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ELECTROMAGNETIC STUDY AND OPTIMIZATION OF THE PM-TRIPS ION SOURCE AND THE RELATED MICROWAVE LINE

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Abstract

The microwave discharge proton source PM-TRIPS (Permanent Magnet TRASCO Intense Proton Source) is under construction at INFN-LNS and its goal is to generate a 40 mA proton current at 80 kV extraction voltage with low emittance and high reliability.
In order to improve the performances of such ion source, an electromagnetic study of the whole source with particular care to the microwave coupling and to the high voltage insulation has been carried out by using the Ansoft HFSS™ code and the results are here reported.

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1. Introduction

The microwave discharge proton source PM-TRIPS (Permanent Magnet TRASCO Intense Proton Source) is an optimized version of the TRIPS (TRASCO Intense Proton Source) ion source (figure 1) designed and built at INFN-LNS, Catania and currently in operation at INFN-LNL, Legnaro. Its aim is to produce intense proton beams with low emittance or to generate intense beams of monocharged light ions. The plasma is created by a 500 W Traveling Wave Tube, coupled to the cylindrical water-cooled OFHC copper plasma chamber through a circulator, a four stub automatic tuning unit and a maximally flat matching transformer. Beam intensities of 50 mA of H^+ and 5 to 20 mA for H_2^+ are considered as the ideal performances. Figure 2 shows the PM-TRIPS ion source on its testbench [1].

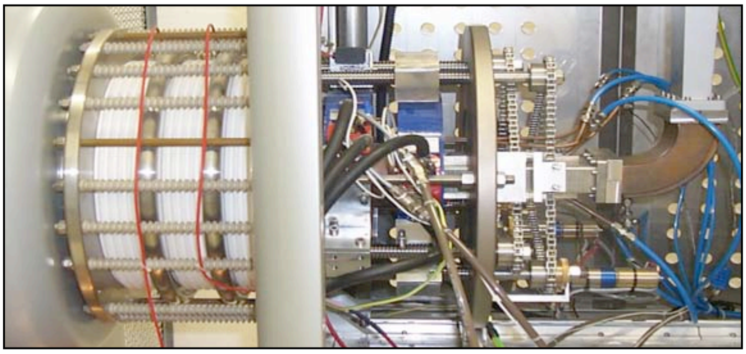

Figure 1: TRIPS ion source.

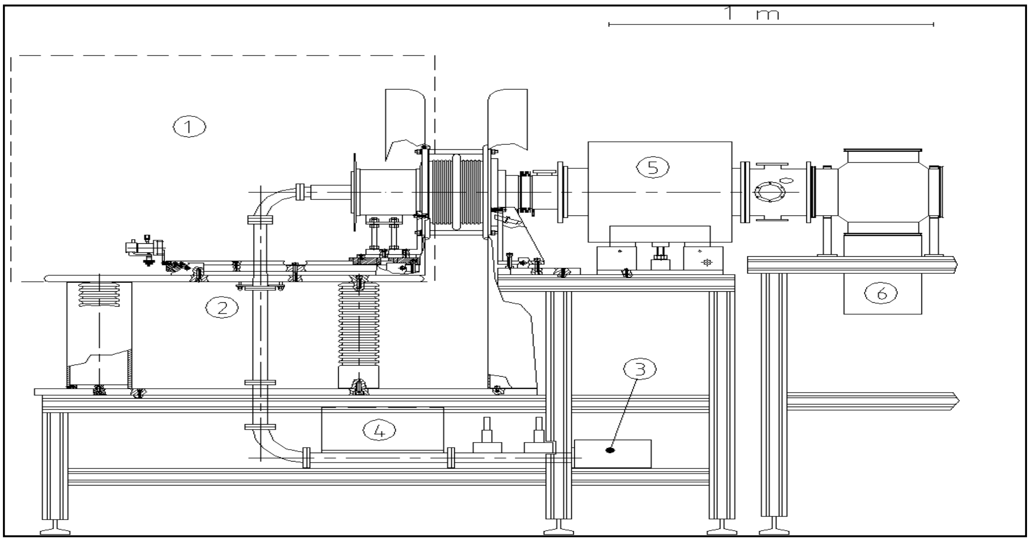

Figure 2: PM-TRIPS ion source on its testbench: (1) High voltage region, 2) DC-Break, 3) Microwave generator, 4) Automatic tuning unit, 5) Focusing solenoid, 6) Turbomolecular pump).

In order to improve the performances of such ion source a detailed electromagnetic study of the plasma chamber as a cavity has been carried out. As a result of these analysis the plasma chamber length has been modified in order to have a dominant resonance frequency at 2.45 GHz and the effect of two different matching transformers on the microwave coupling has been fully studied. Finally a waveguide DC-break that insulates the high voltage region has been designed with regards to the optimization of its electromagnetic properties.

2. Optimization of the plasma chamber dimensions

The TRIPS plasma chamber is a cylinder 100 mm long with a 45 mm radius. An air filled cylindrical resonant cavity with such dimension has a TE_{111} dominant mode at a frequency of around 2.4613 GHz. In order to realize a 2.45 GHz ion source, an analysis of the PM-TRIPS plasma chamber dimensions has been carried out. We have used the Ansoft HFSS™ eigenmode solver [2] to evaluate the resonant frequencies by varying the length *l* and the radius *a* of the cylinder filled with air. In tables 1 and 2 the comparison between the first three simulated values and the theoretical ones obtained by solving the equations [3] is shown:

$$f_{nvr}^{TM} = \frac{c}{2\pi}\sqrt{\left(\frac{x_{nv}}{a}\right)^2 + \left(\frac{r\pi}{l}\right)^2} \quad (1)$$

$$f_{nvr}^{TE} = \frac{c}{2\pi}\sqrt{\left(\frac{x'_{nv}}{a}\right)^2 + \left(\frac{r\pi}{l}\right)^2} \quad (2)$$

where x_{nv} and x'_{nv} are respectively the zeros of order *v* of the Bessel functions of order *n* and its first derivative, while *l* is the plasma chamber length and *a* its radius. In order to obtain a TE_{111} mode, which resonance frequency is 2.45 GHz, the plasma chamber dimensions have to be increased to 101.2 mm in length or to 45.3 mm in radius.

