Collaboration with the Doctoral School of Sapienza University of Rome - Main results and future developments

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PhD program in ENERGY and ENVIRONMENT

- **Fellowship** of the Ph.D. Program in Energy and Environment, **co-funded by ENEA and School of Aerospace Engineering** (SIA) - Doctoral School of Sapienza University of Rome;

- Research topic: "**Plasma thrusters for space transportation**" (37th cycle);

- PhD student: **Daniele Iannarelli**;

- People involved: Francesco Napoli (ENEA tutor), Simone Mannori (ENEA), Antonella De Ninno (ENEA), Prof. Antonella Ingenito (SIA);

- Research program (2022-2024):
  - Design of an electrode-free electric space propulsion (**helicon thruster**);
  - **Conceptual design of a nuclear fusion space propulsion based on PROTO-SPHERA experiment**.

A new indirect method of temperature estimation for the pinch plasma of PROTO-SPHERA

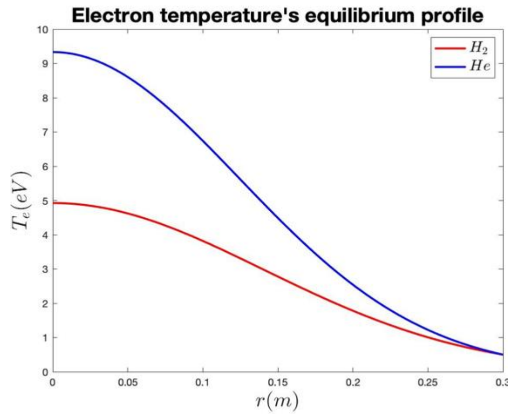
- A new method for estimating the **electron temperature** of the Proto-sphera **screw-pinch** has been developed.

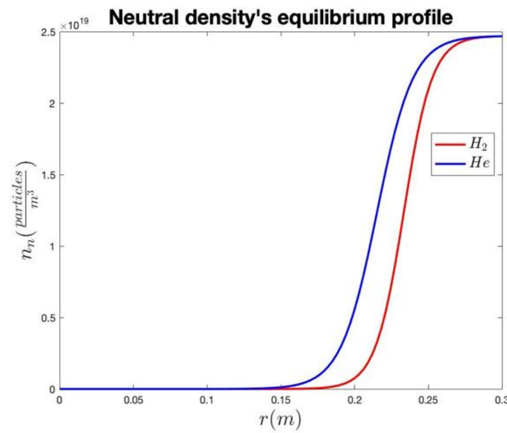
- The plasma is considered in equilibrium with its neutral phase and in constant rotation. A **MATLAB code** has been developed with the aim of estimating the MHD radial equilibrium profiles, the thermodynamic plasma state and the neutrals profile.

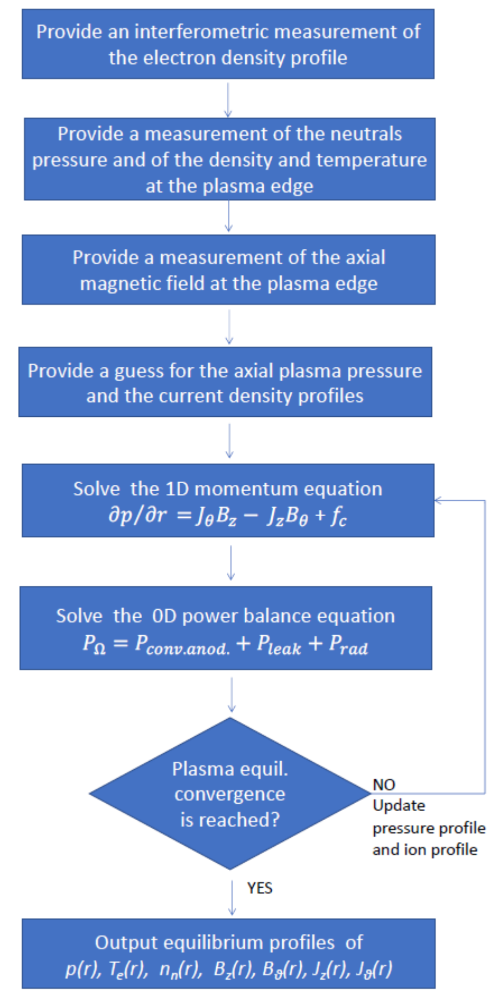
- The temperature radial profile is obtained by a self-consistent modeling of a **1D MHD equilibrium** along with a **0D power balance** of the plasma column, given measurements and estimates of the axial pinch plasma current, of the plasma rotational frequency and, at the equatorial plane, of the electron density radial profile, of the edge poloidal magnetic field, of the edge electron temperature and of the neutrals pressure in the vacuum vessel.

