20 December 1978
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NOTES ON EXCITATION OF CORRECTION AND ADJUSTMENT ELEMENTS

In these notes, I will first make some estimates relating to tolerances on the excitation current delivered to the correction and adjustment magnets of the Energy Doubler. Second, some comments will be made on the waveforms.

At present, there is a set of four trim magnets located within or near each standard main quadrupole - a dipole, trim quad, sextupole, and octupole, all of which are superconducting. Since there are 180 standard main quads, there are so far a total of 720 elements in the correction system. There will be additional elements, especially clusters of special magnets near the long straight sections. However, in the absence of new demands placed on the Doubler, the most numerous elements in the system have already been identified.

I will use the element strengths as they were at the outset of this design study except in the case of the dipole, where allowance will be made for an increase of a factor of two in its field. The nominal maximum current for all elements is taken to be 50A.

Because of their role in orbit correction, the dipoles inherently require independent power supplies. At this writing, each of the other types of magnet plays a number of roles. For example, the trim quads not only provide betatron oscillation tune adjustment but also produce an appropriate azimuthal harmonic for half-integer extraction. Conceivably, the trim quads could also be called upon to correct local quadrupole terms in the main magnets. It will be seen below that, in my estimation, the latter requirement is at odds with adequate performance in the extraction role.

These notes are only an initial attempt to set down some guidelines, and quantitative counterarguments are most welcome.

I. CURRENT TOLERANCES

In this section, the needs of slow extraction will be ignored - that discussion will appear below in the next section. The exception is smoothness of the orbit.

By "instability" or "drift", I mean current changes that are uncorrelated with time in a given supply, and are uncorrelated from supply to supply. By "ripple", I mean a nx60Hz current component that can be highly correlated from time to time in a given supply, and also highly correlated from supply to supply.

A. Dipoles

1. Instability

The rms orbit distortion at a point where the amplitude function is β_0 due to N uncorrelated angular errors θ also located at points with $\beta = \beta_0$ and characterized by $\langle\theta^2\rangle^{1/2}$ is

$$\langle x^2\rangle^{1/2} = \frac{\beta_0}{2\sin\pi\nu}\left(\frac{N}{2}\right)^{1/2}\langle\theta^2\rangle^{1/2}$$

In terms of a fractional error $f = \Delta(BL)/(BL)_{max}$ in a correction dipole, $\langle\theta^2\rangle^{1/2} = (BL)_{max}/B\rho \times \langle f^2\rangle^{1/2}$ and

$$\langle x^2\rangle^{1/2} = \frac{\beta_0}{2\sin\pi\nu}\left(\frac{N}{2}\right)^{1/2}\left(\frac{(BL)_{max}}{B\rho}\right)\langle f^2\rangle^{1/2} = 2.1\,\langle f^2\rangle^{1/2}$$

for $\beta_0 =$ [illegible]", $\nu = 19.4$, $N = 90$

$(BL)_{max} =$ [illegible] kG×inch

$B\rho$ at [illegible] GeV

Suppose one wants 95% odds that the distortion from this source not exceed 0.01 inch (we want the orbit smooth to about 0.1 inch). Then for Gaussian errors, $\langle x^2\rangle^{1/2} \cong 0.01/2$ and $\langle f^2\rangle^{1/2} \doteq 0.24\%$. The errors probably are not Gaussian, but this suggests a stability requirement $\pm 0.24\%$.

2. Ripple

There will probably be a substantial number of partially excited supplies on the 19th harmonic. Suppose correlated ripple fields find themselves (somehow) on this harmonic. Then the maximum displacement would be

$$x \simeq \frac{\beta_0\nu}{(\nu^2 - 19^2)}\,\frac{1}{2\pi}\,\frac{(BL)_{max}}{B\rho}\,\frac{N}{2}\,f = 5.4\,f \text{ inches}$$

For $x < 0.01$ inch, $f < 0.2$[illegible]

3. Conclusion

It looks like, to nearest order of magnitude, 0.1% supplies controlled to 1/[illegible] are about right.

B. Quadrupoles

See next section on extraction.

C. Sextupoles

1. Instability

The rms variation in the chromaticity due to fluctuations in the sextupole strength is

$$\langle(\Delta\xi)^2\rangle^{1/2} = \frac{1}{4\pi}\left(\Sigma\beta^2\eta^2\right)^{1/2} S\left\langle\left(\frac{\Delta S}{S}\right)^2\right\rangle^{1/2} = 17.5\left\langle\left(\frac{\Delta S}{S}\right)^2\right\rangle^{1/2}$$

where S ≡ (B"L/2Bρ) is the maximum sextupole strength and ΔS is its variation. The chromaticity is ξ.

