DELTA-T PROCEDURE FOR SUPERCONDUCTING LINEAR ACCELERATOR

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Abstract

Development of the tune-up procedure for a linear accelerator is the next important stage after the design is complete. Conventional ΔT procedure developed by Crandall for a tuning of a normal-conducting (NC) linear accelerator allows one setting up of the accelerating field amplitude and phase in cavities with design phase velocity. In contrast the quasi-synchronous phase velocity in a superconducting (SC) linac is determined by a RF phasing of cavities. And the phasing itself must be established in frame of the tune-up procedure. Moreover a SC cavity is short and has small phase advance of the longitudinal motion, which leads to an insensibility of particles motion to variation of the electric field inside the cavity. In the paper we consider the modified ΔT procedure adjusted for a SC linac. Proposed technique is developed for the tuning of the COSY linear injector [1], which is supposed to accelerate *P* and *D* beams from 2.5 to 50 MeV using 44 two-cell SC cavities.

NEED FOR THE TUNE-UP PROCEDURE

An accelerating structure of a SC linac represents a sequence of SC cavities with a constant phase velocity. Behavior of the equivalent phase velocity in such a structure is defined by the RF phasing of the cavities and ultimately depends on the accelerating field magnitude [2]. Apparently static errors in the amplitude and phase of the accelerating field lead to changing the equivalent phase velocity of a linac. As a result, the particle that is supposed to be quasi-synchronous in accordance with numerical simulations in reality is nonsynchronous. Consequently beam-dynamics in the real accelerating structure can considerably differ from the design. And therefore the main goal of the tune-up procedure is to realize the design parameters of the particle motion in the real accelerating structure.

Noncoincidence between the experimental and design values of the equivalent phase velocity results in the uncertainty of the final energy. The scale of such an uncertainty can be estimated with a numerical simulation. Below we disregard the question of the dynamic errors of the accelerating field amplitude and phase. RF technique gives ±5% and ±1 deg of inaccuracy in setting up the amplitude and phase of the accelerating field. At the figure 1 we present the most probable location of the bunch centers in the longitudinal phase space. Every specific distribution of the amplitude and phase errors along a linac corresponds to a particular location of bunch center. At the figure 1 we can also see an energetic acceptance 0.3% of the COSY-ring. As it is shown at the figure 1 the uncertainty of the final energy is about 1%, which is substantially higher than the COSY-ring acceptance. So much higher that it becomes impossible to perform an effective injection of the particles into the ring.

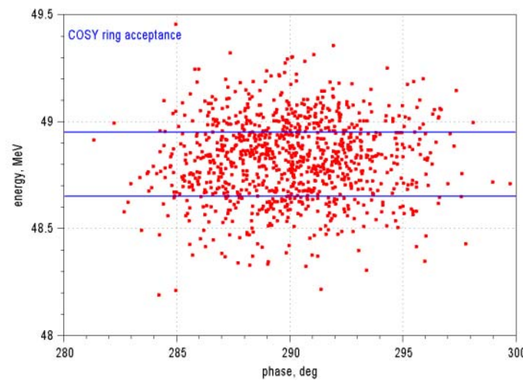

Fig. 1: The most probable location of the beam centers at the exit of the linear injector COSY in the longitudinal phase space.

Consequently, the RF tuning of the SC accelerating structure does not provide the beam with required final energy, although it preserves the stable motion of the particles.

The importance of the tune-up procedure for a SC linac becomes even clearer if we recollect that one of the most attractive features of SC linacs is the possibility of the smooth adjustment of the final energy. The phasing of the cavities, which allows changing the equivalent phase velocity, provides a basis for such a possibility. But without a tune-up procedure the smooth adjustment of the final energy cannot be realized.

Since the equivalent phase velocity defines the energy gain along the accelerator, the main goal of the tune-up procedure will be reached only when the energy in the real structure coincides with the design value. Development of the tune-up procedure can be divided into three stages:

- The first stage concerns the development of the phasing of the cavities, which must be based on the experimental data of the beam. The developed phasing method associates each errors distribution with a particular behavior of the equivalent phase velocity.
- The second stage involves an adjustment of the equivalent phase velocity of the real accelerating structure. The purpose of this stage is to find the maximum possible coincidence between the real and design values of the equivalent phase velocity.

- The third stage ends the tuning of an accelerator. On this stage the conventional ΔT procedure is being applied.

