DESY SUMMER STUDENT PROGRAM 2009

Klystron forward power minimization for optimal RF field control at FLASH accelerator

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Content

1. Introduction

During DESY Summer student 2009 program I was working in Accelerator division at FLASH (**F**ree-electron-**LAS**er in **H**amburg) superconducting linear accelerator.

FLASH (figure 1) is designed to accelerate electrons to energy up to 1GeV. The electron bunches are produced in a laser-driven photoinjector, which consists a 1.5-cell RF cavity (gun) with laser-driven photocathode in a operating at 1.3GHz. The peak accelerating field is 46MV/m on the cathode. The electron injector section is followed by a total of six accelerating modules (ACC). Each ACC contains eight 9-cell superconducting niobium cavities. For RF generation there are 5MW klystrons for RF Gun, ACC1, ACC2,3 and a 10MW klystron for ACC4,5,6. With the accelerated electrons a free electron laser will produce coherent, monochromatic light in an undulator. The 30m long undulator consists of NdFeB permanent magnets with a fixed gap of *12mm*, a period length of 27.3mm and peak magnetic field of 0.47T. The wavelength of the light depends on the energy of the accelerated electrons. It can be tuned between 6.5nm and 60nm.

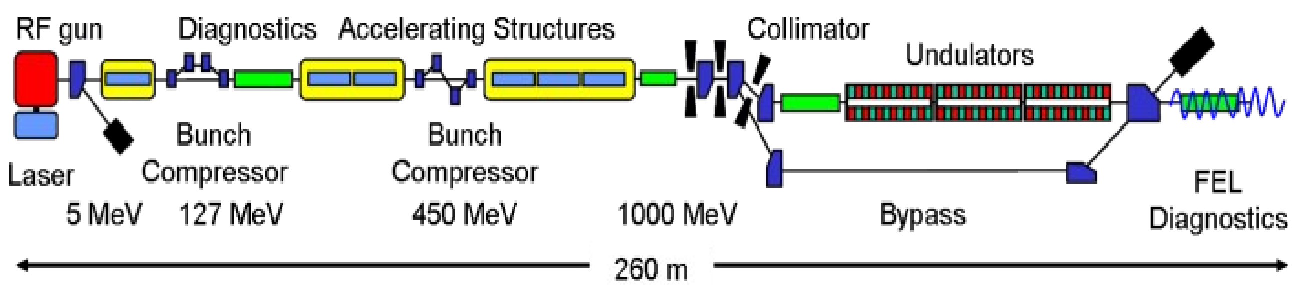

Fig. 1. Layout of FLASH.

The FLASH cavities operate in pulsed mode. The maximum RF pulse length is 1,3ms. There is a filling stage to build up the RF voltage in the cavities (500µs) and then a flattop for beam acceleration follow (800µs). By the limitation of the klystron pulse length, the filling time of the cavity is limited to several hundred micro-seconds. In order to fill the cavity to the dedicated voltage, it usually needs larger RF power for the filling stage.

In my work, I tried to find out which parameters influence the klystron peak power. It is possible to minimize the necessary klystron peak power by choosing cavity parameters in a right way.

2. Theory of superconducting RF cavities *

2.1. Cavity coupled to RF generator

Resonant mode in cavities can be described by means of resonant LCR circuits. To feed the cavity with RF power, an input coupler is necessary. Building a linear accelerator with single-cell cavities would be very expensive and it would require a great deal of effort to equip every cavity with a separate coupler. Therefore, several cells are coupled weakly to a coupled-resonator structure with a single RF feed point. The coupling from cell to cell can be magnetic or electric. The resonator in FLASH (TTF) consist of nine electrically coupled cells and is usually called cavity.

An RF field induces surface currents in the cavity walls resulting in power dissipation P_{diss} . Modeling a resonant cavity by an LCR circuit, the resistor R is defined as a resistor in which the same power is dissipated as in the cavity.

$$P_{diss}=\frac{1}{2}\cdot\frac{V_{cav}^2}{R} \tag{2.1}$$

Our RF power source is a klystron. The coupling from the output cavity of the klystron to the transmission line and from the transmission line to the cavity are represented by lossless transformers. The input coupler of the cavity has a transformation ratio of 1:N. The transformation equations are

$$V_2 = N\cdot V_1 \qquad\qquad I_2 = \frac{1}{N}\cdot I_1 \tag{2.2}$$

and therefore input and output impedance are related by

$$Z_2=N^2\cdot Z_1 \tag{2.3}$$

The transformation line can be a waveguide or a coaxial cable. In the transformation line, forward and backward traveling waves occur due to mismatches of the input and output impedances.

