DEVELOPMENT AND IMPLEMENTATION OF ΔT PROCEDURE FOR THE SNS* LINAC

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Abstract

The Δt procedure is a time of flight technique for setting the phases and amplitudes of accelerating fields in a multi-cavity linac. It was initially proposed and developed for the LAMPF linac in the early seventies [1,2] and since then has been used in several accelerators [3,4]. The SNS linac includes four CCL modules (Side Coupled Structure) operating at 805 MHz for the energy range from 86.8 MeV up to 185.6 MeV. The Δt procedure has been implemented for the SNS CCL linac and was used for initial beam commissioning of three CCL modules. A brief theory of the procedure, the results of the design parameter calculations and the experimental results of phase and amplitude set points are presented and discussed.

BRIEF THEORY OF THE PROCEDURE

In Δt procedure the bunch of the accelerating beam is treated as a single particle executing linear motion in *(Δφ, ΔW)* phase plane with respect to a design particle. Linear motion requirements imply limitations on deviation from nominal values of rf phase and amplitude, and beam energy.

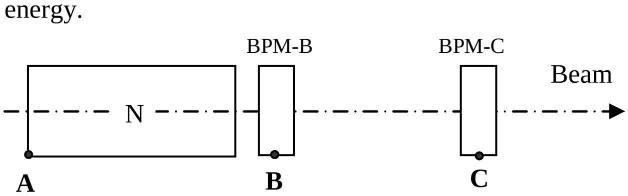

Figure 1: Explanation of Δt procedure.

The Δt procedure can be explained referring to fig. 1. The information about the phase and amplitude of accelerating field in cavity N (in case of SNS CCL Linac N=1,2,3,4) can be derived [*]by processing phases of signals induced by the beam in beam phase probes BPM-B and BPM-C with respect to accelerator reference line and comparing the results with those obtained from beam dynamics simulations. Point A in fig. 1 corresponds to the physical entrance of the cavity. Points B and C correspond to longitudinal coordinates of beam phase probes. In the SNS linac, strip line Beam Position-Phase Monitors (BPM),with shorted strip lines serve for beam phase monitoring [5]. The operating frequency of BPMs in the CCL linac is 402.5 MHz. Usually phase probes located at the exit of the tuned module and at the exit of the downstream switched off module are used for Δt procedure. In the SNS linac there are also BPMs between the segments within the module so the use of another phase probe combinations is possible.

Let t_{AB} and t_{AC} be the times of flight from point A to points B and C correspondingly. The values of interest are the differences of times of flight for the rf field off and on:

$$t_B = t_{ABoff} - t_{ABon}$$

$$t_C = t_{ACoff} - t_{ACon}$$

Typical values of t_B and t_C correspond to hundreds and even thousands of degrees that is why the use of deviations with respect to design values is reasonable:

$$\Delta t_B = (t_{ABoff} - t_{ABon}) - (t_{ABoff,des} - t_{ABon,des})$$

$$\Delta t_C = (t_{ACoff} - t_{ACon}) - (t_{ACoff,des} - t_{ACon,des})$$

Here $t_{ABoff,des}$, $t_{ABon,des}$, $t_{ACoff,des}$ and $t_{ACon,des}$ are the values of t_{ABoff}, t_{ABon} , t_{ACoff} and t_{ACon} for nominal amplitude and phase as well as the nominal energy at the entrance of the cavity.

In the vicinity of the design particle the parameters Δt_B and Δt_C linearly depend on deviation of energy ΔW_A and phase $\Delta \varphi_A$ with respect to nominal values at the entrance of the cavity:

$$\begin{pmatrix} \Delta t_B \\ \Delta t_C \end{pmatrix} = T \begin{pmatrix} \Delta \varphi_A \\ \Delta W_A \end{pmatrix}$$

