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RECYCLER LATTICE (rrv6.)*

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Issues, some answers, some questions, ...

How good (bad) is the lattice as it stands now ?

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* MAD output of rrv6. was given to me by D. Johnson.

Recycler Lattice. (rrv6.)

Issues. some answers. some questions.

> If we are to respect the original intent, how good (bad) is the lattice?

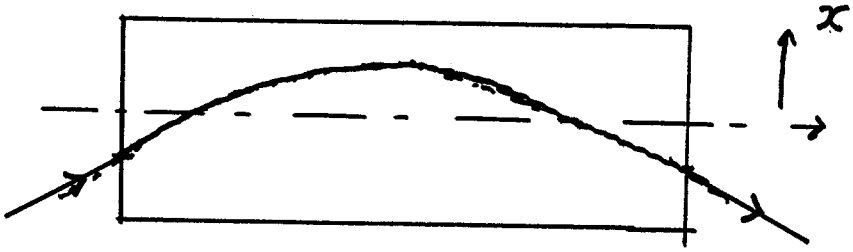
Combined function magnets:

	k_1	k_2	(Q_x, Q_y)
RGF	$+0.012807/m^2$	$+0.011636/m^3$	$-\begin{pmatrix}26.225\\26.215\end{pmatrix}$
RGD	-0.012781	-0.020970	
RGS	± 0.025332	0	
	$(B'/B\rho)$	$(B''/B\rho)$	

b_1: $(634.0, -632.7)$, b_2: $(+7.3, -13.2)$
(± 1.254)

⊙ Quads (RQH, RQS1, ····) are NOT considered.

Sagitta



± 5.30 mm.

↳ Compare this with $|X_p \cdot (\frac{\Delta p}{p})| \lesssim 3$ mm

$B_y(x, y=0) = B_0 \cdot \langle 1 + b_1 x + b_2 x^2 + \cdots \rangle$

my "philosophy"

1. "Dipole" field ——— (closed orbit.)
2. "Quadrupole" field ——— (tunes)
3. "Sextupole" field ——— (chromaticities)
4. "others" ... ——— (amp. dependence of tunes, high-order resonances)

diminishing importance.

Question "Do we care about the linear H-V coupling?"

(i) mixing of orbit distortions. (commissioning)

(ii) Vertical dispersion?

magnet tilt (RGF. RGD. RGS only).

$(Y_p)_{rms} = 75\ m.\ (\theta)_{rms}$ at $\beta_V = 60\ m.$

Try simulation

How difficult is it to roll "a few" magnets to compensate?

Main Ring (6×2) quads rolled "Edwards-Stiening Roll"

I. Closed Orbit

The newly revised version is much better.

- Issues -

(1) Possibility of a few "large" misaligned magnets.

(2). Missing BPMs.

(3). Limiting the move to ≤ 5 mm. Is this always wise?

(4). Minimize (rms) or (peak)?

(5) "Interpolation" of BPM? →(see p. 3a)

Dry runs

Establish the procedures to find a closed orbit using the injection steering magnets and adjusting the beam momentum.

Tolerance Requirements

In order to limit the final closed orbit deviation to ≤ 1 mm (rms), for example, what is the maximum allowed orbit deviation BEFORE correction?

(This may relax some conditions.)

BPM reading

"H" stations	x_1	(x_c)	x_2
"V" stations	y_1	(y_c)	y_2

↑ not available.

Assume perfect (linear) cell (no errors) between x_1 and x_2, or y_1 and y_2.

$$x_2 = m_{11} x_1 + m_{12} x_1'$$

or $$x_1' = (x_2 - m_{11} x_1)/m_{12}$$

Once x_1' is known, one can find x_c.

Any advantage from x_c (y_c)?

Example. RHIC.
Talman's local compensation of linear coupling.

II Tunes

Design: $\mu_{H,V} = 90°/\text{cell}$

Possibility of changing this — will be discussed.

Sensitivity

(arc.)
$$\frac{\Delta k_{1f}}{k_{1f}} = 2.558 * (\Delta\mu_H/2\pi) + 0.638 * (\Delta\mu_V/2\pi)$$
$$\frac{\Delta k_{1d}}{k_{1d}} = 0.638 * (\; " \;) + 2.558 * (\; " \;)$$

disp. supp.
$$(\Delta k_1/k_1) = 3.16 * (\Delta\mu/2\pi)$$
(Remember. $k_{1d} = -k_{1f}$)

– Questions –

(i) Again linear coupling.

