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Plasmas in compact traps: From ion sources to multidisciplinary research

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Summary. — In linear (minimum-B) magneto-static traps dense and hot plasmas are heated by electromagnetic radiation in the GHz domain via the Electron Cyclotron Resonance (ECR). The values of plasma density, temperature and confinement times ($n_e\tau_i > 10^{13}\,\text{cm}^{-3}$ s; $T_e > 10\,\text{keV}$) are similar to the ones of thermonuclear plasmas. The research in this field —devoted to heating and confinement optimization— has been supported by numerical modeling and advanced diagnostics, for probing the plasma especially in a non-invasive way. ECR-based systems are nowadays able to produce extremely intense (tens or hundreds of mA) beams of light ions (p, d, He), and relevant currents of heavier elements (C, O, N) up to heavy ions like Xe, Pb, U. Such beams can be extracted from the trap by a proper electrostatic system. The above-mentioned properties make these plasmas very attractive for interdisciplinary researches also, such as i) nuclear decays rates measurements in stellar-like conditions, ii) energy conversion studies, being exceptional sources of short-wavelength electromagnetic radiation (EUV, X-rays, hard X-rays and gammas, useful in material science and archaeometry), iii) environments allowing precise spectroscopical measurements as benchmarks for magnetized astrophysical plasmas. The talk will give an overview about the state-of-the-art in the field of intense ion sources, and some new perspectives for interdisciplinary research, with a special attention to the developments based at INFN-LNS.

1. – Introduction

Since the mid XX century, plasmas in laboratories have been mostly investigated in the field of high-density, high-temperature and long-living magnetoplasmas self-sustaining nuclear fusion reactions. Compact magnetic traps have also played as ion

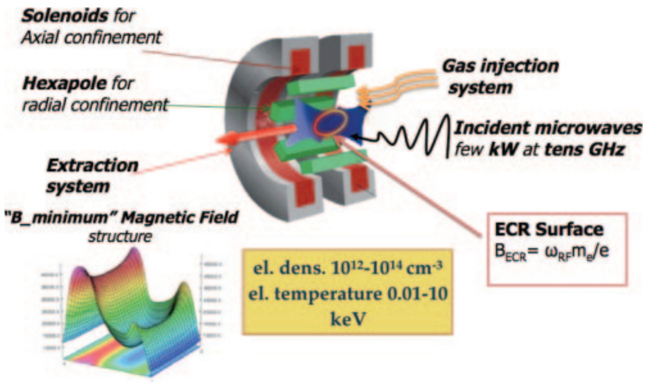

Fig. 1. – Sketch of the experimental setup of a B-minumum magnetic trap, with typical values of density and temperatures in last-generation machines.

sources since the '70 [1]. They still represent environments of relevant interest for interdisciplinary research in Astrophysics, Nuclear Astrophysics, and other disciplines. B-minimum machines, so-called from the peculiar shape of the magnetic field, have allowed multicharged ions production supporting both fundamental science (nuclear and particle Physics especially) and applied research (neutrons spallation sources, subcritical nuclear reactors, hadrotherapy facilities, material treatments, ion implantation). The request of high charge state - high current beams is still constantly growing: *e.g.* FAIR (GSI - Germany) needs 1 emA of U^{28+} ions, LHC the same current of Pb^{27+}.

A compact magnetic trap for plasma production via ECR - Electron Cyclotron Resonance is shown in fig. 1. Gases or vapours are turned in plasma state by microwaves in the range 2.45–28 GHz, in the presence of a few T magnetostatic field allowing the ECR to occur and also confining the plasma in a MHD-stable configuration. Stepwise ionization proceeds for hundreds of milliseconds. The challenge is maximizing the average charge state $\langle q \rangle \propto n_e \tau_i$ as well as the output current $i \propto n_e/\tau_i$, being n_e the electron density and τ_i the ion lifetime in the plasma. For the sake of example, fully stripped uranium would require $n_e \tau_i \simeq 10^{14}\,\text{cm}^{-3}\text{s}$ and electron temperature $T_e \simeq 10^5\,\text{eV}$. This "triple product" ($density \times time \times temperature$) is surprisingly similar to the one occurring in the thermonuclear fusion field, which should allow the so-called "ignition" of the plasma.

