Neutrino Factories in the U.S

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Fermilab
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Format of talk

- Physics Motivation for neutrino factories.
- Description of U.S design of neutrino factory
- Comparison of Study I and Study II
- R&D activities
- Mucool demonstration experiment ideas and status.
- Conclusions

Muon Collaboration

Physics motivation

- Lots of papers, an industry, too numerous to review. Will give highlights from the Collected papers of Barger et al.
- Long baseline physics with a muon storage ring neutrino source; V. Barger, S. Geer, K. Whisnant, hep-ph/9906487.,Phys. Rev. D61:053004 (2000)
- Long baseline study of the leading oscillation at a neutrino factory; V. Barger, S. Geer, R. Raja, K. Whisnant, hep-ph/9911524.,Phys. ReV. D62:013004 (2000)
- Neutrino oscillations at an entry level neutrino factory and beyond; V. Barger, S. Geer, R. Raja, K. Whisnant, hep-ph/0003184., Phys.Rev.D62:073002 (2000)
- Determination of the pattern of neutrino masses at a neutrino factory; V. Barger, S. Geer, R. Raja, K. Whisnant, hep-ph/0004208., Phys.Lett. B485:379-387 (2000)
- Short baseline neutrino oscillations at a neutrino factory; V. Barger, S. Geer, R. Raja, K. Whisnant, hep-ph/0007181., Phys. Rev. D63:033002 (2001)
- Exploring neutrino oscillations with superbeams; V. Barger, S. Geer, R. Raja, K. Whisnant, hep-ph/00012017., Submitted to PRD

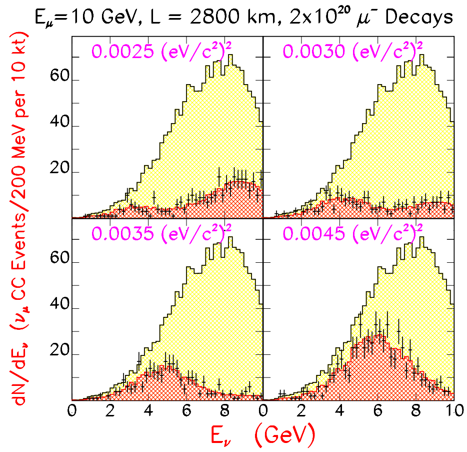


FIG. 11. Predicted measured energy distributions for CC $\nu_\mu \to \nu_\mu$ events shown for four different δm^2_{32} (darkly shaded distributions) as labelled. The predictions correspond to 2×10^{20} decays, $E_\mu = 10$ GeV, $L = 2800$ km, with the values for $\delta m^2_{12}, s_{13}, s_{23}, s_{12}$, and δ given in Eq. (43). The predicted distribution has been used to generate a Monte Carlo dataset with the statistics corresponding to a 10 kt-yr dataset (points with error bars). The lightly shaded histograms show the predicted distributions in the absence of oscillations.

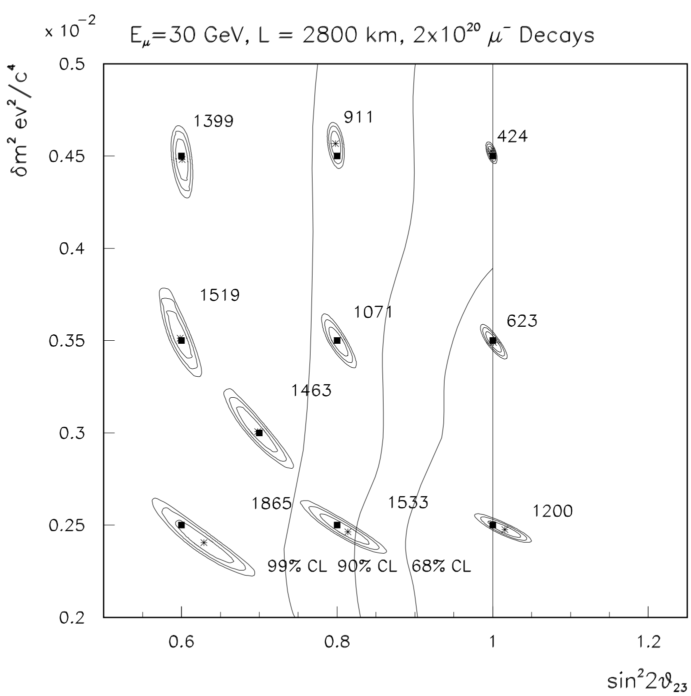


FIG. 13. Fit to muon neutrino survival distribution for $E_\mu = 30$ GeV and $L = 2800$ km for 10 pairs of $\sin^2 2\theta$, δm^2 values. For each fit, the 1σ, 2σ and 3σ contours are shown. The generated points are indicated by the dark rectangles and the fitted values by stars. The SuperK 68%, 90%, and 95% confidence levels are superimposed. Each point is labelled by the predicted number of signal events for that point.

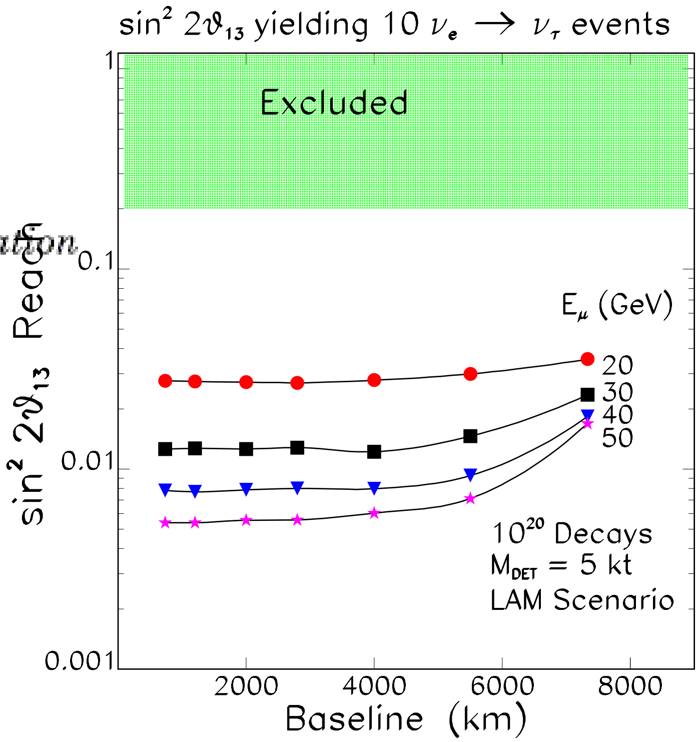


FIG. 7. Reach in $\sin^2 2\theta_{13}$ for the observation of 10 events from $\nu_e \to \nu_\tau$ oscillations, shown versus baseline for four storage ring energies. The oscillation parameters correspond to the LAM scenario in Table I. The curves correspond to 10^{20} μ^+ decays in a 20 GeV neutrino factory with a 5 kt detector.

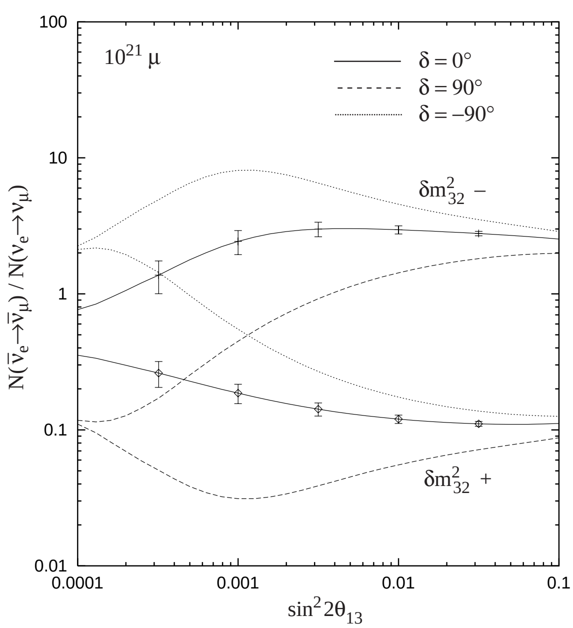


FIG. 13. The ratio of $\bar{\nu}_e \to \bar{\nu}_\mu$ to $\nu_e \to \nu_\mu$ CC events versus $\sin^2 2\theta_{13}$, with $L = 2900$ km, $E_\mu = 20$ GeV, 10^{21} muons, and a 50 kt detector. The other oscillation parameters are the same as the LAM scenario in Table I, and results for both positive and negative δm^2_{32} are shown. Predictions for maximal CP phases $\delta = 90°$ (dashed curves) and $\delta = -90°$ (dotted) are compared with the CP-conserving case $\delta = 0°$ (solid). The error bars show typical statistical uncertainties on the measurements.

