Muon Collaboration

Neutrino Factories, Muon Colliders, and the International Muon Ionization Cooling Experiment (MICE)

Daniel M. Kaplan
U.S. Spokesperson, MICE Collaboration

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ICAR

Physics Seminar
Los Alamos National LLab
Los Alamos, NM
22 May, 2002

Illinois Consortium for Accelerator Research

- 5-university consortium, founded 1999, led by IIT
  D. M. Kaplan (IIT), PI; T. I. Morrison (IIT), PD

- Responds to looming crisis in sustaining progress of accelerator-based particle physics
- Includes >10 faculty, >30 researchers
- Main funding:
  5-year State of Illinois grant at \$2.5M/year
- Main research activities:
  Linear Collider,
  MUCOOL (12 FTE)
- Close collaboration with Fermilab

Outline:

1. Motivation: Neutrino Factory and Muon Collider physics
2. Neutrino Factory Feasibility Studies
3. Need for muon cooling
4. Ionization cooling
5. Neutrino Factory cooling lattices and simulated performance (US, CERN)
6. Cooling experiment
7. Schedule
8. Costs
9. International collaboration
10. Summary

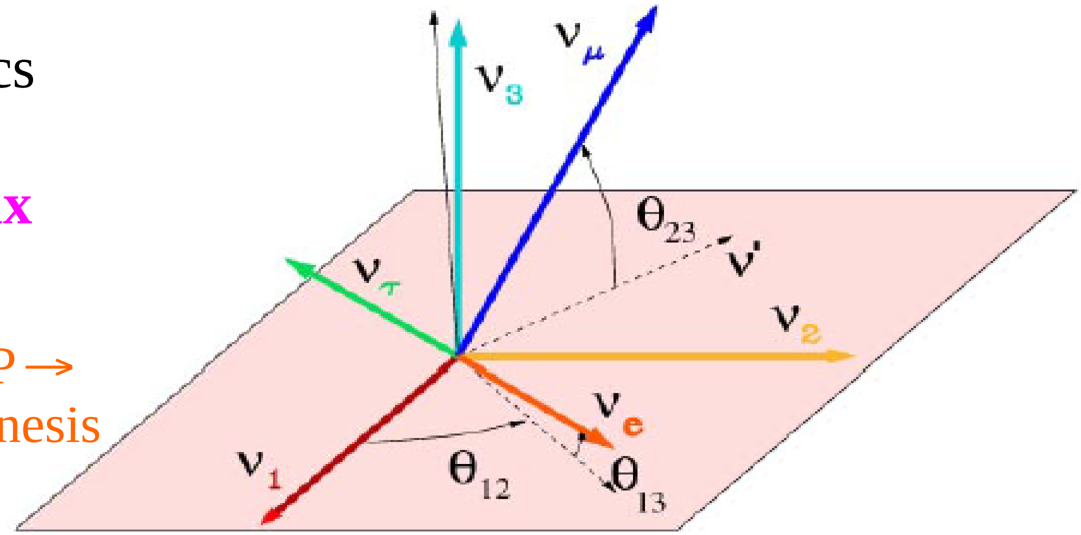
Motivation: Neutrino Factory Physics

1. Most fundamental particle physics discovery of past decade:

   → **neutrinos have mass and mix**

   ⇒ 3 Euler angles (and 1 phase):

   ⇒ neutrino mixing could violate CP → possible mechanism for baryogenesis



2. Pattern of neutrino mixing very different from that of quarks:

CKM matrix: nearly diagonal

$\theta_{12} \cong 12.8°$

$\theta_{23} \cong 2.2°$

$\theta_{13} \cong 0.4°$

MNS matrix (LMA solution):

$\theta_{12} = 20° - 45°$

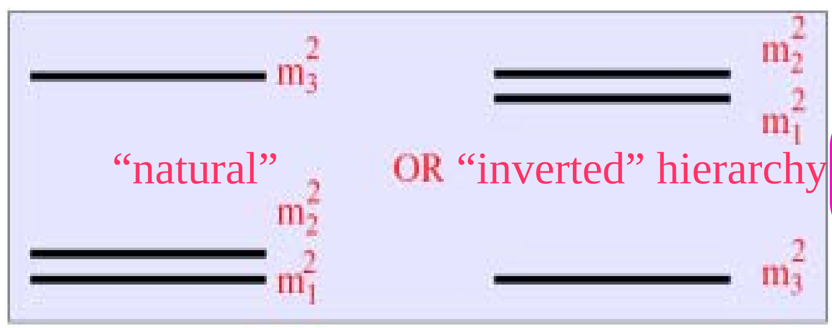
$\theta_{23} = 35° - 45°$

$\theta_{13} < 10°$

Why?

