Study of SPIDER beam current through visible light measured by beam imaging diagnostic

M. Ugoletti[12], M. Agostini[2], A. Pimazzoni[2]

[1] Universita di Padova, 35131 Padova, Italy

[2] Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), C.so Stati Uniti 4, 35127 Padova, Italy

Corresponding author: margherita.ugoletti@igi.cnr.it

SPIDER beam imaging diagnostic

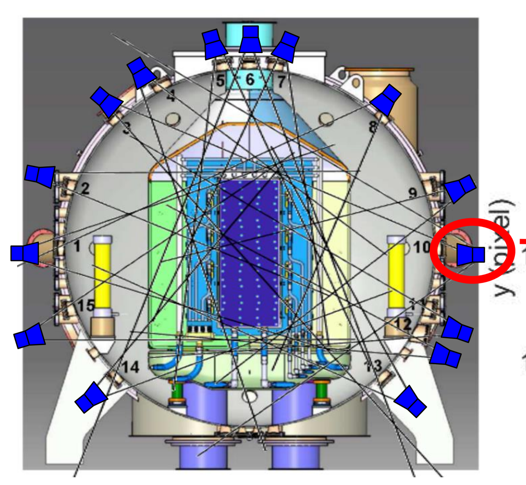
SPIDER (**S**ource for **P**roduction of **I**ons of **D**euterium **E**xtracted from **R**F plasma) test facility is dedicated to the optimization of the negative ion source for the **ITER** (**I**nternational **T**hermonuclear **E**xperimental **R**eactor) heating and current drive **Neutral Beam Injectors** (NBIs) [1]

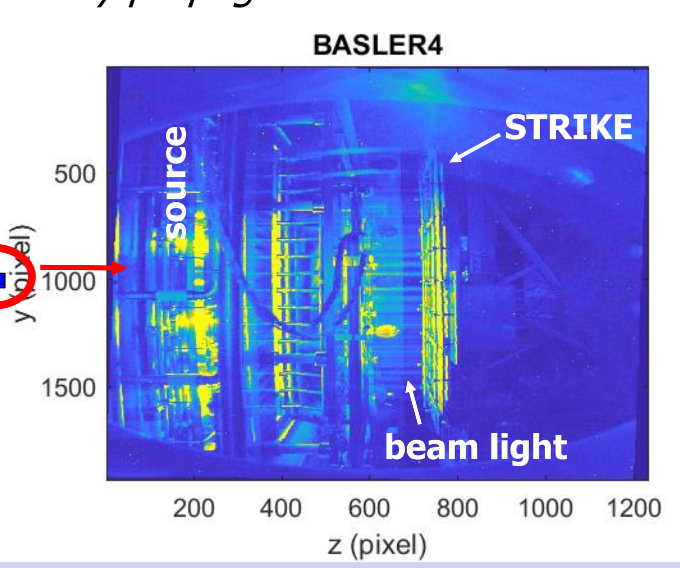
[1] SPIDER in the roadmap of the ITER neutral beams, G. Serianni, et al., Fusion Eng. Des. **146** (2019) 2539, https://doi.org/10.1016/j.fusengdes.2019.04.036.

***SPIDER BEAM*:** **1280 beamlets, 16 groups, 4 × 4 matrix, 16 rows x 5 beamlets each.** Only **28 apertures are now left open.**

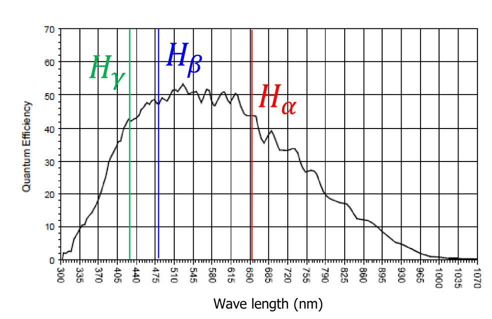
VISIBLE TOMOGRAPHY DIAGNOSTIC

15 visible cameras are installed 40 cm downstream the accelerator, all around the beam.
They collect the light emitted by the beam particles following the interaction with the background gas in which they propagate.



