Three-dimensional calculations of the inductive coupling between radio-frequency waves and plasma in the drivers of the SPIDER device

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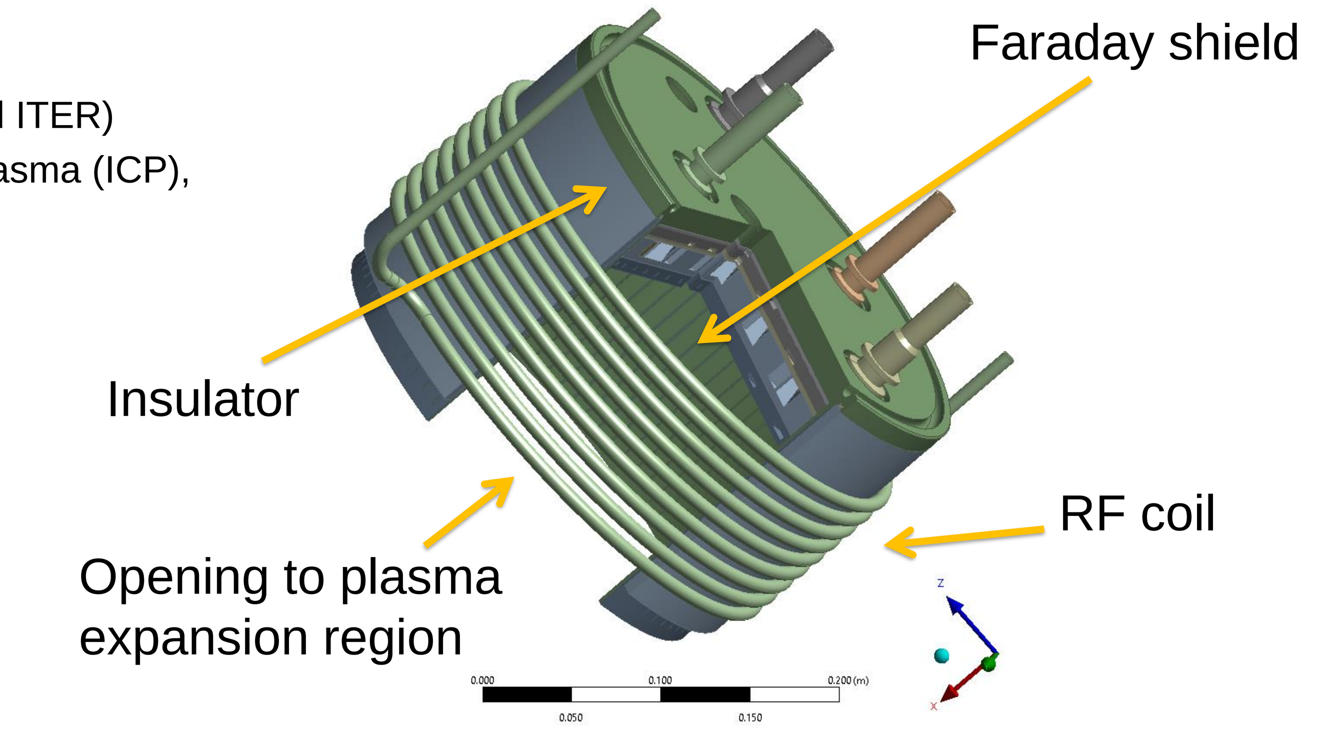
The need for a 3D calculation in SPIDER

The plasma source in the SPIDER [1] (hence MITICA and ITER) source is based on the concept of Inductively Coupled Plasma (ICP), where two important elements are not axisymmetric:

- Faraday shield
- Plasma parameters distribution



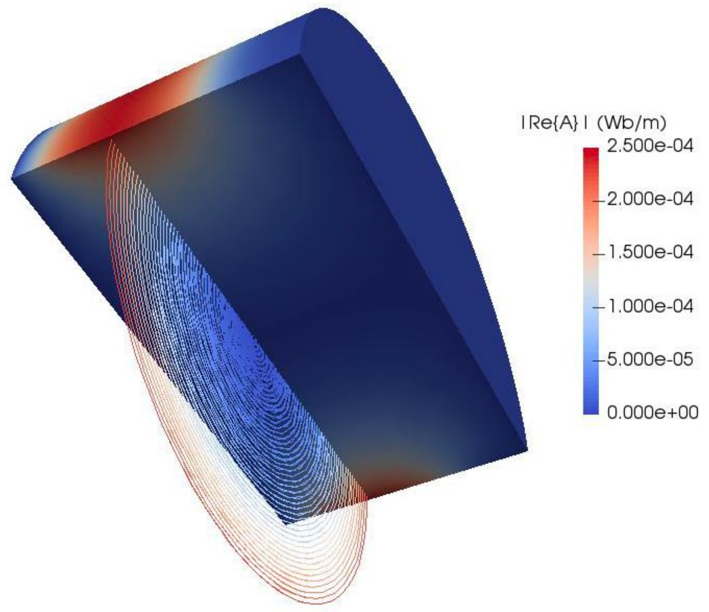
Objective: understand and provide reliable ICP calculations in the conditions of SPIDER discharges. There are two essential parts of the study

- Induction process based on RF drive
- Transport processes in the plasma

Both processes should be coupled for the problem to be solved consistently. Transport is being studied based on the fluid [2] and kinetic approaches [3]. This work is dedicated to the RF-plasma coupling process

Antecedents SPIDER: 2D electromagnetic calculations [4,5]

- Simplified models for electrical conductivity
- Compatibility of results with experimental data

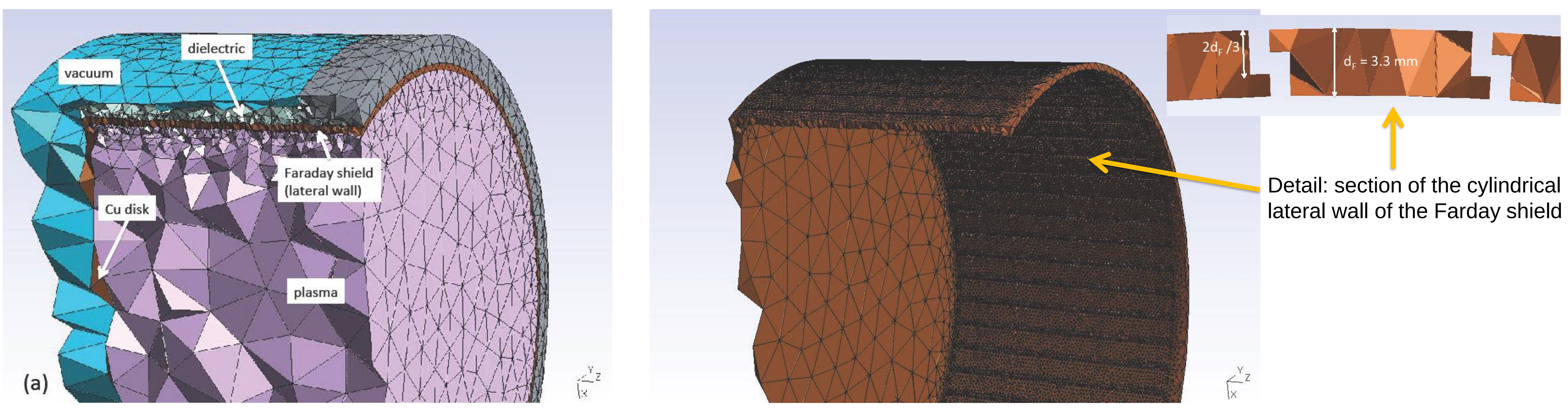


Next step (this work): First exercises in 3D

- Develop 3D calculation tools (Finite Element Method, FEniCS software [6])
- Translate conductivity models and boundary conditions OK
- Check results using 1-domain (plasma) in 3D calculations OK
- Check axi-symmetry OK

