ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-THA2

NUMERICAL DESIGN OF AN INNOVATIVE SUPERCONDUCTING MAGNETIC TRAP FOR PROBING β-DECAY IN ECR PLASMAS

G. S. Mauro*, L. Celona, G. Torrisi, A. Pidatella, E. Naselli, F. Russo, B. Mishra, G. Finocchiaro, D. Santonocito, D. Mascali, INFN-LNS, Catania, Italy
A. Galatà, INFN-LNL, Legnaro, Italy

Abstract

The main aim of Plasmas for Astrophysics Nuclear Decays Observation and Radiation for Archaeometry (PANDORA) project is to build a flexible magnetic plasma trap where plasma reaches a density $n_e \sim 10^{11} - 10^{13}\,\mathrm{cm}^{-3}$, and a temperature, in units of kT, $kT_e \sim 0.1 - 30\,\mathrm{kV}$ in order to measure, for the first time, nuclear β-decay rates in stellar-like conditions. Here we present the numerical design of the PANDORA magnetic system, carried out by using the commercial simulators OPERA® and CST Studio Suite®. In particular, we discuss the design choices taken to: 1) obtain the required magnetic field levels at relevant axial and radial positions; 2) avoid the magnetic branches along the plasma chamber wall; 3) find the optimal position for the set of plasma diagnostics that will be employed. The magnetic trap has been conceived to be as large as possible, both in radial and axial directions, in order to exploit the plasma confinement mechanism on a bigger plasmoid volume. The plasma chamber will have a length of 700 mm and a diameter of 280 mm. The magnetic trap tender procedure has been completed in June 2024 and the structure realization is expected to start in late 2024.

INTRODUCTION AND MOTIVATION

In the last decades, much experimental and theoretical efforts have been dedicated to investigate various possible scenarios which can influence nuclear decays rates. It has been predicted that sizeable variations in the decay properties can be observed in highly ionized nuclides. This would have a strong impact in the stellar nucleosynthesis where a hot plasma is formed and atoms can be found in different ionization states. In particular, β decay properties of radioactive nuclei can be strongly affected by the high-temperature plasma of stellar environment. Few experimental evidences showing variations in the beta decay rates as a function of the atomic ionization state have been collected, up to now, using storage rings. However, the storage ring approach is based on the investigations of a single charge state at a time: while clearly showing the role played by the high ionization state of an atom in the β-decay process, is not able to reproduce stellar-like conditions where, due to the high temperature of the plasma, a Charge State Distribution (CSD) of the ions is established. A totally new and challenging approach, based on the study of decays rates in a plasma whose conditions can mimic the hot stellar environment, has been conceived in the PANDORA project [1]. The main idea is to build a flexible magnetic plasma trap and use it to measure, for the first time, nuclear β-decay rates in stellar-like conditions. The decay rates of the radioactive ions will be measured through the detection of the γ-rays emitted by the β-decaying daughter nuclei, as a function of the charge state distribution of the in-plasma ions by varying plasma conditions. This task will be accomplished by an array of several Hyper-Pure Germanium (HPGe) detectors placed around the trap, in specific positions where holes were made in the cryostat structure to directly look into the plasma through thin aluminium windows. This new approach is expected to have a major impact in the study of nuclear-astrophysics processes and cosmology. The magnetic field, necessary for plasma confinement, will be produced by employing a superconducting magnetic system (as typical for ECR ion sources), consisting of six hexapole coils (for radial confinement) nested inside three solenoid coils (for axial confinement), i. e. a SEXT-IN-SOL configuration. This magnetic system configuration is called *minimum-B* and allows the confinement of a plasma located around the plasma chamber axis (here z axis), providing magnetohydrodynamical (MHD) equilibrium and stability.

