Behavior of the TTF2 RF Gun with long pulses and high repetition rates *

J. Baehr[1], I. Bohnet[1], J.-P. Carneiro[2], K. Floettmann[2], J. H. Han[1], M. v. Hartrott[3], M. Krasilnikov[1], O. Krebs[2], D. Lipka[1], F. Marhauser[3], V. Miltchev[1], A. Oppelt[1], B. Petrossyan[1], S. Schreiber[2], F. Stephan[1]

[1] Deutsches Elektronen-Synchrotron, Platanenallee 6, D-15738 Zeuthen, Germany

[2] Deutsches Elektronen-Synchrotron, Notkestrasse 85, D-22607 Hamburg, Germany

[3] BESSY, Albert-Einstein-Strasse 16, D-12489 Berlin, Germany

Abstract

This paper presents the behavior of the TTF2 RF gun with long RF pulses (up to 900 μs), high peak power (up to 3 MW) and high repetition rate (up to 10 Hz). The experiments have been realized at the Photo Injector Test Facility of DESY Zeuthen from January to March 2003, where the RF gun has been tested prior to its installation at DESY Hamburg on the TTF2 beamline.

1. Introduction

Phase 2 of the TESLA Test Facility (TTF2) is planned as a user facility [1] that will deliver a radiation wavelength of 6.4 nm when operating on its optimal regime. The electron beam will then be produced by an RF gun and accelerated to 1 GeV using 6 cryomodules each containing eight superconducting cavities. The beam will be compressed from 2 mm to 50 μm by two magnetic chicanes located at 130 MeV and 440 MeV. The peak current and the rms normalized emittance at the entrance of the undulator are expected to be 2.5 kA and 1.6 mm-mrad respectively. The length of the overall accelerator is of the order of 250 meters.

The linac will operate with trains up to 7200 bunches at a repetition rate up to 10 Hz delivering a maximum average spectral brilliance of B[1]=3.5×10^{22}. To reach this regime, the RF gun must be able to accelerate electron bunches in trains of 800 μs length (the bunches being separated by 111 ns) at a frequency of 10 Hz and a peak power of 3 MW to keep the beam emittance low. This paper will present the behavior of the TTF2 RF gun with respect to this high duty cycle operation.

2. Layout of the installation

2.1 The RF Gun

The TTF2 RF gun has been designed at DESY Hamburg [2]. It consists of a 1.5 cells cavity resonating in the $TM_{010,\pi}$ mode at a frequency of 1.3 GHz. In its present installation at the Photo Injector Test Facility at DESY Zeuthen (PITZ), the cavity is powered by a 5 MW klystron (that will be replaced by a 10 MW klystron later) through an axial symmetric input coupler to prevent field asymmetries. Table 1 presents the main electrical properties of the RF gun calculated from Superfish [3].

A high quantum efficiency Cs_2Te photocathode, located in the half cell, delivers electron bunches with charges up to 10 nC when triggered by UV light provided by a pulsed laser at a wavelength of 262 nm. To confine the space charge dominated beam, two solenoids (a primary and a bucking to zero the magnetic field on the cathode) are installed around the RF gun. For typical operation, the peak magnetic field is of the order of 0.16 T at $z = 0.25$ m. A large fraction of the RF gun conditioning (up to 10 Hz, 500 μs and 3 MW) has been done with complete solenoids sweeping. Due to time limitation, the conditioning has been done without external magnetic field for higher mean powers. The correspondence

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[1]In units of photons/sec/mrad^2/mm^2/(0.1% bandwidth)

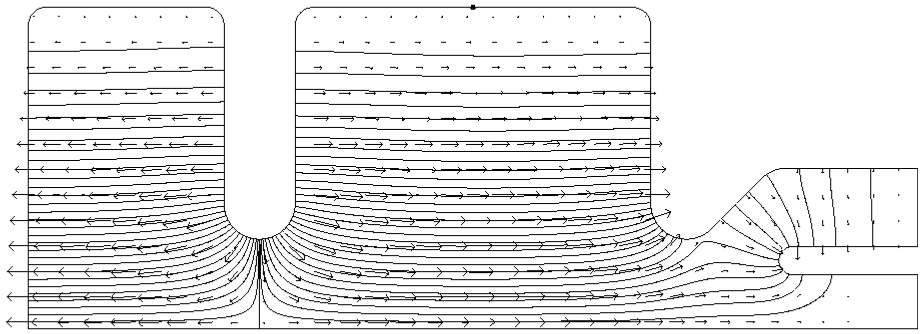


Fig. 1: Electric field lines for the π-mode.

