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MI Power Supply Control Issues for Magnets with Hysteresis

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Contents

Abstract

The power supply control system for the Main Injector will interact with the machine hardware and the operators through sets of programs which share information on the state of the machine. The required currents are determined by the desired beam parameters, lattice properties and the properties of the magnets. A PAC97 paper[1] provides a physics description of the accelerator and magnet issues. This paper will discuss the assumptions which will permit the application of those equations and a model of the program structure for this interaction.

1 Introduction

Control of the momentum (p), tune (ν_x, ν_y) and chromaticity (ξ_x, ξ_y) of the accelerated beam is maintained through the interaction of several power supply systems and the rf system. Within the controls systems one must describe these variables as well as the currents and perhaps the voltages in the power supply loops. To simplify the interactions among these systems, we will attempt to rely on the beam variables rather than such secondary properties as the magnet currents or rf phases. This should allow us to deal with subtleties, such as the history dependent hysteresis of the magnets, in only one place.

The combination of lattice design, accelerator survey and measured magnet properties provide an initial model of the accelerator. Beam-based accelerator measurements may provide a refinement of that model.

This document will provide

1. An overall model of the program system
2. The beam physics equations which describe particle motion
3. A structure for specifying the operational variables
4. A specification of some of the database parameters which will be required to implement this system.

As a preliminary specification document we assume that, at most, only the fundamental equations are specified in final form.

The discussion will be divided into a magnet overview; hardware assumptions; a program overview; a ramp table specification; specifics for momentum, tune, and chromaticity; a discussion of issues; a sensitivity analysis; and a concluding section with some opinions and action items. A section which motivates the design, based on significant differences between Main Ring and Main Injector magnet systems is provided as an appendix.

2 Magnet Overview

The magnet systems[2] which must be considered in this context include the main dipole (IDA, IDB, IDC and IDD) system, the main quadrupole (BQB, IQC, IQD) system, which is divided into a focusing and a defocusing systems, and the chromaticity sextupole (ISA) system which also has two families of sextupoles. We will assume that the average value (0th harmonic) of the correction dipole (IDH and IDV) system is maintained small enough that it can be ignored in the momentum calculation.

Measurements on a variety of ramps have been performed on the magnets listed above. Most measurements have been performed with 'quasi-static' ramps[3][4] in which a ramp segment is executed to create a current change, then the current is maintained at a constant value while the field strength and shape is measured. The actual fields are modified substantially by eddy current effects. We will directly account for the sextupole created by dipole eddy currents. Eddy currents will modify the dominant fields in these magnets but these can be treated as primarily a time delay and, while they can be treated within the context of the systems we describe, they will be ignored in this description.

For an electromagnet, a field which is proportional to the drive current provides most of the design features of the magnet[1]. To achieve the precision required for accurate control of beam variables, we must also account for saturation and remanence of the iron yokes. Iron saturation reduces the available field by a few percent at the design maximum fields of these magnets. Fields due to steel remanence are roughly constant, while the direction of field (current) change is constant, and provide a contribution of a few per mil (.001) of the full field. However, they are hysteretic, depending upon the magnet excitation history. Since the dipoles operate over a dynamic range of 17, the hysteretic contribution is as large as a few percent at low fields. Figures 1, 2 and 3 show the contributions from these fields in the dipole, quadrupole, and sextupole magnets. Note how the hysteresis depends upon the ramp history.

The field strength profile achieved at a given current profile will depend

[1]In note MTF-94-0078[5], the strength contribution to the magnet field due to iron saturation and hysteresis has been extensively explored.

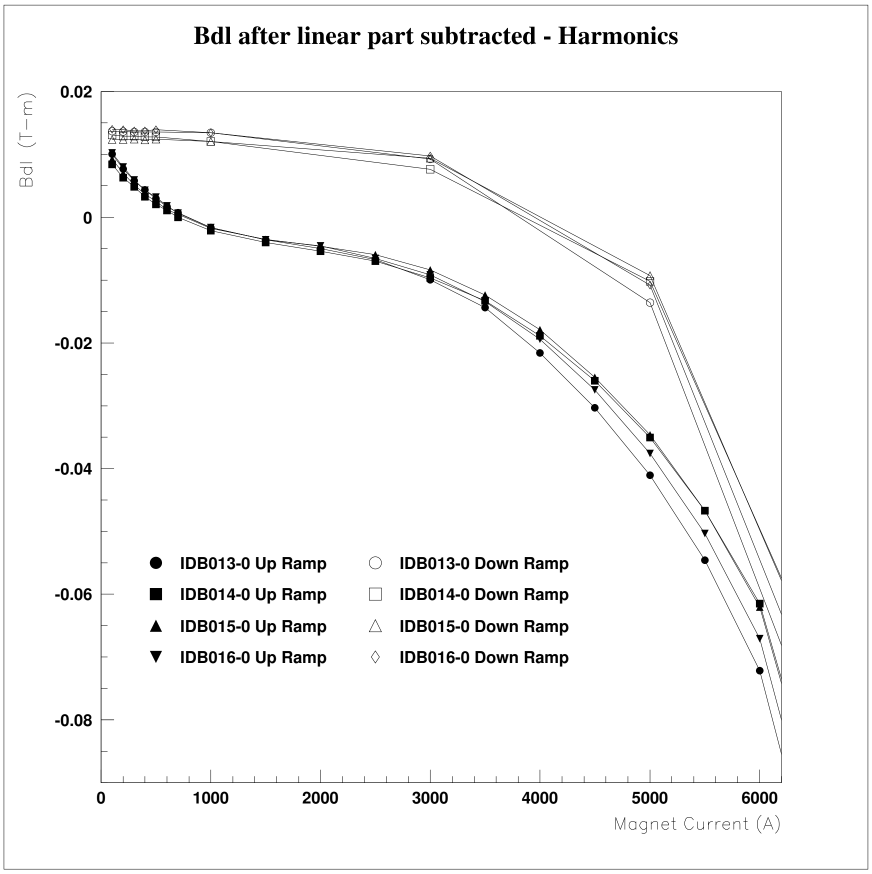

Figure 1: Nonlinear portion of integrated dipole strength for four 6-m Main Injector dipoles as measured by the Harmonics measuring system.

