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Plasma diagnostics update and consequences on the upgrade of existing sources

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Abstract. The development and upgrade of ion sources for accelerators depends more and more on the optimization of the microwave-to-plasma coupling. Proton sources require to optimize the Electron Energy Distribution Function (EEDF) in the range of a few tens of eV. Multicharged ions sources require the optimization of EEDF in the keV scale depending on the needed charge state. The energy tail of EEDF must be damped since hot electrons are detrimental for the source performances. Last but not the least, also the spatial distribution of the EEDF within the plasma chamber should be known since RF power have to be deposited mainly in the regions of the plasma core near to the extraction hole and around the axis. In a few words, plasma parameters diagnostics will play a fundamental role for next developments and upgrade of existing sources, as well as for the design of new ones. This work presents the set of plasma diagnostics (including interferometer, polarimeter, optical emission spectroscopy, Langmuir probe, pin-hole camera and X rays detectors) already installed at the INFN-LNS testbenchs, the characterization of the EEDF as a function on the source parameters (magnetic field profile, microwave power and frequency and neutral pressure) and the expected consequences on the future design of ion sources.

INTRODUCTION

Plasma diagnostics is going to play a increasingly role in the development of high-performance ion sources for accelerators. Currents and charge states of the extracted beams of Electron Cyclotron Resonance Ion Sources (ECRIS) depend on the Electron Energy Distribution Function (EEDF) and on the confinement time [1]. Temperatures in the keV range and ion lifetimes of ms are suitable for the production of multiply-charge ions. Optimization of electron temperature in the range of 5-20 eV with few hundreds of μs confinement time is fundamental for the optimization of the proton current generated by Microwave Discharge Ion Sources (MDIS) [2, 3]. The determination of an EEDF ranging from a few eV to hundreds of keV requires the use of a multi-diagnostics approach [4]. Furthermore, several phenomena occurring in plasmas, as plasma instabilities, non uniform distribution of the plasma density, non-linear response of the electron heating to the pumping wave frequency affects the intensity and emittance of the plasma-generated beams and require an adequate diagnostics to be better understood [5].
Since many years, the R&D INFN Laboratori Nazionali del Sud (LNS) group is working to develop an appropriate set of tools for MDIS and ECRIS with the aim to properly investigate the phenomena above mentioned and create a more detailed model for the wave-to-plasma interaction processes [6].

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Hereinafter, the set of plasma diagnostics already installed at the INFN-LNS testbenchs will be detailed and preliminary results from a multidiagnostics approach applied at LNS will be also shown.

TABLE 1. List of diagnostics tools already developed- or in the developing phase- at INFN-LNS.

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 temperature & 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 measurements through microwave interferometry; • **B3.** Faraday-rotation diagnostics; • **B4.** Langmuir-probe diagnostics;
C. Ion temperature	• **C1.** Measurements of X-ray fluorescence lines broadening through high resolution ($\Delta\lambda/\lambda = 10^{-3}$ X ray spectroscopy, by using doubly curved crystals coupled to polycapillars; • **C2.** Space resolved measurements are possible with a Polycapillar + doubly-curved crystals + CCD (X-ray sensitive) camera in a ”pin-hole method” scenario;
D. On-line Charge State distribution (CSD)	• **D1.** 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); • **D2.** Space resolved measurements: Polycapillar + doubly-curved crystals + CCD (X-ray sensitive) camera in a ”pin-hole method” scenario; • **D3.** X-ray fluorescence lines shift through high resolution ($\Delta\lambda/\lambda = 10^{-3}$) X-ray spectroscopy (curved crystals+polycapillar);
E. Linear & non linear wave-to-plasma coupling	• **E1.** Detection of RF signal from ~ 100 HZ to hundreds GHz by means of RF probe and Spectrum analyser;

PLASMA DIAGNOSTICS AT LNS

Table 1 lists the different diagnostics techniques that we aim to use for the plasma EEDF investigation. Some of them are already available at LNS and work routinely for plasma characterization, namely the ones labelled as A1A3, B1-B4, D1 and E1. C1 and C2 are in developing phase at LNS. D2 and D3 are planned to be commissioned and installed during next year. Since B4 and E1 are invasive methods (the probes perturb the plasma and could get damaged during measurements), many efforts are being spent to improve more and more the reliability of non-invasive diagnostics based on an optically and spatially resolved X-ray imaging and spectroscopy, as well as the intefero-polarimetry setups.

