A HIGH AVERAGE POWER RF PHOTOINJECTOR GUN CAVITY DEVELOPED FOR THE BESSY SOFT X-RAY FEL*

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Abstract

Based on the 1.3 GHz normal conducting RF photogun installed at the Free Electron Laser in Hamburg (FLASH) a new RF gun prototype with an optimized cooling layout has been developed at BESSY with the objective to operate in the 100 kW average power regime. This would significantly enhance the capability of present L-Band guns towards operation at higher accelerating fields or/and duty factors. High power RF-conditioning at the Photo Injector Test Facility at DESY in Zeuthen (PITZ) has recently been performed achieving 47 kW average power and an electric peak field of 53 MV/m in maximum respectively, so far only limited by power constraints of the RF-system. In this paper the RF-conditioning results and relevant simulation results are discussed. Tracking studies for the photoinjector including two linac modules and a subharmonic cavity section are presented.

INTRODUCTION

RF photoinjectors bear the potential to generate electron pulses of extraordinary high peak brightness suitable for future FELs and linear colliders. For the proposed BESSY Soft X-Ray FEL (“BESSY FEL”) [1] with its superconducting CW driver linac a superconducting RF (SRF) gun would be the ideal electron source to deliver most flexible pulse pattern considering the manifold demands of experimental users. Superconducting guns are therefore a very active research area. For example, FZR, DESY, MBI and BESSY are collaborating to commission an SRF 1.3 GHz 3½-cell photoinjector gun cavity at FZR in 2007. Initially, this gun will accelerate 1 nC, but schemes have been identified and investigated that are capable of achieving slice emittances in the order of 1.5 π mm mrad at 2.5 nC bunch charge [2].

At present, though, normal conducting (NC) photoguns are more established and will therefore be used to commission the BESSY FEL. Still, a very high rep rate (1 kHz) is planned to approach CW operation. Later this NC gun can be replaced by an SRF gun. In particular much progress has been made by the PITZ collaboration which has developed a series of 1.3 GHz NC guns (1 ½ cells) characterized at the PITZ facility [3]. So far a minimum projected emittance of 1.6 π mm mrad (geometrical average of horizontal and vertical emittance) for a bunch charge of 1 nC could be demonstrated [4]. This system has also been operational at FLASH. Improvements at PITZ are expected by further optimizing the transverse and temporal profile of the photocathode laser, increasing the electric field at the photocathode to E_c = 60 MV/m and by utilizing a booster cavity, whereby the emittance conversation principle will be studied [5]. Beam operation hitherto was performed typically with E_c = 40-45 MV/m and a duty factor of 0.9 % (10 Hz RF pulse repetition rate) corresponding to an average power in the range of 30 kW. The European XFEL [6] and the proposed BESSY FEL however require even higher values to be achieved as listed in Table 1.

Table 1: Target parameters of NC RF guns as proposed for the European XFEL and the BESSY FEL at commissioning phase

Parameter	European XFEL	BESSY FEL
Frequency / GHz	1.3	
Number of cells (copper)	1½	
Bunch charge / nC	1	2.5
Single bunch rep. rate / MHz	5	1/3
RF pulse rep. rate / Hz	10	1000
Peak field / (MV/m)	60	40
Peak power* / MW	~6.5	~3
Beam pulse length** / µs	650 (max.)	6
Duty factor / %	~0.67	~2.5
Average power / kW	~44	~75
Beam parameters at undulator		
Trans. norm. slice emittance / π mm mrad	1.4	1.5
Max. beam energy / GeV	20	2.3

* depending on Q_0 (~23000), ** excluding RF rise/fall time (~20 µs)

Gun cavity thermal drifts as a source of severe phase and amplitude jitters may then become more apparent. Despite the progress of RF field stability control [7], one challenging task remains the mitigation of these drifts. Thus elaborate cooling concepts for the gun have to be

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considered. With respect to this issue a high average power 1 ½-cell RF gun cavity with an optimized cooling layout has been developed at BESSY ("BESSY Gun") as described below. A prototype of the cavity has been produced and thermal tests without photoemitted electrons were performed at PITZ. This gun also served as the basis for new beam dynamics simulations.

BESSY NC RF GUN CAVITY

A picture of the BESSY Gun and its outer water connections is shown in Fig. 1 (left), whereas the CAD model (right) reveals the inner cooling circuits. To provide sufficient water to the cavity a total number of 43 water inlets and outlets have been implemented with each water circuit separately addressable. Thus a sufficiently high water volume flow can be delivered to the cavity body and the water temperature rise within each meander can be kept rather low. Still emphasis has been placed on a simple conceptual design using drilled water holes of same dimensions throughout except in the iris aperture. Further details on the technical layout and cooling scheme can be found in [8].

