An S-Band Test Cavity for a Field Emission Based RF-Gun

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Abstract

A test-bed is under construction at the Dortmund Electron Test Accelerator (DELTA) which will give the opportunity to investigate cathodes based on field emission in the environment of an S-band cavity. We aim for surface electric fields of 20-200 MV/m to allow for the study of field emitters of various types and the development of a field emission based RF-gun. The special design of the 3 GHz test cavity is given. The strength, uniformity and stability of as-fabricated cathodes of about cm^2 size have been systematically investigated with a field emission scanning microscope. Stable electron currents up to 2 mA over 1 mm^2 at 18 MV/m were reproducibly achieved from nanodiamond-coated Si-tip-array substrates. Nanocrystalline diamond structures on flat Si substrates provided less stable 50 $\mu A/mm^2$ at 75 MV/m.

1 INTRODUCTION

Linac based Free Electron Lasers and high energy linear colliders require very bright electron beams. Injectors consisting of conventional DC-guns and RF-bunchers for longitudinal pulse compression have intrinsic limitations concerning transverse and longitudinal emittance e.g. First studies of electron guns based on an RF-cavity (RF-guns) started in 1984 [1]. Since then two major concepts (RF-guns with thermionic- and photocathode) have been studied intensively [2]. Experience with field emission (FE) cathodes used in an RF-gun however is still limited [3,4]. Though high currents could be accelerated at that time it had been difficult to find stable and reproducible operating conditions.

Meanwhile, remarkable progress on cathode materials has been made for vacuum microelectronic applications [5]. While actual RF devices like FE tube amplifiers are still based on tip arrays of refractory metals, cathodes with nanocrystalline diamond materials would be preferred in case of sufficient FE uniformity and high-current stability. Therefore, microscopic investigations, with a DC field emission scanning microscope e.g. [6], are crucial for the systematic improvement of actual FE materials for RF guns. We have designed a special RF cavity which will permit the insertion and test of various types of cm^2-sized cathodes (see chapter 2). First promising DC FE results on nanocrystalline materials [7,8] will be reported in chapter 3.

2 THE RF-CAVITY

2.1 General Performance

To allow for the test of various types of large size field emission cathodes (up to 14 mm diameter) an ideal RF-test-cavity should combine the following advantages: i.) the electric field on the surface of the cathode should be as high and homogeneous as possible, ii.) the mechanical design must permit a simple change of the cathode material and iii.) the efficiency (shuntimpedance) should be high enough in order to obtain at least 150 MV/m surface electric field at 5 MW input power and 3 GHz operating frequency (available from the transmitter under construction).

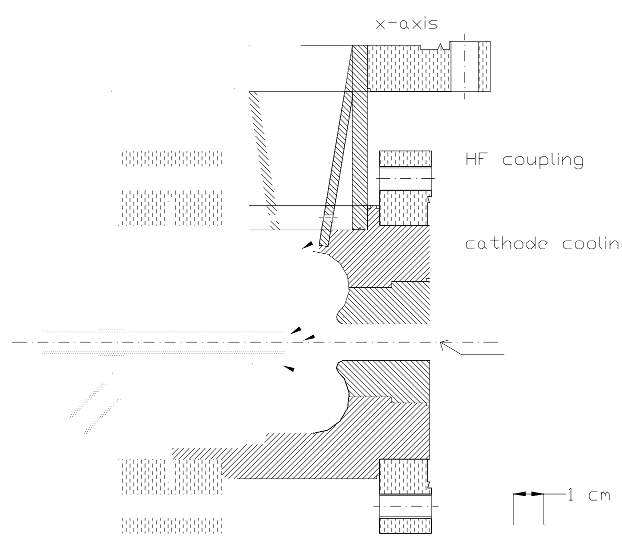

Figure 1: Mechanical layout of the half-cell test cavity

2.2 Design of the Test Cavity

Since the output energy of the emitted electrons does not play a significant role at this first stage of investigations we choose a half-cell cavity. The design is similar to a reentrant resonator operating in usual TM_{010}-mode (see figure 3), here with the cathode in the center of the cavity. Taking the demands mentioned above into account different resonator shapes have been studied.

Figure 1 shows the optimized mechanical layout; table 1 summarizes typical RF-data obtained from SUPERFISH-calculations; table 2 RF-data at 5 MW input power.

