Optics Considerations for ERL Electron Coolers

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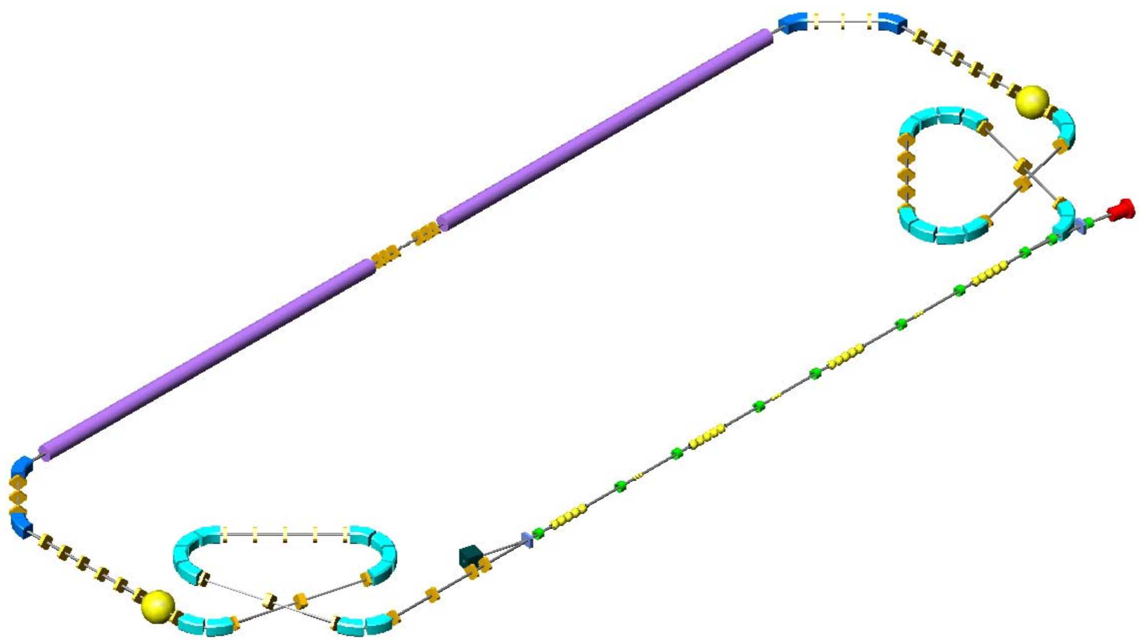
Abstract