upon (at least) the peak field in the previous cycle, the minimum current (reset current) in the present cycle and the ramp rate. However, the range of peak currents and ramp rates which will be used in the Main Injector are limited. We believe that we may achieve the desired field profile for any given ramp cycle with a current profile which is not dependent upon the history of previous ramp cycles, provided we "prepare" the magnet with a suitable reset profile at the end of each ramp. This cannot be exact, but it is possible that such a reset strategy can allow ramps with sufficient precision, independent of previous ramp history. We set that as a goal for this design.

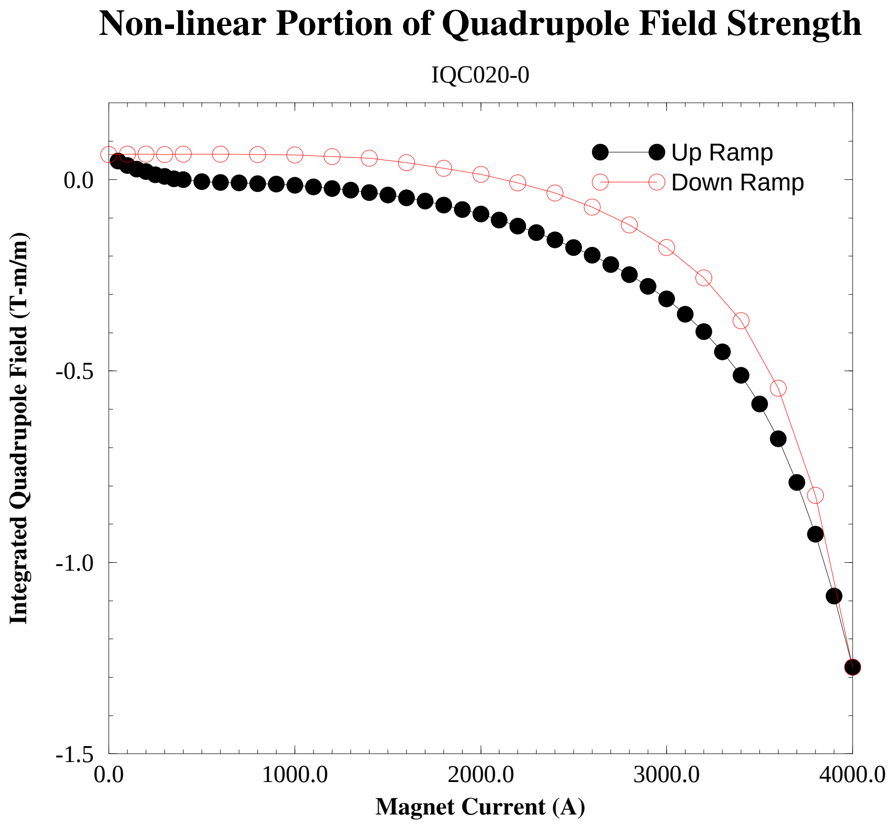

Figure 2: Nonlinear portion of quadrupole strength.

3 Hardware Assumptions

We will assume the following criteria can be met with the hardware we will construct and the measurements we will have on that hardware:

1. We assume that a magnet current ramp I(t) can be specified and the power system will produce that ramp to an accuracy sufficient for the present purposes. The small differences between that ramp and the ramp which is actually achieved is only important in a small number of systems and will be controlled in real time by those systems as required. We assume that the calculated ramp is achieved.

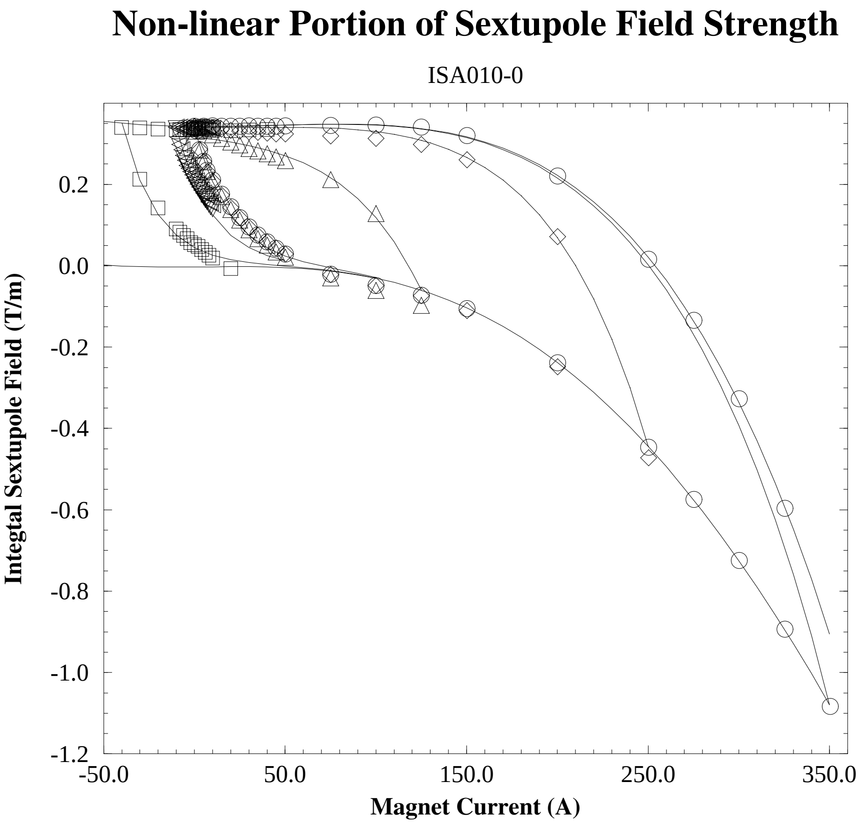

Figure 3: Nonlinear portion of sextupole strength.

