MUCOOL experiment- Options and Plans

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Muon Collaboration Meeting
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Charge from Fermilab

Sep 13, 2000 letter from John Cooper to me states "I am asking you to lead the work at Fermilab on the following tasks:

1. Design of a muon testbeam that can be used to study the performance of a cooling section.
2. Simulation of the response of a cooling test section to the test beam. Hence determine what properties of the cooling channel can and cannot be tested in a muon beam.

I would like a short report on these items to be given to Mike Shaevitz, Steve Holmes and myself by April 1st, 2001".

Three options for Muon Beams

- 1)Low intensity beam for single particle experiment
- 2)Muon beams for a linear cooling channel demonstration which may be also be used for injection into a ring cooler scheme
- 3)8 GeV proton beam for injection into a ring cooler with internal target

- Option 1) is currently out of favor due to difficulty in instrumenting for single particle detection in the presence of RF

Three options for Muon Beams

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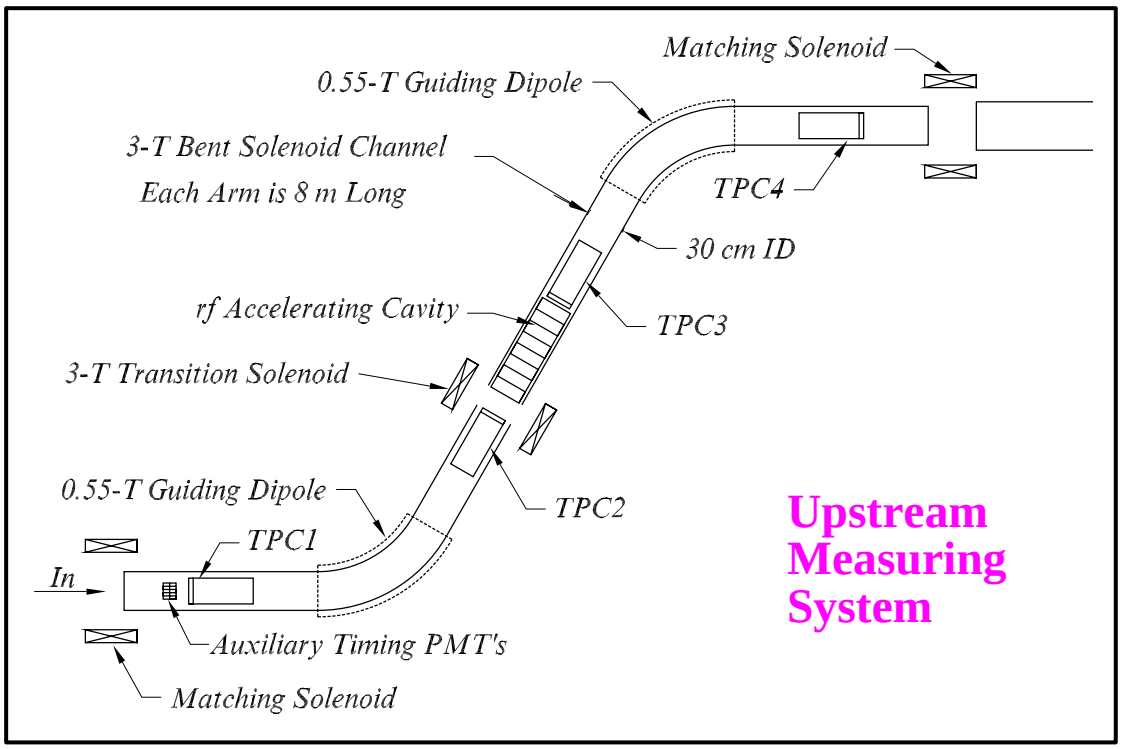
Upstream Instrumentation

(BNL, FNAL, Princeton, Mississippi,UCLA)



- **Auxiliary timing device**

- **TPC 1 –> helix before first bend**
- **Bent Solenoid**
- **TPC 2 –> helix after first bend**

First Momentum Measeurment

- **rf accelerating cavity** — **rf**

- **TPC 3 –> helix before second bend**
- **Bent Solenoid**
- **TPC 4 –> helix after second bend**

Second Momentum Measeurment

Muon Test beam-Targetry

1 Targetry and Primary Focusing

(N.Holtkamp, N.Mokhov)

- 8 GeV proton beam (FNAL Booster)
- Active target
- Li lens for primary focusing

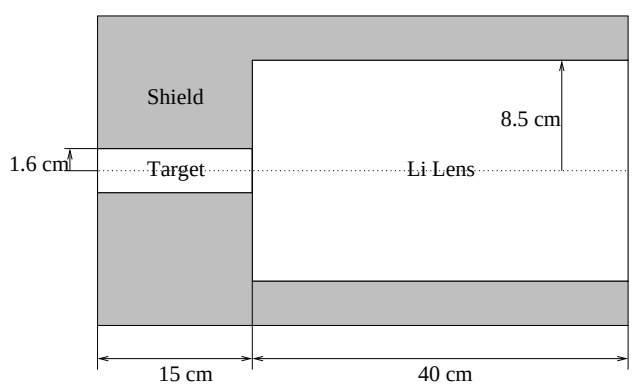


Figure 1: Schematic of the target station.

Proton Beam: 8 GeV, $\sigma_x = \sigma_y = 6$ mm, $\sigma_z = 30$ cm, 750,000 protons
Target: Copper, $L = 15$ cm, $R = 1.6$ cm, $G = 4.39$ T/cm, $B_{max} = 7.0$ T, $J = 560$ kA
Li Lens: $L = 40$ cm, $R = 8.5$ cm, $G = 0.158$ T/cm, $B_{max} = 1.34$ T, $J = 570$ kA

Muon Test beam-Decay channel

2 Beam Characteristics after Li Lens

Yield: $\pi^-/p = 0.119, \quad \mu^-/p = 0.0022$

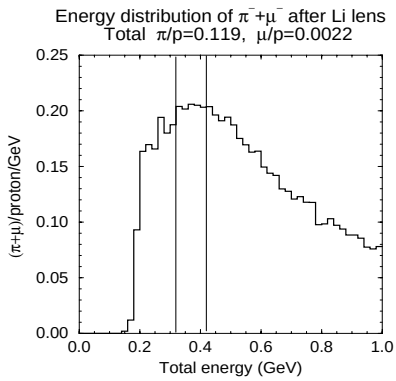


Figure 2:

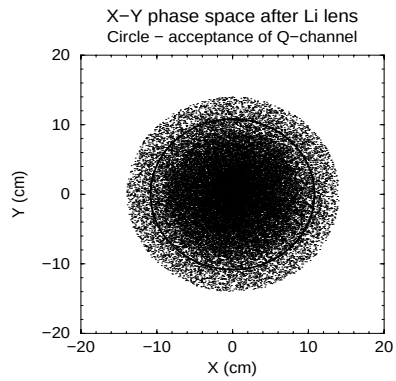


Figure 3:

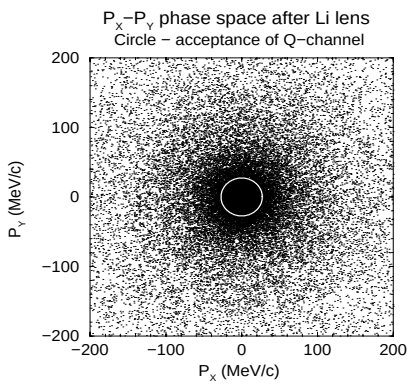


Figure 4:

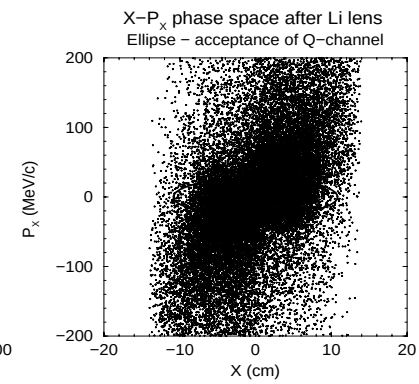


Figure 5:

3

Muon test beam – Decay channel

3 Q-Decay Channel: Lattice and β-functions

- Quads: $L = 36$ cm, $G = 0.059$ T/cm, $R = 13.7$ sm
- Drift 36 cm
- No RF

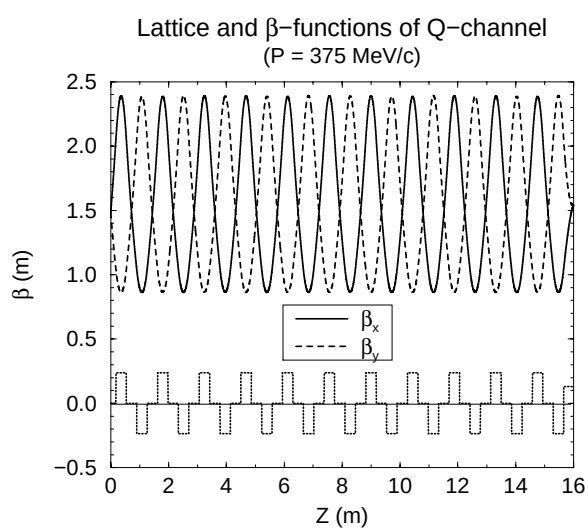


Figure 6:

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Muon test beam –Decay channel

4 Muon Beam Characteristics in Q-Channel

- Radius of aperture 13.7 cm
- E-window 255-355 MeV • T-window ±75 cm

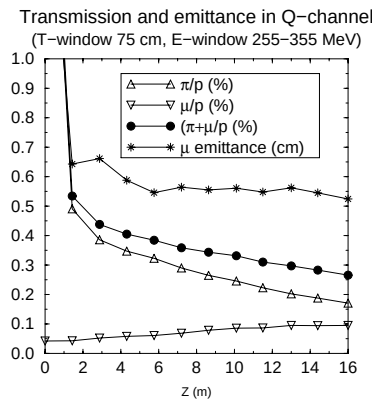


Figure 7:

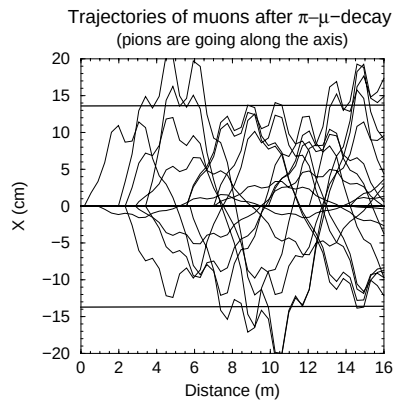


Figure 8:

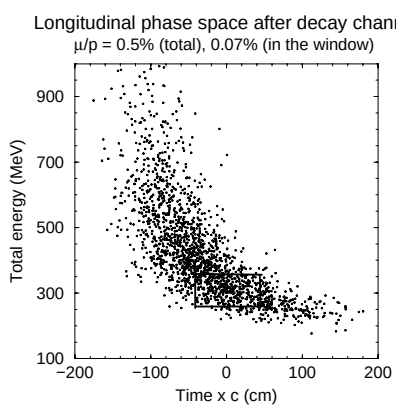


Figure 9:

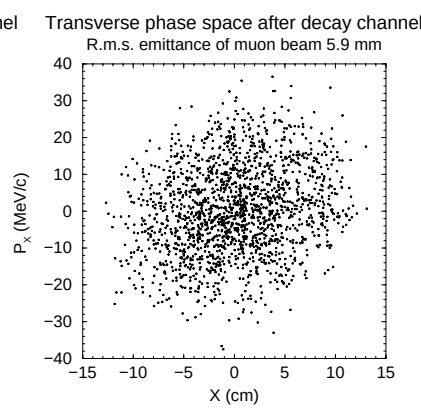
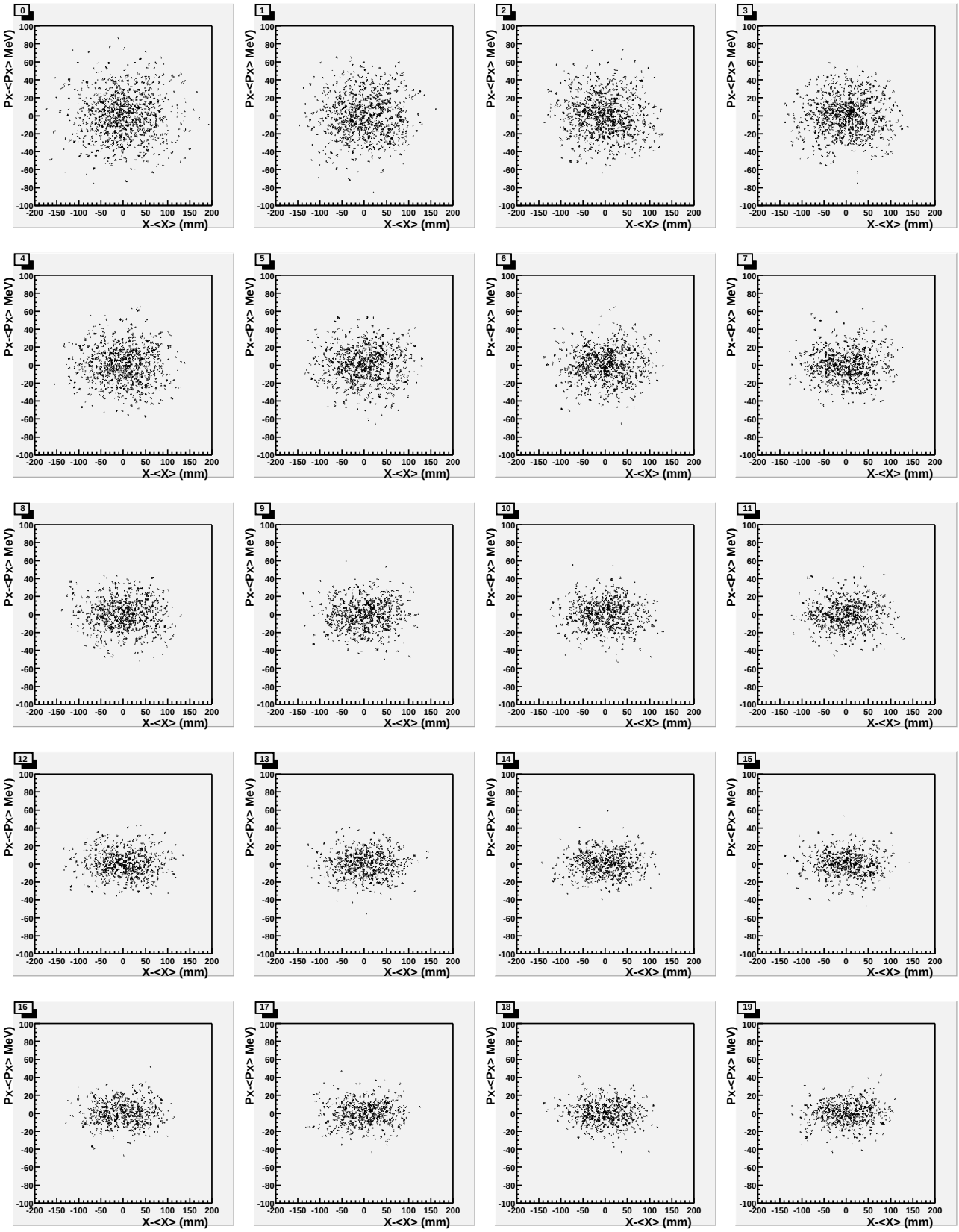
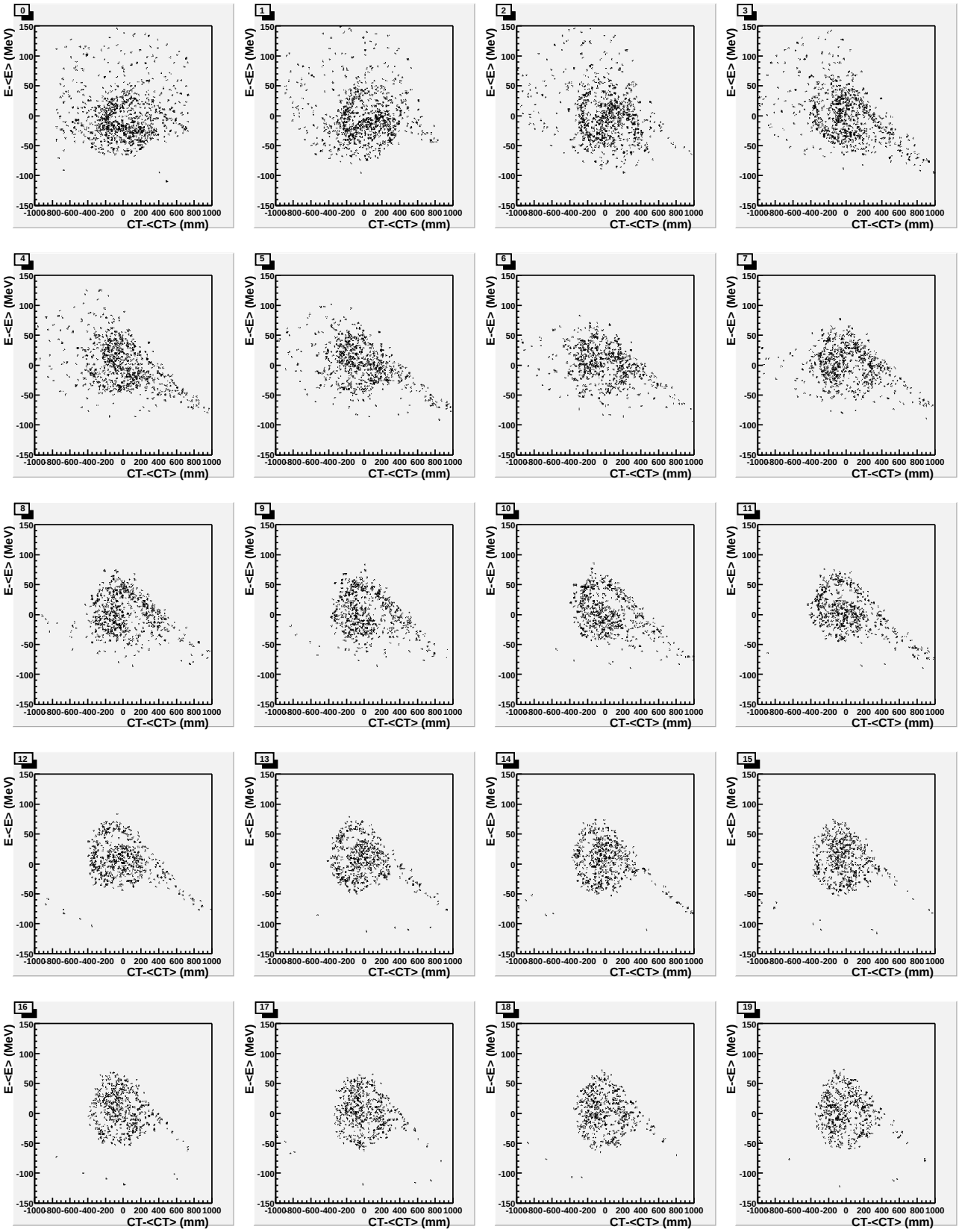


Figure 10:

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

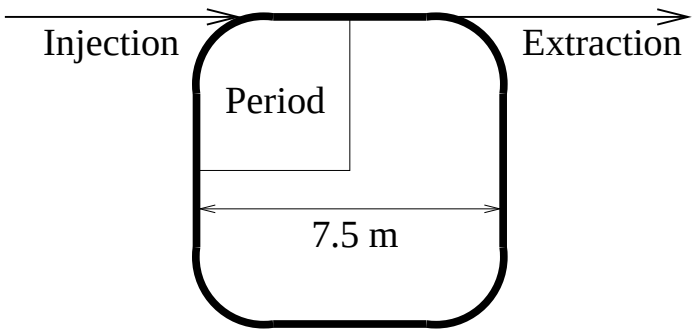


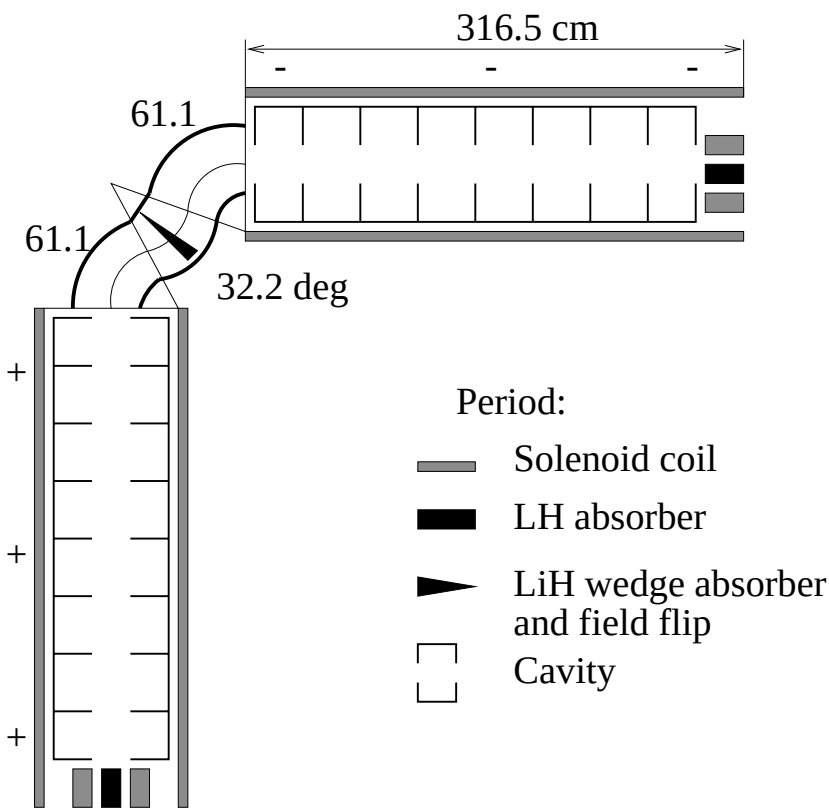
Conventional cooling- Double Flip linear channel-results Every 2.5 meters En-ct plots



Ring Cooler ideas

- Initial scheme from V.Balbekov





Ring Cooler –New scheme from Balbekov

Layout of the ring cooler

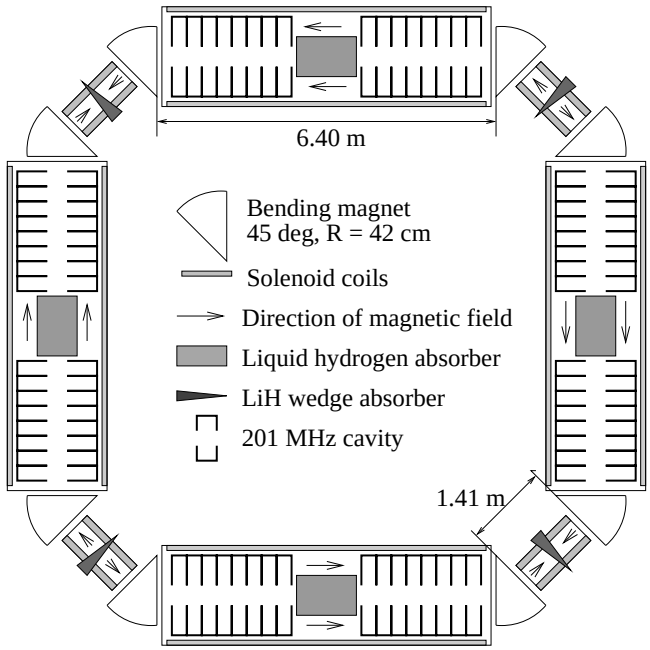


Figure 1: Schematic of ring cooler

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

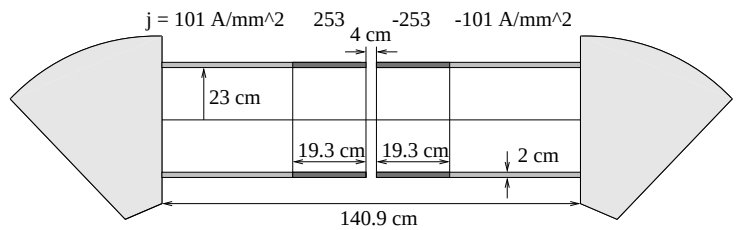


Figure 2: Coils in short straight section (with field flip).

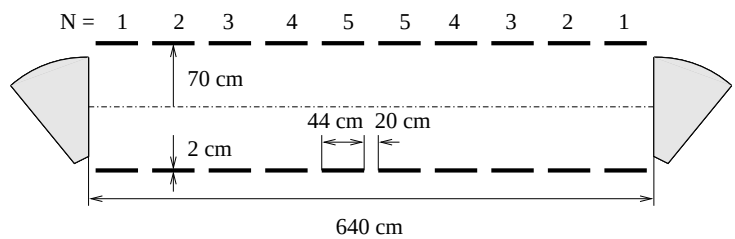


Figure 3: Coils in long straight section.

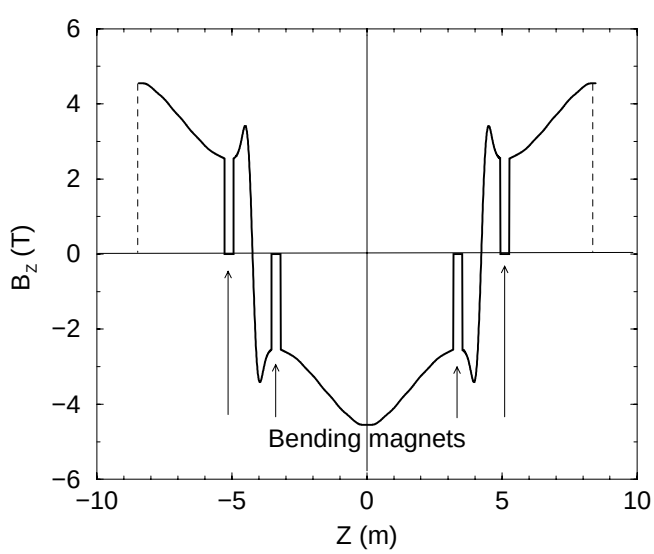


Figure 4: Axial magnetic field of the period (1/2 turn).

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

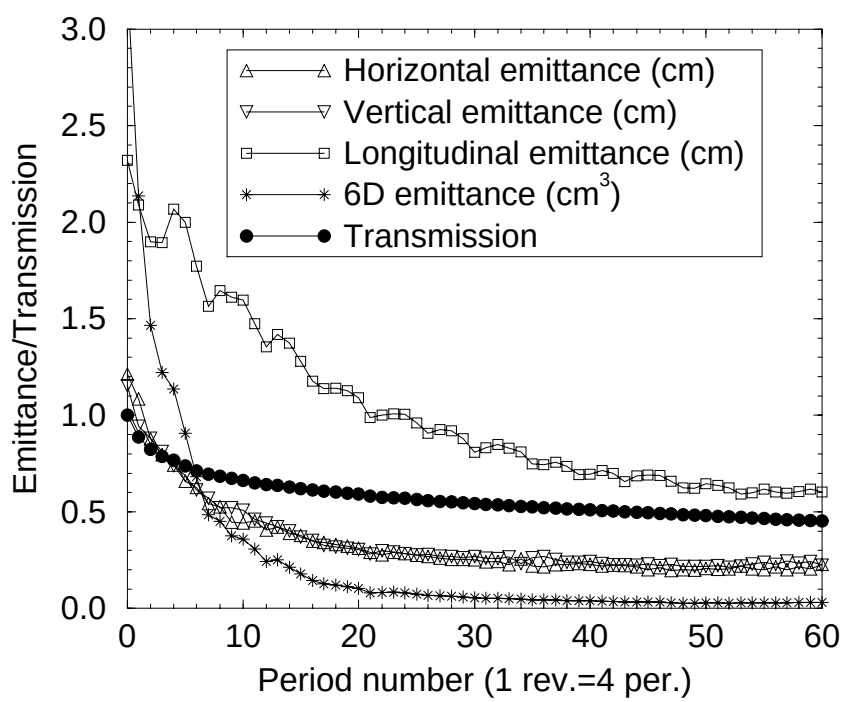


Figure 5: Emittance and transmission at the cooling of bunched beam.

Ring Cooler

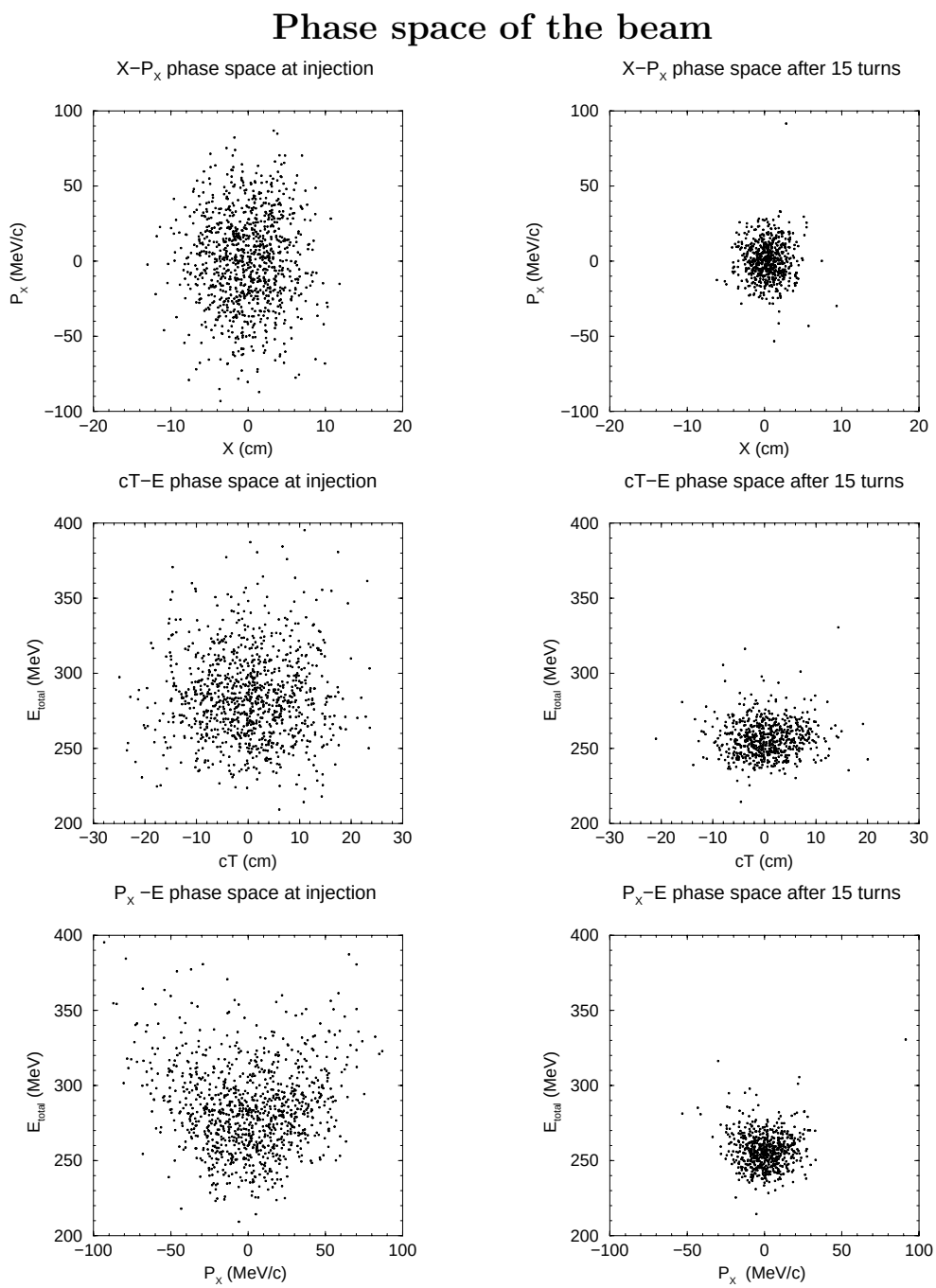


Figure 6:

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

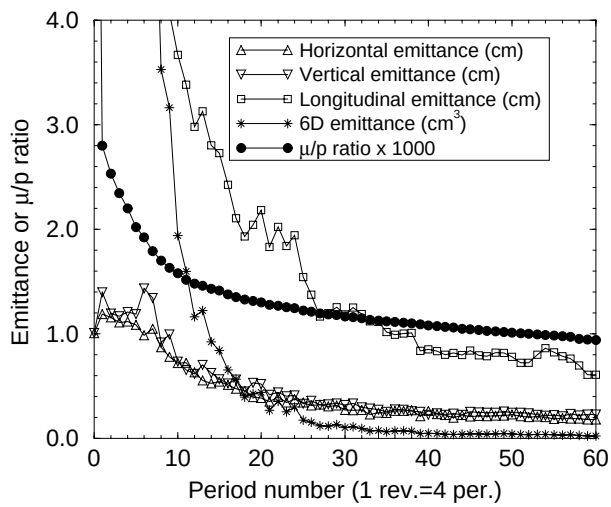


Figure 7: Beam emittance and μ/p ratio in the ring cooler

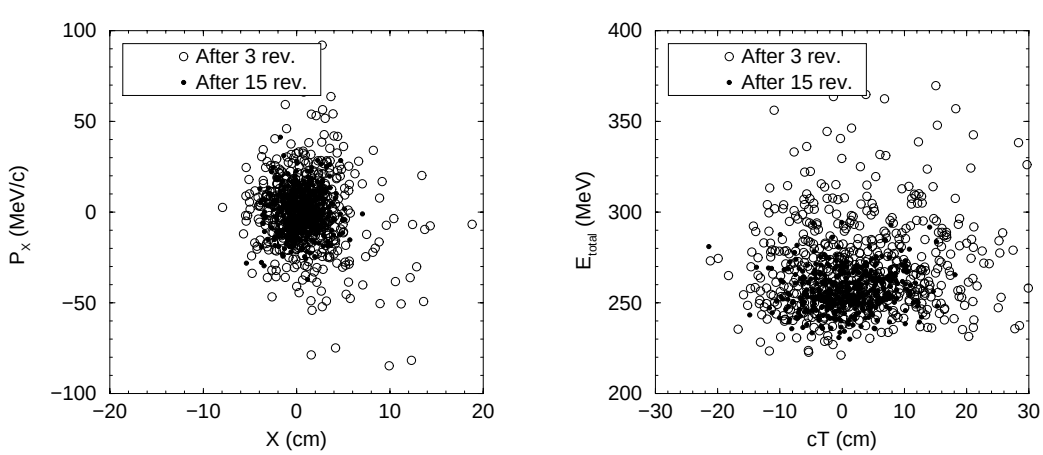


Figure 8: Phase space of the beam after 3 and 15 turns

Ring Cooler -Performance

Muon yield at internal target

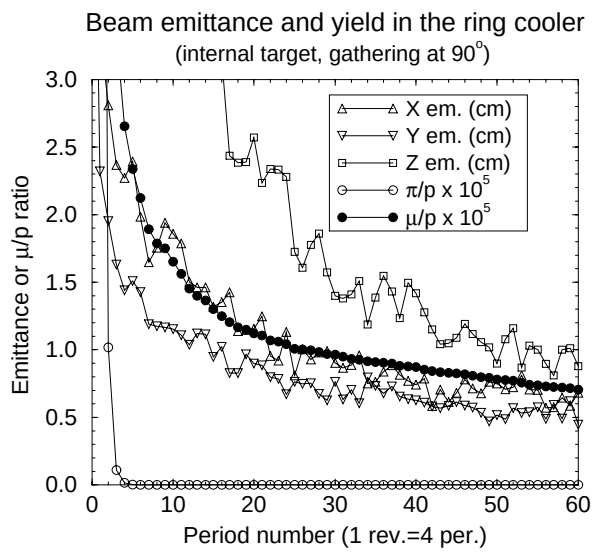


Figure 9: Beam emittance and μ/p ratio in the ring cooler. Wedge absorber is used as a target

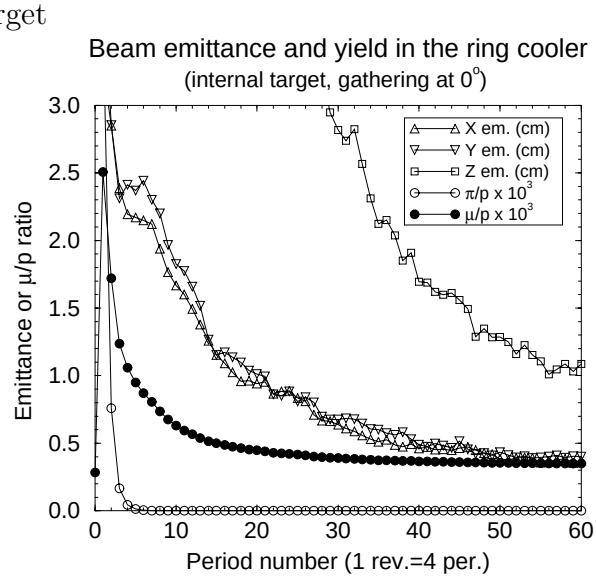


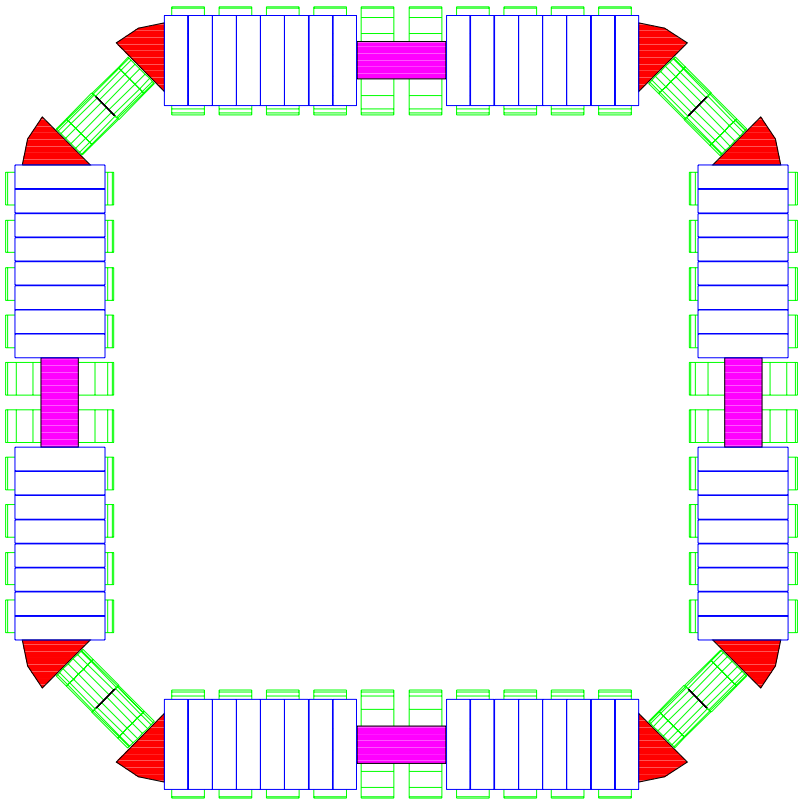
Figure 10: Beam emittance and μ/p ratio in the ring cooler. Internal target: Cu, L=22 cm, R = 7.5 mm. Number of muons is 20 times less if the target is placed out the aperture.

Injection ideas

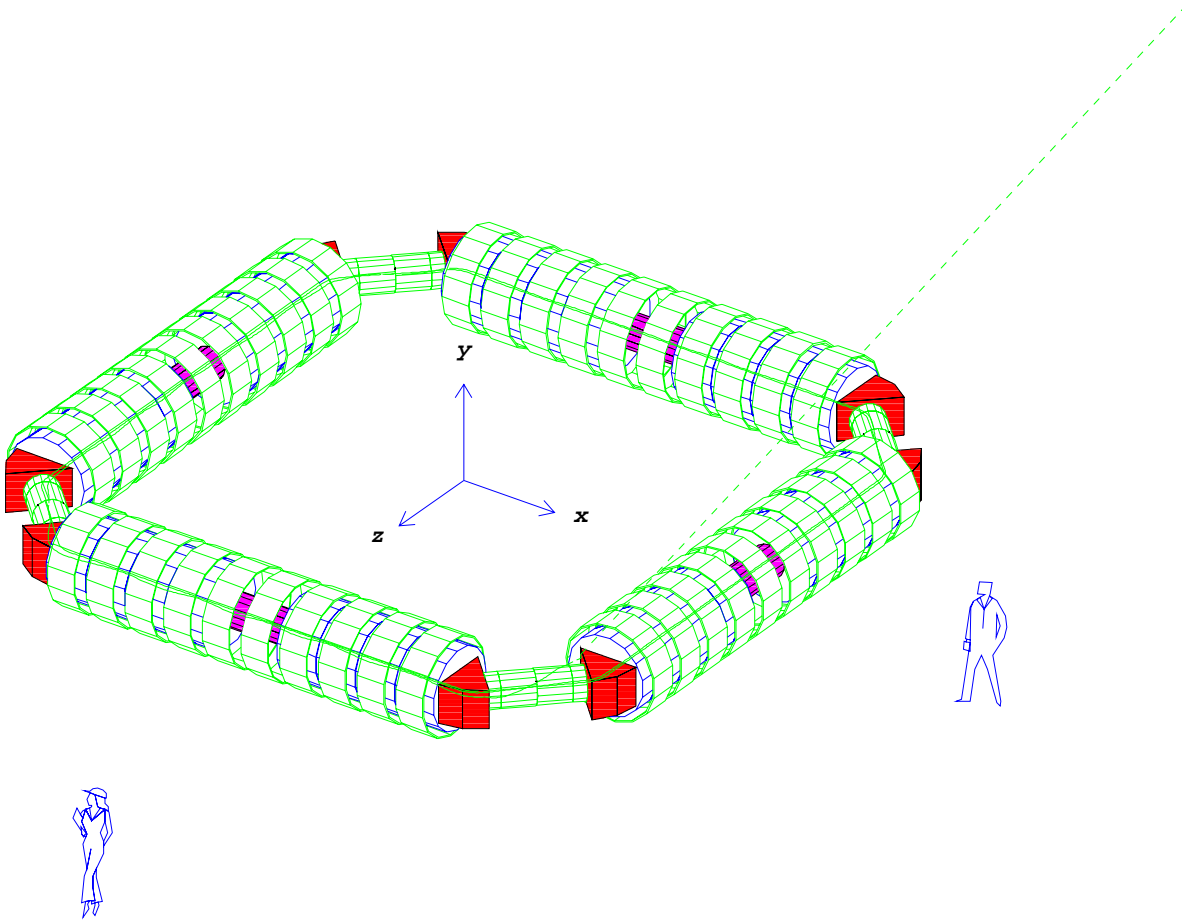
- It is difficult to inject beam of either pions or muons into the ring cooler.
- Try injecting protons (8GeV-1-3ns bunch) and hit one of the wedge targets. Simulation of pion production and capture at 90 degrees is being conducted by N.Mokhov
- Muon Collider/Neutrino factory fellow –Z.Usubov and RR are simulating this setup in Geant321.
- If we can show that it is possible to capture sufficient number of muons this way, then we need to go into an engineering study that will put the design onto a more realistic basis. This can be followed by cost estimates etc.
- The beauty of this scheme (if it works) is that it would demonstrate cooling (6D) on modules that are used by the regular cooling channel. Reusing the modules turn by turn (20 turns foreseen) would reduce the cost of a cooling demonstration channel by that factor.

Geant Simulation of ring cooler

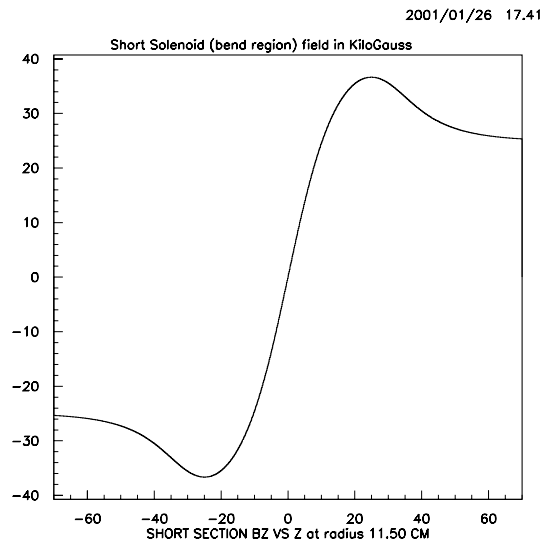
ARTE RING COOLER-NEW SCHEME FROM BALBEKOV 23/04/01

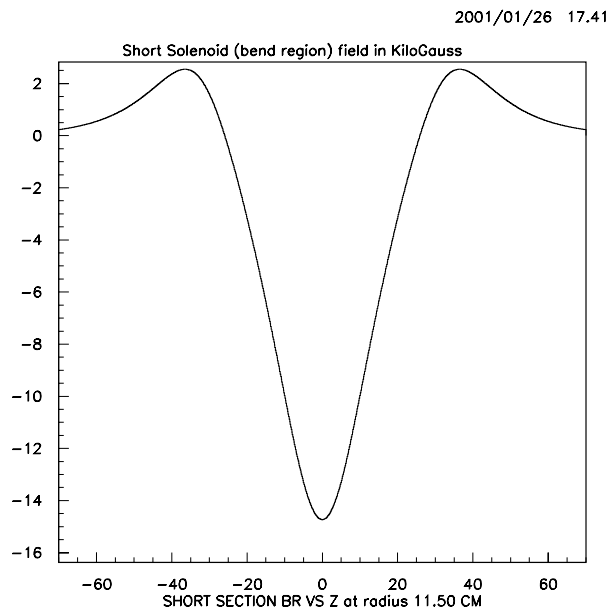


Geant Simulation of ring cooler



Geant Simulation of ring cooler Short Section Solenoid





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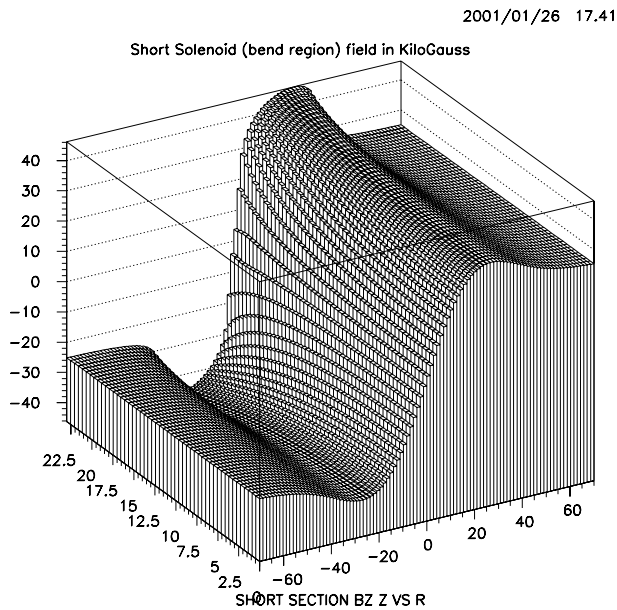
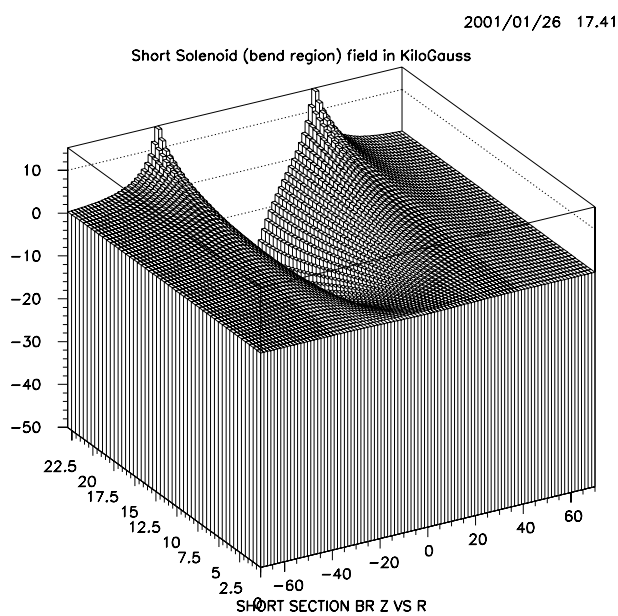
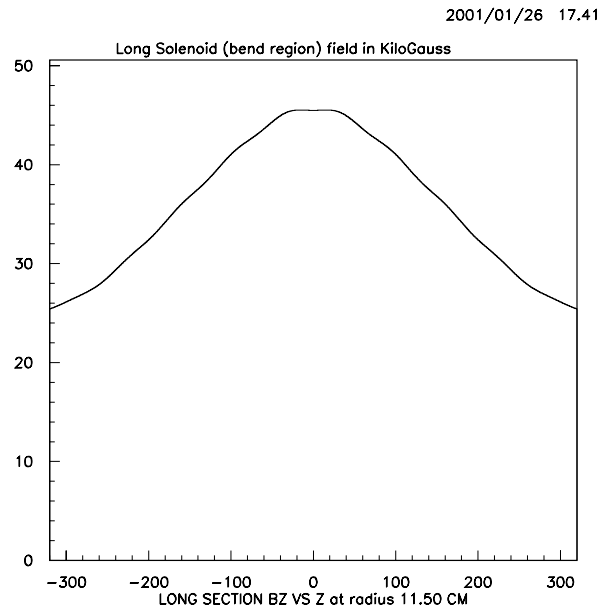
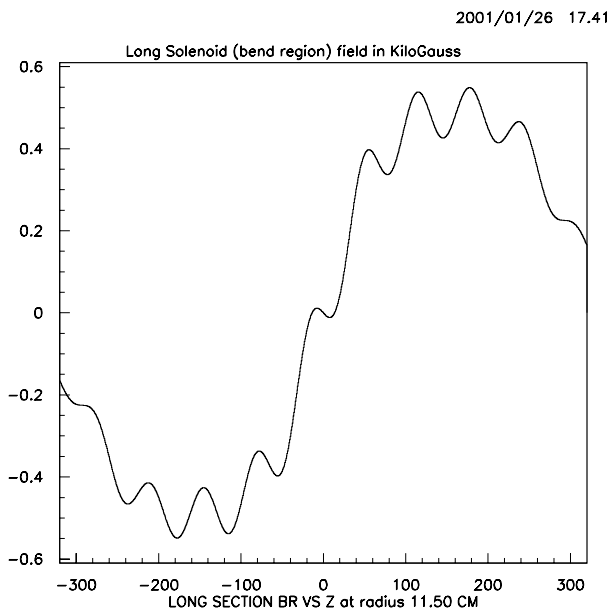




Geant Simulation of ring cooler Long Section Solenoid





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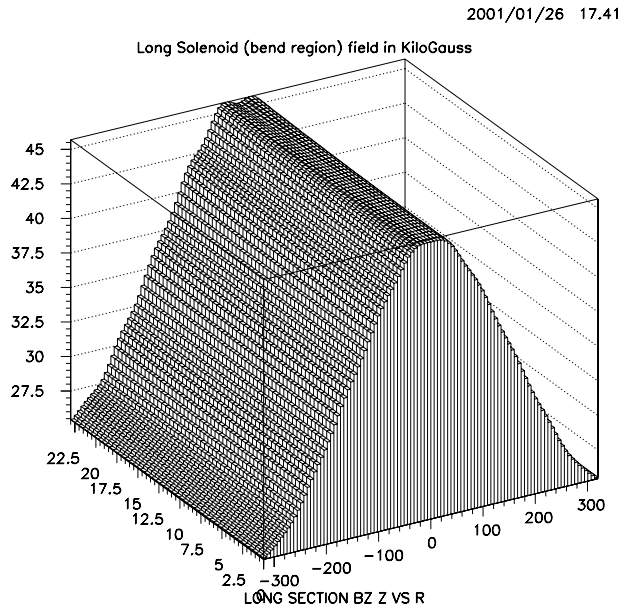
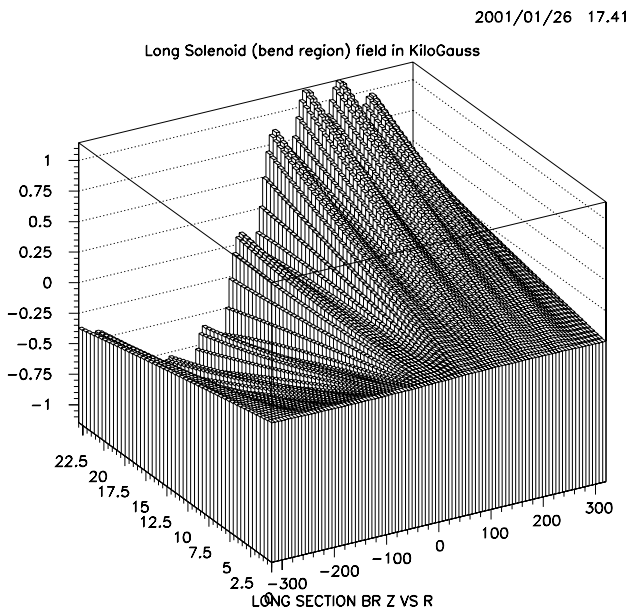
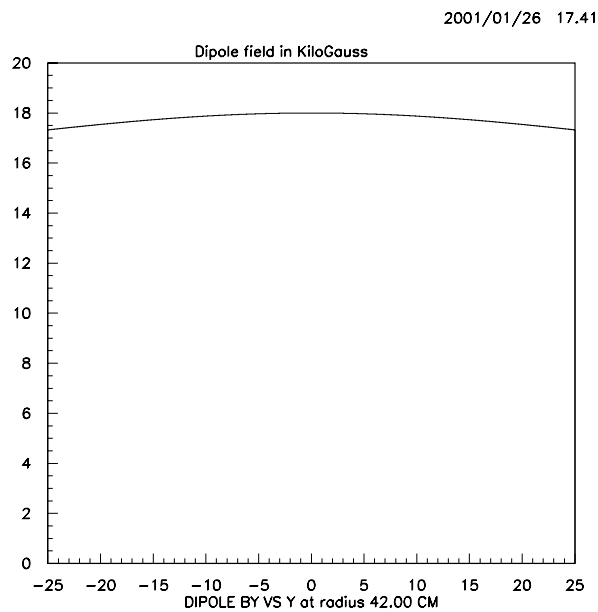
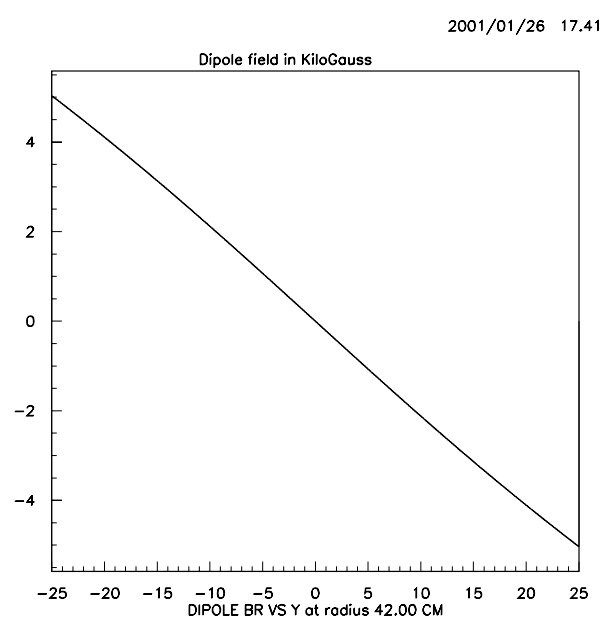




Geant Simulation of ring cooler Bend Dipole





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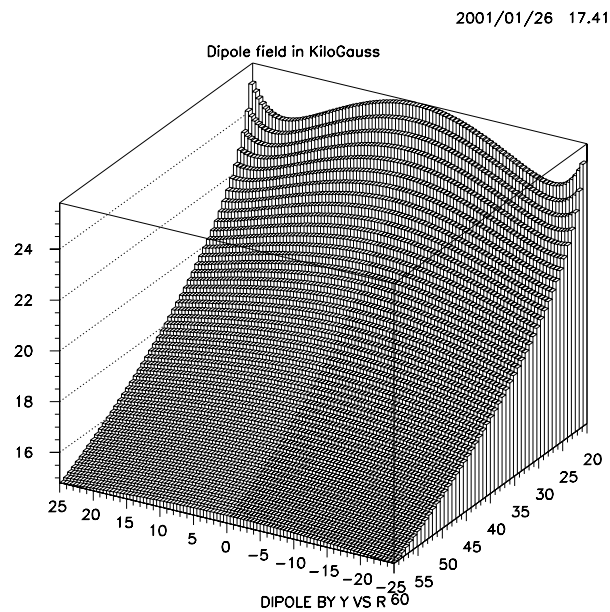
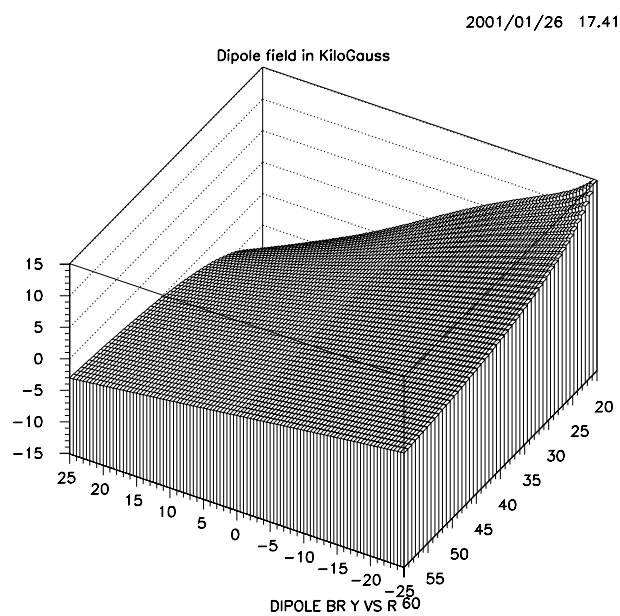




Equations of motion in presence of electric and magnetic fields

$\vec{p}, E$ 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

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

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

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

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

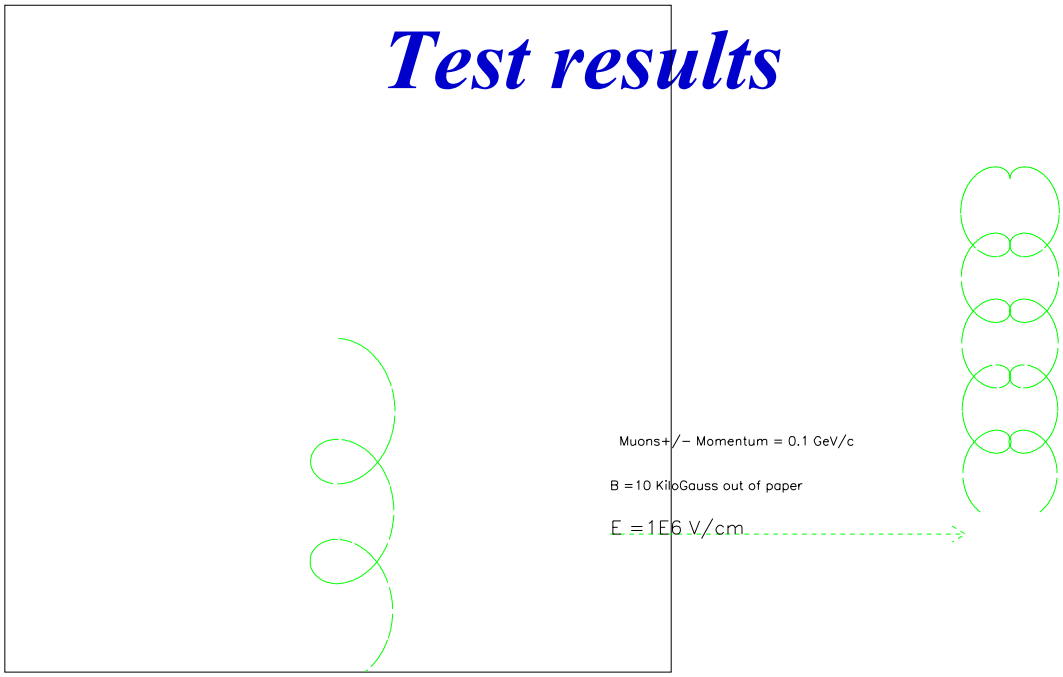
$$y_1 = y(x), y_2 = y_3 = y(x) + (h/2)y'(x) + (h^2/8)K_1$$

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

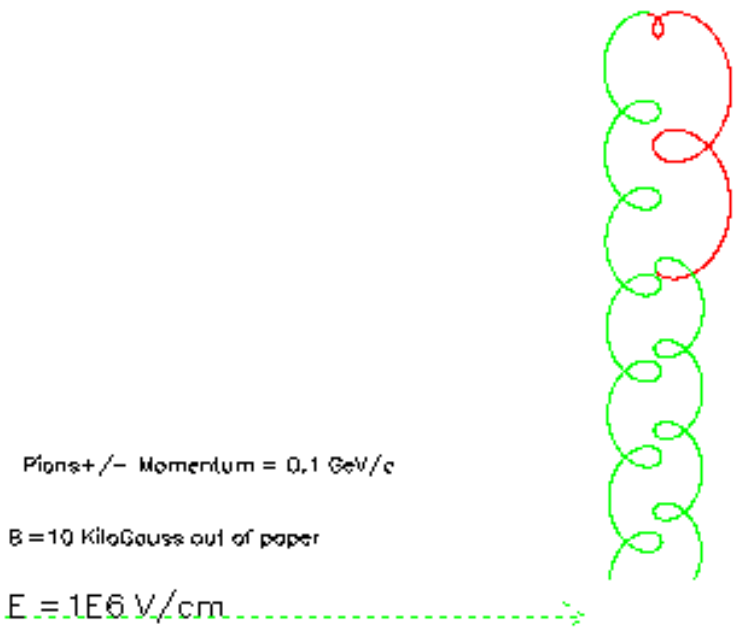
$$y'_1 = y'(x), y'_2 = y'(x) + (h/2)K_1, y'_3 = y'(x) + (h/2)K_2,$$

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

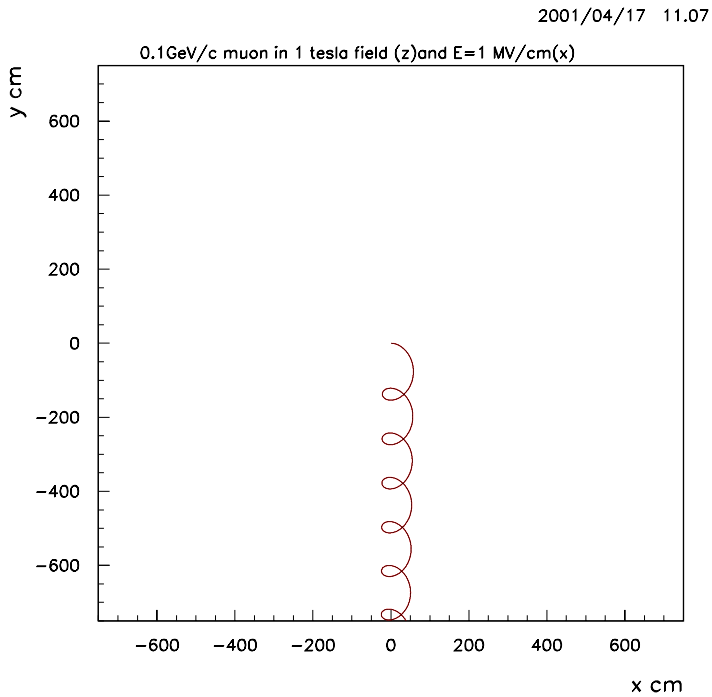
Test results

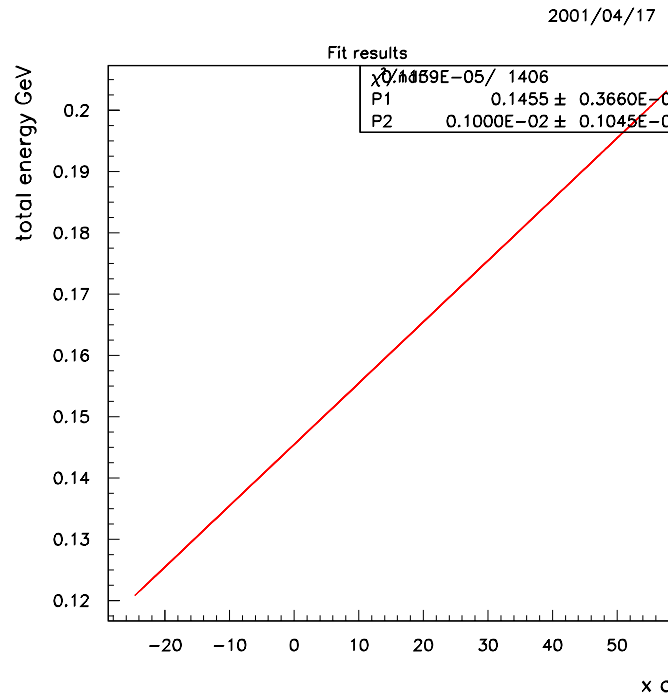


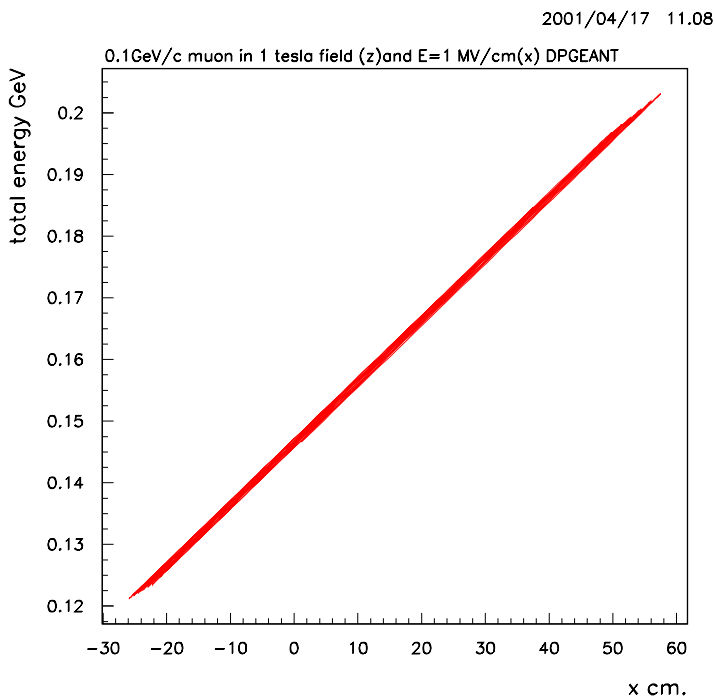
Test results



Runge Kutta results







Solenoid end field kick

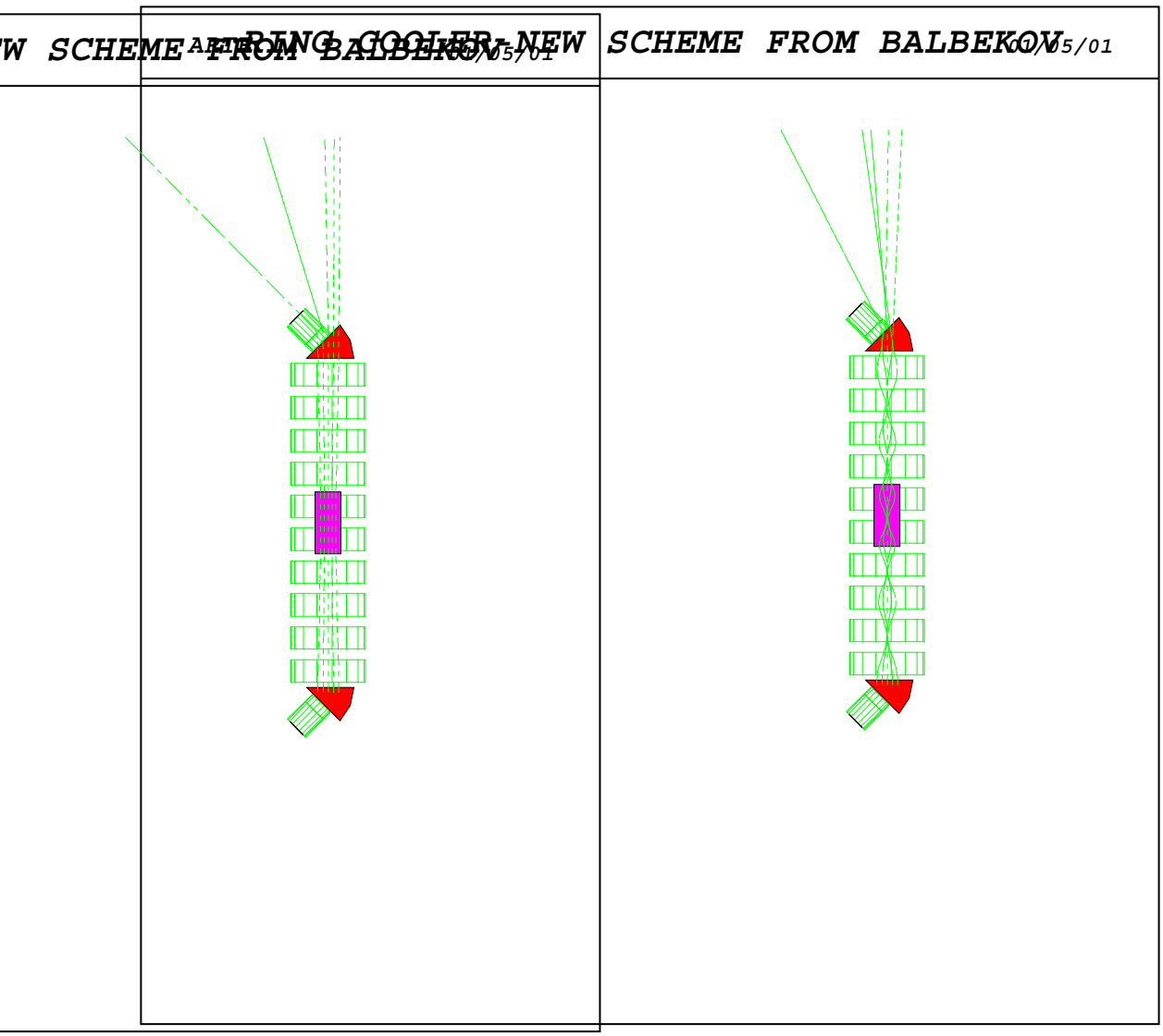
- One needs to simulate the end field of the solenoids by changing the transverse momentum of the particle by the following equations. These assume that the field of the solenoid B_z changes abruptly from its end value to zero while obeying Maxwell's equations. The kicks at entrance is given by

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

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

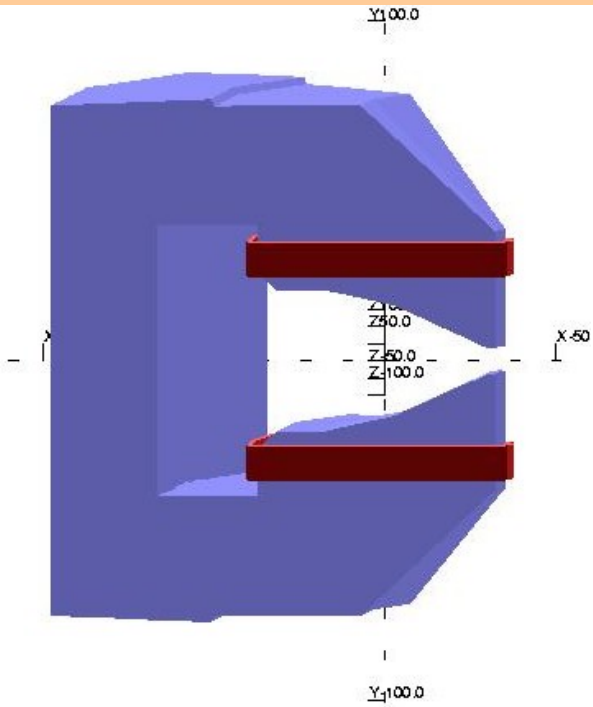
- At exit, the signs are reversed.

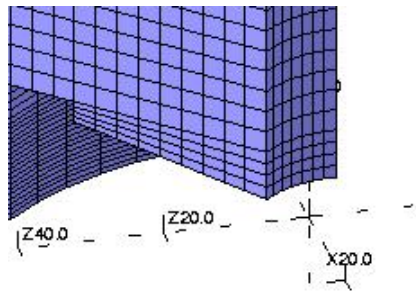
Solenoid end field kick



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

Sketch of Dipole Magnet





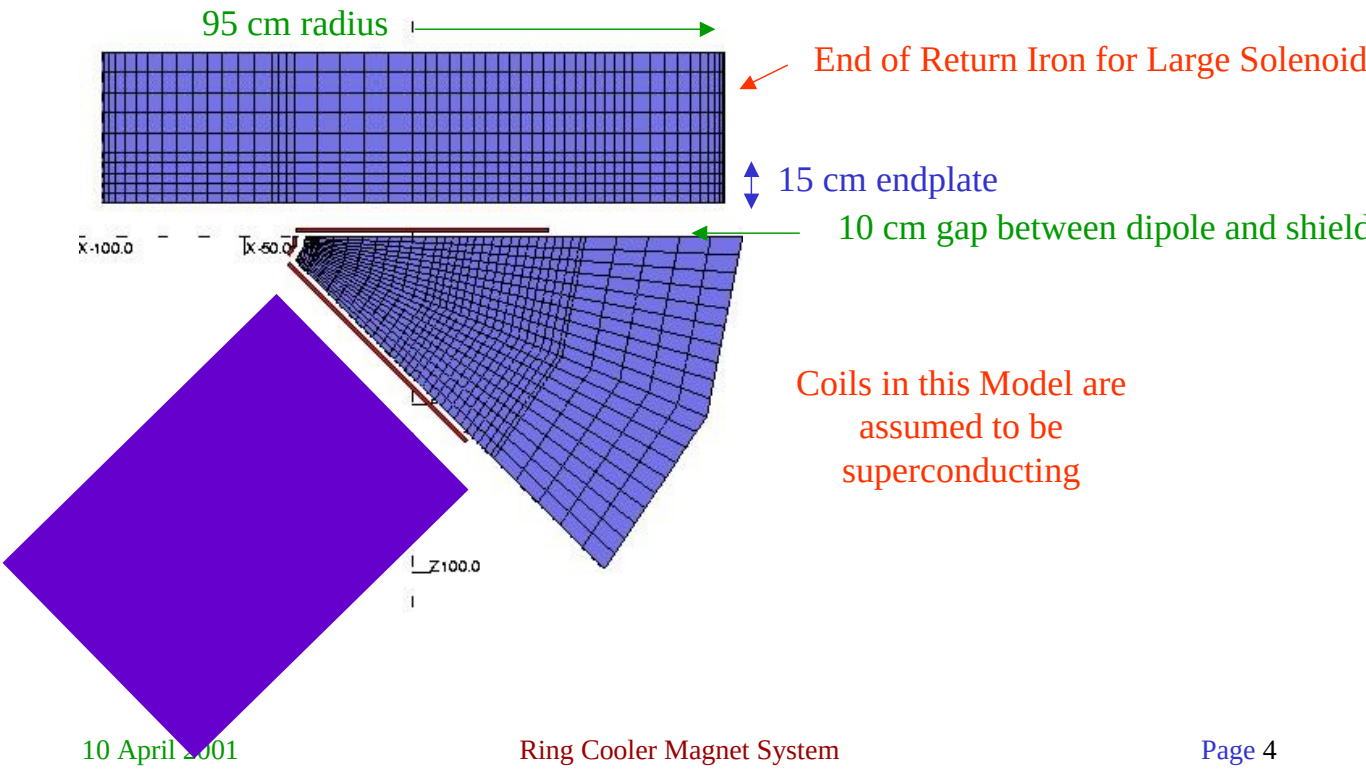
Pole face is shaped to achieve required gradient

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



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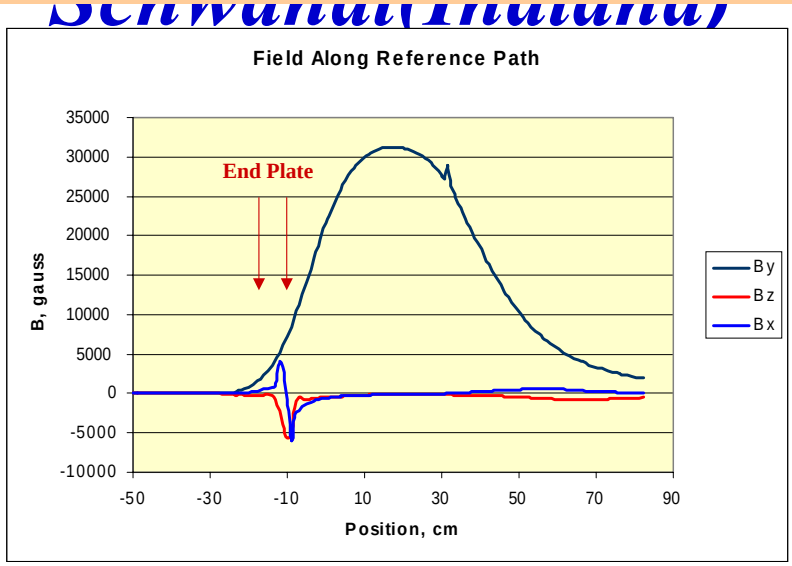
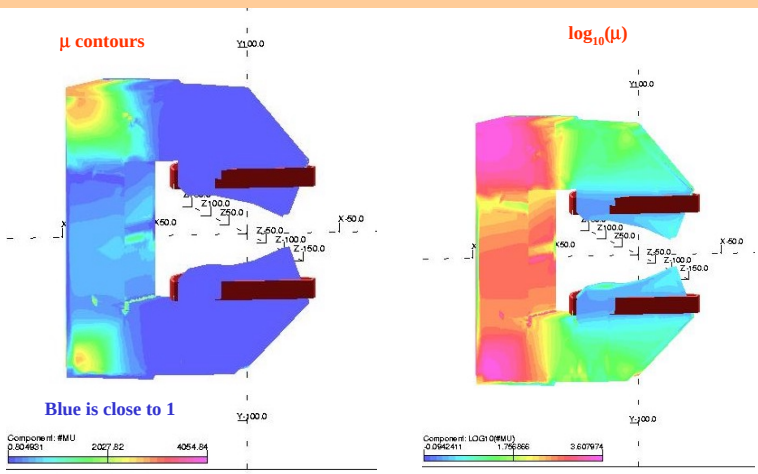
Magnet Design and calculations

B_y along Beam Path in Wedge Magnet

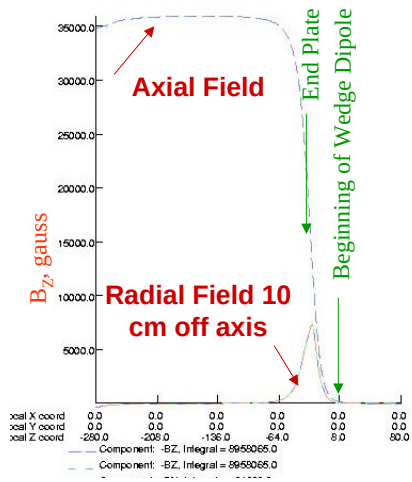


Permeability of Dipole



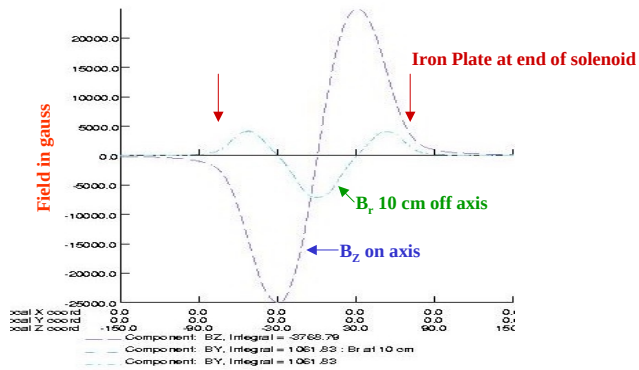
Magnet Design and calculations Steve Kahn(BNL), Peter Schwandt(Indiana)

Fields in Large Solenoid



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

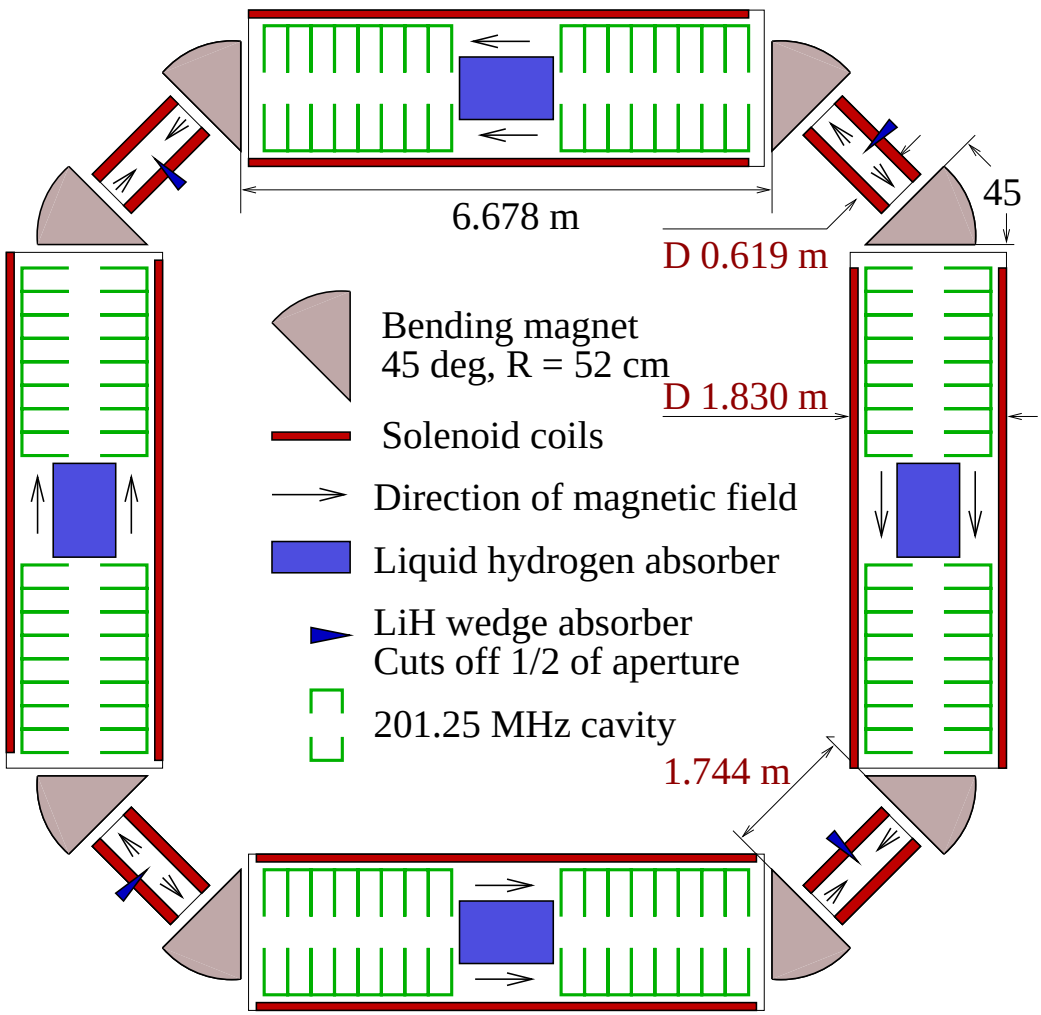
Field in Short Field Flip Solenoid



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

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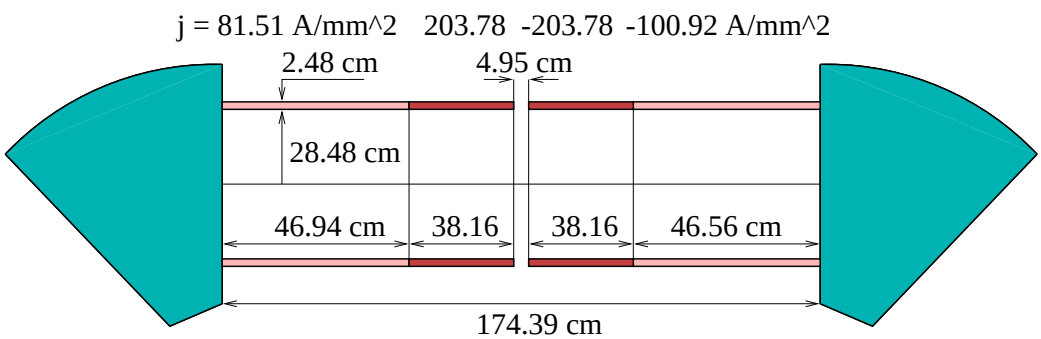
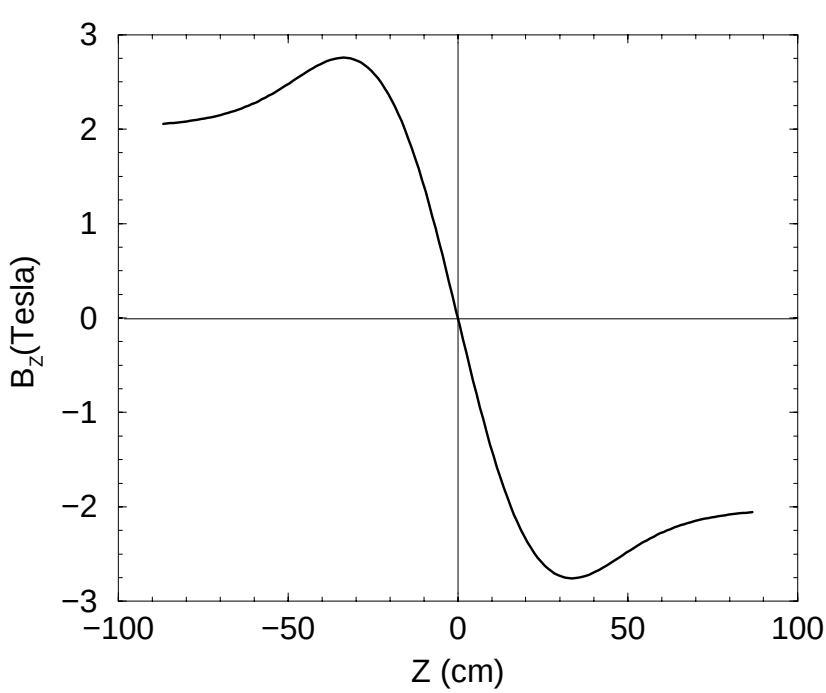
New design with bend magnet radius = 53cm

Short Straight Section

Function of the section: to create dispersion only in SSS



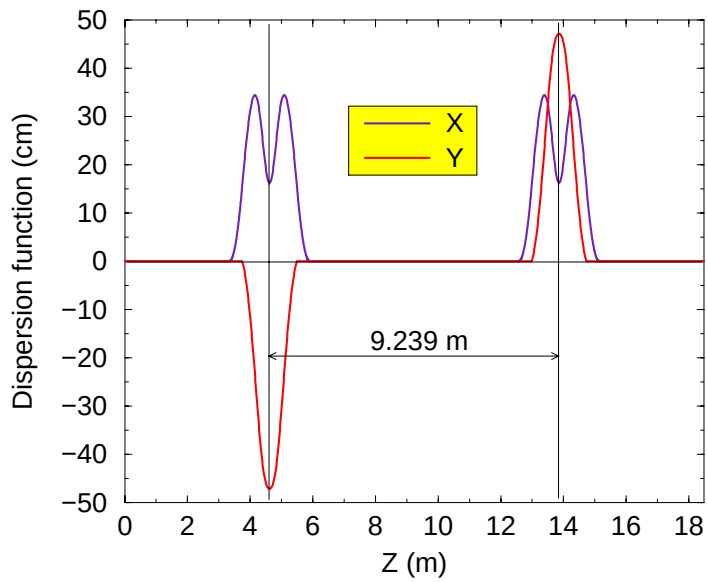
Layout of the Short Straight Section.



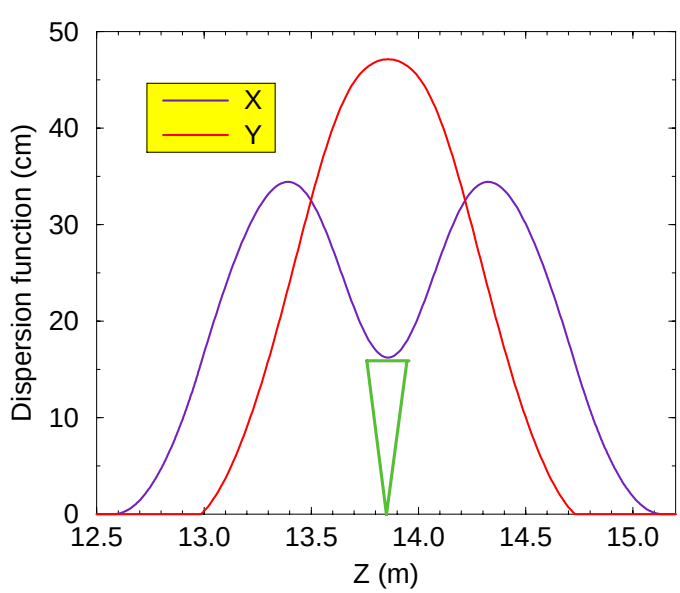
Axial field of the Short Straight Section.

New design with bend magnet radius = 53cm

Dispersion Function



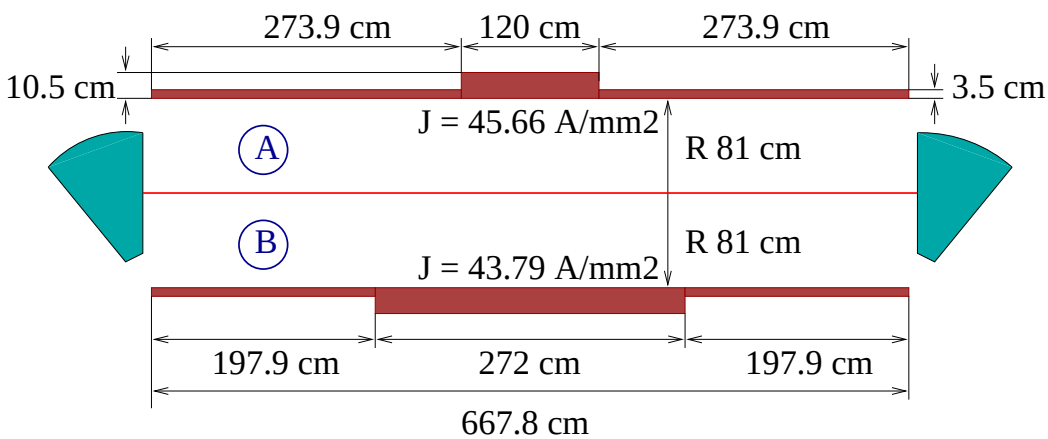
Dispersion function at 1/2 of the ring.



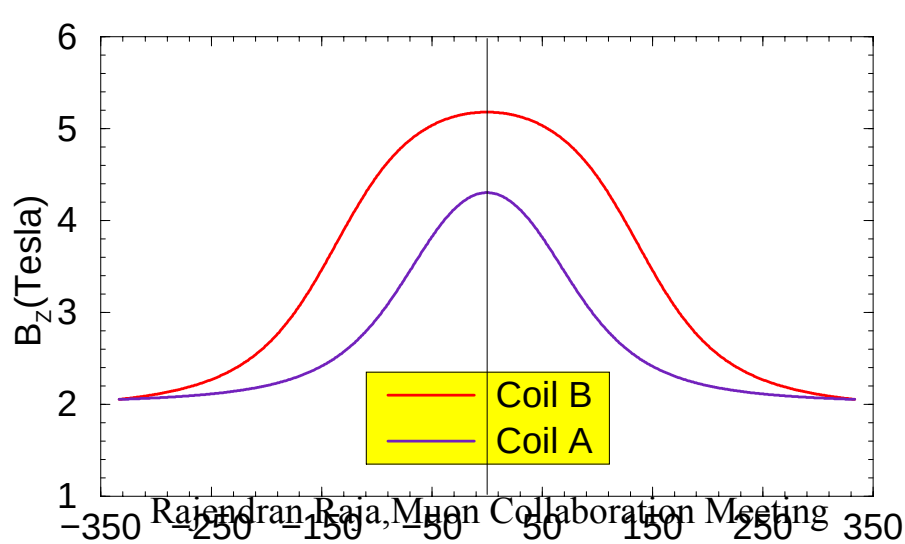
Dispersion function and wedge absorber.

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:

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

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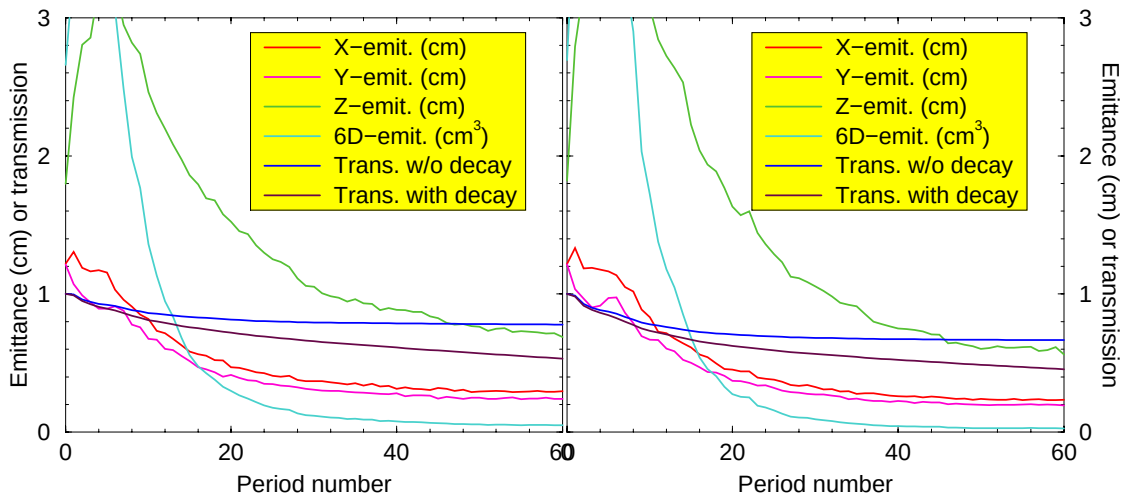
New design with bend magnet radius = 53cm

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

Immediate Plans

- Dipole magnet found to have too short a radius of curvature(Schwandt). Redesign ring (Balbekov) with radius of bend = 53 cm.
- Complete Geant Simulation with a)current Balbekov fields b)More realistic fields using programs such as TOSCA from Steve Kahn and Peter Schwandt (Indiana)
- Write Report for FNAL management on feasibility of MUCOOL experiment
- Look at Instrumentation options to measure emittance in the ring cooler
- Look into Injection and Extraction Schemes from Ring Cooler (Cosy?)