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RHIC Injection Kicker Measurement and Emittance Growth Simulation

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Abstract

RHIC operations with gold beams at energies below the design injection energy of 10.5 GeV/N requires the injection of long bunches to mitigate the effects of IBS and space charge [1]. Bunch lengths can be up to 60 ns in length at 3.85 GeV/N (to be compared to normal 35 ns proton bunches at 25 GeV). Injection of such long bunches requires revisiting the details of the injection magnet pulse to insure sufficient transfer efficiency from the AGS to RHIC. This note details beam-based measurements of the deflection provided by the injection kicker magnet as a function of bunch arrival time using two different terminating resistors: a 25 Ω resistor, which has been standard for several years, and a 40 Ω resistor, which more nearly represents a matched termination. The measured deflection curves are then used as inputs into a simple simulation to estimate the effects of the kicker rise time and shape (flatness) on the transverse emittance of the injected and circulating bunches. The simulations indicate that there is a 12% intrinsic vertical emittance growth associated with the standard 25 Ω kicker configuration not only for the long low energy bunches, but also for nominal 35 ns long polarized proton bunches at the nominal 25 GeV injection energy.

Deflection measurement

The RHIC injection kicker consists of four separate modules, each consisting of a magnet and a Blumlein pulser. The magnets are travelling wave structures with a measured propagation time of ~37 ns across the 1.1 meter magnet [2]. The propagation time is comparable to the rise time of the pulse from the Blumlein and therefore contributes substantially to the effective rise time of the magnet (i.e. to the rise time of the integrated field as sampled by the injected beam). To measure the actual deflection experienced by the beam, bunches were injected with varying delays of the kicker pulse relative to the bunch arrival and the amplitude of the deflection inferred from the downstream beam position monitors.

In order to make the measurement with minimal losses in the injection kicker beam pipe, we prepared the beam in the following way. Gold beam at 10.5 GeV/N is extracted from the AGS and injected into RHIC with the injection kickers timed so as to miss the beam entirely. Injection into RHIC is accomplished instead by using a vertical dipole corrector adjacent to the kickers (yo5-tv9) set to 1.3 mrad, which is sufficient to guide the beam into the RHIC pipe. Beam is transported to IR8 where local orbit correctors are used to direct the beam horizontally onto fully inserted collimators. Beam loss monitors and BPM readings confirm that the whole beam is stopped in one turn. The delay of each kicker module is then timed to coincide with the beam arrival and scanned over nearly the full range of the kicker pulse. Only one module of the four is timed in for any given injection, so the deflection is at most 25% of the nominal angle. Beam is transported to the collimators with relatively little loss and BPM readings can be obtained over the full delay range without further changes to the accelerator. The setpoint voltage for the kicker is 30.5 kV in all cases. The beam is longitudinally quad-mode pumped at AGS extraction to produce small bunch lengths (6 ns at the base) so that each bunch samples as little of the kick duration as possible, providing a high resolution 'probe' of the kicker pulse.

For this measurement two of the kicker modules were terminated with a 25 Ω resistor (modules 3 and 4) which has been the standard operation configuration for RHIC since 2003 [2]. Modules 1 and 2 use a 40 Ω termination. The resulting orbit deflection as a function of the kicker delay is shown in Fig. 1. The rms difference in the vertical orbit caused by the kicker is converted into a deflection angle θ using

$$\langle y_i \rangle = \theta\sqrt{\beta_k}\langle\sqrt{\beta_i}\ \sin\varphi_i\rangle \tag{1}$$

where y is the vertical position, β the vertical beta function, the angle brackets indicate an rms over all the BPMs (of index i) between the kicker and the beam termination point at the collimators and subscript *k* denotes a value at the kicker location. The model value for the rms quantity on the r.h.s of equation 1 for the ramp named Au18-26GeV-e0 at injection is ~4.0$\sqrt{m}$). The values for β at each kicker for modules 1-4 in this lattice are 40.9, 35.2, 30.0 and 25.4 m respectively.

