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Visible Light Spectrometry Measurements for Studying an ECRIS Plasma and especially applied to the MONO1001 Ion Source.

Olivier Tuske, Laurent Maunoury[§], Jean-Yves Pacquet, Christophe Barué, Mickael Dubois,

Gabriel Gaubert, Pascal Jardin, Nathalie Lecesne, Patrick Leherissier, Frederic Lemagnen,

Renan Leroy, Marie-Genevieve Saint-Laurent, and Antonio C.C. Villari

GANIL, bd H. Becquerel BP 55027 14076 Caen cedex 05, France

[§] CIRIL, rue Claude Bloch BP 5133, 14070 Caen cedex 5

Abstract

The cylindrical geometry of the magnetic confinement of the MONO1001 ECR ion source made in GANIL[1], allows us to measure radial characteristics of the working ECR plasma with Helium gas. The physical and the geometrical characteristics of the resonance surface inside the working ECR source have been quantified with the help of a visible light spectrometer. Hence, we have deduced a shape of the ECRIS resonance surface which corresponds closely to our magnetic calculations.

Introduction

Electron cyclotron resonance ion sources (ECRIS) are now usual instruments of accelerators. They are currently used to deliver ion beams of various features to experiments of atomic physics, nuclear physics, as well as physics of high energies. Although the performances of ECRIS have been continuously increased by raising the magnetic field, and also the frequency of the RF generators since they were invented, higher intensities and charge state are still required.

At the GANIL facility and particularly at SPIRAL, we use and develop ion sources of ECR type to ionized radioactive atoms with an aim of producing Radioactive Ion Beam (RIB) as well singly as multiply charged ions. The mechanism of production of ionized atoms from neutral elements (gas, vapor) must be well understood to provide the maximum particle

intensity. To achieve the best RIB, the ionization process which occurs inside ECR source must be as fast and effective as possible. The ionization of these particles is necessary to get high charge state before injecting them inside the CIME cyclotron which finally delivers the high energy RIB. This ECRIS is the core of the radioactive ion production. Due to the radioactive environment, the source must be removed and replaced after 15 days of operation. In order to reduce the connections and the volume of the production system the whole magnetic confinement is realized with permanent magnets instead of coils[2].

A whole R&D project of ECRIS all built with permanent magnets has been realized at the GANIL, and the last ion source MONO1001 that has been designed for singly charged ions, has just been tested with noble gases, metallic gases[3] [4] and even with fullerene[5].

One of the main difficulties is to characterize the physical geometry of the heating zone to compare it with its theoretical dimensions. In this paper we present a non-destructive method to measure those quantities. The only hypothesis taken is that the heating zone is where the visible light is emitted from the plasma.

1-Description of the source and of the experimental setup

The "MONO1001"[6] ECRIS is operating at 2,45GHz and 200W of RF power. Its longitudinal and radial magnetic confinement is realized with two magnetic rings of permanent magnet weighting 11kg each. Those rings are separated by 80mm and their internal diameter is about 50mm. They create an axisymmetric magnetic confinement with a last closed magnetic surface at 2000Gauss. The absence of a hexapole and the space between the two magnetic rings allows us to insert four windows for non-perturbative plasma diagnostics. One of them is a regular glass window and the emitted visible light is lead toward a visible light spectrometer (TRIAX180, Jobin-Yvon). The visible light is diffracted on a 1200g/mm grating blazed at 1500nm and the selected wavelength is collected by a photo-multiplier which is connected to a rate-meter. The combination of the position of the grating with the

intensity of the selected light is a measurement of the spectrum of atomic lines of excited and ionized elements of the plasma. The helium gas was used in this case because it has a simple atomic spectra easier to analyze compared to the other noble gases (Fig. 1).

In order to characterize the profile of the heating zone (or resonance surface at 872Gauss) in a vertical plane located in the middle of the source, we measured the profile of the density of visible light emitted. We fixed the spectrometer on two different wavelengths (see Table. 1) and moved vertically the whole system to scan the plasma in its center. The theoretical diameter of the resonance zone is 28mm (Fig. 2).

2-Quantitative measurements

At the resonance surface electrons are heated by the injected RF wave. The radiative de-excitation process of the excited atoms/ions can be considered to occur at the same place where they were excited/ionized by energetic electrons because the life time of the initial excited state is brief ($\sim 10^{-8}$s). We can assume that the zone where the atomic lines are emitted correspond to the heating zone of the plasma by the RF wave.

