EMITTANCE COMPENSATION IN A SUPERCONDUCTING RF PHOTOELECTRON GUN BY A MAGNETIC RF FIELD

Dietmar Janssen, Forschungszentrum Rossendorf, Germany
Vladimir Volkov[#], BINP SB RAS, Novosibirsk, Russian Federation

Abstract

For compensation of transverse emittance in normal conducting RF photoelectron guns a static magnetic field is applied. In superconducting RF guns the application of a static magnetic field is impossible. Therefore we use instead of a static field a magnetic RF field (TE - mode) together with the corresponding accelerating mode in the superconducting cavity of the RF gun. For a 3 1/2 cell cavity of the superconducting gun with frequencies f = 1.3 GHz for the accelerating mode and f = 3.802 GHz for the magnetic mode, and a bunch charge of 1 nC a transverse emittance of 0.8 mm mrad has been obtained. In this case the maximal field strengths on the axis are Ez = 50 MV/m for the accelerating mode and Bz = 0.324 T for the magnetic mode. This corresponds to Bs(max) = 0.136 T at the surface of the cavity. Possibilities for the technical realization (input of RF power for the TE mode, tuning of two frequencies in one cavity, phase stability) are discussed.

INTRODUCTION

The production of electron beams with a high average currents or high bunch charges and high brightness is the key technology for a large number of accelerating systems. This high brightness (or low emittance at the high bunch charges) is ensured by the RF photocathode guns. They are the first choice for linac-based systems as x-ray FEL, Energy-Recovering Linac (ERL), light sources, and electron cooling of hadron accelerators. The high electrical field strength, which can be reached in an RF guns is the basis to obtain low emittance at high charges.

The application of superconducting cavities in the design of RF guns promises to give a powerful incentive in the development of such systems. The well known reasons for advantages of an RF gun with a superconducting cavity are:

- The opportunity to work in a continuous wave mode or in a mode with a large duty factor at which the modern superconducting linacs are operated.
- The absence of the dissipative losses in a superconducting cavity allows large beam powers, which are not restricted by the existing limits for the RF power transfer, for RF power input and by heating problems.

The application of superconducting RF guns, as the numerical simulations predicts, opens new, unique possibilities. Examples for such possibilities are:

- Obtaining of electron bunches with small emittance, less than 1 πmm mrad, and large bunch charges more than 1 nC, having energies up to 10 MeV [1].
- Obtaining of bunches with sub-picosecond duration having a peak current more than 1000 A [2, 3].
- Obtaining of 1 MeV high-quality electron bunches with the large average current reaching hundred mA [4].
- Putting on the photo cathode of the superconducting RF gun a layer with secondary electron emission which increases the quantum efficiency and allows to apply more simple and cheaper laser systems. [5].
- Manufactoring of super compact industrial acceleratos on the basis of a multi-cell superconducting RF gun equipped with a field emission cathode, working without of any laser system [6].

The electric field strength in a superconducting RF gun should reach 50 MV/m and more. It does not mean, that the same field should be on the cathode. Numerical simulations and theoretical analyses deliver [7], that small emittances are obtained, when the cathode is pulled behind the back wall of the cavity, and the RF field on its surface is diminished up to 10- 30 MV/m. The distance of the cathode to the back wall is between 1 and 5 mm (see fig.3). In this area there is an effect of RF focusing acting by the distortion of force lines of the accelerating field, where the radial electric field component compress the beam. Such "cathode RF focusing" partially reduce the increase of transverse emittance [8].

In normal superconducting RF guns the focusing by a static magnetic field of solenoids is widely applied [9] with the purpose of emittance compensation of the beam. A similar effect of emittance compensation, as the numerical simulations deliver [1], exists also for focusing of the electron beam by the magnetic RF field of a TE mode additionally excited in the RF gun cavity. In the present paper the results of numerical simulations are presented. The effect of emittance compensation in an RF gun with f = 1300 MHz is obtained by a combination of cathode RF focusing and focusing with by the magnetic RF mode TE_{021} with f = 3802 MHz.

The main features of TE modes in superconducting RF cavities are the following:

- No obligate coincidence of its resonance frequency with any harmonic frequencies of 1300 MHz.
- The magnetic field of the TE mode is zero on cathode surface.
- Low RF power demands (see fig.2).

[#]V.N.Volkov@inp.nsk.su

- The peaks of the surface magnetic field of the TE mode are disposed between the peaks of the accelerating TM mode.
- Their magnetic field vectors are perpendicular to each other.
- As a result of the calculation the vector sum of the surface magnetic field is less than the 180 mT limit for RF superconductivity, obtained in [10].

