Future Prospects for Muon Facilities

- **Introduction**
- **History: from colliders to factories**
- **Neutrino factory concept**
- **Neutrino factory R&D**
- **Muon Collider prospects**
- **Summary**

Introduction

- In recent years there has been significant interest in the possibility of building & using a new type of muon source that can deliver a millimole of muons per year.

- Millimole muon sources motivated by:

  Multi–TeV muon colliders

  Higgs factories (sub–TeV muon colliders)

  Neutrino factories

  Intense stopped/low energy muon facilities

- Note that so far the beam toolkit for high energy physics colliders has been limited to stable charged particles –> protons, antiprotons, electrons, positrons. Hence, adding positive & negative muons to the list would significantly improve the choices –> $\mu\mu$, μp, μe colliders ?

Neutrino factory / Muon Collider Collaboration

- 1995: US collaboration (BNL, FNAL, LBNL, Universities) informally formed to study feasibility of multi–TeV muon colliders
  - 480 page report delivered to Snowmass 1996 meeting: "μ+μ– Collider: A feasibility study", BNL–52503, FERMILAB–Conf–96/092, LBNL–38946
- May 1997: the "Muon Collider Collaboration" became a formal entity under the leadership of Bob Palmer, with ~100 physicists participating.
- 1998: Collaboration received first direct DOE funding, & in the following year a multi–lab (BNL, FNAL,LBNL) directorate level oversight group (MUCOG) was set up, together with a technical review committee (MUTAC).
  - Studies focussed on Higgs Factory (low energy μ collider) as first step towards multi–TeV collider.

  "Status of muon collider R&D and future plans", Phys. Rev. ST. Accel. Beams 2, 081001 (1999)
- Summer 1999: no muon collider "show stoppers" had been identified, but there were several important developments which led the collaboration to change its name (–> Neutrino factory and muon collider collaboration) & emphasize neutrino factory studies.
- Present spokesman: Andy Sessler

  Project manager: Mike Zisman

Muon Collaboration

Developments leading to Neutrino Factory R&D

Nov. 1997: Neutrino factory concept presented at the Workshop on physics at the front–end of a muon collider, Fermilab: S. Geer, Phys. Rev. D57 (1998) 6989.

1998: Muon collider studies showed that muon source needed for Higgs Factory is as demanding as for Multi–TeV collider –> Higgs Factory not an ideal first step. Neutrino factories look like a better bet !

1998 – Spring 1999: Enthusiasm for neutrino factories fueled by SuperKamiokande results. Many papers published exploring physics potential. Active R&D group launched in Europe, significant interest in Japan).

Spring 1999: New workshop series: NUFACT99, Lyon –> demonstrated the strength neutrino factory interest.

Spring 1999: First MUTAC review encourages muon collider collaboration, and recommends complete design/study/simulation of one physics facility ... collaboration chooses this to be a neutrino factory.

Fall 1999 – present: Directors request studies:

- Fermilab: 6 month Design Study I: completed April 00
- Fermilab: 6 month Physics Study: completed April 00
- CERN: Design & Physics Study: ongoing
- BNL: Design Study II : started, completion April 01

Neutrino Factory Concepts

1. Make lots of low energy charged pions using a high intensity proton beam incident on a target within high–field solenoid.

2. Pions propagate down long decay channel ($\pi \to \mu\nu$) within solenoid –> low energy muon "gas"

3. Reduce large energy spread using "phase rotation"
   –> drift space produces time–energy correlation
   –> time dependent acceleration (RF or induction linac) reduces energy spread.

4. Reduce the beam transverse phase space using ionization cooling –> bright beam spot that fits within an accelerator.

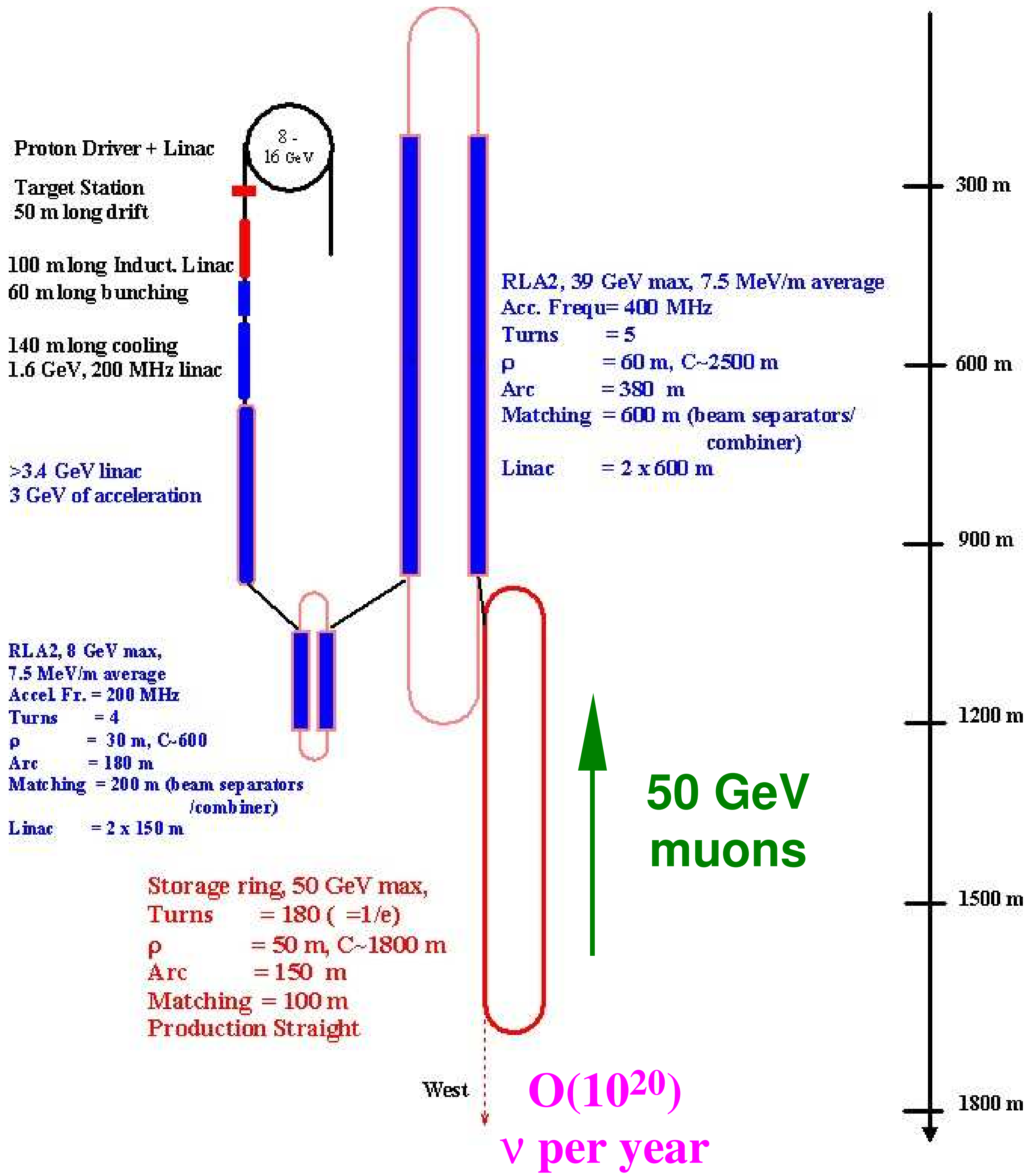
5. Rapidly accelerate beam to energy of choice.