Using two different wavelengths allow us to estimate merely the energetic population of electrons. Intensity results of the H and He atomic lines versus the vertical position of the spectrometer is shown on Fig. 3. One can say :

- the intensity of the line is not equal to zero outside of the boundaries of the plasma. This can be explained with the isotropic reflection of the visible light on the metallic internal wall of the plasma chamber. This effect can be corrected by subtracting an uniform baseline from the measurement.

- at the vertical position y = 0, the spectrometer is scanning the thickest part of the plasma. One could expect to see at this position the most intense light emission. This measurement clearly indicates that the heating zone is not a whole volume, but seemed to be hollow. Otherwise the intensity should have been at its maximum.

3-Two simple models

We model, by two different ways, the heating zone : the approach of the two models are very different. One fits the experimental results with an imposed radial density of light and on the contrary the other one calculates it directly from the experimental results.

3.1-Fit of the gaussian distribution of light on the measured profile

The first model uses a double gaussian radial distribution of light emitted and we convolute it with a narrow window as the spectrometer does. Thus we search the parameters to fit the measured intensity profile (Fig. 4). We adjust the three free parameters of the radial distribution $\varepsilon(r)$: $\varepsilon(r) = K_0 + e^{-\frac{(r-r_0)^2}{2\sigma^2}} + e^{-\frac{(r+r_0)^2}{2\sigma^2}}$ with K_0 a uniform component which includes the reflection of light on the wall of the chamber, r_0 and σ are respectively the position and the width of the heating zone. The radial density is normalized before fitting with the experimental data. The results are summarized in the Table. 2

3.2-Abel Inversion

The second model uses the Abel inversion which is a mathematical tool that gives directly the radial distribution $\varepsilon(r)$ from a measured axisymmetric intensity profile $I(y)$:

$I(y) = 2\int_y^R \frac{\varepsilon(r)r}{\sqrt{r^2 - y^2}}dr$. The radial distribution can be expressed by $\varepsilon(r) = -\frac{1}{\pi}\int_0^R \frac{I'(y)}{\sqrt{y^2 - r^2}}dy$ with

$I'(y) = \left(\frac{\partial I(y)}{\partial y}\right)$. Before applying the mathematical operation, we have smoothed the measured profile (especially for He) with a 3 points adjacent averaging, in order to get ride of the fluctuation. The result of the radial distribution for two wavelengths are shown Fig. 5. All results are summed up in Table. 2.

3.3-Results

With both methods, the radial density is less intense in the center of the plasma chamber. The calculation confirms that the heating zone is not uniform but seemed to be a hollow volume.

Uncertainties on the position and width are quite large due to the low statistic on the measurement, but even with this fact, the error compared with the theoretical value is lower than 15%.

With the Abel calculation, the radial density seemed to be more dense in the center than the first model. Thus the mean position of the plasma is at a lower value. As Abel inversion depends on the derivative of the position, we are very sensitive to the fluctuation of the measurement. Especially in the case of He lines where the noise ratio is much bigger than with hydrogen lines. In general, for the two models, the maximum of the light intensity are in a good agreement with the theoretical magnetic calculations.

4-Conclusion

For the first time, we can show, thanks to a direct measurement the dimension of the heating zone of an ECRIS plasma. The main result is that this zone is not homogenous but seemed to be a hollow volume. As we compare the result of the heating zone dimensions, we can see that a gaussian radial distribution of light emitted is not completely satisfactory to reproduce the measured profile. The mean position is in a quite good agreement for the two models with magnetic theoretical calculations. So we have demonstrated that is possible to measure the resonance surface position and its thickness with a non-perturbative method.

We have made this work with neutral excited elements, it would be interesting to extend those measurements to ionized species as He^{+}.

Acknowledgements

Element	Transitions	Wavelength of the atomic line (nm)	Energy to excite the system from the fundamental state to the initial state (eV)
H	3s→2p	656,2	12,1
He	1s4s (^{3}S)→1s2p (^{3}P°)	471,3	23,58

Table. 1   Characteristics of the two selected wavelengths

Element	H	He
Gaussian radial density		
Mean Position (mm)	14,6 (±2)	15,8 (±4)
Standard deviation (mm)	6,6 (±1,5)	7,5 (±2)
Uniform component K_0	0,1	0,028
Radial density calculation with the Abel inversion		
Mean Position (mm)	11,6 (±1)	12,1 (±1)
Maximum (mm)	14 (±1)	14 (±1)