*Here I have not done some calculations, one can find those in T. Schilcher's dissertation [1]

2.2 General cavity equations

Since the cavity is a resonant device, it is useful to define a measure for its quality, the so-called quality factor Q defined as

$$Q = 2\pi \frac{\text{stored energy in cavity}}{\text{dissipated energy per cycle}} = \frac{\omega_o W}{P_{diss}} \tag{2.4}$$

where W is the stored energy, ω_o is the resonance frequency, and P_{diss} the dissipated power. When only losses occurring in the cavity walls caused by the RF surface resistance (which are also present for superconducting materials) are taken into account, one arrives the unloaded quality factor Q_0.

$$Q_0 = \frac{2\pi}{T} \cdot \frac{\frac{1}{2} C V_0^2}{\frac{1}{2} \frac{V_0^2}{R}} \tag{2.5}$$

where V_0 is the amplitude of the oscillating voltage and T the time period of an RF cycle. In terms of the resonance frequency of an undamped LC circuit, the Q_0 can be expressed as

$$Q_0 = \omega_0 RC = \frac{R}{L\omega_0} = \frac{\omega_0 W}{P_{diss}} \tag{2.6}$$

Energy is not only dissipated in the cavity walls but also extracted through the power coupler and dissipated in an external load. An external quality factor Q_{ext} is defined as

$$Q_{ext} = 2\pi \frac{\text{stored energy in cavity}}{\text{dissipated energy in external devices per cycle}} = \frac{\omega_o W}{P_{ext}} \tag{2.7}$$

where P_{ext} is the dissipated power in all external devices. Finally, the loaded quality factor Q_L is defined as

$$Q_L = 2\pi \frac{\text{stored energy in cavity}}{\text{total energy loss per cycle}} = \frac{\omega_o W}{P_{tot}} \tag{2.8}$$

Energy conservation yields

$$P_{tot} = P_{diss} + P_{ext} \tag{2.9}$$

and with equations (2.6), (2.7) and (2.8)

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \tag{2.10}$$

For superconducting cavities, the loaded Q_0 is more larger then the external Q_{ext}, so $Q_L \approx Q_{ext}$.

$$\frac{1}{R_L} = \frac{1}{R} + \frac{1}{Z_{ext}} \tag{2.11}$$

The load Z_{ext} is a real quantity. From equation (2.6) we obtain

$$\frac{R}{Q_0} = \omega_o L = \frac{1}{\omega_0 C} = \sqrt{\frac{L}{C}}$$

The ratio $\frac{R}{Q_0}$ only depends on quantities L, C and ω_0. It is characteristic of the geometry of a cavity and independent of the surface resistance.

$$\frac{r}{Q} = \frac{R_{sh}}{Q_0} = \frac{2 \cdot R}{Q_0} \tag{2.12}$$

Instead of the transformation ration 1:*N*, it is useful to describe the coupling between transmission line and cavity by so-called coupling factor β. This factor is defied as the ratio of resistor *R* in the LCR circuit to the transformed external load Z_{ext}

$$\beta = \frac{R}{Z_{ext}}, N = \sqrt{\frac{R}{\beta Z_0}} \tag{2.13}$$

With this definition, equation (2.11) can be written as

$$R_L = \frac{R}{1+\beta} \tag{2.14}$$

and therefor

$$Q_L = \frac{Q_0}{1+\beta} \tag{2.15}$$

For superconducting resonators with $Q_0 \gg Q_L$, the coupling factor is in the order of 10^3 to 10^4 .

Taking the 9-cell TESLA cavity as an example, we get for the stored energy at $V_{cav} = 25\text{MV}$, $(\frac{r}{Q}) = 1040\,\Omega$ and $f = \frac{\omega}{2\pi} = 1.3\,GHz$

$$W = 73{,}5\,J$$

Inserting in the Kirchhoff's rule the formulas $\dot{I}_L = V/L\,;\,\dot{I}_R = \dot{V}/R_L\,;\,\dot{I}_C = C\,\ddot{V}$ and replacing the inductance *L* and capacitance *C* by the quantities Q_L and ω_0 , we obtain the differential equation for a driven LCR circuit.

