Impact of Microwave Technology on ECRIS Performances*

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Abstract The coupling between microwave generators and ECR ion sources (ECRIS) is a key point for the design of the new generation ECRIS as well as for the optimization of the existing ones. The electromagnetic characterization of the plasma chamber where the ionization phenomena take place is a fundamental starting point to understand and model such process. In such effort the complex structures of the injection and extraction flanges together with the large dimensions of the chamber and the high frequencies that are typically used make impossible an analytical solution and also create great difficulties in the modelling even with state-of-art electromagnetic simulators (CST, HFSS). In the following paper the results of some numerical calculations for the optimum plasma chamber excitation will be presented along with the experimental measurements carried out with the SERSE ion source at INFN-LNS. A campaign of measurements is also planned to further investigate the microwave coupling and the mode excitation, which determines the efficiency of the ECR plasma heating.

Key words plasma, ion sources, ECR heating

1 Introduction

The Electron Cyclotron Resonance ion sources (ECRIS) are widely used in the accelerator facilities, increasing the beam energy and intensity, as well as for many industrial applications, making more efficient the industrial processes. There are some fundamental processes and parameters in the design of such sources and the optimization criteria changes depending from the final goal:

- Magnetic field profile and working frequency
- Microwave coupling
- ECR heating
- Beam extraction and transport

Up to recent times, the ECRIS performances improvement was strictly linked to the improvement of the magnetic confinement and to the increase of the frequency which, under good confinement conditions, takes to higher plasma density. In fact, the new ECRIS generation will feature boosted performances by shifting up the charge state distribution and the produced ion beam current. The optimization of the first of the previous items is done by using powerful magnetic traps for the axial and radial confinement together with the use of frequencies ranging between 28 and 37GHz according to the ECRIS standard model[1, 2]. The strong magnetic field needed for the plasma confinement originates a high stray field detrimental for beam optics, which makes complicate the beam extraction a transport processes in presence of space charge effects; for these problem

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solutions have been already proposed[3]. Only in the last few years the application of new microwave technologies to the ECR sources with B-minimum field have permitted to improve the microwave coupling to plasma and the amount of energy which is transferred from the microwave field to the warm electrons, responsible of the ionization process[4, 5]. In particular the optimization of such energy transfer and a better understanding and modelling of the ECR heating phenomena will play a fundamental role to enhance the performances of the existing sources and of the upcoming ones.

2 Microwave coupling and modes excitation

An important process, which is not well investigated, is the transfer of energy between the electromagnetic wave and the modes excited in the plasma chamber of an ECR source. In fact, not the whole power given by the microwave generator is coupled to the plasma chamber, but some can be reflected or lost on plasma chamber walls. This phenomenon, which can be seen electrically, oversimplifying the problem, as an impedance mismatch, depends from different parameters: operating frequency, geometry of the chamber, location of the waveguide in the injection flange and used transmission mode. In particular: the operating frequency and the geometry of the chamber define the possible operating mode(s) inside the cavity for the given frequency, while the location of the waveguide is important for the correct excitation of the mode(s) desired. The presence of plasma, which is an anisotropic medium, together with the ECRIS open cavities (holes for pumping, extraction, biased disk, oven, gas inputs, etc...) make more complex the construction of the model for the whole process when simulators for high frequency structures (e.g.: HFSS, CST) are used. Therefore to properly address the problem a numerical approach has been used by supposing an ideal closed cavity without plasma inside. A first step has been the calculation of the modes that can be excited in the cavity together with the determination of their maximum field position. The location of this maximum is extremely important, in fact, to achieve a good coupling for a certain mode the position of the waveguide in the injection flange must be close to the maximum field point. The calculations show that different modes present such maximum for different values of the radius.

Figures 1, 2 show respectively the map of mode $TE_{n,\nu,r}$ and $TM_{n,\nu,r}$ that can be excited in the SERSE ion source with the relative position of maximum.

It can be observed that the maximum location does not depend on the index r. Moreover, by looking into the electric field pattern in the cross section, the index n could be read as the order of symmetry of the mode (i.e. the mode presents $2n$ maxima along the circumference), while ν gives the number of maxima along the radius. From the previous figures it comes out clearly that for a fixed frequency only a discrete set of modes can be excited (i.e.: the modes which lie on the line passing for the operational frequency considered). The location of the waveguide will play a major role determining which of these modes can be really excited depending if the respective electric field presents in that location a hill or a valley (i.e.: if the electric field presents a maximum or a minimum). Finally, the electric field responsible of the electron acceleration in the chamber will be given by the superposition of the electric fields of these "elected modes". An important observation is that such "elected modes" and then the electric field resulting changes a lot by slightly varying the frequency.

