Influence of different magnetic configurations on plasma parameters in SPIDER device

Roman Zagórski[1], Valeria Candeloro[2,3], Emanuele Sartori[2,3], Gianluigi Serianni[2]

[1]National Centre for Nuclear Research, Pl-05-400 Otwock, Poland; [2]Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), C.so Stati Uniti 4, 35127 Padova, Italy; [3]Università degli Studi di Padova, Padova, Italy

Introduction

The ITER fusion reactor will be heated by fast neutral beams generated by accelerating and neutralizing negative ions, produced in a RF inductively-coupled plasma and expanding through a region featuring a magnetic filter. Since the beginning of SPIDER operation in 2018, many issues have been solved, lessons learned and objectives reached, but fixing several major problems requires a long shutdown, started at the end of 2021, in which the whole plasma source and accelerator will be dismounted. In this phase additional modifications with respect to the original design will be introduced in order to improve the system performance, driven by the experience acquired in the last years. These include the addition of further sets of permanent magnets in the plasma source expansion chamber and around the RF drivers, with the aim of improving the plasma confinement and consequently its density and possibly its uniformity.

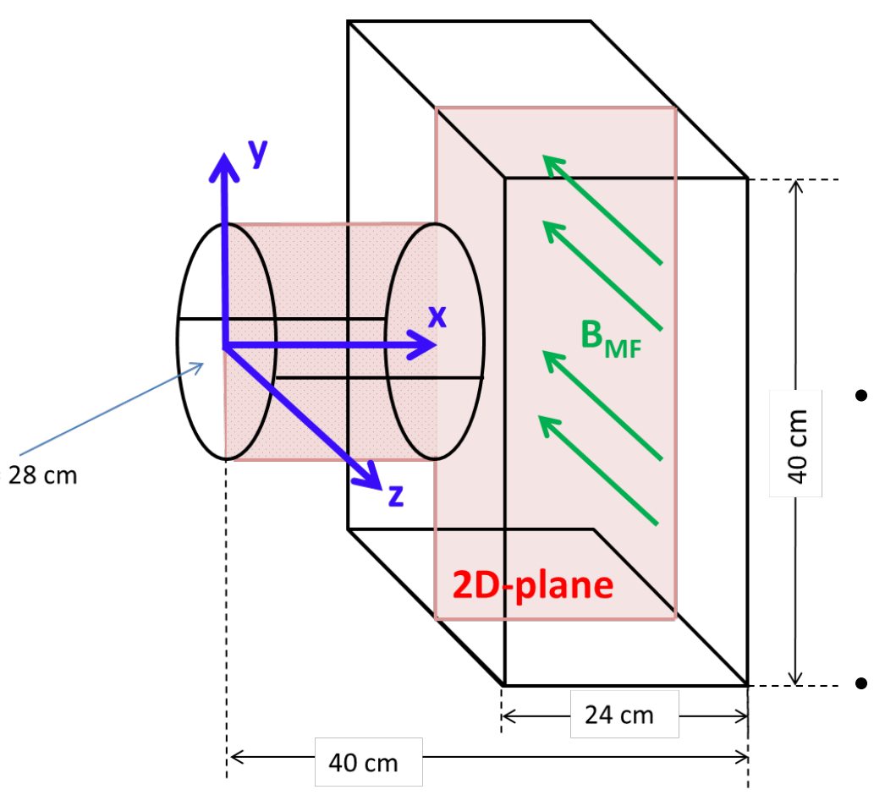
We present results of numerical studies of the plasma parameters in SPIDER source with different types of modifications of SPIDER device including new permanent magnets configurations. Analysis are done by means of the numerical code FSFS2D in which a self-consistent two-dimensional fluid description of the source mostly based on the works of G. Hagelaar [1] and S.Lishev [2] has been implemented. In order to partially account for the 3D flow pattern within our 2D model, simulations are done in two geometrical situation, in the vertical plane with the magnetic filter being perpendicular to the integration domain and in the horizontal plane with the filter field in the integration surface

Fluid Model

$$\frac{\partial n_\alpha}{\partial t} + \mathtt{div}\boldsymbol{\Gamma}_\alpha = S_\alpha \equiv Z_\alpha - L_\alpha,$$

$$\frac{3}{2}en_e\frac{\partial T_e}{\partial t} + \mathtt{div}\left(\frac{5}{2}e\boldsymbol{\Gamma}_\mathbf{e}T_e - en_e\hat{\chi}_e\nabla T_e\right) = P_{RF} - P_e^{coll} - e\boldsymbol{\Gamma}_\mathbf{e}\cdot\mathbf{E} - \frac{3}{2}eT_e\frac{\partial n_e}{\partial t},$$

$$\Delta\Phi = -\frac{e}{\epsilon_0}\left(\sum_{i=1}^{3} n_i - n_e - n_-\right)$$



- The SPIDER source is composed of 8 cylindrical drivers, where plasma generation takes place via inductive coupling, connected to a single expansion chamber. The 2D modelling refers to **only one driver.** The plasma grid (PG), the the first grid of the extraction system, which separates the plasma and the extraction region, is assumed as a solid surface which is biased at a given potential with respect to the other grounded boundaries of the modelling domain.
- We explicitly solve particle balance equations for n_e, each positive ion species (H^+, H^+_2 , H^+_3), negative ions (H^-), and atomic and molecular hydrogen. These equations include contributions from both chemical reactions and transport.
- The electron power balance is solved to calculate electron temperatures, whereas gas and ion temperatures are assumed to be constant.
- Electrostatic potential is calculated from (modified) Poisson's [1].
- Calculation of the density of the hydrogen molecules (H_2) comes from the equation of state of an ideal gas for simplicity.
- Transport of plasma species is based on drift-diffusion approximation. The flux (Γ_α) of each charged species is described by the diffusivity tensor, $\mathbf{D}_\alpha$, and the electric mobility tensor, $\boldsymbol{\mu}_\alpha$. It accounts for the effects due to electric and diamagnetic drifts.
- At the present stage of the development of the model, an analytical form of the magnetic filter field (MF – required to reduce the electron temperature and suppress the co-extraction electrons) has been employed for simplicity
- The model takes into account the collisional processes (22 reactions) having the main contribution to the charged particles and neutral species production and destruction: ionization and dissociation of molecules, dissociation of H^+_2 and H^+_3 ions, dissociative recombination of H^+_2 ions, heavy particle collisions, ionization of atoms and H^- destruction.