Geometrical model for the Faraday shield

Physics studies (e.g. plasma conductivity models) are left for later stages after the calculation tools are ready. Problems associated with the geometry of the device can be already tackled: Faraday shield. The calculation domain is a cylinder just inside the RF coils

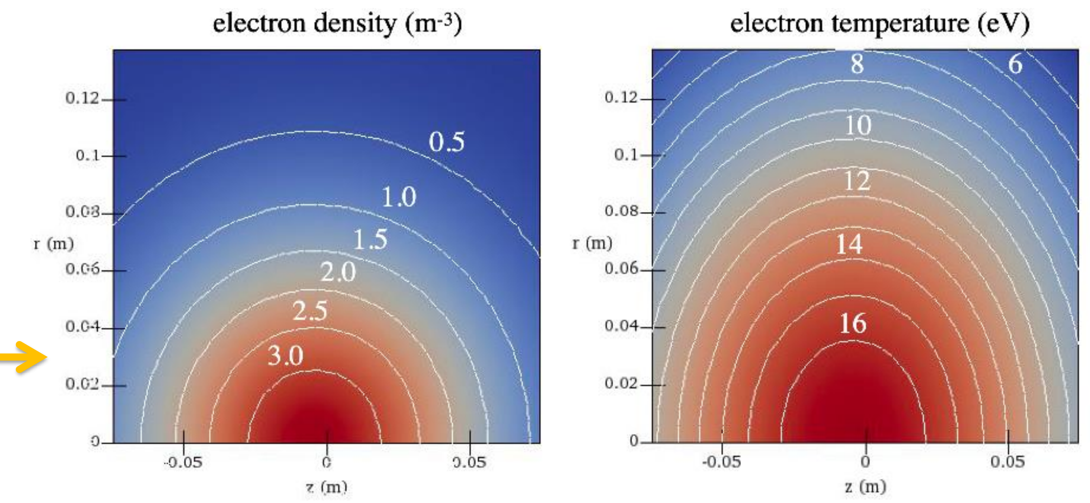


3D meshing of SPIDER drivers for Finite Element Method calculations. Different sub-domains are tagged to associate different properties (conductivity, dielectric constant). The mesh is finer in the Faraday shield cylindrical side, in order to solve the copper skin depth

Experimental data

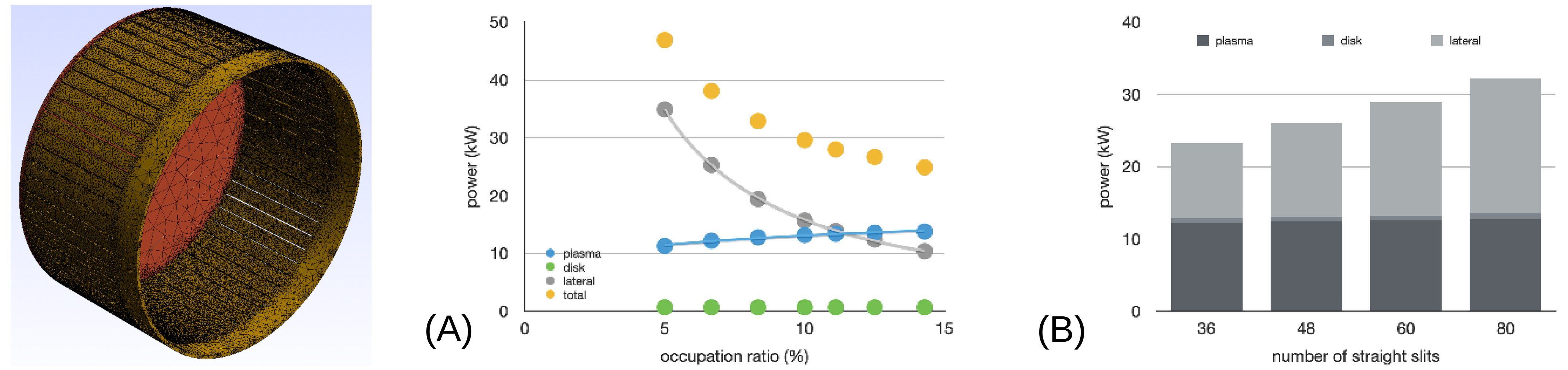
SPIDER experimental campaign S17 (y. 2020) dedicated to characterising the plamas. Discharges at 50 kW per driver, neutral gas pressure 0.34 Pa. Peak values:

- Without filter magnetic field, n_e = 1.2 x 10^{18} m^{-3}, T_e = 11 eV
- With filter magnetic field, n_e = 3 x 10^{18} m^{-3}, T_e = 17 eV



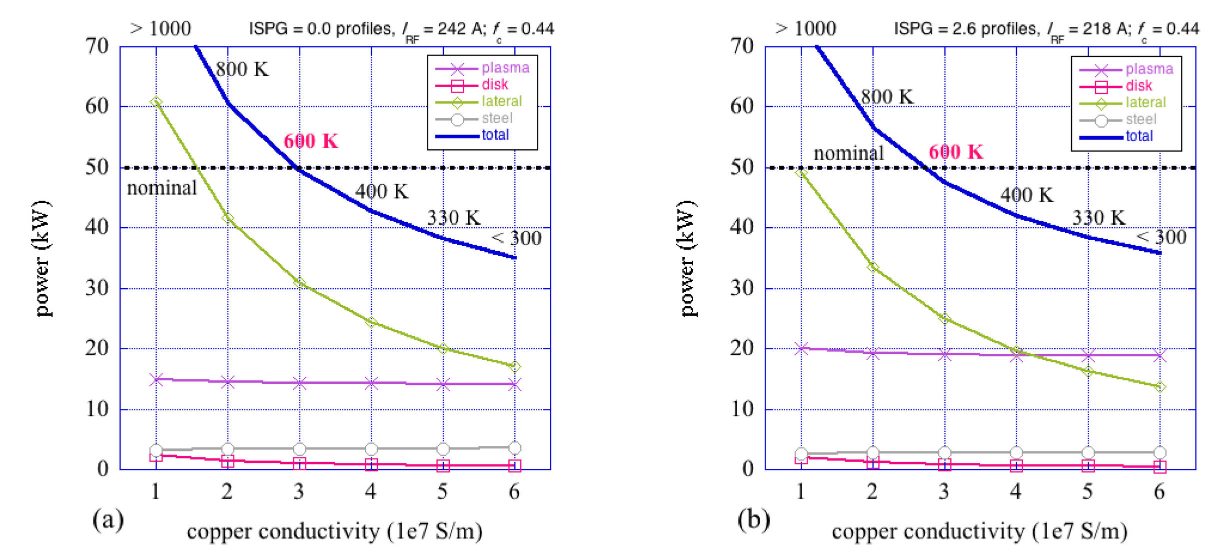
Results

The chosen plasma conductivity models yield dissipated powers that are compatible with the electrical measurements. With these models, a simplified Faraday shield cylindrical wall with straight slits has been used to study the dissipation in the different parts of the driver (including plasma) for different slit apertures (occupation ratio) and number of slits at a given occupation ratio. Cross-check with [8]: dissipation in Faraday shield increases (A) with decreasing occupation ratio at fixed number of slits and (B) with number of slits at *fixed* occupation ratio



