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A Novel Highly Symmetric TM_{01} Mode Launcher for Ultimate Brightness Applications

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Abstract

The R&D of high gradient radiofrequency (RF) devices is aimed to develop innovative accelerating structures based on new manufacturing techniques and materials in order to construct devices operating with the highest accelerating gradient. Recent studies have shown a large increase in the maximum sustained RF surface electric fields in copper structures operating at cryogenic temperatures. These novel approaches allow significant performance improvements of RF photoinjectors. Indeed the operation at high surface fields results in considerable increase of electron beam brilliance. This enhancement requires high field quality in the RF photoinjector and, specifically in the design of the power coupler. In this work we present a novel device for the RF photoinjector: a compact X-band TM_{01} mode launcher with a fourfold symmetry which minimizes both dipole and quadrupole RF components.

1 Introduction

Nowadays, the attainment of higher accelerating gradients and the construction of the so called 5th generation light sources, i.e. hard X-ray Free Electron Lasers (FEL), are two of the hot topics in the modern accelerator technology. While for the first one the bottle-neck remains the RF breakdown, a phenomenon occurring in normal conducting metallic structures, a recent research has shown that accelerating gradients up to 250 MV/m are feasible using cryogenically cooled copper accelerating structures [1].

Further development of X-ray FELs will require a substantial RF photoinjectors R&D in order to improve the electron beam quality. The main component of a RF photoinjector is the RF gun. The higher is the electric field on the cathode surface of the gun the lower the beam emittance [2]. This lower emittance could be degraded by the multipole components of the gun electromagnetic fields. Therefore, the next generation of RF guns should operate at high gradient while maintaining multipole free fields.

Regarding the breakdown, the most promising techniques to reduce its probability in a RF gun is coupling the power from the axis, actually removing the coupler from the main cell where the probability of the RF breakdown is higher [3]. A coupling layout is possible by going from the rectangular TE_{10} mode to the circular TM_{01} mode. This conversion is possible introducing a microwave device called TM_{01} mode launcher [4].

Since this layout is extremely promising, in this contribution we will discuss a novel TM_{01} mode launcher based on a four fold symmetry. It allows the on-axis power coupling, removing at the same time both dipolar modes (occurring in a standard mode launcher) and quadrupole components. This original and compact layout, simulated with the industrial standard HFSS code, keeps the maximum surface electric and magnetic fields sufficiently low to guarantee multi-MW delivery, i.e., up to 200 MW, to a device with this layout.

2 Geometry of the Four Fold Symmetry Mode Launcher

The X-band mode launcher with the four fold symmetry is shown in fig 1. It consists of two standard WR90 waveguides with a = 22.86 mm and b = 10.16 mm and of a circular waveguide with radius r_W = 11.43 mm. The cut-off frequencies of this waveguide are 7.68, 10 and 12.7 GHz, respectively for the TE_{11}, TM_{01} and TE_{21} mode. The rectangular waveguides are crossed at 90 degree and the circular waveguide is placed at the intersection point of the rectangular ones. With this symmetry the simulation requires only an eighth of the device structure. Sharp edges were avoided to reduce electrical and magnetic field enhancements minimizing also the breakdown probability. Finally a pair of inductive matching protrusions (bumps) are included for the tuning of the device.

The reflected power at the rectangular port is minimized by varying the position z_B of the bumps axis and the w_B dimension. The total length of the bumps h_B is maintained constant and the optimized dimensions are z_B = 4.858 mm, w_B = 5.181 mm and h_B =

12 mm. To allow the beam to go through the circular waveguide a beam pipe with a radius of 6.35 mm (TE_{11} cut-off frequency of 13.8 GHz) has been considered. For the design of the mode launcher we used the commercial finite element electromagnetic code ANSYS HFSS [5].

