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PHYSICS AND TECHNOLOGY OF COMPACT PLASMA TRAPS*

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Abstract

ECR Ion Sources are deemed to be among the most performing ion sources feeding particle accelerators, cyclotrons in particular. Improvements of their performances strictly depend on the knowledge of plasma physics in compact magnetic traps. The paper will comment on the results obtained by the INFN-LNS team and international collaborators by means of a multi-diagnostics setup able to monitor the evolution in space and time of several plasma parameters, simultaneously with beam extraction and analysis in the LEBT, in single vs. double frequency operations, including the RF power and magnetic field scalings, and exploring regimes dominated by plasma turbulence. The results are relevant for the operations of existing ion sources and for the design of new ones. Compact magnetic traps fashioned in a similar way of ECRISs can be considered as an experimental environment by itself: we are exploring this opportunity relying to the in-plasma measurements of radionuclides lifetimes (in particular, beta-decaying elements): CosmoChronometers or nuclei involved in the s-process nucleosynthesis are among the case studies, opening new perspectives in the nuclear astrophysics field.

INTRODUCTION

This paper describes the complex setup of diagnostics tools supported and developed in the frame of INFN-LNS activities on ion sources along the years. Efforts about diagnostics for ECR Ion Sources by other groups in the world are also mentioned. Plasma diagnostics have been developed in the ECRIS community for measuring plasma density and temperatures in a space and time resolved way, thus investigating the spatial structure of the plasma and its temporal behaviour, in stable and turbulent regimes. Precise measurements of parameters are crucial to correlate plasma vs. beam properties. Also in the perspective to use ECR ion traps for studying nuclear β-decays, thus correlating eventual variation of the lifetime to the plasma properties, plasma diagnostics play a fundamental role. The relevance on R&D for new diagnostics tools in ECR ion sources is witnessed by a plenty of publications [1-11].

DIAGNOSTICS TOOLBOX AT INFN-LNS

INFN has supported along the years the efforts of LNS R&D group on plasma based ion sources in the design and implementation of advanced diagnostics techniques, under the experiments HELIOS, RDH and VESPRI and, last, in the frame of PANDORA Feasibility Study. Of the list below, it is worth mentioning the A3 technique (the X-ray pin-hole camera) that has allowed to characterize the plasma morphology and to perform space resolved spectroscopy (thus evidencing the local displacement of electrons at different energies, as well as of plasma ions highlighted by fluorescence lines emission) versus the main tuning parameters such as the pumping wave frequency and the strength of the confining magnetic field. A summary of the diagnostics tools now composing the "arsenal" (described in details in [10, 11]) available or under design/installation at INFN-LNS is here presented, grouping them in four cathegories according to ther property of the plasma that we want to measure:

A. Warm & Hot electrons Temperature
  - A1 – Continuous and characteristic X radiation E<30 keV measured by SDD detectors;
  - A2 – Hard X-rays (E>50 keV, up to hundreds keV) by large volume HpGe detectors;
  - A3 –X-rays (1<E<20 keV) pin-hole camera with high energy resolution (around 150 eV) for space resolved X-ray spectroscopy;

B. Cold Electron Temp. & Density
  - B1 – Space Resolved Optical Emission Spectroscopy (space resolution less than 100 μm and spectral resolution of about 10^{-2} nm in the range 200-900 nm;)
  - B2 – Line integrated density measurement through microwave interferometry;
  - B3 – Faraday-rotation diagnostics (horn antennas coupled to Orthomode Transducer for polarimetry);

C. Ion Temperature
  - C1 – Measurement of X-ray fluorescence lines broadening through high resolution) X-ray spectroscopy, by using doubly curved crystals coupled to polycapillars;
  - C2 – Space resolved measurements are possibile with a Polycapillar+doubly-curved-crystal+CCD (X-ray sensitive) camera in a "pin-hole method" scenario;

D. On-line Charge State Distribution (CSD)
  - D1 – Space Resolved Optical Emission Spectroscopy:
  - D2 – X-ray fluorescence lines shift through high resolution); X-ray spectroscopy (curved crystals + polycapillar);
  - D3 – Space resolved measurements: Polycapillar+doubly-curved-crystal+CCD (X-ray sensitive) camera in a "pin-hole method" scenario;

A rendered view of the several diagnostics is illustrated in Fig. 1.