Mode	$TM_{010\pi}$
Resonant Frequency f	1.3 GHz
Transit Time Factor T	0.72
External Quality Factor Q_{ext}	23001
Ratio peak field to accelerating field E_0/E_a	1.62
Peak power for E_0=40 MV/m	2.94 MW
Stored Energy for E_0=40 MV/m	8.28 J

Table 1: Main electrical properties of the TTF2 RF gun (from [3]).

between the peak electric field on the cathode E_0 and the forward peak power P_f in the cavity has been computed by Superfish :

$$E_0 \left[\mathrm{MV}\cdot\mathrm{m}^{-1}\right] \simeq 23.336 \times \sqrt{P_f\,[\mathrm{MW}]} \tag{1}$$

This relation assumes a perfect coupling between the waveguide and the RF gun and that the quality factor of the cavity is close to the one predicted by Superfish. These two assumptions are legitim since the reflected power has been measured to be of the order of 2% of the forward one (for stable operations) and the external quality factor to be of the order of 22000 (close to the Superfish prediction presented in Table 1). Equation 1 indicates that a forward peak power of 2.94 MW is necessary in order to get a peak electric field on the cathode of E_0 = 40 MV/m foreseen for the optimal operation of TTF2 ([1]). When operated at 10 Hz and 900 μs, a mean power of ∼27 kW will then have to be removed from the RF gun. A water system described in section 2.3 has been implemented around the cavity walls for this purpose.

2.2 The RF System

The main elements of the RF system are an oscillator which delivers a signal at a frequency of 1.3 GHz, followed by two amplifiers and a klystron delivering RF pulses up to 5.0 MW of peak power. A circulator has been installed downstream of the klystron in order to protect it from the reflected power. Losses in the circulator has been measured at ∼0.6 dB. The power is transmitted from the klystron to the RF gun through ∼20 meters of waveguides filled with SF_6 and pressurized slightly above atmospheric pressure. The forward and reflected power presented in this paper were measured at the directional coupler located ∼1.5 meters upstream of the RF gun. In the first operations of the RF gun only the first 3 meters of the waveguides (from the klystron to the circulator) and the last 1.5 meters (upstream of the RF gun) were filled with SF_6. We have noticed that filling the whole transport line improves significantly the operation of the RF gun at high power and repetition rates by suppressing sparks.

A vector modulator controlled by a unix station fixes the phase and the amplitude of the RF wave to be amplified. An interlock box is located at the exit of the vector modulator in order to prevent the operation if any interlock (Photo-multiplier, SF_6 pressure, etc...) is fired. It is important to notice that during the experiments presented in this paper we operated the RF gun only with feedforward from the low level RF system and without interlock on the reflected power from the gun. We estimate the precision on the power measurements at the RF gun to be in the order of ± 10 %.

2.3 The Water Cooling System

Figure 2 shows the location of the water channels around the RF gun: 1 in the back plate going twice around, 4 around the half cell, 7 around the full cell and 1 in the front plate . In the iris there is one cooling channels (not shown in Figure 2) making three loops around it. Therefore, there is a total of 14 water cooling channels in the RF gun.

