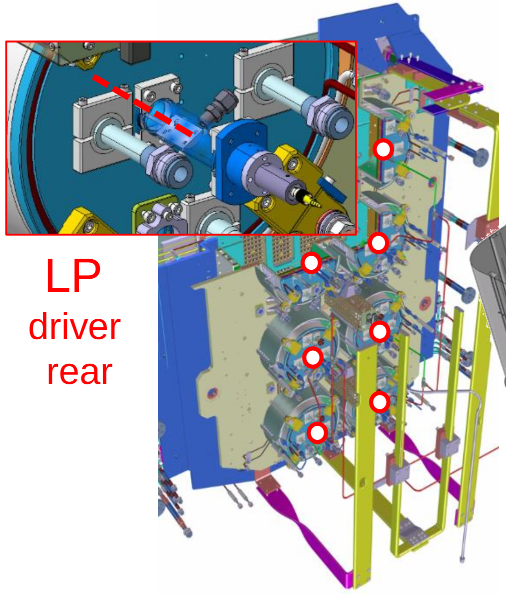
Preparing future investigation of nonuniformities from drivers to extraction region

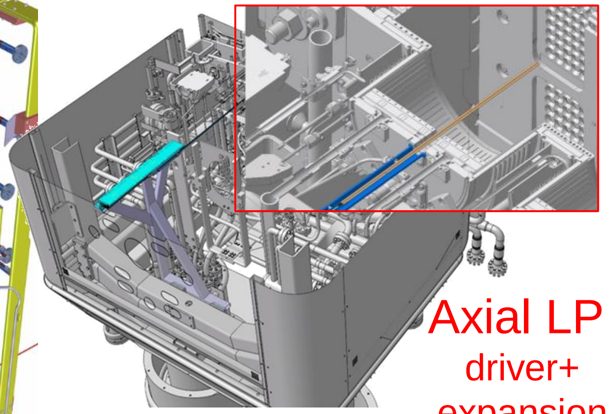


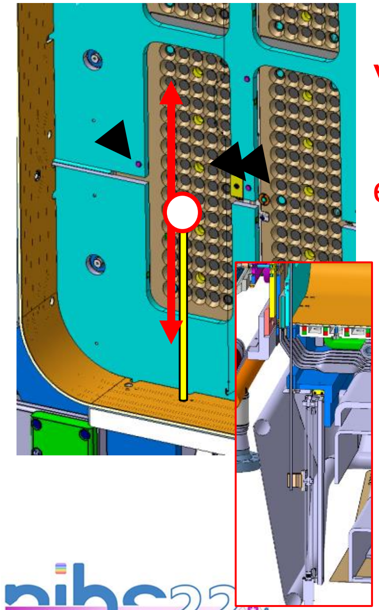
- Model for the analysis of current-voltage characteristics of embedded langmuir probes in highly electronegative plasma[1]
- Optimization of optical emission spectroscopy and collisional-radiative models for its interpretation[2],[3]

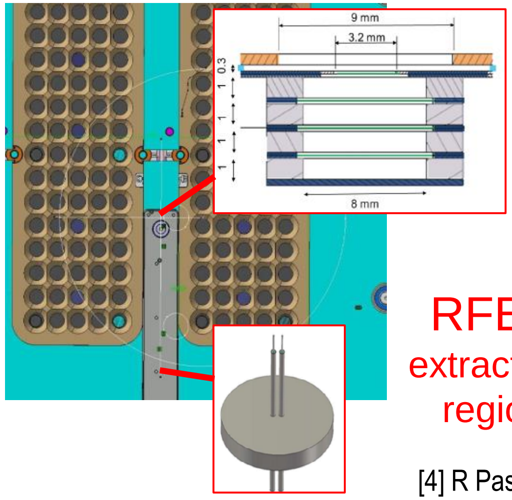
[1] C Poggi, Highly electronegative plasma conditions in the SPIDER negative ion source, NIBS 2022
[2] D Bruno, Rotational and vibrational temperatures of Hydrogen nonequilibrium plasmas from Fulcher band emission spectra, NIBS2022
[3] I Mario, Plasma emission monitored via optical emission spectroscopy during the Cs conditioning at SPIDER, NIBS 2022

Preparing future investigation of nonuniformities from drivers to extraction region





