TM01 MODE LAUNCHER FOR USE IN HIGH BRIGHTNESS PHOTOGUNS*

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Abstract

Photo rf guns are a source of electron beams for X-ray FELs such as LCLS and European XFEL. In existing photoguns power is coupled into the cavity by rectangular waveguides through the cell walls, [1], or use coaxial coupling, [2]. We are considering feeding a gun using a circular waveguide with the TM_{01} mode. To do that we need a mode launcher, a matched device that couples the rectangular TE_{01} mode waveguide to a TM_{01} mode in a circular waveguide. Use of the mode launcher reduces complexity of the gun cavity and increases flexibility of positioning the input waveguide relative to the gun body. Mode launchers have been successfully used at SLAC and elsewhere for X-band high gradient tests. Because the existing mode launchers were not built for high brightness rf guns, they have a significant quadrupole field component. High brightness rf guns have tight requirements on output beam properties. The quadrupole component of the mode launcher adversely affects the beam quality. We have designed a mode launcher free of this disadvantage. We present an example S-band mode launcher with minimized quardupole field component.

MOTIVATION

A collaboration between SLAC and UCLA is developing a cryogenic copper S-band rf gun [3]. The input waveguide,which is at room temperature, must be thermally isolated from the cryogenically cooled gun cavity. The rf gun cavity is placed in a cryo cooler and fed by the cylindrical waveguide. To feed power into this cylindrical waveguie, we need a coupler from rectangular waveguide to excite the TM_{01} circular mode. To provide designed thermal isolation, the circular waveguide should be about a meter long. Fortunately, such a design already exists as the mode launcher at 11.424 GHz [4]. However, this design has a strong quadrupole field component. This quadrupole field component will lead to undesirable emittance growth in the electron beams launched from the rf photoinjector. We propose a modification of the original mode launcher to minimize the quadrupole field component.

GEOMETRY

Original S-band Mode Launcher

We use the basic idea of the original mode launcher [4] to create a version at 2.856 GHz. Our mode launcher starts as a standard WR-284 rectangular waveguide fed directly into a cylindrical waveguide (radius of 45.72 mm) on one side, and a beam pipe on the other. The beam pipe radius (25 mm) is set so that dipole mode is below cutoff. The device is matched using a rounded inductive iris in the rectangular waveguide. See Fig. 1 for the mode launcher geometry and fields, calculated by HFSS [5]. This version will be used as a reference when we minimize the quadrupole component in our new design.

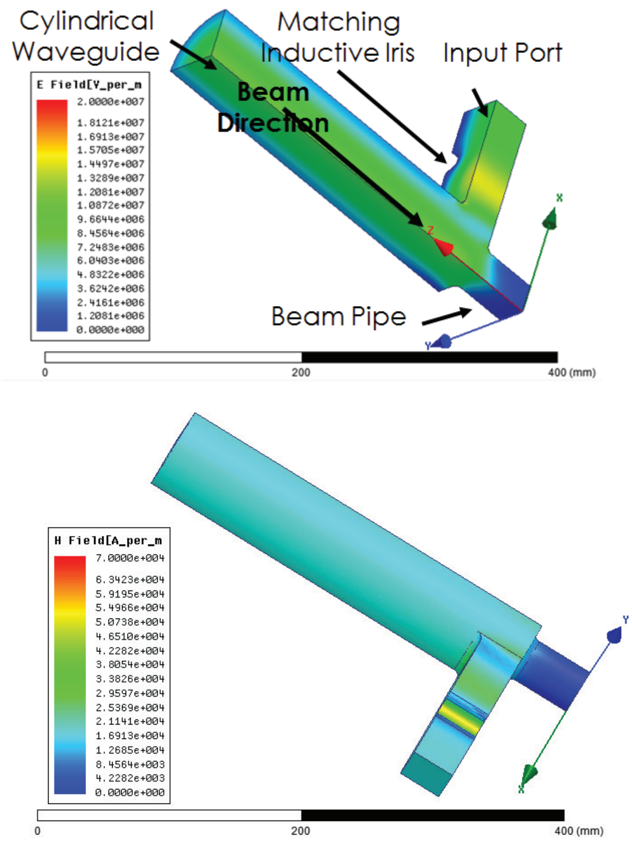

Figure 1: Electric (top) and magnetic (bottom) fields for one quarter of original S-band mode launcher. Fields are normalized to 200 MW input power in full mode launcher.

Minimized Quadrupole Field Mode Launcher

We started optimization by adding a perturbation to the cylindrical waveguide near the rectangular waveguide input, see top picture in Fig. 2. Using only this perturbation we reduced the quadrupole component but were not able to completely remove the quadrupole component, therefore we needed further changes in geometry. The method for calculating the quadrupole component is stated later in a separate subsection of the Comparison section.

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To lower the quadrupole field component further we added a bump in the cylindrical waveguide. This perturbation was chosen to create an opposite quadrupole kick, cancelling that of the coupler. We can see both of the perturbations and the electric and magnetic fields in Fig. 2.