2. – Compact traps development and diagnostics

Despite in the early decades the ECRIS development was based on general scaling laws [1-4], now it is well known that the beam properties (including emittance and brightness) depend on specific features of the plasma, like the local energy content [5], its spatial structure [6, 7], eventual instabilities onset [8], etc. Advanced diagnostics methods are therefore required. Figure 2 illustrates in a pictorial way the different techniques that can be adopted at different energy domains, taking advantage of the electromagnetic radiation emitted by the plasma over all the spectrum, from RF to γ-rays. At INFN-LNS, since 2007–2008, a wide set of diagnostics tools has been developed. The temperature of the so-called warm electrons, at $E < 30\,\text{keV}$, was measured by SDD detectors and a direct correlation to the output currents [5, 7] was found, while for $E > 30\,\text{keV}$ (hot electrons) large volume scintillators or HpGe detectors have been applied [9, 10], discovering their counter-correlation with the production of highly-charged ions. In the recent past, X-rays

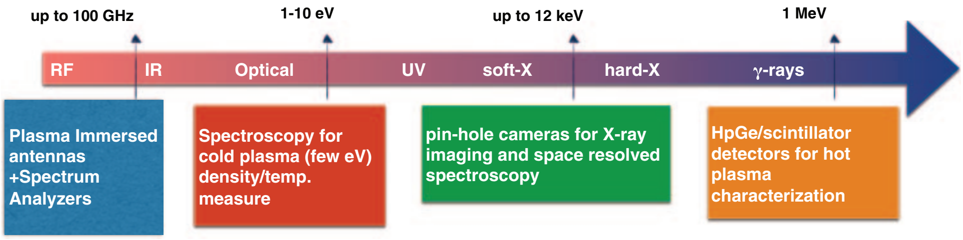

Fig. 2. – Energy domains of the radiation emitted from microwave-generated plasmas and diagnostics tools developed at INFN-LNS.

($1 < E < 20\,\text{keV}$) pin-hole cameras with high energy resolution (around $150\,\text{eV}$) have been used for for space resolved X-ray spectroscopy [7], pointing out a clear effect of the pumping wave frequency on the structural features of the plasma. Some authors [11, 12] have used Optical Emission Spectroscopy for probing the cold plasma (few eV electrons), whose role is relevant in plasma stability or — like in case of ion sources for high intensity proton beams — for establishing the relative abundances of H^+/H^{2+} species. The use of advanced OES is also particularly useful for the on-line characterization of the Charge State Distribution, as will be underlined in the following. A way for investigating the line integrated density over the whole energy domains is through microwave interferometry and polarimetry. LNS team has recently developed the VESPRI interferometer [13, 14] that is now collecting data also as a polarimeter, exploiting magnetoplasma-induced Faraday rotation effect. An attractive experiment (never attempted in the past in the ECRIS field) is to measure ion temperature (critically impacting the beam emittance) by means of X-ray fluorescence lines broadening: high resolution ($\Delta\lambda/\lambda = 10^{-3}$) X-ray spectroscopy is needed, by using doubly curved crystals coupled to polycapillars. Space resolved measurements are possibile by a system made of a poly-capillar coupled to a doubly-curved crystal and to a CCD (X-ray sensitive) camera in a pin-hole method scenario. Such activities, started in the framework of the VESPRI grant, is now continuing in the framework of the PANDORA experiment (see below for more details), supported by INFN National Committees.

3. – Ion sources and plasma traps at INFN-LNS

A list of the plasma-based traps installed at Laboratori Nazionali del Sud is given in table I (see also, in fig. 3, the layouts of the PS-ESS and AISHa sources). The list also includes typical elements that can be turned into plasma state, beams that can be eventually extracted from the plasma (in case the trap is used as ion source) and characteristics densities and temperatures of warm and hot electrons inside the plasma. The machines installed include a variety of magnetic configurations: a) the above mentioned B-minimum; b) the so-called “Magnetic Bottle”, made by three coaxial coils; c) flat-B field, very useful for the MDIS - Microwave Discharge Ion Sources, which are suitable for the production of intense currents of light elements, especially protons; d) “magnetic-beach” profile, to be still deeper investigated for the achievement of extremely energetic plasma states. Such a variety of devices, and the before-mentioned diagnostics tools, make LNS an infrastructure suitable for extending studies of plasmas in compact traps well-beyond the well-established ion sources physics and technology. An example of multidisciplinary applications of such devices is given in the next section.