ΔT PROCEDURE FOR SC LINACS

Layout and technique of the ΔT procedure for SC linacs

In order to tune a SC linac up we uses the layout (see figure 2) resembling to which is used for tuning of a NC linac [2]. Pick-up loops A, B and C give information about the flight time of a particle between pick-up loops A-B and A-C. The essence of the tune-up procedure is to measure how the flight time changes as the amplitude of the accelerating field is varying and the phase at the entrance of the cavity is being scanned over some range. To analyze these changings one can compose the differences:

$$\Delta t_{1,2} = \Delta t_{1,2}^{real} - \Delta t_{1,2}^{design},$$

where:

$$\Delta t_{1,2}^{real} = t_{1,2on}^{real} - t_{1,2off}^{real}, \qquad \Delta t_{1,2}^{design} = t_{1,2on}^{design} - t_{1,2off}^{design}.$$

Indexes 1 and 2 indicate the flight time between pick-up loops AB and AC correspondingly. Indexes “real” and “design” relate to the real and design situations. Last two differences show how the time of flight changes as the module being adjusted (N-th) is on and off. Analyzing the quantities $\Delta t_{1,2}$, which are directly linked to the amplitude and phase of the accelerating field [2], we can get information how much the energy of the real particle differs from the design value. Indeed, the equalities $\Delta t_{1,2} = 0$ mean a perfect coincidence between the real and design particle energies. Therefore, this coincidence can be obtained by a variation of the amplitude and phase of the accelerating field. That is what is being done to tune a NC linac up. But in case of a SC linac before searching the particle with $\Delta t_{1,2} = 0$ we need firstly to adjust the equivalent phase velocity.

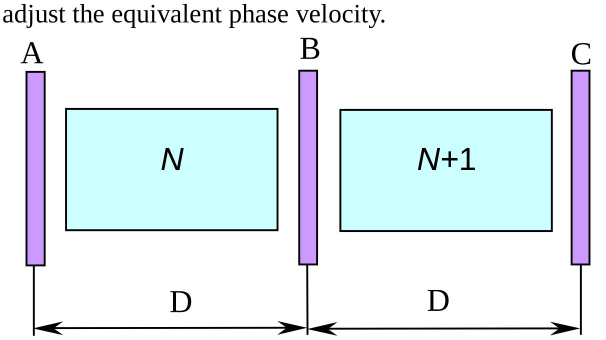

Fig. 2: The layout for the ΔT procedure.

However, small phase advance of the longitudinal motion, which is the feature of the SC cavities, impedes the usage of the pick-up loops. Because of the small phase advance an accuracy of the pick-up loops is greatly insufficient to feel changing of the field amplitude and phase inside the cavity. That means the particle motion remains stable with respect to the amplitude and phase errors. This stability allows one to join several cavities in one module without losing the quality of the beam. And the further tuning deals with such a module. The phase advance equal to the half of one longitudinal oscillation gives the maximum sensitivity. Hence the optimal number of cavities in a module must provide around π of the phase advance. In case of the linear injector for the COSY-ring one module at the beginning of the acceleration (2.5 MeV) contains 4 two-cell cavities. At the end (50 MeV) already 12 cavities provide the necessary sensitivity to the ΔT procedure.

The phasing of the cavities

The main task for the phasing of the cavities is to ensure a quasi-synchronous motion of the particles. In order to realize quasi-synchronous motion in the real accelerating structure the phasing must be based on the measured data of the beam. Assume that we know the phase $\varphi_{in,N}$ at the entrance to the N-th cavity, which realizes the quasi-synchronous motion. The phase $\varphi_{out,N}$ at the exit of this cavity can be measured. Then the phase shift $\Delta\varphi_{N,N+1}$ between two neighbor cavities can be defined as $\Delta\varphi_{N,N+1} = \varphi_{in,N+1} - \varphi_{out,N}$. On this stage we have to find quantities $\Delta\varphi_{i,i+1}$ for all pairs of the cavities. From the assumption above we see that we need to invent the method how to find the phase of the particle at the entrance to all the cavities.

We have studied two methods of determination the initial phase for each cavity. In both methods we scan the initial phase of a particle. The idea of the first method is to find the particle with the maximum energy gain per a cavity with the length L. In accordance with the simple formula $\Delta W = eE_0 T \cdot L \cos\overline{\varphi_s}$, the particle with zero average phase $\overline{\varphi_s} = 0$ has the maximum energy gain. We measure the initial phase of this particle. Than the phase of the sought particle differs from the measured phase by $-\overline{\varphi_s}$. Similar idea is used in the second method with only one distinction: we search for the particle with zero energy gain. Then the phase of the sought particle differs from the measured by $-\left(90^\circ + \overline{\varphi_s}\right)$.

The both methods give comparable results: effective separatrix and the phase trajectory of the quasi-synchronous particle. The choice of the one method can be done after the analysis of uncertainties introduced by each method.

