Particle-in-cell modeling of the inductive discharge inside the drivers of negative ion sources

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1° Conferenza Italiana Plasmi
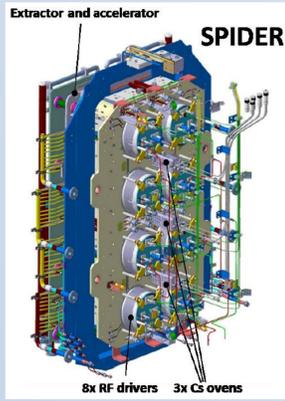
Negative ion sources and applications

- **Negative Ion Sources** (**NIS**) are used mainly for:
  - Material science/industry → reduced charge accumulation on treated surfaces
  - Nuclear confinement fusion → generation of a negative ion beam for **Neutral Beam Injectors** (**NBI**) → much larger neutralization efficiency compared to positive ion beams, at energies **above 100 keV**
- **ITER NIS** are composed of:
  - One or more **RF drivers**
  - An **expansion chamber**, with a **magnetic filter**
  - An **extraction grids system** for negative ions
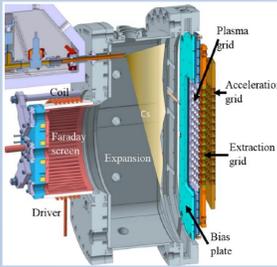
A CAD model of the BUG negative ion source. Picture taken from Ref.[1]
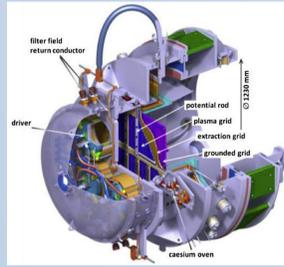
A CAD model of the ELISE negative ion source. Picture taken from Ref.[2]

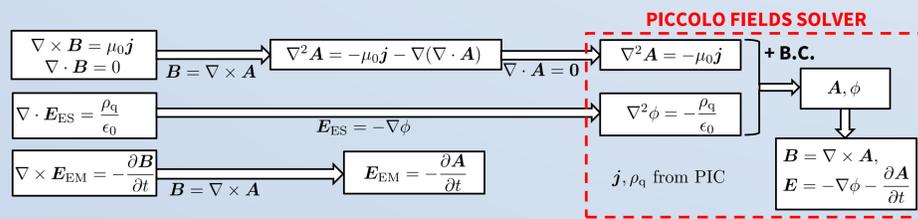*A CAD model of the SPIDER negative ion source. Picture taken from Ref.[3]*

Main goal of this work

- Experimental energy efficiency of NIS is generally low → modeling is crucial to understand how to increase it. Main modeling approaches:
  - **Fully-fluid** simulations [1] → simplified coefficients for both collisional and collisionless electron transport (no kinetic effects and instabilities)
  - **PIC** simulations [4,5,6] → kinetic effects are modeled, although an electrostatic PIC approach with imposed heat deposition maps is generally considered
- No existing approach captures both kinetic effects and consistent plasma heating → this work aims to **model the inductive discharge of a single RF driver** to produce consistent plasma heating maps for full-scale simulations of a NIS

Working physics of negative ion sources

- Neutral D_2 gas is injected inside the RF drivers (cylindrical quartz tubes), where it is ionized through an inductive discharge
  - An RF coil produces an axial oscillating magnetic field, inducing an azimuthal electric field that heats up electrons
- Inside the expansion chamber, the plasma from RF drivers coalesces and expands. A **transverse magnetic field** (filter), prevents electrons from reaching the extraction region, thus producing an **ion-ion plasma** close to the grids
- Negative ions are mostly created because of neutral atoms interaction with the plasma grid, made of **molibdenum** and covered by a layer of **cesium** to enhance negative ion production
- The extraction grid system is composed of a plasma grid and an extraction grid at a high voltage, and extracts negative ions and small amounts of electrons