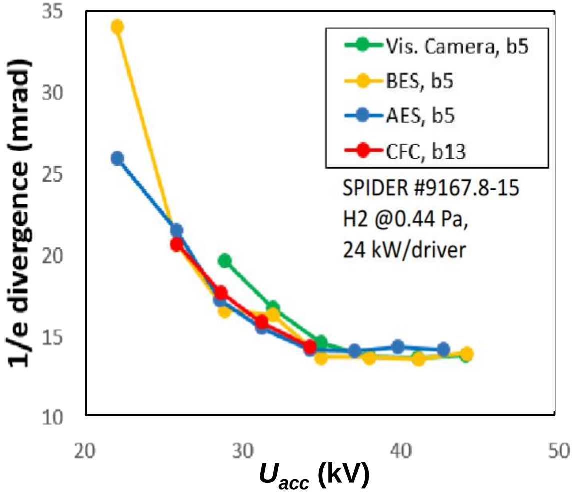




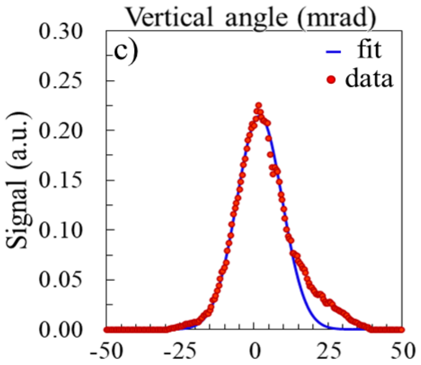
- Model for the analysis of current-voltage characteristics of embedded langmuir probes in highly electronegative plasma[1]
- Optimization of optical emission spectroscopy and collisional-radiative models for its interpretation[2],[3]
- vertical profiles in the plasma within beamletgroup: movable Langmuir probe at the extraction[4], also compatible with the use of Cavity-Ring-Down laser for photodetachment[5]
- Compact Retarding Field Energy analyser on the Bias Plate[5]
- Fast axial movable Langmuit probe, to assess also during caesiation the plasma parameters along the driver axis and hte expansion region[6]
- Role of electrons fundamental: feasibility study for an interferometer [7] , and of a cut-off probe[5] for measurement of the electron density

[4] R Pasqualotto, Improvement of SPIDER diagnostic systems, SOFT 2022
[5] B Segalini, Study and development of diagnostic systems to characterise the extraction region in SPIDER, NIBS 2022
[6] V Candeloro, Design of a movable electrostatic diagnostic for the investigation of plasma prop. in a large neg. ion source SOFT 2022
[7] R Agnello, Numerical and experimental investigations of a microwave interferometer for the negative ion source SPIDER , NIBS 2022

Beamlet optics and possible improvements



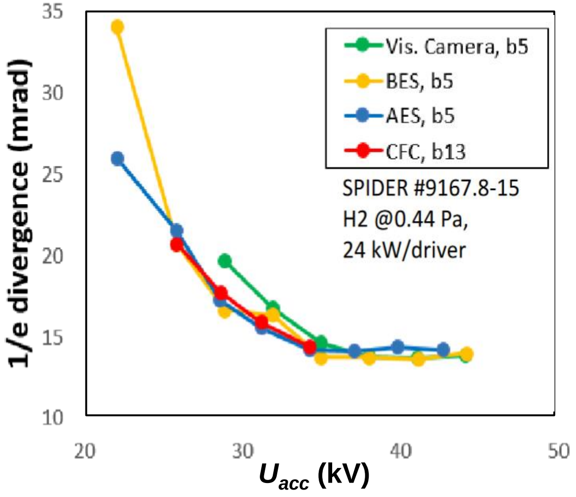
ALLISON EMITTANCE SCANNER



- Study of single beamlet optics in SPIDER important in view of ITER HNB, measurement of angular distribution[1] and confirm required divergence (transmission to ITER & possibility of beam halo interception by accelerator grids)
- Beam divergence in SPIDER can be measured by four diagnostics, good agreement among them, in general not better than 12 mrad[2]

[1] G Serianni, SOFE2021, IEEE-Trans Plasma Sci. (2022)
[2] P Veltri, Towards low divergence beams for the ITER neutral beam injection system , NIBS 2022

Beamlet optics and possible improvements



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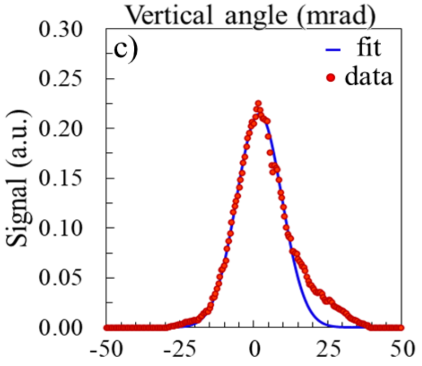
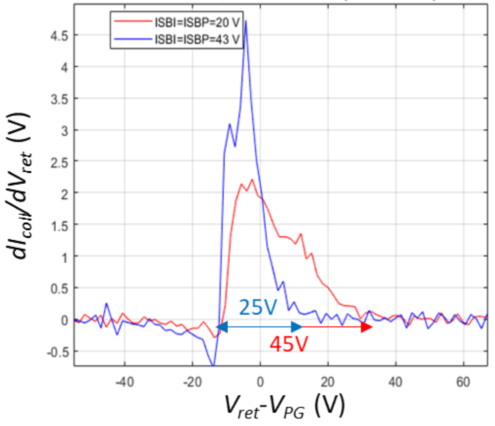
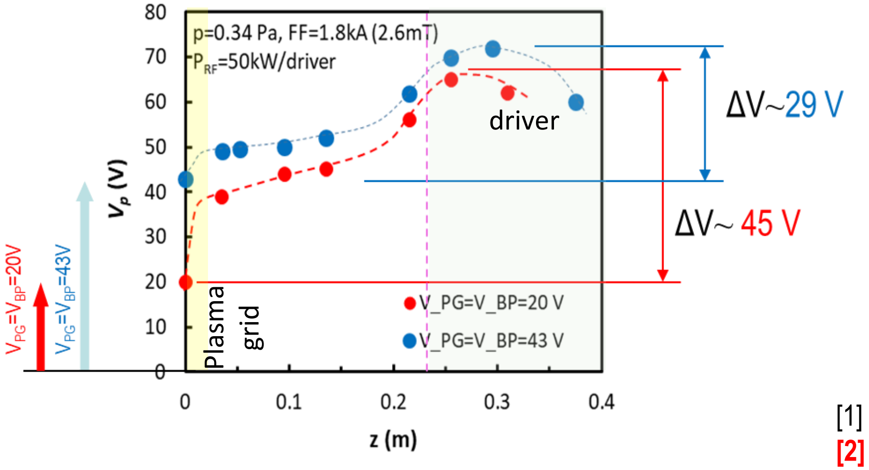


