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FÜR PLASMAPHYSIK

Numerical study of RF power coupling in fusion-relevant single- and multi-driver H^- ion sources

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EUROfusion

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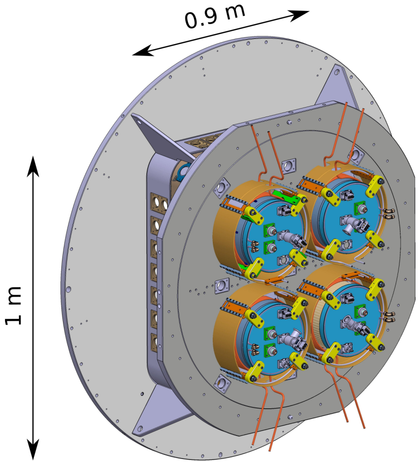
Motivation

- Electrical measurements performed in single-driver NNBI RF ion source[1] to determine RF power transfer efficiency $\eta = \frac{P_\mathrm{plasma}}{P_\mathrm{RF}}$
- Low $\eta \approx \frac{55\,\mathrm{kW}}{100\,\mathrm{kW}} = 0.55$ found
- Recent measurements in multi-driver setup ELISE w/o magnetic filter field (FF): $\eta \approx 0.3$ (0.4 with FF)
- Similar values found in SPIDER[2]
- Why is η decreased in multi-driver setups?
- How can it be improved?



ELISE ion source

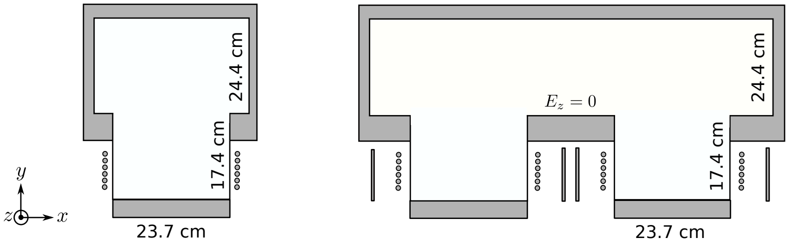
[1]: D. Zielke et al. JPhysD 54 (2021) 155202
[2]: P. Jain et al. PPCF 64 (2022) 095018

RF coupling optimization via numerical modeling

- Experimental optimization difficult
- Large number of external parameters and mixing of different effects
- Model needed for systematic study of RF power coupling in regime of RF ion source
    - Low $p_{\mathrm{fill}} \leq 0.3\,\mathrm{Pa}$
    - Large $P_{\mathrm{RF}} \leq 100\,\mathrm{kW}$ per driver
    - Low RF of 1 MHz
- State-of-the-art numerical fluid-electromagnetic model developed and benchmarked successfully[3],[4]
- Optimization studies revealed large optimization possibilities by increasing axial driver length and RF[5]
- Lower losses, less probability for RF breakdowns → increased performance and reliability

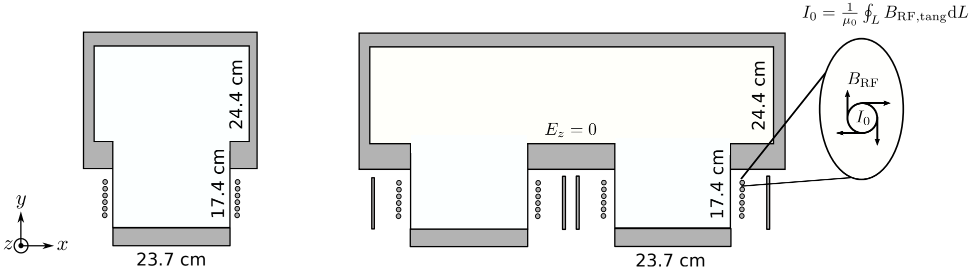
[3]: D. Zielke et al. PSST, 30 (2021) 065011
[4]: D. Zielke et al. PSST, 31 (2022) 035019
[5]: D. Zielke et al. submitted to NF