Hereinafter the relative difference between the simulated and the theoretical values is presented, obtained by subtracting the simulated value to the theoretical one and dividing by the latter. Figures 3 and 4 show a very good agreement between the results of the simulation and the theoretical values. In particular the relative difference is less than 0.012% for the dominant mode TE_{111}. Figure 5 shows the electric field distribution concerning the TE_{111} mode inside the cylindrical resonance cavity. It can be noticed that it increases from the outer parts of the plasma chamber to its center.

Then a further increase of the ion source performances could be reached by introducing a matching transformer that concentrates the electric field inside the plasma chamber.

Table 1: First three modes obtained by varying the chamber radius.

a [mm]	TE_{111} Theoretical resonance frequency [MHz]	TE_{111} Simulated resonance frequency [MHz]	TM_{010} Theoretical resonance frequency [MHz]	TM_{010} Simulated resonance frequency [MHz]	TM_{011} Theoretical resonance frequency [MHz]	TM_{011} Simulated resonance frequency [MHz]
44.9	2464.749053	2464.466336	2555.512869	2555.509806	2962.690327	2962.476502
45	2461.299052	2461.000916	2549.833952	2549.829996	2957.793287	2957.556061
45.1	2457.867179	2457.585845	2544.180218	2544.177365	2952.920745	2952.704393
45.2	2454.453309	2454.159526	2538.551501	2538.546574	2948.072534	2947.848031
45.3	2451.057314	2450.756479	2532.947634	2532.944089	2943.248488	2943.017560
45.4	2447.679069	2447.374092	2527.368454	2527.364199	2938.448443	2938.207336

Table 2: First three modes obtained by varying the chamber length.

l [mm]	TE_{111} Theoretical resonance frequency [MHz]	TE_{111} Simulated resonance frequency [MHz]	TM_{010} Theoretical resonance frequency [MHz]	TM_{010} Simulated resonance frequency [MHz]	TM_{011} Theoretical resonance frequency [MHz]	TM_{011} Simulated resonance frequency [MHz]
99.9	2462.213140	2461.927064	2549.833952	2549.830583	2958.553980	2958.340745
100	2461.299052	2461.000916	2549.833952	2549.829997	2957.793287	2957.556061
100.1	2460.387363	2460.098719	2549.833952	2549.828243	2957.034678	2956.805121
100.2	2459.478067	2459.177611	2549.833952	2549.830304	2956.278145	2956.057084
100.3	2458.571154	2458.277612	2549.833952	2549.830337	2955.523680	2955.304752
100.4	2457.666616	2457.371459	2549.833952	2549.825621	2954.771278	2954.533136
100.5	2456.764446	2456.462238	2549.833952	2549.827426	2954.020929	2953.781180
100.6	2455.864635	2455.584230	2549.833952	2549.828424	2953.272627	2953.053805
100.7	2454.967174	2454.664101	2549.833952	2549.830600	2952.526365	2952.303009
100.8	2454.072057	2453.783661	2549.833952	2549.830355	2951.782134	2951.562348
100.9	2453.179275	2452.887133	2549.833952	2549.829682	2951.039929	2950.790334
101	2452.288819	2451.998545	2549.833952	2549.830043	2950.299741	2950.082507
101.1	2451.400683	2451.100282	2549.833952	2549.828339	2949.561563	2949.320790
101.2	2450.514857	2450.218069	2549.833952	2549.826571	2948.825389	2948.586781
101.3	2449.631335	2449.328896	2549.833952	2549.827897	2948.091210	2947.841263
101.4	2448.750108	2448.460611	2549.833952	2549.830286	2947.359021	2947.144077
101.5	2447.871169	2447.571801	2549.833952	2549.829557	2946.628814	2946.396038

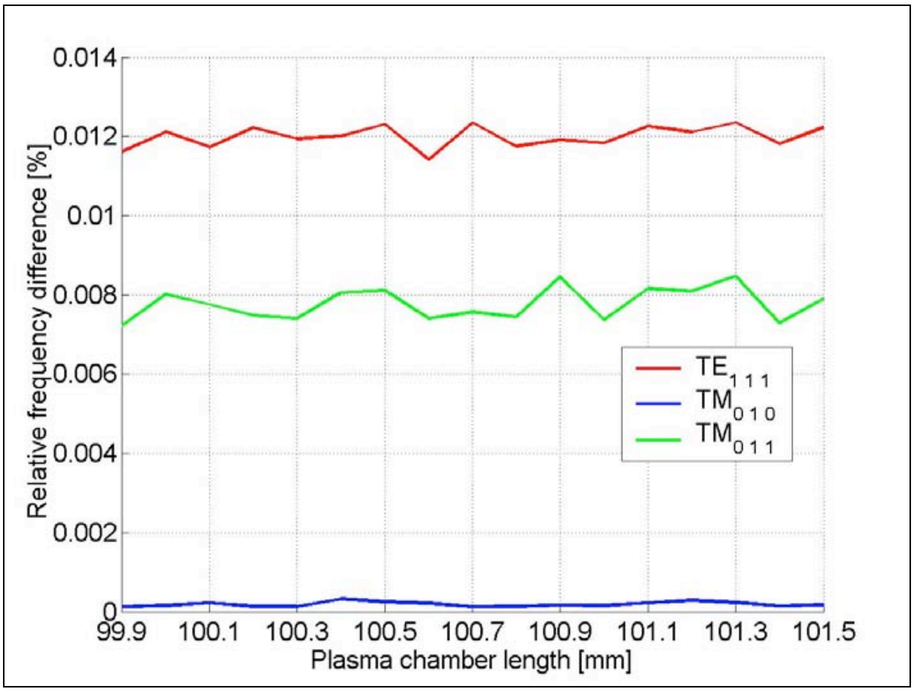

Figure 3: Relative difference between theoretical and simulated resonance frequency vs the cavity length (first 3 modes).