$$\begin{aligned}\ddot{V}(t) + \frac{1}{R_L C}\dot{V}(t) + \frac{1}{LC}V(t) &= \frac{1}{C}\dot{I}(t)\\ \ddot{V}(t) + \frac{\omega_0}{Q_L}\dot{V}(t) + \omega_0^2 V(t) &= \frac{\omega_0 R_L}{Q_L}\dot{I}(t)\end{aligned} \tag{2.16}$$

The bandwidth $\omega_{1/2}$ of a loaded cavity is defined as the frequency bandwidth where the voltage drops to $1/\sqrt{2}$ of a maximum $\hat{V}_0 = R_L \hat{I}_0$. The stored energy therefore drops by half. For bandwidth one can get

$$\omega_{1/2} = \frac{\omega}{2\text{Q}_L} \tag{2.17}$$

2.3. Cavity with beam loading

The beam is represented by an additional current generator. A bunched beam provides a pulsed current. We have to use the Fourier component I_b of the beam current at the frequency ω .

For bunches, whose bunch length is much shorter than the bunch spacing, the Fourier component $|I_b|$ is twice the DC beam current I_{b0}. It is possible to represent the pulsed beam current by an RF current generator with frequency ω if the beam frequency and hence the bunch spacing is synchronized to the same reference frequency as used for the RF generator. Moreover, the bunch length has to be much smaller than the characteristic time constant τ of the cavity.

The beam current I_b' causes a voltage in the transmission line at Z'_{cav}. This leads to a wave which propagates in backward direction along the transmission line and interferes with the reflected wave which would exist without beam loading. To accelerate beam on-crest, the phase between the cavity voltage and the beam current is π. In that case, the beam power is negative, which is equivalent to extracting the energy from the cavity by the beam. The beam phase is usually defined as being the difference to this phase π. Currents are represented as a complex quantities. They have to be added even if phase difference is π because phase information already included.

In case of superconducting cavities ($\beta \gg 1$), the generator power is calculated to

$$P_g = \frac{V_{cav}^2}{(\frac{r}{Q})Q_L}\frac{1}{4}\left(\left[1+(\frac{r}{Q})Q_L\frac{I_{b0}}{V_{cav}}\cos\phi_b\right]^2+\left[\frac{\Delta f}{f_{1/2}}+\frac{(\frac{r}{Q})Q_L I_{b0}}{V_{cav}}\sin\phi_b\right]^2\right) \tag{2.18}$$

The quantity $f_{1/2}$ is the bandwidth of the cavity. The two special cases exist.

- $V_{cav}=25\text{MV}, Q_L=3\cdot 10^6$; no beam:

$$P_g = 50\text{kW}\left(1+(\Delta\frac{f}{f_{1/2}})^2\right)$$

- $V_{cav}=25\text{MV}, Q_L=3\cdot 10^6; I_b=8\text{mA}; \phi_b=0^o$ (on-crest):

$$P_g = 50\text{kW}\left(4+(\Delta\frac{f}{f_{1/2}})^2\right)$$

Detuning the cavity by one bandwidth increase the required power by 25%. In storage rings, it is necessary to operate the cavities off-crest by an angle of Φ_b to guarantee stability with respect to synchrotron oscillations. In linear accelerator, it can also be necessary to inject beam with a phase Φ_b

to minimize the energy spread. In both cases, the required power can be minimized by means of detuning the cavity. Moreover, the coupling of the RF generator to the cavity has to be optimized so as to ensure minimum RF generator power.

Firstly, the optimum tuning has to be found. In case of superconducting cavities, we have

$$\begin{gathered}
\tan\psi_{opt}=2\mathrm{Q}_L\frac{\Delta\omega_{opt}}{\omega}=-\frac{(\frac{r}{Q})Q_L I_{b0}}{V_{cav}}\sin\Phi_b \\
\frac{\Delta\omega_{opt}}{\omega}=-\frac{(\frac{r}{Q})I_{b0}}{2\mathrm{V}_{cav}}\sin\Phi_b \\
(Q_L)_{opt}=\frac{V_{cav}}{(\frac{r}{Q})I_{b0}\cos\Phi_b} \\
\tan\psi_{opt}=-\tan\Phi_b\Leftrightarrow\psi_{opt}=-\Phi_b \\
(P_g)_{min}=\frac{V_{cav}^2}{(\frac{r}{Q})(Q_L)_{opt}}=V_{cav}\cdot I_{b0}\cdot\cos\Phi_b
\end{gathered} \tag{2.19}$$

The optimum coupling, i.e. the optimum loaded Q_L, has to be adjusted in such a way that the beam-induced voltage equal the cavity voltage. The minimum required power is no more than the power transferred to the beam since the dissipated power can be neglected.