- The **numerical estimates of electron temperature** and **radiated power** has been compared with available experimental data showing a **good agreement**.

- Next steps:
  - use this method in the future experimental campaigns of PROTO-SPHERA;
  - extend the 1D MHD equilibrium to the pinch+torus configuration.



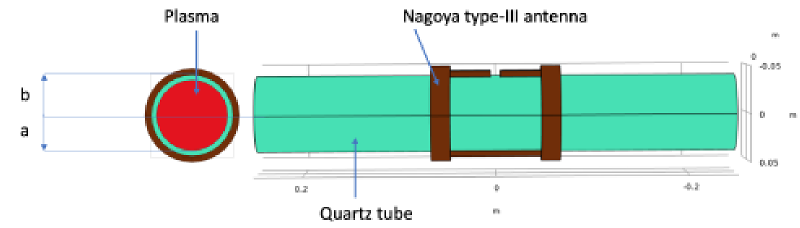


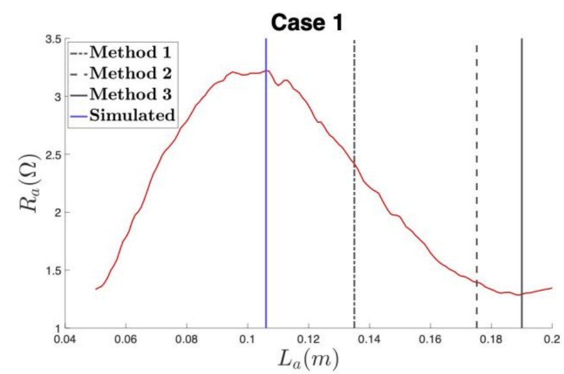


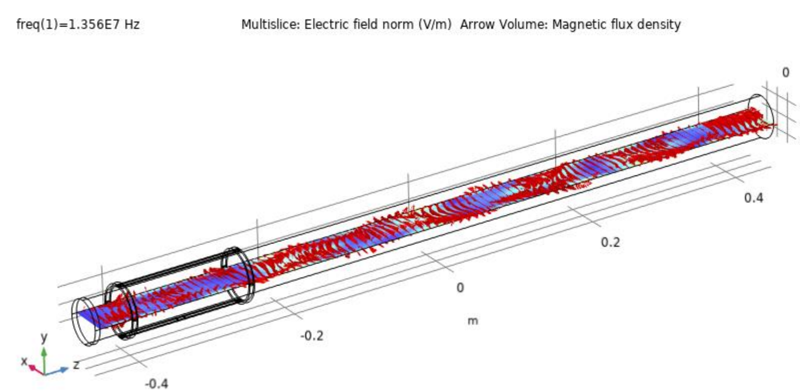
Specie	Shot	I_z (kA)	$T_{e_{num}}$ (eV)	$T_{e_{exp}}$ (eV)	$P_{rad_{num}}$ (kW)	$P_{rad_{exp}}$ (kW)
H_2	2165	10.5	3.32	N.A.	42.0	42.7
He	2180	8.5	6.21	5.5*	46.2	43.9

