SUPERCONDUCTING RF GUN CAVITIES FOR LARGE BUNCH CHARGES

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Abstract

The first electron beam of an RF gun with a 3.5 cell superconducting cavity is expected in July 2007 in FZD. This cavity has been designed for small bunch charges. In this paper we present the design of a similar cavity and of 1.5 cell gun cavities for large bunch charges. For a charge of 2.5 nC, which is the design value of the BESSY-FEL, and a bunch length of 21 ps a projected transverse emittance less then 1 πμ has been obtained (without thermal emittance).

INTRODUCTION

For producing radiation with high power and high luminosity in FEL and in SR sources, and also for other applications, intensive electron beams with short bunches, small emittances and large charges are required.

Now bunches with an emittance ≥1 πμ for Q_{Bunch}≤1 nC are produced in accelerating complexes consisting of a laser driven RF photocathode gun and a superconducting linac. The photo cathode guns are based on normal conducting cavities. In order to obtain a small emittance in these guns beam focusing by the magnetic field of two solenoids and a high accelerating gradient (~30 MV/m) are applied. For this gradient the RF power loss at the cavity surface reaches 16 kW/cm^2. By water cooling it is possible to remove not more than 500 W/cm^2 from a cooper surface [1]. Therefore RF guns with warm cavities can work only in a pulsed RF mode.

The application of superconducting cavities allows working in a continuous mode. Numerical simulations have shown that electric and magnetic RF focusing inside the superconducting cavity can be applied to compensate the emittance growth. In this way the SRF injector is able to produce an electron beam with a bunch charge of 2.5 nC and a pulse length of 21 ps, were the normalized transverse emittance is ~1 πμ. The repetition rate could be > 26 MHz so that a large average current is possible.

SIMULATIONS

By means of a large number of numerical calculations (>100) a set of optimal parameters has been found, which minimizes the emittance after the RF gun and seven TESLA cavities. For E_{acc} = 25 MV/m the final energy is 193 MeV. The results are given in fig. 3, 4 and 5. The calculations show that the resulting bunch emittance differs only insignificantly for the case of a 1-cell, a 1.5-cell and a 3.5-cell gun cavity.

The simulation has been done for 2.5 nC bunch charge and a laser pulse with 21 ps duration and 2 ps rise time. The optimal laser pulse diameter was found to be 4 mm. For large bunch charges the value of the thermal emittance ε_{th} is not well determined. It should be of the order of 1 πμ. In most calculations we did not take into account this value. But we can add the calculated thermal emittance by the formula $\varepsilon_n = 1.07\cdot(\varepsilon_{calc}^2+\varepsilon_{th}^2)^{1/2}$. The factor 1.07 has been verified by additional calculations.

A modified ASTRA code is able to take into account the image charge field of a curved cavity wall and cathode (see fig.1). This new possibility of ASTRA was verified with the USAM code [2] which is the RF modification of the SAM code made by BINP. The results of bunch dynamics simulations of both codes on the first ~10 mm are identical.

The SLANS code was used for the field calculations. A maximal RF electric accelerating field at the axis of the RF gun cavities of E_{max}=50 MV/m was assumed.

Electrical RF Focusing

The deepening (dz=2 mm) of the cathode in the wall of the cavity (see fig. 1) leads to a distortion of the accelerating field. The radial components of this field form a focusing lens. The optical force of this lens exceeds the defocusing forces of the space charge near the cathode. Due to the small velocities of the photoelectrons they experience relatively large focusing impulses near the cathode from the radial force (~1/β ~1/z$^{1/2}$).

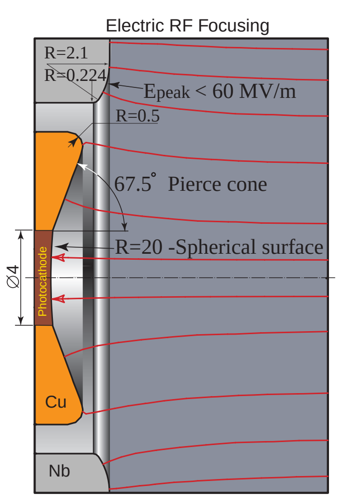

Figure 1: View of the photo cathode stem disposed into the hole of the back cavity wall of the RF gun. The electric field of the image charge in the entire wall was taken into account in the calculations. The optimized sizes are presented in the picture.