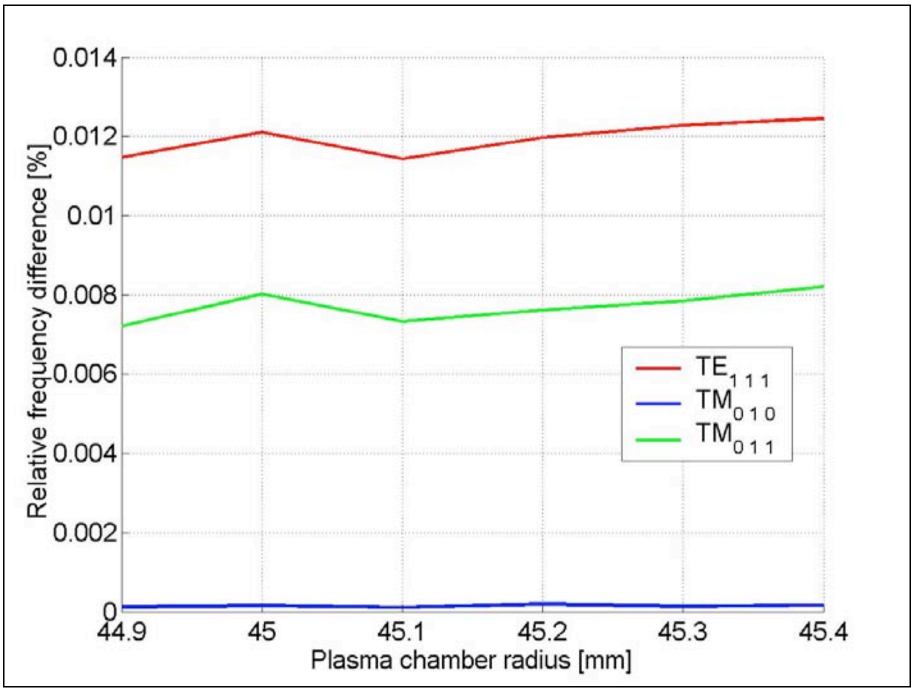

Figure 4: Relative difference between theoretical and simulated resonance frequency vs the cavity radius (first three modes).

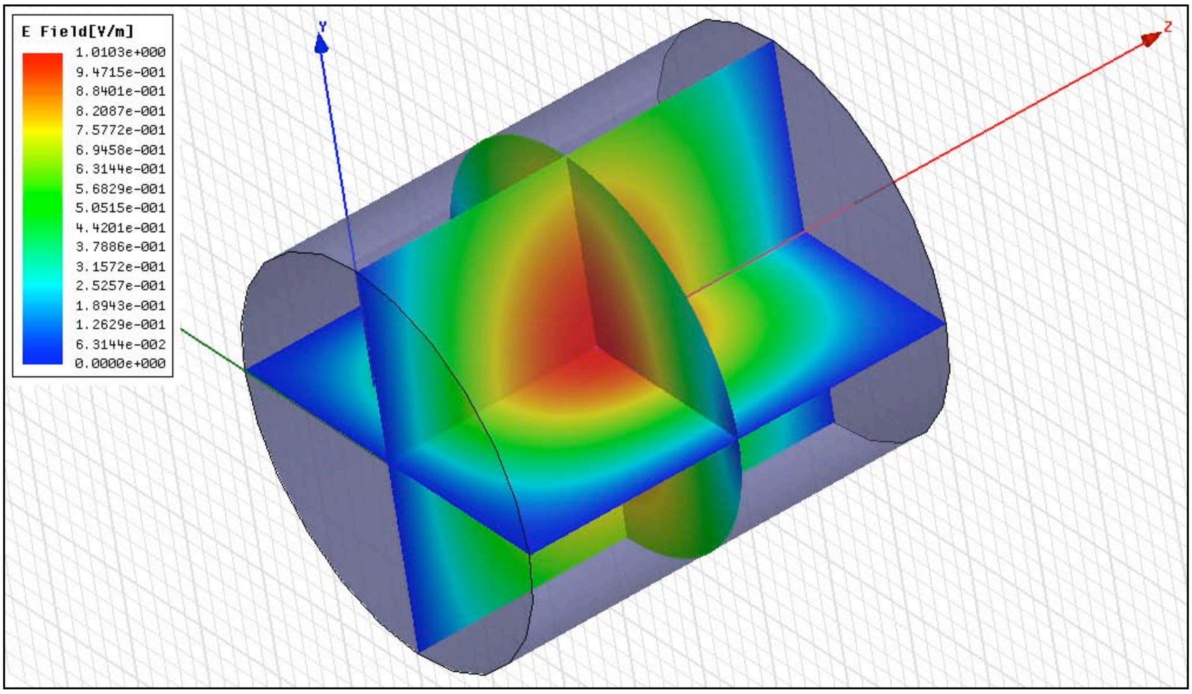

Figure 5: Electric field distribution inside the cylindrical resonant cavity for the mode TE_{111}.

3. Matching transformer simulations

In order to optimize the coupling between the microwave generator and the plasma chamber of the TRIPS source a maximally flat matching transformer (figure 6) has been used [1]. This solution has proven to be highly efficient since it realizes a progressive match between the impedance of the WR284 waveguide (72.136 mm width and 34.036 mm height), that operates in the TE_{10} dominant mode, and the equivalent impedance of the plasma filled chamber, also concentrating the electric field at its center.

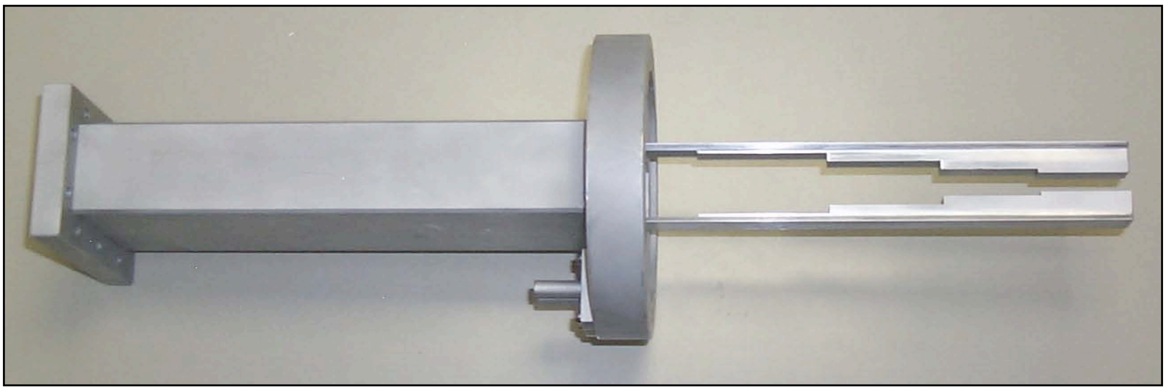

Figure 6: WR284 Matching transformer.