The natural chromaticity is -22. If we want 20/1 odds that $\langle(\Delta\xi)^2\rangle^{1/2}$ will be less than 1 (an arbitrary choice) then

$$\left\langle\left(\frac{\Delta S}{S}\right)^2\right\rangle^{1/2} = \frac{1}{2}\,\frac{1}{17.5} = 0.029 \Rightarrow 2.9\%$$

2. Ripple

For a coherent change in the sextupole strength,

$$\Delta\xi = \frac{1}{4\pi}\left(\Sigma\,\beta\eta\right)S\,\frac{\Delta S}{S} \cong 170\,\frac{\Delta S}{S}$$

and if again we limit $\Delta\xi$ to 1,

$$\frac{\Delta S}{S} \cong 5.9\times10^{-3} \Rightarrow 0.6\%$$

3. Conclusion

According to the above, the requirements on the sextupole supplies would be less stringent than on the dipole supplies - stability at the 1% level and ripple in the 0.1% region. However, even for half-integer extraction, the sextupoles are involved. Some discussion appears in the next section.

D. Octupoles

See next section on extraction.

II. SLOW EXTRACTION

Consider the case of half-integer extraction. The stable phase space $\mathcal{E}$ is of the form

$$\mathcal{E} \propto \frac{Q + 4\pi\delta}{E}$$

where Q, E are quadrupole, octupole harmonics respectively and $\delta = \nu - 19.5$. Zero harmonics of quadrupole control δ. Let us examine the requirements on the latter; given the expression above, similar arguments (with similar conclusions) can be made for Q and E.

Slow extraction is supposed to proceed for about 10 seconds. To obtain orders of magnitude, we assume a uniformly populated phase space. Then we want

$$\frac{1}{\mathcal{E}} \frac{d\mathcal{E}}{dt} = \frac{1}{10\,\text{sec}}$$

Suppose that one wanted to hold the modulation in the spill to 10%. If there is a variation in ($d\mathcal{E}/dt$) due to ripple, instability, etc., then one would require

$$\frac{1}{\mathcal{E}} \left(\frac{d\mathcal{E}}{dt}\right)_v = \frac{1}{100\,\text{sec}}$$

where the subscript v denotes the variations mentioned above. In terms of δ, we would then have

$$\frac{1}{1-k} \frac{1}{\delta} \left(\frac{d\delta}{dt}\right)_v \leq \frac{1}{100\,\text{sec}}$$

where $k \equiv -Q/4\pi\delta$ $(k>0)$. Typical values of k and δ are 0.9 and -.05 respectively. Thus we have

$$\left(\frac{d\delta}{dt}\right)_v = \left(\frac{d\nu}{dt}\right)_v \leq \frac{10^{-1} \times 5 \times 10^{-2}}{100\,\text{sec}} \approx 5 \times 10^{-5}/\text{sec}$$

Now consider a contribution to the trim quad current common to all of the form

$$i = i_o \cos\omega t \; ; \; \left(\frac{di}{dt}\right)_{max} = i_o \omega$$

For the present trim quads

$$\frac{d\nu}{dt} = -22 \times 0.04 \frac{1}{I_{max}} \frac{di}{dt} \approx \omega \frac{i_o}{I_{max}}$$

where I_{max} is the maximum current per trim quad..

Combining the above relations, we would have for 10% modulation

$$\frac{i_0}{I_{max}} \leq \frac{5\times10^{-5}}{\omega} \approx \frac{10^{-5}}{f(Hz)}$$

Regardless of one's choice of ripple frequency, the tolerance implied is exceedingly, and, probably, unrealistically tight. As in the present extraction system, ripple bucking quads will be needed.

For random variations among about 100 individual supplies, the tolerance is ameliorated by $\sim\sqrt{100} = 10$; still difficult.

The feeling that I get from the foregoing is that it is unrealistic to consider individual excitation of the many elements participating in the extraction process. Rather, they should be wired together in functional groups, and powered by a limited number of supplies which are designed at or near the state of the art. That is to say, rather than 180 quads and 180 octupoles each with dedicated supplies, the elements would be arranged in 8 circuits for generation of the appropriate harmonics.

The sextupoles, however, are awkward. Even if we exclude the possibility of third integer extraction, the sextupoles participate in the half-integer process through the chromaticity, or more precisely, through the chromaticity adjustment that they perform. On the other hand, sextupole is the dominant error term in the main dipoles, and individual excitation of the trim sextupoles may be indicated. For the present, let us assume that the latter consideration is dominant, and that the sextupoles are individually powered by supplies of the sort used for the steering dipoles; i.e., 0.1% supplies. It is to be hoped that further insight into the sextupole problem will be forthcoming as the main magnet characteristics settle down.

