A BEAM ENERGY TIME-FLYING MEASUREMENT SYSTEM

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Abstract

This paper introduces a beam energy time-flying measurement system, which measures the energy of the beam bunch with period structure extracted from SFC. The measurement principle and method are described. A beam energy measurement result and the measurement error analysis of the system are also introduced. This system is on-line and the accuracy of the beam energy measurement is better than 5‰ and non-interceptive beam bunch during the energy measurement.

INTRODUCTION

HIRFL system now is composed of two cyclotrons and a Cooling Storing Ring (CSR). The two cyclotrons are Sector Focusing Cyclotron (SFC) and Separated Sector Cyclotron (SSC), whose energy constants are 69 and 450 respectively. Particle accelerated system adopts a series acceleration model. First, charged particles are produced by an ECR ion source, after passing through the transport line, it axial injects into the SFC for the first time acceleration. The extraction beam of SFC can be used for nuclear experiments or radial injects into the SSC or the CSR for the next acceleration. Some nuclear experiments need an accurate energy beam. In addition, particle series acceleration also needs beam energy match between cyclotrons. So it is necessary to measure the energy of the beam extracted from SFC.

Beam energy is the energy of the standard particle in the beam bunch. Suppose that the standard particle is at the central position of a beam bunch and particle distribution of the beam bunch is symmetrical to the standard particle. Beam energy measurement by the time flying method is to measure the flying time of the standard particle in a beam bunch while it passing through a certain distance. After calculation the speed of the particle, we can obtain some physical quantities of the particle motion, including its energy.

We use two phase probes to measure the time flying and the distance flying of the standard particle. These two phase probes are placed on the beam transport beeline segment inside the beam pipe. The time flying of the standard particle can be calculated by the time parameter that measured by the two phase probes. The distance flying of the standard particle is the distance between the two geometrical central points of the two phase probes.

The beam bunches can pass through during the beam energy measurement because the phase probe is non-interceptive. This system has been online since 2003.

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MEASUREMENT PRINCIPLE

Signal of phase probe

Phase probe is made of a conductor with a shape of cylindrical ring. An electric current signal is induced at the phase probe while a beam bunch passes through it. It is a kind of capacitive probe.

The process that the phase probe produces electric current signal induced by the electric field of a beam bunch is shown in Figure 1. The inductive electric charge of the phase probe is

$$Q(t) = \varepsilon_0 \oiint_S \vec{E}(t) \cdot d\vec{S}$$

where $\vec{E}(t)$ is the electric field produced by the beam bunch, the integral area S is the surface of the phase probe. $\vec{E}(t)$ is a function of time because the position of the beam bunch relative to the phase probe is variant with time.

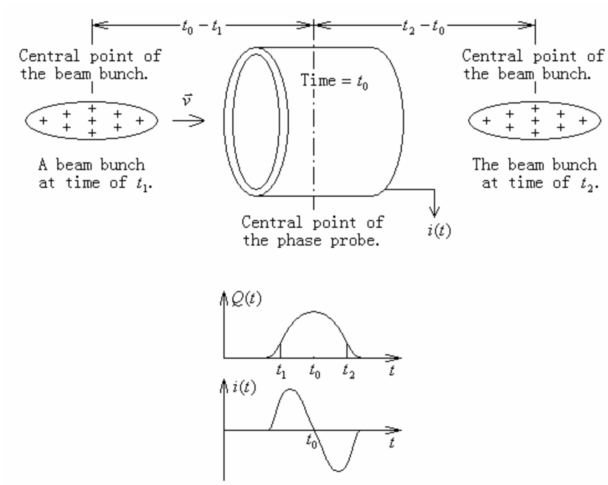

Figure 1: Signal of the phase probe.

The potential function within the beam pipe produced by the beam bunch is expressed with $\varphi(t)$. Then

$$\nabla^2 \varphi(t) = -\frac{\rho(t)}{\varepsilon_0}$$

and

$$\varphi_s(t) = 0$$

where $\rho(t)$ is the electric charge density distribution of the beam bunch, the subscript s of the $\varphi_s(t)$ expresses that the potential is at the inner surface of the beam pipe and the surface of the phase probe. After calculating the potential function $\varphi(t)$, we can obtain the electric field within the beam pipe produced by the beam bunch

$$\vec{E}(t) = -\nabla\varphi(t)$$

The electric magnetic field should be transformed as a four dimensions tensor for the relativity situation.

Now we discuss the relation between the position of a beam bunch relative to the phase probe and the electric current signal waveform of the phase probe according to the geometrical symmetry. According to the symmetrical supposition of the particle distribution in a beam bunch, the electric charge of the phase probe induced by a beam bunch should be the same while the beam bunch is located at the two symmetrical positions to the geometrical centre point of the phase probe, i.e. if

$$t_2 - t_0 = -(t_1 - t_0)$$

then

$$Q(t_2) = Q(t_1)$$

where t_0 is the time when the centre of the beam bunch is at the geometrical centre of the phase probe. So $Q(t)$ is an even function to t_0. To make the $Q(t)$ function has only one maximum by matching the length of the phase probe to the length of the beam bunch. The electric current signal waveform of the phase probe

$$i(t) = \frac{dQ(t)}{dt}$$

will be an odd function to t_0 and passing through zero at the time of t_0. That is, the time when the electric current signal waveform is passing through zero corresponding to the state that the centre of the beam bunch moves at the geometrical centre point of the phase probe.

Time flying measurement

The beam bunches extracted from a cyclotron have a periodic structure. The space between adjacent beam bunches is $2\pi R/h$ while the cyclotron has a single RF cavity, where R is the average radius of extraction, h is the RF harmonic number. The time flying the distance of $2\pi R/h$ is the time period of the RF voltage, expressed with T_{RF}.

