BEAM PARAMETER SIMULATION OF THE ROSSENDORF SRF GUN AND COMPARISON WITH OTHER RF PHOTOINJECTORS

F. Staufenbiel#, A. Arnold, D. Janssen, U. Lehnert, P. Michel, J. Teichert, R. Xiang, FZD, Dresden, Germany, T. Kamps, BESSY, Berlin, Germany, D. Lipka, DESY, Hamburg, Germany

Abstract

For each accelerator the choice of the injector is a crucial topic and the best gun concept for the different demands must be determined. This paper presents simulated beam parameters of the Rossendorfer SRF gun and compares with the RF photo injectors. The difference between normal and superconducting guns leads to different possibilities in the operation modes. Due to the high RF power losses in normal conducting guns the duty cycle is low and cw-mode operation is impossible. For the SRF gun an exterior magnetic field for emittance compensation close to the photo cathode is prohibited due to the Meißner-Ochsenfeld effect. Therefore, other mechanisms for emittance compensation must be used. In the simulations RF focusing with a proper cathode visor and a solenoid focusing after the gun are considered.

INTRODUCTION

For the SRF gun different operation modes are planned. The high charge mode will be mainly used to generate neutrons for nuclear reactions analysed by time of flight measurement. In this case, the repetition rate is determined by the ejected velocity and limits the pulse frequency to less than 1 MHz. Therefore, a high bunch charge of about 1 nC is needed to enhance the reaction yield.

The planned Soft X-ray FEL facility at BESSY needs a beam at the entrance of the FEL sections with a bunch charge of about 2.5 nC, a pulse duration of 40 to 60 ps and a normalized transverse emittance of about 1.5 mm mrad [1].

The ELBE mode will be mainly used to drive the infrared FEL at the ELBE accelerator. A small bunch charge of about 77 pC and a high repetition rate of about 13 MHz are proposed. With these conditions a small transverse and longitudinal emittance is achievable.

THE SRF GUN CAVITY

The SRF gun is designed as 3½ cell TESLA shape cavity [2] shown in Fig.1. The design value of the peak field of the three TESLA cavities is 50 MV/m [3]. The gun half cell is tuned to about 60 % of the peak field of the TESLA cavities caused by the striven uniformly distributed magnetic field in all cavities. The critical magnetic quench field amounts to 110 mT.

At the exit of the cavity a solenoid focuses the electron beam shown in Fig.3. After the solenoid the photo gun laser port is visible.

Corresponding author. E-mail address: F.Staufenbiel@fzd.de

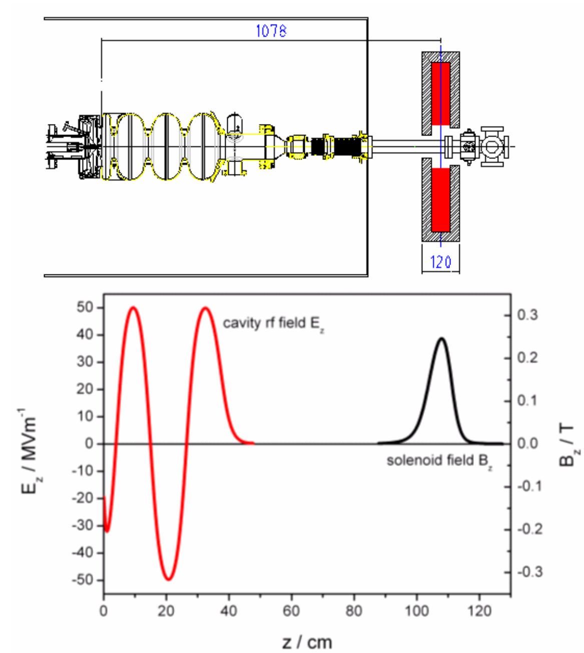

Figure 1: Cavity and solenoid and plots of the axis field components E_z and B_z.

Emittance Compensation for the SRF Gun

Fig.2 shows the cathode inside the gun half cell. To obtain an electric focusing field at the cathode tip the cathode is few millimeters retracted [4].