2. The accelerator parameters which are to be controlled by the major magnet systems are the momentum (p), the tunes (ν_x, ν_y), and the chromaticities (χ_x, χ_y). Corresponding to this are 5 magnet current busses: dipole, quad focusing, quad defocusing, h-sextupole and v-sextupole. We expect to represent the basic equations which relate these with a fundamental set of equations which assume that the design lattice has been created, and perhaps, a second related set of equations which account for lattice imperfections with offsets and slightly modified coefficients.

3. We assume that the magnetic fields are functions of I, dI/dt and history. Sufficient measurements will be taken with adequate precision

that for a given ramp I(t), one will know the fields in each magnet. For the measurements to be sufficient may require certain ramp shape strategies to avoid unacceptable sensitivity of results on details of previous history achieved.

4. Two effects create time dependent fields, *i.e.* fields which are not in phase with the magnet current. Eddy currents (mostly in the beam pipes) produce small amplitude reductions and significant time delays. We could account for these in the control algorithms but that is not described in this document. In addition, there are time dependent effects in the response of the iron (such as magnetic viscosity) which can modify accelerator magnetic fields. Some small effects in Fermilab accelerators have been attributed to these phenomena. We believe these are small effects and we have no measurements of them at present. They will not be discussed further here.

5. We assume that some strategy, such as the reset strategy described above, will permit one to describe the beam parameter and magnet current ramps with sufficient precision, independent of the previous ramp history design.

6. We divide the magnet systems into major ramped systems (dipole, quadrupole, and sextupole) with which control of the accelerator parameters shown in item 2 are maintained, and correction systems (skew quad, steering dipole, harmonic quadrupole...) which we assume are not significant in the control of those parameters. The exception is the dipole correction system, whose interaction with machine momentum may require monitoring.

7. The correction quadrupoles, skew quadrupoles, additional correction sextupoles as well as the higher order correction elements do not interact directly with the five beam parameters which we are controlling. In particular, we will consider a machine in which the horizontal and vertical motions are uncoupled. The control of skew quad may need to reference the tables described here in order to maintain decoupling through the ramp.

8. The closed orbit of the working accelerator will not pass through the centers of quadrupoles and sextupoles. We will assume that the dipole (steering) and quadrupole (tune) effects of these do not require explicit consideration in momentum and tune calculations.

4 Program Overview

Based on the assumptions below, we can specify the following interactions to create the control of the magnet current:

Operator Interface	$\Leftrightarrow$	Application Program	$\Rightarrow$	Ramp Hardware/Software

where all subtle and/or complex calculations (which depend on details of magnet and lattice properties) are hidden in the Application Program. Both the Operator interface and the Ramp system (MECAR...) will be presented with a machine description which is simple and intuitive. The working description of the ramps is captured in two sets of tables which reference a common set of time markers. One set of tables describes accelerator parameters, another set describes the currents in various busses. The Application Program(s) creates these tables based on input from the Operator Interface including selected 'calibration' information about the lattice, magnets, and power systems which it will obtain from the accelerator database. The same time slots (or perhaps all being at most subsets of a single most detailed time list) are used for all tables. By assumption, these are 'played' with sufficient fidelity to permit most systems to assume that they are exact. Real time feedback based on actual current achieved will be required within the current control loop, but otherwise, if at all, only by the RF systems.

Various signals will be broadcast including, *e.g.*, p and dp/dt (at nominal radius) from the power supply system and f_{rev} or f_{rf} from the llrf system. Curve generator systems which require such input will have it available.

Significant properties of the accelerator and magnets will be required to perform the needed calculations. These will not be coded into the application, but will be identified to the application by names and values will be retrieved from the database.

5 Ramp Specification

By accepting a few rules, the description of the system and its implementation can be facilitated. In Appendix A we will discuss possibilities for the actual specification options which may be used for passing information (points for an f.i.r. filter, points and derivatives for a "Taylor Series" ramp specification...). But we will assume that for any breakpoint at which a machine operator wishes to specify any beam property, there will exist (or he can trivially create) a momentum specification. It is proposed that these be locked to some suitably high frequency clock, assumed for the purposes of discussion to be a 1440 Hz.

Ramped parameters to be specified are described as basic ramp which can be (perhaps) described by the machine designer from design studies and offset ramp which is the (small) change in the design characteristics selected by the machine operators to tune for optimal performance. Some may be grouped in sets with the assumption that the operator interface program will maintain consistent sets based on a mixture of specification inputs. We assume the following list of beam parameters require ramp specification:

1. p (momentum), $\dot{p}$ (pdot), $\ddot{p}$ (pdoubledot) and momentum offset
2. ν_x, ν_y for nominal tune and $\delta\nu_x, \delta\nu_y$ tune offset
3. Design chromaticity χ_x, χ_y and $\delta\chi_x, \delta\chi_y$ offset
4. r_{pos} (radial position offset).

