Fermilab
FT at MI Workshop

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Muon Colliders: A Fixed Target Physicists Dream ?

- Motivation
- Muon Collider Overview
- Muon Collider Components and Challenges
- Summary of Fixed Target Prospects
- Conclusions

Why is there a talk about Muon Colliders at this workshop ?

- A muon collider requires a very intense low energy muon source, and a system that accelerates the muons to high energies.
- This means that a muon collider comes along with :

A very intense low energy proton source, for example ... 10 x the Fermilab Booster, –> more protons for the Main Injector, rare kaon decay experiments , etc.

The possibility of providing a tremendous flux of muons for stopped muon experiments.

The possibility of providing very intense muon beams from low energies up to the collider beam energy ... for muon fixed target experiments, and the associated neutrino beams for neutrino experiments.

- In the next 12 – 18 months there is a goal of making a complete feasibilty study for the First Muon Collider. This study should include the physics potential of the collider and its front–end.
- The physics potential of the front–end of the FMC is a natural extension of the physics program being considered in this workshop.

A Brief History

- Old idea ... Muon colliders mentioned by Tinlow(1960), Budker(1969), Skrinsky(1971), Neuffer(1979).
- A key concept for a high luminosity muon collider is ionization cooling: Skrinsky & Parkhomchuk (1981).
- The realization that a high luminosity muon collider might be feasible (Neuffer & Palmer) resulted in a series of workshops. After the Sausalito workshop in 1995, Fermilab and BNL joined in an effort to study the concept and publish a report. The collaboration grew –> Muon Collider Collaboration: 19 institutions and ~ 100 physicists.
- –> $\mu^+\mu^-$ Collider: A Feasibility Study, Snowmass (1996); Fermilab–Conf–96/092 –> feasibility of a 2 x 2 TeV Collider.
- Although many questions were left open in the Snowmass report, no show stoppers were identified .... and the muon collider collaboration has therefore continued to develope the study.
- The goal for the next 12 – 18 months is to produce a report on the feasibility of the First Muon Collder (center–of–mass energy 100 – 400 GeV)