Cusp field at Faraday shield – analytic formulae

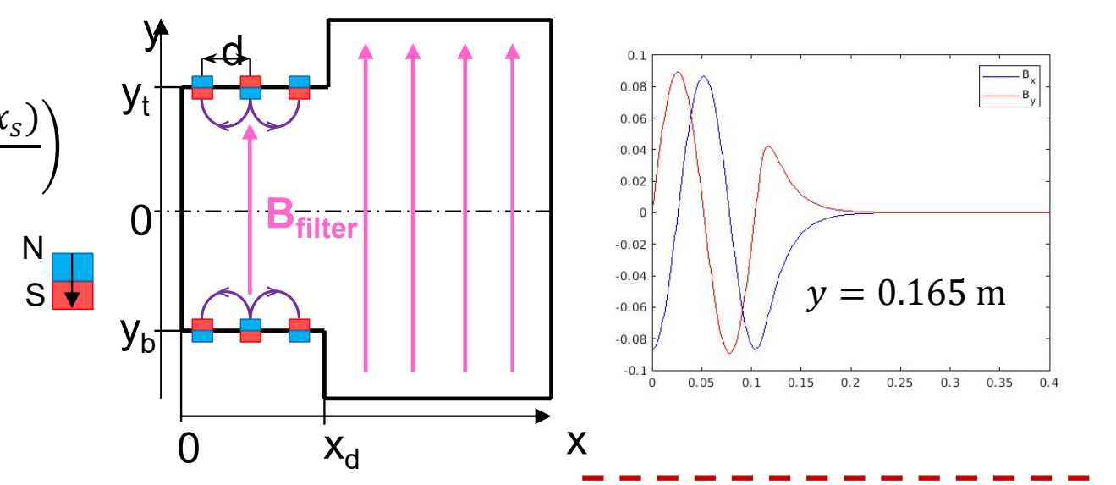
$$B_x = -B_0\left[\mathrm{sgn}(y-y_b)\cdot\exp\left(-\frac{\pi|y-y_b|}{d}\right) + \mathrm{sgn}(y-y_t)\cdot\exp\left(-\frac{\pi|y-y_t|}{d}\right)\right]\cdot\cos\left(\frac{\pi(x-x_s)}{d}\right)$$

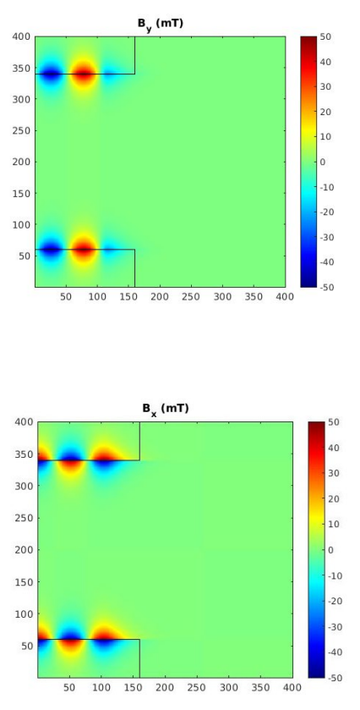
$$B_y = B_0\left[\exp\left(-\frac{\pi|y-y_b|}{d}\right) + \exp\left(-\frac{\pi|y-y_t|}{d}\right)\right]\cdot\sin\left(\frac{\pi(x-x_s)}{d}\right)$$

if $(x > x_{sm})$

$$B_x = -B_0\left[\mathrm{sgn}(y-y_b)\cdot\exp\left(-\frac{\pi|y-y_b|}{d}\right) + \mathrm{sgn}(y-y_t)\cdot\exp\left(-\frac{\pi|y-y_t|}{d}\right)\right]\cdot \cos\left[\frac{\pi(x_{sm}-x_s)}{d} + \alpha\pi\left(1-\exp\left(-\frac{x-x_{sm}}{\alpha d}\right)\right)\right]$$

$$B_y = B_0\left[\exp\left(-\frac{\pi|y-y_b|}{d}\right) + \exp\left(-\frac{\pi|y-y_t|}{d}\right)\right]\cdot\sin\left[\frac{\pi(x_{sm}-x_s)}{d} + \alpha\pi\left(1-\exp\left(-\frac{x-x_{sm}}{\alpha d}\right)\right)\right]\cdot\exp\left(-\frac{x-x_{sm}}{\beta d}\right)$$





$B_0 = 50\ mT$ $\quad x_s = 0.26$ m
$d = 0.052$ m $\quad x_{sm} = 0.11025$ m
$y_b = -0.14$ m $\quad \alpha = 0.38$
$y_t = 0.14$ m $\quad \beta = 0.38$

Cusp field at driver backplate – analytic formulae

- Field along z direction

if $(y > y_b) \wedge (y < y_t)$

$$B_z = B_0\exp\left(-\frac{\pi x}{L}\right)\sin\left[\frac{\pi y}{d}\right]$$

$B_0 = 20\ mT$ $\quad y_b = -0.14$ m
$d = 0.07$ m $\quad y_t = 0.14$ m
$L = 0.02$ m