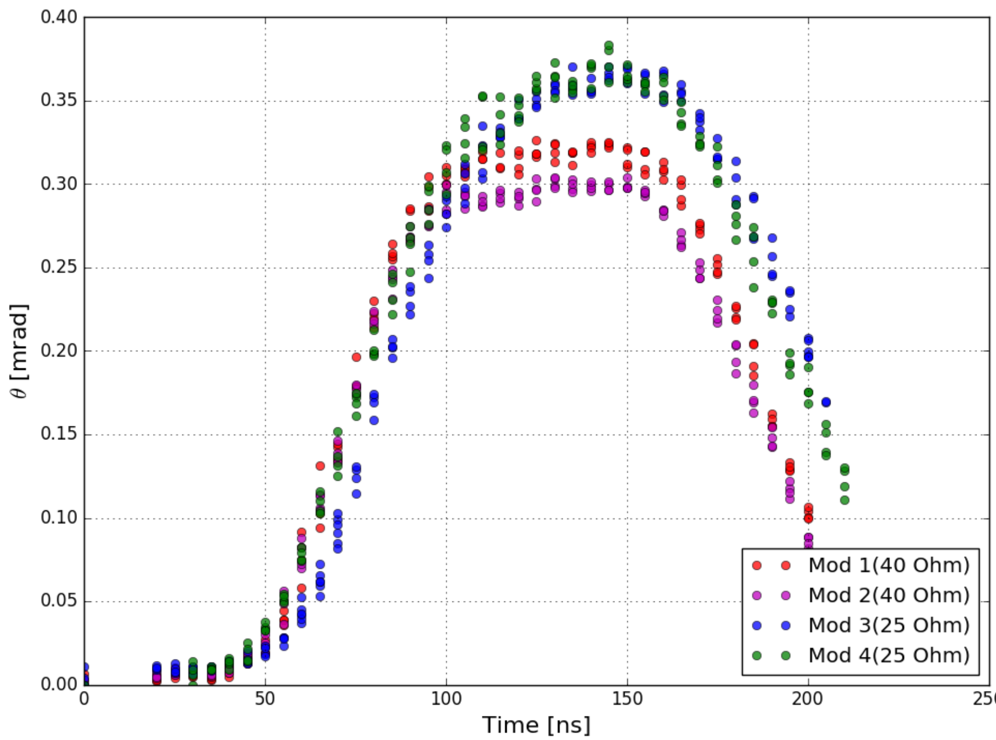

Figure 1 : Deflection of individual kicker modules as a function of delay. Horizontal offset is arbitrary. Kicker deflection angle is inferred from model optics values and measured rms orbit changes caused by the kicker at each delay time.

The modules with 25 Ω (#3 and 4) have an approximately 100 ns rise time with very short or no flat region near the peak. This is in line with expectations and previous measurements of this kind [3]. The modules with the 40 Ω resistors have a rise time of 55-60 ns and flat region (with small slope) of about 50 ns. The 40 Ω modules have a peak amplitude 15-20% lower than the 25 Ω modules for a fixed applied voltage from the pulser.

Linearly scaling the measured peak of 0.36 mrad/module kick to four modules and to a nominal setpoint of 34 kV yields a total deflection of 1.6 mrad, which is 85% of the design value given in the RHIC design manual [4].

Simulation of emittance growth

In order to simulate the time-dependent deflection of the kicker, a kick function (angle as a function of arrival time) is created by using a cubic spline to make a smooth approximation of the measured deflections (Figure 2). The total kick is simulated by choosing one module and scaling the peak kick to the measured operational value value of 1.56 mrad (this is the equivalent of assuming four identical modules). The kick is delivered all at once (as if the kicker is a thin element) and thus the effects of relative timing errors between the modules is also ignored in the present study. In this case module #1 is taken as representative of the 40 Ω kicker and module #4 of the 25 Ω configuration.