III PROVISIONAL CONCLUSION

We must consider the cost implications of a substantial number (about 200 to 400) 0.1% power supplies to control the steering dipoles and possibly the sextupoles. Second, we must recognize the need for a number of "state-of-the-art" supplies for slow extraction.

IV. WAVEFORMS

In the present main ring, most of the auxiliary magnets play a role at or near injection energy only. The major exceptions, of course, are those elements used during extraction. In contrast, the corresponding Doubler system is intended to perform its various functions independent of energy. Frequent position adjustment of the main magnets of the Energy Doubler is at least difficult; this circumstance when combined with a tight closed orbit tolerance for extraction and a concern about possible instability of the high energy orbit yields a number of arguments for high energy steering. The main bends and quads are in series, so the trim quadrupoles must perform tune adjustments at all energies. Substantial sextupole terms in the main magnets are a consequence of coil geometry rather than remanent fields, hence, chromaticity compensation must be extended to high energy.

Thus, the correction and adjustment magnets will all have time-varying excitation currents, though the waveforms are not likely to be complex.

Before discussing the several multipoles, some remarks should be made about the time dependence of the main magnet current. Like the main ring, it is reasonable to suppose that there will be a period of constant current for injection. Following injection, there will be an acceleration period - hopefully, as little as 10 seconds for a peak energy of 1000 GeV. However, the ramp may not be linear, since the quench characteristics of the main magnets may dictate a slowing of the rate of current rise with excitation. I will assume that the ramp is no more complex than a sequence of a few linear segments.

The flat-top may be of about 1 to 10 seconds duration for extraction or of indefinitely long duration for colliding beam work. The downward-going ramp will be of the same form as that for acceleration; unlike the main ring, the current can't go down any faster than it went up.

A. Dipoles

The excitation of most steering dipoles will likely follow the main magnet current relatively closely, though adjustments may be needed between injection and flat-top. (But recall that the dipole excitations differ one from another.) The tolerances of the preceding section pertain to flat-top; while accelerating, the requirements are less strict - it is difficult to state how much less without a better appreciation of the hardware problems than I have at the moment.

A limited number of steering dipoles in and near long straight sections will be used for extraction, colliding beams, injection, and in the abort system. Their waveforms will be somewhat more complex, particularly on flat-top. In some cases, feedback from the beam may be needed.

B. Quadrupoles

1. Tune Control

Until flat-top is reached, the excitation of the tune control quads will, like the dipoles, tend to follow the main magnet current.

For extraction, the tune will be shifted to the extraction resonance on a negotiable time scale. Then the tight tolerances of Section II come into effect. Over a 10 second period, the excitation of the tune control circuits changes by some 2% of full excitation from beginning to end of extraction. It begins to sound like a combination of coarse-fine supplies is indicated. "Coarse-fine" insofar as control is concerned, that is; the same stability and ripple criteria apply to both.

For colliding beams, the turn-on of a low-β insertion will involve a slow (at least several seconds?) change in a number of separately powered main quadrupoles coordinated with substantial ($\sim$50% of full excitation) changes in the tune control circuits. It may be necessary that this exercise be orchestrated by the central control system in a step-by-step fashion. The rigid extraction tolerances do not apply here.

2. Harmonic Generation

Though 39th harmonics may be useful in general to control the stopband at $\nu = 19\frac{1}{2}$, the more difficult case is that of slow extraction as noted in Section II. The harmonics will be turned on as the tune is shifted to the extraction resonance, and held constant as extraction proceeds. As a later embellishment, one may consider a small gradual variation in their strength throughout extraction.

C. Sextupoles

Unlike the dipole and quadrupole cases, the relative sextupole excitation required for chromaticity compensation differs between injection and flat-top, for there is a remanent sextupole moment present in the main dipoles at low excitation. However, this distinction probably doesn't make much difference in the design of the system.

On flat-top, changes in level will be needed for all sextupoles for both extraction and colliding beam work. In the latter case, synchronization with the quadrupole manipulations noted in B. above may be required.

D. Octupoles

These are mainly extraction elements. On flat-top, the octupole circuits - both zero harmonic and 39th harmonic - are turned on, and in the basic form of extraction, held constant throughout the process. Again, as in the case of the 39th harmonic quads, subsequent development in the direction of elegance may be contemplated.