RETARDING FIELD ENERGY ANALYSER

P=0.34 Pa, FF=2kA (3.2mT), D2



PLASMA POTENTIAL FROM MOVABLE LANGMUIR PROBES



- Study of single beamlet optics in SPIDER important in view of ITER HNB, measurement of angular distribution[1] and confirm required divergence (transmission to ITER & possibility of beam halo interception by accelerator grids)
- Beam divergence in SPIDER can be measured by four diagnostics, good agreement among them, in general not better than 12 mrad[2]
- Possible approach for improving divergence:
  - Reduce energy of H^- precursors
  - Increase positive ion density, while diminishing the energy source for positive ions[3]
- Reducing plasma potential would additionally diminish driving forces for vertical drifts

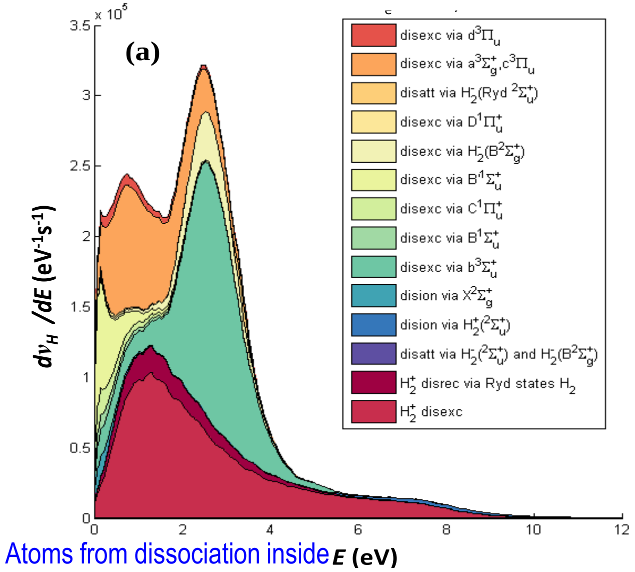
[1] G Serianni, SOFE2021, IEEE-Trans Plasma Sci. (2022)

[2] P Veltri, Towards low divergence beams for the ITER neutral beam injection system , NIBS 2022

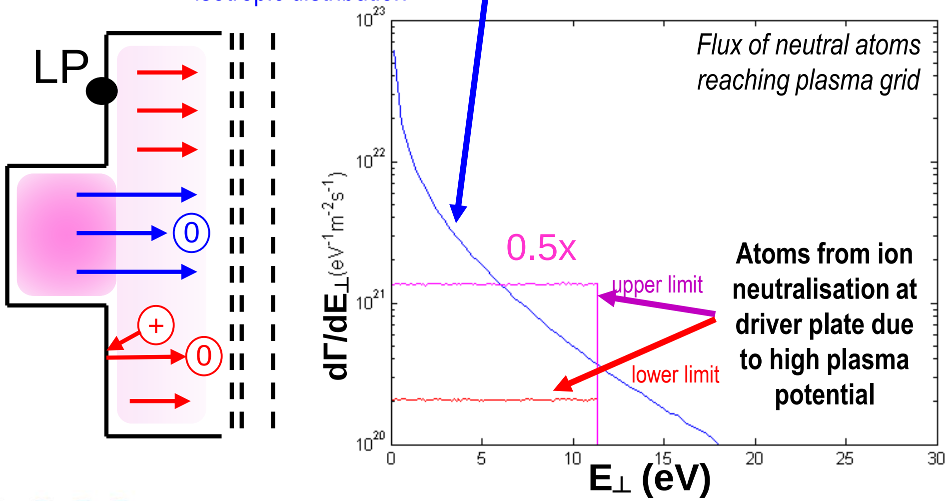
[3] A Pimazzoni, Key parameters for the ion velocity distribution at the plasma meniscus of a caesiated negative ion source, NIBS 2022

Hot atoms and plasma loss at rear walls

Kinetic Energy Release of dissociation H^0 fragments, T_e=15 eV, n_e=3x10^{18} m^{-3}