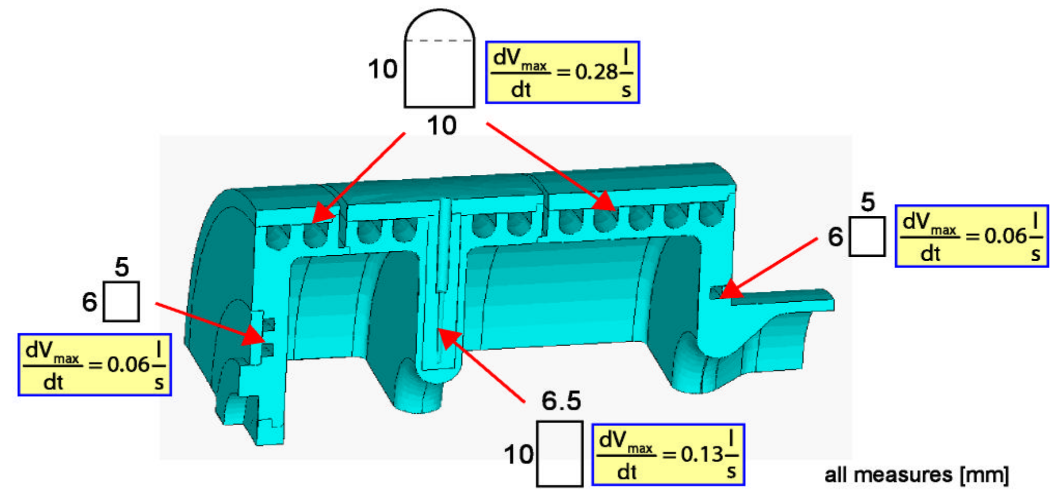


Fig. 2: Schematic view of the RF gun with the location and dimension of the water cooling channels and the estimated maximum water volume flow rate per channel (see text).

The flow velocity ν_{flow} per channel is given by the relation:

$$\nu_{flow} = \frac{dL_c}{dt} = \frac{1}{A_c} \cdot \frac{dV_c}{dt} \tag{2}$$

with L_c, A_c and V_c being the length, the cross section and the volume of the channel.

If we assume an upper limit of ν_{max} ~2.0 m·s^{-1} in order to prevent the channels from erosion then the maximum volume flow rate for a given cooling channel is given by :

$$\dot{V}_{max}\left[\mathrm{l} \cdot \mathrm{s}^{-1}\right] = A_c \cdot \nu_{max} = 0.2 \cdot A_c \left[\mathrm{cm}^2\right] \tag{3}$$

Summing the 14 water cooling channels up leads to:

$$\sum_{i=1}^{14} \frac{dV_{i,max}}{dt} = 3.33 \left[\mathrm{l} \cdot \mathrm{s}^{-1} \right] \quad (4)$$

The maximum water volume rate that can flow into the RF gun is then: ∼12 $\mathrm{m}^3 \cdot \mathrm{h}^{-1}$.

The general idea of the water cooling system is to mix the outgoing warm water of the RF gun with cold water (∼27°C). A heater is located in the warm water circuit in order to heat it up to a maximum temperature of 64°C if necessary. For the mixing to be effective, both circuits need to be at the same pressure (∼6 bars). The temperature can be set with a precision of 0.05°C.

A temperature sensor is located in the iris of the RF gun. A hole of 7.1 cm deepth has been machine in the iris for this purpose as indicated in Figure 2. In its deeper half, the hole is 2.5 mm in diameter and 5.0 mm in its other half. The temperature sensor is 10 mm long and 1.9 mm diameter. The incoming water temperature stabilizes when the temperature of this sensor reaches the set point temperature. Once stable, the water temperature does not fluctuate more than 0.05°C peak-to-peak. The incoming and outgoing water temperatures are measured by thermometers located ∼1.5 meters upstream and downstream of the RF gun. It is important to notice that there was no possibility to measure the rate of the water flowing into the RF gun during the experiments. The installation of a flow rate meter upstream of the RF gun is foreseen at PITZ for operations in 2004.

3. Resonant Frequency

The frequency of the $\mathrm{TM}_{010,\pi}$ mode for an ideal pill-box cavity is given by the relation [4] :

$$f_{010} = \frac{p_{01} \times c}{2\pi \times R} \quad (5)$$

with R the radius of the cavity and $p_{01} = 2.405$. Because of thermal expansion, the temperature changes the radius of the cavity and hence the frequency. An increase of the temperature of the gun will decrease the resonant frequency by :

$$\frac{df_{010,\pi}}{dT} = -\frac{p_{01}}{2\pi}\frac{c}{R^2}\frac{dR}{dT} = -\frac{p_{01}}{2\pi}\frac{c}{R^2}R_0\alpha \simeq -\frac{p_{01}}{2\pi}\frac{c}{R}\alpha \simeq -21.6 \quad \mathrm{kHz/^\circ C} \quad (6)$$