If the values of Δt_B and Δt_C are known, then the deviations ΔW_A and $\Delta \varphi_A$ can be found:

$$\begin{pmatrix} \Delta \varphi_A \\ \Delta W_A \end{pmatrix} = A_t \begin{pmatrix} \Delta t_B \\ \Delta t_C \end{pmatrix},$$

where $A_t = T^{-1}$. In practice the changes of phase of the induced in BPMs signals rather than the changes of time of flight are measured. If $\Delta\varphi_1 = \omega \cdot \Delta t_B$ and $\Delta\varphi_2 = \omega \cdot \Delta t_C$, where ω is an operating frequency of BPMs, then

$$\begin{pmatrix} \Delta \varphi_A \\ \Delta W_A \end{pmatrix} = A \begin{pmatrix} \Delta \varphi_1 \\ \Delta \varphi_2 \end{pmatrix}$$

or
$$\begin{cases} \Delta\varphi_A = a_{11} \cdot \Delta\varphi_1 + a_{12} \cdot \Delta\varphi_2 \\ \Delta W_A = a_{21} \cdot \Delta\varphi_1 + a_{22} \cdot \Delta\varphi_2 \end{cases},$$

where $A = \frac{1}{\omega} \cdot A_t$.

The elements of the transformation matrixes depend on the amplitude of accelerating field and this feature is used

[*] SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy. SNS is a partnership of six national laboratories: Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos and Oak Ridge

to find the amplitude. In practice a more convenient way to find the amplitude is by comparing the slope of theoretical and experimental lines, generated in the $(\Delta\varphi_1,\Delta\varphi_2)$ plane, when the entrance phase $\Delta\varphi_A$ is varied.

If the phase of rf field is varied then the experimental points in the $(\Delta\varphi_1,\Delta\varphi_2)$ plane are located on a phase variable line, defined by the equation

$$a_{21}\cdot\Delta\varphi_1 + a_{22}\cdot\Delta\varphi_2 = \Delta W_A = const\,, \qquad (1)$$

each point of the line univocally corresponding to phase deviation $\Delta\varphi_A$ at the entrance of the cavity.

If the phase is nominal ($\Delta\varphi_A$=0), then

$$\Delta\varphi_2 = -\frac{a_{11}}{a_{12}}\cdot\Delta\varphi_1\,. \qquad (2)$$

The line (1) can be found experimentally by measuring $\Delta\varphi_1$ and $\Delta\varphi_2$ versus cavity phase while the energy variable line (2) is a theoretical one. Each point of line (2) corresponds to a certain value of ΔW_A. The point of intersection of experimental line (1) and theoretical one (2) defines deviation of phase $\Delta\varphi_A$ and energy ΔW_A at the entrance of the cavity with respect to nominal values.

DESIGN PARAMETERS

To implement a Δt procedure the following design parameters are required:

- ($\varphi_{ABoff,des}$- $\varphi_{ABon,des}$) and ($\varphi_{ACoff,des}$ - $\varphi_{ACon,des}$);
- $arctg\left(d(\Delta\varphi_2)/d(\Delta\varphi_1)\right)$ for different amplitudes of accelerating field;
- matrix *A* elements for different amplitudes.

The above parameters have been derived by simulating single particle beam dynamics in CCL modules. As an example, Fig. 2 shows the curves in the $(\Delta\varphi_1,\Delta\varphi_2)$ plane for BPMs #212 and #312, installed at the exit of modules CCL2 and CCL3 correspondingly. The lines are given for three input energies, the nominal one W_0 and W_0±50 keV, and for five amplitudes, 0.96E_0, 0.98 E_0, 1.00 E_0, 1.02 E_0 and 1.04 E_0. The points on the lines relate to different input phases with a step of 2.5° (*f*=805 MHz). The intersection points well correspond to nominal phase. The slope of the lines in the vicinity of intersection point depends on field amplitude and is almost independent of input energy. To avoid nonlinearities the range of module phase adjustment must be within about ±5°.

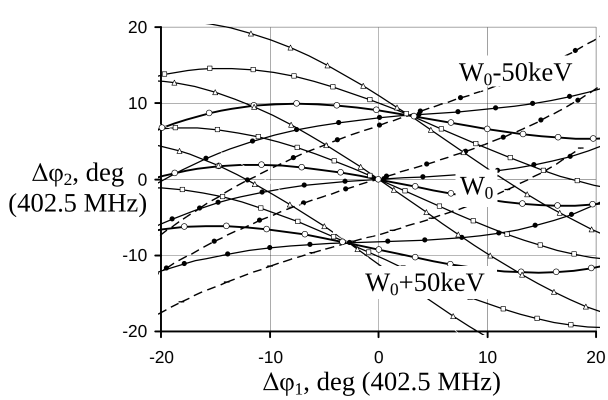

Figure 2: Behavior of lines in $(\Delta\varphi_1,\Delta\varphi_2)$ plane for CCL Module #2 (BPM 212, BPM 312).

