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Tune Shifts Due to Hysteresis

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1 Introduction

The first attempts at acceleration in RHIC were made using "mini-ramps", in which the magnet currents cycled between minimum and maximum values that differed by only about 10%. In order to achieve a relatively rapid cycle time of about 2 minutes, no attempt was made to remove hysteresis before re-injection at the bottom of the mini-ramp. (Hysteresis is conventionally removed by ramping all magnet families down to small or negative currents, before returning to injection conditions.)

Although acceleration was successfully demonstrated in this fashion, much of the beam was lost, even in the best of circumstances. The prime suspect for these large losses is a hysteresis driven tune shift – away from the fractional tune of about 0.2 into either the 1/3 or the integer resonance.

This note makes a crude calculation to show that tune shifts due to hysteresis in the range $-0.2 < \Delta Q < 0.1$ are entirely possible.

2 A crude model

Figure 1 illustrates a naive model of hysteresis. If the current excitation I of a magnet family has changed monotonically by a sufficiently large amount, the strength S lies very close to either the "UP" side or the "DOWN" side of the hysteresis loop. Assuming that the region of interest is very far from saturation, then the magnet strength is just

$$\begin{aligned} S_{UP} &= T\,(I-\Delta) \\ S_{DOWN} &= T\,(I+\Delta) \end{aligned} \tag{1}$$

where T is the linear transfer function – the slope of the linear part of the hysteresis curve.

The width of the hysteresis loop, 2Δ, is recorded for the principal RHIC magnet families in Table 1. These values were measured under conditions where the UP ramp went all the way to the maximum test current – well into saturation

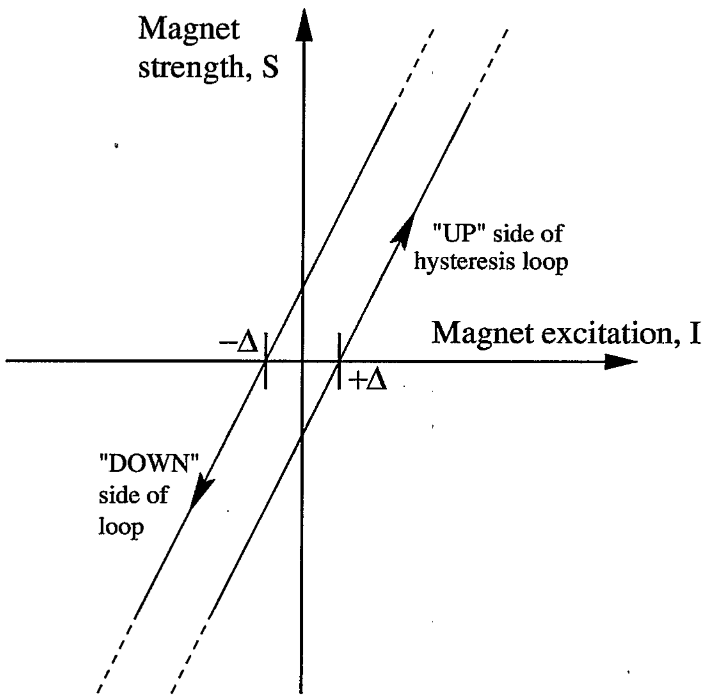

Figure 1: A simple model of hysteresis, far from saturation.

– before starting the DOWN ramp, and vice versa. The dipole and quadrupole widths are well represented by the 1.8 A and 3.1 A values for the arc dipoles and quadrupoles.

In general, hysteresis tune shifts occur when quadrupole and dipole magnetic strengths do not track each other. For example, assuming that the arc quadrupoles and dipoles dominate, then to a *fair* approximation

$$Q \simeq Q_0 \frac{S_{QUAD}}{S_{0Q}} \frac{S_{0D}}{S_{DIPOLE}} \tag{2}$$

where Q_0, S_{0D}, andS_{0Q} are the nominal tune, and dipole and quadrupole strengths. The scale (and probable sign) of the general tune shift is found by calculating the particular shift that occurs when the both the arc quadrupoles and the arc dipoles move all the way from the DOWN side to the UP side of their respective hysteresis loops.

UP and DOWN strengths at a nominal current I_0 are related through

Magnet family	Name	Loop width 2Δ [A]
Arc dipole	DRG	1.80
IR dipole DX	DRX	1.68
IR dipole D0	DRZ	1.58
Arc quadrupole	QRG	3.10
IR quadrupole Q1	QRI	3.39
IR quadrupole Q2	QRK	2.55
IR quadrupole Q3	QRJ	3.36

Table 1: Hysteresis loop widths for the dominant RHIC magnet families.

$$\begin{aligned} S_{UP} &= S_0 \left(1 - \frac{\Delta}{I_0}\right) \\ S_{DOWN} &= S_0 \left(1 + \frac{\Delta}{I_0}\right) \end{aligned} \tag{3}$$

where $S_0 = TI_0$ is the nominal central strength. Hence the UP and DOWN tunes are related by

$$\begin{aligned} Q_{UP} &\approx Q_0 \left(1 - \frac{\Delta_Q}{I_{0Q}} + \frac{\Delta_D}{I_{0D}}\right) \\ Q_{DOWN} &\approx Q_0 \left(1 + \frac{\Delta_Q}{I_{0Q}} - \frac{\Delta_D}{I_{0D}}\right) \end{aligned} \tag{4}$$

and so the tune shift from DOWN to UP is just

$$\begin{aligned} Q_{UP} - Q_{DOWN} &\approx Q_0 \left(\frac{2\Delta_D}{I_{0D}} - \frac{2\Delta_Q}{I_{0Q}}\right) \\ &\approx 30 \left(\frac{1.8}{543} - \frac{3.1}{506}\right) \\ &\approx -.084 \end{aligned} \tag{5}$$

where nominal values from July 1999 have been used.

This rough calculation underestimates the magnitude of the potential tune shifts. For example, if one magnet family moves much more quickly across its hysteresis loop than the other family, then the cancelation in Equation 5 does not necessarily apply. In general the tune shift may vary in time within the range

$$-0.18 \;<\; \Delta Q \;<\; 0.10 \tag{6}$$

Even this is an underestimate, because the approximation in Equation 2 is somewhat conservative. For example, in the case of a pure 90 degree FODO lattice with thin quadrupoles, Equations 2 and 5 underestimate the tune shift by a factor of $\pi/4$.

3 Conclusions

Tune shifts in the range $-0.2 < \Delta Q < 0.1$ are possible when beam is accelerated in RHIC, if hysteresis is not removed before re-injection. Thus, hysteresis induced tune shifts can move beam onto (or across) the integer or the third order resonance.

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