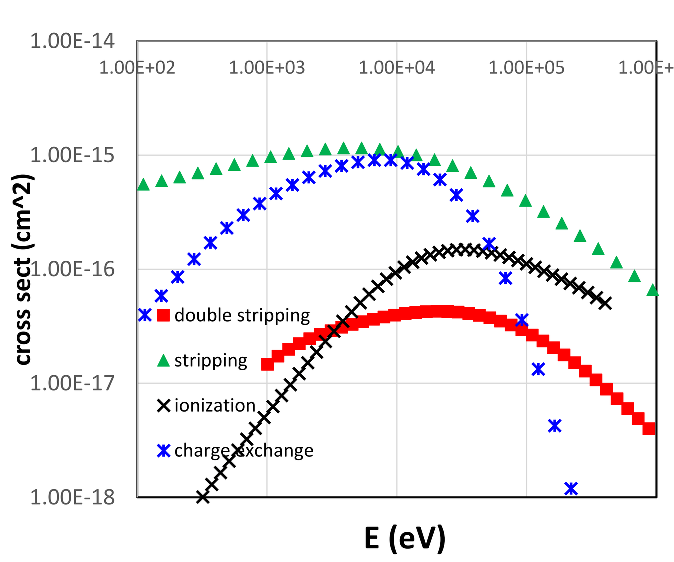


Quantum efficiency of the sensors



MODEL	SENSOR	NUMBER OF PIXELS	SIZE	RESOLUTION	MAXIMUM FRAME RATE
Basler acA1920-40gm	Sony IMX249 CMOS	1920x1200	5.86x5.86 µm	12 bit	45 frames per second
PointGrey BFS-PGE27S5M-C	Sony IMX429 CMOS	1936x1460	4.5x4.5 µm	16 bit	43 frames per second

Beam composition



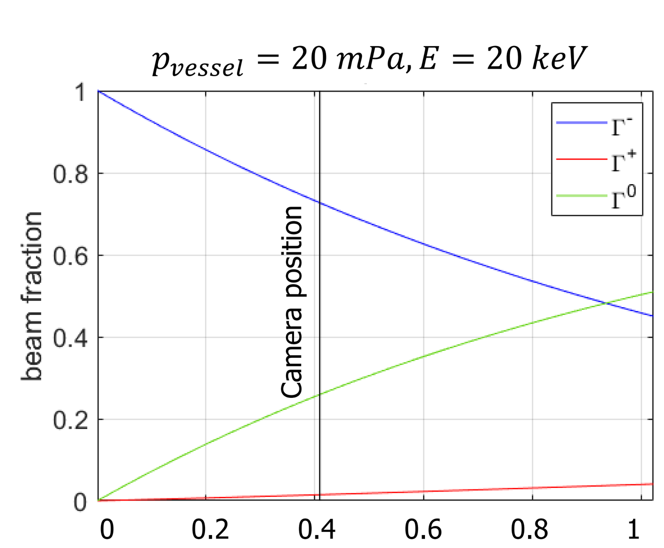
H^- negative ions interact with the background gas n_{bkg} H_2. The charge of the beam evolves during the beam propagation and the particle fluxes of the negative Γ^-, positive Γ^+ and neutral Γ^0 change following

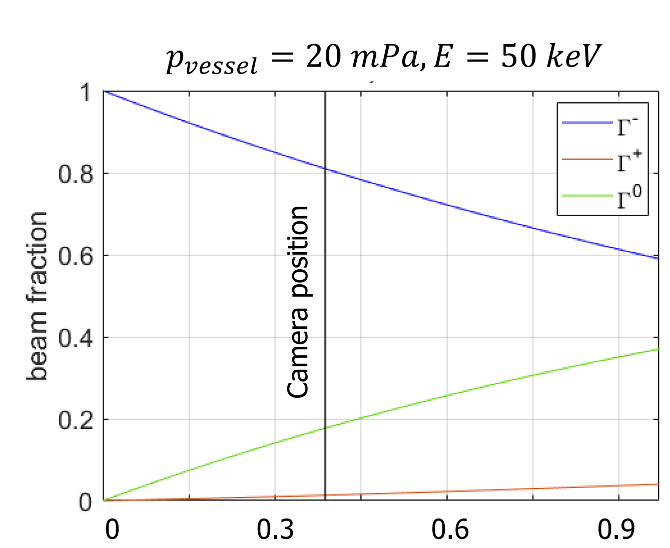
$$\begin{cases} d\Gamma^-/_{dz} = -\Gamma^-(\sigma_{-10}+\sigma_{-11})n_{bkg} \\ d\Gamma^+/_{dz} = \Gamma^-\sigma_{-11}n_{bkg} + \Gamma^0\sigma_{01}n_{bkg} - \Gamma^+\sigma_{10}n_{bkg} \\ d\Gamma^0/_{dz} = \Gamma^-\sigma_{-10}n_{bkg} + \Gamma^+\sigma_{10}n_{bkg} - \Gamma^0\sigma_{01}n_{bkg} \end{cases}$$