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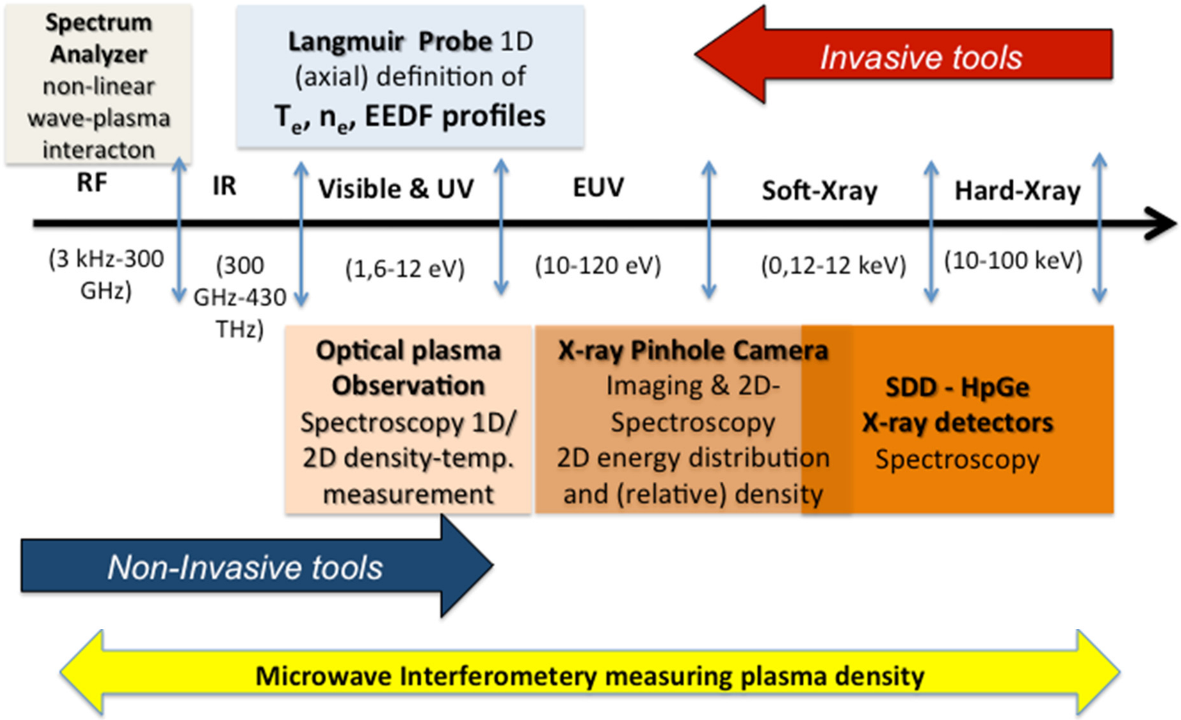

Figure 1: Render view of the several diagnostics tools needed (and already partially available at LNS) for characterizing microwave generated plasmas.

Other groups worldwide have used multi-diagnostics systems to provide a complete picture of how the plasma behaves under different sources parameters, in quiescent and/or turbulent regimes, exploring the role played by the RF field and by the magnetic confinement in simple-mirror and/or B-min configurations [1-6].

DIAGNOSTICS OUTCOMES

The outcomes of diagnostics measurements are of paramount importance in a number of applications. The operations of existing devices can be improved in a relevant way. The design of the new ones, can benefit hugely from a better understanding of ECRIS underlying physics.

The work done by Finnish and Russian groups [8, 11] about study of turbulence in ECRIS and ECRIS-based charge breeders, for instance, allows to find the so-called "stability islands". They are regions in the parameters space (operational power, magnetic field, frequency, etc.) where their combinations allow stable operations (low beam ripple, low plasma pollution by contaminants from the chamber walls, etc.) and high performances.

At INFN-LNS, the special magnetic field of the AISHa source (see Figs. 2 and 3: AISHa is an advanced ECRIS formerly designed for hadrontherapy purposes, but suitable for production of intense beams of any element) has been addressed to minimize the production of suprathermal electrons which are produced under certain profiles of the axial magnetic field [13].

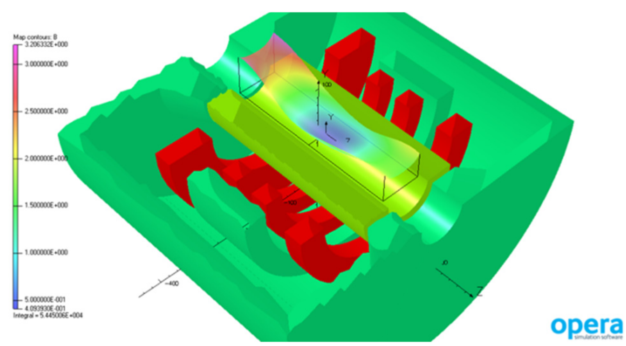

Figure 2: Magnetic system of the AISHa source with the trend of the axial field.

In particular, the field was studied to minimize the hot electron component and to optimize the ECR heating process by controlling the field gradient at injection and extraction and the resonance length. For the AISHa source it has been decided to adopt a solution employing four coils which permits to have a good control on the above cited parameters.

The microwave injection system has been designed for maximizing the beam brilliance and minimizing the beam emittance through a fine frequency tuning within the 17.3-18.4 GHz band.