OES diagnostics

Optical Emission Spectroscopy technique enables a direct in plasma diagnostics measuring not only the electron density and temperature, but also the relative abundances of different neutral species, vibrational temperature of the molecules, and concentration of the different charges states in case of plasmas of multicharged ions. At the INFN-LNS, OES is being developed to determine, in a non-invasive way, the density and temperature of the colder electron plasma population. When applied to hydrogen plasmas, it also allows to know the relative abundances of H atoms versus H_2. The analysis method is based on the line-ratio method, well-described in references [7, 8]. After preliminary tests on the FPT ([9]), OES spectroscopy has been applied to relate the characteristics of the beam extracted from the Proton Source of the ESS project named PSESS [10] to the optical spectrum. Figure 1 on the left shows the comparison between the plasma electron density calculated by line-ratio method (we used the H_β/H_γ ratio) and the extracted current from the PSESS (on the right). Electron density follows the same trend of extracted current does, showing that we are already able to foresee the general behaviour of a proton source, though not yet exactly determined. Our goal is to acquire soon the ability to determine proton fraction and extracted density from the on-line OES monitoring of plasma without any beam extraction. Moreover, this ability will enable to optimize the source parameters for optimization of H_2^+ beams instead of protons, as several projects have already required [11].

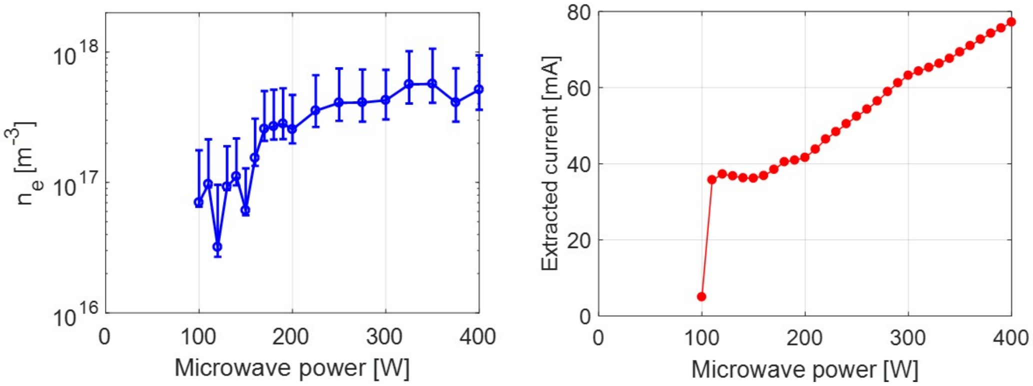

FIGURE 1. On the left, electron density estimated by OES using the line-ratio method, on the right the extracted current from PS-ESS.

X-ray based systems

X-ray volumetric measurements can be a powerful method for measuring the plasma density at medium-high energy ranges. If the plasma emission is properly collimated, the determination of the plasma density is possible via the use of adequate emissivity models [12].