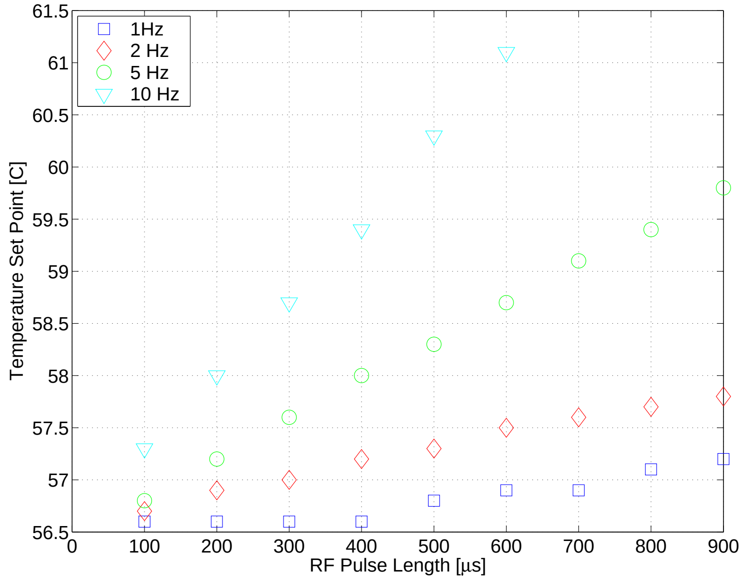
with : $R = R_0\left[1 + \alpha(T - T_0)\right]$, $\alpha = 16.8 \cdot 10^{-6}$ the thermal expansion coefficient of copper per degree and R_0 the radius of the pill-box at temperature T_0. From Equation 5, in order for the π-mode to resonate at 1.3 GHz then $R = 8.83 \times 10^{-2}$ m. An experimental check of this relation yielded to ~ -23 kHz/°C.

4. High Duty Cycle Operation

4.1 Up to 13.2 kW

Figure 3(a) shows the temperature set point versus the RF pulse length for an operation of the RF gun at 1 Hz, 2 Hz, 5 Hz and 10 Hz repetition rates and a forward power of 2.2 MW. Figure 3(b) presents the corresponding dependency of the water temperatures (incoming, set point and outgoing) with respect to the mean power. It is interesting to notice from these results that we had to increase the water set point temperature in order to decrease the temperature of the RF gun. In fact, while increasing the mean power into the RF gun the iris gets warmer than the cavity walls. During this experiment, the temperature sensor was located fully inside the iris hole and the set point temperature was the temperature of the iris (and not the temperature of the incoming water which was obviously decreasing while increasing the mean power).

(a)



(b)

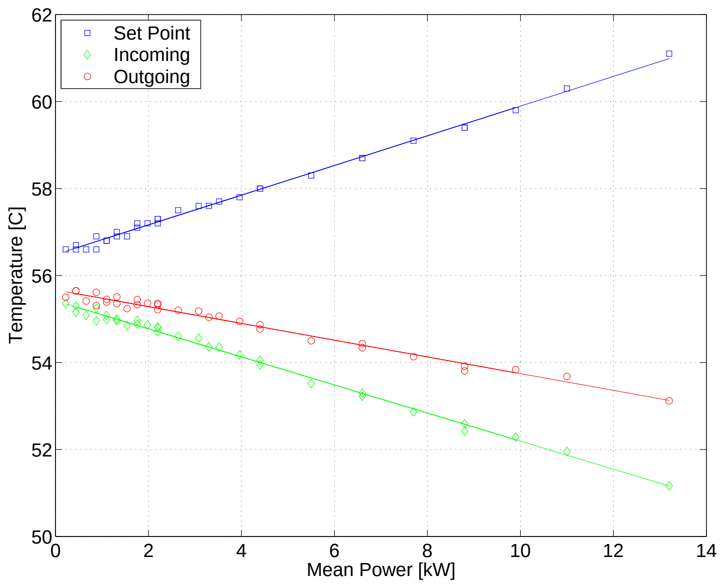


Fig. 3: (a) Temperature Set Point Versus RF pulse length for several repetition rates and a forward power of 2.2 MW and (b) temperatures (set point, incoming, outgoing) variations as a function of mean power.