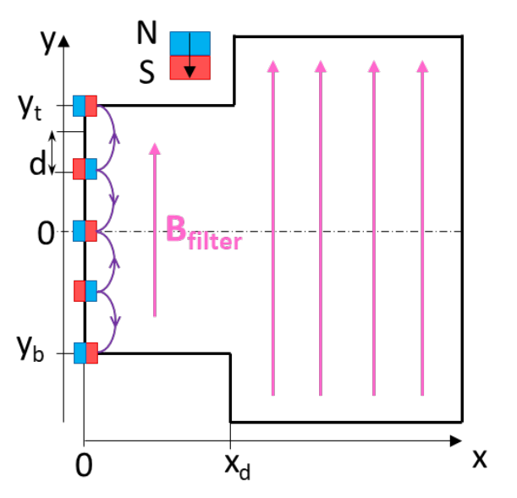
- Field on (x,y) plane

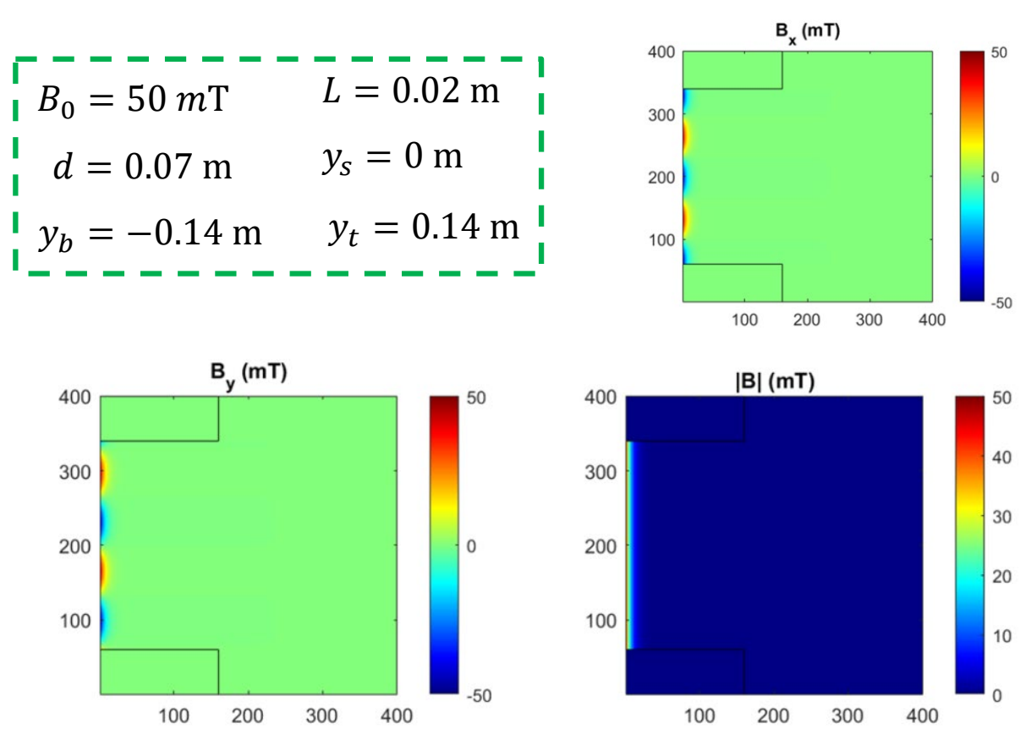
if $(y > y_b) \wedge (y < y_t)$

$$B_x = -B_0\exp\left(-\frac{\pi x}{L}\right)\cos\left[\frac{\pi y}{d}\right]$$

$$B_y = B_0\exp\left(-\frac{\pi x}{L}\right)\sin\left[\frac{\pi y}{d}\right]$$

$$B_y = B_0\exp\left(-\frac{\pi x}{L}\right)\sin\left[\frac{\pi y}{d}\right]$$





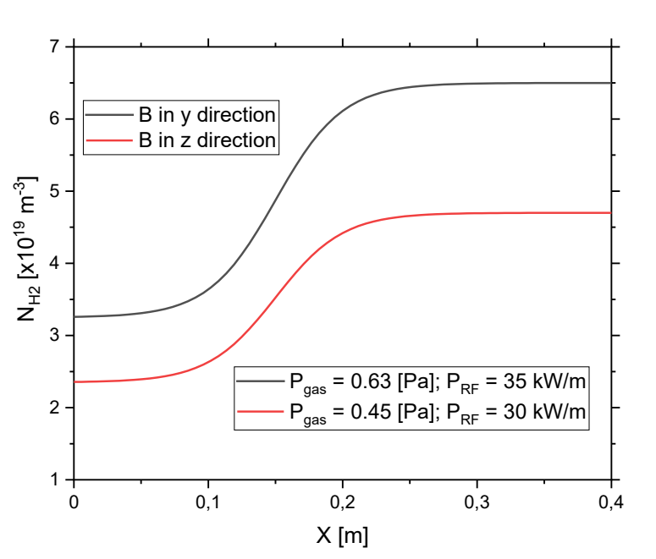
$B_0 = 50\ mT$ $\quad L = 0.02$ m
$d = 0.07$ m $\quad y_s = 0$ m
$y_b = -0.14$ m $\quad y_t = 0.14$ m

Numerical method

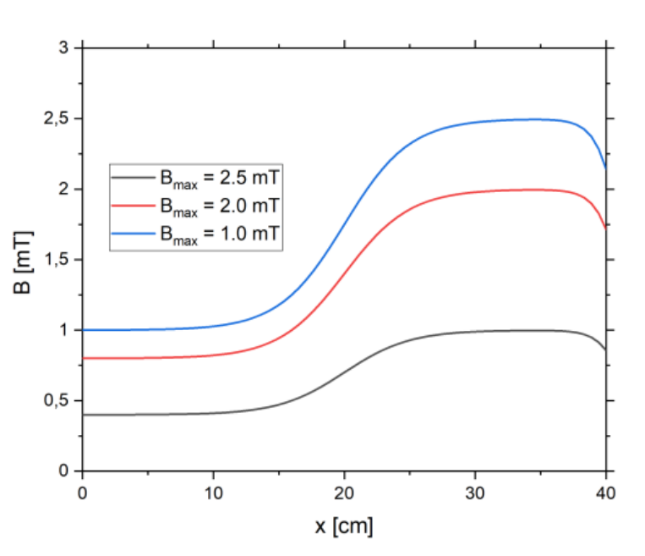
- The system of fluid equations is solved numerically, by a FORTRAN code (**FSFS2D** - **F**luid **S**olver **F**or **S**PIDER in **2D**), taking into account both the time evolution and two spatial dimensions.
- The method is based on finite volume approximation and 9-point discretization on a non-uniform, staggered mesh is used to account on anisotropy due to magnetic field.
- To avoid time step constraints due to coupling with Poisson equation, we include in the Poisson equation a semi-implicit prediction of the space charge density, obtained by simplification of the electron and ion equations which allows for large time steps (> 1000 x explicit time step producing steady-state solution in a reasonable time (10-20 hours for 100x100 mesh) on a desktop computer.

Results of Simulations and Discussion

In all simulations, the SPIDER uniform mesh consisting of **71x71 points** is used.

