International MUON Collider Collaboration

IMCC Annual meeting
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Field quality requirements for RCS

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MuCol

Open questions for RCS magnets

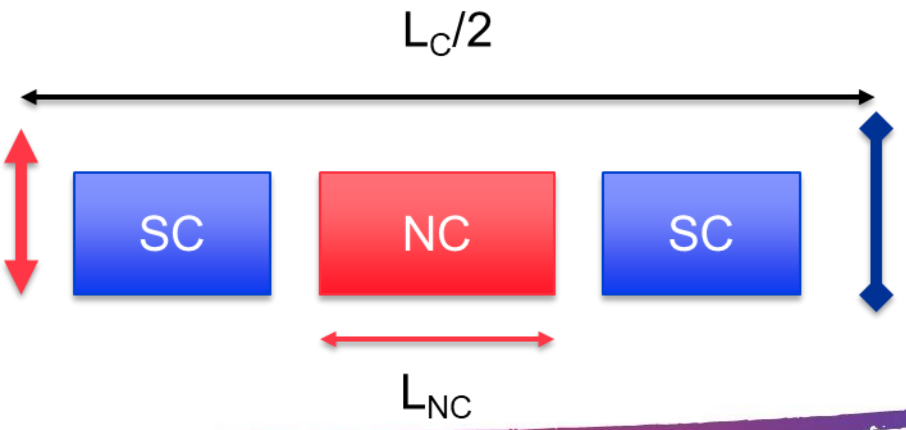
- Pulsed accelerator magnets have eddy currents and rich dynamics.
- We are looking at resistive magnets, SC magnets are probably even more complex (but worth a comment).
  - What are orders of magnitude of dynamic effects ?
  - Aperture is a thin rectangle. The field quality can be defined by harmonics or homogeneity of the field. What are typical values, and do we really want harmonics in a rectangular aperture ?

First thoughts: impact of a dipole error on the orbit

- We can distinguish different dipole errors with a different dynamics:
  - Reproducible error from cycle to cycle (systematic and random part).
    - We can use correction schemes with dipole correctors.
    - The first guess can be state-of-the-art tolerances.
    - **We need fast correctors.**
  - Erratic errors from cycle to cycle.
    - Source:
      - Delay on the ramp (example for RCS1: delay if 1 μs → systematic error on the field of 4.2 mT).
      - Error on the slope (error on the rise time of the magnets).
    - We assume here no feedback to correct these dipole errors.
    - The injection is on-axis and the beam center is oscillating around the closed orbit.
- Very fast acceleration → fast damping of the angular kick from turn to turn.

First thoughts: optics of the RCS

- Currently, we do not have a baseline of the RCS yet.
  - Too early to make MonteCarlo errors.
- We modelize the RCS with a regular pattern as the following:
  - We assume we have n_c cells of length L_c per arc and n_a arcs per RCS.
  - The muon beams run n_t turns of length L_{RCS}.



Reminder: RCS parameters

- **Detailed parameter table (by F. Batsch):** https://cernbox.cern.ch/index.php/s/l9VplTncUeCBtiz
- Parameters of the 4th RCS under study.
- Needs more studies to evaluate the shielding requirements.
- For information, about 40 mm of Tungsten for collider (Anton Lechner).
- Minimum magnet radius probably enlarged to handle collective effects.

Example parameters for the muon RCSs

	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	No	Yes	Yes	Yes
Circumference [m]	5990	5990	10700	26659
Injection/extraction energy [TeV]	0.06/0.30	0.30/0.75	0.75/1.5	1.5/4.2
Survival rate [%]	90	90	90	90
Acceleration time [ms]	**0.34**	**1.10**	**2.37**	**5.75**
Number of turns	17	55	66	65
Energy gain/turn [GeV]	14.8	7.9	11.4	41.5
NC dipole field [T]	**0.36/1.8**	**-1.8/1.8**	**-1.8/1.8**	**-1.8/1.8**
SC dipole field [T]	**-**	**10**	**10**	**16**
NC/SC dipole length [m]	2.6/-	4.9/1.1	4.9/1.3	8.0/1.3
Number of arcs	34	26	26	26
Number of cells/arc	7	10	17	19
Cell length [m]	21.4	19.6	20.6	45.9
Path length diff. [mm]	**0**	**9.1**	**2.7**	**9.4**
Orbit difference [mm]	**0**	**12.2**	**5.9**	**13.2**
Min. dipole width [mm]	**17.4**	**19.6**	**10.7**	**18.8**
Min. dipole height [mm]	**14.8**	**6.4**	**4.2**	**4.4**

