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Non-Conventional Microwave Coupling of RF Power in ECRIS Plasmas

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Abstract. X-ray imaging and numerical simulations demonstrate that the RF power deposition in ECRIS plasmas is not concentrated in the near-axis region, as it would be desirable in order to maximize the ion beam brilliance. There are different arguments to explain this occurrence as due to the symmetry of the plasma chamber. In an "aperture coupled cylindrical cavity resonator, in fact, often off-axial eigenmode solution of Maxwell equations are excited leading to an off-axial concentration of the electromagnetic field. The "aperture-coupling of the rectangular waveguides with the cylindrical chambers (as it is normally for ECRIS) also suffers of an intrinsic, geometrical impedance mismatch. Both these issues suggest that a major optimization of RF coupling efficiency to ECRIS plasmas is still possible, provided that the overall geometry is changed. A reshaping of both the plasma chamber and related RF launching system - in a plasma microwave absorption oriented scenario - is considered as a possible solution, as well as the design of optimized launchers (taking inspiration from tools adopted in the thermonuclear-fusion) enabling "single-pass power deposition, not affected by cavity walls effects.

RESHAPING OF THE PLASMA CHAMBER AND RF LAUNCHING SYSTEM

In the ECRIS community there is a great interest in increasing the efficiency of ECR heating as a way to maximize the current of extracted ions. Experiments have identified a number of useful techniques for maximizing the extracted currents, such as frequency scaling, multiple frequency heating and "frequency tuning" [1, 2, 3]. Recently, experimental data from optical x-ray imaging technique have been used to investigate the plasma of an ECRIS [4]: both the experimental X-Ray imaging and numerical results illustrated in [4] suggest to revise the microwave power deposition mechanism, with the aim to maximize the absorption of the RF power into the plasma core, thus avoiding hollow plasma and (consequently) beam formation leading to lower extracted currents.

Several efforts have been dedicated to improve RF coupling to ECRIS plasmas, most of them devoted to Frequency Tuning Effect and double frequency heating [5, 6, 7], which is now routinely adopted for beam optimisation (both in terms of currents and phase-space parameters) in many ECRIS worldwide. In particular, the best performing ECRISs worldwide such as SECRAL [8, 9], VENUS [10] or SERSE [11], improved their performance for the production of highly charged ion beams by means of: innovative magnetic system, efficient double-frequency heating and innovative launching wave mode. However they also put in evidence the requirement of higher and higher magnetic fields and microwave power according the most straightforward but technologically challenging/risky path to achieve higher source performance. This strategy suffers the intrinsic currents limitations affecting these machines, relying on the well known "omega-squared" law, (due to the electromagnetic cutoff and RF scattering into the loss cone [12]).

One possibility to overcome this problem is changing in ECRIS the coupling schemes, such as XB or OXB

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conversion as attempted in [13]. It is well known in the field of fusion reactors that modal-conversion requires high control of RF launching into the plasma [14]. Taking inspiration from phased multi-waveguide structures (nicknamed waveguide "grill" [15]) designed to launch microwaves at the lower hybrid resonance to heat large toroidal plasmas, a double-waveguide antenna system has been proposed for the FPT [16] because not only the power, but also the launching angle [17] and wave polarisation need to be controlled too. The latter point is deemed as crucial for any future developments of ECRIS. Up to now, in fact, RF launching in these machines has been based on the very simple scheme of rectangular (or, more rarely, circular) waveguides mechanically connected to cylindrical plasma chambers with an intrinsically poor RF coupling.

This article proposes a new development mostly in terms of microwave coupling systems and plasma chamber shapes following the magnetic filed structure. In fact, the physics processes of ECR hot plasma is still poorly understood, mainly due to the difficulties in decoupling the parameters of the different physics processes involved in the ECRISs, like the plasma magnetic confinement, the interaction between electromagnetic waves and plasma, the interaction between plasma and the chamber surface. We describe hereby a reshaping of both the plasma chamber and related RF launching system as a possible new concept and strategy which intrinsically tries to keep unified the various physics processes. The optimum design of a cavity for ion source is the consequence of a series of compromises between different parameters, ranging from RF consideration to mechanical issues, and takes into account specific fabrication constrains.