With these the following control device parameters are specified:

1. DCUR (for dipole current)
2. FQCUR, DQCUR (for horizontally focusing and defocusing quad current)
3. FSCUR, DSCUR (for horizontal and vertical sextupole current)
4. RPOS (radial position offset)

We observe that these can be represented either as many separate time-property tables or as a single large table (with perhaps some empty entries). We designate this table as the MI Acceleration Profile Table.

Note that, with the assumption that all ramps lock to a specified common time base, the above table can be added to with any/all properties and devices, thereby representing, conceptually, all of the needed ramped properties. Interpolations or other operations which are needed for specifying either beam or device ramps only interact with points which can be shown on this table. We note that the number of columns which can be included in this table is quite large. It is likely that the operator interface will need to allow flexibility in selecting which columns are displayed or manipulated.

time	p	ν_x	ν_y	χ_x	χ_y
1.0000	8.9	26.42	25.40	-4.8	-4.8
time	DCUR	FQCUR	DQCUR	HSCUR	VSCUR
1.0000	1000	201	200	1.5	1.9

Table 1: MI Acceleration Profile Table

6 Basic Equations

In Reference [1], we have presented the basic equations for particles on the design orbit of a synchrotron. We will be satisfied here to supplement them with equations for the momentum effect of a radial offset created by the RF system. The llrf system controls the momentum achieved in the accelerator using feedback on beam parameters. If a horizontal (radial) position detector is located at a ring location, s, with dispersion $D(s)$, the measured position change from that of the nominal closed orbit is related to the difference in momentum from the nominal closed orbit momentum by

$$\delta r = \delta x = D(s)\,\frac{\Delta p}{p} \tag{1}$$

from which one concludes that if p_o is the momentum of beam on the offset orbit and p_{co} is the momentum on the unperturbed closed orbit

$$p_o = p_{co}(1 + \frac{\delta r}{D}) \tag{2}$$

While this relation correctly describes the effect of requesting the llrf system to produce a change of δr, great care will be required to integrate this into the control of accelerator parameters, principally because a local orbit bump with steering dipoles can also modify the x position of the beam at the position detector used by the llrf system. We will assume that effort which is not currently available will be required before one will consider using RPOS offsets as part of operationally tuning the machine. We assume that the llrf system is directed to tune beam to the center of the aperture except for special studies[2].

Please refer to Reference[1] for the relations between accelerator parameters, magnet properties and currents.

7 Momentum and the Dipole System

The dipole field controls the momentum. The input to calculating the required dipole ramp is the specified p vs t curve. We may have dipole measurements on the exact ramp which we require[3] If we haven't measured the exact ramp, we understand the hysteresis and saturation effects well enough that we can calculate the $\int B\ dl\ vs.\ I$ anyway. We will use appropriate averages of the installed dipoles if that is required, or perhaps of all dipoles, if that is sufficiently accurate. The mapping from $\int B\ dl$ to momentum (p) is linear. Since the 'input' is a curve of p vs t, several steps of interpolation may be required. One will construct some correct curve of $\int B\ dl$ vs I. One may have to interpolate on both axes to provide the $\int B\ dl$ and I at the specified times. The resulting curve should be 'absolute' since the momentum (on the design orbit) is determined 'simply' from the integral field around the ring.

The energy and momentum of the accelerator are governed by two basic equations.

$$p = \frac{e}{2\pi} \int_C B_y\ ds = e(B\rho) \tag{3}$$

$$f_{rf} = h f_{rev} = \frac{h\beta\gamma}{2\pi R} \tag{4}$$

where p is the proton momentum in GeV/c, e is the proton electric charge, $\int B_y\ ds$ is the integrated dipole field in Tesla-m, f_{rf} is the acceleration frequency and f_{rev} is the revolution frequency in Hertz and $2\pi R$ is the path length of the protons in meters. These equations apply to protons (and

[2] Thanks to Dave Capista for interesting discussions of this point.

[3] The Magnet Test Facility is unable to match the design downramp ramp rate. It is thought that that is not relevant.

antiprotons) on the design orbit for the machine. We wish to associate the field integral with the measured properties of the dipoles. For this, we need to assume

1. The zeroth harmonic of the horizontal correction dipoles is sufficiently small.
2. The net steering due to the quadrupoles is small.
3. The time delay between the field and the current can be neglected.
4. The RF acceleration system has accelerated the beam to keep the protons on the design orbit[4].

The value of $\int B\,dl$ which is used in Equation 3 is constructed from the magnet properties suitably averaged. Based on the lattice (or the installed magnets), one linearly sums the required curves of $\int B\,dl$ *vs.* I and history based on the number of IDA's, IDB's, IDC's and IDD's in the lattice[5].

7.1 Momentum Specification

Successful operation of the accelerator demands that care be taken in the demands which are placed on subsystems at critical times. Both the RF and dipole power supply system have ranges of parameters which demand great care in specifying the momentum. Initial acceleration at the end of the injection period has traditionally required great care. A typical solution has utilized a parabola for the initial acceleration. The operator interface will have to provide techniques to specify a sufficiently smooth and precise curve, including, one assumes, no acceleration, linear acceleration and parabolic acceleration. But, whatever the desired ramp, the application program will create a momentum profile and any required derivatives of that profile which are useful.

[4]In Section 6, we showed how the momentum is affected by a finite radial offset. I assume that this is not to be taken into account in the calculation of dipole current since the operators of the machine will avoid such manipulations during routine operation. Is that correct? Will this aid or interfere with diagnostics such as measurement of chromaticity?