We can see from Figure 3(b) that the water temperature has a linear dependency with respect to the mean power with a slope of -0.32 kW/°C for the incoming water temperature, -0.19 kW/°C for the outgoing and +0.34 kW/°C for the set point one. We had to stop our experiment at a pulse length of 600 μs, 10 Hz because it was not possible anymore to stabilize the incoming water temperature. It has been found [5] that the pressure of the cold water circuit was lower than the pressure of the warm one and that was the reason for which the water could not stabilize. Once this problem fixed, we could reach higher mean powers as presented in the sections 4.2 and 4.3.

While operating at 10 Hz, 2.2 MW and 500 μs corresponding to 11 kW of mean power, the incoming water temperature had to be set to 51.9°C in order to stabilize the resonant frequency of the cavity. The temperature of the outgoing water was then 53.7°C. Equation 7 indicates the power P necessary to increase the water temperature by ΔT:

$$P = \rho_{H_20} \cdot \dot{V} \cdot C_p \cdot \Delta T \tag{7}$$

with ρ_{H_20} = 1000 Kg·m^{-3} the density of water, $\dot{V}$ the volume flow rate, C_p = 4186.8 J·Kg^{-1}·K^{-1} the heat capacity of water. As we mentioned in the section 2.3, we did not have the possibility to measure the water flow rate during our experiments. According to Equation 7, the water flow rate must be in the order of $\sim$1.46 l·s^{-1} for 11 kW of dissipated power. The corresponding flow velocity is then : $\sim$0.88 m·s^{-1}.

The measured results presented in Figure 3(b) have also been simulated by the code ANSYS [6]. These simulations are presented in Figure 4 and show that in order to get a good agreement with the temperature of the measured water, the water flow velocity in ANSYS had to be set to $\sim$0.86 m·s^{-1}, close to our previous estimation. The water temperature in the ANSYS simulations is the mean of the measured incoming and outgoing water temperature.

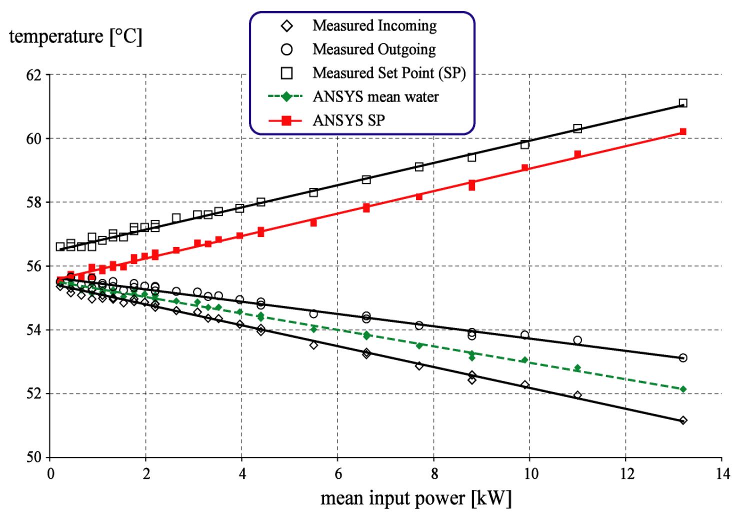


Fig. 4: ANSYS simulation of the temperatures (mean water temperature and set point) variations versus the mean power going into the RF gun. The water flow velocity in ANSYS is set to $\nu = 0.86$ m/s.

4.2 Up to 20 kW

Once the pressure of the two water circuits equalized at $\sim$6 bars (see section 4.1), we operated the RF gun remotely from DESY Hamburg up to $\sim$20 kW of mean power in order to check to stabilization of the water temperature.

We studied the behavior of the RF gun at 10 Hz, with a forward power of 2.2 MW and increasing the pulse length from 100 μs to 900 μs. The results, presented in Figures 5, are very similar to the ones from Figures 3 with a slope +0.35 kW/°C for the set point temperature, -0.36 kW/°C for the incoming water and -0.22 kW/°C for the outgoing water. As presented in Figure 5(a), for a mean power of 19.8 kW, the temperature had to be set to 64°C which is the maximum possible. In order to reach higher mean powers, we decided to sightly pull up the temperature sensor from the iris hole to get the temperature of the iris in a cooler point. More details are given in the following section.