NUMERICAL SIMULATIONS

The tracking calculations has been done with the ASTRA code. An important feature of this code is the possibility to calculate the particle dynamics with combination of TE and TM mode RF fields. Furthermore ASTRA has no limitations concerning the bunch length. An electron bunch of 1 nC is excited by the laser pulse given in fig.1.

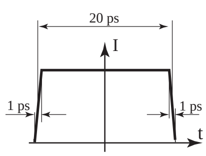

Figure 1: Photocathode illuminated laser pulse intensity vs. time. Bunch charge is 1 nC.

Fig. 2 shows the pattern of the two RF fields in the cavity and the fields along the z – axis.

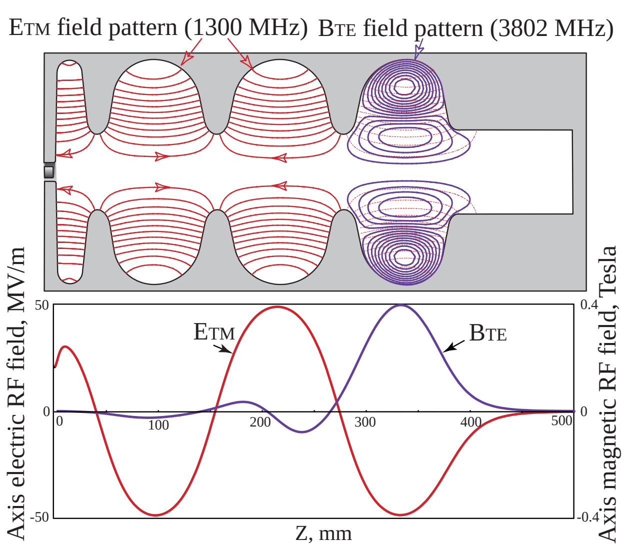

Figure 2: a) RF field pattern of E_{TM010} 1300 MHz and B_{TE021} 3802 MHz. b) Axis fields of the RF modes.(Color picture)

The corresponding peak values of the fields are given in Tab.1

Table 1: Peak values of RF fields in the RF gun.

Peak of axis E_{TM010}, MeV/m	50
Peak of axis B_{TE021}, mT	324
Peak of surface B_{TE021}, mT	136
Peak of surface B_{TM010}, mT	115
Peak of surface $\vert B_{TM010}+B_{TE021}\vert$, mT	144

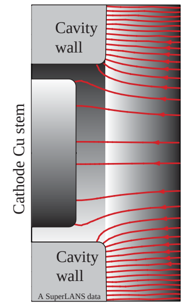

Figure 3: The sketch of RF focusing field pattern E_{TM} close to the cathode.(color picture).

The cathode diameter is 10 mm. The cathode is placed 2 mm behind the cavity wall (see fig.3).

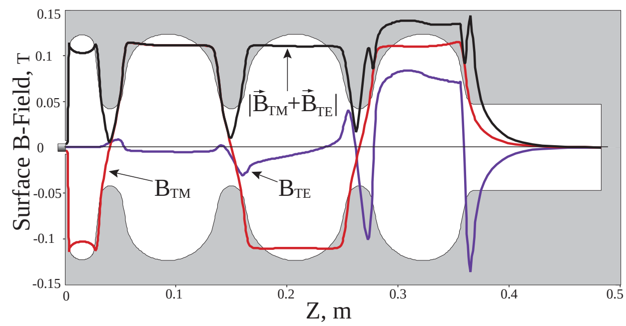

Figure 4: Surface RF magnetic field of both TM and TE modes (color picture).

In fig.4 the surface magnetic field of the separate modes and that of the vector sum of both modes is represented. The maximum field value of 144mT for the superposition of the fields is clear below the limit of 180mT given in [10].

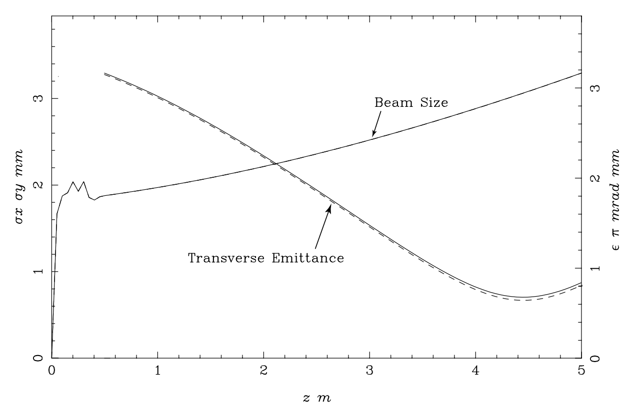

Figure 5: Beam size and transverse emittance vs. distance from the cathode.