[5]This should be constructed outside of this framework and referenced from the database. We need to specify how such curves are stored and referenced.

7.2 Dipole Current Calculation

The calculation of the desired current consists of matching the required field profile to the specified current profile in 6 regions of the ramp: injection, acceleration, peak field, de-acceleration, ejection, and ramp reset. The required algorithm will be described elsewhere. The output of this algorithm is a dipole current profile in the time slots specified in the MI Accelerator Profile Table.

8 Tune

Quadrupole fields are used to set the accelerator tunes (ν_x, ν_y). Operationally, the tunes reflect ratios of quadrupole fields to the momentum (set by the dipole field). Since both the dipole and quadrupole have significant saturation, it simplifies implementation to use the momentum as the link between them. The actual tune equations depend on the lattice which is actually achieved. The ratio of tune to field is not linear so we will describe the coefficients for achieving the design tune separately from coefficients to achieve small corrections. Additionally, a 'tune modifier' which operates with respect to a set of measured tune offsets may prove useful. Whether this or some different system is finally worked out, we assume that the operator interface can provide the desired tune ramps to the Application Program. Let me here describe a scheme. We use the lattice design program to relate integrated quadrupole fields to the momentum for a specified 'design tune' which is taken as energy independent. The Application Program is provided with this design tune and could calculate quad fields which correspond. The Operator Interface also provides a pair of tune vs time (or momentum) tables which are used as tune offset parameters. To determine quadrupole field requirements based on this tune offset information, the Application Program may use both lattice calculations and/or measured machine parameters which have already been corrected by the actual lattice which was achieved. Whatever the combination of inputs, the application program provides to the power supply hardware (and back to the user interface) a pair of current vs time curves for the two quadrupole buses.

We assume that the design tune is determine by

$$\underline{\nu} = \underline{Q}\,\underline{k_1} \tag{5}$$

where $\underline{\nu}$ is a column vector of ν_x and ν_y, $\underline{k_1}$ is a column vector of momentum normalized quadrupole strengths and $\underline{Q}$ is the required sensitivity matrix

(See Reference [1]). Precise control of the tune will be achieved by applying linear corrections based on the tune offsets demanded by the operators and by the tune correction learned from accelerator measurements to correct the model for the achieved properties. Both can be represented as

$$\delta\underline{\nu} = \delta\underline{\underline{Q}}\,\delta\underline{k_1} \tag{6}$$

9 Chromaticity

For the sextupole, one wishes to provide, from the user interface, a simple nominal chromaticity (this may require a ramp-based specification, since a single value is not normally acceptable), and an offset curve for χ_x and χ_y vs time. One will wish to create the desired sextupole field but here it depends on both the sextupole created by the sextupole circuit, and the sextupoles induced by the dipole (and perhaps quadrupole ???) magnets. For the dipole terms, one has history-dependent hysteretic fields, ramp-rate dependent eddy current fields and very important saturation effects. In addition the sextupole strength of the sextupole magnets is hysteretic. Given a dipole and quadrupole ramp, the properties of the dipole eddy current term, the sextupole magnet measurements and a suitable algorithm, one can calculate the desired current ramp for the sextupole magnets. This is not trivial, but if we accept this model in which all calculations are for specified momentum ramps, a self-consistent set of results can be obtained in a straightforward manner independent of what form the relations between fields and currents are presented in. If we wished to calculate this 'on-the-fly', it would be less obvious unless the the relations are both analytic and invertible.

The Main Injector design uses two chromaticity sextupole circuits: MI-SEXF and MISEXD (or should we call them MISEXX and MISEXY) (with magnets at the horizontally and vertically focusing quadrupoles). As discussed in Bogacz and Peggs[6], the chromaticity which results is described by the equation:

$$\underline{\chi} = \underline{\chi_0} + \underline{S_D} K_{2D} + \underline{S}\underline{k_2} \tag{7}$$

One can think of this as expressing the contributions due the natural chromaticity, sextupole fields at dipole locations, and sextupole fields at quadrupole locations. As above, we will expect the sensitivity parameters $\underline{S}$ and $\underline{S_D}$ to be determined by first calculating their values from a lattice model, then measuring them in the machine and adding a difference (tuning) term to the model term.