6. Inject into storage ring with long straight–sections pointing in the desired direction –> neutrino beam

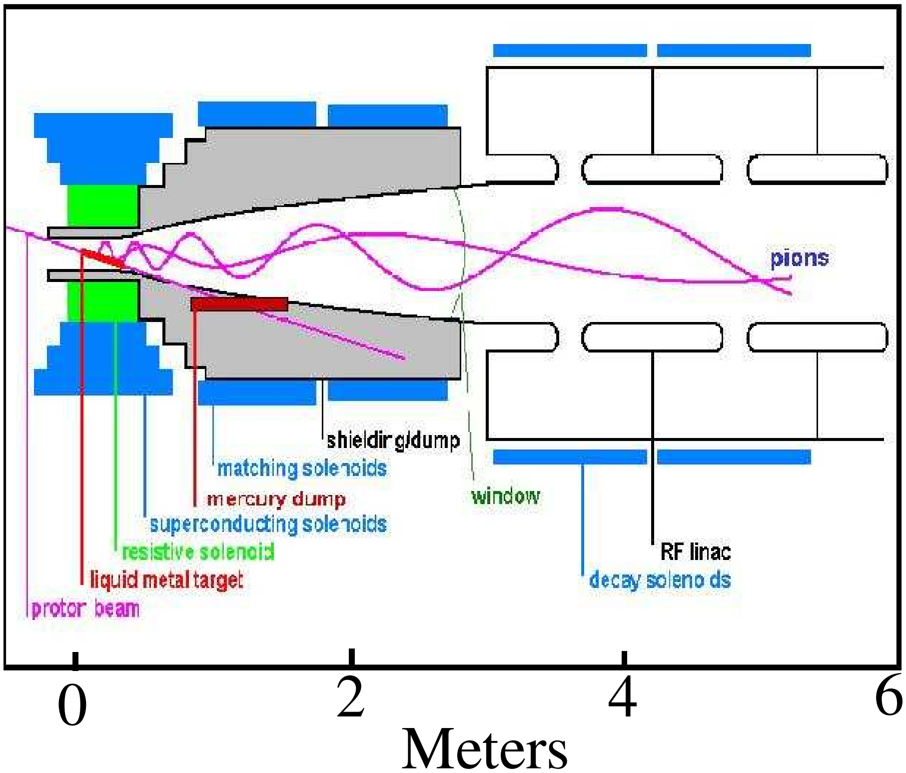
$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ Or $\mu^- \to e^- \nu_\mu \bar{\nu}_e$

Neutrino Factory Schematic

A feasibility study of a neutrino source based on a muon storage ring: Report to the Fermilab director; Editors: N. Holtkamp, D. Finley



Pion Source



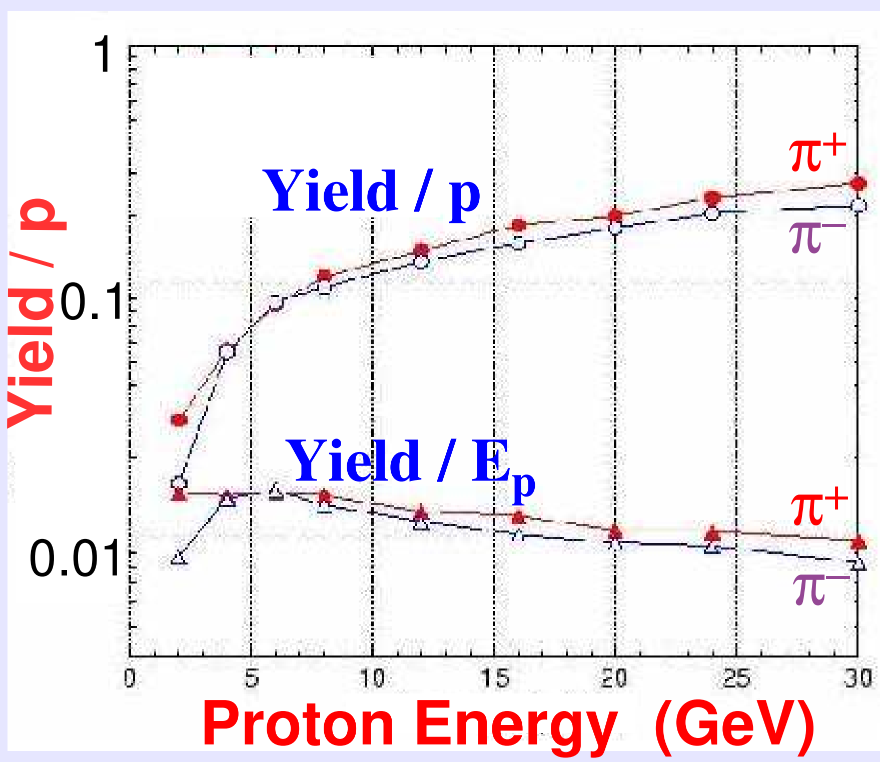
1.5 MW proton source
(upgradable to 4 MW)

e.g. 16 GeV x 15 Hz with 4 x 10^{13} pulse (pulse = 4 bunches spaced by 500 ns)

Carbon target (1.5 MW)
Liq. Hg jet (4 MW)

