URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Slotted Antenna Waveguide for Microwave Injection in Ion Sources

G. S. Mauro(1)(2), G. Torrisi(1), O. Leonardi (1), A. Galatà(3), C. S. Gallo (3)(5), G. Sorbello(1)(4) and D. Mascali(1)
(1) Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS),
Via S. Sofia 62, 95123 Catania, Italy
(2) Dipartimento di Ingegneria dell'Informazione, delle Infrastrutture e dell'Energia Sostenibile,
Università degli Studi Mediterranea di Reggio Calabria Salita Melissari, 89124 Reggio Calabria RC, Italy
(3) Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Legnaro (INFN -LNL),
Viale dell'Università, 2, 35020 Legnaro PD, Legnaro, Padova, Italy
(4) Dipartimento di Ingegneria Elettrica, Elettronica e Informatica, Università degli Studi di Catania,
Viale Andrea Doria 6, 95125, Catania, Italy
(5) Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, 44122 Ferrara, Italy

Abstract

This paper presents the design of an innovative method of microwaves injection inside an Ion source plasma chamber based on slotted waveguide antennas. This microwave launching system placed along the side walls has advantages with respect to the conventional axial end-launch waveguide scheme, and its adoption could be relevant for improving the performances of Electron Cyclotron Resonance Ion Sources (ECRISs) [1]. A better power coupling and a more symmetric power distribution from the multiple radiating waveguide slots, has been obtained by the proposed design. The slotted waveguide, operating in the band [14.2;15.25] GHz exhibits a tuning range of about 7%, thanks to the launcher to cavity coupler optimization carried out with the commercial simulator CST Microwave Studio. The modal distribution coupled inside the plasma chamber by the new launching scheme has been compared with the one obtained by the classical axial launching scheme. Furthermore, a numerical validation of future electric field profile measurement through bead-pull has been performed.

1 Introduction and motivation

Microwave-to-plasma coupling in ECR Ion Sources is based on the matching of the injection waveguide to the plasma cavity. The variation in the performances in terms of extracted current have been explained by taking into account the different patterns of the electromagnetic fields on the resonance surface [2, 3]. In order to improve the ECR heating scheme, some novel microwave launch models are in development. This paper describes the numerical modeling of an innovative microwave launch scheme in ECR ion sources that employs a slotted waveguide placed on the chamber outer wall. This new geometry greatly improves the number of modes that can be efficiently coupled: this could lead to some advantages in terms of ion source frequency tuning [4]. Moreover, this innovative solution also releases spaces on the end flanges of the plasma chamber for the necessary ancillary equipment while offering a distribute and more homogeneous power transfer to the plasma compared to the classical axial injection scheme through rectangular waveguide.

2 Slotted waveguide antenna design

The geometry characterized in this paper is visible in Fig. 1. It is composed of a cylindrical cavity of diameter d = 63.5 mm and length $L = 150$ mm, which are typical dimensions for an ECRIS plasma chamber [5], and two rectangular WR62 waveguides for microwave injection: the standard axial waveguide and a side waveguide running along the chamber outer wall that is coupled to the cavity through several slots.

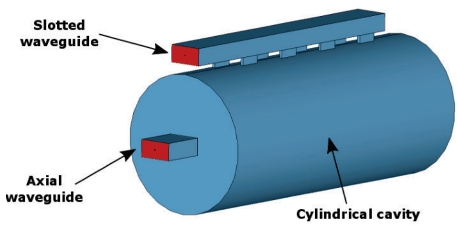

Figure 1. Simulated cylindrical chamber geometry with the axial and slotted waveguide launch structures.