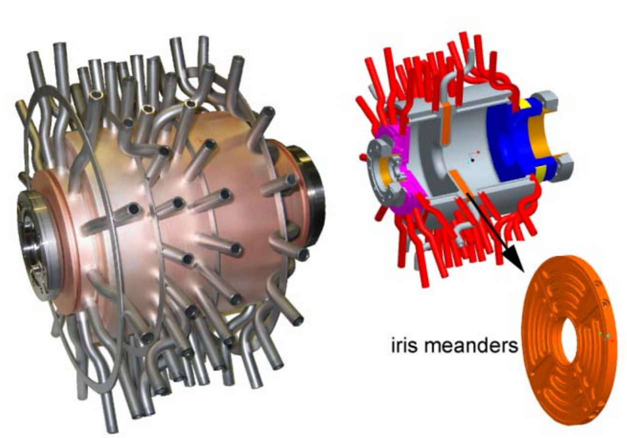

Figure 1: The copper 1 ½-cell BESSY Gun (photo left) with the outer water connections and the corresponding CAD model (right) revealing the inner water circuits.

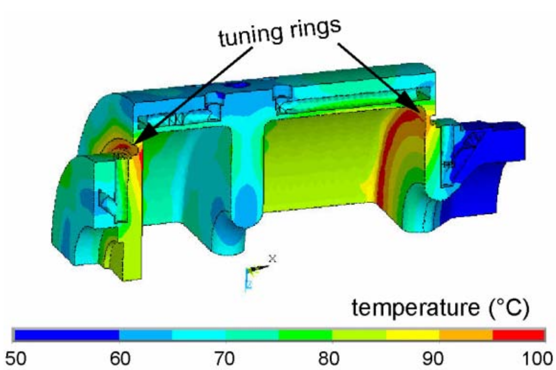

Figure 2: Temperature distribution in the BESSY Gun calculated at P_{ave} = 75 kW with T_{in} = 42°C for a quarter symmetric ANSYS model.

The cooling scheme was optimized with the help of thermal simulations using the FEA Code ANSYS [10]. Hence the BESSY Gun exhibits moderate temperatures (< 100°C) at an average power of P_{ave} = 75 kW, i.e. the nominal operation power for the BESSY FEL. As illustrated in Fig. 2 this has been achieved for a reasonable water inlet temperature of T_{in} = 42°C. Circular notches at each endplate ('tuning rings') have been implemented to ease a possible tuning effort. The reduced cooling efficiency at the tuning rings is taken into account for this prototype yielding the maximum local temperatures. Mechanical stresses however are not an issue [10].

As a feature the BESSY Gun was equipped with a small pickup port (Ø = 8mm) in the full cell implementing an antenna, loosely coupled to produce only a negligible field distortion. The antenna amplitude and phase information is beneficial for RF field stability control, critical for the overall jitter stability of the electron beam. Else - as practised at FLASH - the cavity field has to be artificially determined from the forward and reflected power signals of a directional waveguide coupler [7].

RF CONDITIONING

The first pulsed high power RF-conditioning tests of the BESSY Gun have been completed in May 2006 in the frame of the PITZ-collaboration. The conditioning test stand at PITZ is shown in Fig. 3. A 10 MW multi-beam klystron (MBK) was used to feed in the RF power to the gun via a standard DESY axially symmetric coupler. Due to the limited power capability of state-of-the-art RF vacuum windows the MBK output power is distributed into two separate WR650 waveguide arms. A T-combiner with two RF windows was flanged to the input coupler to add both RF-waves.

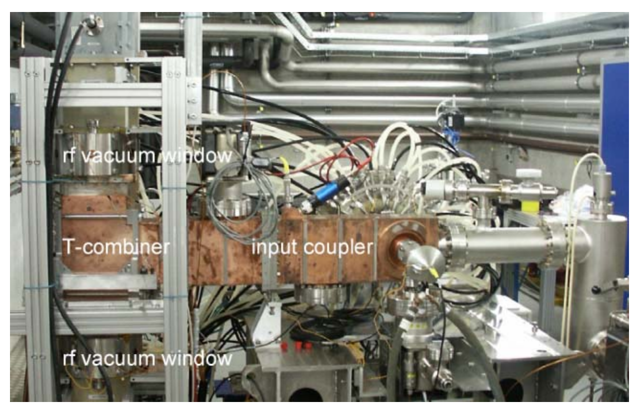

Figure 3: BESSY Gun on the conditioning test stand at PITZ. For conditioning no solenoids were installed.