Pions captured in 20T solenoid –> matched into 1.5T solenoid decay channel

MARS Monte Carlo simulations: π^{+-} yields on carbon target



N. Mokhov

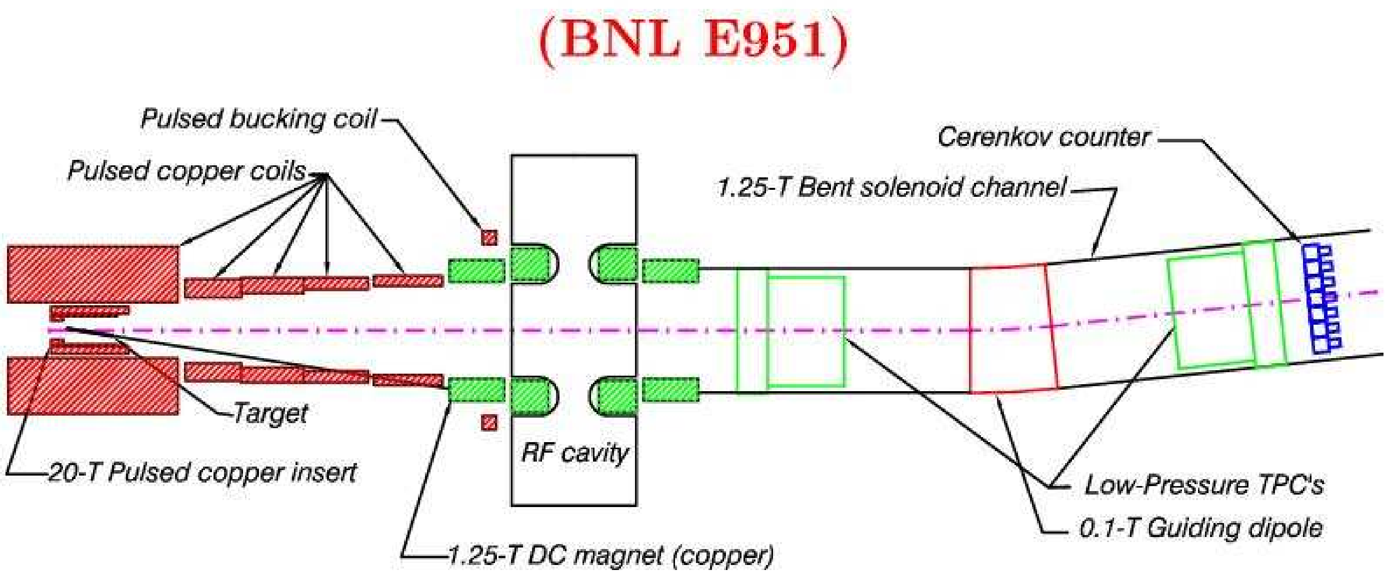
Yields 9m downstream of 80 cm long target tilted at 50 mrad

π,μ accepted with 30 MeV < E < 230 MeV

–> 0.18 π^+/p, 0.15 π^-/p for E_p = 16 GeV

With Hg target yields increased by factors of 1.7 (π+) & 2.1 (π–)

Targetry R&D



6 AGS bunches –> 10^{14} protons on target

Goals of Target experiment at BNL (spokesman; K. McDonald):

1. Demonstrate MW–level target in 20T solenoid
2. Measure pion & neutron yields to benchmark codes
3. Demonstrate target lifetime (Solid & Hg jet)

Status & Plans:

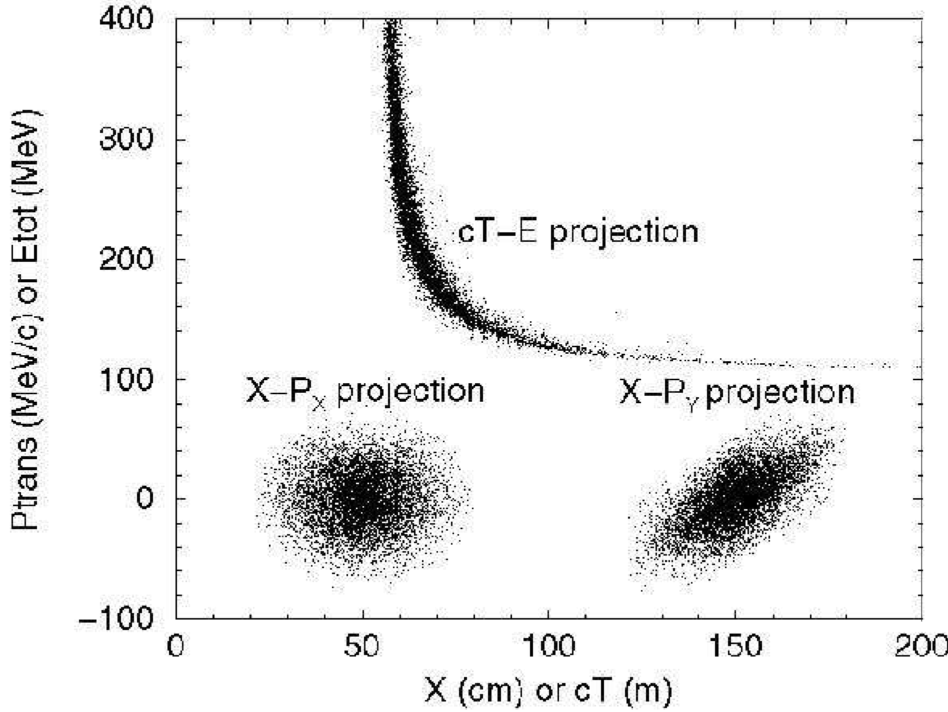
Now: A3 beamline being prepared at BNL
FY01: First target test in with 1 AGS bunch on target
FY02: Tests with 6 AGS bunches on target
FY03: Tests with target in 20T solenoid, and measure particle yields.

Particle production experiments:

E910 (BNL), HARP (CERN), P–907 (FNAL)

Muon Collaboration

Phase Rotation – 1

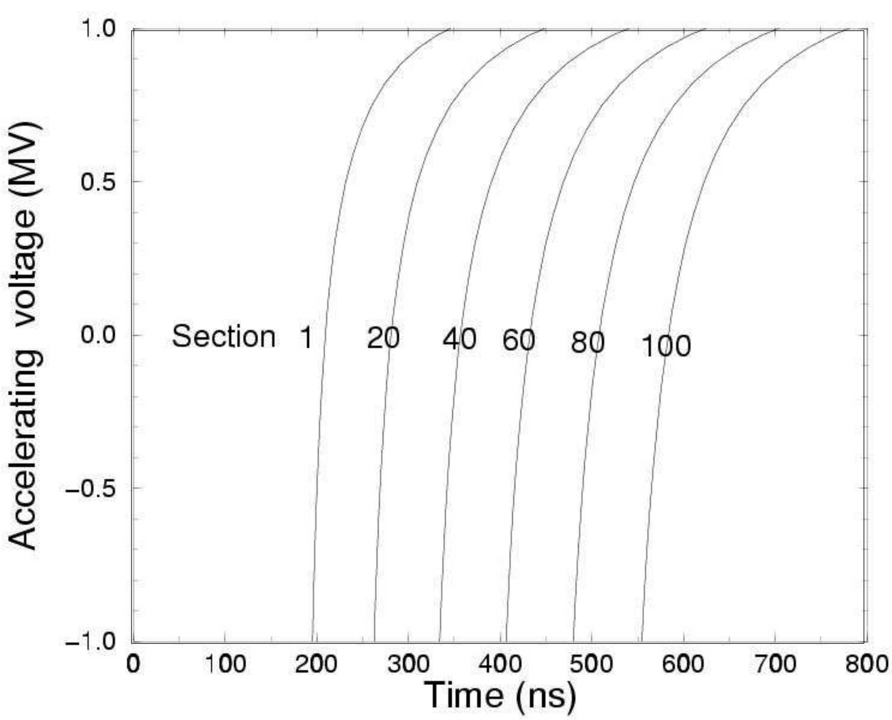


At the end of a 50m long 1.25T solenoid 30cm radius decay channel: 95% of the pions have decayed