with $\sigma_{-10} = stripping, \sigma_{-11} = double\ stripping, \sigma_{01} = ionization$ and $\sigma_{10} = neutralization$.

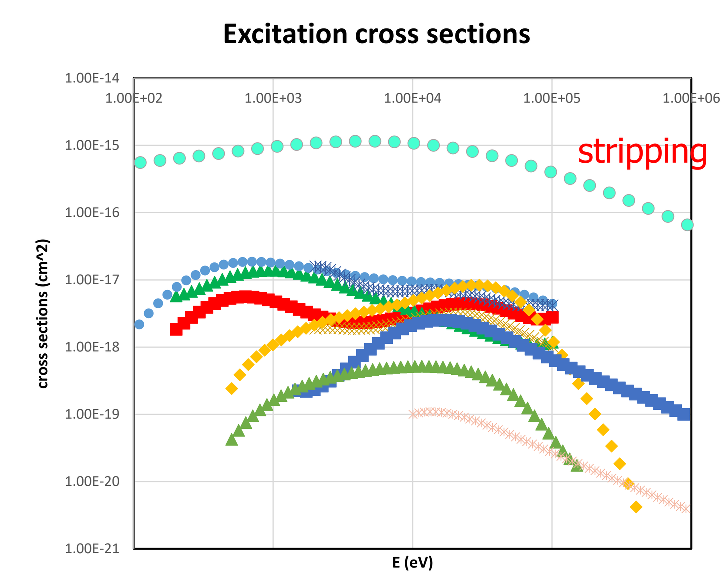
[2] C. F. Barnett et al., Atomic Data for Controlled Fusion Research, 1977.

The fractions of H^-/H^+ and H^-/H^0 along the beam propagation direction depend on the background density (20 - 50 mPa) and on the energy of the beam particles (20 – 50 kV).





Particle energy dependence



$$I_{camera} = n_{beam} * n_{bkg} * \sigma(E) * v = \frac{j_{beam}}{qv} * n_{bkg} * \sigma(E) * v$$

$$j_{beam} = \frac{I_{camera}}{n_{bkg} * \sigma(E)}$$

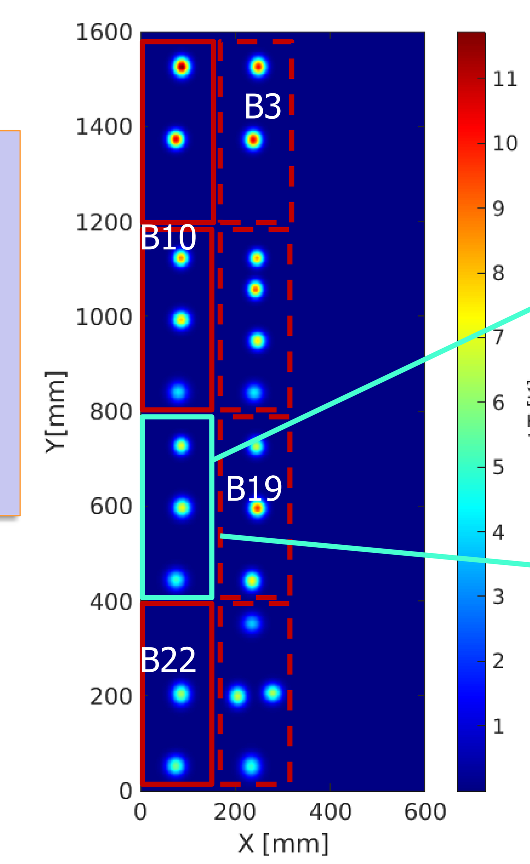
$$\sigma(E) = \sigma_{H^-} * \Gamma^- + \sigma_{H^+} * \Gamma^+ + \sigma_{H^0} * \Gamma^0$$