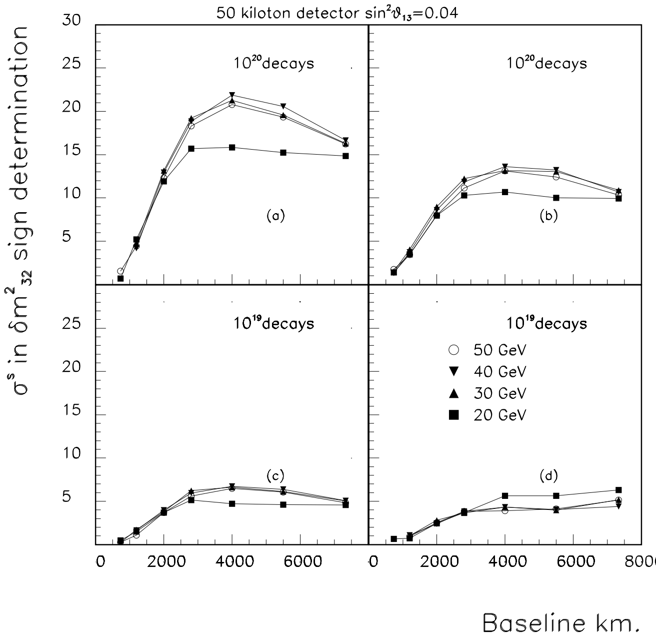


Figure 3: The number of standard deviations to which the sign of δm^2_{32} can be determined versus baseline length for various muon storage ring energies: (a) 50 kiloton detector, 10^{20} μ^+ and μ^- decays and positive values of δm^2_{32}; (b) 50 kiloton detector, 10^{20} μ^+ and μ^- decays and negative values of δm^2_{32}; (c) 50 kiloton detector, 10^{19} μ^+ and μ^- decays and positive values of δm^2_{32}; (d) 50 kiloton detector, 10^{19} μ^+ and μ^- decays and negative values of δm^2_{32}.

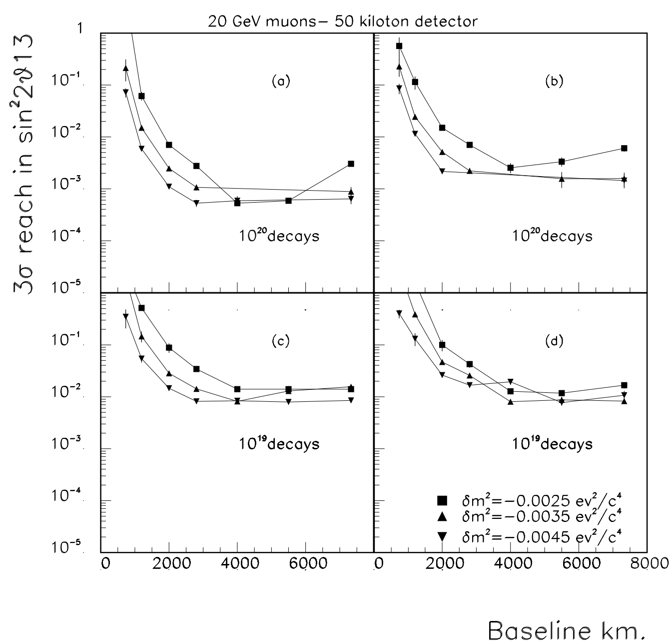


Figure 4: The sensitivity reach in $\sin^2 2\theta_{13}$ at which the sign of δm^2_{32} can be determined to 3 standard deviations versus baseline length for various values of δm^2_{32}: (a) 50 kiloton detector, 10^{20} μ^+ and μ^- decays and positive values of δm^2_{32}; (b) 50 kiloton detector, 10^{20} μ^+ and μ^- decays and negative values of δm^2_{32}; (c) 50 kiloton detector, 10^{19} μ^+ and μ^- decays and positive values of δm^2_{32}; (d) 50 kiloton detector, 10^{19} μ^+ and μ^- decays and negative values of δm^2_{32}.

The Muon Collider/Neutrino Factory Collaboration—a.k.a Muon Collaboration

Contributing Institutions

- Argonne National Lab
- Budker Inst.of Nuclear Physics
- Brookhaven National Lab
- UC Berkeley
- UC Davis
- UCLA
- UC Riverside
- CERN
- Cornell
- ETH, Zurich
- Fairfield University
- Fermilab
- Indiana University
- Illinois Inst. Of Technology
- University of Iowa
- Jefferson Lab.
- Kansas State University
- Research Center Karlsruhe
- KEK
- Lawrence Berkeley National Lab.
- Inst. of Mathematics, Novosibirsk
- Michigan State U
- Univ. of Minnesota
- Univ. Of Mississippi
- Nat. High Magnetic Lab.
- Northern Illinois Univ.

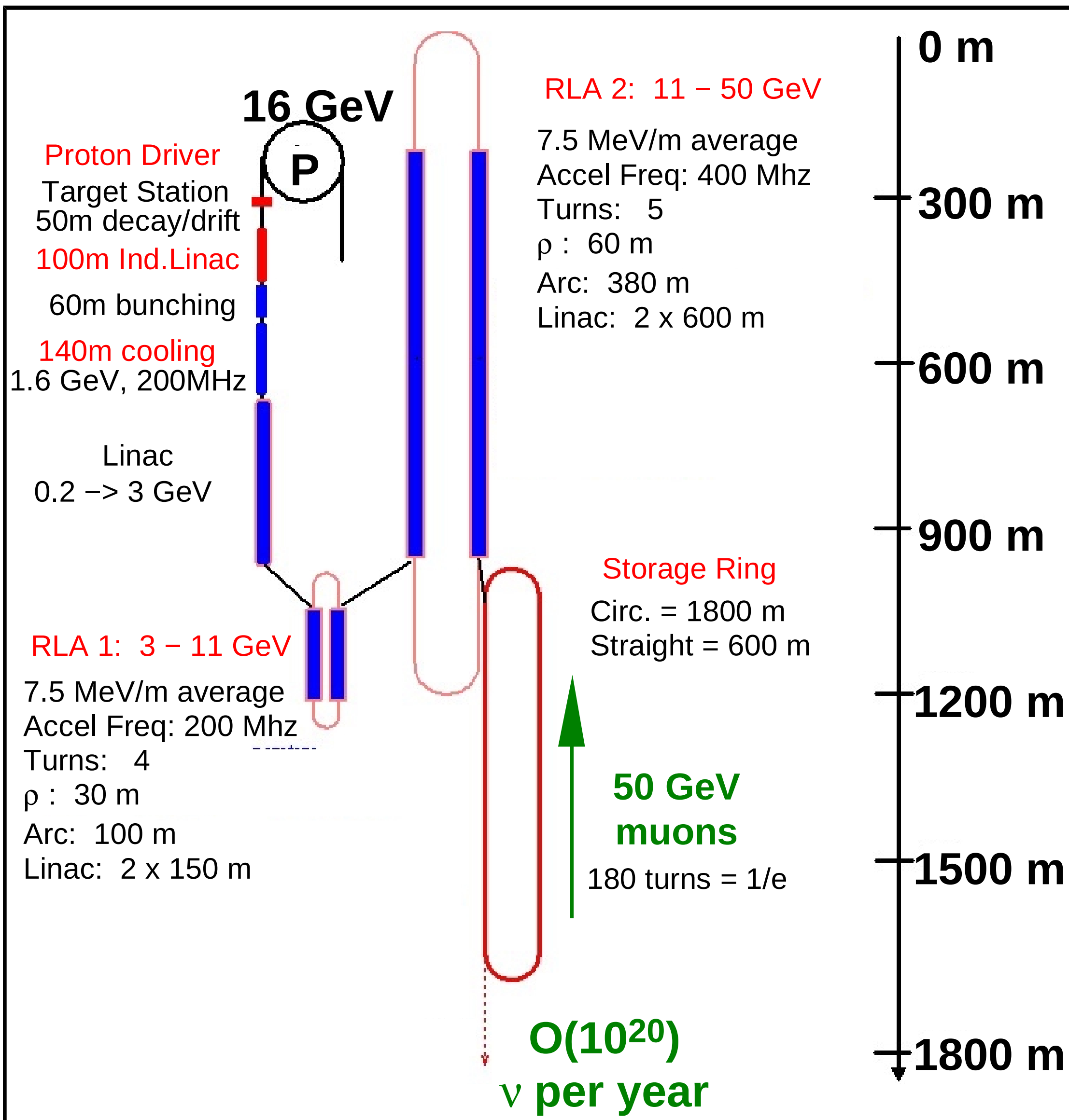
SUNY, Stony Brook
Northwestern University
Oak Ridge National Lab.
Princeton University
Rutherford A. Lab.
Rockefeller University
Tel-Aviv University, Israel
U. of Texas, Pan American
Univ. of Victoria
Univ. of Wisconsin