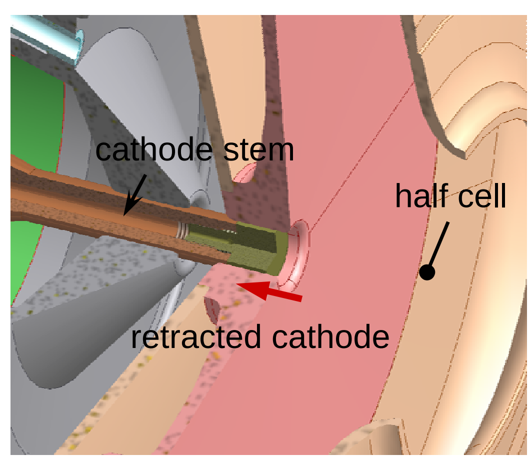

Figure 2: The retracted cathode leads to focusing fields.

Fig. 3 shows the huge improvement of the normalized transverse emittance with a focusing field at the cathode tip for a bunch charge of about 1.0 nC and a flat top laser profile pulse length of about 20 ps with rising and falling time of about 2 ps.

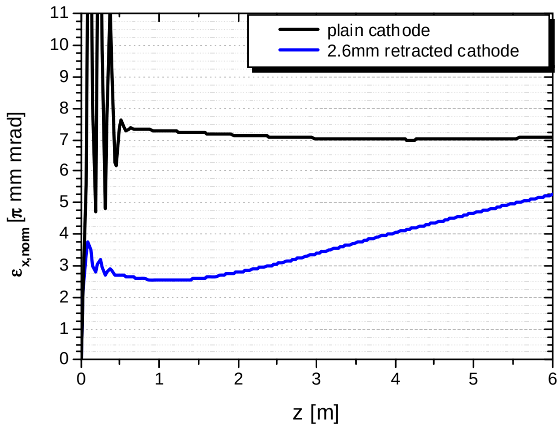

Figure 3: A retracted cathode improves the transverse emittance (1 nC).

Emittance Compensation with a Cathode Visor

For very high bunch charges a cathode visor improves the transverse emittance. The visor (see Fig. 4) influences the focusing electric field and a proper visor shape optimizes the radial focusing electric field. Fig. 5 shows the field map in the vicinity of the cathode tip.

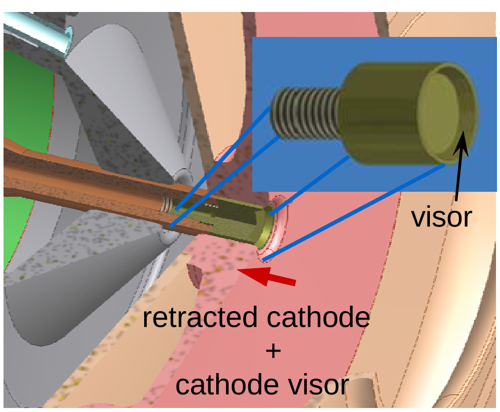

Figure 4: A customized shape of the cathode visor optimizes the focusing field and is effective for beam focusing for very high bunch charges.

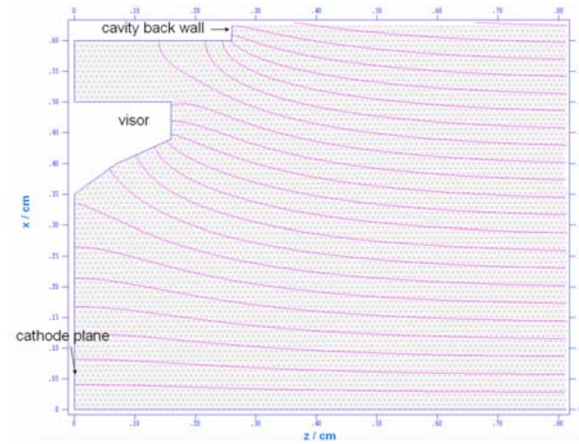

Figure 5: Field map in the vicinity of the cathode tip with a cathode visor.

HIGH CHARGE MODE (1.0 nC, 500 kHz)

ASTRA Simulations [5]

The calculations of the high charge mode with 1.0 nC bunch charge and a longitudinal flat top laser profile at pulse lengths of about 20 ps, 15 ps and 10 ps with rising and falling time of about 2 ps are shown in Fig. 6. The spot radius is varied between $r_{x,y}$ = 1.8 mm and $r_{x,y}$ = 2.4 mm. For smaller spot radii the thermal emittance is reduced and leads to smaller transverse emittance. With an additional varied laser pulse length a large range of states are achievable.

