CW 100 keV ELECTRON RF INJECTOR FOR 40 mA AVERAGE BEAM CURRENT

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Abstract

CW 100 keV electron RF gun for 40 mA average beam current was developed, built, and commissioned at BINP SB RAS. The RF gun consists of normal conducting 100 MHz RF cavity with a gridded thermo cathode unit, CW 16 kW generator with GU-92A tetrode in the output stage, and a set of LLRF electronics. The gun was tested up to the design specifications at a test bench that includes a diagnostics beam line.

The design features of different components of the gun are presented. Preparation and commissioning experience is discussed. The beam test results are summarized.

INTRODUCKTION

A 100 MHz RF electron injector was designed and manufactured at BINP for continuous wave (CW) powerful accelerator in RFNC-VNIIEF [1]. This compact accelerator, similar to the type of «RHODOTRON» [2], is designed for continuous production of short electron bunches with energy of 1.5 ÷ 7.5 MeV with power of 300 kW and higher.

Each bunch passes through a single accelerating cavity of the accelerator several times. After each pass, the beam is turned in the bending magnets. In order to preserve the transverse dimensions of the electron bunches within the aperture after passing through the bends, the bunches should have small enough energy spread (<1%) and be quite short (<0.2 ns).

An advantage of RF guns compared with static guns is the absence of cathode back bombardment with accelerated ions of residual gas ionized by an electron beam. This allows having a long lifetime of the cathodes and operating the gun continuously in the vacuum of 10^{-6} ÷ 10^{-7} Torr. Also, this enables raising the gun voltage and thus increasing the energy of the electron beam from 30-40 keV to 100 keV proportionally to the beam current to the power of 2/3, in-accordance with the Poisson law.

Furthermore, calculations showed that the increased voltage in the RF injector in combination with the effect of the longitudinal beam bunching therein provides a reduction in the energy spread of up to 0.3% (rms) in the first passage of the accelerator and the bunch shortening by up to 18 times.

RF INJECTOR

A grid-controlled thermo-cathode RF gun is based on high frequency quarter wave coaxial 100 MHz cavity shortened by a capacitance. The cavity is fed through an inductive input RF power coupler from 16 kW RF generator (based on tetrode GU-92A with a 500 W transistor preamplifier). The generator is powered by high DC voltage (8 kV) source situated in a separate rack. The control system consists of two parts: i) the control system for the cathode-grid unit consisting of a block inserted into the cavity and the blocks in the control rack, ii) control units for the cavity RF system located in the same rack. Detailed description of similar RF systems is given in [3].

The average beam current is regulated by the bunch repetition frequency and bunch charge adjustment. Bunch length is determined by the bunching effect. Maximum surface RF electric field (4 MV/m at 100 kV) is concentrated at the edges of the focusing electrode (see Fig.1), so field emission dark current from these places does not get into the beam line. Main characteristics of the RF injector are in Table 1.

Table 1: Main characteristics of the RF injector

Average current of the RF injector, mA	>40
Electron energy, keV	50÷100
Bunch duration (FWHM), ns	0.5÷2
Maximum repetition rate, MHz	100
Generator RF power, kW	<16
Operating vacuum, Torr	$<10^{-6}$

RF cavity (see Fig.1) has a bimetallic cylindrical body (1) with a diameter of 500 mm and a length of 550 mm. There is a water-cooled cylindrical electrode (2) inside the cavity with the gridded thermo-cathode unit (3) mounted on its end. The space between the focusing electrode (4) and the end wall of the cavity (5) is the accelerating gap.

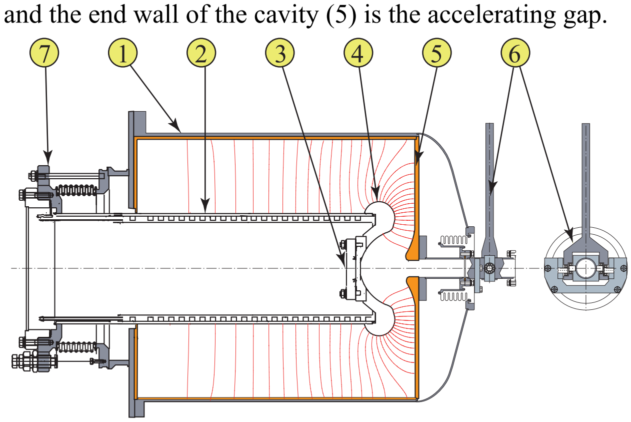

Figure 1: Sketch of the cavity RF gun with the force lines of the accelerating RF field.

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At one end of the cavity there is a device for fixing the electrode and preset of the resonance frequency (7). The control electronic unit (modulator) of the cathode-grid assembly is inserted into the electrode. At the other end the cavity has a frequency tuner (6). The tuning is done by the cavity end wall deformation (5).

