HIGH PEAK CURRENT DESIGN OF A SUPERCONDUCTING CAVITY FOR A SRF PHOTOINJECTOR

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Abstract

A 1.5-cell cavity for a superconducting RF gun has been designed and a magnetic RF mode for emittance compensation is applied. For a peak current of 125A a transverse emittance of 1.8 mm mrad has been obtained.

INTRODUCTION

In collaboration between BESSY, DESY, FZR, MBI and BINP a 3½-cell superconducting RF electron gun is under development. The status of the project and the progress obtained is reported on this conference. The motivation for the design of a new gun cavity is the proposed FEL project at BESSY. This FEL requires a bunch charge of 2.5 nC with transverse slice emittances around 1.5 π mm mrad. In the following we will discuss the design of a 1½-cell cavity with a frequency of 520 MHz for the accelerating mode (TM mode) and 1560 MHz for the magnetic mode (TE mode). The design of a 1½ cell superconducting cavity with a frequency of 1.3 GHz has been also reported in [5].

DESIGN CONSIDERATION USING THE PILLBOX MODEL

In order to find some general rules for the cavity design, we will discuss a simple pillbox model, where the frequencies and RF fields are known analytically.

Figures of merit

In order to avoid a quench of the cavity, the maximum magnetic field on the cavity surface should be clear below 180 mT. Otherwise an optimal beam dynamics needs large electric and magnetic fields on the cavity axis. So the expressions

$$F^{TM}_{nml} = \left|\frac{Ez^{max}_{nml}(r=0)}{Bs^{max}_{nml}}\right|, F^{TE}_{0ml} = \left|\frac{Bz^{max}_{0ml}(r=0)}{Bs^{max}_{0ml}}\right|$$

are essential parameters for the quality of the cavity. For a pillbox with length L and radius R one obtains:

F^{TM}_{0ml} $[\frac{MV/m}{mT}]$	m = 1	m = 2	m = 3
l = 0	0.587	0.587	0.587
l = 1	0.351	0.502	0.543

Table 1: Figures of merit of the TM mode for R = L

From the first table follows, that at the surface limit of 180 mT the pillbox has an accelerating field of 105 MV/m! Therefore our cavity design should be as close as possible to the pillbox geometry. The main difference between a pillbox and a realistic cavity cell is the beam tube. In order to minimize the influence of the beam tube on the RF field of the cavity cell, the ratio of the cell to the tube radius should be large. The lower limit of the beam tube radius is fixed by wake field effects of the bunch charge. Therefore the cell radius should be as large as possible. This radius is inversely proportional to the cell frequency, so we fix the frequency of the TM mode to 520 MHz, which is the TESLA frequency divided by 2.5.

Table 2: Figures of merit of the TE mode for
R/L $\geq J_1^{max}\pi l/\left(J_0\left(q_m\right)q_m\right),\ J_1\left(q_m\right)=0$

F^{TE}_{0ml}	m = 1	m = 2	m = 3
l = 1	2.48	3.33	4.00

The second table shows that the axial magnetic field is enhanced when increasing the radial node number for a given surface field. Therefore a high frequency TE mode should be preferred.

Third order effects

The power expansion of radial RF field components with respect to the radius r starts with a linear term and is followed by third order terms. These third order terms produce an increase of the transverse beam emittance. In the pillbox cavity for the TM modes with l = 0 the third order terms are zero. For the magnetic TE modes the ratio of the third order term divided by the first order term is given by

$$\frac{(Bz''' + \frac{\omega^2}{c^2}Bz')}{Bz'} = \left(\frac{q_m}{R}\right)^2 \qquad (1)$$

Therefore the nonlinear effects increase quadratic with increasing node number m of the TE mode and decreasing radius R of the cavity cell. From this point of view the gun should work at the lowest TE mode frequency.

Comparison of the TE mode with a static magnetic field

Neglecting terms in r^2 in the equation of motion for an electron in the RF field of the TE mode the following equations are obtained:

$$\varphi' = -\frac{eB_z}{2m\gamma}, \quad r'' = -\frac{e^2}{4\gamma^2}B_z^{\,2}r \qquad (2)$$

These are the same equations as in the static magnetic field. Assuming $\beta \approx 1$ we can replace the time dependence in the RF field by z/c and calculate the focal distance of the corresponding magnetic lenses.

$$\frac{1}{f} = \frac{e^2}{4m^2c^2\gamma^2}\int_{-\infty}^{\infty} B_z^{\,2}dz\,,\quad B_z = b(z)\sin(\omega\frac{z}{c}+\varphi_0) \qquad (3)$$

In this case the focal distance is a function of the phase φ_0 of the TE mode. For the case of a pillbox cavity we obtain:

$$\frac{1}{f} = \frac{e^2}{4m^2c^2\beta^2\gamma^2}\frac{L}{\pi}B_0^2\left(\frac{\pi}{4}+\sin(\alpha\pi)\frac{\cos(\alpha\pi+2\varphi_0)}{4\alpha(\alpha^2-1)}\right)$$

$$\alpha = \sqrt{\left(\frac{q_m L}{\pi R}\right)^2+1} \qquad (4)$$

For α = 2,3, … the focal distance is independent of φ_o and for α =1/2 , 3/2, …. we have the maximal phase dependence. These limiting cases can be realized numerically also for realistic cell geometry.