Spokesperson:-A.Sessler

Study I schematic

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

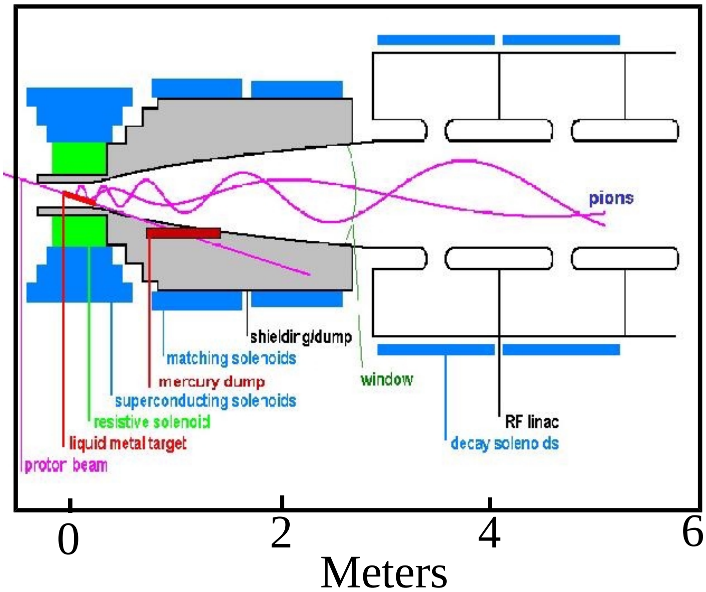


Proton Driver

Design study assumed that the neutrino factory driven by a 16 GeV proton source delivering a 1.5 MW beam :

	PRESENT	ν−FACT	UPGRADED ν−FACT
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	60	80
Pulse length (μs)	25	80	200
H^- per pulse	6.3×10^{12}	3×10^{13}	1×10^{14}
Average beam current (μA)	15	72	240
Beam power (KW)	6	29	240
Pre−Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)			3
Proton per bunch			2.5×10^{13}
Number of bunches			4
Total number protons			1×10^{14}
Norm. trans. Emittance (mm−mrad)			200π
Longitudinal emittance (eV−s)			2
RF frequency (MHz)			7.5
Average beam current (μA)			240
Beam power (KW)			720
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Proton per bunch	6×10^{10}	7.5×10^{12}	2.5×10^{13}
Number of bunches	84	4	4
Norm. trans. Emittance (mm−mrad)	15π	60π	200π
Longitudinal emittance (eV−s)	0.1	2	2
RF frequency (MHz)	53	1.7	7.5
Extracted bunch length σ_b (ns)	0.2	3	1
Average beam current (μA)	12	72	240
Target beam power (KW)	100	1200	4000

Pion Source



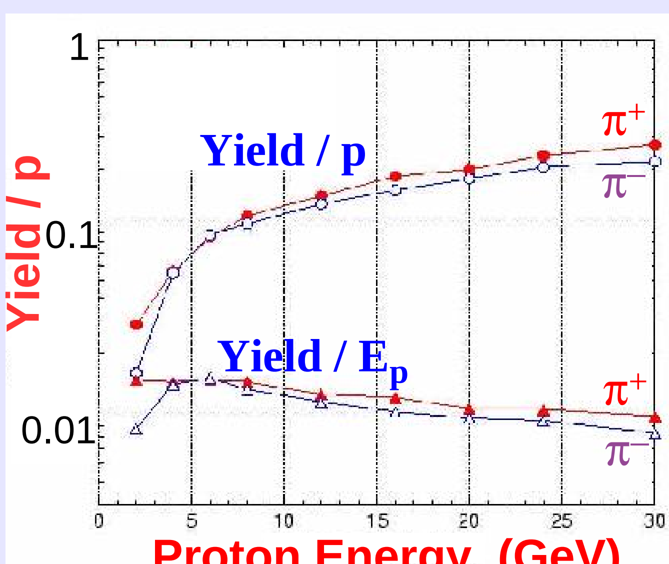
1.5 MW proton source (upgradable to 4 MW)

e.g. 16 GeV x 15 Hz with 4 x 10^{13} p/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

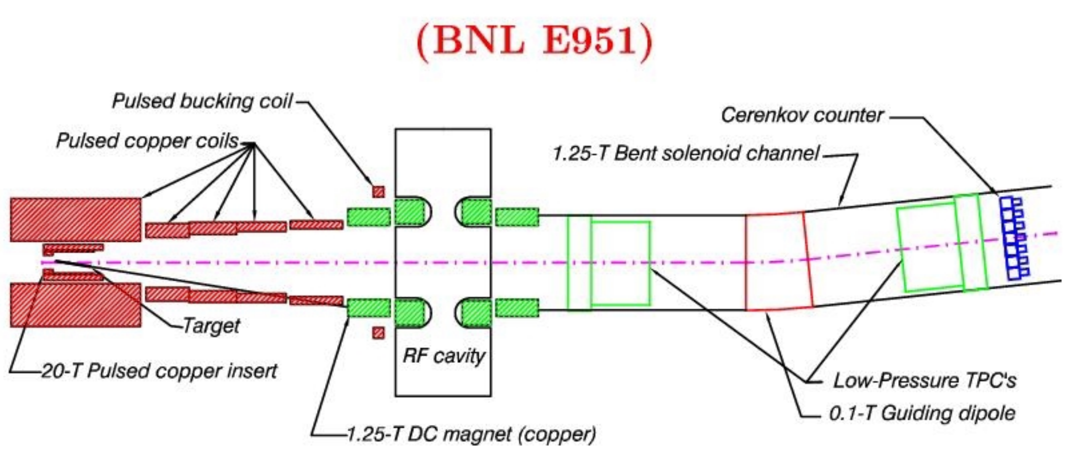
Yields 9m downstream of 80 cm long target tilted at 50 mrad

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)