For the cavity manufacturing technologies were used such as electron beam welding, diamond machining on a CNC lathe, thermo-diffusion brazing in a vacuum oven of bimetallic housing (copper-to-stainless steel), copper plating inside the stainless steel housing and silver plating outside the copper housing. The cavity went through degassing heat treatment followed by an RF conditioning.

CATHODE–GRID UNIT, MODULATOR

RF gun is equipped with a replaceable cathode-grid unit produced in Russia on the basis of metal-ceramic triode RF tube GS-34 with an oxide cathode. The grid electrode of the cathode-grid unit is electron beam welded to a special flange having a vacuum seal of Conflat® type (see Fig. 2). The design is compatible also with a cathode-grid assembly from the EIMAC [4] company.

The cathode has a diameter of 12 mm. Thin grid of a "parquet" type is located at a distance of 80 μm from the cathode surface. The cathode unit provides electron bunches with maximum current of 1.5 ÷ 2.5 A, duration of 1 ns, and repetition rate up to 100 MHz.

Figure 2: Flange welded grid-cathode assembly.

The electronic equipment for cathode current control is located in a special cylindrical container (see Fig. 3), which is inserted into the electrode of the cavity and electrically connected to the cathode assembly using the triple collet.

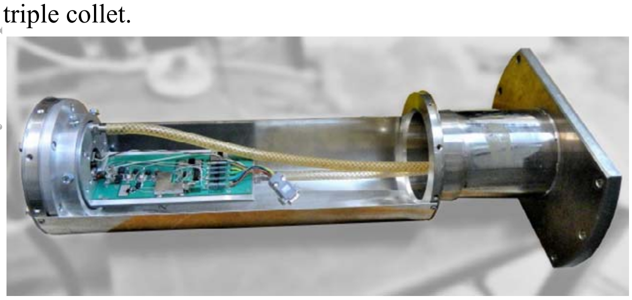

Figure 3: Plug-in container with the modulator unit.

This block works on the basis of the microwave FET transistors operating in the switching mode. This block generates pulses of 1.2 ns with adjustable amplitude of 0 ÷ -120 V and an adjustable repetition rate of 0.003 ÷ 100 MHz. Pulses are synchronized with the accelerating voltage of 100 MHz frequency. The bias DC voltage is adjustable between 30 ÷ 130 V. The unit is controlled from a computer via the communication interface of CAN-Bus type.

NUMERICAL SIMULATION

Numerical start-to-end calculations of the electron beam dynamics of RF injector were carried out for all stages of electron bunch formation: in the accelerating gap of the RF gun taking into account micron grid sizes [8], and in diagnostic beam line (see. Fig.4). Codes SAM, SLANS, ASTRA [5, 6, and 7] were used for the calculations.

Numerical calculations of the beam dynamics in the RF field of the grid-cathode assembly and in the accelerating gap of RF gun for different RF phases were performed taking into account the pulsed unlocking voltage applied to the cathode. The 1.2 ns pulse comes at the rising slope of RF voltage in the phase interval of 31 ÷ 55 degrees, at the amplitude of 50 and 100 kV voltage across the gap, and with the bunch charge of 0.4 nC.

The maximum acceleration is at the phase of 55 degrees. At lower phases the effect of longitudinal bunching appears. For example, when the phase is 31 degrees (the minimum possible phase before the bunch charge is limited) bunches get shortened by 1.5 times at the output of the RF gun (0.25m), and 2.3 times over a drift length of 2 m (see Table 2).

Table 2: Bunch characteristics of 100 kV RF gun

Distance from the cathode, m	0.25	0.25	2
RF phase at emission	55°	31°	31°
Bunch length (rms), mm	47.9	33.7	20.4
Energy spread (rms), keV	1.6	4.3	1.08
Emittance (rms), mm · mrad	10.5	9.5	21.5
Energy, keV	100	96.3	96.3

Calculations of beam dynamics in the diagnostic channel (see Fig.4) includes beam tracking through three focusing coils (2, 6) down to the target (8) made as the transition radiation sensor.

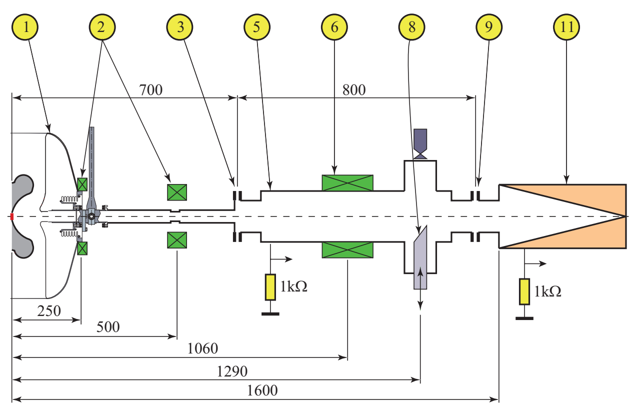

Figure 4: Sketch of the diagnostic channel. Numbering of callouts is common with Fig. 5.