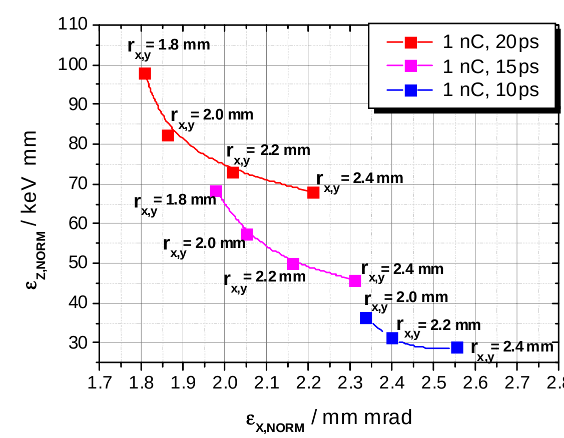

Figure 6: Simulations at 1 nC bunch charge for different laser flat top pulse lengths and laser spot radii.

BESSY MODE (2.5 nC, 1.0 kHz)

For these calculations a higher gradient of about 60 MV/m is assumed. This pushed gradient could be reached by using single crystal niobium sheets [6] in a new cavity fabrication.

ASTRA Simulations

The calculations of the BESSY mode with 2.5 nC bunch charge and a longitudinal flat top laser profile pulse length of about 38 ps with rising and falling time of about

4 ps are shown in Fig. 7. The improvement of the transverse emittance influenced by the visor is obvious. An eight 9-cell TESLA shape cavity (booster) at 3 m accelerates the electron beam up to 150 MeV. The longitudinal emittance with a cathode visor is enhanced due to a slightly smaller electric peak field at the cathode tip as shown in Fig. 8.

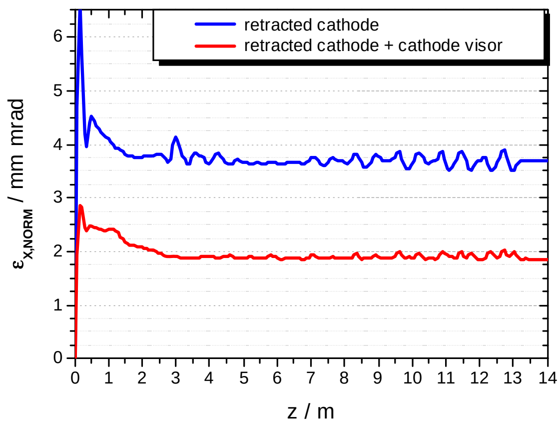

Figure 7: Transverse emittance simulations at 2.5 nC bunch charge for the SRF gun with a cathode visor and followed by a solenoid and a booster cavity at 3 m.

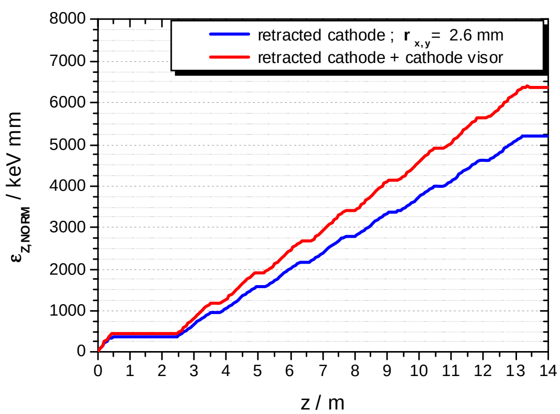

Figure 8: Longitudinal emittance simulations at 2.5 nC bunch charge for the SRF gun with a cathode visor and followed by a solenoid and a booster cavity at 3 m.

ELBE MODE (77 pC, 13 MHz)

The ELBE mode is used for the ELBE accelerator [7] to drive the IR FEL shown in Fig. 9. The necessary parameters for the FEL are a bunch charge of about 77 pC and a normalized transverse emittance of about 10 mm mrad and a maximal beam energy up to 36 MeV.

