CURRENT NANOPULSE GENERATION IN RF ELECTRON GUN WITH METAL-DIELECTRIC CATHODE

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Abstract

The RF gun operation with metal-dielectric cathode is reviewed in the paper. The beam is extracted from the plasma developed during the microwave flashover dielectric in vacuum. The cathode was designed and electron beam dynamics was computer simulated. Modes of the gun operation were researched experimentally on the linear resonance electron accelerator. The beam at the gun output has the pulse current of 3.5-4.5 A with the current pulse duration of 40-50 ns and with particle energy of 300 keV. Some treatments of the beam development and the gun cavity response to the flashover in high intensity RF fields are given.

1 INTRODUCTION

RF electron guns produce electron beams with extreme high brightness providing operation of free electron lasers and injector systems for linear colliders. Thermionic and photoemission RF guns are the most widely used now. Electron beam dynamics in such guns is well studied. The ways of beam brightness increasing are also defined.

The fundamentals of RF gun operation can be applied for the generation of intense high-energy bright beams with nanosecond current pulse duration. The main idea is in the total stored energy absorption in RF gun cavity. The generation of ultra-high current electron beams in thermionic RF guns is limited by the cathode emission current density that is not higher of 10 A/cm^2 for conventional dispenser cathodes. The operation of photoemission RF guns in nanosecond pulse duration mode is followed up by the cathode surface heating up that limits pulsed current value [1]. To provide the required current the plasma cathodes can be used. Such cathodes don't require complicated satellite equipment. Metal-dielectric cathodes with emission from the plasma developed during the microwave flashover dielectric in vacuum are somewhat more promising [2, 3] to be applied as electron sources. The source of the flashover is the metal-dielectric-vacuum contact. Application of metal-dielectric cathode in RF gun with high electric field strength will permit to extract high peak current due to bunched beam structure. Moreover, it's not excepted that the known electron back bombardment can contribute to the flashover development and self-maintenance.

The purpose of the work is to research experimentally S-band RF gun operation with metal-dielectric cathode.

2 EXPERIMENT APPROACH

Two-cavity S-band RF gun [4] was used for the research. The cathode was designed with taking into account RF gun properties and the flashover behaviour in vacuum. There is simplified RF gun design with metal-dielectric cathode and measurement layout on the Fig. 1.

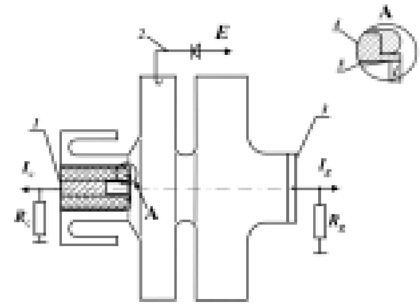

Fig. 1. The simplified RF gun design and measurement layout:
1-cathode; 2-detector; 3-beam current monitor; 4-dielectric cathode cylinder; 5-metalic cathode cylinder

The cathode 1 consists of inner copper cylinder 5 and outer polytetrafluorethylene cylinder 4 enclosed by the shielding tube. The cathode is placed in the quarter-wave line of the gun where the electric field has decreasing distribution along the discharge interval *l*. The copper cylinder has the curvature radius at the end face of ~ 20 µm to increase the electric field strength in the metal-dielectric contact. Besides, the small radius decreases discharge initiation field due to current density increasing through the emitting surface [5].

The flashover process in a spatial scale in S-band RF field is the same as in a pulse electric field [3] due to following the condition $l \ll \lambda_0$, where λ_0 is operating gun wave length. Defining *l* is the compromise between low initiation electric field strength and beam parameters at the gun output that is beam emittance. Thus, the computer simulation using SUPERFISH code [6] has defined that small values of *l* simplifies tuning of the gun cavity eliminating the dependence of the unloaded *Q*-factor Q_0, the operating frequency f_0 and longitudinal electric field distribution in the gun cavity on the dielectric properties. In particular, the relative variation of *Q*-factor and f_0 is 10^{-2} and 10^{-5} respectively for $l = 0.5...1.5$ mm and dielectric cylinder with diameters of 3 and 4 mm and with properties of $tg\delta = 10^{-4}...10^{-2}$ and $\varepsilon = 1...12$. Therefore,

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the discharge interval length was accepted of 1 mm that corresponds to the electric field strength ≅ 6.0 MV/m at the cathode plane with maximum axial electric field strength in the cavity of 30 Mv/m.