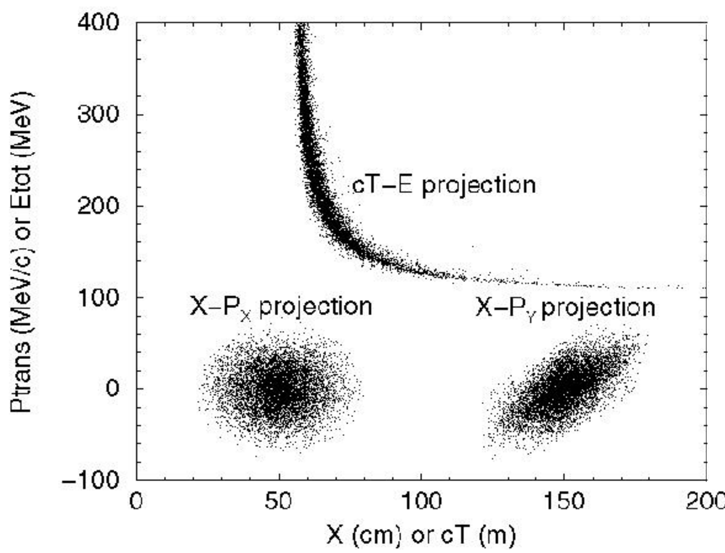
Status & Plans:

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)

Phase Rotation – 1

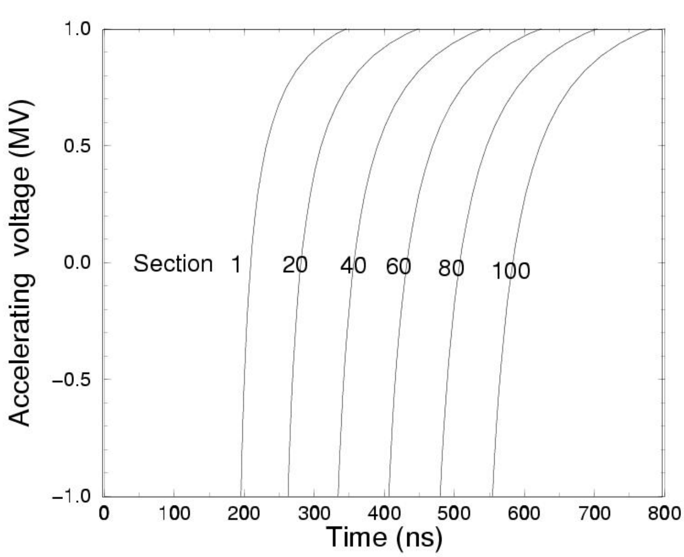


At the end of a 50m long 1.25T solenoid 30cm radius decay channel: 95% of the pions have decayed

0.23 μ / p with E < 500 MeV

σ(pt) = 30 MeV/c

ε(T,n) = 15.9 mm



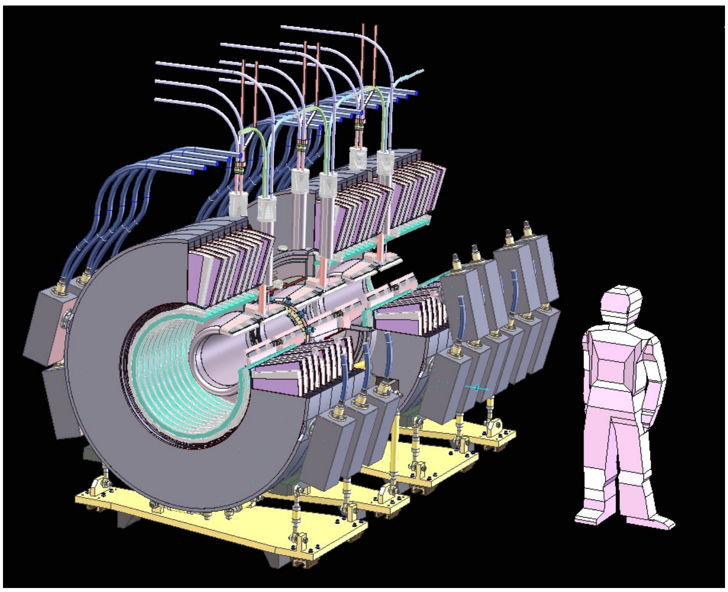
Energy spread too large to capture, cool & accelerate beam.

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



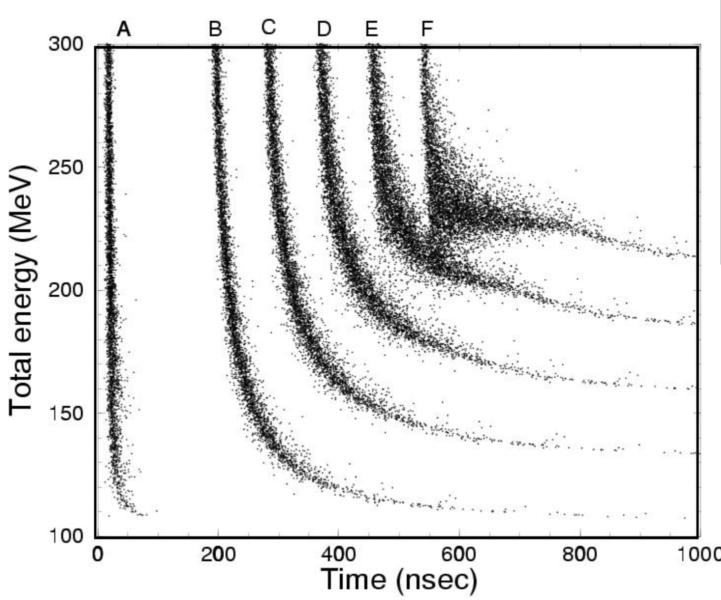
3T superconducting solenoid channel (r = 20 cm) within LINAC

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

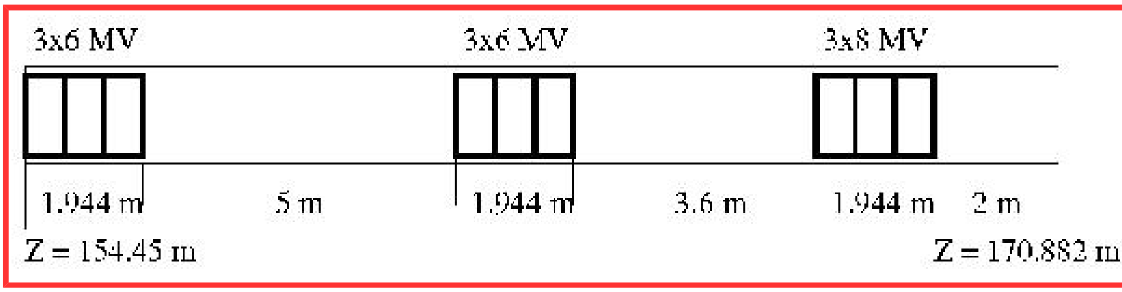
σ(x) = 6 cm

σ(px) = 44.9 MeV

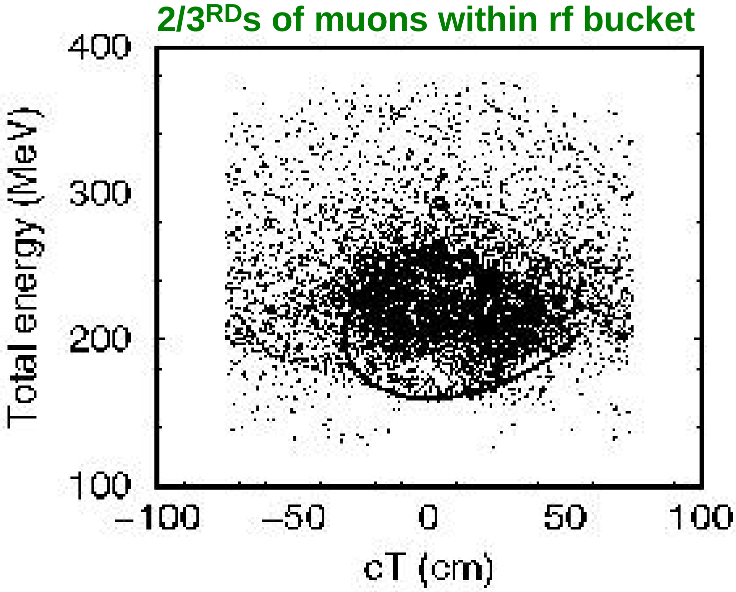
ε(T,n) = 16.3 mm

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.