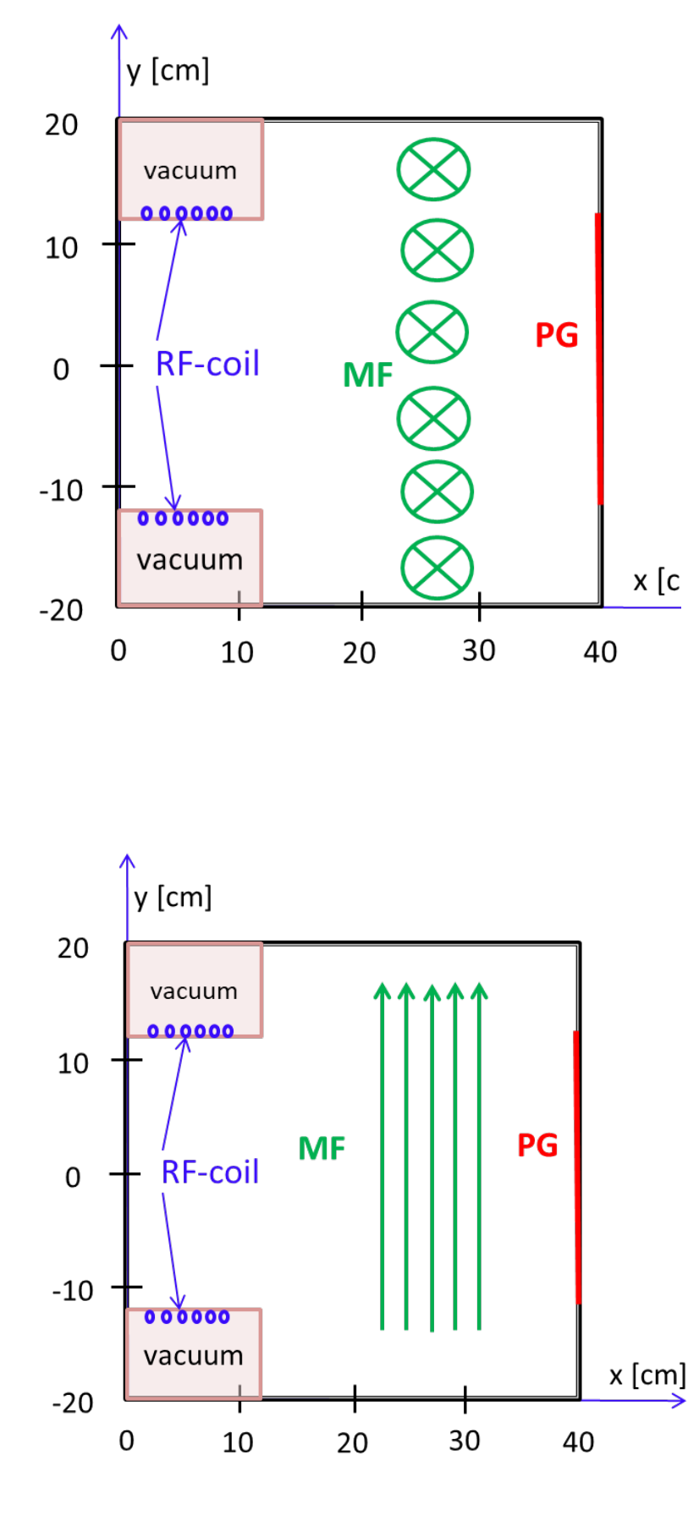


Gas density according to PIC simulations

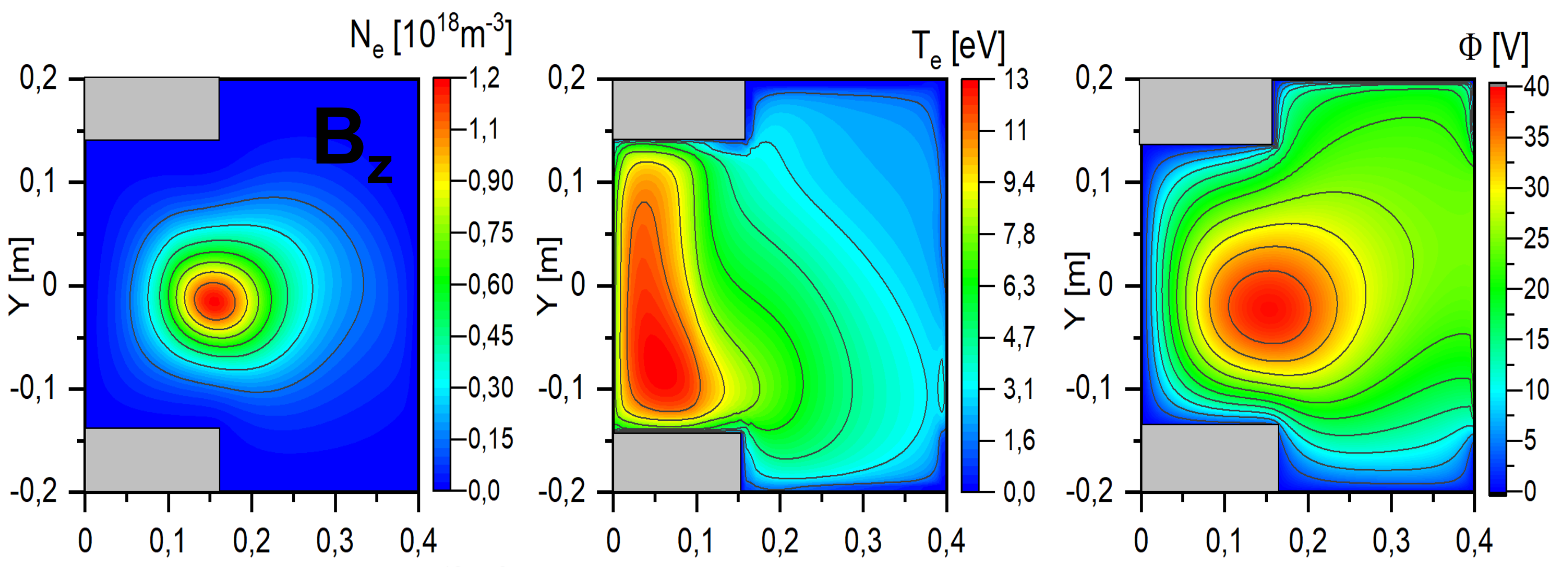


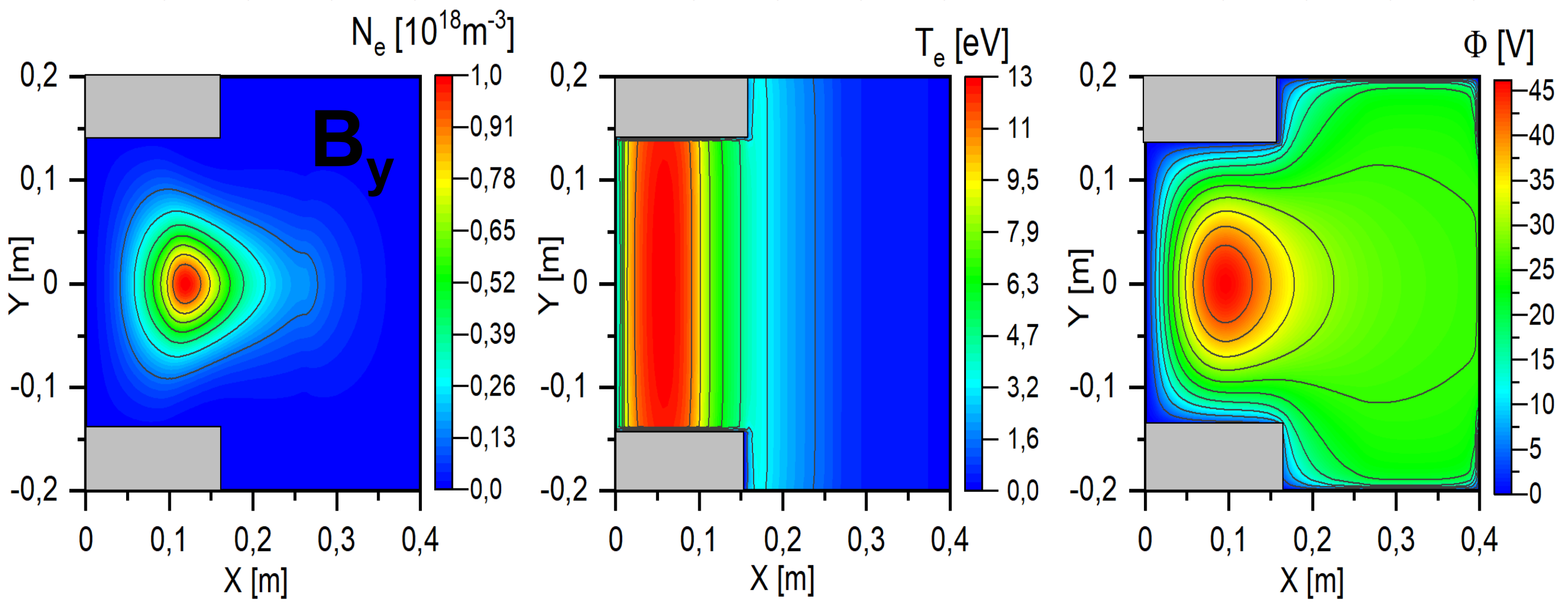
Magnetic Filter Field

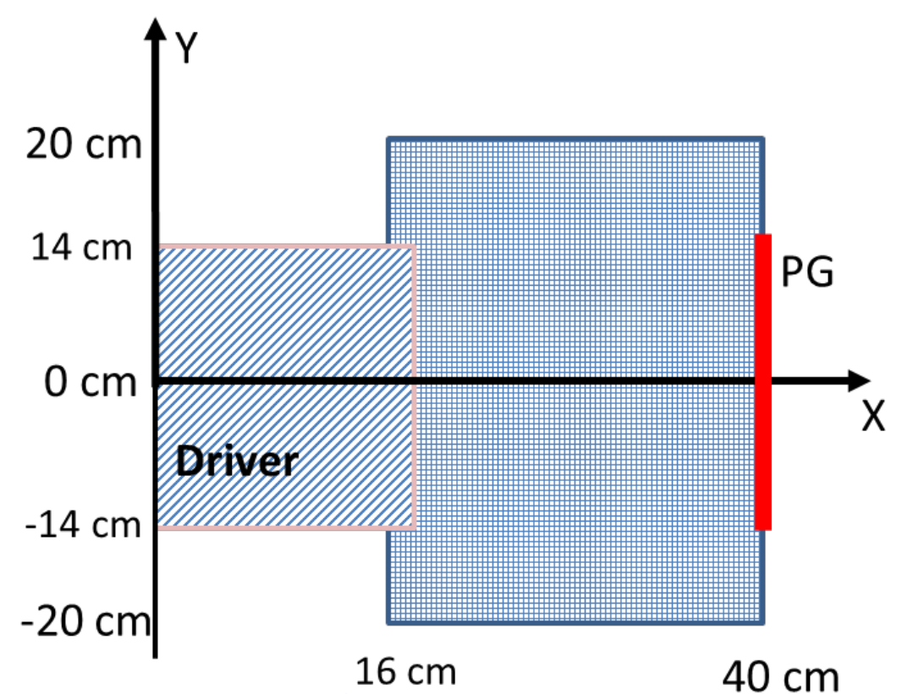
Reference cases: in order to investigate the effect of different configurations on plasma parameters, 2 reference cases have been prepared following the parameters applied in the PIC simulations for similar geometries. For these cases the RF heating is uniformly applied in the driver region ($P_{RF} = n_e\epsilon_{RF}$, where the energy gain per electron ϵ_{RF} is constant): , PG potential Φ_{PG} = 25 V. Gas pressure (p_{gas}) is chosen to be in agreement with PIC simulations and to have similar values of plasma density in the driver for two different geometrical situations (vertical and horisontal integration plane) It results in P_g=0.45 Pa, P_{RF} =30kW (@ B_z) and P_g=0.63 Pa, P_{RF} =35kW (@ B_y). In the reference cases, only MF field is present with B_{max} = 1 mT (B_{min} = 0.4 B_{max} in all our simulations)