Slotted waveguides have found many applications in radar and communication systems due to their low-profile design requirements, mechanical robustness, good efficiency, relative ease of realization and wide operational frequency bandwidth [6, 7, 8]. We started with the design of a slotted waveguide antenna working in free space. Recalling that the guided wavelength for the TE_{10} mode of the rectangular waveguide is $\lambda_g = \frac{c}{f}\frac{1}{\sqrt{1-c/(2af)}}$, where f is the operational frequency and a is the waveguide large dimension, the general rules for the design of a slotted waveguide antenna can be found in [9, 10] and can be summarized as following:

- the center of the first slot on the waveguide aperture size should be placed at a distance $\lambda_g/4$ from it;
- the center of the last slot should be placed at a distance $\lambda_g/4$ from the metallic wall that closes the waveguide;
- the distance between the centers of two consecutive slots should be equal as $\lambda_g/2$;
- the slot length should be equal at $\lambda_0/2$, where λ_0 is the free space wavelength, while the slot width should be much smaller with respect to λ_0.

The exact slotted waveguide antenna dimensions can be finely tuned by the use of the electromagnetic simulator. Another important parameter is the slot number, for which some consideration can be taken into account. In general, the less is the slot number, the larger is the impedance bandwidth [11]. However, the usage of a low number of slots negatively impacts on the antenna efficiency, so this parameter needs to be tuned for each considered case of study. The antenna presented in this paper, designed with the use of CST Microwave Studio and shown in Fig. 2, works in the band [14.2; 15.25] GHz with central frequency 14.7 GHz. The number of slots, eight in our case, has been chosen with the objectives to maximize the $|S_{11}|$ impedance bandwidth and to obtain an almost uniform radiation pattern. Also, this value has been selected considering the available space along the chamber outer wall, in our case equal to 150 mm.

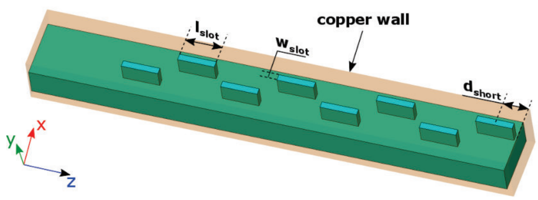

Figure 2. Slotted waveguide antenna model with its fundamental parameters: slot length l_{slot}, width w_{slot} and distance from the short circuit d_{short}. The air volume (blue object) and the copper enclosure (orange semitransparent object) are visible.

A sensitivity study has been performed on the antenna dimensions, it the way to finely tune the performances. Among the others, it is well known that a critical parameter that can affect the width of the impedance bandwidth is the width of the slots [11], or w_{slot}, as depicted in Fig. 3, where the $|S_{11}|$ has been computed for different values of this parameter. A good compromise between impedance bandwidth and antenna efficiency has been found when $w_{slot} = 2$ mm.

3 Cylindrical cavity simulation results

In order to study the cavity modal distribution (eigensolutions) for the proposed setup, the plasma chamber in vacuum, without any external feed, has been simulated with the objective to evaluate the TE and the TM modes excited inside the cavity in the frequency band of [13;15] GHz. The modes inside the cavity are shown in Fig. 4: for each plot, an appropriate symmetry condition has been imposed in the way to excite either TE or TM modes. In the frequency band of interest the number of TM modes is 86 while the number of the TE modes is 79.

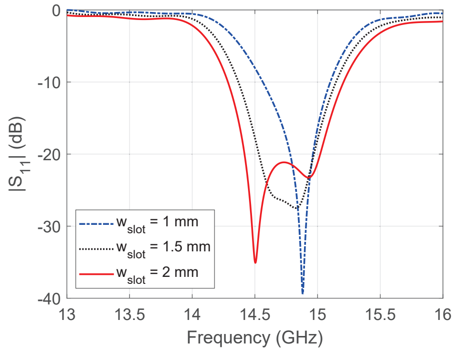

Figure 3. $|S_{11}|$ vs. slot width w_{slot}: it can be seen that this parameter affects the impedance bandwidth.

