A First Order Matched Transition Jump at RHIC

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I INTRODUCTION

RHIC, the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, will be the first superconducting accelerator to cross transition, when ramping begins in 1998. All ion species except for protons will cross transition. Simulations show gold ion losses of 70%, and longitudinal emittance growth of 60%, if nothing is done to ameliorate the crossing [1,2,3]. RHIC will also be the first accelerator to use a *matched first order* transition jump to modify γ_T for a short time, by pulsing a set of quadrupoles, so as to cross transition rapidly, with little beam disturbance. "First order" means that the change in γ_T is proportional to the pulse current. "Matched" means that the quadrupole arrangement minimizes optical distortions. Crucially, the maximum dispersion is only 2.30 meters, compared to the unperturbed value of 1.84 meters. This paper describes the transition jump design, and reports on its performance in the lattice RHIC92.3 [4].

II PERFORMANCE PARAMETERS

Transition comes when the differential of circulation time with respect to $\delta = \Delta p/p_0$, the off momentum parameter, is zero. This happens when the relative rate of change of speed β equals the relative increase in path length - when

$$\frac{1}{\beta}\frac{d\beta}{d\delta} = \frac{1}{\gamma_T^2} = \frac{2\pi}{C_0}\langle\eta\rangle \tag{1}$$

Here C_0 is the circumference of RHIC, and $\langle\eta\rangle$ is the dispersion function averaged over bend angle (in dipoles), leading to a value $\gamma_T = 22.8$ that is a property of the lattice optics. See Table 1 for these and other parameters.

Two time scales characterize transition crossing. The *non-adiabatic* time T_c, given by

$$T_c = \left(\frac{AE_T}{ZeV|\cos(\phi_s)|}\cdot\frac{\gamma_T^3}{h\gamma'}\cdot\frac{C_0^2}{4\pi c^2}\right)^{1/3} \tag{2}$$

with a nominal value of 0.041 seconds, represents the time during which the longitudinal motion of the synchronous particle ($\delta = 0$) is not well represented by a slowly varying Hamiltonian [5]. The *nonlinear* time T_{nl},

$$T_{nl} \doteq \frac{(\alpha_1 + \frac{3}{2}\beta_T^2)\,\delta_{max}\,\gamma_T}{\gamma'} \tag{3}$$

has a nominal value of 0.129 seconds. It parameterizes the Johnsen effect, in which particles with different momenta cross transition at different times [6,7]. Transition is delayed or advanced by $\pm T_{nl}$ for a particle with $\delta = \pm\delta_{max}$ at the edge of the beam. A subsidiary advantage of first order schemes over second order schemes is that the "nonlinear parameter" α_1, defined through

$$\frac{C}{C_0} = 1 + \frac{\delta}{\gamma_T^2}\,[\,1 + \alpha_1\delta + O(\delta^2)\,] \tag{4}$$

is almost constant during the jump [8].

RHIC is unusual in that $T_{nl} \gg T_c$ - the nonlinear time is much longer than the non-adiabatic time. This is mainly because $\gamma' = d\gamma/dt = 1.6\ s^{-1}$ is relatively small - superconducting accelerators ramp slowly. For comparison, $\gamma' = 162\ s^{-1}$, $T_{nl} = 1.5$ msec and $T_c = 3.5$ msec in the normal conducting Fermilab Main Ring. The nominal bipolar jump illustrated in Figure 1 maintains a clearance of

$$|\gamma - \gamma_T| > 0.4 \approx 2\gamma' T_{nl} \tag{5}$$

except for about 60 milliseconds. Transition is crossed at about $d(\gamma-\gamma_T)/dt = 14.9\ s^{-1}$, almost ten times faster than without a jump. Longitudinal simulations predict that these jump parameters lead to no particle loss, and reduce the longitudinal emittance blow up to only about 10% .

