HIGH POWER TESTS OF A HIGH DUTY CYCLE, HIGH REPETITION RATE RF PHOTOINJECTOR GUN FOR THE BESSY FEL*

F. Marhauser#, BESSY II, Berlin, Germany

Abstract

The proposed BESSY Soft X-Ray FEL will use a normal conducting high duty cycle, high repetition rate 1.3 GHz rf photo gun for the commissioning phase. Aiming for an operation at a duty cycle of 2.5% and a peak power of 3 MW the thermal load in the gun cavity equals 75 kW. To cope with this high average power a prototype rf gun with an optimized cooling layout has been built. High power rf-conditioning of the cavity has been completed recently at the Photo Injector Test Facility at DESY Zeuthen (PITZ). The technical layout and cooling scheme of the gun is described and rf-conditioning results are presented.

INTRODUCTION

Rf photoinjectors are the state-of-the-art choice to generate electron pulses of high bunch charge at the same time yielding low transverse emittances as demanded by future FELs and linear colliders. The proposed BESSY Soft X-Ray FEL [1] at commissioning phase provides three independent undulator sections with 2.5 nC electron bunches at a repetition rate as high as 1 kHz.

Table 1: Relevant BESSY Gun parameters.

Parameter			Unit
Vacuum frequency at 20°C	$f_{0,r.t.}$	1300.398	GHz
No. of cells		1 ½	
Unloaded quality factor	Q_0	23100[a]	
Loaded quality factor	Q_l	11800[b]	
Field flatness (A_{cell1}/A_{cell2})		0.999	
Length of e^- bunch train	t_b	6	µs
Distance between e^- bunches	Δt_b	2	µs
RF pulse repetition frequency	f_{rep}	1000	Hz
Peak field at cathode	E_c	40	MV/m
Peak input power	P_{peak}	3	MW
Field rise time	t_{rise}	~18.5	µs
Duty cycle	d.c.	~2.5	%
Average rf power	P_{ave}	75	kW

[a] OFHC copper, [b] measured with a DESY coaxial input coupler

Tracking simulations for the photoinjector section using a normal conducting 1.3 GHz 1 ½-cell rf gun have shown that the desired average projected normalized transverse rms slice emittance of 1.5 π mm mrad can be obtained utilizing emittance compensation and post-acceleration in a booster linac [2]. An electric field amplitude of E_c = 40 MV/m at the photocathode has been presumed as is routinely achieved with a series of rf guns developed at DESY, one of which is currently operating at the Free Electron Laser in Hamburg (FLASH) at a nominal thermal power of P_{ave} = 27 kW. Thus based on the DESY gun design an rf gun prototype has been developed at BESSY ("BESSY Gun") optimized for a more stringent thermal operation. In Table 1 measured cavity parameters of the BESSY Gun are listed together with the desired operational parameters. Actually the field rise time as given by Q_l is larger than the length of the bunch train. Consequently the duty cycle is d.c. ≈ 2.5 % yielding a thermal power of P_{ave} = 75 kW in the copper walls.

* This work is funded by the BMBF and by the Land Berlin and has partly been supported by the European Community, contract numbers RII3-CT-2004-506008 and 011935

#marhauser@bessy.de

TECHNICAL LAYOUT

Operating an L-Band rf gun at a mean power level around 100 kW demands a well optimized cooling layout to guarantee a thermally stable operation. The latter is mandatory to prevent severe rf amplitude and phase jitters, which in turn are converted into beam energy and timing jitters. The BESSY Gun has been built based on numerical results using the FEA Code ANSYS [3] capable of optimizing thermal and structural properties [4]. The cooling scheme was optimized in a way that the cavity exhibits moderate temperatures (< 100°C) at P_{ave} = 75 kW and a rather low temperature rise within the water circuits by using sufficient water inlets. A picture of the gun cavity and its outer water connections is shown in Fig. 1 (left), whereas the CAD model (right) reveals the inner cooling circuits.

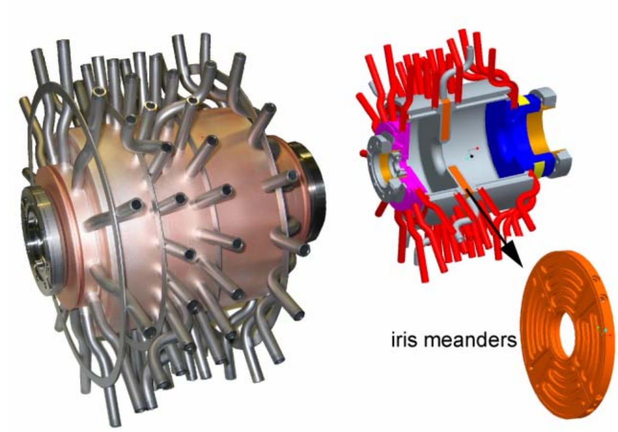

Figure 1: The copper BESSY Gun (photo left) with the outer water connections and the corresponding CAD model (right) revealing the inner water circuits.

The copper constituents of the BESSY Gun are i) a main body including the iris aperture which forms the half and full cell, ii) a meander ring surrounding the iris, iii) a front cap with a hole to implement a photocathode and iv) an end cap with an expanding beam tube to house a coaxial input coupler. All cavity parts including the outer water tubes have been brazed together in a single step eliminating multiple heat treatments. 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. Still emphasis has been placed on a simple conceptual design using drilled water holes of same dimensions throughout except the iris aperture. Here quarter segments each machined with a single meander have been brazed to the body (Fig. 1 right). To control the water volume flow a mobile water distribution system has been built compatible with the water system at PITZ using two separate water feeds for the iris and cavity body respectively. The latter has been divided into four main circuits. All circuits have been connected to the distribution system by flexible water hoses (see Fig.3). Thereby an adequate water volume flow is supplied to different parts of the gun depending on the local power entry to limit the water temperature rise in each main circuit (see Table 2).

Table 2: Main water circuits used, nominal volume flow rate dV/dt, heat transfer coefficient α and estimated water temperature rise ΔT_{H20} at P_{ave} = 75 kW

Main circuit	No. of meanders	dV/dt l/min	α @ 42°C $W \cdot cm^{-2} \cdot K^{-1}$	ΔT_{H20} K
Iris	4	28.8	1.3	8.8
Half cell	6[a]	36.2	1.2	5.7
Full cell	12	72.4	1.2	5.1
Front plate	6	36.2	1.2	3.7
End plate	5[b]	30.2	1.2	4.1
Total	33[c]	203.7	-	5.3

[a] 6 bridged, [b] 4 bridged, [c] out of 43

The pressure drops in the main circuits of the cavity body have been equalized by choosing adequate pipe dimensions and lengths of the distribution system and hoses. Thus for a nominal water volume flow of 204 l/min flow velocities of υ_m ~ 2m/s at the cavity body have been achieved throughout which yields an effective cooling with heat transfer coefficients $\alpha > 1\ W \cdot cm^{-2} \cdot K^{-1}$. Fig. 2 depicts the cavity thermal distribution at P_{ave} = 75 kW as calculated for a quarter ANSYS model.

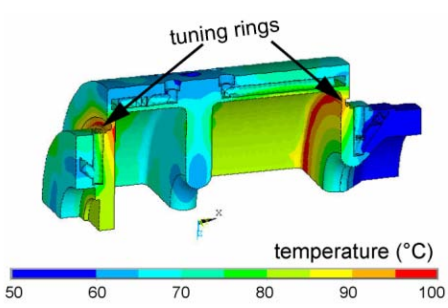

Figure 2: Temperature distribution in the BESSY Gun calculated at P_{ave} = 75 kW (T_{H20} = 42°C, υ_m = 2m/s).

During operation only a fine tuning of the frequency by water temperature control (~-23 kHz/°C) is feasible. A tuner plunger inserted in the gun is prohibited as this would significantly increase the beam emittance. Thus a frequency tuning by plastic deformation of cavity walls has to compensate for mechanical errors as for the various DESY rf guns [5, 6]. As a plastic deformation necessitates relatively large forces, circular notches at each endplate ('tuning rings') have been implemented in the BESSY Gun to ease a possible tuning effort. Fortunately a mechanical tuning of the BESSY Gun could be avoided for rf-conditioning as explained in Section 3. The reduced cooling efficiency at the tuning rings (see Fig. 2) has been taken into account for this prototype. Additionally a small port (Ø = 8mm) has been implemented in the full cell of the rf gun (see Fig. 5 further below) with an antenna feedthrough for field control.

RF CONDITIONING

Within the PITZ-collaboration the BESSY Gun could recently be high power tested on a conditioning test stand using a 10 MW multi-beam klystron (Thales TH1801). The setup at PITZ is shown in Fig. 3. An operation with beam was not intended due to continuous research activities at PITZ with a series of DESY rf guns [7].

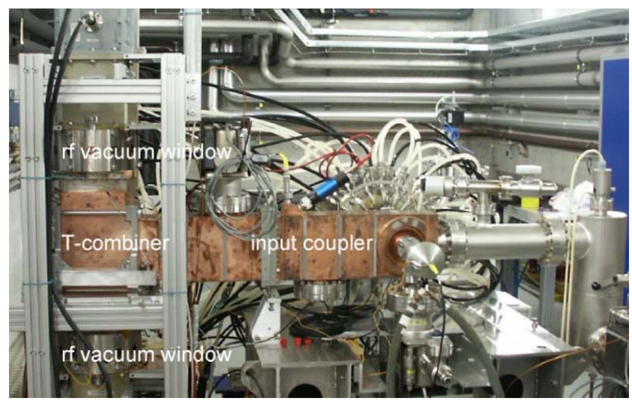

Figure 3: BESSY Gun on the conditioning test stand.

A standard DESY axially symmetric input coupler was used for feeding the BESSY Gun with rf power. Due to the limited power capability of state-of-the-art rf vacuum windows the klystron output power is distributed into two separate waveguide arms (WR650). A T-combiner using two rf windows was flanged to the input coupler to add both rf-waves. For secure conditioning a fast interlock system monitored photomultiplier and e^- signals as well as four ion getter pumps. With a vacuum frequency of 1300.4 MHz at room temperature a plastic tuning procedure for the BESSY Gun was not necessary avoiding any potential damage to the cavity walls. Instead an independent master oscillator has been implemented into the PITZ LLRF-system. Thus the frequency could be chosen freely -well within the bandwidth of the klystron (~± 1 MHz)- to operate the cavity in resonance albeit scanning the water inlet temperature, rf peak power P_{peak} and pulse length t_{rf} over a wide scale. The measurement procedure is implicated by Fig. 4 where P_{ave} is plotted versus the mean water temperature for various branches of constant frequency. Hereby P_{ave} has been varied by changing P_{peak} and/or t_{rf}. The average power for each branch is maximized at the minimum inlet water temperature given by the water system (= 27°C). Non-linear effects could not been observed and are expected to become apparent only at higher power levels [4].

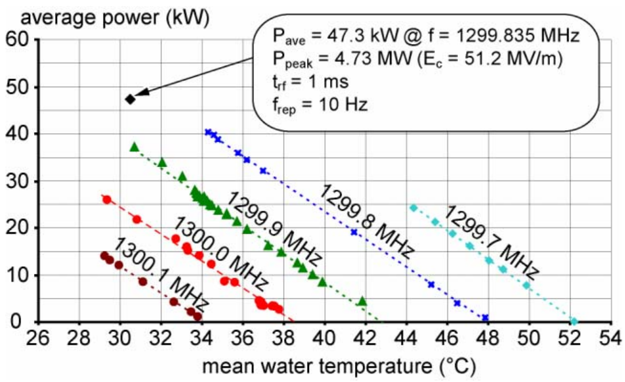

Figure 4: Average power measured in dependence on the mean water temperature at different resonant frequencies (f_{rep} = 10 Hz).

The cavity was first conditioned at the nominal frequency of 1.300 GHz trying to increase P_{peak} at a relatively small pulse length of t_{rf} = 100 µs. Within 90 hours conditioning time P_{peak} = 2.9 MW was reached corresponding to an electric field amplitude of E_c = 40 MV/m at the photocathode with a vacuum interlock threshold set to 10^{-7} mbar. To further increase P_{ave} the gun had to be operated with both P_{peak} and t_{rf} far beyond the desired BESSY-FEL specifications. Fig. 5 illustrates the monitored body temperatures at different locations when operating at a thermal load of P_{ave} = 40 kW. As expected the hottest temperatures are at the tuning rings with still a moderate temperature rise of $\Delta T \sim 25$°C related to the water inlet temperature. Furthermore at the location of the pickup port no significant heat enhancement could be detected.

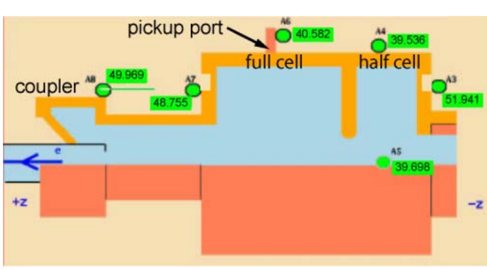

Figure 5: Measured body temperatures (in °C) at different locations when operating at P_{ave} = 40 kW and T_{H20} = 27°C (P_{peak} = 4 MW, f_{rep} = 10 Hz, t_{rf} = 1 ms).

Finally an average power of P_{ave} = 47.3 kW could be achieved without thermal or technical limitations observed attributable to the BESSY Gun. The main rf-conditioning results are summarized in Table 2. The conditioning progress was eventually limited by technical constraints of the rf-system, i.e. i) f_{rep} = 10 Hz (PITZ LLRF timing network), ii) d.c. = 1 %, and iii) P_{peak} ~ 5.0 MW (E_c = 52.9 MV/m) at t_{rf} = 540 µs. Sparcing in the WR650 waveguide arms at high peak power levels prevented a further thermal conditioning and the duty cycle could not been increased beyond 1% due to a severe deterioration of the klystron perveance for t_{rf} > 1 ms. Thus rf operation was limited to f_{rep} = 10 Hz reaching P_{peak} = 4.73 MW at t_{rf} = 1 ms and P_{peak} = 5 MW at t_{rf} = 540 µs respectively.

Table 2: BESSY Gun rf-conditioning results at PITZ.

Parameter	Achieved[a]	Desired	Unit
P_{ave}	47.3	75	kW
P_{peak}	4.73[b]	3	MW
E_c	51.2	40	MV/m
t_{rf}	1000	25	µs
f_{rep}	10	1000	Hz
d.c.	1	2.5	%

[a] limited by rf-system, [b] max. 5 MW @ 540 µs

CONCLUSION

A high duty cycle, high repetition rate photoinjector rf gun prototype has been recently rf-conditioned at the Photo Injector Test Facility at DESY Zeuthen. The achieved peak power was 4.7 MW (51.2 MV/m at the photocathode) at a pulse length of 1 ms. These operating points by far exceed the specifications of the BESSY Soft X-Ray FEL at commissioning phase. The corresponding average power of 47 kW could be handled without thermal or technical problems observed attributable to the rf gun. All measured body temperatures were still moderate and in the expected range. From these observations a thermally stable operation of the gun at the desired average power of 75 kW seems to be feasible. The operation had to be stopped due to technical problems related to either the 10 MW klystron or specific waveguide components.

ACKNOWLEDGEMENT

The author likes to thank the whole PITZ-group and several BESSY colleagues who greatly contributed to this work realizing the installation and operation of the BESSY Gun by running dedicated shifts.

REFERENCES

[1] D. Krämer et al. (editors), "The BESSY Soft X-Ray Free Electron Laser", ISBN 3-9809534-0-8, BESSY, Berlin.
[2] F. Marhauser, "Photoinjector Studies for the BESSY Soft X-Ray FEL", Proc. of the 9th EPAC 2004, Lucerne, Switzerland, MOPKF009.
[3] www.ansys.com.
[4] F. Marhauser, "Finite Element Analyses for Photoinjector Gun Cavities", DESY Hamburg, January 2006, TESLA FEL-Report 2006-02.
[5] I. Bohnet, "Tuning of a 1.5 Cell Copper Cavity", PITZ Note, March 1, 2002.
[6] A. Oppelt, "First Gun 3 Measurements", PITZ-collaboration meeting, February 2006.
[7] F. Stephan, "Status and Perspectives of PITZ", PITZ-collaboration meeting, Zeuthen, February 2006.