On figure 2 the distribution of the axial and radial components of the accelerating field along the axis of the 1 cell cavity are shown. The focusing impulse for the spherical surface is much larger than for a flat one due to the radial components directly at the cathode surface. The radial field distribution at the spherical cathode surface:

$E_r(r)\big|_{z\approx 0} = (E - E_{SC})\cdot r/R$ is a linear distribution.

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Here E is the electric field and E_{SC} is the image space charge field; all orthogonal to the surface. R is the curvature radius of the surface.

For the estimation of the focal length F of such an RF lens for charged particles close to the cathode we consider Lawson's dynamics equation written for a cylindrical coordinate system in the paraxial limit [3]:

$$\frac{d}{dt}(\gamma\cdot v)=\frac{e}{m_o}\left[E_r(z,r,t)-\beta c\cdot B_\theta(z,r,t)\right],$$
$$1/F=-v/\beta c\cdot 1/r_c$$

Here e and m_o are the particle charge and rest mass, E_r and B_θ are the radial electric and azimuthal magnetic fields, γ is the relativistic factor, r and v are the radial particle coordinate and velocity, βc is the axial velocity and r_c is the radial coordinate at the photo cathode.

We write the normalized focusing force as:

$$\beta\gamma\cdot\frac{1}{F}\Big|_{z\approx 0}\approx\sqrt{z\cdot 2e(E-E_{SC})/m_o c^2}\cdot\frac{1}{R}$$

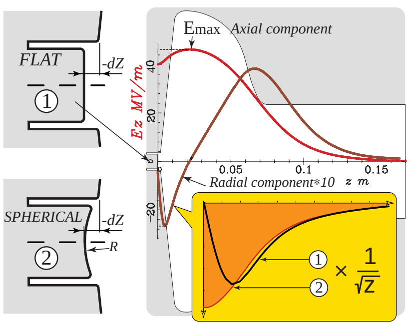

Figure 2: Cathode geometry and accelerating field distribution along the axis of a 1 cell RF gun cavity for r=1 mm.

A positive effect of the Pierce cone is that the linearity of the radial field of the vector sum of the accelerating field and the image charge field becomes better close to the cathode at z ~ 0÷1 mm.

In the simulations the accuracy of the RF field distribution near the cathode was essentially improved by using a 3D RF field obtained by SLANS.

Magnetic RF Focusing

Both, the TE_{021} mode of the 3.5 cell cavity superimposed with the accelerating TM_{010} mode (see fig. 3) and the TE_{011} mode of a separate special cavity following the 1.5 cell RF gun (see fig. 4, 5) play a role as magnetic RF lenses for the emittance compensation.

The vectors of the TE field are orthogonal to the vectors of the TM field. The magnetic field pattern of the TM mode and the electric field pattern of the TE mode show rings symmetrically disposed around the axis. In the superposition of the TE and the TM modes the peak fields (B_{peak}) at the cavity surface have different places.

Because of these properties the added B_{peak} field of the TE and the TM mode on the surface is small. It is lower as the B_{peak} field of a single TM mode with increased field, E_{max}= 60 MV/m instead of 50 MV/m. Values are presented on the right hand side in fig. 3, 4 and 5.

The TE mode is excited with a separate generator with a power of ~30 W. The frequency of the generator is set to the free resonance frequency of the TE mode. A tuning of the TE resonance frequency is excluded.

The temporal variation of the emittance due to the RF focusing has a small value: In the case of the superposition with the TM mode (see fig. 3) it is less then 4%. In the cases of separate RF focusing (see fig. 4 and 5) it is practically zero.

For the estimation of the RF magnetic focusing forces of such RF lenses we consider Lawson's equation [3]:

$$\frac{d}{dt}(\gamma\cdot v)=-\frac{e^2}{4m_o^2}\cdot\frac{r}{\gamma}\cdot B_z(z)^2\cdot\sin(\omega t+\varphi)^2,$$

here $B_z(z)$ is the axial TE field component, ω is the TE mode angular frequency, φ is the phase of the TE mode.

