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The INFN project MAPS_3D

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Summary. — MAPS_3D is a project of Istituto Nazionale di Fisica Nucleare which aims to implement an unprecedented characterisation of magnetised laboratory plasmas by means of high-resolution spectropolarimetry in the visible range. This observational technique is routinely applied to astrophysical plasmas in order to derive physical parameters of stars. Through the experimental set-up of MAPS_3D spatial resolution of the emitting plasma will be obtained, giving the possibility to localise the emitters from hot and cold plasma regions, as well as to estimate the charge state distribution. This innovative plasma characterisation, not achievable by means of the present diagnostic techniques, will allow a better comprehension of laboratory plasma structure, heating processes and magnetic confinement, with strong implications for Accelerator Physics, Plasma Physics, Astrophysics and Nuclear Astrophysics.

1. – Introduction

MAgnetised Plasma Spectropolarimetry 3D (MAPS_3D) is a two-year project of Istituto Nazionale di Fisica Nucleare (INFN) which aims to characterise magnetised laboratory plasmas in an innovative way through high-resolution spectropolarimetry, an observational technique commonly adopted in Astrophysics to determine physical parameters of stellar atmospheres. The project started in 2018 at INFN-Laboratori Nazionali del Sud (INFN-LNS) in collaboration with researchers from Istituto Nazionale di Astrofisica-Osservatorio Astrofisico di Catania (INAF-OACT), Università degli Studi di Catania, University of Michigan, University of Cambridge and European Southern Observatory. It can be considered as a transversal project both from the operating point of view, since it requires instruments and competences from different fields of Physics, and from the application point of view: a detailed plasma characterisation is mandatory for multiple purposes and will have strong implications for Plasma Physics, Accelerator Physics, Astrophysics and Nuclear Astrophysics.

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Laboratory plasmas can be created through the Electron Cyclotron Resonance (ECR) heating in magnetic traps, where gases injected in a chamber are ionised by microwaves and confined by magnetic fields. These plasmas represent a useful test bench for studies involving different fields of Physics: from the astrophysical point of view, the ECR plasmas reproduce many stellar environments, so that the analysis of their physical conditions should allow to obtain advancement in observational Astronomy, improving our knowledge about Cosmos. Also, a better comprehension of the ECR plasma ignition and stability is required to fully control the ion beam extracted from an ECR Ion Source feeding particle accelerators (ECRIS [1]). Large efforts are being made for this purpose and an improvement in the knowledge of physical plasma properties is then mandatory.

2. – Plasma diagnostic techniques: state of the art

In this section I summarise what widely discussed in [2], referring the reader to this article for details.

Present diagnostic techniques developed for laboratory plasma range from X-ray to near infrared. Non-invasive methods are based on imaging and low-resolution ($R = \lambda/\Delta\lambda < 40000$) spectroscopy in the visible range and in the X-ray domain, and do not affect the plasma physics with respect to probes. Anyway all methods only give information about the electron component, in terms of density, temperature and energy distribution, not being able to characterise ions.

2˙1. *Optical emission spectroscopy.* – Indeed in the visible range Optical Emission Spectroscopy (OES) also provides relative abundances of atomic and molecular populations by applying the line intensity ratio method [3]. Nevertheless, a strong limit of OES is the *absence of spatial resolution*: spectra are obtained by averaging the contributions of emitting plasma volumes with very different temperatures and densities, so that it is not possible to localise hot and cold regions inside the chamber.

A further limit is the *low spectral resolution* which prevents line identification, as shown in fig. 1. Only lines with distance equal to, or greater than, the instrumental profile width $\Delta\lambda = \lambda/R$ can be distinguished at wavelength λ, that is the lower the spectral resolution the worst the line identification and then the ion characterisation. Low R-values also affect the determination of emitter velocities v from Doppler shift, which cannot be obtained better than $\Delta v = c \cdot \Delta\lambda/\lambda = c/R$ (where c is the speed of light in vacuum). Analogously, the width of a spectral line has to be larger than the instrumental profile in order to appreciate broadening mechanisms (thermal and collisional).

Table I reports the values of the quantities mentioned above for different spectral resolution and at wavelength $\lambda = 500\,\text{nm}$. Note that the ion temperature (and then the energy) is expected to be of a few eV, measurable only with spectral resolution of the order of 100000.