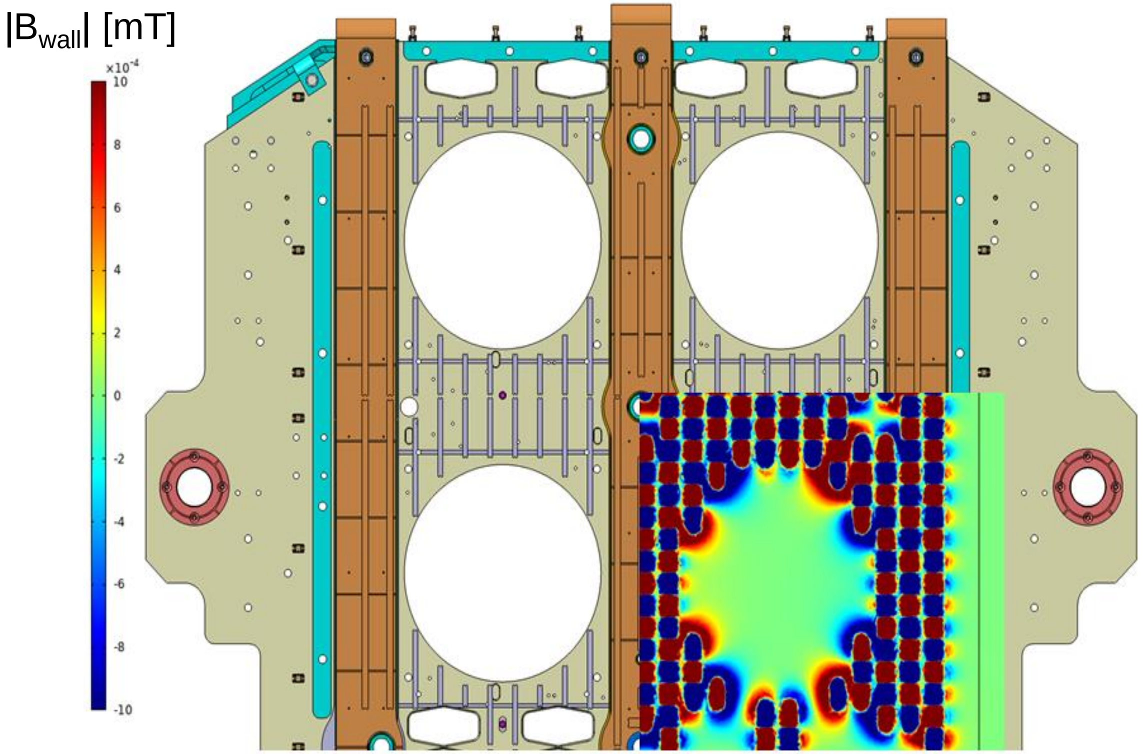
Atoms from dissociation inside RF drivers (1.5x10^{18} m^{-3}), isotropic distribution



- Numerical simulation of energy distribution of atoms generated by dissociation inside ion source[1]
- Measurement of plasma parameter before plasma driver plate (i.e. rear wall of expansion chamber)[2]
- Ion neutralisation at rear walls[3] causes high-energy tail of hot atom reaching Plasma Grid

[1] E Sartori, Energy distribution of fragments in dissociation by electron impact for the use in numerical models applied to negative ion sources, NIBS 2022
[2] V Candeloro, Development of a Triple Langmuir Probe for Plasma Characterization in SPIDER, IEEE TPS
[3] G Fubiani, New Journal of Physics 015002, 2017

Hot atoms and plasma loss at rear walls



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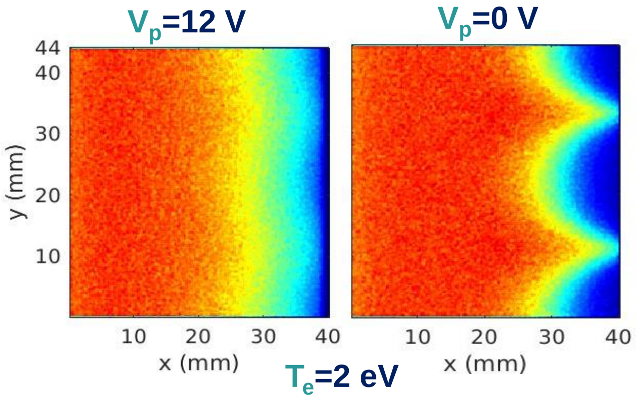
- Measurement of plasma parameter before plasma driver plate (i.e. rear wall of expansion chamber)[2]
- Ion neutralisation at rear walls[3] causes high-energy tail of hot atom reaching Plasma Grid
- Importance of rear walls on the overall plasma loss: quite important reduction of total ion losses (not ambipolar) expected from analytical estimation (about -20%)
- Study of multicusp effectiveness[5] with $V_p > V_{floating}$ (typical of lateral wall and real wall of expansion region)



