Neutrino Factory & Muon Collider R&D

Steve Geer

Fermilab

Muon Colliders – Neutrino Factories

- Significant interest in a new type of muon source
  >> a millimole of muons per year !

- Initial interest in Muon Colliders >> Muon Collider Collaboration formed in US in 1995 (> 100 physicists from BNL. FNAL, LBNL, and many Universities)

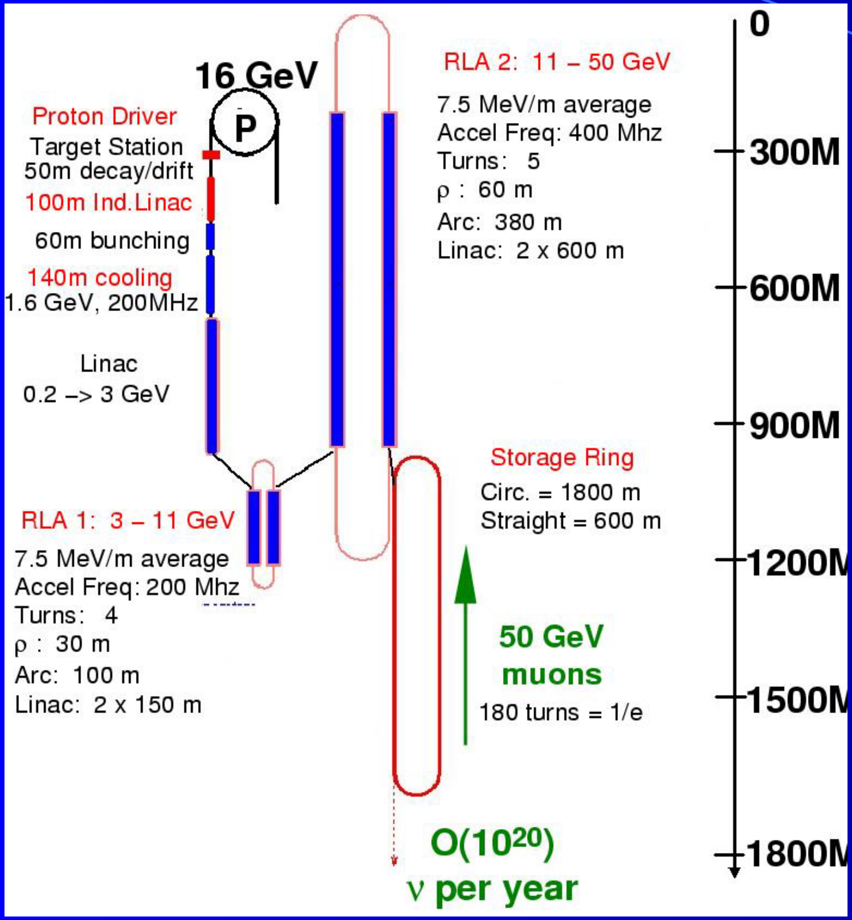
- In 1997: Intense muon storage ring neutrino source (Neutrino Factory) >> natural step towards a muon collider

Super-K results >> neutrino oscillations are exciting
>> World-Wide interest in Neutrino Factories

Neutrino Factories Catch On

- In the US
  - Technical review recommends collaboration focus on end-to-end study of one thing … collaboration chooses ν factory
    - FNAL sponsored Design Study 1 established feasibility
    - BNL sponsored Design Study 2 improved performance
- In Europe
  - Immediate interest >> yellow report
  - R&D Group formed >> complementary technology choices
- In Japan
  - Interest in low energy muons >> PRISM at the JHF
  - Study completely different ν-factory scheme >> large acceptance accelerators

US ν-Factory Scheme



Design Study 1 (completed April 2000)

Proton driver: Upgraded FNAL Booster

Carbon target in 20T capture solenoid

50m decay channel (1.25T)

Muon energy spread reduced using induction linac (phase rotation)

Muons bunched at 200 MHz

Transverse phase space reduced using an ionization cooling channel

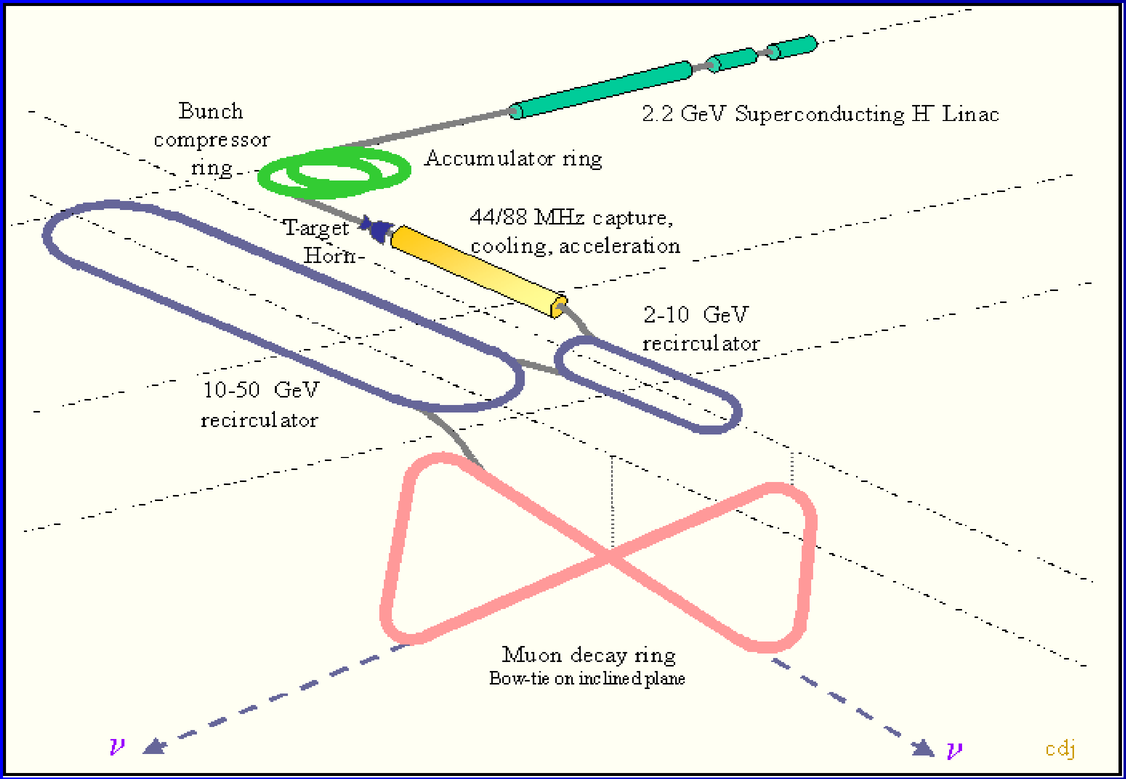
Acceleration to 50 GeV in RLAs

Design Study 2 (completed May 2001, based on upgraded BNL AGS)

Hg jet target, better induction linac & cooling channel designs

Achieved 6 x Study 1 muon rate >> 2 E20 useful μ decays / year

CERN ν-Factory Scheme



Similar to US scheme but explore alternative technology choices:

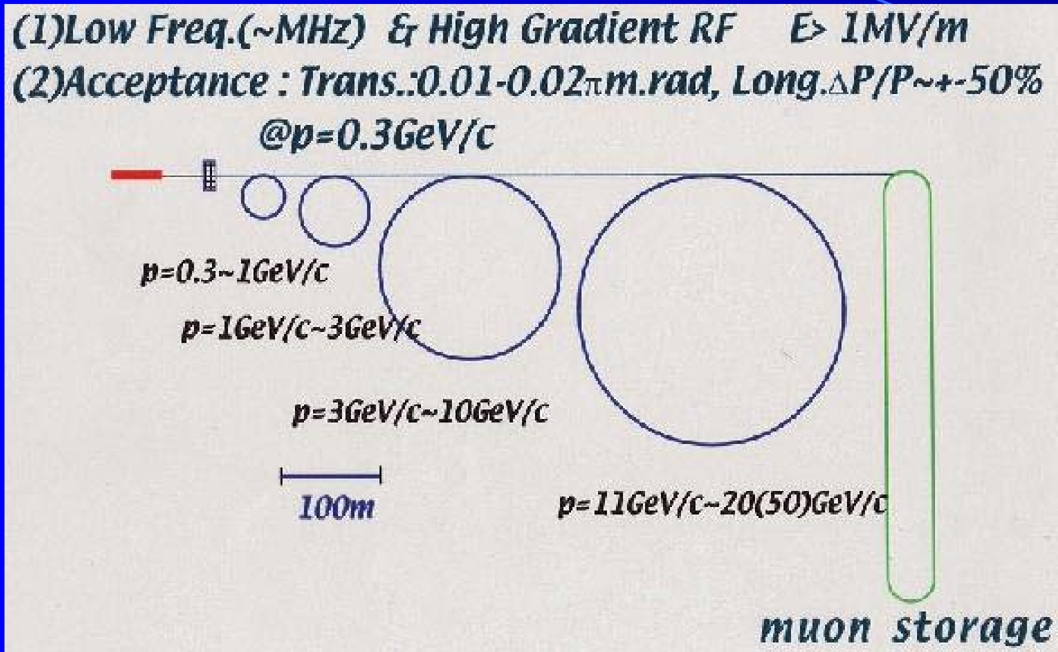
Lower energy proton driver (LEP cavities >> 2.2 GeV protons)

Pion capture with magnetic horn

RF for phase rotation (no induction linac)

Transverse cooling channel at 44/88 MHz (not 200 MHz)

Japanese ν-Factory Scheme

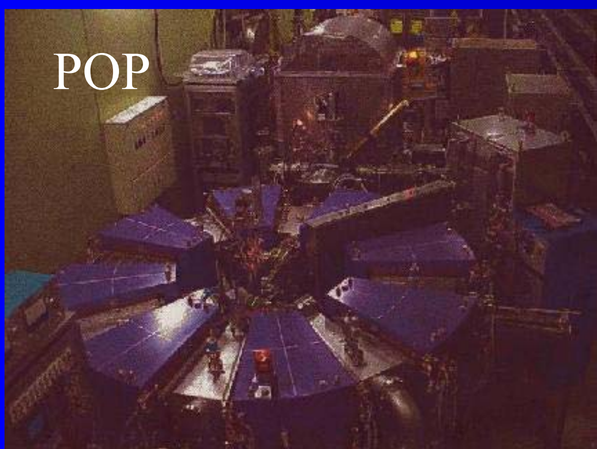


NO PHASE ROTATION OR COOLING (would benefit from some cooling)

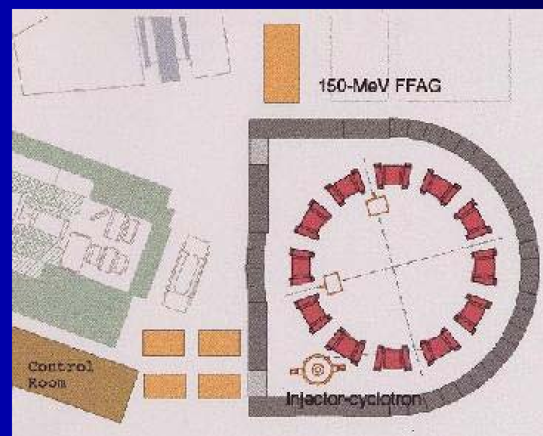
USE LARGE ACCEPTANCE ACCELERATORS - FFAGs

R&D Issues: RF, Injection/extraction, magnet design, dynamic aperture

GOAL: 1.E20 >> 4.4E20 USEFUL muon DECAYS / YEAR @ 20 GeV >> 50 GeV



Proof of Principle (POP) FFAG tested at KEK in June 200

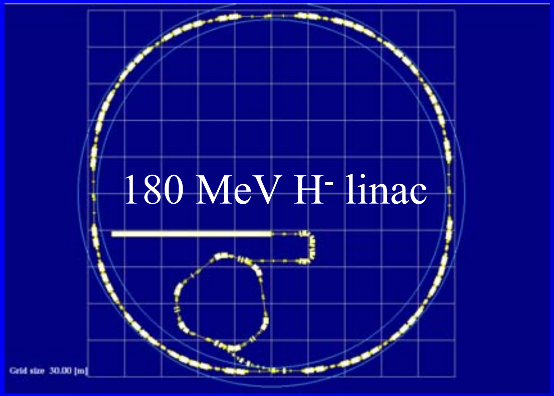


NEXT STEP
150 MeV FFAG
Under construction
At KEK

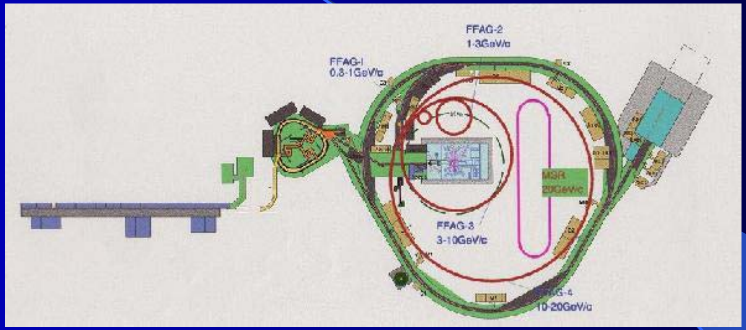
RF R&D: US/Japan collaboration

Proton Sources

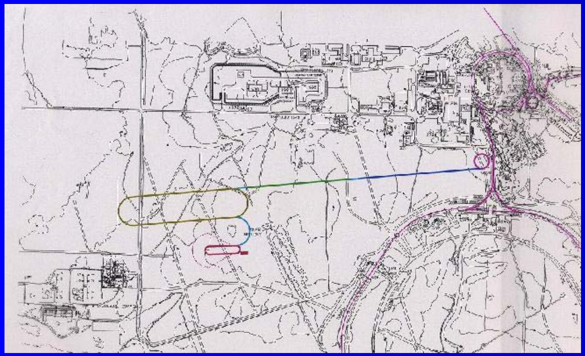
- The starting point – a multi-GeV proton source providing an O(1 MW) beam on target. **Everyone has a viable scheme:**



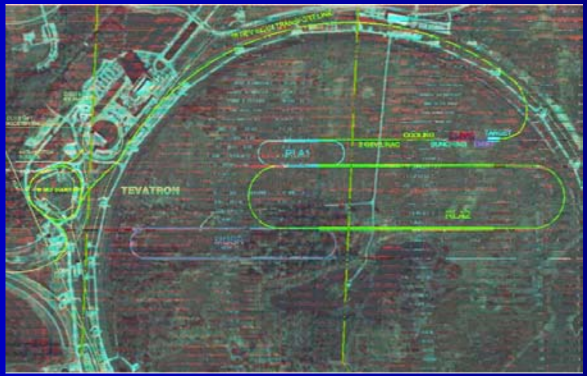
CERN: 2 GeV SPL – 4MW



Japan: 50 GeV, 0.8 MW JHF
(upgrade to 4MW)