The Muon Collider Collaboration

Argonne National Laboratory

Brookhaven National Laboratory

Fermi National Accelerator Laboratory

F. Bitter National Magnet Laboratory, MIT

Lawrence Berkeley National Laboratory

Stanford Linear Accelerator Center

Center for Advanced Accelerators, UCLA

Columbia University

Fairfield University

Indiana University

SUNY, Stony Brook

University of California, Berkeley

University of California, Davis

University of Mississippi

University of Virginia

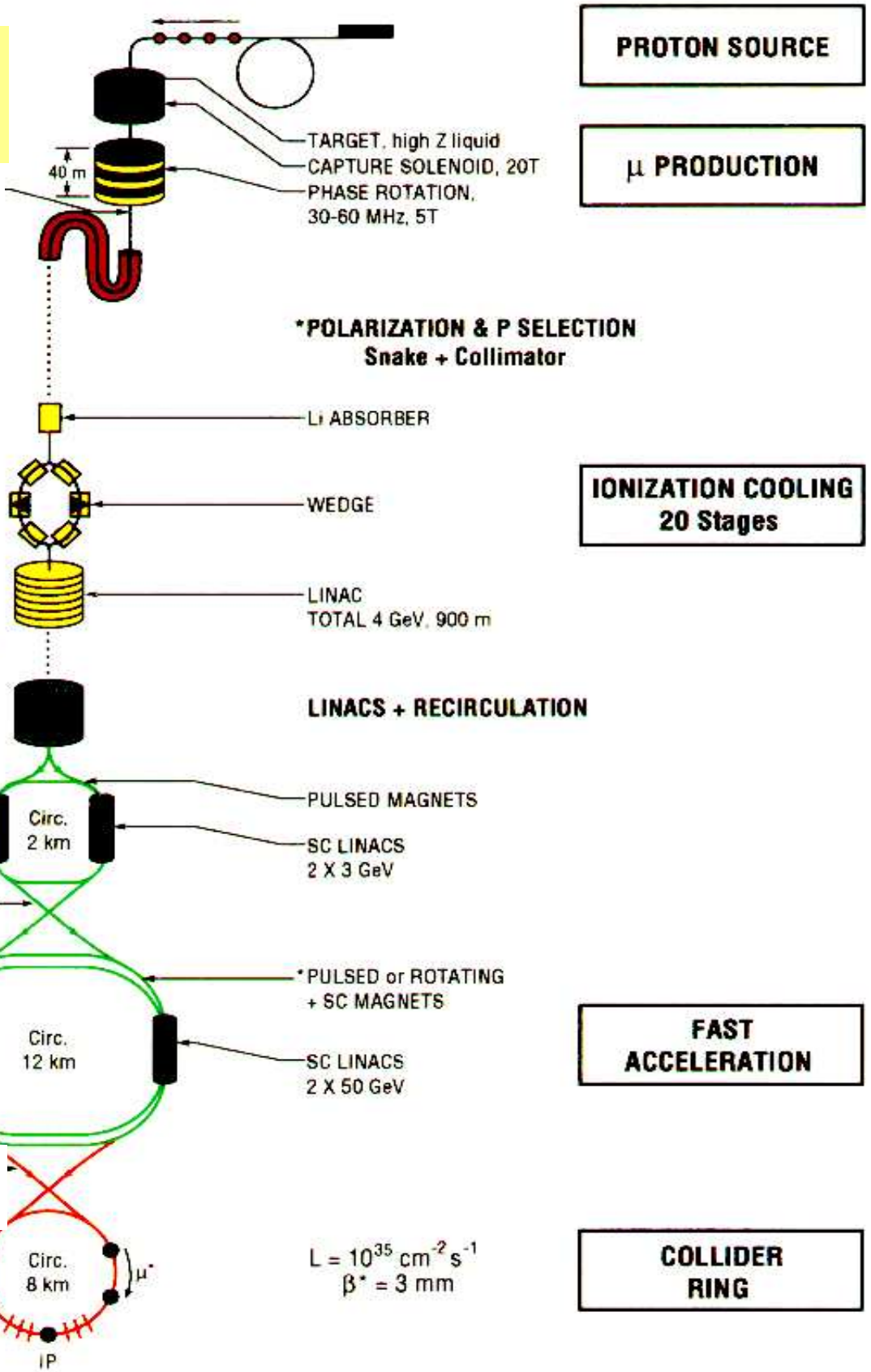
University of Wisconsin

BINP, Novosibirsk, Russia

KEK, Tsukuba–shi, Japan

DESY, Hamburg, Germany

2 x 2 TeV Muon Collider Schematic



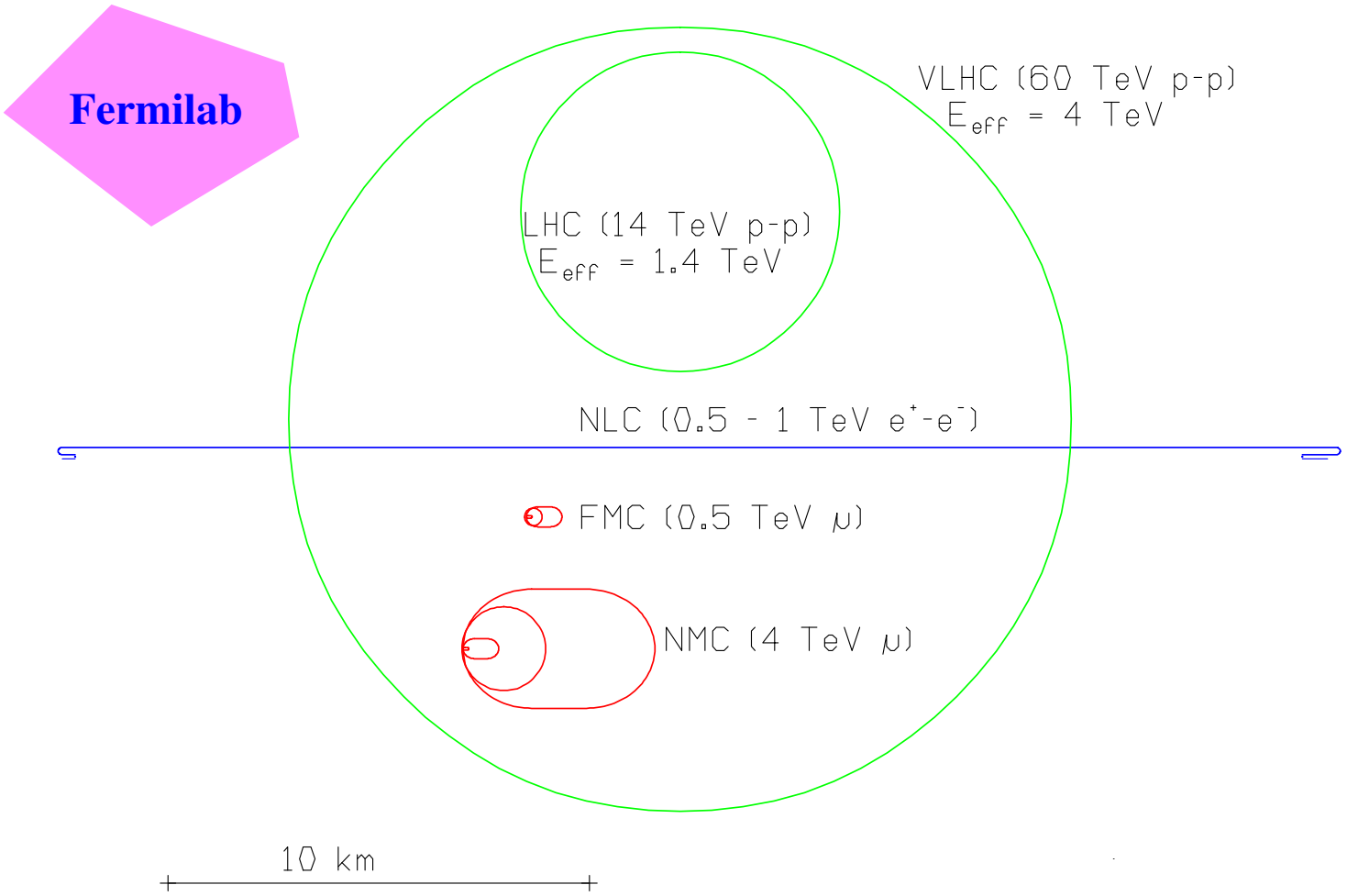
Muon Collider Parameters

- **2 collider energies have been considered in some detail so far, with most attention going to the high energy 2 x 2 TeV muon collider:**

Energy (TeV)	0.5 x 0.5	2 x 2
Rate (Hz)	2.5	15
Muons/bunch	4×10^{12}	2×10^{12}
Bunches	1 x 1	4 x 4
Circumference	1.3 km	8 km
Effective turns	800	900
rms bunch length	8 mm	3 mm
Luminosity ($cm^{-2}\ s^{-1}$)	10^{33}	10^{35}

- **The First Muon Collider would most likely be a demonstration machine with an energy in the range 50 x 50 GeV –> 200 x 200 GeV. A detailed feasibility study is beginning for a machine in this energy range. Assume the average luminosity is in the range 10^{32} –> $10^{33}\ cm^{-2}\ s^{-1}$.**

Muon Colliders can be made very compact. For example, at least 2 generations of collider would fit on the Fermilab Site.



