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Optical emission spectroscopy and microwave reflectometry for magnetised plasmas: Applications to ion sources and fusion machines

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Summary. — Investigation of magnetised plasmas by advanced diagnostics is a relevant topic in the frame of ion sources for high-performance particle accelerators and in thermonuclear fusion research for energetic purposes. In this paper, we propose two different diagnostic techniques to provide complementary information on plasma properties: high-resolution Optical Emission Spectroscopy (OES) and Microwave Reflectometry (MR). Several OES measurements have been carried out at INFN-LNS to determine cold electron plasma density and temperature in the framework of the PANDORA project. Experimental results will be here presented together with an ongoing R&D simulation work for the MR system to be employed in the Divertor Tokamak Test (DTT) facility in view of reconstructing the 1D electron density profile accurately. An overview of the perspectives and challenges of the two diagnostic systems will be given.

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1. – Introduction

Plasma physics and the advanced technology employing plasmas are breaking new grounds in science and industry. Magnetically confined plasmas in compact traps (electron density $n_{\mathrm{e}} \sim 10^{10} - 10^{13}\,\mathrm{cm}^{-3}$ and electron energy $k_{\mathrm{B}}T_{\mathrm{e}} \sim 0.01 - 10\,\mathrm{keV}$) and fusion devices ($n_{\mathrm{e}} \sim 10^{14}\,\mathrm{cm}^{-3}$ and $k_{\mathrm{B}}T_{\mathrm{e}} \sim 10\,\mathrm{keV}$) represent environments of relevant interest for interdisciplinary research: they are widely used not only as ion sources coupled to particles accelerators, but also for fundamental studies and in thermonuclear fusion machines for energetic purposes. Thus, the characterisation of magnetised plasmas constitutes one of the main challenges of these fields. Since plasma emits radiation in the whole electromagnetic spectrum and different types of electromagnetic waves can propagate inside it, a multi-diagnostic system, made of several diagnostics operating simultaneously, is required to probe plasma parameters and properties (*e.g.*, electron density and temperature, possible instabilities, density profile reconstruction) completely and accurately. In this framework, improving high-performing non-invasive diagnostic techniques is important since they probe the plasma without perturbing it. Among these diagnostics, Optical Emission Spectroscopy (OES) [1] and Microwave Reflectometry (MR) [2] find extensive use in both compact traps and fusion machines. On one hand, OES can be employed in ECR ion sources to estimate plasma source thermodynamic parameters and relate them to the intensity, quality, and stability of the extracted ion beam [3, 4]. The development of this diagnostic is relevant for the nuclear astrophysics community as well. It will support the PANDORA (Plasma for Astrophysics, Nuclear Decay Observation and Radiation for Archaeometry) project to determine in-plasma β-decay rate of selected radioactive isotopes involved in nuclear astrophysics processes [5, 6] and the opacity of in-laboratory plasmas resembling the astrophysical scenario [7]. On the other hand, making progress in the optimisation of a reliable MR setup poses new challenges in the roadmap towards the realisation of nuclear fusion power plants. In view of its application in future reactors, this diagnostic system will be implemented in the DTT (Divertor Tokamak Test) facility to be tested and validated in all its aspects [8].

2. – Diagnostic techniques for the characterisation of magnetized plasmas

OES is a non-invasive plasma diagnostic technique used to characterise plasma low-energy electron population ($k_{\mathrm{B}}T_{\mathrm{e}} \leq 30\,\mathrm{eV}$), providing estimates of electron density n_{e} and temperature $k_{\mathrm{B}}T_{\mathrm{e}}$ [1]. We report on systematic spectroscopic measurements performed for the characterisation of a hydrogen plasma in a compact simple mirror plasma trap, called Flexible Plasma Trap (FPT), currently operative at INFN-LNS, where plasmas are generated by means of the ECR mechanism under different magnetic field profiles [9]. The OES experimental setup consisted of an energy-calibrated spectrometer (nominal resolution of 35 pm at 486 nm, spectral range of 300–750 nm), with a relative intensity calibration, coupled to a CCD detector and to an optical fibre (NA = 0.22, core $\varnothing$ = $200\,\mu$m) viewing the plasma via an optical window to the trap.

Concerning the MR, it has been proposed as one of the major diagnostic in fusion devices, especially in the DTT facility, to reconstruct the electron density profile, detect plasma turbulences and monitor plasma position and shape [2, 10]. For this latter purpose, a Plasma Position Reflectometer (PPR), consisting of antennas and their feeding waveguides (WGs), is involved in the DTT reflectometry system [11]. Since its integration on the fusion reactor is a challenging task, a proper R&D simulation work is required developing and optimising a tailored PPR's design suitable for the mechanical constraints