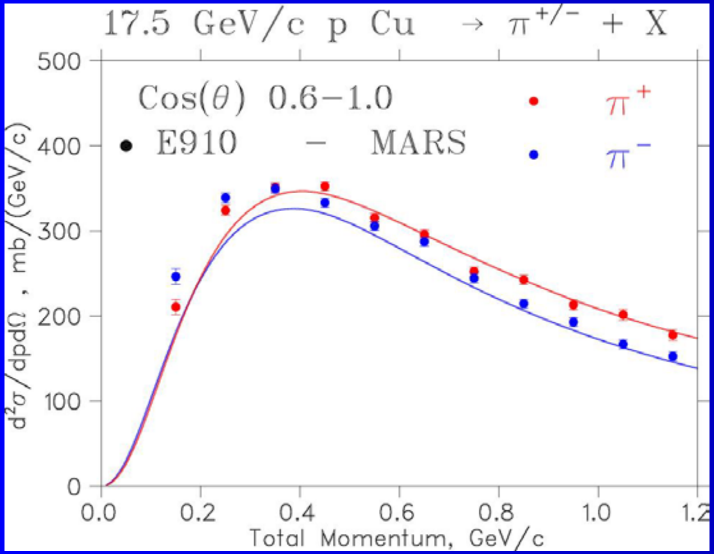
BNL: Upgraded AGS
24 GeV, 1-4 MW

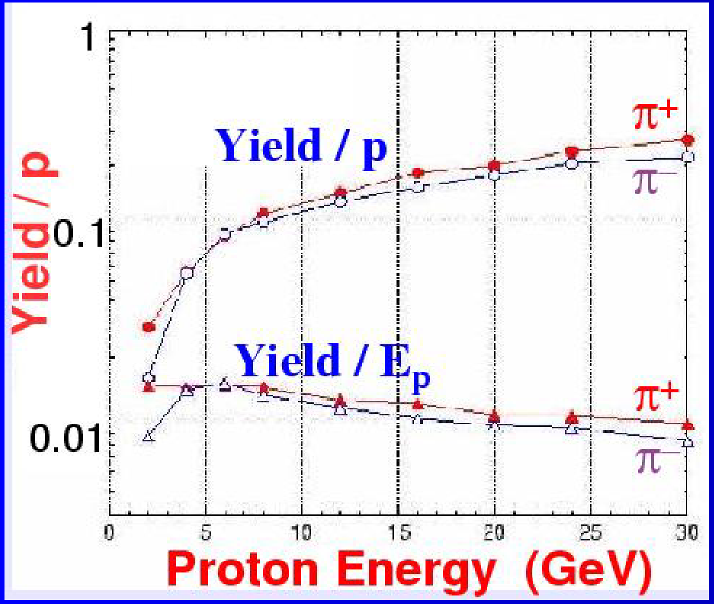


FNAL: Upgrade d Booster
8-16 GeV, 1-4MW

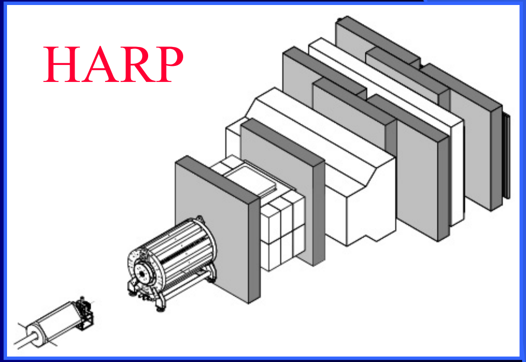
NEUTRINO FACTORIES FIT ON EXISTING SITES & CAN USE UPGRADED EXISTING PROTON DRIVERS >> PLENTY OF CANDIDATE SITES

Producing Pions



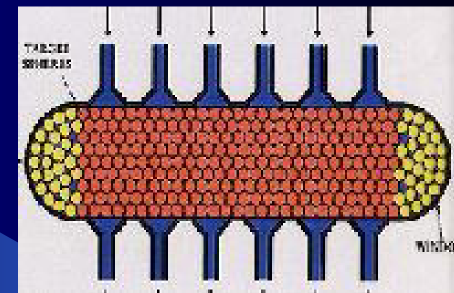


- NEW BNL E910 pion production Results
  - Pion yields peak at few hundred MeV/c
  - Data in fair agreement with MARS predictions (yields may be slightly higher than predicted)
- At constant proton beam power, pion yields vary slowly with proton energy >> broad range of proton driver energies can be considered.
- More particle production data in next few years from:
  - HARP (CERN)
  - Fermilab P907



Target R&D for MW-Scale Proton Beams

- Carbon Target tested at AGS (24 GeV, 5E12 ppp, 100ns)
  - Probably OK for 1 MW beam

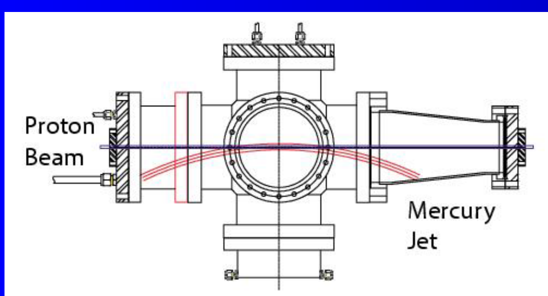


- Target ideas for 4 MW: Water cooled Ta Spheres (P. Sievers), rotating band (B. King), conducting target, Front-runner = Hg jet
- CERN/Grenoble Liquid Hg jet tests in 13 T solenoid
  - Field damps surface tension waves

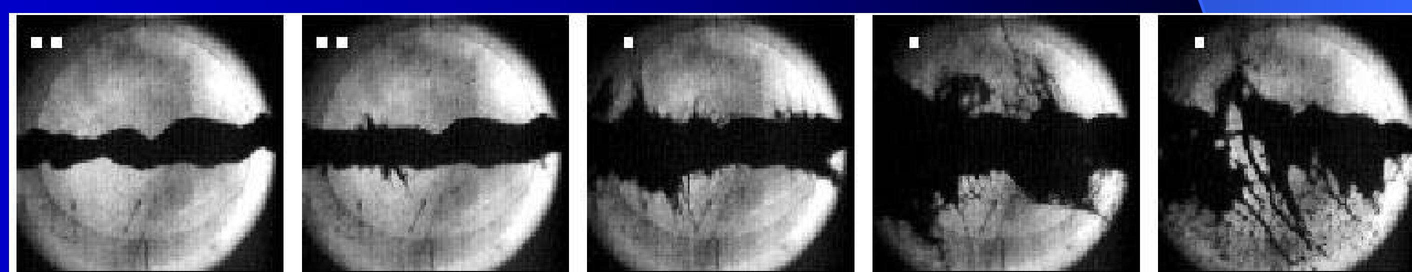
0 Tesla

13 Tesla

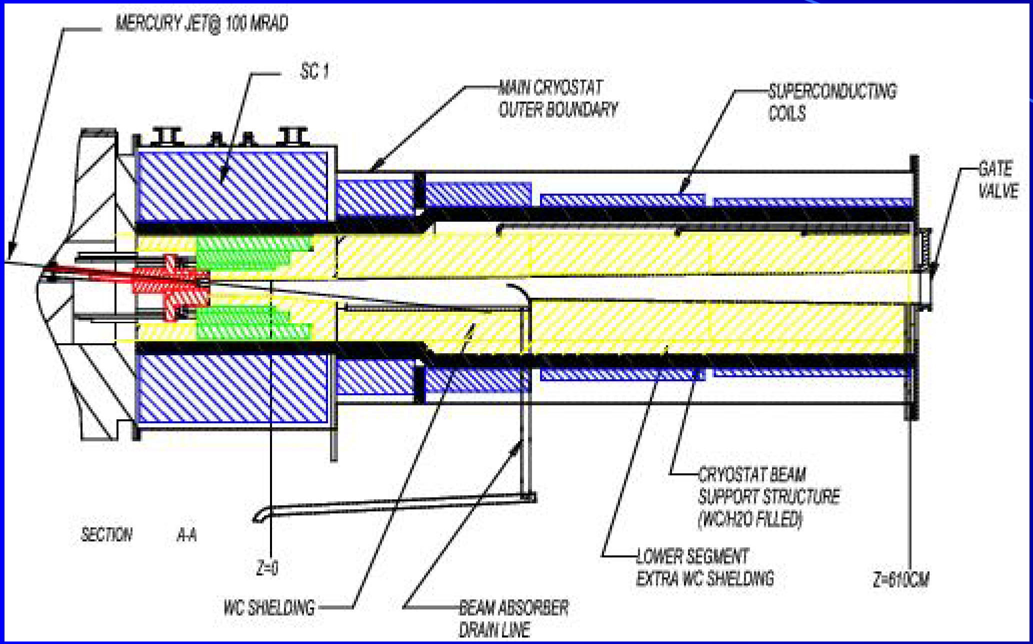
- BNL E951: Hg Jet in AGS beam
  - Jet (2.5 m/s) quickly re-establishes itself. Will test in 20T solenoid in future.

