Design of a γ_T- Jump System for Fermilab Booster

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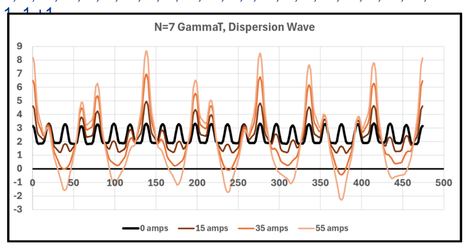
Introduction

The Fermilab Booster crosses transition at ~4.3 GeV with a non-adiabatic time of roughly 0.15ms. As part of the PIP-II accelerator complex upgrade, Booster intensity must increase from ~4.9e12 to ~6.6e12 protons. Simulations indicate that longitudinal emittance growth from transition-crossing at that intensity, may impact PIP-II era performance. Several Booster γT- Jump options are explored.

N=7 or N=6 Resonant γ_T -Jump

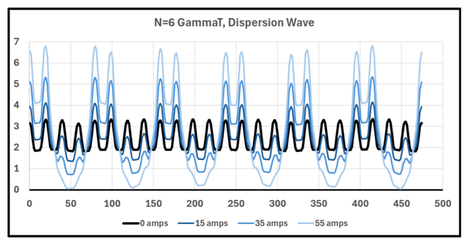
$\mathrm{QS}_n, K_1 \propto \mathrm{sgn}(14\pi n/24)$

0,-1,+1,+1,-1,-1,+1,-1,-1,+1,+1,-1,0,+1,-1,-1,+1,+1,-1,+1,+1,+1,-1,-1,+1



$\mathrm{QS}_n, K_1 \propto \mathrm{sgn}(12\pi n/24)$

-1,+1,+1,-1, -1,+1,+1,-1, ….repeating



Varying quad correctors in an integer multiple creates a resonant dispersion wave which shifts γ_T quadratically with corrector current.

Aperture estimates are that dispersion limits may be as likely to occur in short and long sections.
- Although aperture limits may not be uniform around ring, depending on orbit etc.

Limits on Booster γ_T -Jump

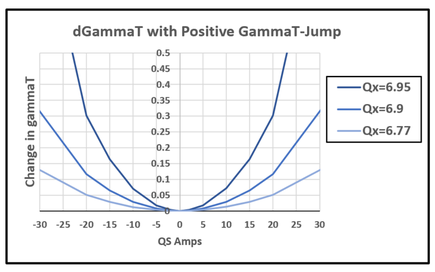
Three known limitations on the magnitude of a Booster γ_T -jump system.

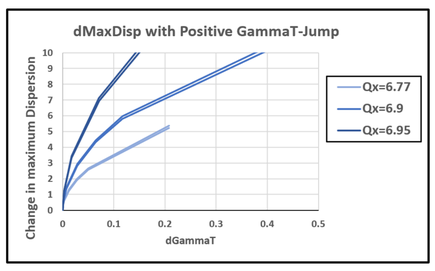
1) Transverse Optics. For momentum spread and horizontal aperture, there is a maximum dispersion wave (γ_T perturbation) that Booster optics can support at transition.

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.

Tune Dependence (Maximum Current vs Max Dispersion Wave)



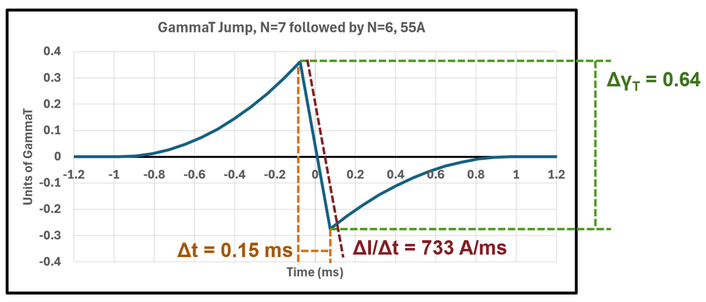


Moving Qx closer to 7 changes the N=7 γ_T effect.
- Greater change in γ_T effect corrector amp.
- Greater dispersion wave needed for same γ_T change.

Fundamental trade-off between maximum corrector current and transverse optics.
- Complicated by the fact that quad-shorts are used to change tune and do γ_T -jump.

Novel γT- Jump Schemes

Double γT- Jump:
Largest change in γT with optics and max current limits

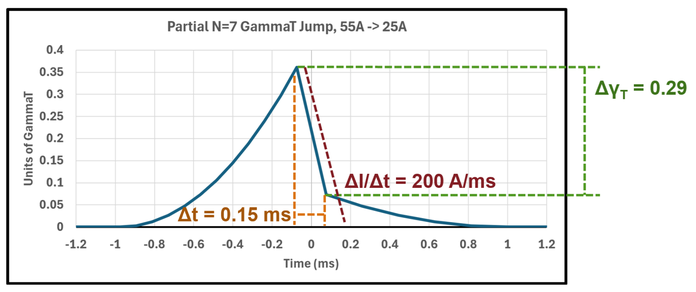


N=7 Jump to push γ_T up quadratically (within limits).