The hollow cathode design was used to take into account intense high current beam acceleration in RF gun. The extracted current density from plasma into vacuum follows up the thermo-field emission on the hypothesis that electron distribution in plasma spot follows Maxwell-Boltzmann statistics and is defined as following [7]:

$$j = en_e \left(\frac{kT_e}{2\pi m_e} \right)^{1/2} \exp\left(\frac{\sqrt{e^3 E}}{kT_e} \right), \qquad (1)$$

where e is electron charge, m_e is electron mass; T_e is plasma temperature; n_e is plasma density; E is electric field strength; k is Boltzmann constant. The computed average current extracted from plasma spot in vacuum for the RF gun is 10.5 A. To accelerate this current and to keep the beam converged particles should meet high electric field strength. Beam dynamics simulation in approach of flat emitting surface using PARMELA code [8] shows that the maximum electric field ratio $\eta = E_1/E_2 > 1$, where E_1 and E_2 is maximum of electric field strength in the gun first and second cavity respectively. Fig. 2 shows normalized beam emittance for 70 % of particles and transverse beam size vs η.

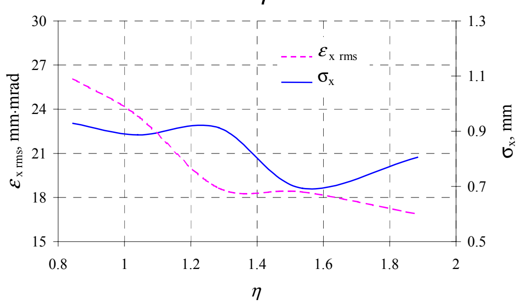

Fig. 2: Beam emittance and beam size vs maximum electric field ratio

For the input power value of 1.5 MW the energy spread (FWHM) and phase spread doesn't depend actually on the value η and is 32 % and 43 % respectively. The electron capture is increased in the range of 0.34..0.4 for the above (Fig. 2) values of η.

3 EXPERIMENTAL RESULT TREATMENTS

The RF gun operation was researched on the single-section linac LIC [9] having accelerating structure with phase velocity that is equal to the light velocity c. There was measured the current from metallic cylinder of the cathode I_c (Fig. 1), output gun current I_g and beam parameters at the linac output for different axial electric field strength E in the first cavity of the gun. For $E \leq 25$ MV/m the current I_c is positive and is up to 1 A. The pulse shape follows up the shape of RF field E in this case. The measured I/E response in terms of the Fowler-Nordheim theory follows up the field emission mechanism in RF field [10]:

$$j = aE^{2.5} \exp(-b/E) \qquad (2)$$

where E is the surface electric field, a and b are constants (Fig. 3). There is no beam current I_g in this mode.

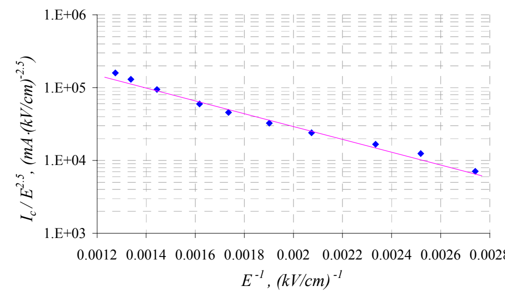

Fig. 3: Fowler-Nordheim plot for the pre-breakdown current

RF power increasing over the electric field strength of 25 MV/m causes the current increasing over than one order of magnitude ($I_c \approx 18$ A). The polarity of this signal is still positive. At the gun output the current pulse amplitude I_g and duration is 6-8 A and 30 ns respectively. During the pulse I_g duration RF field amplitude is decreased considerably (Fig. 4).

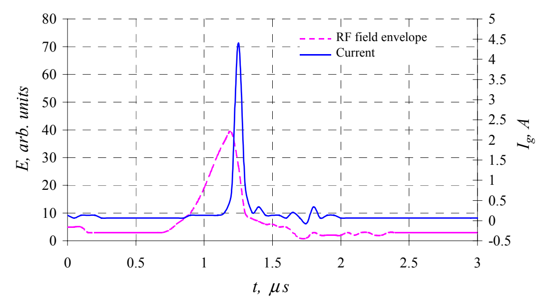

Fig. 4: RF field envelope in the gun cavity and the beam current at the gun output

The sharp current increasing due to beam loading indicates the flashover exciting. Thus, in the investigated RF gun the electric field strength of 25 MV/m is the threshold of the flashover development. Below the threshold the flashover is developed only in some points on the dielectric surface. Beam current at the gun output includes the field emission current from metallic surface and the current extracted from plasma spots. This is the feature of the first RF gun operating mode.

