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CHARACTERIZATION OF AN ELECTRON GUN TEST SETUP BASED ON MULTIPACTING

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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 in continuous wave operation. Based on numerical simulations, an experimental test setup for low-energy electron beams at 2.998 GHz has been established. In this contribution we show a detailed description and characterization of the RF test stand, supported by first results on charge collection measurements of the output current with respect to important operational parameters like power transmission and modifiable mechanical dimensions in the assembly of the experiment. This is a milestone in the development of a MEG setup for higher energetic electron beams and subsequent investigation of essential beam characteristics like emittance and energy distribution for the optimization with regard to best possible beam quality and future fields of application.

INTRODUCTION

In 1969, W. J. Gallagher [1] proposed to make use of the naturally unwanted effect of multipacting discharge for the controllable generation of bunched electron beams. In stable MEG operation, electrons are resonantly accelerated towards two opposing cathode surfaces by the TM_{010} mode of a radio frequency (RF) field, schematically shown in Fig.1.

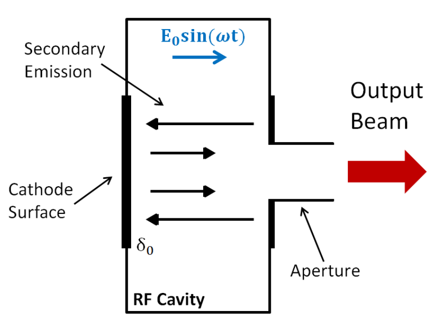

Figure 1: MEG principle.

The effect sustains itself by periodically enhanced secondary emission (SE) every half–cycle of the electric field around the synchronous phase of the electrons, as described in detail by Zhou et al [2]. Thereby, a steady state operation can be achieved, which is a result of cavity loading and space charge debunching of the electron cloud [3, 4]. Although space charge forces have an impact on the particle momenta, a self-bunching effect due to natural phase selection of the particles lead to small bunch sizes of the resulting beam [5]. In order to release electron bunches from the gun cavity, one partially transparent cathode surface is used for the beam to pass through.

MEG TEST STAND

The construction of a functional test experiment on MEGs, following the above-mentioned criteria, is based on previous design studies [6]. Figure 2 shows a picture of the current test stand in our laboratory in the Center for Free–Electron Laser Science at the University of Hamburg.

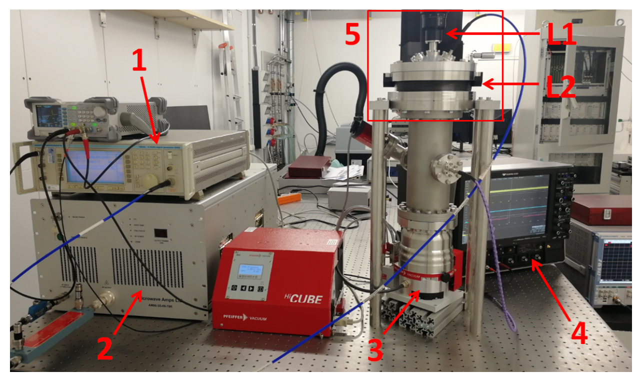

Figure 2: Picture of the MEG experiment as a whole. 1) RF Signal Generator; 2) Power Amplifier; 3) Turbo Pump; 4) Oscilloscope; 5) MEG; L1, L2) Linear Translators.

The heart of the experiment is an aluminium cavity, sitting on top of a linear translator and connected to the vacuum system. Power is provided by a solid-state amplifier, which is electrically pin-coupled into the MEG cavity.

The electromechanical conception of this experiment has been performed using *CST microwave studio* and includes a model, that is illustrated in Fig.3.

The cathode tip (dark grey), attached to a linear translator ($L1$), is guided into the cavity towards an aperture in the opposing back plate of the cavity. It is shorted to the walls by a contact spring. The back plate is fixed and a slit between the two cavity parts is formed for gas evacuation. Here, the cavity is electrically closed by a quarter-wave impedance transformer. A second translator ($L2$) regulates the distance between cavity flange and plate. A combination in the adjustment of $L1$ and $L2$ is used to tune the resonance frequency, while maintaining a defined distance d between the cathode surfaces. This is where the maximum RF field amplitude builds up, as shown in Fig.3b.

