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MODULAR RF GUN CONSISTING OF TWO RF SECTIONS AND AN INTERMEDIATE FOCUSING SOLENOID

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Abstract

In order to increase the beam energy of the electron source for the CERN Linear Collider Test Facility at CERN, the existing RF gun is complemented by a second RF structure of four cells, which boosts the beam momentum from 4.5 MeV/c at the exit of the gun to 11 MeV/c. Both the 1-1/2 cell gun and the 4 cell section are standing wave structures excited in the π -mode at a frequency of 2998.5 MHz, with an accelerating field strength of up to 115 MV/m in the RF gun and 70 MV/m in the 4 cell section. Between the RF gun and the 4 cell section a short solenoid magnet is installed for beam focusing. The solenoid magnet compensates the space charge forces in the drift space, corrects the beam divergence caused by the RF gun and compresses the radial dimensions of the beam at the exit of the 4 cell section. The beam simulations with the computer programme MAFIA have shown that the beam can be made to converge radially at the exit of the 4 cell section, so that electron bunches with high charge density can be produced.

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INTRODUCTION

At the CLIC Test Facility (CTF) at CERN, an RF gun with 1-1/2 cells similar to that at BNL has been constructed and tested for the generation of ultra short electron bunches from a laser driven photo-cathode. The RF gun should produce a pulse train of 2×8 electron bunches with a charge of 10 nC per bunch, a bunch length of 15 - 20 ps FWHM and a bunch interval of 333 ps¹⁾. The electron bunches are created in the RF gun on a CsI photo-cathode illuminated by a Nd:YLF synchrolaser mode-locked at the twelfth sub-harmonic, $f/12$, of the accelerator frequency of CTF ($f = 2998.55$ MHz). The pulse length of the laser pulses is 13 ps FWHM, and the time jitter between the mode-locked frequency $f/12$ and the RF gun frequency, f , is typically 1 ps²⁾.

The RF gun consists of a standing wave structure with a half and a full cell resonating in the π -mode at a frequency of 2998.55 MHz. The nominal accelerating electric field strength is 100 MV/m in both cells for a power pulse of 6 MW during 2.5 μ s into the gun³⁾. At 100 MV/m, the 1-1/2 cell gun provides a beam momentum of $p_1 = 4.5$ MeV/c. The RF gun has already been operated successfully at higher field strengths of 115 MV/m, and tests are possible up to 150 MV/m.

At the exit of the 1-1/2 cell gun, the space charge forces for the high bunch charges are strong enough at 4.5 MeV/c to cause considerable emittance growth in a long beam line. In order to limit the beam blow-up after the gun, it has become necessary to increase the beam momentum to >10 MeV/c by a second accelerating structure of 4 cells immediately after the 1-1/2 cell gun, Fig. 1. At the higher beam momentum $p_2 > 10$ MeV/c, the growth of the transverse beam emittance due to space charge forces in the beam line will be smaller⁴⁾.

The 1-1/2 cell gun and the 4 cell booster actually under construction are both standing wave cavities excited in the π -mode. The two cavities are powered separately, so that the amplitude and phase of the accelerating fields in the two cavities can be adjusted separately. By proper choice of the relative RF phase between the laser, the gun and the booster, a linear relationship between the beam energy and the RF phase of the beam is obtained, so that the bunch length can be reduced by magnetic bunch compression down to 3 ps (FWHM) bunch length, either in a wiggler magnet or by a set of dipoles.

A major difficulty of all existing RF guns built as a single RF structure is the beam divergence at the exit of the RF gun. In our new concept of two separated RF cavities, the beam divergence is corrected by a compact iron-shielded focusing solenoid placed between the 1-1/2 cell gun and the 4 cell booster. The magnetic field of the solenoid not only compensates the space charge forces of the beam in the drift tube between the two RF-sections, but also corrects the beam divergence at the exit of the 1-1/2 cell gun and focuses the beam in the booster section, where the transverse dimensions of the beam decrease continuously. Since the RF phase is equal at the entrance and at the exit of the 4 cell booster, there is no beam divergence caused by the RF fields of the booster. This is explained by the Panofsky-Wenzel theorem⁵⁾ for relativistic beams. As a result of the combined action of the focusing solenoid and of the accelerating 4 cell section, the beam can be made to converge radially at the exit of the 4 cell booster.

