SUPERCONDUCTING CAVITY PHASE AND AMPLITUDE MEASUREMENT IN LOW ENERGY ACCELERATING SECTION*

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Abstract

Superconducting linear accelerator is the tendency in linac design with the development of superconducting RF technology. Superconducting cavities used as accelerating section in low energy Hardon linac are more and more common. The 5-MeV test stand of CADS accelerator Injector I is composed of an ion source, a low energy beam transport line (LEBT), a 325MHz RFQ (room temperature), a medium energy beam transport line (MEBT), a cryogenic module (CM1) of seven SC spoke cavities (β=0.12) , seven SC solenoids, seven cold BPMs and a beam dump. The phase and amplitude setting of superconducting cavity are very important at the operation of accelerator, so beam based measurement of cavity phase and amplitude is necessary. Beam based phase scan is the most simple and effective method. Because the significant velocity changes in superconducting cavity at low energy section, the effective voltage is changing with cavity phase, meanwhile the synchronous phase is non-linear with LLRF phase. Above two problem make the cavity phase determination difficult. New date fitting method is proposed to solve these problem in this paper. Some measurements of spoke cavities in the CADS CM1 are also presented.

INTRODUCTION

Superconducting linear accelerator is the tendency in linac design with the development of superconducting RF technology. Superconducting cavities used as accelerating section in low energy Hardon linac are more and more common. The phase and amplitude setting of superconducting cavity are very important at the operation of accelerator, so beam based measurement of cavity phase and amplitude is necessary.

The 5-MeV test stand of CADS accelerator Injector I is composed of an ion source, a low energy beam transport line (LEBT), a 325MHz RFQ (room temperature), a medium energy beam transport line (MEBT), a cryogenic module (CM1) of seven SC spoke cavities (β=0.12) , seven SC solenoids, seven cold BPMs and a beam dump [1]. Figure 1 shows the layout of elements in CM1, where elements inverse order is SC spoke cavity, cold BPM and SC solenoid.

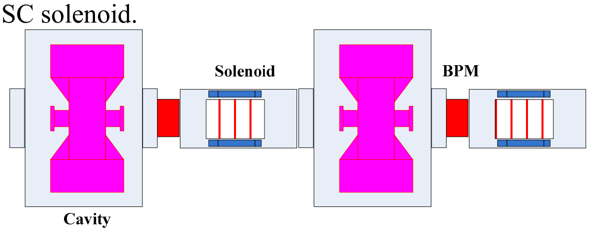

Figure 1: Diagram of elements in CM1.

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Beam based phase scan is the most simple and effective method for measuring cavity phase and amplitude. For the first cavity phase measurement, we detuned the second cavity and use the two following BPMs to measure energy after calibrating the offset between the BPMs. Because the significant velocity changes in superconducting cavity at low energy section, the effective voltage is changing with cavity phase, meanwhile the synchronous phase is non-linear with LLRF phase. Above two problem make the cavity phase determination difficult. New date fitting formula is proposed to solve these problem in this paper. Some measurements in the CADS CM1 are also presented.

ENERGY GAIN AND SYNCHRONOUS PHASE

For a RF cavity with a length *L*, the energy gain for a charged particle with a longitudinal component $E_z(s)$ can be calculated with the formula:

$$\Delta W = \int_{s_0}^{s_0+L} qE_z(s)\cdot\cos\phi(s)\cdot ds \tag{1}$$

Where q the charge of the particle, and s the beam axis coordinate. The function $\phi(s)$ is the RF phase when the particle is at the coordinate s. It is defined by:

$$\phi(s) = \phi_0 + \frac{\omega_{rf}}{c}\int_{s_0}^{s_0+L}\frac{ds'}{\beta_z(s')} \tag{2}$$