0.23 μ / p with E < 500 MeV

σ(pt) = 30 MeV/c

ε(T,n) = 15.9 mm



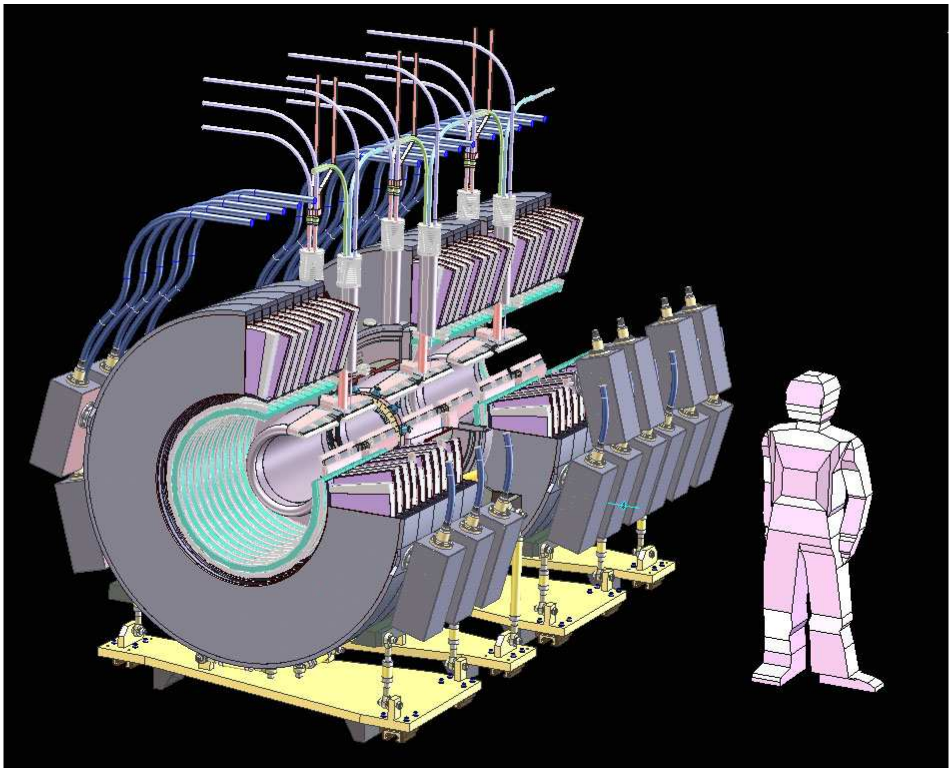
Energy spread too large to capture, cool & accelerate beam.

Reduce σ(E) by exploiting time–energy correlation. Apply a time–dependent accel–eration (accelerate slow muons, deccel–erate fast muons).

–> Induction LINAC

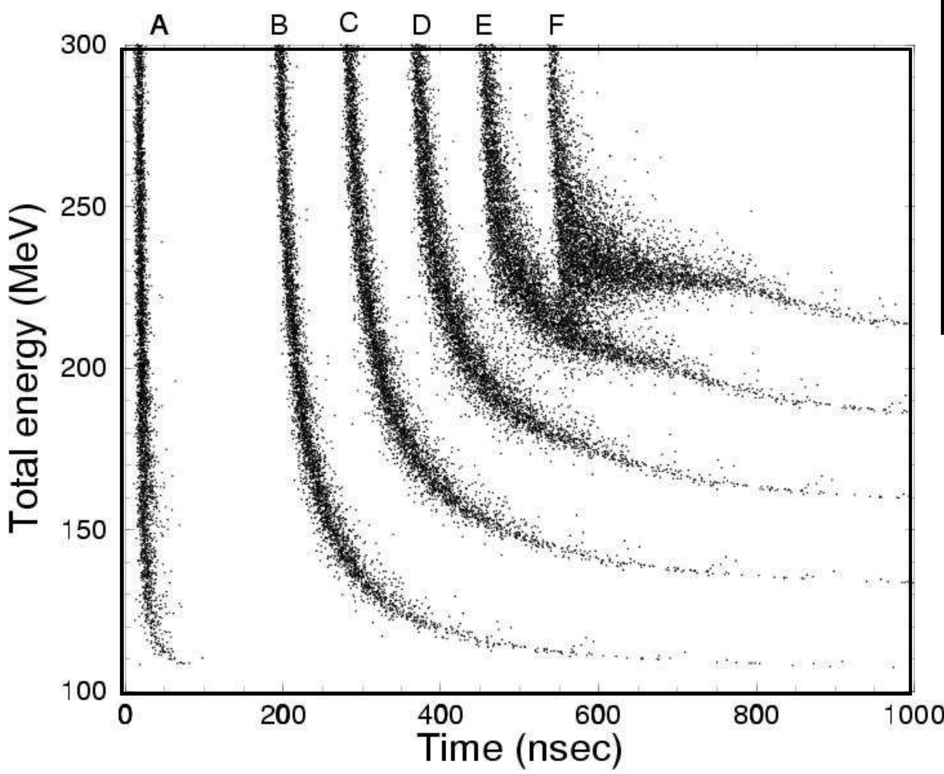
Phase Rotation – 2

Induction LINAC



3T superconducting solenoid channel (r = 20 cm) within LINAC

100 LINAC modules 1m long with 10cm gap providing from –0.5 to +1.5 MV acceleration.



R&D Plans

Demonstrate LINAC cell with internal SC solenoid

Demonstrate pulser system to drive linac (4 pulses separated by 500 ns)