The complete back side of the cavity (Au-contacts) can be removed to make a change of the cathode possible. Therefore a so-called choke-flange design has been integrated, where a half-wavelength (λ/2)-transformer permits the insertion of the cathode substrate at a current-free contact. This choke-flange design turned out to be very crucial but has been optimized with respect to high quality factor and less critical multipactoring and discharge conditions.

operating frequency f_0	2998.55 MHz
RF-pulse-length	1 µs
repetition rate	1 - 10 Hz
unloaded Q_o (60%)	4950
shuntimpedance for a structure length of	38 MΩ/m 0.025 m
local field factor	2.075

Table 1: RF-data of the test-resonator obtained from SUPERFISH-calculations using 60% of the theoretical Q_0-value for OFHC-Cu. The surface electric field at the cathode is given by the mean electric field times the local field factor.

RF-input power	5 MW
mean electric field	88 MV/m
cathode surface field	180 MV/m

Table 2: RF-data of the test-resonator at 5 MW input power. The influence of the cathode has been neclected.

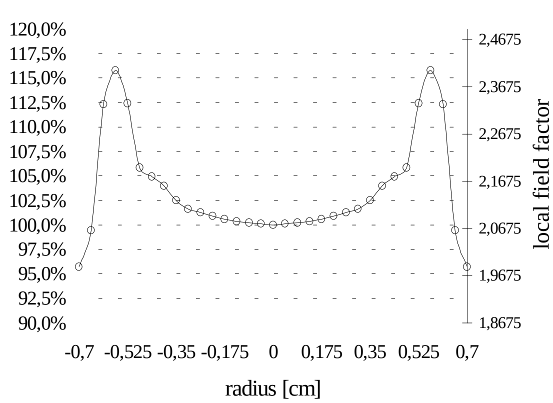

Figure 2: Radial distribution of the electric field on the cathode surface calculated by SUPERFISH.

For a cathode diameter of up to 5 mm the variation of the electric field on the cathode surface is less than 1.3% as shown in figure 2, a value which is acceptable due to the local variation of the field emitting properties.

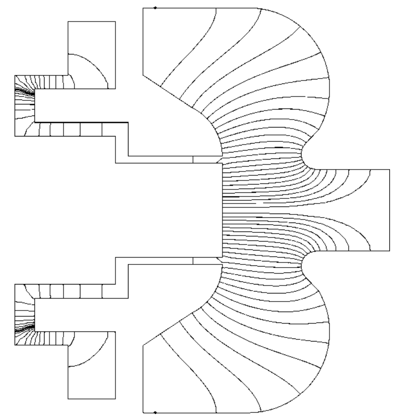

Figure 3: TM_{010}-mode electric field distribution calculated by SUPERFISH

2.3 The Field Emission Cathode

The cathode substrate will be glued to the removable copper socket of 14 mm diameter with a vacuum-stable and well-conducting silver lacquer. As substrate for the nanocrystalline diamond layers with a diameter of 2 - 7 mm and a thickness of a few µm, highly doped Si wafers with a resistivity of about 2 mΩcm are foreseen. The cathode will be thermally stabilized by a special cooling circuit in the Cu socket.

3 DC FIELD EMISSION RESULTS

In order to estimate the achievable FE loading of the RF cavity, the cathode materials were tested by means of an UHV DC field emission scanning microscope (FESM) at Wuppertal which has already been described in detail elsewhere [6]. These measurements allowed to judge about the FE uniformity and stability, i.e. to localize and analyse all emitters of a sample cathode of about cm^2 size individually on a µm scale. Using tungsten anodes of different size, the onset surface fields E_{on} for I=0.5 nA and maximum FE currents I_{max} before and after conditioning were measured locally (Ø 1 µm) as well as semi-integrally (Ø 0.5-1 mm). Moreover, in- and ex-situ SEM analysis revealed the corresponding surface morphology of the emitters and changes due to high currents or discharges. The main results for the two most promising nanocrystalline materials are given here.

3.1 Nanocrystalline Diamond Film

The flat nanocrystalline diamond film (ND) was fabricated at Erlangen by microwave plasma chemical vapor deposition and contains considerable graphitic content [7]. SEM micrographs revealed a coral-like morphology with a surface roughness of a few µm. FE scans with an anode of Ø 0.5 mm yielded E_{on} values between 50 and 80 MV/m everywhere on the ND sample.