Schematic presentation of the source

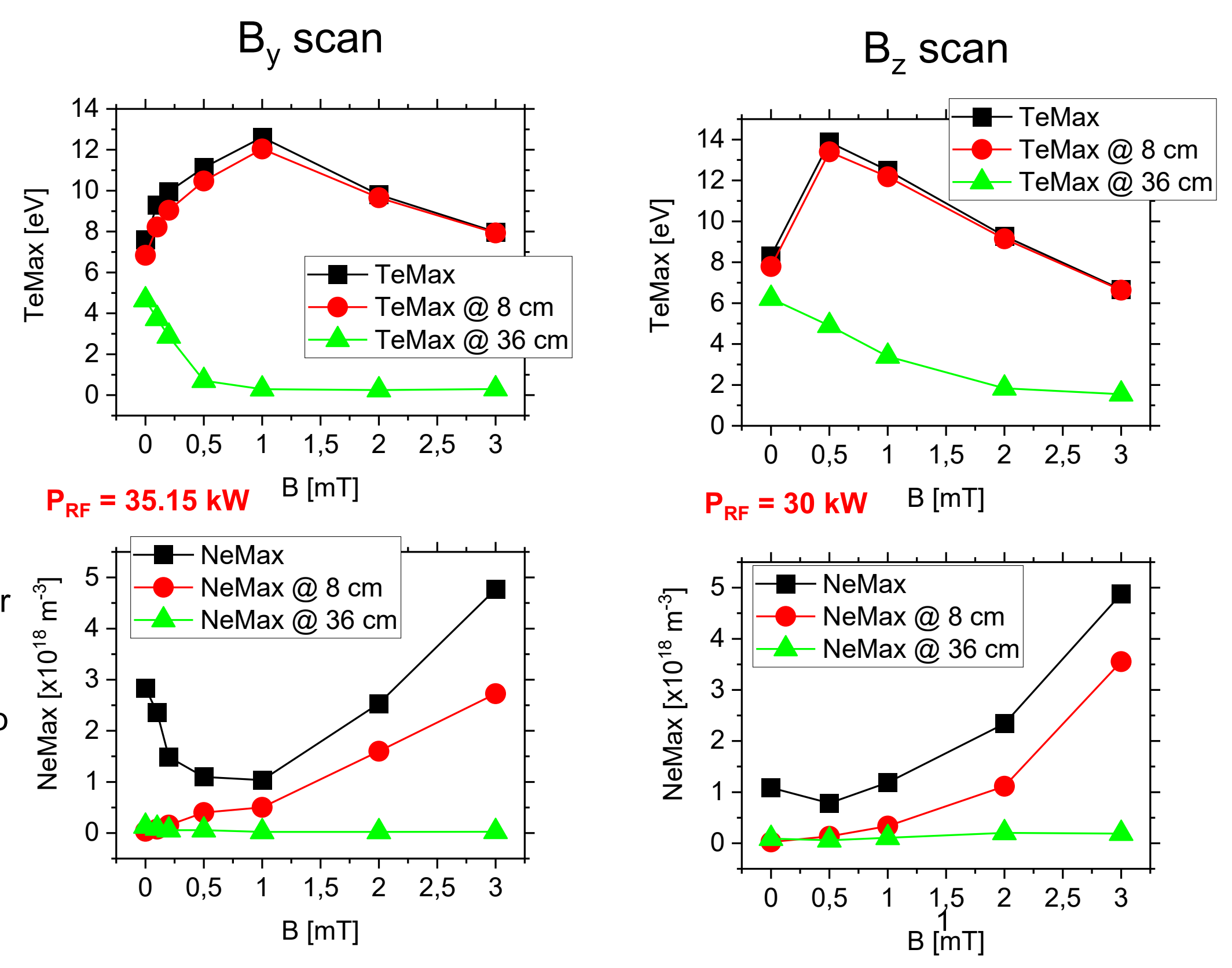


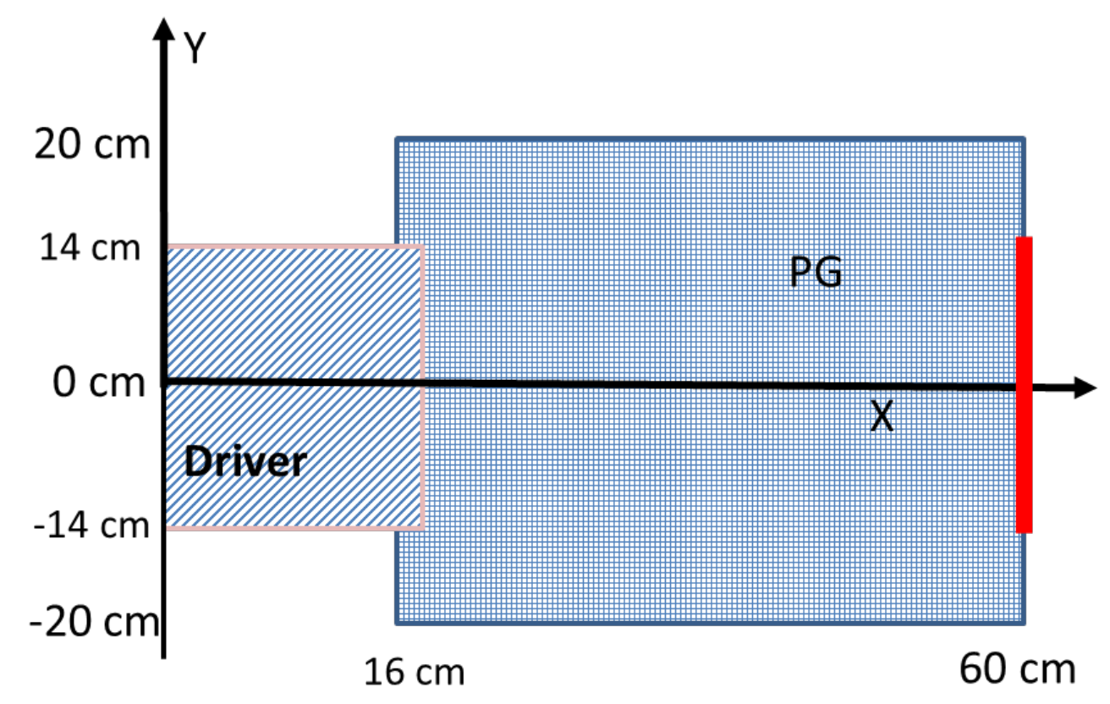


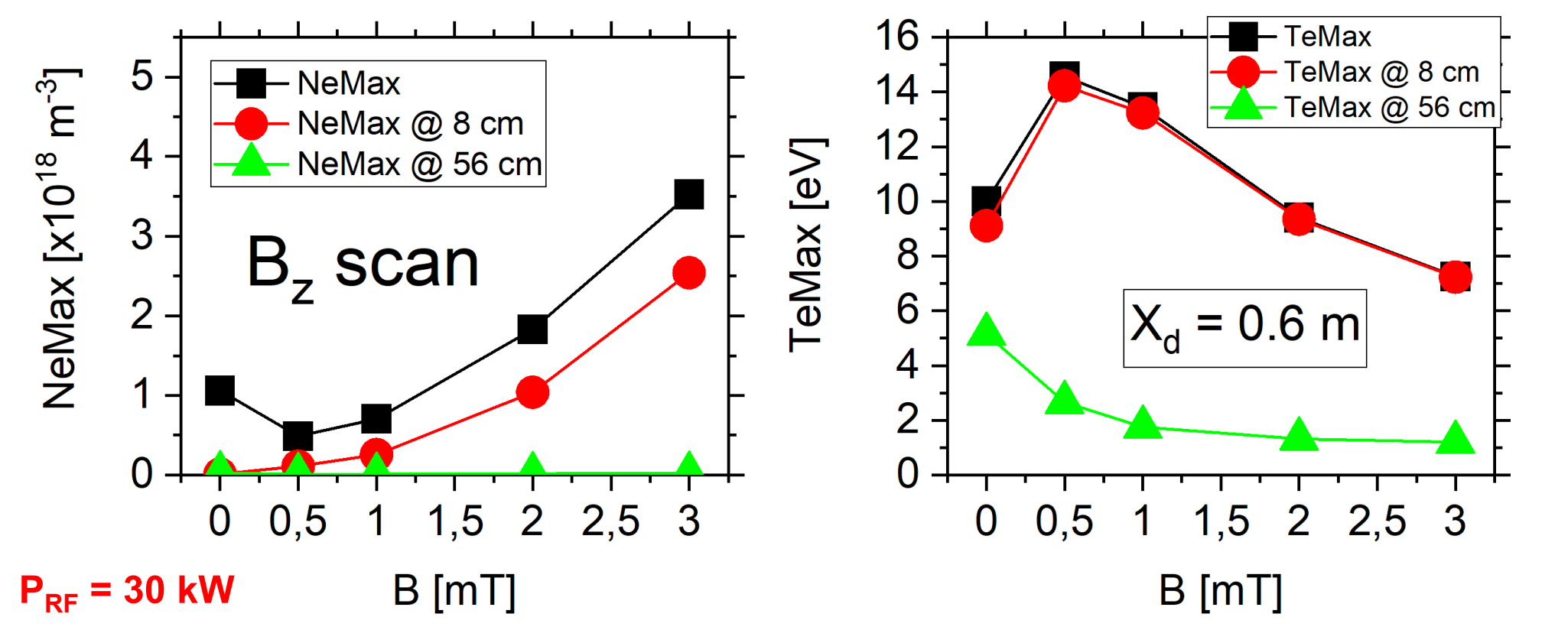


Filter Field Scan

For both geometrical configurations, calculations have been performed for different strengths of the magnetic filter field 0 ≤ B_{max} ≤ 3mT ($B_{min} = 0.4B_{max}$) in order to see the effect of the filter field on the density in the driver. We plot the maximum values of n_e and T_e in the source and at two differen x positions , x=8 cm (middle of the driver region) and x = 36 cm (expansion region close to the PG). It can be seen that after initial deacrese, the density increases with the magnetic field in the driver. The density in the expansion region is only marginally affected by the changes to the MF.