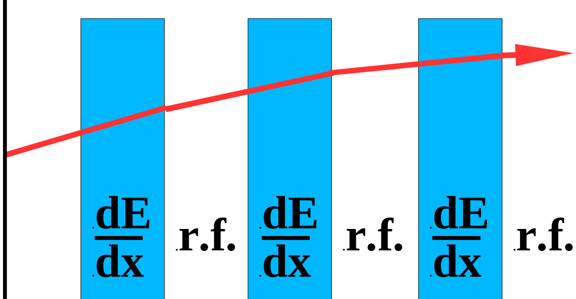
Ionization Cooling

- 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



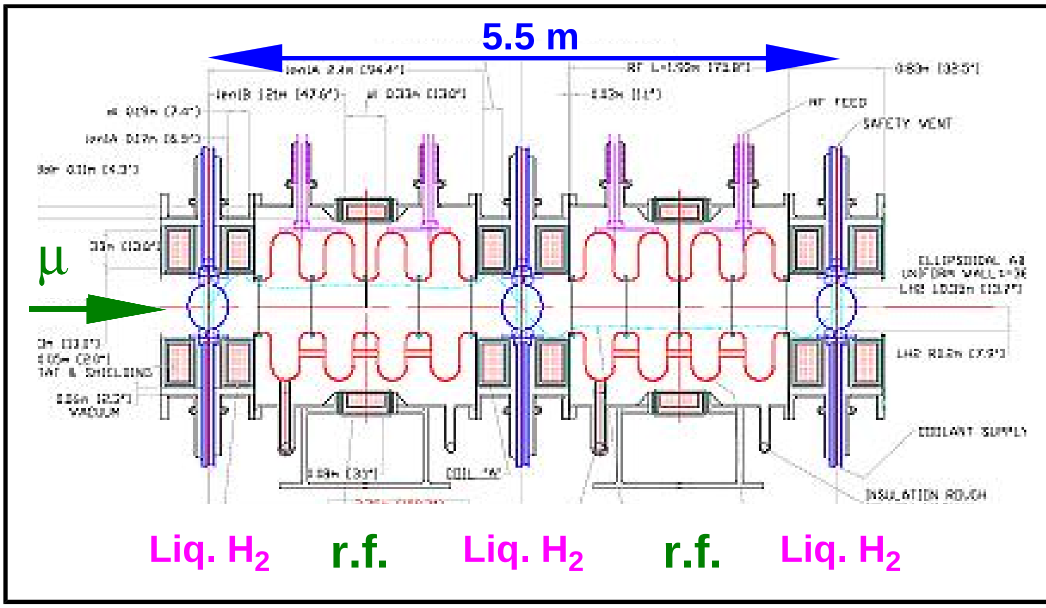
Muons lose energy by dE/dx. Longitudinal momentum replaced by r.f.

→ 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

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.

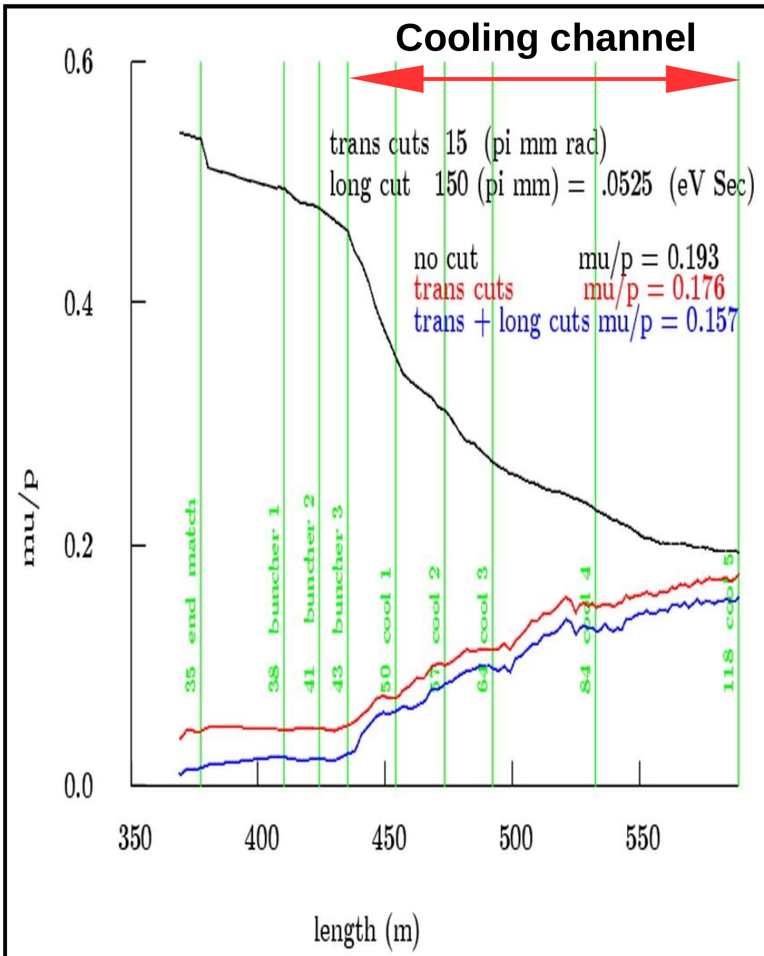
Muon Collaboration

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:

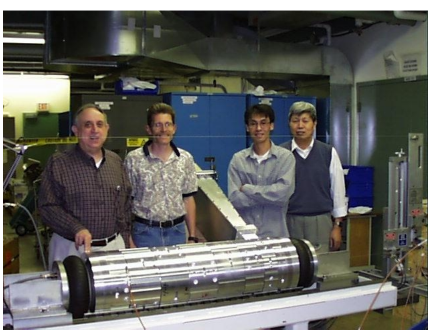
Be window

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.



Open cell cavity: Al model

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.

X−ray cavern at Lab G

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 – Absorbers

- Want lowest Z material in minimize scattering –> liquid hydrogen

P_μ (MeV/c)	dE/dx MeV/(g/cm^2)	$\Delta E^{*)}$ (MeV)	ΔE/pulse$^{**)}$ (10^{14} MeV)	Power$^{+)}$ (W)
106	6.0	13	1.3	300
211	4.2	9	0.9	220
317	4.1	8	0.8	210

*) 30 cm   **) 10^{13} muons/pulse   +) 15 Hz

- Power dissipation requires careful absorber design. Note: SLAC E158 LH_2 absorber with 700W cooling

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, ...

Cooling Channel Beam Diagnostics – 1

Goals: Specify the diagnostics required to debug & operate a cooling channel. Prototype & test candidate beam diagnostics detectors.

Requirements: The diagnostics must introduce "no" additional mass into channel, must work in a hostile (X−rays, high magnetic field) environment, but can have very low efficiency (10^{12} muons / bunch !)