A typical semi-integrally measured current-field characteristic of the ND film is shown in figure 4. The virgin sample provided Fowler-Nordheim like behavior with a β=59 and S=10^{-8} cm^2 (for Φ=4 eV) up to I_{max}=50 µA at 75 MV/m. Obviously, some instability occured then which slightly enhanced the FE strength in the tested area. The second field increase was reproducible and confirmed the current limit of the sample. Zooming into that area with microanodes and SEM revealed locally stable FE current densities up to 1 A/cm^2 but also some material disruption due to processing or discharges [7]. Therefore, the uniformity of the ND films must be improved to enable higher integral FE currents.

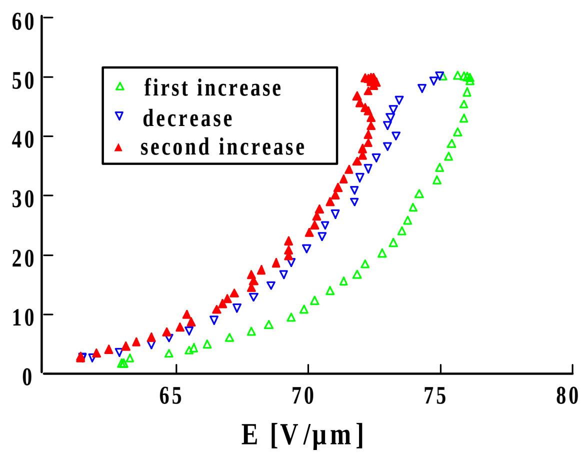

Figure 4: FE current (µA) versus the electric surface field integrally measured over 1mm^2 of a flat ND film.

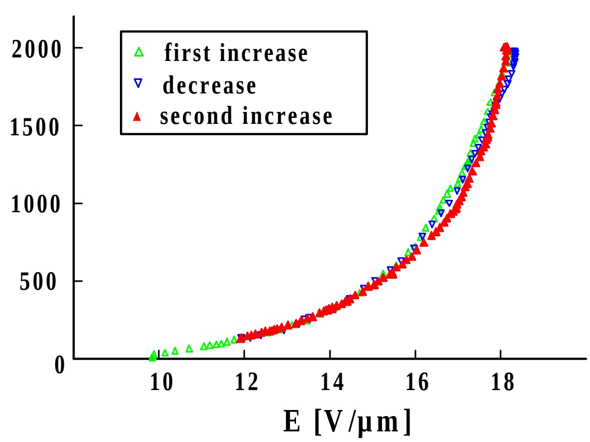

Figure 5: FE current (µA) versus surface field integrally measured over 1mm^2 of ND coated Si tip arrays.

3.2 Nanodiamond-Coated Si-Tips

It is well known that geometric field enhancement reduces the E_{on} of FE. Accordingly, we have tested for comparison ND which was electrophoretically coated onto Si-tip-arrays (16 µm spacing) at Moscow [8]. By means of SEM, spikes of varying height (100±20 µm) and sharp apex radius (typically 25 nm) with statistically distributed ND crystals were found. FE scans with µm resolution revealed that about 50% of these spikes emitted already at an average E_{on} of 7 MV/m. The uniformity of the FE, however, was limited in the DC experiment by the fact that the electrode spacing was in the same order of magnitude as the tip height variations. Despite the locally varying electric fields, integral currents up to 2 mA over 1 mm^2 at 18 MV/m were achieved as shown in figure 5, which reproducibly followed the Fowler-Nordheim law with a β=1204 and S=10^{-12} cm^2 (for Φ=4 eV). Some instabilities combined with the blunting of individual tips were also observed, but strong damage only occured at much higher current densities of up to 2 A/cm^2 [8]. RF tests of this cathode type will be quite challenging because of the expected trade-off between increased FE uniformity and reduced thermal stability.

4 CONCLUSIONS

The DC field emission performance of the two types of nanocrystalline diamond materials have demonstrated low onset fields and high currents which are suitable for cathode tests in the designed RF cavity. After finishing the construction of the test-bed, conductive Si substrates of Ø14 mm coated with precharacterized emission layers of Ø5 mm will be installed and tested to prove the feasibility of our RF gun concept.

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