DESIGN OF A γ_t-JUMP SYSTEM FOR FERMILAB MAIN INJECTOR

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Abstract

In order to control the beam emittance and reduce the particle losses during the transition crossing at high intensity, a conceptual design of a γ_t-jump system for the FNAL Main Injector is presented. It is a first-order system employing local dispersion inserts at existing dispersion free straight sections. The goal is to provide a jump of $\Delta\gamma_t$ from +1 to –1 within 0.5 ms. The system consists of 8 sets of pulsed quadrupole triplets. These quads have pole tips of the hyperbolic shape and thin laminations. The power supply uses a GTO as the fast switch and a resonant circuit with a 1 kHz resonant frequency. The elliptical beamtube is made of Inconel 718, which has high electrical resistivity and high strength. Details of the lattice layout and subsystems design are presented.

1 INTRODUCTION

The Main Injector (MI), which is under construction at Fermilab, is a proton synchrotron with an injection energy of 8 GeV and maximum energy of 150 GeV. The transition energy is about 20 GeV. There is a transition crossing during acceleration, similar to the present Main Ring (MR), which is to be replaced by the MI. During transition crossing, both longitudinal emittance dilution and particle losses are observed in the MR. However, the MI has a number of important improvement in its design, including higher ramp rate, lower machine impedance, smaller beam emittance, larger momentum acceptance and bigger aperture. Furthermore, the design beam intensity of the MI is moderate (3×10^{13} ppp). Therefore, it is believed that there should be no problem when particles cross the transition at nominal beam intensity in the MI. However, from the experience of other machines, *e.g.,* the AGS at BNL, transition crossing could become a severe bottleneck in intensity upgrade. It is thus decided to carry out a conceptual design of a γ_t-jump system for the MI and to make sure there is enough room in the lattice should such a system doom to be implemented.

Two other schemes for dealing with the transition crossing problem have also been considered. One is the imaginary γ_t lattice. It was excluded because of the constraint of the tunnel footprint. Another is the focus free scheme using higher harmonic rf cavities. It is good for tackling nonlinear effects. But its effectiveness is unknown for high intensity beams when the collective effects (bunch length mismatch due to space charge, microwave and negative mass instabilities) are dominant. The γ_t-jump, on the other hand, is a matured technique and has been successfully employed in a number of proton machines such as the PS at CERN and PS at KEK, the AGS at BNL and the Booster at Fermilab. Therefore, it is decided to focus on the γ_t-jump design. Meanwhile, the existence of dispersion free straight sections in the MI lattice provides an opportunity to employ a first order jump system, which has not been possible for the other machines mentioned above due to the lack of such type of regions in their lattice.

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2 DESIGN GOAL

The nominal ramp rate of the MI is about 260 GeV/s. In order to have an effective γ_t-jump, the jump rate should be at least one order of magnitude higher. The two characteristic time scales during the transition, namely, the non-adiabatic time and non-linear time, are about 2 ms in the MI. This implies the jump amplitude, $\Delta\gamma_t$, should be 1.5 or more. Based on these parameters, the following choice is made — The γ_t of the lattice should have a jump from +1 to –1 within 0.5 ms. This gives a jump rate of $\Delta\gamma_t/\Delta t$ = 4000 s^{-1}, about 15 times faster than the ramp rate.

3 LATTICE LAYOUT

The design uses a first-order system, making use of the dispersion free straight sections in the MI lattice[1]. The jump is provided by 8 sets of pulsed quadrupole triplets. Each triplet has two quads in the arc and one of twice integrated strength in the straight section, with a phase advance of π between each quad. The main advantage of such a design is the perturbation to the original lattice is localized. In particular, the dispersion increase during the jump is small. Figures 1-3 show the changes of β-function, dispersion function and tune when $\Delta\gamma_t$ varies between –1 and +1.

4 SUBSYSTEMS DESIGN

4.1 The pulsed quadrupoles

Each quad in the arc has an integrated field of 0.85 T-m/m and a length of 20 inches. Each one in the straight section has double strength (1.7 T-m/m) and double length (40 inches). Thus, a triplet actually consists of four identical quads. In two straight sections (MI30 and MI60), the β-function and phase are mismatched. Therefore, the strength and length of the quads in these two sections need some adjustment.

The pulsed quad has pole tips of the hyperbolic shape. There are two reasons to choose this pole tip: (a) It has higher inductance than that with circular coils. This means it uses lower driving current, which is advantageous to the power supply design. (b) The MI beam pipe is of elliptic shape, which fits better in hyperbolic pole tips than in circular coils.

