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DESIGN OF A GAMMAT-JUMP SYSTEM FOR FERMILAB BOOSTER

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Abstract

A γ_T scheme may be required for the PIP-II era performance or ACE-MIRT era performance of the Booster. PIP-II era operations of the Fermilab proton complex will require the Fermilab Booster to increase beam intensity from 4.5e12 to 6.7e12 protons, while also increasing its ramp from 15 Hz to 20 Hz. These changes pose particular challenges for transition-crossing in the Booster, where longitudinal beam quality must be controlled in order to facilitate slip-stacking in the Recycler Ring later in the Main Injector cycle. Two novel γ_T-jump schemes are proposed, termed "Double γ_T jump" and "Partial γ_T-jump", which optimize the magnitude of the γ_T-jump within optics and power supply constraints.

INTRODUCTION

The Fermilab proton complex is currently constructing the PIP-II Linac [1], the LBNF beamline, and DUNE detectors which constitute an ambitious upgrade of the Fermilab long-baseline neutrino science program and mesonic beamline capabilities. These upgrades will include an increase in Booster beam intensity from 4.5e12 to 6.7e12 and increase in the Booster ramp rate 15 Hz to 20 Hz, requiring a nearly factor of two increase in delivered 8 GeV beam power for neutrino cycles. To reduce beam loss activation under this increased power, successful operations of the PIP-II era Booster requires improved performance at every stage, including transition-crossing.

The recent P5 recommendations [2] illustrate further how the performance of the Fermilab Booster is critical for the advancement of the neutrino science. Area Recommendation 13 specifically states to "assess the booster synchrotron and related systems for reliability risks through the first decade of DUNE operation, and take measures to preemptively address these risks." P5 Recommendation 2 also calls for the implementation of "ACE-MIRT" [3] which will require the Main Injector to occur nearly twice as frequently, the Fermilab Booster neutrino duty cycle to increase, and the beam quality from the Booster to be improved.

In this paper we develop and propose a γ_T-jump system to improve transition-crossing performance of the Booster in the PIP-II era. Although much of the analysis presented here is hardware-agnostic, we further consider the possibility of a γ_T-jump system that could be implemented with existing Booster correctors [4] requiring only a beampipe and power-supply upgrade.

TRANSITION-CROSSING PERFORMANCE REQUIREMENTS

The PIP-II CDR [1] sets out an objective for longitudinal beam emittance $\epsilon_{97\%} = 0.10$ eV·s extracted from the Fermilab Booster to ensure low-loss slip-stacking performance in the Fermilab Recycler. The primary technical justification for this performance target in the PIP-II CDR is the longitudinal acceptance of the slip-stacking RF bucket, however a more careful analysis by Eldred & Zwaska [5] reveals a substantially looser requirement. In reality, the requirement is more complex because a full consideration should account for the momentum spread after bunch rotation, beam-loading effects in slip-stacking RF cavities, and deliberate misphasing to mitigate Recycler instabilities. Consequently, it is prudent to optimize longitudinal beam quality from the Booster regardless and conservatively it should not deviate too much beyond present performance. A γ_T-jump system may also help with mode-coupling instabilities observed at transition [6, 7].

Recent PyORBIT simulations by Ostiguy [8, 9] have studied the longitudinal beam quality delivered by the Booster, driven by the space-charge inducted mismatch while crossing transition.

Table 1 shows a range of longitudinal emittance benchmarks compared to a range of simulated performances with transition-crossing. The 30A γ_T-jump may be sufficient for PIP-II era running to achieve performance not far from present operation of the Booster (at lower intensities).

Table 1: (top) Longitudinal emittance benchmark for present operation and PIP-II era operation. (bottom) Longitudinal emittance from PyORBIT simulations, where the $\epsilon_{95\%}$ has been scaled to match $\epsilon_{97\%}$ in gaussian beams.

Requirements	$\epsilon_{97\%}$	Notes
Present Operation	0.11 eV·s	Elog Apr 2024
Present RF Bucket Limit	0.14 eV·s	[5]
PIP-II requirements	0.10 eV·s	[1]
PIP-II RF Bucket Limit	0.22 eV·s	[5]

Simulations	$1.22\epsilon_{95\%}$	Notes
6.7e12 with quad damper	0.15 eV·s	[9] (no jump)
and with $\Delta\gamma_T = \sim 0.24$	0.115 eV·s	[9] (30A)
and with $\Delta\gamma_T = \sim 0.82$	0.093 eV·s	[9] (55A)

DESIGN CONSIDERATION

Although previously the Booster had a resonant γ_T-jump system [10], it was never used operationally because the Booster had insufficient orbit control. Based on the Teng [11] design, we can estimate the sign and the magnitude of the γ_T perturbation from a resonant modulation of quadrupole

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kicks:

$$\gamma_T^2 \approx Q_X^2 - \frac{9}{8}\frac{a^2}{R^2}\frac{Q_x^4}{Q_x^2 - n^2}$$

$$\Delta\gamma_T \approx -\frac{9}{16}\frac{a^2}{R^2}\frac{Q_x^3}{Q_x^2 - n^2} \qquad (1)$$

where $\Delta\beta \sim (a/Q_s)\sin(n\phi)$ and a proportional to the quadrupole kick strength.