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STAND FOR RF GUN TESTING

A test stand for testing the RF gun with electron beam is shown in Fig. 5. The RF gun was installed on a support with cooling water manifolds; the diagnostic channel was placed on a separate support. The 16 kW RF generator, the high-voltage rack, the rack with LLRF electronics and the modulator of grid-cathode unit are also located in the stand. The stand is controlled remotely via a CAN-Bus interface.

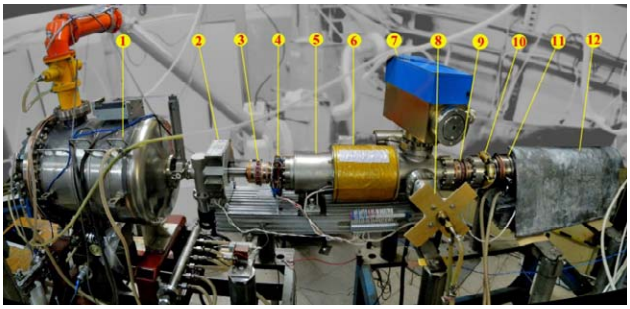


Figure 5: Diagnostic beam line. 1 - RF gun; 2 - focusing solenoid; 3 - first beam current sensor; 4 – beam steerer; 5 - vacuum chamber of 160 mm in diameter; 6 - solenoid; 7 - vacuum ion pump; 8 - movable target; 9 - the second beam current sensor; 10 - rotating beam steerer; 11 - 30 kW beam dump; 12 - lead radiation shielding.

TEST RESULTS

Calculations of the beam dynamics in the diagnostic channel (see Fig. 4) shows that the spot size on the target is substantially proportional to the emittance. When the beam emittance is 10 π·mm·mrad the spot should have a diameter of 5 mm (see Fig. 6). Exactly the same spot was observed in the experiments on the test bench (see Fig. 7).

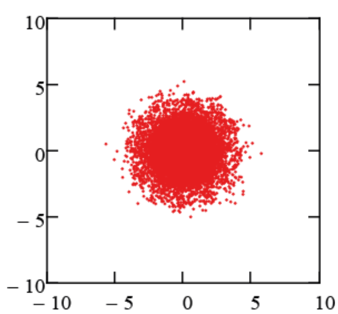


Figure 6: Numerically calculated beam spot on the target, $\sigma_{x,y}$ = 1.35 mm.

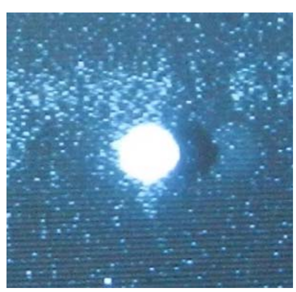
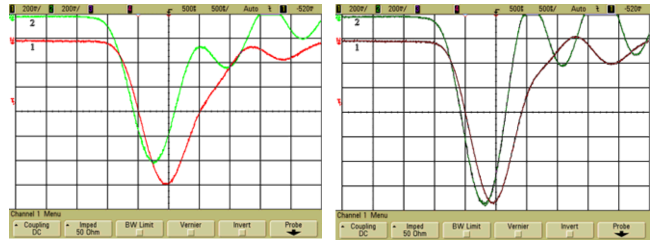


Figure 7: The spot image on the target from the video camera.

Forms of pulses from two current sensors depend on the emission phase in the grid-cathode unit. When the pulses have equal amplitudes then this corresponds to the operating phase of the maximum acceleration. When the second pulse is higher and shorter than the first one then the effect of the longitudinal bunching (shortening) over the drift space of 820 mm takes place; it means that RF phase is less than the operating phase (see Figs. 8a, 8b).



a) b)

Figure 8: Image of sensor signals for different emission phases: a) 55 °, b) 31 °. Resolution of horizontal axis is 0.5 nsec/cell.

Average current of 40 mA was obtained in the whole energy range of 50-100 keV. Continuous test runing during 8 hours at the beam energy of 100 keV, average current of 40 mA, and 100 MHz bunch repetition frequency was completed successfully.

Although the diagnostic beam line did not go through a degassing heat treatment, the vacuum in the cavity and the diagnostic system was 10^{-9} Torr without the beam. Vacuum deteriorates when the beam current increases. Setting the vacuum interlock threshold to $2 \cdot 10^{-7}$ Torr, we had to limit the beam current to 20 mA in the beginning. Within a few days it became possible to raise the current up to 40 mA due to gradual degassing of the vacuum diagnostic chamber.

CONCLUSION

CW 100 keV electron RF gun with 40 mA average beam current was developed, built, and successfully commissioned up to full design specifications at BINP SB RAS. The injector, as has been proven by the tests, is capable to operate reliably with high average beam current above 40 mA at up to 100 kV beam energy and 100 MHz bunch repetition frequency even in a poor vacuum of $10^{-6} \div 10^{-7}$ Torr. The injector will provide the required electron beams for the accelerator with the output beam power of 300 kW and above.

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