Errors & Corrections

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SSC Design Seminar 1/8/88

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Why the Tolerances/Correction Specifications are not Final?

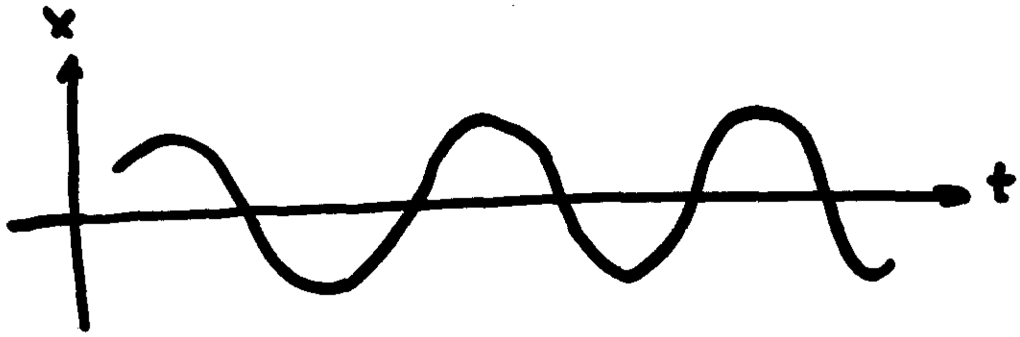
Error-and-correction study is particularly relevant to the SSC because

- error effects scale with E (typically $E^{1/2}$).

- economic consideration to have a small magnet aperture.

The Tunes

With perfect magnets, particle motion is linear, i.e. sinusoidal:



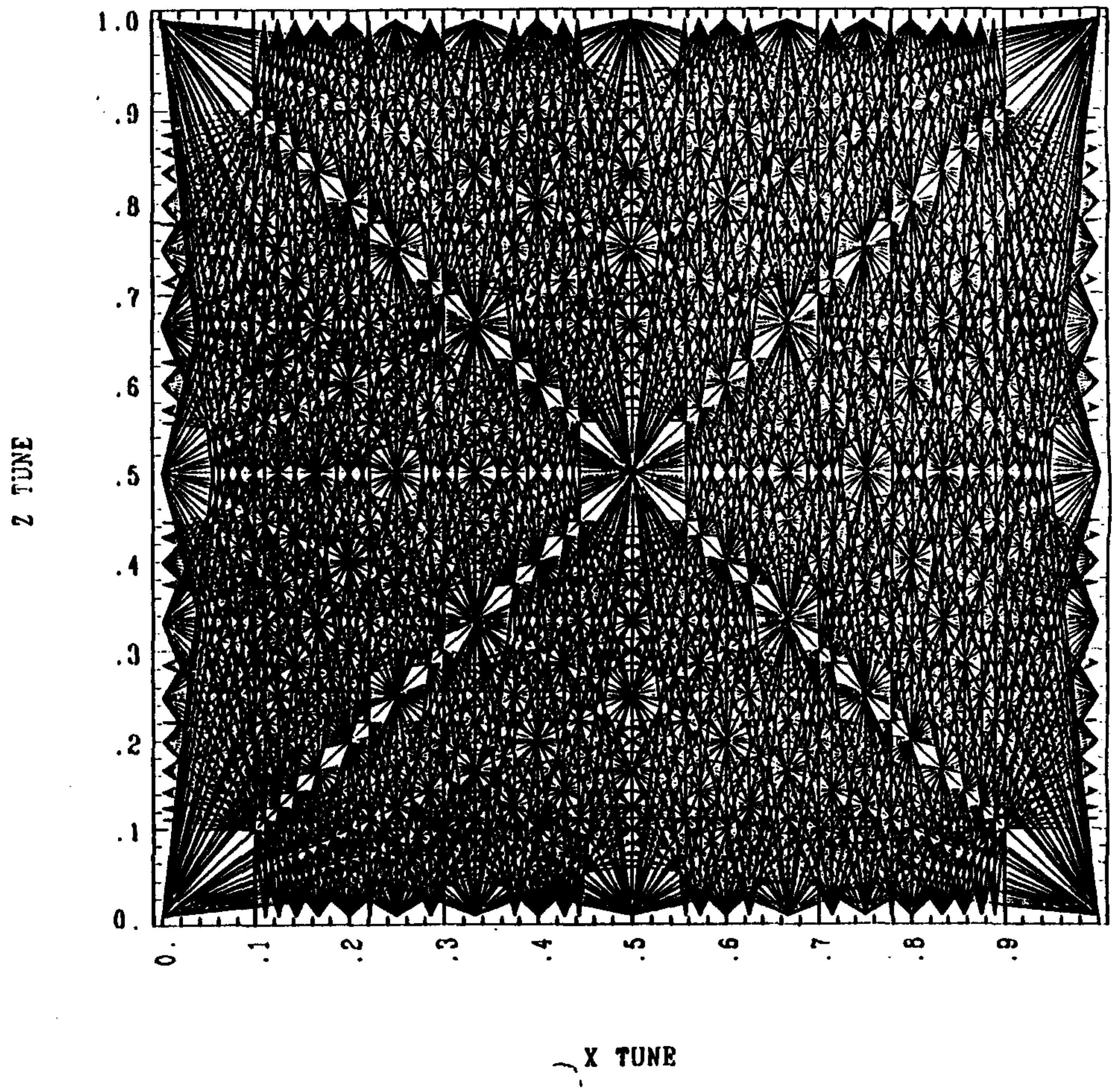
ν = tune = # of oscillations per revolution