MAGNETIC TRAP NUMERICAL DESIGN

Some considerations can be made for the design of a magnetic system for ECRIS plasma confinement [2]. The optimum charge state is proportional to the average magnetic field as $q_{\mathrm{opt}} \propto B^{3/2}$, so it is of our interest to increase the average confining field. The highest value of the magnetic field will be in correspondence of the injection and/or extraction axial coils inner surface, so during the numerical design of the magnetic system one has to be careful at not exceeding the threshold field values relative to the magnet material. In superconducting traps, special attention must be paid to the minimum field, B_{min}, that should be tuneable within a wide range of values: it has been experimental observed that, in order to obtain the highest electron density and to reach the optimal charge state, one has to have $0.65 < B_{\mathrm{min}}/B_{\mathrm{ECR}} < 0.75$ [3–5]. If this ratio exceeds the upper value, sudden non linear effects arise, increasing the plasma x-ray emission and thus the heat load on the cryostat. The requirements and considerations previously discussed, together with the necessity to have enough space for non-invasive diagnostic tools and for the array of γ-ray detectors [6], allowed us to fix the plasma chamber dimensions (internal radius $R_{\mathrm{CH\_IN}} = 140\,\mathrm{mm}$ and axial length $L = 700\,\mathrm{mm}$) and RF pumping frequencies ($f_{\mathrm{RF1}} = 18\,\mathrm{GHz}$, $f_{\mathrm{RF2}} = 21\,\mathrm{GHz}$). Taking into account these values, the PANDORA magnetic system field specifications have been ob-

* mauro@lns.infn.it

ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-THA2

tained. The structure 3D conceptual model is shown in Fig. 1: it is composed by three axial coils and six radial coils: the field values as well as the operative ranges are reported in Table 1. The structure has been simulated with the commercial software packages OPERA® and CST Studio Suite®. The simulated coil dimensions are reported in Fig. 2 and Table 2. This model takes also into account a 25 mm thick iron yoke (ARMCO iron), distant 20 mm from the injection and extraction coils outer radius, employed to minimize the stray field that could otherwise interfere with the external detectors. The realized superconducting coils assembly will be encased inside a cryostat that will include a central warm bore for plasma chamber insertion.

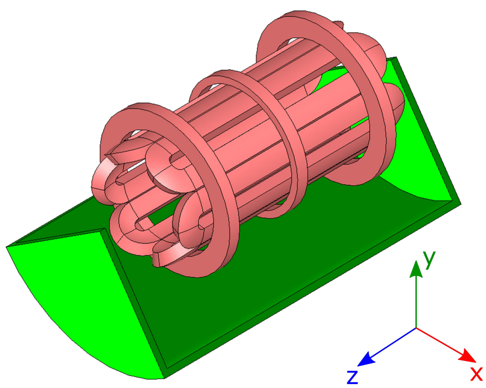

Figure 1: 3D conceptual model of the structure comprehensive of the magnetic system (pale red objects) and the iron yoke (green object, only 1/4 visible).

Table 1: PANDORA Magnetic Field Operative Ranges

Parameter	Value [T]
B_{inj} max @ $z = 350$ [mm]	3
B_{inj} operative range	1.7 - 3
B_{ext} max @ $z = -350$ [mm]	3
B_{ext} operative range	1.7 - 3
B_{min} @ $z = 0$ [mm]	0.4
B_{hex} @ $R_{\text{CH\_IN}}$	1.6

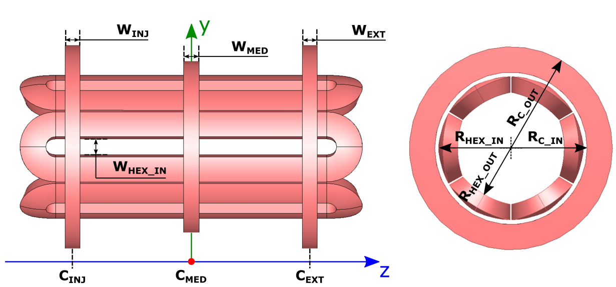

Figure 2: Side and front view of the simulated magnetic system with dimensional parameters. Note: iron yoke does not appear in the picture.

