PRECISE ENERGY MEASUREMENT OF THE CONTINUOUS PROTON BEAM

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Abstract

The method and the results of the proton beam energy measurements carried out on the INR linac injection line are described. The measurements are made by two-cavity buncher. The first cavity is used for a beam bunching and the second one serves as a beam harmonic detector. To find a particle energy destribution a phase difference of RF fields in the two cavities is measured. To measure an absolute value of a beam energy a mechanical movement of the second cavity is used. A cavity displacement corresponds to 2π phase shift of the induced field. Random errors of an absolute energy measurement were due to mainly energy instability and there values were $(1\div4)\cdot10^{-3}$ depending on the experimental conditions. There is a systematic error because a beam energy drift while moving the cavity. This value was $2\cdot10^{-3}$ when special care to decrease energy drift was taken. The accuracy of the energy distribution measurements was of order of 10^{-4}.

Introduction

An absolute value of energy and energy spread at the entrance of ion linac are usually determined measuring a pulse transformer voltage. The measurement accuracy is confined by an impuct noise and an accuracy of calibration. The proton beam energy and an energy spread at the injection line of the INR linac were measured using two-cavity buncher. The method differs from conventional one where the phase difference measurements of induced RF field in two cavities are used[1]. The first cavity as a buncher and the second one as a beam harmonic detector were used. To measure the energy the second cavity is mechanically moved on the distance of $\sim\beta\lambda$, where β is the unknown relative velocity and λ is the RF field wavelength.

Energy spread measurement

The functional circuit used for measurements is shown in Fig.1. The continuous proton beam passes through the first cavity C1 which is fed by RF power amplifier. The second cavity C2 is excited by the bunched beam. The linear relation of phase difference $\Delta\varphi$ of RF fields in two cavities and the relative energy difference $\Delta W/W$ is:

$$\Delta\varphi = -\frac{\pi L}{\beta\lambda}\cdot\frac{\Delta W}{W}$$

To measure phase difference $\Delta\varphi$ the RF signals from C1 and C2 are added on the phase detector PD which consists of phase bridge, two amplitude detectors and differential amplifier. The output PD signal U_{Pd} is proportional to a phase difference of input signals $U_{Pd}=k\Delta\varphi$. If the phase shifter is adjusted to obtain zero output PD signal for a nominal energy W, then the signal due to energy deflection ΔW is:

$$U_{Pd} = -\frac{k\pi L}{\beta\lambda}\cdot\frac{\Delta W}{W}$$

Hence,

$$\frac{\Delta W}{W} = -\frac{\beta\lambda}{k\pi L}\, U_{Pd}$$

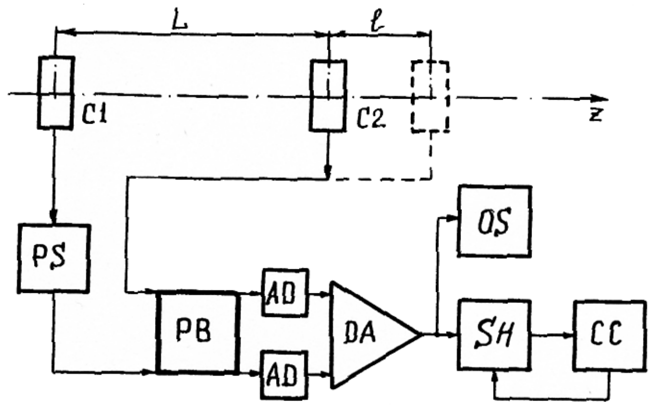

Fig.1. Functional circuit of apparatus. C1, C2 - bunchers, PS - phase shifter, PB - phase bridge, AD - amplitude detector, DA - differential amplifier, SH - sample/hold circuit, OS - oscilloscope, CC - control computer.

The $\Delta W/W$ function is observed with the help of oscilloscope and measured by control computer. The signal from PD output enters to the sample/hold circuit followed by computer. The clocking of sample is adjusted by computer to a selected time within the beam pulse. The gate time is $5\cdot10^{-7}$ s. There are some deterioration of $\Delta W(t)/W$ because of influence of pulse to pulse energy instability. The experimental curve $\Delta W(t)/W$ and rms energy instability are given in Fig.2. The curves were received during one hour at the fixed operation conditions.

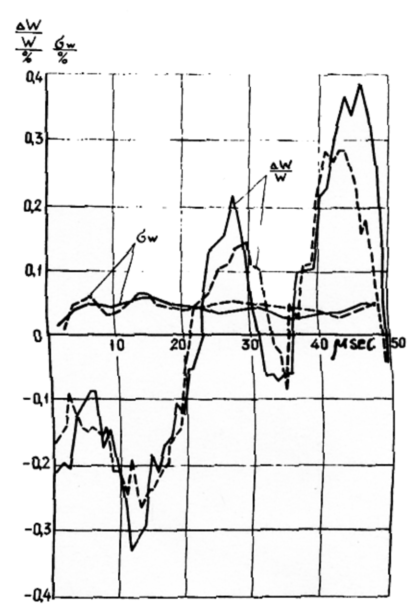

Fig.2. Variation and rms instability of energy within the beam pulse.