Particle-in-cell model of an RF driver

- **PICCOLO** code (**P**article-**I**n-**C**ell **CO**de for **LO**w temperature plasmas)
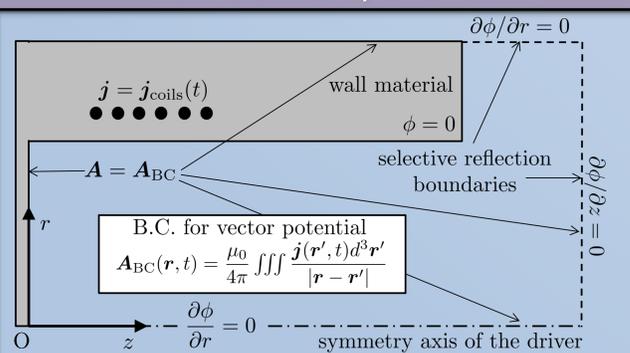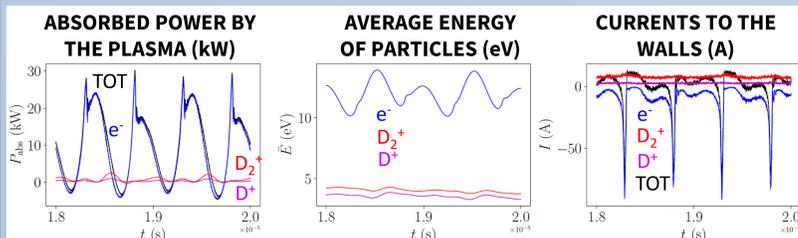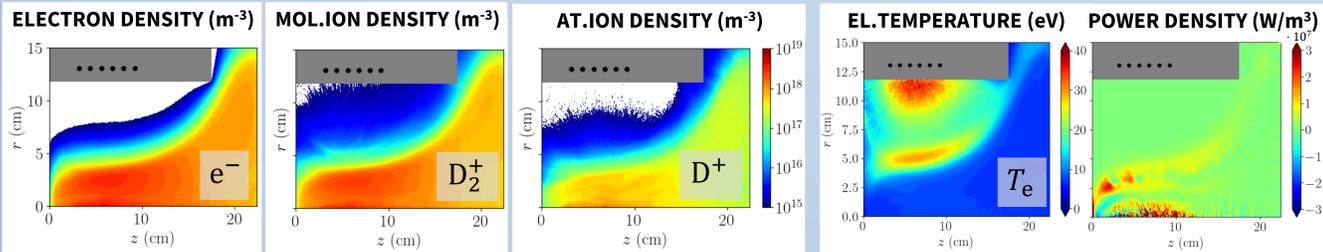 - Solution of a quasi-static version of full Maxwell's equations (Darwin's)

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j} \qquad \nabla^2 \boldsymbol{A} = -\mu_0 \boldsymbol{j} - \nabla(\nabla \cdot \boldsymbol{A})$$
$$\nabla \cdot \boldsymbol{B} = 0 \qquad \boldsymbol{B} = \nabla \times \boldsymbol{A} \qquad \nabla \cdot \boldsymbol{A} = 0$$

PICCOLO FIELDS SOLVER

$$\nabla^2 \boldsymbol{A} = -\mu_0 \boldsymbol{j} \quad + \text{ B.C.}$$
$$\nabla \cdot \boldsymbol{E}_{ES} = \frac{\rho_q}{\epsilon_0} \qquad \boldsymbol{E}_{ES} = -\nabla \phi \qquad \nabla^2 \phi = -\frac{\rho_q}{\epsilon_0}$$
$$\boldsymbol{A}, \phi$$
$$\nabla \times \boldsymbol{E}_{EM} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \boldsymbol{B} = \nabla \times \boldsymbol{A} \qquad \boldsymbol{E}_{EM} = -\frac{\partial \boldsymbol{A}}{\partial t}$$
$$\boldsymbol{j}, \rho_q \text{ from PIC}$$
$$\boldsymbol{B} = \nabla \times \boldsymbol{A}, \quad \boldsymbol{E} = -\nabla \phi - \frac{\partial \boldsymbol{A}}{\partial t}$$

  - Standard **PIC** algorithms (MCC and DSMC) with binary collisions of plasma species (e, D^+, D_2^+, D^-) between themselves and with neutrals (D, D_2)
  - Neutral background (D, D_2) currently assumed to be uniform and constant
  - **Axisymmetric simulation domain** in the meridional plane ($z-r$) of the driver, covering part of the expansion region
  - **Selective reflection of ions/electrons at downstream boundary**, in order to yield, on average, an ampipolar plasma flow (reduced boundary effects)

Simulation domain/B.C. and facts

$$\partial\phi/\partial r = 0$$
$$\boldsymbol{j} = \boldsymbol{j}_{\text{coils}}(t)$$
wall material
$$\phi = 0$$
selective reflection boundaries
$$\boldsymbol{A} = \boldsymbol{A}_{\text{BC}}$$