0.19 μ / p with E < 450 MeV

$\sigma(x)$ = 6 cm

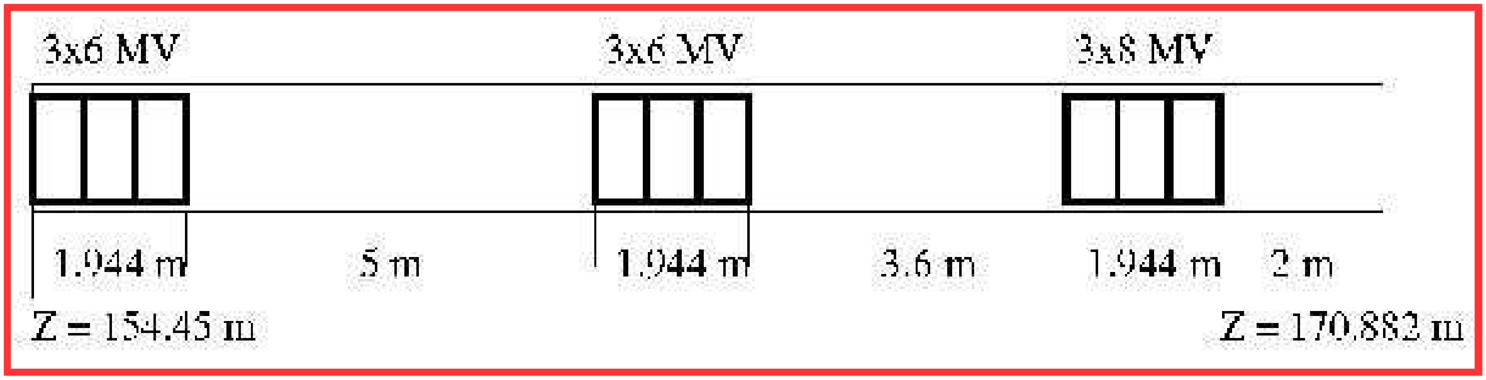
$\sigma(px)$ = 44.9 MeV

$\varepsilon(T,n)$ = 16.3 mm

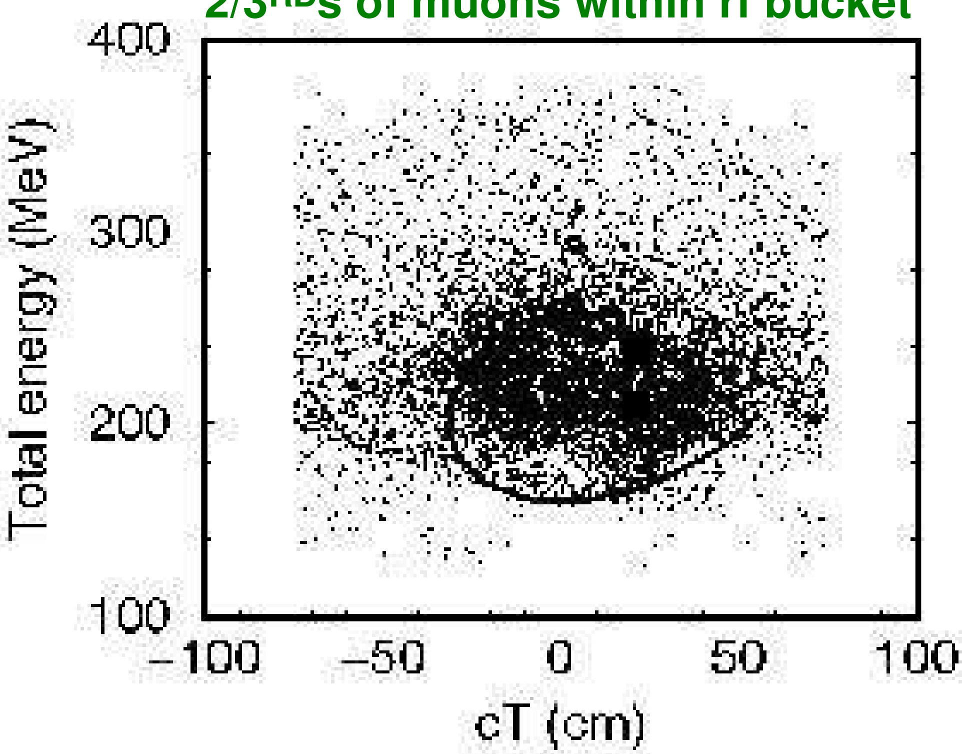
Muon Collaboration

Bunching

- **Need to capture the beam in rf buckets before we can "cool" it in transverse phase–space.**
- **Start by reducing the mean beam energy from ~280 MeV to ~200 MeV by passing through 2.45m liq. H_2 (mini–cooling)**
- **Capture 80m long beam distribution with 16.5 m long 200 Mhz buncher –> ~50 bunches**



2/3RDs of muons within rf bucket



0.12 μ / p in bucket

σ(x) = 4.6 cm

σ(px) = 31.4 MeV

ε(T,n) = 12 mm

Rf bucket full ... so will suffer losses when beam enters cooling channel. Room for further design optimization.

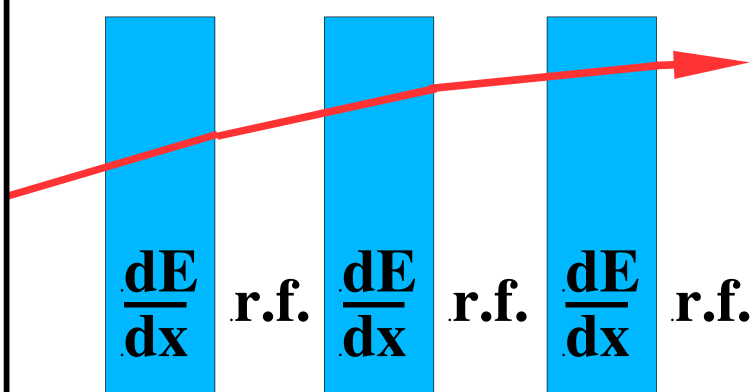
Ionization Cooling

- Before we can accelerate the muons we must reduce their transverse phase–space by at least a factor of a few in each transverse plane –> transverse cooling

- Cooling must be done fast ... before muons decay ... cant use stochastic cooling or electron cooling.

- Propose to use ionization cooling:

Ionization Cooling



Muons lose energy by dE/dx. Longitudinal momentum replaced by r.f.