the single most important beam dynamics parameter

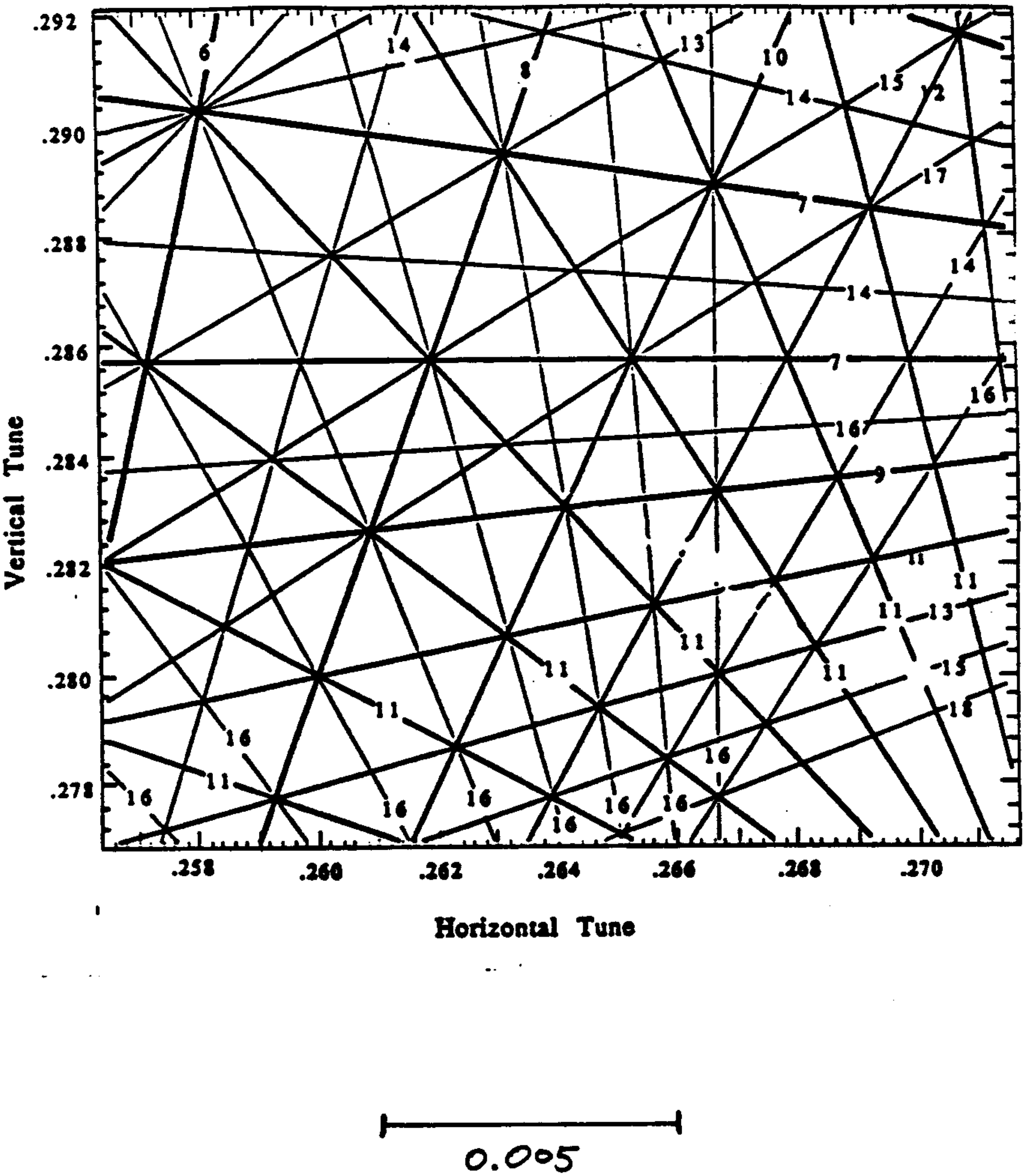
The present design has the nominal tunes ν_x = 95.285 and ν_y = 95.265.

