Numerical Design of RF Antennas For Ion Cyclotron Resonance Heating In ECRIS Environment

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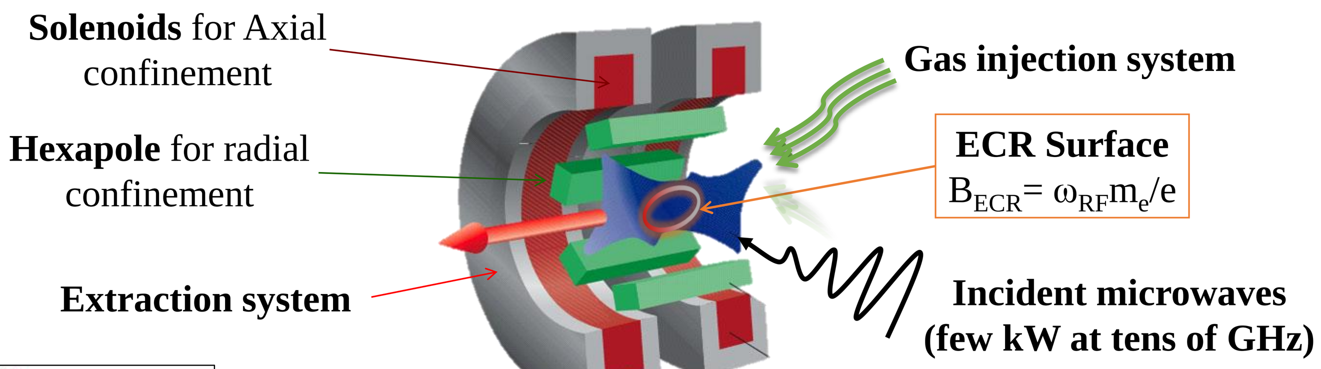
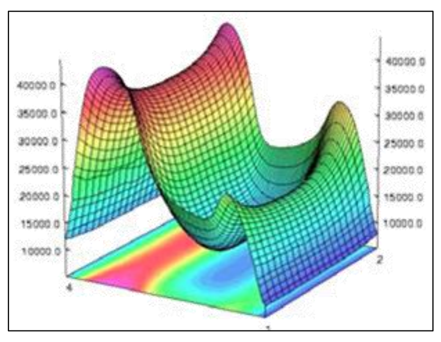
Introduction and motivation

- Ion cyclotron resonance heating (ICRH) is a method used for plasma-heating in, e.g., fusion , ICR isotope separation and ion thruster plasma devices.
- In ECRIS machines, low temperature ions (few eV) are extracted from a high density, high temperature plasma ($n_e \sim 10^{10}$ - 10^{13} cm^{-3}, Te ~ 0.1 – 100 keV) generated by means of the ECR electron heating by microwave power.
- Ion Cyclotron Resonance Heating (ICRH) could be relevant for improving the performances of the ECRIS beyond the Scaling laws.
- In order to obtain the desired ion heating, a loop-type antenna, strapped inside the plasma chamber surface and operating in Left Hand Circular Polarization (LHCP), is typically employed in other (but comparable to ECRIS) design.
- **AIM OF THE STUDY: design and investigate of the performances of RF loop-type antennas working in a ECRIS environment.**

Electron Cyclotron Resonance Ion Source (ECRIS)





B-minimum magnetic field structure

ECR Plasma key parameters
$n_e \sim 10^{12}$ cm^{-3}
$T_e \sim$ tens keV - $T_i \sim$ few eV
$T_{ion} \sim$ eV

- The plasma **electrons** are heated resonantly with microwaves @ **ECR.**
- The plasma **Ions** remain **cold.**