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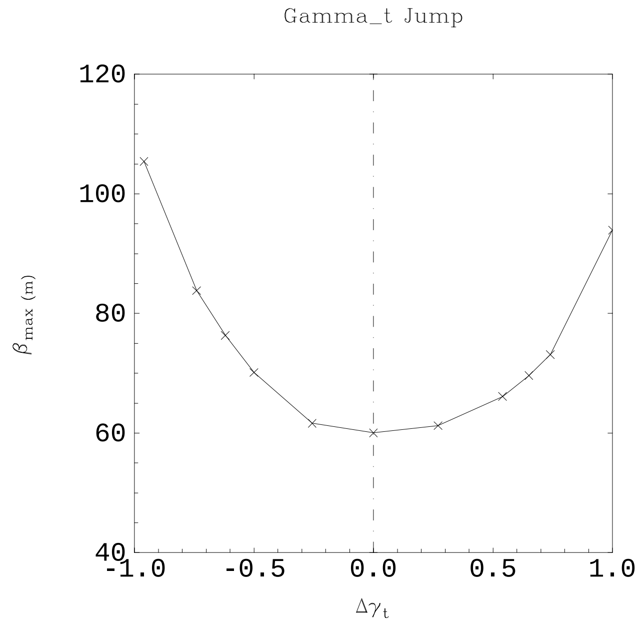

Figure 1: Maximum β-function *vs.* $\Delta\gamma_t$.

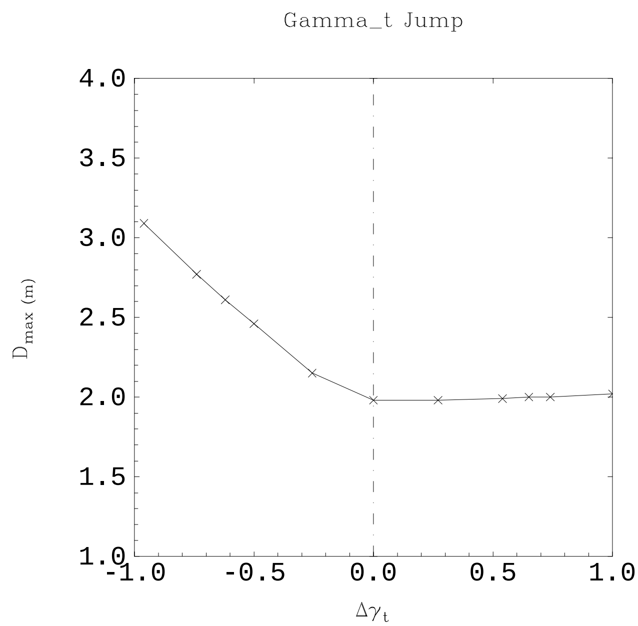

Figure 2: Maximum dispersion function *vs.* $\Delta\gamma_t$.

The laminations use thin (0.025”) silicon steel in order to minimize the eddy current losses.

4.2 *The power supply*

4.2.1 The system

The system consists of 8 power supplies. Each power supply drives a four-magnet quadrupole (*i.e.,* a triplet) string. The turn numbers per pole in the magnet design is chosen such that the magnet current is minimized yet the magnet voltage is limited to below 1.5 kV. This limit is compatible with both magnet insulation values and power supply component ratings. Each magnet has an inductance of 288 μH and a peak current of about 200 A. Its resistance is less than

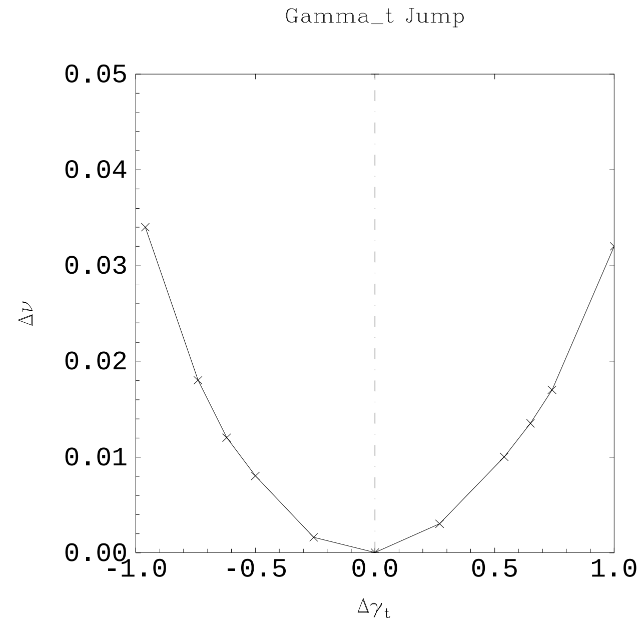

Figure 3: Tune change *vs.* $\Delta\gamma_t$.

20 mΩ. The power supply design is shown in Figure 4.

4.2.2 Circuit operation

The pulse begins when the GTO (gate turn-off thyristor) is turned ON. This applies 125 volts on the load, and charges the load current to 195 A within 3 ms. At this time the GTO is turned OFF, and the magnet load rings with the capacitor (27.5 μF) as a resonant circuit with a 1 kHz resonant frequency. The circuit rings through one half cycle, at which point the magnet current has reversed and the capacitor voltage has come back to zero. The ringing is terminated by the SCR switch in the end-of-pulse clipper, which is turned ON to prevent the capacitor from charging positively. The magnet current subsequently decays with a 3 ms time constant.

