OPTIMIZATION OF FILLING PROCEDURE FOR TESLA-TYPE CAVITIES FOR KLYSTRON RF POWER MINIMIZATION FOR EUROPEAN XFEL

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Abstract

The Free Electron Laser in Hamburg (FLASH) [1] is a user facility providing high brilliant laser light for experiments. It is also a unique facility for testing the superconducting accelerator technologies. FLASH cavities are operating at pulsed mode. There is a filling stage to build the RF voltage in the cavities and then follow a flattop for beam operation. By the limitation of the klystron pulse length the filling time of the cavities is limited to several hundred microseconds. In order to fill the cavities to the dedicated voltage usually large RF power is required for the filling stage. For European XFEL [2] during RF operation the klystrons will be working quite near the saturation point for better efficiency. So lowering the unnecessary klystron peak power under closed loop operation is very important for close-limitation operation. The paper will present the method which allows decreasing the required klystron peak power as well as the reflected power by filling the cavity in resonance. Simulation results will be presented as well as experimental demonstrations at FLASH.

OPTIMIZATION OF CAVITY FILLING PROCEDURE

Cavity Detuning

Filling of the cavity requires to obtain a defined cavity voltage during a defined period with RF power.

If the cavity is detuned, the cavity voltage during filling stage has an oscillation with the frequency same as the detuning, and more RF power is required to obtain the same cavity voltage during the same filling period.

Figure 1 shows the cavity filling with different detuning by simulation. The cavity parameters and driving power have been shown on the figure. For 400Hz detuning, as an example, after 500µs filling, the cavity gradient will be 7% lower than the resonance filling case.

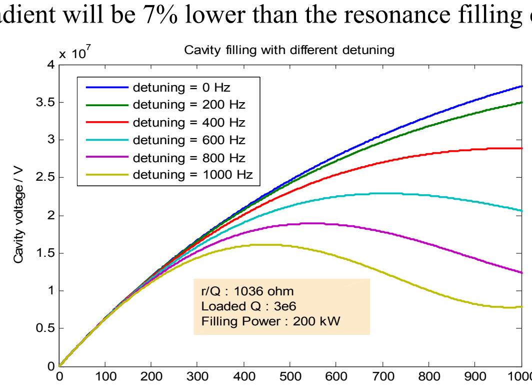

Figure 1: Cavity filling with different detuning.

The FLASH cavities have a typical detuning of several hundreds Hz, see Figure 2, which are the measurements of the detuning for accelerating modules 2 and 3 cavities.

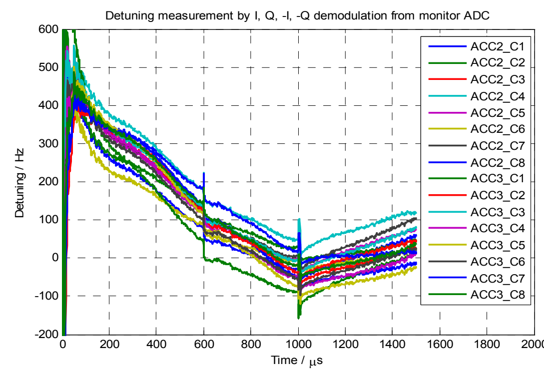

Figure 2: Detuning measurement at FLASH accelerating modules.

To compensate the detuning effect, we can modulate the phase of the filling RF power to track the cavity resonance frequency.

The vector sum of the cavities driven by the same klystron can be viewed as the output of an effective single cavity. The detuning of this effective single cavity can be measured by system identification algorithm, which has a similar shape as the single cavity detuning curve shown in Figure 2.

Assume the detuning is measured as $\Delta\omega(t)$ during the RF pulse, so, in order to perform resonance filling, the phase modulation of the feed forward table and set point table during filling stage should be

$$\Delta\phi(t) = \int_0^t \Delta\omega(\tau)d\tau \,. \qquad (1)$$

Loaded Q and Filling Time

The required RF power during filling stage can be presented as

$$P_{fill} = \frac{V_0^2}{4\left(\frac{r}{Q}\right)Q_L \cdot \left[1 + e^{-\frac{\omega_0 T_{fill}}{Q_L}} - 2e^{-\frac{\omega_0 T_{fill}}{2Q_L}}\right]} . \qquad (2)$$

where V_0 is the desired cavity voltage, r/Q is the shunt impedance, Q_L is the loaded quality factor, ω_0 is the working frequency of the cavity and T_{fill} is the filling time. The cavity detuning is assumed to be zero in equation (2).

By carefully adjusting the loaded Q of the cavity and the filling time, the required klystron RF power during filling stage can also be reduced.

