DESIGN OF A S-BAND 4,5 CELLS RF GUN

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Abstract

In the framework of a R&D program on RadioFrequency (RF) photo-injectors, we report on a design of a 4,5 cells 3 GHz RF gun by using 2 dimensions (2D) and 3D codes. Electron dynamics simulations have also been performed with the code PARMELA* and compared with the performances of a 2,5 cells RF gun.

INTRODUCTION

Since the operation of the first photo-injectors in the middle of the 1980, the technology constantly improved. Regarding the S-band [1] and L-band structures [2], the performances of the state of the art are already impressive, rms normalised emittance of the order of 1 πmmmrad and energy spread below 1 % for a bunch with a charge of 1 nC. Most of these RF guns do only have 1,5 cells. However, when one aims to produce high charge, above 2 nC, increasing the number of the cells can help to fight against the space charge forces and mitigate the degradation of the beam performances. For instance, at LAL, a photo-injector with 2,5 cells was designed and fabricated for the CLIC Test Facility 3 (CTF3) at CERN and produced a train of 750 bunches of 2.3 nC each [3]. One other advantage of a longer RF gun is the possibility to get a very compact accelerator at energy around 10 MeV. Indeed there is a growing need for this kind of accelerators in chemistry for example, for pulsed radiolysis experiments [4]. The accelerator is basically composed of 1,5 cells RF gun and a standing wave booster to bring the beam energy up to 10 MeV. If it could be replaced by one single RF structure, just a gun, the accelerator would be simpler to operate, shorter and therefore cheaper. For the above reasons we decided to design and build a 4,5 cells RF gun that we plan to test in a near future on our home test accelerator dedicated for this kind of experiment, PHIL (PHotoInjector at LaL) [5].

RF DESIGN

As far as the RF model of the 4,5 cells gun is concerned, we decided to start from a previous 2.5 cells RF gun, so called PHIN gun that we have fabricated for CTF3 [3]. Furthermore it relies on tested RF guns at CERN. The goal was clearly to produce high charge per bunch. It implied to have irises with large aperture whose diameter is 40 mm at the expense of lower shunt impedance. A more economic reason to use the PHIN gun is that we already have machined cells of this gun as spares and we think to use it as a part of the 4,5 cells gun. However, before to manufacture new cells, one has to perform a new RF study with numerical codes to tune the gun at 2.99855 GHz.

*PARMELA from Los Alamos National Laboratory, modified by B. Mouton at LAL

2D RF Design

For these simulations we used the code SUPERFISH. The simulations are used essentially to determine the physical dimensions of the photo-injector cavity to fulfil the specifications. The main specifications are to get the accelerator π mode at 3 GHz and a good equilibrium of the electrical field between the cells by changing the radius of the 4,5 cells. The process was very tedious as it required a lot of iterations. Indeed, since the cells are strongly coupled due to the large iris diameter; any change of radius in one cell has a large influence on the electrical field in every other cell. The RF model is visible in figure 1.

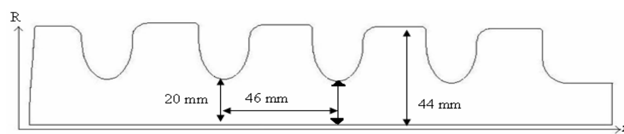

Figure 1 : RF 2D model of the 4,5 cells gun.

The relevant parameters are summarized in table 1. There are 3 noticeable features which are unchanged with respect to the original issue. The first one is an angle of the half-cell wall around the photo-cathode to provide additional transverse focusing. Then, the shape of the iris is elliptical to decrease the surface electrical field and electrical breakdown hazards. Last point, there is a slight asymmetry in the walls of the cavities for mechanical reasons and to try to reduce multipactor risks.

Table 1: RF parameters of the 4,5 Cell Gun

Frequency (GHz)	3.014
Shunt impedance (MΩ/m)	34.7
Quality factor	14956
Power (MW) for E_{acc} = 80 MV/m	15

The frequency we obtained at the end of the iterations is higher, on purpose, than the target, 2.99855 GHz (in vacuum and at 30°C). Indeed the tuning of the real model will be done by widening of the radius of each cell (because we do not use mechanical plungers) and it will inevitably lead to a decrease of the resonant frequency. The obtained electrical field is shown in figure 2.

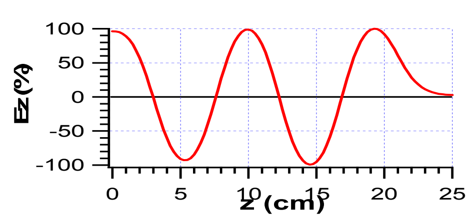

Figure 2 : Normalized electrical field along z axis.