3. – Spectral emission from magnetised plasmas

We here recall that in the presence of a magnetic field $\mathbf{B}$, the atomic energy levels split in sublevels, so that the spectral lines also split in a series of Zeeman components. By indicating with m the magnetic quantum number, these are called π components if related to transitions with $\Delta m = 0$, σ_b (blue-shifted) components for $\Delta m = +1$ and σ_r (red-shifted) components for $\Delta m = -1$. By indicating the average separation between

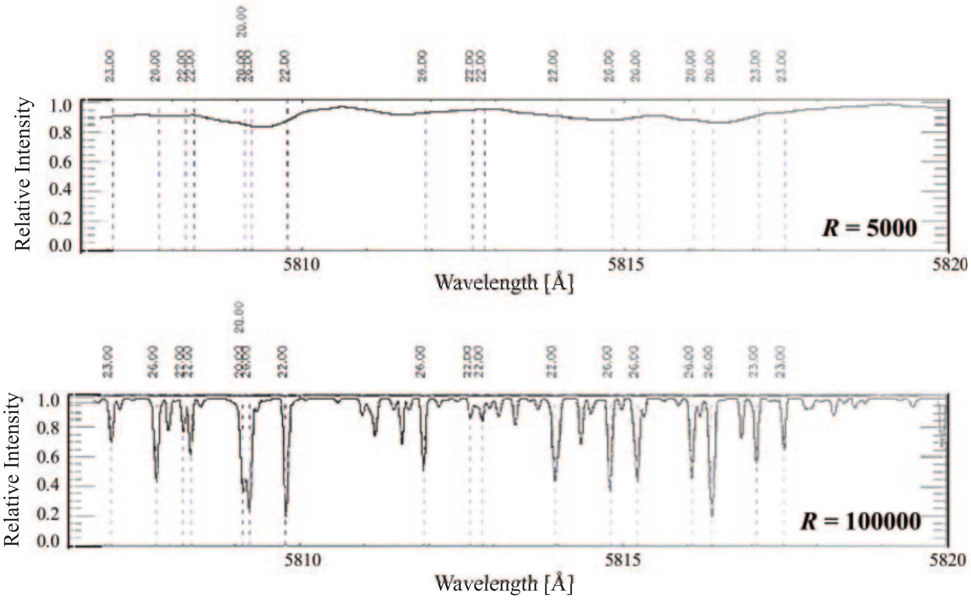

Fig. 1. – Synthetic solar spectra computed in the same wavelength range with low and high spectral resolution R.

the σ_b and σ_r components with $\Delta\lambda_\sigma$, under the weak-field approximation the intensity of $\mathbf{B}$ in G is given by

$$|\mathbf{B}| = \frac{\Delta\lambda_\sigma}{2 \cdot 4.67 \cdot 10^{-13} \lambda^2 g_{\text{eff}}}, \tag{1}$$

where g_{eff} is the effective Landé factor and λ is expressed in Å. Then, Zeeman splittings have to be detected to avoid incorrect results in line identification as well as to determine the magnetic field strength. Since the instrumental profile width corresponds to the minimum $\Delta\lambda_\sigma$ that can be observed, the spectral resolution sets the minimum magnetic field modulus measurable (table I).

TABLE I. – *For different values of spectral resolution R chosen as order of magnitude, at a fixed wavelength $\lambda = 500\,nm$, the instrumental profile width $\Delta\lambda$ (corresponding to the minimum wavelength separation detectable), the minimum ion velocity v_{min} measurable from Doppler shift together with the corresponding kinetic energy K_{min} for a plasma of ${}^{40}Ar$, and the minimum magnetic field modulus $|\mathbf{B}|_{min}$ are listed. The field modulus have been calculated according to eq. (1) by assuming $\Delta\lambda_\sigma = \Delta\lambda$ and $g_{\text{eff}} = 1$.*

R	$\Delta\lambda$ [nm]	v_{min} [km/s]	K_{min} [eV]	$\|\mathbf{B}\|_{min}$ [T]
250	2	1200	$3 \cdot 10^5$	85
5000	.10	60	750	4.3
10000	.05	30	190	2.1
100000	.005	3	1.9	.21

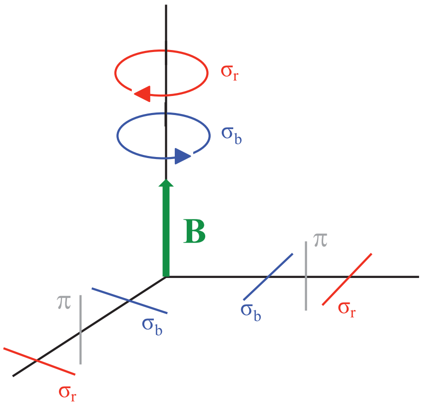

Fig. 2. – Zeeman components as observed along and perpendicular to the magnetic field direction.