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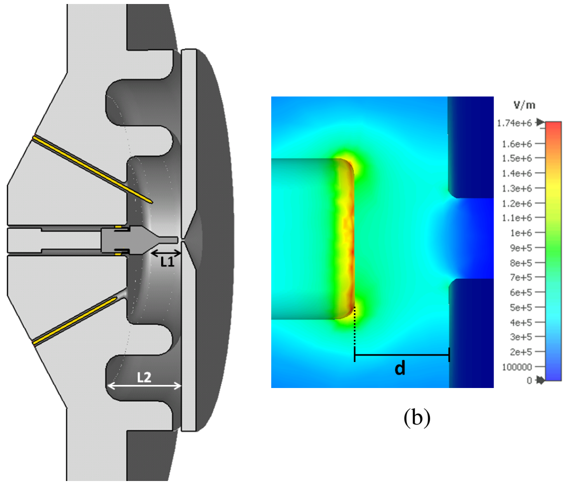


(a) (b)

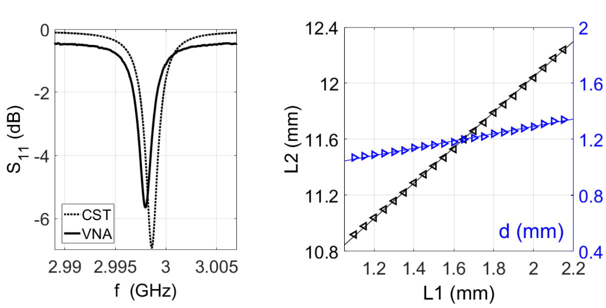
Figure 3: CST model of the MEG cavity (a) and field distribution of the electric field at the cathode surfaces (b), separated by the distance d. Translator $L1$ tunes the distance between the two cathodes, while $L2$ is used to move the whole cavity flange towards the plate.

RF Cavity Properties

General characteristics of RF cavities are derived from the equivalent circuit of a damped oscillator with external excitation, where damping occurs due to energy losses in the cavity walls and transfer to the particle beam [7].
An important measurable quantity to take these losses into account at frequency ω_0 is the loaded quality factor

$$Q_L = \omega_0 \frac{W}{P_{cy}} = \omega_0 \frac{W}{P + P_{ext}}, \quad (1)$$

defined as the ratio of stored energy W to the total of dissipated power per RF period P_{cy}. For the MEG cavity in Fig.2 it is obtained from the signal reflection curve (see Fig.4a), measured by a vector network analyzer (VNA) around resonance. It is comparable to the *CST* simulations of the model at $d = 1.154$ mm.



(a) (b)

Figure 4: Measured (solid) and numerically obtained (dashed) power reflection vs. frequency (a). The cathode distance d as a function of $L1$- and $L2$–setting at the measured resonance frequency $f_0 = 2.998$ GHz is plotted in (b).

Equation 1 also includes external losses P_{ext} from coupling, which are determined by the coupling factor

$$\kappa = \frac{P_{ext}}{P} = \frac{Q_0}{Q_{ext}}, \quad (2)$$

as a ratio of external and internal losses. For the unloaded quality factor we get $Q_0 = (1 + \kappa) \cdot Q_L$.
Figure 4b shows the setting of the cathode tip ($L1$) and cavity translator ($L2$), while $f_0 = 2.998$ GHz for the specific experimental configuration. Under consideration of the mechanical dimensions in the assembly, the cathode distance is adjusted following

$$d = L2 - L1 - (8.750 \pm 0.025)\,\mathrm{mm}. \quad (3)$$

That way, the MEG cavity can be tuned under change of distance d quite handy. It has to be mentioned that κ is not exactly equal for all d, since the coupler-pin length can not be changed easily.

Some important parameters for a specific operation point are listed in table 1. The resonance condition for periodical secondary electron multiplication is heavily influenced by f_0, d and the field gradient E_0, as already worked out in [6]. The design value of the cathode spacing was determined in simulations to be around $d = 1.16$ mm with $E_0 = 0.577$ MV/m.

Table 1: MEG: Parameters

Resonance frequency	f_0	2.998 GHz
Aperture Radius	r	500 m
Cathode Distance	d	1.154 ± 0.025 mm
Quality Factor	Q_L	1100 ± 100
Coupling Constant	κ	0.38 ± 0.02

Experimental Results

MEG electrons, that are passing through the aperture, contribute to the overall beam current. In the test stand they are collected by a specifically designed faraday cup and measured through the voltage drop U at an oscilloscope's 50 Ω input port.

Figure 5 shows the experimental data from one of the first working measurements at $d \approx 1.15$ mm. The RF pulse is 4 µs long with a repetition rate of 100 Hz. During that time, power is transmitted into the cavity and measured via the weakly coupled ($\kappa \approx 0.1$) pick–up pin. The amplitude of both, the reflected and transmitted wave, are rectified by crystal detectors for simultaneously monitoring, as presented in the bottom part of the figure.