TABLE I. – *List of plasma-based ion sources/magnetic traps operating at INFN-LNS, including the main beam produced and the plasma properties in terms of electron density n_e and electron temperature T_e.*

Name	Type	Trap	Species	I	n_e - T_e
SERSE	ECR	B-min S.C.	from H to Pb	$\mathrm{O}^{6+} \sim 500\,\mu\mathrm{A}$ $\mathrm{Ar}^{16+} \sim 20\,\mu\mathrm{A}$	$n_e \sim 10^{13}\,\mathrm{cm}^{-3}$ $T_e^{warm} \sim 1 \div 10\,\mathrm{keV}$ $T_e^{hot} \sim 100\,\mathrm{keV}$
CAESAR	ECR	B-min N.C.	Ne, Ar	H, O, N, $\mathrm{O}^{6+} \sim 80\,\mu\mathrm{A}$ $\mathrm{Ar}^{14+} \sim 20\,\mu\mathrm{A}$	$n_e \sim 10^{12}\,\mathrm{cm}^{-3}$ $T_e^{warm} \sim 0.5 \div 5\,\mathrm{keV}$ $T_e^{hot} \sim 50\,\mathrm{keV}$
PS-ESS	MDIS	B-flat N.C.	Protons, also H^{2+}, D	$\sim 100\,\mathrm{mA}$	$n_e \sim 10^{12}\,\mathrm{cm}^{-3}$ $T_e \sim 15 \div 25\,\mathrm{eV}$
FPT	Trap	Bottle B-flat Beach	gaseous elements		$n_e \sim 10^{12} \div 10^{13}\,\mathrm{cm}^{-3}$ $T_e \sim 15 \div 25\,\mathrm{eV}$
AISHa	ECR	B-min S.C.	C, Li, O, Ar	$\mathrm{C}^{4+} \sim 800\,\mu\mathrm{A}$ $\mathrm{O}^{6+} \sim 800\,\mu\mathrm{A}$	$n_e \sim 10^{12} \div 10^{13}\,\mathrm{cm}^{-3}$ $T_e \sim 15 \div 25\,\mathrm{eV}$
VIS	MDIS	B-flat S.C.	H, H^{2+}, D, He	$\mathrm{H}^{+} \sim 60\,\mathrm{mA}$ $\mathrm{He}^{+} \sim 40\,\mathrm{mA}$	$n_e \sim 10^{12} \div 10^{13}\,\mathrm{cm}^{-3}$ $T_e \sim 15 \div 25\,\mathrm{eV}$

4. – Multidisciplinary research in compact plasma traps

The experience gained along the years about the production, stabilization and diagnostics of magnetoplasmas confined inside B-minimum traps has opened wide a new opportunity of fundamental physics exploration. Synergies among INFN, Catania University, Italian National Institute for Astrophysics (INAF) and CNR has permitted to

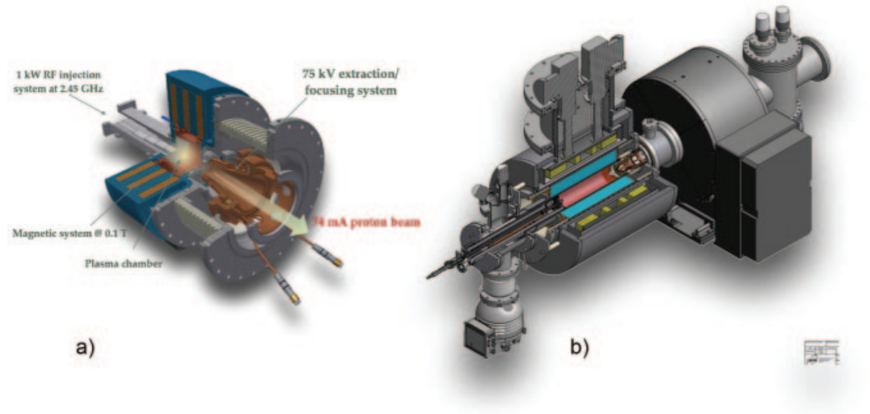

Fig. 3. – a) Layout of the ion intensity Proton Source for the European Spallation Source (PS-ESS); b) layout of the Advanced Ion Source for Hadrontherapy (AISHa).