It has permitted to operate routinely on TRIPS with low values of reflected power (below 5 %) and with a high electric field on the axis, thus increasing either the proton fraction and the current density. Therefore a similar device will be used in the PM-TRIPS experimental setup and the electromagnetic properties have been calculated by means of Ansof HFSS™ Driven modal solver [2]. Table 3 summarizes the parameters of each section of the double ridged waveguide transformer shown in figure 7. The transformer named "a" is the structure employed on TRIPS ion source while the transformer named "b" is an optimized structure with a wider double-ridge. This new structure permits to obtain higher electric field value along the plasma chamber axis and it will be described in the next section.

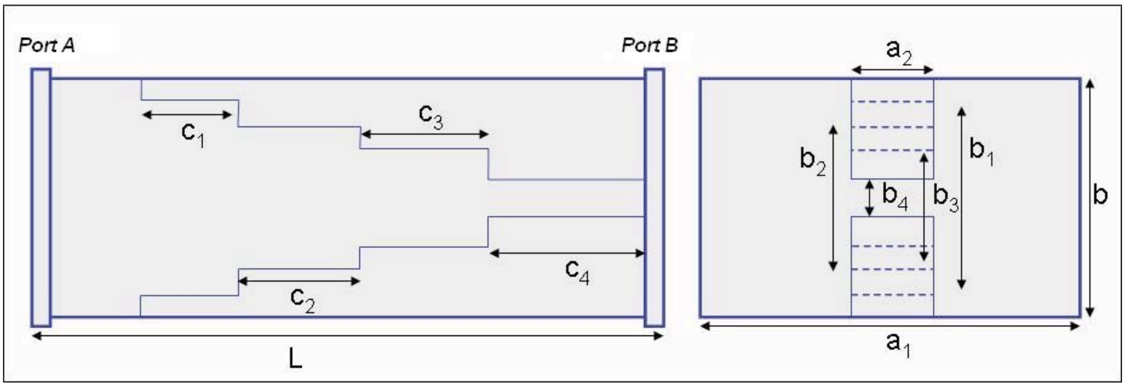

Figure 7: Simulated WR284 matching transformer.

Table 3: Transformers parameters.

Parameter	Transformer "a" Parameters Value [mm]	Transformer "b" Parameters Value [mm]
a_1	72.136	72.136
a_2	12.62	48.136
b	34,036	34,036
b_1	31	31
b_2	22.5	22.5
b_3	13.8	13.8
b_4	9.8	9.8
c_1	55.3	55.3
c_2	47.65	47.65
c_3	40.59	40.59
c_4	37.77	37.77
L	245	245

The simulation results in terms of scattering parameters are reported in figure 8. It can be noticed the very good performances of the two structures in terms of the transmission coefficient over a wide frequency range, in particular for both cases a maximum insertion loss of 0.043 dB within the range 2.3-2.8 GHz is obtained. The characteristic port impedance Z_0 at the two inputs of the structures has been also calculated in order to verify their matching properties and the results at port B are shown in figure 9. In particular at 2.45 GHz the structure "a" transforms the 413.93 Ohm characteristic impedance into 145.4 Ohm, while the transformer "b" in 72.85 Ohm, thus improving the matching to the plasma. In fact we expect an equivalent plasma impedance fairly around 100 Ohm as it was measured on MIDAS ion source at INFN-LNS.

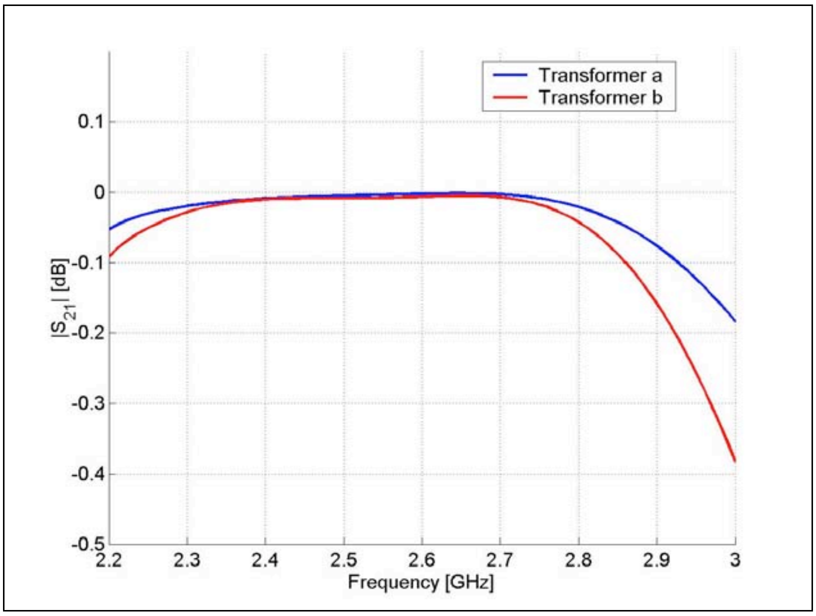

Figure 8: WR284 matching transformer S_{21} versus frequency.