Observation of the RF gun with an Infrared Camera

We looked at the RF gun with an infrared camera [2] while operating at 10 Hz, 2.2 MW and with a pulse length going from 100 μs to 800 μs. Picture 6 shows the RF gun body for a mean power of 17.6 kW (800 μs operation). As shown in this picture, we focussed our attention in three locations: the water channels, the iris and the half cell.

We did not observe any significant temperature changes in these three points of measurements while operating from 2.2 kW to 17.6 kW of mean power. In fact, for these conditions, the temperature of the water channels decreased from 45.9°C to 45.5°C, the one of the iris from 35.3°C to 34.1°C and the one of the RF gun body from 30.1°C to 28.9°C. We looked also with the infrared camera at three different locations in the waveguide for the same operating conditions and observed that its temperature remained constant at $\sim$30°C. These measurements confirmed the general good behavior of the RF gun for a mean power up to 20 kW.

4.3 Up to 27 kW

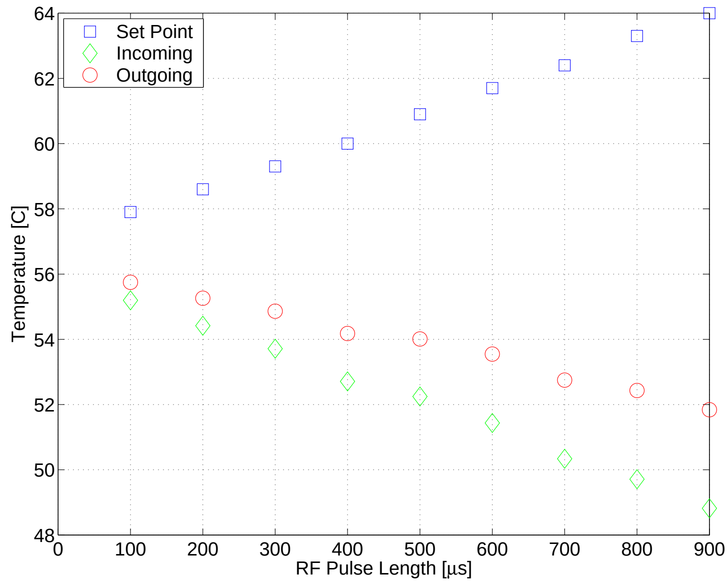
As mentioned in the previous section, to operate the RF gun with mean powers higher than 20 kW, we had to pull the temperature sensor slightly out of the iris hole in order to decrease the temperature set point. Another check showed that when the sensor was totally inserted, the temperature had to be set to 59.0°C to get stable operation at 2.2 kW of mean power (10 Hz, 100 μs and 2.2 MW) which was slightly higher than previous measurements (57.3°C from Figure 3(b) and $\sim$58°C from Figure 5(b)). We think this difference is due to an increase of the ambient temperature of the experimental area. Once the temperature sensor pulled 6 cm out ($\sim$1 cm still remaining inside the iris hole) then the temperature had to be set to 57.9°C to get stable operation for the same mean power. For this position of the sensor, we operated for several minutes the RF gun with a mean power of 27.0 kW (10 Hz, 900 μs and 3 MW). For these conditions, which fulfill the TTF2 specifications, the RF gun was still subject to vacuum interlocks which indicate that some more conditioning is still needed.

Stabilization

Figure 7(a) shows the stabilization of the water temperature and the corresponding reflected power while going from 800 μs to 500 μs and then from 500 μs to 200 μs. The forward power was of the order of 2.2 MW for a repetition rate of 10 Hz. For both cases, a large amount of reflected power ($\sim$800 kW) and two vacuum interlocks were detected during the stabilization of the temperature. Stable operation was reached within 5 minutes.

[2] GottFried Rampl Technology, type TVS-100.