Collective effects and shielding not included

Field quality and aperture

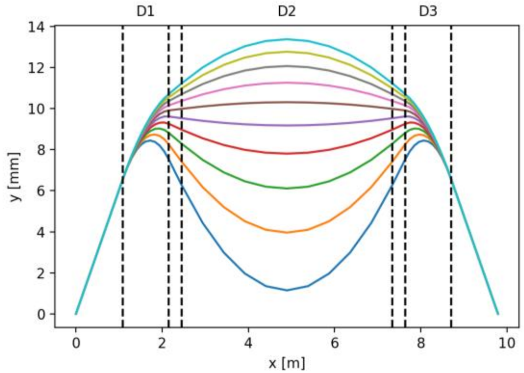
- The number of turns is less than 100 with fast acceleration:
  - Dynamic aperture is less a driver of the field quality.
  - We are between the field quality requirements for a ring (but very small number of turns) and a linac.
  - The main concern should be to keep the beam emittance.
- Stability studies have shown we need to correct the chromaticity. Do we have an estimation of eddy currents? They may be larger than the systematic and random sextupole components of the diple field.
- Even if RCS1 does not have a varying trajectory, we need a quite large aperture due to collective effects and shielding needs.

Trajectory during ramp

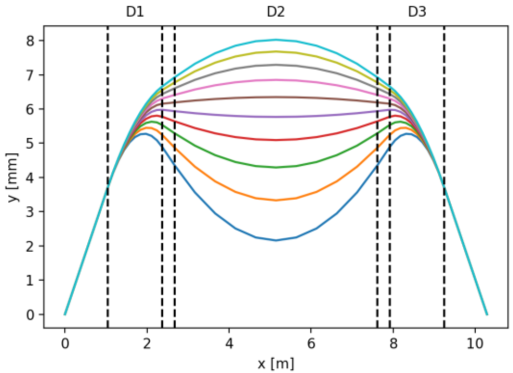
- The trajectory difference is more than 13 mm: the field quality is defined around the reference trajectory.

→ Field quality should be defined in a rectangle.

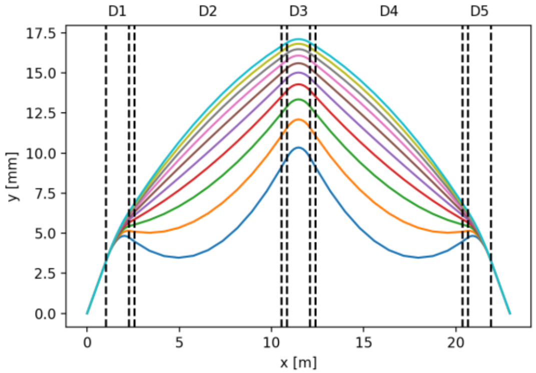
RCS2



RCS3



RCS4



First thoughts: orbit variation

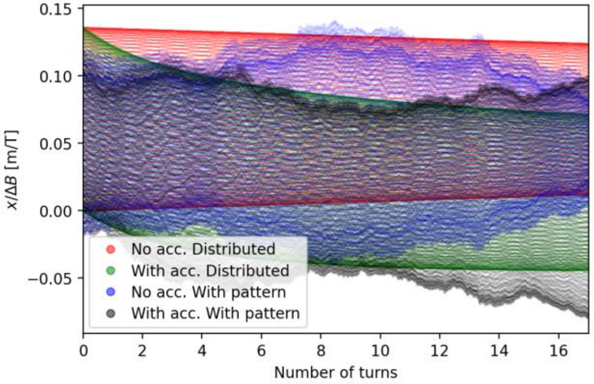
- Continuous focusing channel (fractional part of the global tune: 0.225).
- Orbit evolution given by:

$$x'' + k^2 x = \frac{\Delta B(s)}{B\rho(s)} \quad \text{Acceleration: } B\rho(s) = B\rho_{inj} + \frac{B\rho_{ext} - B\rho_{inj}}{n_t L_{RCS}} s$$

