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An RF-gun of 1 1/2 cells excited in antiphase at 2998.55 MHz has been constructed at CERN for the production of short electron bunches of high charge density. The successful design of a standing wave structure for the BNL RF-gun was adopted with some minor changes for ease of manufacture and operation. After some RF-processing, the gun could be powered up to the nominal RF-power of 6 MW during 2.5 μs providing an accelerating field of 100 MV/m in both cells. The intensity and energy of the dark current produced by a copper cathode has been measured. The field enhancement factor β for the field emission of the copper surfaces is constant up to 87 MV/m. A considerable amount of dark current (40 mA at 100 MV/m with copper cathode) is trapped by the RF-field inside the RF-gun and absorbs RF-energy from the field. The beam loading effect caused by the dark current limits the maximum electric field at which the gun can be used.

INTRODUCTION

The concept of a laser driven RF-gun with a photocathode[1)] as source of very short electron bunches has been selected for the CLIC Test Facility (CTF), which will produce electron pulses of 7 ps duration (FWHM) for RF-power generation at 30 GHz[2)]. The RF-gun consists of a standing wave structure with a half and a full cell resonating in antiphase at a frequency of 2998.55 MHz , as designed for the BNL-accelerator test facility at Brookhaven[3)]. The photocathode is made of a thin layer of CsI evaporated on a copper plug.

For maintaining the low emittance of the electron source, the electrons emerging from the photocathode must be accelerated by the electric field to relativistic speed as quickly as possible. A high electric field is obtained at the cathode, if the first cell is a half cell of approximate length $\lambda/4$. The second cell has a length of about $\lambda/2$. The iris between the two cells is rather thick (20 mm) and small in aperture (Ø 20 mm) providing linear RF-fields and minimum transverse blow-up of the beam emittance[3)].

In our tests, electric fields E_c = 100 MV/m have been obtained on a copper cathode (without photosensitive layer) and E_c = 70 MV/m on CsI photocathodes for routine operation during 100 hours. Increasing the fields further results in an exponentially growing beam loading effect by the dark current.

MECHANICAL CONSTRUCTION

The mechanical construction of the RF-cavity, of the water cooling circuits, of the flanges for the cathode support, piston tuners and monitor loops has been adapted so that all mechanical parts of the gun made of OFHC copper can be brazed together with an Ag-Cu-Pd alloy at temperatures between 860 - 778°C. The brazing gap must be 5 - 25 μm wide. The waveguide is connected tangentially to the circumference of the cavity, fig. 1. A plane is milled parallel to the waveguide on the outer wall of the cavity, and the waveguide is cut off along this plane. A coupling slit of 12 mm width milled into the cavity body connects the waveguide with both cavity cells along the whole length of the cells. The resonance frequency of the slightly overcoupled cells is reduced by the slit by 9.4 ± 0.2 MHz. Critical coupling is obtained by an adjusted short-circuit plane at the end of the waveguide.

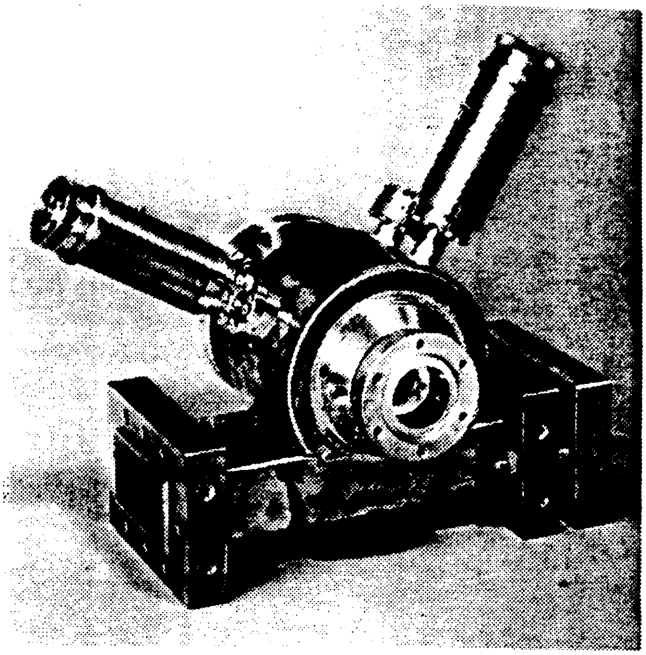

Fig. 1: RF-Gun and Waveguide viewed from beam exit . Each cell has a piston tuner and a field monitor.