The Proton Source

- **Two proton source energies have been considered so far: 8 GeV and 30 GeV.**

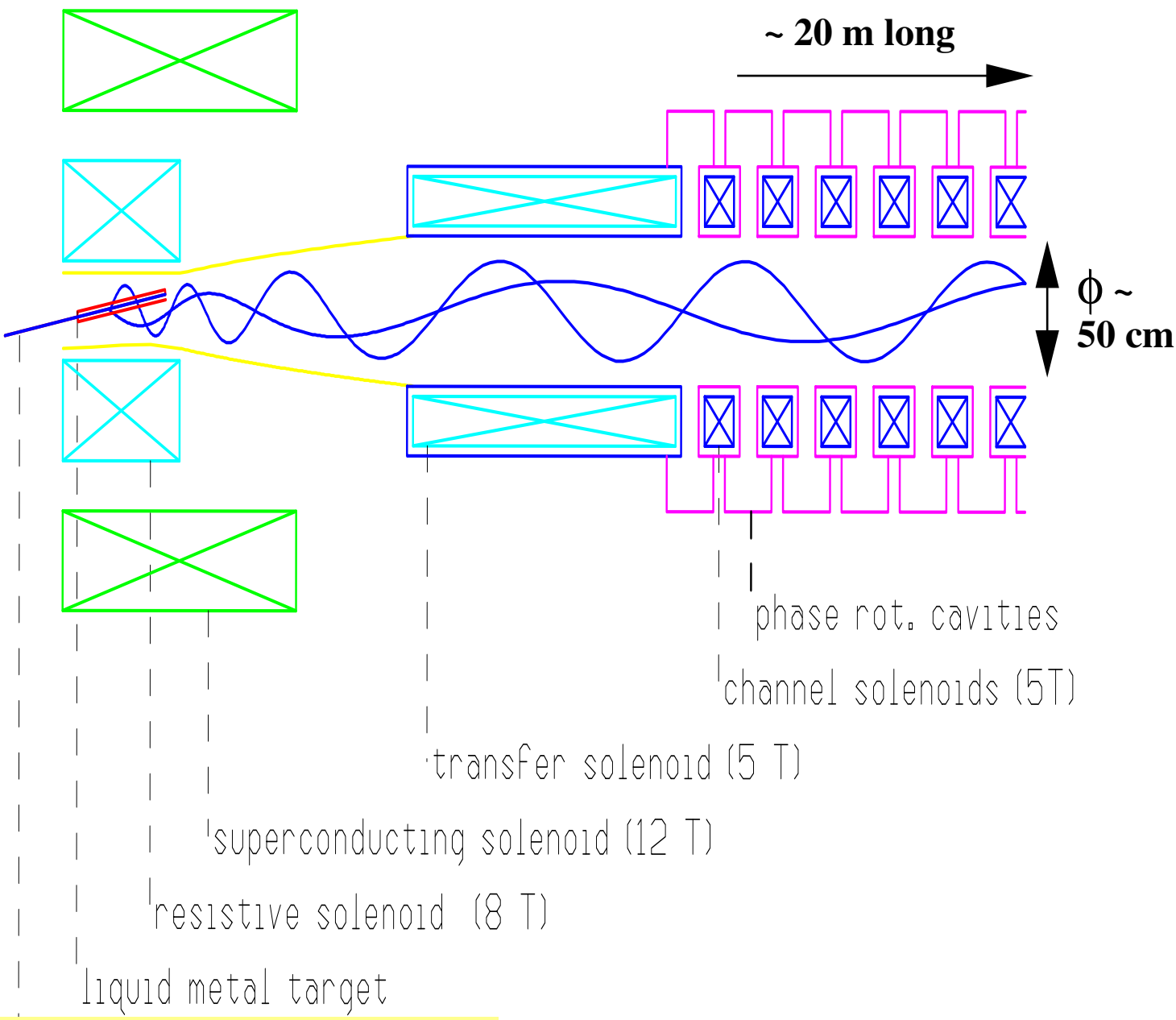
- **The muon production rate is not very sensitive to the choice of proton driver energy since increased pion production at higher energy is compensated by the higher repetition rate possible at lower energy.**

- **The lower energy option has the advantage of easier targetry (less power dumped in the pion production target) but the disadvantage that it is harder to produce very short O(1 ns) pulse lengths required by the muon collider.**

- **If the choice was 8 GeV we would need a Booster like machine .... if ~ 30 GeV perhaps the Main Injector has a role.**

- **To be explicit, consider an 8 GeV front–end proton driver delivering initially ~ 6×10^{20} protons/year and eventually ~ 1.5×10^{22} protons/year !**

The Pion Source and Decay Channel



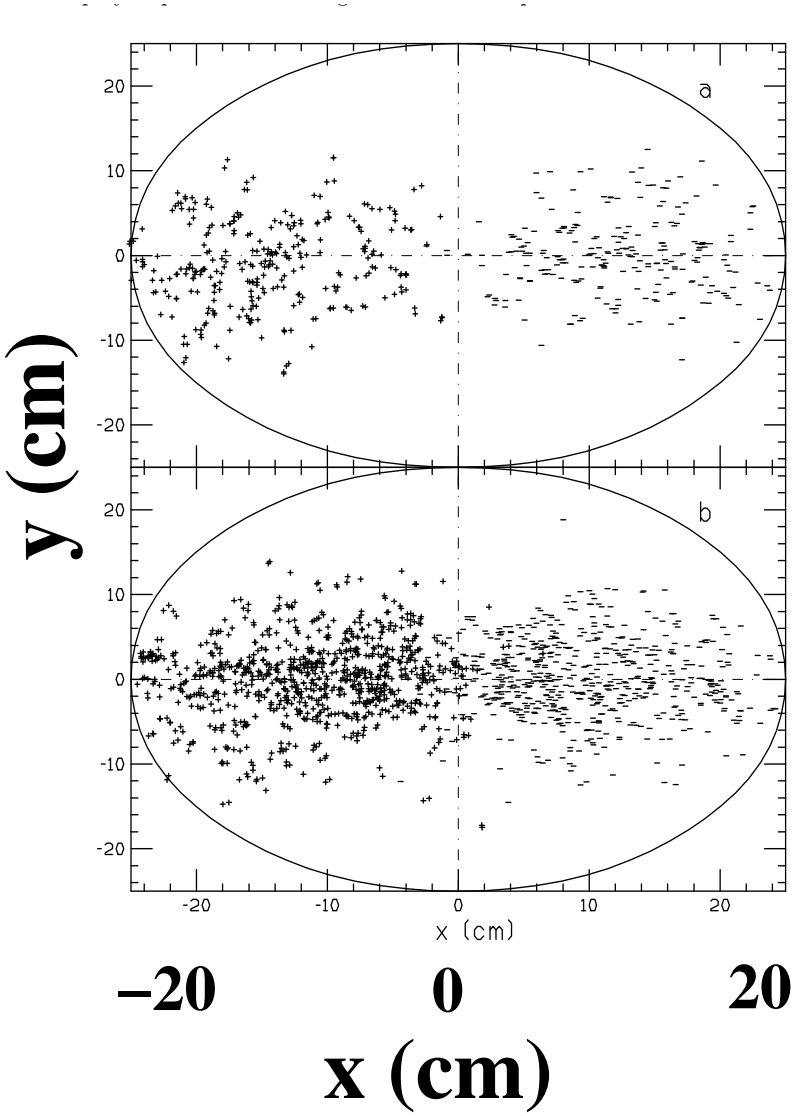
8 GeV Protons

Initially ~ 10^{12} p/bunch
x 4 bunches/pulse x 15 Hz
~ 6 x 10^{20} protons/year

→

0.5 π^+ per proton
peak π K.E. ~ 100 MeV

Bent solenoid decay channel –> charge separation.