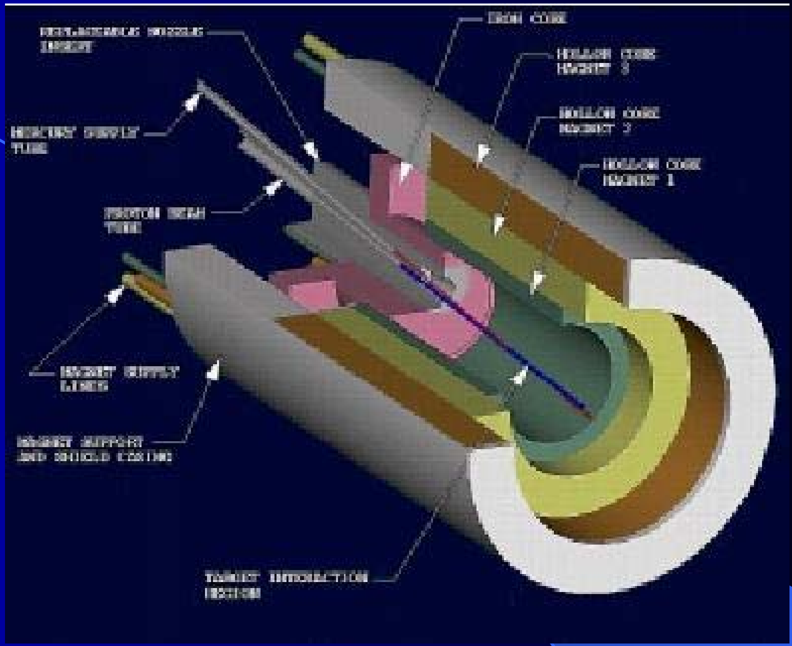


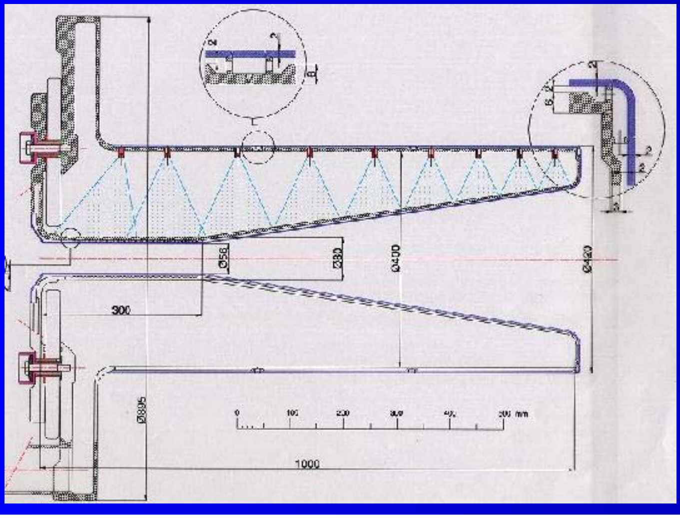
t = 0 | 0.75 ms | 2 ms | 7 ms | 18 ms



Pion Capture





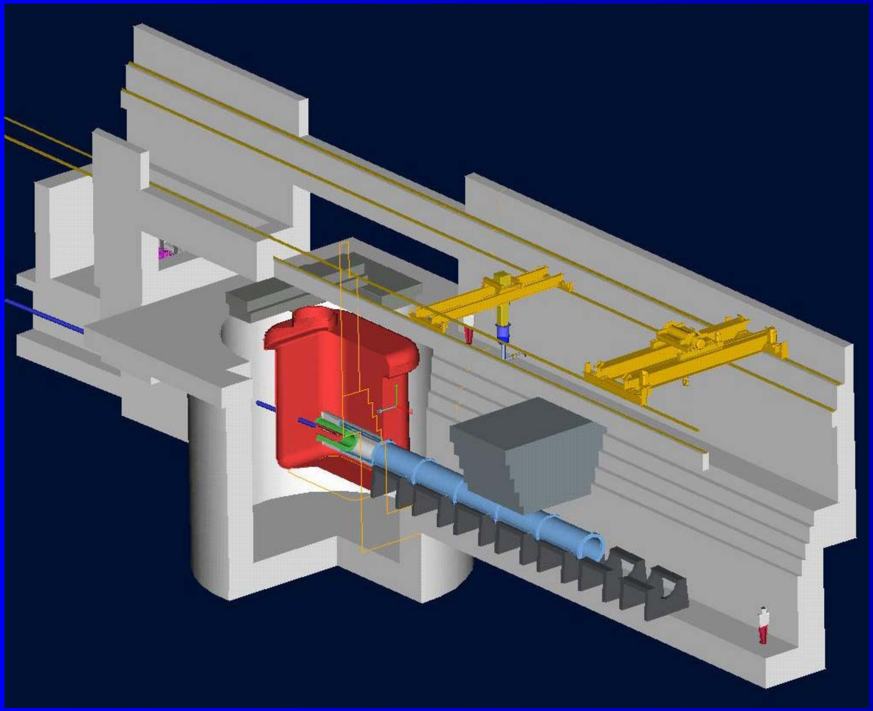


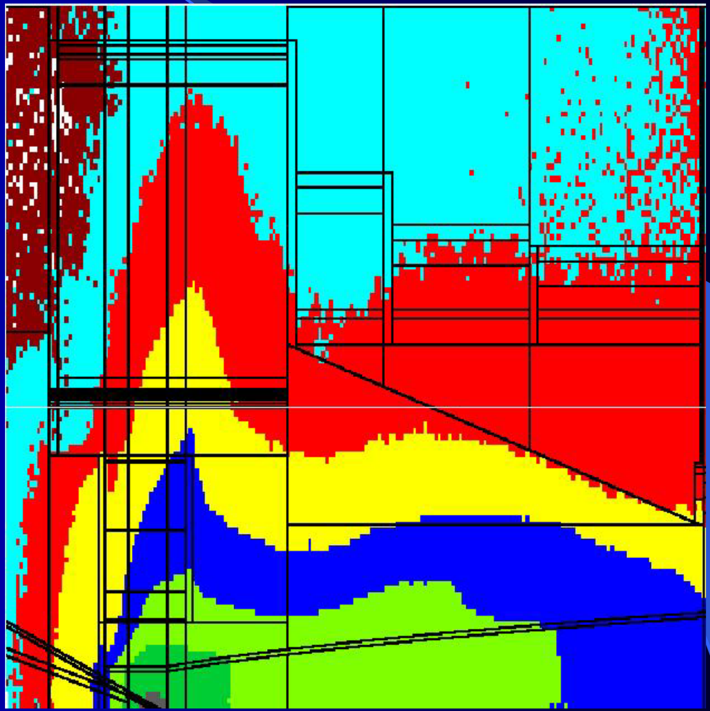
US Design: Target in 20T capture solenoid which tapers down to 1.25T

CERN Design: Use magnetic horn (waist radius = 4 cm, peak current = 300 kA)

Target Facility

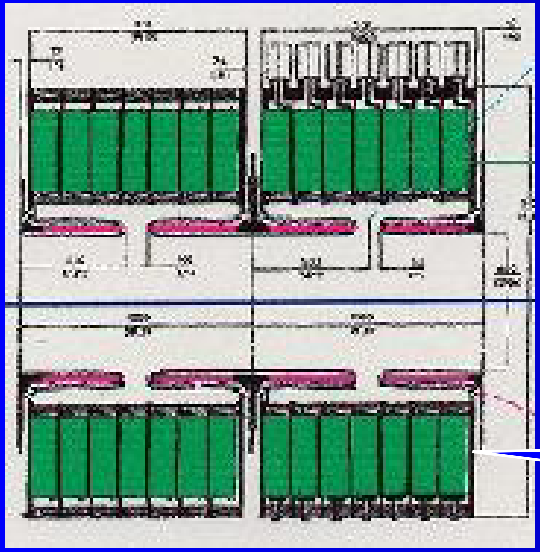
Need remote handling target facility – detailed design made for US neutrino factory studies 1 and 2.