Non-adiabatic time	T_c [s]	0.041
Nonlinear time	T_{nl} [s]	0.129
Transition gamma	γ_T	22.8
Transition jump step	$\Delta\gamma_T$	−0.8
Transition jump time	ΔT [s]	0.060
Acceleration rate, $d\gamma/dt$	γ' [s^{-1}]	1.6
Jump rate, $d\gamma_T/dt$	γ_T' [s^{-1}]	−13.3
Max off-momentum parameter	δ_{max}	0.0043
Max. jump dispersion	η_{Jmax} [m]	2.30
Circumference	C_0 [km]	3.834
Atomic number	Z	79
Atomic weight	A	196.97
Ions per bunch	N	10^9
Transition energy per nucleon	E_T [GeV]	21.4
Peak RF voltage	V [MV]	0.3
Stable phase	ϕ_S	0.16
Harmonic number	h	342
Longitudinal emittance (95%)	ε [eV-s]	0.3
Nonlinear parameter	α_1	0.6

Table 1 Nominal RHIC operating parameters for gold ions.

*Operated by Associated Universities Incorporated, under contract with the U.S. Department of Energy.

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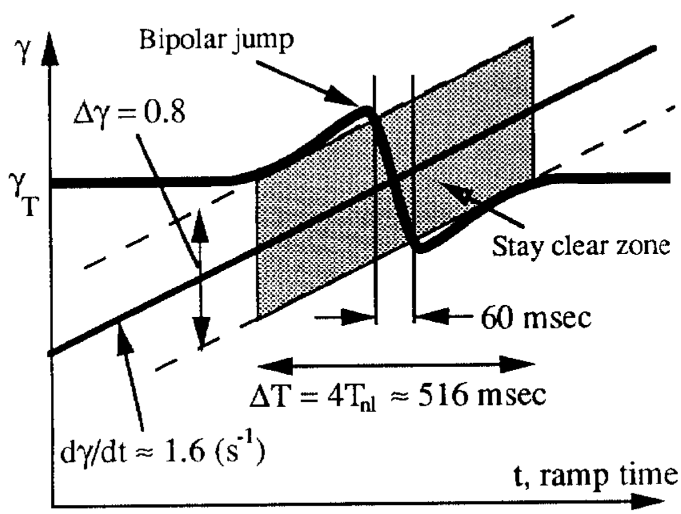

Figure 1 Transition is crossed almost 10 times faster with the nominal RHIC bipolar transition jump than without. Not to scale.

III THE TWO FAMILY DESIGN

When a quadrupole i is perturbed by strength q_i, the horizontal tune shifts to first order by

$$\Delta Q_H = \frac{1}{4\pi} \sum_i q_i \beta_{Hi} \qquad (6)$$

Risselada derives the elegant result, valid to all orders, that

$$\Delta \frac{1}{\gamma_T^2} = -\frac{1}{C_0} \sum_i q_i \eta_i^* \eta_i \qquad (7)$$

where η_i^* is the perturbed dispersion function [9]. All of the existing transition jump schemes at other accelerators (that the authors are aware of) are *second order unmatched* schemes. Most such schemes [9] have only one family of quadrupoles of strength q so that, to first order in q,

$$\eta_i^* = \eta_i + \frac{d\eta_i}{dq} q \qquad (8)$$

ready for substitution into equation (7). Usually all perturbed quads have the same periodic value for η_i and β_i, while their polarities are regularly flipped, so that the first order sums in equations (6) and (7) are identically zero [10]. In all cases, second order schemes deliberately rely on large changes in the dispersion function. This is a major disadvantage, since it intrinsically leads to large beam sizes at transition [11]. However, in the first order analysis that follows, $\eta^* = \eta$, so that the change in γ_T from a single perturbed quad goes like η_i^2, its dispersion squared, while the change in the tune is proportional to β_{Hi}, its beta function.

The lattice of each RHIC ring consists of six arcs connected by six interaction regions. Each of the 12 matched FODO cells in an arc has a phase advance of slightly less than 90 degrees. The crossing point telescope optics at the center of an interaction region are matched to a neighboring arc through 5 half cells, in which the beta functions are very close to arc FODO cell values, but which are (almost) dispersion free. Immediately next to every quadrupole in the arcs and in the interaction regions is a small superconducting correction magnet. Most correctors have one dipole winding, but some have four concentric windings.

