Amplitude and phase stability studies in a DC superconducting injector*

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Abstract: The DC superconducting injector will be used in the PKU-THz facility which consists of a DC-gun and a 3+1/2-cell superconducting cavity. The cavity must accelerate the electron beam to 5.82 MeV which is susceptible to perturbations because of its narrow bandwidth. In this paper, the sources and influences of the perturbations in the 3+1/2-cell cavity are discussed. It is shown that the control system is essential for the cavity. The design of a feedback based digital RF low level control system for the 3+1/2-cell cavity is accomplished.

Key words: energy spread, perturbation, control system

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1 Introduction

The 3+1/2-cell cavity is part of the DC-SC injector, its feasibility was proved in 2004 [1] with beam test. The updated 3+1/2-cell cavity was designed and fabricated from large grain niobium and the vertical test result ($E_{\rm acc}$=23.4 MV/m and $Q_0 > 10^{10}$) obtained at JLAB is promising. It will be used in the PKU-THz facility [2] to provide 5 MeV energy gain for the electron beam with accelerating gradient of 15 MV/m and accelerating phase of −32°. Parameters of the electron beam at the exit of the cavity are listed in Table 1.

In order to minimize the RF power required by the 3+1/2-cell cavity, the external quality factor $Q_{\rm e}$ of the main coupler should be 7.5×10^6 which is chosen for matched condition and the corresponding bandwidth of the cavity is 173 Hz.

Table 1. Parameters of the electron beam at the exit of the cavity [2].

parameters	value
bunch repetition	81.25 MHz
bunch charge	20 pC
energy	5.82 MeV
energy spread (rms)	0.55%
bunch length (FWHM)	1.41 ps
emittance (rms, x)	2.07 mm·mrad
emittance$^{\#}$ (rms, z)	2.49 deg·keV

# denotes normalized emmittance.

2 Requirements of the amplitude and phase

The beam parameters can be partly translated into the requirements of the amplitude and phase stability in the cavity and the energy spread is put into emphasis here. Energy spread of the electron beam is composed of two parts, one is within the single bunch and the other is bunch to bunch.

For a bunch with FWHM length of 1.41 ps at a 1300 MHz cavity, the single bunch energy spread is 0.19% assuming that an ideal accelerating field is employed. To ensure that the total energy spread is less than 0.55%, the bunch to bunch energy spread should be less than 0.52%. For a redundant design, bunch to bunch energy spread is supposed to be less than 0.26%.

The energy gain of central particles in the bunches is

$$E = qV\cos\phi, \tag{1}$$

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The bunch to bunch energy spread (rms) is

$$\frac{\sigma_E}{E}=\sqrt{\frac{1}{3}\left(\frac{\Delta V}{V}\right)^2+\frac{1}{3}\left(\frac{\Delta\phi}{\phi}\right)^2\tan^2\phi}, \qquad (2)$$

here ΔV, $\Delta\phi$ are the maximum fluctuations of cavity field amplitude and phase and both fluctuations are postulated with uniform distribution ranging from $-\Delta V$ to $+\Delta V$, $-\Delta\phi$ to $+\Delta\phi$ respectively. Fig. 1 depicts the contour of bunch to bunch energy spread as a function of ΔV and $\Delta\phi$ with $\phi=-32°$.

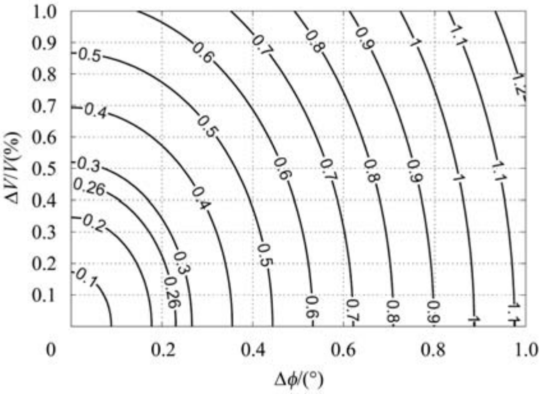

Fig. 1. Contour of bunch to bunch energy spread (%) with $\phi=-32°$.

From Fig. 1, it is concluded that the bunch to bunch energy spread can be less than 0.1% providing that the amplitude and phase stability is better than ±0.1% and ±0.1° respectively. For the 3+1/2-cell cavity used in PKU-THz, the stability of amplitude and phase should be better than ±0.2% and ±0.2° respectively.