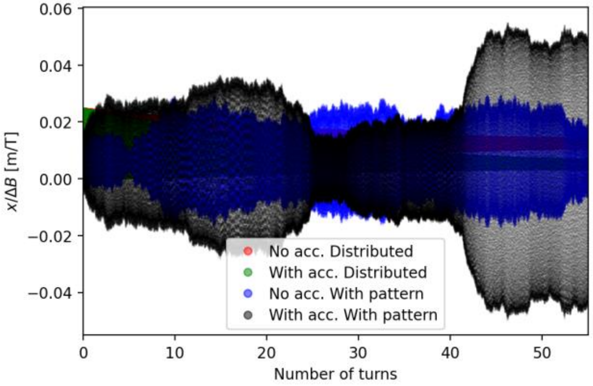
- Several cases:
  - Constant field error ΔB
  - Constant field slope error $\Delta B(s) = B_{inj} + \frac{B_{ext} - B_{inj}}{n_t L_{RCS}} s$
  - Resonance: $\Delta B(s) = \Delta B \cos k\, s$
  - Distributed: Dipoles are all along the RCS.
  - Pattern: Error only in the NC dipoles: $\Delta B(s) \times (mod(s, Lc) < L_{NC})$

Constant dipole field error

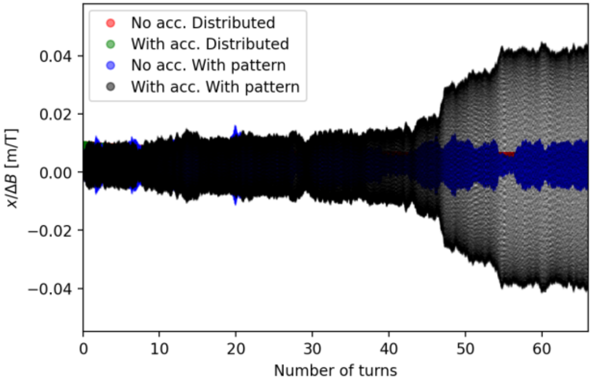
RCS1



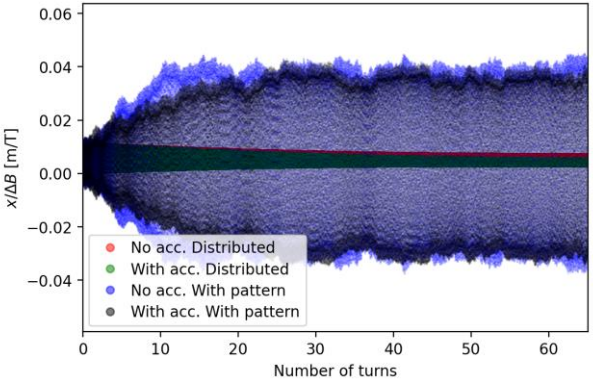
RCS2



RCS3

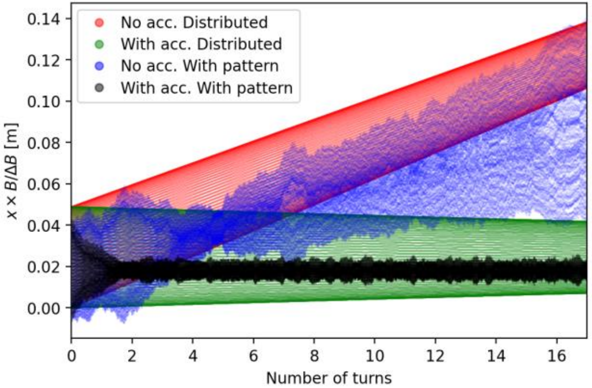


RCS4

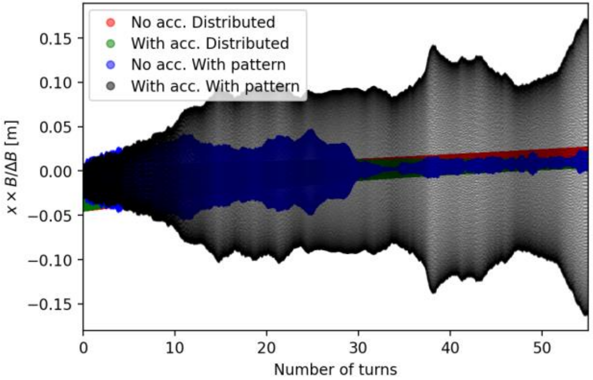


Dipole slope field error

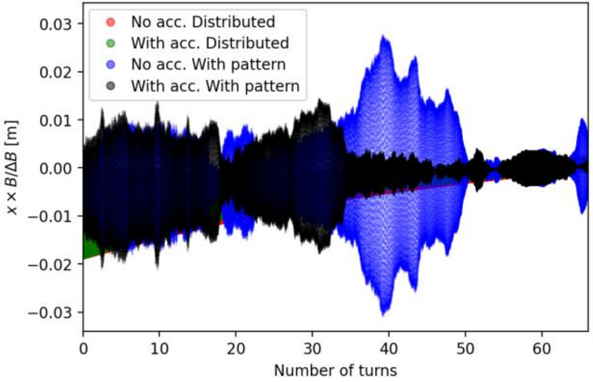
RCS1



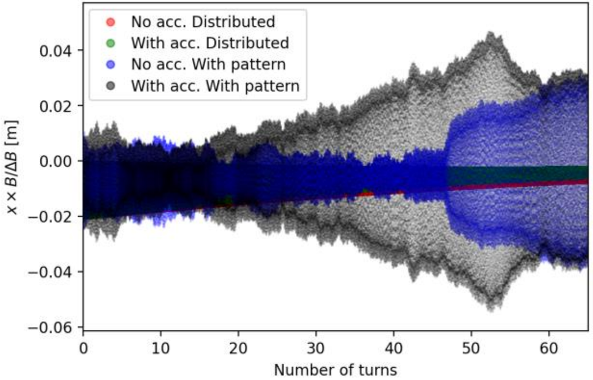
RCS2



RCS3

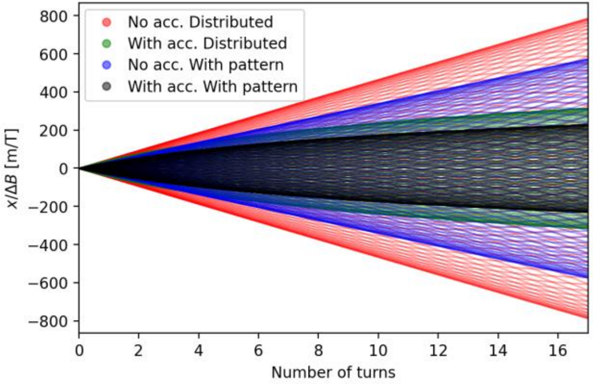


RCS4

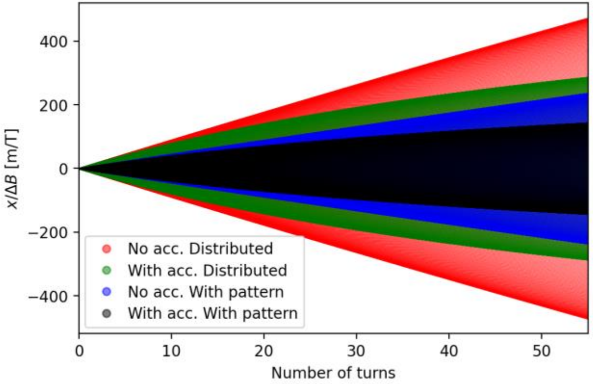