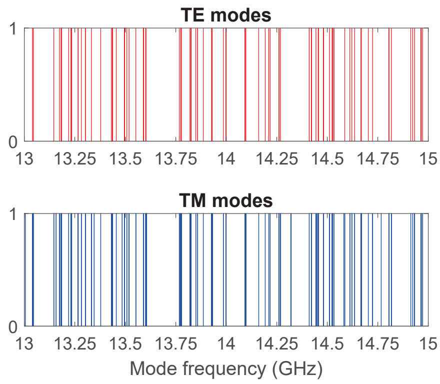

Figure 4. Bar plot of the TE and TM modes inside the cylindrical cavity in the frequency interval of [13;15] GHz.

3.1 Side coupling scheme vs. axial coupling scheme

The slotted waveguide antenna presented in the previous section has been optimized by following the well known guidelines that are given for slotted waveguides radiating in free space. This study represents a first step in the design of the proposed, novel coupling scheme of microwaves to plasma chambers. The second step considers the coupling of the slotted waveguide to the actual plasma chamber. The cylindrical cavity has been simulated considering two microwave launch geometries: (a) a standard axial launch with a rectangular WR62 waveguide and (b) a launch along the camber outer wall by the use of a slotted waveguide. For the second case (side coupling), the slotted waveguide antenna optimized in free space has been taken as starting point and then the whole geometry has been further tuned in the way to select modes with a strong axial component at a frequency near the slotted waveguide antenna central frequency of 14.7 GHz. The numerical study can be divided into three steps:

- (a) simulation of the cylindrical cavity with only the presence of a launch axial waveguide;
- (b) simulation of the cylindrical cavity with only the presence of a launch side coupled slotted waveguide;
- (c) simulation of the cylindrical cavity with the presence of both launch geometries (see Fig. 1).

The $|S_{11}|$ for cases (a) and (b) is visible in Fig. 5. From the figure it can be observed that the slotted waveguide launch scheme (b) excites a larger number of modes inside the cavity with respect to the axial launch scheme. The presence of a large number of modes could be an advantage in single frequency operation of the ion source when the frequency tuning effect is applied.

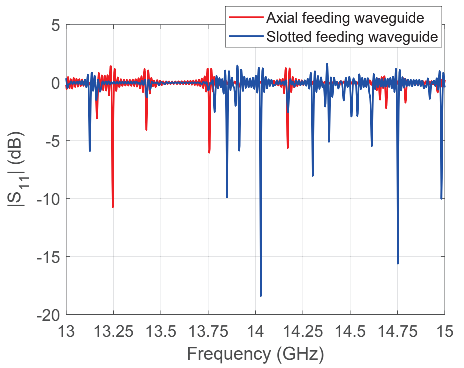

Figure 5. $|S_{11}|$ for the launch configurations (a) and (b). The slotted waveguide launch excites a large number of modes inside the cavity with respect to the classical axial launch scheme.

For case (c), both waveguides have been fed through two waveguide ports. The $|S_{11}|$ and $|S_{22}|$ for the case (c) are shown in Fig. 6: it can be seen that the modal distributions inside the band of interest remains the same, that is the two launch schemes do not interfere with each other.

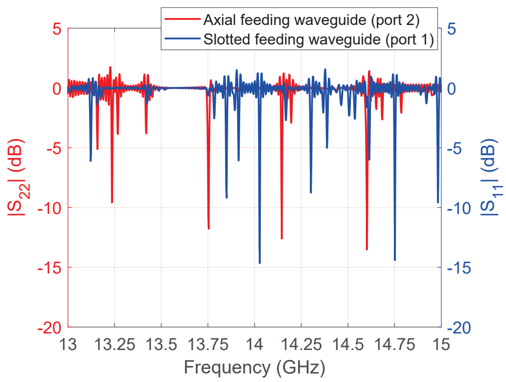

Figure 6. $|S_{11}|$ and $|S_{22}|$ for the launch configuration (c). The presence of both launch schemes do not alter the modal distribution inside the band of interest.