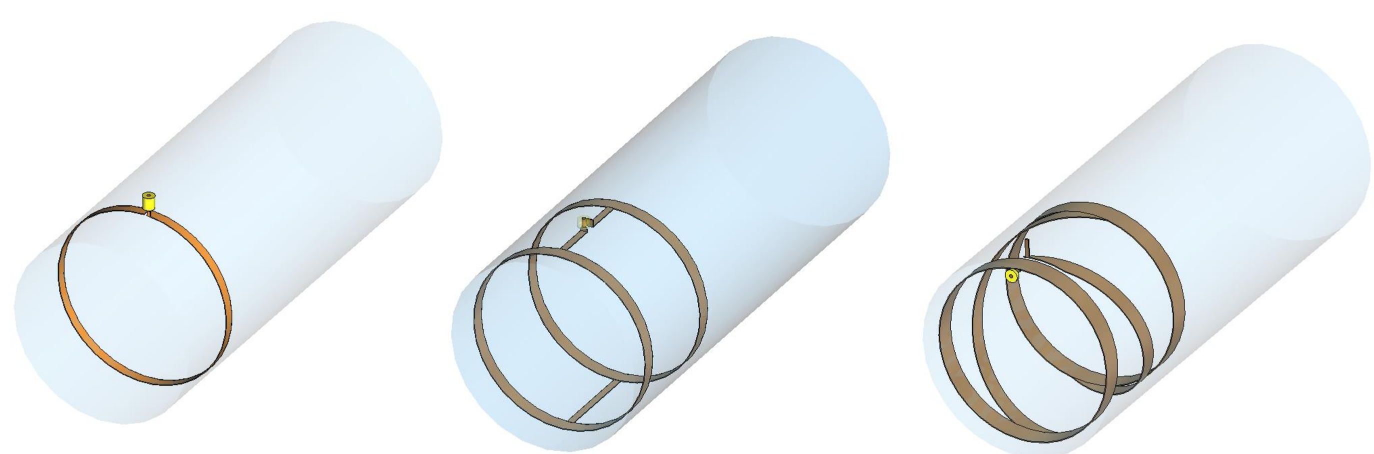
High Charge State Ion Sources driven by the need to use high charge states to increase the final energy for the **accelerator.**

1) Charge State depends on Ion Confinement Time
2) **Ion Temperature affects the Ion Confinement Time**

Selective Ion Cyclotron Resonance Heating (ICRH) could be relevant for both improving the performances of the ECRIS beyond the Scaling laws...

Antenna numerical design

- The presented setup consists of a plasma chamber with diameter **D = 280 mm** and length **L = 700 mm**. Inside the cavity, a loop-type antenna, fed by a coaxial connector, is placed for ICRH purposes.
- In particular, three antenna types have been designed and compared: a) **single-loop**, b) **Nagoya III** and c) **helical** type.



(a) (b) (c)

- The structures have been initially simulated with vacuum-filled chamber, using the software COMSOL.
- By considering $^{16}O^{4+}$ as ion species, a value of B_{ECR} = 0.64 [T] (18 GHz ECRIS operative frequency) and by imposing $B_{ICR} = 0.9 B_{ECR}$, the ion cyclotron frequency results:

$$f_{ci} = 15.2\ [MHz]\ \frac{Q}{A}\ B_{ICR}\ [T]$$

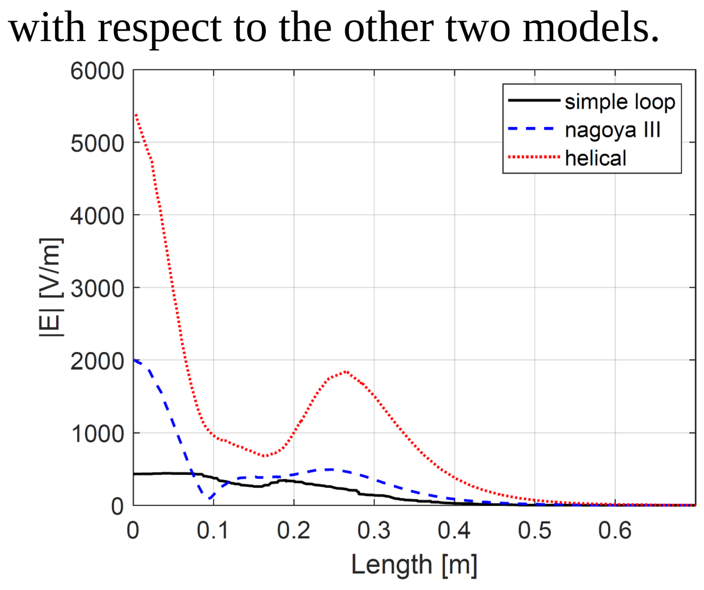
- The antenna operating frequency results f_{ci} = 2.2 MHz.
- Defining $P_{coupled}$ the power coupled to the whole structure (cavity + antenna), $P_{incident}$ the power at the coaxial connector input and $P_{reflected}$ the power reflected back at the coaxial connector input, we have:

$$P_{coupled} = P_{incident} - P_{reflected} \Rightarrow P_{coupled} = P_{incident} - |S_{11}|^2 P_{incident}$$