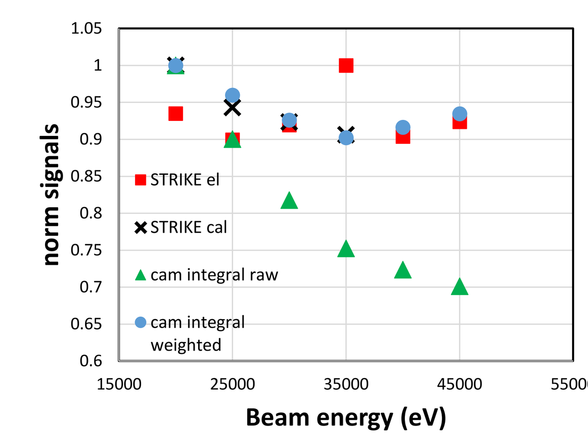
Where $\sigma_{H^-}, \sigma_{H^+}$ and σ_{H^0} are the cross sections of excitation respectively

$$H^-, H^+, H^0 + H_2 \rightarrow H^0(n = 3, n = 4) + \cdots$$

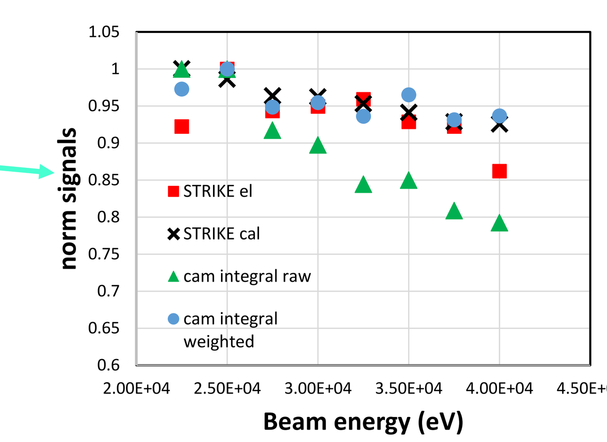
which is the visible light seen by the cameras

STRIKE Calorimeter: 16 tiles of CFC which measure both the electrical current and the calorimetrical current through thermocameras





4x100 kW RF power
20 mPa bkg pressure



4x90 kW RF power
20 mPa bkg pressure

[3] *Assessment of the SPIDER beam features by diagnostic calorimetry and thermography* , A. Pimazzoni et al., Rev. Sci. Instrum. **91**, 033301 (2020); https://doi.org/10.1063/1.5128562