Radial bunch compression by subsequent pairs of focusing solenoids and accelerating RF sections allows an increase of the beam radius on the photo-cathode of the RF gun, and ultimately increases the beam intensity of the electron source. It has been revealed by beam simulations with the MAFIA-code, that bunches with 50 nC charge can be accelerated without any losses by the present 1-1/2 cell gun, the solenoid magnet and the 4 cell booster under construction.

PERFORMANCE OF THE 1-1/2 CELL GUN FOR CTF

The first RF gun with 1-1/2 cells constructed in 1990 and similar to that at BNL⁶⁾, has been replaced in 1992 by another gun, which is connected on the rear side to a vacuum chamber with a robot arm for changing the photo-cathodes under vacuum conditions, Fig. 2. The CsI photo-cathodes are changed when the quantum efficiency, which is about 3% at the beginning, has dropped to 1% typically after 200 hours of RF operation with a field gradient of 100 MV/m on the photo-cathode. Handling under vacuum is necessary for the alkali and Cs₂Te photo-cathodes, and is also useful for the CsI photo-cathodes employed most of the time. With the help of the robot arm, the RF gun could be kept continuously under vacuum at 10^{-8} ... 10^{-11} Torr pressure for several months. As a result, the new gun has been conditioned in a few hours for the nominal field strength of 100 MV/m after changing a photo-cathode.

The RF contact between the shaft of the photo-cathode and the back plane of the cavity is made by a radial spring ring machined from copper-beryllium, which has already been used in the first gun³⁾. No sparking of the RF spring of the photo-cathode has since been observed. At high field gradients above 90 MV/m, it has been measured on the reflected RF power from the gun, that the cavity resonance frequency is detuned by 50 - 100 KHz, which can be corrected either by the temperature of the cooling water or by the two movable piston tuners of the RF gun.

Thanks to the clean working conditions during the manufacturing and handling of the RF gun and the photo-cathodes, the dark current measured at the exit of the RF gun has been reduced drastically. For a field strength of 104 MV/m on a new photo-cathode, the dark current amounts to 3 mA for a CsI photo-cathode of 8 mm diameter and 350 nm thickness, and only 1 mA for a Cs₂Te photo-cathode of 20 mm diameter and 30 nm thickness. This clearly shows that the dark current is produced mainly by the photo-cathodes. Despite a much larger surface, the Cs₂Te photo-cathode emits less dark current than the CsI photo-cathode, which has a volume of cathode material twice as large. With the aim of reducing the dark current of the CsI photo-cathodes and improving the lifetime of the photo-cathodes, it seems to be useful to reduce the thickness of the CsI layer.

The maximum field gradient applied to a CsI photo-cathode in 1992 was 115 MV/m. The dark current measured at the gun exit went up to 11 mA, but the sparking rate did not increase noticeably when the field gradient was raised from 107 to 115 MV/m. It can be expected that the CsI photo-cathodes withstand higher electric field strengths without damage by occasional RF-breakdowns. The maximum bunch charges measured at the exit of the 1-1/2 cell gun were 10 nC for a single bunch and $8 \times (2.3 \pm 0.3)$ nC for a train of 8 bunches in 1992.

DESIGN OF THE BOOSTER RF STRUCTURE

A standing-wave cavity of 4 cells excited in π -mode has been chosen as second accelerating structure to boost the beam momentum of 4.5 MeV/c at the gun exit to 10 ... 11 MeV/c for the CTF beam line. The cells of the booster cavity have nearly the same shape as for the 1-1/2 cell gun and have a 20 mm thick iris for optimum linearity of the RF field⁶⁾. However, the iris diameter has been increased to 30 mm for more beam aperture and stronger coupling between cells. The corners of the cell have been rounded off in order to avoid multipacting⁷⁾. The spherical shape of the cavity also improves the quality factor Q_0 of the cell and compensates a good fraction of the loss of shunt impedance, R_{eff} , caused by the larger iris diameter, see table 1 A.