The loaded Q of the cavity will influence both the time constant of the cavity and the power coupling factor into the cavity. The trade-off between these two effects will lead to an optimized loaded Q for minimizing the filling power [3].

Extending the filling time also allows to reduce the required RF power, but it is limited by the klystron maximum available RF pulse length.

Figure 3 shows the RF filling power for different loaded Q and filling time for the desired cavity voltage of 35MV.

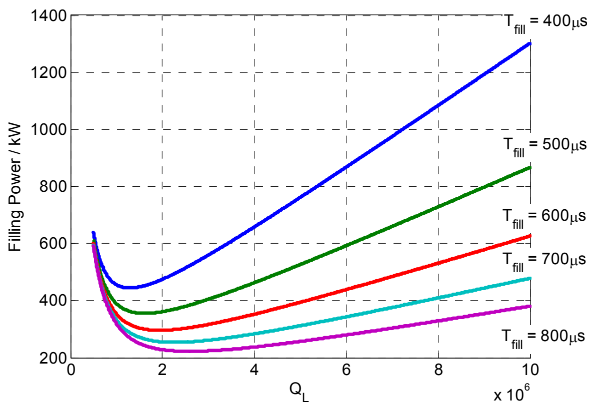

Figure 3: RF filling power for different loaded Q and filling time.

Resonance Filling Test at FLASH

The resonance filling method was tested at FLASH. The low level RF controller server [4] has been extended to allow regeneration of the control tables according to operation settings and required shape of feed forward and set point tables in amplitude and phase (see Figure 4). As approximation, the phase of the feed forward and set point tables was modulated as an exponential function of

$$\varphi(t) = \Delta\varphi\left(1 - e^{-\frac{t}{\tau}}\right). \tag{3}$$

where $\Delta\varphi$ is the phase offset and τ is the time constant.

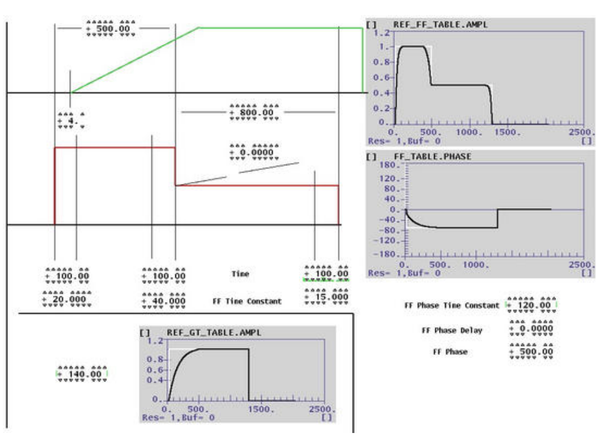

Figure 4: Advanced table generation for resonance filling.

Different phase modulation parameters were chosen to optimize the filling procedure so that the vector sum voltage was maximized for constant RF power. Figure 5 shows the results with different phase offset and time constant.

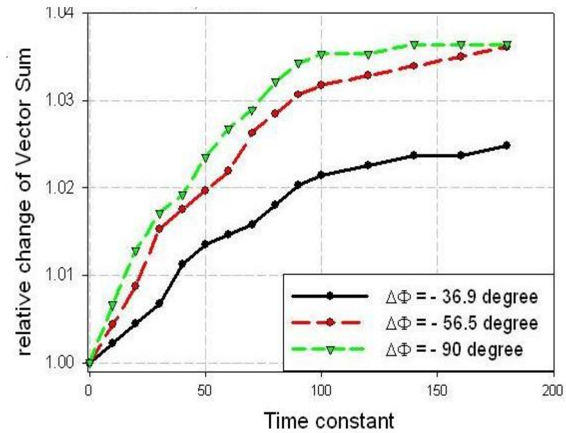

Figure 5: Resonance filling parameters optimization.

For the best case, the energy gain of the RF station was increased by about 3% with the resonance filling method (see Figure 6).

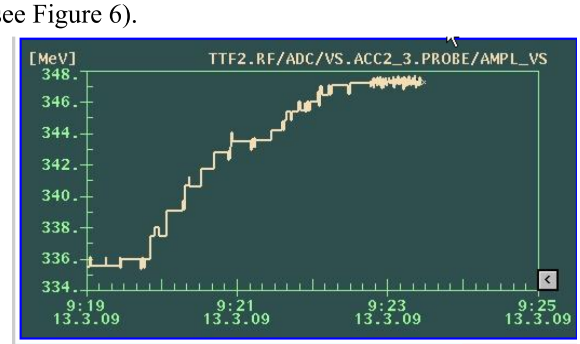

Figure 6: Energy gain increase by phase modulation.

