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

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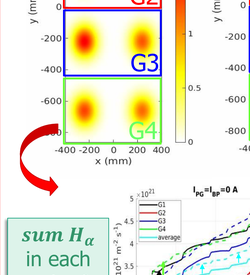
1. ITER Neutral Beam Test Facility: SPIDER experiment

SPIDER: full-size ITER negative ion source



In operation since 2018

- Largest RF plasma source with 3D magnetic and electrical field ($1.8 \times 0.8\ m^2$, 1280 beamlets)
- **4 pairs of RF drivers** fully immersed in the same vacuum as the beam
- **3 grids accelerating system**, up to 100 keV

Parameter	Desired
Beam current density (A/m^2)	$> 355\ (H)$, $> 285\ (D)$ (4 $\times$ 200 kW)
Beam energy (keV)	100
Beam divergence (mrad)	**≤ 7**
Beam − on time (s)	3600
Co − extracted electron fraction	$< 0.5\ (H), < 1\ (D)$
Beam homogeneity (%)	**10 %**

Spatially resolved plasma diagnostics

In the driver: Plasma emission measured inside each driver

$H_\alpha \rightarrow direct\ e^- collision \propto n_e$

✚

Dedicated campaign with movable Langmuir Probes and Retarding Field energy Analyzer

In the expansion region: Spectroscopy LoSs perpendicular to the horizontal direction (x) in front of BP and PG

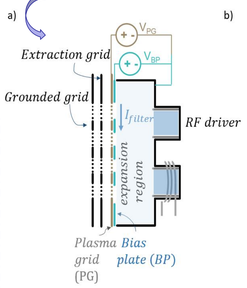
$H_\beta \propto n_e$ in front of the BP

$H_\alpha / H_\beta \propto n_{H^-}$ in front of the PG

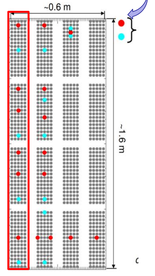
✚

Embedded Langmuir Probes on the BP and PG

Horizontal section of SPIDER source



Scheme of the open beam apertures



[B. Zaniol et al., First measurements of optical emission spectroscopy on SPIDER negative ion source, Rev. Sci. Instrum. 91, 013103;(2020)].

2.1 Beam divergence: dependence on source parameter

Negative ion temperature → Voltage ratio

Perveance → $f = \frac{4V}{E_d - E_u}$

Proportionality constant which links the extractable ion beam current I to $U_{extr}^{3/2}$

$P = I/U_{extr}^{3/2}$

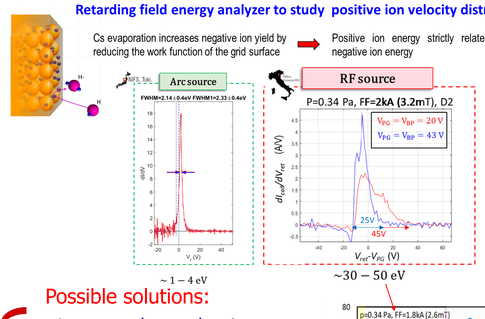
Minimum of divergence measured in SPIDER ~ $10 - 14\ mrad$

It is comparable with the divergence measured in other RF sources

BUT the divergence measured in arc sources is lower, ~ $4\ -7\ mrad$

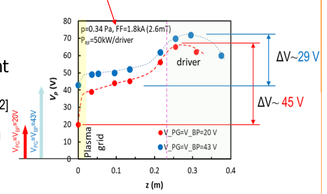
Retarding field energy analyzer to study positive ion velocity distribution

Cs evaporation increases negative ion yield by reducing the work function of the grid surface → Positive ion energy strictly related to the negative ion energy



Possible solutions:

- Increase plasma density
  -> Under development in current SPIDER shutdown!
  [N. Marconato et al. contribution SOFT22]
- Reduce ΔV driver-extraction region
  -> By modifying Bias Plate and Plasma Grid polarizations
  [Poster #51, M. Agostini et al]

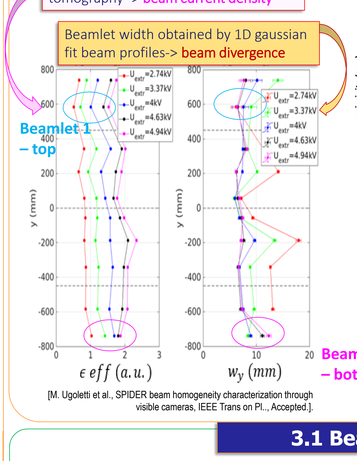


[E. Sartori et al., Development of a set of movable electrostatic probes to characterize the plasma in the ITER neutral beam negative-ion source prototype, Fus. Eng. and Des. 169 (8), 112424 (2021)]