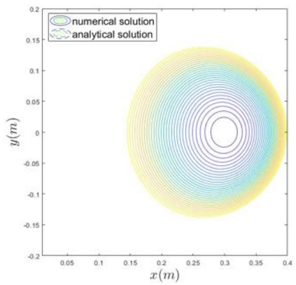
Helicon waves

- We developed **simulation tools** based on COMSOL and MATLAB.
- The interaction between the electromagnetic antenna and the plasma is modeled using a **full-wave approach** to design an antenna capable of efficiently coupling the desired RF power to the plasma within a realistic geometry.
- The plasma is treated as a homogeneous, anisotropic, **equivalent dielectric** whose permittivity is described by the Stix dielectric tensor with collisional corrections.
- We are trying to develop a **global model** of an helicon thruster, simulating the plasma both within the helicon thruster ionization chamber (full-wave 3D electromagnetic simulations) and in the magnetic nozzle (PIC code), in order to estimate the overall propulsive performance of the device.
- We focused on a structured approach to the design of the helicon antenna, specifically the **Nagoya type III antenna**, a key component of helicon thrusters.
- We developed a new rational design methodology for determining the **optimal antenna length**, which is critical for maximizing plasma generation efficiency.
- **Next steps**:
  - compute the antenna impedance matching out of COMSOL;
  - include plasma and magnetostatic field inhomogeneity in the 3D full-wave simulations;
  - include ionization and excitation of neutrals in the 3D full-wave simulations;
- **Next goal**: publish a paper on **Journal of Electric Propulsion** (within July) and a poster at **IEPC 2025** (next September).
- **Acknowledgments to F. Cichocki** for his valuable help in plume simulations computed by the thrusted PIC code PICCOLO.

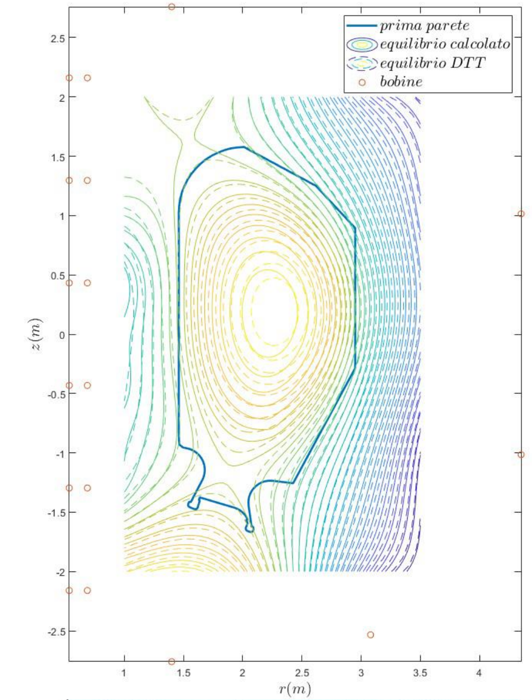








MHD Equilibrium



- A new MHD equilibrium code, called **LIBRA**, has been developed;

- The new equilibrium code solves the Grad-Shafranov differential equation by means of the **Picard method** for an axisymmetric 2D equilibrium of a nonresistive (ideal) static plasma;

- The code implements a **finite element method** (FEM) with meshes of triangular shape;

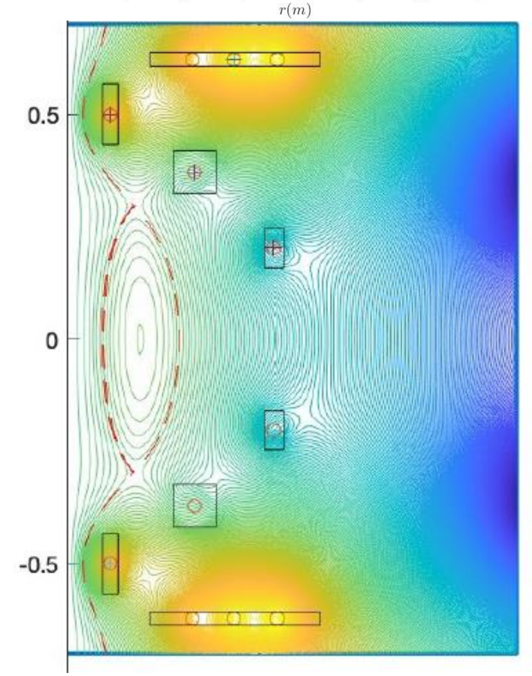
- The present implementation solves a **free boundary** formulation of the equilibrium problem;

- At the moment it is possible to compute the following equilibria:
  - Diverted/limited MHD equilibria of a tokamak plasma (e.g FTU, DTT);
  - MHD equilibria of a screw-pinch (e.g. the pinch of PROTO-SPHERA);
  - MHD equilibria of a spherical torus with a plasma centerpost (e.g. the pinch + torus of PROTO-SPHERA).