The emittance compensation in a RF gun is based on the focussing of electrons inside a magnetic field. Therefore the quotient of cell radius and cell length defines the phase dependence of the focal distance and the phase dependence of the emittance.

CAVITY DESIGN AND RF FIELDS

As mentioned in the first section, the TM mode frequency of our gun cavity is 520 MHz. At this frequency the beam energy of a 1½-cell cavity with E_{peak} = 30MV/m is already greater 10 MeV. The cell radii are determined by the TM frequency and the field amplitudes on the cavity axis. We place the TE mode in the second cell. After this the phase slippage of the TM mode and the TE mode frequency define the width of the cells. As discussed in the previous section, the TE frequency can be defined by different arguments. In this calculation the frequency of 1560 MHz is used. This mode has the radial node number m = 2 and the field ratio $Bz_{max}(r=0)/Bs_{max}$ is 2.69. Furthermore, the integer value of the TE/TM frequency ratio allows the operation of the RF gun with the same TE - phase φ_o for each bunch. In this case it is meaningful to minimize the emittance with respect to this phase. The cell geometry and the field distribution of the gun are given in Fig.1 and Fig. 2 respectively.

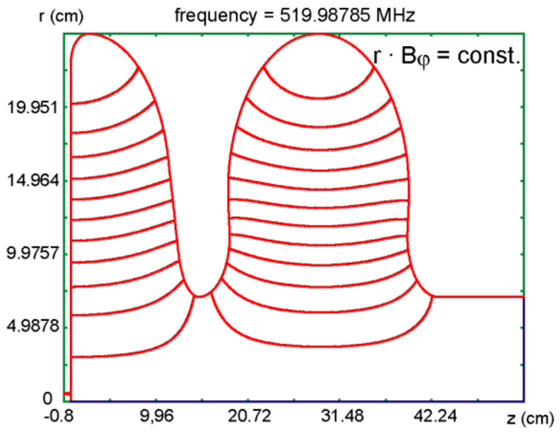

Figure 1: Cavity shape and electric field distribution of the TM mode.

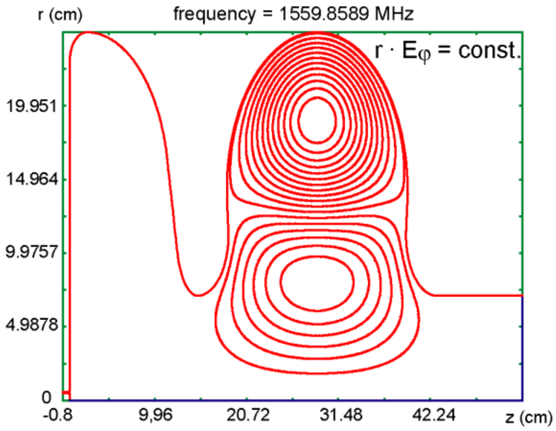

Figure 2: Cavity shape and magnetic field distribution of the TE mode.

Fig. 3 shows the fields on the cavity axis.

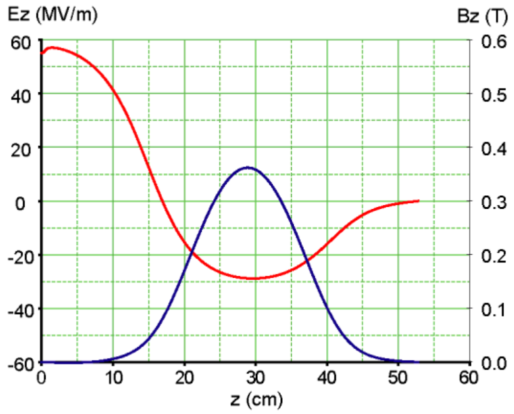

Figure 3: Axis fields of the cavity.

FIELD AMPLITUDES

The magnetic surface fields of the TM and the TE mode are perpendicular to each other. Therefore we have to evaluate the vector sum of both surface fields to compute the limiting field. Table 3 lists the maximal field limits used in the calculations. They are clearly below the critical limit. In Fig.4 the two surface fields and the sum of both fields are shown.