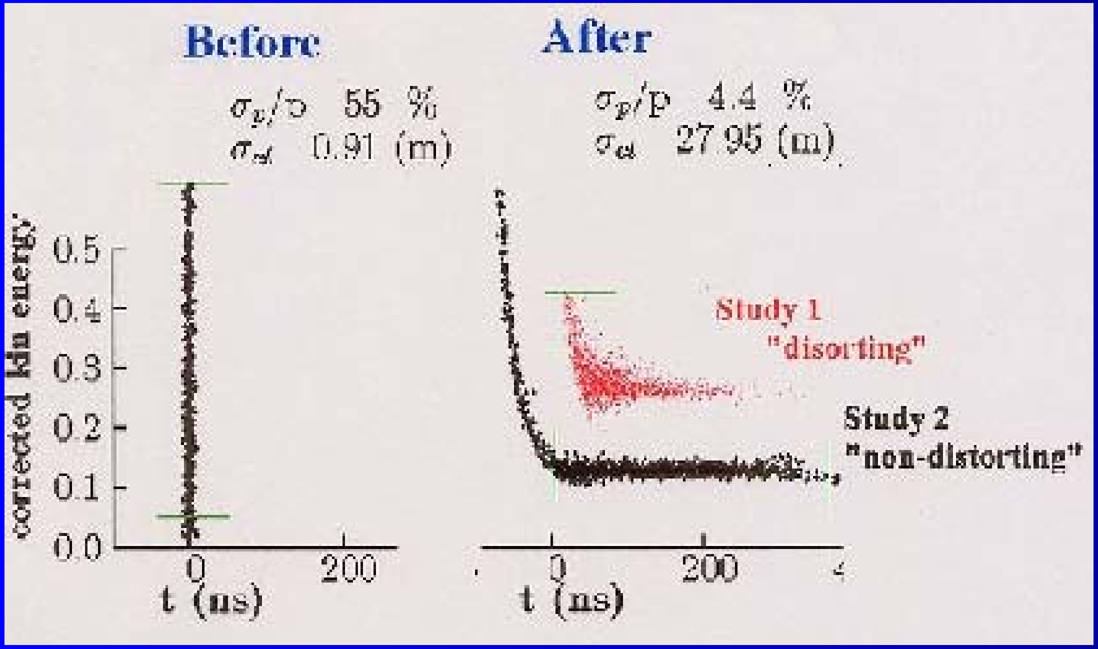
Based on SNS (Oak Ridge) design experience.
Detailed radiation simulations (MARS, N. Mokhov) >> facility lifetime OK

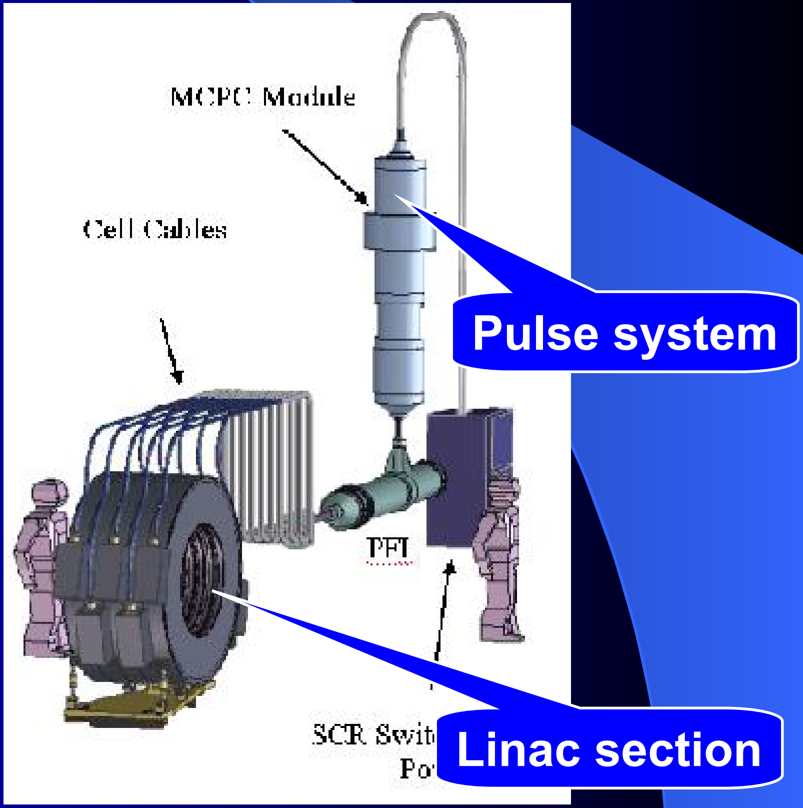
Reducing the μ Energy Spread



PHASE ROTATION: Drift followed by a time-dependent Acceleration (fast particles de-accelerated, slow accelerated)

US Scheme: use 260m long (r = 95 cm) Induction Linac with internal 1.25T solenoid: $\sigma(p)/p$ = 55% >> 4.4%





Reducing the Transverse Phase Space

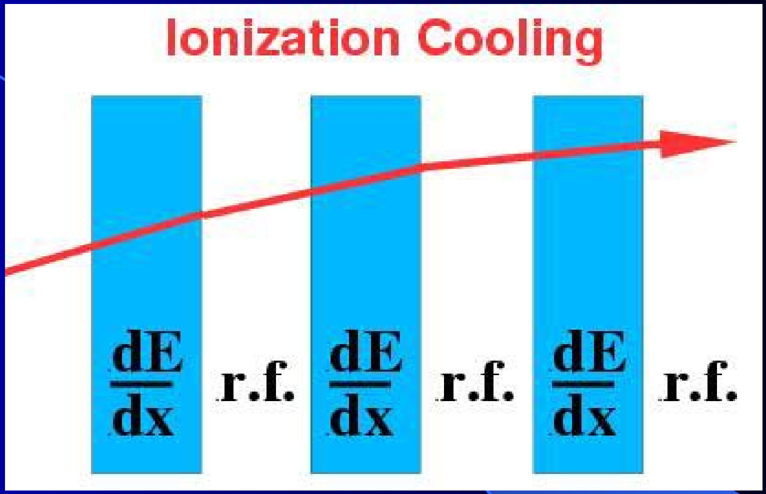
Transverse phase space too large to fit within normal accelerator

Must "cool" the beam fast – Before muons decay

Electron cooling & stochastic Cooling too slow
>> USE IONIZATION COOLING

An ionization cooling channel Can be thought of as a LINAC Filled with material

Need high gradient RF to keep the muons captured



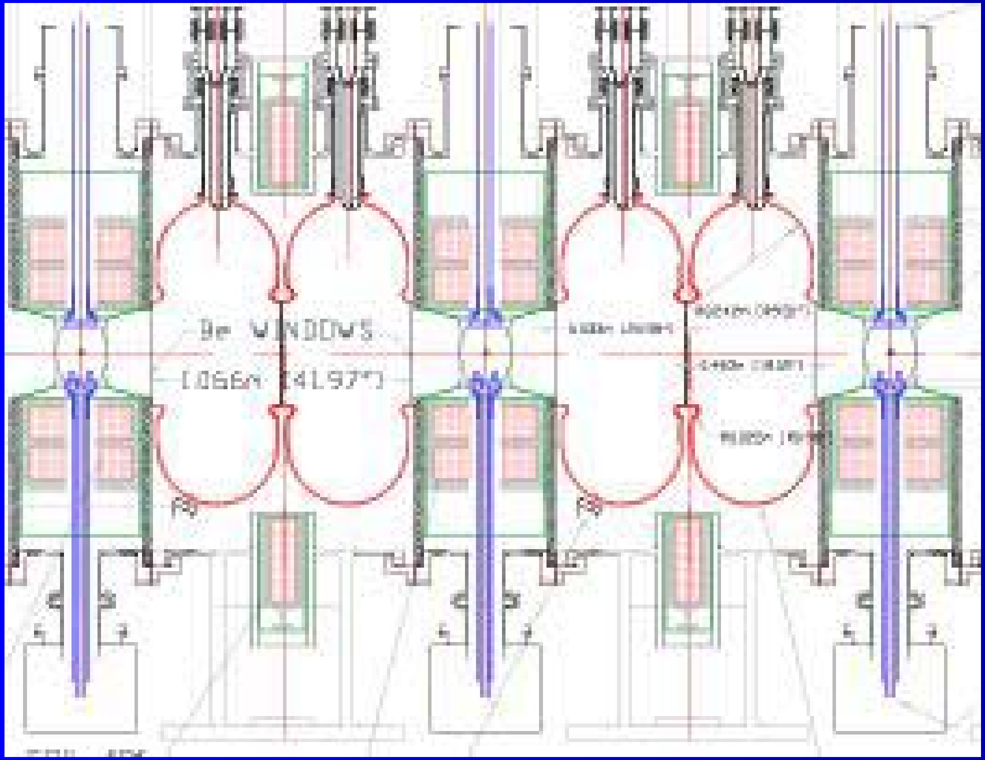
Coulomb scattering tries to heat beam

Use Liquid Hydrogen absorbers

Use strong radial focusing
>> high field solenoid channel

Cooling Channel Design

3.3 m long section



Liq. H RF Liq. H RF Liq. H

21 cm long Liquid hydrogen absorbers in high-field solenoid with field reversing direction at absorber

Study 2 Design (R. Palmer)

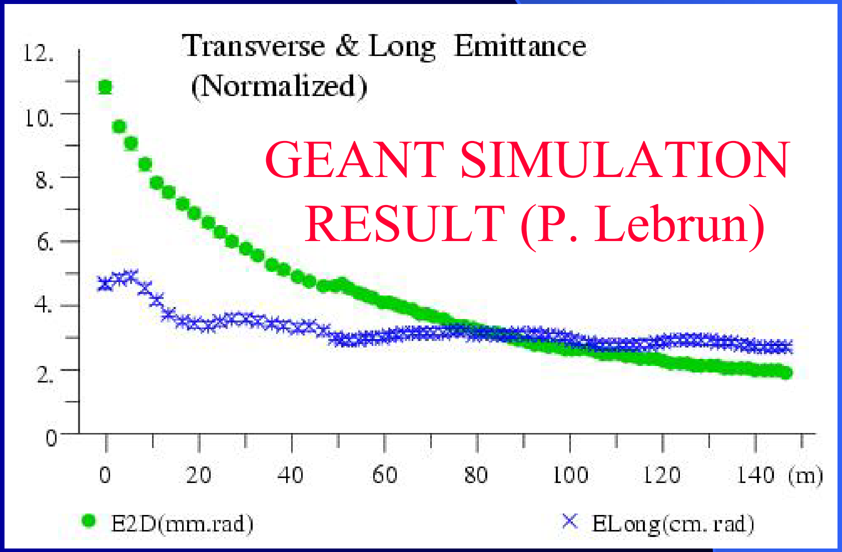
Channel Length: 108 m

Lattice period: 5.4 m >> 3.3 m

High field solenoid : 3T >> 5T

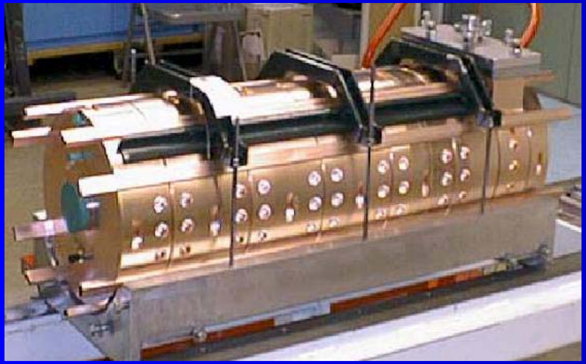
Solenoid radius: 33 cm >> 20 cm

RF: 17 MV/m @ 200 MHz



MUCOOL RF R&D

Initial R&D at 805 MHz (end of Muon collider cooling channel)

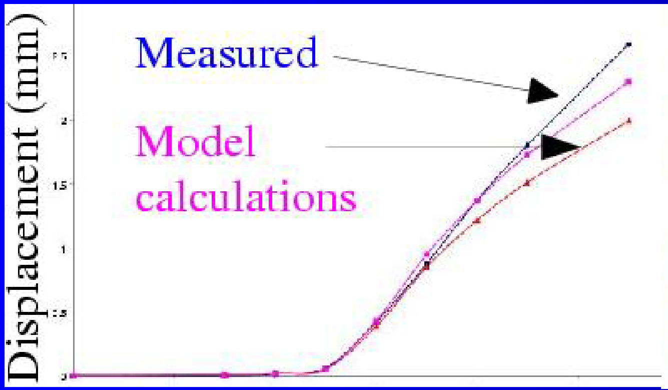


Open cell cavity >> push on surface fields

Need 30 MV/m gradient on axis

Prototype built & tuned (FNAL)

High power tests in progress



Window Displacement vs Power dissipated

Close aperture with conducting foil/grid
(at fixed peak power this doubles gradient)

Initial R&D with Be windows

Window deflection as it heats up measured & understood

High power test cavity being constructed (LBNL, Mississippi)

200 MHz cavity (ν factory) >> 17 MV/m being designed >> high power tests in ~ 2 years

MUCOOL Liquid H2 Absorber R&D

Need thin windows to minimize scattering

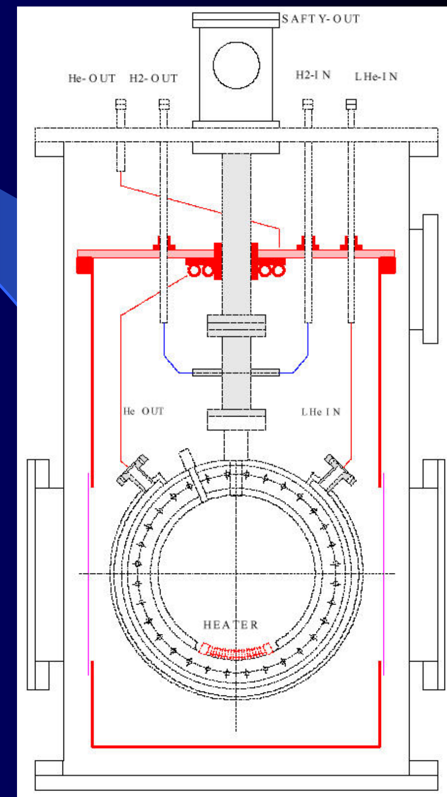
125 µm window
Made (Mississippi)
& measured (FNAL)

Pressure test under
Way (NIU)