Fluid-electromagnetic model inputs



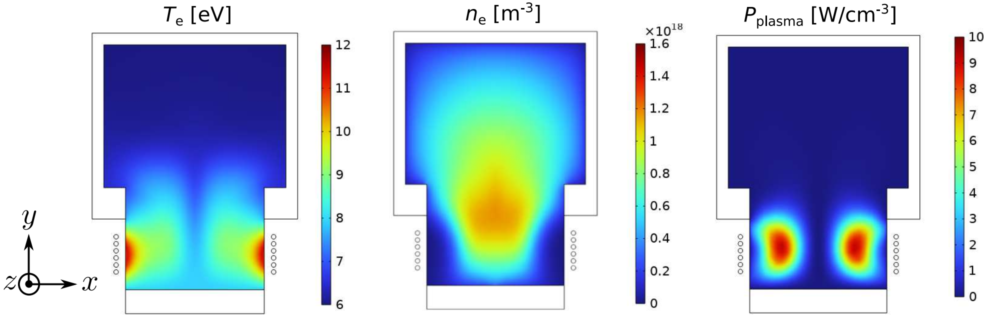
- 2D cartesian geometry (horizontal cut)
- Uniform $n_{\mathrm{H}}, n_{\mathrm{H}_2}$ ($\widehat{=}$ 0.3 Pa)
- No cusp field in driver backplate, no magnetic filter field
- $P_{\mathrm{plasma}} = 25\,\mathrm{kW}$ per driver
- Backplates and EM-shields assumed perfect conductors → $E_z = 0$
- Measured network resistances $R_{\mathrm{net,SD}} = 0.6\,\Omega$, $R_{\mathrm{net,MD}} = 1.2\,\Omega$

Fluid-electromagnetic model equations & outputs



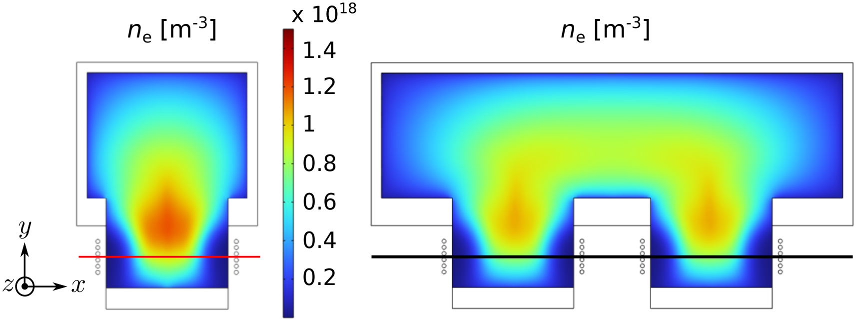
- Fully time dependent spatial distributions of $n_{\mathrm{H}_\mathrm{i}^+}, u_\mathrm{i}, \mathrm{i} \in \{\mathrm{H}^+, \mathrm{H}_2^+, \mathrm{H}_3^+\}, \phi_{\mathrm{plasma}}, n_\mathrm{e}, u_\mathrm{e}, T_\mathrm{e}, q_\mathrm{e}, E_{\mathrm{RF}}, B_{\mathrm{RF}}$
- Low RF of 1 MHz and $B_{\mathrm{RF}} \sim 100\,\mathrm{G} \rightarrow$ viscosity, Lorentz force, RF-magnetized heat flux
- Self-consistent RF coil current amplitude I_0 controlled by integral controller
- $\eta = \frac{P_{\mathrm{plasma}}}{P_{\mathrm{RF}}} = \frac{P_{\mathrm{plasma}}}{(P_{\mathrm{plasma}} + \frac{1}{2} R_{\mathrm{net}} I_0^2)}$