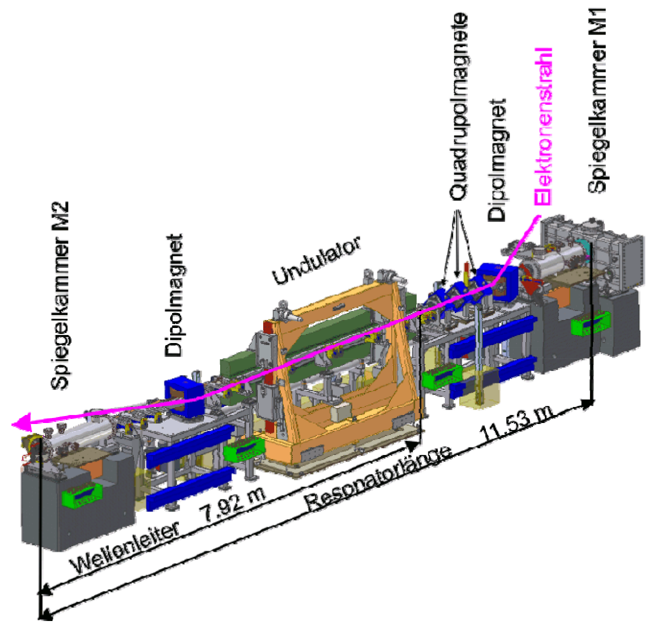

Figure 9: CAD model of the ELBE IR-FEL U27.

ASTRA Simulations

Fig. 10 shows the simulations of the transverse and longitudinal emittances for 4 ps and 1 ps laser pulse lengths with a Gaussian shape. The transverse emittance (at z = 3 m) does not change significantly but the longitudinal emittance and the energy spread is smaller at the shorter pulse length of about 1 ps.

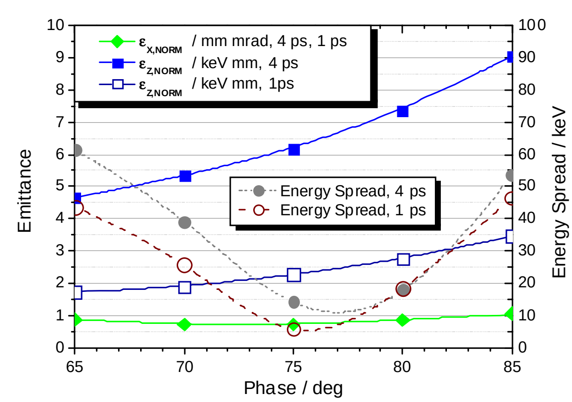

Figure 10: Phase scan simulations at 77 pC bunch charge for two Gaussian pulse lengths.

PITZ GUN (1.0 nC, 5 Hz)

The Photo Injector Test Facility in Desy Zeuthen (PITZ) is developed for the planned X-FEL at DESY Hamburg. The required parameters for the FEL are a bunch charge of about 1.0 nC and a normalized transverse emittance of about 1.0 mm-mrad and a maximal beam energy up to 20 GeV. The first summarized transverse emittance studies were done in 2004 with a prototype gun

[8] which is now used for the FLASH VUV-FEL at DESY, which needs a bunch charge of about 1.0 nC and a normalized emittance of about 1.5 mm mrad and a maximal beam energy up to 1 GeV [9]. Fig. 11 shows the measured transverse emittance with a bunch charge of about 1.0 nC.

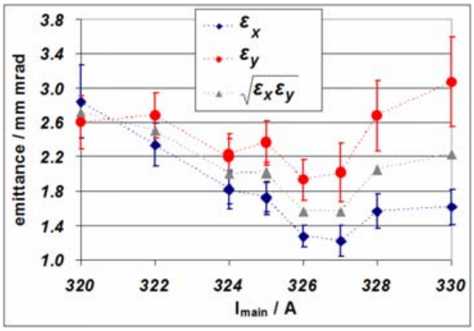

Figure 11: [8] Measurements with cavity prototype #1.

The electric field gradient amounts to 41 MV/m. For an improved transverse emittance of about 1.0 mm mrad the electric field gradient must be increased. With higher gradients the acceleration of the electron bunch is stronger and the space charge force decreases earlier. But dark current occurs at gradients above 20 MV/m [10] and increases with higher gradients as shown in Fig. 12.