~~[illegible]~~

$|Q_H - Q_V| <$ (some value) ?

(ii) $3Q_H$, $Q_H + 2Q_V$, ~~[illegible]~~

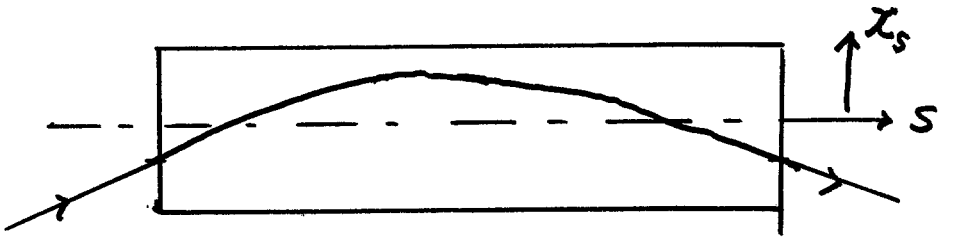
$\simeq$ (odd integers)

Does this help?

(There is no superperiod, but ....)

example 26.25 → 79 (−0.25) better?
26.75 → 80 (+0.25)

(iii) Sagitta effects (feed-down from b_2)



For $(\Delta p/p) = 0$ particles.

$$\Delta Q = \left(\frac{1}{4\pi}\right) \cdot \int_0^L ds \cdot \left(\frac{B''}{B\rho}\right) \cdot (x_s \cdot \beta) \; ; \quad x_s(0) = x_s(L) = -5.3 \text{ mm}.$$

$$x_s(L/2) = +5.3 \text{ mm}.$$

108(RGF) + 108(RGD):

$\Delta Q_H = +0.0218$
$\Delta Q_V = -0.0584$

should be checked.

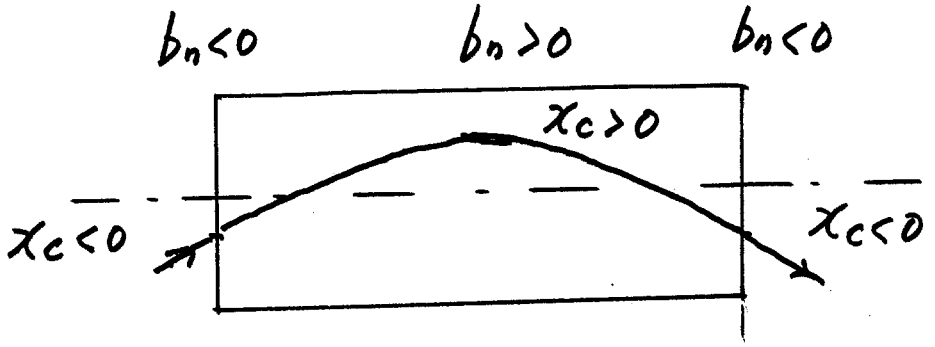
Compare with $|\Delta Q| \simeq 0.035$ for $|\Delta p/p| = 0.1\%$ BEFORE correction.

This effect is "visible" in the main ring. (Craig Moore — systematic misalignments) in particular, in the energy dependence of $|Q_H - Q_V|$.

Danger of "Endpack Correction".

— [illegible].

see p. 5a



$$b_2 (x_c + x_\beta)^2 \longrightarrow (2 b_2 x_c) \cdot x_\beta$$

↳ "quadrupole" > 0 everywhere.

$$b_3 (x_c + x_\beta)^3 \longrightarrow (3 b_3 x_c) \cdot x_\beta^2$$

↳ "sextupole" > 0

Suggestion

If $|b_2|$ or $|b_3|$ deviates more than 3σ, reject.

Between σ and 3σ → sorting.