- **Next steps**:
  - add the plasma rotation;
  - add the bootstrap current;
  - add the eddy currents (metallic wall);
  - add also the electric field to design new PROTO-SPHERA experiments (interesting for the lab?).

- **Next goal**: publish this work on **Applied Physics Journal** (MDPI).

- **Acknowledgments to A. Castaldo** for his valuable help in LIBRA validation on DTT equilibrium computed by the thrusted MHD code (CREATE-NL+) developed by the CREATE consortium.



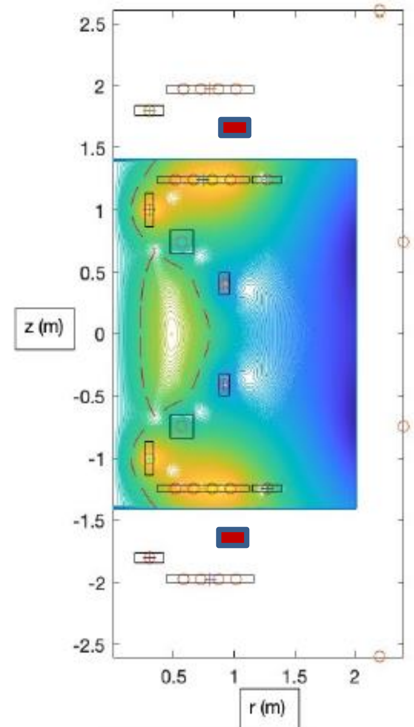
Nuclear Fusion Propulsion

- A new **conceptual design for a nuclear fusion thruster based on the PROTO-SPHERA experiment** has been developed;

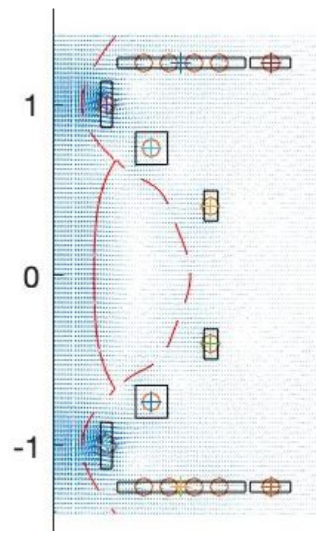
- A new code, called **NUCLEUS**, has been developed which is able to compute the machine scaling of PROTO-SPHERA to the burning plasma regime, considering stability limits and technological constraints (machine geometry with its poloidal coils, neutron wall load <= 5-10 MW/m^2, current density at electrodes <= 50-100 A/cm^2).

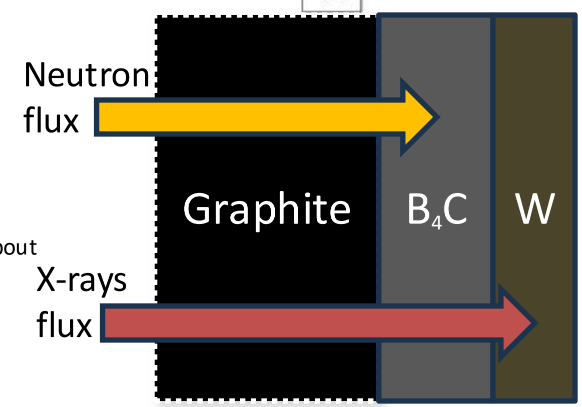
- **Nuclear fusion reactions** (DT and DH3) can take place **in the toroidal plasma region** ensuring plasma heating and on-board electric energy generation;

- A **propulsive thrust** can be achieved by the ejection of a controlled **plasma outflow from the anodic open-field-line region** (pinch). Old hypothesis based on prompt losses of charged fusion products has been discarded by means of **Monte Carlo simulations** (also here a new code has been developed).