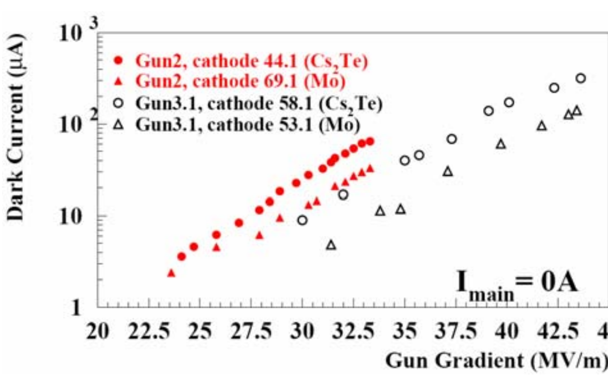

Figure 12: [10] Dark current without solenoids produced with two gun cavities for different cathodes at PITZ.

NORMAL CONDUCTING BESSY GUN (2.5 nC, 1.0 kHz)

The normal conducting 1.5 cell RF gun is related to the Photo Injector Test Facility in Desy Zeuthen (PITZ) [11,12]. The required parameters for the BESSY FEL are a bunch charge of about 2.5 nC and a normalized transverse emittance of about 1.5 mm mrad and a maximal beam energy up to 2.3 GeV. Fig. 13 shows the elaborate cooling system [13]. A duty cycle of about 2.5 % is achievable [14].

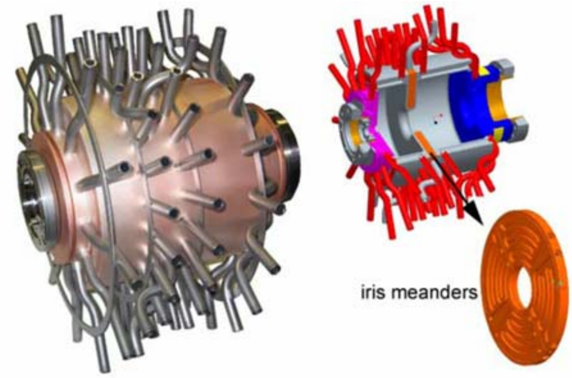

Figure 13: [13] The copper BESSY Gun (photo left) with the outer water connections and the corresponding CAD model (right) revealing the inner water circuits.

ASTRA Simulations

Fig. 14 shows the normalized transverse emittance and the 95% core emittance with bunch charge of ~ 2.5 nC and longitudinal flat top laser profile pulse length of ~38 ps with rising and falling time ~4 ps. The longitudinal emittance and beam energy are shown in Fig. 15. For comparison with the SRF gun calculations the distance of 14 m is suitable.

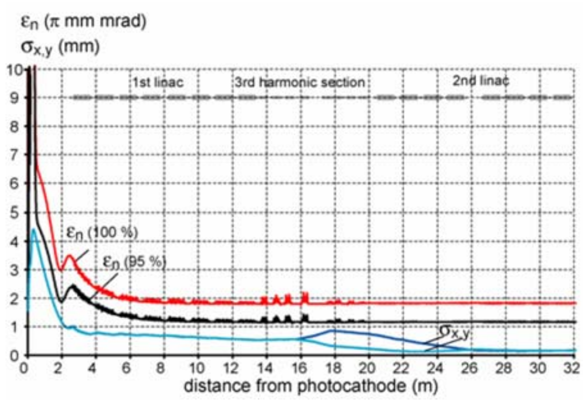

Figure 14: [15] Evolution of the normalized transverse rms emittance ε_n (100% and 95% core emittance) and beam size $\sigma_{x,y}$ for a bunch charge of 2.5 nC up to the exit of the 2nd linac module.

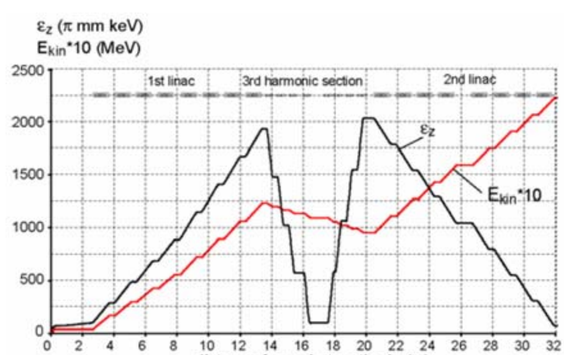

Figure 15: [15] Evolution of the longitudinal rms emittance ε_z and beam energy E_{kin} for a bunch charge of 2.5 nC up to the exit of the 2nd linac module.