The computer simulations of the RF fields in a cell have been carried out with the program URMEL⁸⁾. The beam loading factor, $k_0 = \omega_0 R_{eff}/2Q_0$, becomes smaller as the iris diameter is increased. The coupling factor k_{12} between adjacent cells rapidly increases as the iris diameter is enlarged.

For a π -mode multicell structure, the coupling factor between cells must be large enough to separate the frequencies of the parasitic modes which are too close to the accelerating mode. The 4 cell structure has four oscillation modes, the nearest parasitic mode being separated by 4 MHz from the accelerating mode. Fortunately none of the parasitic modes can be excited efficiently by the beam because of the odd phase relationship of these modes. By increasing the iris diameter from 20 mm to 30 mm, the transverse RF-forces of the accelerating E_{010} -mode are reduced by 50 %.

TABLE 1

RF - PARAMETERS OF ACCELERATION CELL VERSUS IRIS DIAMETER dA. Fundamental Monopole Mode E_{010} (URMEL 2 half cells)

All cavities are spherical ($R = 10$ mm), except cell Ø79* is angular

Iris Ø d[mm]	Cell Ø D[mm]	Freq.(f_{π}) [MHz]	Q_0	k_{12} [10^{-3}]	R_{eff} [M Ω]	k_0 [V/nC]
20	79*	3023	14120	0.517	1.056	710
20	82	3015	15250	0.52	1.116	693
30	85	3008	15690	4.32	0.912	549
40	89	3003	16390	15.5	0.717	413

The eff. shunt impedance scales as $R_{eff} \approx 1 / \sqrt{d}$ and the coupling as $k_{12} \approx d^5$.

B. Fundamental Dipole Modes HEM - E_{11}/H_{11} (URMEL full cell)

Iris Ø d[mm]	Cell Ø D[mm]	Freq.(E) [MHz]	k'_0 (E) [V/nC mm]	Freq.(H) [MHz]	k'_0 (H) [V/nC mm]	Run
20	82	4467	28.9	4920	11.2	56
30	85	4189	27.3	4153	10.7	54
40	89	3868	19.8	3434	5.5	52

Table 1B shows that the resonance frequency of the H_{11} -like dipole mode drops towards 3 GHz if the iris diameter is increased towards $d \sim 45$ mm. If the lowest dipole frequency is too close to the bunch repetition frequency, a multibunch beam will suffer from emittance growth by the transverse forces exerted by the RF structure⁹). A measure of the transverse forces of the RF structure on a single bunch is the beam loading factor k_0 . In a short structure, the risk of beam break-up is acceptable if the iris diameter does not exceed 40 mm.

The 4 cell booster is powered by a wave guide connected tangentially to the two inner cells of the structure by means of two coupling slots of size 20 mm x 10 mm x 2 mm. The coupling slots reduce the eigen-frequency of the inner cells by 9.5 MHz. In order to compensate for the radial beam deflections caused by the coupling holes, the coupling slots of the booster and of the gun are arranged on opposite sides of the beam (Fig. 1).

The wave guide excites, by its broad side, the two inner cells of the booster with a phase shift π between cells. The two outer cells are aperture coupled to the inner cells and oscillate with a phase shift π with respect to their neighbour cells. The wave guide coupling is provided by the magnetic fields, and the aperture coupling is due to the longitudinal electric fields. The wave guide coupling is slightly over-critical (VSWR = 1.06), and can be adjusted by varying the distance of the short-circuit plane of the wave guide at $\approx \lambda_g/4$ downstream from the coupling slots. Overcoupling is necessary to compensate for the dark current and the beam loading of the 4 cell structure.

In a standing wave structure, the dark current emitted by RF field emission⁷⁾ from the copper surface of the irises, is accelerated forward and backward depending on the RF phase at the time of field emission. A fraction of the backward electrons fall on the photo-cathode and heat it up. Both the intensity and energy of the back bombardment electrons are a limiting factor for the lifetime of the photo-cathode. In our new design for a gun assembly with two separate RF sections, the distance ℓ between the two sections has been chosen to be an odd multiple of $\lambda/4$: $\ell = 5\lambda/4$. Most of the backward dark current of the 4 cell booster reaches the 1-1/2 cell gun at a time when the gun is accelerating electrons in forward direction. The backward electrons from the booster section are stopped in the gun section, and only those booster electrons hit the photo-cathode, which have gathered a backward momentum higher than the accelerating momentum in the RF gun. For an accelerating gradient of 100 MV/m in the 1-1/2 cell gun and 70 MV/m in the 4 cell booster, the peak kinetic energy of the dark current from the booster hitting the photo-cathode is about 4 MeV. These electrons originate from the last two downstream irises of the 4 cell booster, and their intensity is considerably smaller than the dark current of the 1-1/2 cell gun because of the lower field strength in the booster. Following the Fowler-Nordheim law for field emission, the dark current produced by the booster section at 70 MV/m is a factor ten smaller than the dark current produced by the RF gun at 100 MV/m³⁾.