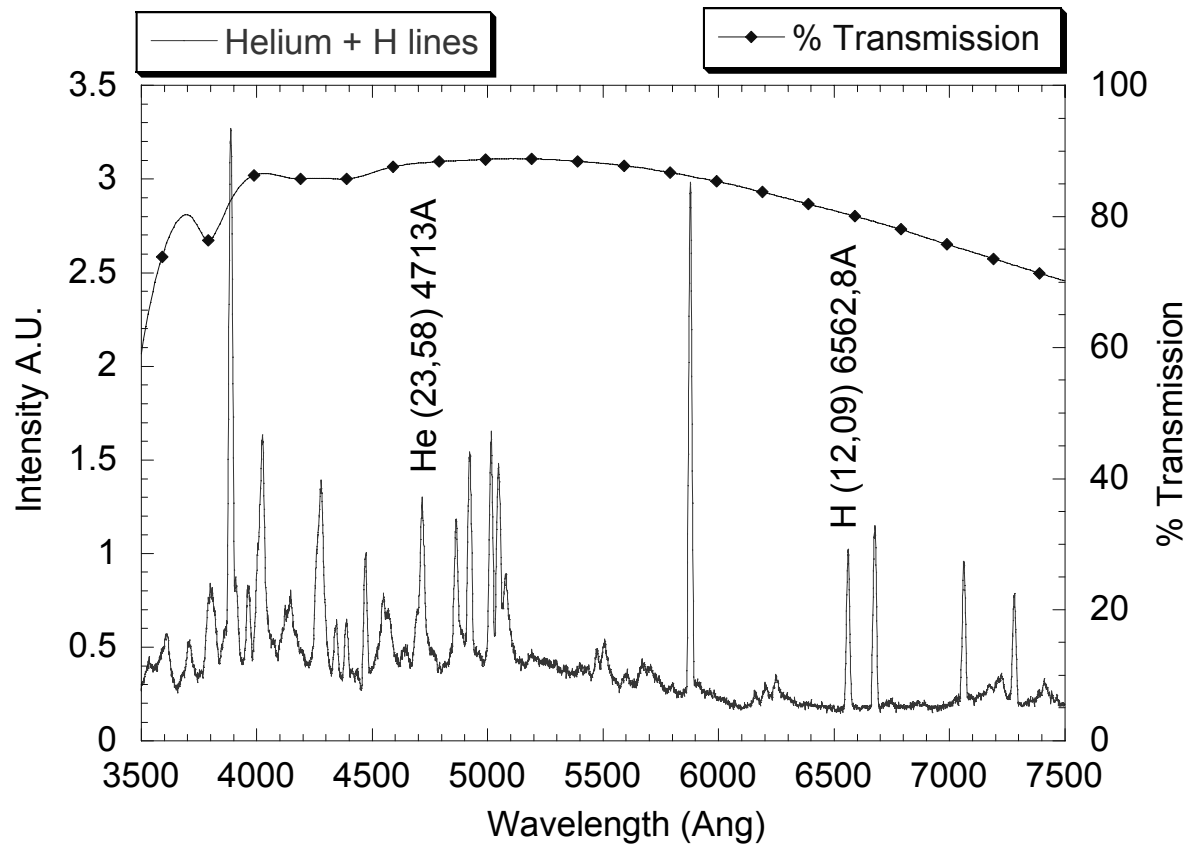**Table. 2   Physical dimensions of the radial density of light deduced with from two simple models.**