Benchmark at 0.3 Pa and P_{plasma} = 25 kW



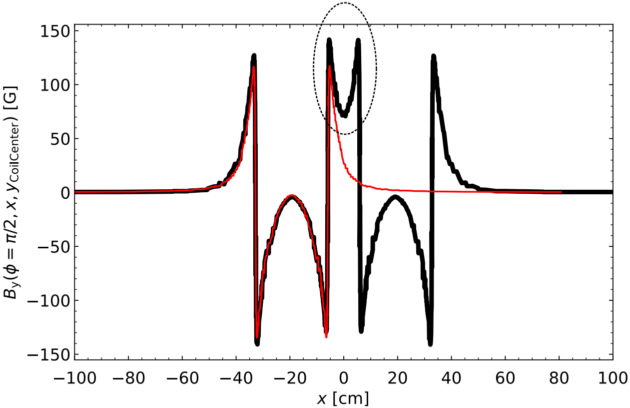
- All quantities shown above RF averaged over one steady state RF cycle
- Calculated and experimentally measured T_e and n_e agree well ✓
- Calculated $I_0 = 263$ A ($\eta = 0.55$) agrees well with experimental $I_0 = 250$ A ($\eta = 0.57$) ✓
- More model results see contribution of S. Briefi to this conference

Multi-driver at 0.3 Pa and P_{plasma} = 25 kW per driver



- No EM-shields for illustrative purposes
- Similar distributions of $T_{\mathrm{e}}, n_{\mathrm{e}}, P_{\mathrm{plasma}}$ in all drivers
- However, $I_{0,\mathrm{MD}} = 284$ A > $I_{0,\mathrm{SD}} = 263$ A $\rightarrow \eta_{\mathrm{MD}} = 0.51 < \eta_{\mathrm{SD}} = 0.55$
- Compare RF magnetic field component B_y along line-of-sights

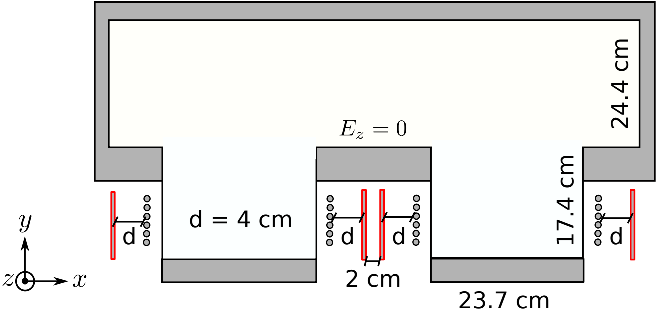
Comparison RF magnetic fields



- Changed spatial distribution of B_{RF} due to presence of second driver
- On RF coil circumference: $I_0 = \frac{1}{\mu_0} \oint_L B_{\mathrm{RF,tang}} \mathrm{d}L \rightarrow$ larger applied I_0

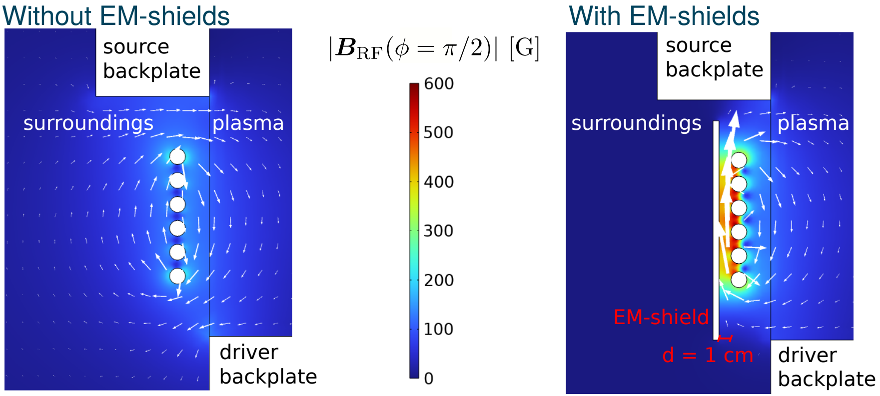
Conductive EM-shields in ELISE numerical model

- In multi-driver ion sources, conductive 'EM-shields' are present to avoid electrostatic and electromagnetic mutual coupling
- Model of ELISE ion source