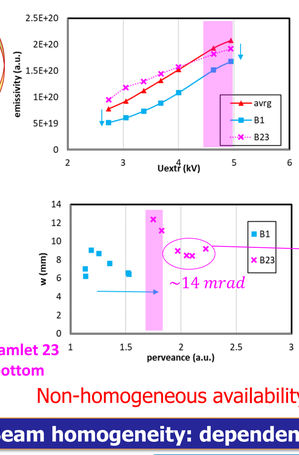
2.2 Beam divergence: experimentally measured by visible cameras

Beam emissivity obtained by visible tomography -> beam current density

Beamlet width obtained by 1D gaussian fit beam profiles-> beam divergence

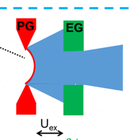


[M. Ugoletti et al., SPIDER beam homogeneity characterization through visible cameras, IEEE Trans on Pl.., Accepted.].



Beamlet 1 – top

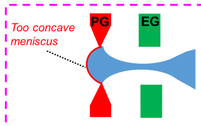
Too convex meniscus



Case 2: too low $U_{extr}^{3/2}$ applied wrt the negative ion amount: *beamlet scraping on the EG*

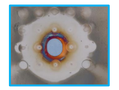
Beamlet 23 – bottom

Too concave meniscus

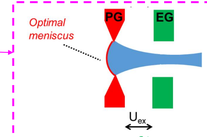


Case 1: too large $U_{extr}^{3/2}$ applied wrt the negative ion amount: *under-perveance*

Part of its current is lost on the EG -> under-estimation of current density



Optimal meniscus



Case 3: optimal $U_{extr}^{3/2}$ applied wrt the negative ion amount: *perveance match*

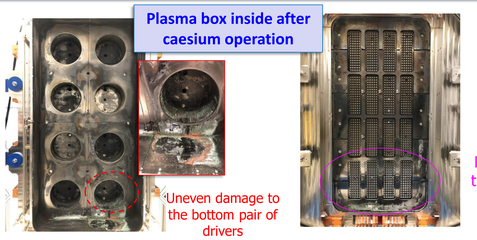
Non-homogeneous availability of negative ions!

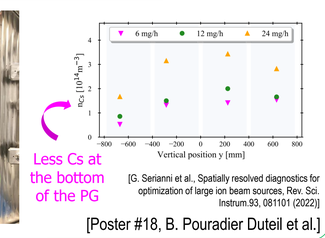
3.1 Beam homogeneity: dependence on source parameters

Source complexity: **4 pairs of radio-frequency drivers operating simultaneously** (coupling between each other, coupling with the plasma, etc)

Caesium coverage: **large-scale distribution of caesium**, injected from 3 evaporators on the rear side of the source

Electrical and magnetic filter fields: very complex **plasma drifts 3D dynamics**





Less Cs at the bottom of the PG

[G. Serianni et al., Spatially resolved diagnostics for optimization of large ion beam sources, Rev. Sci. Instrum.93, 081101 (2022)]

[Poster #18, B. Pouradier Duteil et al.]

3.2 Radio-Frequency plasma source

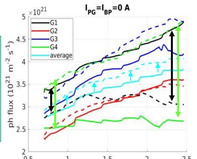
H_α *in the drivers*

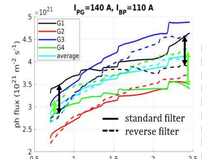
Standard direction / Reversed direction

- **Top/Bottom** plasma emission **reversed** with the **inversion of the filter field**
- **Top/Bottom** inhomogeneity gets worse as **filter field increases**
- **More symmetric plasma light emission** in the **reversed filter field** configuration

