Specification of APS Corrector Magnet Power Supplies from Closed Orbit Feedback Considerations.

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1 Goal

To specify or confirm the strengths and resolutions of the corrector magnets and their power supplies.

The photon beam must be stable to 5% of the phase space dimensions of the beam (10% of the emittance). Specification of the closed-orbit displacement in the insertion device appears in the CDR, page II.1-42:

$$\begin{array}{ll} \Delta\sigma_x < 16\ \mu\text{m}; & \Delta\sigma_{x'} < 1.2\ \mu\text{rad}; \\ \Delta\sigma_y < 4.4\ \mu\text{m}; & \Delta\sigma_{y'} < 0.45\ \mu\text{rad}; \end{array} \tag{1}$$

Global and local correction systems will remove DC and oscillatory components of the orbit distortion. The oscillatory orbit distortion is usually attributed to the ground motion coupling to the quadrupole supports, but one should not assume that ground motion is the unique source.

2 Formulae, Design Handbook Data, and Assumptions Used

The deflection angle of a corrector magnet is related to the magnetic field by

$$\theta[\text{rad}] = 0.3\frac{B[\text{T}]L_{\text{eff}}[\text{m}]}{E[\text{GeV}]} \tag{2}$$

The impedance Z of a magnet is given by

$$Z = R + i2\pi f L \tag{3}$$

where R is the resistance and L is the inductance which could be substantial compared to R at the frequencies concerned. The cutoff frequency,

$$f_c = \frac{R}{2\pi L}, \tag{4}$$

is defined as the frequency at which the magnitude of the impedance is twice the value of R. The lower the value of f_c listed in Table 1 the larger role the magnet inductance will play in determining the power supply voltage specification.

The data on corrector magnets and power supplies shown in Table 1 appears in the Design Handbook. The sextupole dipole coils are used for vertical steering. The power supply voltage specification assumes a 50% chopping duty cycle. The corrector power supplies can be run as high as about 90% duty cycle, generating a voltage as high as twice the magnet DC IR drop.

Table 1: Design Handbook Magnet and Power Supply Data

Magnet	Horizontal Correction	Sextupole Dipole Coils	Horizontal H/V Combination	Vertical H/V Combination
Max. field T	.23	.11	.16	.16
L_{eff} (m)	.14	.28	.20	.20
Max. DC deflection at 7 GeV θ_{DC} (mrad)	1.3	1.2	1.2	1.2
Max. current I (A)	89	113	116	134
θ/I [μrad/A]	14.6	10.6	11.4	9.8
Impedance (mΩ)	$127 + 77f$	$187 + 54f$	$133 + 25f$	$95 + 19f$
f_c (Hz)	1.6	3.4	5.3	5.0
Impedance at DC (Ω)	0.127	0.187	0.133	0.095
Impedance at 25 Hz (Ω)	2.05	1.54	0.76	0.57
Max. voltage at DC (V)	11.4	21.1	15.4	12.7
Power Supply Specification (V)	13	23	17	14
$\theta_{\text{DC}}/V_{\text{DC}}$ [μrad/V]	114	57	86	103

The eddy current attenuation of the magnetic field through the vacuum chamber is shown in table 2. The attenuation depends on the vacuum chamber thickness, the shape of the vacuum chamber, and the configuration of the magnetic poles. The attenuation of the vacuum chamber for the dipole field produced by the H/V combination magnet was not measured. We know, however, that the thickness of the H/V magnet elliptical vacuum chamber is half that of the regular vacuum chamber. The attenuation is going to be less for these dipoles than for the others.

3 Global vs Local and DC vs AC Orbit Corrections

One can divide the orbit correction into four systems:

1. Global correction at DC
2. Global correction up to 25 Hz
3. Local correction at DC
4. Local correction up to 25 Hz

Each use different position monitors and different sets of corrector magnets. Table 3 lists parameters for the above correction systems.