- Boundary condition $E_z = 0$ at each EM-shield changes RF field distributions

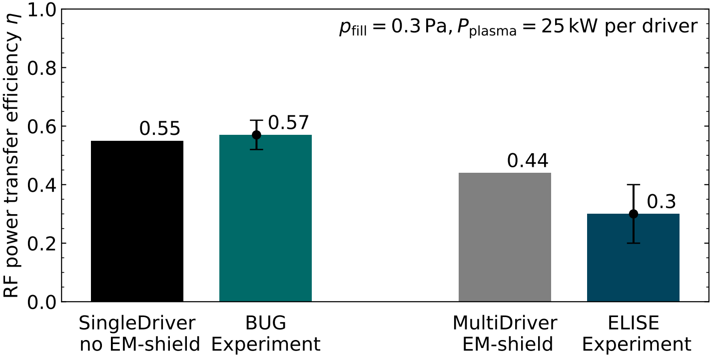
Changed B_{RF} field distribution due to EM-shields



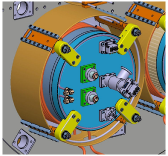
- Uniform distribution of low B_{RF} around RF coil circumferences
- Resulting low $I_0 = \frac{1}{\mu_0} \oint_L B_{\mathrm{RF,tang}} \mathrm{d}L$

- Highly non-uniform distribution of B_{RF}
- Increased $B_{\mathrm{RF,tang}}$ → larger I_0 needed

Comparison with experimentally obtained η

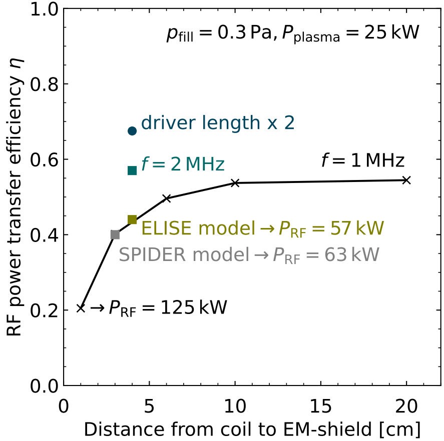


- Impact of EM-shields on η more pronounced in experiment
- Possibly caused by 3D effects: EM-shields support structure and RF coil feedthroughs

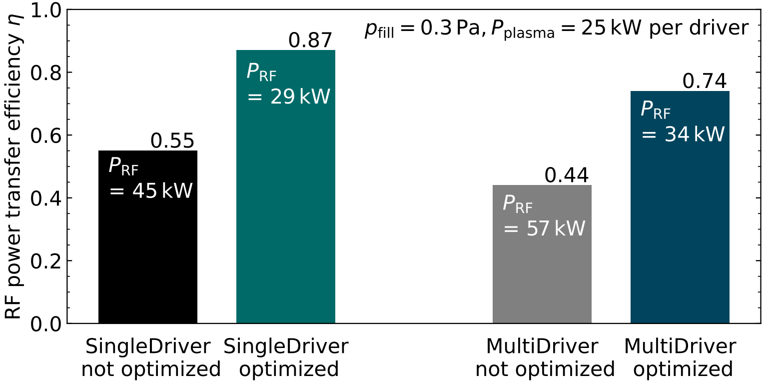


Impact of distance RF-coil - EM-shield on η

- Isolate effect of distance between RF coil and EM-shield
- Study performed using single-driver
- Highly nonlinear behavior of η found
- Optimization measures proposed for single-driver without EM-shields still apply



Optimized single- and multi-driver setups



- Optimized setup: doubling the axial driver length and doubling the RF
- Needed P_{RF} per driver is greatly reduced

Conclusion

- Advanced state-of-the-art 2D fluid-electromagnetic model self-consistently describes RF power coupling in NNBI RF ion sources
- Why is η decreased in multi-driver setups?
  - EM-shields change spatial distribution of EM-fields around RF coil
  - Larger $I_0 \rightarrow$ lower $\eta \rightarrow$ higher P_{RF} needed
- How can it be improved?
  - Effect highly nonlinear with distance between coil and EM-shield
  - Optimization measures found for single driver apply for multi-driver as well
  - Increasing axial length and RF beneficial
  - Needed P_{RF} greatly reduced
- What comes next?
  - 3D implementation of the model

Literature [1], [2], [3], [4]

D. Zielke et al.
RF power transfer efficiency and plasma parameters of low pressure high power ICPs.
Journal of Physics D: Applied Physics, 54(15):155202, feb 2021.

