Contributo presentato alla Riunione GTTI-SIEm, Pavia 26-28 giugno 2019

RF Experimental Test and Conductor Losses Calculation of a quadrupole-free X-Band TM_{01} Mode Launcher

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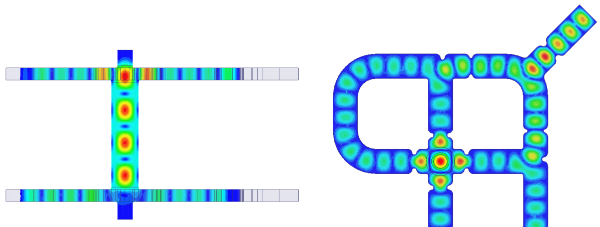
Abstract. In this work we present the low power RF characterization of a novel TM_{01} X-band mode launcher for the new generation of high brightness RF photo-injectors. The proposed mode launcher exploits a fourfold symmetry which minimizes both the dipole and the quadrupole fields in order to mitigate the emittance growth in the early stages of the acceleration process. The one-to-four rectangular waveguide branching line of the proposed design lies entirely in the waveguides H-plane and can be studied with a 2D reduced model that correctly accounts for the surface losses. With the aim to evaluate the conductor losses of the full height 3D component, we propose a modified expression for the waveguide top/bottom wall conductivity considering a reduced quasi-2D simulation domain with benefits for computational cost and time. Numerical 2D simulations are validated against results from full wave 3-D commercial electromagnetic simulator. Two identical aluminum mode launchers have been assembled and measured in back-to-back configurations for three different central waveguide lengths. From the back-to-back results we infer the performance of each mode launcher. The low power RF test, performed at the Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud (INFN-LNS), validate both the numerical simulations and the quality of fabrication. An oxygen-free high-conductivity copper version of the device is being manufactured for high power and ultra high vacuum tests that are planned to be conducted at SLAC.

1. Introduction and motivation

The R&D of high gradient radiofrequency (RF) devices is aimed to develop innovative accelerating structures and achieve higher accelerating gradient in order to increase brilliance of accelerated bunches. Recent research has shown that accelerating gradients up to 250 MV/m are feasible using cryogenically cooled copper accelerating structures [1, 2]. A high brilliance requires high field quality in the RF photoguns and in its power coupler. In this work we present a novel X-band power coupler which consists of a TM_{01} Mode Launcher (ML) (from the rectangular TE_{10} mode to the circular TM_{01} mode), with a fourfold symmetry which minimized both the dipole and the quadrupole RF components [3]. In particular we will show the low-power-microwave tests of two identical MLs joined back-to-back. This configuration allows a direct measurement of S-parameters using a two-port vector network analyzer (VNA), Agilent N5230A 10 MHz-50 GHz, Agilent Technologies.

2. Mode Launcher RF design

The proposed X-band ML design is based on four symmetric sidewall coupling apertures that reduce the converter length and allow on-axis power coupling of the azimuthally symmetric TM_{01} mode. The symmetry of the configuration removes all non-fourfold symmetric modes i.e. dipolar modes (as the standard mode launcher does) and quadrupole components [4] (see Fig. 1) of this structure. Details on the TM_{01} mode launcher feeding layout, the delay line to match



(a) side (b) top

Figure 1. Side and Top view of the longitudinal (beam-axis) Electric field component E_y of simulated back-to-back MLs.

the phase at the sidewall coupling apertures, and matching bumps can be found in [3]. The H-plane branching network has been optimized with a reduced model [5] which takes advantage of symmetry to reduce the computational domain.

The TE_{10} rectangular waveguide branching line shown in Fig. 1 can be studied taking advantage of the y-invariance of the TE_{10}-mode fields. This allows very fast 2D simulation as compared a full wave 3D model. However 2D models (except for the case of ideal PEC waveguides) fails to correctly evaluate the waveguide losses. (see Fig. 2).

It is possible to restore the correct attenuation by introducing a fictitious conductivity σ' for the top/bottom a-wide side of the waveguide:

$$\sigma' = CF \cdot \sigma = \left(\frac{b}{b'}\right)^2 \cdot \sigma \tag{1}$$

where the correction factor $CF = (b/b')^2$, introduced, is given by the ratio between the initial 3D height b and the reduced one b' of the quasi-2D model. Thanks the correction factor on top/bottom waveguide walls of the reduced b'-height model, now all terms scale in the same manner with b' restoring the correct value of α. The correction introduced above is limited to

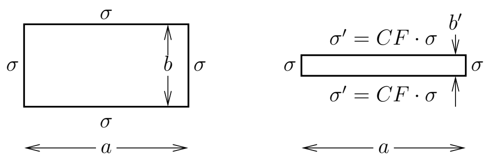


Figure 2. Full height and reduced b'-height models.

