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Optimization of high efficiency and high intensity ECR and Microwave Discharge Ion Sources

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Different ion sources have been developed and built at INFN-LNS during the last decades. Electron Cyclotron Resonance and Microwave Discharge Ion Sources have been designed at 2.45, 14, 18 GHz, as well as intermediate operating frequencies. Some 2.45 GHz microwave discharge ion sources have been built for different purposes, ranging from high efficiency ionization of light ions to high current proton beams production. Higher frequencies ECR sources have been developed for the production of low current (eμA level) of high charge states and high currents (emA level) of medium charge states. The optimization of the microwave coupling to plasma has been carried out in order to improve the performances of such sources. The description of the methods will be given, along with a detailed discussion of the results.

Introduction

When microwaves are injected into a gas-filled chamber in the presence of high magnetic field, an energy transfer between the high frequency electromagnetic wave and the free electrons may take place. In this case the electrons momentum is increased by the microwave field to the extent that collisions with neutral atoms lead to the gas ionization; plasma produced by this process is therefore confined by an adequate magnetic field. Two different principles can be applied in order to generate and sustain the plasma under these conditions: *Electron Cyclotron Resonance (ECR),* and *Off-resonance heating* [1, 2]. At INFN-LNS both types were considered for the development of ion sources, both for high charge states ion production as SERSE [3] and CAESAR [4] which are ECRIS-type sources, and for high efficiency or intense beam production as MIDAS [5] and TRIPS [6] which are Microwave Discharge-type sources. In order to improve the efficiency of these sources, a proper coupling optimization for the microwave power supplied by the generator (Klystron, TWT, Magnetron) to the source chamber was required. Today, the wave-plasma coupling structures are mainly based on an empirical approach, rather than on techniques where everything is totally precalculated. This is most true when high frequencies are used, and further development is expected for sources working at 28 GHz or more.

Microwave Discharge ion sources

The coupling scheme is equal for the two sources: the microwave power is supplied by a 2.45 GHz, 2 kW Magnetron coupled to a cylindrical plasma chamber (100 mm long and with 100 mm diameter) through a circulator, a directional coupler and an automatic tuning unit. The matching of the microwave supply to these sources was obtained by a multi-section quarter wavelength transformer [7], optimized to adapt the characteristic impedance of a WR284 waveguide working in the dominant mode (TE_{10} mode) to the “equivalent impedance” of the plasma filled chamber. This impedance was measured at LNS on the MIDAS source and it was found to be, according to the literature, around 100 Ω. The transformer, made of four consecutives $\lambda/4$ sections, was placed immediately ahead the microwave window. Because of the low frequencies, in this case the source cavity may be thought as single mode excited [1], for instance, with the TE_{111} mode of a cylindrical chamber. This is true only for first order approach, because for very over dense plasma nonlinear wave conversion may take place. The transformer insertion enhanced the efficiency of the microwave coupling between waveguide and plasma filled cavity. Moreover, it was designed to concentrate the electric field at the center of the plasma chamber (in our design the field enhancement ratio is almost 2), as it was confirmed by the spot of the plasma on the vacuum window (more intense at the center and decreasing towards the peripheral region with two horizontal lobes). The overall result was a significant increase in the extracted current density.

