# DESIGN OF A SUPERCONDUCTING CAVITY FOR A SRF INJECTOR

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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 a collaboration between BESSY, DESY, FZR, MBI and BINP a 3 ½ cell superconducting RF electron gun is under development. The status of the project and the progress obtained in the last year is reported in the paper WEPLS043 of this conference. The motivation for the design of a new gun cavity is the FEL project at BESSY. This FEL needs a bunch charge of 2.5 nC and the transverse emittance should be around 1.5 mm mrad. In the following we will discuss the design of a 1.5 cell cavity with a frequency of 520 MHz for the accelerating mode (TE mode) and 1560 MHz for the magnetic mode (TE mode).

## 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:

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

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

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

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

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. The second table shows that the axial magnetic field increases with increasing radial node number for a given surface field. Therefore a high frequency TE mode should be the best choice.

### *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 maximum of the third order terms is given by

$$\left| bz''' + \frac{\omega^2}{c^2} bz' \right|_{\max} = \left( \frac{q_m}{R} \right)^2 \frac{\pi l}{L} \quad . \qquad (1)$$

Therefore the nonlinear effects increase drastically with increasing node number m (and increasing frequency) of the TE mode. 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*

For the TE mode one obtains the following equation:

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

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.

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

In this case the focal distance is a function of the phase $\varphi_0$ of the TE mode. In the case of the 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 $\alpha = 2,3, \ldots$ the focal distance is independent of $\varphi_o$ and for $\alpha = 1/2$ , $3/2, \ldots.$ 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 also of the phase dependence of the emittance.

## THE CAVITY SHAPE AND THE 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 1 ½ cell cavity is already greater 10 MeV. Therefore the design is restricted to 1 ½ cells. The cell radii are determined by the TM frequency and the field amplitudes on the cavity axis, which should be the same for each cell. 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 1540 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 run of the RF gun with the same TE - phase $\varphi_o$ for each bunch. In this case it is meaningful to minimize the emittance with respect to this phase. For comparison calculations with the TE mode frequency of 1047 MHz has been done too. The cell geometry and the field distribution of the gun are given in Fig.1 and Fig. 2.

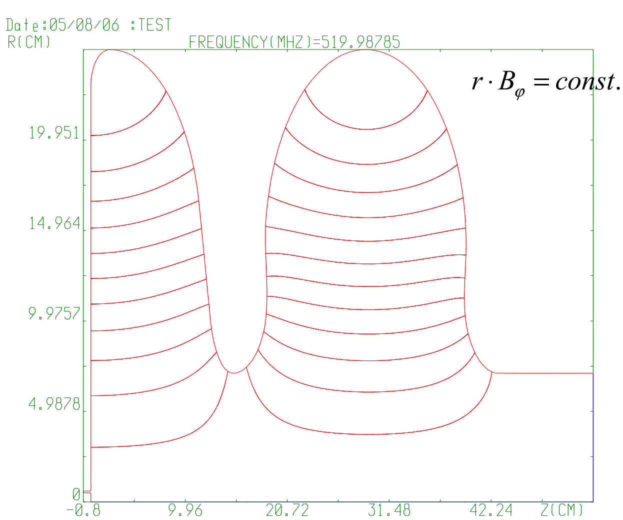


Figure 1: Cavity shape and field distribution of the TM mode.

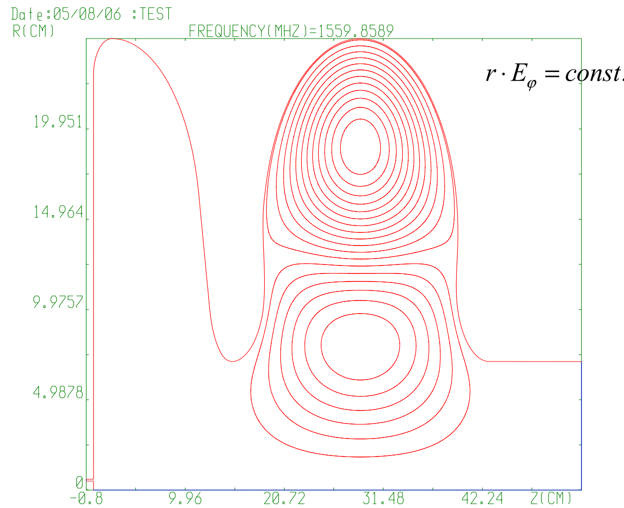


Figure 2: Cavity shape and field distribution of the TM mode.

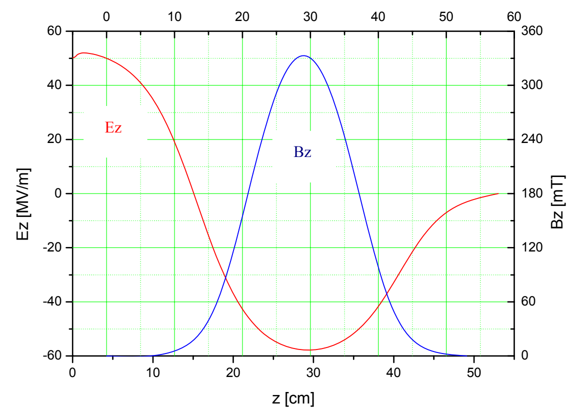


Figure 3: Axis fields of the cavity.