MECHANICAL CONSTRUCTION OF THE BOOSTER RF STRUCTURE

The gun assembly consists of three different modules : 1-1/2 cell gun, solenoid magnet and 4 cell booster. Each of the three modules is manufactured and tested individually before it is mounted on the girder of the gun assembly. The alignment of the mechanical axis of the RF structures and the solenoid magnet is done with a precision of ± 0.1 mm. The beam holes of the iron yoke of the solenoid magnet are drilled concentrically with a reference face for centring the solenoid housing onto the booster structure. In this way the fringe fields at both ends of the solenoid are perfectly aligned with the RF field of the booster. For the compactness of the gun assembly, the flanges of the beam tube at the exit of the gun are just inside the solenoid yoke and can be pulled out for access to the bolts (Fig. 1).

The mechanical construction of the 4 cell booster is similar to that of the 1-1/2 cell gun³⁾. The structure is made of OFHC copper cells brazed together at temperatures between 860°C and 780°C in several brazing operations. A particularity of the new brazing technique for the booster cavity is that the brazing alloy Ag-Cu-Pd does not penetrate onto the inner surface of the RF cavity. The brazing gap at the cavity surface is closed by a copper nose which is bonded under pressure with the other copper face by diffusion of brazing material into the copper faces¹¹⁾. The brazing alloy between cells is introduced through the water cooling channels which are not yet completely drilled at this stage. After the brazing of the cells, the plane and the coupling slots for connecting the wave guide are milled into the 4 cell booster structure. In another brazing operation the wave guide is brazed to the cavity.

Before the brazing of the wave guide, the radial flanges made of inox for the piston tuners and field monitors are brazed onto the structure at an intermediate temperature, and RF measurements are made to check the tuning and coupling of the 4 cell structure. As already included in the 1-1/2 cell gun, every cell of the booster structure has its own piston tuner and field monitor. The piston tuners allow the manufacture of the cells with a reduced mechanical precision of 0.01 mm, and the individual adjustment of the relative field strength among the four cells. After the tuning of the structure and the RF perturbation measurements, the piston tuners can be clamped to their adjusted position and the micrometer screws are removed.

The booster structure is temperature stabilised to $30.0 \pm 0.1^\circ\text{C}$ by cooling water flowing through parallel water channels drilled longitudinally into the body of the brazed copper structure.

BEAM CONFINEMENT BY SOLENOID MAGNET

Between the RF gun and the booster section, a short solenoid magnet is installed for focusing the beam. The solenoid coil is housed in an iron yoke made of soft iron plates of 20 mm thickness, with overall dimensions $\varnothing 460 \times 100$ mm and a bore diameter of $\varnothing 56$ mm for the beam tube. The pole faces in the end plates of the yoke are machined and aligned precisely, as well as the coil of the solenoid. The copper coil is very compact and is divided into four sections of 200 turns each which are cooled by water. The four coils are powered in parallel by a total current of 200 A, which produces a magnetic field strength $B_z = 8330$ gauss on axis. Due to the shielding effect of the yoke, the stray field of the solenoid is low and amounts to only $0.005 B_z$ on the the photo cathode. Such a low magnetic field on the photo-cathode does not appreciably increase the beam emittance of the RF gun.

The magnetic field of the solenoid compensates the space charge forces of the beam drifting at 4.5 MeV from the gun to the booster, but more importantly it corrects the beam divergence caused by a transverse beam deflection at the gun exit.

