ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPML054

DESIGN STUDIES OF AN S-BAND MULTIPACTING ELECTRON GUN

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Abstract

A multipacting electron gun (MEG) is a micro-pulse electron source based on secondary electron emission in a resonant microwave cavity structure for the generation of low emittance electron bunches with high repetition rate. By theoretical simulations a suitable radio-frequency gun design at 3 GHz is established, simultaneously meeting the demands of bunch production and amplification process as well as including the effects of space charge and beam loading for the evolution of a stable beam. In this contribution we show detailed simulation studies of the impact of important design parameters like mechanical dimensions and choice of material on the average output current, which is in the order of mA. For the experimental investigation a test setup is under construction, which may demonstrate the application of MEG's as a serious alternative or addition to commonly used electron sources like thermionic and photocathodes.

INTRODUCTION

A well-established way of electron generation for particle accelerators is by utilizing the principle of laser-driven emission from photocathode materials [1]. However, since 1969 there are ongoing investigations on the mulitipacting electron gun concept [2], where electrons are resonantly accelerated towards opposing surfaces for synchronous charge amplification by secondary emission (SE) using a radio frequency (RF) field. One partially transparent surface is used to release electron bunches from the gun cavity.

Since the effects of beam loading and space charge forces are heavily affecting important beam properties, but cannot be taken into account analytically with sufficient accuracy, detailed numerical simulations using the *ASTRA* code [3] were performed.

MULTIPACTING GUN

A simplified model of the planned MEG presented in this work, is, similarly to [4], an RF cavity structure with two rotundly shaped opposing surfaces of which one has a centered aperture for decoupling of the generated electron bunches.

Via coupling of an alternating electric field gradient into the cavity, in first approximation electrons are following the equation of motion

$$\ddot{z} = \frac{e}{m_e} E_0 \sin(\omega t + \phi)\,, \qquad (1)$$

where E_0 is the field amplitude, ω its phase, ϕ the particles phase deviation and e and m_e are the elementary charge and electron rest mass respectively. z denotes the field direction

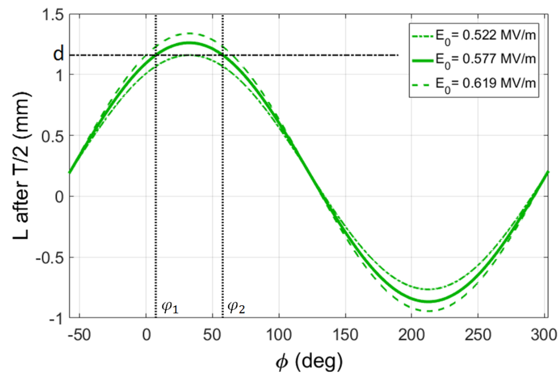

Figure 1: Traveling distance of an electron after a half-period of the RF field as a function of the particles initial phase ϕ for three different field amplitudes. Figure in analogy to [5].

between the two cathodes, in which electrons travel, driven by the TM_{010} mode.

For a stable gun operation, electrons have to meet the requirements of charge amplification, meaning particles of resonant phase hit the cathode surfaces alternatively every half-cycle of the applied radio frequency and generate further SE electrons . Figure 1 illustrates one electron's traveling distance in the cavity after $t = T/2$ with phase. It is derived from integrating Eq. (1), giving

$$L = z(T/2) = \frac{eE_0}{m_e\omega^2}\left[2\sin(\phi) + \pi\cos(\phi)\right] + v_0\frac{\pi}{\omega}\,, \qquad (2)$$

neglecting influences of statistical and collective effects. By solving Eq. (2) for ϕ, φ_1 is the phase at which the electron travels a predefined distance d from one cathode to the other. From 0° until φ_2 self-bunching is taking place, due to natural phase selection of the resonant particles [6].