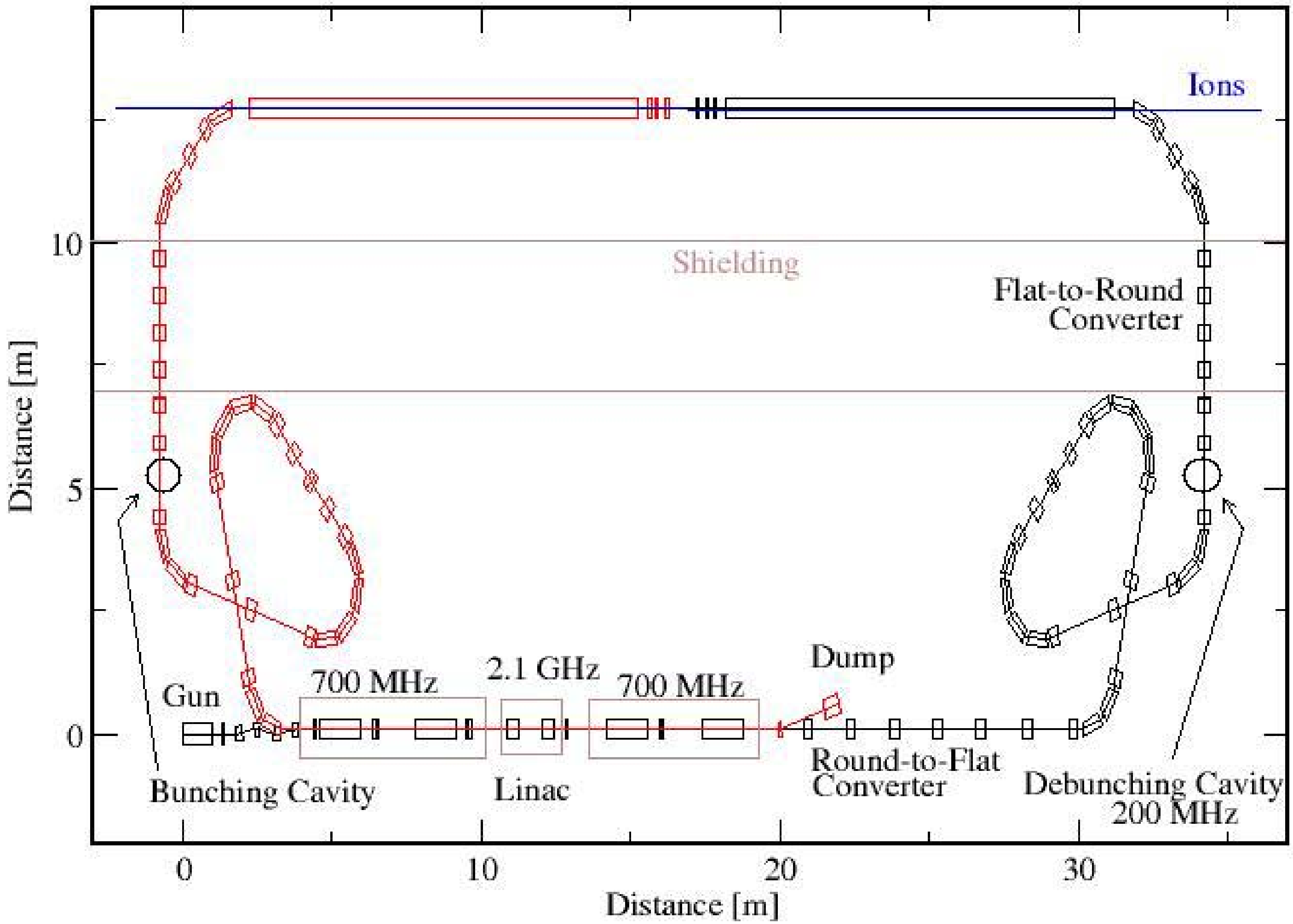
The RHIC electron cooler employs an ERL to archive a electron beam current of 200 mA at an energy of 55 MeV. Critical for sufficient cooling is a normalized beam emittance of 40 mm·mrad and an energy spread of less than $3 \cdot 10^{-4}$ in the cooling section.

In addition the beam must be "magnetized". The cathode is immerged in a longitudinal field. The resulting angular momentum is necessary to cancel the beam rotation caused by the fringe field of a strong (5 Tesla) solenoid magnet used in the cooling section to enhance the cooling process.

The talk presents methods to minimize this emittance growth during the transport of the magnetized beam from the gun to the cooling section.