(a)



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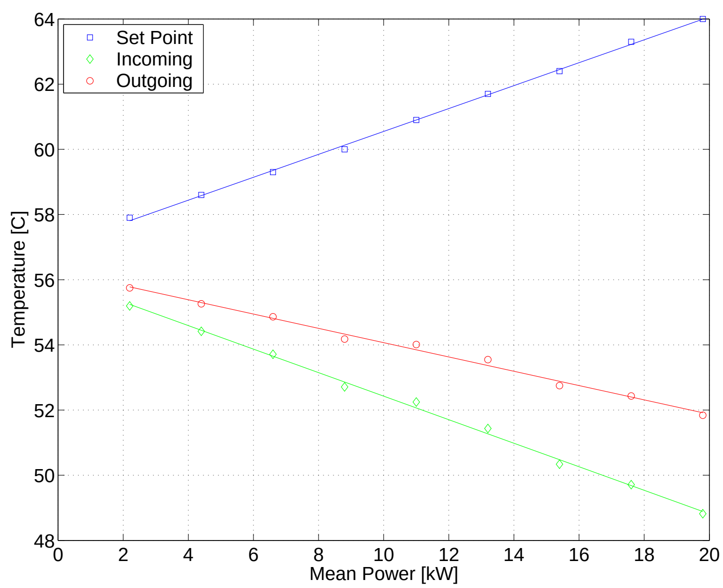

Fig. 5: (a) Temperature Set Point Versus RF pulse length for a forward power of 2.2 MW and 10 Hz repetition rate and (b) temperatures (set point, incoming, outgoing) variations as a function of mean power.

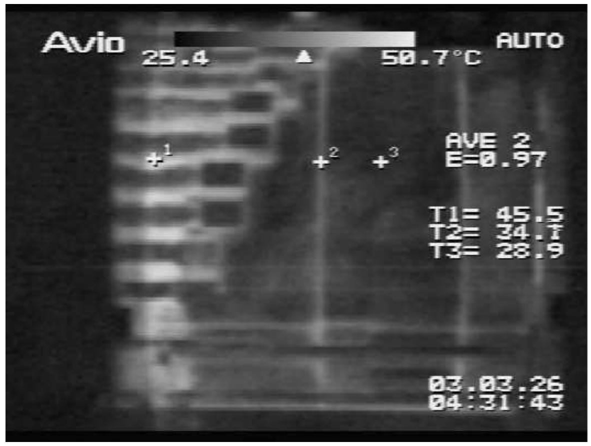

Fig. 6: Infrared camera observation of the RF gun.

The same experiment is presented in Figure 7(b) but while going from 200 μs to 500 μs and then from 500 μs to 800 μs. For the 200 μs to 500 μs step, the reflected power was measured in the order of 400 kW and stable operation was reached within 5 minutes without any interlocks. While going from 500 μs to 800 μs, the temperature had difficulties to stabilize and reflected power higher then 1 MW was detected leading to vacuum interlocks. For this case, the cavity took close to 20 minutes to stabilize.

From these studies we conclude first that the duty cycle of the RF gun should be changed in steps that avoid getting more than ~ 500 kW of reflected power (avoiding therefore reflected power interlocks) and second that it looks easier to warm up the RF gun rather than to cool it down.

5. Towards 50 Hz operation

Figure 8 shows ANSYS simulations of the temperature distribution in the RF gun for a mean power of 27 kW and a water velocity of 2 m$\cdot$s^{-1}. The iris of the front plane is the region with higher temperatures in the order of 70°C and the temperature at the photocathode is in the range of 60°C. This simulation confirms our experimental results : we expect the RF gun to operate at 27 kW without any problems.

The same simulation has been done for the case of 50 Hz operation (leading to a mean power of $\sim$130 kW) and a water velocity of 2 m$\cdot$s^{-1}. The iris of the front plane is then heated up to 170°C and the photocathode to 120°C. With its present cooling system, the corresponding stress analysis predicts stresses in the waveguide iris for such mean power in the order of 130 MPa which is above the 0.2% proof stress of OFHC copper (124 MPa). The operation of the RF gun at a repetition rate of 50 Hz would necessitate adding some more cooling channels in the back plane, front plane and the iris of the RF gun. Previous studies [7] showed that Cs_2Te photocathodes are able to operate at 120°C since their quantum efficiency does not decrease significantly while heated up to 130°C (from $\sim$3.8% at ambient temperature to $\sim$3.5% at 130°C).