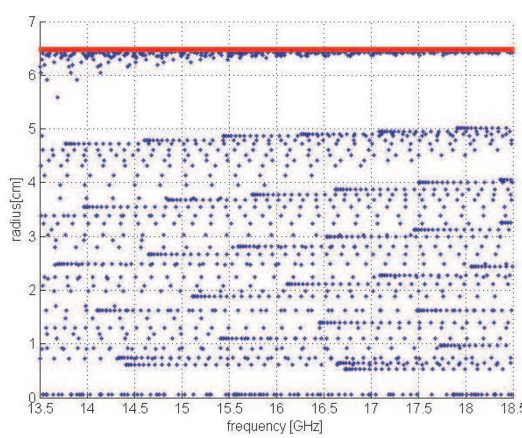

Fig. 1. The map of the SERSE $TE_{n,\nu,r}$ modes (the line at 6.5cm represents the plasma chamber walls).

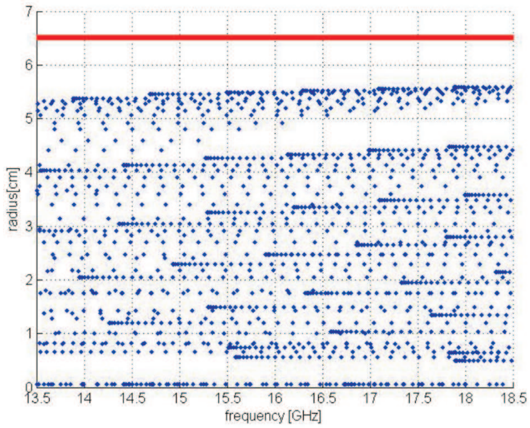

Fig. 2. The map of the SERSE $TM_{n,\nu,r}$ modes (the line at 6.5 cm represents the plasma chamber walls).

Therefore, a sort of "butterfly effect" happen in ECRIS by slightly varying the working frequency: little variations of the operational frequency can cause dramatic changes in the source performances. This effect was already observed by different laboratories employing TWTA and it clearly comes out the importance of the accelerating electric field in the electron heating phenomena. The first systematic observations were performed at the end of 2001 on the ECR ion sources SERSE and CAESAR at INFN-LNS[6] and recently on a SUPERNANOGAN source.

From the previous figures it seems also that there are some frequency intervals where it is not possible to excite any mode; however, taking into account the open structure of the ECR plasma chamber, because of the frequency dispersion of the microwave signal and the waveguide's physical dimensions, it is always possible to excite a mode for a given frequency even if with a poor coupling. Finally, from this analysis we can state that to optimize the microwave coupling a frequency tuning is needed. The most appropriate device to explore this technique is certainly a high power broad band amplifier with at least 1GHz bandwidth. However it could be also possible by employing a classical klystron based generator. In fact, standard klystrons have a tuner mechanism which permits to work on different channels (each one up to 80MHz wide) so that a maximum frequency coverage around 800MHz can be obtained.

In order to characterize the SERSE plasma chamber in terms of mode distribution and then to study the coupling of the two waveguide ports, measurements have been performed by employing a vector network analyzer Agilent PNA-L 5230 A able to work up to 50GHz. The two SERSE waveguide inputs, called in the following as $WG1$ and $WG2$, were connected respectively with the port 1 and 2 of the network and the scattering parameters have been recorded in absence of plasma inside the source plasma chamber. The S_{11} parameter indicates the power reflected by the plasma chamber through the waveguide WG1 and the S_{22} the one reflected by the waveguide $WG2$, while the parameter S_{12} represents the power measured at port 1 coming from the port 2. By analyzing these parameters it is possible to characterize the modes that exist inside the plasma chamber. In fact the frequencies which show the minimum values of the S_{11} or S_{22} and at the same time the maxima of the S_{12}, represent modes excited by the microwaves from the waveguides $WG1$ and $WG2$ respectively. Fig. 3 represents a full scan in the whole operating range. Below 9.5GHz the cut-off of the $WR62$ waveguide occurs, consequently there is no longer wave propagation inside it. Figs. 4 and 5 show the S-parameter in a narrow range around 14GHz and 18GHz which is the frequency range used during normal operations (it must be remarked that the measurements were done with a step of 125kHz).

These measurements give clear confirmations of all the theoretical observation previously mentioned, also providing the experimental evidence of the need for frequency tuning need.

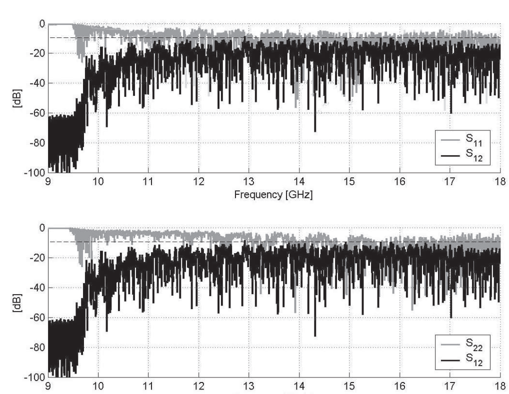

Fig. 3. SERSE scattering parameters (9—18GHz).