With a time ($\approx 8 \cdot 10^4$ pulses) the cathode operation is changed in another mode. The signal I_c is positive only up to the moment of the flashover exciting and the amplitude of this pre-breakdown current is not over of 1 A. The threshold electric field strength is decreased down to ~ 20 MV/m. After the moment of the flashover development the polarity of the signal I_c becomes negative and is kept in this state during the next time of RF power pulse. The beam current at the gun output I_g has the amplitude of 4.5 A and the current pulse duration of 40 ns in this mode (Fig 5).

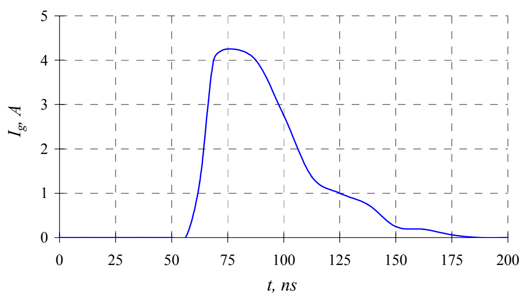

Fig. 5: The featured current pulse shape at the gun output

It's absolute evident that the dielectric is charged positively in points of plasma spots. The radial component of the electric field gets more strength. This causes the potential redistribution over the discharge surface and additional electric field amplifying in the metal-dielectric contact. Such positive feedback spreads plasma spots along the discharge interval. Finally, with the time required the charge distribution to be stable the dielectric surface is filled by plasma throughout the discharge interval. This provides the discharge self-maintenance and is the feature of the gun second operating mode. Some of secondary emission electrons reaches the metallic surface of the cathode and shunts field emission current. Beam current at the gun output is defined in this case only by the current from plasma spot.

The time to pass into the second operating mode can be reduced by the increasing of the pulse repetition frequency and by the electric field strength increasing over the threshold level.

The current amplitude instability is not over of 15 %. The time instability is defined by the time-position of output current relatively the RF power pulse duration and is in range of ± 5 ns during the rise time of the RF power pulse. The almost total stored RF power is absorbed during the flashover. The electric field amplitude falls down to near zero values and is kept in this state during the next time of RF power pulse (Fig. 4). The last fact with combination of the observed reflected RF power shape indicates the gun cavity detuning during the time of 2 µs that is much higher of the flashover duration time ~50 ns. The reasons of such detuning are not established and require further investigations. It's obviously that the gun operates in the stored energy mode because of the current pulse duration is $\tau \ll Q/\pi f_0$. The current pulse duration is defined by the flashover development rate and by the energy stored in gun cavities.

In the second gun operating mode beam current at the accelerator output has the amplitude over 2 A with the current pulse duration of 30 ns and electron energy of 13 MeV. Estimations of the electron capture into the linac accelerating waveguide shows that the electron energy at RF gun output is over 300 keV for the 50 % of particles.

The order of the above operating modes is saved after over 3600 s after the previous RF power switching off. The dielectric is discharged (due to dielectric conductivity and ions of the residual gas in the cavity) and the system state is changed into initial one.

4 CONCLUSION

Experiments have shown that metal dielectric cathode can be applied in S-band RF gun. The insertion of dielectric detunes resonance system of the gun in the range that is acceptable and doesn't change axial electric field distribution and cavity parameters significantly. For the electric field strength in the gun cavity of 25 - 30 MV/m there was obtained at RF gun output the stable beam current with amplitude of ≈ 3 - 4 A, current pulse duration of 30 - 40 ns and particle energy of over 300 keV.

Some questions concerning the emission mechanism in high intensity RF fields are still uncertain. In particular, the subject of interest is the role of back electrons, the effect of dielectric properties and dimensions on the flashover exciting and maintenance and resonance system optimization to extract higher beam currents. These questions are the subject of our further investigations.

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