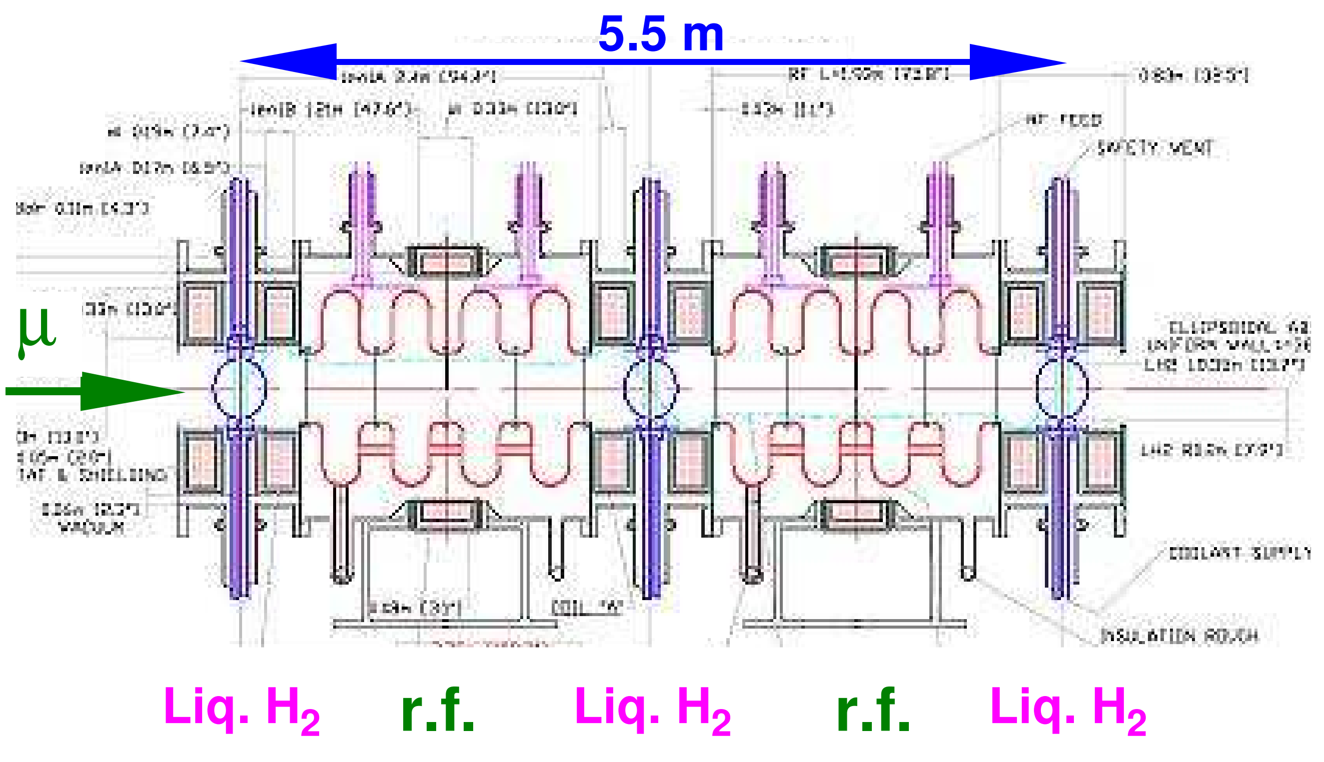
→ Transverse Cooling

To minimize heating from Coulomb Scattering:

- Small $\beta_\perp$ (strong focussing):
  –> High–field solenoids
- Low–Z absorber:
  –> Liquid H_2 with low Z very thin windows

Muon Collaboration

Cooling Channel



Channel length, solenoid & absorber parameters depend on detailed lattice design

Total cooling channel length ~100 m
RF: 200 Mhz –> 15 MV/m peak gradient
High–field solenoids: B ~ 3.5 T on axis
Liq. H_2 absorbers: L ~ 30 cm, r ~ 15 cm

Cooling channel can be thought of as a LINAC filled with material. We must keep the beam bunched, as well as cool it ... this is a design challenge !

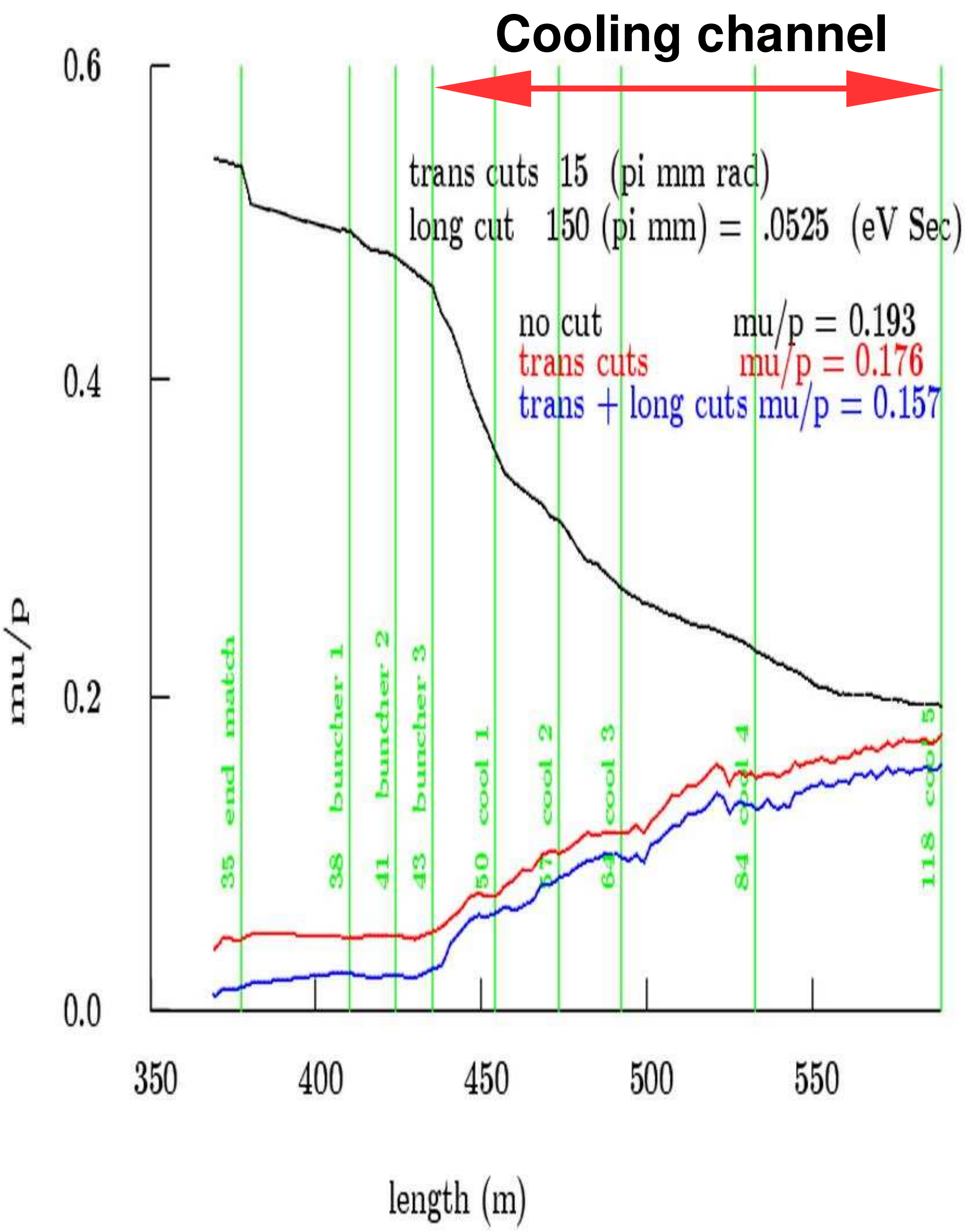
MUCOOL Collaboration (spokesman: Steve Geer)
Mission: Design,prototype, bench–test, all cooling channel components, & eventually beam–test a cooling section.

Muon Collaboration

Cooling Channel Simulation

- **Use two detailed tracking codes which include full geometry, solenoidal fields, rf , scattering, straggling:**

  DPGEANT: P. Lebrun et al.
  ICOOL: R. Fernow et al.



Simulation of recent cooling lattice design from R. Palmer

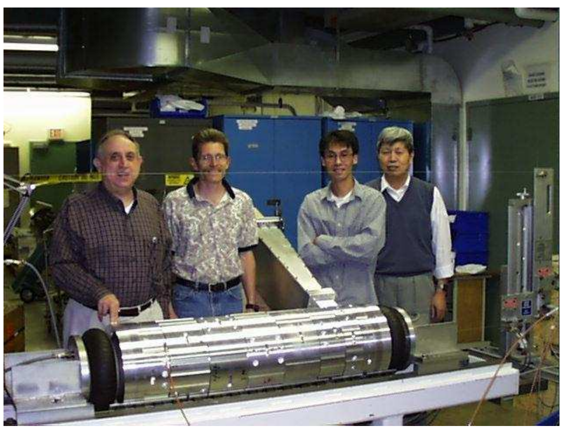
Present channel design increases muons captured by acceleration system by factor of ~5

Further design optimization in progress – lots of variants to study.