Each cell has a moveable piston tuner to adjust the resonance frequency. The front end of the tuning pistons of diameter 6.5 mm penetrates by 2 mm into the cavity, and can be displaced by ± 3 mm from this center position by a micrometer screw with 0.01 mm precision. The micrometer screws allow for small and accurate adjustment of the resonance frequency shift required for perturbation measurements and for adjusting the relative field intensity between the two cells. The shift of the eigenfrequency by the tuning plunger in the half cell is 1100 kHz/mm and 500 kHz/mm in the full cell.

The RF-fields of the two cells are monitored by two loops which couple to the azimuthal magnetic field of the gun. The coupling factor is -60 dB. The monitor signals allow us to observe the energy exchange between cells and the beam loading of the gun by dark current and photocurrent[6)], fig. 2.

The photocathode is mounted from the rear side of the gun. A good RF-contact is provided by a hardened BeCu spring, fitted around the shaft of the cathode plug 3 mm behind of the cathode surface.

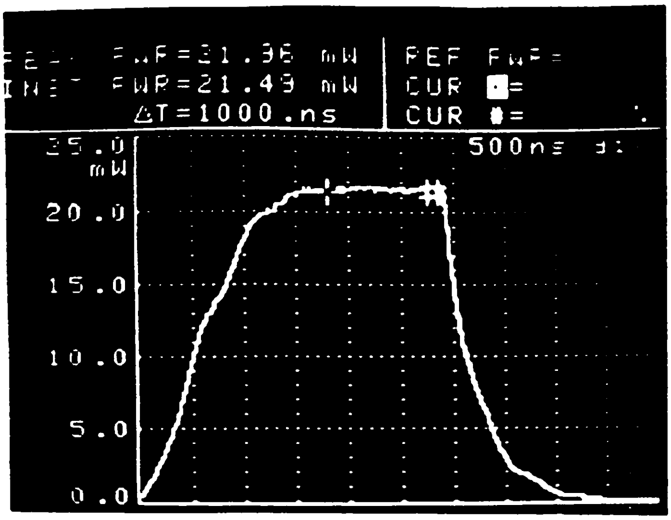

Fig. 2: RF-power monitor of cell 2, 0.5 µs/div.
peak field $\hat{E}_2$ = 97 MV/m

RF-MEASUREMENTS AND CELL TUNING

The resonance frequency f and the quality factor Q_o of each cell have been measured with the other cell completely detuned. The quality factor of the half cell is $Q_{01} = 8500$, for the full cell it is $Q_{02} = 12800$. If both cells are tuned for equal field strength, as discussed later, the external quality factor of the gun measured at the input of the waveguide amounts to $Q_L = Q_o/2 = 5600$, which is close to the theoretical value $Q_L = 5980$. For equal fields $E_1 = E_2$ in cell 1 and cell 2, which have the volume V_1 and $V_2 = 2V_1$, Q_L is given by $Q_L = 0.5\,(Q_{01}V_1 + Q_{02}V_2)/(V_1 + V_2) = 5680$.

The coupling factor k between the two cells is measured from the difference between the resonance frequencies f_3 and f_4 of the zero-mode and the π-mode respectively, if both cells are tuned to the same eigenfrequency $f_1 = f_2$.

$$k = \sqrt{k_1 k_2} = (f_4 - f_3)/f_1 = 1.95\ \text{MHz}/3\ \text{GHz} = 0.65\text{x}10^{-3}.$$

The coupling factors k_1 and k_2 of the half and full cell are related by $k_2/k_1 = 2$, hence $k_1 = k/\sqrt{2}$ and $k_2 = k\sqrt{2}$.

If the two cells are tuned to equal eigenfrequencies $f_1 = f_2$, the energy W of the electric field E is equal in both cells, but the fields are different: $E_1 = \sqrt{2}\,E_2$. This relationship has been used to calibrate the field monitors of the gun.

For $f_1 \neq f_2$, the ratio E_1/E_2 is determined by a system of characteristic equations for two coupled resonators with the angular eigenfrequencies $\omega_1 = 2\pi f_1$ and $\omega_2 = 2\pi f_2$. The system is excited at angular frequency ω, and is practically lossless due to the high Q_L-factor. Therefore the driving terms $U_{1,2}$ can be neglected[4].

$$(1-\omega_1^2/\omega^2)\,E_1 + k_2\,E_2 = U_1 \equiv 0.$$

$$k_1\,E_1 + (1-\omega_2^2/\omega^2)\,E_2 = U_2 \equiv 0.$$

The eigenfrequencies $\omega_{1,2}$ are determined by

$$\omega_1^2 = \omega^2\,(1 + k_2E_2/E_1), \quad \omega_2^2 = \omega^2\,(1 + k_1\,E_1/E_2).$$

For $E_1 = -E_2$: $\omega_1 \cong \omega(1 - k_2/2)$, $\omega_2 \cong \omega\,(1 - k_1/2)$.