ECRISs are microwave-driven plasma devices originated from fusion research [18]: their own origin suggests a variation of the morphology of the plasma chamber. The fusion reactor plasma vessels have tipically a shape that mimics that of the magnetic field; also the surrounding magnetic coils have an appropriate shape that generate the helical field required for confinement. Herein we propose for ECRISs: a novel cavity resonator shape, (see Fig. 1a-bottom) with a non-uniform cross section matched to the twisting magnetic structure (see Fig. 1a-top).

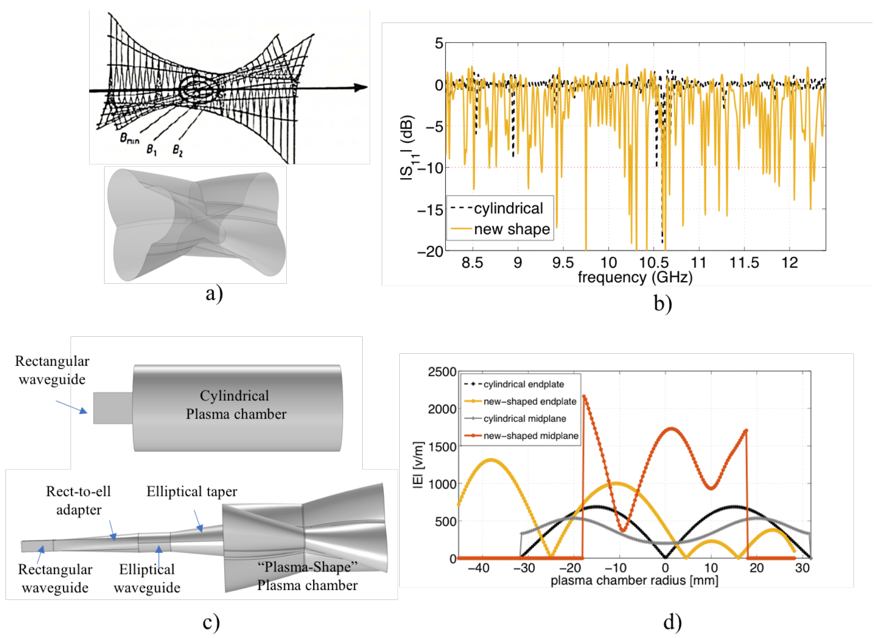

FIGURE 1. a) top: minimum-B field magnetic field structure, bottom: plasma chamber new shape. b) Simulated Reflection coefficient $|S_{11}|$: Cylindrical plasma chamber presents a poor RF matching compared with the new shaped-cavity; c) top:"aperture-coupling by rectangular waveguide ; bottom: new RF launching on "new-shaped" plasma chamber; d) Simulated Electric field profile at 10.3 GHz along the plasma chamber extraction end-plate and mid-plane diameter: Cylindrical plasma chamber presents a zero-field on axis compared with the peak electric field the "new-shaped" plasma chamber.

Moreover, a new RF launching scheme ((see Fig. 1c-bottom) based on properly matched fundamental mode operating H_{c11} elliptical waveguide and tapered elliptical waveguide [19] in order to obtain a better geometrical and RF matching to the new "plasma-shaped" plasma chamber, has been proposed. This avoids the typical geometrical mismatch of the wave launching scheme commonly used in ECRIS, the traditional off-axis rectangular waveguides

”aperture-coupled with cylindrical chambers (see Fig. 1c-top). Moreover, elliptical waveguides are well-suited thanks to their low attenuation, easy of handling and design also with extra-low attenuation by overmoding. Commercial standard flexible solutions allow a continuous length of waveguide to be run directly from a Klystron or TWT power-amplifier to the plasma chamber, thanks to their inherent strength and flexibility . This results in reduced installation cost compared to rigid rectangular waveguides due to flexibility, no need of flange joints, twist section and bends.