P. Jain et al.
Investigation of RF driver equivalent impedance in the inductively coupled SPIDER ion source.
Plasma Physics and Controlled Fusion, 64(9):095018, aug 2022.

D. Zielke et al.
Self-consistent fluid model for simulating power coupling in hydrogen ICPs at 1 MHz including the nonlinear RF lorentz force.
Plasma Sources Science and Technology, 30(6):065011, jun 2021.

D. Zielke et al.
Modeling inductive radio frequency coupling in powerful negative hydrogen ion sources: validating a self-consistent fluid model.
Plasma Sources Science and Technology, 31(3):035019, mar 2022.

Backup: Why were EM shields introduced in ELISE?

- Observation in RADI: inertia-cooled Faraday shields were destroyed during short-pulse operation
- Countermeasures were taken to prevent this at ELISE
  - Water-cooled bridges of Faraday shields
  - Monitoring impurity levels (oxygen was present in RADI)
  - Coil ’symmetrization’
  - Connection of potentials at the Faraday shields (grounded vs. floating)
  - EM shields (which suppress electromagnetic and electrostatic coupling between drivers)
- Observation: no damage of Faraday shields at ELISE

Backup: PDEs for description of RF power coupling

$$\partial_t n_\mathrm{e} + \nabla \cdot n_\mathrm{e} \boldsymbol{u}_\mathrm{e} = \mathcal{R}_\mathrm{e}$$

$$m_\mathrm{e} n_\mathrm{e} (\partial_t \boldsymbol{u}_\mathrm{e} + (\boldsymbol{u}_e \cdot \nabla) \boldsymbol{u}_\mathrm{e}) = -\nabla n_\mathrm{e} \mathrm{e} T_\mathrm{e} - \nabla \cdot \underline{\underline{\pi_\mathrm{e}}} - \mathrm{e} n_\mathrm{e} (\boldsymbol{E} + \boldsymbol{u}_\mathrm{e} \times \boldsymbol{B}) - \mathcal{F}_\mathrm{e}$$

$$\partial_t \frac{3}{2} p_\mathrm{e} + \nabla \cdot (\frac{5}{2} p_\mathrm{e} \boldsymbol{u}_\mathrm{e} + \underline{\underline{\pi_\mathrm{e}}} \boldsymbol{u}_\mathrm{e} + \boldsymbol{q}_\mathrm{e}) + \mathrm{e} n_\mathrm{e} \boldsymbol{u}_\mathrm{e} \cdot \boldsymbol{E} = \delta_t E$$

$$\underline{\underline{\pi_\mathrm{e}}} - \frac{\mathrm{e}}{m_\mathrm{e} \nu_\mathrm{en}} (\boldsymbol{B} \times \underline{\underline{\pi_\mathrm{e}}} - \underline{\underline{\pi_\mathrm{e}}} \times \boldsymbol{B}) = -\mu_\mathrm{e} \left(\nabla \boldsymbol{u}_\mathrm{e} + (\nabla \boldsymbol{u}_\mathrm{e})^\intercal - \frac{2}{3} (\nabla \cdot \boldsymbol{u}_\mathrm{e}) \underline{\underline{I}} \right)$$

$$\boldsymbol{q}_\mathrm{e} + \frac{\mathrm{e}}{m_\mathrm{e} \nu_\mathrm{en}} \boldsymbol{q}_\mathrm{e} \times \boldsymbol{B} = -\kappa_\mathrm{e} \nabla \mathrm{e} T_\mathrm{e}$$

Backup: Experimental observations regarding R_{network}

- $2 \cdot R_{\mathrm{network,BUG}} \approx R_{\mathrm{network,ELISE}}$
- $R_{\mathrm{network,SPIDER}} \approx 1.5 \cdot R_{\mathrm{network,ELISE}}$
- Good agreement with EM simulations
- Conclusion: R_{network} behaves as expected

Backup: Measured η in ELISE