III. Chromaticities

$$\begin{cases} \Delta\xi_H = 796.0\left(\frac{B''L}{B\rho}\right)_F + 111.4\left(\frac{B''L}{B\rho}\right)_D \\ \Delta\xi_V = -196.0\,(\ \ ) - 448.9\,(\ \ ) \end{cases}$$

$$\begin{cases} \left(\frac{B''L}{B\rho}\right)_F = 0.001338\,(\Delta\xi_H) + 0.000332\,(\Delta\xi_V) \\ \left(\frac{B''L}{B\rho}\right)_D = -0.000584\,(\Delta\xi_H) - 0.002373\,(\Delta\xi_V) \end{cases}$$

or $$\begin{cases} b_{2f} = 0.2070\cdot(\Delta\xi_H) + 0.0514\cdot(\Delta\xi_V) \\ b_{2d} = -0.0903\cdot(\Delta\xi_H) - 0.3671\cdot(\Delta\xi_V) \end{cases} \quad (10^{-4}/in^2)$$

$\xi_H = -33.90 \rightarrow -5.0$; $\Delta\xi_H = +28.90$

$\xi_V = -34.76 \rightarrow -5.0$; $\Delta\xi_V = +29.76$

$b_{2f} = +7.51$, $b_{2d} = -13.53$. $(10^{-4}/in^2)$

* Correction sextupoles should NOT have a large horizontal orbit distortion.

$$\begin{cases} \Delta\xi_H = 5.145\,(b_{2f}) + 0.720\,(b_{2d}) \\ \Delta\xi_V = -1.267\,(b_{2f}) - 2.902\,(b_{2d}) \end{cases}$$ (Sensitivities)

$\hookrightarrow 10^{-4}/in^2$

Assume, at the sextupole locations,

(SF) $x_p = 1.882\,m$, $\beta_H = 54.0\,m$, $\beta_V = 10.9\,m$.

(SD) $= 0.982$ " $= 10.7\,m$. $= 54.0$ "

$$\begin{cases} N * (B''L/B\rho)_F = 0.128 \cdot (\Delta\xi_H) + 0.026 \cdot (\Delta\xi_V) \\ N * (B''L/B\rho)_D = -0.050 \cdot (\Delta\xi_H) - 0.247 \cdot (\Delta\xi_V) \end{cases}$$

$N \equiv$ number of sextupoles ($= 2$ expected).

max. $|B''L/B\rho|$ for $\Delta\xi_H, \Delta\xi_V = +10. \Rightarrow 1.49/m^2$. with $N = 2$.

If $\Delta x_{co} = 3\,mm$,

$$\Delta Q = \frac{1}{4\pi} \cdot \left(\frac{B''L}{B\rho}\right) \cdot (\Delta x_{co}) \cdot \beta_{\rightarrow 54\,m} \simeq 0.02$$

Desirable: BPM close to correction sextupoles.

Δy_{co} at the sextupole location will create skew quadrupole field. But I doubt its importance.

⊙ I still don't believe the significance of linear coupling in Recycler. (stochastic cooling?)

IV. Resonances (Sextupole and Octupole)

Now we have to "play a game" — "resonance width"

TM-1247 (3/84)

Fundamental assumptions.

(i) Single isolated resonance.

(ii) No detuning (phase-independent) terms — no amplitude-dependence of tunes due to average $b_3, b_5, \cdots$.

(see p.8a)

p.8 IV. 1 Systematic (built-in) b_2.
p.12 IV. 2 Random (deviation from the design) b_2
p.13 IV. 3 Average b_3.
p.18 IV. 4 Random b_3.

IV. 1 Systematic b_2 in RGFs and RGDs.

$$(B''/B\rho) = (+0.011636, -0.020970)\ m^{-3}$$

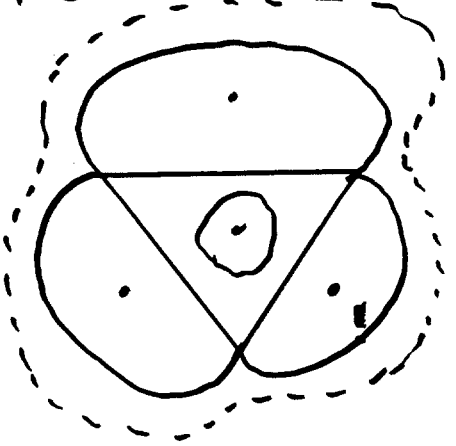
There are altogether 5 driving terms (complex) for $3Q_H$, Q_H, $Q_H \pm 2Q_V$ resonances. They control the second-order effects also.