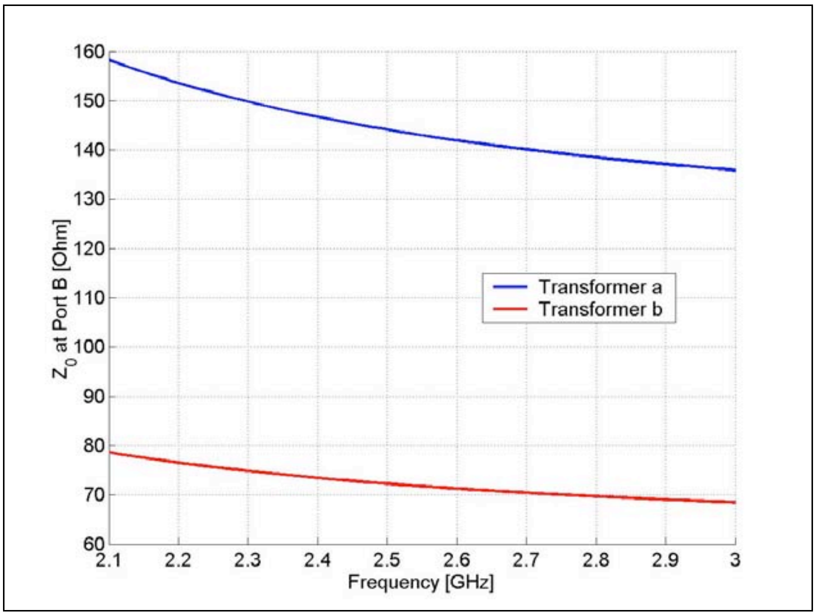

Figure 9: Characteristic port impedance at the port B of the WR284 matching transformers versus frequency.

The electric field distribution and the TE_{10}-like mode field pattern at the port A of the two structures are reported in figure 10. The electric field values at the port B of the two transformers are shown in the figures 11 and 12. The maximum electric field amplitude along the z axis is around 23500 V/m at the port A and 43083 V/m at the port B for the structure ”a” and 30973 for the structure “b”, (for 500 W at 2.45 GHz operating frequency). Therefore both matching transformers also concentrate the electric field around its axis in a smaller region than the WR284 cross section. This feature has been observed in the traces on the boron nitride (BN) disk at the injection side of TRIPS plasma chamber and it is particularly remarkable for the production of ion beams, because the extraction system is centered on the axis of the plasma chamber and any enhancement of the plasma density at the center of the cavity takes to similar increase of the ion beam current.

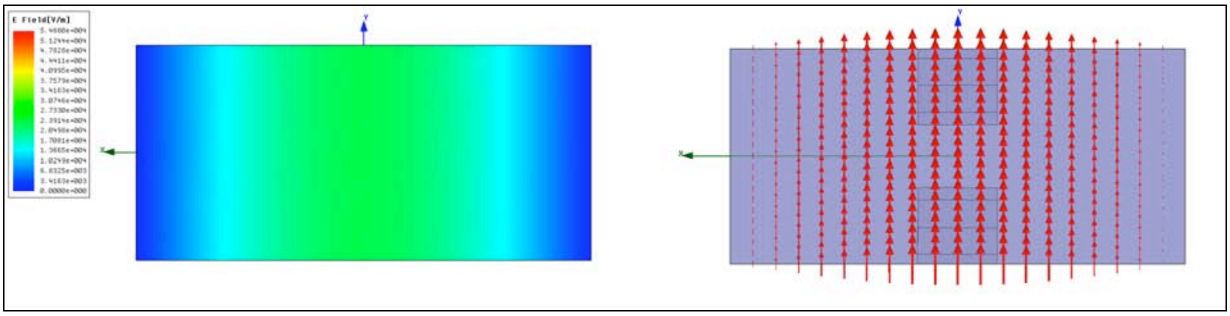

Figure 10: Electric field distribution and field lines at the WR284 port (A) of the structures.

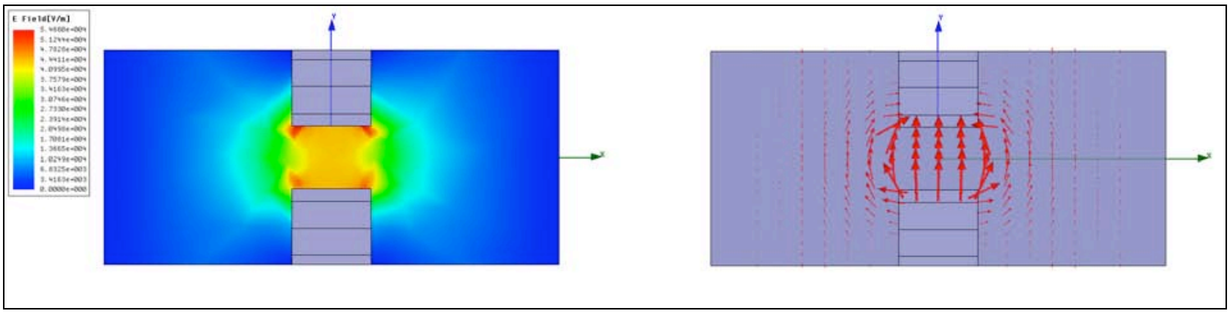

Figure 11: Electric field distribution and field lines at the WR284 double ridged port (B) of the structure “a”.

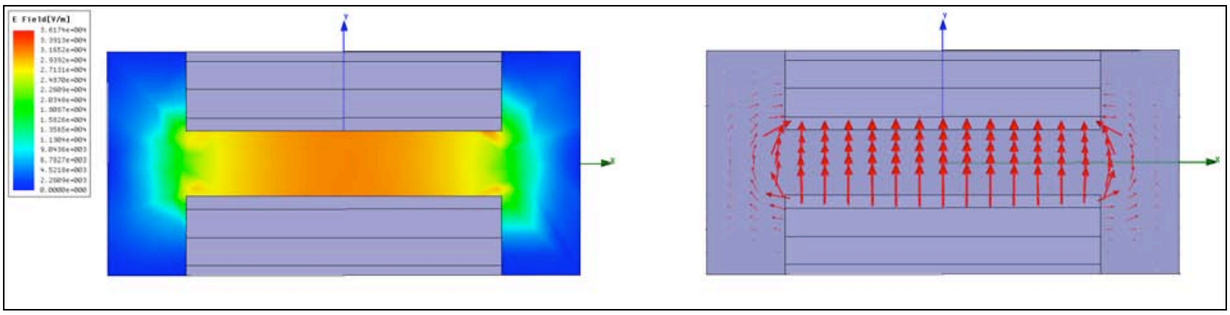

Figure 12: Electric field distribution and field lines at the WR284 double ridged port (B) of the structure “b”.

