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TIME-OF-FLIGHT TECHNIQUE FOR MATCHING ENERGIES IN ELECTRON COOLER*

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Abstract

Electron cooler with bunched electron beam is being commissioned at the Relativistic Heavy Ion Collider at BNL. For the cooler to operate the energies of the hadron and electron beams should be matched with high accuracy. We have developed time-of-flight technique based on the phase measurement of the beam induced signal in the beam position monitors separated by a drift. We present the method description and experimental results.

INTRODUCTION

The purpose of the low energy RHIC electron cooler is (LEReC) is to provide luminosity improvement for the operation at low energies [1]. Unlike other electron coolers LEReC uses bunched electron beam accelerated to the desired energy using RF cavities [2].

For the successful cooler operation, the energy match between hadrons and the electrons should be better than 10-3. Such accuracy is hard to achieve with low-energy beams (relativistic factor γ=4-6). For this purpose, for redundancy three techniques have been developed. The 180-degree magnet and recombination monitor are described in [3]. This paper is focused on the approach based on measurement of the phase difference of two signals excited by the beams on two beam position monitors (BPMs) with RF processing.

For the two BPMs separated by distance Ldrift the propagation time t of the bunch depends on its relativistic factor

$$t = \frac{L_{drift}}{c\sqrt{1-1/\gamma^2}} \tag{1}$$

where c is speed of light and phase difference ϕ at processing frequency F_{proc}

$$\phi = 2\pi t F_{proc} \tag{2}$$

Measured phase difference is affected by the delays in the cables and shifts in the electronics which makes it difficult to use this technique for absolute measurement of the beam relativistic factor. However, if the drifts are small then phase information can be used for matching of the beam velocities. For difference in relativistic factor Δγ the phase difference will be

$$\Delta\phi = \frac{2\pi F_{proc} L_{drift}}{c\sqrt{1-1/\gamma^2}} \frac{1}{\gamma^2} \frac{\Delta\gamma}{\gamma} \tag{3}$$

From Eq. 3 one can see that sensitivity to the energy change quickly goes down with beam energy and this technique is applicable for not very relativistic beams. Having long distance between pick-up electrodes increases sensitivity, therefore they were placed at the ends of the cooling sections. For the highest energy the accuarcy

The layout of the LEReC accelerator is shown in Fig. 1. The electron beam is generated by a DC gun with photocathode and then accelerated with superconducting 704 MHz booster cavity. The electron beam structure is defined by a drive laser and the structure is formed by trains of the 30 bunches separated by 1.4 nsec and repetition frequency of 9.4 MHz to match the hadron beams circulating in RHIC.

There are five implemented time-of-flight (ToF) subsystems. The first one is in the injection line and uses two BPMs separated by 2.273 meters. The signal is processed at 713.4 MHz frequency to avoid interference from the RF field from the booster cavity. Each cooling section has two subsystems one at high frequency (704.0 MHz) to monitor energy stability of the electron beam and one at low frequency (9.4 MHz) to perform matching of the relativistic factors. In the yellow ring distance between pick-up electrodes is 17.857 meters and in the blue ring it is 18.958 meters.

Signal processing is performed in the BPM modules [4] with modified firmware. The two raw signals pass from separate pick-up electrodes through the analogue filters and digitally processed in the same module to the desired bandwidth. Processing in the same module is critical to avoid systematic errors introduces by different ADC clocks.

Since the signal level is sufficiently high then the Johnson noise is well below the noise due to the ADC clock jitter σ_{clock}. The signal to noise ratio in the phase is

$$S/_N = \phi/_{2\pi\sigma_{clock}F_{proc}} = \frac{t}{\sigma_{clock}} \tag{4}$$

As one can see it does not depend on the processing frequency. Choosing the low processing frequency reduces the cable losses and phase shifts.

We have utilized the specialized modules but signal processing can be done in the regular BPMs – the amplitude of the signal used for position and phase for relativistic factor monitoring.

EXPERIMENTAL RESULTS

Verification of the proposed method was done using measurement of the phase difference between two BPM

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signals in the injection part as a function of the booster cavity voltage. The measured dependence is shown in Fig. 2.