- A **scaled solution (x7.2)** has been found (DT reactions):
  - Cylinder: height = 18 m & width = 14.4 m;
  - Pinch current = 1.555 MA;
  - Torus current = 6.901 MA;
  - Torus electron density = 1e20 m^-3;
  - Torus temperature = 31 keV;
  - Energy conf. Time = 1.8 s;
  - Nuclear fusion power = 456 MW;
  - External heating power = 5 MW;
  - Q-gain = 91.3
  - Recirculating power = 26 % (95%);
  - Propulsion system mass = 535 tons;
  - Thrust = 2016 N;
  - Specific impulse = 8110 s;





- A mission analysis has been performed for an **interplanetary travel to Mars**. It seems possible a transfer to Mars in about **three months** with a **mass ratio of 1.22.**

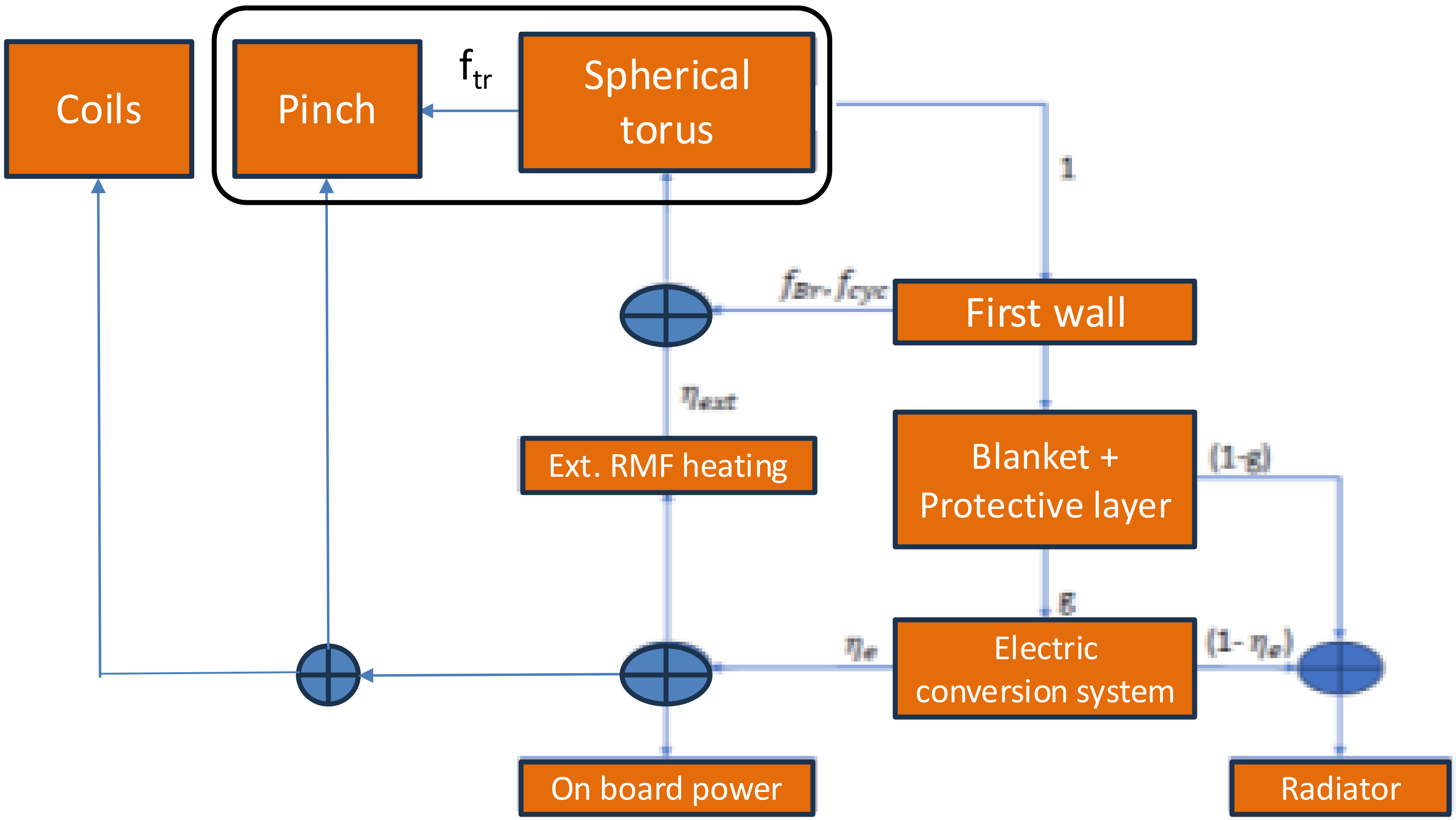
- **Next steps**:
  - compute the local MHD equilibrium in the region of the annular electrodes;
  - simulate the anodic plasma ejection with a PIC method;