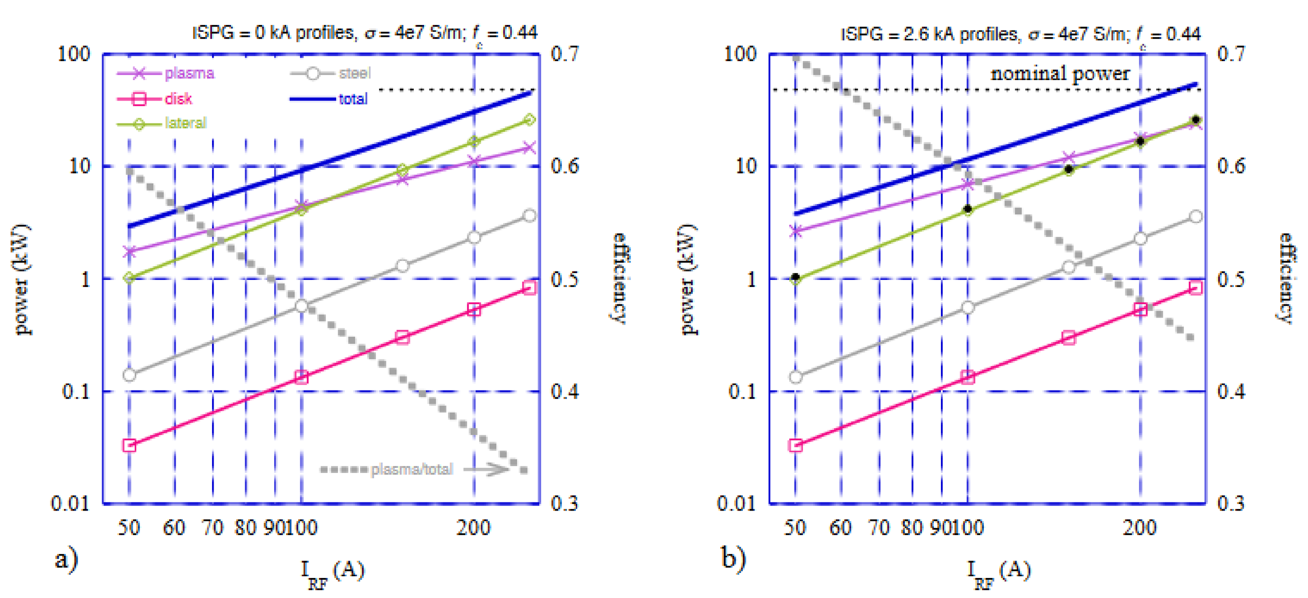
Dissipation depending on driver temperature: Copper conductivity changes considerably with temperature, and so does dissipation in the cylindrical wall of the Faraday shield. The figures show dissipated power as a function of the copper conductivity (see associated temperatures in labels) for two types of discharge, w/wo magnetic filter field

- Dissipation dominated by cylindrical lateral wall
- Admissible temperatures < 400 K (homogeneous)



Driver efficiency: The dissipated power scales differently in plasma and copper parts with RF current. Consequently, the efficiency decreases with RF current. An estimate of the Driver efficiency is obtained by scanning the RF current and comparing the net dissipated power with the electrical measurements of amplitude/phase at the RF-generator output.

- Currents above 200 A (in agreement with [4])
- Efficiency 30-50% (higher with filter field)



NOTE: Efficiencies around 50% are common in this type of source according to different studies

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[2] R. Zagórski *et al.* 2022 IEEE Trans. Plasma Sci., doi: 10.1109/TPS.2022.3175527.
[3] V. Candeloro "Influence of plasma parameters on the effectiveness of multi-cusp magnetic field confinement in negative ion sources" (this conference)
[4] P. Jain *et al* 2022 Plasma Phys. Control. Fusion **64** 095018
[5] M. Recchia *et al.* "Studies on power transfer efficiency in drivers of the SPIDER inductively coupled ion source" (PSST submitted)
[6] https://fenicsproject.org/
[7] C. Geuzaine and J.-F. Remacle 2009 Intl J Numerical Methods in Engineering **79** 1309
[8] S. Briefi *et al.* 2022 Rev. Sci. Instrum. **93** 023501

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