Gamma-t Jump AIP for PIP-I+ Functional Requirements Specification

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Document Approval

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Revision History

Revision	Date of Release	Description of Change
A		Initial release

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1. Purpose

An FRS describes the programmatic or project needs and/or requested behavior of a system or component. The document typically outlines what is needed by the end user as well as the requirements and requested properties of inputs and outputs. The FRS specifies the functions that a system or component must perform and establishes consensus among stakeholders on what the system is expected to provide.

This FRS documents functional requirements for needed upgrades to the Main Injector sub-systems WBS element. Since PIP-I+ is the transition piece to PIP-II, the problems identified and solved in PIP-I+ in beam physics will be applicable to the success of PIP-II.

2. Scope

This FRS addresses the functional requirements of

i. The Main Injector gamma-t jump system.

3. Acronyms

FESHM	Fermilab ES&H Manual
FRCM	Fermilab Radiological Control Manual
FRS	Functional Requirements Specification
ALAP	As low as possible
L3	WBS Level 3
PIP	Proton Improvement Plan
PIP-I+	Proton Improvement Plan I+ AIP
PIP-II	Proton Improvement Plan -II
2SC	Two Stage Collimator
CHG0	Charge zero detector
DCCT	Direct current Transformer
SCD	System Configuration Document
HLRF	High Level RF
LLRF	Low Level RF
HEP	High Energy Physics
ppp	protons per pulse
TC	Teamcenter
WBS	Work Breakdown Structure

4. Reference

#	Reference	Document #
1	Proton Driver study II	TM-2169 ch16
2	Fermilab Engineering Manual	NA
3	Fermilab Environmental Safety and Health Manual	NA
4	Fermilab Radiological Control Manual	NA
5	TRANSITION CROSSING IN THE MAIN INJECTOR FOR PIP-II	FERMILAB-CONF-17-143-AD

5. Key Assumptions

Conventional utilities (painting, lighting, fire protection, sump/drainage, impediments) cable trays and work on penetrations will be outside the scope of this FRS and completed prior to 2SC. Any M&S cost related to acquire/running computer programs for beam simulations, upgrading computers hardware and computer software, purchasing any material supplies are also outside the scope of this FRS.

6. Functional Requirements

I. Overview:

The goal of the Gamma-t jump system is to eliminate the transition loss in the Main Injector. As we increase intensity this loss becomes more problematic and the resulting residual tunnel activation increases as a result. The system consists of 4 sets of pulsed quadrupole triplets. Each triplet has two quads in the arc and one of twice integrated strength (or two magnets) in the straight section, with a phase advance of π between each quadrupole. The perturbation to the original lattice is localized. In particular, the dispersion increase during the jump is small ($\Delta D_{max} \approx 1$ m), which is the main advantage of a first-order jump system. Each triplet is optically independent from the others and provides roughly 1/4 of the total required jump amplitude (i.e., $\Delta_{\gamma t} \approx 0.25$ per triplet). The power supply is required to act as a fast switch to flip magnetic field polarity in 0.5ms and produce +/- 0.5 unit change in gamma-t. The beam pipe is made of ceramic in to keep the inductance of the magnet as low as possible.

II. Physics:

Different γ_t scenarios were simulated using Synergia. Two cases were investigated based on the original scheme discussed above both using 4 triplets, looking at a +0.5 to −0.5 jump and a +0.75 to −0.75 jump. Even though a first order jump scheme is used, there are still large effects on the optics of the lattice that cannot be ignored. The lattice functions for the different schemes considered can be seen in Figure 3.

Figure 2 shows the effect of the γ_t jump on the horizontal and vertical tune during the jump for the 1/2 unit jump using 4 triplets. At the beginning of the jump, the pulsed quads are ramped linearly for 5 ms and then the polarity is swapped linearly over 0.5 ms and the ramped back down to zero over another 5 ms. Transition crossing occurs during the middle of the polarity swap. It can be seen that the $d\gamma_t/dt$ is half of $d\gamma/dt$, this because a 1/2 unit jump is used but based on the full unit jump parameters. The effect on the horizontal tune is very large and needs to be compensated to avoid hitting any resonances.