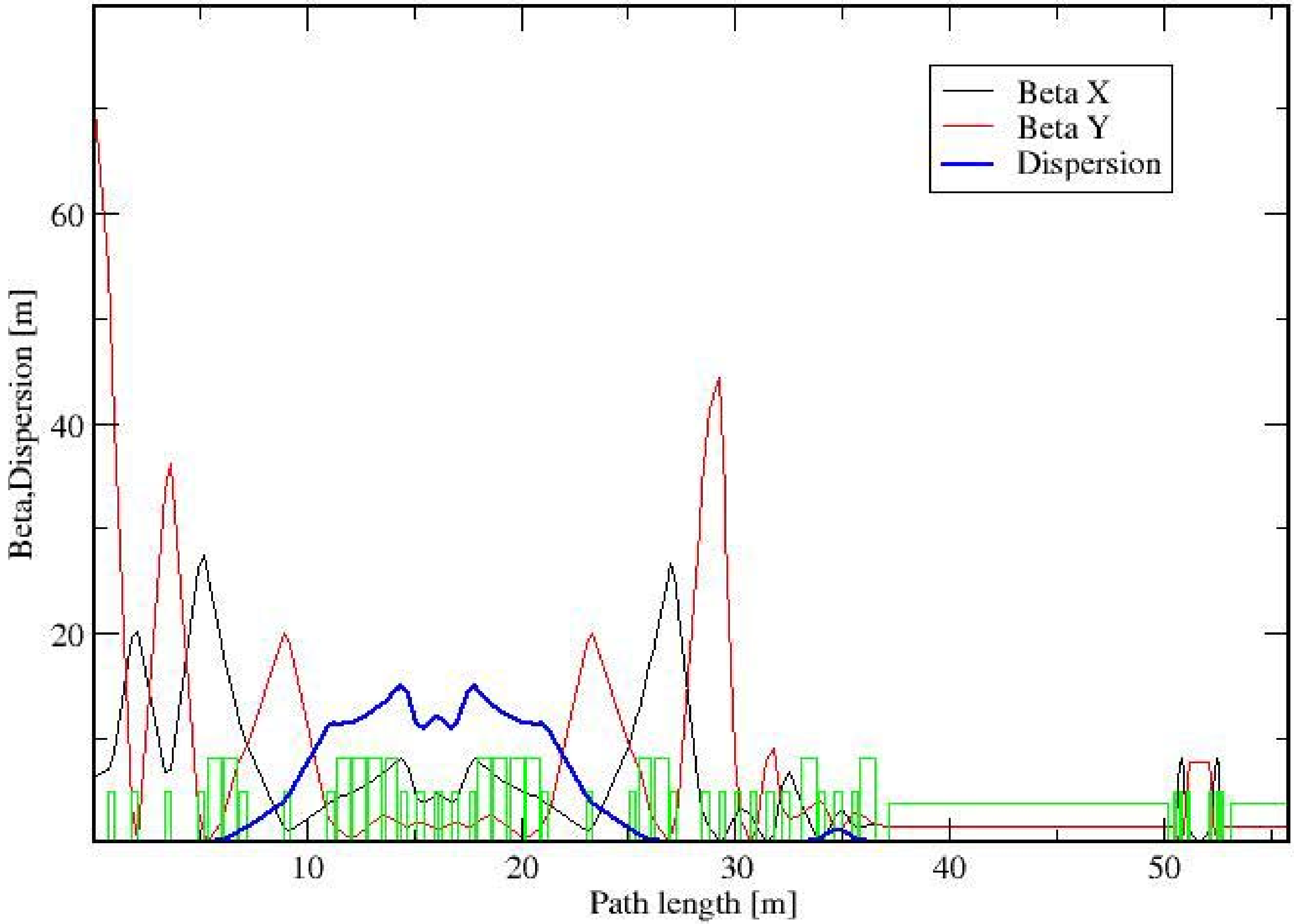
Cooler Layout




Ions
Shielding
Flat-to-Round
Converter
Distance [m]
10
5
0
Gun
700 MHz
2.1 GHz
700 MHz
Dump
Bunching Cavity
Linac
Round-to-Flat
Converter
Debunching Cavity
200 MHz
0
10
20
30
Distance [m]

-

Optics at 55 MeV



What is a "Magnetized Beam", Busch's Theorem

When a non-magnetized beam enters a solenoid, the fringe field increases the normalized emittance:

$$\varepsilon^2_{inside} = \varepsilon^2_{outside} + R^2\sigma^4\gamma^2 \qquad \textbf{with} \qquad R = \frac{1}{2}\frac{e}{pc}B_s$$

A magnetized beam rotates around the longitudinal axis (x′= R*y, y′=-R*x), so that the effect of the fringe field is canceled.

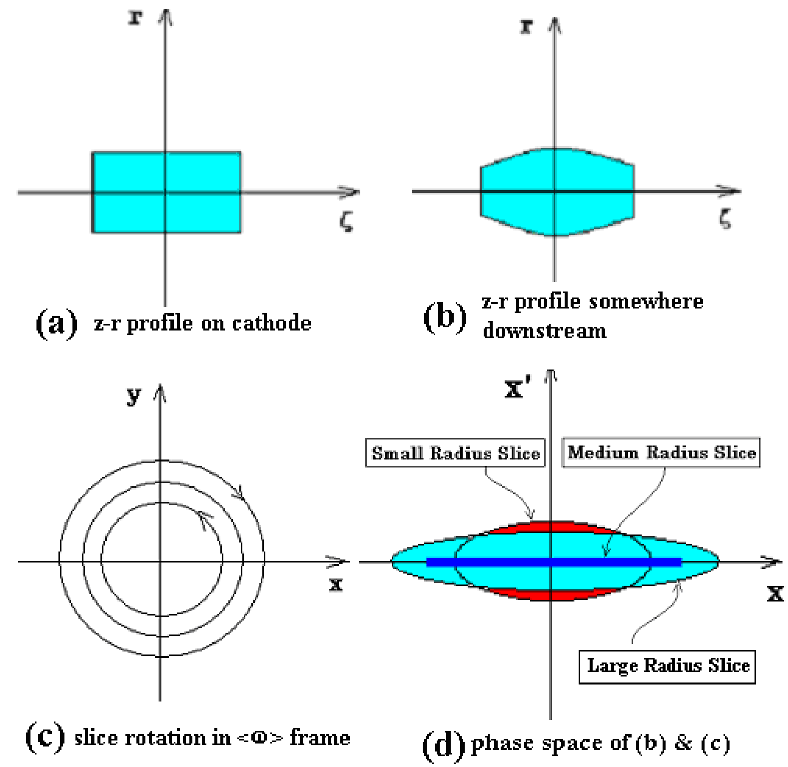
Busch's Theorem: If only axial symmetric fields are applied then:

$$r^2 \cdot \Theta' + r^2 \cdot \frac{e}{p} \cdot B = r_0^2 \cdot \frac{e}{p} \cdot B_0 \qquad \textbf{with} \qquad \Theta' =< \frac{y \cdot x' - x \cdot y'}{r^2} >, p = m_e\gamma\beta c$$

- **A magnetized beam can only be made using a magnetic field on the cathode!**
- **The beam transport matrix from the cathode to the cooling section must be axial symmetric.**
- **Non-linearities disturb the balance.**

Magnetized Emittance Compensation

- For a magnetized beam a variation of radius causes strong emittance growth.
- Traditional emittance compensation (Serafini-Rosenzweig) minimizes the spread in phase advance for different longitudinal slices.
- Chromaticity compensation is essential for good compensation.
- Variations in radius can not be avoided, but can be minimized by making the envelope large:



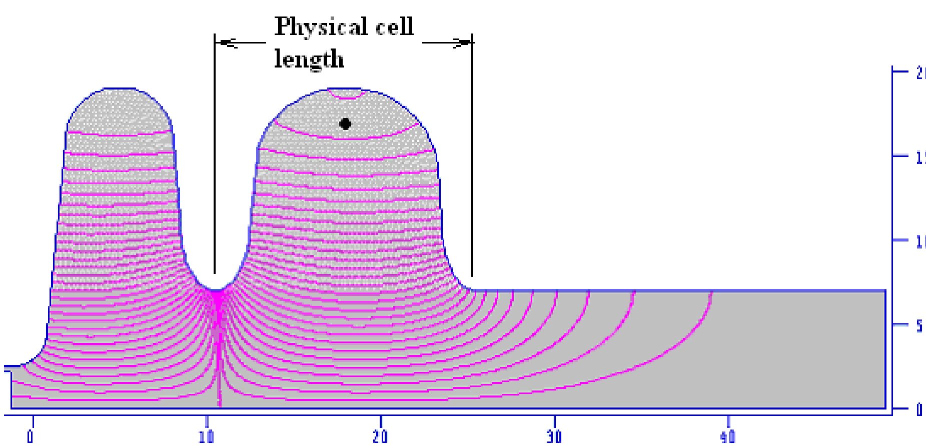
$$\frac{K_s}{\beta^3\gamma^3\sigma} \approx \left(\frac{p_\theta}{\beta\gamma mc}\right)^2 \frac{1}{\sigma^3}$$

$$\sigma'' + \sigma'\frac{\gamma'}{\beta^2\gamma} + K_r\sigma - \left(\frac{p_\theta}{mc\,\beta\gamma}\right)^2\frac{1}{\sigma^3} - \left(\frac{\varepsilon_n}{\beta\gamma}\right)^2\frac{1}{\sigma^3} - \frac{K_s}{\beta^3\gamma^3\sigma} = 0$$

$$K_s = I/2I_0$$

1½ Cell Superconducting Gun

- Cathode is recessed to focus the Beam
- Small solenoid magnet behind cathode creates magnetized beam (turned on after cool-down)