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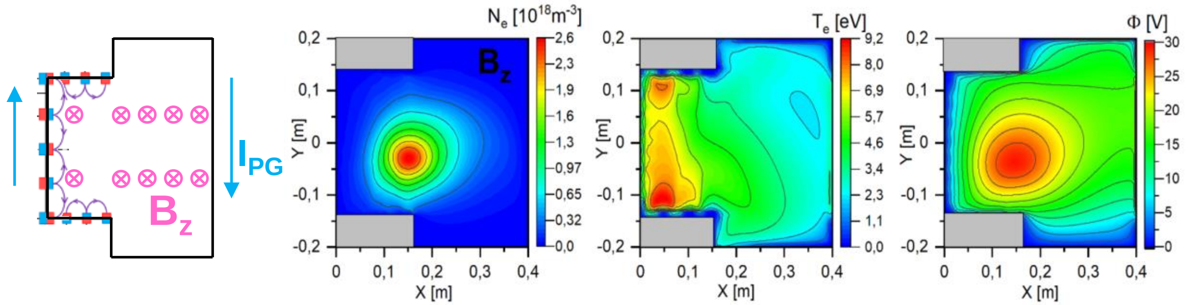
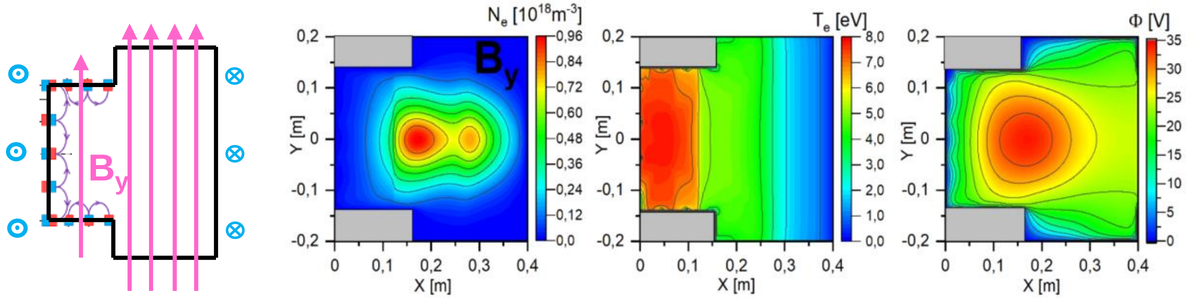
[3] G Fubiani, New Journal of Physics 015002, 2017

[4] N Marconato, Integration of new sets of magnets for improved plasma confinement in the SPIDER experiment, SOFT 2022

[5] V Candeloro, Influence of plasma parameters on the effectiveness of multi-cusp magnetic field confinement in negative ion sources, NIBS 2022



wrt case without magnets: +150% n_e , -25% T_e, -20% V_p

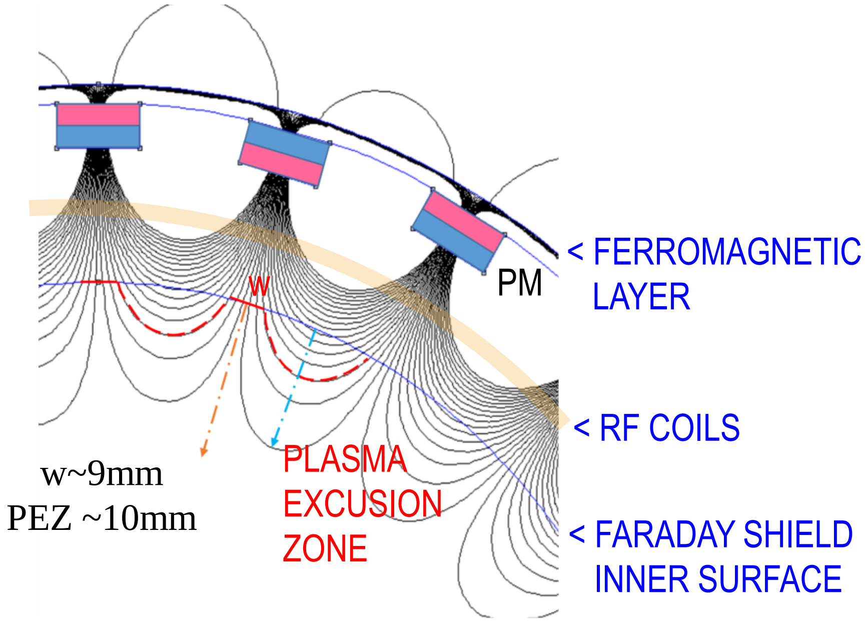


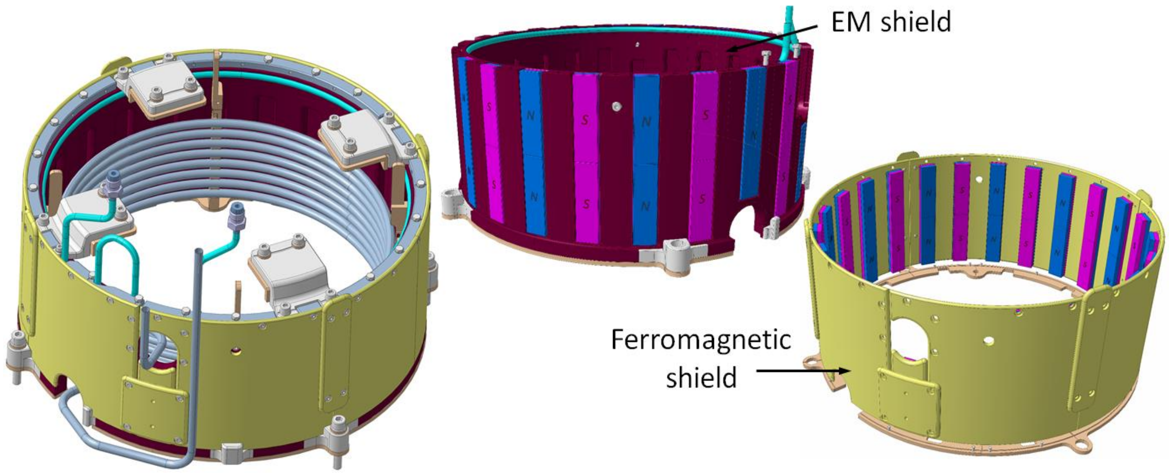
30 kW, $B_{\perp}(x)$ from 1mT to 2mT, depleted n_{H2} 2.5 to 4.5x1019 m^{-3}

wrt case without magnets: +60% n_e, -40% T_e , -22% V_p

- Aim: increasing plasma density and reducing plasma potential via multicusp confinement
- In the absence of 3D models: 2D fluid simulations[1] on planes perpendicular rather than parallel to B yield. $n_e \uparrow$, $V_p \downarrow$