The values of ($\varphi_{ABoff,des}$- $\varphi_{ABon,des}$) and ($\varphi_{ACoff,des}$ - $\varphi_{ACon,des}$) for CCL2 and BPMs #212 and #312 are equal to 629.20° and 1911.17° correspondingly.

Elements of matrix *A* slightly depend on field amplitude. Though this is a second order effect from the point of view of influence on procedure accuracy, nevertheless it should be taken into account. That is why matrix elements were calculated for different amplitude values.

EXPERIMENTAL DATA TREATMENT

To carry out a Δt procedure, phase signals from two BPMs are measured for several phases φ_c of CCL Module N with the field on, as well as with the field off. The module N+1 for these measurements is always off. Then the values of $\Delta\varphi_1$ and $\Delta\varphi_2$ are calculated. The points in $(\Delta\varphi_1,\Delta\varphi_2)$ plane are rms fitted by linear functions of φ_c:

$$\begin{cases}\Delta\varphi_1 = k_1\cdot\varphi_c + b_1\\ \Delta\varphi_2 = k_2\cdot\varphi_c + b_2\end{cases}$$

The above functions can be treated as parametric equations of a line in the $(\Delta\varphi_1,\Delta\varphi_2)$ plane:

$$\Delta\varphi_2 = k\cdot\Delta\varphi_1 + b\,, \qquad (3)$$

where $k=\frac{k_2}{k_1}$, $b=\frac{b_2\cdot k_1 - b_1\cdot k_2}{k_1}$. The slope of this line $arctg(k)$ is compared with the calculated values thus enabling determination of the current relative amplitude of accelerating field. Each point of the line (3) corresponds to a fixed phase of accelerating field φ_c. Nominal phase can be found as a joint resolution of equations (2) and (3):

$$\varphi_{cS} = -\frac{b_1\cdot a_{11} + b_2\cdot a_{12}}{k_1\cdot a_{11} + k_2\cdot a_{12}}$$

The corresponding values of $\Delta\varphi_1$ and $\Delta\varphi_2$ can be found as:

$$(\Delta\varphi_1)_S = k_1\cdot\varphi_{cS} + b_1$$
$$(\Delta\varphi_2)_S = k_2\cdot\varphi_{cS} + b_2$$

Deviation of energy at the entrance of the cavity can be found by substituting the determined values of $(\Delta\varphi_1)_S$ and $(\Delta\varphi_2)_S$ in (1):

$$\Delta W_A = \frac{b_2\cdot k_1 - b_1\cdot k_2}{k_1\cdot a_{11} + k_2\cdot a_{12}}\cdot\left(a_{11}\cdot a_{22} - a_{12}\cdot a_{21}\right)$$

Data acquisition and data treatment are done with two separate codes. Figure 3 shows a LabView screen representing the results of data treatment for the CCL Module #1. Two plots in the left part of the window represent the measured functions $\Delta\varphi_1(\varphi_c)$ and $\Delta\varphi_2(\varphi_c)$. The central plot represents a $(\Delta\varphi_1,\Delta\varphi_2)$ plane. This plot shows experimental points and a corresponding best fit line as well as a theoretical energy variable line (2). The plot in the right part of the window represents a calculated relation of slope angle and the amplitude. This function is used to determine the amplitude using the experimental slope value which is displayed and indicated in the plot.

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The results of data treatment are nominal amplitude set point E_0 and deviation of the current amplitude set point E with respect to nominal value, input energy deviation ΔW estimated to be within ±1% for amplitude, ±(1°÷2°) for phase and ±(10÷20) keV for energy. As for systematic errors, further studies are required.