Merge of Low Energy and High Energy Beam

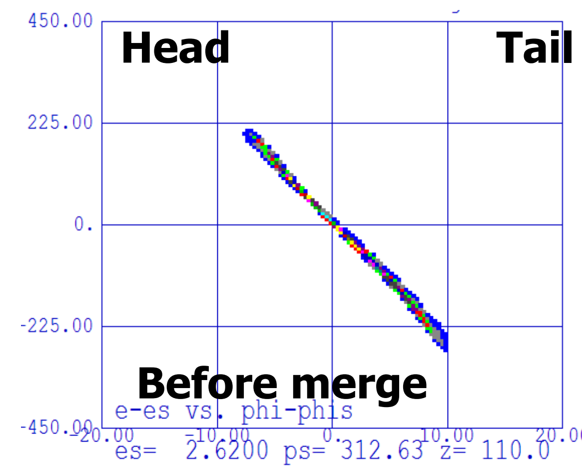
Beam are merged using dipoles

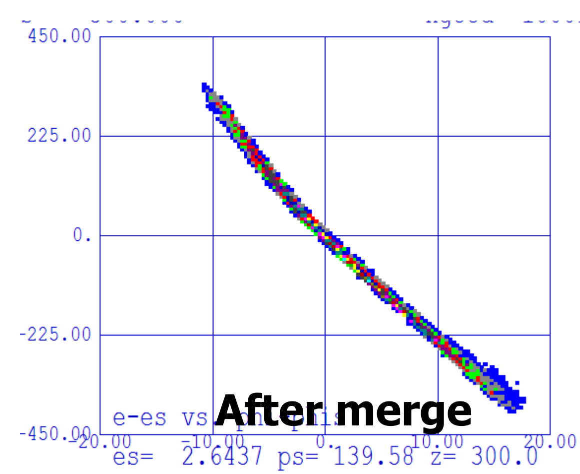
The space charge forces change the momentum of electrons in the dispersion region, affecting the transverse emittance.

Assuming the momentum spread grows linearly with path length the following integrals should be made zero:

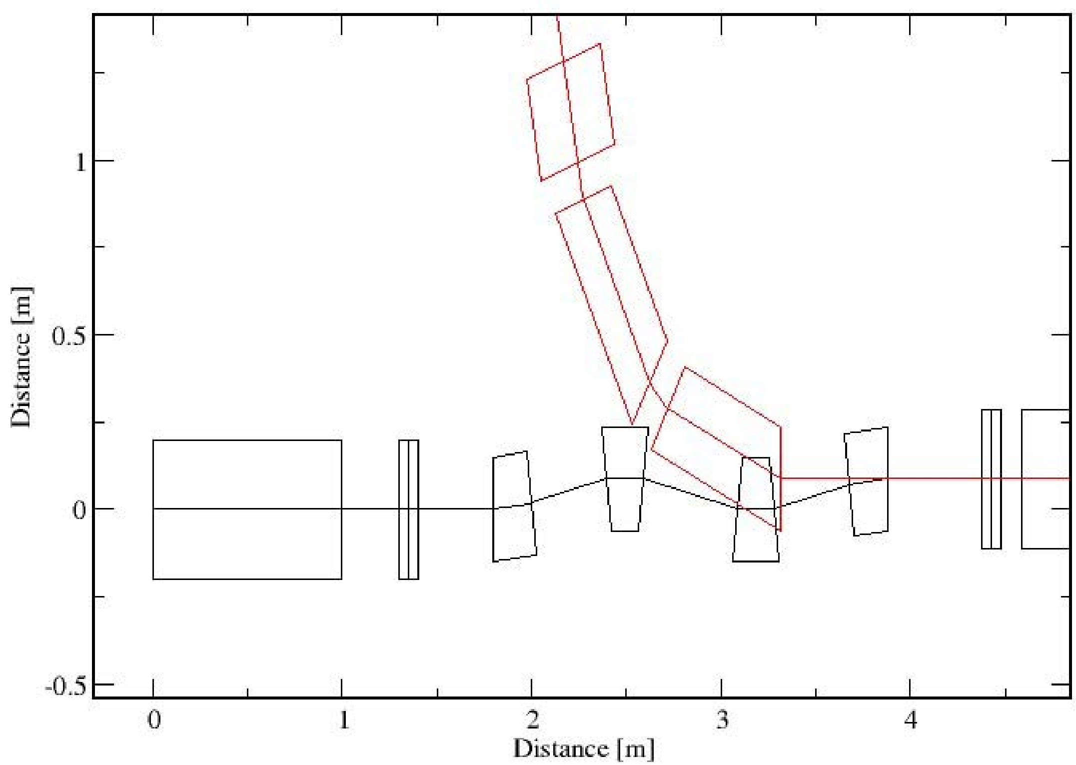
$$\int \frac{D}{\beta}\sqrt{\beta}\cos\phi\, ds = 0 \qquad \int (D' + \alpha\frac{D}{\beta})\sqrt{\beta}\cos\phi\, ds = 0$$

$$\int \frac{D}{\beta}\sqrt{\beta}\sin\phi\, ds = 0 \qquad \int (D' + \alpha\frac{D}{\beta})\sqrt{\beta}\sin\phi\, ds = 0$$