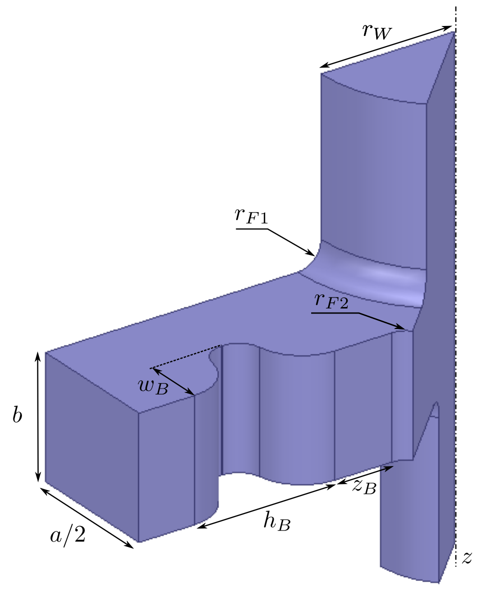

Figure 1: Geometry of the four folded TM_{01} mode launcher. Only an eighth of the device is used for the simulation due to its symmetry. The dot dashed line is the symmetry axis and the propagation trajectory of the electron bunch.

In a real scenario the mode launcher should be fed by a dedicated matched 4-harm power delivery network whose parameters are discussed in the next section.

3 Power Delivery Network

The TM_{01} mode launcher can be fed by a standard branched power network with three 3dB power splitters and symmetric waveguide lines. However, the more compact design shown in fig. 2 can be considered. The new feeding layout employs only one symmetric 3dB splitters and is confined in two-dimensions in the H-plane. In this new layout the network is composed by two symmetric arms and one input waveguide. In the middle of each arm an asymmetric 3dB power splitter is inserted to feed the ports labelled as 2 and 4, nearest to the input port. In this configuration the output ports (n. 3 and 5) are the endpoints of the symmetric arms. The power flows through the port 1, which is directly connected to the klystron.

Thanks to this power distribution scheme, the power level at the output ports is the samw when the four input ports of the mode launcher are excited with the same field amplitude. The power difference between adjacent ports is 0.02 dB.

To properly feed the TM_{01} mode launcher both amplitude and phase of the field

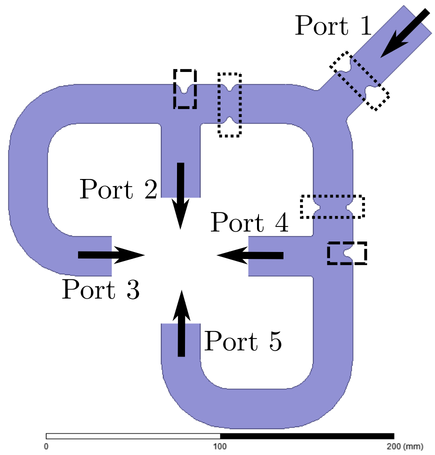

Figure 2: Geometry of the feeding network where the mode launcher is set in the center.

has to be the same. In a standard tree design, the same phase at the output ports is guaranteed by the symmetry of the power delivery feeding network employing 3dB splitters. However, the present asymmetric design needs a tuning delay line. The bending arm between the port 2 and 3 can be tuned as a delay line to match the phase at the output ports. Other solutions could be used for the phase matching modulation of the propagation constant or using different straight waveguide width. Our solution is simple and keeps the device compact. The mode launcher and the entire feeding network can be enclosed in a box with a transverse dimension of 0.25 x 0.25 m^2 for a typical X-band device. The phase difference between any pair of ports is equal to 0.08 deg. Compared to the standard tree design, actually, the only bottleneck of this configuration, is the large sensitivity to frequency variations. However, the issue does not represent an obstacle for the present application for which only the frequency must be defined with a great accuracy.

The design is completed with three pairs of matching bumps to minimize the reflected power and a couple of bumps before each splitter to avoid the presence of standing wave patterns in the bent radii (see dashed box in fig 2). Indeed, if only two matching bumps are added to the layout. Although the reflected power can be minimized a standing wave can be trapped inside the bends. The whole system including thepower delivery network and the mode launcher has been simulated and the related S_{11} is shown in fig. 3.

With this layout the surface electric and magnetic peak fields are sufficiently low for a high gradient operation when an input power of 200 MW is used. Actually, the peak surface electric field is 75 MV/m while the magnetic field is 25 kA/m, see fig. 4 [6].