4. Electric field enhancement inside the plasma chamber

The electromagnetic performances of the PM-TRIPS ion source are strongly related to the energy inside the plasma chamber. The electric field distribution in a cylindrical cavity, excited in the TE_{111} dominant mode and the enhancement of the electric field between the two ridges of the proposed matching transformers have been reported above. Then the whole structure have been simulated by means of Ansoft HFSS™ Driven modal solver in order to evaluate the enhancement of the electric field inside the plasma chamber (101.2 mm length and 45 mm radius) due to the above proposed WR284 waveguide matching transformers. In figures 13 and 14 the result of the simulation in terms of electric field distribution in the whole structure (500 W at 2.45 GHz) for the transformers "a" and "b" are respectively reported. A comparison with the simulation result of the same cylindrical cavity fed by a WR284 waveguide (figure 15) is reported in figure 16. It is evident that the matching transformers also enhance the electric field inside the plasma chamber. It can be observed that the field is more than doubled (around 2.45 times higher for the transformer "b") with the use of the two proposed matching transformers and this enhancement factor is observed also over the whole volume of the plasma chamber.

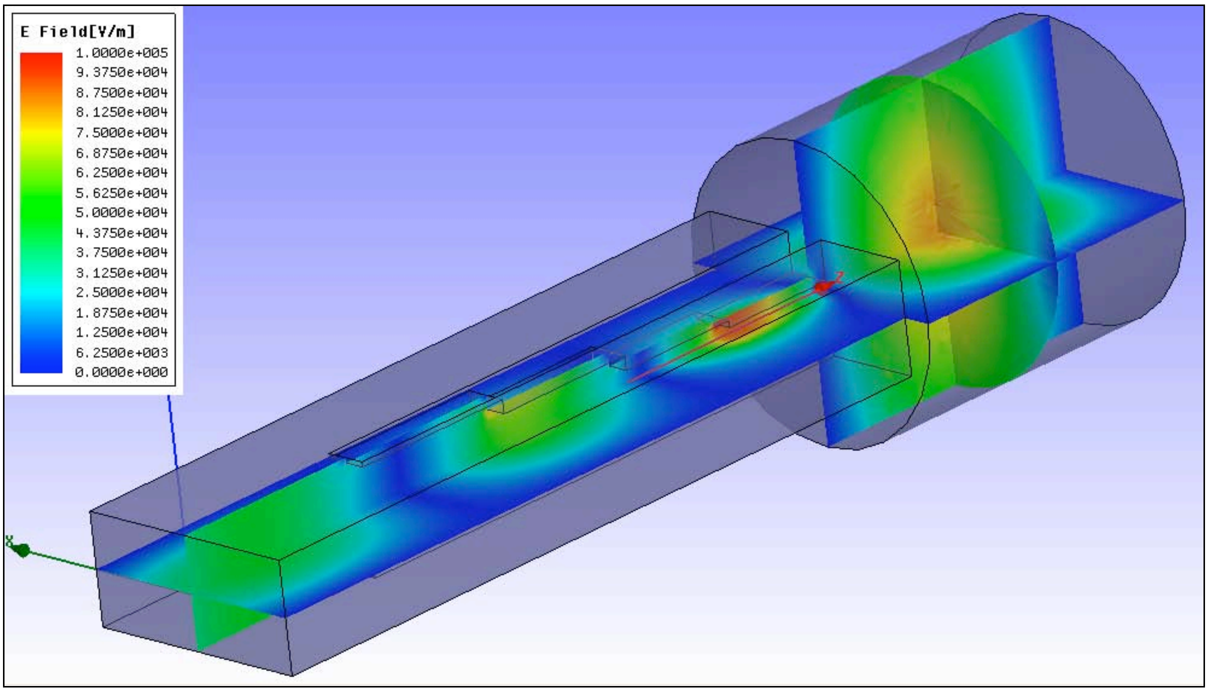

Figure 13: Electric field distribution of the optimized plasma chamber (101.2 mm long and 45 mm radius) coupled to the matching transformer "a".

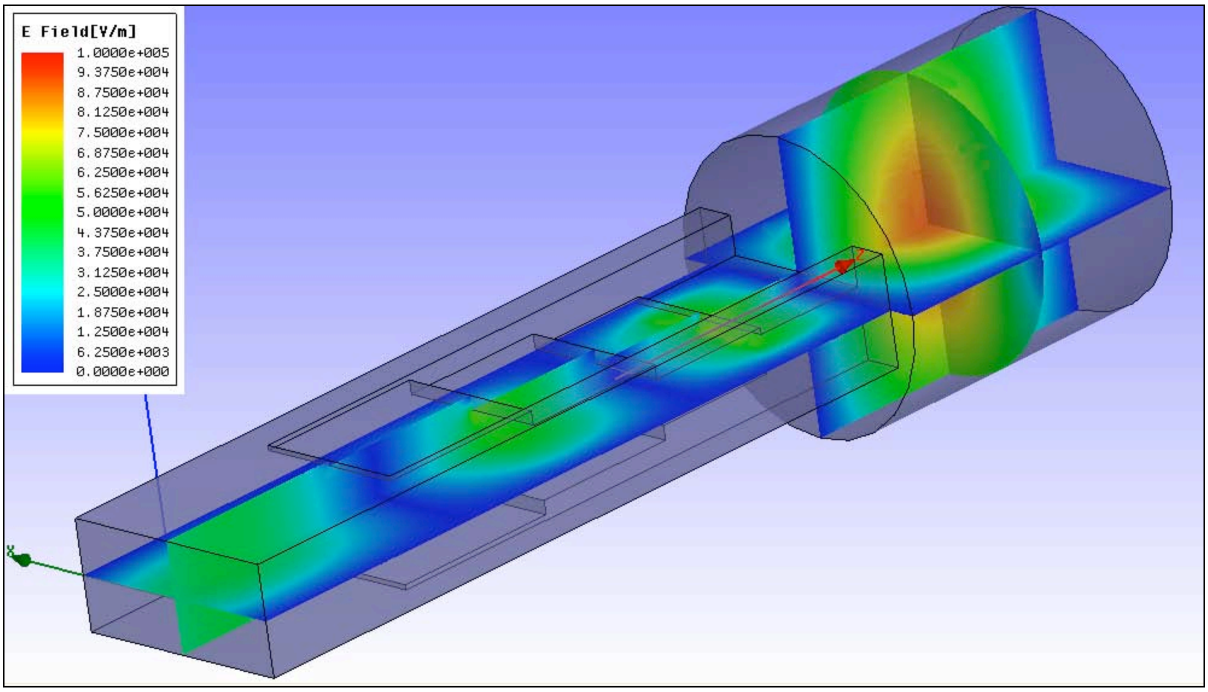

Figure 14: Electric field distribution of the optimized plasma chamber (101.2 mm long and 45 mm radius) coupled to the matching transformer "b".