3.1 Global Correction at DC

The DC global correction will be used to correct the orbit of a stored beam. The DC orbit at the photon sources must be set to within the resolution of the RF beam position monitors (BPMs) located there. The Design Handbook-specified resolution for the RF BPMs is 25 μm, but 5 μm

Table 2: Eddy Current Attenuation for Magnet/vacuum Chamber Systems

Frequency (Hz)	Horizontal Correction*	Sextupole Dipole Coils**	Horizontal H/V Combination	Vertical H/V Combination
.1	1.0	1.0	1.0	1.0
1	0.96			
5	0.67	0.97		
10	0.38	0.89		
15	0.32			
20	0.20	0.69		
25	0.15	0.61		

* Measured by Y. Chung
** Calculated by L. Kettunen

Table 3: Specification of Correction Systems

	Global DC	Local DC	Global 25 Hz	Local 25 Hz
Orbit measurement device	All of the RF BPMs	X-ray BPMs	RF BPMs at sources only	X-ray BPMs
Correctors	All correctors	Local bump	Subset of correctors	Local bump
Specified orbit measurement resolution	25 μm	Not specified	25 μm	Not specified
Achievable resolution	5 μm	1 μm	5 μm	1 μm
Required range of orbit correction	$\pm$ 20 mm	$\pm$ 100 μm	$\pm$500 μm	$\pm$100 μm

is achievable. For the undulator an RF BPM will be installed on the small cross-section vacuum chamber. The resolution there will be better by approximately a factor of four in both planes. Since the time interval between corrections is relatively long, one can use all of the RF BPMs amd correctors for the correction.

Because the resolution of the RF BPMs used in the global correction is 25 μm, the smallest orbit displacement achievable is 25 μm. In order to comply with the CDR specification in equation (1) a local orbit distortion is planned.

3.2 Local correction at DC

For the local correction, the orbit at the photon sources are measured by X-ray BPMs with a position resolution of 1 μm and an angular resolution of 0.1 μrad. The position and angle coordinate of the orbit are controlled by a set of four correctors. Figures 1 and 2 show the position of the correctors producing the local orbit distortion for both types of photon source. `CH` and `CV` are horizontal and vertical correctors, respectively.

Dynamic range Because the X-ray BPMs have better resolution than RF BPMs, the DC local correction can steer the orbit closer to the design orbit. In order for the local correction system to work, the dynamic ranges of both the global and local systems must overlap. This means that the range of the local correction should exceed the resolution of the RF BPMs used in the global correction. With a safety factor of 4 in the overlap, we take the required dynamic range of the DC local correction to be ± 100 μm.

This number is reasonable from the point of view of the global feedback system designer. Global stability significantly better than 100 μm could be difficult to achieve. In addition, the correction magnets may be required to run with a DC offset, reducing the effective dynamic range. Furthermore, it may be desirable to use the same magnet for two or more feedback systems which would require greater dynamic range.

3.3 AC Global Correction

If the amplitude of oscillatory orbit motion is very large — especially because of amplification due to the lattice focusing — a global correction system is necessary to correct the orbit. Because of time delays in communicating the orbit information, the number of RF BPMs used is limited. For the same reason, only a subset of correctors is used. In general distributed correctors can correct the orbit more efficiently than local bumps, and much larger orbit motions can be controlled.

The range of orbit correction is specified somewhat arbitrarily at 500 μm. Although calculations based on a few ground motion surveys indicate that the beam motion at frequencies up to 25 Hz is already within the tolerances defined by the CDR without feedback, the feedback system must be capable of correcting even larger orbit motions from sources other than ground motion.

3.4 AC Local correction

This uses the same hardware system as the DC local correction. The special consideration is that, at high frequencies, the magnetic field is strongly attenuated by the vacuum chamber (Table 2), and the inductance in some of the magnets (Table 1) causes a 15-fold increase in their impedances.

Dynamic range The same argument is made for local correction at AC as was put forth for the local correction at DC. The required range of the local correction is therefore set at ± 100 μm.