Must remove O(100) W heat deposited by dE/dx >> good radial mixing

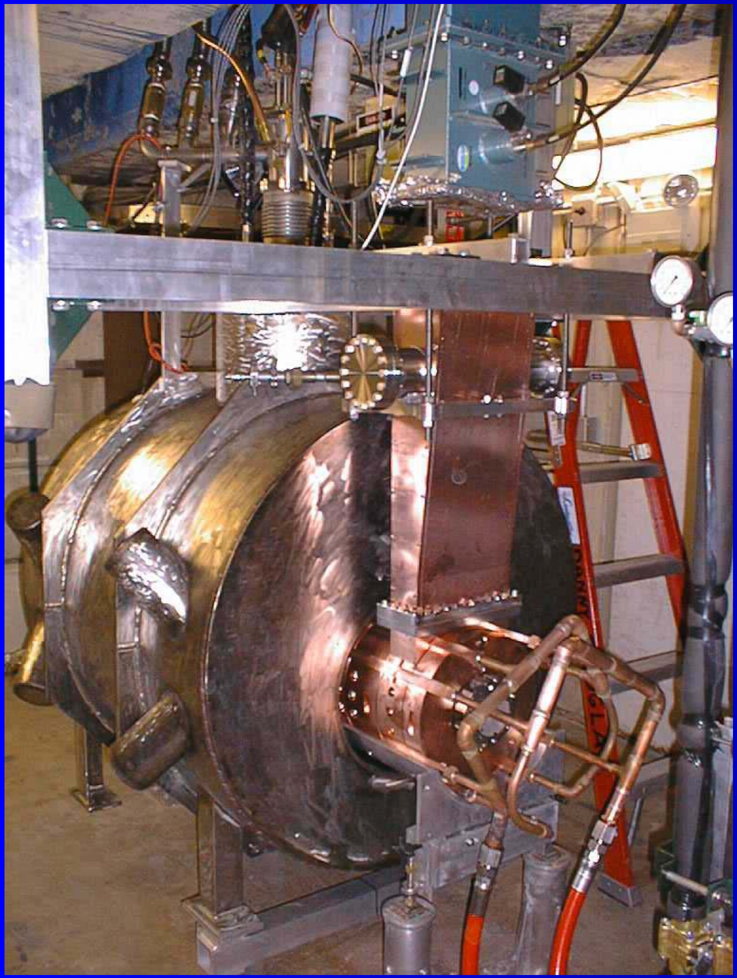
TWO CONCEPTS

1. Forced flow through nozzles: Prototype being built by University consortium >> test at FNAL
2. Driven convection: Prototype being built by KEK & Osaka >> test at FNAL



KEK, Osaka design

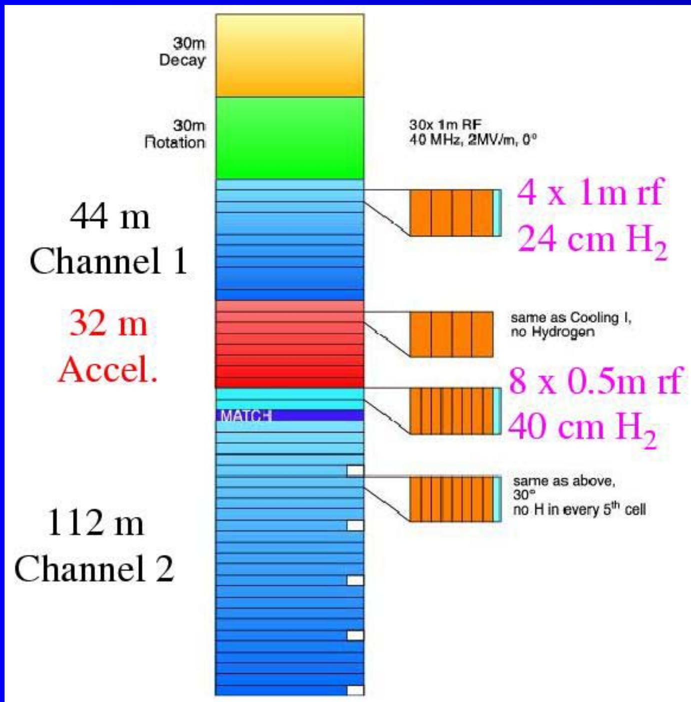
MUCOOL Test Facilities



1. High Power RF test facility (FNAL Lab G) with 5T solenoid (LBNL) began operation in May 2001)
   >> 805 MHz high power cavity tests
   >> cooling channel instrumentation studies

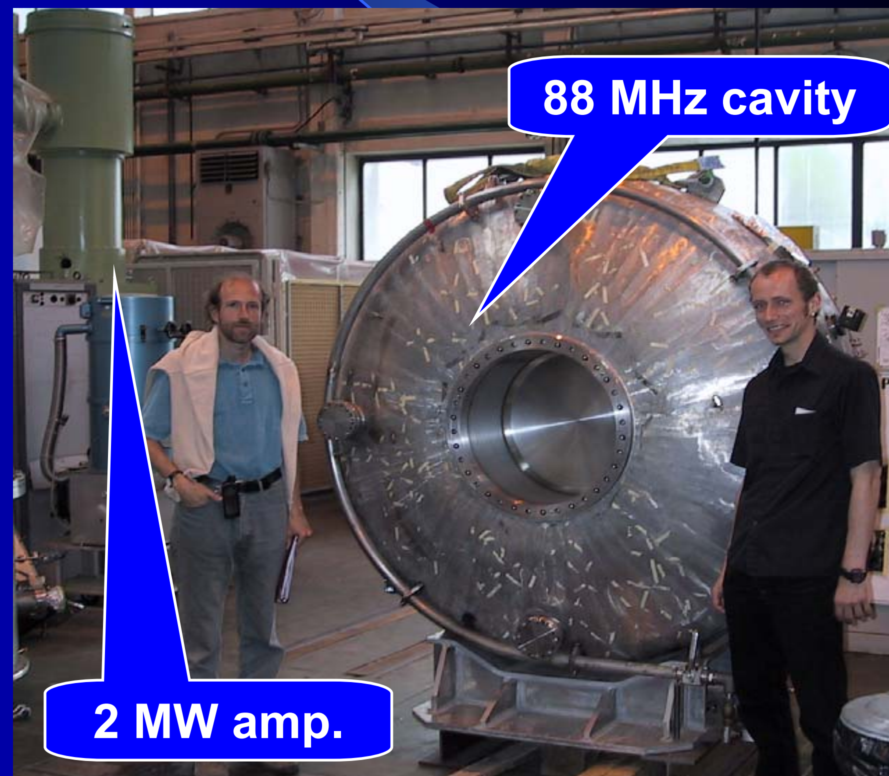
2. FNAL Linac Area: Under construction
   >> LH2 filling facility in a few months
   >> 400 MeV proton beam in a year
   >> 200 MHz high-power test facility in 2 years

CERN Phase Rotation & Cooling



No Induction Linac – use drift + 44 MHz cavities for the phase rotation

Cooling channel based on 44 MHz & 88 MHz cavities with some acceleration in middle



88 MHz High Power test at CERN next year

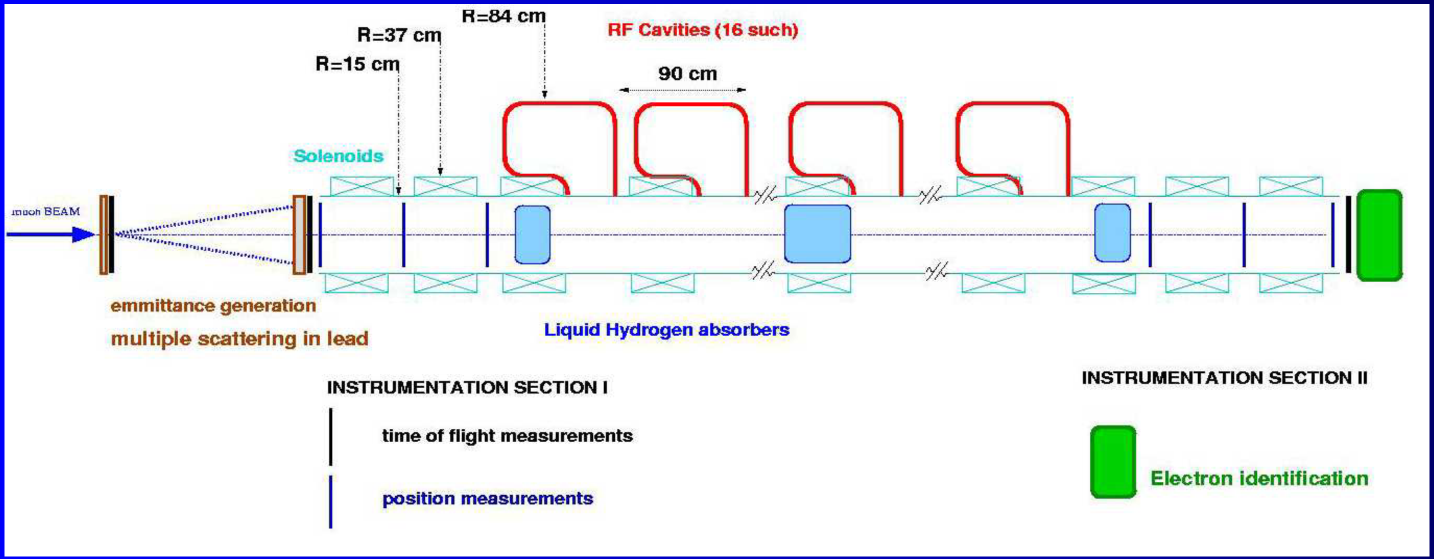
	Channel 1	Channel 2
Length	46 m	112 m
Diameter	60 cm	30 cm
Solenoid B	2.0 T	2.6 T
RF Freq.	44 Mhz	88 Mhz
RF Gradient	2 MV/m	4 MV/m
Beam Energy	200 MeV	300 MeV