3 Influences of perturbations

To ensure the beam characteristics, it is desirable to maintain the cavity field amplitude and accelerating phase stable for bunches, which is realized by low level control system. Several perturbations such as beam loading, microphonics, Lorentz force detuning shift the resonance frequency of the cavity, resulting in cavity field change. The evaluations of the perturbations are in the following.

It is worth noting that the electron bunch is off-crest in the 3+1/2-cell cavity, so the frequency deviation caused by beam loading must be considered [3]. The amount of detuning is

$$\frac{f-f_0}{f_0}=\frac{I_0R_\mathrm{a}\sin\phi}{2Q_0V_\mathrm{c}}, \qquad (3)$$

here f_0 is the resonance frequency without beam, I_0 is the average beam current, V_c is the accelerating voltage, ϕ is the accelerating phase. So the detuning caused by beam loading is −45 Hz for the 3+1/2-cell cavity.

Pressure fluctuation of liquid helium is unavoidable. In our system, the pressure stability is ±0.2 mbar and the frequency fluctuation is supposed to be 4 Hz [4] while the shifting is quite slow. With respect to the mechanical vibrations of Roots pumps in the cooling system, vacuum pumps and so on, it also shifts the resonance frequency, the amount of detuning from microphonics is strongly dependent on the cryomodule and associated environment. Here 10 Hz detuning is postulated [5].

Lorentz force detuning is an important problem in high gradient cavity, especially in the case of pulsed operation. The Lorentz force detuning constant of the 3+1/2-cell cavity is 1.2 Hz/(MV/m)^2 [6] and the static detuning is 270 Hz when the gradient is 15 MV/m, which is even larger than the bandwidth of the cavity. The amplitude and phase errors must be suppressed in the low level control system. All the perturbations are listed in Table 2.

Table 2. The amount of frequency shift by perturbations.

perturbations	value
beam loading	−45 Hz
liquid helium	4 Hz [4]
microphonics	10 Hz [5]
lorentz force detuning	−270 Hz

In case only the slow tuner is installed in cryomodule, the frequency shift will still exist even with low level control system due to microphonics and then to achieve stable field, more RF power will be needed. The forward RF power is

$$P_\mathrm{g}\approx\frac{P_\mathrm{b}}{4}\frac{Q_\mathrm{e}}{Q_\mathrm{ed}}\left[\left(1+\frac{Q_\mathrm{ed}}{Q_\mathrm{e}}\right)^2+4\left(\frac{\Delta f}{f_0/Q_\mathrm{ed}}\right)^2\right], \qquad (4)$$

here P_b is the power transferred to the beam, Q_ed is the external quality factor under matched condition. The amount of the necessary RF power is shown in Fig. 2 as a function of Q_e and Δf. The figure indicates a reasonable Q_e should be chosen.

Frequency shift introduces phase deviation as shown in the following

$$\tan\varphi=2Q_\mathrm{L}\frac{\Delta f}{f_0}, \qquad (5)$$

here Q_L is the loaded quality factor of cavity. Slow

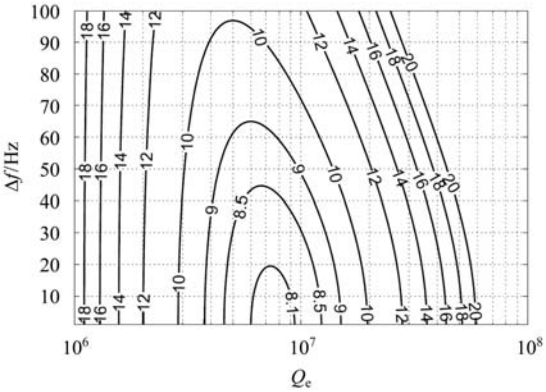

Fig. 2. Contour of P_g (kW) with 15MV/m, −32° in the 3+1/2-cell cavity.

tuning system is installed to put the resonance frequency within 1/20 of the bandwidth. Assuming Q_L is 7.5×10^6, the amount of phase deviation is 3.3° introduced by 8 Hz frequency detuning.

4 RF control system for the DC-SC injector

To achieve stable field in the cavity, the RF control system is required. The scheme of the low level control system of the DC-SC injector is shown in Fig. 3. The amplitude feedback loop will maintain a stable gradient while the phase loop will lock the phase of cavity field with the reference signal and feed forward will be considered in the future.