Cooling R&D – RF

To keep the muon bunch captured need high gradient RF:

Be window



Open cell cavity: Al model

X–ray cavern at Lab G

ν–factory cooling: 15 MV/m at 200 MHz
Late cooling (μ collider): 30 MV/m at 800 MHz

Concept 1: Open cell cavity.
R&D issue: very high surface fields

Made Al model of 805 Mz open cell cavity, measured properties, constructing Cu cavity for high power test.

Almost completed 805 MHz high power test facility at Fermilab (Lab G) including 5T solenoid. Start testing open cell cavity in Fall.

Concept 2: Cavity with Be windows
R&D issue: window stability, multipactoring.

Tested small Be foils in RF gun –> OK.

Measured mechanical properties of Be windows when heated at LN_2 temperatures

Built prototype 805 Mhz Cu cavity with Be windows, measured properties.

Plan to make high power test of 805 Mhz cavity with windows in ~1 year.

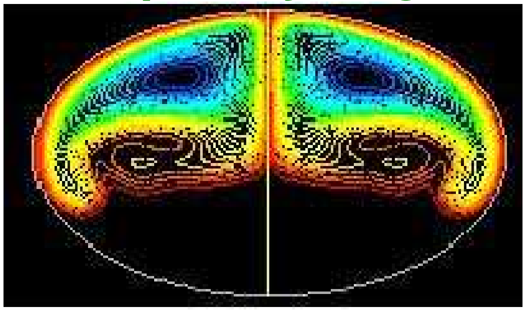
Designing 200 Mhz cavity. Planning 200 Mhz high power test facility at Fermilab.

Expect 200 Mhz development + testing to take 3 years.

Muon Collaboration

Cooling R&D – 2

- **Liquid Hydrogen Absorber R&D**



Convection calculation
K. Cassels

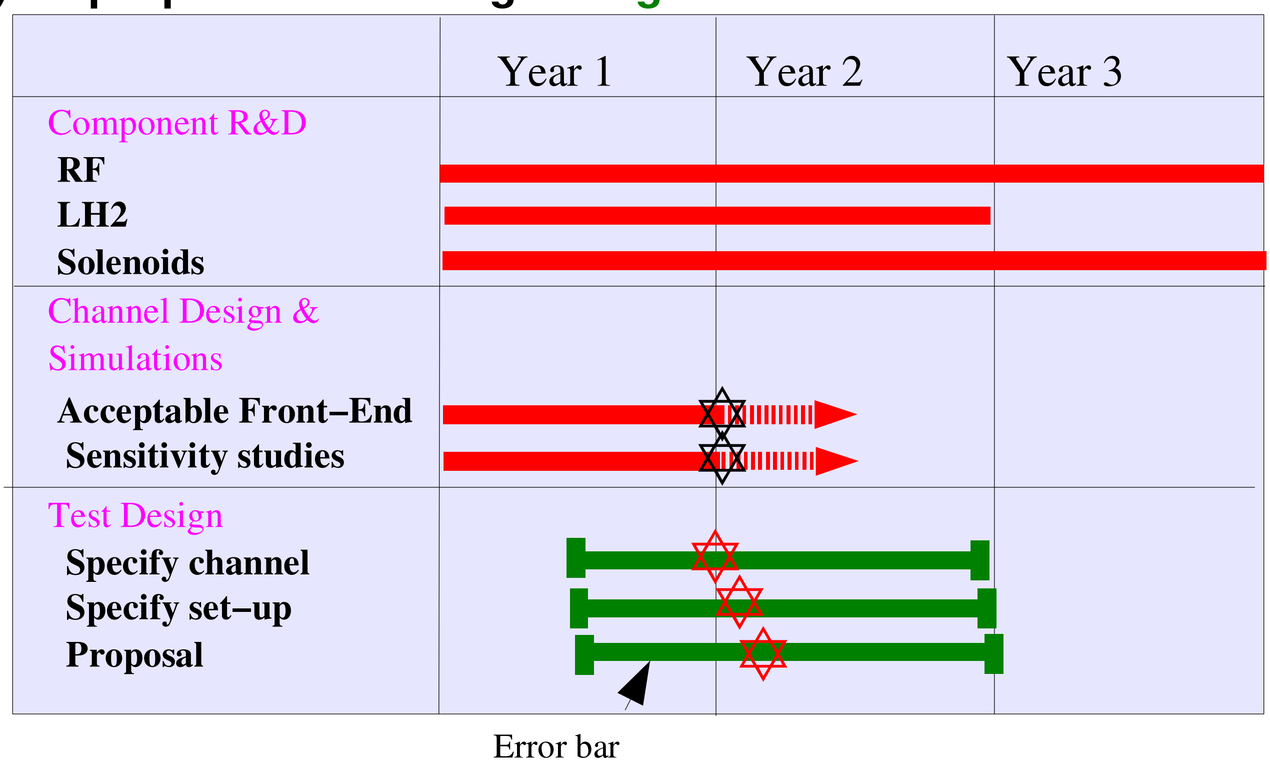
Must remove O(100 W) heat from dEdx losses: Two designs to test: (1) forced flow, (2) driven convection

Calculations non–trivial: Plan to prototype designs, bench–test, & beam test.

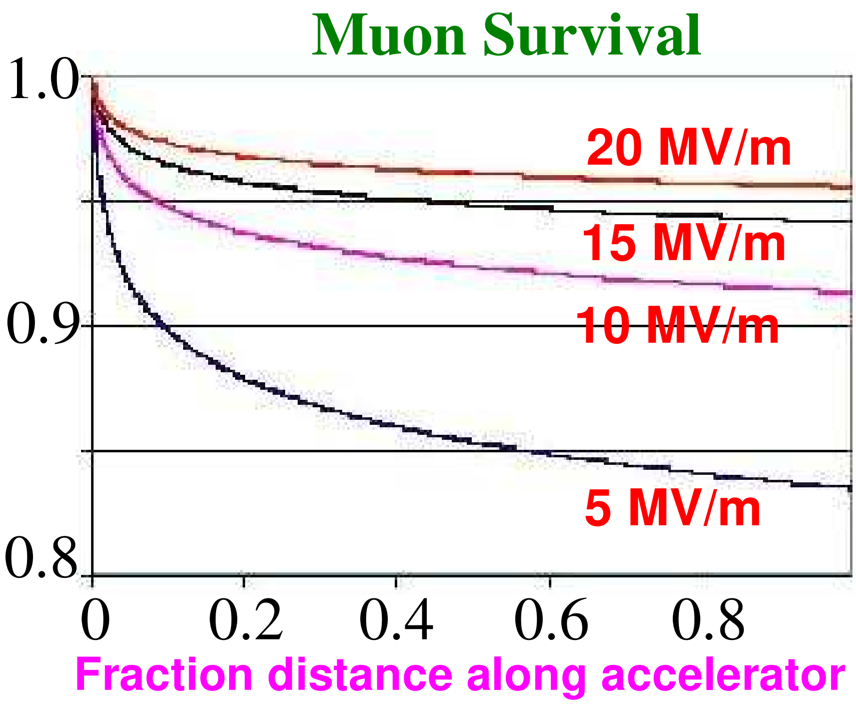
Need thinnest low–Z windows. Will try Al, AlBeMet, ...