From $\sin(\omega t+\phi)^2=1/2-1/2\cdot\cos(2\omega t+2\phi)$ follows:

$$\beta\gamma\cdot\frac{1}{F}=\frac{e^2}{4m_o^2c\cdot r_c}\int\left(\frac{B_z}{\sqrt{2}}\right)^2\cdot\frac{r}{\gamma}dt-\frac{e^2}{4m_o^2c\cdot r_c}\int\left(\frac{B_z}{\sqrt{2}}\right)^2\cdot\cos(2\omega t+2\varphi)\frac{r}{\gamma}dt$$

The normalized focusing force consists of two parts – the first one is the usual focusing force of a static solenoid field with the same field distribution as the effective TE field $B_z(z)/2^{1/2}$ and a second part depending on the phase and frequency of the TE field which diminishes exponentially with increased TE frequency.

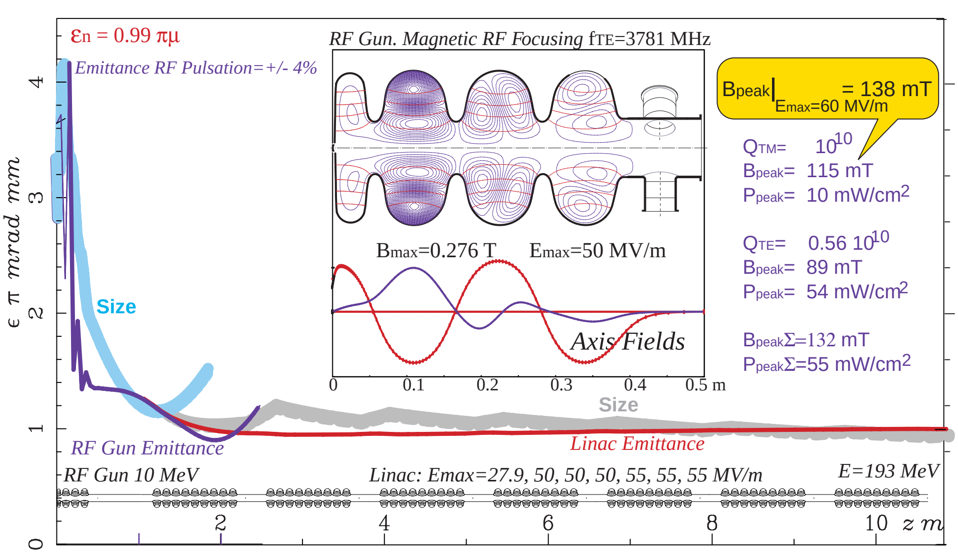

Figure 3: Transverse normalized emittance and rms beam size of bunches in a super-conducting 3.5 cell photo cathode RF gun and a linac with TESLA cavities. Fig. 1 shows the RF focusing.

The RF gun beam is here matched to the linac, i.e. the beam waist and the location of the emittance minimum are expanded due to the acceleration up to the end of the linac.

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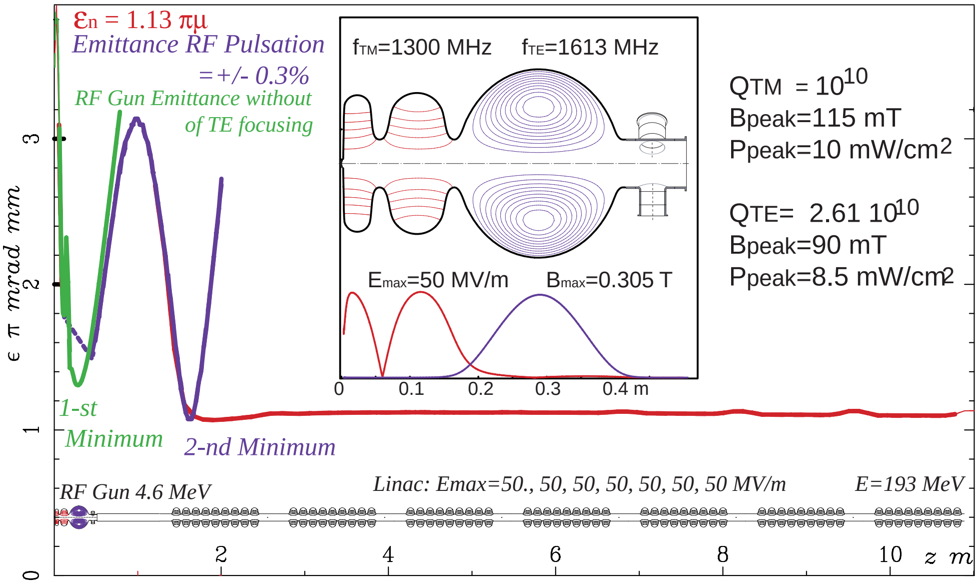

Figure 4: Transverse normalized emittance of bunches in a super-conducting 1.5 cell photo cathode RF gun and in a linac with TESLA cavities. The electric RF focusing is shown in fig. 1. The RF power feed for the TM mode has to be made from the side of the cathode assembly. The RF peak power density at the surface for the TE mode (P_{peak}) is close to the TM mode peak density.