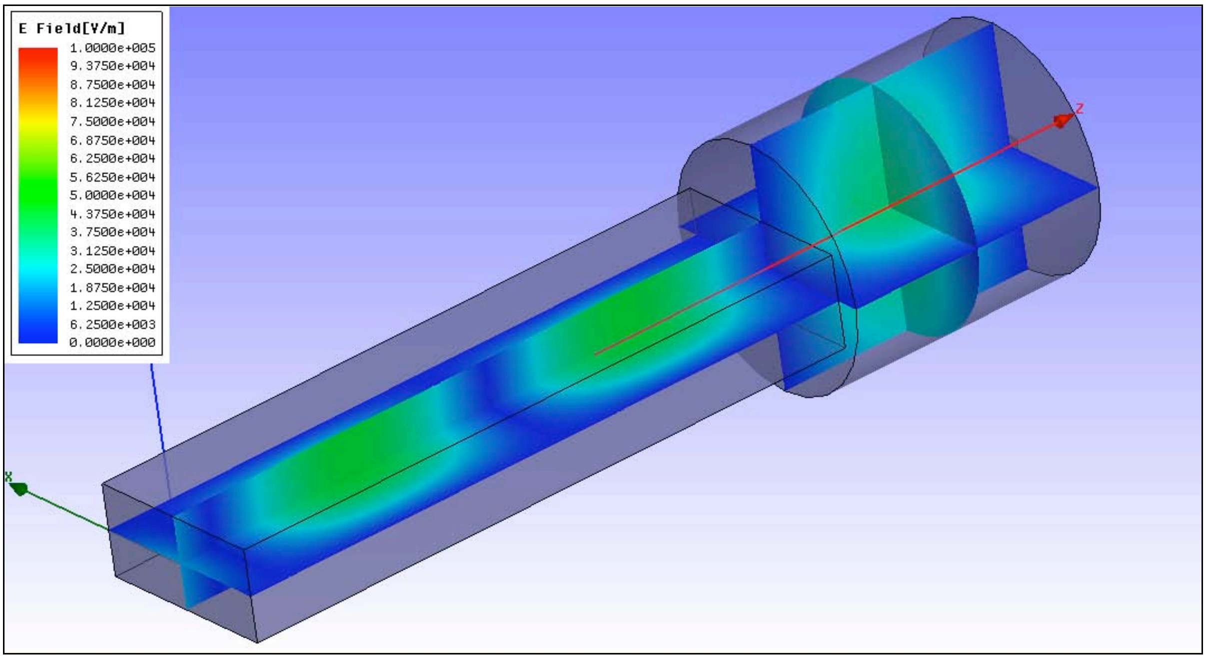

Figure 15: Electric field distribution of the optimized plasma chamber (101.2 mm long and 45 mm radius) coupled to a 245 mm long WR284 waveguide.

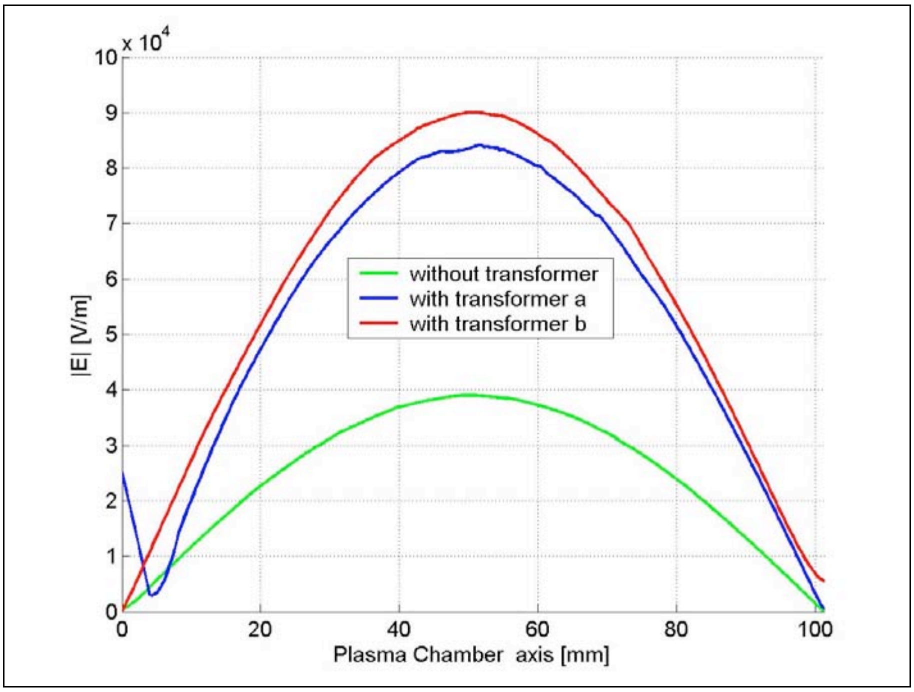

Figure 16: Electric field amplitude along the plasma chamber axis.

