SYNCHRONIZATION OF LONGITUDINAL HOLLOW ELECTRON BEAM AND ION BEAM IN A STORAGE RING*

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Abstract

In the cooling storage ring, a low-temperature electron beam from the electron cooling device overlaps with a high-temperature ion beam in the storage ring. The overlap occurs at the same average velocity for a certain distance. Through Coulomb interaction, electrons absorb excess energy from ions. This reduces the transverse emittance and longitudinal momentum spread of the ion beam, and increases its phase space density. When cooling a Gaussian-distributed pulsed ion beam with a longitudinal hollow electron beam, the pulses must align at the longitudinal center. This article introduces a synchronization scheme for longitudinal hollow electron beams and ion beams. The scheme includes pulse measurement, triggering delay, synchronization monitoring, and future feedback for automatic correction. This ensures the pulses are always synchronized. The scheme will be used in longitudinal hollow electron beam cooling experiments and will support future investigations into the cooling process.

INTRODUCTION

Electron cooling can improve the quality of ion beams in storage rings by reducing their transverse emittance and longitudinal momentum spread, increasing the phase space density of the ion beams, and thus enhancing collision luminosity.

The basic principle of electron cooling involves overlapping an ion beam with an electron beam moving at the same average velocity. Through Coulomb interactions, the hotter ion beam transfers excess energy to the cooler electron beam, thereby reducing the transverse emittance and longitudinal momentum spread of the ion beam and achieving a higher phase space density.

The electron cooling force is proportional to the electron density, and the cooling force presents a nonlinear distribution. Within a certain range, the cooling force is linearly related to the relative velocity difference between the ion and electron [1].

A direct current electron beam was used in the traditional low-energy electron cooling, which is continuous and generated by an electrostatic high-voltage accelerator with a uniform longitudinal distribution [2].

At higher energy levels, the electron beam is generated by a radio-frequency accelerator, and it consists of a series of short pulses with a uniform distribution of electron beam intensity in the longitudinal direction [3-5].

The ion beam in the storage ring presents a Gaussian distribution in the longitudinal direction. Under continuous electron cooling, the ion beam distribution deviates from the Gaussian distribution, forming a dense core in the central region and a tail in the edge region [6].

A novel solution was proposed in the reference [7]. A longitudinal hollow electron beam was proposed. The traditional DC electron beam in the electron cooler was modulated into an electron bunch with different longitudinal distributions. The stronger cooling was expected in the tail of the ion beam, and the weaker cooling was performed in the tail of the ion beam. The particle on the outside will experience stronger cooling and will be driven back into the center of the ion beam.

The longitudinal hollow electron beam is expected to obtain benefits in the following aspects.

- Suppress intra-beam scattering.
- Control the longitudinal distribution of the ion beam.
- Make the beam bunch contain as many particles as possible.
- Increase the lifetime of ion beams in the storage ring.

The basic requirement for electron cooling is that the electron beam can completely envelop the ion beam. Therefore, it is required that the center of the ion beam pulse and the electron beam pulse remain consistent in the longitudinal direction.

The ion beam pulse rotates in the storage ring with a bunch length of approximately 400 nanoseconds before electron cooling. It presents a Gaussian distribution in the longitudinal direction.

The electron beam is generated by an electron gun, which is a capacitive structure. The voltage applied to the control electrode of the electron gun determines the electron beam intensity. If a pulse cosine waveform voltage is applied to this electrode, a cosine waveform electron beam pulse will be obtained. The pulse length is approximately 500 nanoseconds. The frequency of the electron beam pulse output is exactly the same as the revolution frequency of the ion beam in the storage ring.

In order to ensure that the electron beam and ion beam pulses are always synchronized, the generation time of the electron pulse needs to be adjusted to ensure the centers of the two pulses overlap, and the synchronization is less than 1 nanosecond.

Some primary investigations have been performed in some references, such as the formation of a bunched electron beam at the electron cooler of CSRm [8], double-bunch of electrons [9], and a longitudinal multi-bunch chain of electrons [10]. Some electron cooling experiments using a bunched electron beam have been completed in the CSRm storage ring, in collaboration with the team from Jefferson Lab [11-16].

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SYNCHRONIZATION OF THE ELECTRON BEAM AND THE ION BEAM

The basic requirement for electron cooling is that the electron beam overlaps with the ion beam. In the longitudinal direction, the electron beam pulse should be longer than the ion beam pulse. The length of the ion beam bunch will decrease during the cooling process. Therefore, the longitudinal centers of both beam pulses must always remain consistent. In this case, the ions at the pulse edge region always receive stronger cooling than those at the central region.