H-plane devices supporting TE_{p0} modes. However, as far as the waveguide height b is kept low, higher TE_{pq} with $q \neq 0$ are not supported by the structure. Usually standard waveguide devices fulfill this requirement.

The commercial code Ansys HFSS has been used for the numerical analysis and validation. For all the considered devices the simulations with standard waveguide height, highlighted in bold in the tables of results, are used as reference value for both the S-parameters, memory footprint and computation time. When $CF = 1$, it means that no correction factor has been used for the simulation and the scattering parameters evaluation. If the operating frequency is close to cut-off frequency f_c, the waveguide loss becomes very high. However, the presented reduced model is still valid since relies on a local property based on the surface impedance concept. This microwave device (see Fig. 3), is designed to obtain a power ratio of one third between two ports arranged with a 90 degree angle. From the $|S_{21}|$ and $|S_{31}|$ values of the preliminary

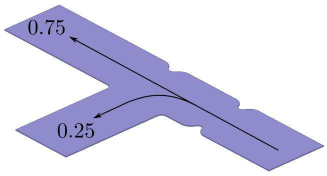


Figure 3. CAD draw of the H-plane splitter designed to obtain an un-balanced power division.

reference simulation with standard dimension of the waveguide, (see Table 1, first row), we can verify that the power division obtained is satisfactory ($|S_{21}|^2 = 0.8673^2 = 0.752 \approx 0.75$ and $|S_{31}|^2 = 0.244 \approx 0.25$).

Table 1. Results for the asymmetric power splitter at 11.424 GHz.

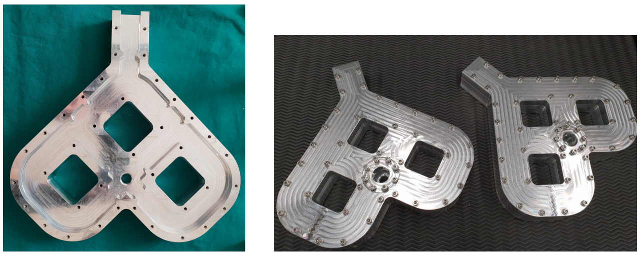
b' (mm)	CF	σ'	Mem. (GB)	Time (s)	$\lvert S_{21}\rvert$	$\lvert S_{31}\rvert$
b	**1**	**5.80e7**	**10.35**	**545**	**0.8673**	**0.4939**
b/32	1	5.80e7	1.59	54	0.8382	0.5204
b/32	1024	5.94e10	1.50	53	0.8673	0.4939

The same device has been simulated with a reduced height without ($CF = 1$) and with the correction factor ($CF = 1024$) on conductivity. In both cases, the time required has been reduced by an order of magnitude and the memory employed by a factor of 7. Thanks to the correction factor, the same value of the reference simulation for the S-parameters is again obtained, therefore succesfully validating the method here proposed.

By taking advantage form the fast simulations, the branching network of Fig. 1 was optimized. After the optimization, full height 3D simulations were carried out to model the side coupling in the 4 rectangular-to-circular side aperture transitions.