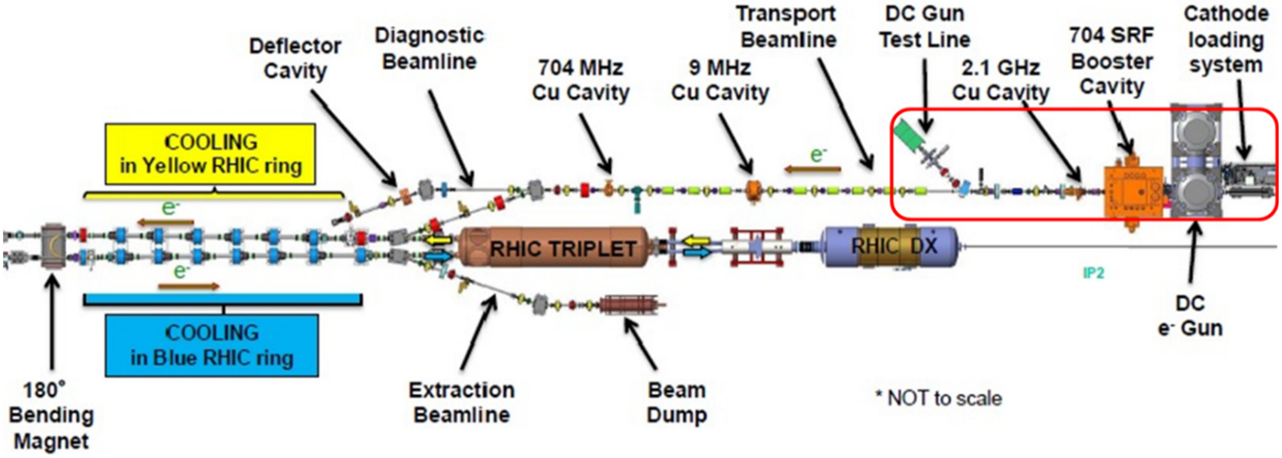

Figure 1: Layout of the LEReC electron accelerator. The electron beam is generated by DC photogun and accelerated by 704 MHz booster cavity. 9 MHz cavity provides compensation for the beam loading, while 2.1 GHz and 704 MHz copper cavities provide for small energy spread. The electron beam interacts first with hadrons circulating in the yellow RHIC ring and after 180-degree turn with hadrons circulating in the blue ring.

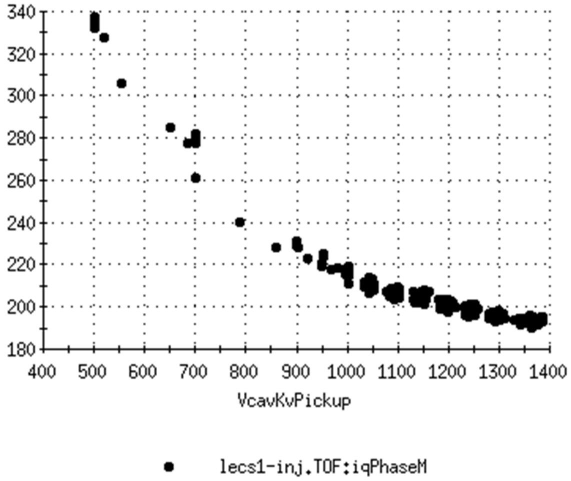

Figure 2: Dependence of the phase difference (in degrees) between two BPM signals vs booster cavity voltage in kV. Electron energy from the gun is 375 keV.

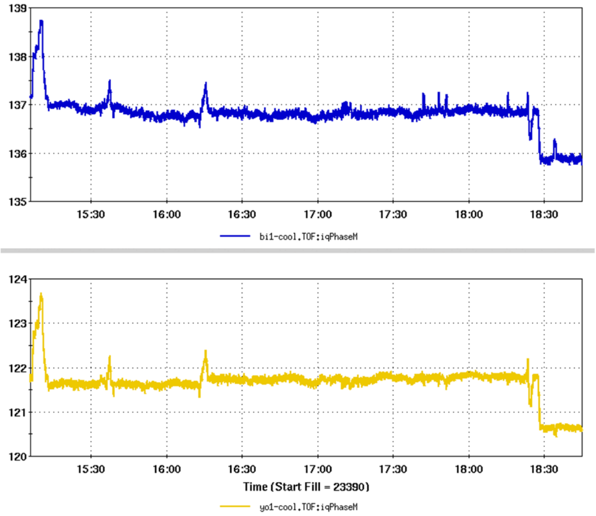

Figure 3: Time dependence of the phase difference in the high frequency ToF subsystems in the blue and yellow cooling sections.