One crucial requirement is that $\nu_{x,y}$ must not hit a low-order resonance value (a rational number n/p with p<10, say).

[resonance diagram]



1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.
Z TUNE
0.
.1
.2
.3
.4
.5
.6
.7
.8
.9
X TUNE



.292
.290
.288
.286
.284
.282
.280
.278
.258
.260
.262
.264
.266
.268
.270
Vertical Tune
Horizontal Tune
6
14
8
13
10
14
15
12
7
17
14
14
7
16
16
9
11
11
11
13
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11
11
15
11
18
16
16
16
11
16
16
16
16
16
16
0.005

To assure stability of beam particles:

- The nominal tunes must be tightly controlled.

- We suggest that all particles do not at any point during operation have tune shifts from the nominal values by more than ±0.005.

Control of the Nominal Tunes

The nominal tunes are controlled by the trim quadrupoles (2 families) in the primary corrector packages. Considerations:

- The nominal tunes must stay away from resonances by > 0.005
  + 0.001 (tune ripple allowance),
  and for very low order (<6, say) resonances,
  + 0.007 (synchrotron tune).

- The trims need to compensate for the tune errors, $\delta\nu$. CDR estimate $\delta\nu \approx \pm 0.012$. But past experiences (mostly unexplained) => $\delta\nu \approx$ 1-2% of the nominal tune $\approx \pm 1$ to 2.

- tracking error of ±1% between dipoles and quadrupoles => tune wondering of ≈±1 during acceleration.

- The telerances of the systematic a_n's are set by assuming a $\nu_{x,y}$ split of ±1. (Otherwise the tolerances would be very tight.)

In the CDR, the trim quadrupole strength is capable of a tune range of ±2.

Present thinking: this ought to be increased, perhaps to ±3 to 4.

<u>Control of Shifts from Nominal Tunes</u>

This is to be done to an accuracy of $\Delta\nu/\nu < 5\text{x}10^{-5}$ (difficult for large accelerators !)