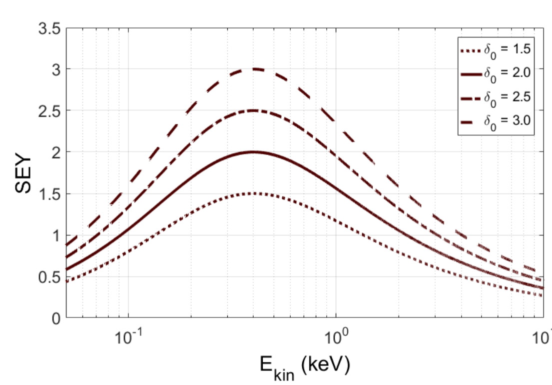

Figure 2: SE yield curves with electron impact energy E_{kin} for different maximum yield δ_0.

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It is very important that on average every initial electron excites more than one secondary in order to keep the gun operational. Therefore d, E_0 and frequency $f = \omega/2\pi$ are chosen so that electrons at φ_1 deliver energy for the maximum excitation probability. From the secondary electron yield (SEY) curves in Fig. 2 it can be seen that this value E_{pm} is supposed to be 400 eV, in accordance to [7], for aluminum. However, for this work the curves are calculated analytically like they are used numerically in the SE generation via

$$SEY(E_{\mathrm{kin}}) = \delta_0 \frac{E_{\mathrm{kin}}}{E_{\mathrm{pm}}} \frac{f_{\mathrm{s}}}{f_{\mathrm{s}} + \left(\frac{E_{\mathrm{kin}}}{E_{\mathrm{pm}}}\right)^{f_{\mathrm{s}}}}, \tag{3}$$

where δ_0 is the maximum SEY and f_{s} is a parameter, describing the functional dependence, which is set to 1.7 after [7]. Because of beam loading, the multipactor discharge will saturate in steady state operation to a constant amount of active electrons inside the RF cavity on average [8].

A surface plot of E_{kin} as a function of field strength and frequency is presented in Fig. 3. The gun's frequency in operation is desired to be 2.998 GHz in the S-band. For meeting the resonance condition at 400 eV, a peak electric gradient of $E_0 = 0.577\,\mathrm{MeV/m}$ needs to be applied. The other lines of resonance stand for different cathode distances, showing that other gun dimensions would change the required set of parameters significantly.

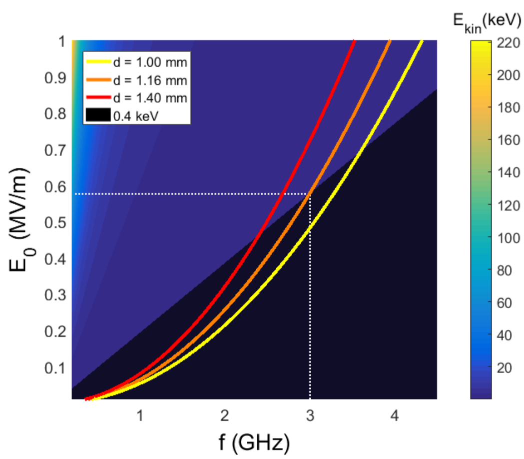
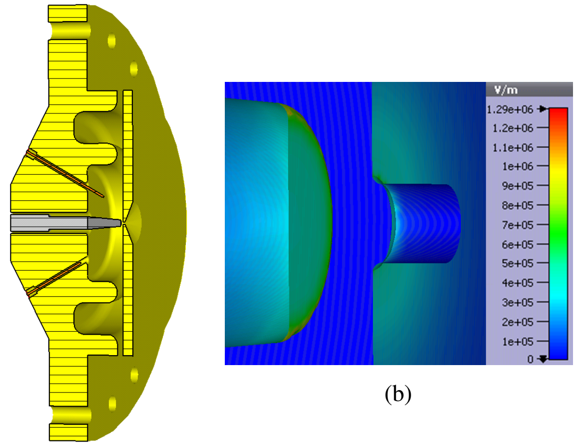


Figure 3: Kinetic impact energy E_{kin} versus field amplitude and frequency, together with lines of resonance for different cathode distances d.