## FIELD NORMALIZATION

The magnetic surface fields of the TM and the TE mode are perpendicular to ea are given ch other. Therefore we have to add both fields quadratic. In Fig.4 the two surface fields and the sum of both fields are given. Table 3 shows the maximal field values used in the calculations. They are clearly below the critical limit.

Table 3: Maximum axial and surface field values

| field | dimension | value |
|---|---|---|
| $Ez_{max}$ | MV/m | 57 |
| $Bz_{max}$ | mT | 333 |
| $Bs_{max}$(TM) | mT | 130 |
| $Bs_{max}$(TE) | mT | 124 |
| $Bs_{max}$ | mT | 158 |

## THE LASER PULSE SHAPE AND THE THERMAL EMITTANCE

In a RF photo cathode gun the laser pulse determines the bunch shape at the cathode. In the present calculation the laser pulse has a flat top profile in longitudinal direction with a length of 20 ps and a rise time of 2ps. The radial distribution is uniform and the radius r = 1.2 mm is optimal in the present calculation. At a laser wave length of 260 nm the electrons leave the cathode with a thermal energy of 1eV isotropically in the whole space. This seems to be a set of realistic parameters [1].

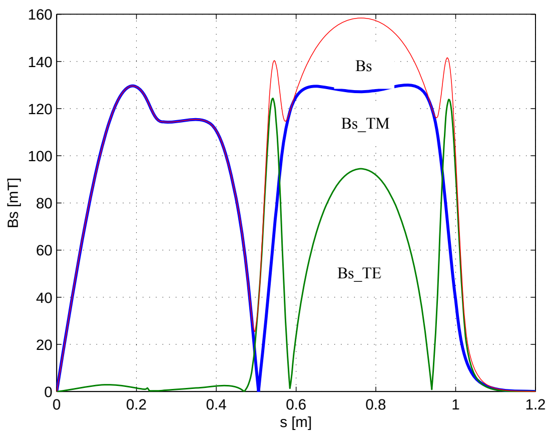


Figure 4: Magnetic surface fields in dependence on the surface coordinate s, $Bs = \sqrt{(Bs\_TM)^2 + (Bs\_TE)^2}$ .

## RESULTS OF THE TRACKING CALCULATION

The optimal result of a tracking calculation with 30000 particles is given in Tab. 4. The calculation is very sensitive with respect to the shape of the initial distribution. With a shorter rise time or a larger bunch length the transverse emittance decreases by more than 0.5 mm mrad. The phase of both modes must be stable with accuracy less than 0.5°. In Fig. 5 and Fig.6 dependence of the transverse emittance on the TE - phase and on the axial magnetic field are given.

In a second calculation for the magnetic mode $TE_{011}$ a transverse emittance of 1.6 mm mrad has been obtained. But in this case the surface field maximum is 200 mT.

## CONCLUSION

In the present paper we optimize the cavity shape of a superconducting RF gun, which produces bunch charges of 2.5 nC with a bunch length of 20 ps. A magnetic focussing inside the cavity is realized by a TE mode in the second cell. For a surface field maximum of 158 mT a transverse emittance of 1.8 mm mrad has been obtained

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Table 4: Results of the tracking calculation

| parameter | dimension | value |
|---|---|---|
| E | MeV | 13.54 |
| ΔE | keV | 68 |
| $\sigma_z$ | mm | 2.45 |
| $\varepsilon_z$ | mm keV | 50.5 |
| $\sigma_x$ | mm | 4.52 |
| $\varepsilon_x$ | mm mrad | 1.8 |

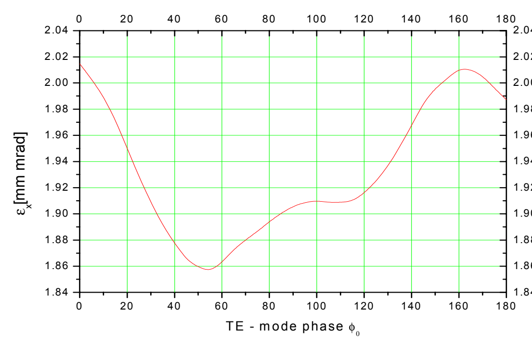


Figure 5: Transverse emittance in dependence on the TE – Mode.

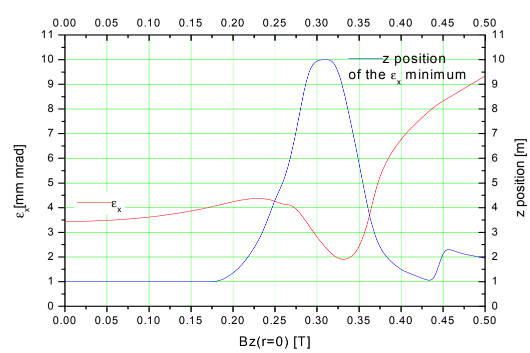


Figure 6: Transverse emittance in dependence on the magnetic axis field.

## REFERENCES

[1] I.Will, MBI Berlin, private communication.