The first source of tune shift comes from the chromaticity:

(tune for a particle with E+ΔE)
  = (nominal tune) + chromaticity * ΔE/E

The sextupole magnets in the primary corrector packages make the chromaticities zero. Otherwise, the chromaticities = -220 => $\Delta E/E=10^{-3}$ gives a tune shift of -0.22. Sextupole magnets are a must.

The chromaticity sextupoles are not a dominating source of nonlinearities in the SSC.

The second source is the error multipoles in the magnets (later).

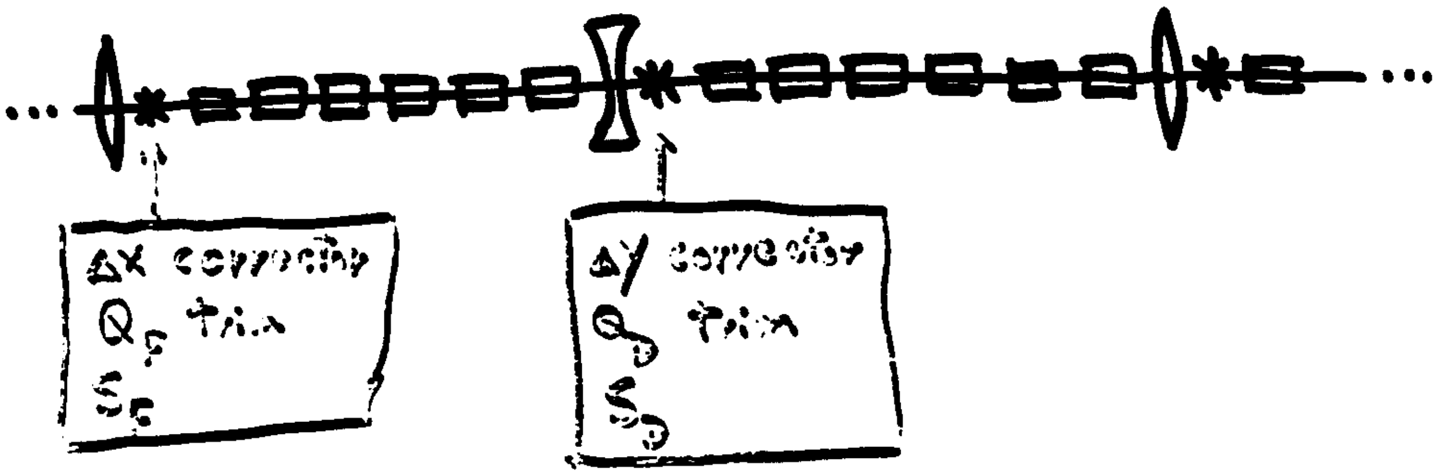
$$B_y + i\,B_x = B_o \Sigma_n (b_n + ia_n)(x + iy)^n$$

Orbit Error and Correction

Orbit error comes from

- quadrupole misalignment ±0.5 mm
- random a0 and b0 errors in the dipoles ±6 units
- dipole roll misalgnment ±0.6 mrad
- dipole strength error $\Delta BL/BL$ $\pm 6\times10^{-4}$
- BPMs misalignment w.r.t quad centers ±0.1mm

2 types of primary corrector packages in the arcs:



Several possibile algorithms of orbit correction exist. After correction, the rms orbit ≈ 0.25 mm. The rms corrector strength ≈ 8 mrad.

Orbit correction is in relatively good shape. Yet to do:

- only a non-optimized correction scheme exists for the IRs

- missing BPMs or correctors.

Injection Operation

This is one subject being studied by the SUN workstations.

First turn guidance : done, no surprises.
Injection errors : later.
Injection in the presence of persistent current multipoles : high priority, being studied.
b2 drift with time (due to temperature drift,e.g.): later.