5. Effects of the DC-break insertion

The 80 kV extraction voltage of the PM-TRIPS ion source requires a waveguide insulator that separates the high voltage region from the microwave line at ground voltage. It will be placed just below the high voltage region as shown in figure 2. The waveguide dimensions are referred to a WR340 waveguide (86.4 mm width and 43.2 mm height), that is the output of the microwave generator. The simulated structure sketched in figure 17 is composed by 30 disks of 2 mm thick Boron Nitride separated by 31 disks of 12 mm thick copper. The modular structure of this DC-break allows to operate at higher extraction voltages and at higher microwave power than the single gap DC-break commonly used. In order to optimize the trasmission performances of this structure, different materials have been considered. The Boron Nitride has shown to be the best performing one and figure 18 shows the Ansoft HFSS™ simulation results in terms of S_{21} scattering parameters for four different types of BN [4],[5]. It can be noticed a 0.45 dB maximum insertion loss in the 2-2.8 Ghz frequency range for all the considered materials. The Boron Nitride grade HBC, with a 0.33 dB insertion loss at 2.45 GHz and a 0.66 dB maximum value in the 2-3 Ghz frequency range appears to be fully satisfactory as it may permit long term operations with a high reliability at the maximum RF power. The expected losses for 500 W operating power at 2.45 GHz are around 37 W.

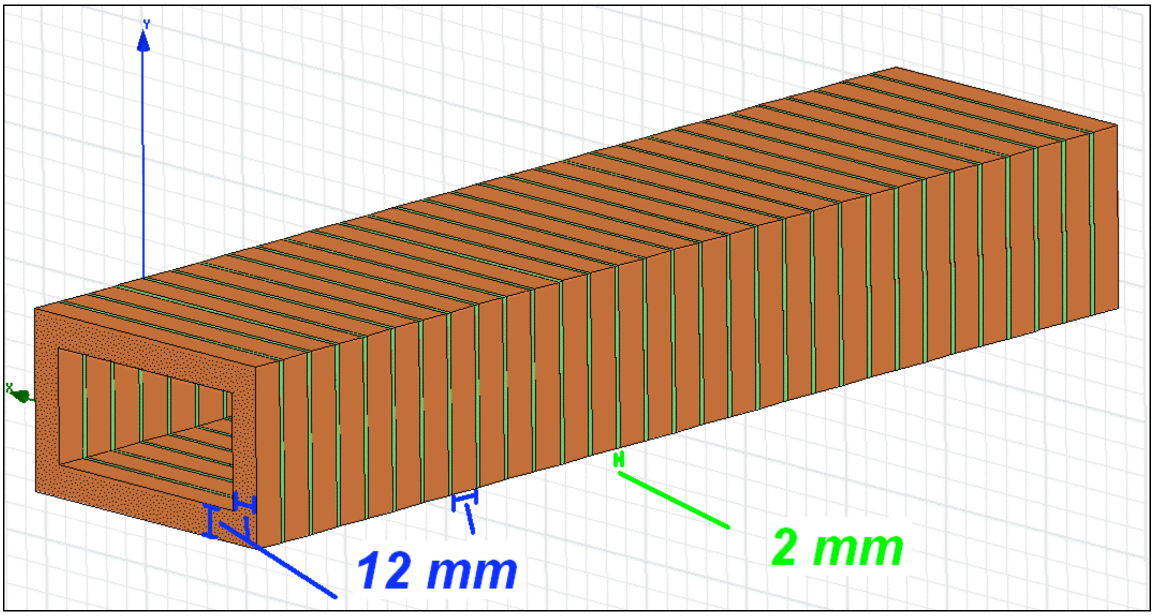

Figure 17: Simulated WR340 DC-break.

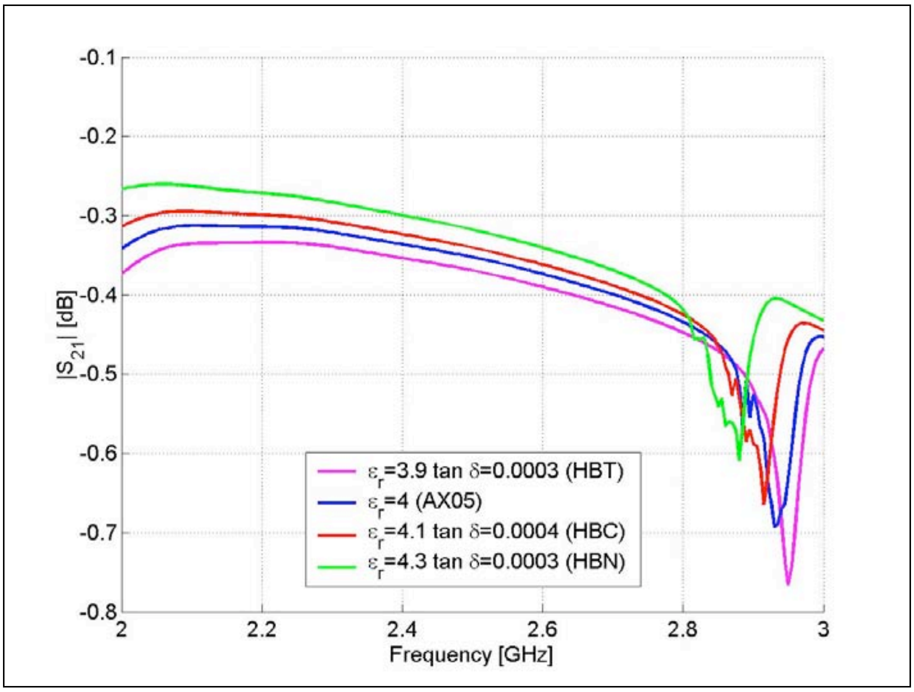

Figure 18: WR340 DC-break S_{21} versus frequency.

6. Conclusions and future perspectives

The electromagnetic studies carried out with the HFSS™ code on the PM-TRIPS source are a key point to optimize its performances by enhancing the microwave coupling efficiency. A next step is to take into account the presence of plasma and, in order to do that, accurate measurements of electron density with a Langmuir probe are needed by varying the operating parameters (gas pressure, microwave power and microwave frequency). A new DC-break with modular structure was conceived and it is currently under construction. We plan to start the operations and do the first plasma in the next summer, working at the beginning with proton beams and N_2^+ before to check the ability to generate other species for the production of intense monocharged light ions.

ACKNOWLEDGMENTS

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