6. Conclusion

The TTF2 RF gun has been successfully tested at the Photo Injector Test Facility of DESY Zeuthen for a maximum mean power of 27.0 kW, corresponding to an operation at 10 Hz repetition rate, with 3 MW of forward power and a pulse length of 900 μs. For these conditions which fulfill the TTF2 specifications, the RF gun was still subject to vacuum interlocks which indicate that some more RF conditioning is still needed at this power. A good agreement between our measurements of the heat taken by the cavity and

(a)

(b)

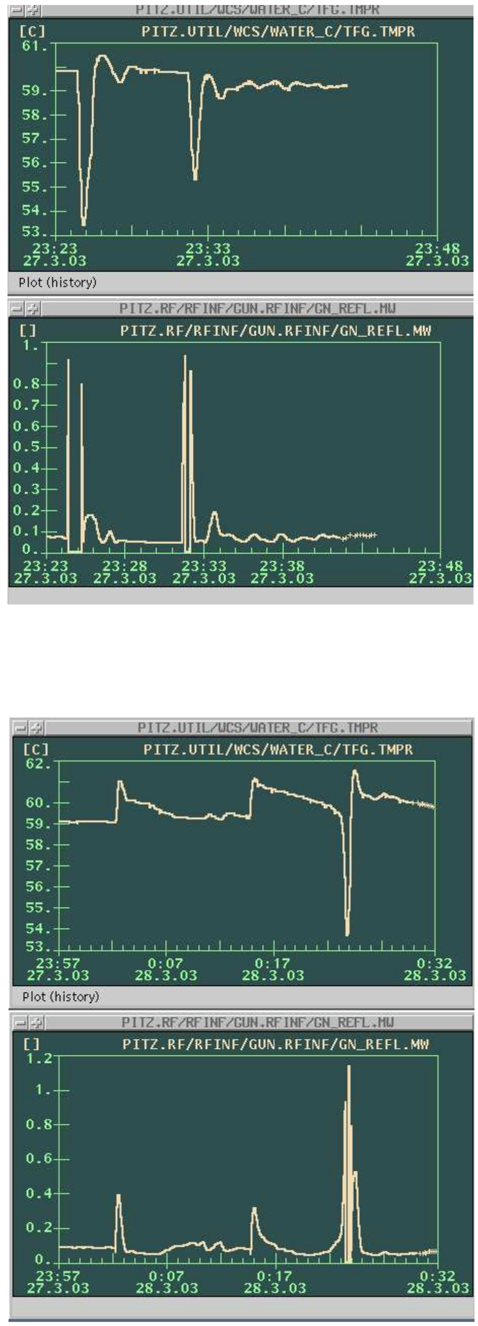

Fig. 7: Stabilization of the temperature of the RF gun and corresponding reflected power while going from (a) 800 μs to 500 μs to 200 μs and (b) 200 μs to 500 μs to 800 μs. The forward power was 2.2 MW and 10 Hz repetition rate were used.

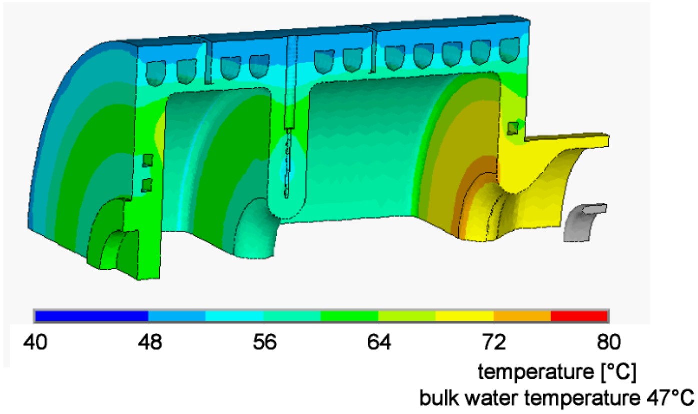

Fig. 8: ANSYS simulations of the temperature distribution in the RF gun for 27 kW of mean power.

ANSYS simulations was found for a water velocity of $\sim$0.86 m$\cdot$s^{-1} corresponding to a water flow of $\sim$1.43 l$\cdot$s^{-1}. We did not have sufficient time to operate the RF gun above 27 kW. Nevertheless, due to the excellent behavior of the RF gun up to now we do not expect any major problems for an operation slightly above 27 kW of mean powers. These predictions are supported by ANSYS simulations. If the average RF power gets significantly higher (in the order of 100 kW), then ANSYS simulations indicate that an improved water cooling is required, especially at the waveguide iris.

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