3.2 Simulation of the bead-pull measurement

Once the modal distribution has been observed inside the cylindrical chamber for both launch schemes, it could be useful to evaluate the electric field for a selected mode. In the case of standing wave cavities, the measure of the electric field is made through the bead-pull technique and it is based on the classical Slater perturbation theory [12]. A tiny metallic or dielectric perturbing object, for example a properly dimensioned sphere, is moved along a specific direction inside the cavity; the bead movement perturbs the stored energy inside the cavity and this results in a small frequency shift $\Delta f = f - f_{perturbed}$ of the mode being considered. The frequency shift is related to the electric and magnetic field strengths presents in the area adjacent at the perturbing bead through the Slater theorem

$$\frac{\Delta f}{f} = -\frac{3\Delta V}{4U}\left[\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\varepsilon_0|E|^2 + \frac{\mu_r - 1}{\mu_r + 2}\mu_0|H|^2\right] \tag{1}$$

where ΔV is the bead volume, U is the stored energy inside the cavity, $|E|$ and $|H|$ are the electric and magnetic field of the mode being considered. Using the slotted waveguide feeding scheme, a mode at (unperturbed) frequency $f =$ 14.612 GHz with a predominant electric field along the cavity axis has been chosen as the objective of the simulation. A small metallic spherical bead of diameter 1.4 mm has been moved along the cavity axis for a distance of 140 mm, with a step of 2 mm, and the $|S_{11}|$ of the mode of interest has been acquired at each step. In this work, instead of the frequency shift, the phase-shift $\Delta\angle|S_{11}|$ has been measured due to the higher sensitivity of the latter, at the resonance frequency, that helps to reconstruct the electric field with more precision. Once the samples have been acquired, through (1) the 'measured' electric field can be related to the frequency (or phase) shift as $|E| \sim \sqrt{\Delta\angle|S_{11}|}$. Fig. 7 shows the simulated electric field obtained with the bead-pull technique vs. the electric field profile evaluated along the cavity axis through a standard simulation. The curves have been normalized to their maximum value. It can be seen that the two curves are in excellent agreement between each other.

4 Discussion and conclusions

In this paper, a novel microwave launching scheme for ECRIS plasma chambers, based on the use of a slotted waveguide placed along the chamber outer wall, has been presented. The slotted waveguide has firstly been studied as an antenna in free space, with the objective to study its behaviour against its fundamental design parameters. In a second step, the slotted waveguide has been jointed to a cylindrical plasma chamber and the modal distribution has been evaluated and compared with that found, for the same plasma chamber, with a standard microwave axial injection scheme. It has been found that the use of this launching scheme greatly improves the number of modes that can be coupled in the considered operational frequency bandwidth: this could be an advantage if the

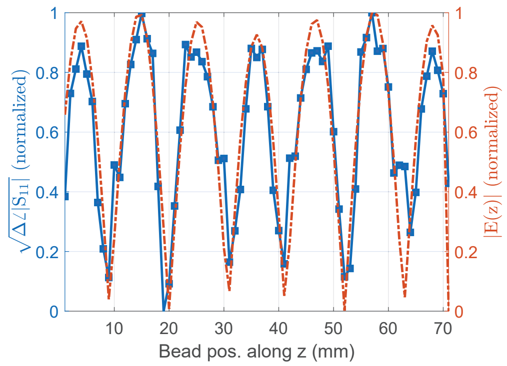

Figure 7. Field profile obtained with the bead-pull technique (blue marked curve) vs. simulated field profile extracted along the cavity axis for a length of 140 mm (red dot-dashed curve).

frequency tuning effect is applied on the ECR source in order to improve its performances. Other advantages with respect to the axial launch scheme include the more uniform launch of microwaves inside the chamber and the possibility to have more space on the injection flange usually employed for gas injection and other ancillaries. Finally, an electric field measurement setup, based on the Slater perturbation theorem, has been optimized and validated through full wave simulations, resulting in an optimal field reconstruction. The presented microwave launch scheme is currently not applicable to existing ECR machines, since the reduction of the plasma chamber radius would cause a decrease of the maximal magnetostatic field available for plasma confinement. But, in perspective, a radical change in the shape of the chamber itself, allowing space along the lateral chamber walls without affecting the confinement, will also permit to radically change the microwave coupling scheme, implementing slotted waveguides. This is part of the IRIS project [13, 14], that is now entering its executive phase.

