The Muon Collider:

1.5 TeV acc

Collider

Physics Opportunities, Technical Challenges

p source

K.T. McDonald

Princeton U.

1 km

Seminar at U. Penn.

April 28, 1998

Muon Collider main page:

`http://www.cap.bnl.gov/mumu/mu_home_page.html`

My muon collider page:

`http://www.hep.princeton.edu/˜mcdonald/mumu`

Continuing the Miracle of Creation

- Basic theme of high-energy physics:

  Understand nature via creation of new particles.

  $\Rightarrow$ Pursue the **energy frontier**.

- But it takes big machines to reach high energies.

  Can/will our society bear the costs?

- Hadron collider (LHC, SSC): $\approx$ \$100k/m [superconducting magnets].

- e^+e^- collider (SLAC, NLC(?): $\approx$ \$200k/m [rf].

  Are there other options?

- Muon collider:

  Well-defined leptonic initial state.

  $m_\mu/m_e \approx 200 \Rightarrow$ Little beam radiation.

  $\Rightarrow$ Can use storage rings.

  $\Rightarrow$ Smaller footprint.

  Technology: closer to hadron colliders.
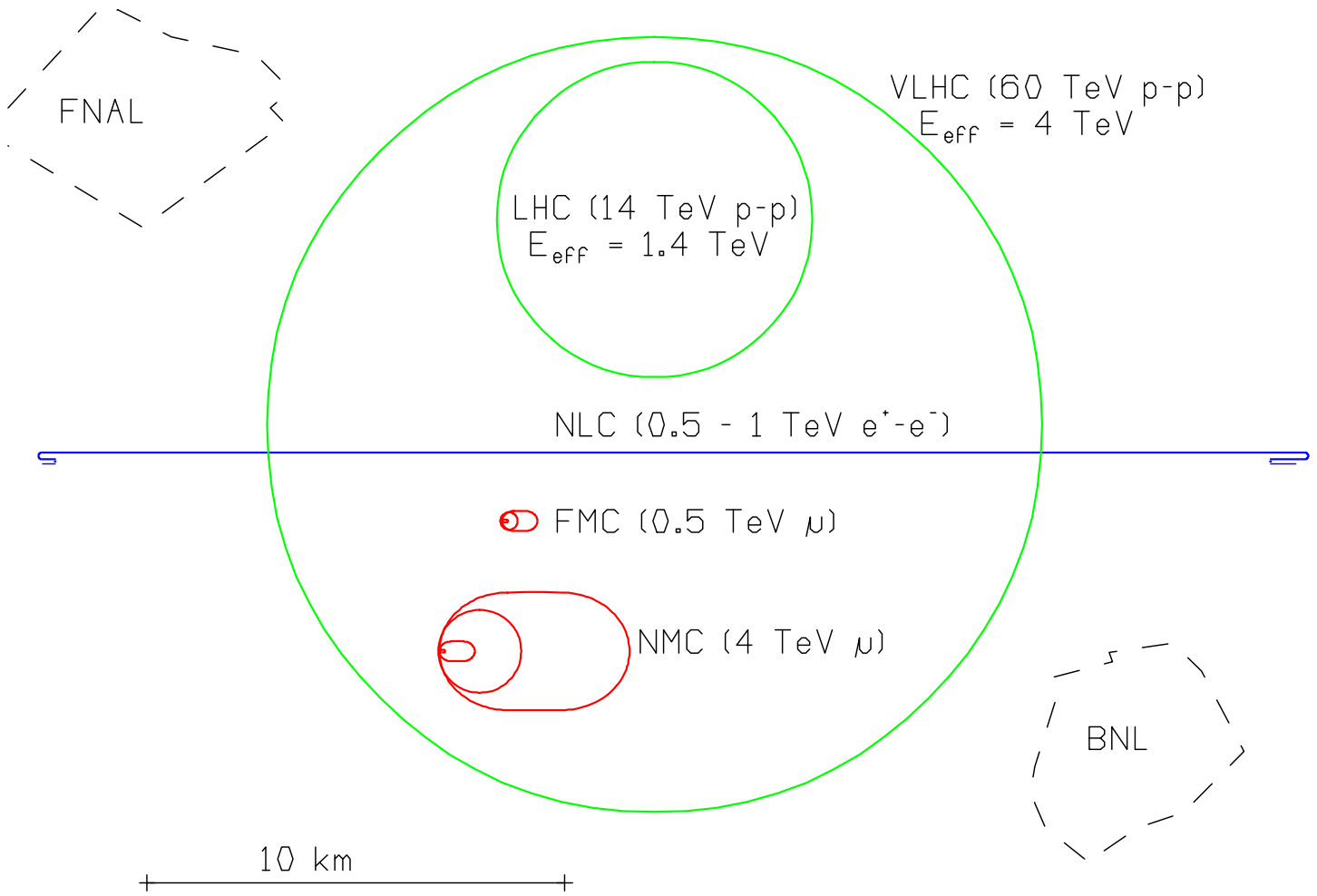
Ingredients of a Muon Collider?

An accelerator complex in which

- Muons (both μ^+ and μ^-) are collected from pion decay following a pN interaction.

- The muon phase volume is reduced by ionization cooling.

- The cooled muons are accelerated and then stored in a ring.

- $\mu^+\mu^-$ collisions are observed over the useful muon life of ≈ 1000 turns at any energy.

Muons decay: $\mu \rightarrow e\nu \qquad \Rightarrow$

- Must cool muons quickly (stochastic cooling won't do).

- Detector backgrounds at LHC level.
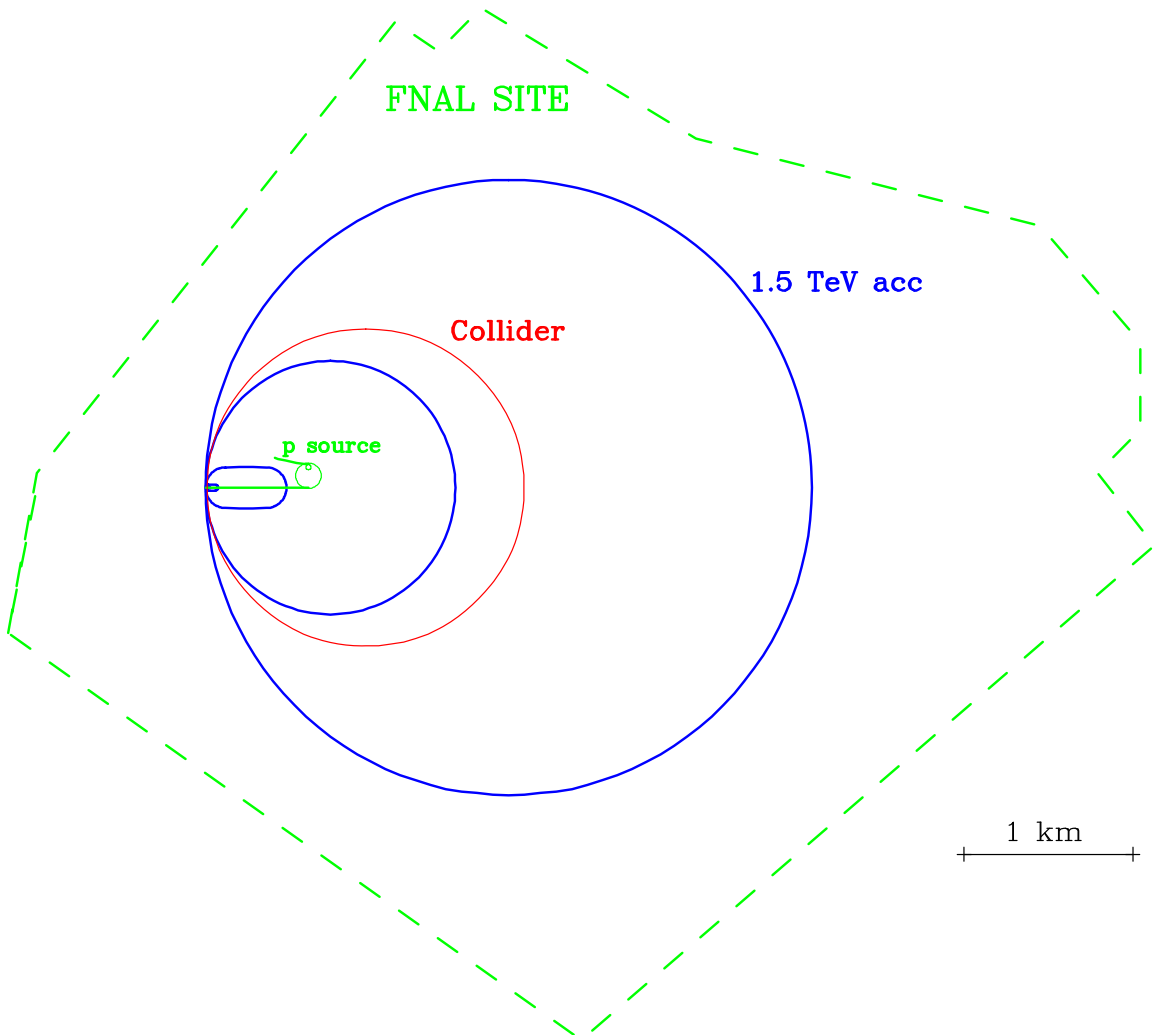
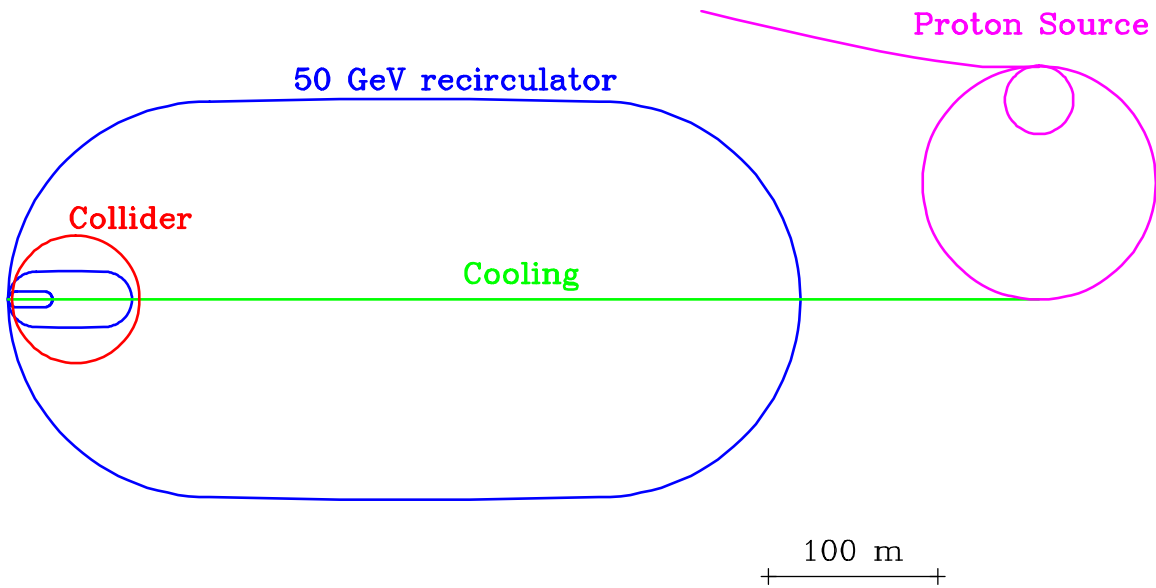- Personnel background from ν interactions.

Footprints

FNAL

VLHC (60 TeV p-p)
E_{eff} = 4 TeV

LHC (14 TeV p-p)
E_{eff} = 1.4 TeV

NLC (0.5 - 1 TeV e^+-e^-)

FMC (0.5 TeV μ)

NMC (4 TeV μ)

BNL

10 km

Muon collider:

- Significant base cost ($\approx$ \$1B) at any energy,

  plus 'modest' cost ($\approx$ \$100k/m) for storage rings.

- Up to 4 TeV on existing sites at cost below LHC.

- Technology path to $\approx$ 100 TeV before limited by radiation

  losses.

Footprints

Proton Source

50 GeV recirculator

Collider

Cooling

100 m

FNAL SITE

1.5 TeV acc

Collider

p source

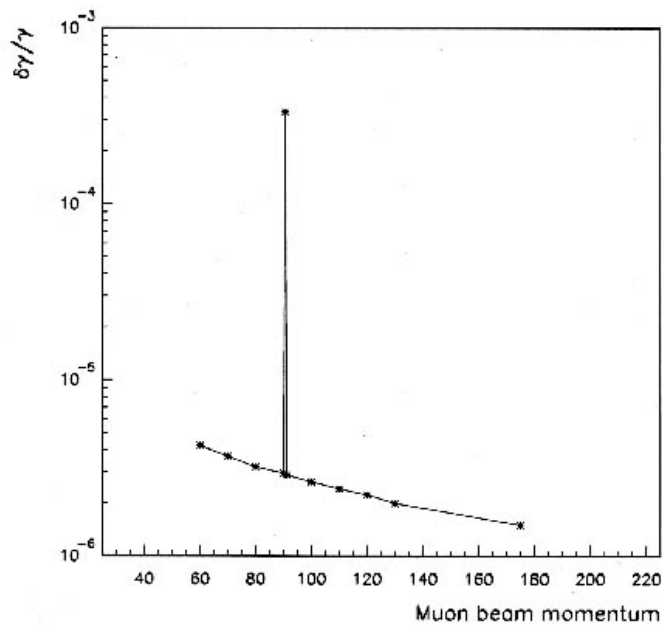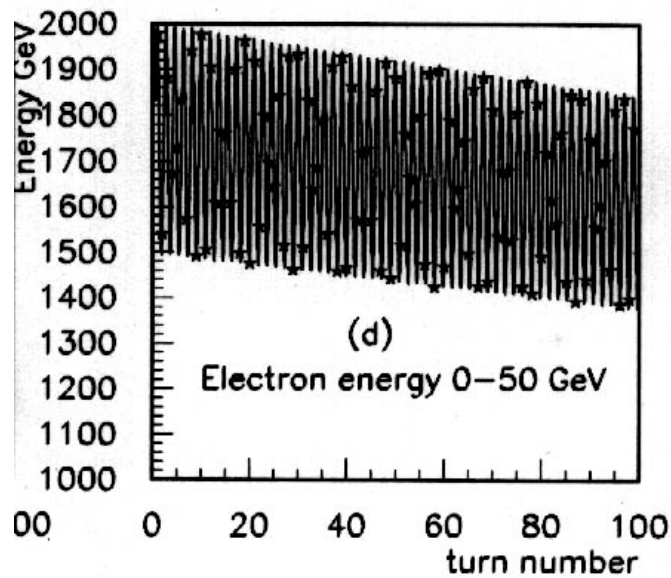1 km

5

Physics Opportunities

- Full CoM energy available for particle production.

- Beam energy spread: 10^{-5} at 100 GeV, 10^{-3} at 3 TeV.

- "Natural" beam polarization $\approx 20\%$ from π-decay at 200 MeV/c.
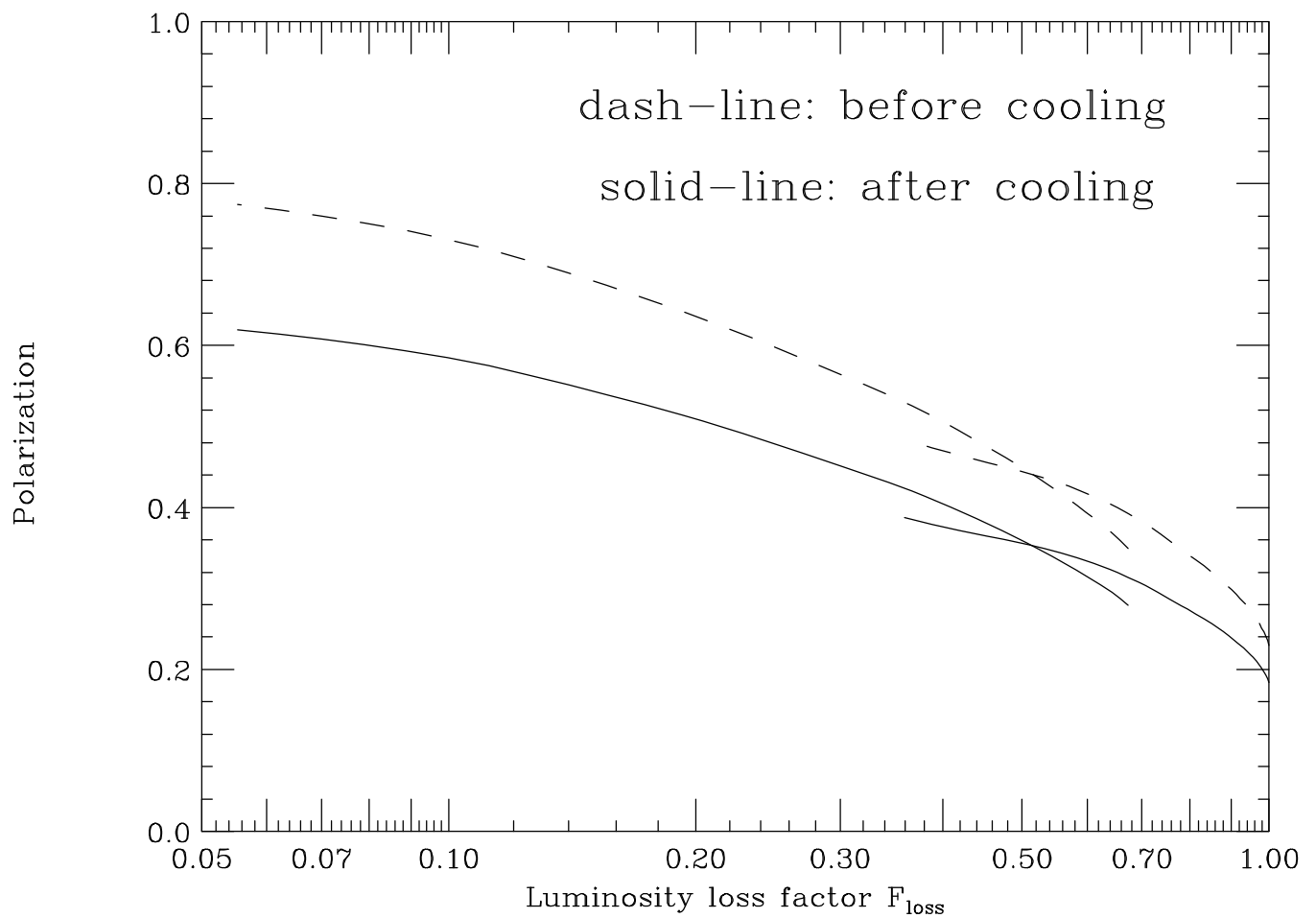
Precision Beam Energy Measurement

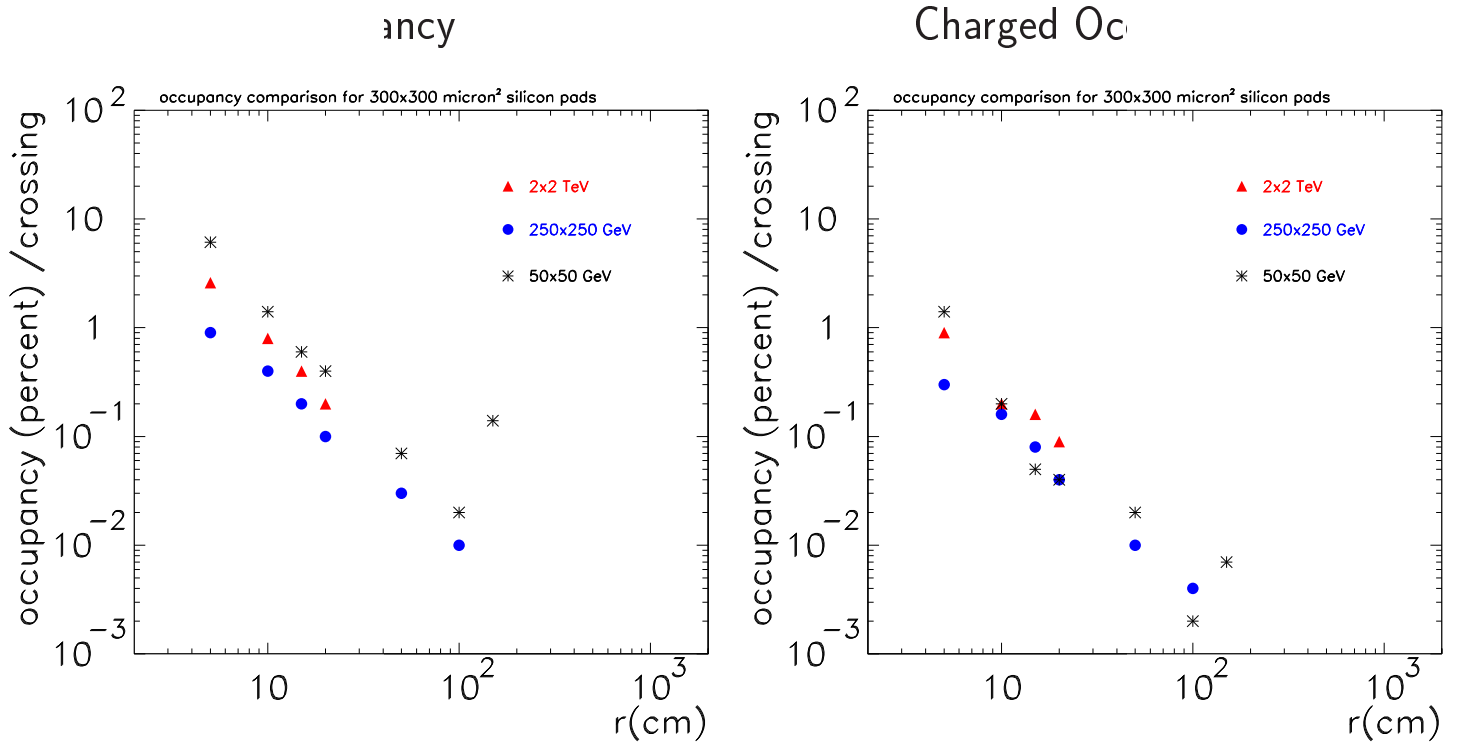Via decay asymmetry of polarized muons.

[Raja and Tollestrup, FERMILAB-Pub-97/402]

$\Rightarrow$ Can measure width (2 MeV) of light Higgs.

Physics Backgrounds

1. Electrons (+ photons) from μ decay:

occupancy comparison for 300x300 micron² silicon pads

- ▲ 2x2 TeV
- ● 250x250 GeV
- ✴ 50x50 GeV

O.K., if use pixel vertex detector.

Radial Fluences at 2x2 TeV

particles/cm^2/crossing for two bunches of $10^{12}\mu$'s each

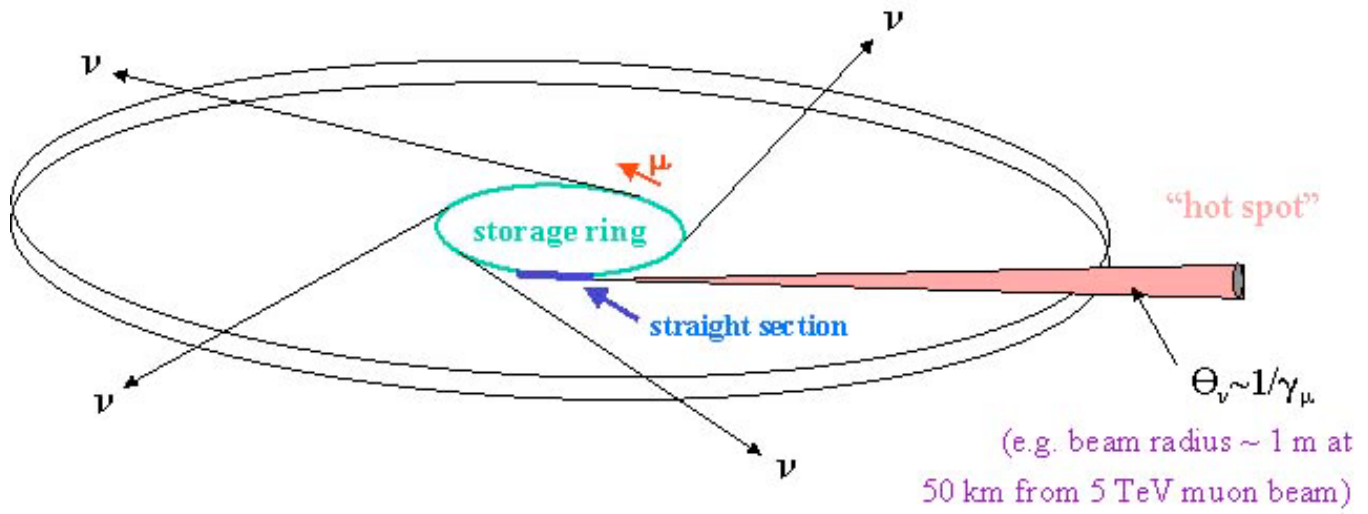| radius (cm)	photons	neutrons	protons	pions	electrons	muons
5	2700	120	0.05	0.9	2.3	1.7
10	750	110	0.20	0.4		0.7
15	350	100	0.13	0.4		0.4
20	210	100	0.13	0.3		0.1
50	70	120	0.08	0.05		.02
100	31	50	0.04	0.003		.008
calo						.003
muon						.0003
threshold	25 keV	40 keV	10 MeV	10 MeV		

2. 'Bethe-Heitler' muons $[\mu \rightarrow e \rightarrow \gamma \rightarrow \mu^{+}\mu^{-}]$:
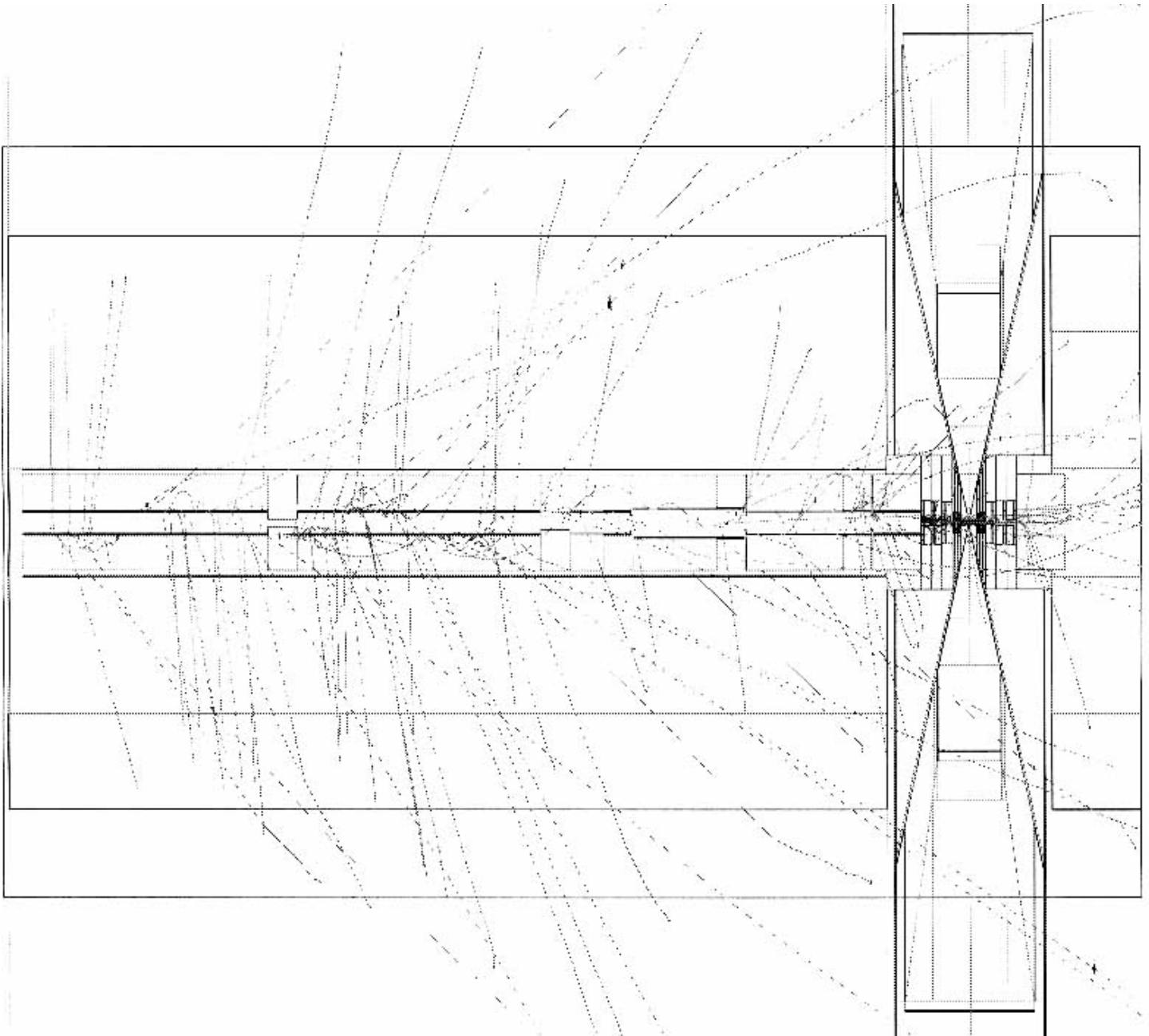
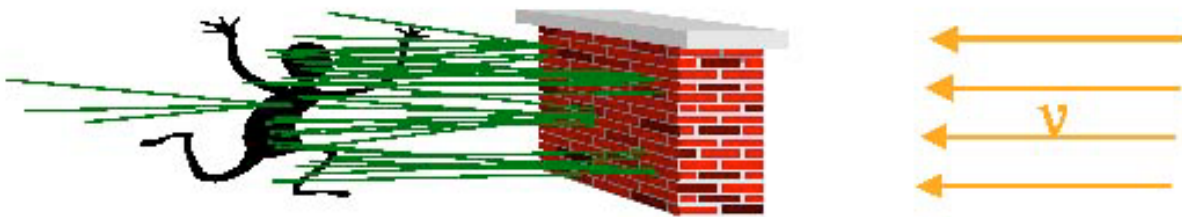Affects calorimeter performance at CoM energies above 1 TeV.

[Iuliu Stumer]

Dose from Neutrino Interactions

storage ring

μ

"hot spot"

straight section

$\Theta_\nu \sim 1/\gamma_\mu$

(e.g. beam radius ~ 1 m at 50 km from 5 TeV muon beam)

Much worse at straight sections: e.g. even <u>0.1 m</u> str. section is ~ <u>twice</u> disk ave.

Hazard is charged particles from ν interactions in surroundings...

Predicted dose downstream from straight section:

$$\frac{\mathrm{Radiation\,Dose}}{\mathrm{U.S.Fed.Limit}} \cong 0.4 \times \left(\frac{\mathrm{length\,of\,str.\,section}}{\mathrm{collider\,depth}}\right) \times \left(\frac{\mathrm{muon\,current}}{10^{20}\ \mu^{-}/\mathrm{year}}\right) \times \left(\frac{E_{\mathrm{CoM}}}{1\,\mathrm{TeV}}\right)^{3}$$

(spherical Earth & non-tilted ring)

Neutrino Problem 'Stabilizes' above 10 Tev
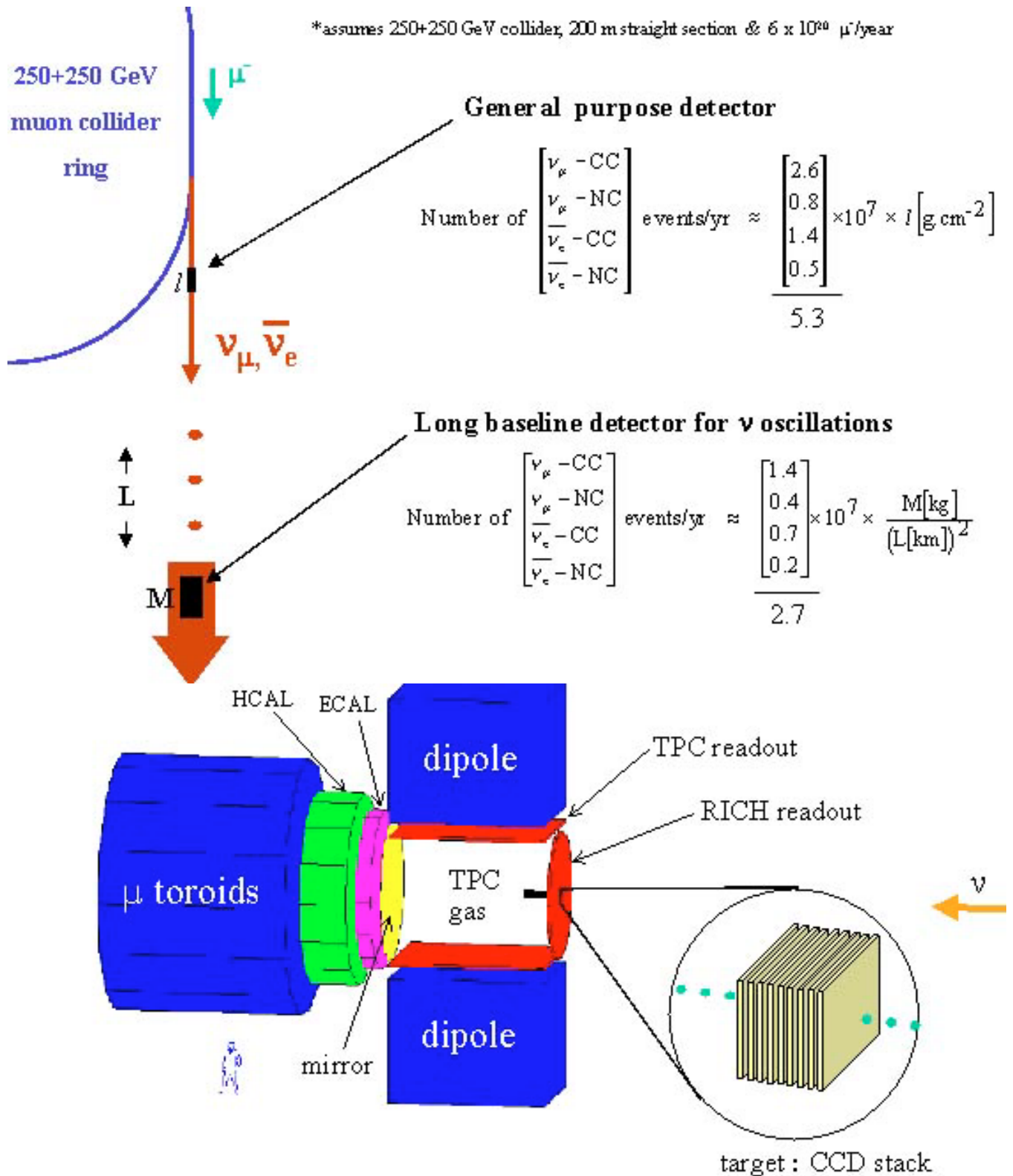
- Neutrino cross section levels off at high energy:
$$\frac{\sigma(E_\nu = 100 \text{ TeV})}{\sigma(E_\nu = 1 \text{ TeV})} = 33, \qquad (\text{rather than } 100).$$

- Previous formula overestimates dose once ν spot is smaller than 1 m.

- Better cooling schemes will permit low emittance for smaller muon beam current.

- $\Rightarrow$ May never need ring deeper than 500 m.

Neutrino Physics at a Muon Collider

*assumes 250+250 GeV collider, 200 m straight section & 6×10^{20} μ^-/year

250+250 GeV muon collider ring

μ^-

l

$\nu_\mu, \overline{\nu}_e$

L

M

General purpose detector

$$\text{Number of} \begin{bmatrix} \nu_\mu - CC \\ \nu_\mu - NC \\ \overline{\nu}_e - CC \\ \overline{\nu}_e - NC \end{bmatrix} \text{events/yr} \approx \underline{\begin{bmatrix} 2.6 \\ 0.8 \\ 1.4 \\ 0.5 \end{bmatrix}} \times 10^7 \times l\left[\text{g.cm}^{-2}\right]$$
$$5.3$$

Long baseline detector for ν oscillations

$$\text{Number of} \begin{bmatrix} \nu_\mu - CC \\ \nu_\mu - NC \\ \overline{\nu}_e - CC \\ \overline{\nu}_e - NC \end{bmatrix} \text{events/yr} \approx \underline{\begin{bmatrix} 1.4 \\ 0.4 \\ 0.7 \\ 0.2 \end{bmatrix}} \times 10^7 \times \frac{M[\text{kg}]}{(L[\text{km}])^2}$$
$$2.7$$

HCAL   ECAL

dipole

μ toroids

TPC gas

TPC readout

RICH readout

ν

mirror

dipole

target : CCD stack

- <u>HUGE</u> statistics: 50 g/cm^2 target $\Rightarrow$ 3x10^9 events/year
- outstanding reconstruction of CC & NC event kinematics
- full particle ID $\Rightarrow$ ID of struck quark

Muon Collider Parameters

CoM energy	TeV	3	0.4		0.1	
p energy	GeV	16	16		16	
p's/bunch		2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill		4	4		2	
Rep. rate	Hz	15	15		15	
p power	MW	4	4		4	
μ/bunch		2×10^{12}	2×10^{12}		4×10^{12}	
μ power	MW	28	4		1	
Wall power	MW	204	120		81	
Collider circumf.	m	6000	1000		300	
Depth	m	500	100		10	
$\frac{\Delta p}{p}$ (rms)	%	0.16	0.14	0.12	0.01	0.003
6D ϵ_6	$(\pi\text{mm})^3$	170	170	170	170	170
ϵ_n (rms)	π mm mrad	50	50	85	195	280
β^*	cm	0.3	2.3	4	9	13
σ_z	cm	0.3	2.3	4	9	13
σ_r	μm	3.2	24	82	187	270
Tune shift		0.043	0.043	0.05	0.02	0.015
Luminosity	cm^{-2}s^{-1}	5×10^{34}	10^{33}	1.2×10^{32}	2×10^{31}	10^{31}
CoM $\frac{\Delta E}{E}$		8×10^{-4}	8×10^{-4}	8×10^{-4}	7×10^{-5}	2×10^{-5}
Higgs/year				**1,600**	**4,000**	**4,000**

Technical Challenges

- 16-GeV proton driver, 15 Hz, 4-MW beam power, **1-ns bunch length**.

		Linac	Pre-Booster	Booster
Final energy	GeV	1.0	4.5	16
Protons/bunch			5×10^{13}	5×10^{13}
No. of bunches			2	2
Rep. rate	Hz	15	15	15
Circumference	m		180.6	474.2
Norm. 95% emit.	π mm mrad		200	240
Sp.-ch. tune shift			.39	.39
Final field	T		1.3	1.3

- Targetry and Capture

- **Muon Cooling**

  [Storage rings have beautiful, highly corrected solutions due to heroic work of Al Garren, Carol Johnstone and Dan Trbojevič.]

Overview of Targetry for a Muon Collider

- Get muons from pion decay: $\pi^{\pm} \to \mu^{\pm}\nu$.

- Pions from proton-nucleus interactions in a **target**.

- Goal: $1.2 \times 10^{14} \ \mu^{\pm}/\text{s}$.

- $\Rightarrow$ High-Z target,

  High-energy proton beam,

  High magnetic field around target to capture soft pions.

- $\mu/p = 0.08$ at 16 GeV $\Rightarrow 1.5 \times 10^{15} \ p/\text{s}$.

- 15-Hz proton source.

- 4 MW power in p beam.

- Compare: 0.1 MW in 900-GeV extracted p beam at FNAL;

  0.25 MW in 30-GeV extracted beam at BNL AGS.

Baseline Scenario
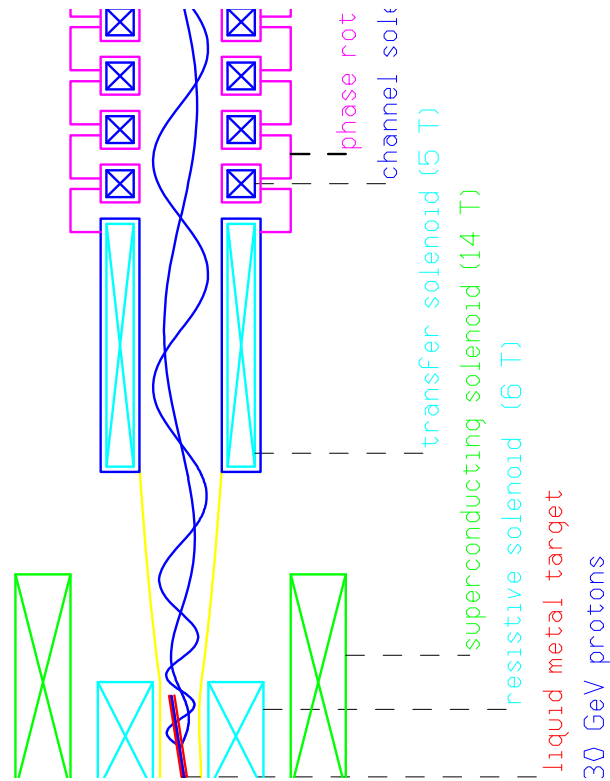
- Liquid metal target: Ga, Hg, or solder (Bi/In/Pb/Sn alloy)

- 20-T capture solenoid followed by 5-T phase-rotation channel.

- 20 T = 8-T, 8-MW water-cooled Cu magnet

    + 12-T superconducting magnet.

- Cost of 12-T magnet ≈ 0.8 M\$ $(B[\text{T}]\ R[\text{m}])^{1.32}(L[\text{m}])^{0.66}$

    $\approx$ \$6M.

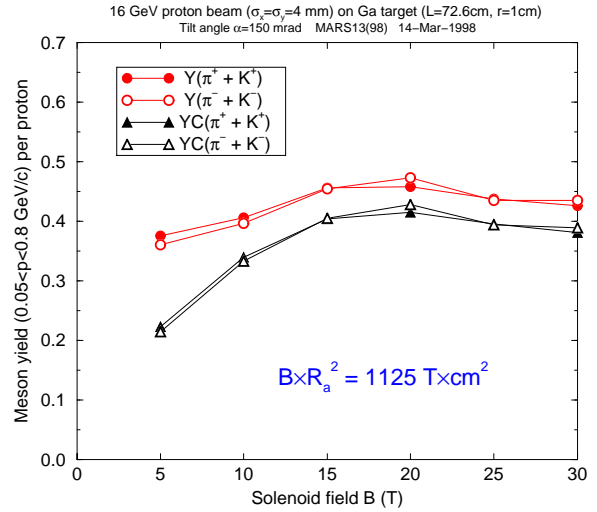- Capture pions with $P_\perp < 220$ MeV/c.

- Adiabatic invariant: $\Phi = \pi r^2 B$ as B drops from 20 to 5 T.

- $r = P_\perp/eB =$ radius of helix.

- $\Rightarrow P_{\perp,f} = P_{\perp,i}\sqrt{B_f/B_i} = 0.5$ (and $P_{\parallel,f} > P_{\parallel,i}$).

- Tilt target by ≈ 0.1 rad to minimize absorption of spiralling pions (factor of 2 effect).

- Target should be short and narrow,
  $\Rightarrow$ high density; no cooling jacket.

- High power of beam + radiation damage would crack stationary target.

  - 10% of beam energy deposited in target $\Rightarrow$ 30 kJ/pulse.

  - $M_{\text{target}} = \pi r^2 l \rho \approx 10$ kg $\Rightarrow$ ≈ 0.1 eV/atom/pulse.

  - 10% of TNT $\Rightarrow$ Shock damage.

  - 1% of atoms ionized each pulse $\Rightarrow$ embrittlement....

- $\Rightarrow$ **Pulsed heavy-metal liquid jet** as target.
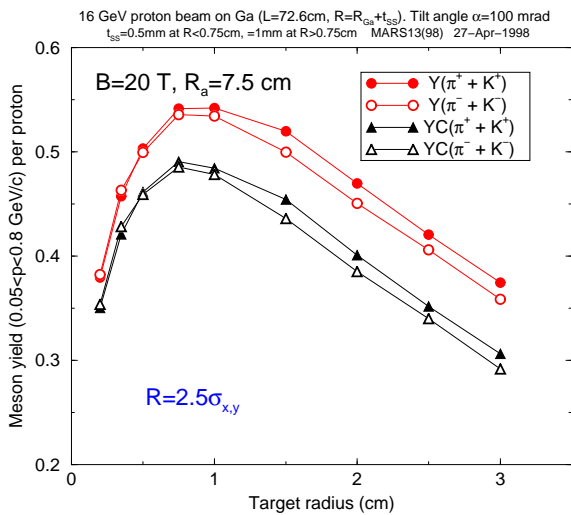
Target Optimization via MARS Code
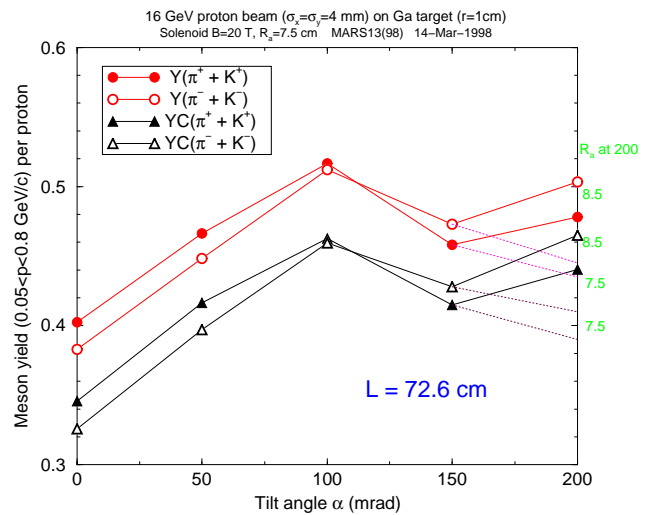
Yield *vs.* Beam Energy
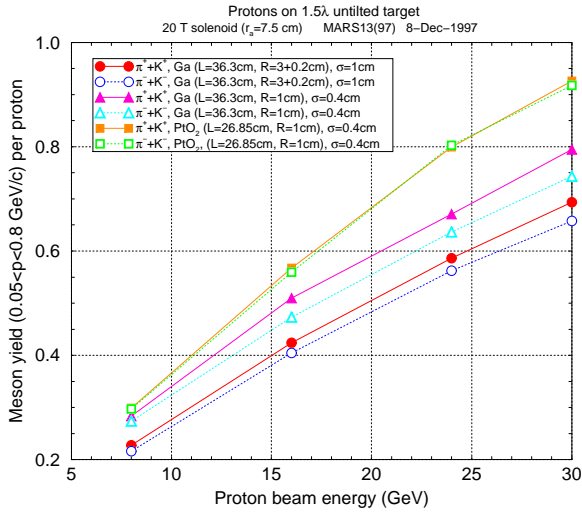
Protons on 1.5λ untilted target
20 T solenoid (r$_a$=7.5 cm)   MARS13(97)   8–Dec–1997

Yield *vs.* Magnetic Field

16 GeV proton beam (σ$_x$=σ$_y$=4 mm) on Ga target (L=72.6cm, r=1cm)
Tilt angle α=150 mrad   MARS13(98)   14–Mar–1998

B×R$_a^2$ = 1125 T×cm^2

Yield *vs.* Target Radius

16 GeV proton beam on Ga (L=72.6cm, R=R$_{Ga}$+t$_{ss}$). Tilt angle α=100 mrad
t$_{ss}$=0.5mm at R<0.75cm, =1mm at R>0.75cm   MARS13(98)   27–Apr–1998

B=20 T, R$_a$=7.5 cm

R=2.5σ$_{x,y}$

Yield *vs.* Target Angle

16 GeV proton beam (σ$_x$=σ$_y$=4 mm) on Ga target (r=1cm)
Solenoid B=20 T, R$_a$=7.5 cm   MARS13(98)   14–Mar–1998

L = 72.6 cm

[Nikolai Mokhov, http://www-ap.fnal.gov/MUMU/mumu.html]

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High Radiation Dose Around Target

- 1×10^{10} rad/h
- 5×10^{9} rad/h
- 1×10^{9} rad/h
- 5×10^{8} rad/h
- 1×10^{8} rad/h

- 5×10^{19} hadrons/cm²/year

Isodose contours show radiation dose in rad/h for 1.5×10^{15} protons/s on target (from A.H. Sullivan) based on measurements in AA and ACOL target areas

Neglecting the water cooling spaces in the heavy metal absorber, the mean power deposited in the region of the solenoids is shown approximately in W/kg of absorber.

Pion production target and capture solenoids

Mercury Jet Studied at CERN
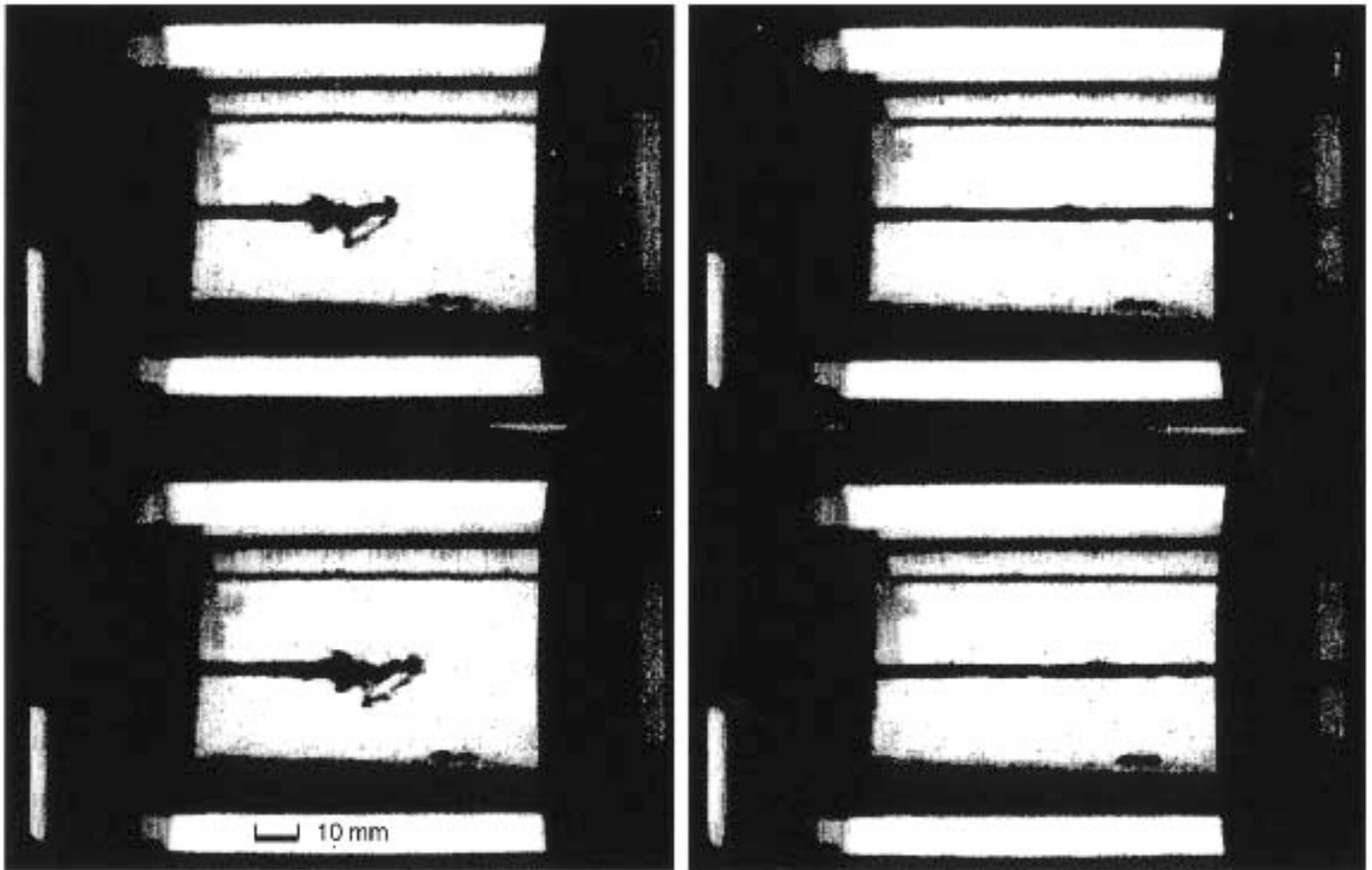
High-speed photographs of mercury jet target for CERN-PS-AA. (laboratory test)
4,000 frames per second, Jet speed: 20 ms^{-1}, diameter: 3 mm, Reynold's Number: >100,000

A. Poncet

Colin Johnson has joined the muon collider targetry group.

Eddy Current Effects on Conducting Liquid Jets

- In frame of jet, changing magnetic field induces eddy currents.

- Lenz: Forces on eddy current oppose motion of jet.

- Longitudinal drag force $\Rightarrow$ won't penetrate magnet unless jet has a minimum velocity: $\sigma = \sigma_{\text{Cu}}/60$, $\rho = 10$ g/cm^3, $\Rightarrow$
$$v_{\min} > 60 \text{ m/s} \left[\frac{r}{1 \text{ cm}}\right] \left[\frac{r}{D}\right] \left[\frac{B_0}{20 \text{ T}}\right]^2.$$
  Ex: $B_0 = 20$ T, $r = 1$ cm, $D = 20$ cm, $\Rightarrow v_{\min} = 3$m/s.

- Drag force is larger at larger radius $\Rightarrow$ planes deform into cones:
$$\frac{\Delta z(r)}{r} \approx -3\alpha \left[\frac{r}{1 \text{ cm}}\right] \left[\frac{B_0}{20 \text{ T}}\right]^2 \left[\frac{10 \text{ m/s}}{v}\right].$$
  Ex: $\alpha = L/D = 2$, $r = 1$ cm, $v = 10$ m/s $\Rightarrow \Delta z = 6$ cm.

- Radial pressure: compression as jet enters magnet, expansion as it leaves:
$$P \approx 50 \text{ atm.} \left[\frac{r}{1 \text{ cm}}\right] \left[\frac{r}{D}\right] \left[\frac{B_0}{20 \text{ T}}\right]^2 \left[\frac{v}{10 \text{ m/s}}\right].$$
  Ex: $P = 2.5$ atm for previous parameters.

- Will the jet break up into droplets?

- Need both FEA analysis and **lab tests**.

Phase Rotation Channel

- Capture pions with large ΔE about $E \approx 150$ MeV.

- Squeeze energy in linac phased for zero gain at 150 MeV.
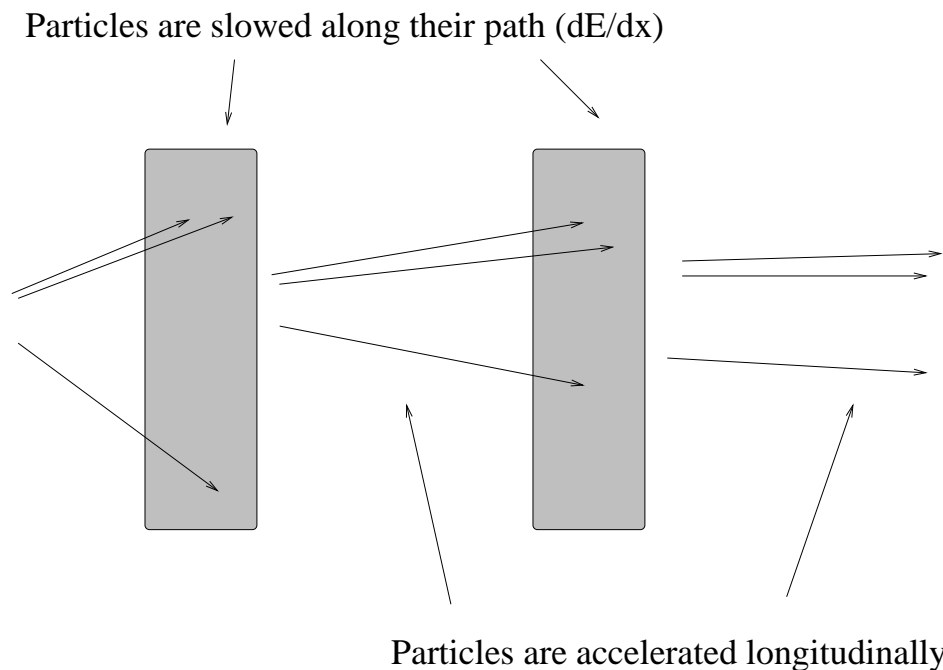
- RF cavities interspersed with 5-T magnets.
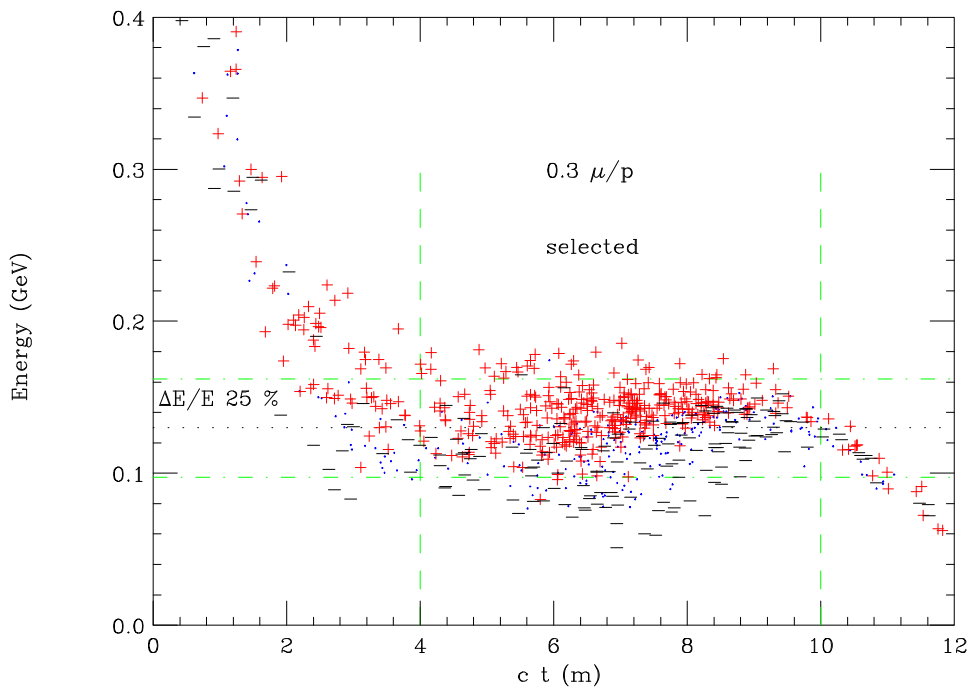
$[+ \leftrightarrow$ positive polarization, $- \leftrightarrow$ negative$]$

Linac	Length m	Frequency MHz	Gradient MeV/m
1	3	60	5
2	29	30	4
3	5	60	4
4	5	37	4

Ionization Cooling

- Need to reduce 6-D phase volume of muon beam by 10^5-10^6.

- No time for stochastic cooling.

- Ionization: takes momentum away

- RF acceleration: puts momentum back along z axis.

- $\Rightarrow$ Transverse cooling.

Particles are slowed along their path (dE/dx)

Particles are accelerated longitudinally

- Multiple scattering 'heats' the beam.

- If no heating, 'stop' the beam once, and reaccelerate.

- In practice, 'stop' the beam ≈ 10 times, $\Rightarrow$ 6-GeV acceleration.

Ionization Cooling Theory

Transverse cooling by ionization, heating by multiple scattering:

$$\frac{d\epsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_n}{E_\mu} + \frac{\beta_\perp(0.014)^2}{2\beta^3 E_\mu m_\mu \, L_R},$$

$\epsilon_n = \sigma_x \sigma_{P_x}/m_\mu c,$

$\beta_\perp =$ Betatron function at the absorber,

$L_R =$ Radiation length of absorber.

$$\Rightarrow \text{Equilibrium} \quad \epsilon_n \propto \frac{\beta_\perp}{\beta L_R(dE_\mu/ds)}.$$

$\Rightarrow$ Low-Z absorber (liquid hydrogen is best),

$\Rightarrow$ Put absorber at low-$\beta_\perp$ (beam-waist),

$\Rightarrow$ Need strong focusing (15-T solenoids, Li lens...),

$\Rightarrow$ Keep $\beta = v/c$ near 1.

[Economics favor $\beta < 1$ since must restore the beam energy many times,]

But the **energy spread rises**:

$$\frac{d(\Delta E_\mu)^2}{ds} = -2\,\frac{d\left(\frac{dE_\mu}{ds}\right)}{dE_\mu}(\Delta E_\mu)^2 \;+\; \frac{d(\Delta E_\mu)^2_{\text{straggling}}}{ds}.$$

Both terms are positive if operate below minimum of dE_μ/ds curve.

$\Rightarrow$ Must exchange longitudinal and transverse emittance frequently to avoid beam loss due to bunch spreading.
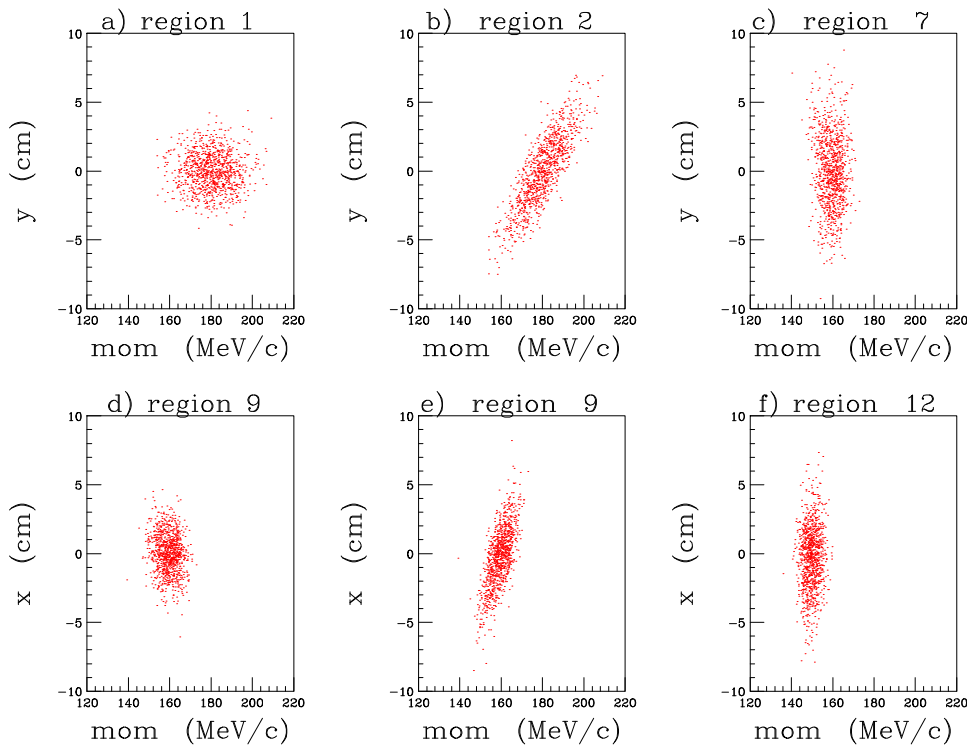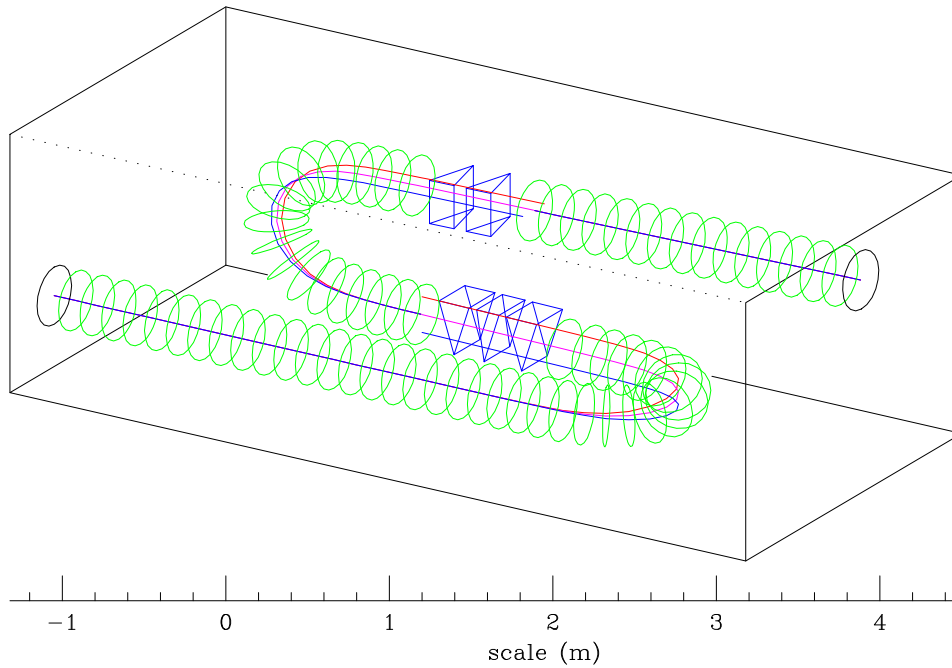
Can reduce energy spread by a wedge absorber at a momentum dispersion point:

Absorber wedge

Energy too high

Nominal energy

Equal energies

Energy too low
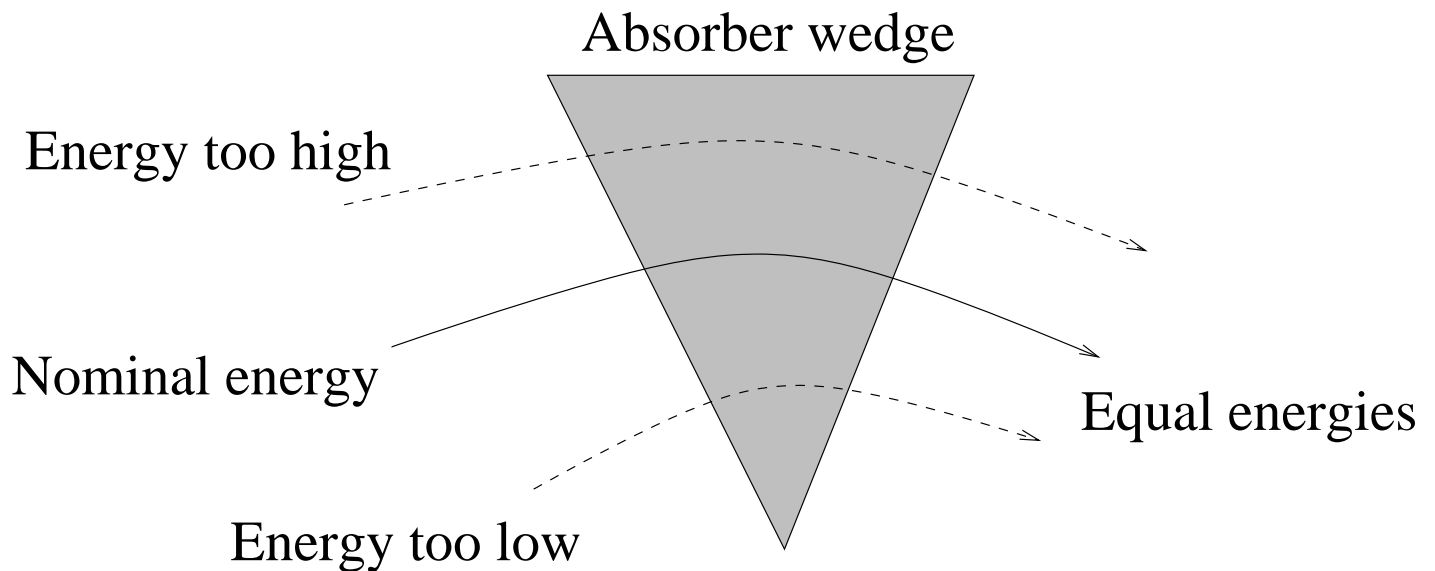
[6-D emittance constant (at best) in this process.]

Emittance Exchange Via Wedges + Bent Solenoids

LONGITUDINAL COOLING

scale (m)

a) region 1

b) region 2

c) region 7

d) region 9

e) region 9

f) region 12

Ionization Cooling of ν-Produced μ's

The muon toroids of the CCFR neutrino experiment form an ionization-cooling channel

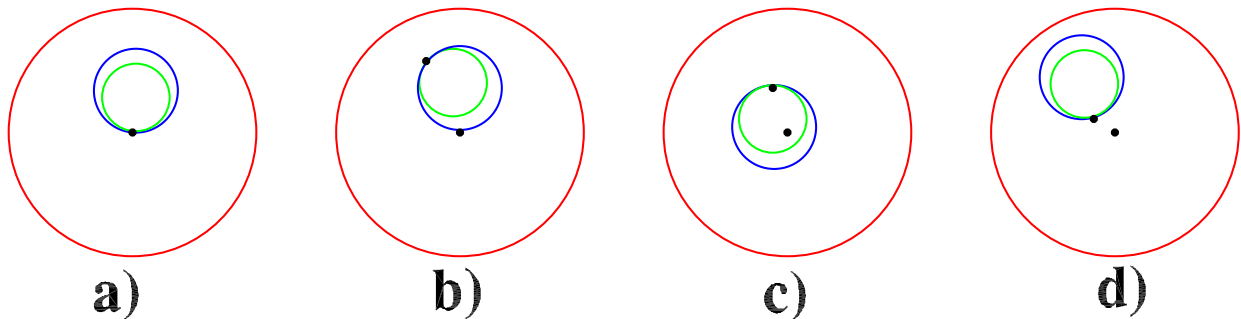(muons generated by Monte Carlo)

Entry
- 200 tracks
- $p = 10$ GeV/c
- $\sigma_x = \sigma_y = 60$ cm
- $\sigma_{px} = \sigma_{py} = 1$ GeV/c

$L = 14.7$ m
$R_{outer} = 180$ cm
$R_{inner} = 12.5$ cm
frac. Fe = 0.33
$B_{ave} \sim 0.56$ Tesla

Exit
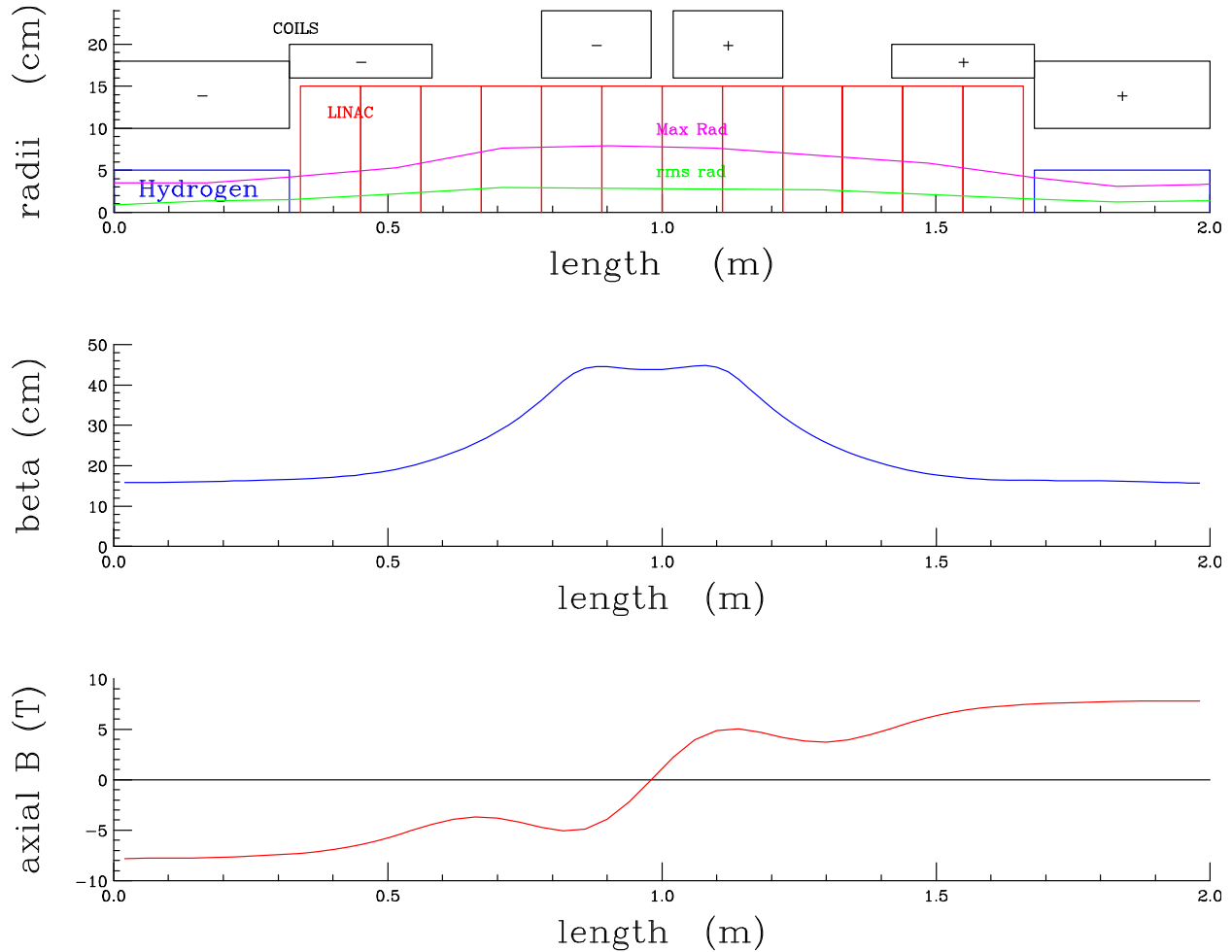$p \sim 2.4$ GeV/c

100 cm
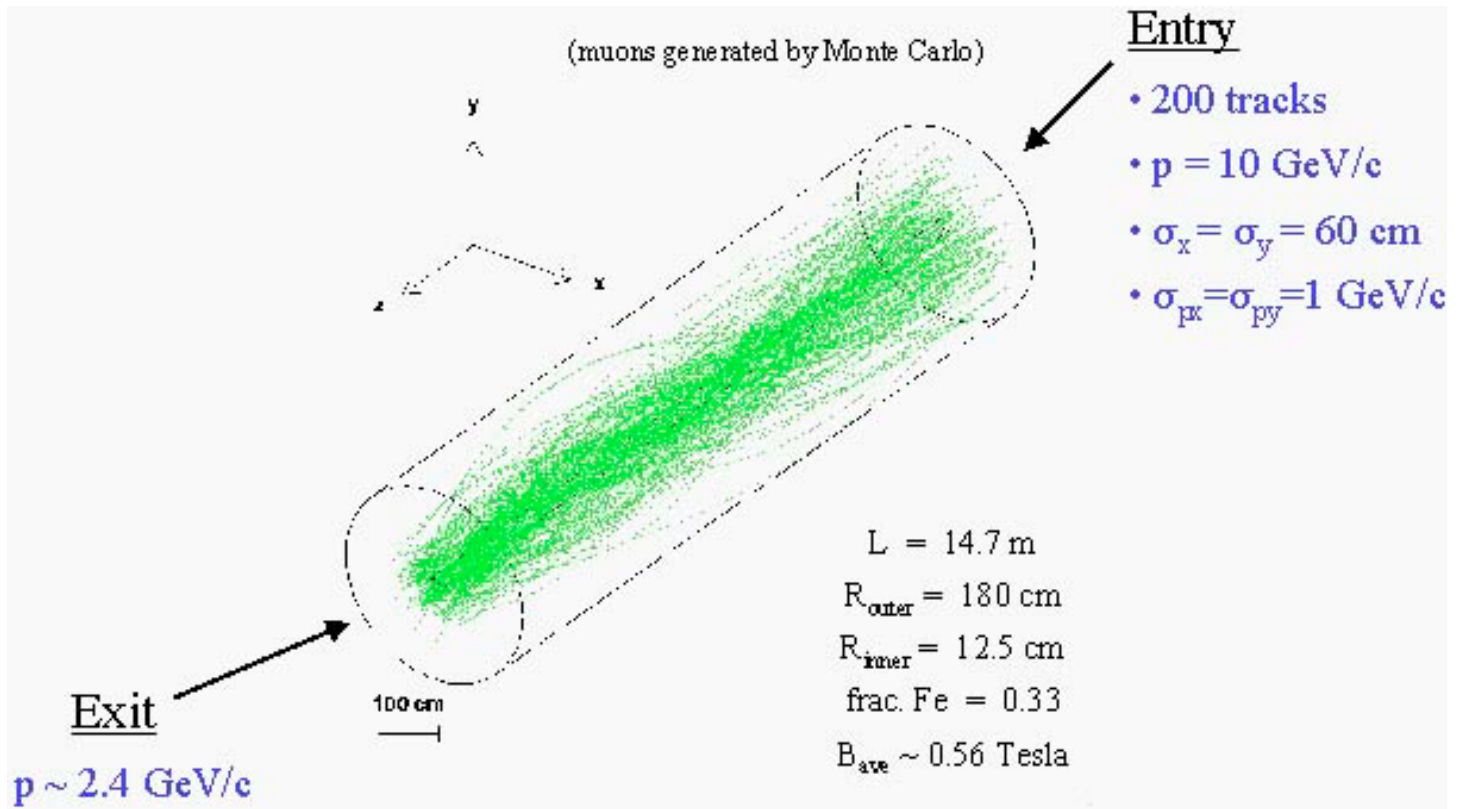
Simulation indicates $\epsilon_n \rightarrow \epsilon_n/4$.

Data analysis underway [Bruce King].

Cooling in a Channel of Alternating Solenoids

Must alternate direction of **B** to avoid buildup of canonical angular momentum.

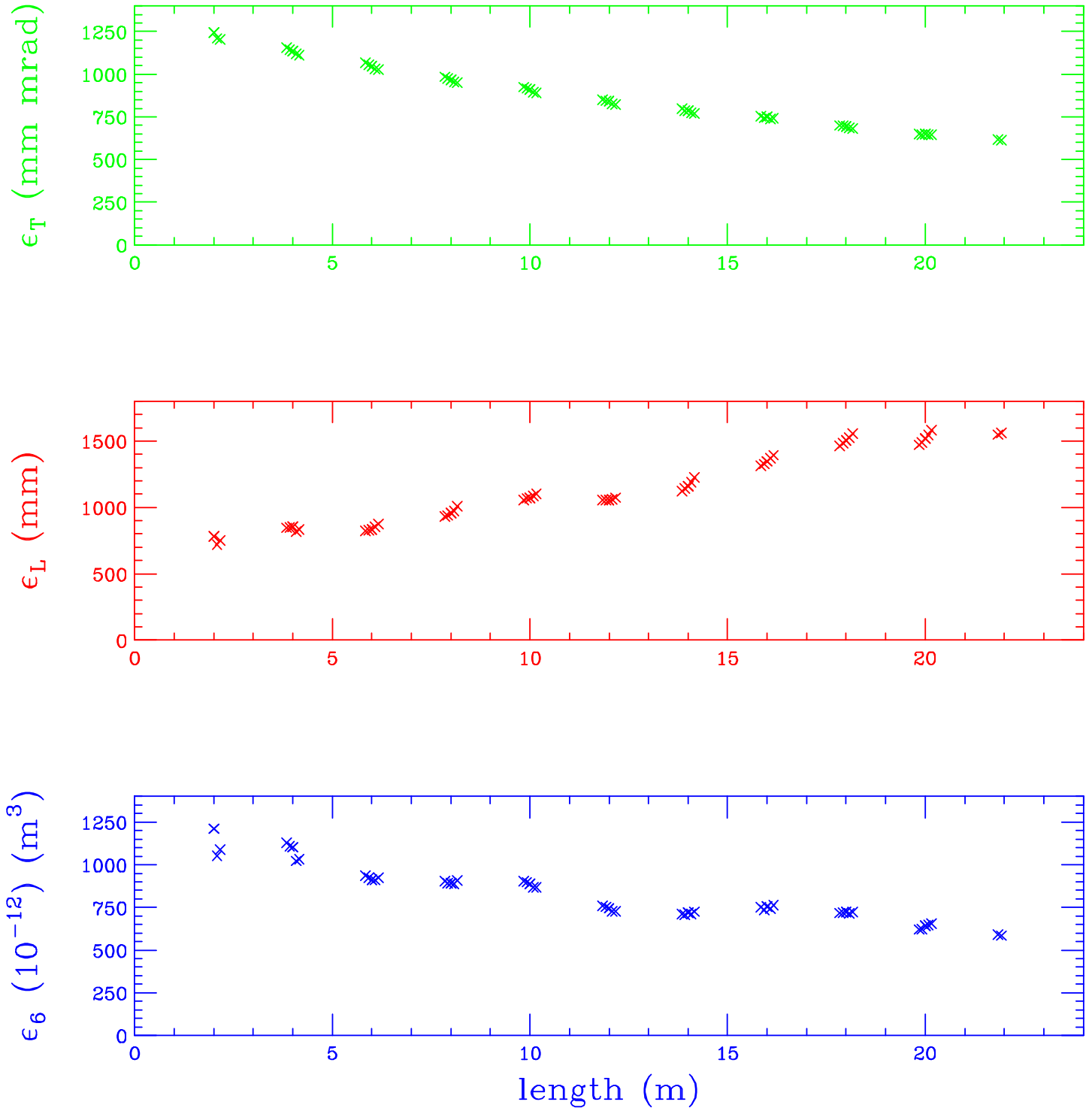A cooling **section** contains 10 2-m-long **cells** as above:

- 64 cm of LH$_2$ around the low-$\beta_\perp$ point inside a 15-T solenoid,

- 4 lower-field solenoids to flip sign of magnetic field.

- 12 $\pi/2$ mode **rf cavities**, 800-MHz, 5-mil Be windows, 30 MV/m gradient.
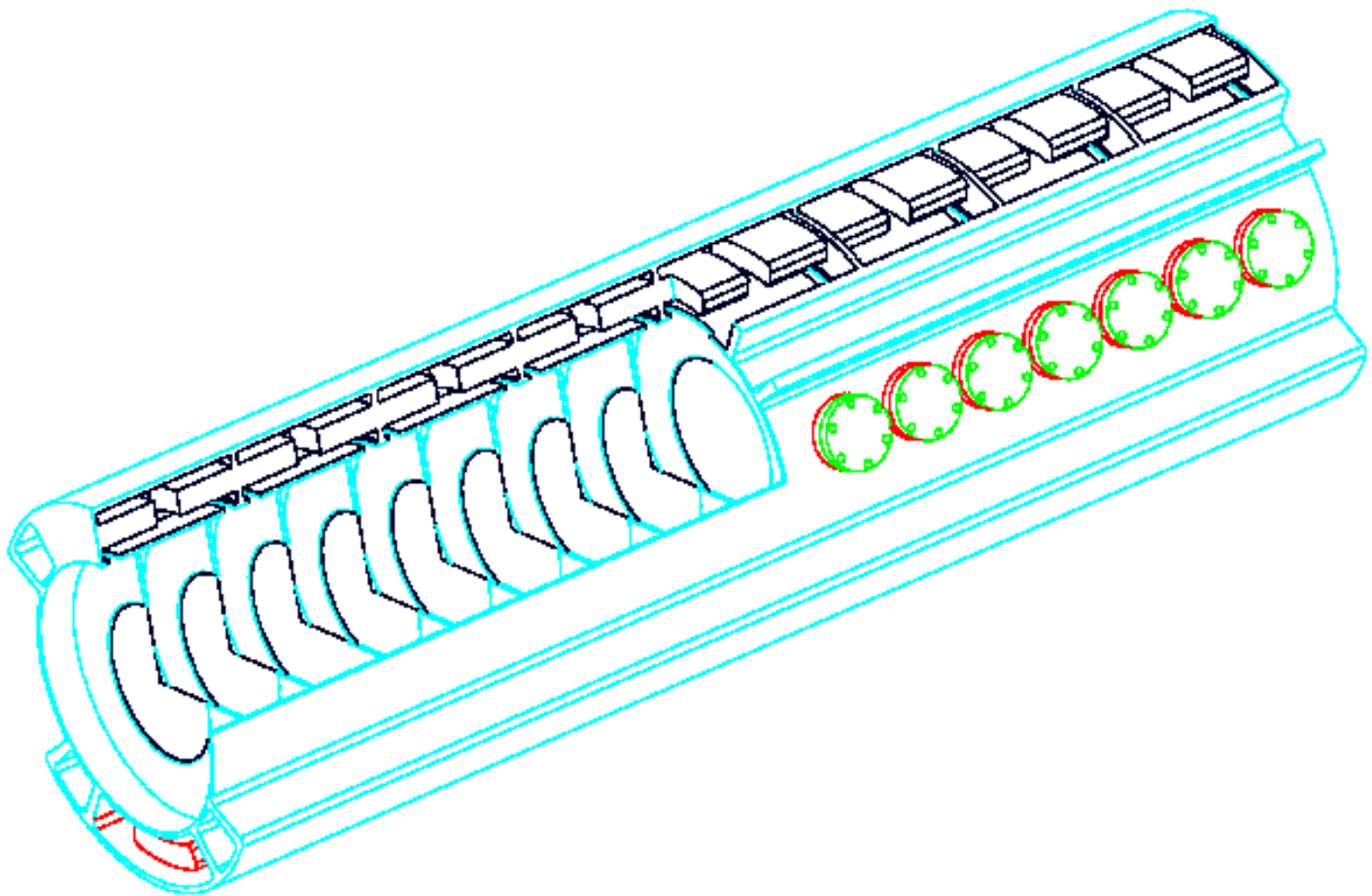
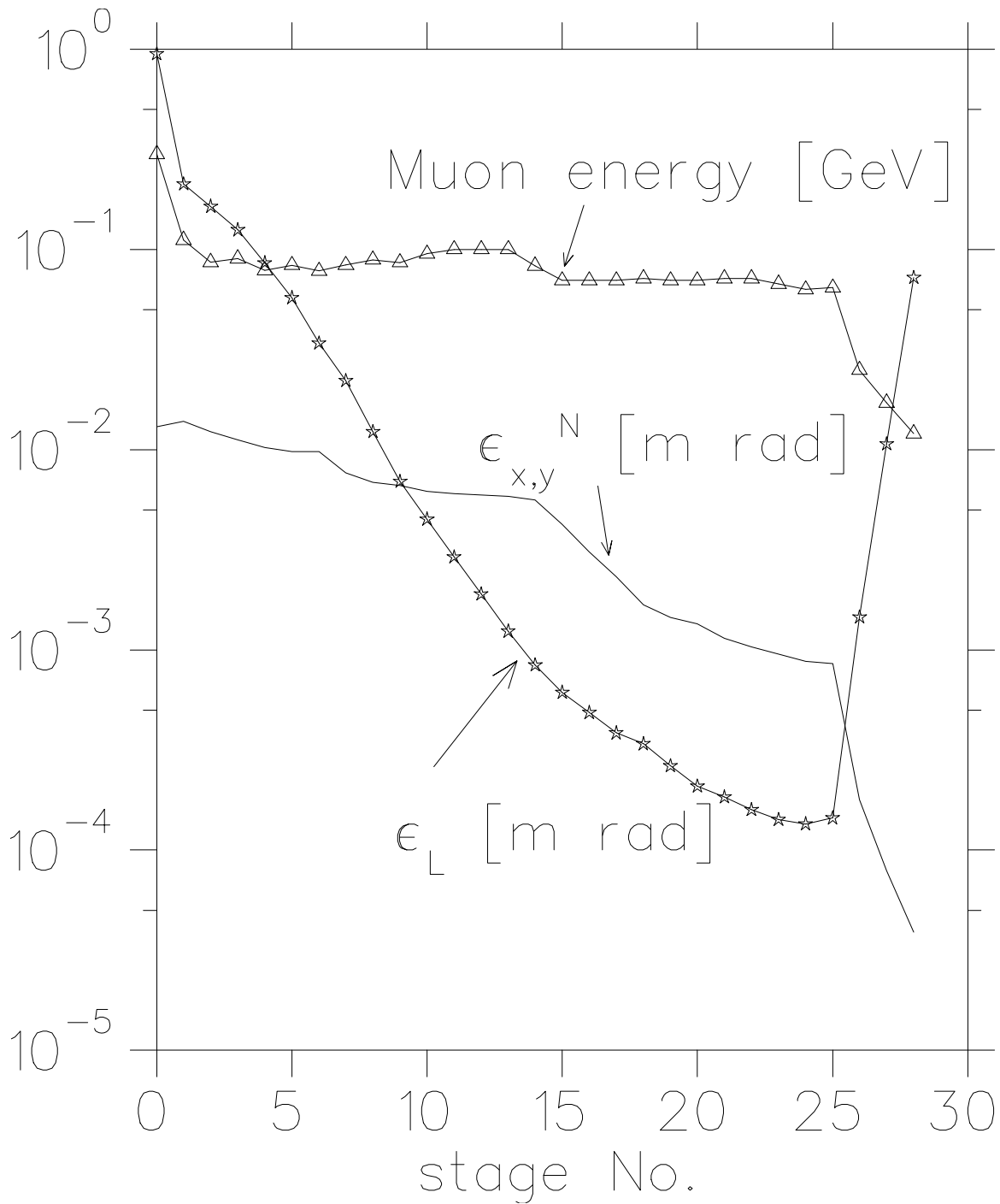
Interleaved side coupled, standing-wave structure.

[Al Moretti]

Simulated Cooling Performance

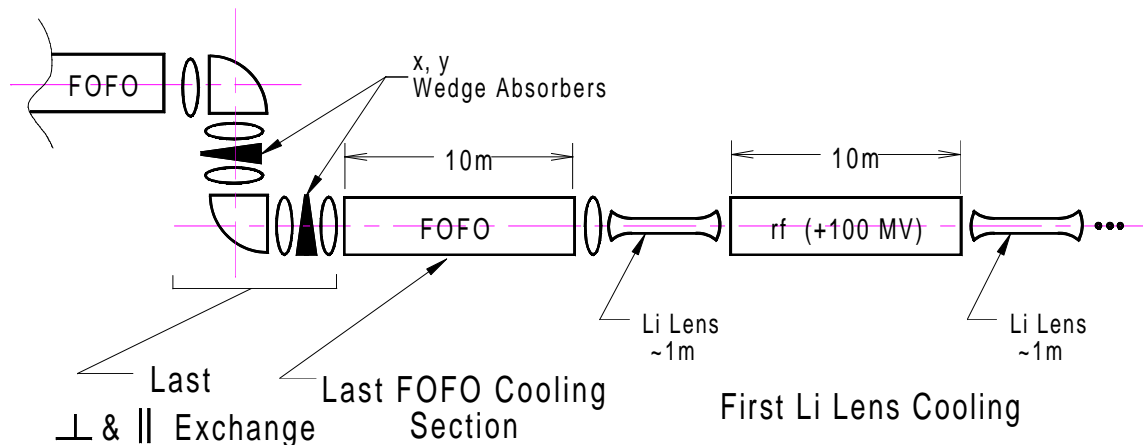Factor of 2 reduction in 6-d emittance in a 20-m stage.
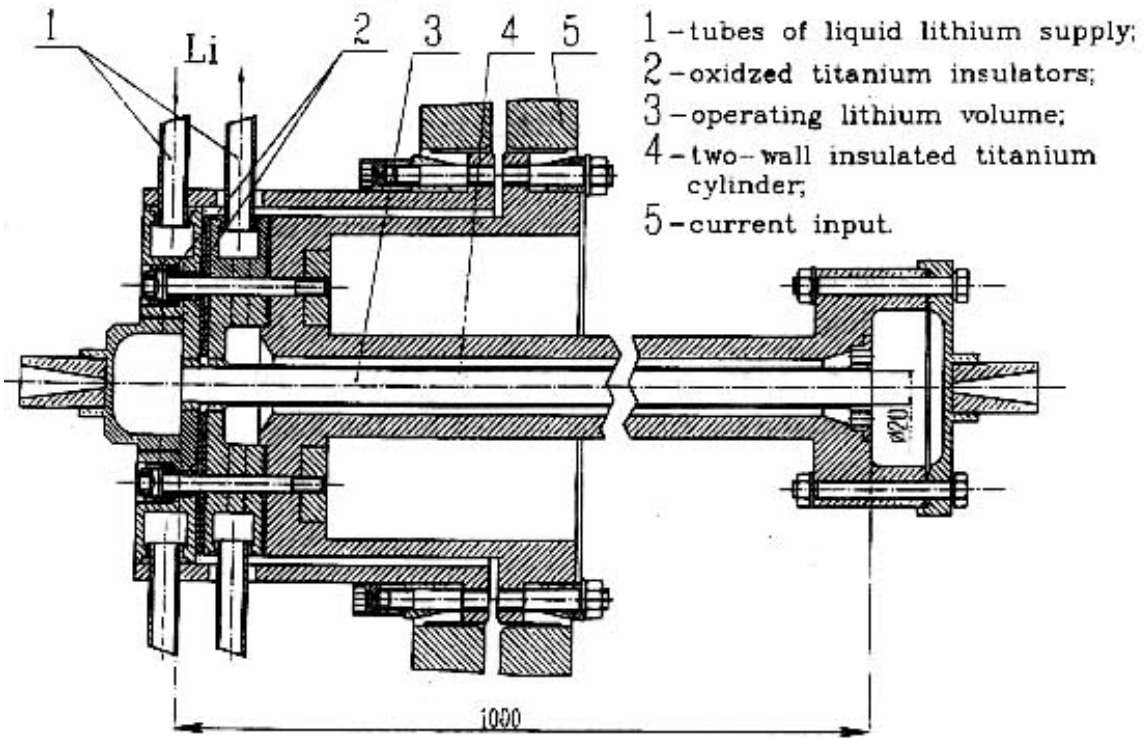
Simulated Cooling Performance

Alternating-solenoid scheme becomes difficult after ≈ 25 stages.

But more cooling is desirable.

Cooling in Lithium Lenses

FOFO

x, y
Wedge Absorbers

10m

10m

FOFO

rf (+100 MV)

Li Lens
~1m

Li Lens
~1m

Last
⊥ & ∥ Exchange

Last FOFO Cooling
Section

First Li Lens Cooling

LITHIUM CURRENT CARRYING COOLING ROD

1   Li   2   3   4   5

1 – tubes of liquid lithium supply;
2 – oxidzed titanium insulators;
3 – operating lithium volume;
4 – two-wall insulated titanium
    cylinder;
5 – current input.

1000

Simulation of Cooling in Lithium Lenses
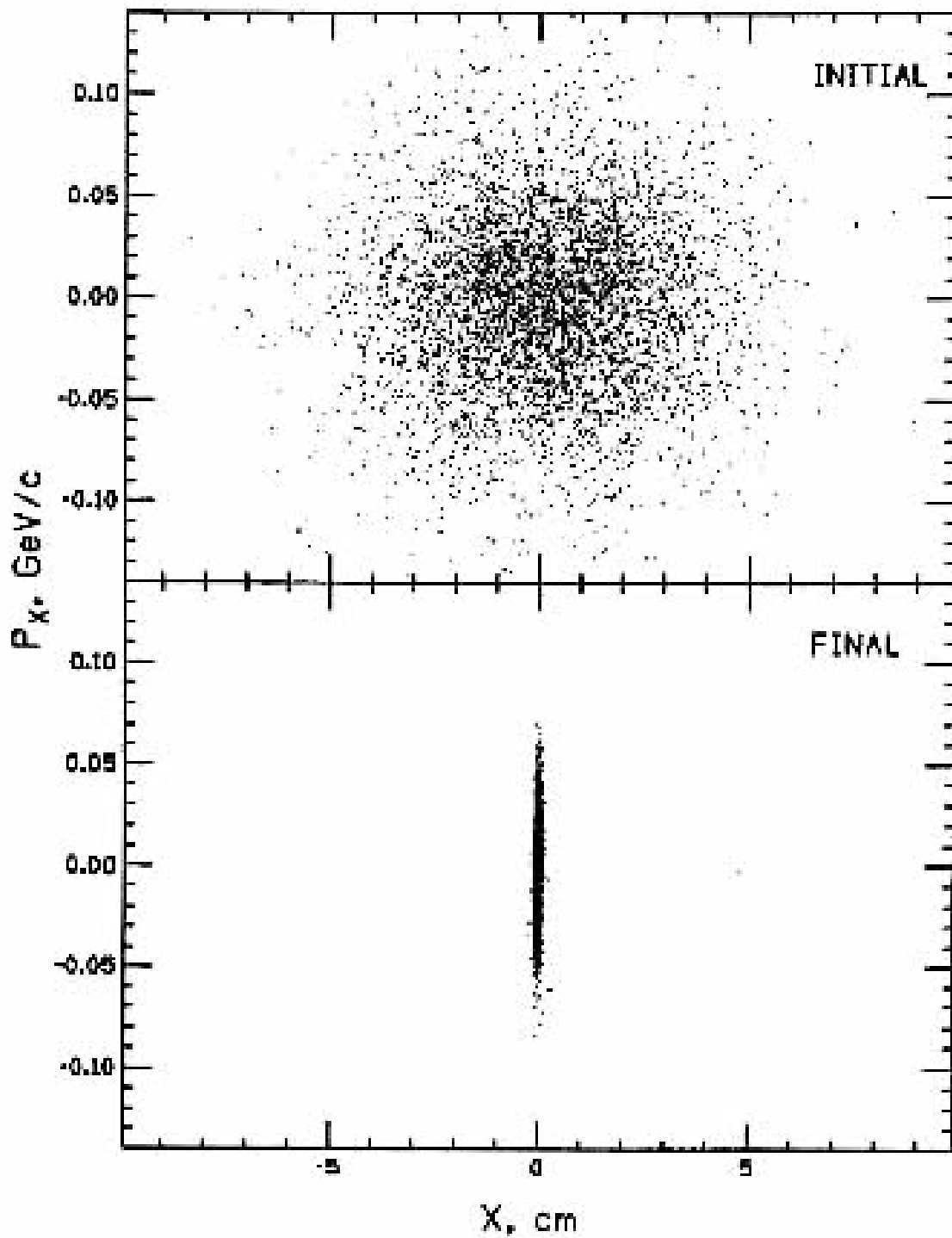
Even lower emittance 'possible' with optical stochastic cooling.

The Muon Collider Collaboration

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Collaboration Organization

Spokesperson: Bob Palmer (BNL)

Associate Spokesmen: Alvin Tollestrup (FNAL), Andy Sessler (LBNL)

Executive Committee: Bob Palmer, Juan Gallardo (BNL),
   Steve Geer, Alvin Tollestrup (FNAL),
   Andy Sessler, Jonathan Wurtele (LBNL)
   Dave Cline (UCLA), Kirk McDonald (Princeton),
   Sasha Skrinsky (BINP),Don Summers (U. Miss)

Technical Committee: Bob Palmer, Rick Fernow (BNL),
   Bob Noble (FNAL), Ron Scanlan (LBNL)

Theoretical R&D: Organizer: J. Wurtele

Cooling Experiment: Spokesman: Steve Geer (FNAL),
   Coordinators: Rick Fernow (BNL), Bill Turner (LBNL)

Target and Capture Experiment: Spokesmen:

Kirk McDonald (Princeton), Bob Weggel (BNL)

Pulsed Accelerator Magnet: Organizer:

Don Summers (U. Miss.)

Superconducting Accelerator Magnet: Organizer:

R. Scanlan (LBNL)

BNL E-910 (Pion Production): Spokesman: Harold Kirk (BNL)

FNAL E-932 (Proton Compression): Spokesman:

Jim Norem (ANL)

R&D Priorities

- Theoretical Studies:

    - Cooling scenarios (now working 'on paper'!)

    - 4-TeV Collider

    - 'Demonstration' Machines

        * $\approx$ 100-GeV Higgs Factory

        * 200- and 400-GeV Upgrades

- Experimental Programs:

    - Prototype Superconducting Accelerator Magnets and RF Cavities

    - Cooling Demonstration

    - Target and RF Capture Demonstration

    - Prototype Pulsed Ring Magnets

Cooling Demonstration Experiment
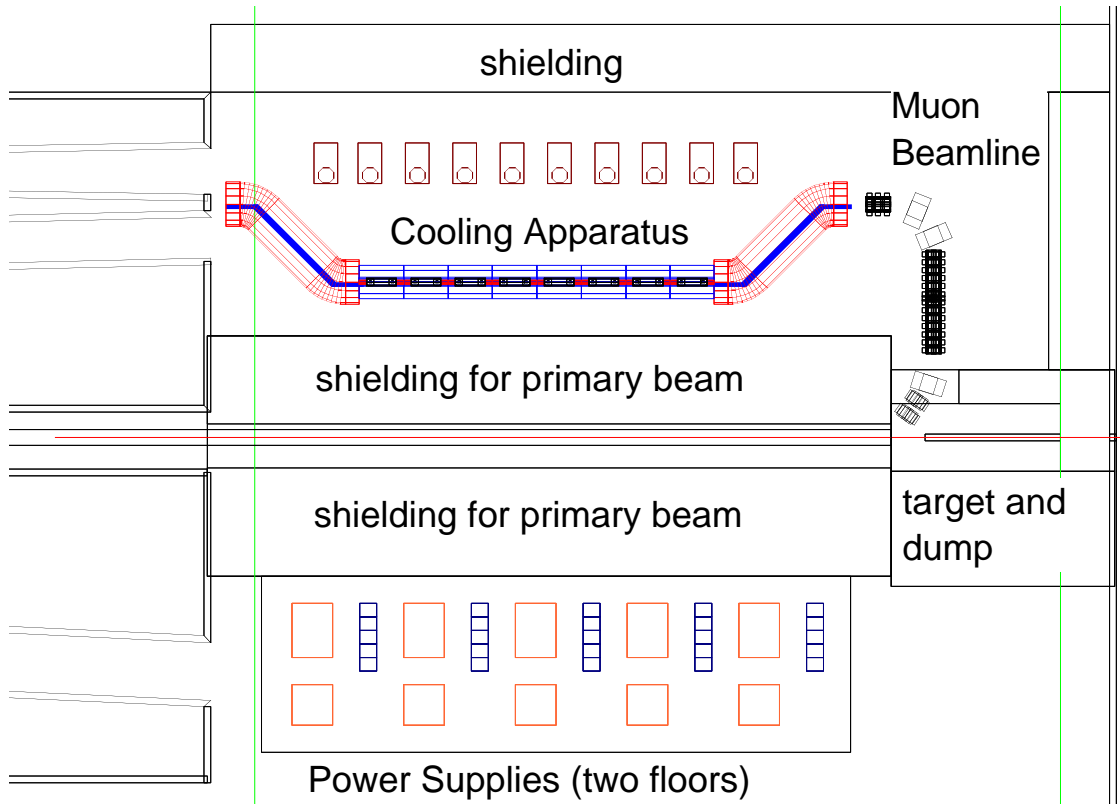
Test basic cooling components:

- Alternating solenoid lattice, RF cavities, LH$_2$ absorber

- Lithium lens (for final cooling)

- Dispersion + wedge absorbers to exchange longitudinal and transverse phase space

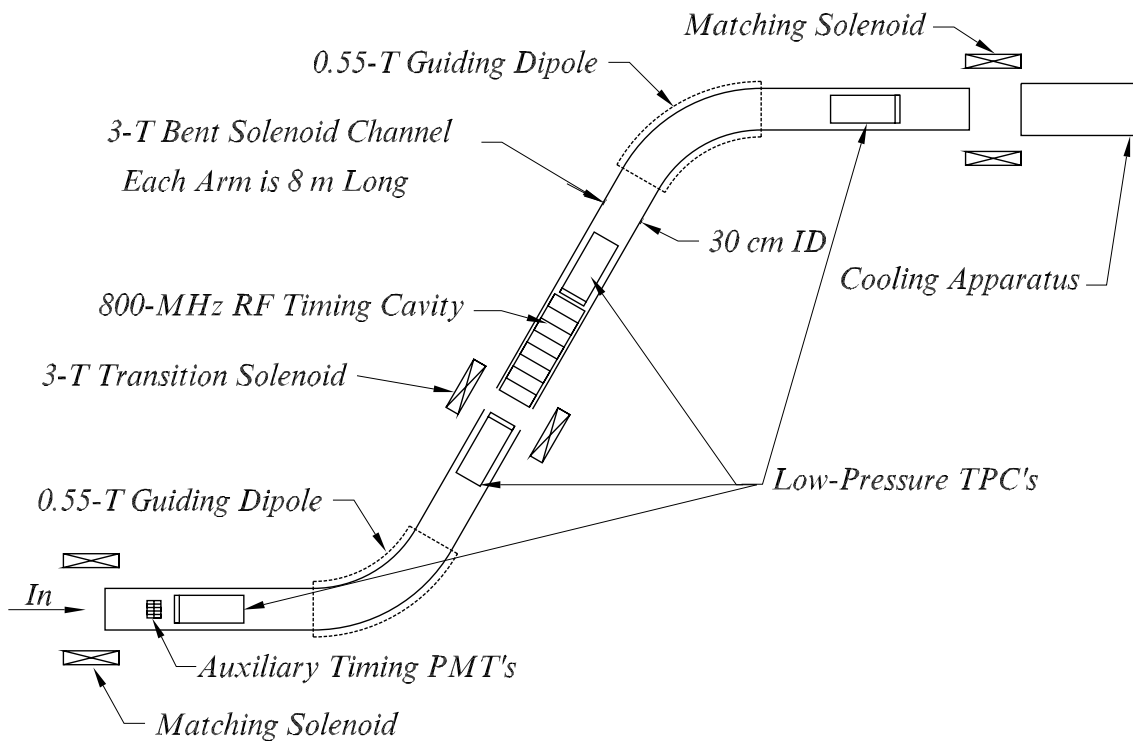Phase I: Track individual muons; simulate a bunch in software

Phase II: Cool a muon bunch from prototype source

Cooling Demonstration Experiment

Possible site: Meson Lab at Fermilab:

shielding

Muon
Beamline

Cooling Apparatus

shielding for primary beam

shielding for primary beam

target and
dump

Power Supplies (two floors)

Measure 6-D emittance before and after cooling:

Matching Solenoid

0.55-T Guiding Dipole

3-T Bent Solenoid Channel
Each Arm is 8 m Long

30 cm ID

Cooling Apparatus

800-MHz RF Timing Cavity

3-T Transition Solenoid

Low-Pressure TPC's

0.55-T Guiding Dipole

In

Auxiliary Timing PMT's

Matching Solenoid

HEPAP Subpanel Report on
PLANNING FOR THE FUTURE OF
U.S. HIGH-ENERGY PHYSICS

February 1998

Recommendation on R&D for a Muon Collider

The Subpanel recommends that an expanded program of R&D be carried out on a muon collider, involving both simulation and experiments. This R&D program should have central project management, involve both laboratory and university groups, and have the aim of resolving the question of whether this machine is feasible to build and operate for exploring the high-energy frontier. The scale and progress of this R&D program should be subject to additional review in about two years.

Options for Future Colliders at CERN

J. Ellis, E. Keil, G. Rolandi

January 23, 1998

6   RECOMMENDATIONS

3. CERN should launch technical studies of $\mu^+\mu^-$ colliders, notably in the areas of the source and beam cooling, and should explore the possibility of locating such machines on or in the neighbourhood of the CERN site.

6. These studies should be carried out in collaborations with other laboratories, since most technical problems do not depend on the site. CERN's goal in these collaborations should be to contribute to the global pool of technologies for future collider options. It should confirm its reputation as a valuable and reliable partner in the international collaborations that will form to develop proposals for future collider projects.