Zig-Zag Merging system



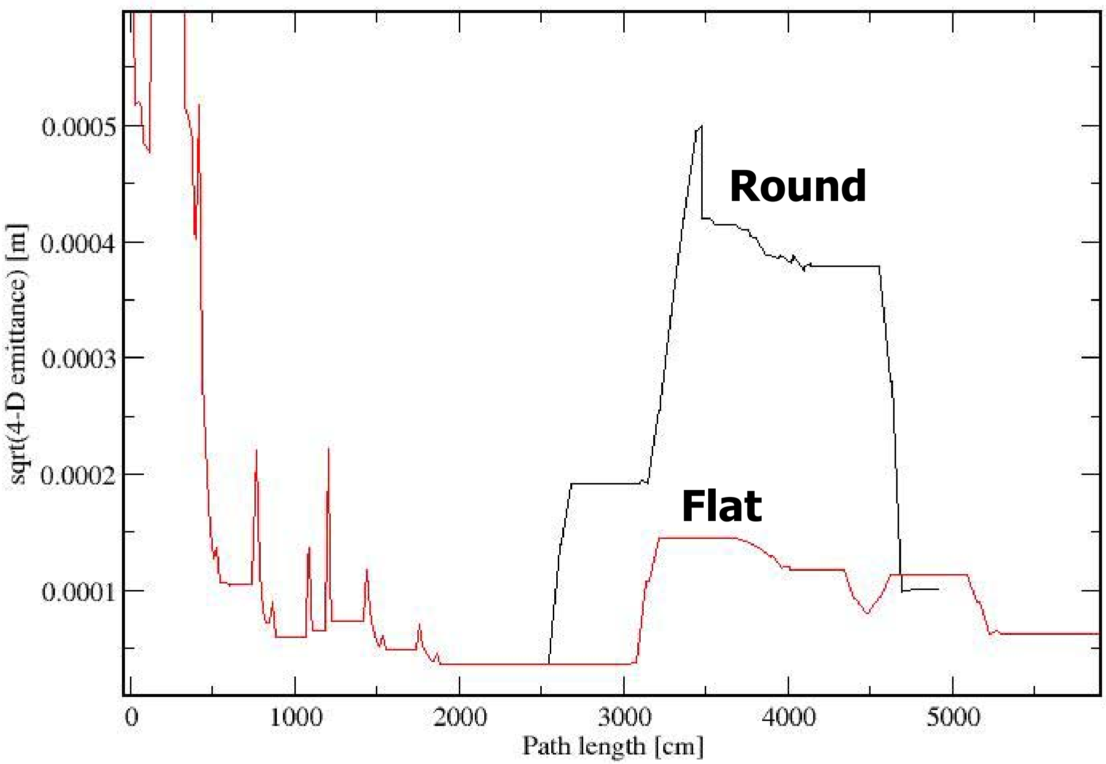
Stretcher/Compressor

- **Energy spread reduced from $3 \cdot 10^{-4}$ to $1 \cdot 10^{-4}$ (rms)**
- **Arc provides $\Delta l = 60m \cdot \frac{\Delta p}{p}$, expands bunch length from 2.5 cm to 20 cm. Maximum dispersion is 20 m, maximum beam radius 5 cm.**
- **Longer bunch reduces electron density, so that Debye shielding does not limit the maximum impact parameter.**
- **200 MHz normal conducting RHIC cavity used to remove energy spread.**
- **Second 200 MHz cavity introduces opposite energy spread**
- **Second arc shortens bunch length for energy recovery.**