3. Fabrication and low-power-microwave tests

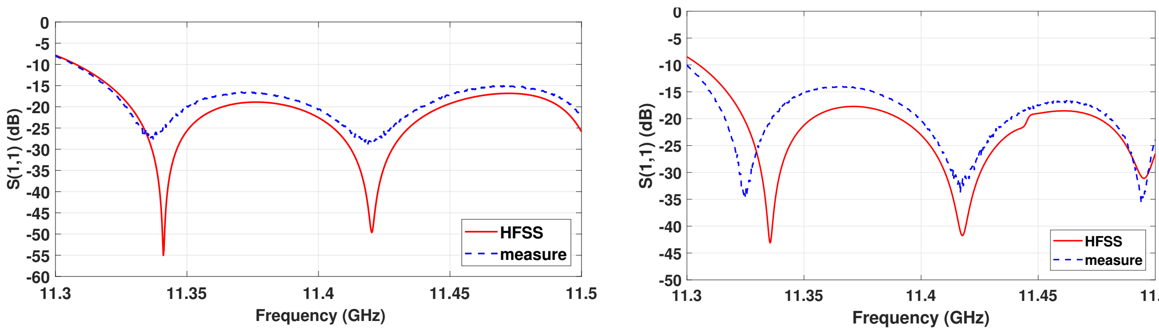
Figure 4(a) and 4(b) show the final assembled identical MLs in back-to-back configuration. Each ML is composed of two separate metal aluminum halves: a milled plate where the waveguide branching is machined (see Fig. 4(a)) and a plane cover. The milling of aluminum blocks has been operated using a tolerance of 10 μm and a surface roughness of 100 nm. Being the "low-power-microwave test" aluminum structure based on two pieces, it requires a large number of screws to ensure good rf contact. During the device assembling, care should be taken to ensure the flange screws are symmetrically tightened in order to obtain a good electrical contact and alignment between the two pieces. When the two halves are joined together, they form the complete ML. Two identical aluminum prototypes (Fig. 4(b)) have been fabricated and measured in three back-to-back configurations for three different circular waveguide connection lengths (3, 6 and 12 cm) through a well-calibrated (Keysight X11644A Mechanical WR90 Waveguide Calibration Kit, 8.2 to 12.4 GHz, WR-90) VNA.



(a) Slotted plane of the Mode Launcher. (b) Two identical fabricated MLs for back-to-back measurement.

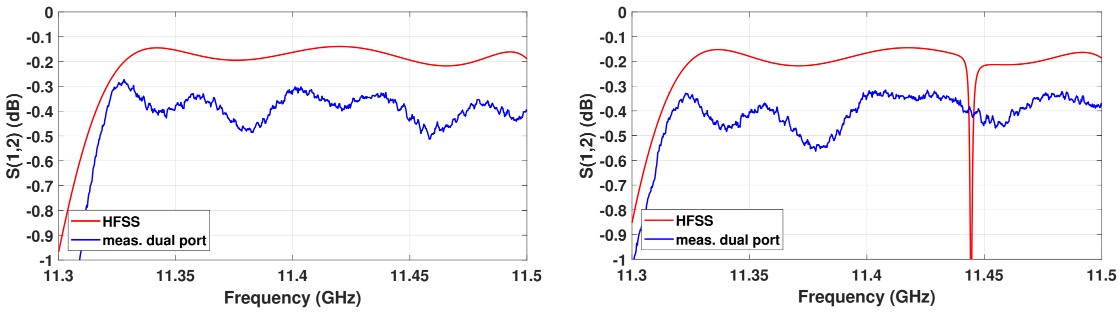
Figure 4. Photos of the manufactured aluminum Mode Launchers for low-power-microwave tests.

Figures 5 and 6 show the comparison between the simulated and experimental scattering parameters ($|S_{11}|$ and $|S_{12}|$ respectively) of the X-band TM_{01} MLs back-to-back connected. The sub-figures (a), (b) show this comparison for the different circular waveguide central sections of length 3 cm, 6 cm respectively.



(a) $l = 32$ mm (b) $l = 62$ mm

Figure 5. Comparison of measured and simulated reflection coefficient $|S_{11}|$ for the full devices in back-to-back configuration. At the working frequency $|S_{11}|$ is about-30 dB.



(a) $l = 32$ mm (b) $l = 62$ mm

Figure 6. Comparison of measured and simulated Transmission coefficient $|S_{12}|$ for the full devices in back-to-back configuration. At the working frequency $|S_{12}|$ is -0.4 dB.

The device is well matched, $|S_{11}|$ below -10 dB, in the frequency range 11.3-11.5 GHz; at the operating frequency 11.42 GHz, $|S_{11}|$ is about -25 dB for all the three connected sections.

Back-to-back measurement shows that the averaged loss of the mode launcher is about 0.2 dB higher than that of the simulation. This is likely due to the losses resulting from imperfect electrical contact in this low-power-microwave test prototypes.

4. Conclusion

A novel RF power coupler for RF photoinjector designed for high brightness applications has been presented. The design has been partially automated by taking advantage of an ad-hoc developed 2D model with reduced simulation time. Te resulting modhe launcher could be used with both for room temperature photoinjectors, and as a part of a cryostat assembly for normal-conducting cryogenic structures. As an example of the mode-launcher usage you can refer to [6]. The proposed mode launcher is a X-band TM_{01} waveguide mode launcher which minimizes dipole and quadrupole field components. A low-power-microwave version of the mode launcher has been fabricated and successfully tested. This launcher features good back-to-back performances. We plan to test a brazed version of this mode launcher for high power test at SLAC.

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