PHOTOINJECTOR STUDIES FOR THE BESSY SOFT X-RAY FEL*

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Abstract

Photoinjector studies based on a high power, high repetition rate normal conducting (n.c.) RF photo gun have been performed for the proposed linac driven BESSY Soft X-Ray Free Electron Laser (FEL) facility. Thermal and structural finite element analyses for the gun cavity using ANSYS are detailed complemented by ASTRA beam dynamic studies including the booster linac section. A feasibility study for a superconducting (s.c.) RF gun operable together with an external solenoid for emittance compensation is presented.

INTRODUCTION

A soft X-Ray FEL multi-user facility based on the High-Gain-Harmonic Generation (HGHG) principle [1] has been proposed at BESSY with the aim to produce high brilliance photon beams covering the VUV to soft X-ray spectral range from 24 eV to 1 keV [2]. The driver linac shall operate in CW mode by utilizing superconducting RF technology which is essential to provide the users with flexible bunch patterns. This calls for a s.c. RF photo gun as the ultimate choice to fully exploit the capabilities of the CW linac. However, no s.c. RF gun exists yet to fulfill the specific requirements of the BESSY FEL aiming for electron beams with normalized transverse slice emittances of 1.5 π mm mrad at a bunch charge of 2.5 nC at the entrance of the undulator sections. It is therefore planned to implement well established room temperature RF gun technology at the initial state (*phase I*) providing three independently tunable FEL-lines in parallel at a pulse repetition rate as high as 1000 Hz each. For this mode of operation the cooling layout of the n.c. gun cavity has been designed to cope with a thermal power of 75 kW. At a later stage with a foreseen upgrade to five FEL-lines the n.c. gun shall be replaced by a s.c. RF gun (*phase II*) giving the potential to vary the pulse sequence freely only limited by the maximum allowable beam loading in the linac. A s.c. RF gun concept has been investigated with promising results using an external focusing magnet for emittance compensation placed sufficiently far behind the s.c. surface as proposed in [3].

THE NORMAL CONDUCTING PHOTOINJECTOR

High Power, High Repetition Rate RF Gun

A schematic of the n.c. RF gun as proposed for *phase I* is depicted in Fig. 1 together with the solenoid arrangement used to compensate for the emittance dilution due to linear space charge forces [4]. Table 1 lists the corresponding operational parameters. The cavity design is based on a copper 1½-cell L-band photo gun operated successfully within the PITZ-I collaboration at the Photoinjector Test Facility at DESY Zeuthen. The PITZ-I gun has been tested with up to 900 µs long macropulses at a repetition rate of 10 Hz and 27 kW mean power corresponding to a peak field of 40 MV/m at the photocathode and has already been installed for operation at the VUV-FEL at DESY Hamburg [5].

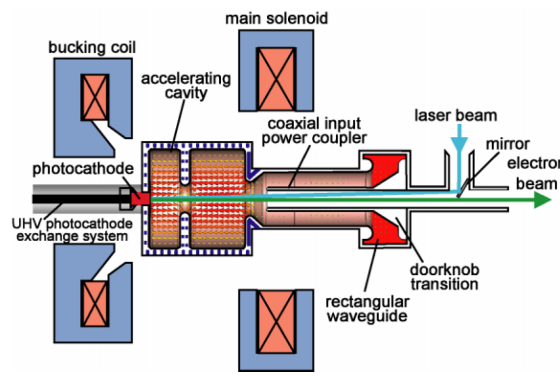

Figure 1: Schematic of the n.c. RF photo gun.

Based on the achievements at PITZ-I a peak field of 40 MV/m at the photocathode has been adopted. However, the higher repetition rate of 1000 Hz at a duty cycle of ~2.5% yields an average power loss of 75 kW generated in the cavity walls. As RF phase and amplitude mismatch due to thermal frequency drifts are of major concern during operation a well optimized cooling scheme is mandatory.

Table 1: Operational parameters of the n.c. RF gun

Resonant frequency	1.3	GHz
Unloaded quality factor	~22000	
Coupling factor ($Q_0 \approx Q_{ext}$)	~1	
Field rise time	17.5	µs
Length of bunch train	6	µs
Repetition frequency	1000	Hz
Duty cycle	~2.5	%
Peak field at cathode	40	MV/m
Peak input power	3	MW
Average RF power	75	kW
Beam energy at exit	4.2	MeV

To optimize the cooling layout finite element analyses have been carried out for a 3D 1/6 cavity model (see Fig. 2) using the multi-physics package of ANSYS [6]. In a first step the RF induced heat flux distribution at the inner cavity surface was calculated and applied as a heat source to the cavity body [7]. The heat sink is defined by reasonable convection coefficients assigned to the different water channels to simulate the coolant flow. Thus the temperature distribution in the cavity walls can

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be readily evaluated. The thermal results are eventually used as a load for the structural analysis to assess cavity internal wall stresses and deformations allowing also for the atmospheric pressure. Figure 2 depicts the temperature rise ΔT and the equivalent von Mises stresses in the cavity body at 75 kW thermal power yielding maximum values of 39°C and ~50 MPa respectively. The latter is well below the 0.2% proof stress of OFHC copper (124 MPa).

