FAST AUTOMATIC RAMPING OF HIGH AVERAGE POWER GUNS

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Abstract

The electron guns at PITZ, FLASH and European XFEL are standing wave structures which operate at high average power (>40 kW) to produce long trains of high quality beams. This amount of power heats the cavity surface enough to change significantly the gun resonance frequency. As consequence, to keep the reflection low, the RF power ramp must be enough slow to permit the water cooling system to keep the gun temperature close to the set-point. Also, as the temperature probe sits close to the surface of the iris, the required gun temperature set-point to maintain the gun on resonance is a function of the average power. The RF power ramping is a difficult process in which temperature and reflection must be monitored to adjust accordingly the temperature set-point and the ramping speed of the RF power.

An automatic software to adjust the RF frequency and the temperature set-point of the PITZ gun in parallel to the RF power ramping has been developed. The use of this software has significantly reduced the time spent to start up the gun or to recover from interlocks, increasing the time spent at nominal parameters which would also be very important for user facilities.

NORMAL CONDUCTING CAVITY OPERATION

The reflection coefficient (ratio of the reflected power P_{ref} over the forward power P_{forw}) for a resonant cavity (with a resonance frequency f_0) fed by RF with a frequency f is [1]:

$$\frac{|P_{ref}|}{|P_{forw}|} = \frac{(\beta-1)^2 + (2\frac{\Delta f}{f}Q_l)^2}{(\beta+1)^2 + (2\frac{\Delta f}{f}Q_l)^2} \tag{1}$$

where β is the mismatch parameter which depends on the tuning of the coupler, Q_l is the cavity loaded quality factor and $\Delta f = f - f_0$ is the detuning. To protect the klystron, the reflected power from cavities has to be kept low (typically much below 2 MW). It means that the resonant frequency must be kept close to the RF frequency.

The temperature of the cavity is controlled to maintain the resonance frequency close to the RF frequency, as due to thermal expansion, the resonant frequency of a cavity has a linear relation with the temperature of the cavity. d is the coefficient relating the frequency shift to the temperature. Fig. 1 shows the reflection function of the cavity temperature T_c for an example cavity. T_0 is the temperature of the cavity at which the resonance frequency matches the RF frequency. The side of the curve with $T_c > T_0$ is called over-heated cavity, he side of the curve with $T_c < T_0$ is called over-cooled cavity and when $T_c = T_0$ the cavity is called on-resonance.

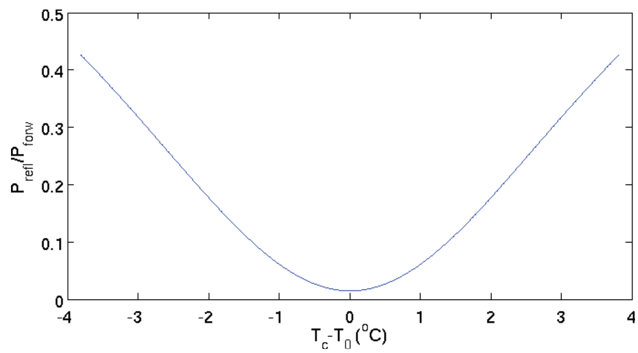

Figure 1: Reflection coefficient function of the cavity temperature with $Q_l = 12264$, $d = -21\,\mathrm{kHz\,°C^{-1}}$ and $\beta = 0.7837$ (values taken from [2]).

In case of an over-cooled or on resonance cavity, without RF feedback, a small decrease in temperature will increase the reflection, which will decrease the power in the cavity, which will further decrease the temperature: such operation is unstable. On the other hand, over-heated cavities are stable, so normal conductive cavities are usually operated slightly over-heated.

CAVITY TEMPERATURE CONTROL

During high average power operation of a normal conductive cavity, all the power going to the cavity is converted to heat by ohmic loss, so it is necessary to cool the cavity. The cavity is cooled with water passing through channels inside the body of the cavity. The temperature of the cavity is regulated by the Water Cooling System (WCS) to limit the resonant frequency variation, using a temperature sensor within the cavity body. The WCS and its modeling is presented in [3]. Because of the cavity cooling, there is a temperature gradient between the inner surface of the cavity (where the RF heating takes place) and the cooling pipes in the cavity body:

$$T(z) = T_w + \frac{z}{L}(T_c - T_w) \tag{2}$$

where $T(z)$ is the temperature inside the cavity body at a distance z from the cooling channel, T_w is the cooling water temperature, L is the distance between the cooling channel and the inner surface of the cavity and T_c is the temperature of the surface of the cavity. Equation 3 (1D Fourier's law) represents the average power P_{avg} fed to the cavity:

$$P_{avg} = kA\frac{T_c - T_w}{L} \tag{3}$$

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with k the material conductivity and A the area of the inner surface. The temperature sensor is placed in the cavity body at a position $0 < l < L$. Using $T_s = T(z = l)$ as the temperature measured by the sensor and kept constant by the WCS, we get:

$$T_s = \text{const.} = T_c - (L - l)\frac{P_{avg}}{kA} \quad (4)$$

The equation shows that T_c is independent from the power only when the sensor is on the surface of the cavity ($l = L$). However, that is not possible as the sensor has to be shielded from RF, so the sensor is typically placed as close as possible to the surface. Due to that, there is a small linear residual temperature variation of the cavity surface with power which translates into a small linear frequency shift. As consequence, while changing the power fed into a normal conducting cavity, the temperature set-point of the WCS has to be adjusted. Also the variation of power must be slow enough to allow the WCS to regulate the temperature of the cavity and prevent large reflection or over-cooled operation.