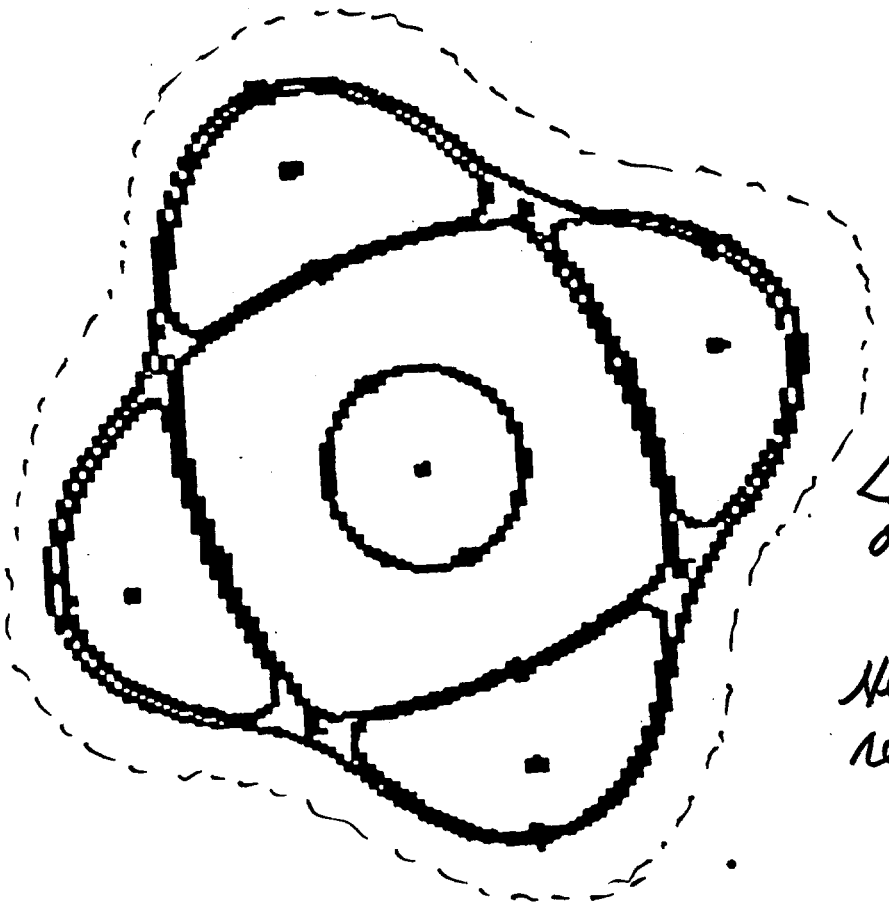
Impact of average b_3 (octapole)

1. <u>Good</u> Stabilize the beam(?)

2. <u>Bad</u> Shrink the "linear" stable area.

Lowest-order sextapole resonance.





Lowest-order octapole resonance

OR

Next-order sextapole resonance.

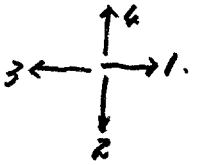
$$\sum \left(\frac{B''L}{B\rho}\right)\cdot \beta_H^{3/2} e^{i3\psi_H}, \quad \sum \left(\frac{B''L}{B\rho}\right)\cdot \beta_A^{3/2} e^{i\psi_H}$$

$$\sum \left(\frac{B''L}{B\rho}\right)\sqrt{\beta_A}\cdot\beta_T\cdot e^{i\psi_H}, \quad \sum \left(\frac{B''L}{B\rho}\right)\cdot\sqrt{\beta_H}\beta_V\cdot e^{i(\psi_H \pm 2\psi_T)}$$

Lattice structure (arc magnets only)

→ (1 cell) → (1 cell) → (19 cells) → (6 cells) → (twice)

If $\psi = 90°$/cell, all five terms are zero for $(4n)$ cells.



– Questions –

(a) Is it worth considering $\psi \neq 90°$/cell?

example. $\psi = 88.421°$ → No $e^{i3\psi}$ contributions from 19 cells.

Because of many conveniences of 90° cell, (cooling, sorting, commissioning, ···)

& prefer 90°.