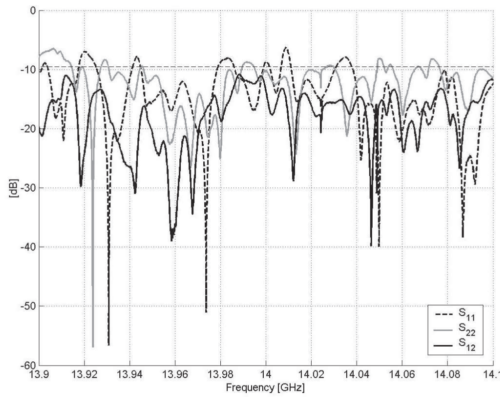

Fig. 4. SERSE scattering parameters (13.9—14.1GHz).

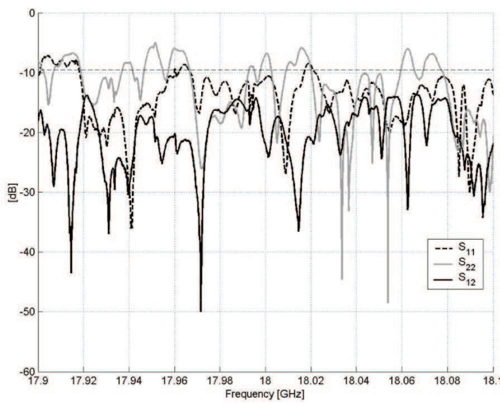

Fig. 5. SERSE scattering parameters (17.9—18.1GHz).

3 ECR heating

In an ECR ion source, if we neglect the Doppler and relativistic effect, the energy transfer between the microwaves and the electrons occurs where the electron cyclotron frequency is equal to the frequency of the monochromatic electromagnetic wave. This condition will be exactly achieved when electrons pass through the egg-shaped surface characterized by a static magnetic field $B=B_{\mathrm{ECR}}$. A first way to improve such energy transfer is to use a multiple set of discrete frequencies as actually featured by the most performing ECR sources. In this case two different processes happen macroscopically inside the cavity. The first one is the increase of the number of “elected modes” which superposition creates the electric field responsible of the electron acceleration. This modification could improve the performance of the source or could be also detrimental depending from the excited modes and from the amount of power used for each frequency. The second process concerns the transfer of energy that will take place on a set of surfaces nested instead of a single one. A new approach is also being developed by providing microwaves with a certain bandwidth to the cavity. In this case, considering the non uniform magnetic field, the electron resonance phenomena will take place in a volume, instead of a simple surface (or multiple set of surfaces). Consequently more electrons can be involved in the resonant interaction and they can also reach higher energy because, for a given power level, the interaction lasts for the whole time spent by passing through this resonance zone. It can be easily understood that this effect positively influences the performance of the source thus making the number of energetic electrons larger and the ionisation process more probable. However, in this case a great number of “elected modes” is triggered and most of them will be excited only with low power especially if a TWTA is responsible of the amplification of the whole bandwidth. Moreover, increasing the bandwidth such number of “elected modes” increases and the changes in the electric field responsible of the electron acceleration are difficult to be evaluated. A possible drawback of this operational regime is that the microwave coupling not optimized on some frequencies can lead to strong impedance mismatch and then to a higher reflected power. Therefore, even if such operational mode seems to be promising, further evaluations and experimental tests are needed to give a final answer about the most effective operational mode to heat the ECR plasma. Since the mode distribution depends from the plasma chamber dimensions and from the operating frequency, it is not possible to have a general criteria, but evaluation for each source should be performed.

4 Discussion

The results here reported clearly indicate that an improvement of the microwave coupling can significantly increase the performance of the existing and forthcoming ECR ion sources. The frequency tuning is a powerful method which permits the optimization of the coupling by changing the operating frequency. To perform such trick on 2[nd] generation ECR sources the development of broadband microwave generators able to produce up to 2kW at 18GHz with at least 1GHz bandwidth is mandatory. The actual microwave technology already permits to obtain a TWTA which can meet these requirements even if is too expensive. Nevertheless, as previously mentioned, even working with a classical klystron based generator it is possible to cover a significant frequency range by changing the operating channel. The main constraint of this kind of generator is that once fixed the working channel the available bandwidth is only around 80MHz. This value will certainly does not permit to fully exploit the possibility given by the multiple frequency heating or broadband operations with only one unit. Concerning the coming 3[rd] generation ECR sources the problem should be deeply studied by means of simulations and with a set of measurements like the one performed on SERSE. Our calculations clearly show that the number of modes strongly increase by increasing the frequency, therefore to optimize the coupling and the ECR heating the development of a high power high frequency microwave generator with similar bandwidth is needed (e.g.: a 10kW GyroTWT working in the range 30—35GHz). In the near future further tests are planned to check if the picture of the coupling process here presented changes substantially with the plasma. From our simulations, we expect only a shift in frequency of the modes with respect to vacuum operations. This will not affect the generality of discussion but it will introduce an offset in the Figs. 1 and 2. Finally ECR heating experiments will be carried out with discrete set of frequency and broadband signals by paying attention to the shape of the electric field responsible for electron acceleration which is, from our preliminary calculations, the discrimination factor.

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