Towards a Cooling Experiment

Dialogue between R&D groups in Europe, US, Japan >> explore possibility of a World Wide collaboration >> cooling experiment

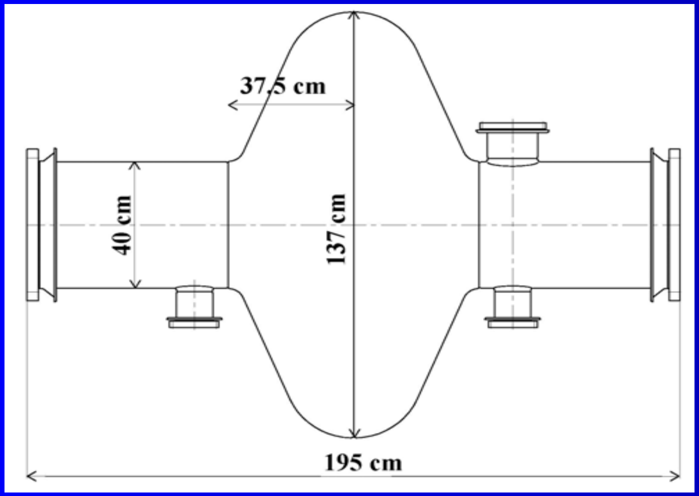
Need to pursue individual concepts & component development for next 2-3 years, & then decide on best technical design … easier to decide if we cross-participate in each others component development BUT NEEDS ADDITIONAL R&D SUPPORT

Cooling experiment good step toward World Wide Collaboration



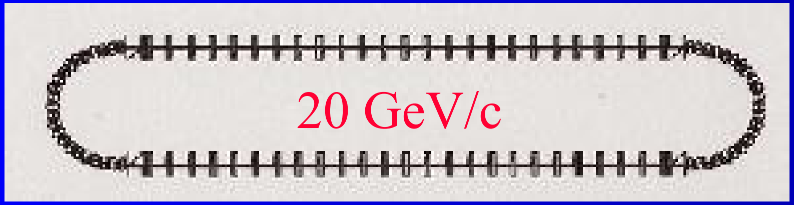
Single particle concept developed (most recently) at CERN >> World Wide effort now in progress to see if its feasible.

Muon Acceleration & Storage Ring



After cooling, early acceleration with Linac, Later acceleration with RLAs

SC 200 MHz cavity (Niobium sputtered on Copper) being built at CERN for tests at Cornell



Japanese Version

Everyone has a muon storage ring design; they come in various shapes, but all have long straight sections

1.E20 useful muon decays / year

Muon Collider Challenges

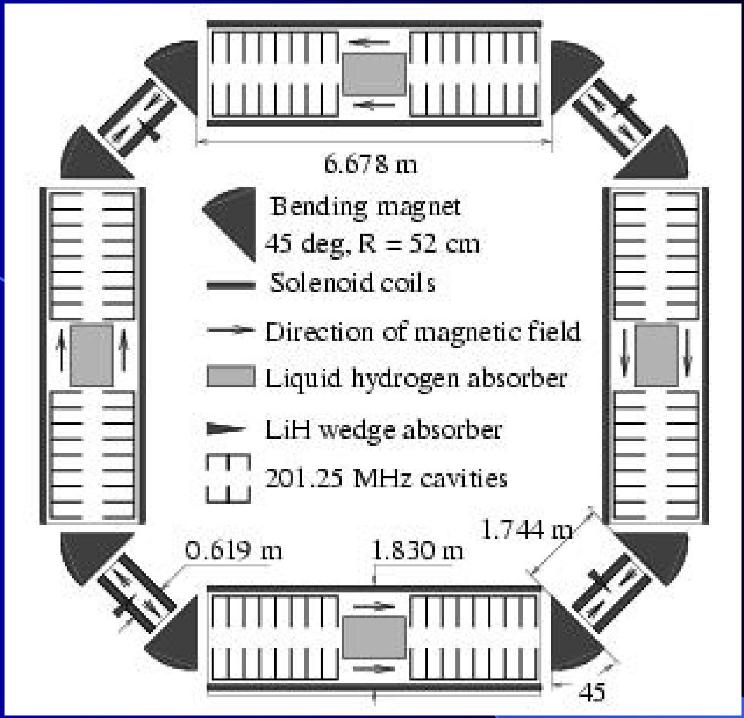
A ν-factory would move us up the learning curve towards a multi-TeV Muon Collider … but there are Additional challenges that must be met before we have a realistic Muon Collider design:

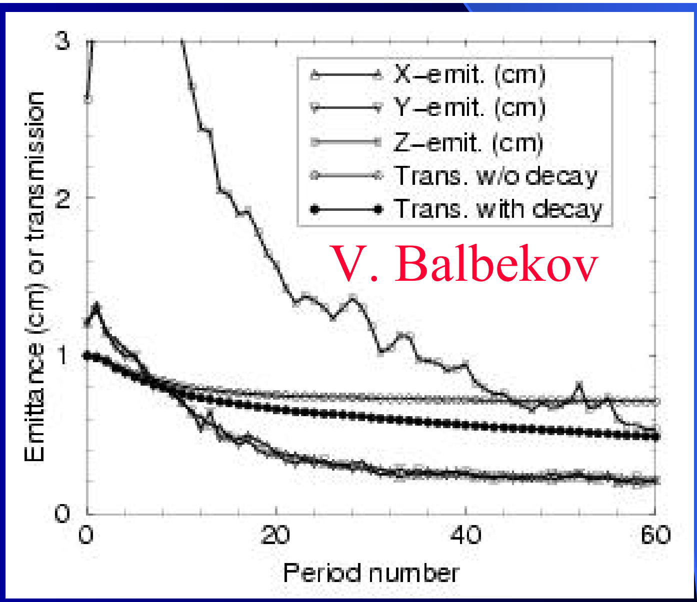
Need much more cooling
 >> EMITTANCE EXCHANGE

All muons in one bunch

Cost-effective acceleration

Detector backgrounds (probably OK)





Conclusions

- Very active ν-Factory design & component prototyping in Europe, US, & Japan
- US studies have shown ν-Factory feasible after a few years of R&D
- CERN & Japanese studies show alternative technology choices may be promising … must be pursued until we are ready to make a choice
- Much interest in World-Wide collaboration in critical R&D areas …. but will need additional support !
- R&D pursued by Lab and University physicists … particle physicists & accelerator physicists.

Bibliography

Muon Collider Papers

4 TeV Collider Feasibility Report (Snowmass 1996)

Higgs Factory Design Study, Phys.Rev.ST.Accel Beams 2, 081001 (1999)

Neutrino Factory Papers

S. Geer, PRD 57, 6989 (1998)

Design Study 1 (Eds. D. Finley, N. Holtkamp) ;
http://www.fnal.gov/projects/muon_collider/nu-factory/

Design Study 2 (S. Osaki et al) ;
http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

Physics Study: (Eds. S. Geer, H. Schellman) hep-ex/0008064

Front-End Physics Study: M. Mangano et al, hep-ph/0105155

CERN Study (Eds. Autin, Blondel, Ellis) CERN 99-02