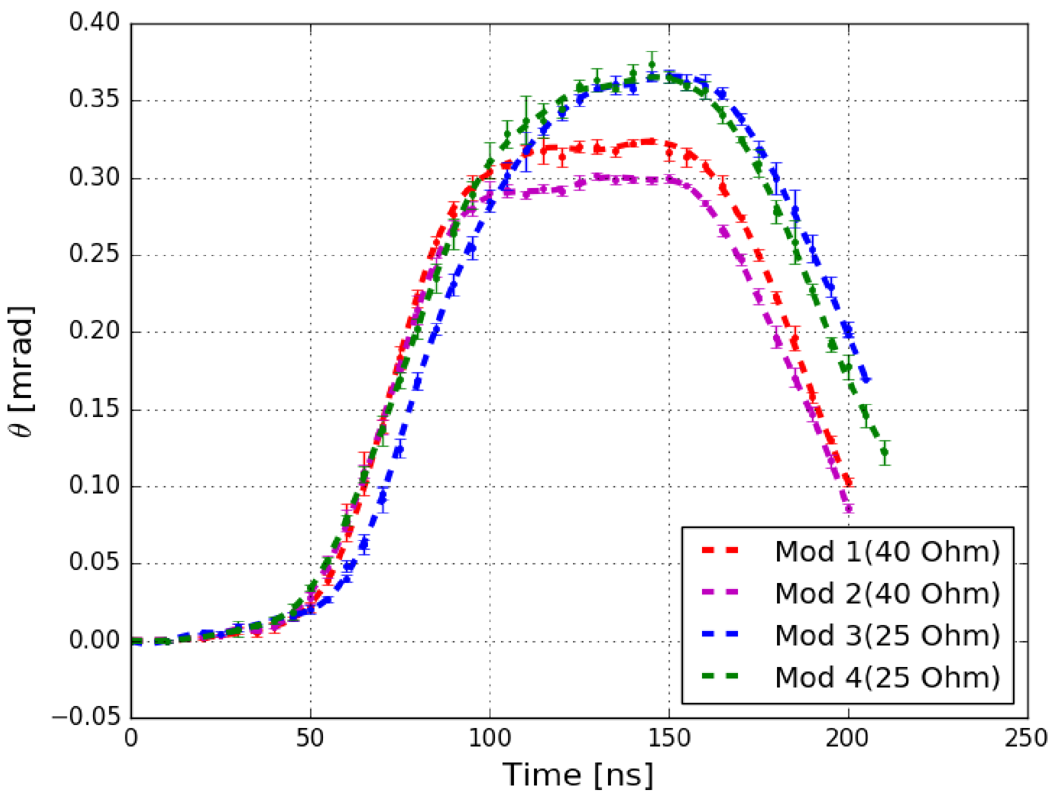

Figure 2: Approximations of the deflection as a function of time using cubic splines to the measured data.

The transverse emittances of bunches injected into RHIC are affected by the shape of the injection kicker pulse in two ways. First, if the kick from the magnet is not perfectly constant during a bunch transit, then the particles in a bunch of finite length will each experience a different kick according to their different arrival times as they are injected. We will assume here that the center of charge of the injected distribution is always matched exactly to the closed orbit by magnets in the transfer line, so that the transverse emittance of the incoming beam is only affected by the flatness of the kicker pulse at the bunch arrival time.

Second, the rising edge of the kicker pulse needs to be fast enough that it reaches the optimal current for the injected bunch without perturbing a significant fraction of the previously injected circulating bunch. To the extent that this is not true, the previous bunch will experience an additional vertical deflection and grow in emittance. The bunch spacing for 111 bunch operation in RHIC is 110 ns at 3.85 GeV/N (this changes slightly to 107 ns at 10.5 GeV/N).

The beam is given a Gaussian distribution in the vertical and longitudinal directions (the horizontal plane is ignored). The model optics at the kicker are used to generate a transverse distribution (assumed perfectly optically matched) of a given emittance. Each particle is assigned an arrival time at the kicker from a Gaussian distribution with a given mean (the arrival time of the center of the bunch) and sigma (rms arrival time of a given particle relative to the central particle). The deflection at the arrival time of each particle is applied and the resulting transverse distribution is allowed to filament out (in this case no tracking is performed, it is assumed that transport is perfectly linear, so that each particle stays on its original transverse invariant ellipse, but is assigned a random phase).

The vertical distribution is then kicked again in the same way, but using the kicker function shifted by 110 ns, simulating the effects of the kick on the same distribution, but this time as the circulating bunch during the next injection, when it is kicked away from the closed orbit by the rising edge of the pulse.

Shown in Figure 3 is the vertical emittance growth seen by a low energy bunch. Depicted are the growth of the bunch caused by its own injection and the injection of the subsequent bunch as well as the overall emittance growth.

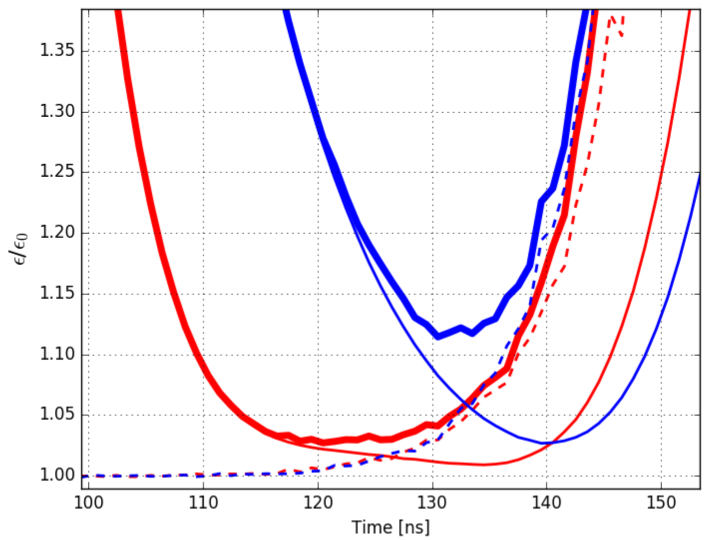

Figure 3: Vertical emittance growth factor for 40 Ω kickers (in red) and 25 Ω kickers (in blue). Thick solid lines indicate the total emittance growth seen by a single bunch. The emittance growth experienced during injection and while circulating are indicated by thin solid and dashed lines, respectively. This simulation is for a typical low energy bunch with relativistic γ=4.1, initial normalized rms vertical emittance of 1.2 μm and a 10 ns rms bunch length.

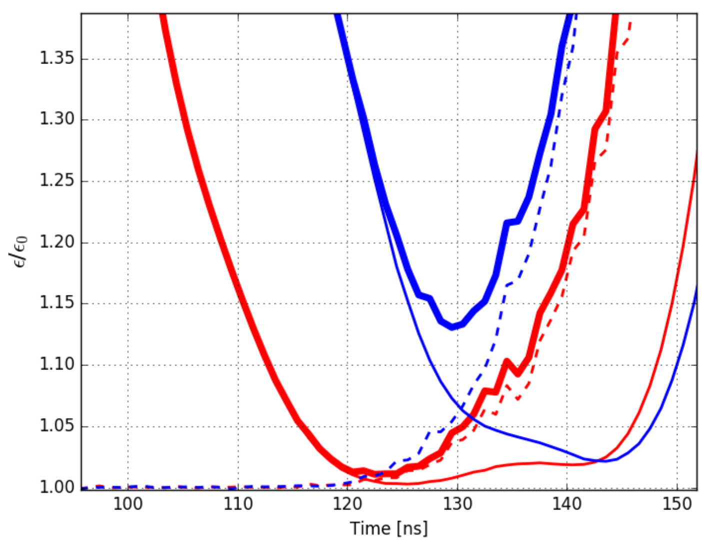

Figure 4: Vertical emittance growth factor for 40 Ω kickers (in red) and 25 Ω kickers (in blue). Quantities are the same as for Figure 3, but this simulation is for a typical polarized proton bunch with a relativistic γ=25.5, initial normalized rms vertical emittance of 1.2 μm and a 6 ns rms bunch length.

Discussion

As one can see from Figs 3 and 4, the optimal vertical emittance growth scenario for both 3.85 GeV/N Au and 25.5 GeV protons is an emittance growth of about 12.5%. This is for kickers with optimal timing with respect to the beam as well as relative to one another. This is consistent with operational experience at nominal injection energies, where it has been observed that there is always trade-off between optimal kick for the incoming bunch and preservation of the emittance of the preceding circulating bunch. The margins are quite small for both beams: 10 ns mistiming from the optimal raises the emittance growth from 15 to 25%. This is to be compared to the optimal scenarios with 40 Ω termination, which are 3% and 1% emittance growths for the 3.85 GeV/N Au and 25.5 GeV protons, respectively. The spec for emittance growth due to the injection kicker is 6% (derived from Table 5-5 'Parameters and Tolerances of Beam Transfer", of the RHIC Design Manual [4])

It can also be seen that the tolerance for timing errors for polarized protons is actually lower than that for low energy Au despite the shorter proton bunches. This is because of the substantially smaller geometric emittance, which increases the sensitivity of the fractional emittance growth to dipole errors.

Note also that the optimal timing for the injection of bunches on the 25 Ω (standard) kicker is not at the peak. The peak, which is also the flattest part of the pulse, occurs late in the pulse (150 ns in the plots), but owing to the kick on the circulating bunch, the incoming beam cannot be placed there.

Conclusions and recommendations

Beam-based deflection measurements were made of the RHIC yellow injection kicker modules using two different terminating resistors. The matched 40 Ω resistor configuration has rise time and flatness characteristics that are clearly preferable for low energy operation. Simulation of the expected vertical emittance growth for the kick function produced by both resistors shows that the optimal emittance growth attainable in the standard 25 Ω configuration is about 12% for both 3.85 GeV/N Au beam and polarized proton beam at the standard injection energy of 25.5 GeV.

Since the mismatched 25 Ω resistor configuration imposes operational cost on both low energy Au and polarized protons, we recommend re-examining the kicker lifetime concerns at 38-40 kV, which would be the necessary voltage to inject polarized protons using the 40 Ω resistors. This is not an unprecedented voltage: according to the note by Hahn [2], "In the 2003 run, the kicker with 25 Ω termination runs conservatively at ~38 kV".

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