Three Types of Corrector Packages In the Arcs

(a) Primary packages

corrector	function	strength
Δx, y correctors	orbit correction	CDR*
$Q_{F,D}$ trims	nominal tune control	?
$S_{F,D}$	chromaticity correction	CDR* if beam-tube ? if lumped

(* update for 90° cells)

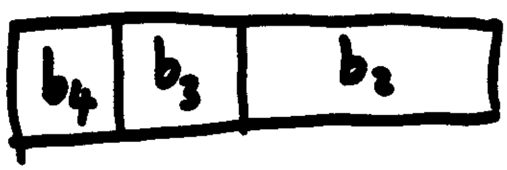
(b) Multipole packages:

The CDR has beam-tube windings for correcting the systematic b2, b3, b4. Much has happened since CDR.

Post-CDR studies =>

(i) These windings do not have to overlap.
(ii) These windings can be used to deal with the random b2, b3, b4 by the "binning" technique.

Each dipole now is equiped with:



full length equivalent

where b2, b3, b4 windings are capable of 4, 0.4, 0.4 units at 20 TeV.

(iii) Recently, a "lumped correction scheme" has been suggested as backup to the beam-tube scheme. See later.

(c) Secondary packages:

CDR has a1, b1, a2, b2, a3, b3 packages (2 each per sector).

Purpose : to have some control over the random multipoles.

Problems : Not clear how to use them. Complication imposed on beam diagnostics may not be worth it.

Present thinking : Get rid of them. The multipole packages + binning should be sufficient for any good the secondary packages could do.

In addition to the corrector packages in the arcs, there are

- orbit correctors in the straight sections
- skew quadrupole correctors in the straight sections
- multipole corrector windings in the IR triplets

Decoupling

Coupling is caused by

- quadrupole roll misalignment ±0.5 mrad
- orbit error in sextupoles
- random a1 error in dipoles ±0.7 units

Correctors are 16 skew quadrupoles, 2 per straight sections forming 2 families.

Operations simulation => The scheme works for injection optics with corrector strength = 1/10 arc quadrupole.

Yet to do:

- the collision optics
- the systematic a1 of ± 0.2 units.

Beam Tube Aperture

The beam tube aperture = maximum envisioned aperture need during operation. A possible decomposition:

dynamic aperture = 13 mm
(10 σ = 6 mm)
(maximum orbit error = 4 mm)
(room for measuring the nonlinear chromaticities = 3 mm)
max. dipole misalignment = 2 mm
max. cold mass sagging= 0.5 mm

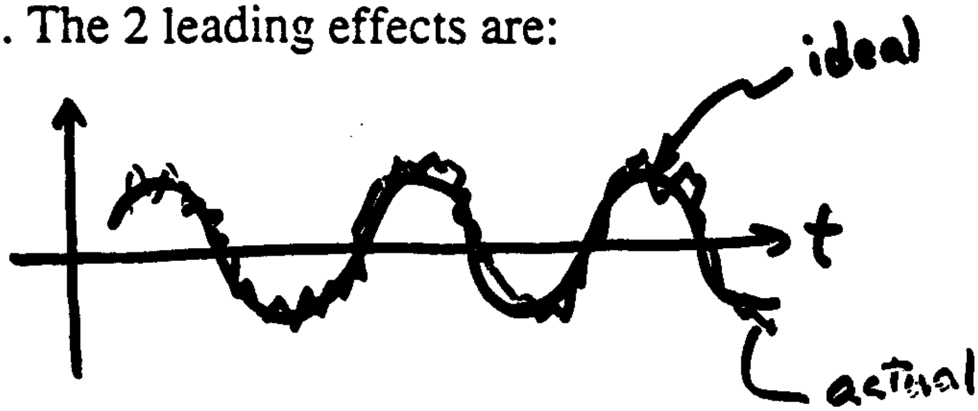
Ideally, the total beam tube aperture need (radius) is therefore 15.5 mm.

Impedance also depends on the beam tube aperture.