There are two families of 24 γ_T quads in each of RHIC's two rings, in the second layer of some four layer correction magnets. The "G" family is at locations next to focussing quadrupoles where η, β_H and β_V are all close to their matched FODO cell values. This family has a strong effect on γ_T, and also on the horizontal tune, according to equations (6) and (7). The "Q" family is located next to the 4 focussing quads in every interaction region where the dispersion η is almost zero, but where β_H and β_V are still close to their FODO cell values. This second family is used to null out the horizontal tune shift (and also the much smaller vertical shift), with only a minor effect on γ_T. The two family strengths have opposite signs, and only a small difference in absolute value - 6% for the nominal jump - so that $q_G \approx -q_Q$.

Figure 2 shows how lattice parameters of interest vary as a function of q_G, the strength of the G family. The inner pair of vertical dashed lines are drawn through $\Delta\gamma_T = -0.4$ and 0.4, requiring $q_G = -0.0036$ and $0.0043\ m^{-1}$, respectively. This is well inside the extreme performance obtained when the power supplies are run at their nominal maximum current of 50 Amps, when $q_G = \pm 0.0084\ m^{-1}$, as shown by the outer pair of vertical dashed lines. Although some curvature is visible on the $\Delta\gamma_T$ line, this jump scheme is very linear. Extended performance is available, if necessary.

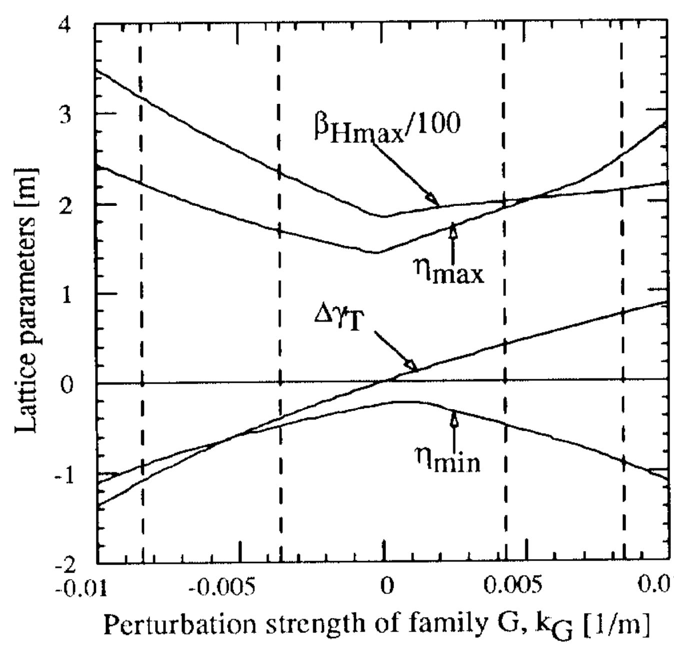

Figure 2 Change in γ_T and optical distortions versus the strength of the transition jump perturbation. Dashed lines show nominal and extreme excitation strengths.

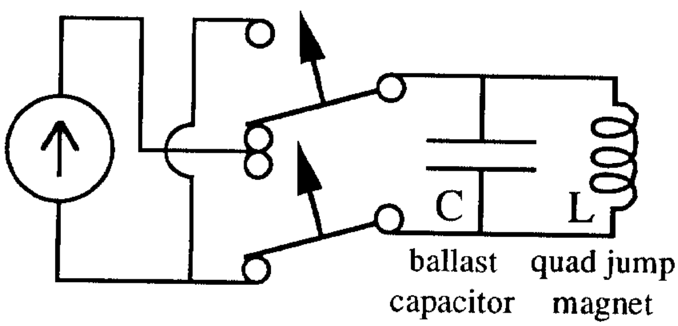

Figure 3 Equivalent circuit of the transition jump quadrupole families. There is a total of 12 power supplies per RHIC ring.

Figure 3 shows the equivalent circuit of the bipolar switching power supplies. The magnet current profile has the same shape and timing as the γ_T curve shown in Figure 1 (since the response is linear). That is, the excitation current slowly ramps up to a value of about 24 Amps over about 0.23 seconds, according to a programmable curve pre-loaded into a function generator table. Then the solid state switches open, so that the current in the magnet reverses polarity in half the natural period of the LC combination of the correction winding and the ballast capacitor, about 0.06 seconds. The switches close with reversed polarity when the voltages across them are near zero. Finally, the current again follows a function generator table as it ramps down to zero.