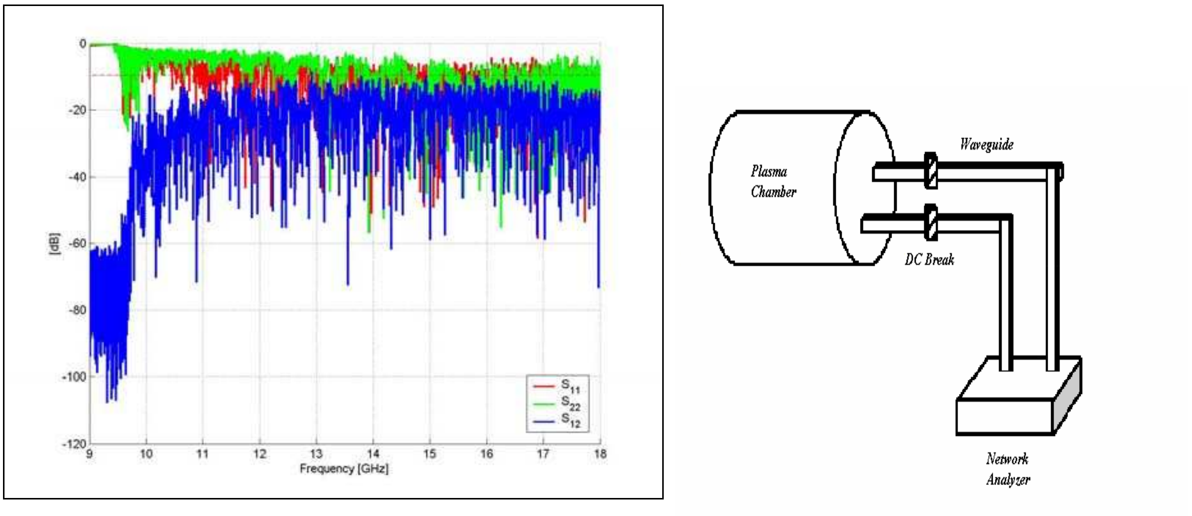
ECR ion sources

The definition of the coupling structure for ECR sources working at higher frequencies, like the 14 and 18 GHz SERSE, takes care of many considerations. In this case we are generally in presence of multi-mode structures, and the SERSE cylindrical cavity, with 13 cm diameter and 48 cm length follows this rule. It was shown [8] that for its vacuum filled chamber it is possible to excite many modes simultaneously, when operating both at the 14 and at the 18 GHz frequencies. It was also demonstrated that this modes bunching increases with the microwave excitation frequency. The presence of holes in the cavity and even more of the

ECR resonance process, lead to a broader frequency superimposition for the modes. In order to show it, some simulations were performed by both CST MICROWAVE STUDIO™ [9] and ANSOFT HFSS™ [10] numeric electromagnetic solvers. It was possible in this way to calculate the resonant frequencies of the holed air filled chamber and to analyze the coupling between the cavity and its microwaves supply ports [11]. If all the interested modes will be excited by the incoming electromagnetic wave, we could have some isotropic-like distribution of field inside the chamber [1,8]. When the cavity is filled with plasma, the modes are forced to increase their resonance frequency, and it causes a debunching, increasing for higher electron densities, that was described for the case of a not-collisional uniform plasma. This investigation included the performing of some preliminary experimental measurements on the microwave input coupling of the SERSE chamber, executed by a 50 GHz Vector Network Analyzer. The measurements were carried out with and without the presence of the Teflon dielectric microwave window. They have been performed for the air filled cavity, by connecting directly the two WR62 waveguide microwave ports of the SERSE chamber to the network analyzer. The S_{11}, S_{22} and S_{12} parameters were measured, and they are shown in Figure 1, together with the corresponding experimental measurement setup. By analyzing these parameters it is possible to obtain information about the modes excited in the cavity, and to study its relative coupling to the WG1 and WG2 waveguides input ports. From Figure 1 it is clearly noticed that in proximity of 9.3 GHz there is the waveguide cut-off frequency, and therefore for frequencies below it the wave propagation is not possible in the waveguides. Thus, the determination of the resonant modes in the cavity by this method can be accomplished only for higher frequencies. Some electromagnetic simulations have shown that the accurate study of the electromagnetic properties of the plasma chamber is possible at the moment only for low frequencies, up to some GHz. With more powerful calculation resources a detailed electromagnetic study and modelling of the plasma chamber may be carried out also for higher frequencies.

Conclusions

The microwave coupling enhancement is a key point to optimize the performance of future Microwave Discharge or ECR ion source. For the first, well consolidated schemes permit to obtain a very good coupling between plasma chamber and microwave generators; for the second the problem is well addressed, even though further developments are needed before to obtain a complete electromagnetic characterization of the plasma chamber. With the purpose to determine the conditions for the optimised coupling between cavity and generators, some other measurements are planned in future also with the presence of plasma inside the chamber.



(a) (b)

Figure 1: (a) Measured scattering parameters in the 9-18 GHz frequency range. (b) Experimental setup for the performed measurements.

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