(b) Should we remove sextupole component from some magnets to balance?

example. 108 each → 92 each with $k_2 \neq 0$
16 each with $k_2 = 0$

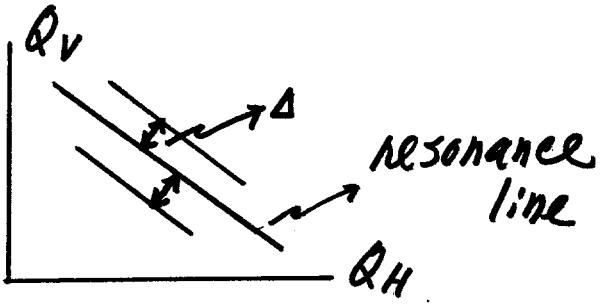
~~– Advantage –~~

Disadvantages

(i) Need to build one more class of magnets with $k_2 = 0$ (may be two more classes.)

(ii) 108 → 92 : 17% increase in k_2
: 38% increase in $(k_2)^2$
(second-order effects).

How about WIDTHS?



Δ(10%):

For $\Delta > \Delta(10\%)$, No particle loss and the expected emittance growth is $\lesssim 10\%$.

In calculating the width for systematic (built-in) sextupole components, we take the most pessimistic assumption:

effects from each half of the ring are to be added. (no partial cancellation)

(1) $\boxed{3Q_H = 79 - 0.325}$ or $Q_H = 26.333 - 0.108$.

$\Delta(10\%) = 0.00523 * \sqrt{\epsilon_N \text{ in } \pi\text{-mm-mr}}$ ↕ ok.

example: $\epsilon_N = 60\pi$ mm·mr → $\Delta(10\%) = 0.0405$.

(2) $Q_H + 2Q_V = 19 - \underline{0.345}$.

$\Delta(10\%) = 0.00936 * \sqrt{\epsilon_N \text{ in } \pi \cdot mm \cdot mr}$

example: $\epsilon_N = 60\pi \cdot mm \cdot mr \rightarrow \Delta(10\%) = 0.0725$

This means. $|Q_H + 2Q_V - 19| = 0.162$. ($*\sqrt{5}$) (ok).

Remember that $\Delta(10\%)$ is a very conservative criterion. It tries to define the "linear" phase space area.

How about the effect of average octupole? It will shrink the stable area, or for a given emittance, the resonance width will go up. This effect is difficult to estimate for $Q_H + 2Q_V$ resonance. For $3Q_H$ resonance,

$\epsilon_N = 40\pi \cdot mm \cdot mr \rightarrow$ 20% increase in width.

$= 60\pi$ " $\rightarrow$ 25% increase in width.

assuming. $(b_3)_{rms} = 1 \times 10^{-4}/in^3$

$\rightarrow (b_3)_{average} \simeq 2 \times (b_3)_{rms} / \sqrt{216}$ ← number of arc magnets

$= 0.14 \times 10^{-4}/in^3$.

However, this is no better than "semi-quantitative".

IV.2 Random b_2 (sextupole)

$3Q_H$: $\Delta(10\%) = 0.81 \times 10^{-3} \times (b_2)_{rms} \times \sqrt{\epsilon_N}$ (arc)

where $(b_2)_{rms}$ is in $10^{-4}/in^2$ and ϵ_N in $10^{-6}\pi \cdot m$

$\Delta(10\%) = 0.32 \times 10^{-3} (b_2)_{rms} \cdot \sqrt{\epsilon_N}$ (disp. suppressors)

example. $\epsilon_N = 60\pi \cdot mm \cdot mr$.

$(b_2)_{rms} = 2 \times 10^{-4}/in^2$

$\Delta(10\%) = 0.0125$ from arc magnets,

$= 0.0050$ " dis. suppressor magnets.

$Q_H + 2Q_V$: $\Delta(10\%) = 0.87 \times 10^{-3} (b_2)_{rms} \cdot \sqrt{\epsilon_N}$ (arc)

$\Delta(10\%) = 0.33 \times$ " " " (disp. suppressor)

If we impose the condition

"No particle lost"

but nothing about the emittance growth,

the width will be 20% of $\Delta(10\%)$ for $3Q_H$ and 22% of $\Delta(10\%)$ for $Q_H + 2Q_V$, indicating the ~~severity~~ severity of the condition ~~satisfying~~ "less than 10% emittance growth".