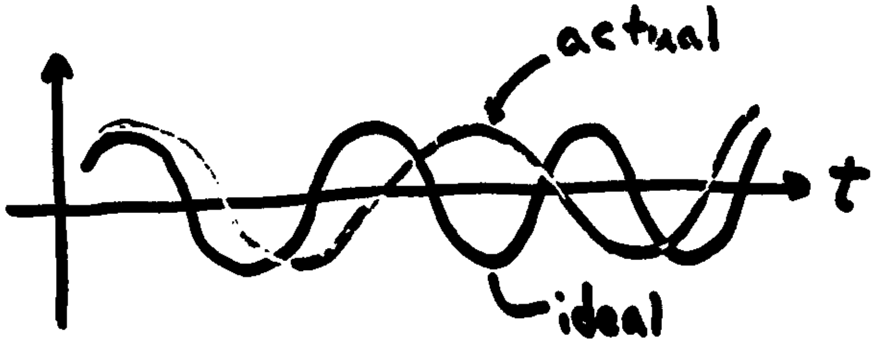
Error Multipoles

Magnet nonlinearities perturb particle motion in many ways. The 2 leading effects are:

smear



tune shift



Effect of tune shifts:

- A particle becomes unstable if its tune is shifted to a low-order resonance.

Effect of smear:

- Figure of merit for deviation from linearity.

In addition, resonance strengths also characterize the nonlinearity. In fact, knowing all resonance strengths fully characterizes the nonlinearity, including the smears and tune shifts.

effect	# of quantities
smear	2 (can be combined into 1)
tune shift	2
resonances	many (2 per resonance)

For SSC, the multipole specs are set by imposing:

(a) the smear criterion: rms smear $< 6.4\%$
(b) the tune shift criterion: tune shift $< \pm 0.005$

The present set of specifications for the SSC dipoles is

	random (rms)	systematic
a1	0.7	0.2
a2	0.6	0.1
a3	0.7	0.2
a4	0.2	0.2
a5	0.2	-
a6	0.1	-
a7	0.2	-
a8	0.1	-
b1	0.7	0.2
b2	2.0	1.0
b3	0.3	0.1
b4	0.7	0.2
b5	0.1	0.04
b6	0.2	0.07
b7	0.2	0.1
b8	0.1	0.2

Smear mainly comes from the random multipoles. Tune shift mainly comes from the systematic multipoles.

The specified rms random multipoles satisfy the smear criterion if sorting/binning => a factor of 5 reduction in the effective b2 spread.

The specified systematic multipoles satisfy the tune shift criterion if b2, b3, b4 multipole packages are available.

	tolerance no correction	expected (5 μm filament)
b2	0.01	4.7
b3	0.017	-
b4	0.03	0.3
b5	0.06	-
b6	0.1	0.07
b7	0.2	-
b8	0.3	

Aperture Experiment

The magnet coil aperture must be chosen to assure the tolerance specifications. CDR has 4 cm coil I.D.

The final choice still awaits (among other things)

- the final analysis of the Tevatron aperture experiment at Tevatron.
- whether the multipole tolerances are indeed met by the real magnets.

I.e. coil aperture could not be finalized unless these issues are addressed.

2 possible outcomes of the Tevatron experiment:

a. The 4 cm aperture is satisfactory as advertised in CDR.
b. The 4 cm aperture is adequate for the envisioned immediate needs, but whether it provides sufficient safety margin requires more study.

The possibilities that the 4 cm aperture fails to meet (or far exceeds) the envisioned needs and must be increased (decreased) are unlikely at this moment.

Binning and Sorting

These are techniques to deal with the random multipoles.

CDR had only sorting, applied to b2 only.

Binning can be applied to b2, b3, b4. And it still leaves sorting available. Binning* is one of the great post-CDR ideas.   (* Talman)

Present thinking : Apply binning to b2, b3, b4 with 7 bins for b2. (How many bins for b3, b4 ?) Sort on a2 in addition.

Lumped Multipole Correctors

Beam tube multipole correctors are still the present design. (They are great from accelerator physics point of view.) But lumped schemes are possible backups.