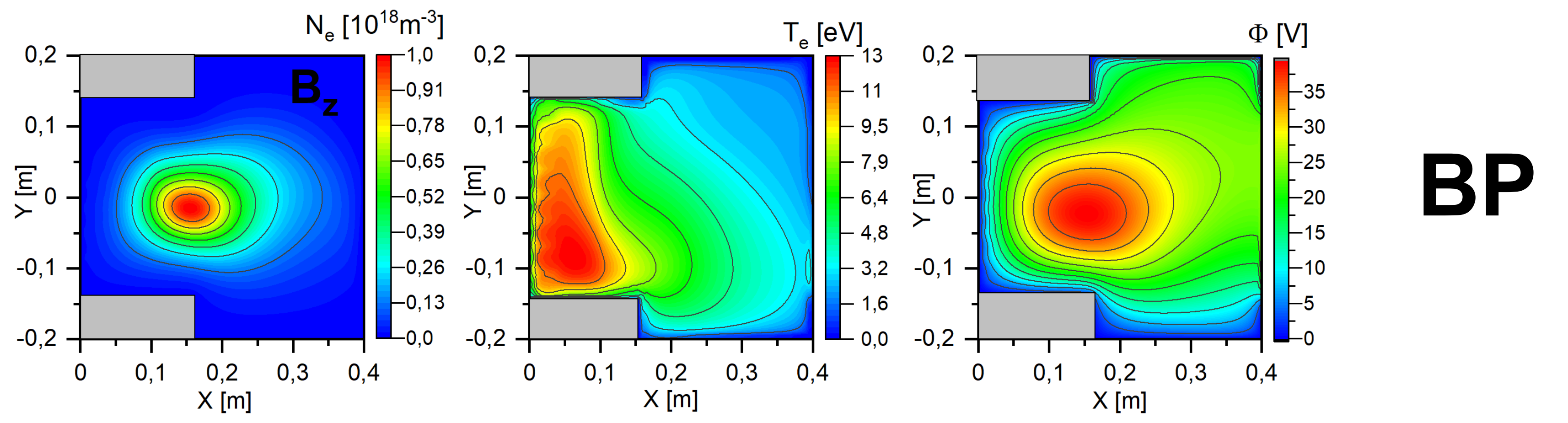


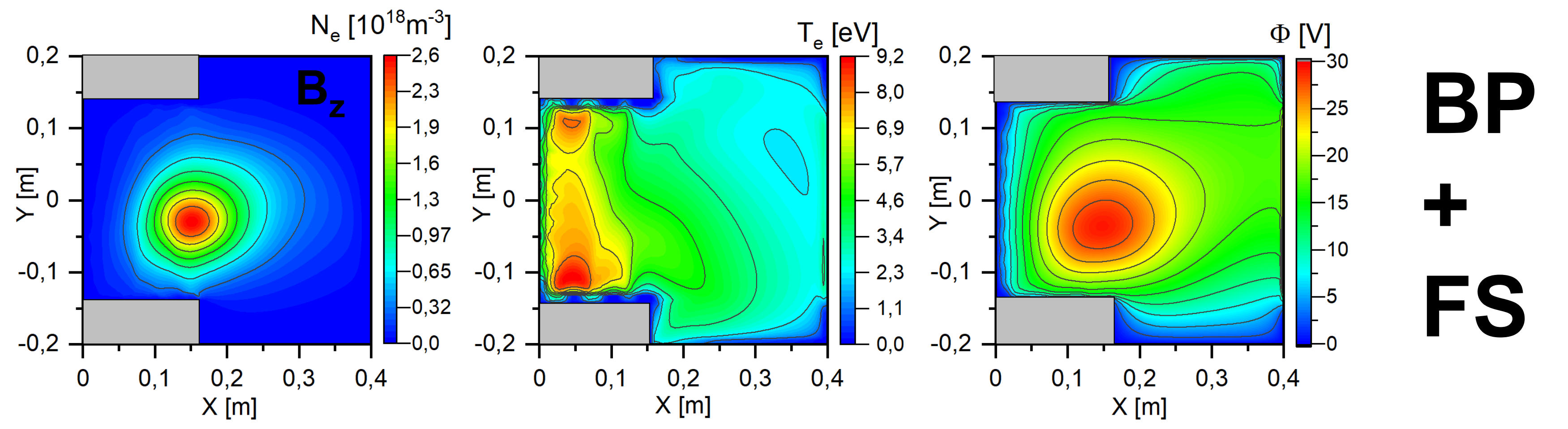


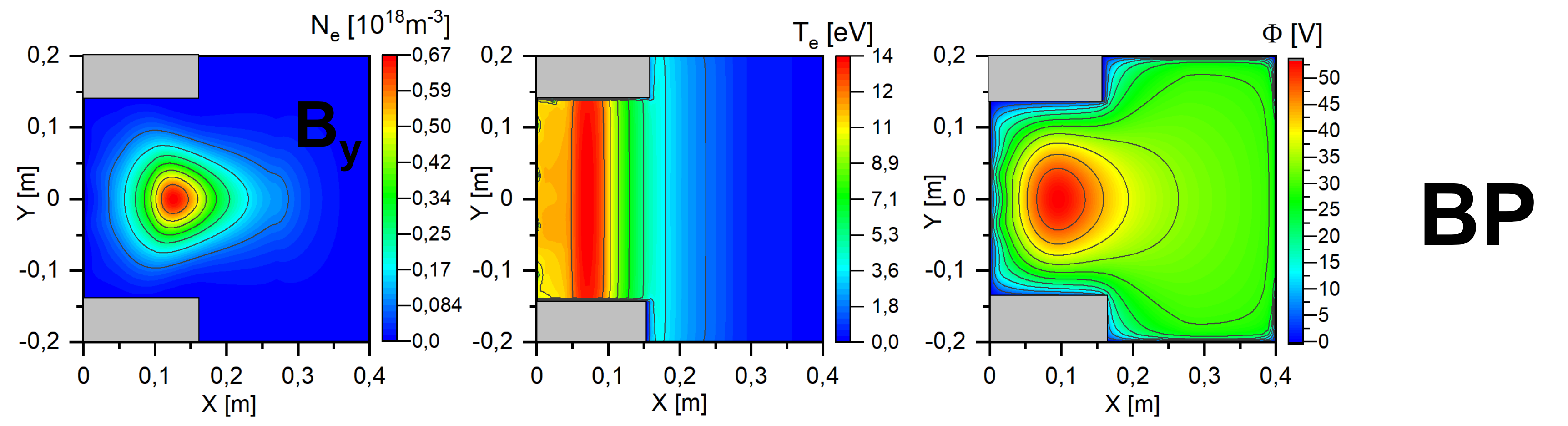


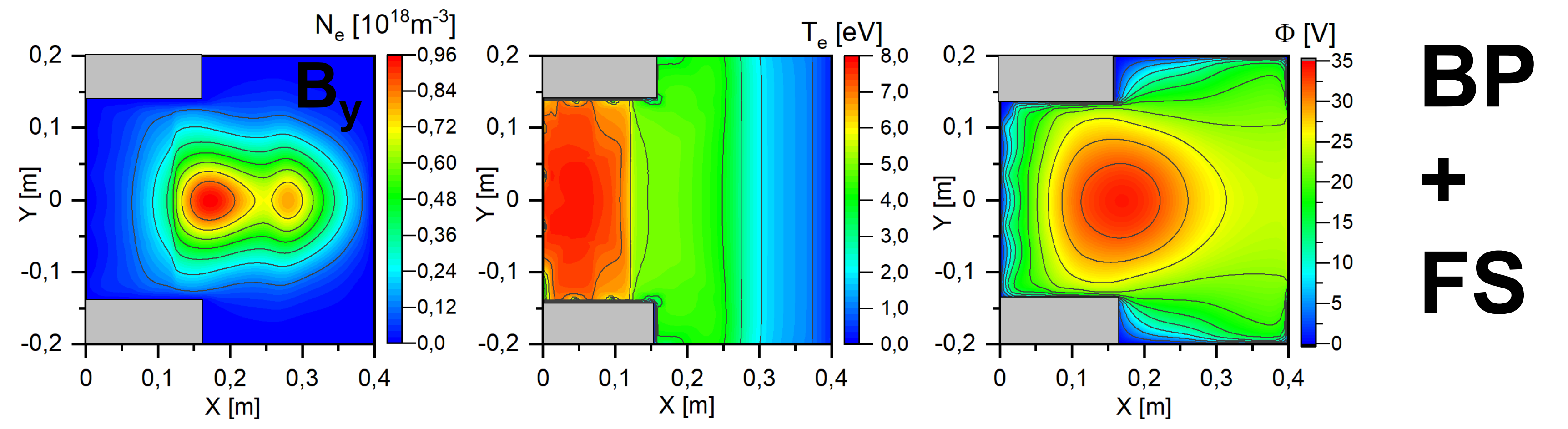
Increasing the size of the expansion region leads to lower densities in the source.

Effect of Permanent Magnets









Conclusions

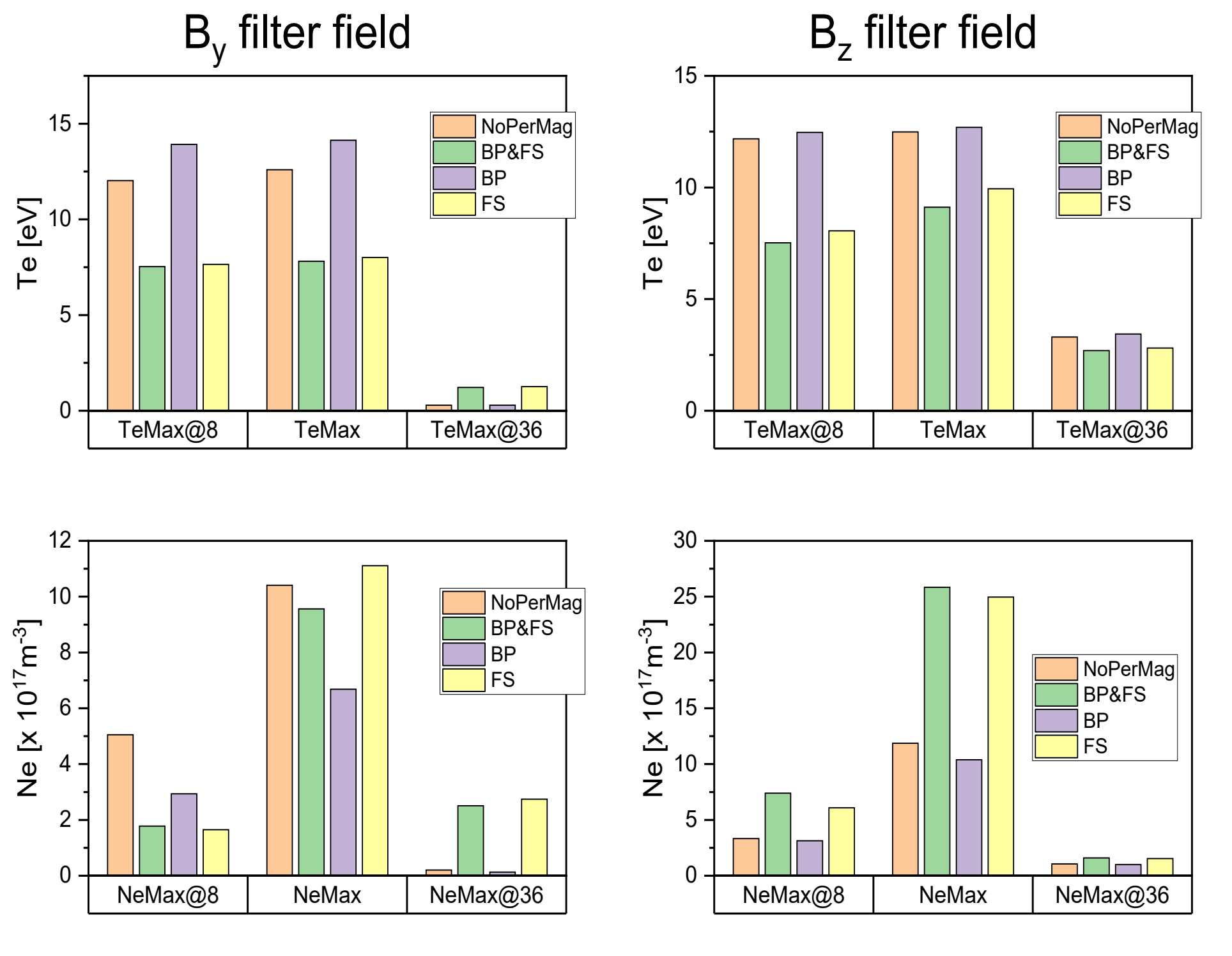
- MF field increases density in the driver (after initial deacrese) .
- The density in the expansion region is only marginally affected by the changes to the MF.
- Cusp Field at lateral walls has no influence on the plasma parametrs in the SPIDER.

B_z configuration

- Cusp Field at Faraday Shield increases strongly plasma density in the driver. Density in the expantion region only slightly increases.
- Effect of the Cusp Field at driver back plate is weak and even in the oposit direction.

B_y configuration

- Cusp Field at Faraday Shield leads to strong increase of plasma density in the driver and expansion zone.
- Cusp Field at driver back plate leads to reduction of the plasma density in the SPIDER source



Influence of different permanent magnets configurations on plasma parametrs in SPIDER

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.

REFERENCES
[1] Hagelaar G J M, Fubiani G and Boeuf J-P 2011 Plasma Sources Sci. Technol. 20 015001
[2] S Lishev, L Schiesko, D Wuenderlich, C Wimmer and U Fantz, Plasma Sources Sci. Technol. 27 (2018) 125008

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.