Figure 1: Local correction at an undulator section

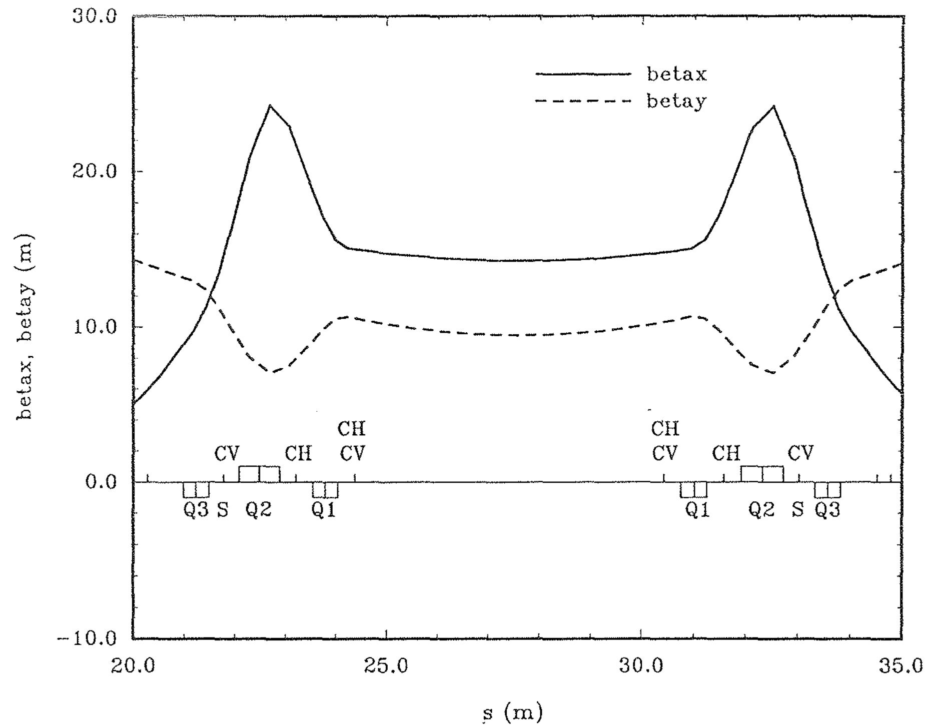

Figure 2: Local correction at a bending magnet section

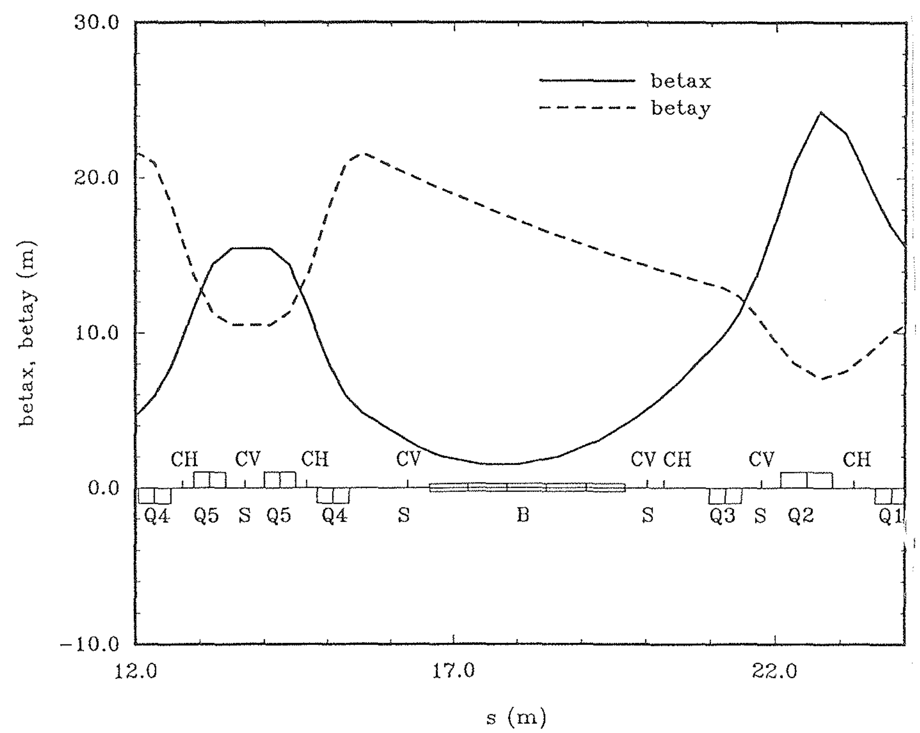

Table 4: Power supplies at 25 Hz

Magnet	Horizontal Correction	Sextupole Dipole Coils	Horizontal in H/V Combination	Vertical in H/V Combination
Orbit motion (μm) at 25 Hz	100	100	100	100
Corrector effective strength (μrad) at 25 Hz	90	62	100	38
Vacuum chamber attenuation at 25 Hz	0.15	0.60		
Corrector actual strength (μrad) at 25 Hz	600	104		
Corrector current (A) at 25 Hz	42	9.8		
Magnet impedance (Ω) at 25 Hz	2.05	1.54	0.76	0.57
Required Power supply voltage (V) at 25 Hz	86	15		
Power supply voltage specification (V) with 90% duty cycle	23.4	41.4	30.6	25.2