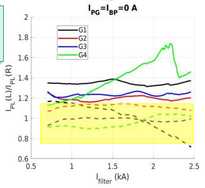
Optimization of RF driver operation

$sum\ H_\alpha$ in each pair of drivers



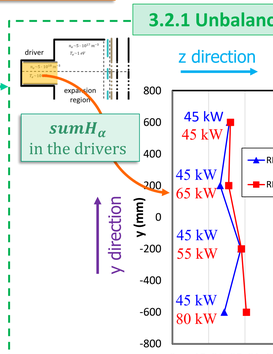


Ratio left to right

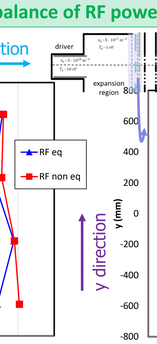


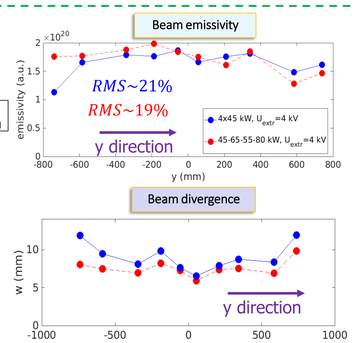
3.2.1 Unbalance of RF power

$sumH_\alpha$ in the drivers



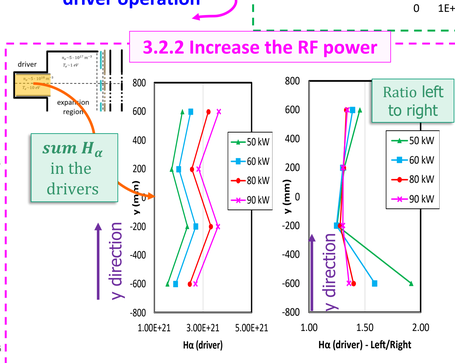
H_β 35 mm from PG





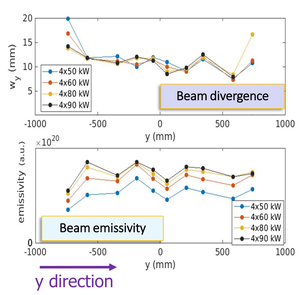
3.2.2 Increase the RF power

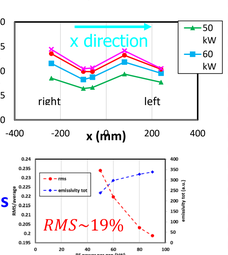
$sum\ H_\alpha$ in the drivers



Ratio left to right

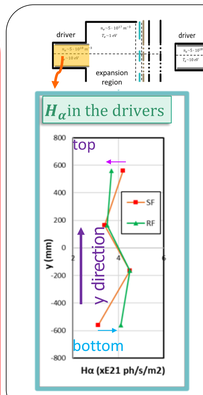
- **In the standard filter field direction, more left-to-right symmetric plasma light emission** as the RF power is increased

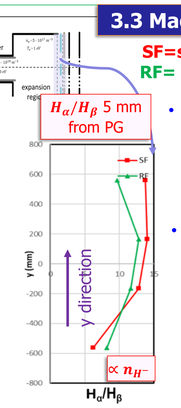




More homogeneous beam

3.3 Magnetic filter field direction

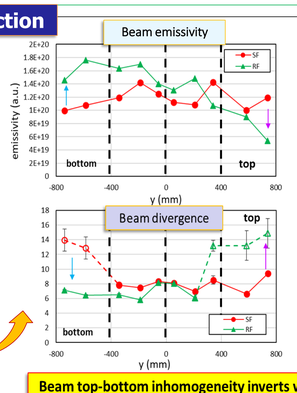




SF=standard dir
RF= reversed dir

- H_α vertical profile in the drivers **inverts** when **the magnetic filter field direction** does
- This results in a **non-homogeneous availability of negative ions** in front of the PG

Vertical profile of the beam



Beam top-bottom inhomogeneity inverts when the direction of the filter field is reversed

Conclusions

- **Minimum** of **beam divergence** in **RF source** ~ **10-14 mrad** ➡ RFEA measurements suggest that it may be related to the too large positive ion energy. **Possible solution:** increase the plasma density
  Beam homogeneity ~ **18-20 %.**

➡ Plasma density is strongly affected by the RF power, filter field current and direction, biasing of the PG and BP, Cs coverage ➡ The beam feels the combination of all these effects.

If we want a more homogeneous - less divergent beam we need to start from the modification of the source (partially ongoing in the current SPIDER shutdown)

Parameter	Achieved
Beam current density (A/m^2)	~150 − 200 (H), (4 × 100 kW)
Beam energy (keV)	50
Beam divergence (mrad)	**~10 − 14**
Beam − on time (s)	20 − 30
Co − extracted electron fraction	> 0.3 (H)
Beam homogeneity (%)	**18 − 20 %**

"This work has been carried out within the framework of the ITER-RFX Neutral Beam Testing Facility (NBTF) Agreement and has received funding from the ITER Organization. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization."