Ring Cooler Simulations- An update

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Emittance Exchange Workshop
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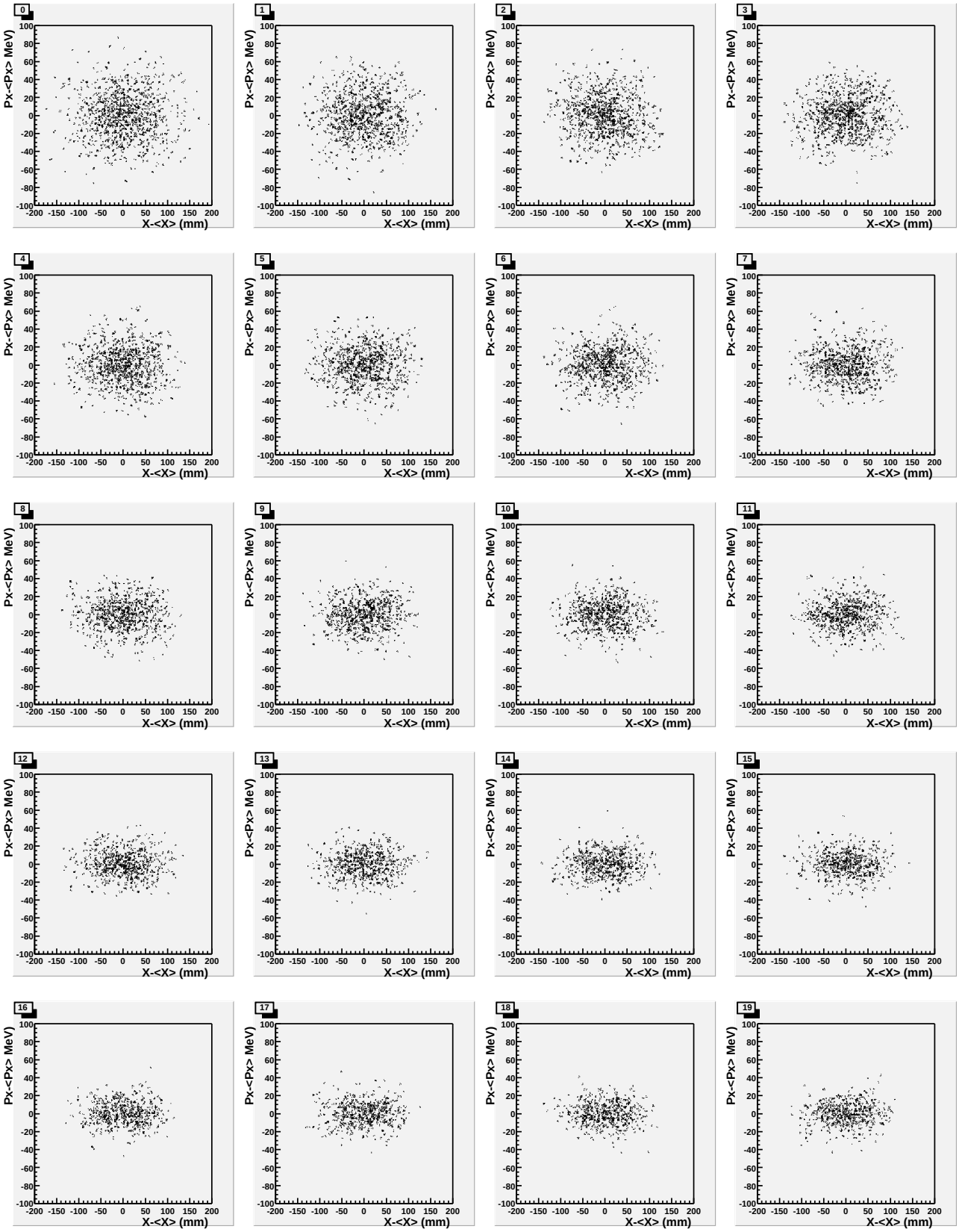
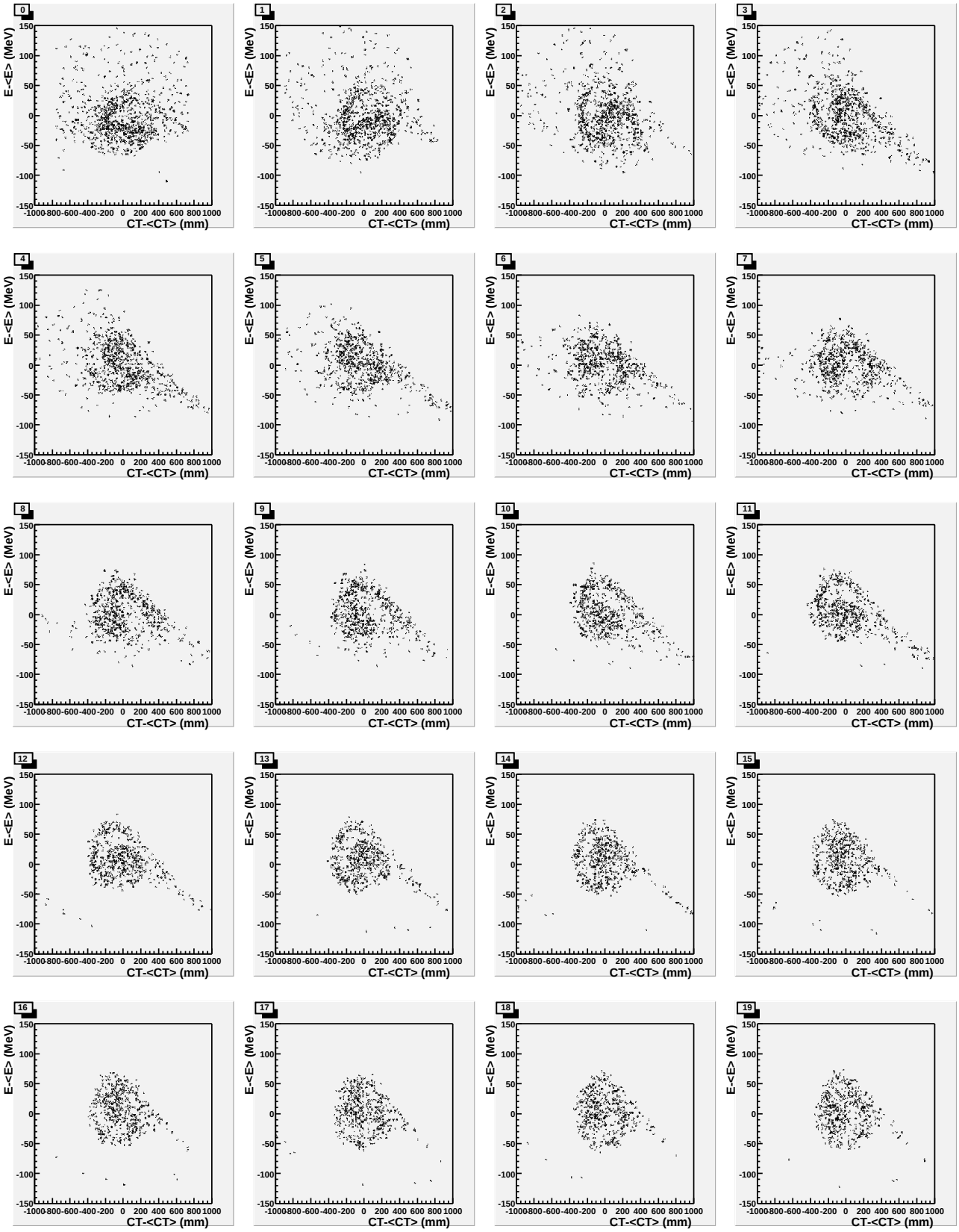
Conventional linear cooling channels

- Conventional linear cooling channels cool in transverse direction only.
- Longitudinal direction is unaffected.
- The following two plots show the double flip channel beam every 2.5 meters. The first 50 meters are shown.
- At the end of 50 meters, cooling in transverse dimension (x,p_x) is evident.
- Next slide shows longitudinal dimension. No cooling is evident. There is loss of beam from the outskirts of the plot. No increase in central density.

Conventional cooling- Double Flip linear channel-results Every 2.5 meters xpx plots



Conventional cooling- Double Flip linear channel-results Every 2.5 meters En-ct plots



Ring Cooler –New scheme from Balbekov

Layout of the ring cooler

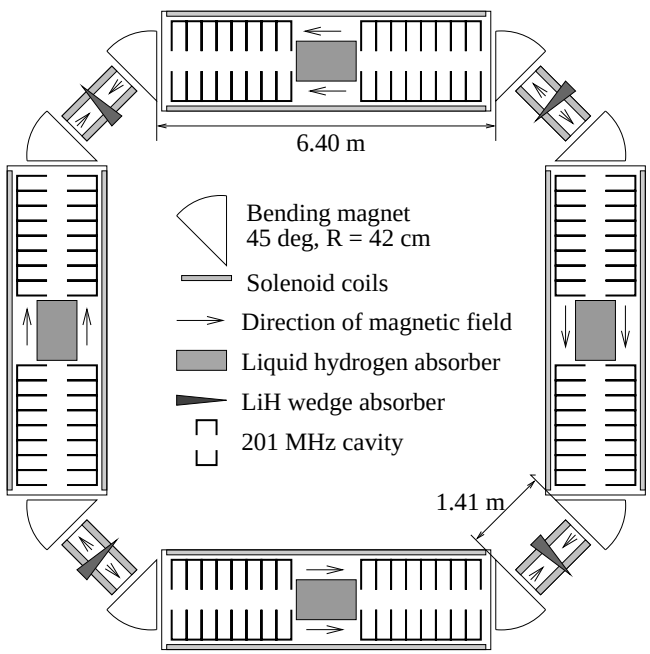


Figure 1: Schematic of ring cooler

Parameters of the ring cooler

1.	Circumference	35.1 m
2.	Kinetic energy of muons	125-164 MeV
3.	Revolution frequency	7.05 MHz
4.	Bending radius	42 cm
5.	Bending field	1.80 T
6.	Solenoid field	$\pm(2.5 - 4.5)$ T
7.	RF frequency	201.25 MHz
8.	Accelerating gradient	15 MeV/m
9.	RF harmonic number	25
10.	Main absorber	LH, 120 cm 120 cm
11.	Wedge absorber (LiH)	$dE/dy = 0.5$ MeV/cm
12.	β-function	33-60 cm
13.	Long SS	6.4 m
14.	Short SS	1.41 m

Ring Cooler

Layout and field of SS

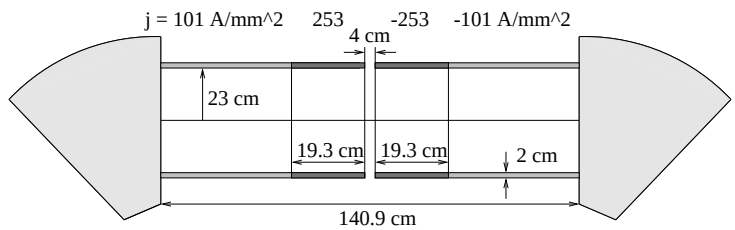


Figure 2: Coils in short straight section (with field flip).

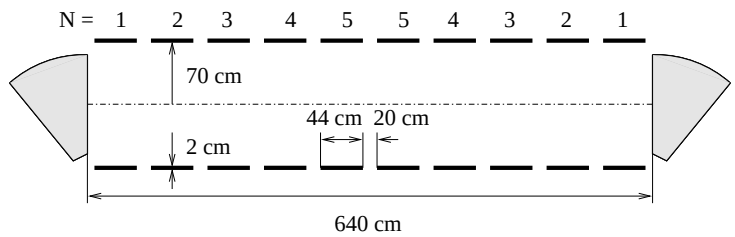


Figure 3: Coils in long straight section.

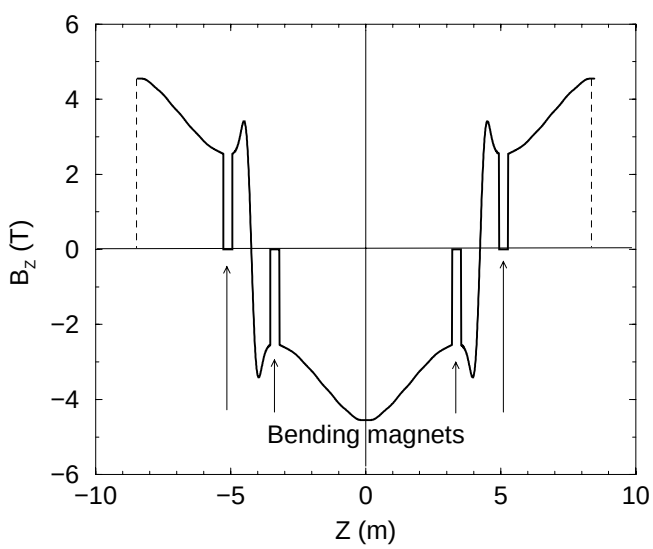


Figure 4: Axial magnetic field of the period (1/2 turn).

Ring Cooler

Cooling of a bunched beam

Injected beam:	$\sigma_X = \sigma_Y = 4.1$ cm $\sigma_{P_x} = \sigma_{P_y} = 31$ MeV/c $\sigma_Z = 8.5$ cm, $\sigma_E = 19$ MeV $\varepsilon_X = \varepsilon_Y = 1.2$ cm, $\varepsilon_Z = 1.5$ cm
After 15 revolutions:	$\varepsilon_X = 0.22$ cm $\varepsilon_Y = 0.22$ cm $\varepsilon_Z = 0.60$ cm
Transmission:	64% without decay 45% with decay

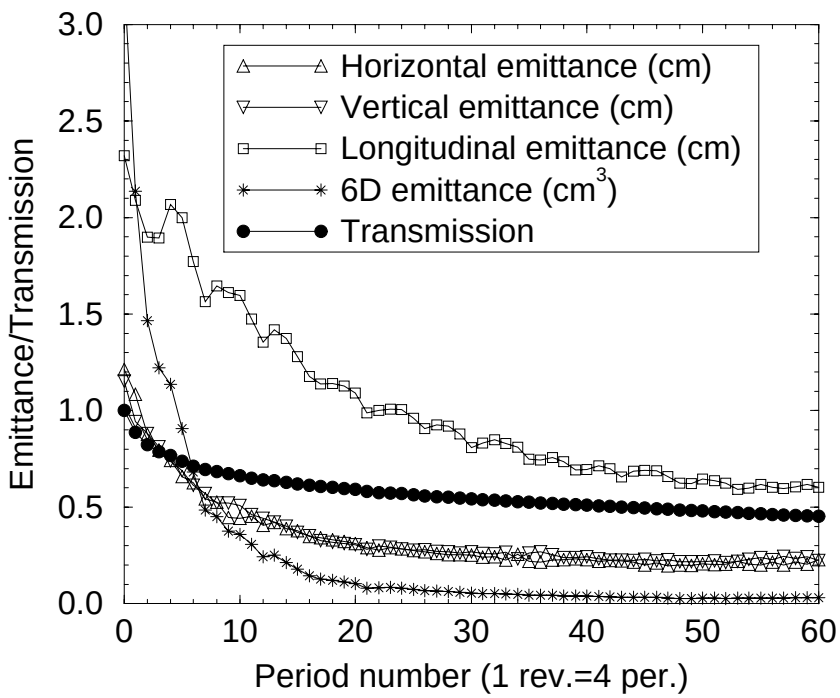


Figure 5: Emittance and transmission at the cooling of bunched beam.

Ring Cooler

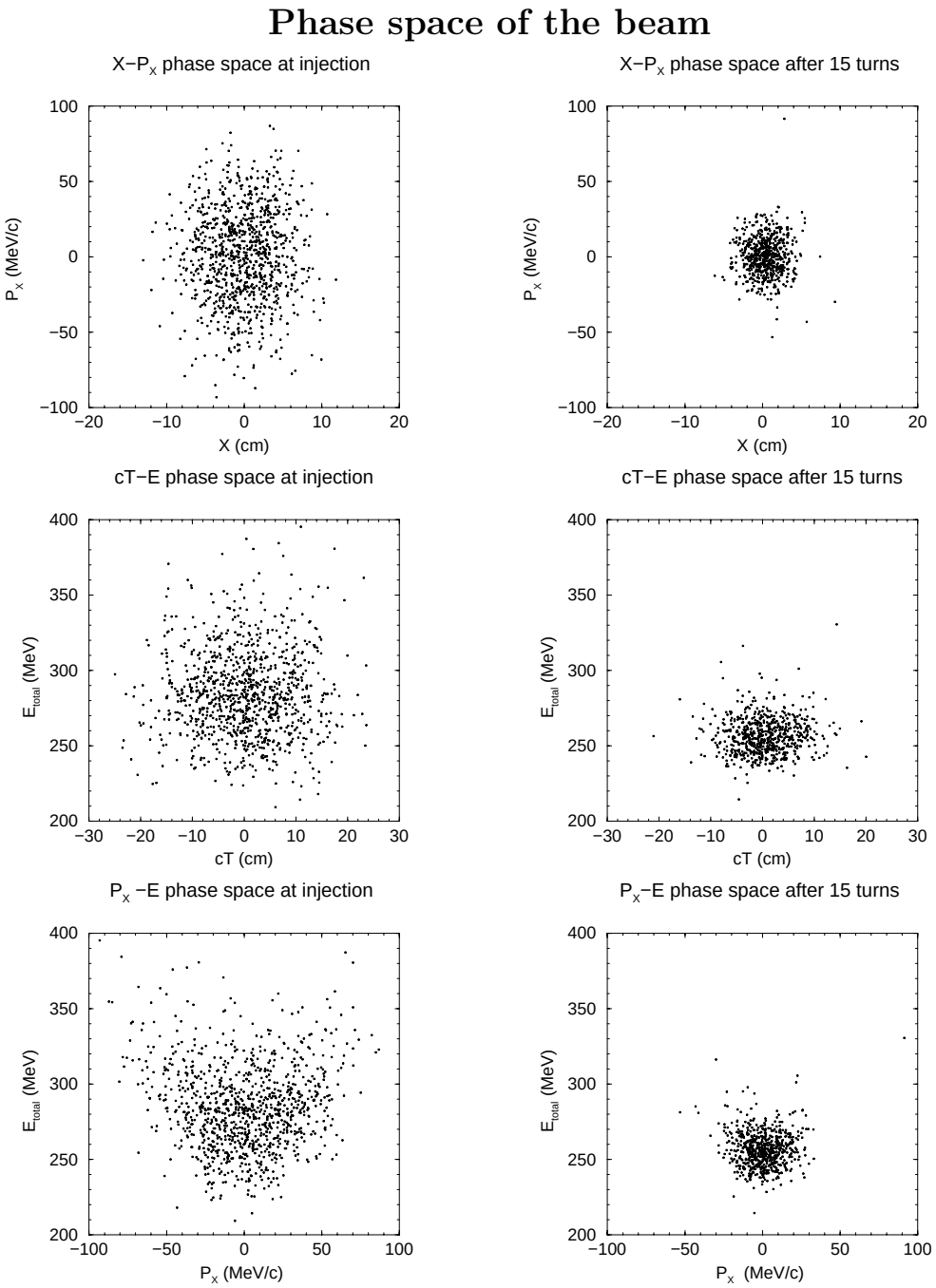


Figure 6:

Ring Cooler -Performance

Bunching in the ring

- Current carrying target 15 cm Cu
- Primary focusing: Li lense
- Decay channel: solenoid $B = 3.56$ T, $R = 15$ cm, $L = 16$ m

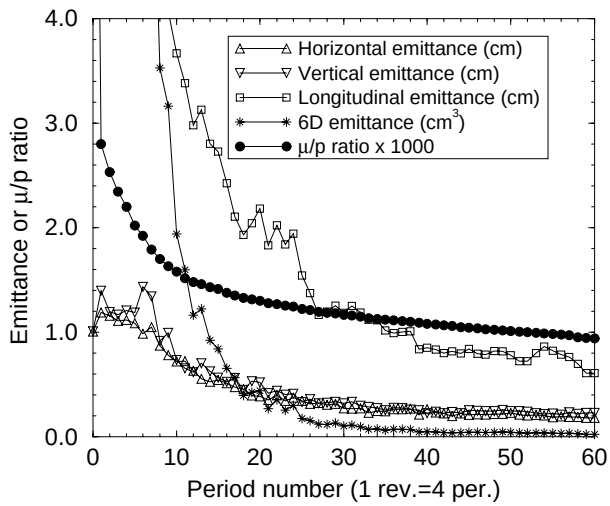


Figure 7: Beam emittance and μ/p ratio in the ring cooler

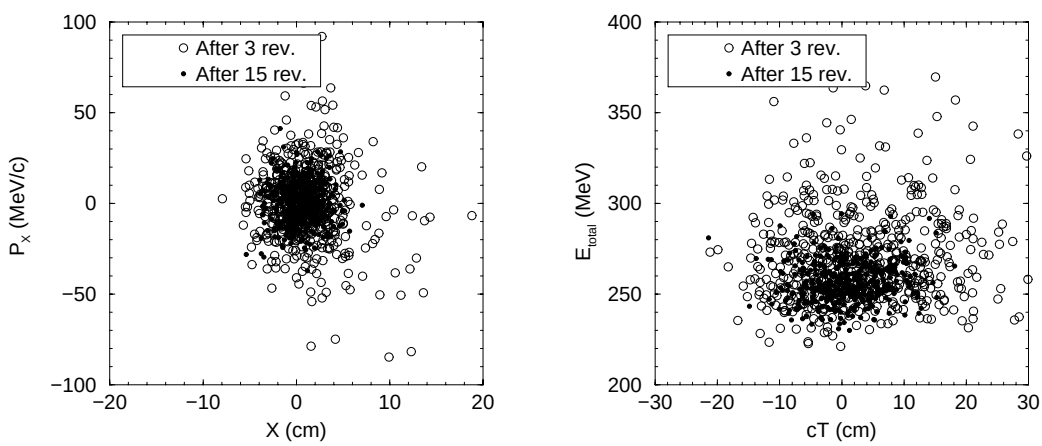


Figure 8: Phase space of the beam after 3 and 15 turns

Ring Cooler -Performance

Muon yield at internal target

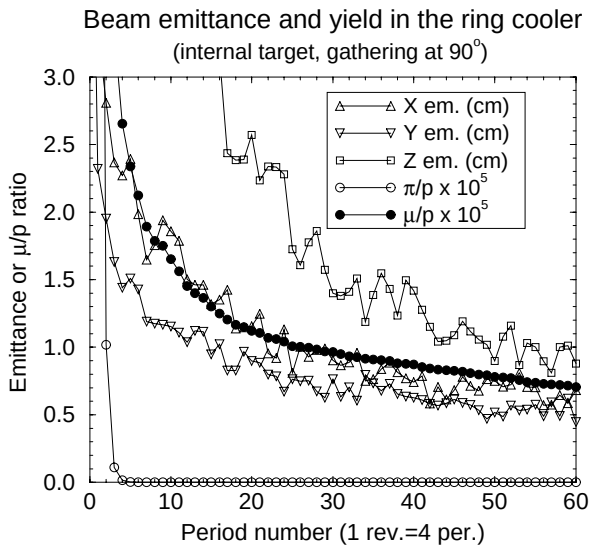


Figure 9: Beam emittance and μ/p ratio in the ring cooler. Wedge absorber is used as a target

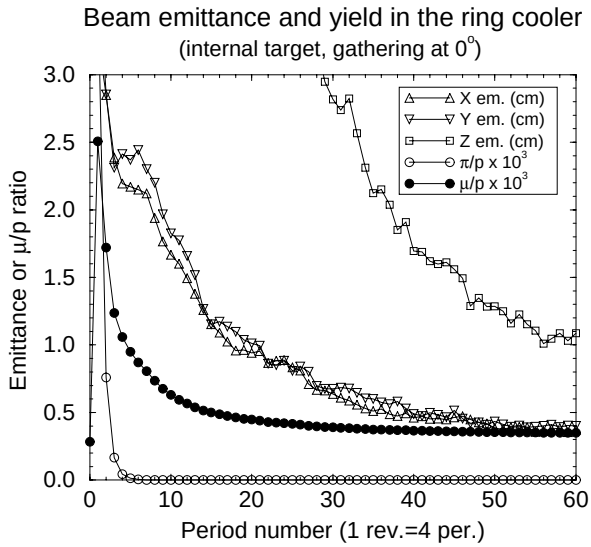
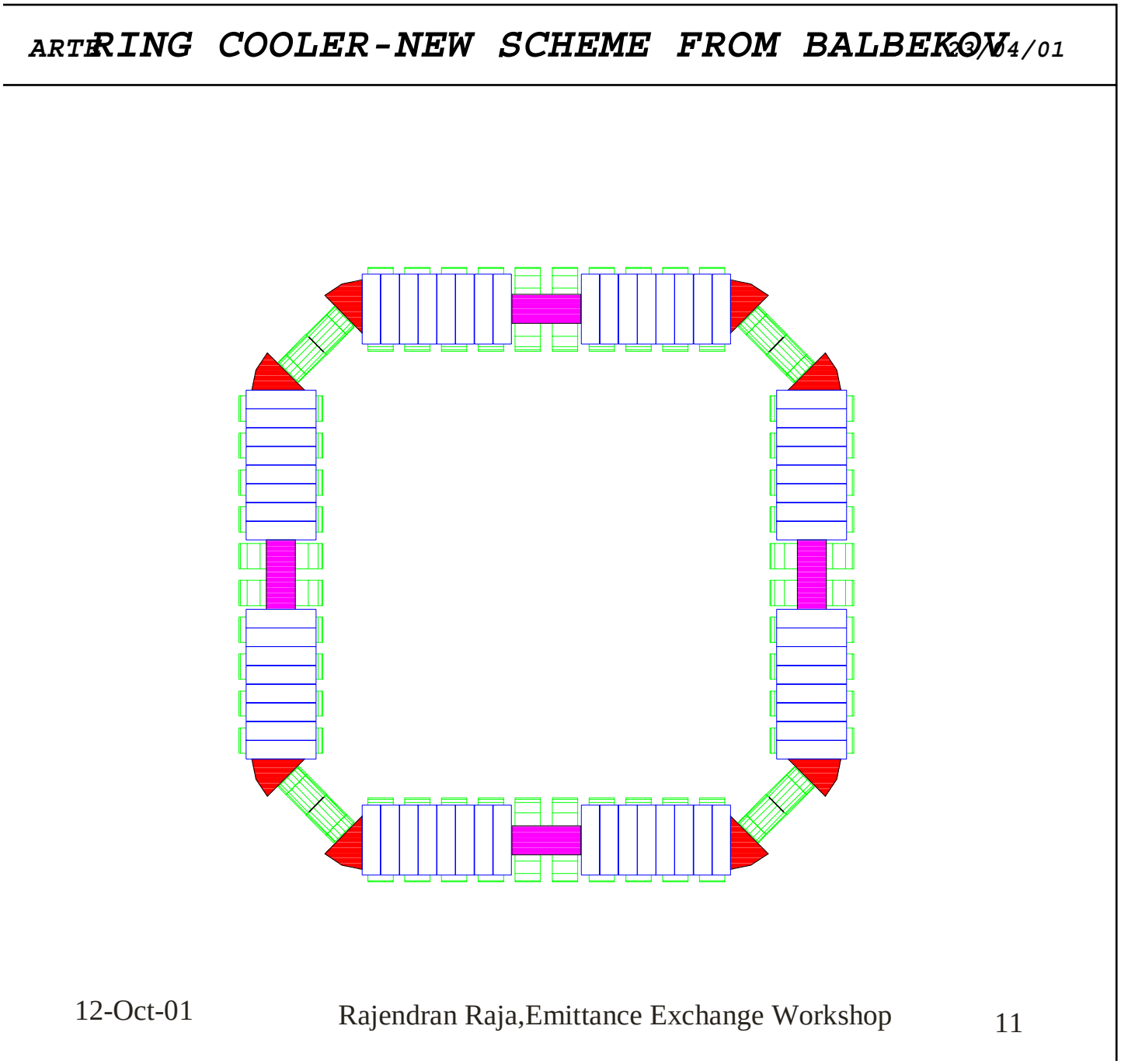


Figure 10: Beam emittance and μ/p ratio in the ring cooler. Internal target: Cu, L=22 cm, R = 7.5 mm. Number of muons is 20 times less if the target is placed out the aperture.

Geant Simulation of ring cooler



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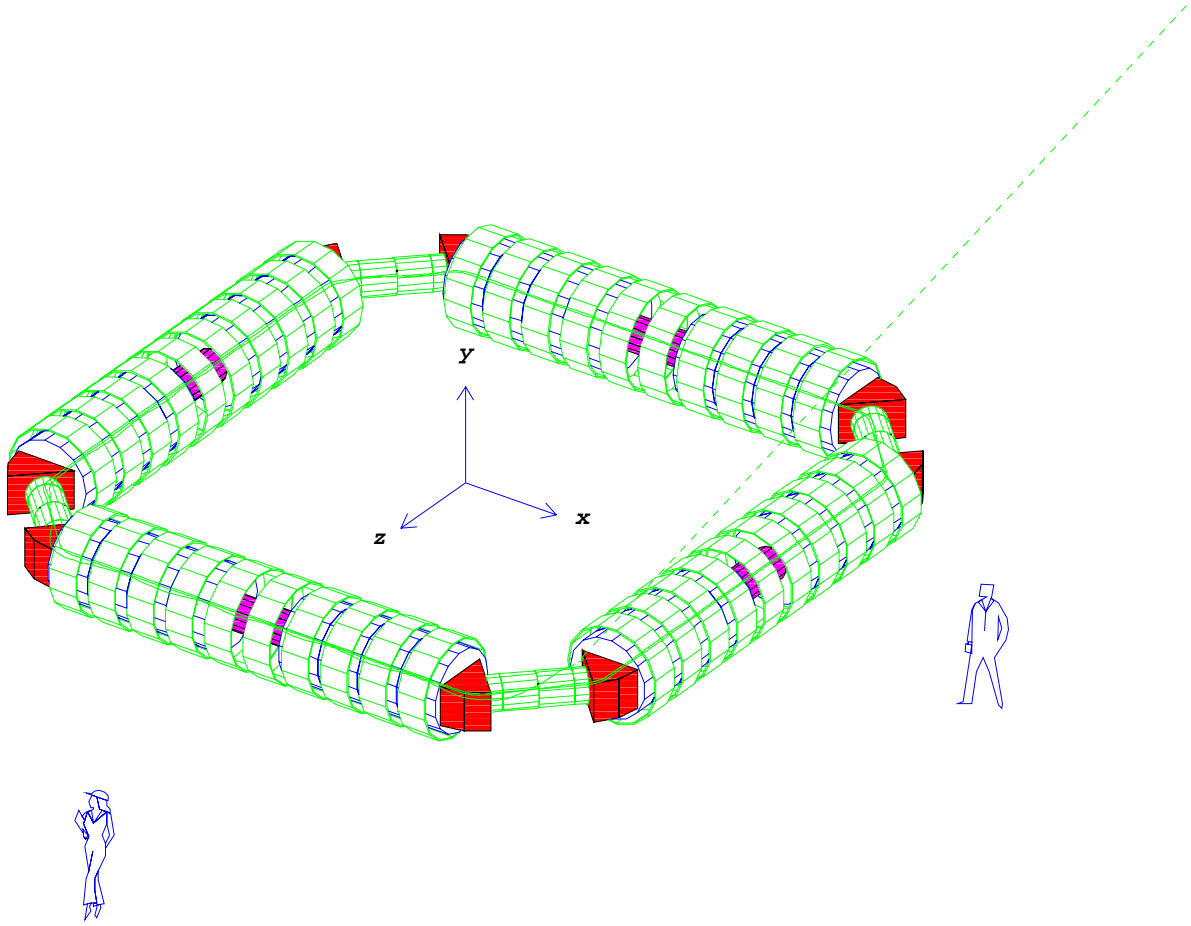
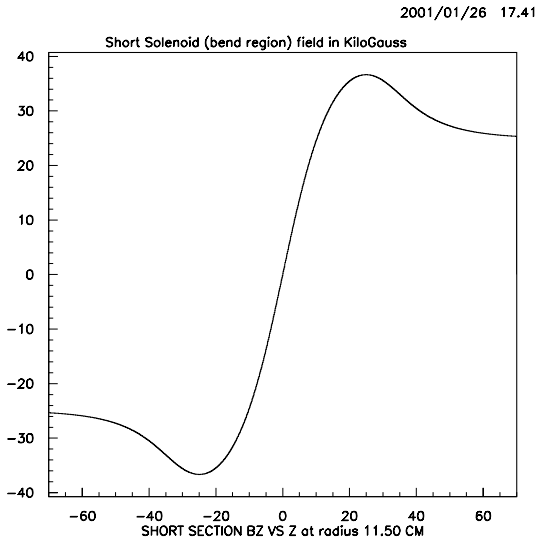
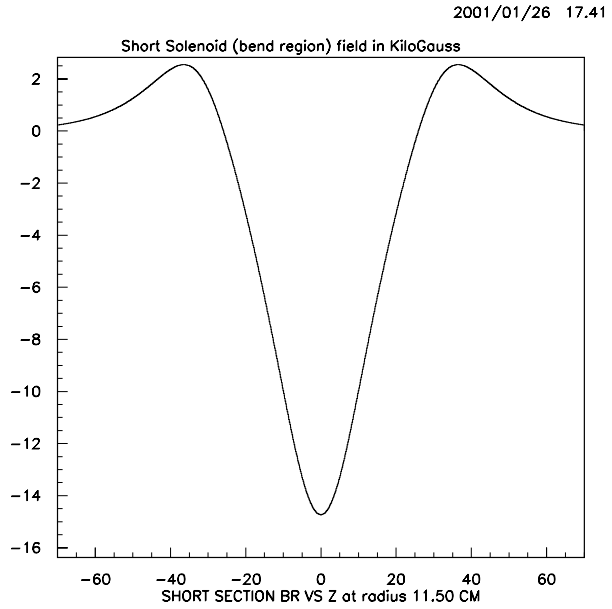


Geant Simulation of ring cooler Short Section Solenoid





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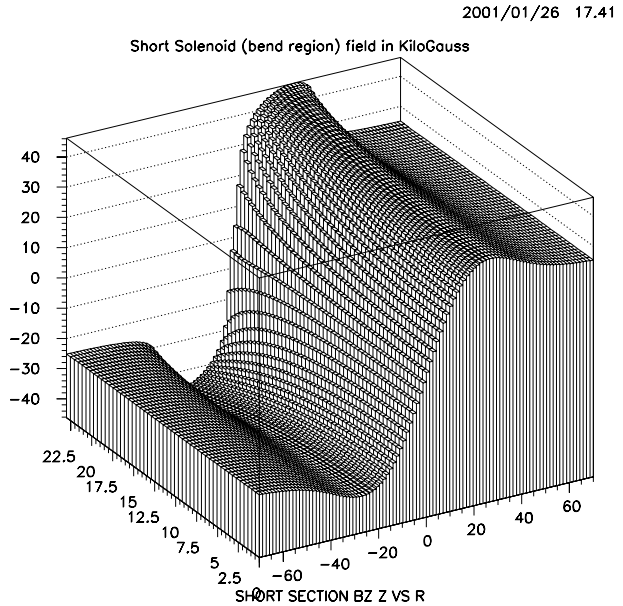
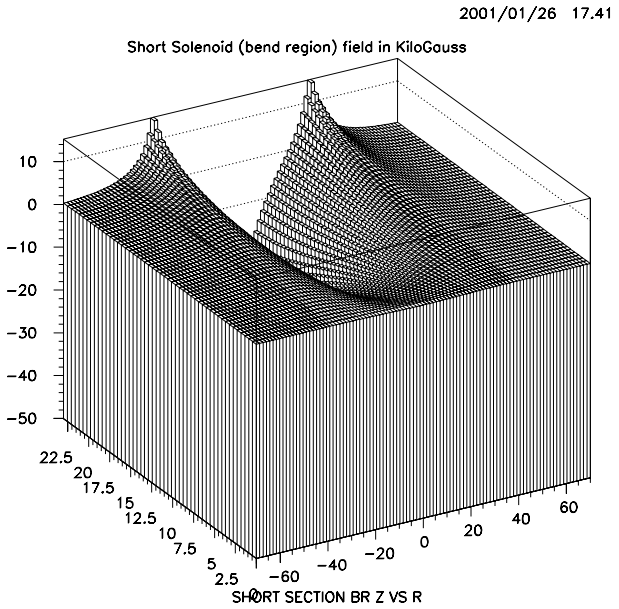
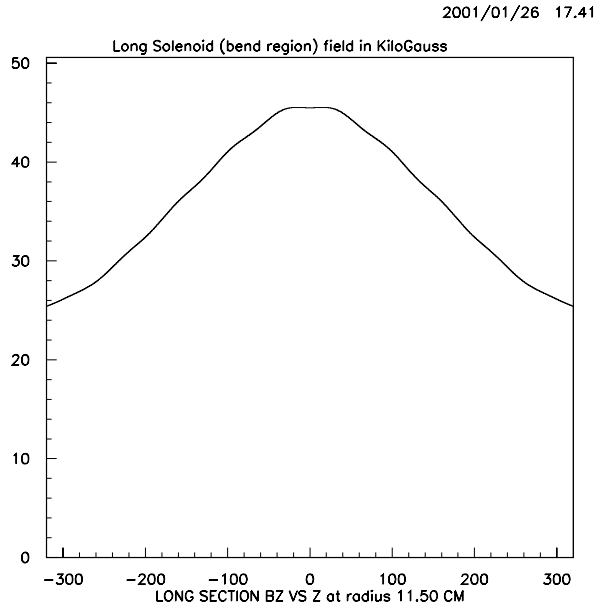
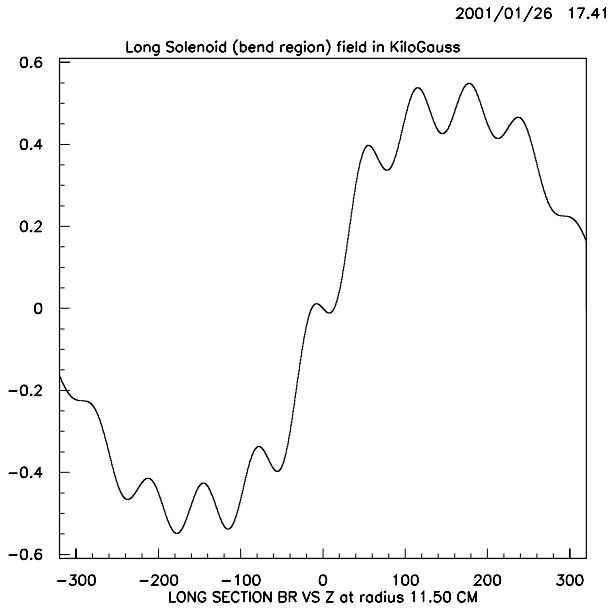


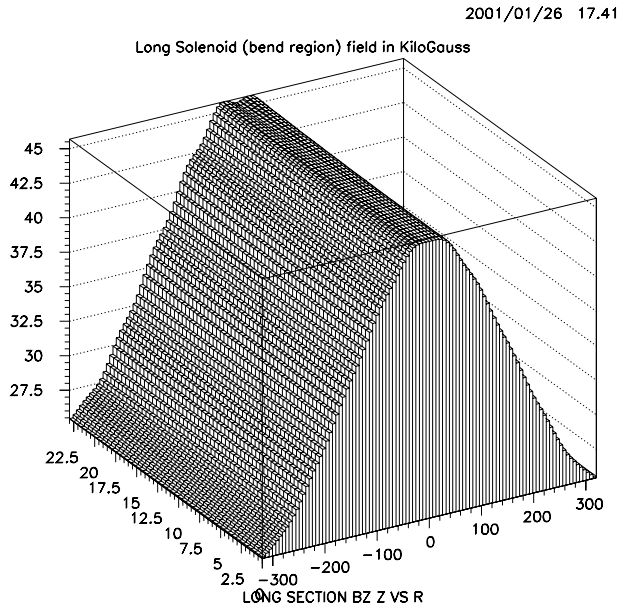


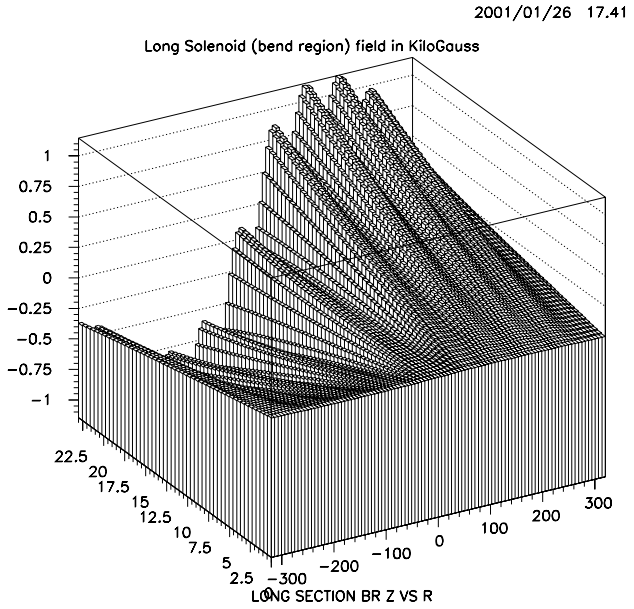
Geant Simulation of ring cooler Long Section Solenoid



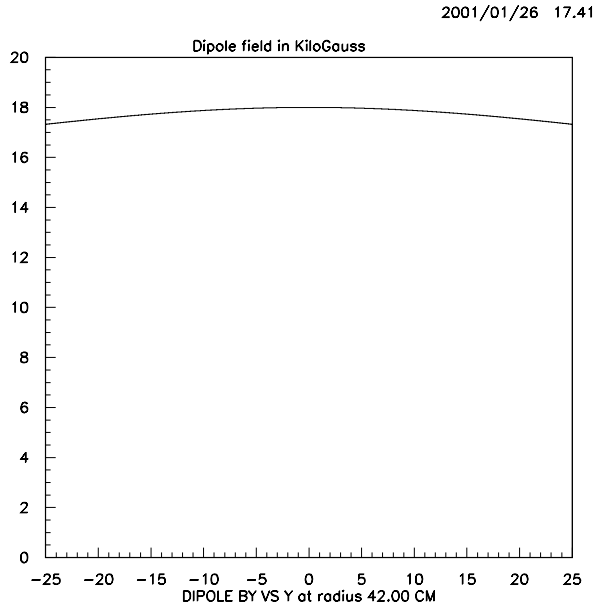


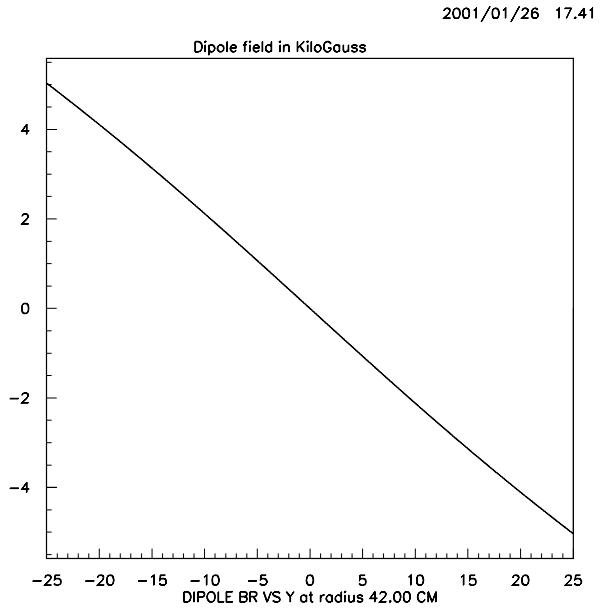
Geant Simulation of ring cooler Long Section Solenoid





Geant Simulation of ring cooler Bend Dipole





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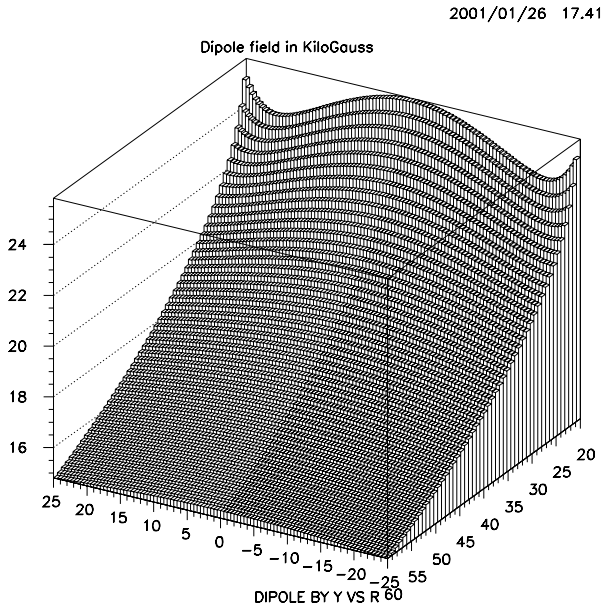
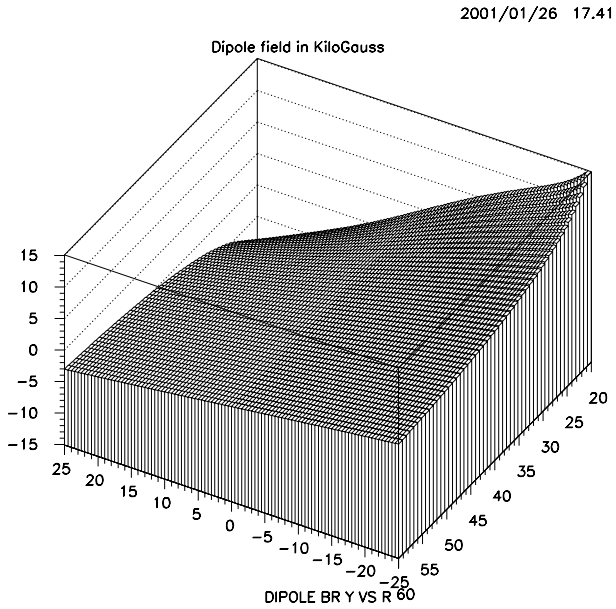




Equations of motion in presence of electric and magnetic fields

$\vec{p}, E$ is the particle 4 vector, $\vec{u}$ is the tangent to the trajectory, s the arc length, v the velocity, η is the Lorentz factor c the velocity of light, m_0 the particle mass, q the charge $\vec{\varepsilon}$ is the electric field, $\vec{B}$ is the magnetic field

$$\frac{d\vec{p}}{dt} = q(\vec{\varepsilon} + \vec{v} \times \vec{B})$$

$$\frac{d\vec{p}}{dt} = \frac{d\vec{p}}{ds} \times \frac{ds}{dt} = v\frac{d\vec{p}}{ds}$$

$$\vec{p} = \vec{u} m_0 c \eta$$

$$p\frac{dp}{ds} = \vec{p} \circ \frac{d\vec{p}}{ds} \Rightarrow \frac{dE}{ds} = q(\vec{\varepsilon} \circ \vec{u}) \quad (1)$$

$$\frac{d\vec{u}}{ds} = \frac{d^2\vec{x}}{ds^2} = \frac{q}{p}\left(\vec{u} \times \vec{B} + \frac{\vec{\varepsilon}}{v} - \frac{\vec{\varepsilon} \circ \vec{u}}{v}\vec{u}\right) \quad (2)$$

$$\frac{dt}{ds} = \frac{1}{v} \quad (3)$$

Runge-Kutta Equations

- Runge-Kutta is performed on 3 equations simultaneously.Nystrom algorithm

$$y'' = f(y', y, x)$$

solves to

$$y(x+h) = y(x) + hy'(x) + (h^2/6)(K_1 + K_2 + K_3) + O(h^5)$$

$$y'(x+h) = y'(x) + (h/6)(K_1 + 2K_2 + 2K_3 + K_4) + O(h^5)$$

$$K_j = f(y'_j, y_j, x_j) \text{ for } j = 1,2,3,4$$

$$x_1 = x, x_2 = x_3 = x + h/2, x_4 = x + h$$

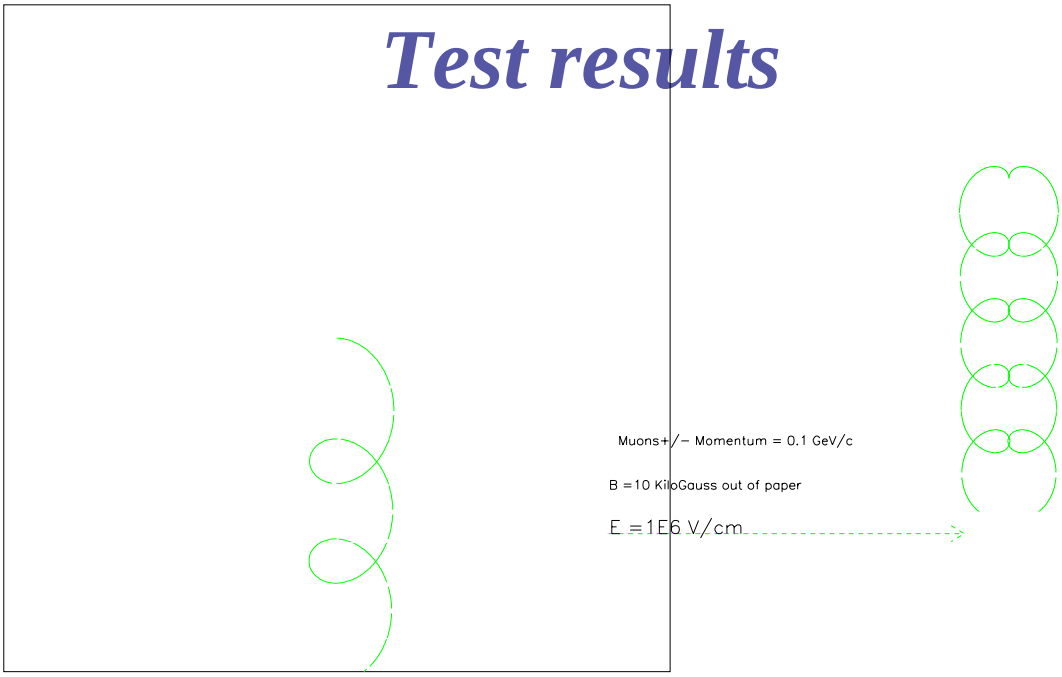
$$y_1 = y(x), y_2 = y_3 = y(x) + (h/2)y'(x) + (h^2/8)K_1$$

$$y_4 = y(x) + hy'(x) + (h^2/2)K_3$$

$$y'_1 = y'(x), y'_2 = y'(x) + (h/2)K_1, y'_3 = y'(x) + (h/2)K_2,$$

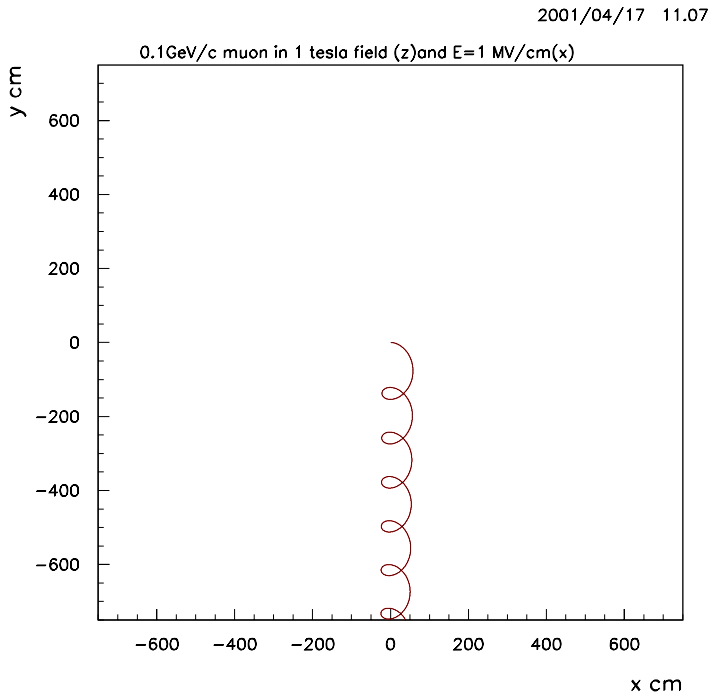
$$y'_4 = y'(x) + hK_3$$

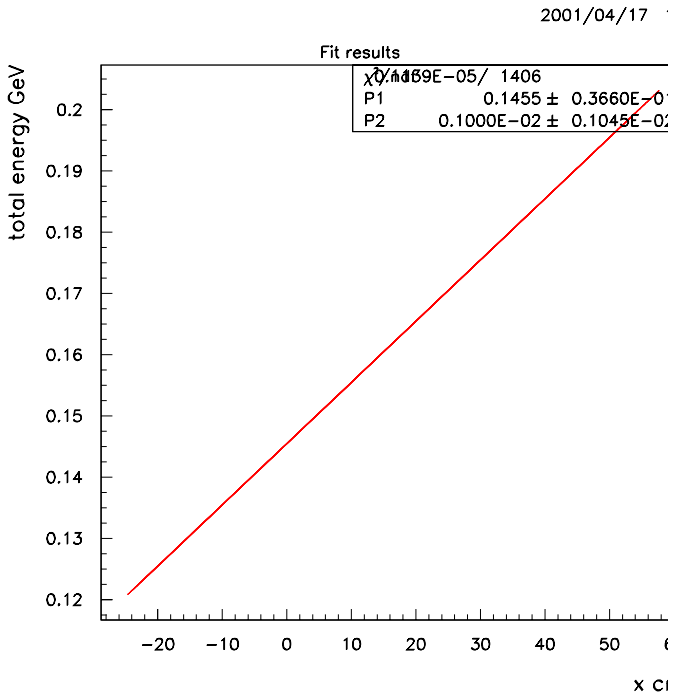
Test results

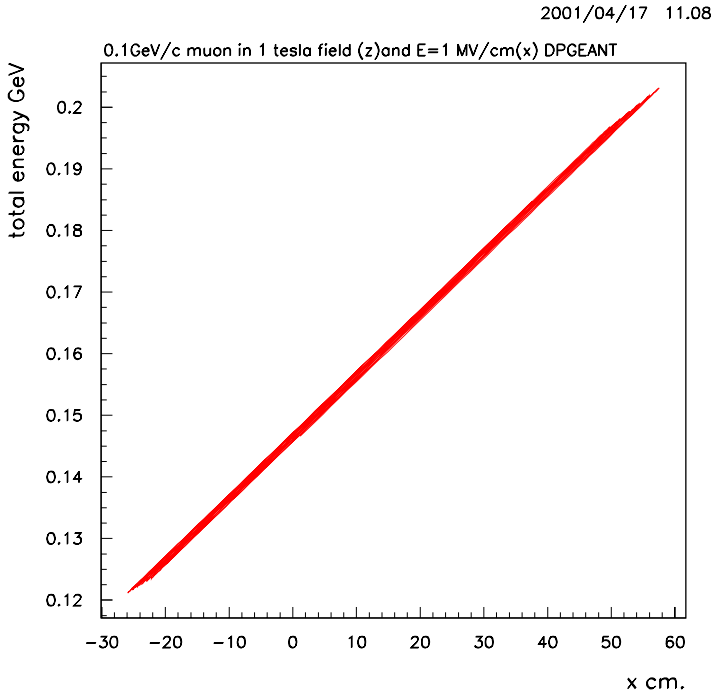


Test results

Runge Kutta results







Solenoid end field kick

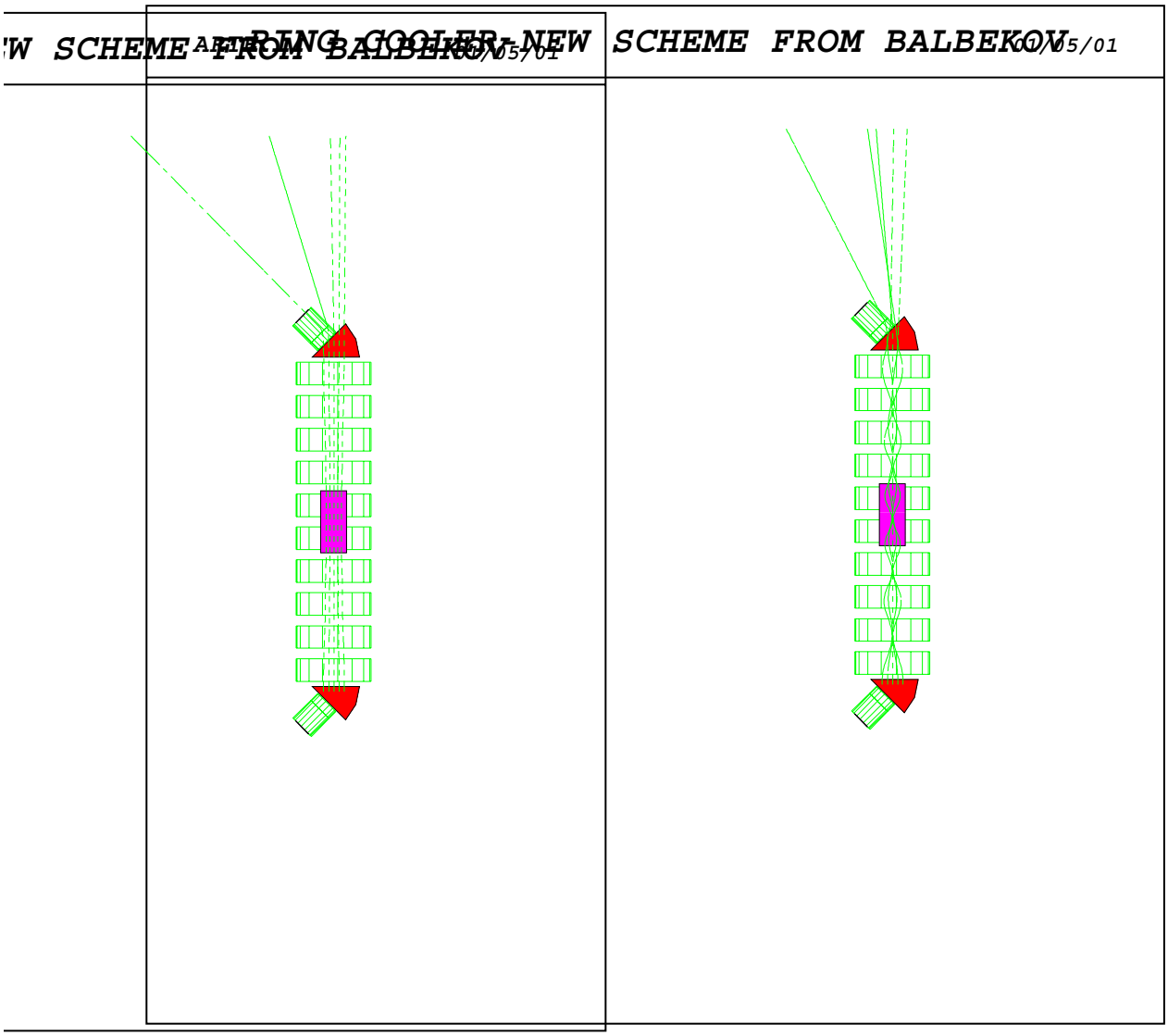
- One needs to simulate the end field of the solenoids by changing the transverse momentum of the particle by the following equations. These assume that the field of the solenoid B_z changes abruptly from its end value to zero while obeying Maxwell's equations. The kicks at entrance is given by

$$\Delta p_x = \frac{e}{2}(2.99\times10^{-4})yB_z$$

$$\Delta p_y = -\frac{e}{2}(2.99\times10^{-4})xB_z$$

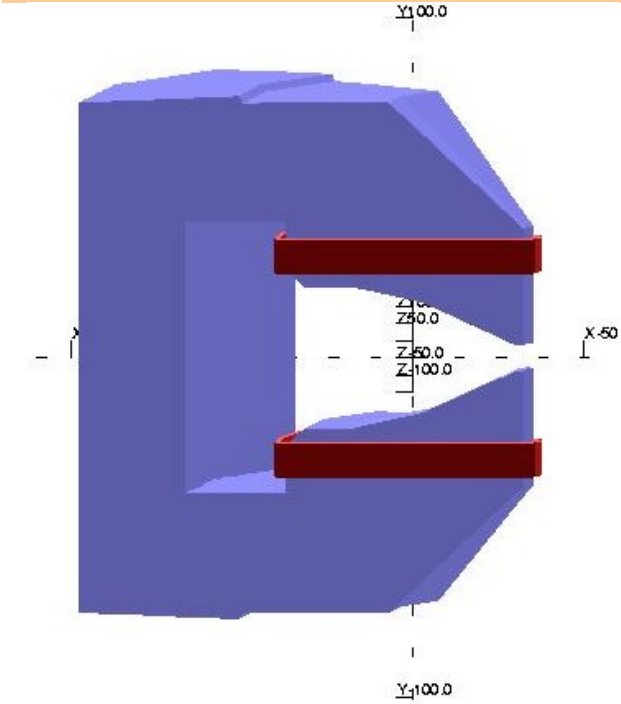
- At exit, the signs are reversed.

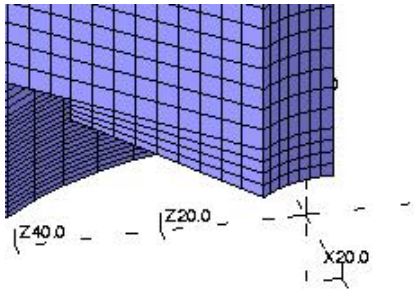
Solenoid end field kick



Magnet Design and calculations Steve Kahn(BNL), Peter Schwandt(Indiana)

Sketch of Dipole Magnet





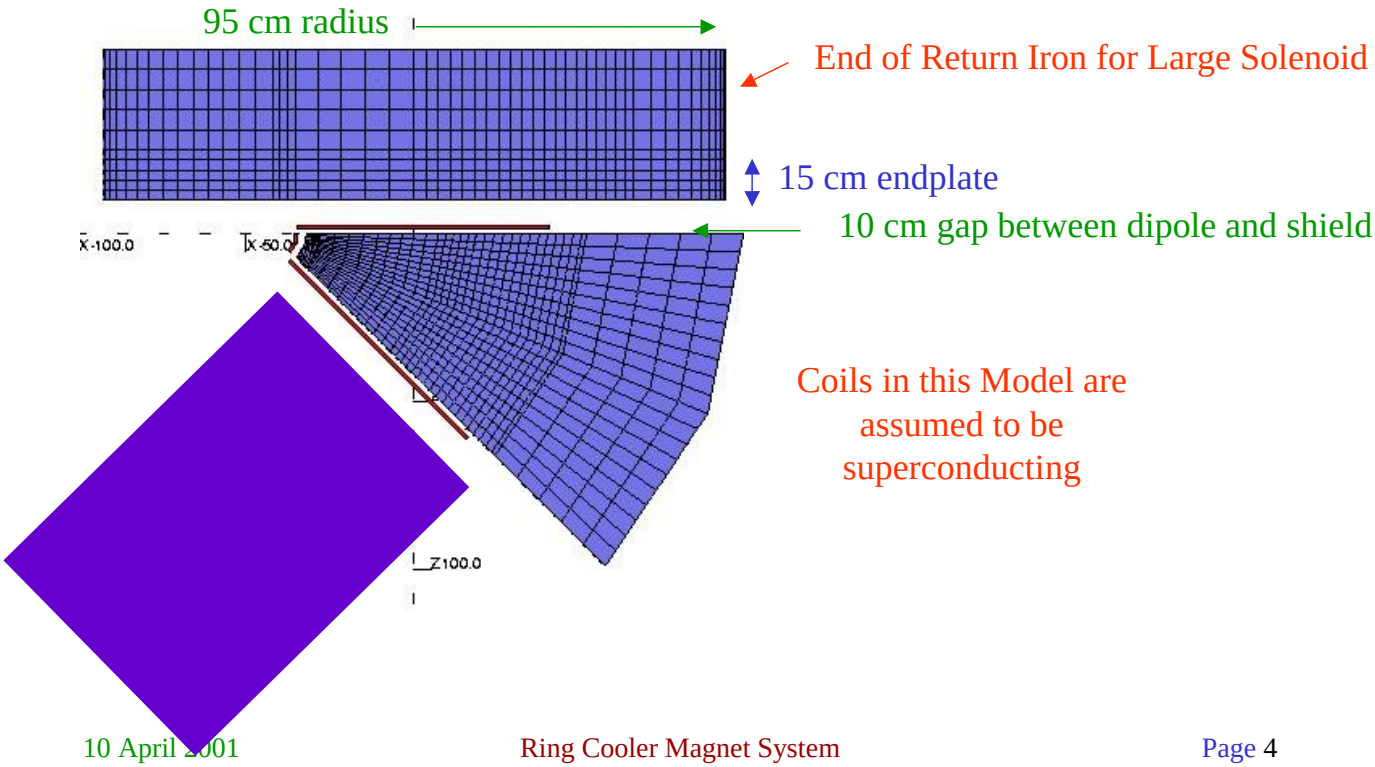
Pole face is shaped to achieve required gradient

The design of the wedge magnet is from P. Schwant

(dated 30 Jan 01)

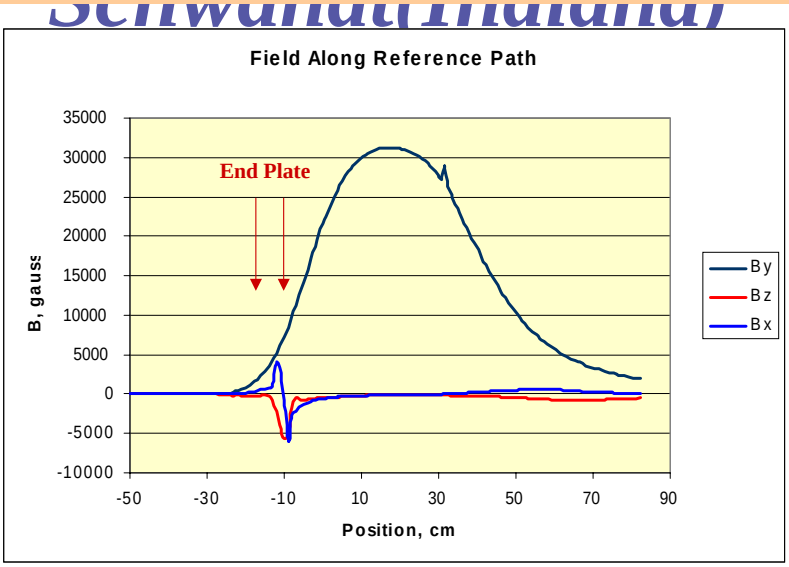
Magnet Design and calculations Steve Kahn(BNL), Peter Schwandt(Indiana)

Tosca Model for Wedge Dipole

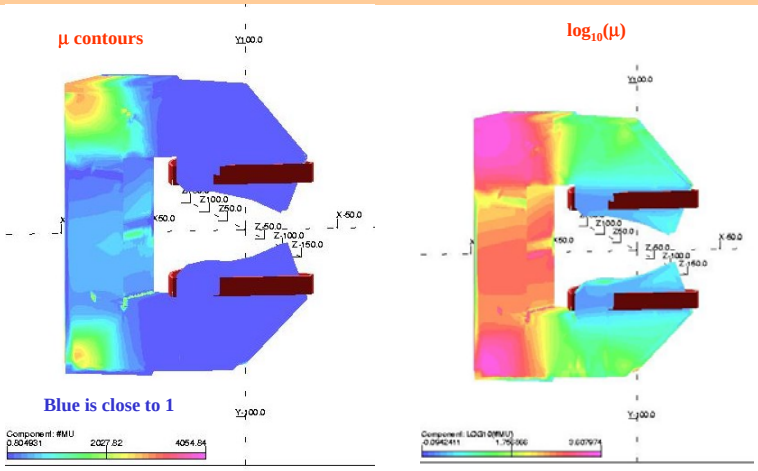


Magnet Design and calculations

B_y along Beam Path in Wedge Magnet

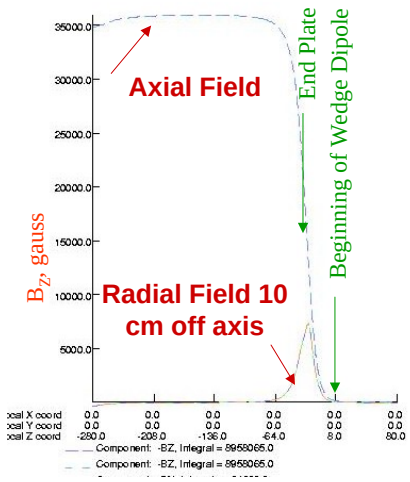


Permeability of Dipole



Magnet Design and calculations Steve Kahn(BNL), Peter Schwandt(Indiana)

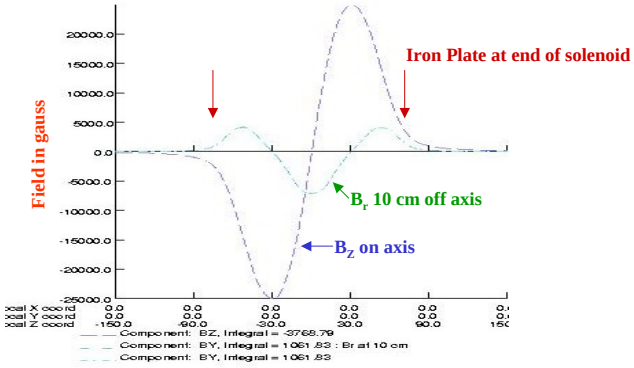
Fields in Large Solenoid



- **Note: Coils are inside cavity R_c=18 cm.**
- Run with coils outside RF cavities failed and is being recalculated.

10 April 2001 Ring Cooler Magnet System S.Kahn Page 9

Field in Short Field Flip Solenoid

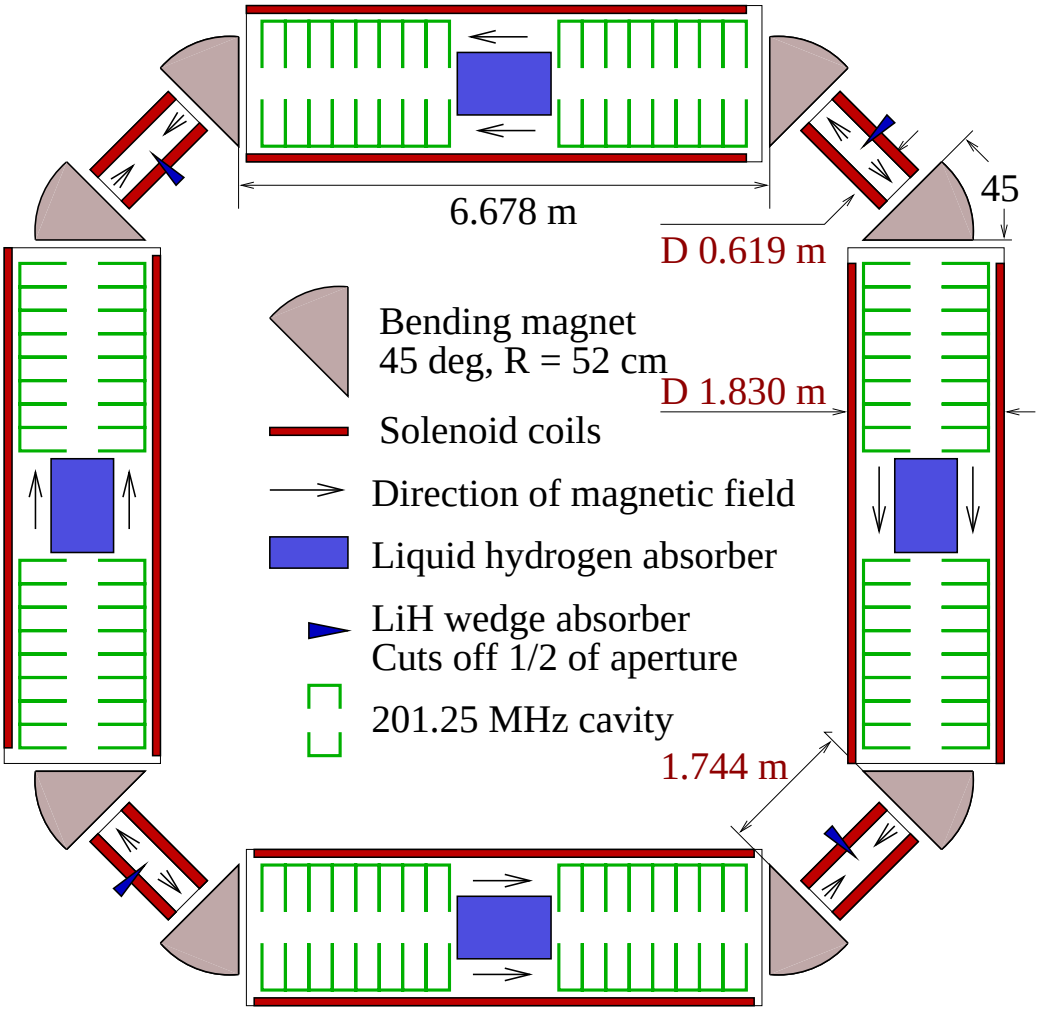


10 April 2001 Ring Cooler Magnet System S.Kahn Page 10

New design with bend magnet radius = 53cm

Ring Cooler Update

V.Balbekov 04/24/01



The ring cooler layout (new version, $R_{bend} = 52$ cm).

New design with bend magnet radius = 53cm

Table of Parameters

	Parameter	Old	New
1.	Circumference	32.555 m	36.955
2.	Equilibrium energy (total)		
	minimal	232 MeV	230 MeV
	middle	250 MeV	250 MeV
	maximal	268 MeV	270 MeV
3.	Number of bending magnets	8	8
4.	Bending angle	45^0	45^0
5.	Bending radius	42 cm	52 cm
6.	Bending field	1.80 T	1.453 T
7.	Normalized field gradient	0.5	0.5
8.	Length of short SS	1.409 m	1.744 m
9.	Length of long SS	6.070 m	6.678 m
10.	Maximal axial field of solenoid	4.32 T	4.30 T
			(5.18 T)$^{(*)}$
11.	Revolution frequency	8.378 MHz	7.1875 MHz
12.	RF harmonic number	24	28
13.	RF frequency	201 MHz	201.25 MHz
14.	Accelerating gradient	15 MeV/m	15 MeV/m
15.	Main absorber	LH,120 cm	LH,140 cm
16.	Wedge absorber	LiH,	LiH
	$dE/dx = 2 \times 0.42$ MeV/cm		0.75 MeV/cm

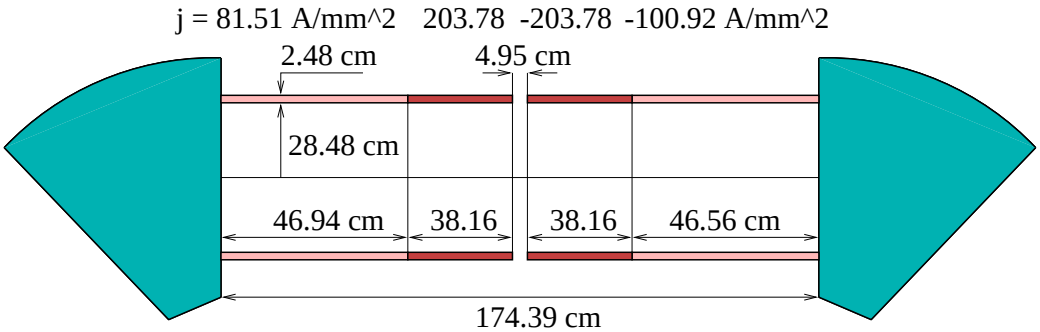
$^{(*)}$ as an option

2

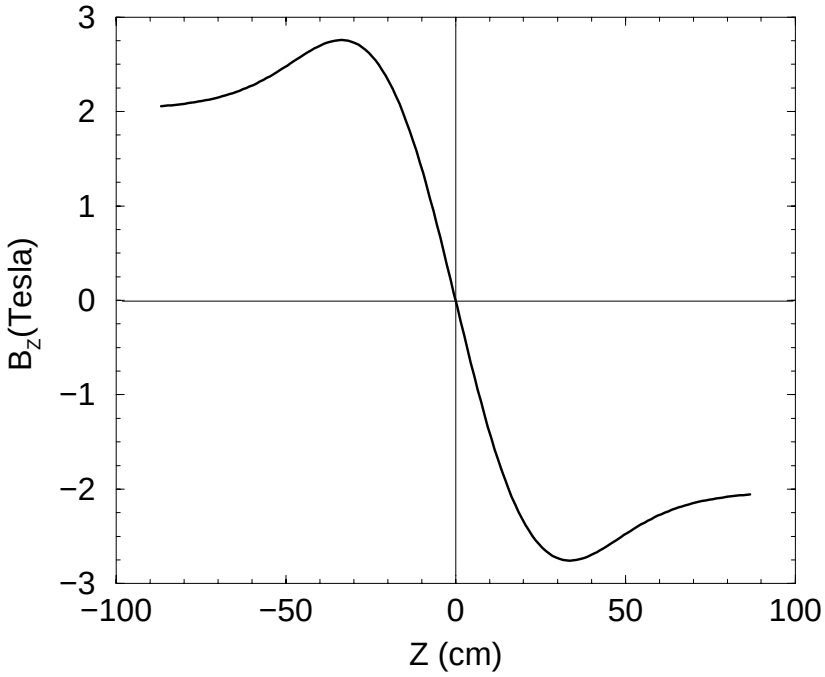
New design with bend magnet radius = 53cm

Short Straight Section

Function of the section: to create dispersion only in SSS



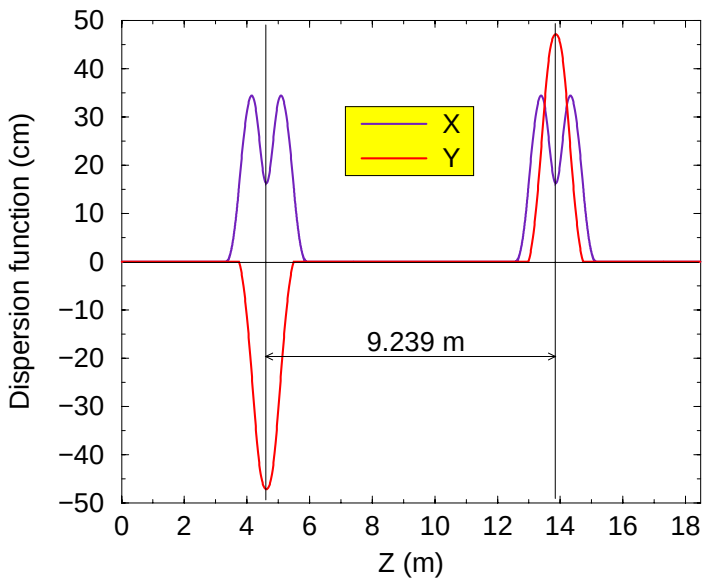
Layout of the Short Straight Section.



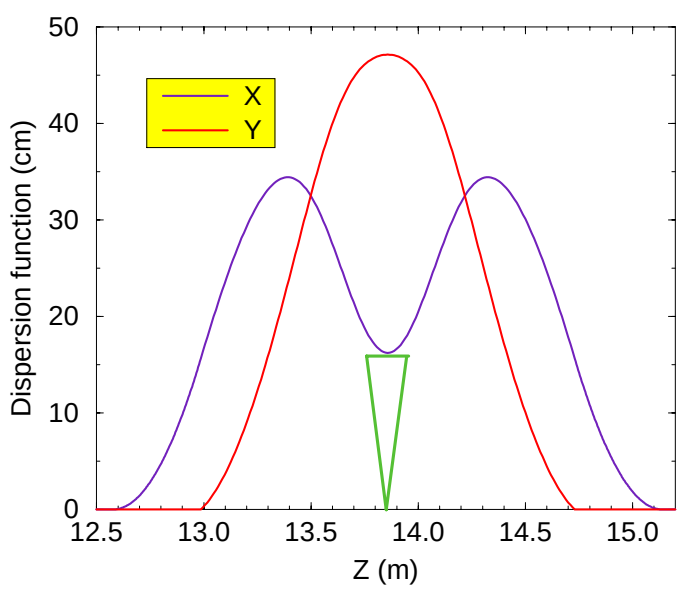
Axial field of the Short Straight Section.

New design with bend magnet radius = 53cm

Dispersion Function



Dispersion function at 1/2 of the ring.



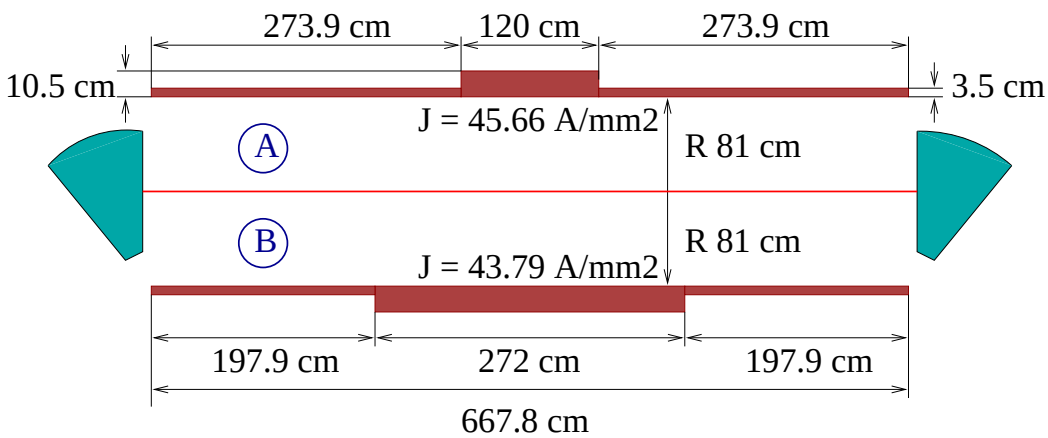
Dispersion function and wedge absorber.

Progress on cooling single muons

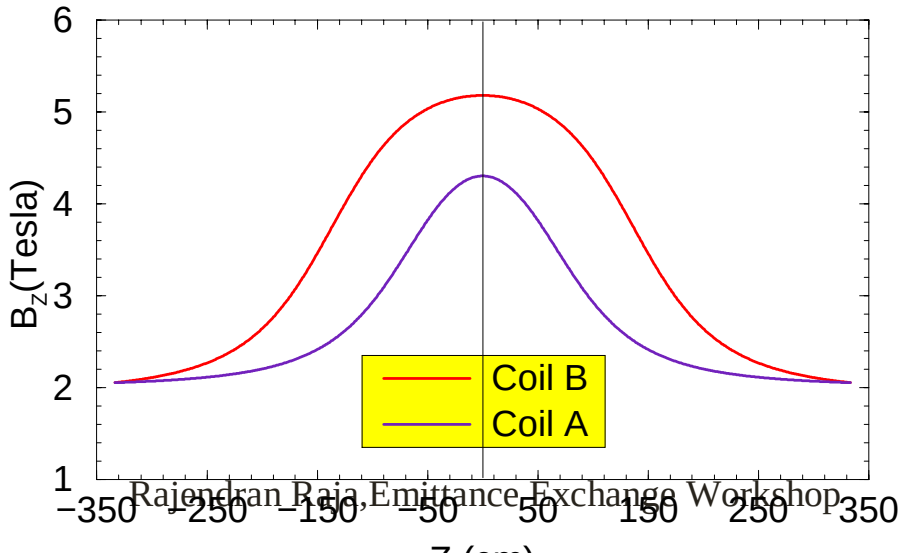
- We have added rf and determined the relative phases of the modules.
- We now are able to produce transfer maps from any two points in the ring automatically.
- We are able to track particles through many turns in the machine.
- We now show cooling for a muon of non-zero pt.
- Next step is to examine the acceptance of the machine and add realistic fields. See talks by Kahn and Usubov.

New design with bend magnet radius = 53cm

Long Straight Section



Long Straight Section. A, B - different designs.



New design with bend magnet radius = 53cm

Gaussian Beam

Parameters of injected beam

- Injection point – beginning of long SS
- 6D Gaussian distribution, 5000 muons
- R.m.s. beam size:

$$\sigma_X = \sigma_Y = 6.6 \text{ cm}$$
$$\sigma_{P_x} = \sigma_{P_y} = 20 \text{ MeV/c}$$
$$\sigma_{cT} = 9 \text{ cm}$$
$$\sigma_E = 18 \text{ MeV}$$

- Normalized emittance:

$$\varepsilon_X = \varepsilon_Y = 1.2 \text{ cm}$$
$$\varepsilon_Z = 1.5 \text{ cm}$$
$$\varepsilon_6 = 2.2 \text{ cm}^3$$

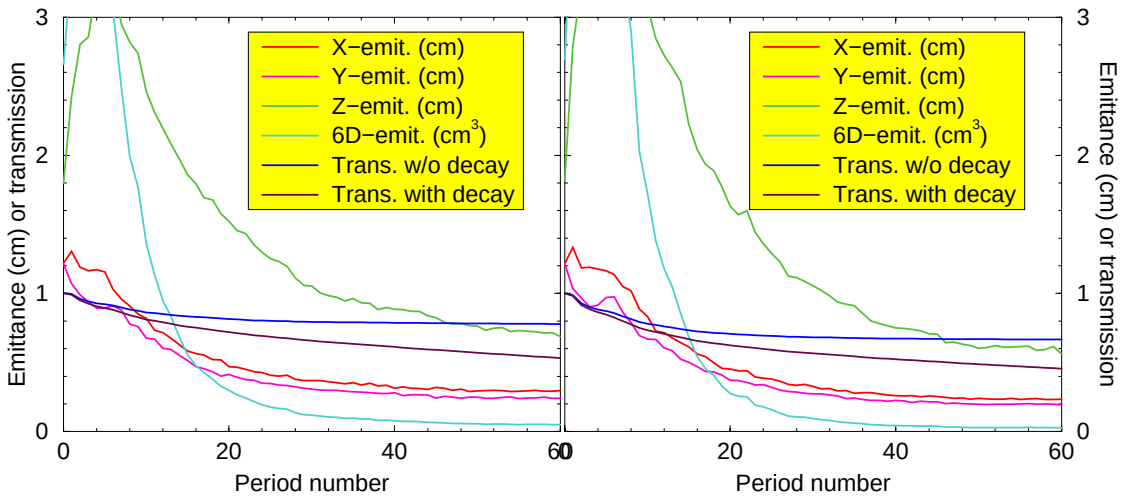
- Correlation:

$$E = E_{ref}\sqrt{1 + \frac{(p_t^2 + r^2/\hat{\beta}_{inj}^2)_{random}}{m^2c^2}} + \Delta E_{random}$$

6

New design with bend magnet radius = 53cm

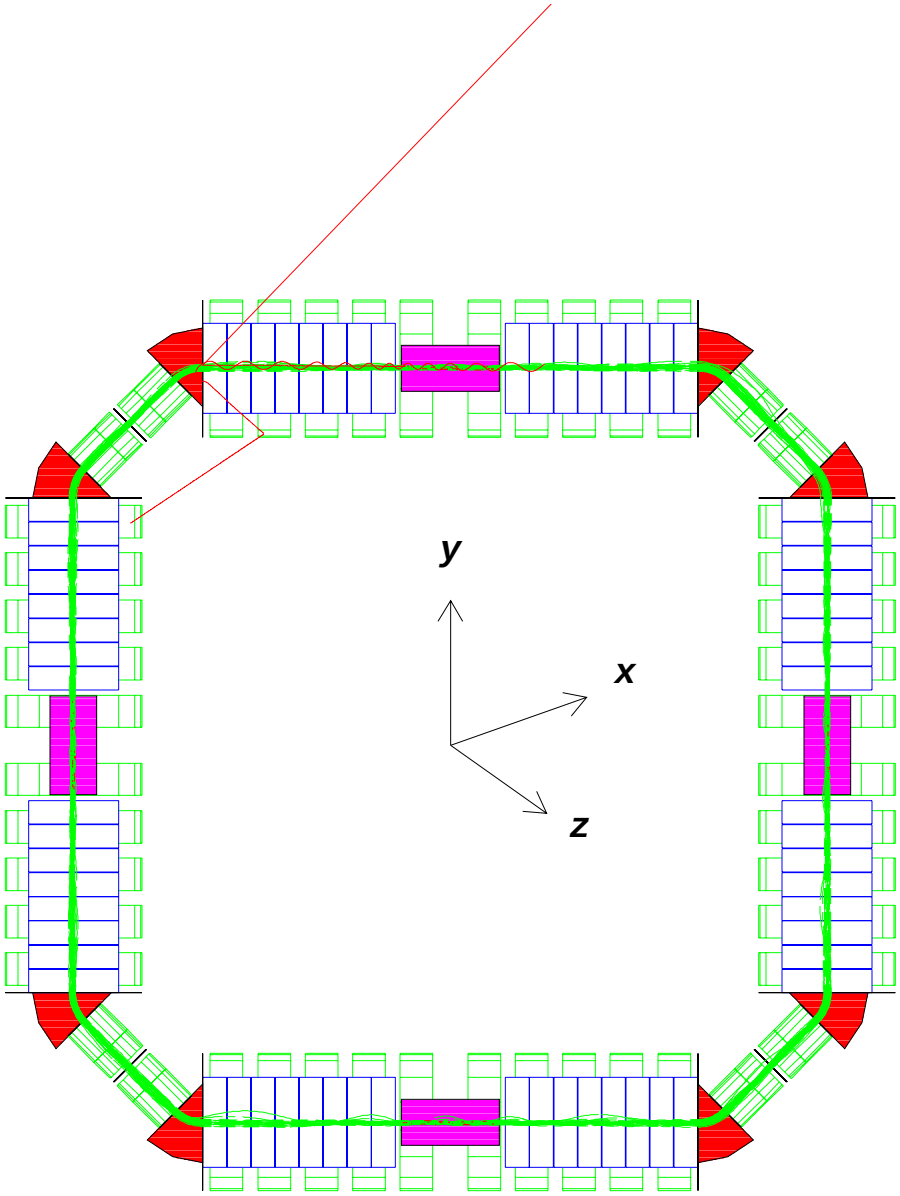
Cooling of the Gaussian Beam



Evolution of the beam emittance and transmission.
Left – coil A, right – coil B

Beam Parameters after 10 Turns

Parameter	Inject.	Old Des.	Des. A	Des. B
X-emittance (mm)	12.0	2.7	3.1	2.6
Y-emittance (mm)	12.0	2.3	2.8	2.3
Z-emittance (mm)	15.0	6.5	8.7	7.5
6D-emit. (mm^3)	2160	40	78	44
Trans. w/o decay	1	0.79	0.79	0.67
Trans. with decay	1	0.63	0.62	0.52


y
x
z

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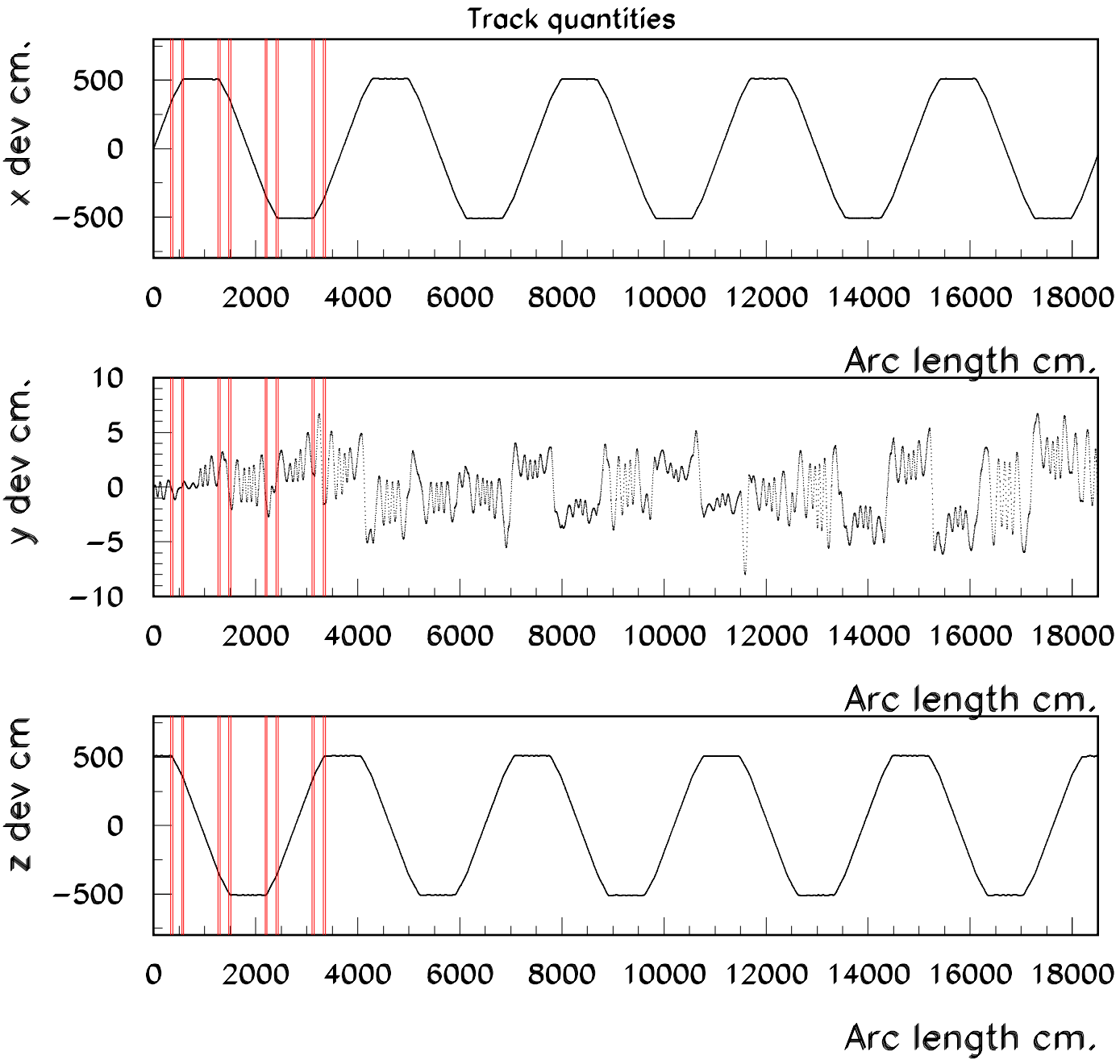

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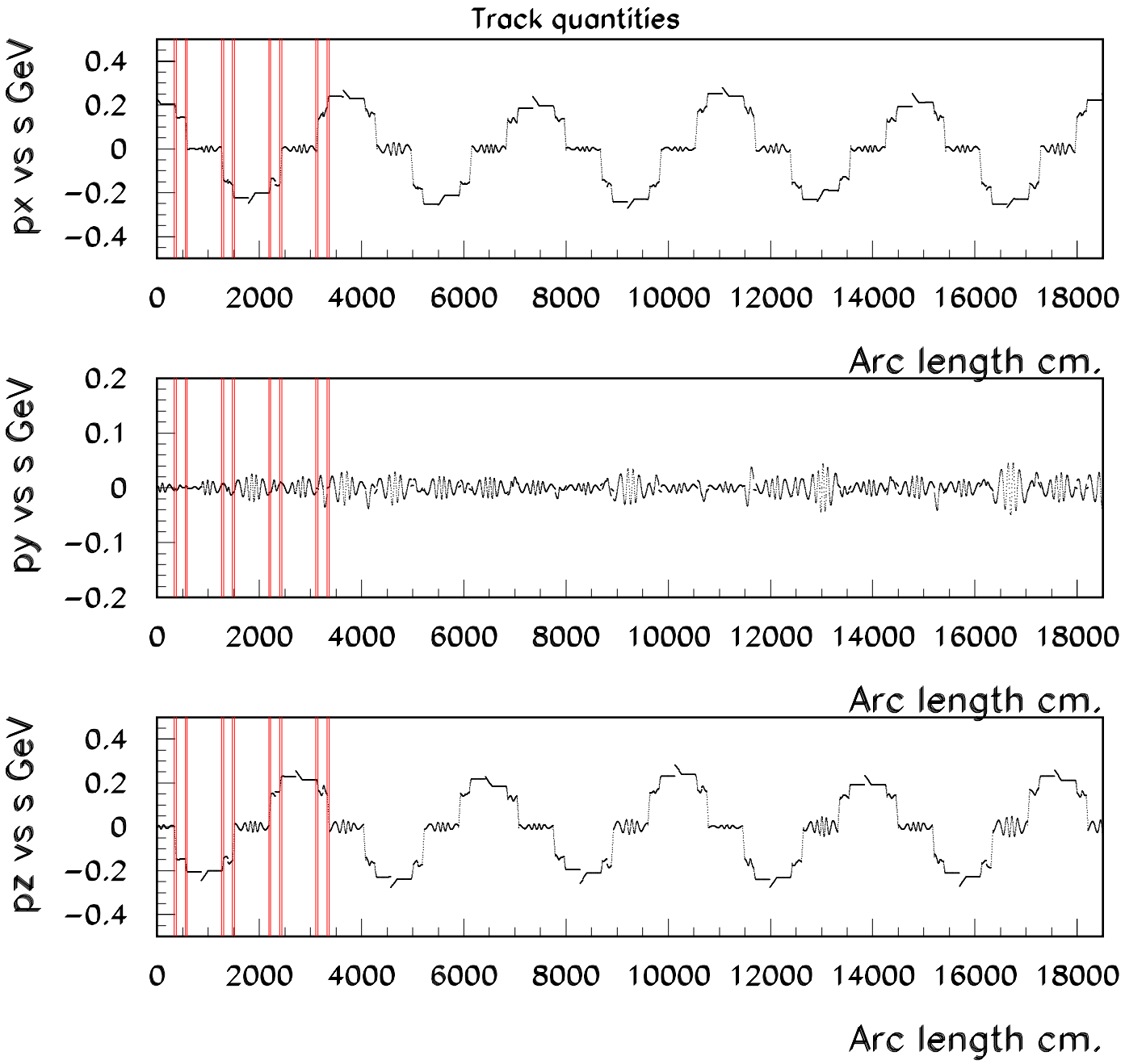

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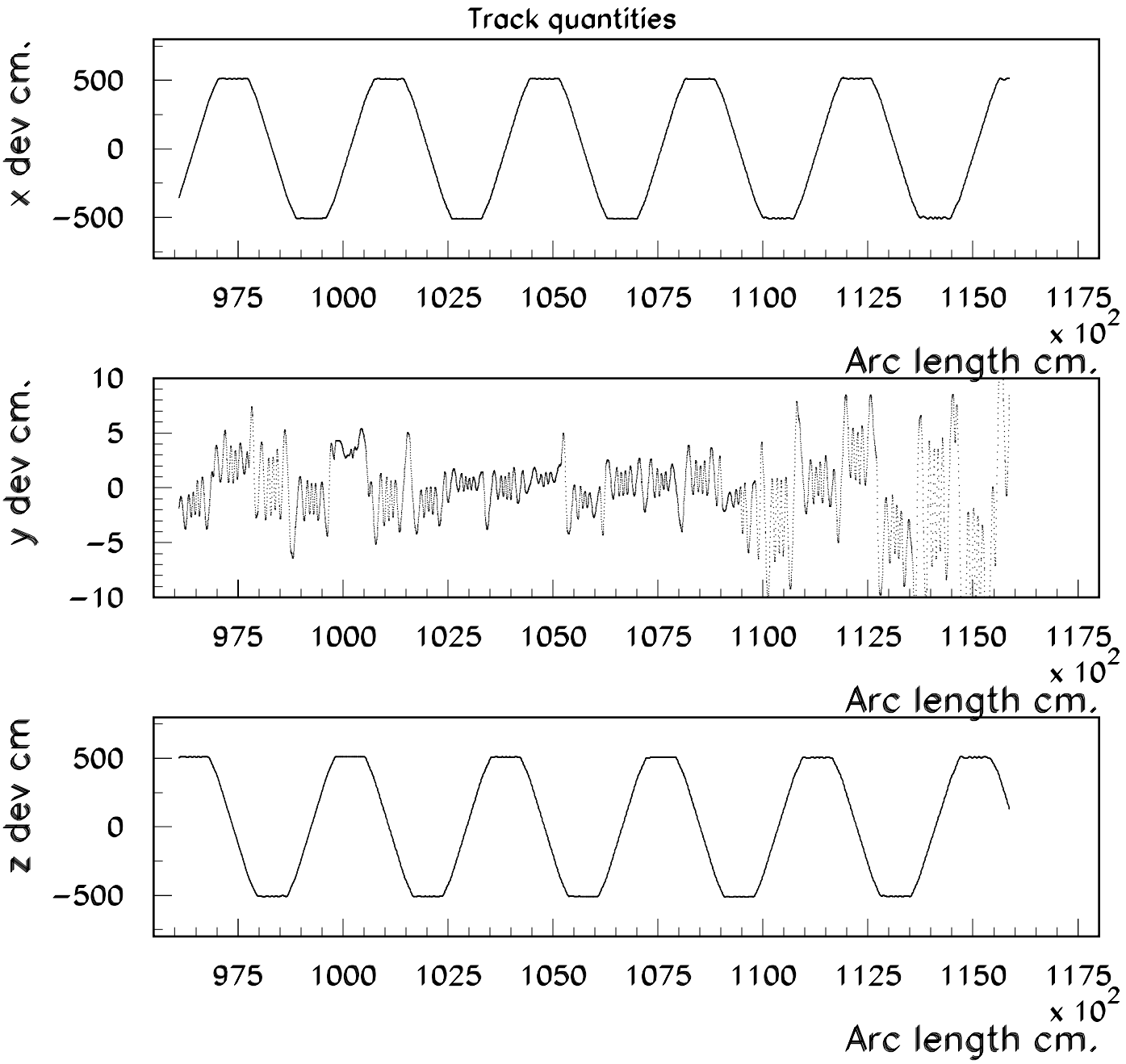

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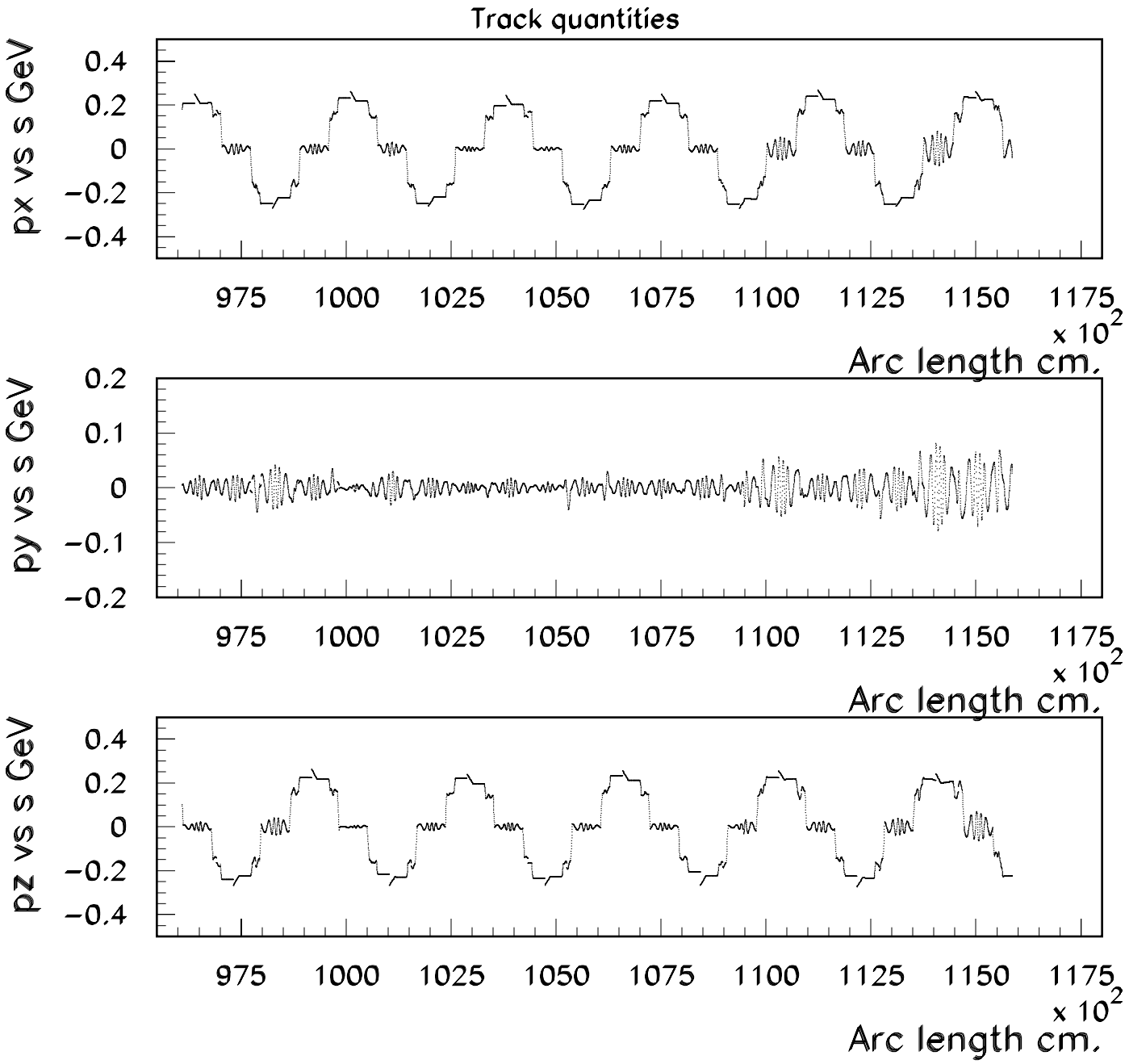

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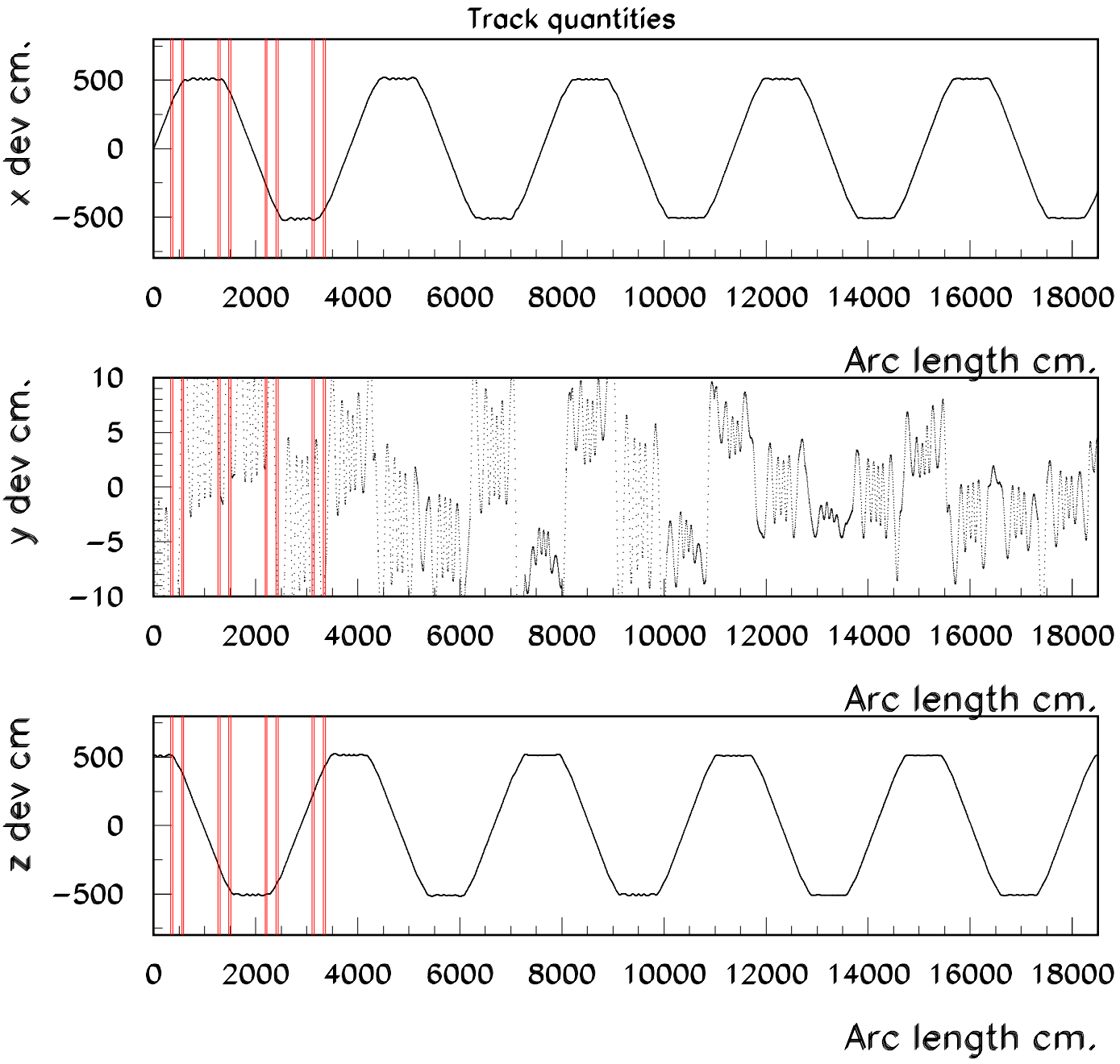

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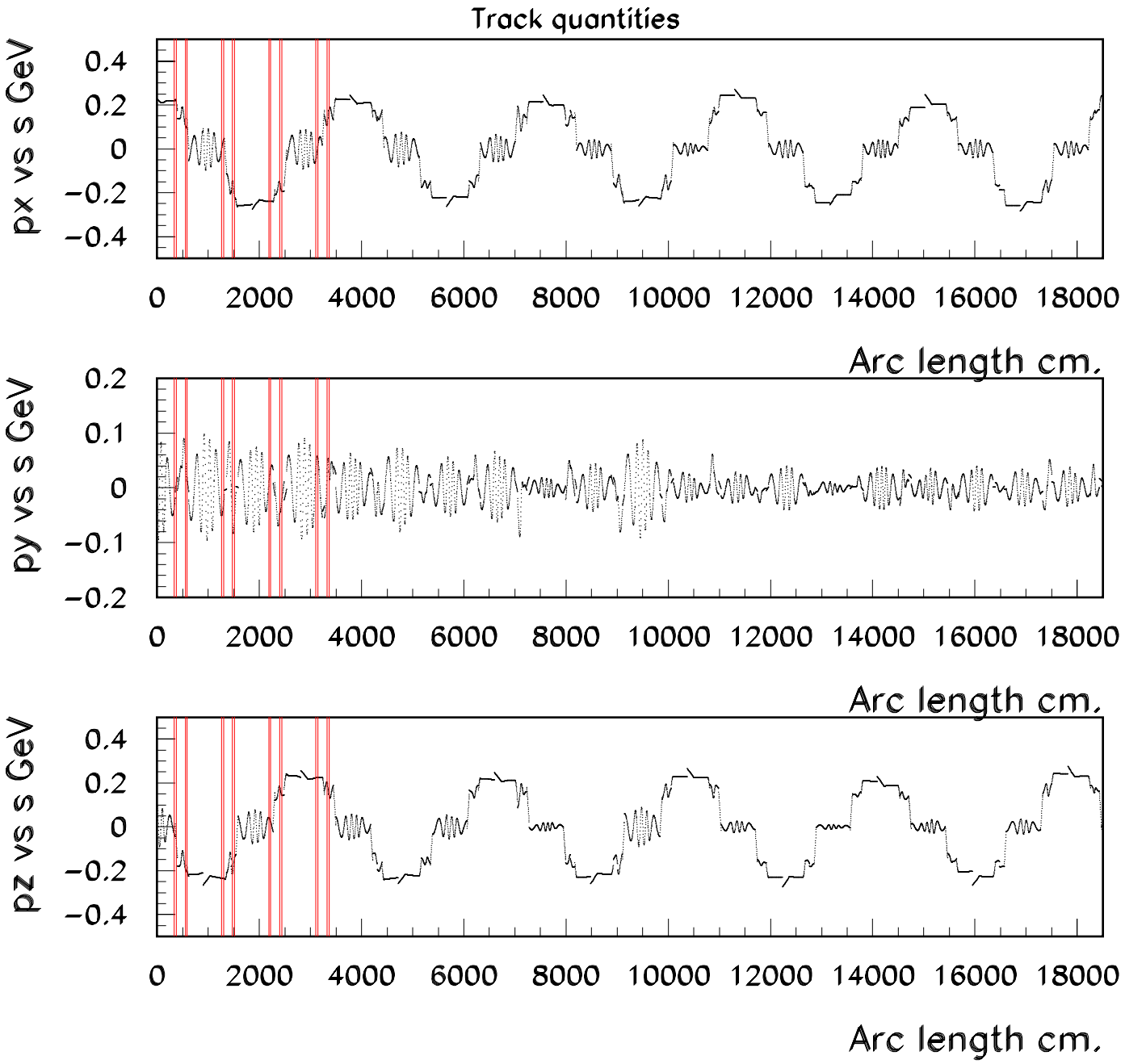

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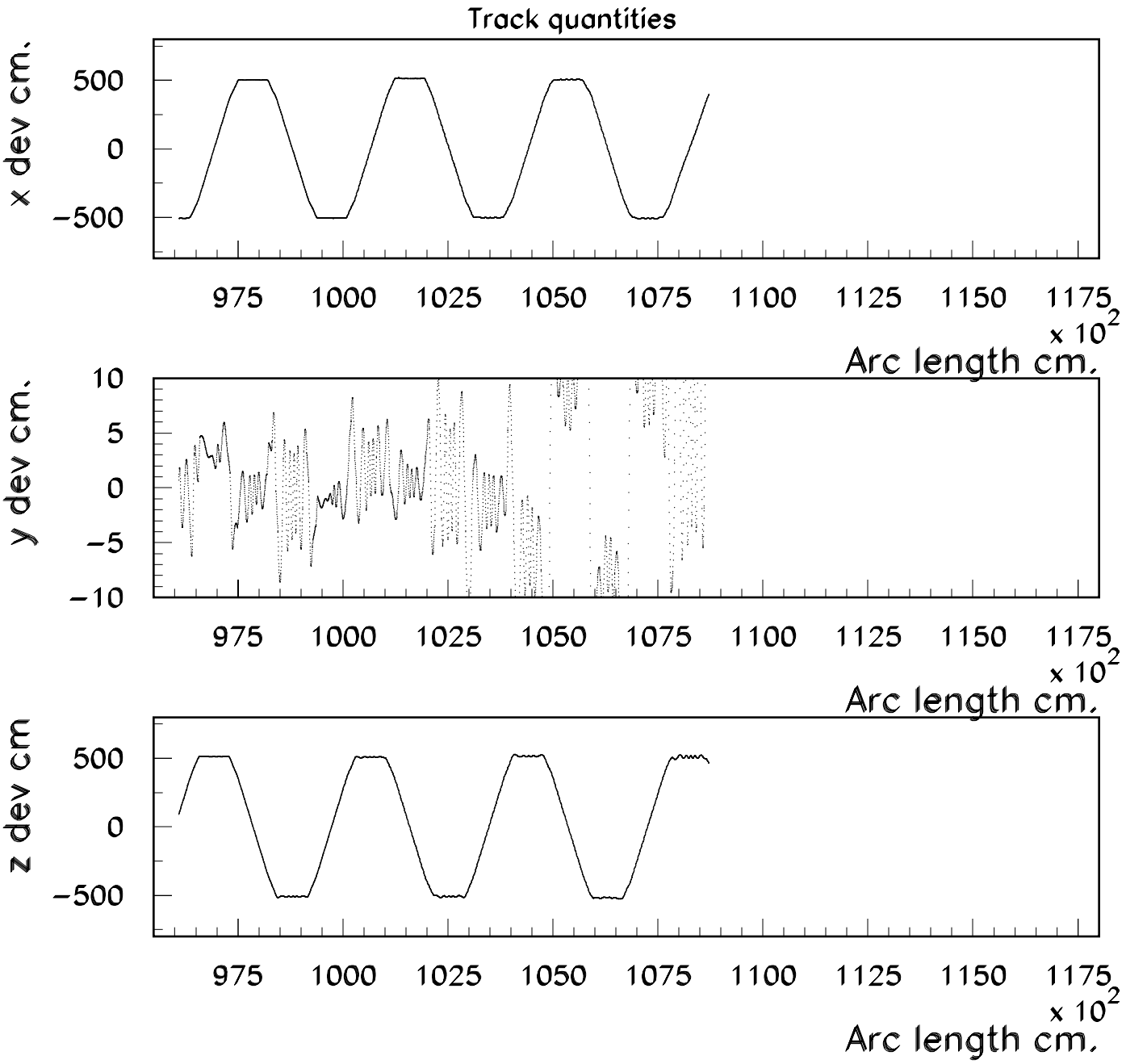

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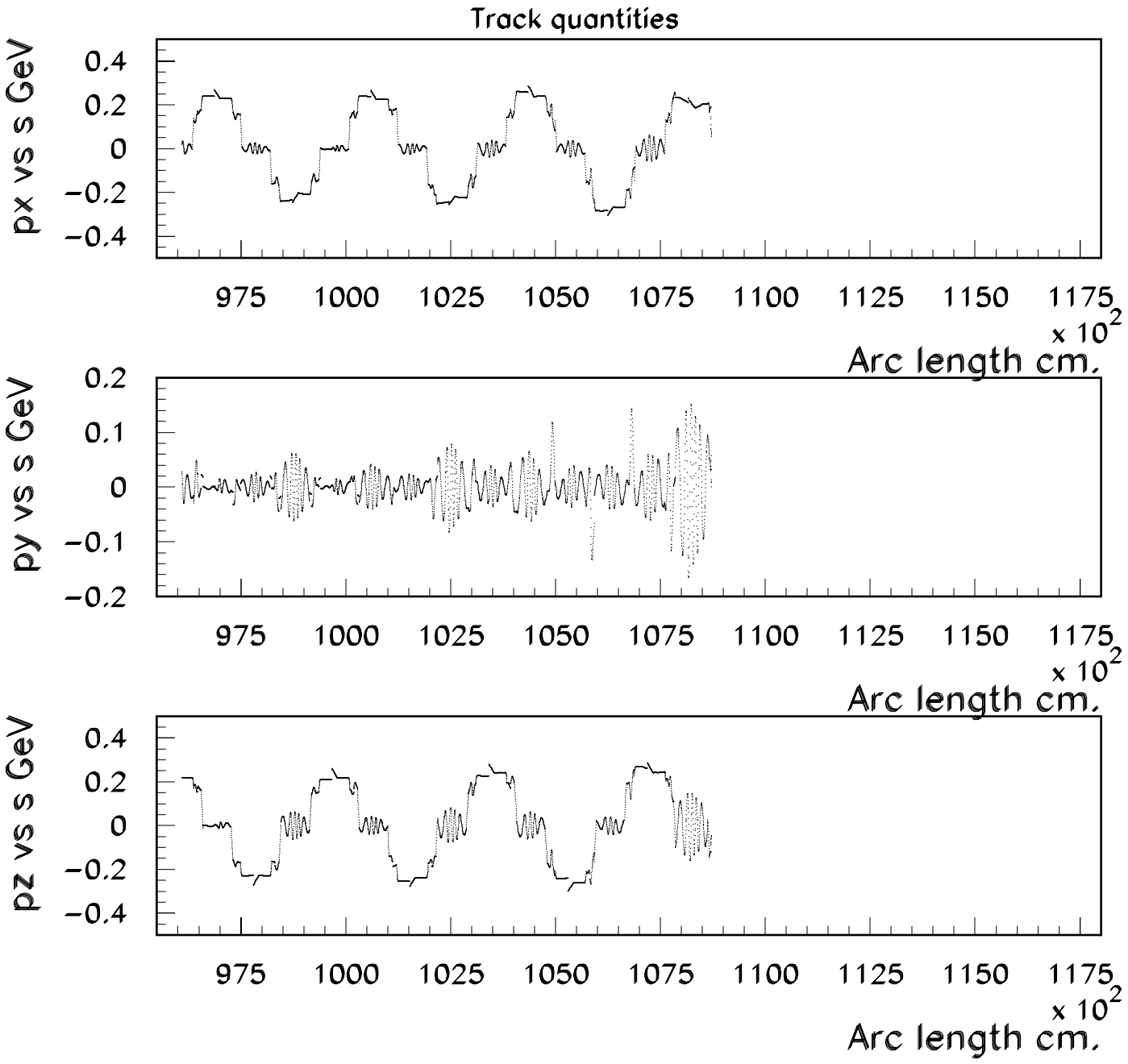
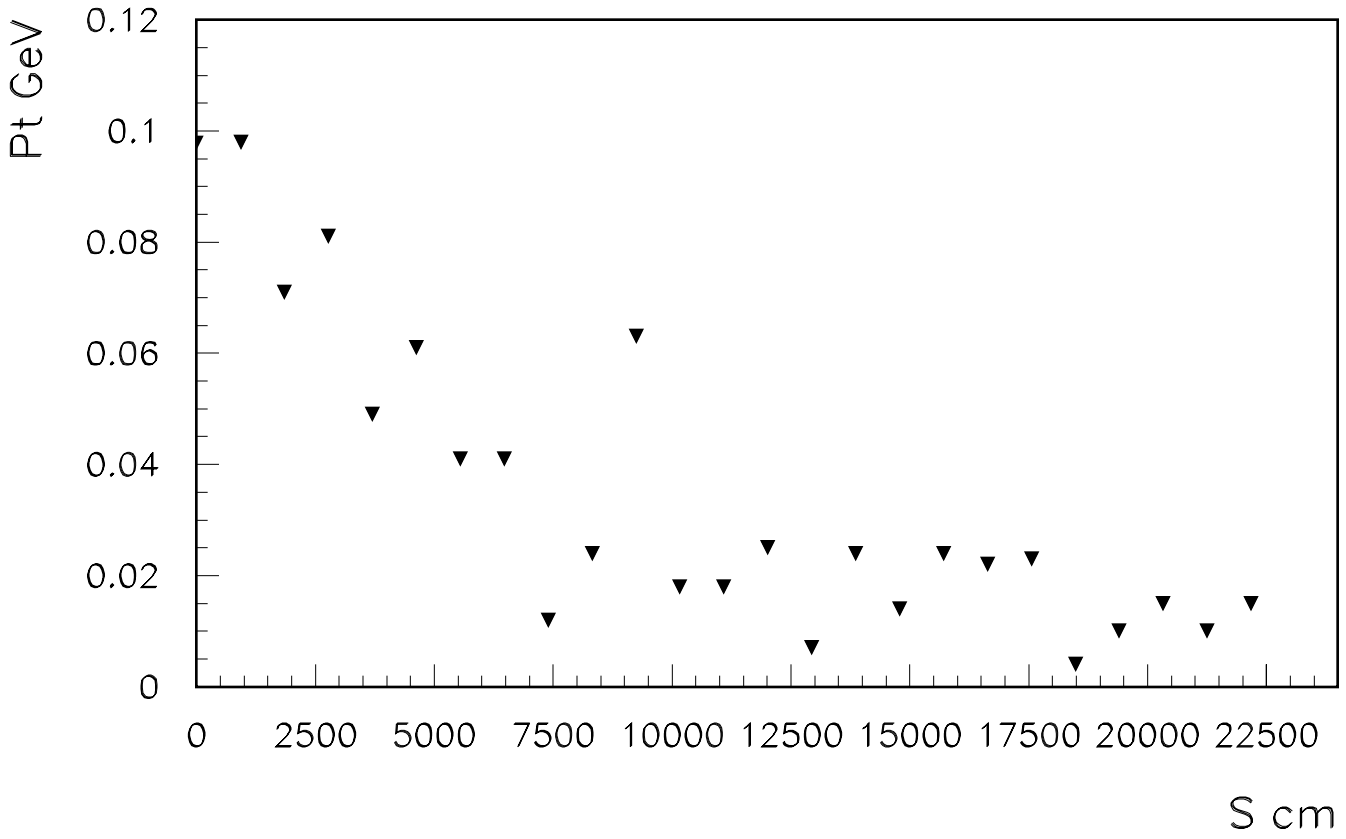
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