The axial and radial magnetic field profiles are reported in Fig. 3 and Fig. 4, scaled for the case $f_{\text{RF}} = 18$ GHz.

Table 2: Simulated Coil Dimensions

Axial coils	
Parameter	**Value [mm]**
$R_{\text{C\_IN}}$	225 / 225 / 225
$R_{\text{C\_OUT}}$	300 / 253 / 300
$C_{\text{INJ,MED,EXT}}$	-350 / 0 / 350
$W_{\text{INJ,MED,EXT}}$	44 / 46 / 44
Hexapole	
Parameter	**Value [mm]**
$R_{\text{HEX\_IN}}$	165
$R_{\text{HEX\_OUT}}$	212
$W_{\text{HEX\_IN}}$	78

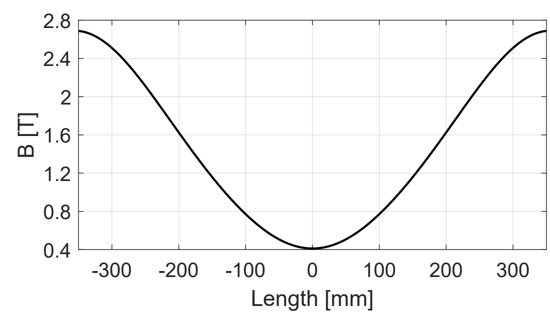

Figure 3: Magnetic field module, $|B|$, along plasma chamber z-axis for pumping frequency $f_{\text{RF}} = 18$ GHz.

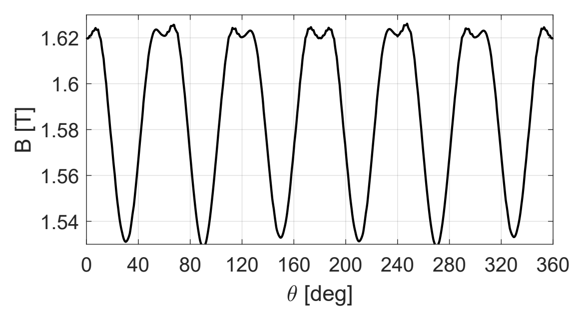

Figure 4: Magnetic field module, $|B|$, along a circumference of radius $R_{\text{CH\_IN}} = 140$ mm (plasma chamber inner radius) and axial position z = 0 mm.

Numerical simulations have also been performed to identify the positions of the magnetic branches that need to be avoided when placing the array of gamma ray detectors. In fact, in these positions a rather strong Bremsstrahlung radiation generated on the plasma chamber wall is present due to the intense flux of electrons escaping the magnetic trap, leading to a high background rate on the detectors and thus limiting their performances. The magnetic branches are clearly visible in Fig. 5, which shows the $|B|$ vector plots (normalized to the value of 2.7 T) in the xy plane at the axial positions $z = -100, 0, 100$ mm.

By employing the magnetic field profile obtained in the simulations, the distribution of lost electrons on chamber walls due to the magnetic branches has been calculated

ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-THA2

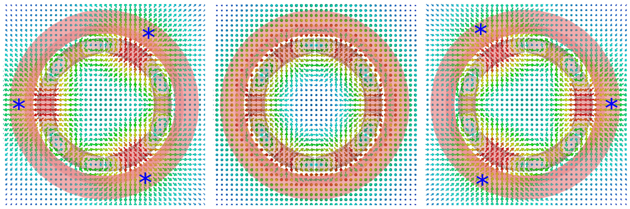

Figure 5: From left to right, $|B|$ vector plot along the xy plane at the positions $z = -100,\ 0, 100$ mm. The magnetic branches position are indicated by a blue marker.

through the use of a MATLAB particle mover code. Figure 6 shows the obtained lost electrons mask on chamber walls. The numerical study matches the expected branches position given from CST® and at the same time provides a lower boundary thickness of particle loss regions along the branches. These information are relevant for both designing the size of the bias-disk foreseen at the injection, and to find the optimal position for plasma diagnostics, microwave injection waveguides along the injection flange, as well as for the isotope injection systems (e. g., resistive oven).

