CHROMATICITY CONTROL IN THE FERMILAB MAIN INJECTOR

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Abstract

Chromaticity control in the Fermilab Main Injector will be important both in accelerating protons and antiprotons from 8 GeV to 150 GeV (or 120 GeV) and in decelerating recycled 150 GeV antiprotons to 8 GeV for storage in the Recycler Ring. The Main Injector has two families of sextupoles to control the chromaticity. In addition to the natural chromaticity, they must correct for sextupole fields from ramp-rate-dependent eddy currents in the dipole beam pipes and current-dependent sextupole fields in the dipole magnets. The horizontal sextupole family is required to operate in a bipolar mode below the transition energy of 20 GeV. We describe methods used to control chromaticities in the Fermilab Main Injector. Emphasis is given to the software implementation of the operator interface to the front-end ramp controllers. Results of chromaticity measurements and their comparison with the design model will be presented.

1 INTRODUCTION

Chromaticity control in the Fermilab Main Injector [1] is one of the important issues for the early design of the Main Injector. The Main Injector will be used to accelerate high intensity protons and anti-protons ($\bar{\mathrm{p}}$) from 8 GeV to 150 GeV for Tevatron injection and protons to 120 GeV for $\bar{\mathrm{p}}$ production and fixed target physics experiments and to decelerate the unused $\bar{\mathrm{p}}$s from the Tevatron and store them in the Recycler Ring [2] at 8 GeV. The modes of operation for acceleration and the deceleration of the beams may be fundamentally different from one another because of the initial beam emittance and the hysteresis of the magnets of the FMI lattice. For example, longitudinal emittance of the 8 GeV beam at injection from the Fermilab Booster is expected to be $\leq$0.1 eV-sec, while, that for the anti-protons at 150 GeV from the Tevatron is expected to be 3-4 eV-sec.

2 REQUIREMENTS AND HARDWARE

The natural chromaticity of the FMI is about -33 units in both horizontal and vertical planes. The head-tail instability growth rate of the beam suggests that a chromaticity of about -5 units below transition energy and +5 units above transition is desired to keep stable beam in the Main Injector. Similar conclusions have been reached by particle tracking studies carried out at 8 GeV(injection energy) and at 120 GeV [1]. To avoid head-tail instability after the transition energy of 20.49 GeV, the chromaticity must quickly jump to the new required value. To achieve the required chromaticity and control it through the acceleration/deceleration cycle, two families of 54 sextupole magnets [1],[3] are inserted in the FMI lattice. A model of chromaticity compensation in the presence of beam-pipe eddy current, dipole geometric and saturation sextupole fields have been developed [4] and subsequent improvements [5] have been made to include remnant fields of the sextupole magnets for different operating scenarios. Implementation of the fast ramps with $\dot{\gamma}$ $\approx$267 sec^{-1}near transition, has resulted in dominance of the eddy current contribution to sextupole components at low momenta. Some of our early studies indicate that below transition the focusing set of sextupole magnets may have to run in bi-polar mode. Besides, it is extremely important that the sextupole magnet fields to be exactly identical at the end of each acceleration/ deceleration cycle for reproducibility of the beam behavior from cycle to cycle since any ramp may have been preceded by a variety of other possible ramps.

To drive the two families of sextupole magnets, new sextupole magnet power supplies which are capable of operating from -400 to 400 Amp have been built[6] and are used in the Main Injector chromaticity compensation scheme. These supplies are controlled using Fermilab C453 programmable ramp controllers housed in CAMAC. The output of the C453 is the sum of its three function generators which are 'clocked' by time, p and $\dot{p}$ respectively.

3 SOFTWARE IMPLEMENTATION

Control of chromaticity $\underline{\xi}$ requires control of the magnet strength $\underline{g}$ thus the currents $\underline{I}$ of the two sextupole families. Their relationship in vector form were formulated [4][5][7] as follows

$$\underline{g} = \frac{p}{A} M^{-1} [\underline{\xi} - \underline{\xi_0} - \underline{\varepsilon}\theta(b^{eddy} + b^{sat})] \qquad (1)$$

$$b^{eddy} = \delta \frac{\dot{p}}{p} \qquad (2)$$

$$b^{sat} = \sum a_n \frac{p^n}{A\rho^n} \qquad (3)$$

where p is beam momentum in GeV/c, A relates momentum to magnetic rigidity, $\underline{\xi_0}$ natural chromaticity. The elements of the 2x2 matrix M^{-1} and vector $\underline{\varepsilon}$ are simulated for the FMI lattice. b^{eddy} is the normalized sextupole harmonics contributed by beam pipe eddy current, b^{sat} is the bending dipole contribution due to the static sextupole moment which is largely due to saturation fields. δ is given

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by calculation[8][9] confirmed by experiment[10][11], the a_n are fitted parameters of the dipole measurements, ρ is the design beam curvature radius in the dipoles and θ is the bending angle of the dipole magnet.