Maintaining synchronization between the ion beam and electron beam will be a key issue in achieving effective electron cooling.

The electron cooling device is equipped with beam position monitors at both ends, which can measure the positions of the electron beam and ion beam in the cooling section of the electron cooling device. The beam position monitor at the entrance can be used to measure the flight time of the electron beam reaching the electron cooling section, while the beam position monitor at the exit can be used to measure the flight time for the electron beam leaving the electron cooling section. Two measurement results can be used for mutual calibration and inspection.

Due to the electron gun's capacitive load, its response time and any possible time delay relating to the high-voltage power supply should be measured beforehand. The time from triggering the power supply to generating the control electrode and electron beam pulse waveforms should be measured in advance. Furthermore, there is a distance from the electron gun's cathode to the entrance of the cooling section, where the beams overlap. The electron beam also takes time to travel through this region.

Several beam position monitors are installed in the storage ring to measure the position of the ion beam. When the ion beam passes through the beam position monitor, a signal representing the ion beam is induced, which serves as a reference signal for measurement and triggering.

Through repeated measurements, the measurement results are calibrated and mutually verified to determine the arrival and departure times of the ion beam and electron beam pulses in the electron cooling section, as well as the triggering and response times of the high-voltage pulse power supply. These two parameters are set in the synchronous control system.

VOLTAGE ON THE CONTROL ELECTRODE OF THE ELECTRON GUN

In electron cooling, the cooling force is proportional to the electron density, while the cooling time is inversely proportional to the electron density. When the anode voltage of the electron gun is fixed, the current intensity of the electron beam is proportional to the control electrode voltage of the electron gun. If a constant voltage is applied to the control electrode, the electron beam is a direct current (DC). When a pulsed voltage is applied to the control electrode, the electron beam becomes a pulsed current. If the amplitude of the pulsed voltage on the control electrode remains constant over time, the pulsed electron beam current is also constant, producing a uniform pulsed current. However, if the amplitude of the voltage applied to the control electrode varies over time, the pulsed current also changes. When the amplitude of the applied pulsed voltage follows a certain regular shape, the corresponding distribution of pulse waveform is obtained.

PATH LENGTH AND FLY TIME OF ION BEAM IN CSRM

The circumference of the storage ring CSRm is 161 meters. A $^{12}C^{6+}$ ion with an energy of 7MeV/u rotates in the CSRm storage ring at a frequency of 227kHz and a period of approximately 4400 nanoseconds.

The path length from the cathode emission surface to the entrance of the cooling section is 1.942 m. The flight time for the electron beam from the cathode to the entrance of the cooling section is 53 nanoseconds. The path length from the exit of the cooling section to the bottom of the collector is 2.262 m. The flight time of the electron beam from the exit of the cooling section to the collector is 62 nanoseconds.

The path length from the beam position monitor (BD22PXY1), which is located upstream of the electron cooling device in the storage ring, to the entrance of the cooling section is 76.02 m. The flight time of the ion beam from the beam position monitor (BD22PXY1) to the entrance of the cooling section is 2077 nanoseconds. The path length from the exit of the cooling section to the first beam position monitor (BD24PXY1), which is located downstream of the electron cooling device in the storage ring, is 7.963 m. The flight time of the ion beam from the exit of the cooling section to the beam position monitor (BD24PXY1) is 220.6 nanoseconds.

SYNCHRONIZED IMPLEMENTATION SCHEME

A beam position monitor in the storage ring serves as the probe to measure the time signal of the ion beam pulse reaching that position. After this signal is amplified and processed, the center position of the ion beam pulse is found, and this signal is used as the trigger signal. After electro-optical conversion, it is transmitted to the high-voltage power control system of the electron gun through an optical fiber.

Based on the parameters of the species and the energy of the ion beam in the storage ring, the flight time of the ion beam from a beam position monitor in the storage ring to the beam position detector at the entrance of the electron cooling section is measured.

And then, the flight time of the electron beam pulse after the electron gun was triggered to reach the beam position detector at the entrance of the electron cooling section is measured. In this measurement, the response times of the high-voltage pulse power supply, high-voltage pulse switch, and electron gun were determined.