After only 90 hours conditioning time -with a cavity vacuum interlock threshold of 10^{-7} mbar- a peak power of P_{peak} = 2.9 MW at t_{RF} = 100 µs was reached (P_{ave} = 2.9 kW) corresponding to a peak field of E_c = 40 MV/m as required for the BESSY FEL. It should be noted, that prior to the installation at PITZ the integrity of the gun was checked at BESSY operating several days in CW mode at 10 kW, which might have been beneficial to achieve this rather rapid progress. Since the repetition rate of the low level RF-system at PITZ is limited to f_{rep} = 10 Hz, the average power could only be increased by operating with both the peak power and the pulse length far beyond the desired BESSY FEL specifications (see Table 1). This "thermal" conditioning was time consuming, particularly because of sparking in the waveguide arms of the klystron at peak power levels above 3 MW. Despite the constraints of the RF-system, conditioning could be carried out successfully to a maximum operable peak power of P_{peak} = 5 MW with t_{RF} = 540 µs corresponding to an electric field of E_c = 53 MV/m. The maximum average power of P_{ave} = 47 kW was reached at the maximum pulse length of t_{RF} = 1 ms with P_{peak} = 4.7 MW (E_c = 51 MV/m). Higher power levels and longer pulse lengths could not be reached because of operational limitations of the RF-system. However up to 47 kW average power no thermal or technical limitations attributable to the gun were encountered. The main RF-conditioning results are listed in Table 2.

Table 2: BESSY Gun RF-conditioning results at PITZ

Parameter	Achieved at limit of RF system	Desired	Unit
P_{ave}	47	75	kW
P_{peak}	4.7*	3	MW
E_c	51*	40	MV/m
t_{RF}	1000	25	µs
f_{rep}	10	1000	Hz
d.f.	1	2.5	%

* max. P_{peak} = 5 MW corresponding to E_c = 53 MV/m at t_{RF} = 540 µs

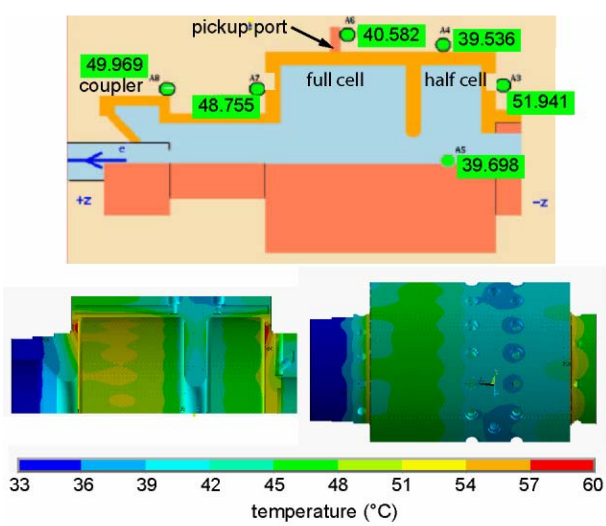

Figure 4: Measured (top) and simulated (bottom) gun temperatures when operating at P_{ave} = 40 kW and T_{in} = 27°C (P_{peak} = 4 MW, f_{rep} = 10 Hz, t_{RF} = 1 ms).

Fig. 4 (top) depicts a screen shot of the measured gun cavity temperatures using external PT100 sensors at distinctive locations (green dots). Here the temperatures are shown when operating at a thermal load of P_{ave} = 40 kW with an inlet water temperature of T_{in} = 27°C. At the bottom corresponding numerical results using ANSYS are plotted in good agreement with the monitored data. This is also true for the hot spots located at the tuning rings. At the antenna port no significant heat enhancement has been produced. The antenna port has been omitted in the calculation due to mesh size constraints.

To further check the reliability of numerical data, the frequency shift Δf caused by thermal deformation of the gun cavity has been measured at a constant inlet water temperature of 27°C when increasing the average power. Hereby the resonance was kept adjusting the master oscillator frequency to gain a reflected power below 1%. To evaluate Δf the resonance frequency at room temperature is taken as reference. In Fig. 5 the measured data are plotted as compared with numerical results. The latter have been computed by transferring the thermally deformed cavity profile given by ANSYS to Superfish [11]. This method has been extensively described in [12]. A linear drift in the order of Δf ~ -10 kHz/kW over the observed power regime at T_{in} = 27°C was obtained, consistent with the simulations.

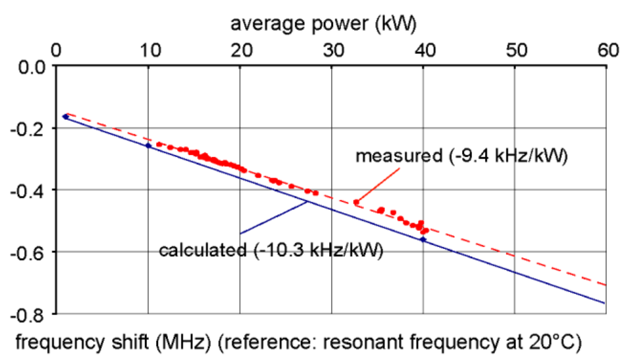

Figure 5: Thermal frequency drift in dependence on the average power as measured (red dots, f_{rep} = 10 Hz, t_{RF} = 1 ms) and calculated (blue line) both at T_{in} = 27°C.