π

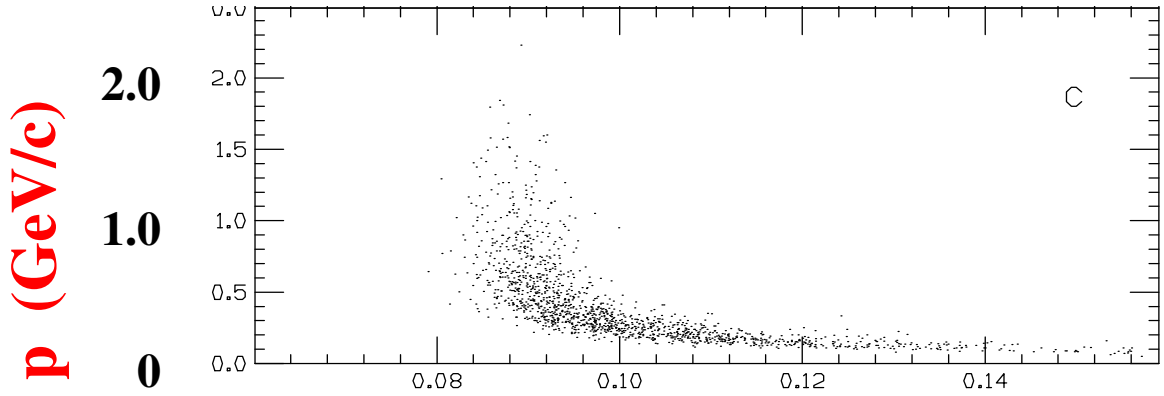
μ

Particle distributions at end of 20 m long bent solenoidal decay channel (R = 25 m)

–20 0 20

x (cm)

Muon momentum vs time at end of solenoid



p (GeV/c)

2.0

1.0

0

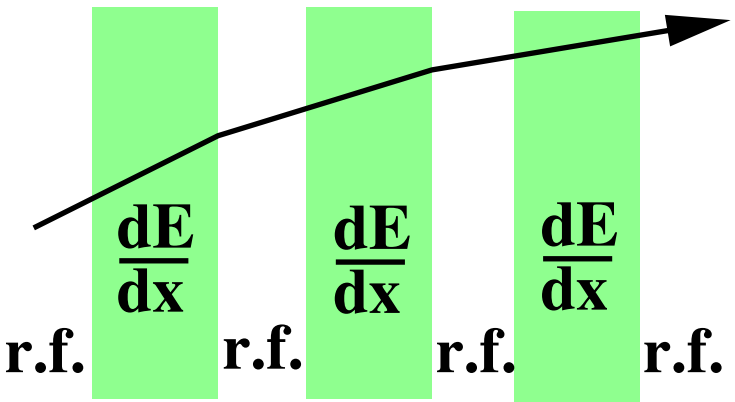
0.08 0.10 0.12 0.14

t (μs)

The Cooling System

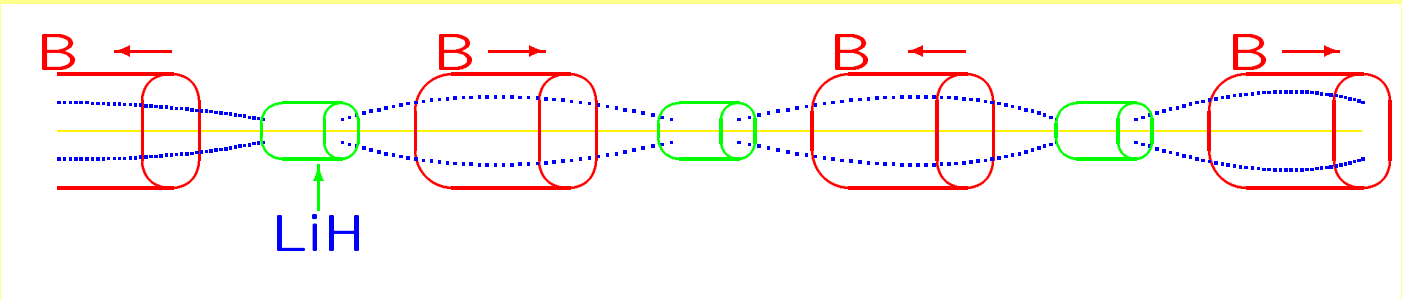
- Need to reduce the 6–dimensional "beam" phase–space by a factor of ~10^6.

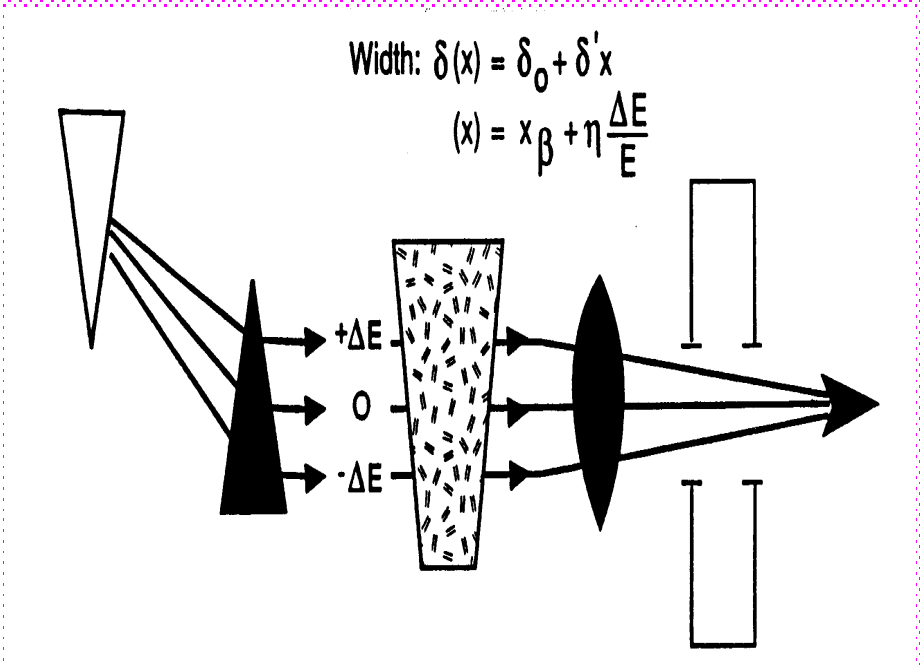
Ionization Cooling



Transverse Cooling

Muons loose energy by dE/dx and long–itudinal momentum replaced by r.f.