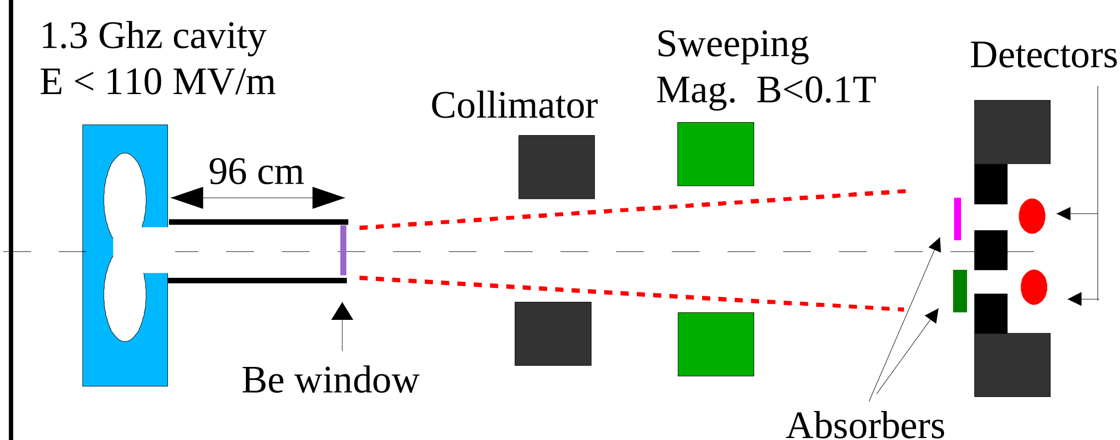
Ideas: Very early stage ... the diagnostic requirements need to be studied. Nevertheless, there are ideas:

Cherenkov light from LH2
Scintillation light from LH2
Transition radiation from LH2 window
High T_c resistive strips on window
.....

Cooling Channel
Beam Diagnostics – 2

X–ray Flux

Measured flux downstream of 1.3 Ghz cavity at ANL (J. Norem) with surface field of 110 MV/m –> 10^7 γ/cm^2 /sec at ~100KV.

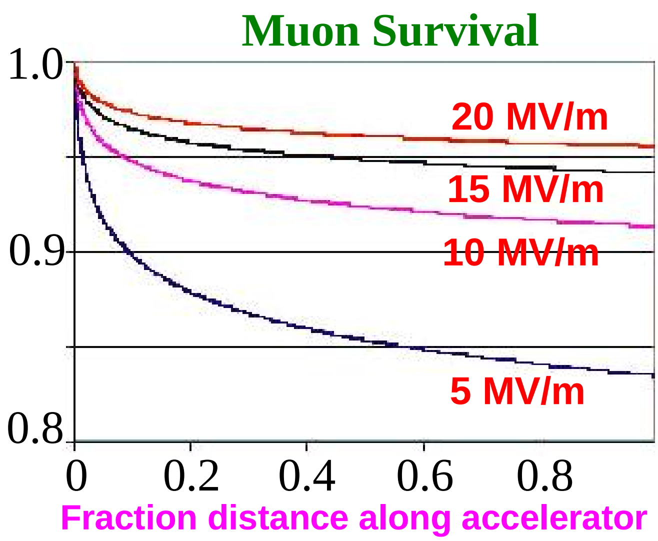


Beam diagnostics must work in high solenoidal fields when exposed to large X–ray fluxes.

We have a setup at FNAL (Lab G) with a high–power 805 Mhz cavity within a 5T solenoid ... ideal for instrumentation tests !

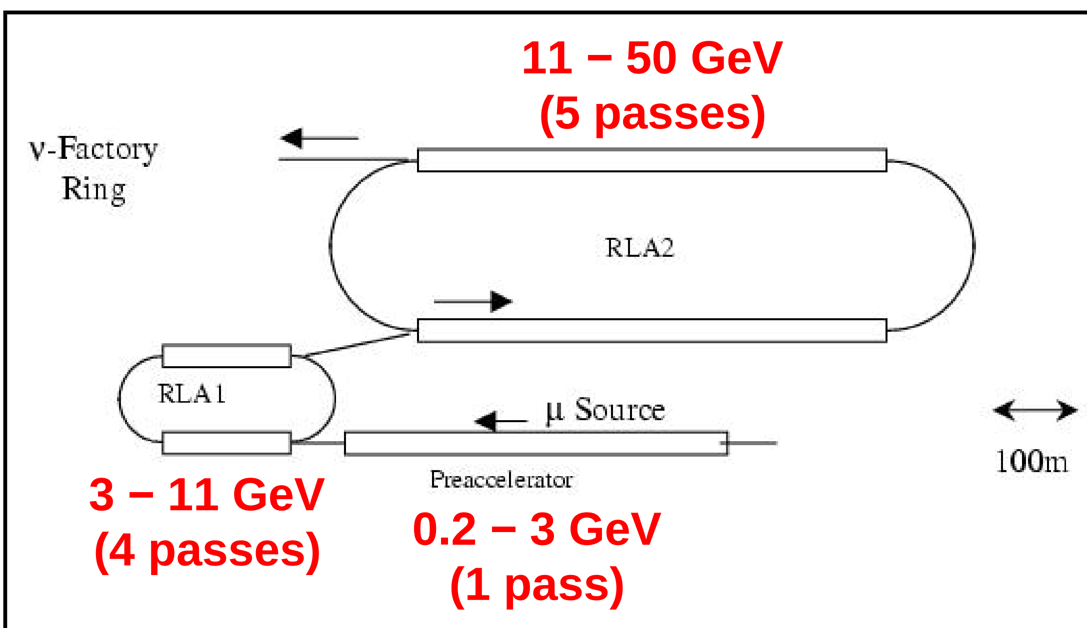
Plan to re–measure X–rays at Lab G and see if fast (secondary emission, Faraday cup) detectors can operate close to cavity.

Acceleration



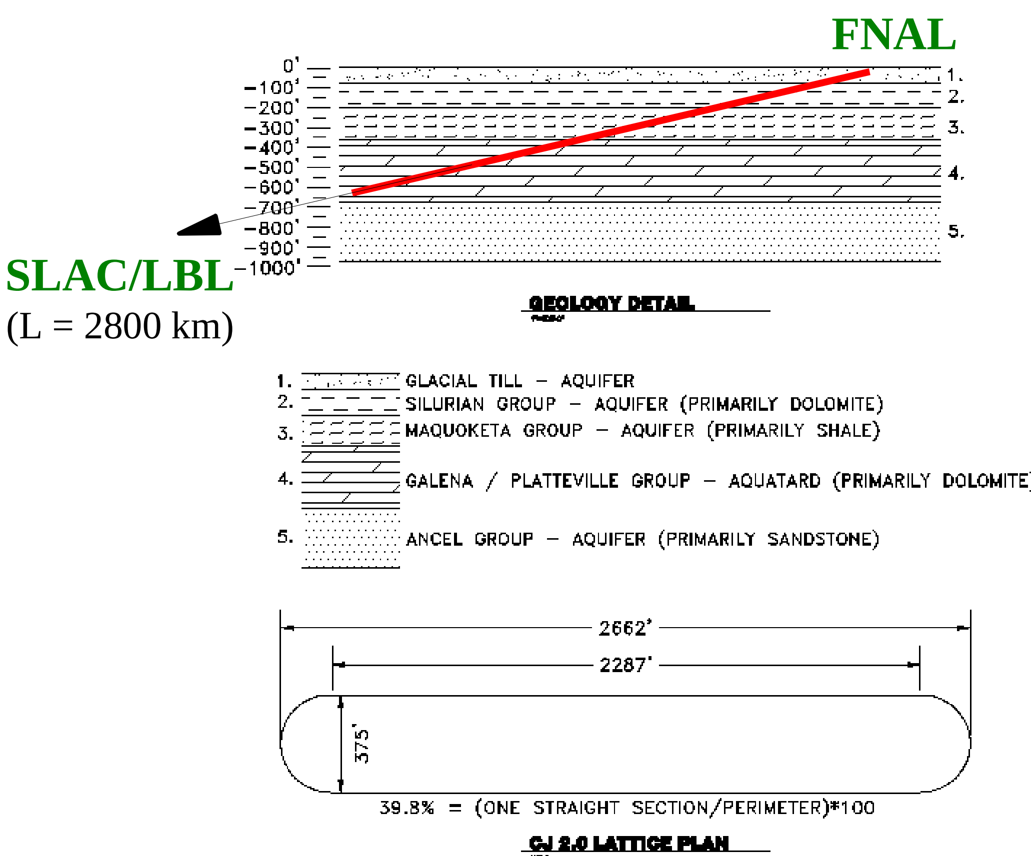
Need high accelerating gradients to get muons to high energy before they decay

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}).