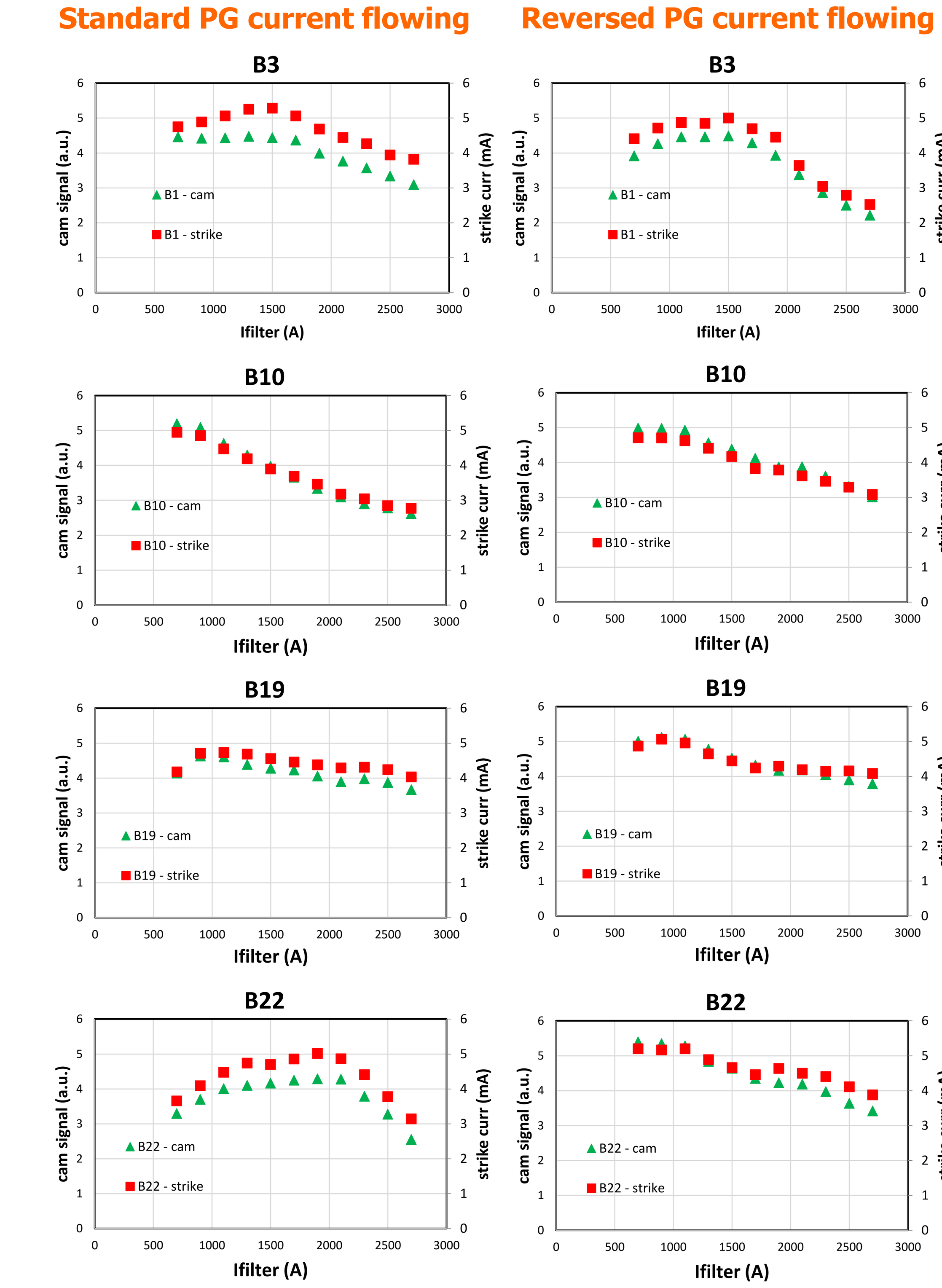
Conclusions

- Beam imaging is a **powerful non invasive diagnostic** which allows to estimate not only the **beamlet divergence and position**, but also its **current**.
- A simple model to estimate the **beam charge composition along the beam propagation direction** as a function of the **background gas density** and the **beam energy** is developed.
- The reactions which produce **excited neutrals** are used **to weight the signal** measured by the cameras as a function of the beam particle energy.
- It is now possible **to directly compare the light measured with the beam current**, with a good agreement both with calorimetrical and electrical measurements.
- The **complete profile of the beam** is reconstructed through tomographic inversion, allowing a complete carac-therization of the beam vertical profile.
- The **effect of the filter field** is studied for the two different directions of the current: as expected, it acts in the opposite way on the external beamlets groups, while the effect is the same on the central groups (plasma drift).

Single beamlet profiles

Filter field current: a current flowing through the Plasma Grid which produces a magnetic field aiming at reducing the electron temperature, close to the extraction region.

Standard PG current flowing — Reversed PG current flowing



Both the trend and the quantitative relation between the light collected by the cameras and the calorimetrical measurement of the beamlet current on STRIKE are in agreement.

2D beam emission profile reconstruction : tomographic inversion

$$I_j = \sum_{i=1}^{n_{beamlet}} \epsilon_i a_{ij}$$

$$\epsilon_i^{k+1} = \epsilon_i^k + \frac{\sum_{j=1}^{nlos}\left(a_{ij} \cdot \frac{I_j - \sum_{i=1}^{npix} \epsilon_i^k \cdot a_{ij}}{\sum_{i=1}^{npix} a_{ij}}\right)}{\sum_{j=1}^{nlos} a_{ij}}$$

Iterative error correcting algorithm
Simultaneous **A**lgebraic **R**econstruction **T**echnique (**SART**)

[4] *First results of SPIDER beam characterization through the visible tomography*, M. Ugoletti et al., Fus. Eng. and Des. **169**, 112667, (2021); https://doi.org/10.1016/j.fusengdes.2021.112667

Right filter field — Reversed filter field