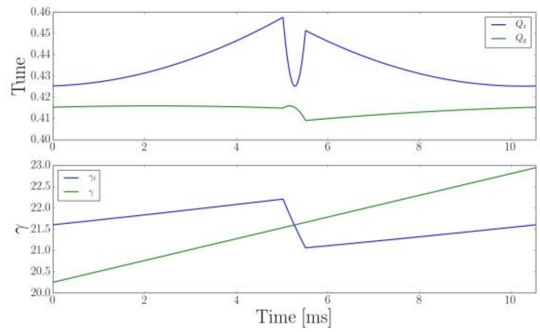

Figure 2: The effect on the tunes and the γ_t of the lattice during the jump scheme.

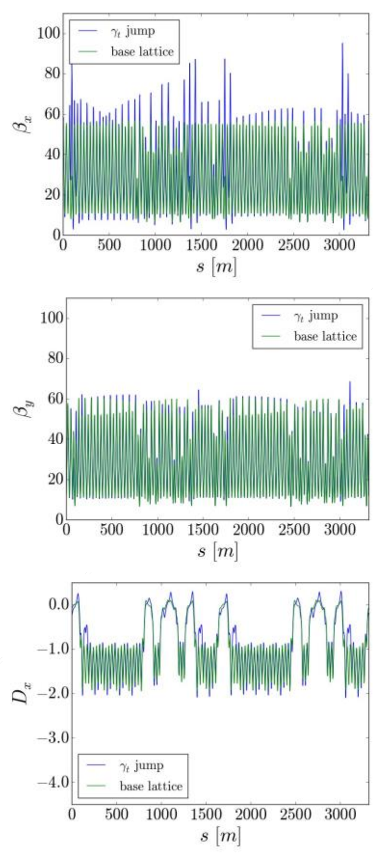

Figure 3: Lattice functions at the maximum γ_t of the jump for the 1/2 unit jump.

For the 1/2 unit jump the horizontal tune was reduced by 0.035. For the 3/4 unit jump, the horizontal tune was reduced by 0.06.

Figure 4 compares the effect on the longitudinal phase space for PIPII with and without a γ_t-jump scheme. For the no jump case, large oscillations can initially be seen while the bunch filaments inside the bucket. Focusing on just the momentum spread, it can be seen that it slowly increases to a maximum at transition and then drops down again undergoing oscillations on the way.. The number of particles lost is also shown with the biggest loss occuring around 9 GeV in which the out of bucket beam hits an aperture restriction. After that point, losses occur multiple times after transition is crossed.

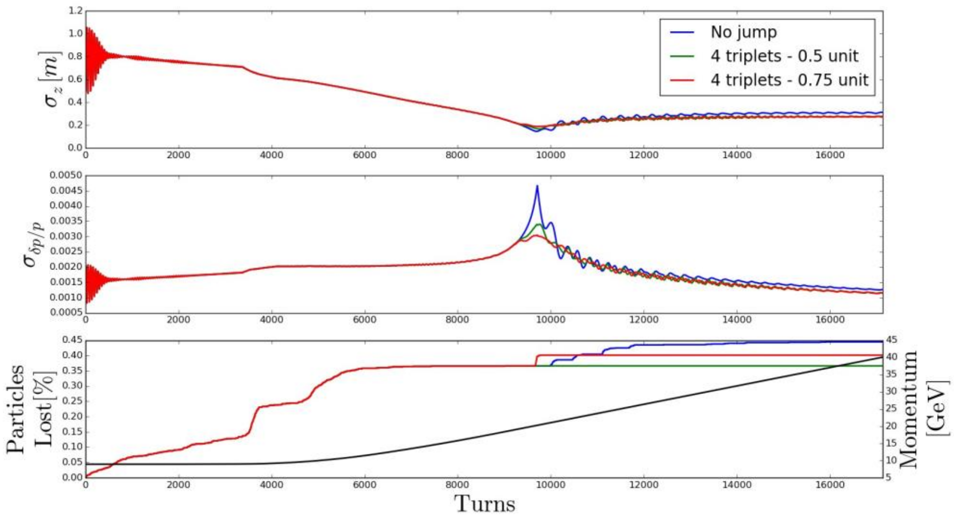

Figure 4: The evolution of the bunch length momentum spread throughout the simulation.