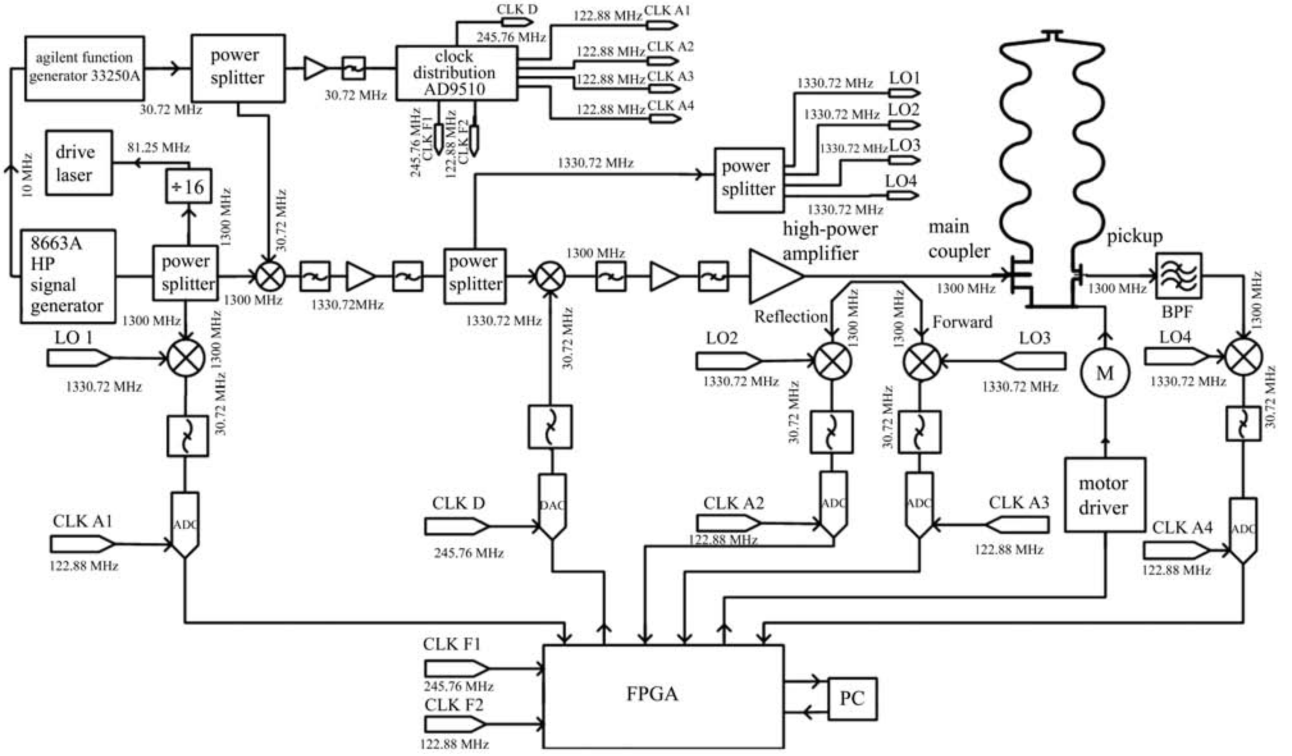

Fig. 3. The low level control system of DC-SC injector.

For the RF feedback, the generator driven resonator rather than self-excited loop is adopted and traditional Amplitude and Phase control but not Inphase and Quadratur-phase control is employed. In order to get high stability and reduce latency, the digital control system based on Field-Programmable Gate Array is chosen. Four RF signals are put into the digital part, including forward signal, reflected signal, pickup signal and reference signal and down converted to intermediate frequency of 30.72 MHz and sampled at the rate of 122.88 MHz. The feedback control algorithm is implemented as proportional-integral controller. Presently under study is active compensation scheme based on power reinforcing to maintain the field stable even without a fast tuner.

5 Conclusion

First we deduced the stability of filed amplitude and phase in the 3+1/2-cell cavity should be better than ±0.2% and ±0.2° respectively from the energy spread of the electron beam for PKU-THz facility. Then the perturbations and their influences are evaluated, which demand great power from the RF power source since the cavity is mounted without fast tuner even with low level control system. Finally a completely digital control system is designed and will be employed for the stability. The analysis is essential for designing the low level control system for the cavity and the method of analyzing requirements of field stability introduced here can be adopted somewhere else.

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