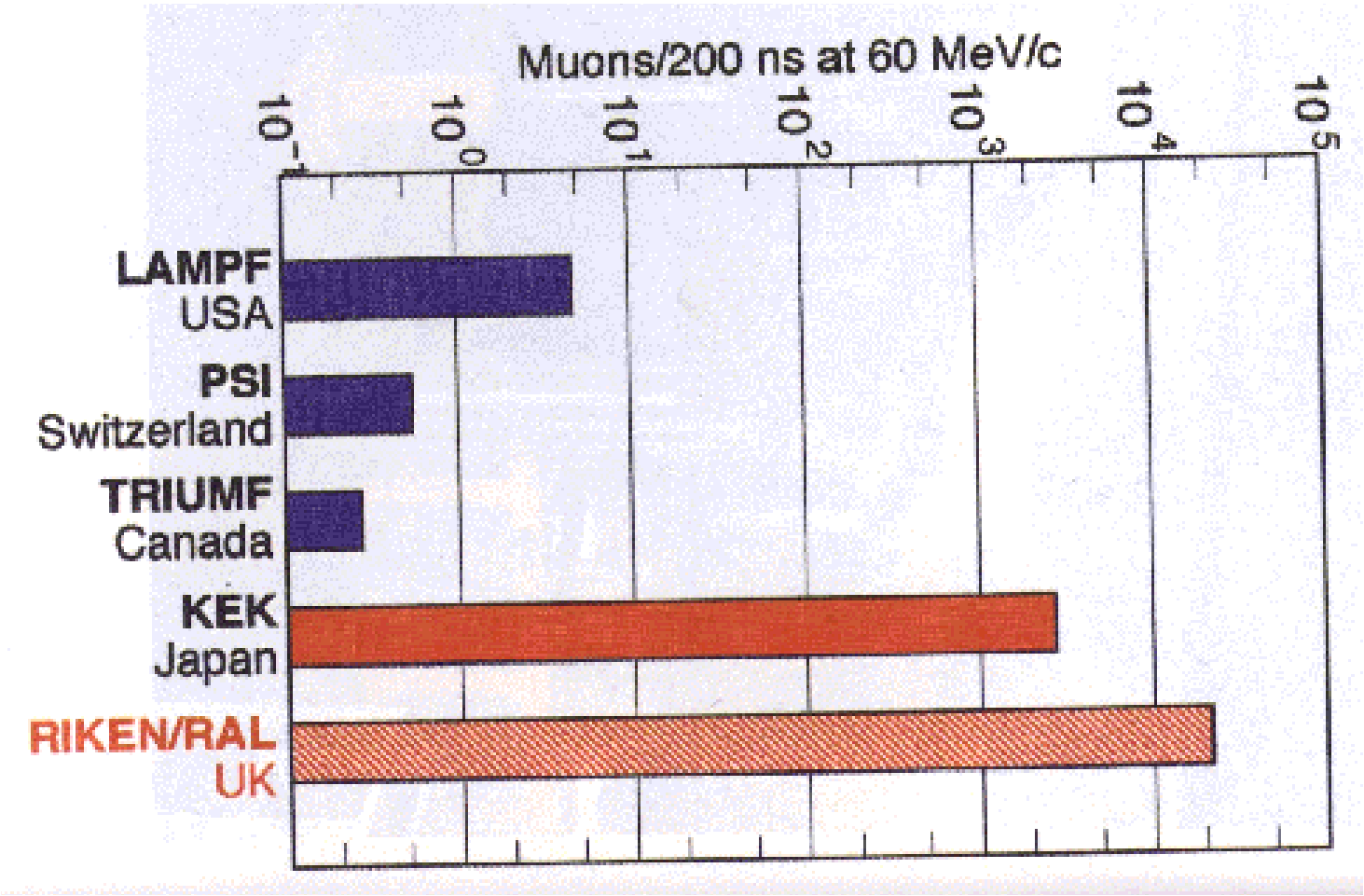


Energy Cooling

Ionization cooling using a wedge plus dispersion.

Yields initially 8 x 10^{19} muons/yr and ultimately 2 x 10^{21} muons/yr at ~ 100 MeV/c.