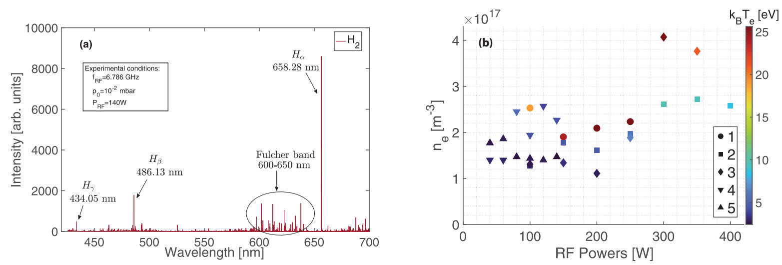

Fig. 1. – (a) Typical spectrum of emission lines from pure hydrogen plasma. (b) Experimental values of n_e [m^{-3}] and k_BT_e [eV] as function of P_{RF} [W] for 5 experimental run for two p_0 (config. 1 at 10^{-4} mbar, configs. 2, 3, 4, 5 at 10^{-2} mbar).

of the machine. Specifically, to fit in the available space, bent WGs with a multi-curved irregular path will be employed in the system for signal propagation. However, their curvature can cause spurious mode conversion leading to lower system performances and signal attenuation, thus a numerical modelling of this effect is mandatory.

3. – Experimental results and numerical simulations

Concerning OES measurements, a systematic data acquisition has been carried out in the visible range by tuning source parameters as the microwave power (P_{RF}), the heating frequency (f_{RF}), the gas neutral pressure (p_0) and modifying the magnetic field profile. An example of the typical spectrum acquired for an H_2 plasma is shown in fig. 1(a), where the Balmer's emission lines —H_α, H_β, H_γ— and the Fulcher band are indicated. The parameters of interest have been estimated from the comparison between the experimental emission line ratios, namely $H_{\alpha\beta} = H_\alpha/H_\beta$ and $H_{\beta\gamma} = H_\beta/H_\gamma$, and the expected theoretical ratios from the Collisional Radiative model YACORA [12]. The applied "line ratio method" agrees with the relatively calibrated system and such low temperature plasmas [1, 13]. Results of experimental spectroscopic measurements are reported in fig. 1(b). In general, density turns out to be of the order of $10^{17}\,m^{-3}$, while temperatures range from few eV up to 30 eV. In most of the cases, these plasma parameters are affected by small uncertainties, not included in the figure for the sake of clarity, but within 20% and 50% for density and temperature, respectively.

As regards the MR technique, we report on commercial simulation tools, namely CST studio suite® and COMSOL Multiphysics®, whose results have been adopted in support of the WG routing design. Starting from regular WGs to single- and then double-bent WGs, that will be employed in DTT, the quantitative impact of mode conversion has been evaluated for the proposed geometry in fig. 2(a). Preliminary results concern the study of the transmission coefficient as a function of frequency, known as scattering parameter S21 (or S-parameter), between the fundamental mode TE10 and higher-order modes. From a more in-depth analysis of the S2(TE20)1(TE10) shown in fig. 2(b), it is possible to assess the amount of power transferred between the TE10 and the second-order mode TE20 when varying the WG radius of curvature: as the radius of the curvature decreases, an increasingly higher percentage of power (*e.g.*, ∼20% for frequencies between 30 and 35 GHz and ∼40% for frequencies above 45 GHz) couples with the TE20 mode. The results, obtained through the comparison of CST and COMSOL simulations, confirmed the presence of mode conversion impacting on the WG design.

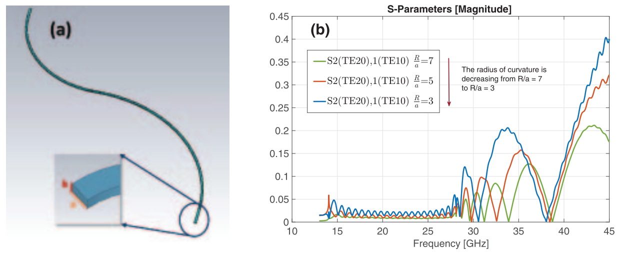

Fig. 2. – (a) Simulated geometry of the WR42 WG with $a = 10.668\,\text{mm}$ and $b = 4.318\,\text{mm}$. (b) S-parameters behaviour as a function of frequency in a range 13–45 GHz for the fundamental mode TE10 and the first spurious mode TE20.

4. – Conclusions and perspectives

This paper describes the use of two diagnostic techniques, the OES and MR, to investigate magnetically confined plasmas in compact traps and fusion devices. Through OES, it was possible to probe plasma parameters, n_e and $k_\mathrm{B}T_\mathrm{e}$, relevant for astrophysical investigations in the framework of the PANDORA project main goals. In detail, the configurations 4 and 5 of fig. 1(b) are the most promising among all the ones explored because in such configurations densities of the order of $10^{17}\ \mathrm{m}^{-3}$ and few eV of temperatures have been achieved. These outcomes will be of impact to better recreate the astrophysical scenario of the early-stage kilonova plasma ejecta, characterised by $n_\mathrm{e} \sim 10^{17}\ \mathrm{m}^{-3}$ and $T_\mathrm{e} \sim \mathrm{eV}$, in laboratory [5, 7]. Further measurements are expected at INFN-LNS for measuring some observables not yet explored in the ECR plasma physics field (*e.g.*, plasma opacity). The MR simulations, instead, highlighted the presence of mode conversion that impacts on the signal propagation. Thus, new WG geometries will be explored to support the evaluation of the system performance. In future experimental campaigns, the possibility to employ the OES in combination with MR for innovative applications in ECR compact traps turns out to be very appealing to retrieve information on plasma density and monitor plasma stability.

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