4 Harmonic Analysis of the Fields

In order to evaluate the enhanced performances we have to quantify the minimization of the quadrupole component. To this purpose a Fourier analysis of the field has been performed. The integrated voltage has been calculated for both co-propagating and counter-propagating particles:

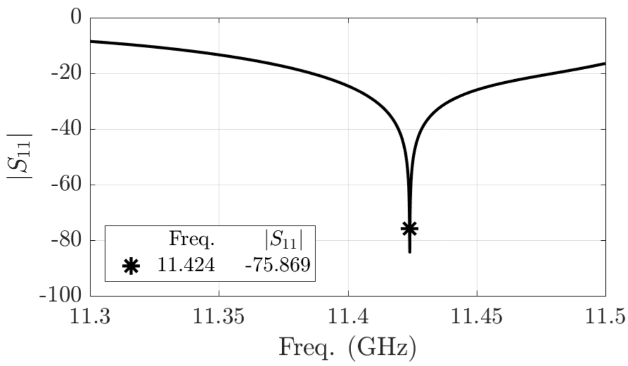

Figure 3: Reflection *vs.* frequency for the device in fig. 4. At the working frequency of 11.4240 GHz, $|S_{11}|$ is below -75 dB, and the bandwidth at -20 dB is 90 MHz.

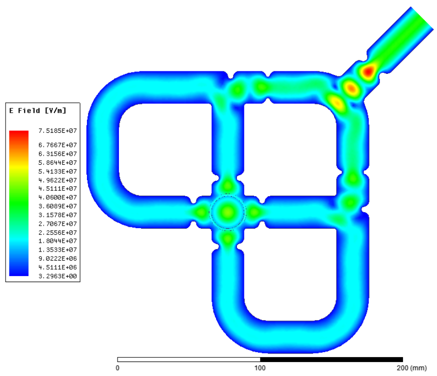

Figure 4: Plot of the electric field of the proposed design with the maximum located in the first splitter region.

$$V_{\mp}(r,\theta) = \int_{z_0}^{z_f} E_z(r,\theta,z) e^{\mp i k_0 z} dz \tag{1}$$

where r is the radius, θ the azimuthal coordinate, k_0 the wavenumber of the RF input power and z_0, z_f the limits of integration on longitudinal axis. Therefore the discrete Fourier transform coefficients has been calculated as in [7]:

$$M_{\mp,s}(r) = \frac{1}{\sqrt{n}} \sum_{j=1}^{n} V_{\mp}(r,\theta_j) e^{2\pi i (j-1)s/n} \tag{2}$$

where n is the number of azimuthal variations of the voltage and $s = 0, 1, 2, 4, \ldots$ is the index of the modes. The coefficients have been calculated for the proposed design and for a dipole compensated one with only two feeding ports.

In both cases, co- and counter-propagating particles, the quadrupole coefficients, $M_{\mp 1,2}$, are reduced at least of one order of magnitude while the coefficients of higher modes $M_{\mp 1,4}$ and $M_{\mp 1,8}$, (octupole and 16-pole) are slightly increased.

The discrete Fourier coefficients have been plotted in fig. 5 and 6 for a graphical comparison. The designs proposed here could be also used for a high overcoupled gun,

	$M_{-,1}$	$M_{-,2}$	$M_{-,4}$	$M_{-,8}$
Dipole comp.	1.64	2.77	1.02	2.15
Quadrupole comp.	0.26	0.09	3.29	0.12

Table 1: Discrete Fourier coefficients for counter-propagating particles. Results have been multiplied by 10^3.

	$M_{+,1}$	$M_{+,2}$	$M_{+,4}$	$M_{+,8}$
Dipole comp.	2.27	2.91	3.60	1.39
Quadrupole comp.	1.04	0.25	9.36	2.96

Table 2: Discrete Fourier coefficients for co-propagating particles. Results have been multiplied by 10^3.

because the cancellation of the quadrupole fields acts on both co- and counter-propagating fields.