Several possible lumped schemes have been studied. Simplest example:

$$Q_F * B\ B\ B * B\ B\ B\ Q_D * B\ B\ B * B\ B\ B$$
$$= *3*3 \quad *3*3$$
$$= \text{"Simpson scheme"}$$

Tolerance of systematic multipoles:

	no correction	expected	Simpson
b2	0.01	4.7	6
b3	0.017	-	1.6
b4	0.03	0.3	0.9

Like the beam tube scheme, lumped schemes can be used also to deal with random multipoles by binning - provided they are made strong enough.

Example: Assume 20% binning, the rms x-smear at (5, 5)mm amplitudes (due to σ_{b2}=2 units alone)

correction scheme	x-smear after binning	# correctors per half cell
no correction	5.5 %	0
*2*2*2 *2*2*2	1	3
*3*3 *3*3	1.1	2
1*4*1 2*2*2	1.6	2
*4*2 *4*2	1.2	2
1*4*1 3*3	3.0	1.5
6 3*3	2.2	1.5

Present thinking :

- Try to determine whether beam tube scheme does work - ASAP.
- Adopt the Simpson scheme as lumped backup.
- Work out the details of the Simpson scheme (strength, cost, space,..).

Error Fields in Quadrupoles

The expected multipoles of the arc quadrupoles easily meet the smear & tune shift criteria.

Systematic

	b_5	b_9
20 TeV	0.2	0.1
1 TeV	2.0	0.2

Random (rms)

a_2	a_3	a_4	a_5
3.0	1.2	0.3	0.2

b_2	b_3	b_4	b_5
3.0	0.6	0.3	0.3

Attention may be needed at a later time.

IR triplets require special attention. CDR assumes individual compensation coils up to a5 and b5. (There got to be a better way ....) The corresponding tolerances:

Systematic

	b_5	b_9
20 TeV	0.2	.04
1 TeV	2.0	0.2

Random (rms)

	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
before corr.	3.0	1.2	0.3	0.2	.06	.05	.05	.04
after corr.	0.1	0.1	0.1	0.1	.06	.05	.05	.04

	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
before corr.	3.0	0.6	0.3	0.3	.06	.05	.05	.04
after corr.	0.1	0.1	0.1	0.1	.06	.05	.05	.04

Magnet Ends

Tune shift criterion determines the tolerance of the integrated field error, i.e. (2 ends + body).

Tentatively,

	tolerance (random)	tolerance (systematic)	
∫ds multipole	each end (rms)	each end	2 ends + body
a1	1.9 unit-m	3. unit-m	3.3 unit-m
a2	1.7	6.	1.7
a3	1.9	1.	3.3
a4	0.6	1.4	3.3
a5	0.6	2.	-
b1	1.9	3.	3.3
b2	1.1	14.	17.
b3	0.8	5.	1.7
b4	1.9	6.	3.3
b5	0.3	0.2	0.66

The systematic tolerances are set by

Σ (resonance widths) = 0.02 at 1cm amplitude.

The random tolerances are set by

(2 ends) = 1/3 (2 ends + body).

Note that (b2=14 unit-meters) x (magnet sagging of $\pm$0.5mm) => the effective systematic a1 $\approx$ 0.2 unit, which is the present tolerance.

Why the tolerance/correction specifications are not final?

(1) "our best judgements at the time" $\neq$ "final".

More discussions/studies are needed in many cases. Example: the values used in the smear and tune shift criteria.

(2) trade-offs are possible.

Examples:
- random multipoles with n>4.
- More sophisticated correction scheme allows looser tolerances. Trade-off is between tolerances and operation complexity.

3. Some requirements are soft.
Example: higher multipoles (CDR compromised the systematic b6, e.g.)

4. New tricks can (sometimes) be invented.
Examples: binning, lumped correction schemes.

The 3 important things to do are:

iterations, iterations, iterations