Both the role of the magnetic field and frequency tuning were for a long time investigated in terms of plasma relative parameters, measured by X-ray spectroscopy especially [13-16].

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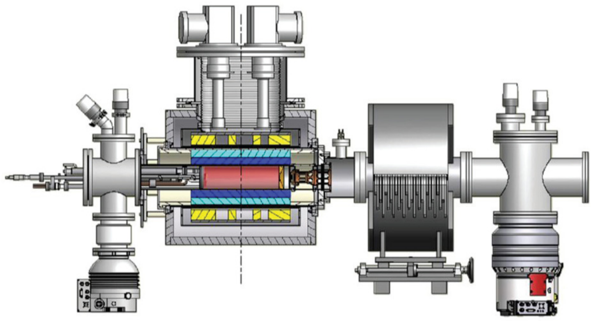

Figure 3: AISHa The layout of the source.

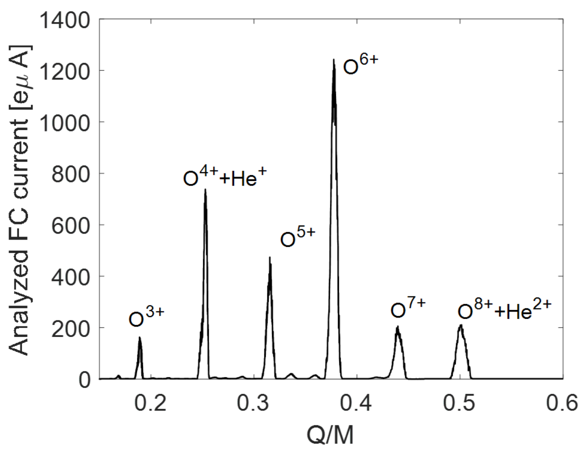

Figure 4: AISHa produced Oxygen charge state distribution for the ion source tune optimized on O6+ charge state.

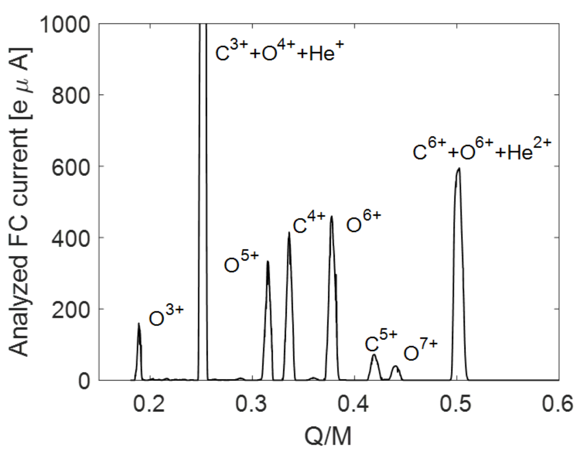

Figure 5: AISHa produced Carbon charge state distribution for the ion source tune optimized on C4+ charge state.

AISHa is now under the commissioning phase, which has been addressed especially to the production of light elements for hadron therapy and fundamental physics.

Table 1: AISHa First Performances

Charge State	Beam current [μA]	Requirement [μA]
$^{16}O^{6+}$	1200	400
$^{16}O^{7+}$	200	200
$^{12}C^{4+}$	420	400
$^{12}C^{5+}$	75	200
$^{40}Ar^{11+}$	155	//
$^{40}Ar^{12+}$	140	//

The ion beam currents produced by AISHa are reported in Figs. 4 and 5, for oxygen and carbon [17]. Table 1 summarizes beam currents for several ions, comparing them with the design requirements and goals. It is remarkable that more than 1 mA of O^{6+} has been produced. In particular, the requirements about the performances of AISHa for these beams were determined, other than from expectations of future hadrontherapy facilities, especially from the requirements of the INFN Superconducting Cyclotron upgrade project. AISHa, in fact, it is expected to become the main ion injector for the upgraded accelerator, that should be able to produce intense ion beams for fundamental research in the 2-10 kW range of output beam power [18].

From Table 1 it can be seen that most of the requirements have been already fulfilled, whilst for some others further commissioning and upgrades are needed. In particular, it is expected to achieve higher performances by an upgrade of the RF heating system through the installation of a 21+18 GHz Klystron Amplifier, in order to operate in Two Frequency Heating mode up to 21 GHz, that should be still feasible according to the maximal B-field in the trap.