As the gun is excited at frequency f = 2998.55 MHz, the eigenfrequencies of the cells for $E_1 = -E_2$ must be set to:

$$f_1 = f(1 - k/\sqrt{2}) = f - 1380\ \text{kHz}$$

$$f_2 = f(1 - k/2\sqrt{2}) = f - 690\ \text{kHz}$$

By measurement, the eigenfrequency of each cell can be calibrated very accurately as a function of the tuner position. For beam tests with the gun, the field ratio between the two cells can be adjusted within the limits $0.25 \leq -E_1/E_2 \leq 4$ by setting the tuners to the theoretical eigenfrequencies.

RF-POWER TESTS

The first power tests of the RF-gun were carried out with a copper plug in place of the photocathode. Despite the sparking in the RF-choke of the cathode plug, the gun could be powered to the design value of 6 MW corresponding to an accelerating field of 100 MV/m on the copper cathode. At this field level, the vacuum pressure rose to $3\text{x}10^{-9}$ Torr. For a lower field of 80 MV/m, the vacuum pressure measured at the pumping manifold of the waveguide was only $3\text{x}10^{-10}$ Torr. Without RF-power applied to the gun, the vacuum pressure was as low as $1.5\text{x}10^{-11}$ Torr after the gun had been baked out at 150°C and titanium had been sublimated. From the outgassing rate without RF it can be concluded that the vacuum pressure in the gun was a factor 10 higher than in the pumping manifold.

In the following test runs, the cathode plug has been equipped with a spring contact fitted around the shaft for an RF wall current of 7400 A. No more sparking was observed in the RF-choke, except once when the spring contact was loose.

The dark current at the exit of the RF-gun was measured with a Faraday-cup during the first test run with the copper cathode. Figure 3 shows that the integrated charge Q of the dark current follows the modified Fowler-Nordheim law for field emission on metal surfaces[5]. The relatively high field enhancement factor β indicates that the RF-surfaces were not clean. At 97 MV/m on the copper cathode, the dark current measured by the Faraday-cup amounted to 14 mA.

Inside the RF-gun, the dark current was 40 mA and caused considerable beam loading of the RF-field. The RF-power reflected to the waveguide by the beam loading amounted to 6.4% at the end of an RF-pulse of 2.5 µs duration and 97 MV/m on the copper cathode[6]. The dark current causing this power reflection in the cavity was about three times larger than the dark current measured by the Faraday cup. Only a third of the electrons emitted by field emission of the cavity surface left the gun exit and arrived at the Faraday cup.

In the following tests, a thin layer of 350 nm CsI was evaporated onto the cathode plug. The CsI-photocathodes have the advantage that they can be exposed to air, and that their lifetime is not limited by the vacuum pressure of the RF-gun. Six different photocathodes of CsI were used at field gradients between 65 - 79 MV/m providing a beam momentum of 2.9-3.5 MeV/c at the exit of the RF-gun, as measured by the beam spectrometer (fig. 4). The CsI-photocathodes were illuminated by a laser pulse of 8 ns duration and 20 - 30 µJ energy at a wavelength of 213 mm. The quantum efficiency of the CsI-photocathode was typically 2% at the beginning and reduced to about half of the initial value after 100 hours of RF-operation.

The beam intensity measured by a beam current transformer installed 1.2 m downstream of the RF-gun was typically 3.4 A during 8 ns. The dark current measured by the same beam monitor was 22 mA during 1.5 µs at 79 MV/m field intensity on the CsI photocathode. As the beam loading of the RF-gun is proportional to the total charge of the dark current emitted by the photocathode, the beam loading caused by the dark current at 79 MV/m is larger than the beam loading of the laser triggered photocurrent. The dark current of the CsI-photocathode is shown in fig. 5. The field emission from the dielectric layer is assumed to follow the Richardson law for quasi-thermionic field induced hot electron emission[5].

At field gradients above 70 MV/m, frequent RF-breakdowns have been observed. For safe operation of the RF-gun and a long lifetime of the CsI photocathode, the electric field at the photocathode was limited to 65 MV/m.