IV. 3 Average b_3 (octupole)

Three effects. (1) Amplitude dependence of tunes.
(2) Reduction of stable area. (p. 15)
(3) Drive resonance $4Q_H$, $4Q_V$, $2Q_H + 2Q_V$. (p. 16)

(1) Amplitude-dependence of tunes

Basic relations: ↳ Note #324 (7/83)

From each magnet

$$\Delta Q_H = \left(\frac{\theta_B}{2\pi}\right)\cdot\left(\frac{3}{8}\right)\cdot b_3\cdot\left(\beta_H^2\epsilon_H - 2\beta_H\beta_V\epsilon_V\right)$$

$$\Delta Q_V = \left(\frac{\theta_B}{2\pi}\right)\cdot\left(\frac{3}{8}\right)\cdot b_3\cdot\left(\beta_V^2\epsilon_V - 2\cdot\beta_H\beta_V\epsilon_V\right)$$

108 RGFs, 108 RGDs. 64 RGS(F)
64 RGS(D)

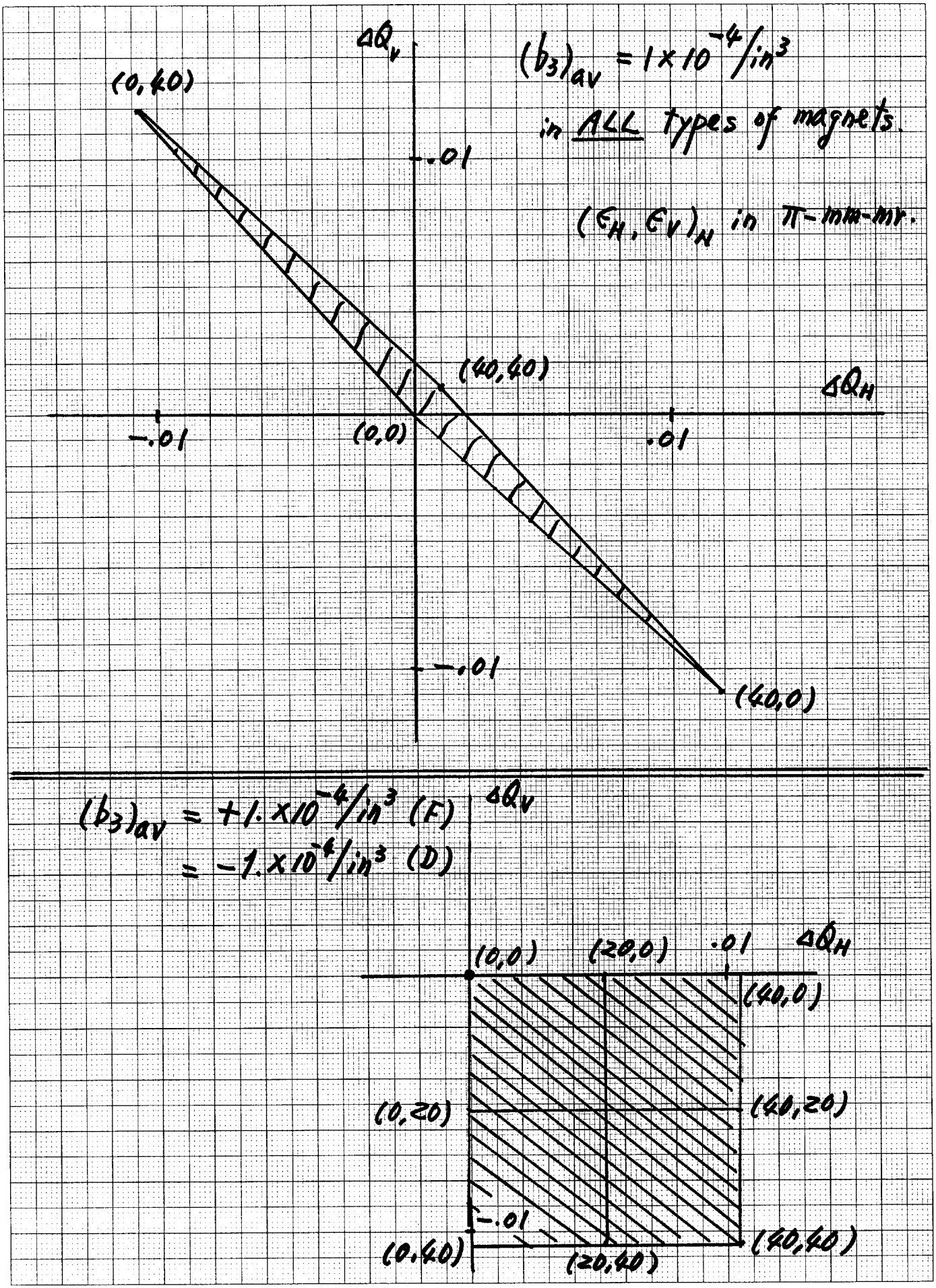
— Very important question. —

If $b_1 > 0$, $b_2 > 0$ (RGF), is it more likely to have $(b_3)_{av} > 0$, or $(b_3)_{av}$ is totally unrelated to the sign of (b_1, b_2)?

Specifically, is it reasonable (unreasonable) to assume $(b_3)_{av}$ in RGF $\simeq (b_3)_{av}$ in RGD?

Extent of footprint quite different

See p. 13a.



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108 RGFs $\begin{cases} \Delta Q_H = 2.22\times10^{-4}(\epsilon_H) - 1.08\times10^{-4}(\epsilon_V) \\ \Delta Q_V = 0.14\times10^{-4}(\epsilon_V) - 1.08\times10^{-4}(\epsilon_H) \end{cases}$

108 RGDs $H \longleftrightarrow V$ in the above formulas.

where $(\epsilon_H), (\epsilon_V)$ = ϵ normalized in $\pi \cdot mm \cdot mr$.