10 Concerns and Issues

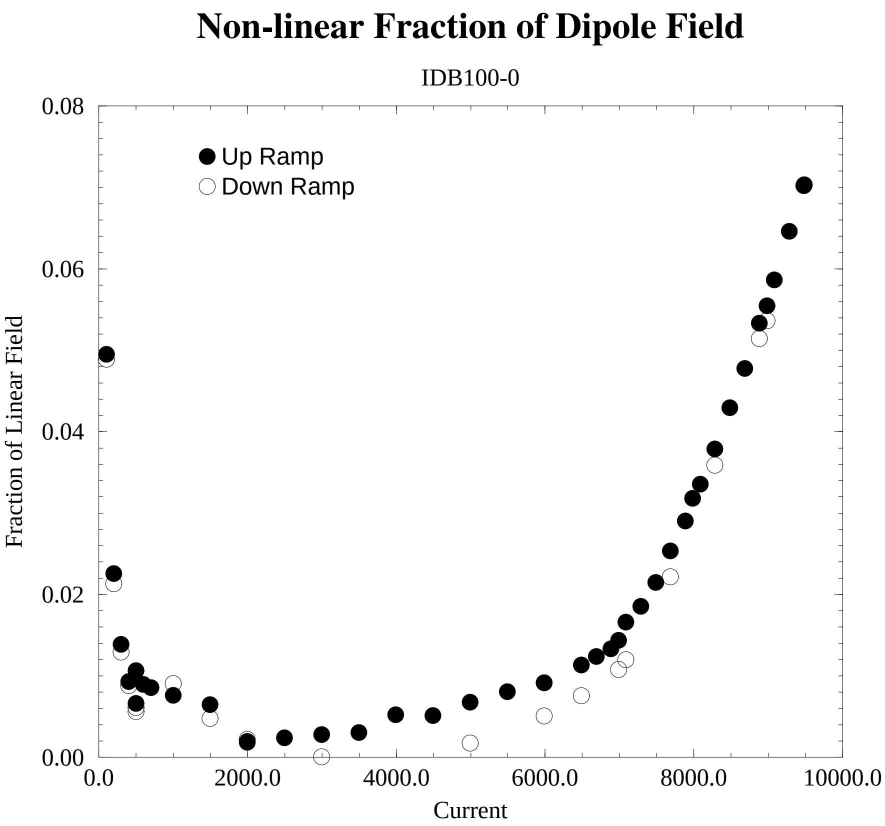

Figure 4: Nonlinear portion of IDB100-0 strength as a fraction of the linear field.

1. We assume (but must confirm) that the currents required for each operational ramp (150 GeV to Tevatron, 120 GeV Pbar production...) is sufficiently independent of previous ramp(s) as to allow one to fully specify the ramp and AT MOST have a separate small correction to apply which depends upon the previous history.

2. The language to describe reset current issues needs to be resolved and perhaps some issues in hardware are involved. We believe that the quadrupole and dipole bussed will require 'reset' currents below the

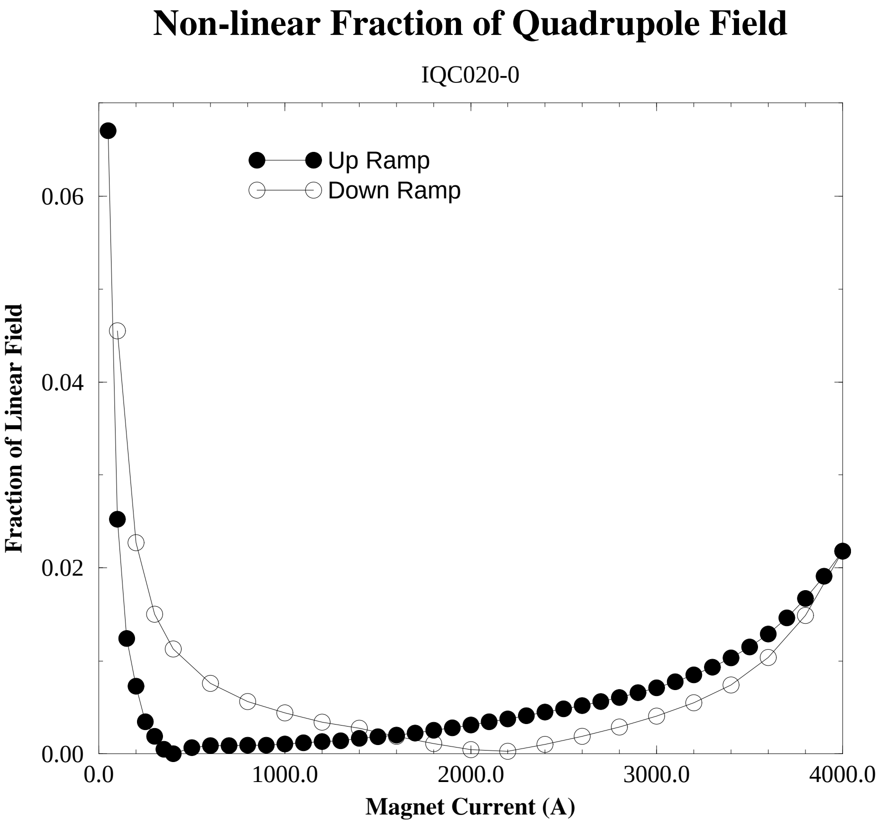

Figure 5: Nonlinear portion of IQC020-0 strength as a fraction of the linear field.

injection current. It would be 'natural' to include the reset portion of the ramp with the up-ramp portion, since that pairing may permit more flexibility within a simple system. But clock definitions may preclude that. It should be examined. Note that a special concern will be the $2D cycles which remain at the 8 GeV injection level. For now we may wish to assume that the reset portion of the ramp occurs just prior to the end.

3. The plan described for including measured tune and chromaticity effects has been presented quite casually. Considerable thought is required to permit a realistic system using measured tune and chro-