Table 3: Maximum axial and surface field values

field	unit	value
Ez_{max}	MV/m	57
Bz_{max}	mT	363
Bs_{max}(TM)	mT	130
Bs_{max}(TE)	mT	118
Bs_{max}	mT	130

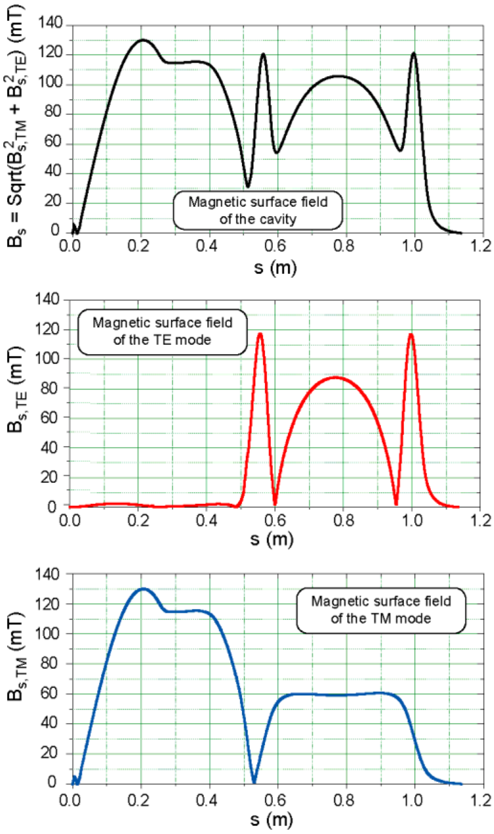

Figure 4: Magnetic surface fields in dependence on the surface coordinate s, $Bs = \sqrt{(Bs\_TM)^2 + (Bs\_TE)^2}$.

LASER PULSE SHAPE AND THERMAL EMITTANCE

In a RF photo cathode gun the laser pulse determines the bunch shape at the cathode. In the present calculations a temporal flat top laser pulse profile up to L_t = 40 ps and a rise and fall time of 2 ps have been used. The radial distribution is uniform. At a laser wavelength of 260 nm the electrons leave the cathode with a thermal energy of 1 eV isotropically in the whole space. This seems to be a set of realistic parameters [1].

RESULTS OF TRACKING CALCULATIONS

Tracking studies using ASTRA [2] have been performed for the gun cavity followed by a drift space and a booster linac section comprising 3 x 4 1.3 GHz standard 9-cell TESLA cavities to investigate emittance conservation. A Simplex routine has been utilized for a multi-parameter optimization. Hereby the transverse emittance at the linac exit has been minimized by varying the laser spot size at a given laser pulse length L_t and the operational parameters of the RF gun (TM and TE mode) and booster cavities with E_{acc} = 20 MV/m in maximum for the latter. To reduce the computation time four TESLA-cavities have been combined to one section. Typically for 1 nC bunch charge the reasonable laser pulse length is in the order of L_t =20 ps regarding space charge effects arising just at the cathode. To mitigate the enhanced space charge at 2.5 nC the laser pulse length could be further increased sacrificing some longitudinal emittance. First without the booster linac we have studied the behaviour for L_t = 20 ps resulting in a minimum transverse emittance of ~1.8 π mm mrad at a distance of ~5.3 m behind the photocathode for Bz_{max} = 363 mT as shown in Fig. 5.

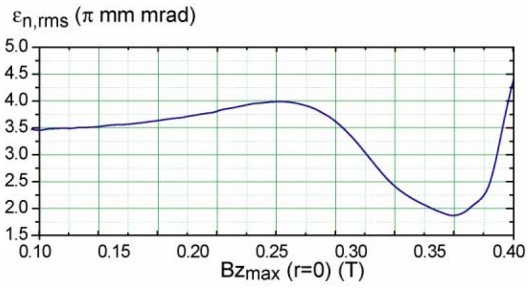

Figure 5: Dependence of the projected transverse emittance on the axial TE mode amplitude (position behind cathode z = 5.3 m, laser spot radius 1.25mm).

With these settings however one operates apart from the usual emittance compensation in the drift. Thus when including the booster we observed that the beam can not be matched according to the so-called invariant envelope (I.E.) [3]. Instead the beam is strongly focussed within the linac due to RF-focussing and without measures tends to extend behind the focal point.