IV OPTICAL PERTURBATIONS

The RHIC FODO cell phase advance, nearly 90 degrees, is very favorable for reducing unwanted optical perturbations - beta waves and dispersion waves. Downstream from one of the γ_T quads there is a free horizontal beta wave

$$\frac{\Delta\beta}{\beta} = -q\,\beta_q\,\sin[2(\phi-\phi_q)] \qquad (9)$$

with a phase advancing twice as fast as the betatron phase. There is also a free horizontal dispersion wave, given by

$$\frac{\Delta\eta}{\sqrt{\beta}} = -q\,\eta_q\,\sqrt{\beta_q}\,\sin(\phi-\phi_q) \qquad (10)$$

advancing in step with the betatron phase. If two γ_T quads with the same strength are arranged in a doublet, at focussing quadrupoles one cell apart, their free beta waves are launched almost 180 degrees out of phase. That is, although the beta function is significantly perturbed between the two quads, very little of the wave escapes into the rest of the ring. Further, if two doublets in a dispersive region are placed next to each other in a quadruplet, so that γ_T quads are next to four focussing quadrupoles in sequence, then the dispersion wave will also be almost completely confined within the four quads.

The G family is arranged as six quadruplets, one at the beginning of each of the six arcs. By contrast, the Q family is arranged as twelve isolated doublets, one on either side of each of the six interaction points. These do not generate a significant dispersion wave, because they are at almost non-dispersive locations. Some global optical distortions do exist in practice, since the phase advance is somewhat less than 90 degrees, and since the γ_T quads do not have perfectly matched values (even by design). Figure 2 shows how the ring wide values for $\beta_{H\,max}$, η_{max}, and η_{min} vary as a function of q_G, the G family strength. The variation of $\beta_{V max}$ is less than 4% over the entire range, and so it is not shown.

An alternative arrangement, that was also investigated for RHIC, is to place one G family doublet on either side of an interaction point. This generates a dispersion wave across the interaction region, but because the unperturbed dispersion is almost zero there, anyway, this is not a problem. The phase advance between doublets still must be 180 degrees (plus an integer times 360 degrees) if the dispersion wave is to be canceled before it reaches the arcs. This is more difficult to guarantee when the doublets are far apart, than when the doublets are close together in neighboring FODO cells.

V CONCLUSIONS

Transition is the time when the momentum spread of the beam is at its largest. Since δ_{max} = .0043 and η_{max} = 2.3 meters for the jump presented here, the displacement of the momentum edge of the beam is 9.9 mm, much larger than the betatron root mean square beam size of about 1.6 mm. The total beam size is well within the available aperture.

Although RHIC is unfortunate in being the first superconducting accelerator to cross transition, it is fortunate in being the first accelerator to support a matched first order transition jump. This jump is expected to prevent particle losses, and to almost entirely eliminate emittance growth. RHIC can support such a jump, while other accelerators cannot, because it has relatively many dispersion free quadrupoles with standard FODO cell beta functions, and because the phase advance per cell is close to 90 degrees.

VI ACKNOWLEDGEMENTS

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VII. REFERENCES

[1] S.Y. Lee and J. Wei, Proc. EPAC, Rome, (1988), p. 764
[2] J. Wei, Ph.D. thesis, State Univ. NY at Stony Brook, (1990)
[3] J. Wei, Proc. European Part. Acc. Conf., Berlin, (1992)
[4] RHIC Design Manual, RHIC, BNL, Upton NY 11973
[5] A. Sorenssen, Particle Accelerators, **6**, 141, (1975)
[6] K. Johnsen, Proc. CERN Symposium on HE Accelerators and Pion Physics, Geneva, (1956)
[7] K. Takayama, Particle Accelerators, **14**, 201, (1984)
[8] S.A. Bogacz, S. Peggs, IEEE PAC, San Francisco (1991), p. 1657
[9] T. Risselada, CERN PS/90-51, Geneva, (1990)
[10] W. Merz, C. Ankenbrandt, K. Koepke, IEEE PAC, Washington, (1987), p. 1343
[11] S. Peggs, S.A. Bogacz, F. Harfoush, IEEE PAC, San Francisco (1991). p. 1160