Low Energy Muon Beams for Stopped Muon Physics

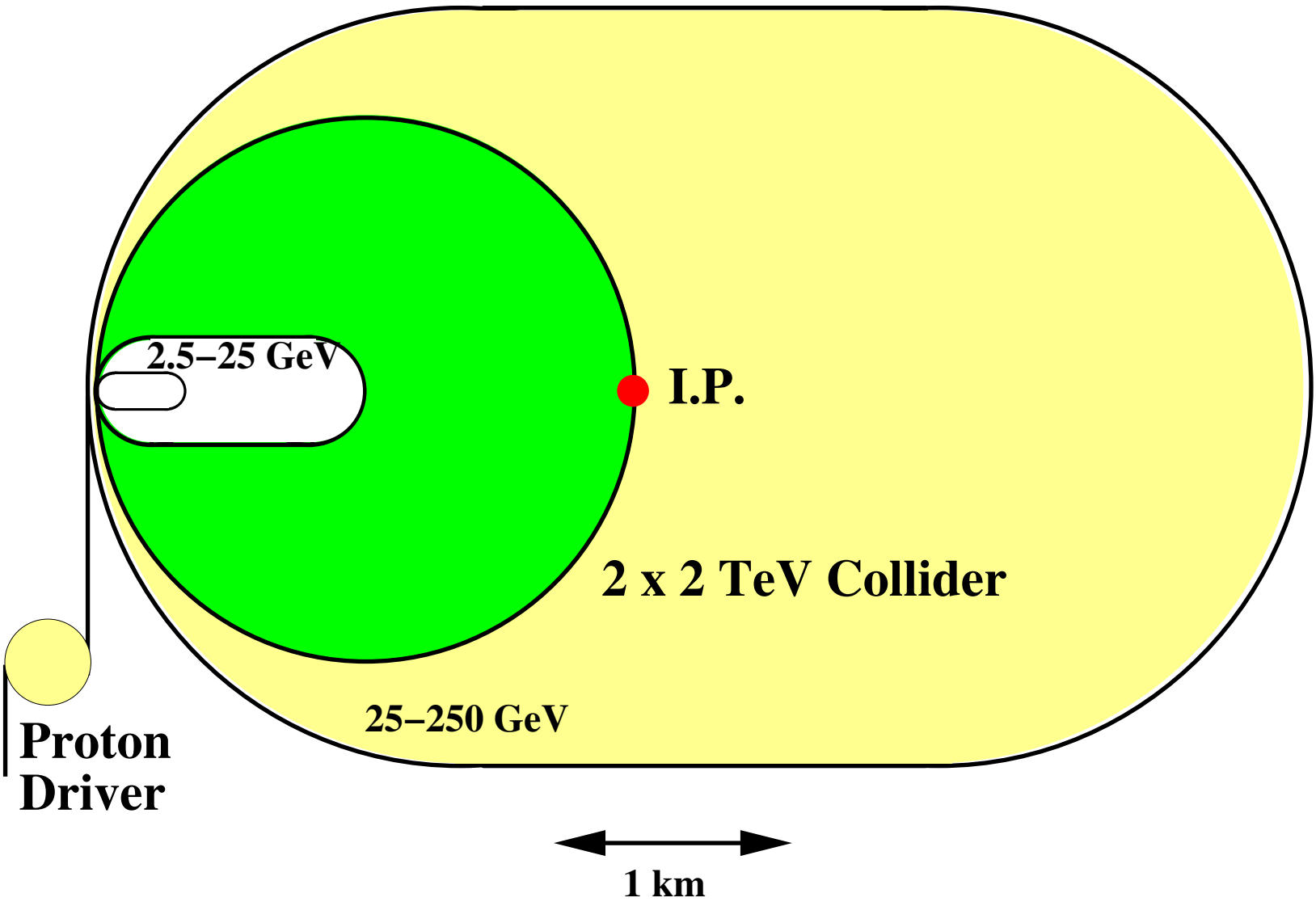


- **Front–End muon collider –> initially delivers muons at an average rate of 1.6 x 10^6 per 200 ns, ultimately 4 x 10^7 per 200 ns at ~ 100 MeV/c.**

- **Fantastic resource for $\mu \rightarrow e\gamma$ searches, $\mu \rightarrow e$ converversion, muonium – antimuonium oscillition searches etc ????**

- **Have to think carefully about bunch length and bunch rate requirements etc.**

Acceleration



- Use a series of CBAF–like recirculating LINACs and/or rapid cyclying synchrotrons.
- Could extract intense muon beams with energies from O(100 MeV) up to the collider beam energy.

Neutrino Thoughts

- **Muon beams could be extracted into a decay channel, selecting positive or negative muons, and doing this for a variety of energies up to the full collider beam energy.**

- **Number of decays in a 1 km decay channel**

Muon momentum (GeV/c)	Decays per Year Initial	Final
1	1.3×10^{19}	3.3×10^{20}
10	1.4×10^{18}	3.5×10^{19}
50	2.8×10^{17}	7.0×10^{18}
200	7.0×10^{16}	1.8×10^{18}

Where Initial = 8×10^{19} muons per year out of the cooling system, and Final = 2×10^{21} muons per year out of the cooling system.

Critical Issues

Components: Many components need modelling and design work, including lithium lenses for cooling, pulsed magnets for acceleration, high–field quadrupoles for the final focus, and large aperture dipoles for the collider ring.

Proton Driver: Need very intense and short O(ns) bunches. May need a dedicated ring to manipulate bunch length.

Targetry: Power dissipation.

Cooling: Although the principle is simple, ionization cooling has never been done .... needs a convincing ionization cooling demonstration experiment to test and tune the design calculations.

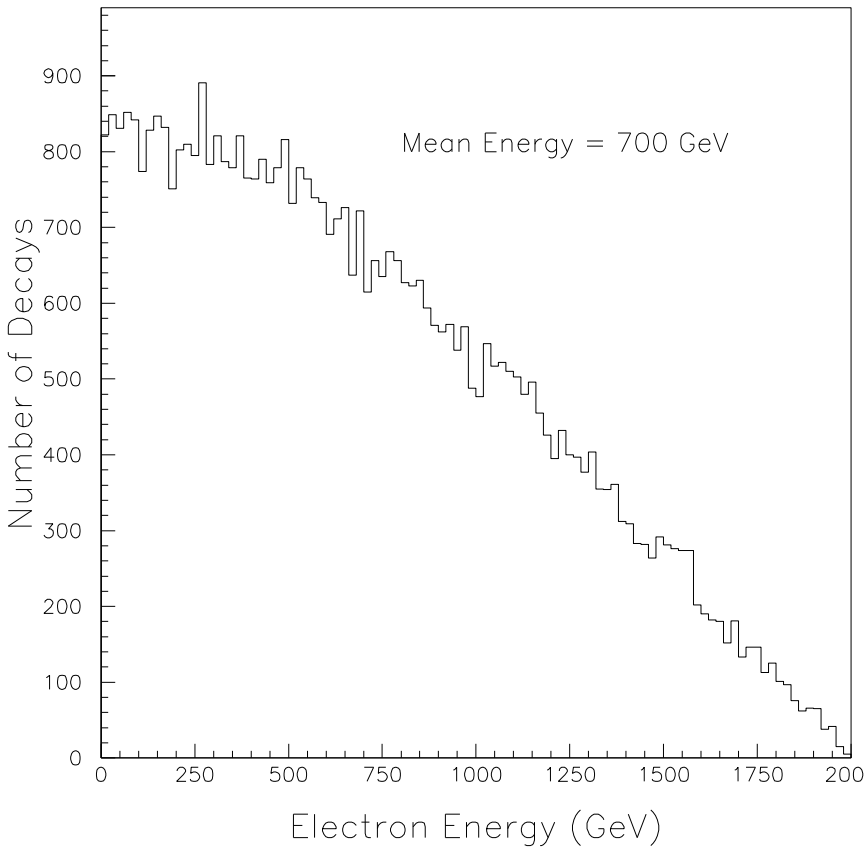
Detector Backgrounds: Need to understand whether physics can be done in the background environment of a muon collider .... intense background from muon decays.

Neutrino Background: At a sufficiently high muon collider energy the neutrinos from muon decays in straight sections of the ring are sufficiently energetic & collimated that special consideration must be given to the resulting off–site radiation dose.