[1] R Zagorski, Influence of different magnetic configurations on plasma parameters in SPIDER device, NIBS 2022



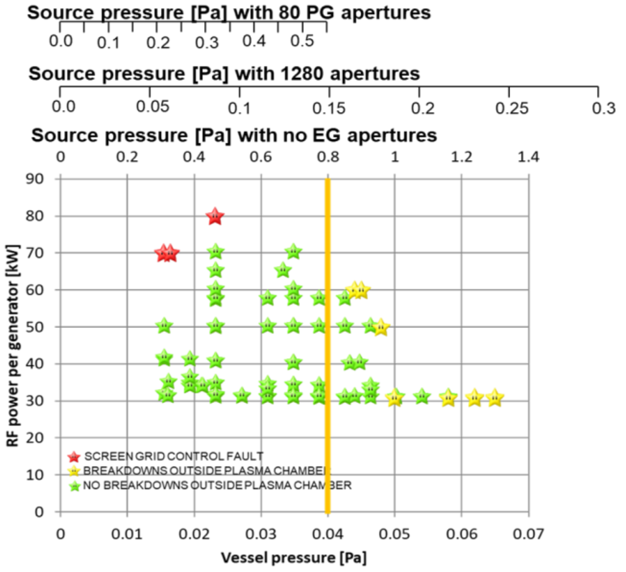


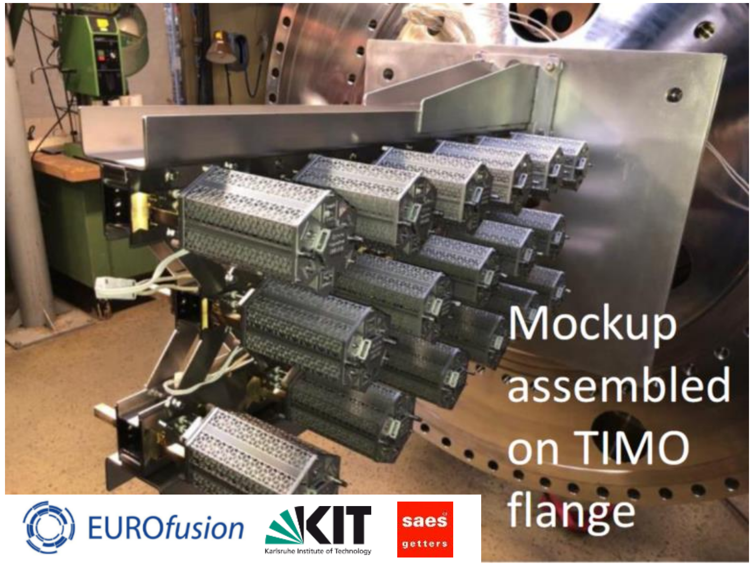
- Aim: increasing plasma density and reducing plasma potential via multicusp confinement
- In the absence of 3D models: 2D fluid simulations[1] on planes perpendicular rather than parallel to B yield. $n_e \uparrow$, $V_p \downarrow$
- Implementation in cylindrical coordinates[2] exploits the possibility to install ferromagnetic layer outside
- First order figure of merit: increase of plasma density (thanks to reduced leak width w) times decrease of plasma volume (due to plasma exclusion zones) ~3.5x

[1] R Zagorski, Influence of different magnetic configurations on plasma parameters in SPIDER device, NIBS 2022

[2] N Marconato, Integration of new sets of magnets for improved plasma confinement in the SPIDER experiment, SOFT2022

SPIDER Operating scenarios with improved pumping system





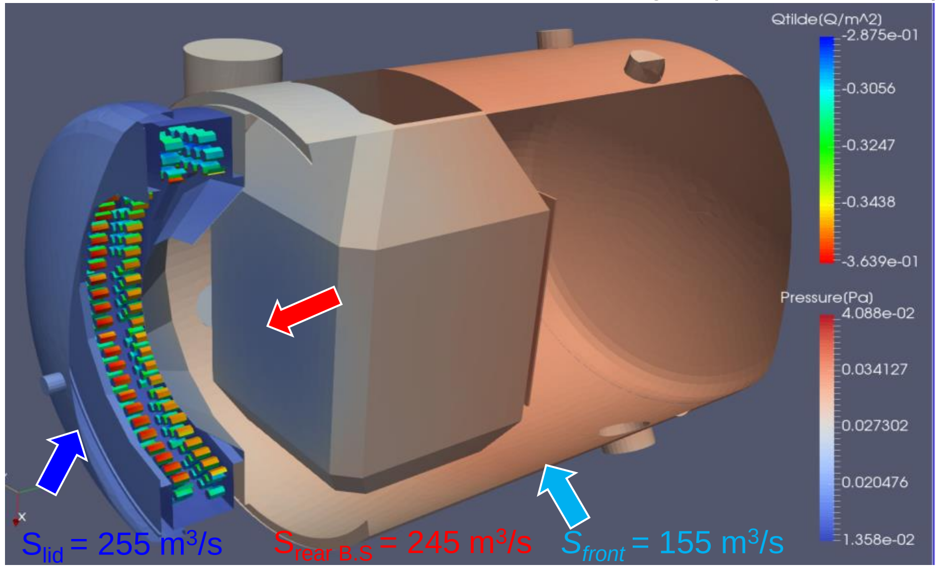
- vessel pressure limited by breakdowns on rear side of RF source (when operating multiple RF generators)
- Improved pumping system based on NEG: pumping speed of one cartridge based on characterisation at KIT, taken at RT and 0.2 Torr L/g of H_2 concentration (i.e. beginning of gas injection; of at 4.7 Torr L/g, it is about 25% lower)