Fig. 1 First order of diffraction of the atomic lines produced inside the ECRIS. One can see the name of the element, the energy needed to reach the initial state and the wavelength of the radiative de-excitation in angström. The dot line shows the transmission of the glass windows.
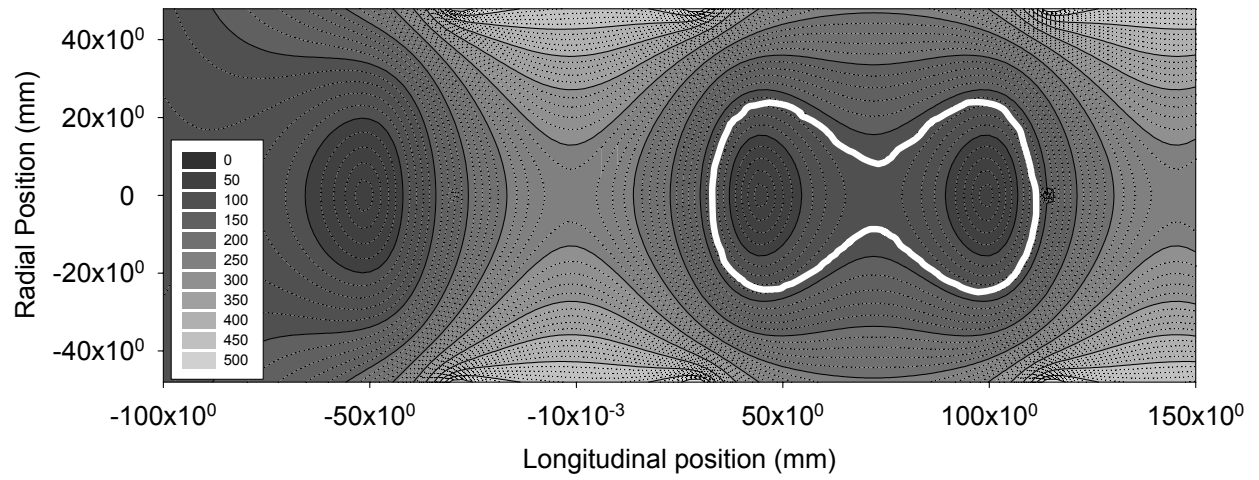
MONO 1000

Fig. 2 Magnetic field iso-modulus of the ECRIS "MONO1001". The intensity is expressed in Gauss. The white line indicate the 872 Gauss magnetic iso-surface.
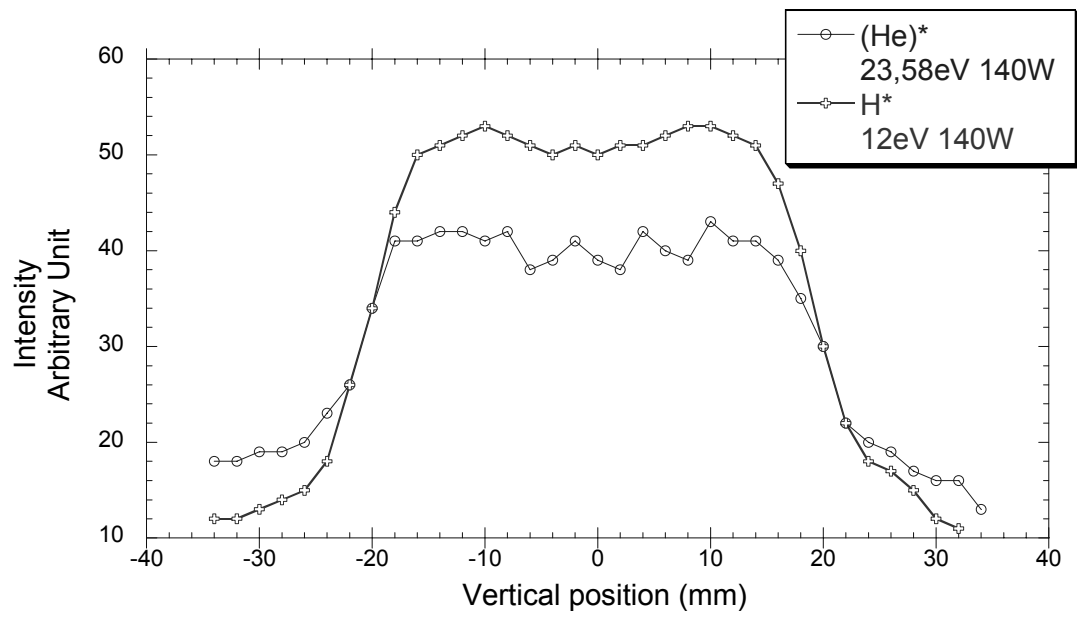
Fig. 3   Profile of the intensity of the line at different vertical positions of the spectrometer.
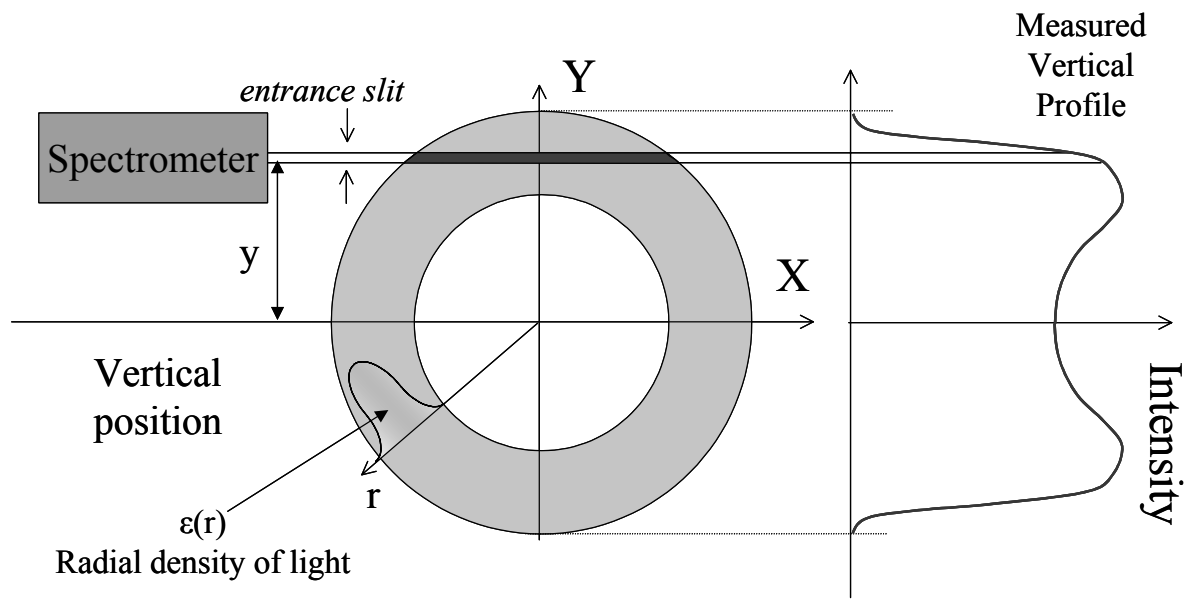
Fig. 4 Vertical cut of the "hollow" heating zone. The spectrometer at the y vertical position measured the intensity of the atomic lines emitted from a thin slice of plasma.
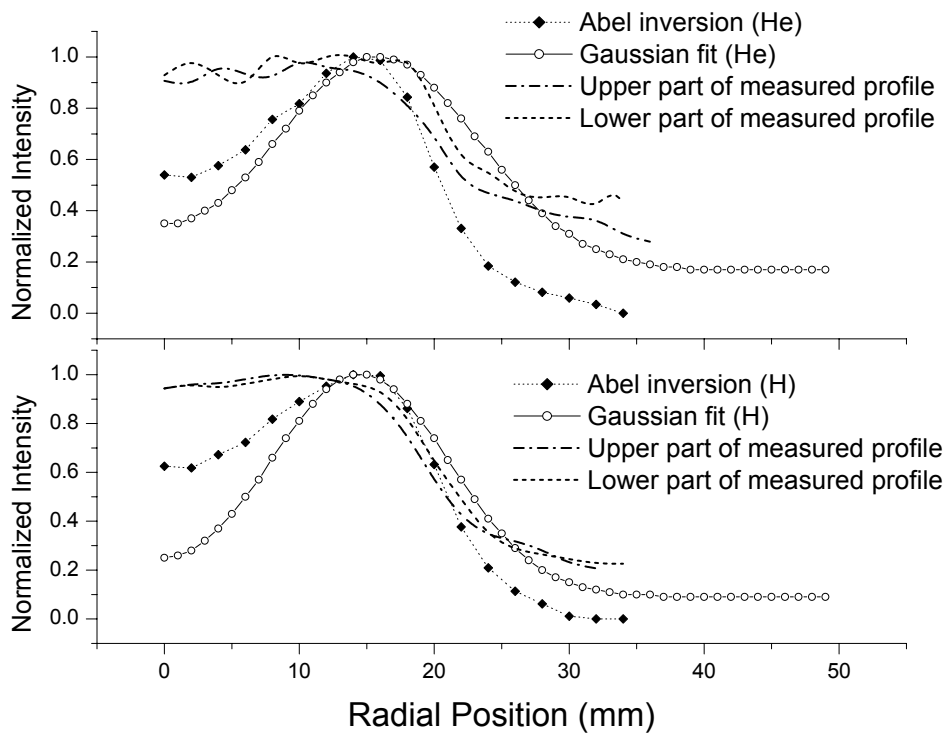
Fig. 5 Normalized radial profile of the density of light emitted inside the plasma for each wavelength. The resonance zone of 872Gauss is represented by the straight line.

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