BEAM DYNAMICS

Former beam dynamical studies using the accelerating field of the BESSY Gun as an input revealed that the photoinjector is able to deliver the required transverse slice emittances [10]. Further studies employing a multiparameter optimization with ASTRA [13] have been performed, the results being depicted in Figs. 6 and 7. Here 100000 macro particles have been tracked through the first two cryogenic linac modules comprising eight standard 1.3 GHz 9-cell TESLA-cavities. An intermediate section with quadrupoles as well as eight 9-cell 3.9 GHz cavities (under investigation at FERMILAB [14]) have been implemented to linearize the longitudinal phase space serving the needs of the subsequent first bunch compressor. A thermal energy of 0.55 eV for electrons emitted from a Cs_2Te photocathode illuminated by a UV laser (262 nm) has been taken into account. For the laser a temporal profile of 38 ps (flat top) with 4 ps rise/fall time and a spot size of 3.3 mm have been chosen. Furthermore a peak field of E_c = 40 MV/m has been presumed, which already has been exceeded by the BESSY Gun during the high power tests. As mentioned above this value however is rather constrained by thermal considerations.

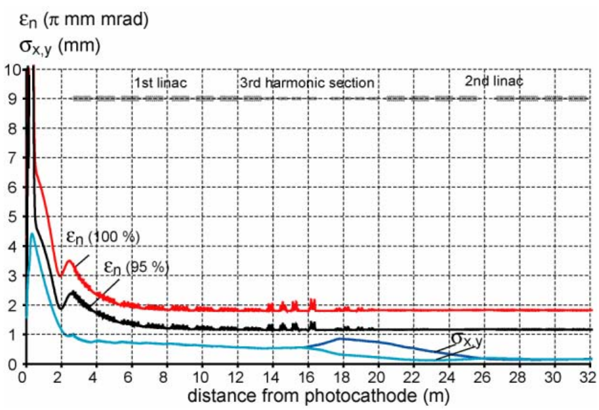

Figure 6: Evolution of the normalized transverse rms emittance ε_n (100% and 95% core emittance) and beam size $\sigma_{x,y}$ for a bunch charge of 2.5 nC up to the exit of the 2nd linac module.

For a bunch charge of 2.5 nC the normalized projected transverse emittance “frozen” at the exit of the second linac module (E_{kin} = 223 MeV) is 1.8 π mm mrad (1.2 π mm mrad for the 95% core emittance). At this point the slice emittance averaged over the whole bunch amounts to 1.5 π mm mrad fulfilling the design goal of the BESSY FEL.

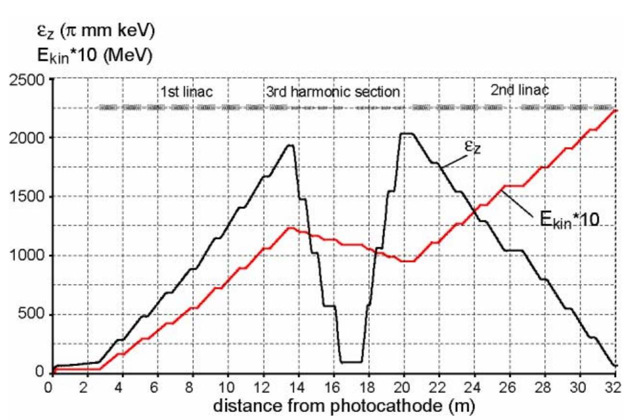

Figure 7: Evolution of the longitudinal rms emittance ε_z and average beam energy E_{kin} for a bunch charge of 2.5 nC up to the exit of the 2nd linac module.

The rms bunch length is 3.5 mm and a projected longitudinal rms emittance of 65 π keV mm has been obtained due to phase space linearization with the subharmonic cavity section (Fig. 7).

CONCLUSION

A high average power RF gun prototype developed at BESSY has been high power conditioned at the Photo Injector Test Facility at DESY in Zeuthen. The gun was tested up to an average power of 47 kW so far only limited by the maximum operable power of the RF-system. Similarly, the maximum electric field achieved at the cathode was 53 MV/m so far. All observations at present indicate that the gun is thermally stable at the desired power level of 75 kW or beyond. This is confirmed by corresponding thermal calculations. Operation of this prototype with photoemitted beams was not planned. However, new numerical tracking studies demonstrate that the gun is capable of producing the beam quality required for the BESSY FEL.

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