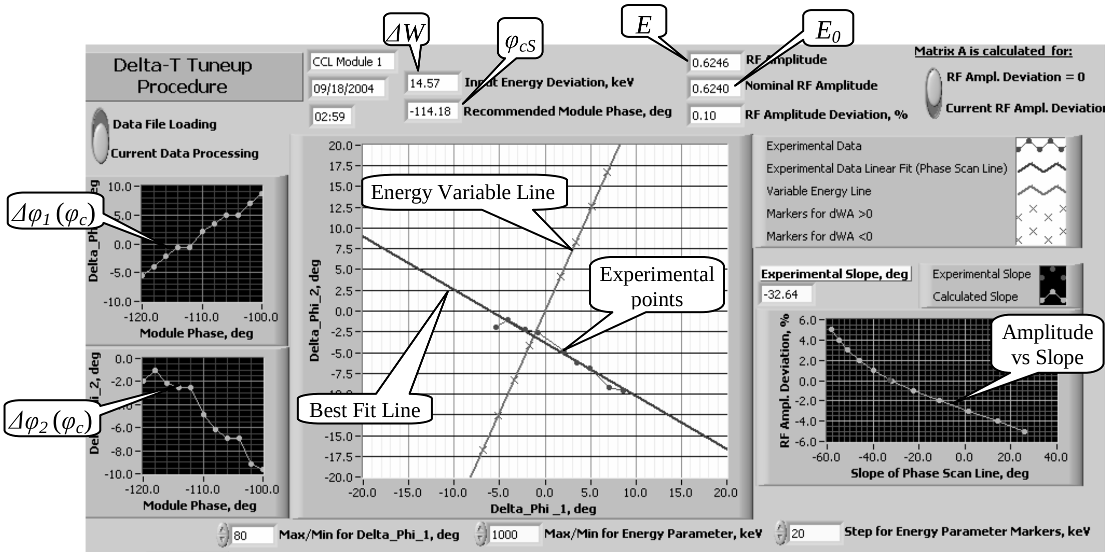

Figure 3: Presentation of data treatment results.

with respect to nominal value and nominal phase set point φ_{cS}. Matrix elements used for data processing can be selected either for nominal amplitude or for the current value found experimentally.

EXPERIMENTAL RESULTS

The Δt procedure has been used to determine rf set points in three of four CCL cavities. The technique described above is correct and precise only in the vicinity of the nominal set point. Initial approximation for the phase was found by observing amplitude of BPM signal, beam loading effect as well as $\Delta\varphi_1$ (φ_c) and $\Delta\varphi_2(\varphi_c)$ functions throughout the full period of accelerating field. In case of sufficient amplitude the above observations enabling clear identification of the longitudinal stability region, its central position being a good approximation for the phase.

In case of CCL Module #1 additional difficulties result from a strong dependence of the energy at the exit of the upstream DTL Tank #6 on its phase. This effect requires additional Δt procedure scans with different DTL Tank #6 phases but as a result a precise value of Tank #6 phase can be found. Figure 3 demonstrates the results obtained after multiple step by step fine adjustment of Tank #6 phase: only 14 keV energy deviation is indicated.

The results for Modules #2 and #3 are shown in fig. 4. For the properly longitudinally tuned upstream part of the accelerator the energy deviation at the entrance of the cavity under study obtained from Δt procedure is within several tens keV. This fact indicates a consistency of experimental results and design parameters and confirms absence of rudimentary errors.

Random errors depend on instability and uncertainty of rf parameters during the scan. With the phase and amplitude uncertainty of 1÷2° and 1÷2 % the errors are

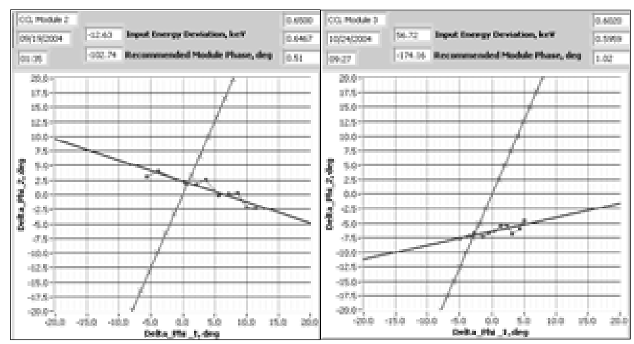

Figure 4: Results of Δt scan for Modules #2 and #3.

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