Because of the rather high quality factor and its linear proportionality to the filling time constant, the field inside the cavity builds up slowly from the beginning of the RF pulse. Once a sufficient field gradient is reached, initial electrons are generated by field emission. In this process, the stored energy inside the cavity is transferred to the electrons, leading to an acceleration towards the other surface. While

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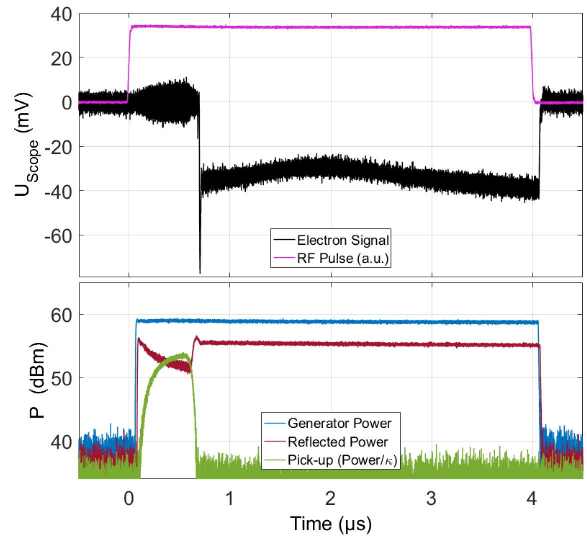

Figure 5: Measured Faraday–Cup signal, voltage U (top) and Power P (bottom) as a function of time during gun operation.

more particles are created through multipacting, the power transfer to the beam then leads to a reduction of the acceleration field and thus stable emission at resonance condition. Thereby, the electron impact energies settle down to a point where the material dependent SE yield value of about one is met.

From the data (Fig.5), no single pulses can be resolved due to the cup's low bandwidth. The peak in the beginning is, in accordance to [8], indicating the situation of an unstable multipacting process with higher electron energies. There is a delay of ~0.6 sec since the critical gradient for initial field emission has to build up inside the cavity. After a few RF cycles, the peak decays and an average beam current of $I_{ave} \approx 0.7$ mA sets in. It is in agreement to numerical results using the "*ASTRA*" code, where an average current of ~1 mA is predicted.

Emission starts at a transmitted power of $P_{in} \approx$ 53.5 dBm = 220 W. After the multipacting process is initiated, no cavity field is measured above the resolution limit. This may be a result of strong detuning and decoupling due to cavity loading. Stronger coupling ($\kappa > 5$) would provide energy much faster in that regard. Furthermore, the output current is not quite stable during electron emission. This might be related to a slight drift in the generator power over the pulse length, which is very sensitive to the number of secondary electrons. However, the form of the electron signal inside the RF window is in agreement to previous attempts, [5, 8] for instance and gives the opportunity for further investigation.

CONCLUSION

For the generation of small bunch size and high repetition rate electron beams at low energies in the order of a few hundred eV, a MEG has been designed, built and operated. The design considerations for the RF cavity and cathode tip are based on numerical *ASTRA* and *CST* calculations. Measurements on the RF properties of the constructed MEG cavity are in good agreement with theoretical expectations. Hereby, the applied RF field meets the TM_{010} mode resonantly, weakly coupled ($\kappa \approx 0.38$) at f_0 = 2.998 GHz. An unloaded quality factor of $Q_0 \approx 1500$ is derived. The combined adjustment of two linear translators in the assembly allows to tune the cavity without changing important mechanical parameters for the SE resonance condition.

The working point of a resonant multipacting process was found at $d \approx 1.15$ mm, starting at an input power supply of around 220 W. The average gun current under those conditions is about 0.7 mA. It is likely to increase both, bunch charge and current stability under more convenient coupling conditions. Faster filling of the cavity and thus achievement of higher field gradients would lead to more secondary emission in the equilibrium state of gun operation beside the strong cavity loading. However, the shape and amplitude of the macroscopic output current are comparable to the experimental results found in literature.

With better understanding of the parameter space for a stable MEG output current, it will be possible to improve the setup to higher electron energies and also address other crucial beam parameters like emittance and energy spread. This is of high interest with regard to possible application as a particle source in small accelerators, ERLs or medicine. Therefore, in future it is planned to further accelerate the electron bunches, including a diverse investigation on beam parameters.

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