3.Klystron power minimization

We can take the parameters for FLASH 9mA test from Table 1, and with (2.19) equations one can calculate the values of $(Q_L)_{opt}$ and Δf_{opt}

$$Q_L=3.59\cdot10^6$$

$$\Delta f_{opt}=-65\mathrm{Hz}$$

$(\frac{r}{Q})$	f	Φ_b	I_b	Gradient
1036 Ω	1.3 GHz	20^0	9 mA	31.5 MV

Table 1. Parameters for FLASH 9mA test.

If one will set up $(Q_L)_{opt}$ and Δf_{opt} in this way, the value of flattop power, which is the minimum power for parameters from table 1 will be

$$P_{flat}^{min}=266.4\,kW$$

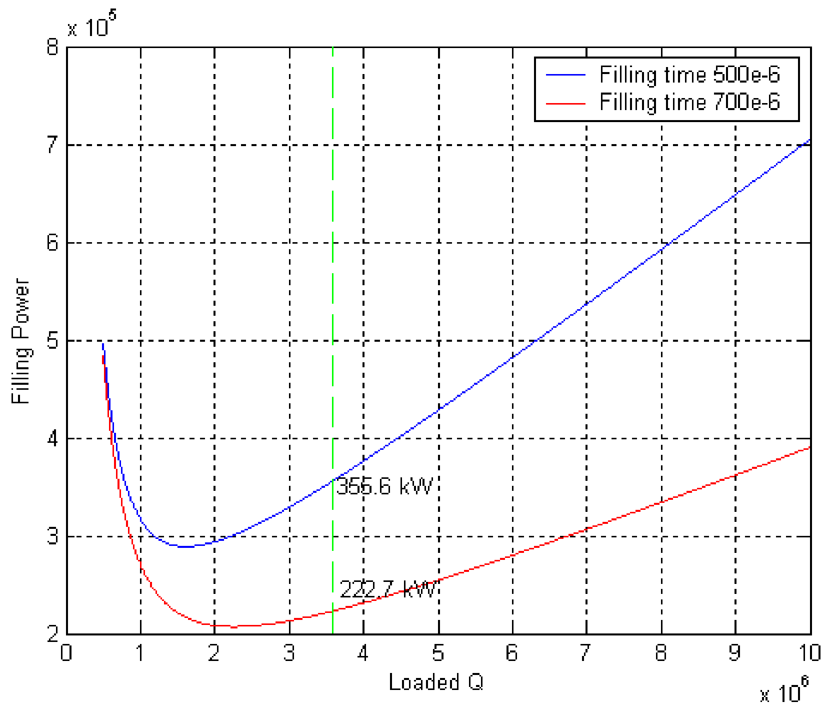

Fig.3.1. Filling power for different filling times.

Figure 3.1 shows that when the filling stage gets longer, there is less filling power needed for reach the same (31.5MV) cavity voltage with the same loaded quality factor (in this case $Q_L=3.59\cdot10^6$).

The beam pulse length is 600µs, and the maximum RF pulse length is 1300µs, so we can get the filling stage not longer, than 700µs. For 700µs filling time 222.7kW power is necessary to reach 31.5MV cavity voltage. In this case we will have a cavity driving signal waveform shape which is shown in figure 3.2. Here the beam is large enough, so the flattop power is bigger than filling power.