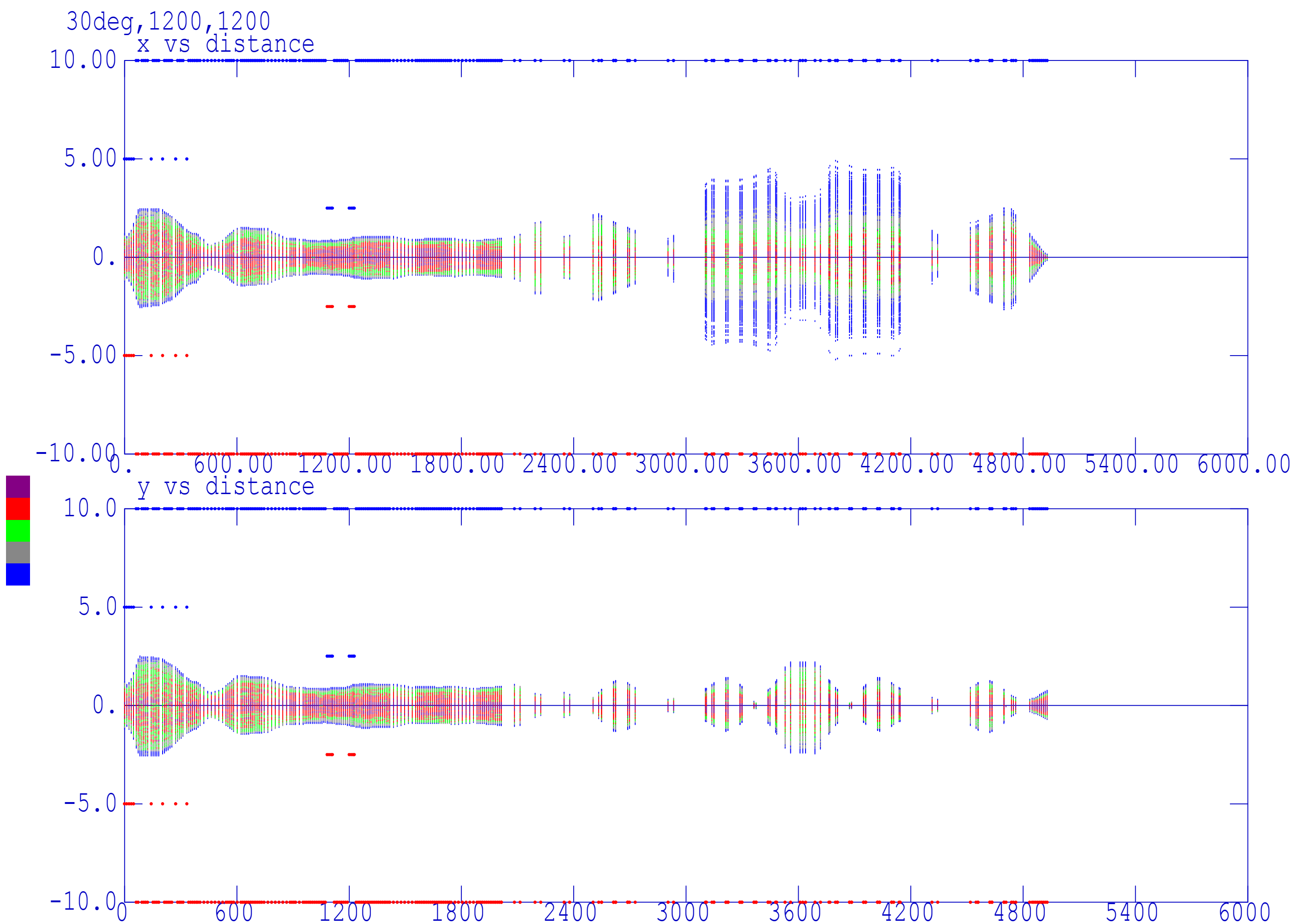
Design Criteria for the Stretcher

1. **Make stretcher short:**
   - minimizes energy spread growth
   - Minimizes chromaticity
   - Minimizes non-linearities
2. **Make M56 large**
   - Minimizes required energy spread (by mis-phasing the linac)
3. **Make energy spread from linac small**
   - Minimizes chromatic effects
   - Minimizes beam size, therefore minimizes non-linearities
4. **Use sextupoles only to correct non-linearities of dipoles**
5. **Make integrals zero**
   - Minimizes coupling between longitudinal and transverse motion
   - Makes stretcher long: **goto item 1.**