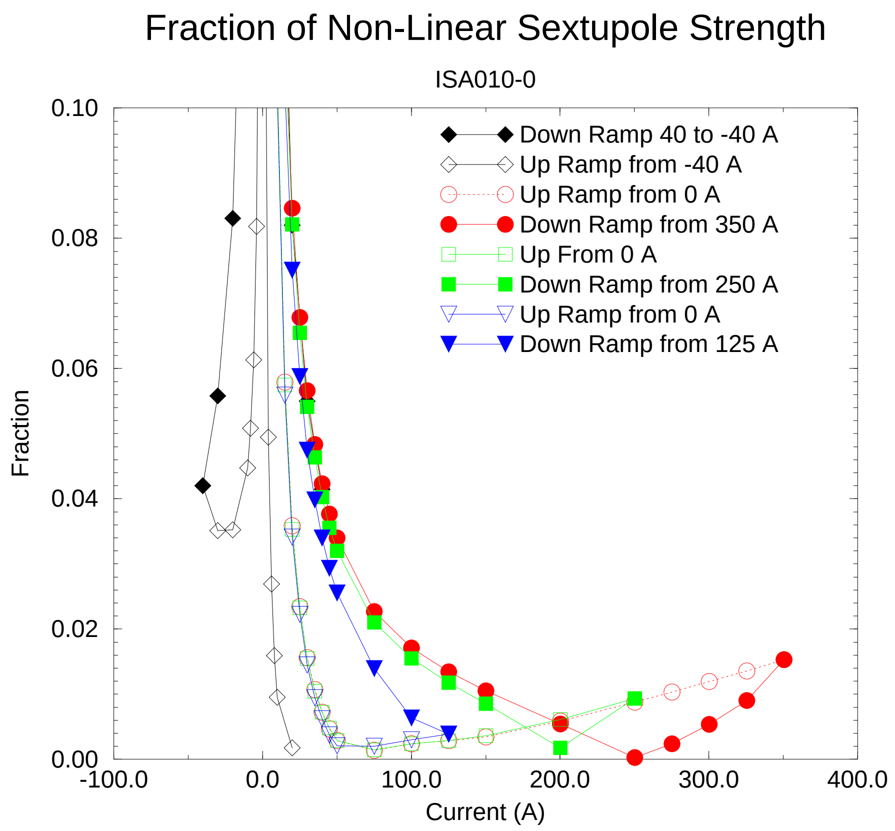

Figure 6: Nonlinear portion of ISA010-0 strength as a fraction of the linear field showing full range of current.

maticity effects, which will be time dependent, to be inserted into the framework above. I speculate that it can be done without compromising the fundamental plan. This requires thought.

11 Importance of Nonlinear Fields

The proposed mechanisms for dealing with hysteresis and saturation which have been described will require substantial new analysis and software effort. Is it required? In Figures 4, 5, 6 and 7, we plot the non-linear field as a fraction of the linear field.

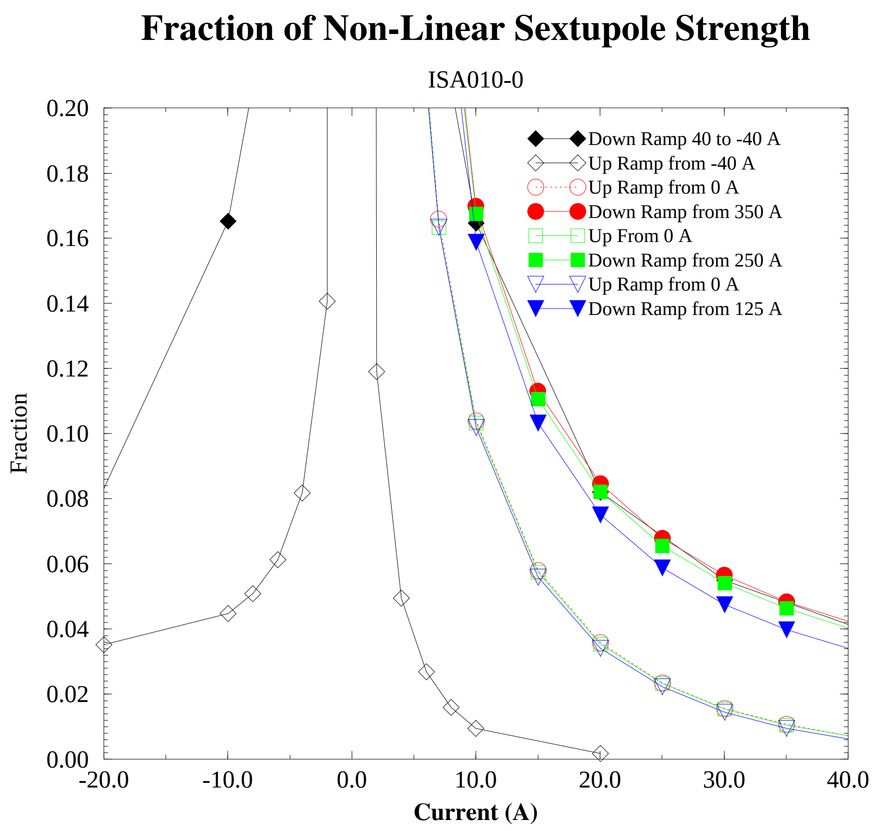

Figure 7: Nonlinear portion of ISA010-0 strength as a fraction of the linear field with limit range of current to illustrate low field behavior.

We note that for the MI Dipole, high field saturation has the largest non-linear effect. But the hysteretic low field non-linear terms are much to large to ignore in setting the momentum precisely. For the sextupole, the saturation creates only about a 1% change in the field. However, the hysteresis at low fields is very important. Since the current at which the fields are reset varies with the ramp, there are effects which are typically 10% of the linear field. To see what effect this will have on machine operation, one needs to examine the sensitivity results presented in Reference [7].

A quantitative measure of the importance of hysteresis can be obtained by observing that the hysteresis is characteristically weakly current dependent and approximately the same magnitude as the integrated remanent field (See Figures 1, 2, and 3). We can calculate the current required to create such a change. By comparing this characteristic current (I_{Rem}) to the currents of interest (such as the current required at injection or transition), we can readily ascertain the relative significance of hysteresis and gauge with what care we must set the hysteretic fields. These results are shown in Table 2[6]

N	Magnet	B_N^{Rem}	B_N^{Lin}/I	δI_{Rem}	Injection Effect
1	IDA	.01335 T-m	.001203 T-m/A	11.09 A	$\delta p/p \approx 2\%$
2	IQC	.06654 T-m/m	.01459 T-m/m/A	4.56 A	$\delta\nu \approx 0.89$
3	ISA	.3311 T/m	.2022 T/m/A	1.637 A	$\delta\chi \approx 6.5(3.3)$

Table 2: Characteristic effects of hysteresis. The difference between up ramp and down ramp fields is typically with 30% of the magnitude of the remanent field. δI_{Rem} characterizes the corresponding change in current on the up ramp to achieve the field obtained at the same nominal current on the down ramp. The effect on machine parameters is characteristically proportional to $1/p$. The magnitude of the effect at injection is shown in the final column.