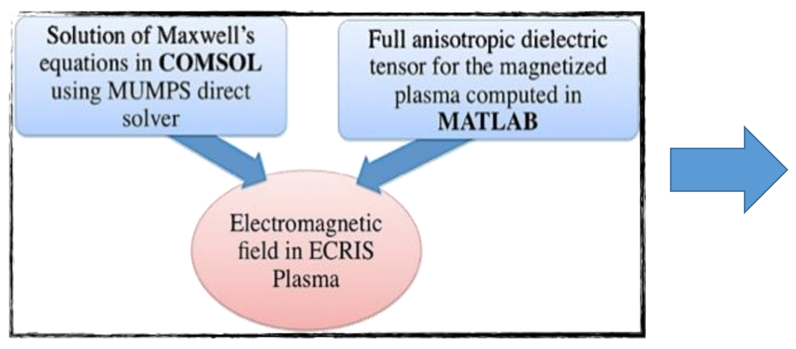
- The procedure consists of two steps for each antenna: 1) the |S11| is calculated from a simulation with an arbitrarily imposed incident power at the coaxial port; 2) by substituting the obtained |S11| value and $P_{coupled}$ = 2 kW, the correct value of $P_{incident}$ can be calculated and a second simulation can be performed with the new power value at the coaxial port.

Simulation results

- The electric field along the cavity axis generated by the three antennas inside the vacuum-filled cavity has been calculated, showing that the helical antenna allows to obtain higher electric field values with respect to the other two models.

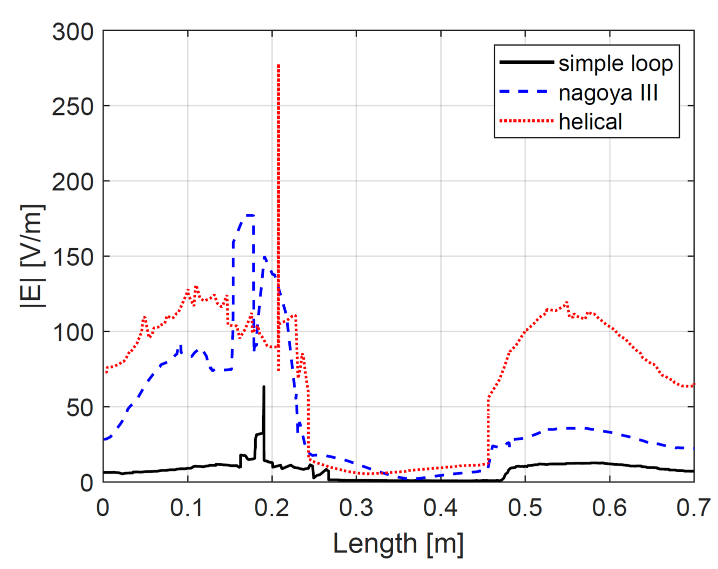


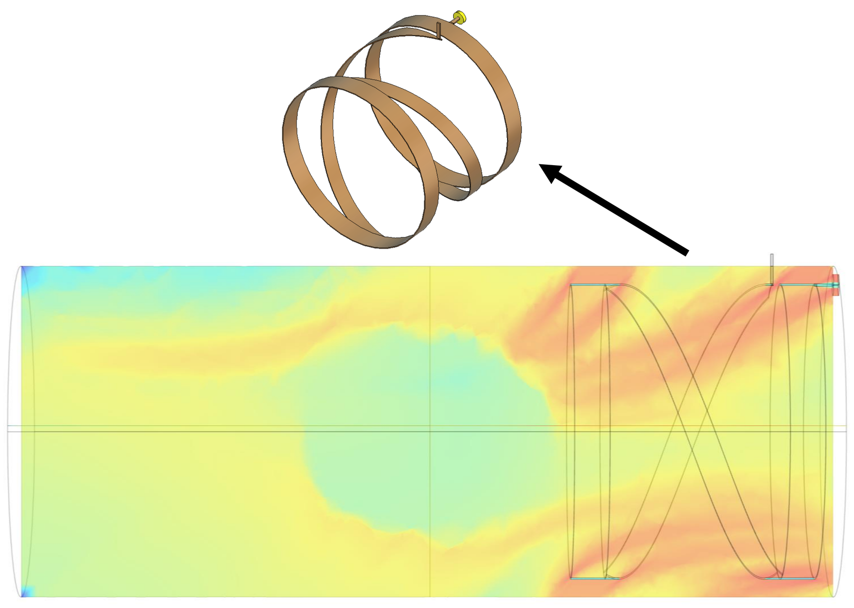
- The following step has been the introduction of a non-homogeneous lossy anisotropic plasma medium in the COMSOL simulations, obtained through the use of a MATLAB code.



1. **Plasma modeled through MATLAB script;**
2. **Plasma data imported into COMSOL 3D model;**
3. **E.M. solution inside the plasma chamber.**

- Results show that even when interacting with a lossy medium, the field irradiated by the helical antenna has a larger magnitude if compared with the other two antennas.