The length of the bunchlets emitted by the photocathode illuminated continuously by a Nd-YAG laser during 8 ns has been measured after the bending magnet of the CTF beam line[2]. Momentum-scraping of the beam led to bunchlets of 36 ps FWHM. Optimum 30 GHz power generation will need bunchlets of 17 ps FWHM.

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B. Canard and G. Rossat have actively participated in the installation and operation of the gun and Faraday-cup and have masterfully tuned the CTF beam line. The laser and the photocathode were prepared by K. Geissler, S. Hutchins, A. Braem, G. Suberlucq and M. Wurgel. The RF-gun was constructed by G. Chanel, N. Mézin, B. Trincat, F. Vair and their collaborators, K. Batchelor and W. Pirkl gave their advice about the design of the RF gun.

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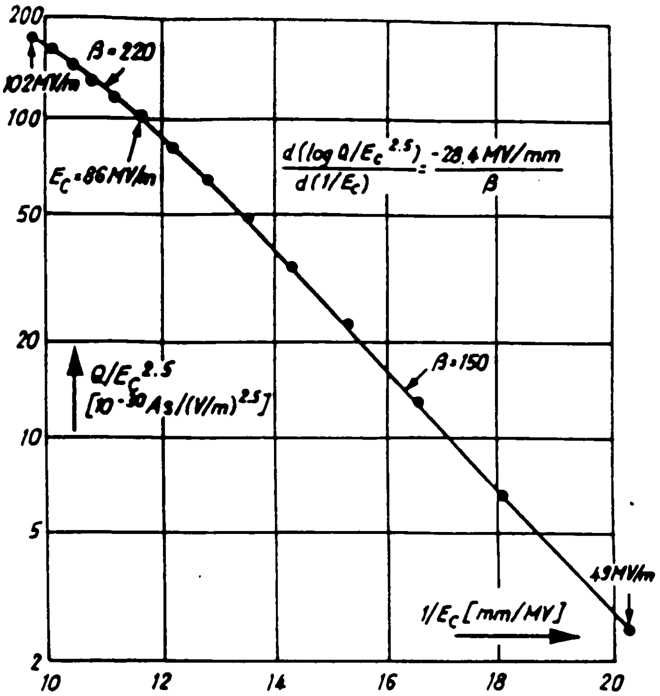

Fig. 3: Fowler-Nordheim plot of integrated dark current Q versus electric field E_C on copper cathode

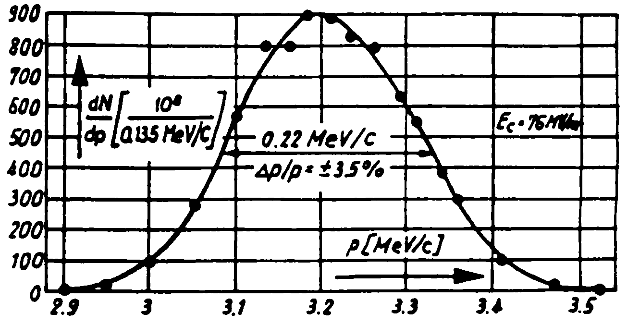

Fig. 4: Beam momentum p versus number dN of particles measured after bending magnet BHZ 190, Number of particles at gun exit: 1.7 x 10^{11}

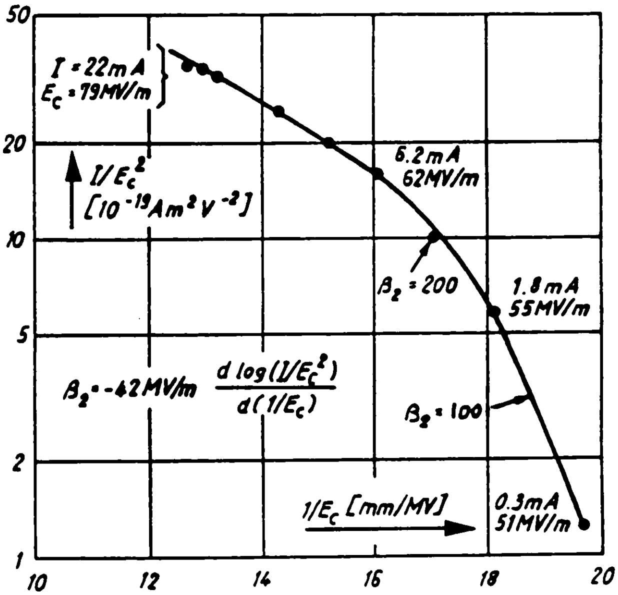

Fig. 5: Dark current I versus electric field E_c on CsI-photocathode, plotted for field induced hot electron emission[5]