FAST AUTOMATIC RAMPING

In a high average power normal conducting cavity, ramping the RF power involves changing both the power and the temperature set-point while monitoring the reflection. Such a procedure is error prone and quite long (typically > 30 minutes to recover the PITZ gun after an interlock). Therefore, there was a strong motivation to automatize and speed up that procedure.

Fast ramping procedures have been proposed which change the RF frequency to follow the resonance frequency [4]. Such procedures have shown reduced ramping time down to ~5 min but they were limited to the recovery of previous operating states (peak power and pulse length) after an interlock as they were not able to determine the right temperature set-point for the WCS.

A new fast automatic ramping procedure has been developed which is independent of the present and goal operating state. In the new procedure, the temperature set-point of the WCS is continuously adjusted for slightly overheated operation during the ramping.

Fig. 2 and Fig. 3 shows the power in the gun and the reflected power during ramping to nominal parameters at PITZ. Fig. 2 shows it with manual ramping and Fig. 3 with automatic fast ramping. The automatic procedure is clearly faster and the reflected power is kept smaller.

After an interlock, the WCS continues to cool the cavity for several seconds while no power is deposited, so the cavity temperature drops steeply (typically ~10 °C when the average power was 42 kW, see Fig. 2). The cavity is then totally out of resonance. So, with manual ramping, RF power cannot be used to heat the cavity up and it was needed to wait 5 min to 10 min for the WCS to heat the cavity close to resonance. As the fast ramping procedure sets the RF frequency to the cavity's resonance frequency, ramping can be started right away (see Fig. 3).

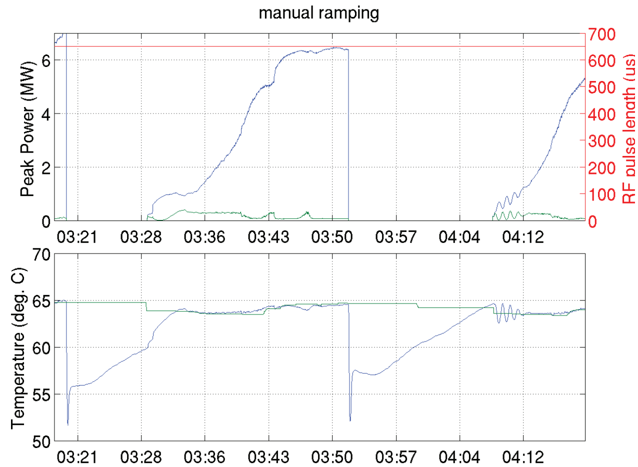

Figure 2: Manual ramping from 0 kW to 42 kW on 16/07/2016. 1 h interval is shown. In the top plot, the blue line is the power in the gun, the green line is the reflected power and the red line is the RF pulse length. In the bottom plot, the blue line is the temperature of the cavity, and the green line is the WCS temperature set-point. Temperature must be kept close to resonance temperature to have power in the gun.

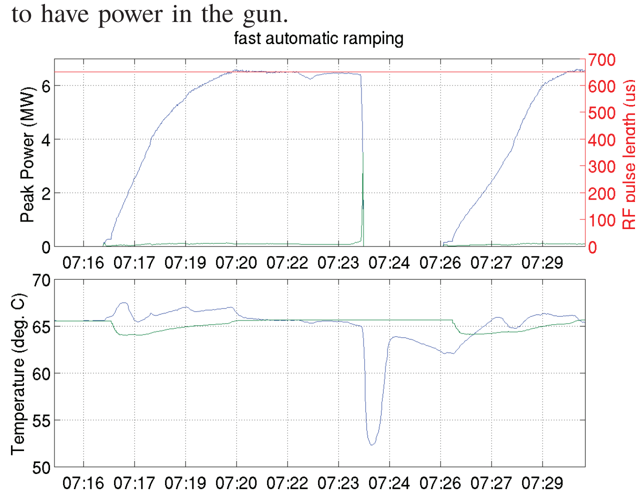

Figure 3: Fast automatic ramping from 0 kW to 42 kW on 26/01/2017. 15 min interval is shown. See Fig. 2 description for the color code.