The RF field of the 1-1/2 cell gun imparts to the electrons a transverse momentum $p_\perp$ which is proportional to their radial positions r , the electric field strength E_0 , and the RF phase ϕ when they leave the gun ¹⁰⁾:

$$p_\perp = e r E_0 \sin \phi / (2 c) = 150 \text{ keV}/c, \quad \text{for } E_0 = 100 \text{ MV/m}, r = 3 \text{ mm}, \sin \phi = 1.$$

At the gun exit the longitudinal beam momentum amounts to $p_1 = 4.5 \text{ MeV}/c$ and the maximum beam divergence is therefore $\delta = p_\perp / p_1 = 33 \text{ mrad}$.

Another effect which increases the beam radius is the space charge force inside the electron bunch. The space charge forces generate a radial momentum p_d which is given by the time integral of the space charge force along the drift length L between the two accelerating sections ($\beta = 0.99$):

$$p_d \cong eQLr / (2\pi\epsilon_0 a^2 \ell \gamma^2 \beta c) = 12 \text{ keV}/c$$

for $Q = 10 \text{ nC}$, $L = 125 \text{ mm}$, $\epsilon_0 = 8.86 \text{ pF/m}$, $r = a \cong 4 \text{ mm}$, $\ell = 6 \text{ mm}$ (bunch length), $\gamma = 8.8$.

The task of the solenoid is to correct the radial momentum component of the beam and to make the beam converge in the booster section. The first computer simulations with a solenoid between the two RF sections were carried out with the programme PARMELA. Optimum beam focusing was obtained with a field strength of $B_z = 0.25 \text{ T}$ over an effective length of 75 mm. The computer simulations have shown that the beam radius was reduced from 8 mm to 4 mm at the exit of the 4 cell booster.

Because of the iron yoke for the solenoid, the drift length between the two RF structures had to be increased by 50 mm and amounts now to 125 mm. For the new layout, a new set of computer-simulations with MAFIA was done. The results are given in Table 2. Especially if the bunch charge is increased to $Q = 50$ nC and the laser spot radius to $r_0 = 6$ mm, the solenoid allows us to pass all particles from the gun through the booster without any beam loss¹²⁾, see Fig. 4 and Table 3. At the end of the drift tube of 30 mm diameter, the bunch of $Q = 50$ nC nearly touches the drift tube. The computer simulations show, that the transverse emittance ϵ of the beam does not increase proportionally to the bunch charge. It seems that the brightness I/ϵ^2 of the beam is about constant for charges $10 \text{ nC} < Q < 50 \text{ nC}$. The beam intensity I is given by $I = Q/T$ and amounts to $I = 4 \text{ kA}$ for $Q = 50 \text{ nC}$ and $T = 12.5 \text{ ps}$.

Table 2 : Performance of 5-1/2 cell gun for a bunch charge of 10 nC with and without solenoid. Values in parentheses for a bunch charge of 0.1 pC. RF field in gun : $E_1 = 100 \text{ MV/m}$, $\phi_1 = 30^\circ$. RF field in booster : $E_2 = 70 \text{ MV/m}$, $\phi_2 = -60^\circ$. Laser spot radius : $r_0 = 3 \text{ mm}$. Laser pulse duration : $T_0 = 15 \text{ ps}$ (FWHM).

Solenoidal field /T		0.25	0.30	0.0	0.0
$\epsilon_N/\text{mm.mrad}$	(rms)	72.4	73.5	120	(52.4)
ℓ_b/mm	(rms)	3.2	3.2	3.2	(2.6)
r_b/mm	(rms)	4.6	3.1	8.3	(5.2)
$r_{b \text{ max}}/\text{mm}$		7.0	4.7	12.6	(8.1)
γ	(rms)	22.4	22.4	22.5	(22.7)
$\Delta\gamma/\gamma/\%$	(rms)	0.34	0.33	0.36	(0.8)
div./mrad	(rms)	0.85	5.3	11.4	(6.1)
$\langle xx' \rangle/\text{mm mrad}$	(rms)	-1.1	-8.0	47.1	(15.9)

Table 3 : Performance of 5-1/2 cell gun for 50 nC bunch charge. RF field in gun : $E_1 = 120 \text{ MV/m}$, $\phi_1 = 20^\circ$. RF field in booster : $E_2 = 70 \text{ MV/m}$, $\phi_2 = -70^\circ$. Solenoidal field : $B_z = 0.4 \text{ T}$. Laser spot radius : $r_0 = 6 \text{ mm}$. Laser pulse duration : $T_0 = 15 \text{ ps}$ (FWHM).