With optimized phase modulation parameters, the cavity reflected power can also be reduced. Figure 7 shows the reflection power of different cavities as a function of the time constant of the phase modulation.

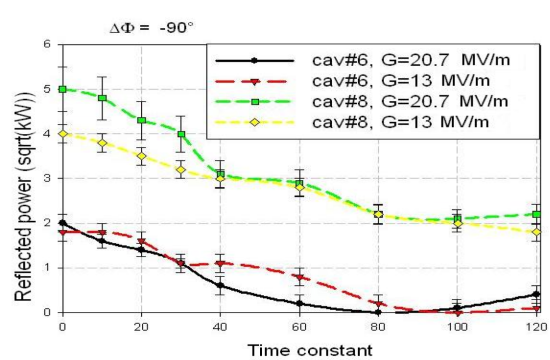

Figure 7: Minimization of reflected power.

VARIABLE GAIN EFFECTS

The low level RF control loop has a typical loop delay of several hundred nanoseconds to several microseconds. And because of the delay, when the feedback gain is large, there will be an overshoot on the driving signal at the start of the RF pulse (see Figure 8).

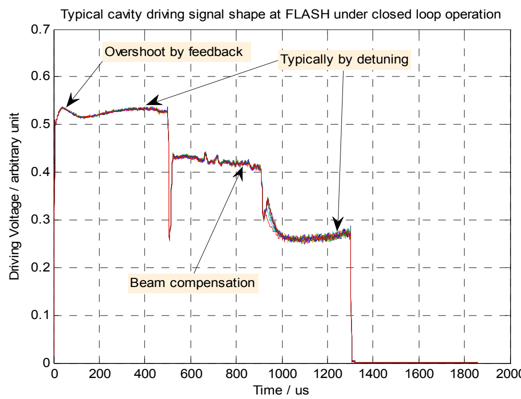

Figure 8: Typical cavity driving signal at FLASH under closed loop operation.

To solve this problem, the feedback gain can be set smaller at the start of the RF pulse, and then ramp to the designed value, this is the so-called gain scheduling.

The figure below shows that the forward power is smoothed by adjusting gain values in several portions of the table. Feedback loop was running with gain of 100 without significant oscillations. Peak forward power was reduced by about 15% during the cavity filling stage.

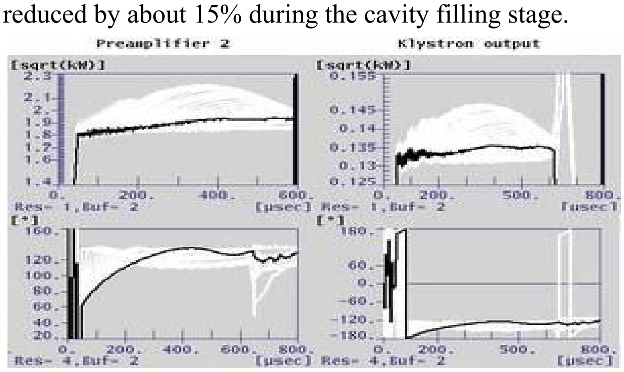

Figure 9: Reduction of peak forward power by gain scheduling during filling time.

SUMMARY

For managing the RF power required for LLRF control, the loaded Q and filling time can be decided by the desired cavity voltage, beam current and beam phase.

The set point phase and feed forward phase can be modulated to track the cavity detuning during filling stage. Feedback gain can be scheduled (ramping gain during filling) to reduce the power overshoot at the RF pulse start.

With the optimization of the cavity filling procedure, the reflected power was reduced significantly, and the cavity gradient/energy gain was increased by about 3% with the same forward RF power.

Reduction of around 15% peak forward power required for feedback regulation during filling time was achieved with the gain scheduling. And the feedback loop was operated with relatively high gain (100) without significant oscillations.

More stable operation of the klystron against interlock trips has been achieved by reducing the reflection power and peak power.

FUTURE PLANS

Future plans include:

- Study the effects on beam and SASE stability
- Study the effects on different gradient levels with optimum pre-detuning
- Implement and apply for all modules. It is more important for multi-beam klystron since high voltage rise time is about two times longer (~200µs)
- Continue improvements for full beam loading experiment.

REFERENCES

[1] http://flash.desy.de

[2] http://www.xfel.eu

[3] T. Schilcher, "Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities", DESY, TESLA 98-20 (1998)

[4] V. Ayvazyan et al, "Digital RF Control System for DESY FLASH Linear Accelerator", EOROCON'07, Warsaw, Poland, September 2007, pp. 1178-1185 (2007)