Dipole resonant field error

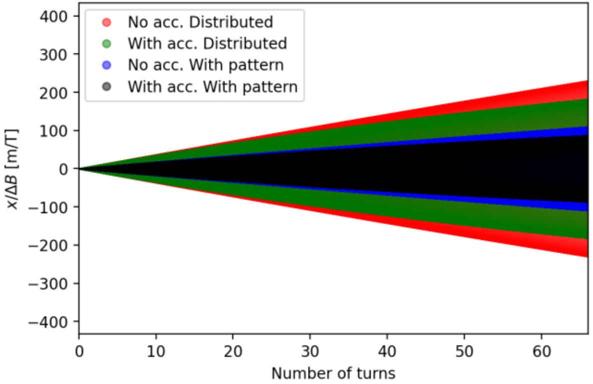
RCS1



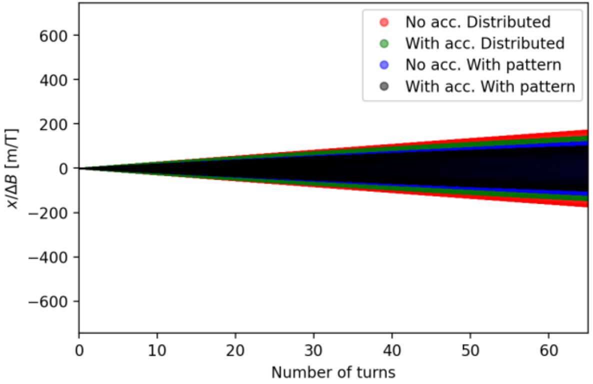
RCS2



RCS3



RCS4



First results on dipole errors

- We cannot neglect the damping on the dipole errors from turn to turn due to the fast acceleration.
- The pattern of the NC dipoles in the RCS modifies the orbit expansion during the acceleration and thus the field tolerances.
  - Parametric resonances can be excited.
  - That would be useful to get the error spectrum (time variation of the dipole field).
- Some solutions could be to have a phase advance of π between dipoles to cancel the dispersion wave and orbit distortion due to systematic errors (but not reproducible from cycle to cycle) in the dipoles.
- Currently, only one power supply was assumed for the dipoles.