64 RGS(F) $\begin{cases} \Delta Q_H = 0.58\times10^{-4}(\epsilon_H) - 0.27\times10^{-4}(\epsilon_V) \\ \Delta Q_V = 0.035\times10^{-4}(\epsilon_V) - 0.27\times10^{-4}(\epsilon_H) \end{cases}$

64 RGS(D) $\begin{cases} \Delta Q_H = 0.037\times10^{-4}(\epsilon_H) - 0.28\times10^{-4}(\epsilon_V) \\ \Delta Q_V = 0.58\times10^{-4}(\epsilon_V) - 0.28\times10^{-4}(\epsilon_V) \end{cases}$

→ Small deviations from symmetry are caused by two DS_60 dispersion suppressors.

Is it reasonable (and safe) to assume

$|(b_3)_{av}|$ between $(b_3)_{rms}/\sqrt{\#\text{ of magnets}}$

and $2*(b_3)_{rms}/\sqrt{\#\text{ of magnets}}$?

(2) Reduction of stable area.

See p. 11 for $3Q_H$ resonance.

For $4Q_H$ and $4Q_V$ resonances, if

~~(a) $A(b_3)$ systematic only.~~

$(b_3)_{av} = 2 \cdot (b_3)_{rms} / \sqrt{216}$ (for 216 arc magnets),

the width Δ is increased by a factor ~5 because of $(b_3)_{av}$.

example $(b_3)_{rms} = 1 \times 10^{-4}/in^3$.

$(b_3)_{av} = \pm 0.14 \times 10^{-4}/in^3$.

~~Δ ("No particle lost") = 7.2×10^{-6} (ϵ_N in $\pi \cdot mm \cdot mr$)~~

Δ ("No particle lost") = 7.2×10^{-6} (ϵ_N in $\pi \cdot mm \cdot mr$)

if $(b_3)_{av}$ is ignored

Δ ("No particle lost") = 4.0×10^{-5} (ϵ_N in $\pi \cdot mm \cdot mr$)

if $(b_3)_{av}$ is taken into account.

Remember: $(b_3)_{av}$ stabilizes the beam.

The increase in Δ (or decrease in the inner stable area) may or may not cause loss of particles.

"No particle lost" should be interpreted in this spirit!

(3) $4Q_H$, $4Q_V$, $2Q_H+2Q_V$ resonances by $(b_3)_{av}$.