4.2.3 Eddy current losses

The ringing described above indicates what would happen in a high Q system with small losses. However, the ac losses at 1 kHz are substantial in both the magnet and the beam pipe. From measurements on various magnets at the laboratory,[2] and from calculations of expected eddy current and core losses, one expects the losses to be equivalent to those in a 4 Ω resistor placed in parallel with each magnet. The 16 Ω resistor in Fig. 4 represents the total magnet loss elements. With this resistance, the Q of the circuit is less than 0.5, and the magnet will not ring close to its peak current.

4.2.4 The current pump

In order to ring to the full negative current of 195 A, a section called the current pump is added. It consists of a 1.6 mH choke and a diode. During the time the GTO is turned ON, the choke charges up to 200 A parallel with the magnet

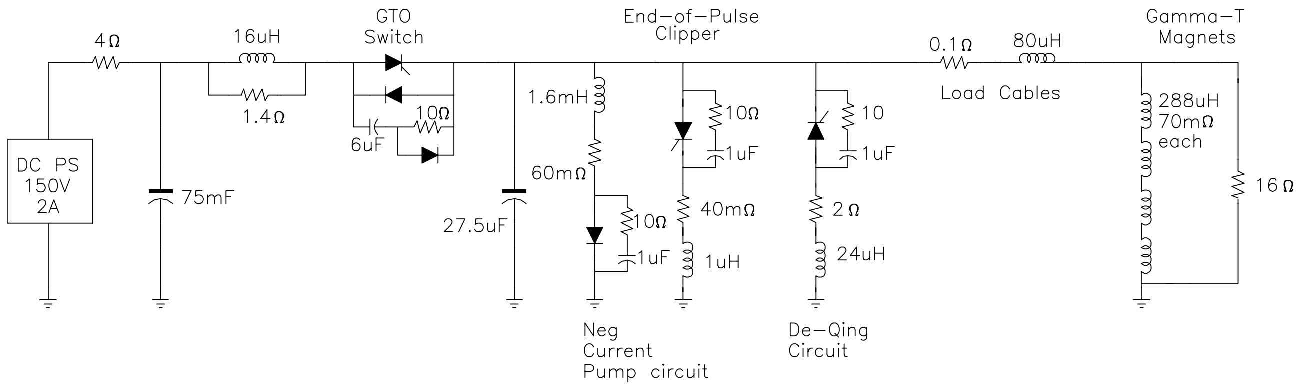

Figure 4: The power supply circuit design.

load. When the GTO is turned OFF, the current stored in the choke draws charge out of the capacitor and allows it to generate as large enough pulse to reverse the magnet current fully. The advantage of introducing a current pump is to enable us to fully reverse the load current without switching in a negatively charged capacitor. The disadvantage is the GTO must conduct twice the current as it would in the lossless case. Moreover, the choke is a substantial component; it stores more energy than the entire magnet load.

4.2.5 De-Qing

The magnitude of $\Delta\gamma_t$ on the negative side can be controlled by the de-Qing circuit, which is triggered if it is desired to terminate the pulse early and create an asymmetric current waveform. This feature is useful for the bunch length match before and after the jump.

4.3 The beam pipe

The beam pipe in the γ_t-jump section is elliptical, matching the regular MI beam pipe size, and is made of Inconel 718. Inconel has higher yield strength than the stainless steel. The wall thickness t is 0.025”, thinner than the MI stainless steel pipe which is 0.060”. It also has low electrical conductivity σ. The product σt of Inconel 718 pipe is four times smaller than that of the stainless steel pipe. This means the eddy current losses and magnetic field distortion will be smaller by the same ratio. This is the main reason for choosing this material. Compared with ceramic pipes, the manufacturing of Inconel pipes is easier, and the transition from Inconel to stainless steel is simpler. Several prototype pipes have been made. Vacuum tests show they are mechanically stable and vacuum tight. The stress and deflection analysis using theoretical model and 3-D ANSYS simulations is in agreement with the measurement. For more details the reader is referred to Ref. [3].

5 SPACE INVENTORY IN THE LATTICE

The present MI lattice is already crowded. In order to find space to install the eight triplets, the following measures would have to be taken:

1. To remove four (out of a total of 54) horizontal sextupoles.
2. To remove four (out of a total of 62) octupoles and the adjacent ion pumps.
3. To move the antiproton extraction kickers and proton abort kickers downstream by one meter, respectively.
4. To adjust the position of some diagnostics (Schottky, multiwire and low level rf pickup).
5. To shorten the BPM ends by 1” and bellows by 2” at four locations. (At these locations, the maximum available space is only about 16”, which means the magnet current would have to be increased by 20% in order to reach the same integrated field strength as a 20” magnet.)

6 CONCLUSIONS

This paper presents a feasible design of a γ_t-jump system for the Main Injector. It is by no means optimized. The purpose is to demonstrate there is a solution if such a system needs to be installed, even though it may not be the best one. At this moment, the magnet design is being revised, in particular, the end part, which could have appreciable contribution to the ac losses due to the longitudinal field component[4]. A complete conceptual design report, including the cost estimate, is being prepared.

7 ACKNOWLEDGEMENTS

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