Where c the Einstein constant, ω_{rf} the RF circular frequency, ϕ_0 is the RF phase when the particle is at the cavity entrance, and $\beta_z(s')$ is the longitudinal component of the particle reduced speed at the s' location. Writing $\phi(s)$ as $\phi(s)+\phi_s-\phi_s$, with ϕ_s being synchronous phase, the energy gain can be written:

$$\begin{aligned}\Delta W = \cos\phi_s\int_{s_0}^{s_0+L} qE_z(s)\cdot\cos[\phi(s)-\phi_s]\cdot ds\\ -\sin\phi_s\int_{s_0}^{s_0+L} qE_z(s)\cdot\sin[\phi(s)-\phi_s]\cdot ds\end{aligned} \tag{3}$$

define ϕ_s such as:

$$\int_{s_0}^{s_0+L} qE_z(s)\cdot\sin[\phi(s)-\phi_s]\cdot ds = 0 \tag{4}$$

It gives:

$$\phi_s = \arctan\left[\frac{\int_{s_0}^{s_0+L} qE_z(s)\cdot\sin\phi(s)\cdot ds}{\int_{s_0}^{s_0+L} qE_z(s)\cdot\cos\phi(s)\cdot ds}\right] \tag{5}$$

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Then the energy gain can be rewritten:

$$\Delta W = qV_0 \cdot T \cdot \cos\phi_s = \left[q\int_{s_0}^{s_0+L} q\left|E_z(s)\right| ds \right] \cdot T \cdot \cos\phi_s \quad (6)$$

with

$$T = \frac{1}{V_0}\int_{s_0}^{s_0+L} qE_z(s)\cdot\cos[\phi(s)-\phi_s]\cdot ds \quad (7)$$

From Eq. (7) and Eq. (2) one can get that the effective voltage is changing with energy and synchronous phase and related to field distribution.

PHASE SCAN METHOD

Beam based phase scan method is the most simple and effective method for measuring cavity phase and amplitude. One can measure the output energy with scan the cavity phase (LLRF phase). According to Eq. (6), we can get the output energy at the exit of cavity:

$$W_o = V_{eff}\left(W_i, \phi_s, E_f\right)\cdot\cos(\phi_s) + W_i \quad (8)$$

Where W_i is the input energy, E_f is field gradient and ϕ_s is synchronous phase. From the Eq. (5) the synchronous phase is non-linear with entrance phase which is linear with LLRF phase. In this paper we take the entrance phase and LLRF phase as same parameter just have one offset and in some case we do not distinguish them. If the non-linear effect between synchronous phase and LLRF is not very big, we can use LLRF phase instead of synchronous phase for convenience and simple. So we can get the general fitting formula for phase scan as:

$$W_o = V_{eff}\cdot\cos(\phi_{LLRF} + \Delta\phi) + W_i \quad (9)$$

We should pay attention to the V_{eff} which is changing with energy and LLRF phase but in Eq. (9) is independent to them. To study the accuracy of Eq. (9) and find one better fitting formula, we take the spoke012 cavity of CADS CM1 as an example, which of field is shown in Fig. 2. In our thoughts we want to get one better fitting formula also base on the Eq. (6), so we should consider two problem: one is the LLRF phase to synchronous phase and another is effective voltage. The fitting formula will be as:

$$W_o = V_{eff}\left(W_i, \phi_{LLRF}, E_f\right)\cdot\cos[\phi_s(W_i, \phi_{LLRF}, E_f)] + W_i \quad (10)$$

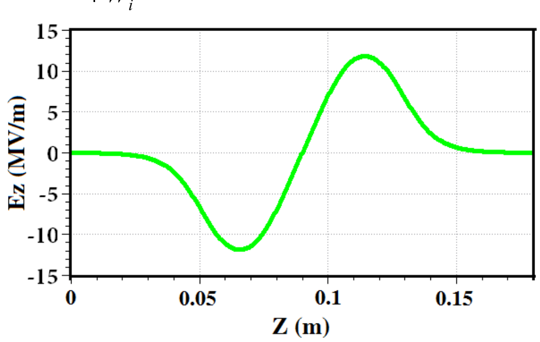

Figure 2: Field of SC Spoke012.