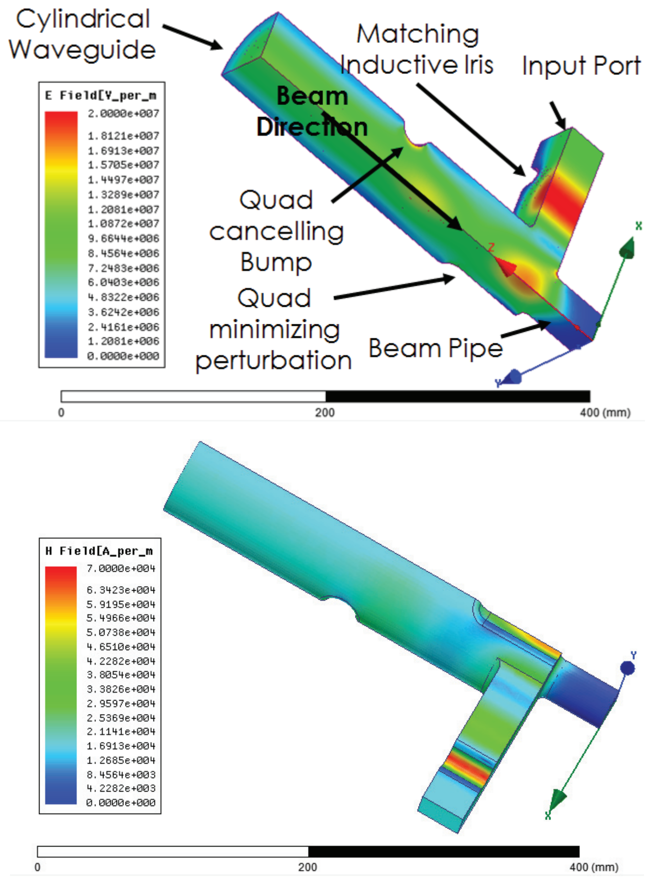

Figure 2: Electric (top) and magnetic (bottom) fields for one quarter of the quadrupole minimized S-band mode launcher. Fields are normalized to 200 MW input power in full mode launcher.

COMPARISON

Now we compare the original S-band mode launcher, with our optimized version to verify that the perturbations do not degrade performance. First, we examined the electric field on axis. The fields in the perturbed model are not significantly increased. The electric field along the z-axis (the center axis of the cylindrical waveguide) are shown in Fig. 3. The fields are plotted from the beginning of the beam pipe to the end of the cylindrical waveguide.

The 20 dB bandwidth of the coupler decreased from 66 MHz to 20 MHz as shown in Fig. 4, but is still large enough for our uses.

Calculation of Quadrupole Kick

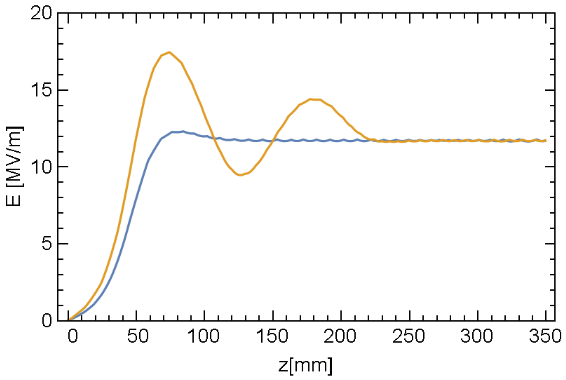

Figure 3: On axis fields in the cylindrical waveguide of the original mode launcher (blue) and redesign (orange) with 200 MW input power. 0 mm starts at the beginning of the beam pipe and 350 mm is the end of the cylindrical waveguide.

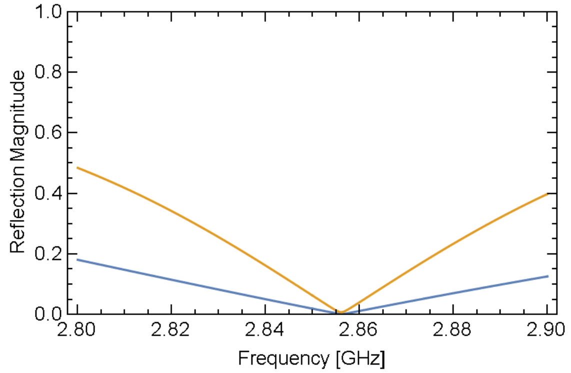

Figure 4: Reflection of input power from the rectangular waveguide port for the original mode launcher (blue) and redesign (orange).