Assuming that the sextupole strength is linear in the current, the above expression can be re-written in terms of currents $\underline{I}$ in the two sextupole circuits and in a form that separates contributions from p and $\dot{p}$.

$$\underline{I} = \frac{1}{A\kappa} M^{-1}[(\underline{\xi} - \underline{\xi}_0)p - \theta\underline{\varepsilon}\sum a_n \frac{p^n}{A\rho^n} - \theta\delta\underline{\varepsilon}\dot{p}] \quad (4)$$

where κ is a conversion factor between integrated magnet strength and current. In principle κ represents a complicated conversion due to hysteresis and saturation effects of the sextupole magnets [7]. In the FMI commissioning κ is taken as a crude constant. When a variety of magnet ramp cycles are required the sextupole magnet excitation and excitation history have to be described in greater accuracy. But this will involve the same method being developed for the bending and focusing magnets [7].

4 MEASUREMENTS AND RESULTS

In the course of commissioning, both tunes and chromaticities are adjusted and measured repeatedly. Shown in Figure 1 are results of one set of systematic chromaticity measurements and the momentum ramp profile. Figure 2 shows data points plotted in coordinates of set and measured chromaticity values. The set values are the end results of efforts put into the whole scheme of chromaticity control - physics modeling,magnet measurements, software and hardware implementations. The fact that the data points are narrowly populated along a straight line with slope close to one satisfies us for the commissioning stage.

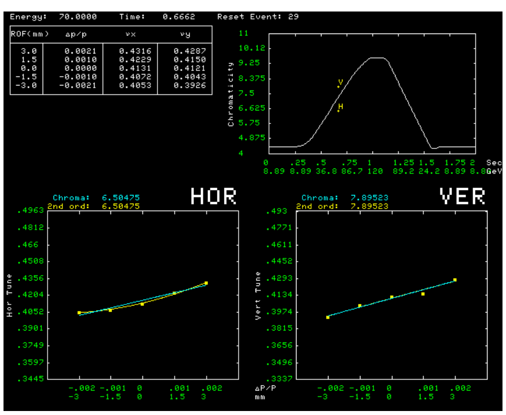

Figure 1: Horizontal and vertical chromaticity measurements for Main Injector at 70 GeV. The top right FMI ramp, bottom shows tune *vs* radial position: left ξ_H and right ξ_V.

5 SUMMARY

We have implemented a chromaticity compensation scheme (both hardware and software) in the Main Injector and have

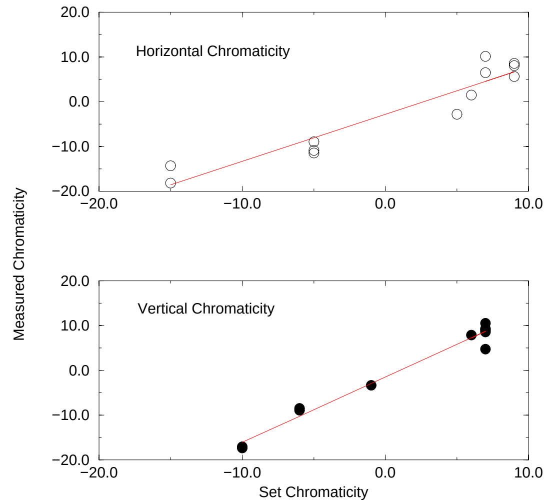

Figure 2: Comparison between measured and set horizontal and vertical chromaticities for the Main Injector in the energy range from 9 GeV to 110 GeV.

tested it during the 1998-1999 FMI commissioning runs. We have measured the chromaticities corresponding to the set values in an energy range of 9-110 GeV during the acceleration cycle. They are fairly in good agreement. Results of these studies will be used to control the chromaticities in the deceleration mode of the FMI.

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