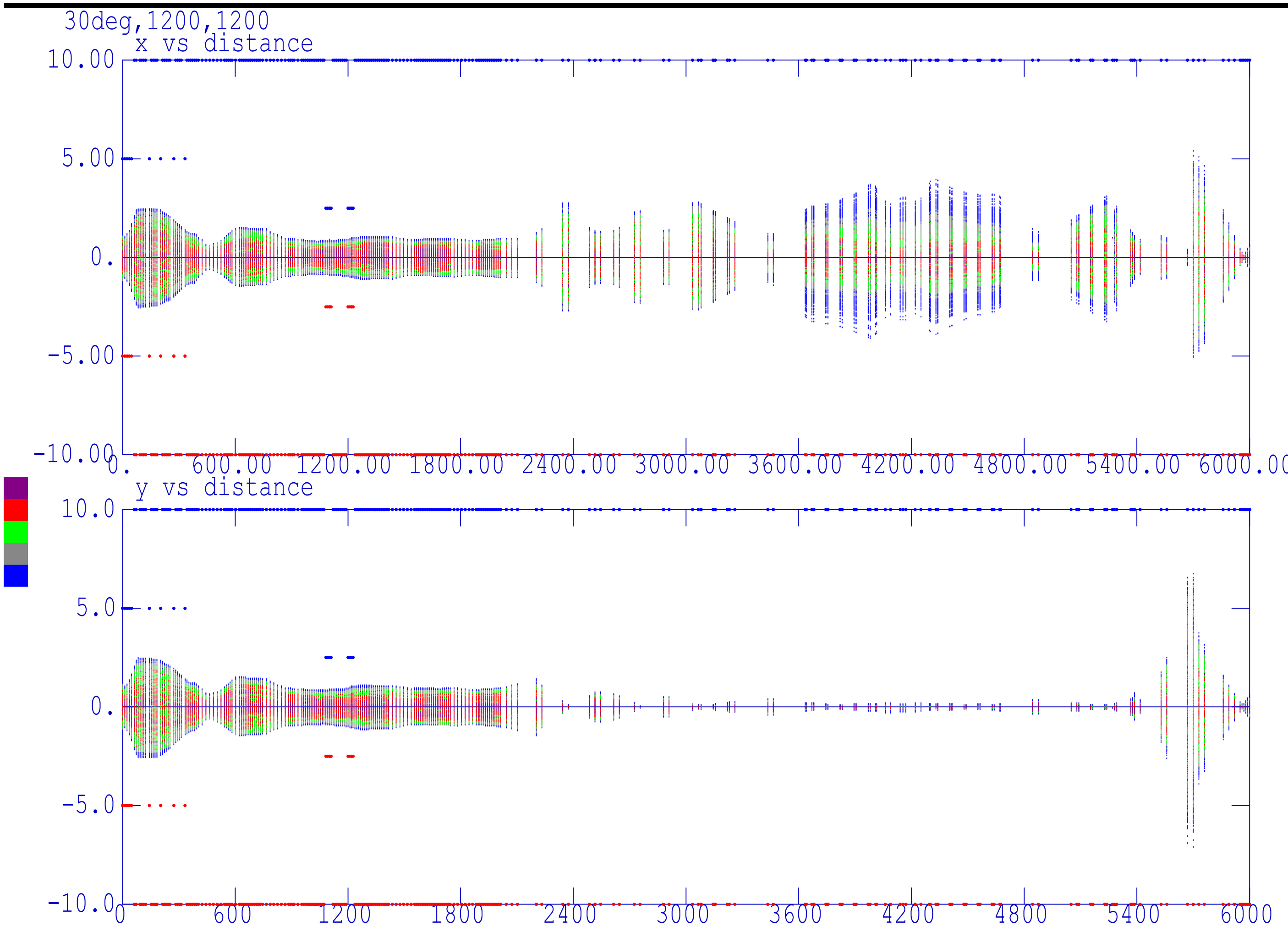
Emittance preservation in the stretcher with round vs. flat beams



Beam Profile with Round Beam



Beam Profile with Flat Beam



Solenoid Gap

- For technical reasons the cooling solenoid will be split into two sections. Extra focusing is necessary to maintain magnetization.
- We will use quadrupoles to obtain 180°/360° phase advance. This allows opposing field direction in the solenoid halfs.