Now we would like to measure the quadrupole kick experienced by relativistic electron beams, to verify that we have reduced it in our new mode launcher design. We calculated the quadrupole kick by first integrating the longitudinal electric field, E_z, seen by a particle moving at the speed of light in the direction indicated in Fig. 2. The particles will only feel forces from the integrated longitudinal component. We will then find the quadrupole component of that integrated kick. We assume that this particle is moving parallel to the center axis of the cylindrical waveguide, but is offset by a given radius r. The equation for the voltage $V_{\mp}$ is:

$$V_{\mp}(r,\theta) = \int_{z_{start}}^{z_{end}} E_z(r,\theta,z)e^{\mp ik_0 z}\mathrm{d}z,$$

where k_0 is the wavenumber of the input rf power, θ is the azimuthal angle, and $i = \sqrt{-1}$. z_{start} should be chosen in the beam pipe where the fields are near zero, and z_{end} will be in the cylindrical waveguide after the quadrupole fields in the coupler have decayed (on the order of a diameter of the cylindrical waveguide past any perturbations). The plus or minus sign in the equation should be chosen based on direction of electron beam travel versus direction of rf power flow. Minus for electrons counterpropogating with the rf power in the cylindrical waveguide, and plus for beams copropogating with the rf power. $V_{\mp}(r,\theta)$ was calculated for different θ but same r. Fig. 5 shows $V_{-}(r,\theta)$ versus θ for $r = 10$ mm and integrated from 0-350 mm in the z direction (from the beginning of the beam pipe to the end of the cylindrical waveguide in our model).

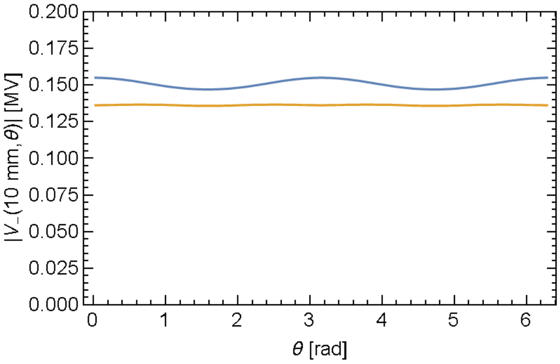

Figure 5: $V_{-}(r,\theta)$ in the mode launcher versus θ around the center axis of the cylindrical waveguide for 350 mm (beginning of the beam pipe to end of the cylindrical waveguide). Values are for 200 MW input for the whole mode launcher. The original design is in blue and new design is orange.

We determine the quadrupole component by taking the discrete Fourier transform versus θ_j of $V_{\mp}(r,\theta)$, where j is index of the sampled azimuthal angles;

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

where n is the number of azimuthal variations calculated for $V_{\mp}(r,\theta_j)$, and $M_{\mp,s}$ is the mode being calculated, with index s. In this case $M_{\mp,0}$ is the monopole component and $M_{\mp,1}$ will be the dipole component. In our case the dipole component is identically zero due to symmetry of the model. The quadrupole voltage will be $M_{\mp,2}$. Fig. 6 shows the multipole modes of the voltage, with $M_{\mp,1} = 0$. $M_{-,2}$ is reduced from the original S-band mode launcher by an order of magnitude.

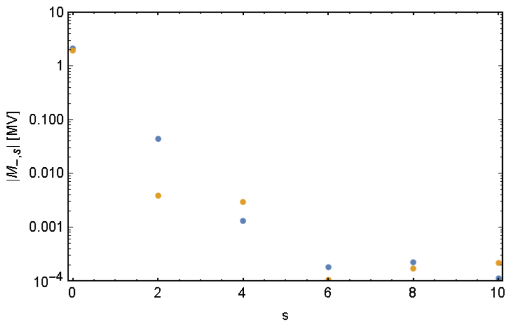

Figure 6: $M_{-,s}$ in the mode launcher by azimuthal angle for 200 MW input rf power. The original design is in blue and new design is orange.

Quadrupole Impedance To characterize quadrupole voltage independent of rf power, we introduce the

Quadrupole Impedance, $Z_{Q,\mp}$ as

$$Z_{Q,\mp} = \frac{|M_{\mp,2}(r)|^2}{r^4 P},$$

where P is the rf power transmitted through the mode launcher and the units for $Z_{Q,\mp}$ are Ω/m^4. The quadrupole impedance is independent of r for ultrarelativistic electrons.

The quadrupole impedance for the original S-band mode launcher is $Z_{Q,-}$=1850 $M\Omega/m^4$, and the quadrupole impedance of the redesigned mode launcher is $Z_{Q,-}$=13.6 $M\Omega/m^4$. For this beams copropogating with the rf power will see a larger quadrupole kick: $Z_{Q,+}$=2011 $M\Omega/m^4$ for the original mode launcher and $Z_{Q,+}$=2669 $M\Omega/m^4$ for the redesign. In our design, we have minimized the quadrupole field component for beams counterpropogating with the rf power.

CONCLUSION

We designed a mode launcher at 2.856 GHz that creates a TM_{01} in a cylindrical waveguide. The quadrupole component that adversely affects the electron beam was minimized. We plan to use this mode launcher to feed a cryogenic normal conducting rf photogun. We plan to do beam dynamics simulations to verify the effect of fields from this mode launcher on the electron beam.

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