Absolute energy measurements

The phase difference between two cavities is proportional to a distance L . Hence , the absolute velocity and energy can be determined by measuring a phase difference change Φ when C2 is mechanically moved on the distance of ℓ . The energy measurement error depends on the accuracy of both distance and phase measurements . The error of Φ measurement can be avoided if the value of ℓ is checked to satisfy $\Phi = \pi \cdot n$ condition , where n=1,2,... . In this case the U_{Pd} signals before and after movement must be equal . The accuracy of U_{Pd} measurement depends on the RF amplitude , the beam current stability and the beam bunching factor change while C2 is moved. To avoid this effects the initial phase difference is adjusted by means of mechanical phase shifter to satisfy $U_{Pd}=0$ condition before the movement and the amplitude of RF field in C1 is regulated to obtain maximum amplitude in C2 . The systematic error of the measurements can lead to unequality of Φ to πn if n is odd. To exclude these possible error n must be even, e.d. desplacement of cavity must be multiple of $\beta\lambda$ .Due to mainly instability of beam energy it is impossible to get the exact equality of signals before and after cavity movement . Therefore the real value of U_{Pd} is determined after statistical processing of multiple U_{Pd} measurements . The displacement corresponding to equality of signals before and after movement is determined by linear interpolaition owing to linearity of PD characteristic in vicinity of zero .

Thus the absolute energy measurement is accomplished in the following way . By using a computer programmable timer the moment of sampling is adjusted to the most stable point of U_{Pd} pulse and all measurements are done in this point . The position of phase shifter is adjusted to obtain U_{Pd} close to zero . Multiple measurements (N=100÷300) of U_{Pd} are done to calculate the average value $U_1 = \langle U_{Pd} \rangle$ and U_{Pd} rms deflection σ_1 . Cavity C2 is mechanically moved until PD signal becomes approximately equal to U_1 .The distance of displacement ℓ ($\ell \approx \beta\lambda$) , the average value of PD signal $U_2 = \langle U_{Pd} \rangle$ and rms deflection σ_2 are measured . The cavity C2 is moved at a distance $\Delta\ell \ll \ell$, U_3 and σ_3 are measured . The accuracy of the ℓ and $\Delta\ell$ measurement is equal to $2\cdot 10^{-5}$ m . The absolute value of a beam average velocity is calculated in the following way :

$$\beta = \frac{\ell}{\lambda} + \frac{\Delta\ell}{\lambda}\cdot\frac{U_1-U_2}{U_3-U_2}$$

The accuracy of energy measurement depends on the errors of $\Delta\ell$, ℓ and U_i measurements as $t_{n\alpha}\sigma_i/\sqrt{N}$,where $t_{n\alpha}$ is Student's coefficient . Let us assume that all above errors are independent , then the total error is:

$$\frac{\delta W}{W} = \left[\frac{\beta^2\gamma^2}{\ell(\gamma-1)}\right]\left\{(\delta\ell)^2 + \left[\frac{U_1-U_2}{U_2-U_3}\delta\Delta\ell\right]^2 + \left[\frac{\Delta\ell}{U_3-U_2}\cdot\frac{t_{n\alpha}\sigma_1}{\sqrt{N}}\right]^2 + \right.$$
$$\left. + \left[\Delta\ell\frac{U_1-U_3}{(U_3-U_2)^2}\,\frac{t_{n\alpha}\sigma_2}{\sqrt{N}}\right]^2 + \left[\Delta\ell\frac{U_1-U_2}{(U_3-U_2)^2}\cdot\frac{t_{n\alpha}\sigma_3}{\sqrt{N}}\right]^2\right\}^{1/2} \qquad (1)$$

The described method was used to measure the injection energy of protons in INR linac for L=0.6 m , λ =1.5124 m , $\delta(\Delta\ell) = \delta\ell = 2\cdot 10^{-5}$ m , σ_i =0.1 V , $\Delta\ell$ =1÷2 mm , N=100÷300 . The value of random error (1) varied from $1\cdot 10^{-3}$ up to $4\cdot 10^{-3}$ depending upon the experimental conditions .

Besides a random error there is a systematic error $\delta W_1/W$ due to energy drift $\delta W_0/W$ during mechanical movement of C2 (about two minutes) :

$$\frac{\delta W_1}{W} = \frac{L}{\beta\lambda}\cdot\frac{\delta W_0}{W}$$

To decrease this error a special care was taken . The value of drift is $2\cdot 10^{-4}$ which leads to systematic error $\delta W_1/W = 2\cdot 10^{-3}$. To decrease $\delta W_1/W$ the distance L must be as small as possible .

The advantage of the described method compairing with the conventional one[1] is that a precise mechanical displacement instead of phase measurements are used . One should notice that the distance measurement error $2\cdot 10^{-5}$ m is equivalent to the phase measurement error of 0.12^{0}.It is possible to improve this error an order of magnitude using a step motor for mechanical movement of cavity .

The method of absolute energy measurement can be extended to higher energy provided n-th beam current harmonic is used . The measurements are possible if $\beta\lambda/2n > \ell_B$, where ℓ_B is a bunch length . The formula (1) remains valid for error calculation . For example, for 160 MeV proton beam of INR linac $\ell_B = \beta\lambda/30$,the value n can be taken 15 and the value of C2 displacement is $5\cdot 10^{-2}$ m . At the exit of linac W=600 MeV , $\ell_B = \beta\lambda/50$, n=20 , $\ell = 6\cdot 10^{-2}$m .

Reference

1. Linear ion accelerators. Ed. by B.P.Murin, V.2,Atomizdat ,Moscow , 1978 (in Russian)