In general, the data on the Fig.2 behave in accordance with Eq. 1 and Eq. 2. However, the attempt to fit the with three parameters (gun voltage, initial phase shift, and scaling factor for the booster voltage) gave unreasonable values. There are two main reasons of it: a) due to the substantially non-relativistic beam from the gun the energy gain in the booster cavity is not proportional to the cavity voltage, b) for the same reason cavity phase needs to be adjusted for each voltage.

Fig. 3 shows phase differences in the yellow and blue cooling sections in the high frequency subsystems with 13.8 mA of the electron current present. The energy changes obtained with 180-degree dipole during the same time period are shown in Fig. 4. Correlation of phases and energy is clear.

Fig. 5 shows the phases obtained with low frequency systems excited with the electron beam. To obtain the desired accuracy the matching of the relativistic factors the phase difference should be determined with 0.004°. While the r.m.s. noise can be easily suppressed by averaging the drifts are substantial and are the limiting factor for this system. We also observed steps in the phase readings similar to one shown in Fig. 5. Their origin is unknown.

Figure 4: Electron beam kinetic energy during the same time period as Fig. 3.

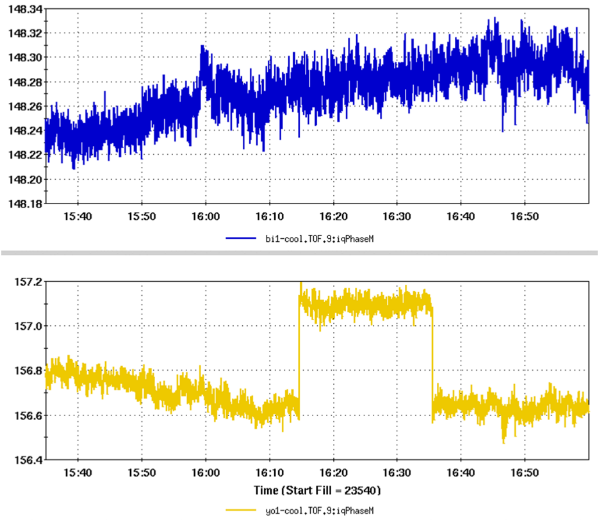

Figure 5: Time dependence of the phase difference in the low frequency ToF subsystems in the blue and yellow cooling sections when only electron beam is present. The phase noise is substantially smaller than for the high frequency subsystems.

For the hadrons circulating in the both RHIC rings at the same energy intended for the LEReC operation the phase differences are shown if Fig. 6. There is repeatable fill dependence of the phase in both systems with amplitude of 0.1°. There are also uncorrelated phase drifts on order of 0.2° in both systems (similar to the data shown in Fig. 5). The difference between electron beam phase and hadron beam phase is about 1.5° degrees which is well above the requirements. It should be noted that the measurements were separated in time by two weeks and long-term drift is a probable cause.

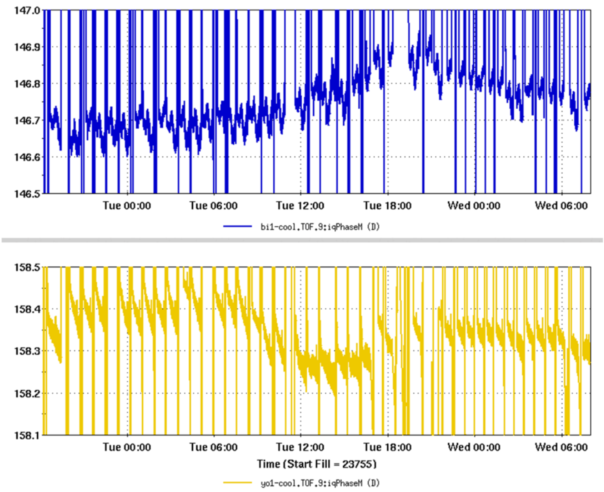

Figure 6: Time dependence of the phase difference in the low frequency ToF subsystems in the blue and yellow cooling sections with hadrons circulating in both rings. The time span is over two days with multiple fills.

CONCLUSIONS

The time-of-flight system for matching of the relativistic factors of the electron beam and hadron beams circulating in RHIC showed close but still not sufficient accuracy. We did not try out to bring the system to the specification because goal of matching was achieved by other means.

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