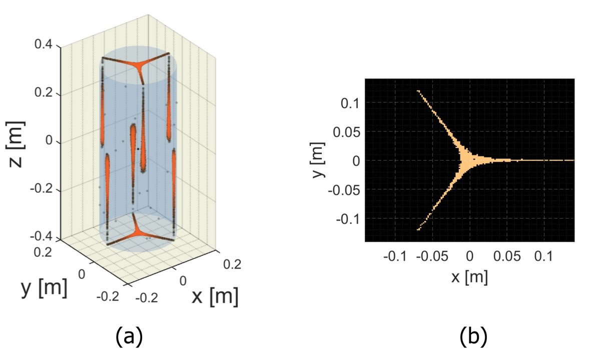

Figure 6: (a) 3D lost electron mask on chamber wall due to PANDORA magnetic branches disposition; (b) detail of lost electron mask on the injection end-plate ($z = 350$ mm, see reference system of Fig. 2).

CONCLUSION AND PERSPECTIVES

In this work the numerical design of the PANDORA magnetic system, for plasma confinement, has been presented. The design, whose scaling is based on the employment of 18 and 21 GHz pumping frequencies, has been carried out by using the commercial simulators OPERA® and CST®, whose results are in agreement between each other. By employing the obtained magnetic field profiles, the positions of the magnetic branches have been identified. These positions, along the plasma chamber side walls, are critical due to generated strong Bremsstralhung radiation and needs to be avoided when placing the gamma array detectors. Furthermore, the lost electron maps on the plasma chamber end plates have been calculated through the magnetic field profile: this information will be relevant both for the design of the bias-disk (at the injection end-plate) and for the correct placement of the plasma chamber diagnostics.

ACKNOWLEDGMENTS

The authors wish to thank INFN for the support through the project PANDORA Gr3 funded by 3rd Nat. Sci. Comm., and to thank the whole PANDORA collaboration.

REFERENCES

[1] D. Mascali *et al.*, "A novel approach to beta-decay: Pandora, a new experimental setup for future in-plasma measurements", *Universe*, vol. 8, no. 2, p. 80, 2022. doi:10.3390/universe8020080

[2] D. Leitner, "High Performance ECR Sources for Next-Generation Nuclear Science Facilities", in *Proc. 10th Int. Part. Accel. Conf. (IPAC'19)*, Melbourne, Australia, 19-24 May 2019, pp. 2224–2229. doi:10.18429/JACoW-IPAC2019-WEXPLS1

[3] J. Benitez, C. Lyneis, L. Phair, D. Todd, and D. Xie, "Dependence of the bremsstrahlung spectral temperature in minimum-B electron cyclotron resonance ion sources", *IEEE Trans. Plasma Sci.*, vol. 45, no. 7, pp. 1746–1754, 2017. doi:10.1109/TPS.2017.2706718

[4] M. Mazzaglia *et al.*, "Study of the Influence of Magnetic Field Profile on Plasma Parameters in a Simple Mirror Trap", in *Proc. ECRIS'18*, Catania, Italy, Sep. 2018, pp. 144–147. doi:10.18429/JACoW-ECRIS2018-TUP25

[5] D. Neben *et al.*, "X-ray investigation on the superconducting source for ions (SuSI)", *J. Instrum.*, vol. 14, no. 02, pp. C02008–C02008, 2019. doi:10.1088/1748-0221/14/02/c02008

[6] E. Naselli *et al.*, "Design study of a HPGe detectors array for β-decays investigation in laboratory ECR plasmas", *Front. Phys.*, vol. 10, 2022. doi:10.3389/fphy.2022.935728