SUMMARY

The SRF gun achieves in the high charge mode and the BESSY mode similar transverse emittances as the PITZ prototype gun and the BESSY gun respectively. The SRF gun has more potential for high average current due to the better duty cycle. The normal conducting guns have no limitations in the magnetic surface fields and a higher gradient at the cathode, and thus better longitudinal emittances are achievable.

Effective emittance compensation for the ELBE mode is achieved with retracted cathode. The pulse length τ_p of the photo gun laser should be kept as short as possible. A realistic value of τ_p = 1 ps (FWHM) with a Gaussian profile is achievable. The projected normalized transverse emittance less than 1.0 mm mrad is more than sufficient to drive the ELBE infrared FEL.

In Table 1 the parameters and simulation results of the different SRF gun modes are summarized.

Table 1: SRF gun parameters and simulation results

	ELBE mode	**high charge mode**	**BESSY mode**
RF frequency	1.3 GHz		
beam energy	9.5 MeV		11 MeV
average current	1 mA	0.5 mA	2.5μA
repetition rate	13 MHz	500 kHz	1 kHz
bunch charge	77 pC	1 nC	2.5 nC
longitudinal laser profile	gaussian	flat top	flat top
laser pulse shape length (rising time)	1 ps (FWHM)	20 ps (2 ps)	38 ps (4 ps)
peak current	45 A	50 A	65.8 A
expected norm. transverse emittance	< 1.0 mm mrad	1.8 - 2.5 mm mrad	< 2.0 mm mrad

ACKNOWLEDEMENT

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395) and the support of the German Federal Ministry of Education and Research grant 05 ES4BR1/8.

REFERENCES

[1] D. Krämer et al. (editors), “The BESSY Soft X-Ray Free Electron Laser”, Technical Design Report, ISBN 3-9809534-0-8, BESSY, Berlin, 2004.

[2] J. Teichert et al., “A Superconducting Photo-Injector with $3^1/_2$-Cell Cavity for the ELBE Linac”, EPAC 2004, Lucerne, 2004.

[3] A. Arnold et al., “First RF-Measurements at the 3.5-Cell SRF-Photo-Gun Cavity in Rossendorf”, FEL 2006, Berlin, 2006.

[4] D. Janssen, V. Volkov, Nucl. Instr. and Meth. A452 (2000) 34.

[5] K. Flöttmann, ASTRA (Version 1.0), http://www.desy.de/~mpyflo, 2007.

[6] P. Kneisel et al., “Preliminary Results from Single Crystal and Very Large Crystal Niobium Cavities”, PAC 2005, Knoxville, 2005.

[7] P. Michel et al., “The Rossendorf IR-FEL ELBE”, FEL 2006, Berlin, 2006.

[8] V. Miltchev et al., “Transverse emittance measurements at the photo injector test facility at DESY Zeuthen”, FEL 2004, Trieste, 2004.

[9] FLASH, "F"reie-Elektronen-"LAS"er in "H"amburg, http://vuv-fel.desy.de/

[10] A. Oppelt, “Tuning, conditioning and dark current measurements of a new gun cavity at PITZ”, FEL 2006, Berlin, 2006.

[11] F. Stephan et al., “First Measurements at the Photo Injector Test Facility at DESY Zeuthen”, EPAC 2002, Paris, 2002.

[12] F. Stephan et al., “Recent results and perspectives of the low emittance photo injector at PITZ”, FEL 2004, Trieste, 2004.

[13] F. Marhauser, “High Power Tests of a High Duty Cycle, High Repetition Rate RF Photoinjector Gun for the BESSY FEL”, EPAC 2006, Edinburgh, 2006.

[14] F. Marhauser, “Photoinjector Studies for the BESSY Soft X-ray FEL”, EPAC 2004, Berlin, 2004.

[15] F. Marhauser et al., “A High Average Power RF Photoinjector Gun Cavity Developed for the BESSY Soft X-Ray FEL”, FEL 2006, Berlin, 2006.