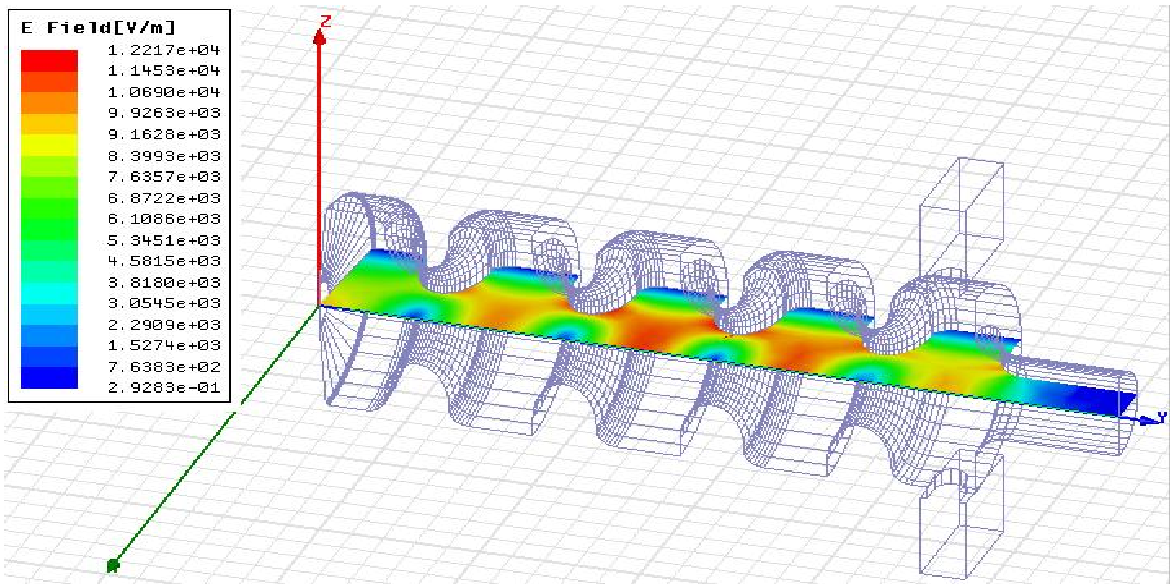

Figure 3 : Half view of 3-D model of the 4,5 cells RF gun with the amplitude of the electrical field.

3D RF Design

The numerical simulations were performed with ANSOFT HFSS. The RF power is transmitted to the photo-gun via 2 symmetric wave-guides and enters the gun through coupling holes whose aperture must be adjusted to, in principle, minimise the reflected power while keeping a good equilibrium of the electrical field among the cells. However, as we recycle the cells of the PHIN gun, we have to cope with a coupling factor, β, equal to 2.9 which allowed the PHIN gun to be at critical coupling in the presence of a beam at the nominal current of 3.51 A. We plan to close one port with a short circuit, hence we will be left with a β of 1.5 which means a S11 = -14 dB. The 3-D design is shown in figure 3. With the 2 opened ports, the S11 = -8 dB and the field is quite balanced; the values of the radius of the cells are given in Table 2.

Table 2: Radius of Cells of the Gun

cell	Radius (mm)
Half cell	43.9
1st cell	44.7
2nd cell	44.7
3rd	44.7
Coupling cell	43.2

At the end of these 3D simulations, the resonant frequency is still above the target, at 3008 MHz but we prefer to keep a margin for the machining of the gun.

BEAM DYNAMICS

The simulations have been performed with PARMELA and are based on the real longitudinal electric field calculated with SUPERFISH (fig. 2) for the 2D model shown in figure 1. Most of the simulations are done with 600 macro-particles for the study of the beam performances as a function of the parameters as the accelerating phase and gradient. Several aspects of the beam dynamics have been investigated. First, calculations on the gun alone will be illustrated. Then, a study of the compensation of the beam emittance increase due to the space charge forces will be presented. About the latter subject, a comparison with the performances of the 2,5 cells gun will show the advantages and drawbacks of the 4,5 cells gun.

Phase of the Gun

The production of charge of 1 nC with a gradient of 85 MV/m is very tolerant with respect to the phase between the laser and the RF, with a plateau of 90°. The other parameters of the electron beam depend strongly on the phase as it is shown in figure 4.

The comparison with previous simulations with the same input parameters on the 2,5 cells gun shows that the main difference is the behaviour of the mean kinetic energy of the bunch. With the 2,5 cells gun, the curve of energy is rather flat, below 60°. At the opposite, in the 4,5 cells gun, the curve exhibits a clear peak at 50° up to 9.22 MeV and drops down to 7.4 MeV at 0°. The explanation is rather simple, the accelerations length is almost 2 times larger in the 4,5 cells gun, hence a phase difference inducing 10 % of energy change in the 2,5 cells gun will cause an energy change of almost 20 % in the 4,5 cells gun. About the others parameters, extracted charge, emittance and energy spread both guns have roughly the same values. But it is not true anymore when one looks the evolution of these parameters in a space drift after the gun, see table 3.