In addition, the absence of information about the magnetic field geometry can lead to wrong estimation of plasma parameters when spectroscopically determined, since both the strength and the shape of spectral lines from magnetised plasma depend on the angle θ between the line of sight and the field direction. As shown in fig. 2, it means that by observing along $\mathbf{B}$ only the σ components circularly polarised at their maximum intensity are present, since the π component (always linearly polarised) is parallel to the field and disappears. As θ increases, the intensity of the π component also increases, while σ components appear to be elliptically polarised and their intensity decreases. Spectra obtained at $\theta = 90°$ will show the π component at its maximum intensity and σ components linearly polarised perpendicularly to $\mathbf{B}$ at their minimum intensity.

Then simultaneous measurements of magnetic field intensity and geometry are needed in order to avoid wrong interpretation of spectra, *i.e.*, of the plasma physical condition. For this purpose the only non-invasive technique is polarimetry. Polarisation can be described by Stokes parameters, obtained through high-resolution spectropolarimetric observations. As an example, fig. 3 shows synthetic Stokes profiles recorded for the case $\theta = 0°$: Stokes I (representing the line intensity, *i.e.*, the observed spectrum) shows two lines, Stokes Q/I (related to linear polarisation parallel and perpendicular to $\mathbf{B}$) and Stokes U/I (related to linear polarisation at 45° with respect to $\mathbf{B}$) are null, while Stokes

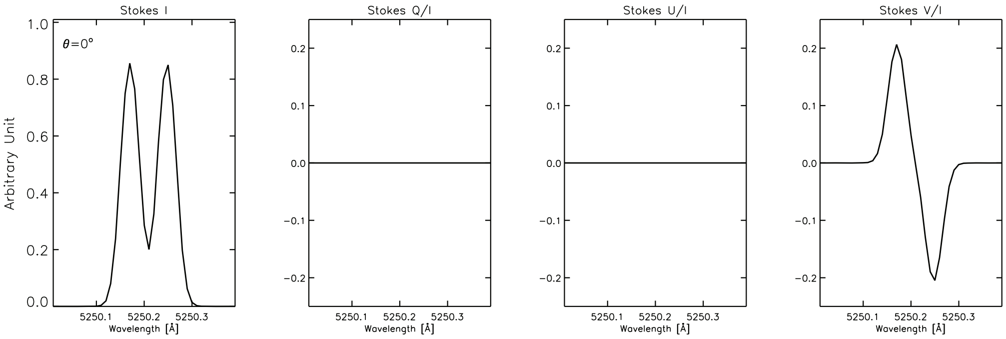

Fig. 3. – Synthetic Stokes profiles as observed when the line of sight and the magnetic field direction are coincident (*i.e.*, $\theta = 0°$).

V/I (related to circular polarisation) presents clockwise and counter-clockwise profiles, *i.e.*, the two σ components.

In conclusion, a deeper knowledge of plasma properties, mainly in terms of Charge State Distribution (CSD) and ion temperatures, needs new diagnostic tools based on high-resolution spectroscopy spatially resolved. Polarimetric observations are also required for determining the magnetic field geometry, in order to properly analyse spectra from magnetised plasmas.

4. – MAgnetised Plasma Spectropolarimetry 3D

MAPS_3D was born from the idea to improve our knowledge about ECR plasma properties by means of instrumentations and methodologies imported from Astrophysics. The project aims to obtain an innovative characterisation of magnetised laboratory plasmas through high-resolution spectropolarimetry in the visible range. As stated before, this is a well-consolidated observational technique routinely applied to astrophysical plasmas in order to correctly estimate physical parameters of stellar atmospheres, such as effective temperature, surface gravity, chemical composition, and magnetic field intensity and geometry. MAPS_3D is a fundamental step for the INFN project PANDORA (Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry [4]).

MAPS_3D takes place at INFN-LNS, which hosts the necessary equipment. In particular, the Flexible Plasma Trap (FPT [5]) where the plasma is generated and longitudinally confined through a simple mirror magnetic configuration. It consists of a copper cylindrical chamber of length 260 mm and diameter 82 mm, surrounded by three coils for a maximum magnetic field intensity $|\mathbf{B}|_{max} = 0.5\,\mathrm{T}$, and equipped with three guides, orthogonal to each other, for microwave radio frequency launching parallel and perpendicular to the **B**-direction.