Hence we need a serious feasibility study. Note however that no show stoppers have been identified yet. Also note that the technology being modelled and studied for the front–end of the muon collider opens up some interesting fixed target possibilities.

Muon Decay Backgrounds

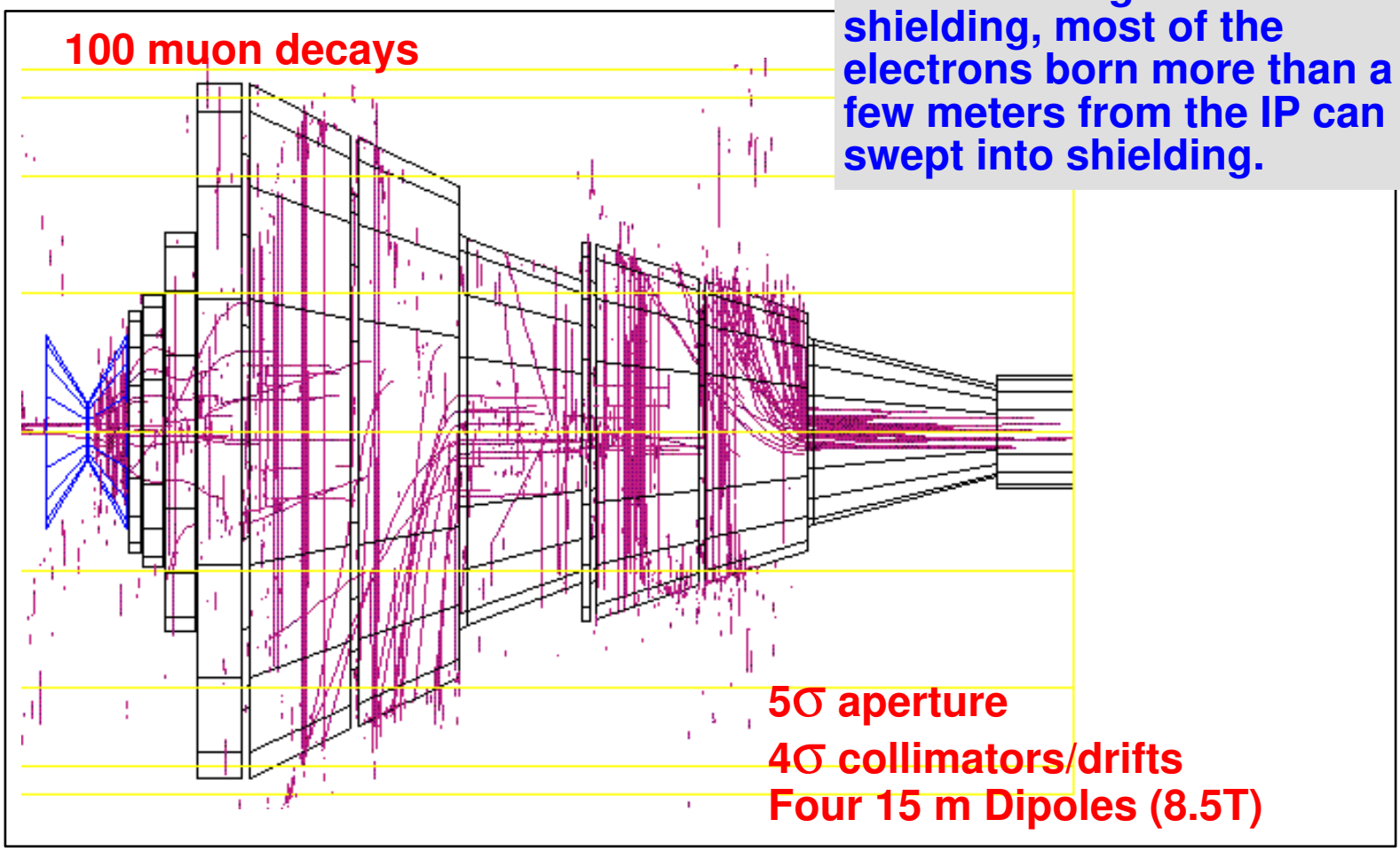
2 x 2 TeV



- 2×10^{12} muons/bunch
- 2×10^{5} decays / m
- Mean decay electron energy = 700 GeV

Electron decay angles are O(10) microradians. Therefore electrons born within a few meters of the IP do not contribute to backgrounds seen in the detector.

With carefull design of the final focus region and the shielding, most of the electrons born more than a few meters from the IP can swept into shielding.



Background Calculations

- **Two detailed complementary calculations have been performed:**

  GEANT calculation (I. Stumer, BNL)

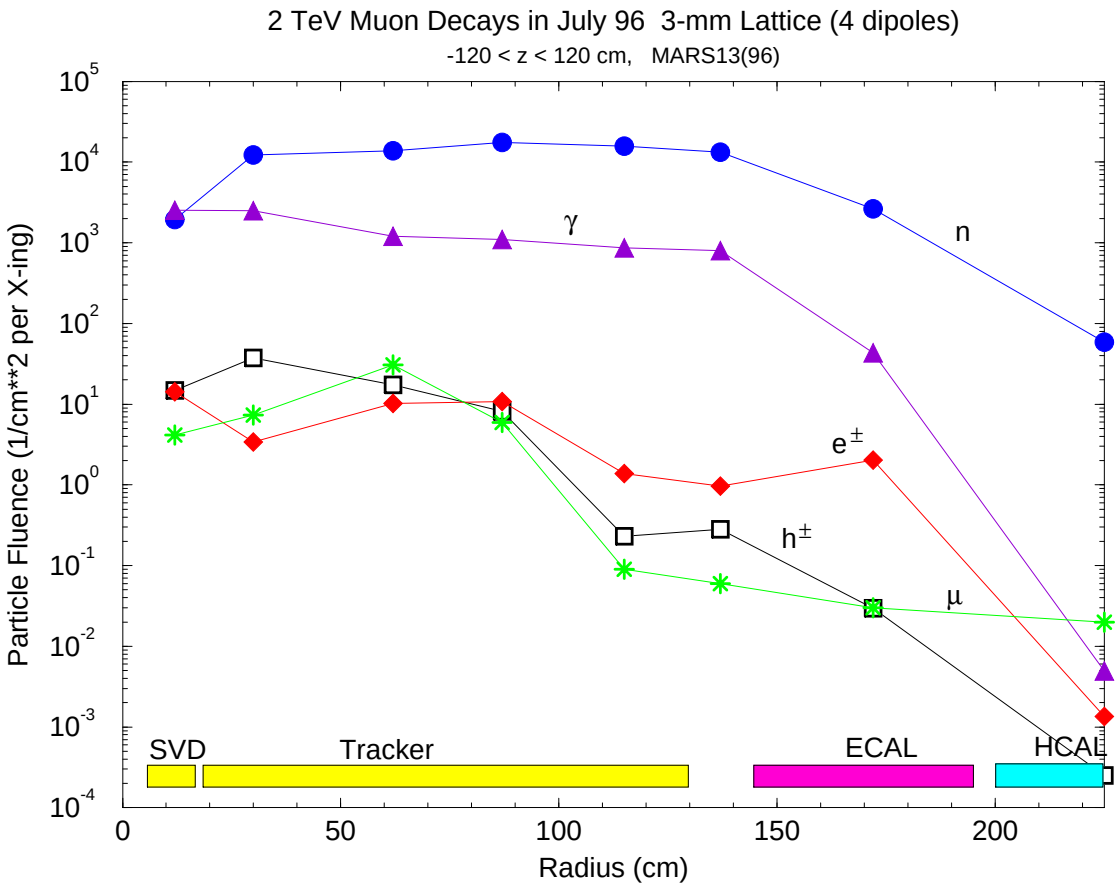
  MARS calculation (N. Mokhov, FNAL)