Synchronous Phase

In the simulation, we use field factor instead of field gradient and Fig.2 shows the field of field factor equal to 1.0. According to the definition by Eq. (5), the synchronous phase is the function of LLRF phase with input energy 3.5 MeV and field factor 1.0. Figure 3 shows the synchronous phase minus LLRF phase as a function of LLRF phase. From the results we present a formula to fitting the synchronous phase:

$$\phi_s = A\cdot\cos(\phi_{LLRF} + B) + C + \phi_{LLRF} + \Delta\phi_{sys} \quad (11)$$

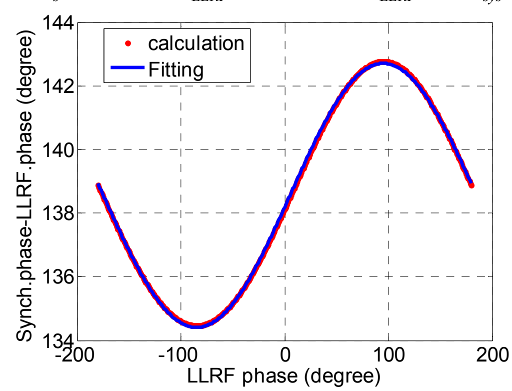

Figure 3: The synchronous phase minus LLRF phase VS LLRF phase.

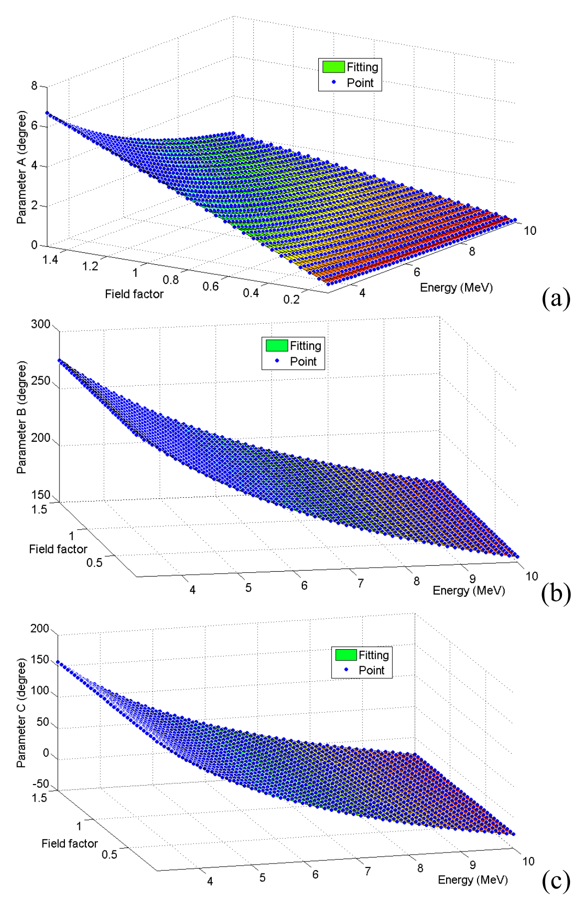

Figure 4: Parameters *A* (a), *B* (b) and *C* (c) in Eq. (11) with different energy and field factor.

Considering the changing energy and field gradient, we can get the parameters *A*, *B* and *C*. We have calculated the synchronous phase with different input energy and different field factor and then fitted the synchronous phase by Eq. (11). The range of energy is from 3.0 MeV to 10 MeV and the range of field factor is from 0.3 to 1.5. The parameters *A*, *B* and *C* in Eq. (11) with different energy and field factor are shown in Fig. 4 and the formula of parameters as:

$$A=\left(14.45\cdot W_i^{-\frac{1}{3}}-5.306\right)\cdot E_f$$

$$B=567.2\cdot W_i^{-\frac{1}{3}}-108.7 \qquad (12)$$

$$C=758.3\cdot W_i^{-\frac{1}{2}}-266.8$$

Effective Voltage

Similar method have been used to study effective voltage with LLRF, input energy and field factor. Figure 5 shows effective voltage changing with LLRF phase when input energy is 3.5 MeV and field factor is 1.0. We can use the formula to fitting effective voltage:

$$V_{eff}=a\cdot\cos(\phi_{LLRF}+b)+c\cdot\cos[2(\phi_{LLRF}+d)]+e \qquad (13)$$

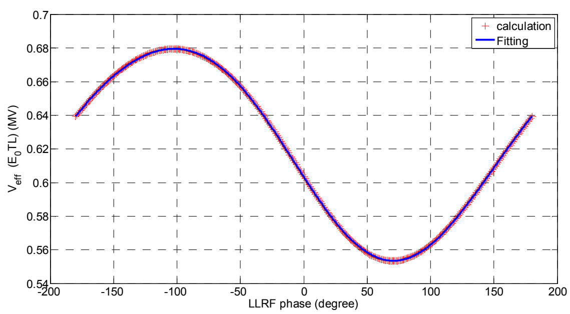

Figure 5: Effective voltage changing with LLRF phase when input energy is 3.5 MeV and field factor is 1.0.

According to the simulation results, one can get the parameters *a*, *b*, *c*, *d* and *e* in Eq. (13). Figure 6 shows parameters *e* in Eq. (13) with different energy and field factor and the formula as:

$$e=\frac{24.23W_i-38.23}{W_i^2+19.7W_i+26.53}E_f \qquad (14)$$

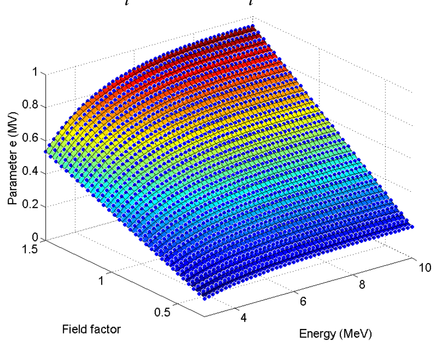

Figure 6: Parameters *e* in Eq. (13) with different energy and field factor.

CAVITY PHASE MEASURMENT

We have finished the beam commissioning of 5MeV test stand of CADS injector-I, and finished all the cavities' phase scan measurement. Here we present the phase scan of the second cavity with two fitting formulas, which is shown in Fig. 7. From the results, we can see that the new fitting formula is better.

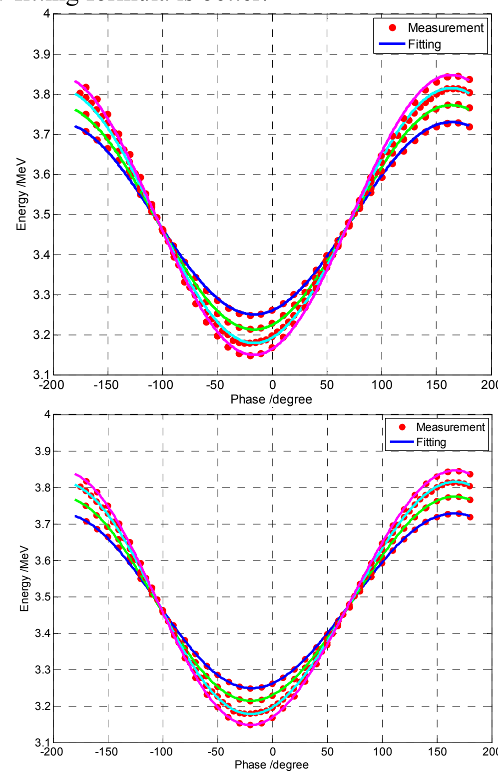

Figure 7: Phase scan with two fitting formulas. Up is Eq. (9) and down is Eq. (10).

CONCLUSION

Beam based phase scan is the most simple and effective method for measuring cavity phase and amplitude. In this paper two fitting formulas for phase scan have been discussed and one measurement results of SC spoke012 cavity of CADS 5 MeV test stand.

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