$\epsilon_N/\text{mm.mrad}$	(rms)	172
ℓ_b/mm	(rms)	3.41
γ	(rms)	22.2
$\Delta\gamma/\gamma/\%$	(rms)	1.02
div./mrad	(rms)	19.0
$\langle xx' \rangle/\text{mm mrad}$	(rms)	-13.2

ENERGY DISTRIBUTION FOR MAGNETIC BUNCH COMPRESSION

For maximum power generation in the CTF-transfer structure at 30 GHz, the electric charge of the bunch train must be as high as possible and the bunch length should be shorter than 10 ps. It has been observed from the CTF beam tests with CsI photo-cathodes, that the bunch length was 20 ... 25 ps (FWHM) for bunch charges of 10 nC, even if the laser pulse duration was 15 ps (FWHM). If other photo-cathode materials have the same relaxation effect at high emission currents, the length of the bunch has to be compressed after the gun assembly by a magnetic compressor consisting either of a wiggler magnet or of a set of dipole magnets. This magnetic bunch compression requires an energy distribution over the bunch length with an energy increasing linearly from the head to the tail of the bunch. Such a particle distribution is shown in Fig. 5. Assuming linear beam optics in the magnetic compressor, the particle distribution of Fig. 5 can be compressed theoretically from a bunch length of 4.5 mm to less than 1 mm. The linear energy distribution over the bunch length has been obtained by lowering the RF phase of the laser pulse to $\phi_1 = 20^\circ$ and by keeping the RF phase-shift, $\phi_1 - \phi_2 = 90^\circ$, between the gun and the booster. The RF phase ϕ_1 of the laser

pulse is measured when the photo-cathode is hit by the head of the laser pulse, which has a gaussian intensity distribution in time truncated at $\pm 3\sigma_t = \pm 22 \text{ ps} \hat{=} \pm 20^\circ$. The peak intensity of the laser pulse is reached at the phase angle, $\phi_1 + 20^\circ$.

By setting the RF phases $\phi_1 = 30^\circ$ for the gun and $\phi_2 = -60^\circ$ for the booster with respect to the laser, it is possible to minimise the energy spread of a bunch of $Q = 10 \text{ nC}$ at the exit of the booster to 0.34% rms (Fig. 6).

CONCLUSIONS

The new RF gun assembly consisting of two RF sections and an intermediate focusing solenoid is a flexible test arrangement which can be optimised for different beam parameters like bunch charge, emittance, energy dispersion, bunch dimensions and beam convergence. The individual adjustment of RF power and RF phase for the 1-1/2 cell gun and for the 4 cell booster together with the individual tuning of the field strength in each RF cell allows testing of a variety of acceleration and RF focusing schemes. The only limiting factor for producing high bunch charges larger than 10 nC is the photo-cathode, which should be increased in radius from 4 mm to 8 mm, so that the maximum bunch charge is quadrupled. By the modular construction of the two RF sections and the solenoid, the RF gun assembly is a versatile high intensity electron source which can be adapted to different applications.

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Fig. 1 RF gun assembly of 5-1/2 cells and solenoid.

Fig. 2 1-1/2 cell gun with photo-cathode.

Fig. 3 View of RF gun assembly.

Fig. 4 Bunch of $Q = 50$ nC moving through RF gun assembly. RF field in gun : $E_1 = 120$ mV/m, $\phi_1 = 20^\circ$. RF field in booster : $E_2 = 70$ MV/m, $\phi_2 = -70^\circ$. Solenoidal field : $B = 0.4$ T. Laser spot radius : $r_0 = 6$ mm. Laser pulse duration : $T_0 = 15$ ps (FWHM).

Figure 5: Particle distribution in the longitudinal phase space: $\varphi_1 = 20^\circ$, $\varphi_2 = -70^\circ$.

Figure 6 : Particle distribution in the longitudinal phase space: $\varphi_1 = 30^\circ$, $\varphi_2 = -60^\circ$.