The impact of the quadrupole modulation on γ_T can be considered as equivalent to an integer-resonance dipole resonance, except that dispersion and quadrupole-steering effects combine to create the resonance only for the off-momentum particle.

For the 24 quadrupole correctors in the short sections of Booster focusing cells, we can modulate the strength of the kth quadrupole by

$$K_{QSk} \propto \mathrm{sgn}[\cos(2\pi nk/24 + \phi_0)] \qquad (2)$$

From Eq. 1 and $Q_x \approx 6.77$, we can clearly see that modulating that Booster quadrupole correctors with the n=6 resonance will push γ_T down while modulating with n=6 resonance will push γ_T up. Fig. 1 shows the impact of the two modulations one the dispersion function of the Booster. The peak dispersion will occur at several specific short straights of the Booster, although the long straights have a narrower horizontal aperture which must also be considered for transverse acceptance. The location of the dispersion wave (i.e. the cell which starts the pattern) can be tuned for maximum acceptance.

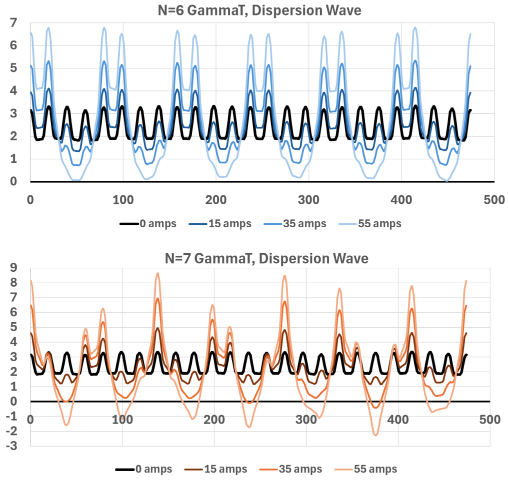

Figure 1: Dispersion functions for n=6 (top) and n=7 (bottom) modulation of 24 quadrupole corrector kicks.

The Booster γ_T-jump design is further informed by the interplay of three main constraints:

1. Transverse Optics. For momentum spread and horizontal aperture, there is a maximum dispersion wave (γ_T perturbation) that Booster optics can support at transition.

2. Maximum Corrector Current. The quad kick is linear with corrector current, but the change in γ_T is quadratic with the quad kick.

3. Maximum Corrector Slew Rate. The γ_T change must occur within the 0.15ms non-adiabatic time of transition. For a given magnet inductance, the slew rate limit can be expressed as a voltage limit. And the magnetic field must get past beampipe shielding effects.

In the case of the $n = 7$ near the horizontal betatron tune Q_x, a tradeoff between the transverse optics and maximum corrector current can be made. As the Q_x approaches the n=7 γ_T resonance, weaker quadrupole kickers are required to achieve the same magnitude of γ_T jump. On the other hand (not shown in Teng [11]), closer to the resonance the peak dispersion for the same magnitude of γ_T will be higher, generating a meaningful tradeoff between the efficient use of quadrupole kicks and a dispersion wave within transverse acceptance.

The interplay between the two constraints is further complicated by the fact that for our proposed system, the quadrupole correctors which control the horizontal betatron tune are the same as though used to execute the γ_T jump and the quadrupoles are typically set to be positive amps values (i.e. enhancing Q_X). This means that for a weak γ_T jump, a depressed tune requires a weaker maximum current and for a strong γ_T jump, an enhanced tune requires a weaker maximum current. For our set of parameters, the effect roughly cancels and the transition value of Q_x alongside the must be tuned to optimize performance (and for these reasons the magnitude of γ_T jump per amp will slightly vary across this paper).

Without any constraint from the maximum corrector slew rate, the largest achievable γ_T jump (within optics and maximum current limits) will be achieved by performing the maximum $n = 7$ γ_T perturbation and jumping to the maximum $n = 6$ γ_T perturbation. We term this novel combination of γ_T resonances, a “Double γ_T-Jump”, as shown in Fig. 2. To execute Double γ_T-Jump with Booster correctors, roughly half the quadrupoles do not change and the other half of the quadrupoles must make the maximum change from one polarity to another.

On the other hand, if one is predominately constrained by the maximum corrector slew rate, the γ_T change that actually takes place within the non-adiabatic time (in this case 0.15 ms) predominates. Because the γ_T change scales quadratically with corrector current, the largest achievable γ_T jump will come from using the maximum γ_T perturbation (within optics and maximum current limits) and taking the maximum corrector change (within the non-adiabatic time) back towards nominal optics, as shown in Fig. 2. We term this novel use of γ_T resonant a “Partial γ_T-Jump”. The fast slew-rate of the γ_T-jump can continue past the non-adiabatic time, however the effect will be minimal. A nominally full but functionally partial γ_T-jump such as that could be inadvertently implemented at a synchrotron facility.