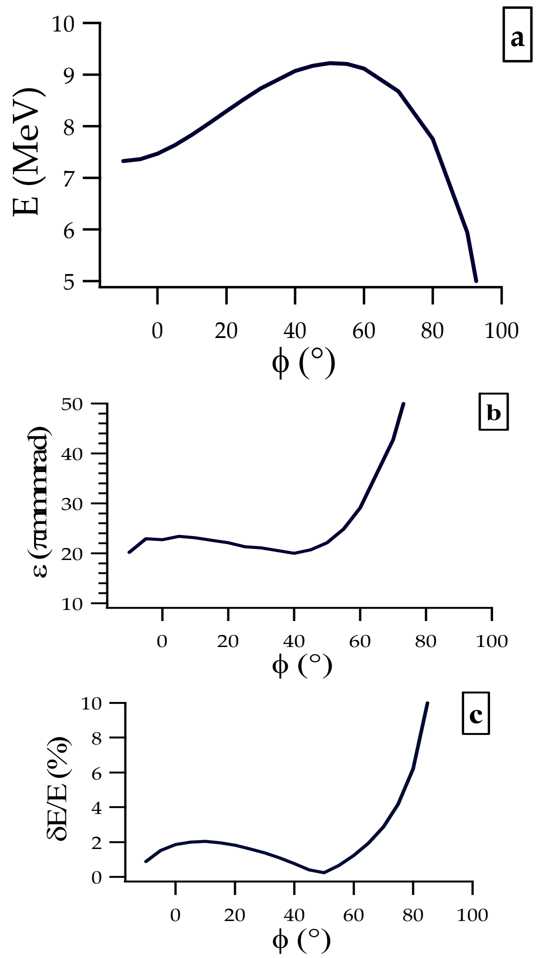

Figure 4: Dynamics simulations with PARMELA at the output of the 4,5 cells gun as a function of the phase between the RF wave and the laser, 600 particles, input distributions are gaussian with $\sigma_r = 1.4$ mm and $\sigma_t = 4$ ps . In a), mean kinetic energy; in b), rms normalized emittance; in c), rms energy spread.

Table 3: Electron Beam Parameters after 1.25 m of Space Drift after the Output of the Gun. Q = 1 nC, the Other Input Parameters are the Same as in Figure 4.

	2,5 cells gun	4,5 cells gun
$\sigma_{x,y}$ (mm)	14.4	9.2
$\varepsilon_{x,y}$ (πmmmrad)	15.4	12.6
σ_z (ps)	3.3	3.4
$\delta E/E$ (%)	0.8	0.42

The comparison between both guns shows clearly the advantage of the 4,5 cells gun for which the emittance and the energy spread are less degraded thanks to a higher beam energy which reduces the space charge force.

Compensation of Space Charge with a Solenoid

We performed simulations with a solenoid (same as the 2,5 cells gun) around the gun for the compensation of the emittance growth in the space drift. In the simulations of the 2,5 cells gun, we added a small booster (2 cells) in order to get the same energy (9.5 MeV) of the beam as in the 4,5 cells gun case. Results are illustrated in figure 5.

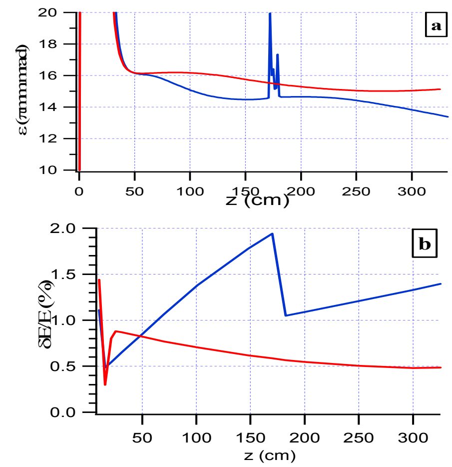

Figure 5: Q=2 nC, a), normalized rms emittance versus the distance; b), rms energy spread versus distance; blue line, 2,5 cells gun + booster at z=170 cm; red line, 4,5 cells gun.

At equal energy, it seems that the configuration 2,5 cells + booster is more efficient than the 4,5 cells gun for the reduction of the emittance growth. At the opposite, the energy spread growth is much more damped (by a factor 3) with the 4,5 cells gun.

CONCLUSION

A RF gun at 3 GHz of 4,5 cells has been designed, dynamics simulations showed that better performance, mainly on the energy spread, can be achieved with respect to shorter RF guns thanks to the higher beam energy.

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