4 Determination of Required Dynamic Range of Local Corrector Magnet Power Supplies

In the previous section, the range for local correction at DC and AC was established. The requirements for the corrector power supplies are examined in this section. The power supply voltage is determined by the orbit correction capability at the upper end of the frequency range, which is set at 25 Hz.

Table 4 lists various power supply parameters for a 100-μm orbit correction at 25 Hz. The progression of the rows is as follows. The necessary beam deflection angles produced by correctors are related to the desired orbit correction by the 4×2 bump matrices as determined by the lattice optics. (These matrices are displayed in the next section.) The largest deflection angle for each corrector type is listed in the second row of the table.

Then the attenuation due to eddy current losses in the vacuum chamber at 25 Hz is repeated from an earlier table. This, in effect, increases the power supply current for a desired angular deflection. This is more pronounced for horizontal correction (vertical magnetic fields) than for vertical correction mainly because the vacuum chamber is thinner at the vertical correctors. Row 4 shows the required corrector strength in terms of deflection angle. In row 5, this deflection angle is converted to a magnet current using data from Table 1.

Next the impedance of the magnets at 25 Hz is displayed. The inductance of the magnets causes the power supply voltage for a given current to increase roughly in proportion to the operating frequency. This effect on the voltage is larger for the stand-alone horizontal corrector. The power supply voltage is simply the product of the magnet current and impedance. The power supply voltage required for a 100-μm orbit correction at 25 Hz is listed in the second to last row of the table. The voltage specification of the power supplies from Table 1 is repeated here at the bottom of the table. The required power supply voltage for the stand-alone horizontal corrector exceeds the specification with 90% duty cycle. The required power supply voltage for the other magnets are within specification.

The impedance at 25 Hz for the horizontal corrector in Table 4 is pessimistic because the magnet impedance calculations reported in the Design Handbook don't take into account the eddy currents in the vacuum chamber. In general, the vacuum chamber eddy currents cause the circuit inductance to decrease with frequency, and the real part of the impedance to increase with frequency. A computer simulation that includes the effects of eddy-currents was done for the horizontal corrector with a vacuum chamber of wall thickness 0.10" instead of the regular 0.50". Using the calculated magnet-vacuum chamber system inductance and the vacuum chamber attenuation factor for the magnetic field on axis, the required power supply voltage is found to be 28 V. The reduction from the value of 86 V in Table 4 is due to the combination of including the eddy currents and using a much thinner vacuum chamber wall. Practically speaking, the 0.1" thick vacuum chamber wall is machined from the 0.5" thick wall while leaving 0.50" high "ribs" for support. For this case the eddy currents are not easy to simulate, but the required power supply voltage will be greater than 28 V.

5 Power Supply Resolution Determination

The required resolution for the local corrector magnet power supplies is estimated. We want the resolution of the local correction system to be such that the beam motion will be easily controlled to within 10% of the emittance, therefore 1% of the emittance is taken as the lowest order bit change of the programming voltage.

The resolution is determined by the operation of the correctors at DC. At higher frequencies, the effective resolution is improved because of the attenuation of the magnetic fields by the eddy currents in the vacuum chamber.

The corrector strengths for a local orbit distortion (also called a bump) are related to the desired orbit change by a 4×2 matrix. The matrix elements may change by a few percent depending on the final position of the correctors. Because of a constraint of the beam optics computer program used, the vertical dipole trims of the sextupoles are modeled as a stand-alone vertical corrector adjacent to the sextupoles.