- **The assumed final focus system and shielding configurations assumed for the two calculations are similar in general, but the details are very different.**

- **Both the GEANT and MARS calculations track all particles through the final focus and 2 Tesla detector solenoidal fields and fully simulate:**

  Electron showers
  Synchrotron radiation
  Photonuclear interactions
  Bethe–Heitler muon pair production

Background Results



MARS RESULTS

radius (cm)	Particle Type γ	n	p	π	e	μ
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	–	0.02
100	31	50	0.04	.003	–	0.008
calo						0.003
muon						0.0003

GEANT RESULTS
Radial fluxes / cm² per crossing

Implications for a Vertex Detector

- **Consider a layer of Silicon at a radius of 10 cm. The GEANT results for the radial particle fluxes per crossing yield:**

750 photons/cm^2	–>	2.3 Hits/cm^2
110 neutrons/cm^2	–>	0.1 Hits/cm^2
1.3 charged tracks/cm^2	–>	1.3 Hits/cm^2
TOTAL		3.7 Hits/cm^2

–> 0.4% occupancy in 300 x 300 μm^2 pixels.

- **The corresponding numbers at 5cm radius are 13.2 Hits/cm^2 –> 1.3% occupancy.**
  This doesnt sound too bad. For comparison, SLD has about 40 Hits/cm^2 on the inner layer of their CCD detector.

- **Radiation Dose –> Similar to LHC environment**

MARS predictions (1 year = 10^7 secs)

	Non–Ionizing Energy Loss (particles/cm^2/year)
2 x 2 TeV muon collider	7 x 10^{13}
LHC at 10^{34} cm^{-2}s^{-1}(CMS)	8 x 10^{13}

Implications for Central Calorimeters

- **Electromagnetic:** Consider a calorimeter at r = 120 cm, 25 r.l. deep, 4 m long, 2 x 2 cm² cells:
  - GEANT –> about 400 photons/tower/crossing with a mean energy of ~ 1 MeV.
  - –> Mean E_{Tower} = 400 MeV
  - $\sigma_E \sim \sqrt{2 \langle n_\gamma \rangle} \langle E_\gamma \rangle$ = 30 MeV

    For a shower occupying 4 towers:

    $\langle E \rangle$ = 1.6 GeV and σ_E = 60 MeV

- **Hadronic:** Consider a calorimeter at r = 150 cm, 2.5 m deep (~10 λ), covering 30–150 degrees, 5 x 5 cm² cells:

  Mean E_{Tower} = 1 GeV

  $\sigma_E \sim \sqrt{2 \langle n_\gamma \rangle} \langle E_\gamma \rangle$ = O(100 MeV)

These estimates were made at Snowmass when the final focus + shielding configuration yielded an order of magnitude higher backgrounds ... guess that with current configuration calorimeter background fluctuations reduced by about x 3

Muon Collider Front–End

- An intense low energy proton source delivering initially ~ 6 x 10^{20} protons/year and ultimately ~1.5 x 10^{22} protons/year at 8 GeV/c.

- An extremely intense very low energy muon source producing initially 8 x 10^{19} muons/yr, and ultimately 2 x 10^{21} muons/year at ~100 MeV/c.

- A muon accelerator complex producing muon beams with energies up to a max imum of, for example, 200 GeV, and the accompanying neutrino beams.

- The First Muon Collider ring, providing $\mu^+\mu^-$ collisions with a center – of – mass energy to be choosen in the range 100 – 400 GeV with average luminosities of $10^{32} - 10^{33}$ cm^{-2} s^{-1}

Workshop on Physics at the First Muon Collider and at the Front–End of a Muon Collider

The purpose of the workshop is to develop an understanding of the physics potential of the First Muon Collider, including the potential of the front–end of the collider complex. In particular the work–shop will consider the potential for:

(a) Exploiting the proton source for kaon rare decay search experiments and precision measurements.

(b) Using the very low energy muon beam to do high statistics stopped muon experiments.

(c) Using low and high energy muon beams.

(d) Making and exploiting intense neutrino beams from parent μ^+ and μ^- beams at a variety of energies.

(e) The physics capabilities of the collider itself as a function of center of mass energy.

Summary

- The front–end of a muon collider would provide a great facility for fixed target physics with an intense proton source, stopped muon source, muon beams, and neutrino beams.

- As a part of the muon collider feasibility study, in the next 12 – 18 months we need to under–stand the physics potentialof the front–end of the First Muon Collider, and how this would fit into the overall Fermilab physics program –> there will be a workshop on this later this year. If you are interested in the workshop, or want to know more about muon colliders, please let me know (sgeer@fnal.gov).

- Even if you are not interested in attending another workshop this year, whilst thinking about fixed target physics at the main injector please also think a bit about what you could do if the facilities at Fermilab were extended to include the front–end of a muon collider ... any thoughts or ideas you might have would be useful input for us.