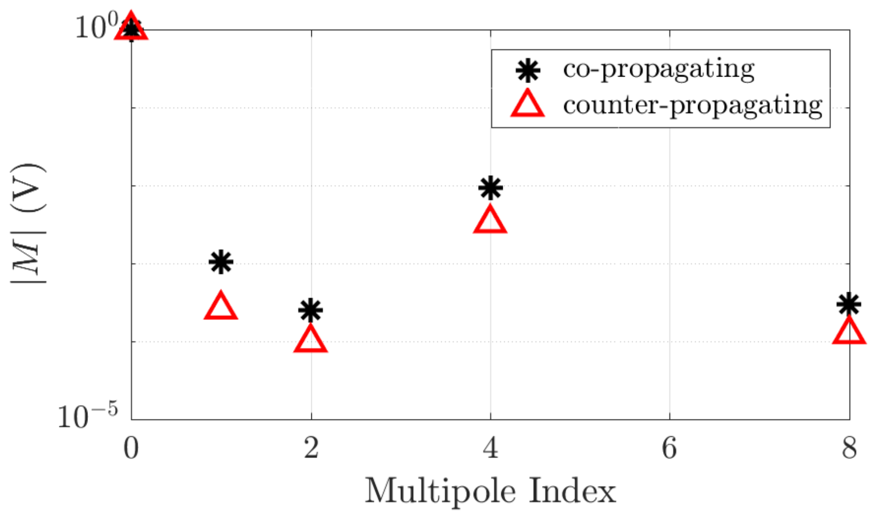

Figure 5: Discrete Fourier coefficients for the four ports device.

5 Conclusion

A novel RF power coupler for RF photoinjector designed for ultra high-brightness applications has been presented. The X-band TM_{01} waveguide mode launcher that minimizes both dipole and quadrupole field components. The minimization of the multipole field components was achieved by using a power delivery network with four symmetric waveguide ports. For a transmitted RF power of 200 MW, the surface peak electric field is 20 MV/m and the magnetic field is 80 kA/m, which corresponds to a pulse heating of 3 degree C for 5 μs pulse. Event at this high power the fields and the peak pulse surface heating are well within safe operational characteristics.

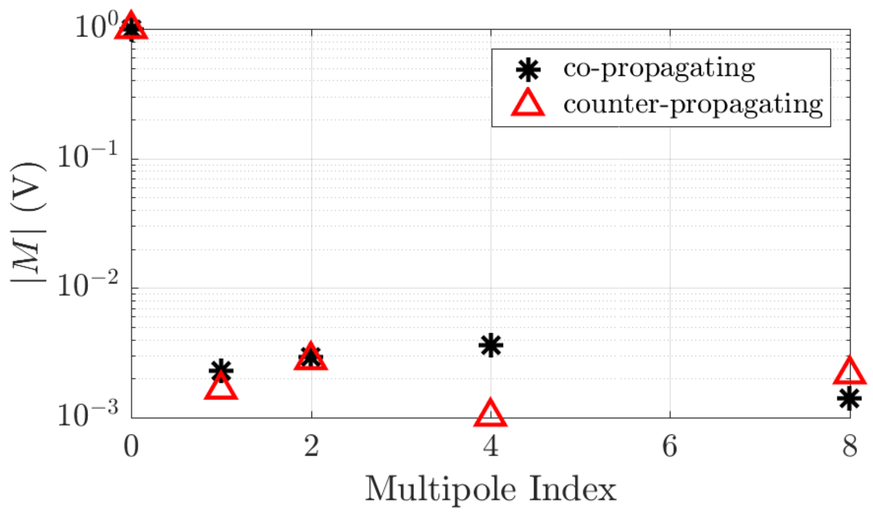

Figure 6: Discrete Fourier coefficients for the two ports device.

The minimization of the quadrupole component has been quantitatively estimated by analysis of the discrete Fourier coefficients. At least a reduction of one order of magnitude has been obtained for the considered cases.

A prototype of the device here described is under realization at LNS-INFN. The measurements and the comparison with simulations will be object of a successive dedicated manuscript.

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