Plan to improve dynamic orbit studies

- To implement a more realistic pattern of the dipoles and cavities.
  - We have assumed a length of 0 between the arcs: we should use the transparency condition between the arcs instead.
  - The muon energy variation is linear with time: can be refined with a stepwise function.
  - Fast correctors/dipoles should correct the curvature difference between the NC dipoles between 2 cavities: constant energy but field quasi-linearly varyiing with position.
- To use an optics file instead of a continuous focusing channel.
  - To choose the phase advances to mitigate parameteric resonances.
- To perform MonteCarlo errors with systematic and random errors on the power supplies: do we have a first guess?
- Do the same exercise for beta-beating with quadrupoles.

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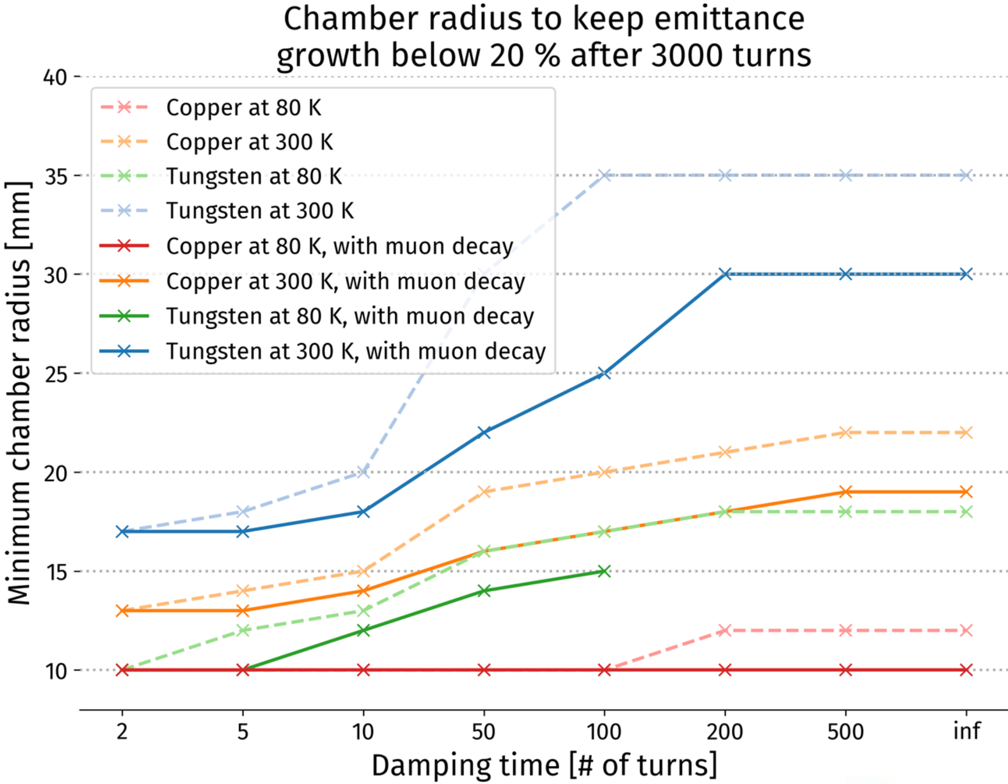
Thank you for your attention

10 TeV collider: Minimum chamber radius achievable versus material

Courtesy: David Amorim

- Investigate different materials for the vacuum chamber
  - Tungsten 300 K and 80 K, Copper 300 K and 80 K
- Find the chamber radius such as the **emittance growth** stays **below 20 %** for different damper gains.
- With **100-turn damper**: **17 mm radius** required with **Copper at 300 K**, versus **25 mm** with **Tungsten at 300 K**



See presentation at Collaboration Meeting

First thoughts: impact of a dipole error on the orbit

- Let us consider one dipole error source θ_n at one position (dipole component error, quadrupole misaligment,…) which varies turn after turn.
- Let be ν_x the horizontal tune of the RCS.
- The term which transforms this angular kick to orbit distortion is given by

$$\mathrm{R}_{12} = \sqrt{\beta_0 \beta} \sin(\mu(s) - \mu_0)$$

(if $\mu(s) < \mu_0$ add $2\pi\nu_x$to the tune difference).