In an agreement of collaboration between INFN-LNS and INAF-OACT, a *Memorandum of Understanding* was signed in August 2017 and the Spettrografo Alta Risoluzione Galileo (SARG [6]) was moved from Telescopio Nazionale Galileo (TNG, La Palma, Canary Island) to LNS. The white-pupil échelle spectrograph SARG allows to obtain spectra between 370 and 1000 nm in a single shot with constant resolution $R = 164000$, *e.g.*, lines separated up to 0.003 nm at 500 nm can be distinguished. This high-resolution spectrograph represented a valuable tool in Astrophysics, since it has been widely used for stellar spectroscopic observations (*e.g.*, [7-11]). When mounted at TNG, SARG was equipped with a polarimetric unit implemented by OACT researchers [12]. Magnetic fields weaker than 100 G have been measured on the surface of stars (see [13, 14]).

Two are the main goals of MAPS_3D: the realisation of three polarimeters for the tridimensional spatially resolved spectropolarimetric analysis of plasma, and the implementation of a novel on-line diagnostic tool for magnetised plasma based on high-resolution spectropolarimetry, as described in the following.

4·1. *Instrumental tools.* – The spectropolarimetric analysis aimed by MAPS_3D requires three polarimetric units (left panel of fig. 4) coupled to FPT 90° from each other, *i.e.*, located at the microwave launching entrances (right panel of fig. 4), and fibre-linked to SARG. By varying the polarimeters focus it will be possible to point-by-point map the plasma. This experimental set-up allows, for the first time, a tridimensional characterisation of plasma and magnetic field inside the chamber, with spatial resolution up to $1\,\mathrm{mm}^3$.

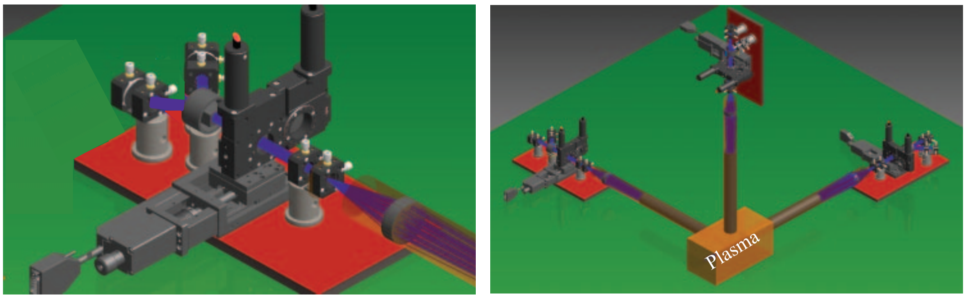

Fig. 4. – Left: mechanical drawing of a polarimetric unit of MAPS_3D. Right: the experimental set-up: the three polarimeters will be coupled to the Flexible Plasma Trap and fibre-linked to the high-resolution spectrograph SARG, in order to point-by-point map the plasma up to $1\,\mathrm{mm}^3$.

Following the successful configuration of the most sensitive spectropolarimeters, *e.g.*, SARG at TNG, CAOS (Catania Astrophysical Observatory Spectrograph) at OACT [15] and PEPSI (Potsdam Echelle Polarimetric and Spectroscopic Instrument) at LBT (Large Binocular Telescope) [16], to build up each polarimeter, the dual beam swapping technique configuration was adopted. Data reduction and Stokes parameters are obtained as in [15].

Figure 5 shows one polarimeter that I have assembled together with the OACT researchers involved in the project. It was tested at OACT by acquiring spectra of a Th-Ne lamp, both without and with a uniform magnetic field $|\mathbf{B}| \sim 100\,\mathrm{G}$ directed along the line of sight. The polarimeter was fibre-linked to the spectrograph FRESCO (Fiber-optic Reosc Echelle Spectrograph of Catania Observatory, see [17] for a description and [18] for a spectropolarimetric use) with $R = 20000$. Figure 6 shows the observed Stokes profiles: Stokes I (left panel) has the same shape for both cases (with and without $\mathbf{B}$), since the spectral resolution of FRESCO does not allow to detect the Zeeman splitting. Stokes V (not normalised with respect to I) is shown in the right panel without (dashed line) and in the presence of (solid line) magnetic field. In the latter case, the profile reveals the two σ components, helping us to correctly interpret the spectrum.