B.C. for vector potential
$$\boldsymbol{A}_{\text{BC}}(\boldsymbol{r}, t) = \frac{\mu_0}{4\pi} \iiint \frac{\boldsymbol{j}(\boldsymbol{r}', t) d^3 \boldsymbol{r}'}{|\boldsymbol{r} - \boldsymbol{r}'|}$$

$$\partial\phi/\partial z = 0$$
$$\frac{\partial\phi}{\partial r} = 0$$ symmetry axis of the driver

PARAMETERS	VALUES	PARAMETERS	VALUES
RF coil frequency	1 MHz	D_2 to D density ratio	4.0
RF coil current amplitude	200 A	Axial length of the driver	17.4 cm
RF coil radius	13.05 cm	Cell size in $z-r$ plane	0.25 mm
Radius of the driver	11.85 cm	ϵ_0 scaling factor	1000
Total gas pressure (D_2 + D)	0.2 Pa	N. macro-particles	$54 \cdot 10^6$

Preliminary PIC results for the BUG driver

TIME AVERAGED MAPS OVER A FULL RF CYCLE

ELECTRON DENSITY (m^{-3}) — e^-

MOL.ION DENSITY (m^{-3}) — D_2^+

AT.ION DENSITY (m^{-3}) — D^+

EL.TEMPERATURE (eV) — T_e

POWER DENSITY (W/m^3)

ABSORBED POWER BY THE PLASMA (kW) — TOT, e^-, D_2^+, D^+

AVERAGE ENERGY OF PARTICLES (eV) — e^-, D_2^+, D^+

CURRENTS TO THE WALLS (A) — e^-, D_2^+, D^+, TOT

- Plasma is **heated off-axis** because of the induced electric field pattern
- **Electrons are lost massively to the walls** twice per period → a **depletion region** forms at lateral and back walls
- **Self-consistent heating map** can be used in full-scale NIS simulations

INSTANTANEOUS MAGNETIC AND RF ELECTRIC FIELDS (INDUCED BY COILS AND PLASMA)

$\phi \approx \pi/8$ $\phi \approx \pi/4$ $\phi \approx 3/8\pi$ $\phi \approx \pi/2$ $\phi \approx 5/8\pi$ $\phi \approx 3/4\pi$ $\phi \approx 7/8\pi$ $\phi \approx 2\pi$

$\boldsymbol{B}$ (T)

$E_{\text{RF},\theta}$ (kV/m)
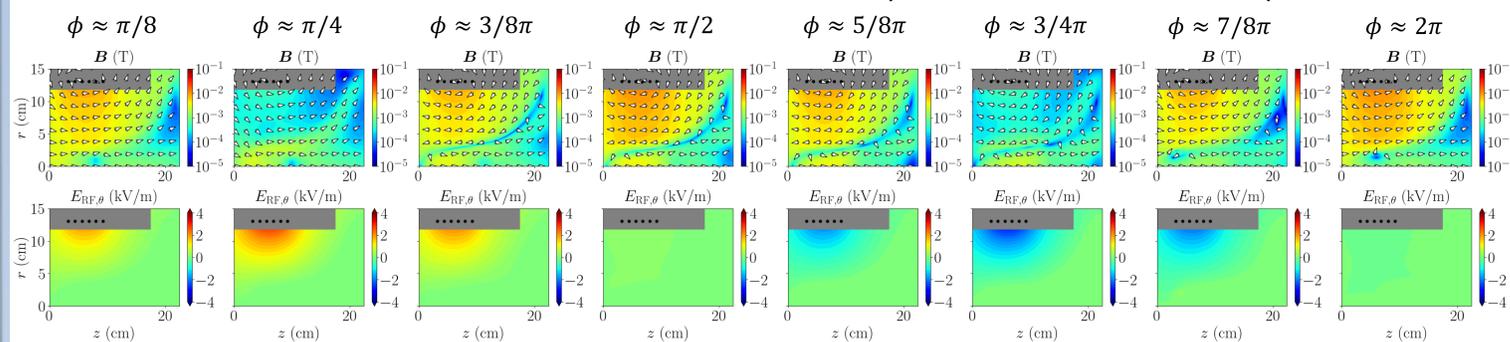
Validation efforts

- Sensitivity study to ϵ_0 scaling factor is needed to confirm these findings
- Ongoing validation against both fluid simulations and experiments
  - Comparison for varying RF current and frequency, and neutral gas pressure
  - Need to include a self-consistent model for neutral depletion

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