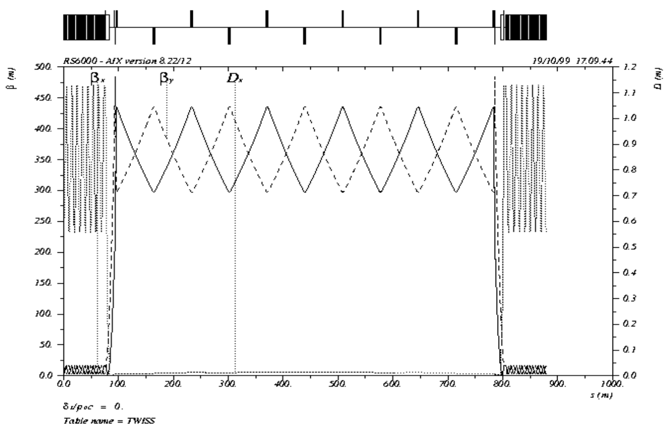
Storage Ring Layout



ORIENTATION:

NAME	AZIMUTH (DEG-MIN-SEC)	VERT. ANGLE (DEG-MIN-SEC)	DISTANCE (KM)
PALO ALTO CA.	271-20'-42.27"	-13-09'-26.99"	2910

Storage Ring Design



The straight section is not just a drift region but has structure. The design criteria was that the mean muon divergence < 0.1 / γ

Beam diagnostics ideas & questions

To obtain well known flux at far site need to measure the beam current, polarization, direction and divergence (see S. Geer & C. Crisan, FERMILAB−TM−2102)

Trickiest to precisely determine is probably divergence :

Cherenkov light: Low pressure gas in ring
Discrete radiators

Beam profile monitors

Satellite detectors

.....

Muon Collaboration

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

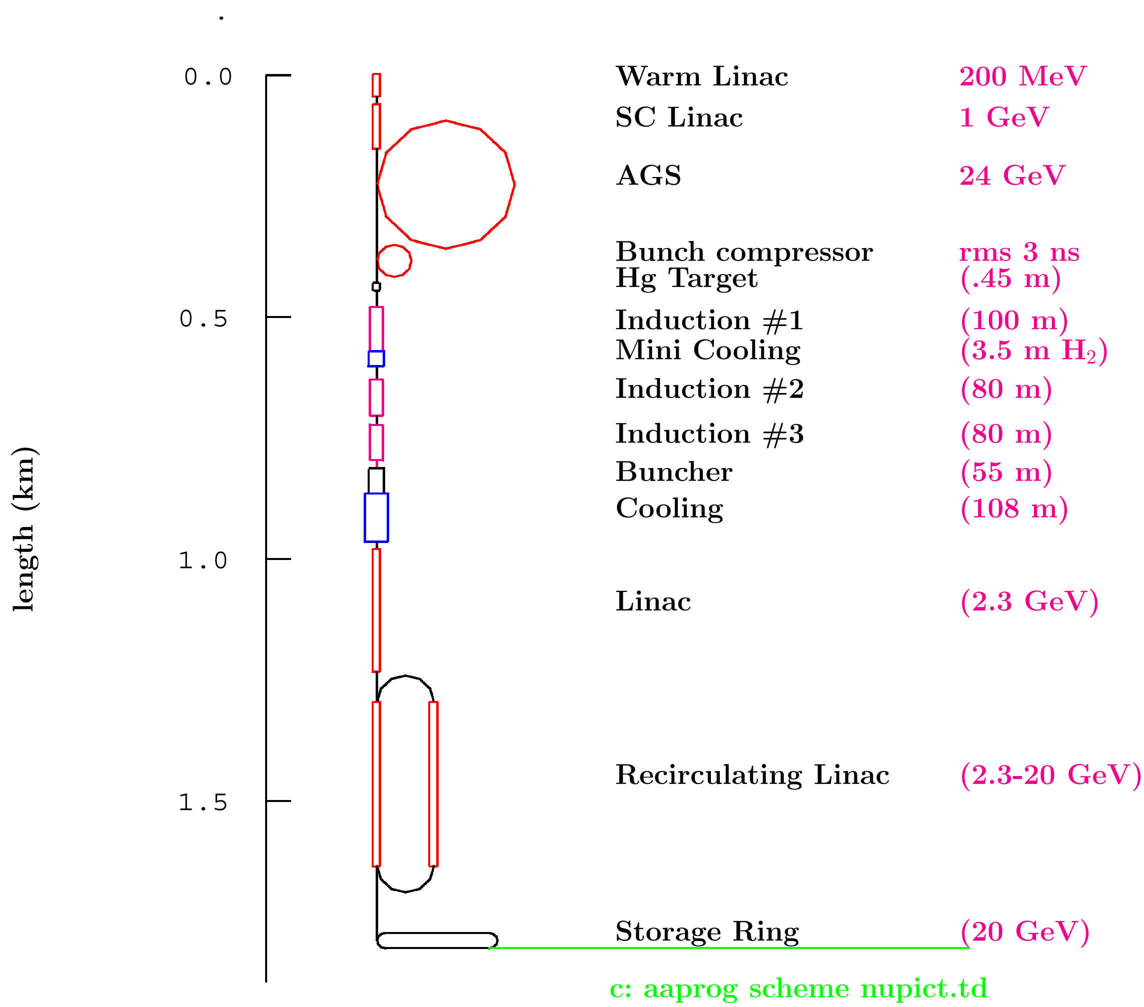
Acceleration
- Develop cost effective 200 Mhz superconducting RF

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.

STUDY 2 SCHEMATIC



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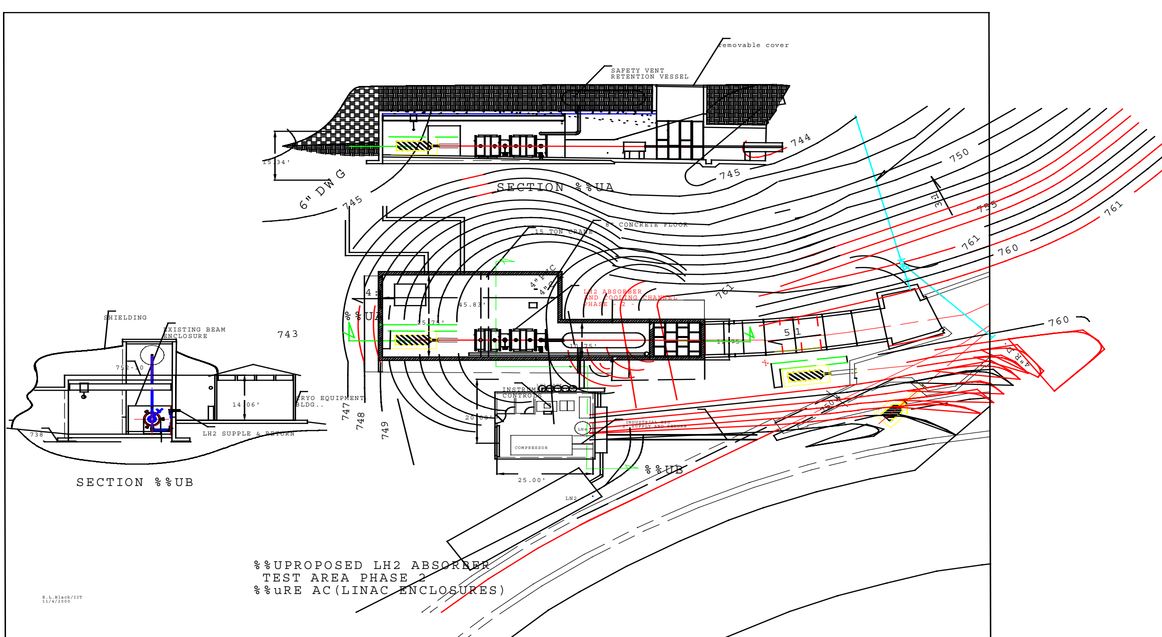
Comparison of Study 1 and 2