This non-axisymmetric shape breaks the RF field symmetry which in classical cylindrical plasma chamber is deemed to produce a plasma shape (as examined in [4]) intrinsically “hollow”. The “hollowness” of the plasma structure can be associated with RF eigenmode solution of Maxwell equations which prefer off-axial concentration of the electromagnetic field (see Fig. 1d), black and grey curves). Also the MHD stability which depends on the morphology of the magnetostatic field could be optimized with such a camera design (there is more room, for example, for the mid-coil (s) thanks to the new plasma-chamber shape). The geometric constraints would depend on the last closed surface-B, which as we can see in [4] does not differ much from the ECR-surface in the median plane.

A full-wave electromagnetic model for this new plasma chamber and RF launching system has been developed in order to validate our previous statements. The full-wave 3D simulation of a complete elliptical waveguide connected to the “plasma-shaped” plasma chamber, performed in the monomodal-bandwidth of the WR90 waveguide (8.2-12.4 GHz), demonstrates the capability of achieving reliable results by using the proposed approach and confirm the validity of our assumptions. Figure 1 b) shows the reflection coefficient $|S_{11}|$ values for the simulated model (in CST) for both the classical cylindrical plasma chamber driven by standard rectangular waveguide and the new-shaped plasma chamber including thew new RF mode launcher.

The new structure has a better impedance match with respect to the classical scheme because $|S_{11}|$ is less than -10 dB for a greater number of frequencies. Note that power flowing back into the port at extremely bad matched frequencies and poor numerical precision cause the $|S_{11}|$ to be slightly unphysically greater than zero. This numerical artifact could be reduced by a finer meshing.

Full-wave electromagnetic model for this new plasma chamber and RF launching system confirm that the matching could be significantly improved. A reshaping of both the plasma chamber and related RF launching system - in a plasma microwave absorption oriented scenario - is considered as a possible solution for a better wave-to-plasma coupling in ECRIS and to avoid the “hollowness” of the plasma structure.

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REFERENCES

[1] Geller R., et al. Proc. 8th Int. Workshop ECR Ion Sources, Vol. 1 (1987), p. 22; report MSUCP-47.
[2] S. Gammino and G. Ciavola , Plasma Source Sci. Technol., 5 19 (1996).
[3] D. Mascali et al., Rev. Sci. Instrum. 83(2):02A336. (2012
[4] R. Racz et al, Plasma Source Sci. Technol., **26**,7,075011, (2017)
[5] L. Celona et al., Rev. Sci. Instrum. **79**, 2,023305, 2008, 10.1063/1.2841694
[6] Z. Q. Xie and C. M. Lyneis, in Proc. of the 12th ECRIS, Wako, INS-J-182, p. 24 (1995).
[7] V. Skalyga et al.,, Physics of Plasmas 22 , 083509 (2015); doi: 10.1063/ 1.4928428.
[8] L. T. Sun et al., (invited), Rev. Sci. Instrum. 87, 02A707 (2016).
[9] H.W. Zhao, et al. Phys. Rev. Accel. Beams **20**, 094801 2017
[10] C. Lyneis, D. Leitner, M. Leitner, C. Taylor, and S.Abbott, Rev. Sci. Instrum. **81**, 02A201 (2010).
[11] S. Gammino, G. Ciavola, L. Celona, D. Hitz, A. Girard, and G. Melin, Rev. Sci. Instrum. 72, 4090 (2001).
[12] A. Girard et al., Phys. Rev. E, 62(1), 1182, (2000).
[13] G. Castro et al., Plasma Sources Sci. Technol. 26, 055019, (2017).
[14] A Kohn, G Birkenmeier, E Holzhauer, M Ramisch and U Stroth, Plasma Phys. Control. Fusion 52 (2010) 035003 (13pp) doi:10.1088/0741-3335/52/3/035003
[15] M. Brambilla, NUCLEAR FUSION 16, (1976)
[16] S. Gammino et al; JINST **12**(07), 07027 (2017).
[17] G. Torrisi, G. Sorbello, O. Leonardi, D. Mascali, L. Celona, and S. Gammino, Microw. Opt. Technol. Lett., 58: 26292634. doi:10.1002/mop.30117
[18] R. Geller, IEEE Trans. Nucl. Sci. 23, 904 (1976).
[19] L. Accatino, G. Bertin and M. Mongiardo, IEEE Trans. Microw. Theory Techn., **45**, 12, 2393 (1997)