FEEDBACK ON FREQUENCY DETUNING

To measure the frequency detuning, the slope of the phase of the reflected power at the end of the RF pulse is used. As there is no forward power anymore at that time, the electric field is freely oscillating at the resonance frequency and, as the RF pickups are tuned for the nominal RF frequency, the detuning appears as a slope on the phase. That method allows a precise detuning determination at the end of the RF pulse:

$$\Delta f_{endRF} = \frac{d\Phi}{2\pi dt} \quad (5)$$

with Φ the phase of the reflected power just after the end of the RF pulse and Δf_{endRF} is the detuning at the end

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of the RF pulse. However, due to pulse heating [5], the frequency detuning is linearly decreasing within the RF pulse and the slope is proportional to the RF peak power:

$$\Delta f(t) = \Delta f_{endRF} + B(T_{RF} - t)P_{peak} \quad (6)$$

with $\Delta f(t)$ the detuning within the RF pulse, B is a coefficient to be experimentally determined, T_{RF} is the length of the RF pulse and P_{peak} is the peak power in the gun (constant within the RF pulse). Using the previous equation, the average frequency detuning $< \Delta f >$ can be determined within the RF pulse:

$$< \Delta f(t) >= \Delta f_{endRF} + BT_{RF}P_{peak}/2 \quad (7)$$

To determine the B coefficient, the detuning at the end of the RF pulse has been measured (using Eq. 5) for different pulse lengths and peak powers, while keeping a constant reflection (equivalent to a constant average detuning). Experimental measurements at PITZ are shown in Fig. 4 for gun 4.6 and give $B = 0.135 \times 2 \times 10 = 2.7\,\mathrm{kHz\,kW^{-1}}$ since $P_{avg} = P_{peak}T_{RF} \times 10\,\mathrm{Hz}$.

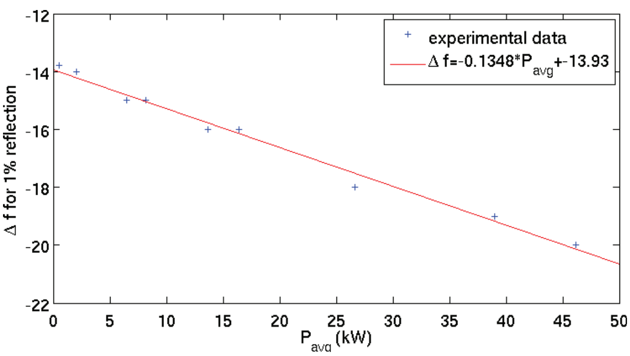

Figure 4: Frequency detuning (in kHz) at the end of the RF pulse for different average power in the gun (P_{avg}) while keeping 1% reflection.

While doing the fast ramping, the frequency detuning is measured at the end of the RF pulse according to Eq. 5, the average frequency detuning $< \Delta f >$ is calculated according to Eq. 7 and the frequency of the RF is shifted by δf to have a slightly overheated gun (typically $< \Delta f >_{goal} = 0.2 Q_l$ for $\sim 1\%$ reflection):

$$\delta f =< \Delta f >_{goal} - < \Delta f > \quad (8)$$

The RF frequency shift is introduced by setting a slope on the phase during the RF pulse. As the detuning is calculated just after the end of the RF pulse, the frequency shift applied to the RF does not affect the detuning calculation.

For very low power (<100 kW) and large detunning ($|T_c - T_0| > 5\,°\mathrm{C}$), the described detuning determination may fail due to a too weak signal. More advance methods to measure detuning could be used instead [2].

DETERMINATION OF TEMPERATURE SET-POINT FOR THE WCS

Assuming a linear thermal expansion and a linear relation between the cavity expansion and its resonant frequency, the temperature detuning is proportional to the average frequency detuning. The resonance temperature can then be calculated from the current cavity temperature T_s and from the average frequency detuning:

$$T_0 = T_s - \frac{< \Delta f >}{d} \quad (9)$$

By setting the temperature set-point of the WCS to:

$$T_{goal} = T_0 + \frac{< \Delta f >_{goal}}{d} \quad (10)$$

when the temperature of the cavity T_s reaches T_{goal} the frequency shift introduced by the feedback (FB) goes to 0:

$$\begin{aligned} \delta f &=< \Delta f >_{goal} - < \Delta f > \\ &=< \Delta f >_{goal} - d(T_s - T_0) \\ &=< \Delta f >_{goal} - d(T_{goal} - T_0) \\ &= 0 \end{aligned} \quad (11)$$

The new fast ramping procedure can be summarized as follow:

- start FB on RF frequency and wait for stable reflection.
- start FB on temperature set-point and ramp power.
- wait until the temperature is stable and stop FBs.

CONCLUSION

In high average power normal conducting cavities, a method to control the reflection while fast ramping has been described. Also determination of the temperature set-point for the WCS has been shown. That fast power ramping method has been used at PITZ for the last year and has proven to be much more reliable and fast than manual ramping. It has been very valuable especially for the conditioning of the gun when typically tens of interlocks per day can occur.

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