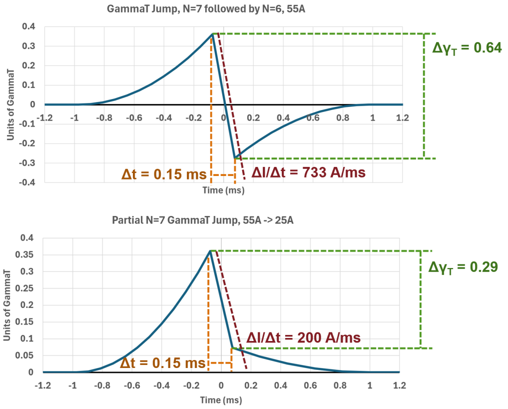

Figure 2: (top) Double γ_T-Jump system not limited by slew rate and (bottom) Partial γ_T-Jump system limited by slew rate.

TRANSVERSE OPTICS EXPERIMENT

On 5/22/22, 2/23/23, 5/8/24, and 6/24/24 beam studies were conducted in the Booster to test maximum dispersion waves allowable at transition within the horizontal aperture of the Booster. These γ_T perturbations were deliberately not jumped at transition, to cleanly separate the longitudinal effects of the jump (and limitations in corrector slew rate) from the transverse optics limit. After adjusting the horizontal tune downward and the beam orbit at transition (towards the center of quadrupole correctors), both the N=6 and N=7 dispersion waves were tested at low-intensity and again at full-intensity beam.

Table 2 show the experimentally determined maximum γ_T perturbations acceptable within the transverse optics of the Fermilab Booster in the vicinity of transition. The tolerable γ_T perturbation is smaller in the case of the high-intensity beam operations, due to the increased longitudinal [12] and transverse emittance [13] beginning with space-charge effects during the capture process.

N_p	Dispersion Wave	I_{QS}	$\Delta\gamma_T$	max D_x
1.6e12 protons	N=7, ΔQx=-0.1 N=6, ΔQx=-0.1	-50 A +50 A	+0.36 -0.20	8.9 m 6.0 m
4.4e12 protons	N=7, ΔQx=0.0 N=6, ΔQx=0.0	+40 A +40 A	+0.32 -0.11	9.6 m 5.1 m

Table 2: The γ_T perturbations empirically demonstrated to occur with minimal losses.

For a partial γ_T-jump from 40A to 10A, a γ_T change of 0.3 units is achieved within the accelerator acceptance. On the other hand, the same magnitude should also be sufficient to maintain the longitudinal beam quality needed for the PIP-II era slip-stacking in the Recycler.

DESIGN HARDWARE

The quadrupole correctors have an inductance of 1.8 mH, therefore a 30A change in the quadrupole current over 0.15ms (i.e. 200 A/ms) requires a 360 V power supply. Although this power supply voltage is comparable to that required for a PIP-II era dipole power supply upgraded needed for the flat injection system, the required power output is much higher and it is yet to be determined if the same power supply design will serve both purposes.

The quadrupole corrector slewing at 200 A/ms also corresponds to a 500 T/s integrated quadrupole kick slew rate, which is difficult to transmit through a conductive beampipe without attenuation and diminished slew rate. A recent report by Podobedov [14] provides straightforward calculation of the magnetic multipole in the pipe after taking into account shielding effect:

$$\frac{B_i(f)}{B_e(f)} \approx \frac{1}{1 + j(f/f_{crit})/m}$$
$$f_{\text{crit}} \equiv 1/(\pi\mu_0\sigma a d) \qquad (3)$$

where σ is the pipe material conductivity, a is the pipe radius, d the pipe thickness, and m the multipole order ($m = 2$ for quadrupole).

The corrector currently use 316L steel beampipes, 3/8" thick with a 5" diameter, and consequently the characteristic frequency can be calculated to be $f_{\text{crit}} = 3.77$ kHz. We applied this distortion to a simple model of the γ_T-jump profile by taking the FFT, multiplying by the ratio given in Eq. 3, and transforming back. The existing beampipe is permits only ~60% of the necessary field change in the 0.15 ms interval.

Consequently, implementing the γ_T-jump will require replacing the beampipe with a thinner and more resistive material. Either Inconel 718 or Titanium Grade 5 possess the appropriate tensile strength for a reduction in thickness, and a 1/16" would be resistive enough that the necessary quadrupole fields could be readily transmitted.

FUTURE WORK

In this paper we have converged on a design of a 0.3 unit Partial γ_T-jump system using existing Booster correctors to improve longitudinal beam quality from the Fermilab Booster during the PIP-II and ACE-MIRT operation.

A couple of other considerations remain. Transmission of quadrupole fields through a replacement beampipe material will be tested on a dedicated corrector test stand. Corona discharge tests will also be performed to verify that the correctors can sustain the 360 V in corona discharge testing. Finally the 360 V power supplies themselves must be designed.

It is still to be determined whether Fermilab will implement the γ_T-jump system in anticipation of PIP-II operations, or reserve it as a performance upgrade option for a later date.

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