In the case with +/- ½ unit of gamma-t, there is no beam loss after transition. For the +/- ¾ of a unit jump, the beam loss is due to the transverse tune shift.

The total beam power loss per particle at transition is larger that than at low field loss. This transition loss creates significant residual activation in the tunnel.

The maximum $\delta p/p$ is much reduced for the γ_t-jump schemes compared to the no jump case. For the 1/2 unit jump case, no losses are seen during the jump or after it. For the 3/4 unit jump, some losses are seen near transition crossing. This is a transverse loss caused by the large tune shift when the pulsed quads are close to maximum. An 8 triplet case was also explored but it was found very difficult to keep losses low due to the large disturbances on the lattice from having 8 inserts.
Figure 5 shows the longitudinal phase space distribution for the 1/2 jump simulations after the same number of turns as where the first $\delta p/p$ maximum occurs for the PIPII case. The much smaller emittance explains why losses don't occur for the γ_t-jump case.

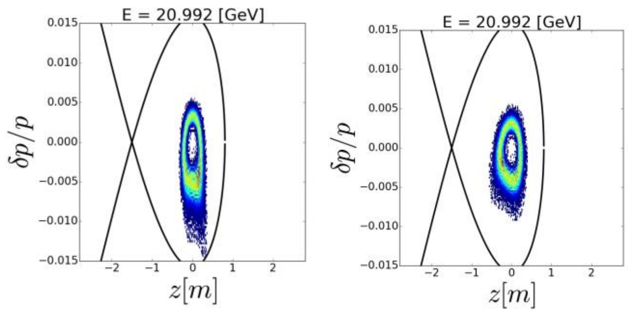

Figure 5: The longitudinal phase space distribution at the first maximum after transition of PIPII (left) and for the 1/2 unit jump (right) simulations as the same time .

The Gamma-t jump system is required to be able to provide +/- ½ unit jump in 0.5ms. to meet the physics requirements.

The gamma-t system will not cause a transverse tune shift greater than 0.035

III. Power Supplies:

The MI gamma-t jump power supply system consists of 4 power supplies. Each power supply drives a four-quadrupole magnet string. An example power supply design is shown in Figure 16.8.

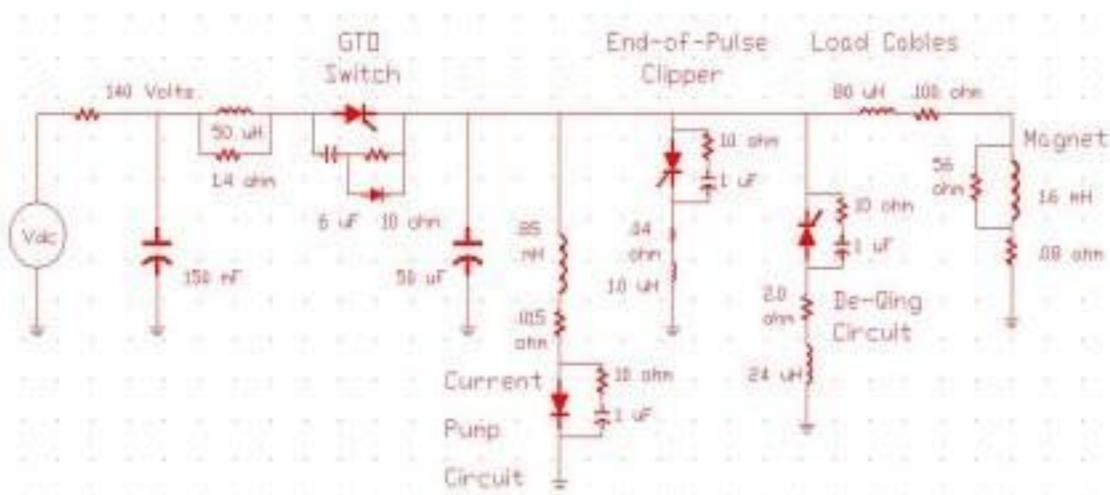

Figure 16.8. Circuit diagram of the MI gamma-t jump power supply system.
Figure 16.9 shows the various magnet current waveforms that can be produced by the power supply:

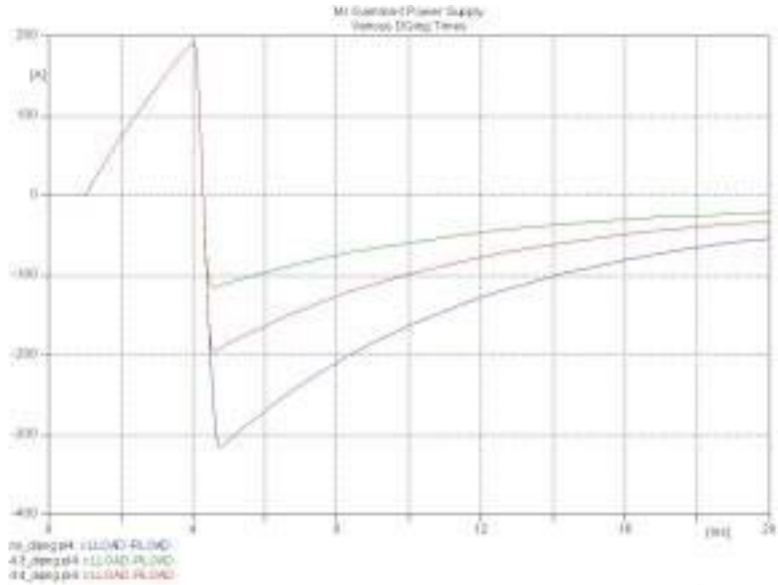

Figure 16.9. The magnet current waveforms for various De-Qing times.

A short description of circuit operation follows. The pulse begins when the GTO (gate turn-off thyristor) is turned ON. This applies 140 volts to the load and charges the load current to 195 amps in 3 ms. At this time the GTO is turned OFF and the magnet load acting as a resonant circuit with the 50 μF capacitor rings through one half cycle.
Turning ON the End-of-Pulse clipper SCR allows the magnet current to return to zero following the L/R time constant of the load and load cables. To control the peak negative current, the De-Qing circuit SCR can be turned ON before the pulse reaches its maximum negative value. The current will then return to zero as mentioned above. The waveforms in Figure 16.3.2 show two such De-Qing events at –200 amps and –120 amps. The current pump circuit is charged while the GTO is ON. When the GTO is turned OFF the current in the pump circuit adds to the negative load current thereby producing the maximum desired negative current.

The Gamma-t jump power supplies are required to drive the quadrupole magnets to produce +/- ½ unit jump in 0.5ms. It is further required to be capable of powering a single magnet to be used during beam alignment.

IV. Magnets:

The quadrupole magnets will have the following properties:

Pulsed Quadrupole System Parameters

Required integrated gradient (T)	0.85
Vacuum pipe cross-section half h ight (elliptical) (inch.)	2.4 × 1.125
Field quality within 1 inch radius circle	2%
Maximum quadrupole length (inches)	17
Maximum current (A)	200
Inductance	ALAP
Maximum voltage (V)	ALAP

The magnets will have sorting relays to be used for beam alignment.

7. Safety Requirements

Engineering, design, fabrication, assembly and tests of the given system shall abide by Fermilab ES&H (FESHM) and all Fermilab Radiological Control Manual (FRCM) requirements.

Any changes in the applicability or adherence to these standards and requirements require the approval and authorization of appropriate authority.

In addition, the following codes and standards in their latest edition shall be applied to the engineering, design, fabrication, assembly and tests of the given system.