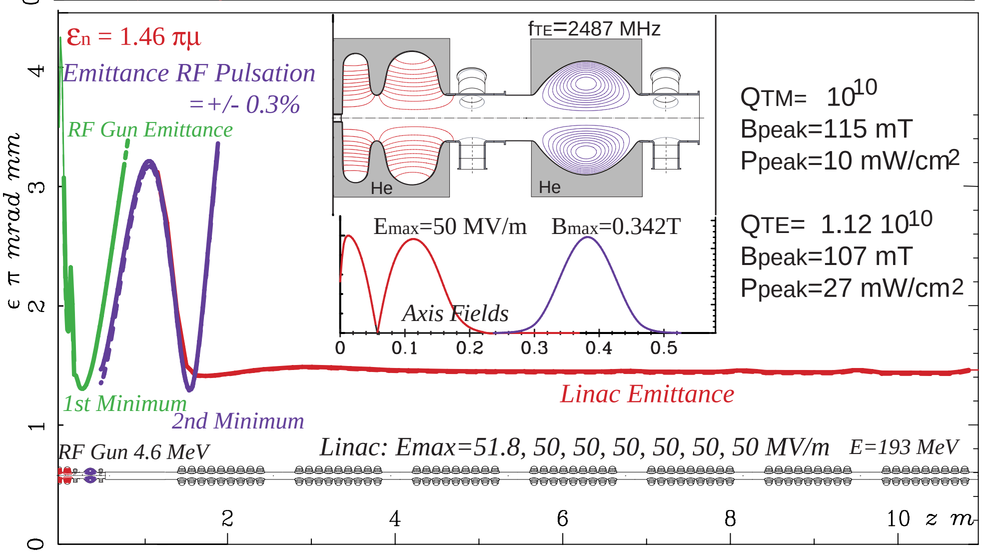

Figure 5: Transverse normalized emittance of bunches in a super-conducting 1.5 cell RF gun and in a linac with TESLA cavities.

In both cases with separate RF focusing two emittance minimums appear at the axis. The RF gun beams are matched with the linac, i.e. the RF gun beam waist and the location of the emittance minimum are expanded up to the end of the linac.

The second part of the equation is similar to the Fourier equation for the spectrum density of $B_z[z(t)]^2 \cdot r(t)/\gamma(t)$. The frequency dependence of the maximal value of this part has many maximums and zero minimums. But the envelope decreases exponentially with increasing TE mode frequency. Due to this fact the variations of the emittance for a high TE_{021} mode frequency of 3781 MHz presented in fig. 3 is less then 4 %.

In the simply case when the RF magnetic lens is made as separate cavity we can be free for choosing the cavity geometry and can provide the appropriate resonance frequency (ω_{TE}) at which this second part is equal to zero.

In the figures 4 and 5 we obtain the frequencies of the TE modes assuming in the above equation: γ=const and $r \sim r_c$=const and $z(t)=\beta ct$, where β = 0.995 (E=4.6 MeV), from the resulting formula written for any phases of φ as:

$$\left[\int B_z(\beta ct)^2 \cdot \sin(2\omega_{TE} t)dt\right]^2 + \left[\int B_z(\beta ct)^2 \cdot \cos(2\omega_{TE} t)dt\right]^2 = 0$$

It was found that the geometry of the TE cavity must have an elliptic shape in the cross section to minimize the peak field at the surface.

CONCLUSION

- Application of a concave spherical surface of the tip of the photo cathode stem gives the possibility to obtain ~1πμ emittance for doubled bunch charge (2 nC instead of 1 nC).
- Using a Pierce cone and taking into account the image charge in the wall we were able to obtain the same emittance for a bunch charge of 2.5 nC .
- RF focusing is suitable to match the beam into a linac and expand the location of the emittance minimum and the waist up to the exit of the linac.

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