Driving terms $b_3\beta_H^2 e^{i4\psi_H}$, $b_3\beta_V^2 e^{i4\psi_V}$, $b_3\cdot\beta_H\beta_V e^{i2(\psi_H+\psi_V)}$ all add up with 90°/cell phase advance.

Is this so bad that we should consider $\neq 90°$/cell phase advance?

Example: phase advance $= 90° \pm 180°/38$ /cell.

Then, no contribution from 19 cells!

If $90° + 180°/38 = 94.737°$: there will be no contribution for $3Q_H$, Q_H, $Q_H \pm 2Q_V$ resonances as well, arising from built-in sextupole components in RGFs and RGD's. (19 cells only, NOT in 6 cells.)

If fourth-order resonances due to $(b_3)_{av}$ are stronger than those due to $(b_3)_{rms}$, we may be forced to adopt $\neq 90°$/cell phase advance.

Better estimate of $(b_3)_{av}$ desirable.

$(b_3)_{av} \equiv (b_3)_{av}$ in $1 \times 10^{-4}/in^3$

(ϵ_H), (ϵ_V) = normalized emittance in π · mm · mr.

4QH $\quad \Delta(10\%) = 2.30 \times 10^{-4} (b_3)_{av} (\epsilon_H)$ RGF

$= 0.14 \times 10^{-4}$ " " RGD

$= 0.60 \times 10^{-4}$ " " RGS(F)

$= 0.04 \times 10^{-4}$ " " RGS(D)

4QV Same as 4QH, with $(\epsilon_H) \rightarrow (\epsilon_V)$
RGF $\longleftrightarrow$ RGD, RGS(F) $\longleftrightarrow$ RGS(D)

2QH + 2QV

$\Delta(10\%) = 1.86 \times 10^{-4} \sqrt{(\epsilon_H)(\epsilon_V)}$ RGF

$=$ same RGD

$= 0.46 \times 10^{-4}$ " RGS(F)

$= 0.48 \times 10^{-4}$ " RGS(D)

Reminder: RGF = arc magnet, positive gradient.

RGD = arc magnet, negative gradient

RGS = short (2/3) magnet in dispersion suppressors.

IV.4 Resonances driven by random b_3 (octupole)

$4Q_H$, $4Q_V$

From arc magnets.

$$\Delta(10\%) = 0.224 \times 10^{-4} (b_3)_{rms} (\epsilon_{H,V})$$

ϵ in 10^{-4}/in^3 — normalized, in $\pi \cdot$ mm $\cdot$ mr.

From short magnets (RGS)

$$\Delta(10\%) = 0.082 \times 10^{-4} (b_3)_{rms} (\epsilon_{H,V})$$

$2Q_H + 2Q_V$

arc magnets: $\Delta(10\%) = 0.253 \times 10^{-4} (b_3)_{rms} \sqrt{(\epsilon_H \epsilon_V)}$

short magnets: $\Delta(10\%) = 0.088 \times 10^{-4} (b_3)_{rms} * \sqrt{(\epsilon_H \epsilon_V)}$

Beyond octupoles, tracking is the only way to make reliable estimates.

I don't trust anything else.

Concluding Remarks

The greatest asset of the Recycler is the empty space all around the ring. It is quite possible (and likely) that you may end up with all kinds of correction elements, permanent or regular magnets.

It is nevertheless desirable to try to make it work as it was originally intended, that is, with as few "knobs" as possible.

Everything depends on what sort of magnets will be used. The question of tolerances is always a matter of "give-and-take" between magnet group and accelerator group so that the tolerances will be developed as more and more magnets are built and measured.

More than anything else, I should like to see "Dry Runs" of the commissioning done by computers. These will eventually become applications programs in the control room.

1. Establishment of a closed orbit with injection steering only.
2. Finding of magnets to be moved to straighten the closed orbit.
3. Tune and chromaticity measurements and their adjustments (for the ring with various expected imperfections).
4. Finding magnets to be rolled from the coupling measurements.
5. Simulation of the entire rf manipulation from the injection to the extraction.
6. For tracking, once the "seed" is chosen and magnet errors are specified, sorting of twenty or so magnets as a group should be tried before calculating the aperture. It is assumed here that some twenty magnets would be available at a time for installation.