BEYOND ECRIS: ECR ION TRAPS FOR NUCLEAR DECAY STUDIES

This section presents the underlying idea of the PANDORA project [19]: it is a new plasma trap designed to perform interdisciplinary research. The main goal is specially to make for the first-time nuclear β-decays measurements of astrophysical interest in magnetized plasmas as a function of ionisation state [20, 21]. The basic idea is that inside a compact plasma trap (sketched in Fig. 6, including the diagnostics surrounding the setup) the radionuclides can be trapped in a dynamical equilibrium for several hours or even days, with a locally stable density, temperature and charge state distribution (CSD). The latter can be modulated according to the RF power level sustaining the plasma, the magnetic field strength, the background pressure, etc. This will allow to characterize decay rates with respect to the CSD variation, and versus the plasma density and temperature, in a stellar-like condition at least as concerns the CSD conditions (e.g., like in the stellar cores or resembling primordial nucleosynthesis conditions).

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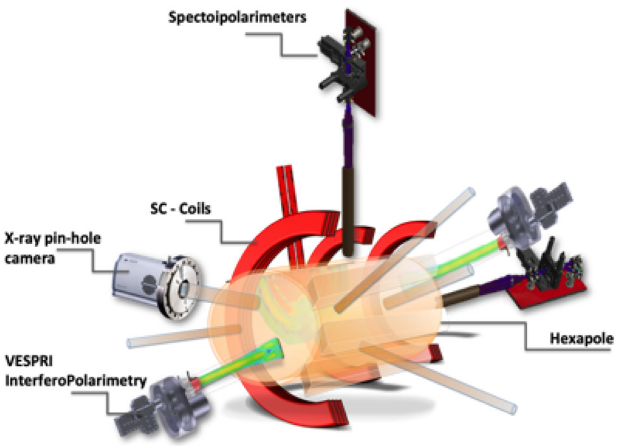

Figure 6: Sketch of the ECR ion trap surrounded by several diagnostics tools for investigating β-dacays in plasmas.

The densities of the multiply-charged ions to be confined for providing meaningful information concerning decay rates in plasmas will require a MHD - MagnetoHydroDynamically stable regime of trapping. MHD stability will be an important condition to investigate nuclear decays, since a stationary plasma state is needed in order to correlate nuclear phenomena with plasma observables, especially average charge state, temperature and density.

In summary, the experimental procedure includes:

- A "buffer plasma" is created by He, O or Ar up to densities of 10^{13} cm^{-3};
- The isotope is then directly fluxed (if gaseuous) or vaporized by appropriate ovens and then fluxed inside the chamber to be turned into plasma-state;
- Relative abundances of buffer vs. isotope densities range from 100:1 (if the isotope is in metal state) to 3:1 (in case of gaseous elements);
- The plasma is maintained in dynamical equilibrium by equalizing input fluxes of particles to losses from the magnetic confinement.

The in-plasma activity can be determined by measuring the number of decays vs. time, and this can be done by tagging them from products-emitted γ-rays, and as a function of the average ionisation state (predictions and extrapolations to astrophysical plasmas are also here included). Calculations say that under dynamical equilibrium the number of decays scales linearly with the radio-isotope activity λ.

Figure 7 illustrates a render view of the whole setup, including the magnetic trap and the array of HpGe detectors needed for tagging the decays via γ-rays detection (14 detectors are needed to achieve 1% approximately of overall efficiency).

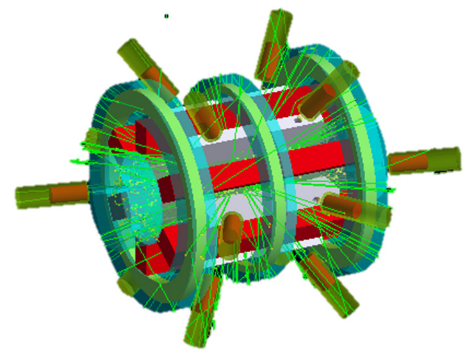

Figure 7: Geant-4 simulation of the overall PANDORA setup, including the trap and the array of 14 HpGe γ-rays detectors.

In this perspective, the simultaneous use of different diagnostics is crucial, since if and how the decay times would be affected by the plasma environment critically depend on local values of plasma density and temperature.

PANDORA has been funded as a feasibility study during 2017-2019, and for the full realization in the period 2020-2024. First results, after completing the construction of both the trap and the detector array, are expected by 2023.

CONCLUSION

The paper has reported about role played by the plasma diagnostics in research and development in ECR ion source field. Some recent results about the AISHa source, whose magnetic system as well as RF injection have been designed according to previous experiment on plasma properties measurements by X-ray diagnostics, have been reported, in view of the major upgrading of the INFN-LNS superconducting cyclotron. The efforts paid in diagnostics and design of advanced sources has produced a relevant outcome for application of ECR Ion Trap in the field of Nuclear Astrophysics. The PANDORA project has been presented, discussing about the future measurement of β-dacaying isotopes lifetimes in magnetized plasmas.

In perspective, the diagnostics could allow to tune the ECR Ion Source in a better way, also finding precursor of instabilities and/or allowing to implement new techniques for suppressing plasma turbulences, thus getting more stable and more intense beams [22, 23].

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