A step forward for understanding the heating and confinement mechanisms of microwave generated plasmas is given by space-resolved X-ray imaging and spectroscopy. This technique allows to investigate the dimensions and geometry of the plasma source in the high energy domain, as well as the spatial distribution of X-ray energies in the plasma, allowing to distinguish the region where heat is deposited. Typically a Si-Pin and a HpGe X ray detector are used. The first one allows to investigate density and temperature of electron in the range 2-30 keV, nominally the warm electron population. The second one allows the investigation of the hot electron population, emitting X-radiation with energies up to hundreds of keV. Several experiments on ECRIS sources [13, 14] have shown that hot electrons are detrimental for ECRIS performances, while warm electrons help to improve the mean charge state distribution of plasma. Therefore, the monitoring of the X-ray temperature represents an important tool for improve the ECRIS performances. Also on MDIS, the monitoring of X-ray emission represents an important check of the source performances. High intensity proton currents require the generation of a cold electron plasma (few tens of eV) since cross sections for H_2 ionization are maximized at very low energy between 20 and 40 eV [15]. Any generation of X-rays in MDIS means that some energy is get lost for the generation of high temperature electrons, totally useless to the ionization process.

X-rays based systems allow also to determine the 2D distribution of warm electrons. At INFN-LNS, an X-ray sensitive silicon back illuminated device (IKON-M DO934 BR-DD by ANDOR) allows the direct detection of X photons in the range 0.3 - 30 keV. The device can work in two different counting mode, each one able to give different information about the plasma [16]. In Full-Count mode, the exposure time is long with respect to the X-ray emission rate (counts/s), i.e. there is large probability that more than one photon strikes the same pixel during single acquisition. This configuration provides valuable information on the overall structure of the plasma. More information can be collected when operating in Photon Counting (PC) mode. In this case, any single pixel is stricken at most one time by X-ray photons. PC-mode operations are set by tuning appropriate exposure times of the CCD camera.

This technique has been already applied either to ECRIS and plasma reactor with valuable results [12, 17]. In ECRIS it has been possible to determine the regions where warm and colder are placed (within the energy domain of the CCD) as a function of the pumping frequency, showing how frequency tuning can affect the source performances. In plasma reactor the PC technique allowed to discriminate the displacement of the different ions inside the magnetic trap, due to the ion motion within the plasma.

Interfero-polarimetry

Microwave interferometry and polarimetry have been developed for estimate the electron density of the whole plasma population along a line of sight. They are both non-invasive methods and can be considered as the more reliable techniques for the whole plasma density measurement, conversely from OES and X-ray-based diagnostics, focused to cold and hot electron population respectively. Microwave interferometer determines the line averaged electron density, along a line of sight, by means of the swept-frequency method. A beating signal is obtained by the superposition of the plasma leg signal with a reference one, while both the signals sweep in time in a given frequency range (from 22.5 to 26.5 GHz). By performing a fast Fourier transform analysis of the obtained beating pattern, it is possible to filter out the dominant component from the multipath contributions; hence, the beating frequency is correlated to the plasma density. Figure 2 A shows the swept-frequency microwave interferometer block scheme according to the Mach-Zehnder scheme. More details can be found in references [18].

The polarimetric method is based on the measurements of the so-called Faraday angle θ_F as a function of the probing wavelength λ_p. θ_F is proportional to the line integrated density n_e and to λ_p^2. The measurement of the magnetoplasma induced rotation of the polarization plane has been based on broadband waveguide OrthoModeTransducers (OMTs) system. OMTs were inserted along the plasma leg, upstream and downstream to the emitting/receiving antennas. Figure 2B shows the set up for polarimetry. The measurement strategy consists of transmitting the probing microwave signal from the OMT (A) inside the plasma chamber and received by the other OMT (B); the position of the OMT (B) is rotated (via in-vacuum rotatable joint connection in circular waveguide standard) in order to minimize the received power on the Cross-polar port of the OMT (B) itself [19]. The two diagnostics techniques have been tested and commissioned by using the same experimental set-up already described in references [18, 20] at $1.5 \cdot 10^{-4}$ mbar neutral pressure and 100 W Microwave power. The interferometric technique estimated a density equals to: $n_e = (2.1 \pm 0.4) \cdot 10^{12}\ cm^{-3}$ [21], while the polarimetric technique estimated $n_e = (2.8 \pm 0.6) \cdot 10^{12}\ cm^{-3}$. The two values are mutually agreed and are around a factor four larger than the electron density evaluated by means of Langmuir probe diagnostics ($\sim 0.7 \cdot 10^{12}\ cm^{-3}$)[20]. The disagreement between invasive LP diagnostics and non-invasive interfero-polarimetry puts in evidence how much invasive diagnostics can distort the plasma parameters evaluation.

