# Transient Measurement of the Betatron Phase Advance Around the Recycler Ring

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## Abstract

A widely used diagnostic of the lattice properties of a storage ring is the measurement of the phase advance between beam position monitors. Since the betatron tune of the Recycler is 24.421/24.417 in the horizontal/vertical plane [1], the total phase advance around the ring is 8792°/8790°. Therefore, even with 8°-9° error bars on phase measurements, the lattice functions can be determined to a precision approaching 0.1%. In this paper phase advance measurements will be performed using a kicker magnet which excites betatron oscillations. By recording turn-by-turn information in the ring beam position monitor system, the phase of each monitor can be determined.


## 1. Recycler Ring

In the Recycler there are approximately 208 horizontal and 208 vertical beam position monitors, distributed around the ring one of each in every half cell. This means on average there is a beam position monitor in each plane every 45° of phase advance.

On the other hand, there are virtually no dipole or quadrupole correction magnets in the lattice. Therefore, more traditional approaches of measuring the beta function or looking for quadrupole gradient errors, such as measuring tune shift vs. quadrupole current, are not possible.

Precise techniques are needed for finding the source of beta-function distortions, magnet errors, and intensity-dependent effects. One powerful and widely used method is the measurement of the betatron phase between beam position monitors [2].

The Recycler beam position monitor system is capable of recording the single turn position of every monitor simultaneously, or in each of the 6 Main Injector houses it can measure one horizontal and one vertical monitor simultaneously on a turn-by-turn basis. For the turn-by-turn measurement, if every monitor must be recorded then a maximum of 40 separate turn-by-turn acquisitions must be performed, one acquisition for each monitor per house.

## 2. Transient Phase Advance Measurement

Imagine a bunched proton beam circulating in the Recycler ring. In the absence of a transverse kick the signal on the beam position monitor at each monitor is simply the closed orbit position. If a kick at some azimuthal location is applied to the beam in the horizontal or vertical direction, then the resultant betatron oscillation in that plane would be registered on every monitor. But because the monitor electrodes are distributed around the ring at distinct azimuthal locations, the phase of the measured oscillation will vary by the wavelength times the azimuthal position.

This phase is determined by performing a Fast Fourier Transform (FFT) on the turn-by-turn measurement of the beam centroid after a kick. The tangent of the imaginary over real part of the spectrum at the betatron frequency yields the phase relative to the kicker.

There are two ways to perform this measurement in the Recycler ring. Early on before stored beam is maintained by the RF system, it is anticipated that 6000 turn operations will be commissioned. This is because the shortest time between RR40 kicker triggers is 50 ms, and the beam does not debunch significantly in this time. Therefore, 40 transfers of mis-steered beam into the Recycler is sufficient to measure the betatron phase vs. beam position monitor position in a given transverse plane. Another 40 transfers are then needed to induce oscillations in the other transverse plane. In this scenario no emittance growth issues are relevant, but the time to do this measurement will be many minutes due to the fact that injections into the Recycler will be limited. Jitter in the strength of the kicker is irrelevant since the amplitude of oscillation is negated by taking the ratio of the imaginary and real parts of the Fourier transform of the betatron oscillation.

The second approach is to apply small repeated kicks to a stored beam. This will be the fastest and most sensitive method for measuring the betatron phase at each beam position monitor. By programming this measurement into the monitor system readout computers, the rate of small ~1 mm amplitude kicks can be as large as 5 Hz, or a total measurement time of both transverse planes of 16 seconds.

## 3. Emittance Growth from Repeated Kicks

In the method in which a stored beam is kicked repeatedly, the resultant coherent oscillations are transformed via the process of chromatic decoherence into transverse emittance growth. This emittance growth is quantified in the equation

$$\frac{\varepsilon}{\varepsilon_o} = 1 + \frac{1}{2}\left(\frac{\Delta}{\sigma}\right)^2 \quad , \qquad (3.1)$$

where $\varepsilon_o$ is the emittance before the kick, $\varepsilon$ is the emittance after the kicker, $\Delta$ is the betatron amplitude of the kick, and $\sigma$ is the rms beam size at the location where the betatron amplitude is measured.

For the Recycler, the rms beam size is described by the equation

$$\sigma = \sqrt{\frac{\varepsilon \beta}{6\beta_r \gamma_r}} \quad , \qquad (3.2)$$

where $\varepsilon$ is the normalized 95% emittance, $\beta$ is the beta function, $\beta_r$ is the relativistic velocity, and $\gamma_r$ is the relativistic energy. For example, if the initial emittance is 10 πmmmr, the beta function is 52 m, and the relativistic velocity and energy are 0.9945 and 9.53, then the initial rms beam size is exactly 3 mm.

Assuming a 1 mm oscillation, a spreadsheet was written using equation (3.1) to simulate the effect of 40 kicks. The emittance and beam size grow to 32 πmmmr and 5.4 mm respectively. This is well within the aperture of the Recycler ring. Assuming that both planes are measured with the same initial beam, and assuming that the coupling in the machine is small, then each plane will end up with the larger emittance. If the coupling is very large, then half of the emittance growth goes to each plane each kick. Over 80 kicks, the resultant emittance and rms beam size in now both planes are exactly the same due to energy conservation.

## 4. Kick Implementation

In the implementation in which proton injections are used, the horizontal and vertical steering dipoles at the downstream end of the MI32 proton injection line can be used to induce the horizontal and vertical betatron oscillations. No special hardware is required.

In the case of a stored beam, ~1 mm amplitude betatron oscillations require a kick of 19 μrad at a beta function of 52 m. Note that the RR20 and RR40 kickers generate a ~1 mrad kick, which is roughly 50 times larger than required. Even if the kickers could be turned down by a factor of 50 and still operate, the fact that they only kick horizontally eliminates them as candidates for the kick implementation.

Below are three possible kicker implementation options. In all cases a kicker with ~10% flattop flatness is desired. The flattop should be 2 μsec long and the risetime and fall time can each be similarly long.

### *4.1. Magnetic Deflection*

The deflection from a magnetic deflecting magnet is described by the engineering equation

$$\theta[\mathrm{rad}] = 0.2997925\frac{B[T]\,L[m]}{P[\mathrm{GeV}/c]} \qquad . \qquad (4.1)$$

The Recycler beam has a momentum of 8.889 GeV/c. Assuming a kicker length of 1 m, the magnetic field required to generate a 20 μrad deflection is 5.7 Gauss. If one assumes a Helmholtz deflector in which 4 conductors inside the vacuum chamber form a square in which the distance from the beam center to the wires is 2.54 cm, the current in the conductors required to generate this magnetic field is ±25 Amps. A drawing of this geometry is found in figure 4.1. The equation describing the field in the center of this Helmholtz geometry as a function of wire radius $r_o$ and wire current $I_w$ is

$$B = \frac{\mu_o}{4\pi}\frac{\sqrt{2}}{r_o}4I_w \qquad . \qquad (4.2)$$

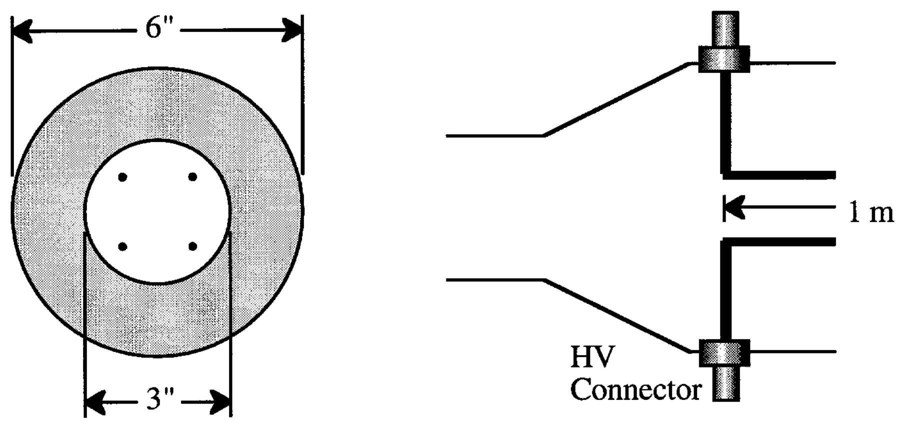


Figure 4.1: Sketch of a possible geometry for a dual horizontal/vertical magnetic kicker which would be installed in a straight section with a 3" beam tube.

### *4.2. Electrostatic Deflection*

The deflection from an electrostatic deflector is quantified by the engineering equation

$$\theta[\text{rad}] = \arctan\left(\frac{E[\text{GV/m}]\,L[\text{m}]}{\beta_r\, P[\text{GeV/c}]}\right) \quad . \tag{4.3}$$

Using beam parameter values already used above and again a length of 1 m, the electric field needed to generate the required kick angle is 1.7 kV/cm. If the deflecting plates are 5 cm apart, the voltage on each plate is ±8.5 kV.

### *4.3. Stripline Deflection*

If one constructs the above electrostatic plates such that they each form a 50Ω transmission line with the vacuum chamber and are terminated into 50Ω at the upstream end, then a ±4.25 kV signal applied at the downstream end is sufficient to get the same kick. This is because the magnetic portion of the signal carried by the plates gives an identical kick to the electric portion of the signal.

## 5. Control System Implementation

Since it is important to synchronize the starting turn of beam position monitor data acquisition and the turn of the kick, a RRBS event should be used to trigger both. The beam position monitor should use the continuously operating RRBS turn marker to synchronize sample-and-hold triggering with the leading edge of the beam distribution.

## References

[1] G. Jackson, ed., "Recycler Ring Technical Design Report", Internal Fermilab Technical Memo TM-1991 (November 1996).

[2] F. Zimmermann, "Measurement and Correction of Accelerator Optics", Proc. Joint US-CERN-Japan-Russia Accelerator School, Montreux, Switzerland (May 1998).