Gun Design

The electromechanical conception is performed using *CST microwave studio* and includes a model of the aluminum cavity (Fig. 4) and the derivation of RF parameters, important for the overall performance.

The model in Fig. 4a is showing the RF cavity and opposing hole plate in yellow. It is possible to change the gap distance D_g between cavity wall and plate, which are electrically connected by quarter-wavelength impedance transformation through the inner wall, but mechanically open for



(a) (b)

Figure 4: MEG cavity flange (a) and field distribution at the cathode surfaces (b).

Table 1: Changeable Design Parameters for the MEG Setup

Description	**Name**	**Default Value**
Hole Length in Cavity Plate	$\mathrm{L_h}$	1.0 mm
Hole Radius in Cavity Plate	$\mathrm{R_h}$	0.5 mm
Cathode Plug Surface Radius	$\mathrm{R_c}$	1.5 mm
Cavity–to–Plate Gap Distance	$\mathrm{D_g}$	3.0 mm

gas evacuation. A linear translator is able to change the distance between cathode plug (grey) and hole plate, which are both changeable for setup optimization. Adjustable parameters are given in Table 1, together with values for working operation. The TM_{010} mode is fed into the cavity by an antenna, creating a field distribution at the cathodes as shown in Fig. 4b, which is increased by a factor of 2–3 at the rounded edges of both, cathode plug and aperture.

By simulation with optimum parameter set, given antenna length and cathode distance of 1.16 mm, the reflection and transmitted power of a 0.5 W test pulse are illustrated in

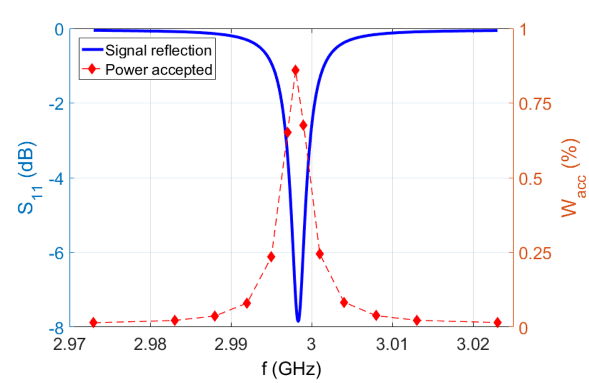


Figure 5: Signal reflection and normalized transmitted power of the RF cavity for optimized mechanical parameters.

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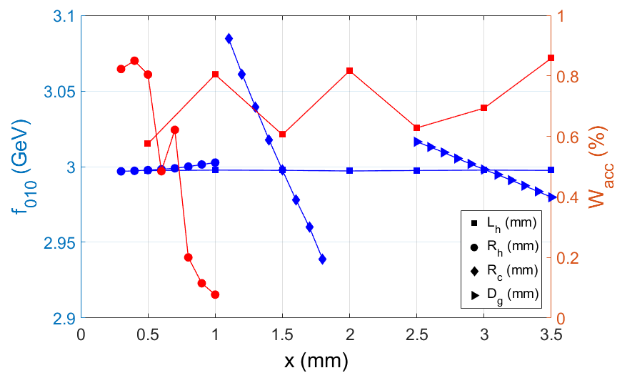


Figure 6: Simulated TM_{010} mode frequency (blue) and normalized transmitted power at 2.998 GHz (red) under variation of one out of four adjustable parameter dimensions x. $x = L_h, R_h, R_c$ or D_g for each set of data.

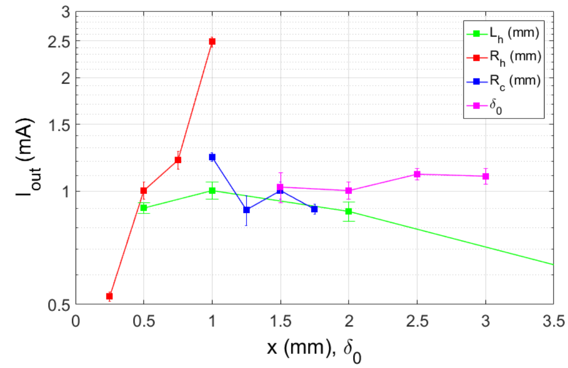
Fig. 5. It is tuned such that the resonance frequency of the cavity matches the minimum in reflection for coupling at 2.998 GHz. Here, coupling is not critical since the antenna dimensions are set to certain constant values, but it's not crucial for the gun operation anyway. A rather small loaded quality factor of $Q = 1419$ is obtained numerically, that is sufficient here and enables a short filling time as needed.