	Study 1	Study 2
Proton Driver	FNAL-16 GeV	BNL-24 GeV
Target	Carbon	Hg Jet
Phase rotation	1 Ind. Linac	3 Ind. Linacs (simpler pulsing)
Cooling	Solenoid problem identified	Solenoid problem resolved
Acceleration	Large acceptance	Very large acceptance
Number of decays	$6x10^{19}$decays/ $2x10^{7}$secs 1.5 MW proton driver	$3.2x10^{20}$ decays/ $2x10^{7}$ secs 1.2 MW proton driver
Ring	50GeV, deep	20GeV, on a hill

View from the top of Wilson Hall

Phase I&II



Linac Area Plans

Any usage of the facility should be completely parasitic to Linac Operations and maintenance. Construction will should require only modest, ~ three weeks of invasive interaction with Linac, which should be schedule as part of regular shutdowns.

1. Liquid Hydrogen Absorber test facility

a. Engineering Tests no Beam----Jun-2001

b. Beam Related Hydrogen Absorber test ------Jun-2002

c. Short Fully Integrated Cooling Section, H-Abs., Be-Window RF Cavity, SC Solenoid----Sep-2002

2. High Power RF Test Bed, 200MHz and 805MHz

a. Be Window RF Cavity, High Power RF Test---Sep-2002

b. Grid Based RF Cavity, High Power Test—Sep-2002

c. Cryo Cold Copper Cavity

1. Superconduting Test Facility

200MHz Superconduting Cavity, NSF-Cornell

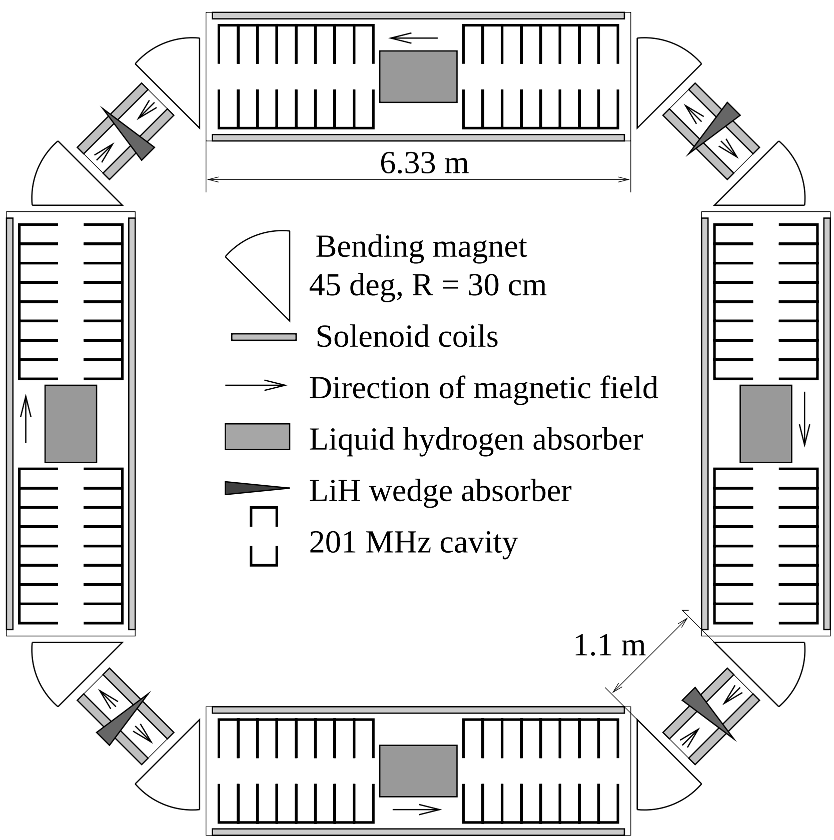
SNS maybe

805MHz Cavity for Linac Energy Upgrade

2. Any H-, 400MeV Beam Related Experiment

Experiment to demonstrate Muon cooling

- Ring Cooler Ideas- V.Balbekov
  - » Group looking into this possibility- R.Raja,Z.Usubov,S.Kahn,N.Mokhov,G.Hanson P.Schwandt,V.Balbekov

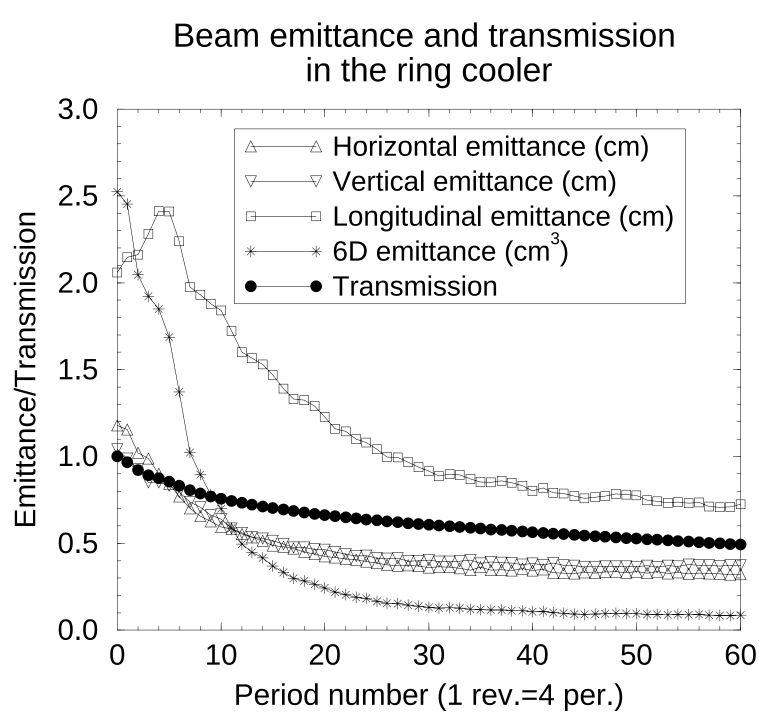


Ring Cooler

- Internal Target, Geant Simulations on going. Injection and extraction difficult.

6 Cooling in the Ring

Injected beam:	$\sigma_X = \sigma_Y = 4.87$ cm
	$\sigma_{P_x} = \sigma_{P_y} = 26$ MeV/c
	$\sigma_Z = 8.5$ cm, $\sigma_E = 18.8$ MeV
	$\varepsilon_X = \varepsilon_Y = 1.2$ cm, $\varepsilon_Z = 1.5$ cm
After 15 revolutions:	$\varepsilon_X = 0.32$ cm
	$\varepsilon_Y = 0.37$ cm
	$\varepsilon_Z = 0.68$ cm
Transmission:	68% with decay
	49% without decay



Conclusions

- There is a strong case to build a neutrino factory, if you believe that neutrinos have mass and they oscillate. CP violation in the lepton sector as well as the mass heirarchy structure is best studied using a neutrino factory.
- Neutrino factories provide a challenging frontier in accelrator physics and have in fact envigorated that field.
- Neutrino factories are complementary machines to the NLC, VLHC etc and should be done irrespective of what other machine is built.
- Muon Cooling demonstration would be desirable to demonstrate as a first step to building a neutrino factory.
- Neutrino factories may pave the way to a muon collider, which can open up new energy frontiers.