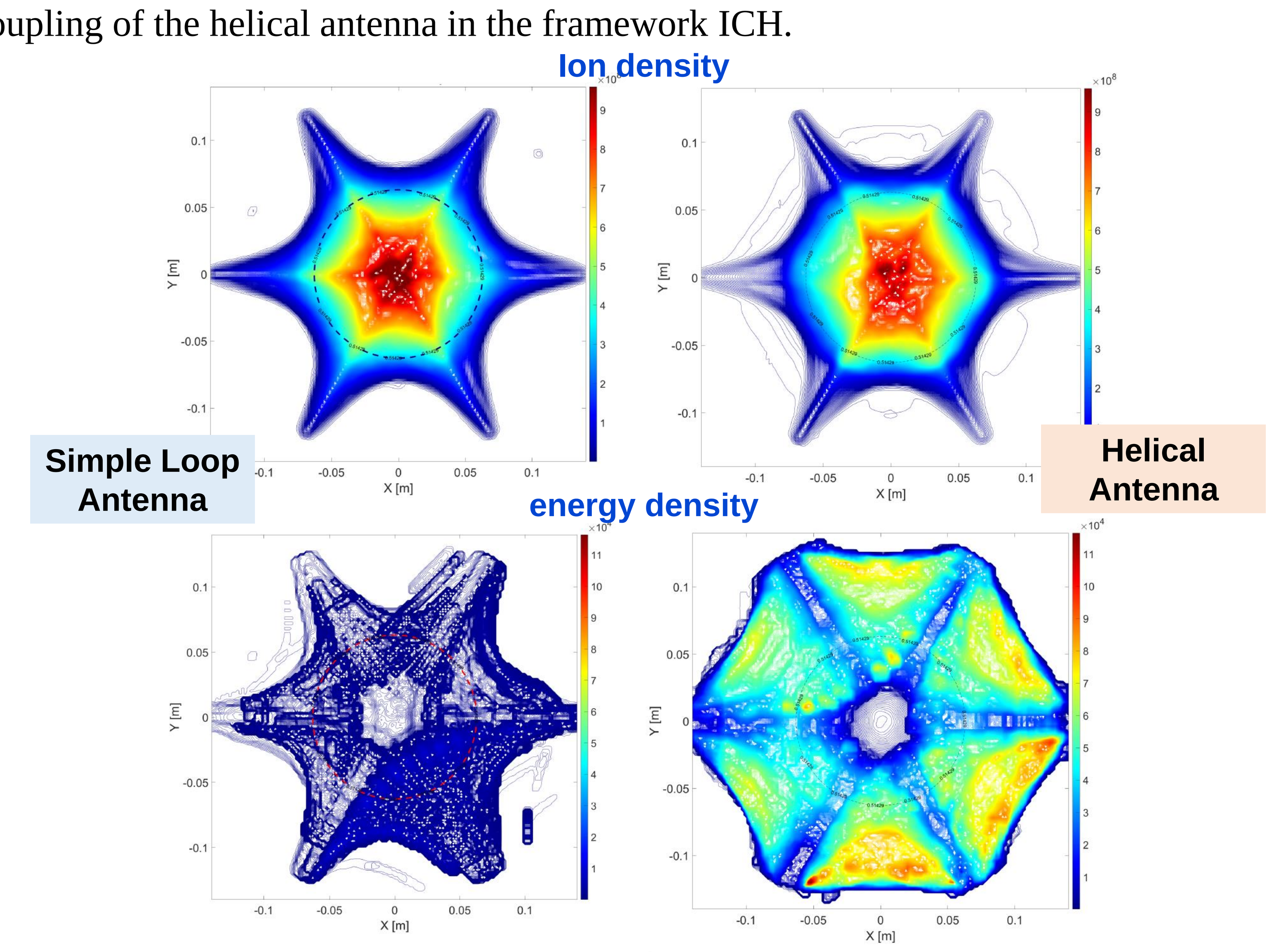




Electric field intensity, on a cylindrical plasma chamber cut, produced by a helical antenna (right side).

ICRF antenna impact on ion dynamics

- A further step forward has been done, by studying **how the propagating EM field** previously calculated **affects the ion dynamics in the plasma**.
- Two cases have been chosen as exemplary scenarios of ICRF antennas for ECRIS: the **simple-loop vs. the helical antennas**.
- The electric field 3D map obtained with the plasma-filled chamber simulations has been extracted and employed as the input of a particle mover code written in MATLAB environment.
- Despite the ion density prole inside the cavity maintains a similar structure for both the cases, the helical antenna provides a larger ion energy density than that led by the simple loop one. This could be considered as a preliminary numerical evidence for a better coupling of the helical antenna in the framework ICH.



Projection maps along the cavity z-axis of particle numerical density (top) and energy density (bottom) in [eV/ion], resulting from kinetics simulation of ions $^{16}O^{4+}$ under the presence of cavity-coupled EM field for simple loop (left) and helical (right) antennas.