For the undulator straight section, the necessary corrector strengths that produce a horizontal orbit change Δx and $\Delta x'$ are given by

$$\begin{pmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{pmatrix} = \begin{pmatrix} 0.898\mathrm{m}^{-1} & -2.815 \\ -1.018\mathrm{m}^{-1} & 4.191 \\ -1.018\mathrm{m}^{-1} & -4.191 \\ 0.898\mathrm{m}^{-1} & 2.815 \end{pmatrix} \begin{pmatrix} \Delta x \\ \Delta x' \end{pmatrix} \tag{5}$$

where the k values are the kick angles of the correctors taken in sequence along the ring segment.

For the vertical direction,

$$\begin{pmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{pmatrix} = \begin{pmatrix} 0.379\mathrm{m}^{-1} & -1.132 \\ -0.300\mathrm{m}^{-1} & 1.896 \\ -0.300\mathrm{m}^{-1} & -1.896 \\ 0.379\mathrm{m}^{-1} & 1.132 \end{pmatrix} \begin{pmatrix} \Delta y \\ \Delta y' \end{pmatrix} \tag{6}$$

Using 10% of the values in equation (1) as 1% of the emittance, the required resolution for the horizontal plane is

$$\begin{aligned} \Delta k_{1,4} &= 0.1\min(0.9\Delta\sigma_x, 2.8\Delta\sigma_{x'}) \\ &= 0.1\min(14\ \mu\text{rad}, 3\ \mu\text{rad}) \\ &= 0.3\ \mu\text{rad} \end{aligned} \tag{7}$$

$$\begin{aligned} \Delta k_{2,3} &= 0.1\min(1.0\Delta\sigma_x, 4.2\Delta\sigma_{x'}) \\ &= 0.1\min(16\ \mu\text{rad}, 5\ \mu\text{rad}) \\ &= 0.5\ \mu\text{rad} \end{aligned} \tag{8}$$

We take the resolution for the horizontal plane to be .3 μrad. For the vertical plane, the required resolution is

$$\begin{aligned} \Delta k_{1,4} &= 0.1\min(0.3\Delta\sigma_y, 1.0\Delta\sigma_{y'}) \\ &= 0.1\min(1.3\ \mu\text{rad}, .5\ \mu\text{rad}) \\ &= .05\ \mu\text{rad} \end{aligned} \tag{9}$$

$$\begin{aligned} \Delta k_{2,3} &= 0.1\min(0.3\Delta\sigma_y, 1.8\Delta\sigma_{y'}) \\ &= 0.1\min(1.3\ \mu\text{rad}, 0.8\ \mu\text{rad}) \\ &= .08\ \mu\text{rad} \end{aligned} \tag{10}$$

We take the resolution for the horizontal plane to be .05 μrad.

The above is repeated for the corrector magnet set for the bending magnet source. The local bump matrices are:

$$\begin{pmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{pmatrix} = \begin{pmatrix} 0.780\text{m}^{-1} & -2.651 \\ -0.529\text{m}^{-1} & 2.650 \\ -0.410\text{m}^{-1} & -1.915 \\ 0.417\text{m}^{-1} & 0.929 \end{pmatrix} \begin{pmatrix} \Delta x \\ \Delta x' \end{pmatrix} \tag{11}$$

for the horizontal set and

$$\begin{pmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{pmatrix} = \begin{pmatrix} 0.432\text{m}^{-1} & -0.728 \\ -0.268\text{m}^{-1} & 1.451 \\ -0.541\text{m}^{-1} & -2.124 \\ 0.633\text{m}^{-1} & 1.313 \end{pmatrix} \begin{pmatrix} \Delta y \\ \Delta y' \end{pmatrix} \tag{12}$$

for the vertical set. The matrix elements are of the same order of magnitude, therefore the resolution for undulator local correctors also applies to these.

Table 5 lists the necessary resolutions for the local correctors at DC. If full scale DC steering is taken to be 1.2 mrad, 13 bits and 16 bits are required for the horizontal and vertical corrector power supplies, respectively.

6 Conclusion

Since the required range of the local horizontal corrector power supplies exceed the specification in the present design, we suggest the following choice of possible action items:

Table 5: Local corrector required resolutions

	Horizontal μrad	Vertical μrad
Undulator	0.3	0.05
Bending magnet	0.3	0.05

- Remove material from the vacuum chamber to reduce the magnetic field attenuation. This will decrease the required power supply AC current.
- Increase the power supply voltage limit.
- Redesign the horizontal corrector magnet to reduce the resistance and inductance.