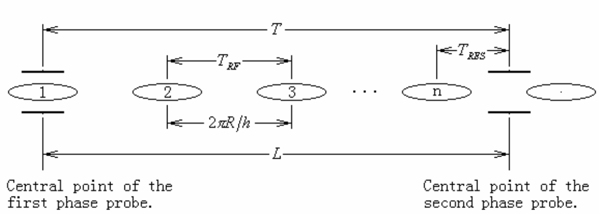

Figure 2: Beam bunches between the phase probes.

The situation of the beam bunches between the two phase probes is shown in Figure 2 while the centre of a certain beam bunch moves at the geometrical centre of the first phase probe. Beam bunch sequence is numbered as Figure 2 shows, where the beam bunch n is the last one between these two phase probes. Assuming the distance between the two geometrical centre points of the two phase probes is L. Then

$$n = \left[\frac{L}{2\pi R/h}\right] + 1$$

where n is an integer, using $[x]$ to express the integral part of x here. The time when the centre of the beam bunch n moves from its present location to the geometrical centre of the second phase probe is expressed with T_{RES}. Then the time flying of the centre of a beam bunch from the geometrical centre of the first phase probe to the second one is

$$T = (n-1)T_{RF} + T_{RES}.$$

T_{RES} can be measured by electric circuit or oscilloscope. For the oscilloscope, the electric current signal waves-form of the two phase probes displayed on the oscilloscope are shown in Figure 3.

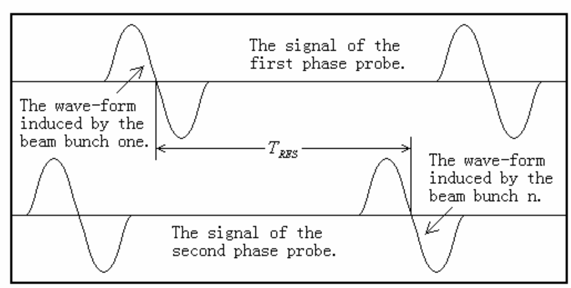

Figure 3: The measurement of T_{RES}.

If an electric current signal of the first phase probe is regarded as to be caused by the beam bunch one, thereafter, the first electric current signal of the second phase probe should be caused by the beam bunch n. Then T_{RES} is the time interval between the two passing through zero times of the two electric current signal waves-form produced by the two phase probes.

T_{RES} should be corrected if the delay times of the two electric current signals amplified and transmitted are different.

Distance flying measurement

Distance flying is the distance between the two geometrical centre points of the two phase probes. Make the distance flying longer to improve the measurement precision of the beam energy. The measurement result of L is 18474.6mm by the laser distance measurement equipment.

BEAM ENERGY MEASUREMENT RESULT

We measured the energy of the beam bunch extracted from the SFC with this system. For a beam of $_{12}C^{4+}$-7.0000MeV/u, the measurement result of T_{RES} is 119 ns, as shown in Figure 4. The measurement energy of the carbon beam is 7.0445MeV/u, it is higher than the theoretic energy by 0.6347%. Where the correctional quantity of the T_{RES} caused by the different delay times of the two electric current signals amplified and transmitted is 1.9 ns.

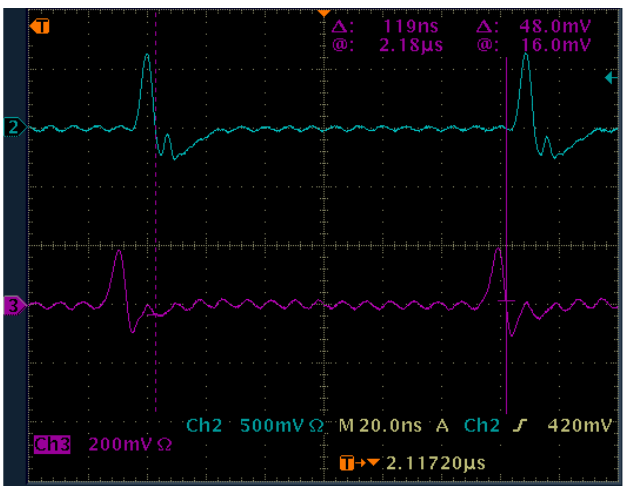

Figure 4: The measuring of T_{RES} .

MEASUREMENT ERROR ANALYSIS

The relative variation of the beam energy is

$$\frac{dW}{W} = \gamma(\gamma+1)\frac{d\beta}{\beta}$$

In the case of low energy, it becomes

$$\frac{dW}{W} \approx 2\left(\frac{\partial L}{L} - \frac{\partial T}{T}\right)$$

The maximum relative error of the beam energy measurement is

$$\frac{\Delta W}{W} = 2\left(\frac{\Delta L}{L} + \frac{(n-1)\Delta T_{RF}}{T} + \frac{\Delta T_{RES}}{T}\right)$$

$$\leq 2\left(\frac{\Delta L}{L} + \frac{\Delta T_{RF}}{T_{RF}} + \frac{2\pi R f_{RF} \Delta T_{RES}}{hL}\right)$$

where f_{RF} is the frequency of the RF voltage.

In the case of ours

$$\frac{\Delta L}{L} \leq \frac{0.5mm}{18474.6mm}, \quad \frac{\Delta T_{RF}}{T_{RF}} \leq 1.05e^{-5}$$

$$R = 0.75m, \quad \frac{f_{RF}}{h} \leq \frac{9.33MHz}{1}$$

and

$$\Delta T_{RES} \leq 0.6ns$$

We obtain

$$\frac{\Delta W}{W} \leq 2.93e^{-3}$$

In which the error part caused by the symmetrical supposition of the particle distribution in a beam bunch has not be included.

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