12 Summary

The following items would be labeled conclusions, were they that, but instead can be appropriately labeled opinions:

1. The portions of strengths of magnetic fields for the Main Injector magnets which are not linear with magnet current are sufficiently large as to demand careful attention in specifying the magnet current ramps. The deceleration option has made this significantly more important.

2. A hysteresis model of the sextupole which make no error larger than 5% of the remanent field is sufficient. At low momentum, it will be useful if the dipole and quadrupole models make errors which are typically smaller than 0.5%.

[6] The remanent fields shown in Table 2 for dipoles are from Reference [8]. Quadrupole and sextupole remanent field averages were calculated from measurements extracted from the **results** database. Quadrupole sensitivity is calculated using results in Reference [9]. Sextupole sensitivity is calculated with results from Reference [7].

3. The assumption that the current control system achieves the specified ramp is critical to the design which is outlined above. Since the beam dynamics requirements for current control are quite tight, unless we choose very aberrant ramps, the hysteretic effects should not create a more demanding requirement for current regulation control.

Issues which have arisen in this context include:

1. It is known that the saturation differences between Main Ring 84″ quadrupoles and the IQC and IQD quadrupoles which were fabricated from the new steel for the Main Injector result in strength ratios which change as a function of current. One would expect that this will result in changes in the lattice at high fields. What will be required to permit sufficiently well controlled operation? Since the effects will predominately affect the lattice above 120 GeV only, can we ignore them for acceleration and make only a final correction just prior to 150 GeV extraction? OR will we need to provide a series of lattices which describe operations at different field levels?

2. In like manner, one may wish to add to the calculated machine description with parameters determined from measurements. The description presented here assumes that the accelerator description is momentum independent. what mechanism will be used to permit one to use a set of several (many) lattice descriptions in place of one. Will matching at points be sufficient or will derivatives also need to match, for example?

3. The calculation of the required ramps to achieve the magnetic fields which match a specified set of machine parameters must involve maintaining information about the hysteresis state of each set of magnets. A single application which does the conversion from required field to ramp is desirable.

4. Description of the ramps must be passed from the applications programs to the power supply control software. it will soon be appropriate to select the description which is to be used. (see Appendix A).

Finally, we know of one effect which violates the assumptions of this discussion. The coherent Laslett tune shift [10] depends upon the beam current and thus cannot be pre-specified from the ramp design. The correction will have to be applied in real time by the current control system (MECAR). this is likely to be sufficiently small as to not change the hysteretic state, thereby not modifying the basic assumptions from which we are working. Are there other such effects?

A Options for Ramp Description

The precise description of a time sequence of values is a problem which does not have a unique solution within the Fermilab Accelerator control system. Generally, to provide sufficient information one can pass lessor information on a more detailed set of values [(time,value) pairs, for example], or pass fewer points (less data) but with more detailed information or a more complex data processing scheme for that data. We will describe schemes which imply an increasingly complex data processing for interpretation of the data passed.

Value Tables One passes complete sets of times and values as (t,v) ordered pairs with sufficient time resolution to permit the complete specification of the ramp with the required accuracy.

Linear Interpolation One passes a set of times and values as (t,v) ordered pairs. The receiving program is instructed to provide linear interpolation between points. Simple variations could include a spline interpolation.

Taylor Series Interpolation This system, used for some existing controls problems passes the ramp definition as sets of $(t, v, \dot{v}, \ddot{v} \ldots)$ with the specification that the receiving program interpret them as coefficients for a Taylor series.

Finite Impulse Response One passes a set of times and values as (t,v) which are to be processed by an FIR filter program whose output describes the desired ramp.

The correct choice of ramp specification has elicited some vigorous discussion. It has been said that the clear engineering choice is an FIR. Some limitations in fidelity of the ramp have been observed with the Taylor Series specification as implemented for the Main Ring. This document will not resolve this discussion.

B Differences from Main Ring System Operation

This construct of the overall system is different from the present Main Ring system primarily by accounting for the non-linear behaviors of magnets in a coherent and simple way. This is demanded due to several differences:

1. For 150 GeV operation, the MI Dipoles experience a much larger ($\approx$ 10%) saturation field error (when compared to a linear B vs. I. This is mostly because there are 301 1/3 *vs.* 774 dipoles of $\approx$ 6 m length so the Main Ring dipoles were operating at only 0.7 T whereas the Main Injector requires more than 1.7 T. The dipole control of the Main Ring uses a saturation table which is important for operation at energies above 400 GeV, but other systems relied upon scaling the dipole current to determine momentum.

2. Deceleration is expected by design in the MI and differences of up to 1% are expected (current dependent) in the down ramp vs up ramp behavior.

3. Main Ring operation determines the eddy current correction for chromaticity on-the-fly. The higher ramp rate of the main injector creates sufficient eddy current sextupole that explicitly accounting for it using well-confirmed algorithms and more direct determination of the field sources is likely to be more important than for the Main Ring.

4. Hysteretic differences associated with different ramp reset values can be accommodated in a straightforward manner in such a system.

Since these dominant issues are to be accounted for explicitly, the parameters which are provided for operator tuning will be free to solve smaller or more subtle effects without being forced to provide for larger, well understood effects.

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