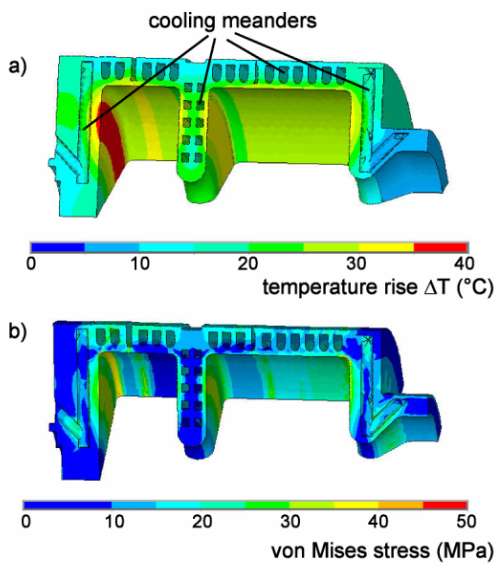

Figure 2: Temperature rise (a) and von Mises stresses (b) at 75 kW mean power (water flow velocity 2m/s).

In order to assess the temperature induced frequency shift the ANSYS nodal displacements along the internal cavity outline have been combined with corresponding geometrical frequency sensitivities determined from Slater's perturbation theorem using SUPERFISH [8]. Due to the thermal deformation the resonant frequency strongly drops by 1.1-1.8 MHz when varying the bulk water temperature within 27-57°C. This has to be considered during fabrication as no tuning plunger is provided to avoid beam emittance dilution due to field distortions. A course tuning will rather be done by plastic deformation of the endplates, whereas a fine tuning is facilitated during operation by variation of the inlet water temperature. The combined ANSYS/SUPERFISH simulation resulted in a frequency shift of -22.5 kHz per increase of 1°C water temperature.

Beam Dynamics

Tracking studies for the photoinjector were carried out using the ASTRA code [9]. These include the first linac section comprising eight s.c. standard 1.3 GHz 9-cell TESLA cavities housed in a single cryostat (cryomodule). For a bunch charge of 2.5 nC the evolution of the projected normalized transverse rms emittance $\varepsilon_{n,rms}$ and beam size $\sigma_{x,y}$ up to the exit of the cryomodule is shown in Fig. 3 with the initial beam parameters as given in the inset. A thermal emittance of 0.64 π mm mrad has been assumed for a Cs_2Te cathode excited with a UV laser. The magnetic flux density of the solenoid was optimized adopting the concept of the new working point [10]. Thereby the beam is injected into the subsequent booster cavity at its focus position behind the gun, which also coincides with the location of a local maximum of $\varepsilon_{n,rms}$.

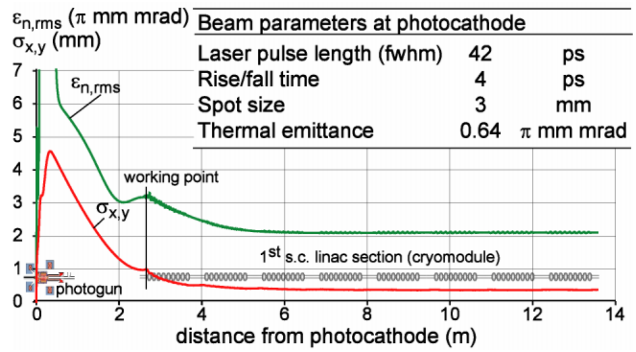

Figure 3: Evolution of $\varepsilon_{n,rms}$ (green) and $\sigma_{x,y}$ (red) at 2.5 nC up to the exit of the 1st linac cryomodule.

The accelerating field of the booster cavities is chosen with regard to the invariant envelope matching criterion [11]. Thus $\sigma_{x,y}$ and $\varepsilon_{n,rms}$ can be further diminished during acceleration finally resulting in $\sigma_{x,y} = 0.37$ mm and $\varepsilon_{n,rms} = 2.1\ \pi$ mm mrad respectively at the exit of the cryomodule. As the projected transverse emittance is usually diluted by head and tail particles, the average normalized rms slice emittance actually amounts to only 1.5 π mm mrad fulfilling the design goal of the BESSY FEL. The mean beam energy at the linac exit is 129 MeV. A subsequent second linac module further boosts the energy to 228 MeV necessary to overcome the space charge dominated regime before the beam is injected into the first bunch compressor stage thereafter. This energy includes the deceleration effect of a preceding subharmonic cavity section used to linearize the longitudinal phase space. Thus an rms bunch length of 3.7 mm at a projected longitudinal rms emittance of 213 π keV mm is provided at the entrance of the first bunch compressor.

PROSPECTS FOR A SUPERCONDUCTING PHOTOINJECTOR

The replacement of the n.c. by a s.c. CW RF-gun is envisaged at *phase II*. However, R&D programs for s.c. RF guns are still ongoing, although not fulfilling the specific requirements of the BESSY FEL yet. A major drawback is the prohibition of static magnetic focusing fields in the direct vicinity of the s.c. surface. Under the premise of a strong accelerating field however, a promising approach has been followed placing the focusing solenoid sufficiently behind but still close enough to the cavity wall to initiate an effective emittance compensation process. Figure 4 illustrates the investigated setup. A n.c. solenoid might be positioned outside, a s.c.

magnet inside the cavity cryostat. It has been shown recently, that accelerating fields in the range of 35 MV/m can be achieved for multi-cell niobium TESLA-cavities [12]. Therefore a 1.3 GHz 1.625-cell cavity has been designed based on the TESLA-cell geometry.

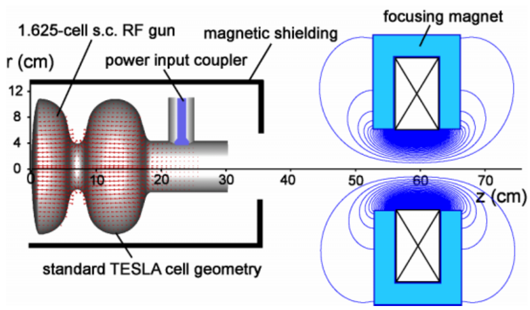

Figure 4: Illustrative view of the proposed s.c. photo gun setup utilizing an external focusing solenoid.

The minimum allowable distance of the solenoid to the cavity is given by the constraint, that an accelerating field as high as E_{acc} = 35 MV/m requests for a quality factor Q_0 in the range of 10^{10}. Besides operating at a cryogenic temperature of ~2 K this demands for a minimization of the ambient static magnetic fields down to the µT-level as static magnetic flux lines can be trapped upon cool-down in the niobium surface giving rise to an increase of the magnetic surface resistance by 3.5 nΩ/µT at 1.3 GHz [13]. Therefore the s.c. walls have to be shielded anyway from the earth magnetic field (~50 µT at the BESSY site), which can be done by surrounding the cavity with a high-permeability cylinder. For TESLA cryomodules such a shielding results in residual fields of about one µT along the cavities when combined with the conventional shielding of the steel vacuum vessel [13].

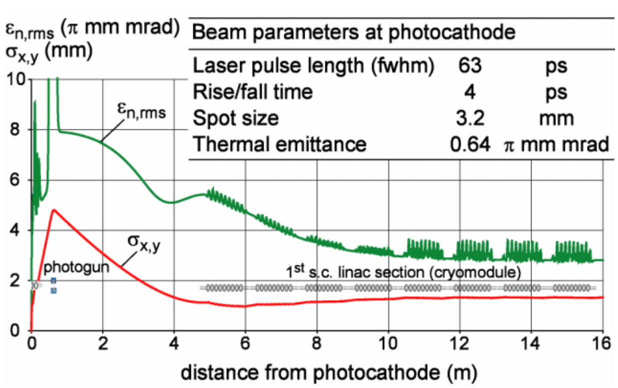

Figure 5: Evolution of $\varepsilon_{n,rms}$ (green) and $\sigma_{x,y}$ (red) at 2.5 nC up to the exit of the 1st linac cryomodule.

As a result with a moderate shielding of ambient magnetic fields (factor 25) a $Q_0 = 10^{10}$ can be obtained in principle with a solenoid centered 60 cm behind the photocathode when operating at an accelerating field of 34.5 MV/m. The latter corresponds to a field amplitude of 60 MV/m at the photocathode for the given cavity geometry. With the above mentioned assumptions $\varepsilon_{n,rms}$ evolves to 2.8 π mm mrad for 2.5 nC at the booster linac exit (see Fig. 5). The corresponding average rms slice emittance amounts to 2.3 π mm mrad with center slice emittances in the order of 1.5 π mm mrad. The proposed concept has still room for further optimizations, for instance by using a solenoid with low fringe fields or additional shielding to place it even closer to the cavity. E.g. for a gaussian shaped magnetic field profile (σ = 7 cm) centered 50 cm behind the cathode, an average rms slice emittance of 1.9 π mm mrad with center slice emittances in the order of 1 π mm mrad could be achieved at 2.5 nC.

CONCLUSION AND OUTLOOK

A room temperature high power, high repetition rate RF gun cavity based on the PITZ-I photo gun has been thermally optimized for operation at the proposed s.c. linac driven BESSY FEL. Beam dynamic studies revealed that the photoinjector is able to deliver the desired high brightness electron beams with an average transverse slice emittance of 1.5 π mm mrad at 2.5 nC. Preliminary studies for a photoinjector based on s.c. CW RF gun indicate good prospects for the concept of emittance compensation with an external focusing magnet. Further work is in progress to also address technical aspects. In a joint project with the Forschungszentrum Rossendorf, the Max Born Institute and DESY a s.c. 3½-cell RF photo gun will be built to generate high brightness electron beams at an accelerating field of ~25 MV/m implementing a n.c. photocathode into the s.c. environment [14].

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