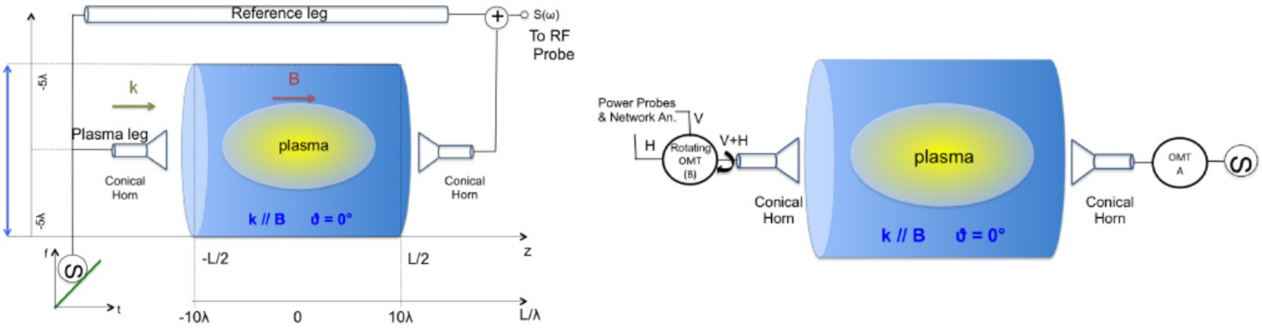

FIGURE 2. On the left, the set-up for interferometry . On the right, the set-up for polarimetry.

CONCLUSIONS AND PERSPECTIVES

The set of diagnostics developed in the last years at INFN-LNS is now suitable for multi-component analysis of a magnetoplasma of an ECRIS-type plasma trap. At the present time, the first measurements of line-integrated plasma densities have been carried out via the interferometric and polarimetric methods, providing mutually agreed value of plasma density. In next months, the technique will applied to the FPT testbench [9] and to the ECR ions source named AISHa (Advanced Ion Source for Hadrontherapy) [22], currently under commissioning at LNS. Preliminary results from OES, carried out with low resolution instruments (2 *nm*), have shown the technique is able the determine electron density and temperature along a line of sight. Moreover, also the relative abundances of neutrals have been determined by the spectra analysis. This information has allowed the on-line monitoring of the PS-ESS source and a first correlation of extracted current with optical spectra. In order to determine the charge state distribution of lighter elements, such as Beryllium, or molecular rovibrational modes of H_2, high-resolution OES is needed. In the frame of PANDORA (Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry) project [23], the powerful spectropolarimeter named SARG formerly installed at the Telescopio Nazionale Galileo, Canary Islands is now going to be transferred to INFN-LNS for performing advanced spectropolarimetry of magnetoplasmas inside the FPT. SARG allows to reach very high resolution: R=160.000 in the range: 370-900 nm, i.e. fractions of Angstroms, which are suitable to discriminate plasma-emitted spectra coming from different CSD. A high resolution X-ray spectrometer having $\Delta\lambda/\lambda = 10^{-3}$, suitable for ion temperature measurements and/or on-line discrimination of the ionisation states of the ions inside the plasma (for elements heavier than oxygen) is being commissioned in the FPT testbench. The determination of ”in-plasma” ion temperature will allow the determination of the conditions leading to high beam emittance, since thermal emittance is proportional to the squared root of the ion temperature. The combination of such a variety of diagnostics tools provides the exciting opportunity to investigate plasmas in compact traps as test-benches, or experimental simulators, of physical phenomena involved in ECRIS and MDIS plasmas.

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