The time relationship between the ion pulse and electron pulse was established according to these measurements, and the delay time from the trigger to the generation of the electron pulse was determined.

Finally, according to the measurement results, the delay time was finely tuned and set previously. The longitudinal center of the ion beam pulse coincides with that of the electron beam pulse.

PREVIOUS MEASUREMENT OF ELECTRON BEAM AND ION BEAM

A certain energy ion beam undergoes rotational motion in the storage ring with a certain frequency and period. The circumference of the storage ring is fixed, and the precise flight time for the ion beam from one position to another can be measured in the storage ring.

The electron beam departs from the cathode surface of the electron gun, passes through a solenoid and a toroid, and merges and overlaps with the ion beam in the cooling section. After interaction, the electron beam separates from the ion beam and then passes through another toroid, a decelerating section, and reaches the collector. The path length of the electron beam is also fixed. The flight time for the electron beam from the cathode surface of the electron gun to the beam position monitor located at the entrance of the cooling section can be measured precisely.

If the beam position monitor BD22PXY1, which is located upstream of the electron cooling device in the storage ring, is selected as the initial position for measuring the ion beam pulse. The path distance is approximately 76 meters from the beam position monitor at the entrance of the cooling section. The ion beam signal obtained from this monitor is amplified and processed as a trigger signal, which is transmitted through an optical fiber to the high-voltage power supply control system of the electron gun. After triggering, the power supply outputs a pulse voltage, which is loaded onto the control electrode of the electron gun to generate electron beam pulses. The flight time of the electron beam pulse from the trigger moment to the beam position monitor at the entrance of the cooling section is measured carefully.

Here, the total time includes the ion beam signal acquisition time, amplification processing time, electro-optical conversion time, optical fiber transmission time, trigger signal electro-optical conversion time, high-voltage power supply response time, high-voltage switch response time, and electron gun response time, etc.

Comparing the flight time difference between the ion beam and the electron beam at the beam position monitor at the entrance of the cooling section, the delay time can be determined for the trigger signal. The delay time of the trigger signal will be set previously. In this situation, the ion beam and electron beam reach the entrance of the cooling section simultaneously, achieving longitudinal synchronization between the ion beam and electron beam.

MONITORING AND CONFIRMATION OF SYNCHRONIZATION

After the interaction between the ion beam and the electron beam in the cooling section, the electron beam and the ion beam separate. The electron beam passes through a toroid, a deceleration section, and reaches the collector. And the ion beam continues to rotate in the storage ring.

The flight time of the electron beam from the beam position monitor at the exit of the cooling section to the collector can be measured. At the same time, the flight time of the ion beam from the beam position monitor at the exit of the cooling section to the first beam position monitor BD24PXY1, which is downstream of the electron cooling device in the storage ring, can also be measured synchronously. Due to the same average velocity of the ion beam and electron beam, the synchronization of the ion beam and electron beam can be monitored by the flight time difference at different path distances. The path length experienced by electrons and ions during their respective movements is fixed and measurable.

If the ion beam and electron beam depart from the same position, the flight time is fixed. When the difference between the measurement results and the theoretical value is less than 1 nanosecond, it indicates that the ion beam and electron beam reach synchronization.

VERIFICATION OF SYNCHRONIZATION

After electron cooling, the ion beam and electron beam will separate at the exit of the cooling section and move along their respective orbits. With the help of measuring the difference in flight time at different distances, the synchronization between the electron beam and the ion beam will be verified. There are two pairs of electrodes in each beam position monitor. One pair will be used to measure the signal of the electron beam, and the other pair will measure the signal of the ion beam. The flight times of the ion beam and electron beam will be measured simultaneously. In order to check the measurement results, the signal of the electron beam will be measured alone in the case of turning off the ion beam, and vice versa. To further verify the accuracy of the measurement, the electrode pairs of the beam position detector used for measurement can be exchanged to eliminate errors caused by different electrode pairs in the measurement. Comparing the measurement results with the theoretical results, if the flight time difference is less than 1 nanosecond, it indicates that the ion beam pulse and the electron beam pulse have reached synchronization.

SUMMARY AND PROSPECT

In summary, a solution is the application of nanosecond-level synchronization of two pulses in storage rings and electron cooling devices. By utilizing existing components in the storage rings and electron cooling devices, nanosecond-level synchronization of ion beam pulses and electron beam pulses can be implemented, and real-time monitoring and confirmation of synchronization can be obtained.

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