Table 2: results of the tracking calculation

Bunch transv. norm.emitt., mm mrad	0.78÷0.98
Rms Beam Size, mm	3.06
Longitudinal Emittance, keV mm	72.4
Average Energy, MeV	8.82
Rms Energy Spread, keV	53.9
Rms Bunch Length, mm	2.79
Distance from the cathode, m	4.44
RF phase of TE 3802 MHz mode	0÷360º
RF phase of TM 1300 MHz mode	74.6º
Laser spot size, mm	2.6

The results of the tracking calculation is given in fig.5 and tab.2. The bunch starts with a length of 20 ps. At a distance of 4.44m after the cathode the bunch has a length of 9.3 ps and the transverse emittance changes in dependence from the phase of the magnetic mode between 0.78 and 0.98 mm mrad. Furthermore it is interesting to do some checks of the results with respect to changes of the optimal parameter set. Tab. 3 gives some possible changes, which gives rise to a growth of 10% for the transverse emittance.

Table 3: Parameter changes, which increases the transverse emittance by 10%

Changing of magnetic TE field at the axis, mT	97
Changing of TM 1300 MHz mode RF phase	3.27º
Changing of laser spot size, mm	1.0

The dependence of transverse emittance from the phase of the TE mode field is given in fig.6 and can be described by the following formula:

$$\varepsilon = 0.88 + 0.1 \cdot \sin\left(2 \cdot \varphi_{TE} - 11°\right) \qquad (1)$$

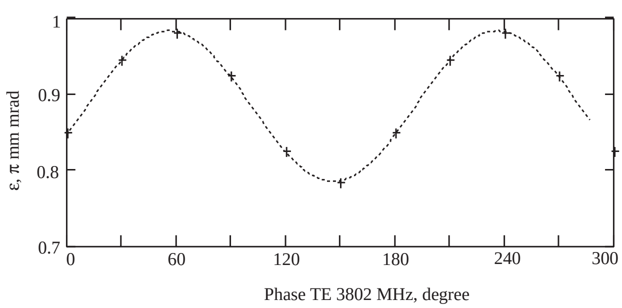

Figure 6: Transverse emittance variation vs. RF phase of TE_{021} mode (φ_{TE}), fitted by a sinus function.

CONCLUSION

Numerical simulation of a superconducting RF photo electron gun with a combination of RF focusing and TE mode for emittance compensation gives excellent results. If we try to compensate the increasing of the emittance separately either by cathode RF focusing or by TE mode the emittance increases by a factor two with respect to the optimal value. The field concentration of the TE mode in last cell of the cavity allows a good coupling of TE mode by an input power loop placed at the beam pipe. At the same time further numerical simulations are required in order to find a shape of the RF gun cavity cells or other types of TE modes, which reduce the emittance dependence from TE mode phase.

REFERENCES

[1] K.Floettmann, D.Janssen, V.Volkov, “Emittance compensation in a superconducting RF gun with a magnetic mode”, submitted to Physical Review S.T:,

[2] V.N.Volkov, “Ultra short electron bunches with low longitudinal emittance in multi-cell superconducting RF Guns”, 2003 Particle Accelerator Conference, May 12-16, 2003, Portland, Oregon USA.

[3] V.N.Volkov, “Generation of Sub-Picoseconds Electron Bunches in Superconducting RF Photocathode Injector”, 2003 Particle Accelerator Conference, May 12-16, 2003, Portland, Oregon USA.

[4] Numerically simulated by V.N.Volkov. Not published.

[5] Ilan Ben-Zvi, Xiangyun Chang, Peter D. Johnson, Jörg Kewisch, Triveni S. Rao, “Secondary Emission Enhanced Photoinjector”, Collider -Accelerator Department1, Physics Department, Instrumentation Division, Brookhaven National Laboratory, Upton NY 11973 USA.

[6] V.N.Volkov, S.G.Konstantinov, A.M.Kudryavtsev, O.K.Myskin, V.M.Petrov, A.G.Tribendis, D.Janssen, “Application of auto cathode in a superconducting electron RF injector for the industry accelerators”, APAC01, September 17-21, 2001, Beijing, China.

[7] V.Volkov, D.Janssen, “RF Focusing - an Instrument for Beam Quality Improvement in Superconducting RF Guns”, 7th European Particle Accelerator Conference, Austria Center Vienna, June 2000, p.2055-2057.

[8] D.Janssen, V.Volkov, “RF focusing-an instrument for beam quality improvement in superconducting RF guns”, Nuclear Instruments and Methods in Physics Research, A 452 (2000) 34-43.

[9] M.Ferrario, et al., TESLA-FEL Report 2001-03.

[10] K.Saito, Proc. of the PAC2003, page 462, Portland, Oregon.