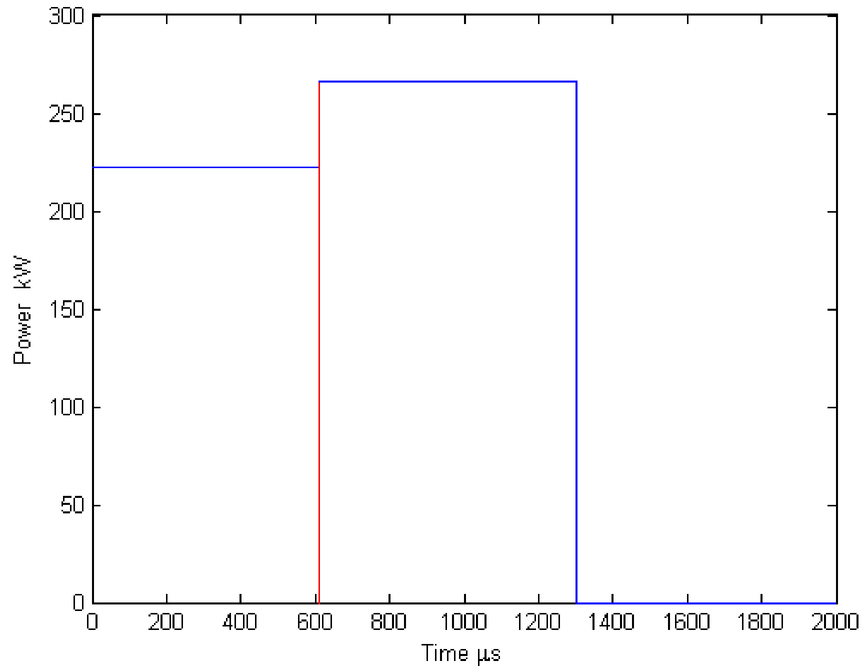

Fig.3.2. Cavity driving signal waveform shape for large beam loading.

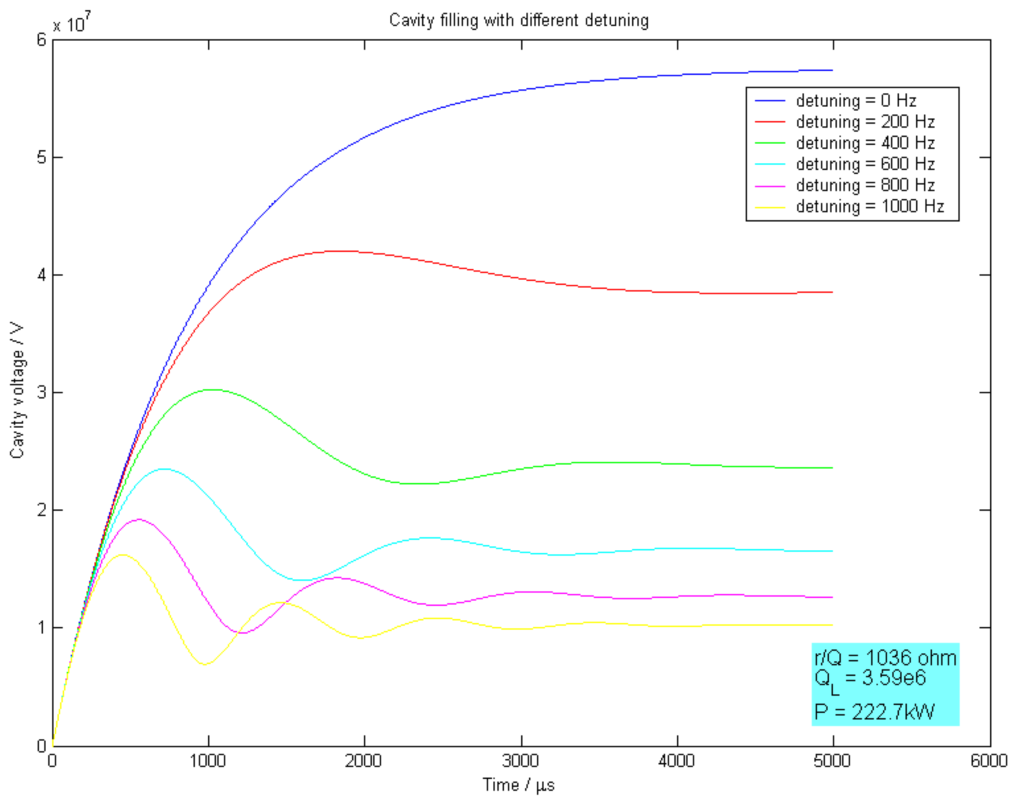

Fig. 3.3. Cavity filling with different detunings.

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

If the cavity has detuning, the cavity voltage during filling stage will have an oscillation with the frequency same as the detuning frequency, and more power will be needed to obtain the same voltage during the same filling period. Figure 3.3 shows the cavity filling with different detunings.