- **Next goal**: poster at **IEPC 2025** (next september) and publish a new paper on **Acta Astronautica** (within 2025).

$^{10}B+n \rightarrow {}^{7}Li+\alpha+\gamma(0.48\ MeV)+2.31\ MeV\ (94\%)$

$^{10}B+n \rightarrow {}^{7}Li*+\alpha+2.79\ MeV\ (6\%)$

Nuclear Fusion Propulsion



A proposal for a new FRC experiment in C.R. FRASCATI

- We studied **the scaling of the PROTO-SPHERA experiment in the fusion regime**, considering stability limits and technological constraints.

- While the device has the great advantage of eliminating the need for a central magnet and external toroidal field coils, the current configuration has **two main limitations in the fusion regime** that yield to a low energy efficiency:
  - the relatively **low temperature** of the central plasma discharge;
  - the **high current** and **high current density** at the electrodes.

- A **new idea** came out: to study a promising compact magnetic configuration, **a field-reversed configuration (FRC)**, within the PROTO-SPHERA experiment;

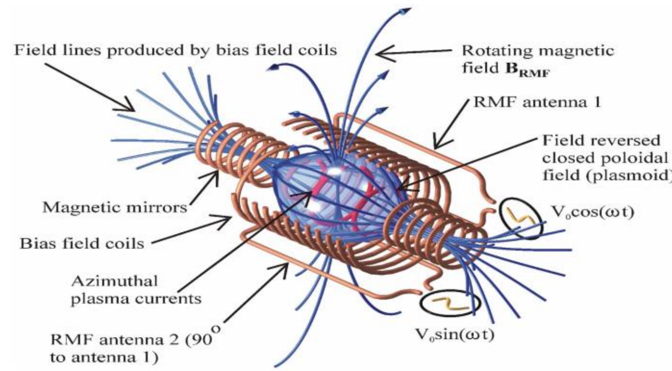
- It is possible to obtain an FRC configuration in the PROTO-SPHERA vessel by setting **proper currents in the poloidal field coils** of the machine and installing **a new toroidal current drive system based on Rotating Magnetic Fields (RMF)**.

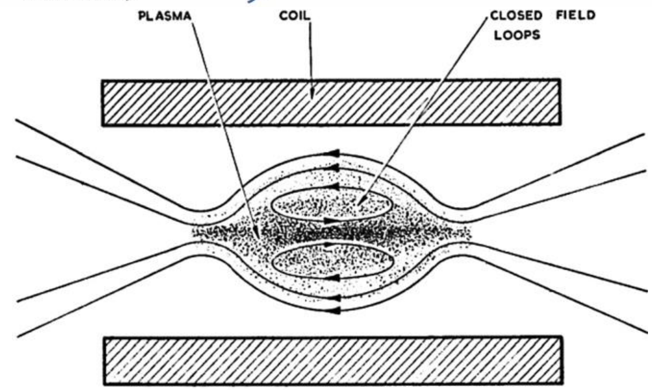
- In this newly proposed working mode of the machine, **the spherical plasma configuration of PROTO-SPHERA** should serve as the **initial plasma state** from which the FRC configuration can be generated with greater efficiency:

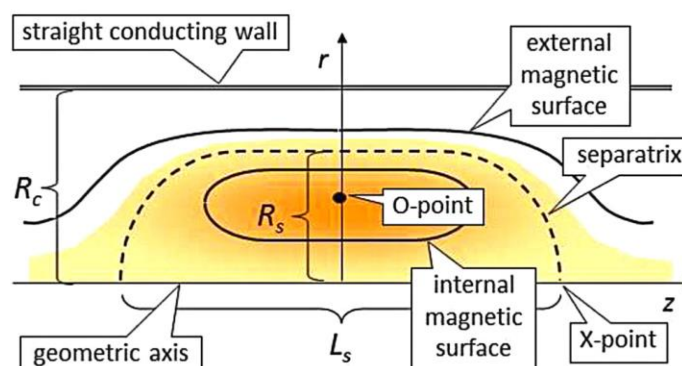
$$B_{\omega_{\mathrm{RMF}}} > \sqrt{\frac{\mu_0}{2}}\, e n_e r \sqrt{\eta_p \omega_{\mathrm{RMF}}} \propto \frac{1}{T_e^{0.75}}$$

- By adopting the FRC approach, we believe that the machine can achieve a more favourable nuclear fusion scaling with these characteristics:
  - a nuclear energy gain with a **more compact** configuration;
  - a **more efficient** energy production;
  - an **electrode-free** solution.

- This study is ongoing, and it will be presented at the 2nd European Conference on Magnetic Reconnection in Plasmas (Torino, June 17-19, 2025).







A proposal for a new FRC experiment in C.R. FRASCATI

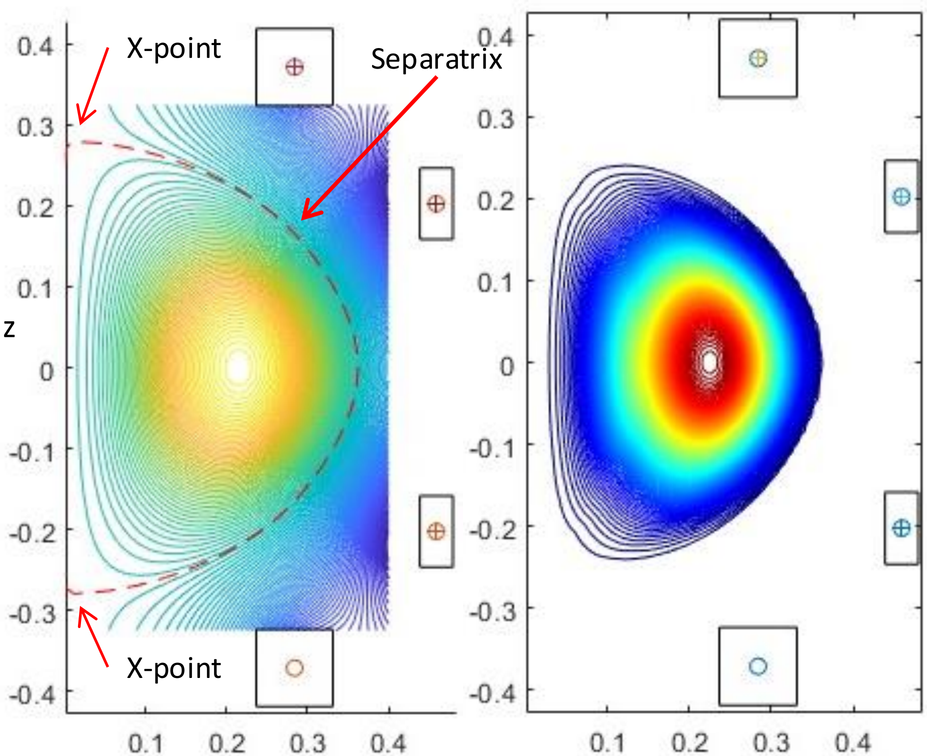
First FRC solution:

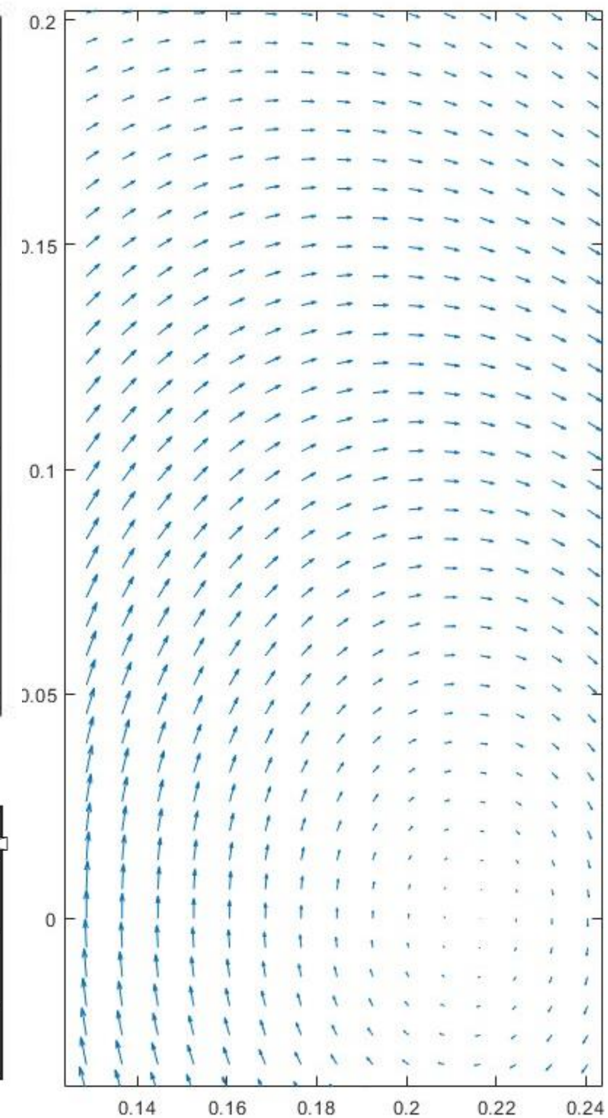
B0 = 20 mT
I_PF1 = 158 A
I_PF5 = 333 A
P_RMF = 5-10 kW
omega_RMF = 100 kHz

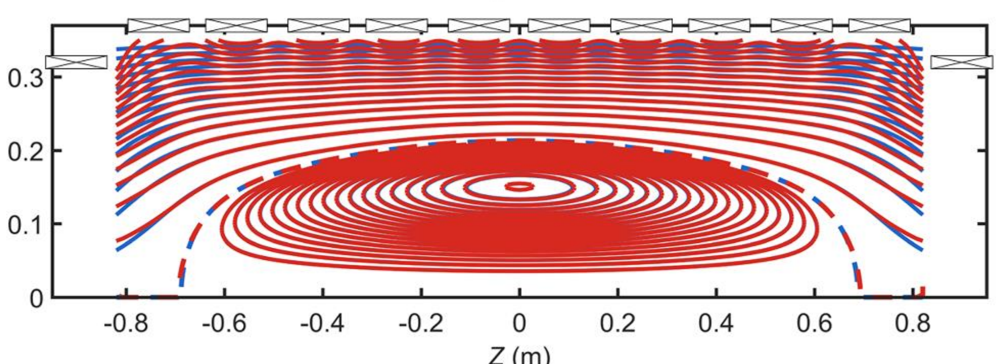
Ip = 12 kA
ne = 1.0E19 m^{-3}
Te = 125 eV
p0 = 200 Pa
Beta_p = 1

Rs = 0.36 m
Ls = 0.56 m

GAS: He







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Publications

- D. Iannarelli, F. Napoli, S. Mannori, A. De Ninno, A. Ingenito, P. Teofilatto, *Plasma thruster design through a predictive model of the Proto-sphera experiment arc state*, Symposium SYNC 2022, Sapienza University, Roma 20-23 June 2022;

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- D. Iannarelli, A. Ingenito, F. Napoli, C. Castaldo, F. Cichocki, A. De Ninno, S. Mannori, A. Cardinali, *Antenna optimization for helicon plasma thrusters*, submitted to IEPC, London 14-19 September, 2025;

- F. Napoli, F. Cichocki, A. De Ninno, S. Mannori, D. Iannarelli, A. Ingenito, *Conceptual design of a nuclear fusion thruster based on the PROTO-SPHERA experiment*, submitted to IEPC, London 14-19 September, 2025.

Thank You!