N=6 Jump to push γ_T down quadratically (within limits).

see **beams-9326** (Eldred 2022), **beams-10115** (Neufer 2024)

Partial γT- Jump:
Largest change in γT within slew rate and voltage limits

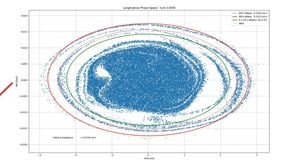


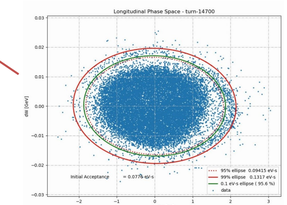
Maximum γ_T perturbation for one-side (within limits), then biggest change possible within the 0.15ms window (within limits).

Can keep slewing rapidly past 0.15ms, but the first 0.15ms really does the work.

Longitudinal Emittance Requirements

Requirements	$\epsilon_{97\%}$	Notes
Present Operation	0.11 eV·s	Elog 258086 (at 4.2e12) *April 2024*
Present RF Bucket Limit	0.14 eV·s	Eldred-Zwaska PRSTAB 2014
PIP-II requirements	0.10 eV·s	PIP-II CDR
PIP-II RF Bucket Limit	0.22 eV·s	Eldred-Zwaska PRSTAB 2014
Simulations	$1.22\epsilon_{95\%}$	**Notes**
6.7e12 with quad damper	0.15 eV·s	Ostiguy (no jump)
and with $\Delta\gamma_T = \sim 0.24$	0.115 eV·s	Ostiguy (30A double-jump)
and with $\Delta\gamma_T = \sim 0.82$	0.093 eV·s	Ostiguy (55A double-jump)





To meet PIP-II CDR requirements about $\Delta\gamma_T = 0.3$ is needed.
- This would also help with transition instabilities.

Beam Studies

Transverse Optics Limits

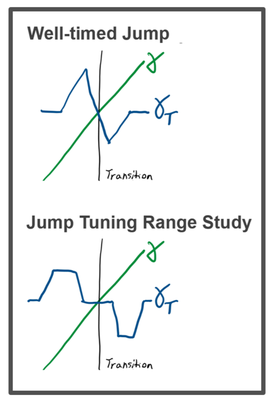
Conducted beam studies on **5/22/22**, **2/23/23**, **5/8/24**, and **6/24/24** to measure the largest γ_T perturbation that optics can support, after orbit tuning.

Results Summary Table:

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

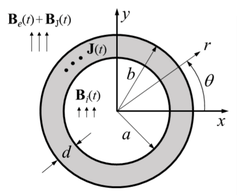
Limits smaller for high-intensity beam (i.e. bigger emittance).

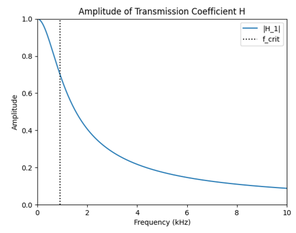
Double γ_T -Jump Scenario:
ΔγT = 0.43, ΔI = 80A (V_{max} = 960V), I_{max} =51-65A,
Partial γ_T -Jump Scenario:
ΔγT = 0.30, ΔI = 30A (V_{max} = 360V), I_{max} =51-65A,

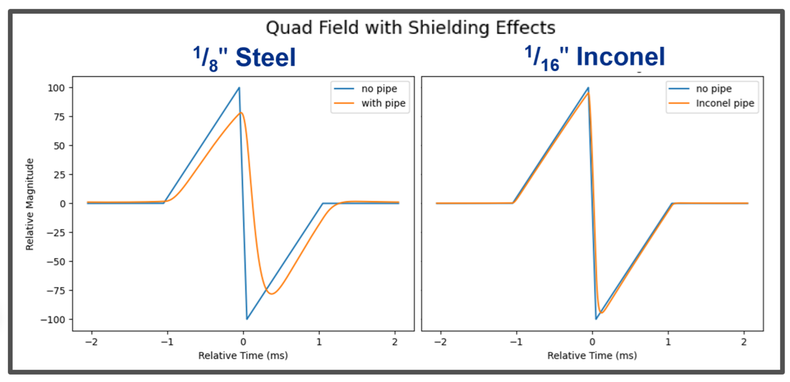


Formula for Shielding Effect (Podobedov 2023)

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







Inconel 718 beampipe would also be needed to change quad magnetic field quickly enough. True of any Booster γ_T -jump scheme.

Titanium Ti-6Al-4V (Grade 5) is actually another beampipe material option.

Existing Correctors: Voltage & Slew Limits

Each coil has an inductance, so the voltage limit is a current slew limit:

$$\frac{dI}{dt}[A/ms] = V[V] \;/\; L[mH]$$

References for corrector coil inductances: **beams-1881**, **beams-2520**
Booster Corrector Magnet Normal Quad inductance is **1.8 mH**.

		Normal Quadrupole	
	Inductance	1.8mH	
	Voltage Limit	Current Slew, A/ms	Field Slew, Tm/m /s
Present Case:	120 V	66.7	165.9
Upgrade Case:	360 V	200.0	497.8
Very High Voltage:	960 V	533.3	1327.5

γT- Jump Design Conclusions

1) For any Booster jump system, beampipe in short sections need to be replaced with Inconel or resistive Titanium.
2) With a high-voltage upgrade, existing Booster correctors can be used.
3) About at least 0.3 units of γT- Jump are needed to maintain longitudinal emittance at PIP-II intensities.
4) Booster transverse optics can’t support dispersion wave more than 0.3 units.

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