A performance study under variation of parameters mentioned in Table 1 is given in Fig. 6. Emphasis lies on the cavity's resonance frequency and the transmitted power at 2.998 GHz. The mode frequency, biasing power coupling at given f, heavily changes with R_c and D_g. It was found that by changing the gap distance, problems of mismatching could be adjusted, giving control for the experimental feasibility and power coupling.

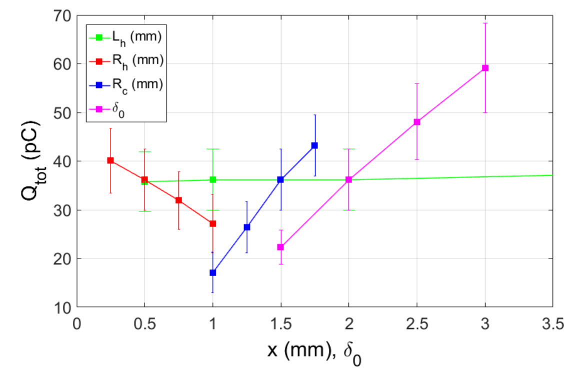
Charge Tracking Simulations

Under variation of one out of four chosen setup parameters, this time also including the maximum SEY (see Fig.2), space charge tracking simulations for the first 10–15 ns of gun operation are performed. This also includes beam loading and space charge forces, as they are heavily influencing beam parameters in the low-energy regime, reported by many sources, [9] for instance. The same initial input power of ≈ 250 W was used for all calculations. Under consideration of beam loading the actual field gradient never exceeded 0.577 MV/m.

Results are shown in Fig.7. The first important factor with respect to feasibility of stable operation is the output current, which remains ~ 1 mA under change of cathode radius and material SEY, but shifts with aperture dimensions. Furthermore, the current is expected to increase with higher input power leading to a stronger cavity field and thus more secondary emission in the equilibrium state of gun operation. The hole radius R_h is a promising parameter for huge output increase, even though less active charges remain for the amplification process between the two cathodes. This could



(a) Average current.



(b) Active gun charge.

Figure 7: Simulation results of the average output current (a) and active charge in the cavity (b) under variation of one out of four adjustable parameters from Table 1 and Fig.2. $x = L_h, R_h$ or R_c; δ_0 is the maximum SEY.

easily be compensated by using high-yield material, since it increases the density of active gun electrons.

Once the analysis section for this kind of tracking geometry is further advanced, other beam parameters can easily be extracted. So far bunch length $z_{rms} \sim 250\ \mu$m and energy spread $\Delta E_{kin,z} \sim 80$ eV are estimated from the numerically solved particle distributions.

CONCLUSION

For small bunch size and high repetition rate electron bunches an MEG has been designed, supported by numerical calculations. It is shown that in certain configurations, an aluminum RF cavity can be built, where an applied radio frequency meets the TM_{010} mode resonantly for critical coupling at 2.998 GHz. Variation of gap size D_g between cavity flange and hole plate, electrically connected by a quarter-wavelength impedance transformation, gives the option to find optimal coupling in the experimental setup.

Space charge tracking simulations support the feasibility of the proposed MEG. For the default setup configuration an average output current of ~ 1 mA is calculated. By increase of the aperture diameter and well suited choice of cathode material, the current could be enhanced significantly. Fur-

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ther experimental and theoretical investigation in the near future is supposed to give insight into crucial beam properties like transverse emittance, bunch size and longitudinal energy spread.

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