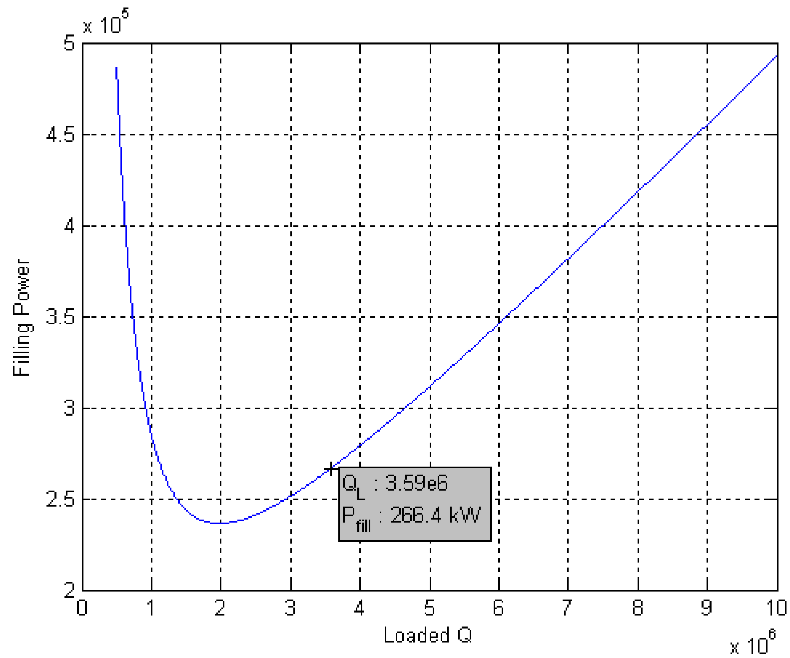

Fig. 3.4. Filling power for 612µs.

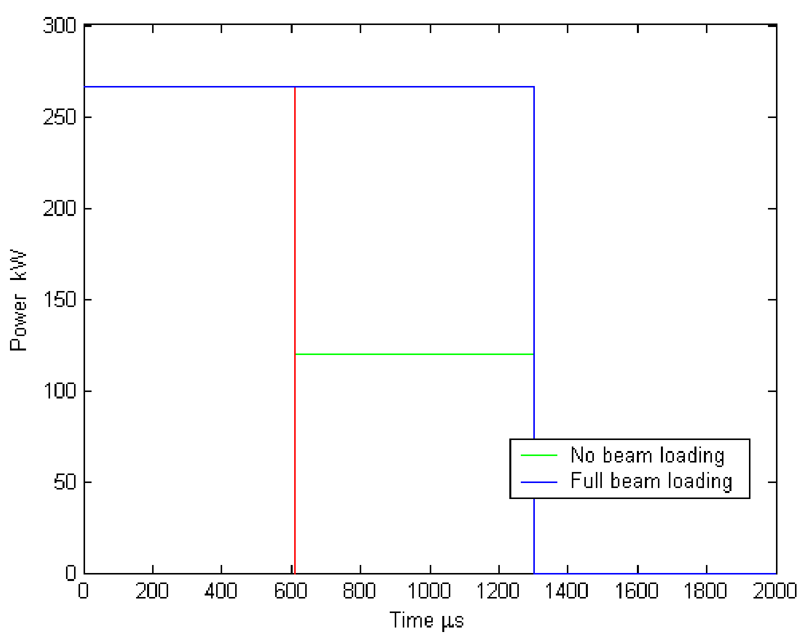

Fig.3.5. Cavity driving signal waveform shape for matched beam loading.

This simulation made with parameters from table 1 (9mA test). Figure 3.3 shows that the filling power will be minimum, if there is no detuning.

We can minimize the filling time, to increase the filling power, and make it equal to the flattop power. Figure 3.4 shows filling power for 612µs, we can see that the filling power for $Q_L = 3.59 \cdot 10^6$ is 266.4kW, which is equal to flattop power.

So we'll have a cavity driving signal waveform shape which is shown in figure 3.5. But if it is necessary to minimize the filling power, one can do it by increasing the filling time. If the filling time is extend from 612µs to 700µs, the filling power will be lowered from 266.4kW to 222.7kW.

Summary

So, the parameters which influence to the klystron peak power is filling time, loaded quality factor and detuning. I got from 9mA test parameters following:

- $Q_L = 3.59 \cdot 10^6$;
- $\Delta f = -65\text{Hz}$;
- $t_{fill} = 612 \mu s$.

For this one has to:

- Solve the equations (2.19) from theory of superconducting cavities and find out the optimum loaded quality factor and detuning for flattop stage.
- Make simulations with different filling times, and if it is necessary change also loaded quality factor and detuning, to reach the minimum klystron peak power and make filling power equal to flattop power.

References

[1] *T. Schilcher. "Vector sum control of pulsed accelerating fields in Lorenz force detuned superconducting cavities", Hamburg 1998.*

[2] *V. Ayvazyan et al.,"RF control system for the DESY VUV-FEL linac" Proc. of PAC 2005 conference*

[3] *Zh. Geng. "RF Power Consumption for LLRF Control".*

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