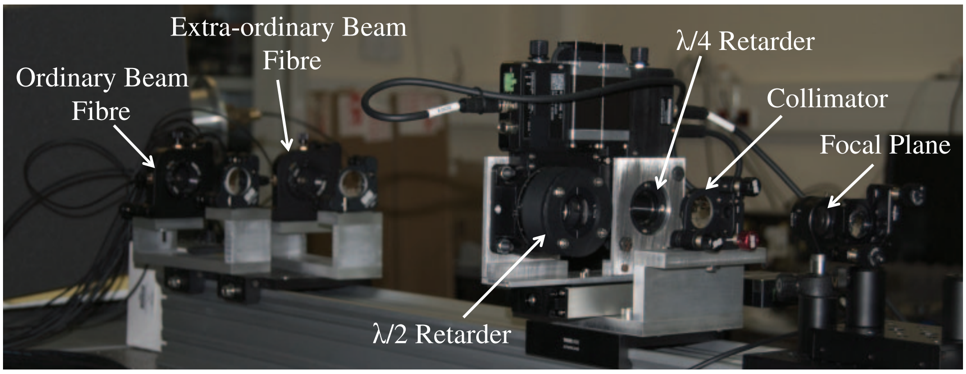

Fig. 5. – Polarimetric unit of MAPS_3D as assembled at OACT. The Wollaston prism is not visible in the picture.

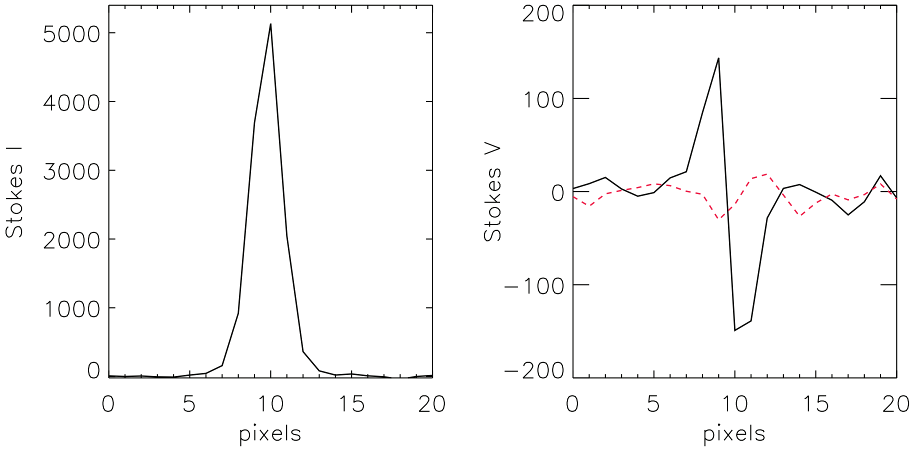

Fig. 6. – Observed Stokes I and V profiles of a Th-Ne lamp spectral line, obtained at OACT with the spectrograph FRESCO ($R = 20000$) and the polarimeter shown in fig. 5, both without (dashed line) and with (solid line) a uniform magnetic field of about 100 G along the line of sight. The Stokes I one is the same with and without the field, since the spectral resolution does not allow to detect the wavelength separation of Zeeman components.

4·2. *Diagnostic tools.* – Contrarily to stellar atmospheres, for which the Local Thermodynamic Equilibrium (LTE) approximation is assumed, ECR plasmas are described by the Collisional Radiative model. Then a proper interpretation of emission spectra from FPT plasmas needs a novel numerical code taking into account the non-LTE population and the Zeeman splitting of lines. This code will be developed on the basis of CHIANTI [19, 20], the nowadays most advanced database and code for calculating the emissivity of solar optically thin plasma. In addition, a pipeline for on-line reduction and analysis of spectropolarimetric data is planned in order to: 1) measure the ion temperature versus single/gas mixing operations, and/or in presence of kinetic/cyclotron turbulences; 2) provide spatially resolved measurements of the plasma distribution of ions at different charge states in order to investigate the mechanism of ion confinement and the build-up of the multiply charged ions; 3) measure the plasma magnetic field, with particular interest in the local effects of magnetic reconnection and turbulence on-set due to the magnetic curvatures. Indeed, these measurements are routinely obtained in the case of solar corona, stellar magnetism and planetary nebulae.

The implementation of such a diagnostic tools is now ongoing, according to the milestones timetable of the project.

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