Acknowledgment

The authors wish to thank the 5th Nat. Comm. of INFN, under the PANDORA Grant, for the financial support. Part of this work has been carried out within the Grant73/IRIS project, also supported by INFN (Italian patent pending n. 102020000001756).

References

[1] R. Geller, *Electron cyclotron resonance ion sources and ECR plasmas*. Institute of Physics, 1996.

[2] D. Mascali, L. Neri, S. Gammino, L. Celona, G. Ciavola, N. Gambino, R. Miracoli, and S. Chikin, "Plasma ion dynamics and beam formation in electron cyclotron resonance ion sources," *Rev. Sci. Instrum*, vol. 81, 2010.

[3] S. Gammino, G. Ciavola, L. Celona, D. Mascali, and F. Maimone, "Numerical simulations of the ECR heating with waves of different frequency in electron cyclotron resonance ion sources," *IEEE T PLASMA SCI.*, vol. 36, no. 4, 2008.

[4] L. Celona, S. Gammino, G. Ciavola, F. Maimone, and D. Mascali, "Microwave to plasma coupling in electron cyclotron resonance and microwave ion sources," *Rev. Sci. Instr.*, vol. 81, no. 2, p. 02A333, 2010.

[5] D. Mascali, L. Ando', G. Castro, L. Celona, L. Neri, S. Gammino, F. P. Romano, C. Altana, C. Caliri, G. Sorbello, and G. Torrisi, "Ecr ion sources developments at infn-lns for the production of high brightness highly charged ion beams," in *Proceedings of LINAC2014, Geneva, Switzerland*, 2014, pp. 254–256.

[6] F. Werner, D. Korzec, and J. Engemann, "Slot antenna 2.45 GHz microwave plasma source," *Plasma Sources Science and Technology*, vol. 3, no. 4, pp. 473–481, nov 1994.

[7] A. Woodard, K. Shojaei, C. Berrospe-Rodriguez, G. Nava, and L. Mangolini, "Electron emission from particles strongly affects the electron energy distribution in dusty plasmas," *Journal of Vacuum Science and Technology A*, vol. 38, 2020.

[8] R. V. Gatti and R. Sorrentino, "Slotted waveguide antennas with arbitrary radiation pattern," in *34th European Microwave Conference, Amsterdam, The Netherlands*, 2004, pp. 821–824.

[9] R. S. Elliott and L. A. Kurtz, "The design of small slot arrays," *IEEE Trans. Antennas Propagat.*, vol. 26, pp. 214–219, 1978.

[10] R. S. Elliott, "The design of traveling wave fed longitudinal shunt slot arrays," *IEEE Trans. Antennas Propagat.*, vol. 27, no. 5, pp. 717–720, 1979.

[11] S. S. Sekretarov and D. M. Vavriv, "A wideband slotted waveguide antenna array for sar systems," *Progress In Electromagnetics Research M*, vol. 11, pp. 165–176, 2010.

[12] T. P. Wangler, *RF Linear Accelerators*. WILEY-VCH, 2008.

[13] G. Torrisi, D. Mascali, G. Sorbello, G. Castro, L. Celona, A. Galatà, O. Leonardi, E. Naselli, and S. Gammino, "Non-conventional microwave coupling of RF power in ECRIS plasmas," *AIP Conference Proceedings*, vol. 2011, no. 1, p. 020014, 2018.

[14] C. Gallo, A. Galatà, D. Mascali, and G. Torrisi, "A possible optimization of electron cyclotron resonance ion sources plasma chambers," *Journal of Instrumentation*, vol. 13, no. 11, pp. C11 011–C11 011, nov 2018.