- The orbit distortion Δx after N turns by this dipole source is thus:

$$\Delta x(s) = \sum_{n=0}^{N-1} \theta_n \sqrt{\beta_0 \beta(s)} \, \sin(\mu(s) - \mu_0 + n\, 2\pi\nu)$$

First thoughts: impact of a static dipole error $\theta_n = \theta$ constant

- We get:

$$\Delta x(s) = \frac{\theta\sqrt{\beta_0\beta(s)}}{2\sin\pi\,\nu}[\cos(\mu(s)-\mu_0-\xi\pi\nu)-\cos(\mu(s)-\mu_0+(2N-\xi)\pi\nu)]$$

$\xi = 1$ if $\mu(s) > \mu_0$ else $\xi = -1$

If we do not correct the systematic error on the orbit, the maximum orbit distortion is thus:

$$\Delta x(s) = \frac{\theta\sqrt{\beta_0\beta(s)}}{\sin\pi\,\nu}$$

- The RCS is made of FODO cells with phase advances of 90 degrees of length L_c.

$$\beta_{x,\max} \approx L_c\left(1+\frac{\sqrt{2}}{2}\right)$$

- We have an upper boundary on the orbit distortion: $\Delta x_{max} < \frac{\theta L_c\left(1+\frac{\sqrt{2}}{2}\right)}{\sin\pi\,\nu}$

First thoughts: impact of a dynamic dipole error

$$\theta_n = \theta \sin n\, \omega\tau + \phi_0$$

- With $\xi = 1$ if $\mu(s) > \mu_0$ else $\xi = -1$

$$\Delta x(s) = \frac{\theta\sqrt{\beta_0\beta(s)}}{2}\left[\cos\left(\mu(s) - \mu_0 - \phi_0 + (N-\xi)\pi\nu - \frac{N-1}{2}\omega\tau\right)\frac{\sin N\left(\pi\nu - \frac{\omega\tau}{2}\right)}{\sin\left(\pi\nu - \frac{\omega\tau}{2}\right)} - \cos\left(\mu(s) - \mu_0 + \phi_0 + (N-\xi)\pi\nu + \frac{N-1}{2}\omega\tau\right)\frac{\sin N\left(\pi\nu + \frac{\omega\tau}{2}\right)}{\sin\left(\pi\nu + \frac{\omega\tau}{2}\right)}\right]$$

We can have a resonance if $2\pi\nu + \omega\tau = 0$ or $2\pi\nu - \omega\tau = 0$ modulo 2π.

$$\Delta x(s) = \frac{\theta\sqrt{\beta_0\beta(s)}}{2}\left[N\cos(\mu(s) - \mu_0 - \phi_0 + (1-\xi)\pi\nu) - \cos(\mu(s) - \mu_0 + \phi_0 + (2N - \xi - 1)\pi\nu)\frac{\sin N(2\pi\nu)}{\sin(2\pi\nu)}\right] \text{ if } 2\pi\nu = \omega\tau$$

First thoughts: impact of a dipole error on the orbit

- If we have an integrated error of $\Delta B L_d$ on the dipole field and make the thin lens approximation (not completely true) we get an angular kick of: $\theta \approx \frac{\Delta B L_d}{B\rho}$.
- The maximum orbit perturbation is given by $\mathrm{R}_{12}\Delta \mathrm{k}$ where R is the transfer matrix between the dipole and the observation point. We have: $|\mathrm{R}_{12}| = |\sqrt{\beta_{x,1}\beta_{x,2}} \sin \Delta\mu_{1,2}| < \beta_{x,\max}$
- The RCS is made of FODO cells with phase advances of 90 degrees of length L_c.
- $\beta_{x,\max} \approx L_c\left(1+\frac{\sqrt{2}}{2}\right)$.
- Finally, we get: $\Delta x_{\max} \approx L_c\left(1+\frac{\sqrt{2}}{2}\right)\frac{\Delta B L_d}{B\rho}$ and $\frac{\Delta x_{\max}}{\sigma_{x,\max}} \approx \sqrt{\frac{L_c\left(1+\frac{\sqrt{2}}{2}\right)}{\epsilon_{N,x}\gamma}}\frac{c\Delta B L_d}{E_\mu}$.