Uncertainty in a measurement of the beam phase by the pick-up loops is $\delta\varphi = 1^\circ$. Uncertainty in the time of flight measurement is $\delta t = \delta\varphi/\omega \sim 3\,ps$ (frequency of the pick-up loops is 6•160 MHz). An estimation of the uncertainty in initial phase gives $\pm 2°$ for the first method in the energy range from 2.5 MeV. Uncertainty of the second method is negligible. Thus the phasing of the cavities experimentally bases on the search for the particle with zero energy gain.

Equivalent phase velocity adjustment

After all the cavities have been phased we are ready to adjust the equivalent phase velocity of the structure. One way to change the equivalent phase velocity of some particular module is to vary an average field level in the whole module, after which it is necessary to rephase the cavities inside the module.

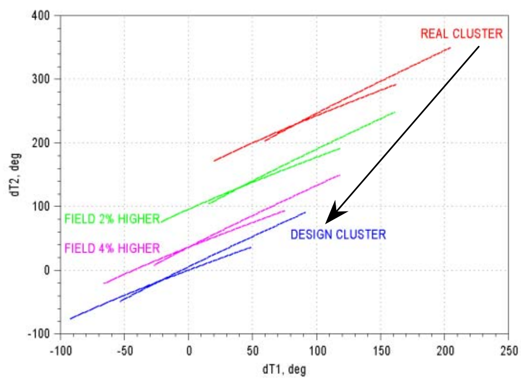

Fig. 3: Adjustment of the equivalent phase velocity.

In order to control the behavior of the equivalent phase velocity and to compare it with the design value we analyze the ΔT plane with axes Δt_2, Δt_1 as ordinate and abscissa correspondingly. Scanning of the initial phase of a particle can be represented at the ΔT plane as a single curve that is called ΔT curve. In the region of the linear motion the ΔT curve is very close to a straight line. ΔT curves that correspond to the different field levels in the module form a cluster of the ΔT curves, which have different slope angles at the ΔT plane. An intersection point of the ΔT curves corresponds to the quasi-synchronous particle. The intersection point of the perfectly tuned module is to be located at the origin of coordinates. But numerical simulations of the real module show that the intersection point does not coincide with origin of coordinates, despite the initial energy of the particles is correct. This confirms that the amplitude and phase errors change the equivalent phase velocity. We investigated how variation of field amplitude and phase along one module with discontinuity of one cavity affects on the equivalent phase velocity.

As it was stated above, we can adjust the equivalent phase velocity most successfully by varying the average field level in the entire module. The rephrasing of the cavities inside the module must follow the field level changing. At the figure 3 we see how the ΔT cluster of the real module comes closer to the design cluster as the field level is changing. This stage ends as the maximum possible coincidence of real and design cluster is achieved. Certainly, it is impossible to get the perfect coincidence. Errors distribution inside the module has complex character and simple varying of the average field level cannot compensate them. On this stage we can only gather all real clusters in the small vicinity of the design cluster.

Completion of the tune-up procedure

After we adjusted the equivalent phase velocity of the real accelerating structure we use the conventional ΔT procedure to finalize tuning. Here we take as Δt_2 the difference in time of flight through the module N+1, which is the next to the module being tuned. By this way it is possible to control the final energy of the particles because Δt_2=0 means equality the real and design energy. Therefore on this stage we search for a particle that has Δt_2=0. Figure 4 shows the result of the COSY-injector tuning. Three green bunches represent the possibility of the smooth adjustment of the final energy. Indeed, taking $\Delta t_2 = a = const$ and varying the constant we get the beam with a different final energy.

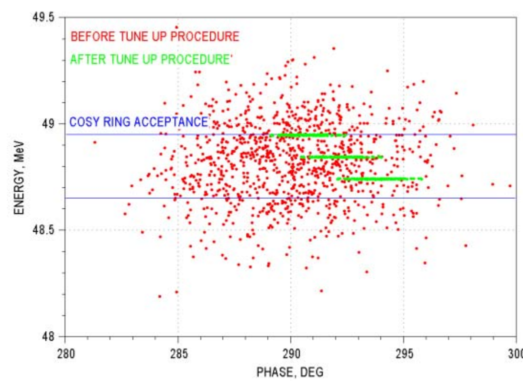

Fig. 4: The most probable location of the bunch centers at the exit of the COSY-injector before and after ΔT procedure.

CONCLUSION

As it was shown, the revised ΔT procedure has the next main features. Firstly, we tune up several cavities at once. Secondly, before we can use the conventional ΔT procedure, it is essential to adjust the equivalent phase velocity of the real accelerating structure. This adjustment can be done by variation of the field level inside the module being tuned up. And only after that we are able to apply convenient ΔT procedure for the final tuning.

REFERENCES

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