Need to design the right cooling channel beam test(s).

MUCOOL Plan: (i) build & bench–test components in 3 years, (ii) study channel sensitivity to things that can go wrong & what can be tested/measured vs length of channel & test–beam props, (iii) –> proposal for testing ... might be international in scale.

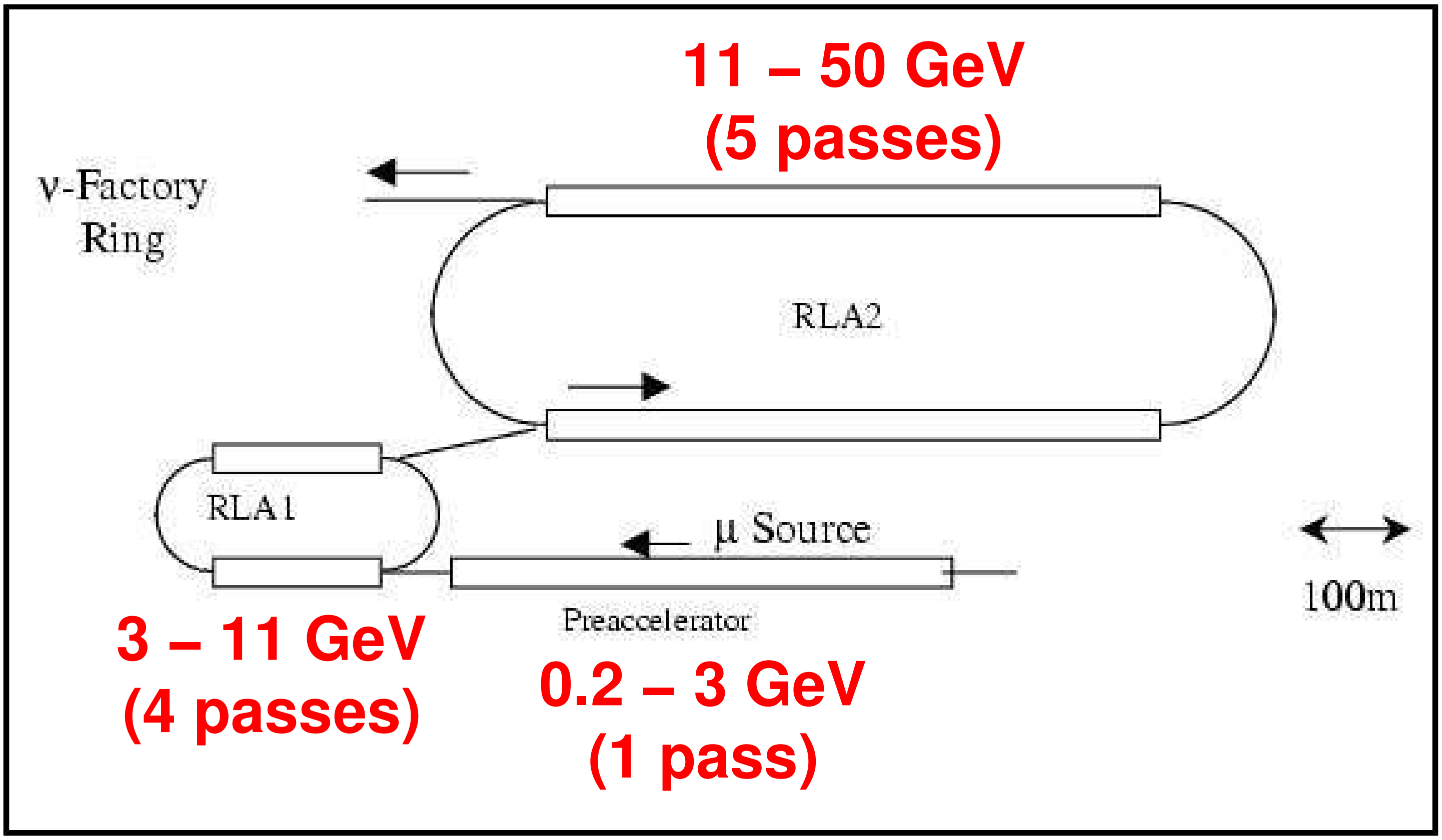


Acceleration



Need high accelerating gradients to get muons to high energy before they decay

Choose "slow fill" super conducting RF to get high gradients with acceptable peak power



Feasibility study I design –> 6 x 10^{19} decays/yr in beam–forming straight section of storage ring (goal was 2 x 10^{20}).

R&D List

Front–End Design

Design higher–performance cost–effective μ source

Target

Develop solid and liq. Hg targets in 20T
Test survivability in proton pulse
Measure particle production

Induction Linac

Build/test 1 cell with suitable pulser

Cooling

Develop 200 Mhz high gradient RF
Develop absorbers, test survivability
Develop cost–effective solenoids
Beam test prototype cooling section

Acceleration

Develop 200 Mhz superconducting RF

Other Initiatives

CERN Study Group: Report within next year. Similar design approach but with different sub–system choices (2 GeV linac p–driver, horn pion collection, ...)

PRISM: JHF low energy muon source: Very different design approach; phase rotation in large acceptance (FFAG) accelerator. Neutrino factory phase with no phase rotation or cooling, use FFAGs for acceleration.

Muon Collider Issues

Would like to develop the technology & know–how to go beyond a neutrino factory, & in the longer– term build a muon collider.

–> All muons in a single bunch
–> Much more cooling
} **Maximize luminosity**

–> Cost–effective acceleration an issue

Most challenging issue is probably cooling:

To continue transverse cooling (beyond neutrino factory level) will require reducing the beam energy spread –> "emittance exchange" for which we don't yet have a solution on paper yet.

Cost effective acceleration may demand cooling beyond the realm of ionization cooling ... (optical stochastic cooling ?). Need more design studies to understand this.

Neutrino factories plus emittance exchange design studies & further acceleration studies should prepare the way for multi–TeV muon colliders !

Summary

- **Milli–Mole / year muon sources are very actively under study in the US, Japan, and Europe.**

- **Main physics driving force is neutrino oscillation physics. But also stopped/low energy muon physics, & in the longer term muon colliders (μp, μe, ..)**

- **First end–to–end design study completed –> neutrino factories feasible; substantial hardware R&D needed**

- **Other design studies (CERN, US, PRISM–Japan) in progress ... hope to end up with higher–performance cost–effective neutrino factory design within 1 year**

- **Substantial hardware R&D has begun:**

  Particle production (HARP, ...)
  Target experiment (BNL E951)
  Muon scattering experiment (TRIUMF)
  Cooling hardware development (MUCOOL)
  Induction LINAC design (LBNL)
  Superconducting RF development (Cornell)
  FFAG (KEK)
  + more ....