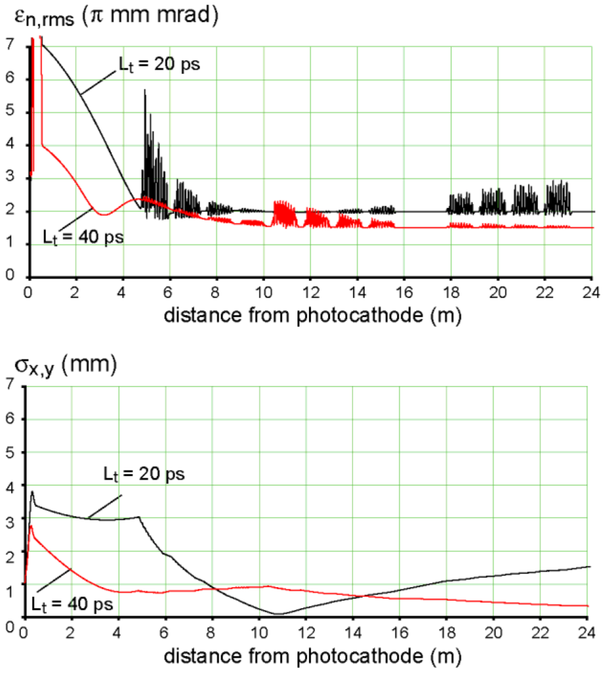

Figure 6: Evolution of the projected transverse rms emittance (top) and rms beam size (bottom) through the linac for L_t = 20 and 40 ps respectively (30000 particles).

The projected emittance can not be further minimized but rather stays constant. This is illustrated in Fig. 6 showing the evolution of the projected transverse rms emittance (top) and rms beam size (bottom) for L_t = 20. However the projected emittance is largely deluted by mismatched fringe particles which are responsible for the oscillations of the projected emittance within the linac cavities. Actually the slice emittance as the figure of merit amounts to only 1.1 π mm mrad in average.

We then tried to match the beam to the booster by following more closely the I.E.. This necessitates to adjust the electric field of the gun according to Bz_{max} to balance the repelling and focussing forces. Thus a typical emittance compensation accompanied by an emittance oscillation with a double emittance minimum in the drift [4] can be produced. Holding the I.E. criterion in this mode of operation the minimum projected emittance obtained for L_t =20 ps however is rather large (~4 π mm mrad). Moreover the accelerating fields in the first TESLA-cavities would be in the order of E_{acc} = 40 MV/m. However, the situation relaxes once the pulse length is further increased. This has been done using L_t =40 ps in a next step as shown in Fig. 6 as well. Here a projected transverse emittance of only 1.5 π mm mrad is achieved. As more particles follow the I.E., the average slice emittance is ~1.4 π mm mrad only marginally below the projected emittance.

Table 4 and 5 summarizes the optimized parameter settings and achieved results at the booster exit (z = 24m) for L_t = 20ps and L_t = 40ps respectively. Albeit the results are not regarded as an overall optimum yet, the required specifications of the BESSY FEL can be well fulfilled.

Table 4: Parameter settings for the photocathode laser, RF gun (TM and TE mode) and booster cavities respectively

parameter settings	unit	value	
laser			
flat top	ps	20	40
rise/fall time	ps	2	2
spot radius	mm	1.2	1.35
thermal energy	eV	1	1
thermal emittance	π mm mrad	0.69	0.77
RF gun			
gun TM field (max.)	MV/m	54.8	54.6
beam energy	MeV	9.8	9.7
magnetic TE field (max.)	mT	354	360
peak surface field	mT	128	127
booster cavities			
acc. field (cavities #1-4)	MV/m	10.5	7.5
acc. field (cavities #5-8)	MV/m	19.9	20
acc. field (cavities #9-12)	MV/m	17.6	17.4

Table 5: Achieved beam parameters with a bunch charge of 2.5 nC at the exit of the booster linac (z = 24m)

achieved parameters	unit	value	
laser pulse length (z = 0)	**ps**	**20**	**40**
normalized transverse projected rms emitttance	π mm mrad	2	1.5
average slice emittance	**π mm mrad**	**1.1**	**1.35**
trans. rms beam size	mm	1.45	0.37
long. rms beam size	mm	2.7	3.6
average kinetic energy	MeV	218	204
long. rms emittance	keV mm	1438	3250
correlated energy spread	keV	129	305

DISCUSSION AND SUMMARY

For two different lengths of the laser pulse it has been shown, that the design parameter of the injector for the BESSY FEL can be obtained, using a 1½-cell superconducting RF gun. In the calculation a maximal surface field of 130 mT has been assumed. This value corresponds to accelerating field strength of ~28MV/m in a TESLA cavity. For cavity frequencies in the order of 1.3 GHz this value is standard, but the frequency of the accelerating mode in the gun cavity is 520 MHz. For this frequency the maximal surface field, which can be obtained, is an open question.

In the present calculation the cathode has a flat surface, which is inside of the back wall of the cavity. In this simple arrangement we have near the cathode no focussing RF forces and possible wake fields from the cavity surface are absent.

In analogy to [6] we plan to place a Cs_2Te cathode into the superconducting cavity. For this material and λ_{laser} = 260 nm a quantum efficiency of 5% is realistic. In this case the bunch charge of 2.5 nC demands a laser pulse energy of 0.24 µJ.

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