promote the project named PANDORA - Plasmas for Astrophysics, Nuclear Decay Observation and Radiation For Archaeometry. The goal of the project is to explore phenomena of interest in Nuclear Physics, Astrophysics and Material Analysis in a new environment, based on an extremely energetic, dense/overdense plasma. In particular, the fields of interest are listed below:

- **Nuclear astrophysics**: the plasmas becomes the environment for measuring for the first time nuclear decays rates in stellar-like conditions (such as ^{7}Be electron capture decay and other β-decays), especially as a function of the ionisation state of the plasma ions. These studies are of paramount importance for addressing several astrophysical issues in both stellar and primordial nucleosynthesis environment (*e.g.* determination of solar neutrino flux and the Cosmological Lithium Problem-CLiP [15,16]);

- **Astrophysics**: laboratory magnetoplasmas represent an unique, tunable light source complementing stellar spectroscopy measurements. Measurements in laboratory would allow for a better understanding of spectropolarimetric observations [17] in the visible, UV and X-ray domains, offering breaking-through advancements in observational astronomy. As to magnetic fields, the experimental validation of theoretical first and second order Landé factors will certainly drive the layout of polarimetric units for the high resolution spectrograph of the 39 m European-Extremely Large Telescope of the European Southern Observatory. Even more pioneering will be the study of that polarised X-ray emission theoretically expected from compact and strongly magnetised stars;

- **Material analysis**: according to the new plasma heating schemes now under investigation [18] the plasma is made prone to efficient energy conversion: the pumping microwave power is in fact partially converted into visible, UV, X-rays, thus making the plasma as an exceptional source of electromagnetic radiation. Applications of such intense radiation in material science and Archaeometry is currently under investigation.

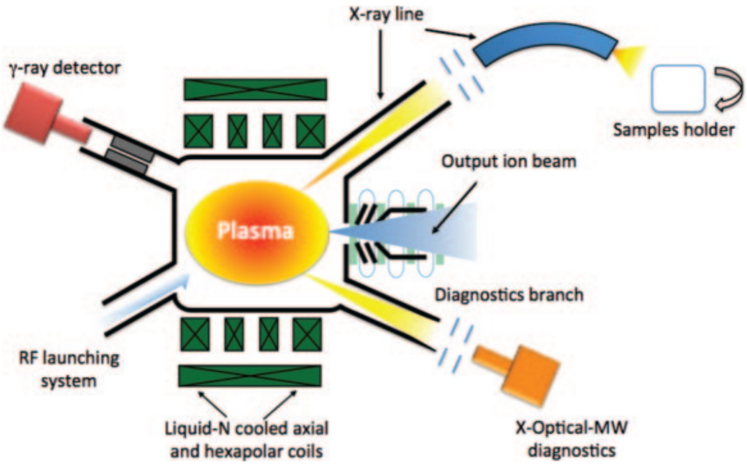

Fig. 4. – Conceptual layout of the PANDORA experiment.

The basic idea of the project is schematically summarized in the sketch of fig. 4. A compact plasma trap —made of a multiplicity of coils for the axial confinement, plus an hexapole for MHD stability— is used for trapping radionuclides via Charge-Breeding technique [19], 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. Especially as concerns the CSD, the experiment aims at reproducing stellar and primordial nucleosynthesis conditions, thus making PANDORA an experiment for probing, among the other issues, the already mentioned CLiP. Our approach, particularly suitable for long-living radionuclides is complementary to other methodologies, like storage-ring measurements, where beams of given charge-state ions are injected for in-flight half-life measurements.

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