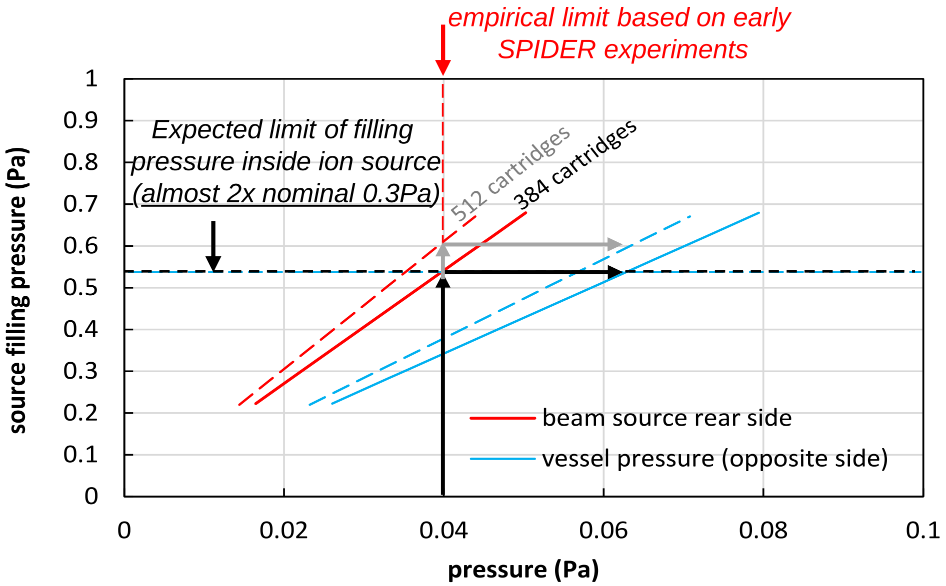
[1] M. Pavei, et al., Fus Eng Des 161 (2020) 112036
[2] S Hanke, Experimental characterisation of a large NEG pump towards its application in DEMO neutral beam injectors, SOFT 2022
[3] M Siragusa, SPIDER Vacuum Enhancement: a NEG-pump based project, presented AIV conference 2022

SPIDER Operating scenarios with improved pumping system

Source filling pressure p_{source}=0.283 Pa

4+2 TMPs (13.5 m³/s), 8 cryo (80 m³/s), 384 NEG cartridges (0.87 m³/s each)





- vessel pressure limited by breakdowns on rear side of RF source (when operating multiple RF generators)
- Improved pumping system based on NEG: pumping speed of one cartridge based on characterisation at KIT, taken at RT and 0.2 Torr L/g of H_2 concentration (i.e. beginning of gas injection; of at 4.7 Torr L/g, it is about 25% lower)
- 3D simulations show the ratio expected for <u>source pressure vs vessel pressure</u> (with all 1280 apertures, almost 0.6 Pa filling pressure is possible) and gas load on each cartridge (uniform within 5%)

[1] M. Pavei, et al., Fus Eng Des 161 (2020) 112036
[2] S Hanke, Experimental characterisation of a large NEG pump towards its application in DEMO neutral beam injectors, SOFT 2022
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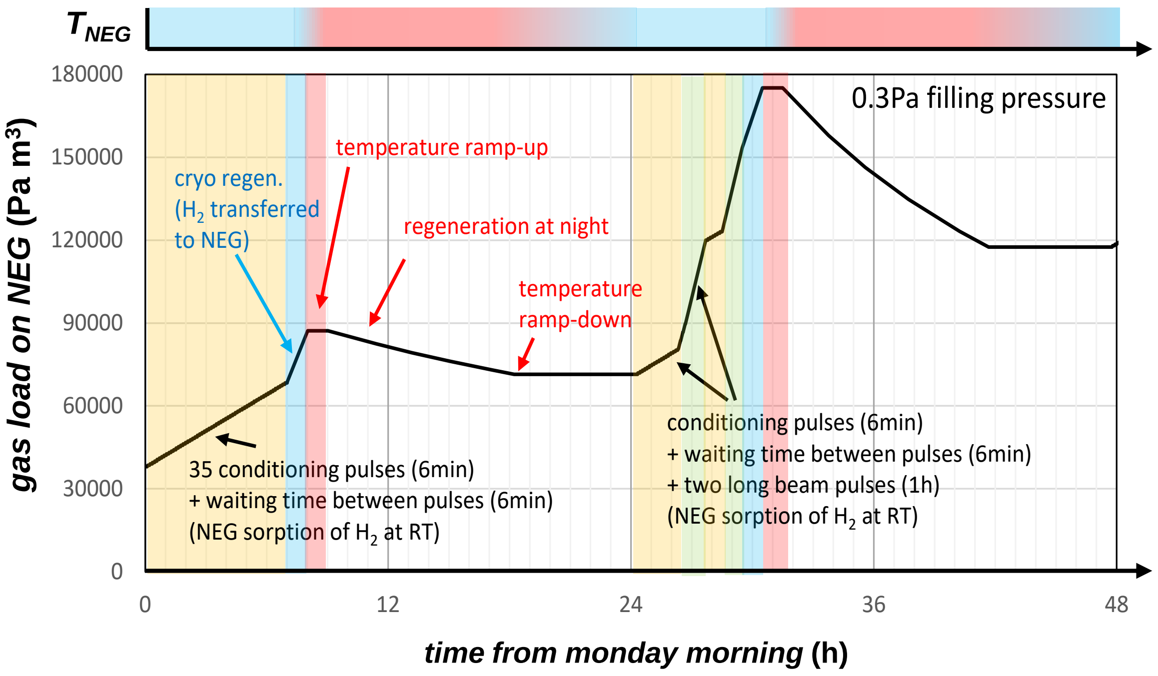

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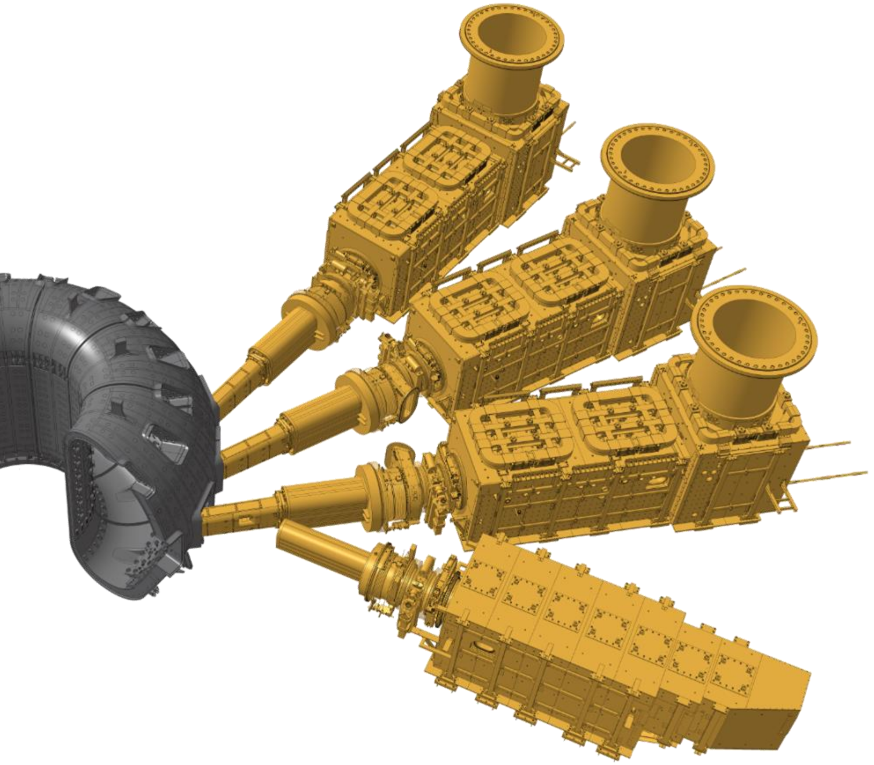
- Improved pumping system based on NEG: pumping speed of one cartridge based on characterisation at KIT, taken at RT and 0.2 Torr L/g of H_2 concentration (i.e. beginning of gas injection; of at 4.7 Torr L/g, it is about 25% lower)
- 3D simulations show the ratio expected for source pressure vs vessel pressure (with all 1280 apertures, almost 0.6 Pa filling pressure is possible)
- Operating scenario with NEG pumping at RT
  (for NEG protection in case of water leak, investment protection level)
  - Pumping speed vs hydrogen load curve
  - Effect of background gas over time (H_2O, outgassing, minor leaks) slowly decrease the NEG performance, independently of hydrogen load → performance fully restored by short reactivation cycles at night
  - Long regeneration during weekends
- Cryogenic pumps and turbopumps operate in parallel, and deal with non-getterable gases → hydrogen load transferred to NEG at the end of every day

[3] M Siragusa, SPIDER Vacuum Enhancement: a NEG-pump based project, presented AIV conference 2022

Summary & perspectives



- SPIDER results are in line with smaller RF sources, of similar design
- Experience of first 3.5y of SPIDER operation: we studied beam and plasma performances to anticipate as much as possible future issues
  - Nonuniformities of extracted current density on the unexpected scale of bemlet group
  - High divergence and presence of tails in the angular distribution
- After the present shutdown, we should be in the conditions to really assess the performances of the full-scale ITER source!
- In view of the future operations of ITER HNB, the study and test of solutions to decrease divergence and to mitigate non-uniformities shall start ASAP