atmos ⇒ $|\delta m^2_{32}| \sim 3 \times 10^{-3}$ eV^2

solar ⇒ $|\delta m^2_{21}| \sim 5 \times 10^{-5}$ eV^2



Distinction is sgn(Δm^2_{32})

Neutrino Factory Physics (cont'd)

3. Leading-order oscillation probabilities (natural hierarchy):

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2(1.267\,\delta m^2_{32} L/E_\nu)$$

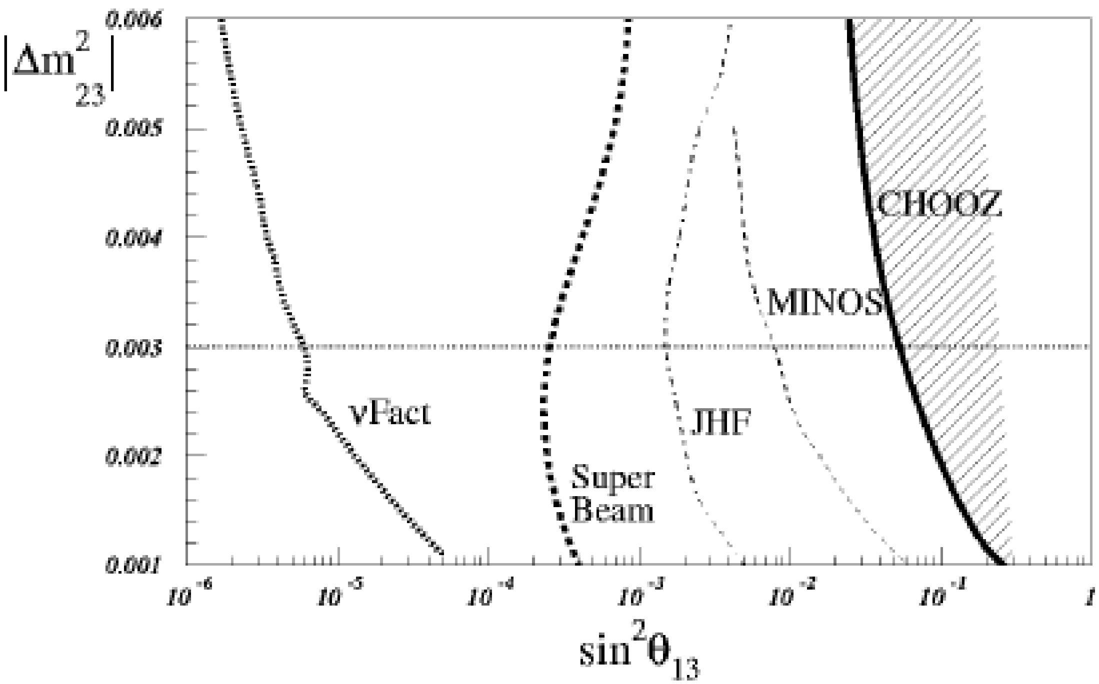
$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2(1.267\,\delta m^2_{32} L/E_\nu)$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\,\sin^2 2\theta_{23}\,\sin^2(1.267\,\delta m^2_{32} L/E_\nu)$$

where L = baseline (km) and E_ν = energy (GeV)

⇒ A high-energy ν_e beam offers unique possibilities!

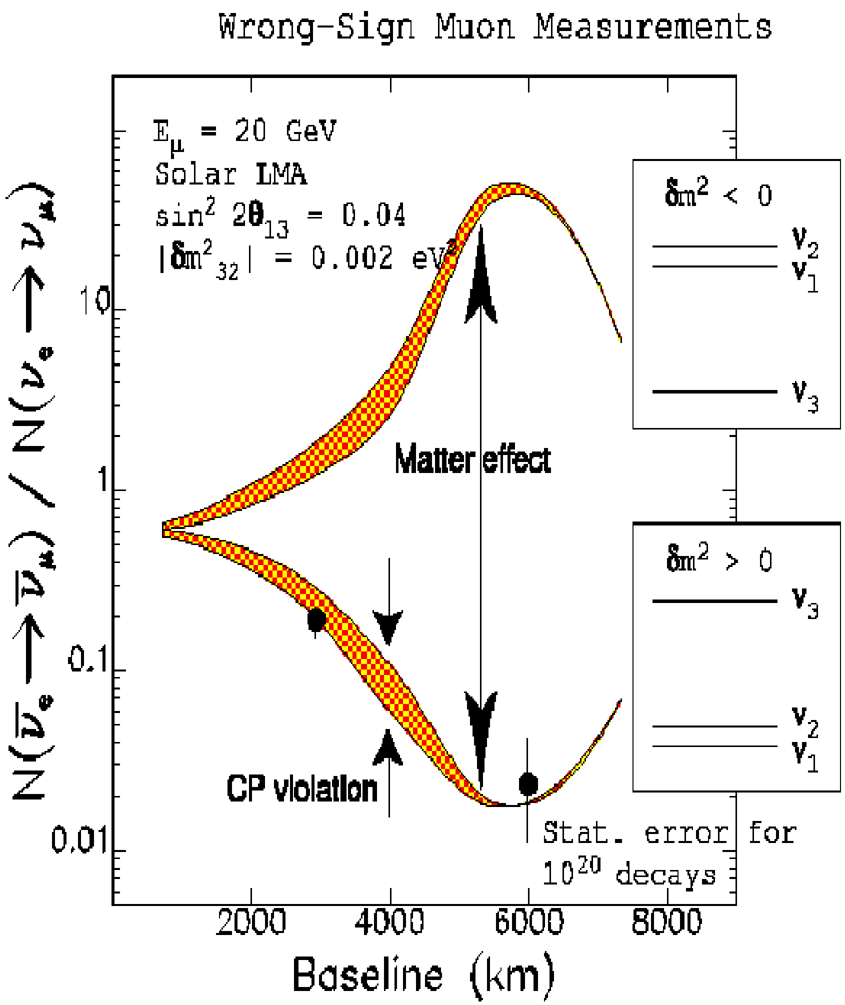
→ Gives best sensitivity to θ_{13} of any technique:

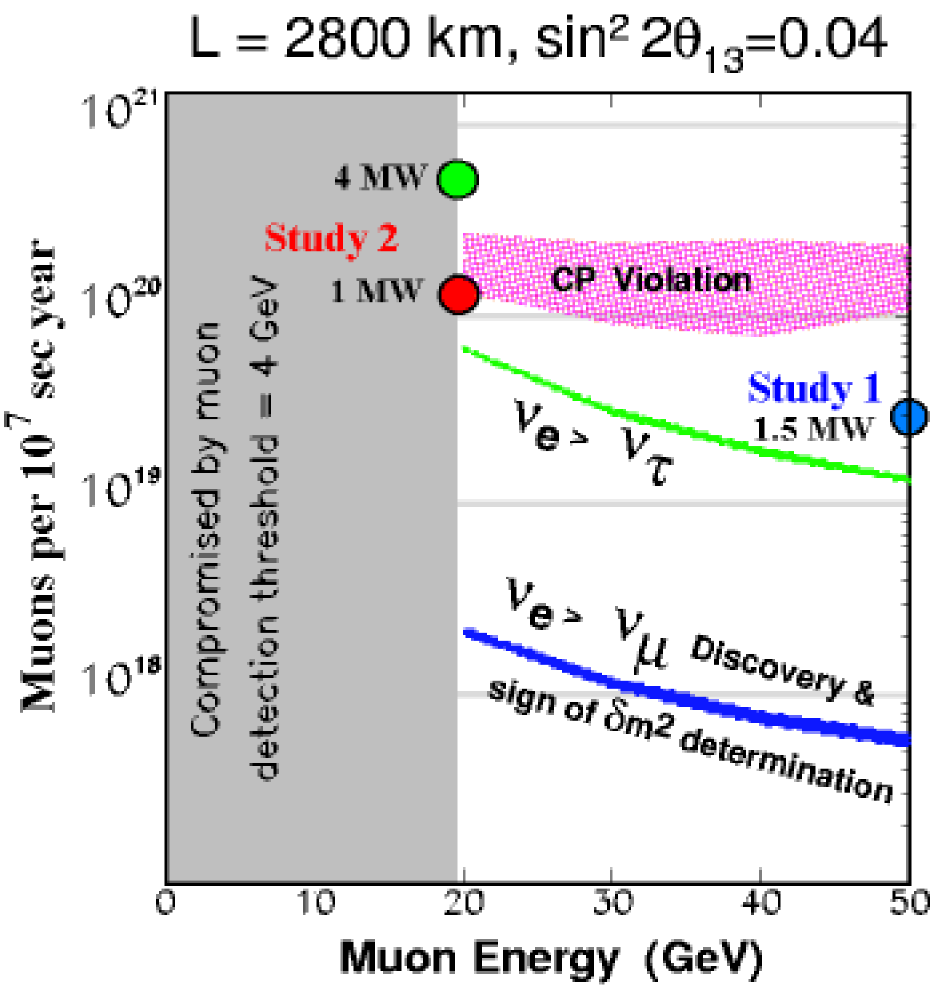


Neutrino Factory Physics (cont'd)

4. Comparing $\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$ gives both sgn(Δm^2_{32}) and CP phase:

$$A_{CP} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} \approx \frac{4\sin 2\theta_{12} \cdot \sin\delta \cdot \sin(2\Delta m^2_{12}\, L/4E)}{\sin\theta_{13}}$$



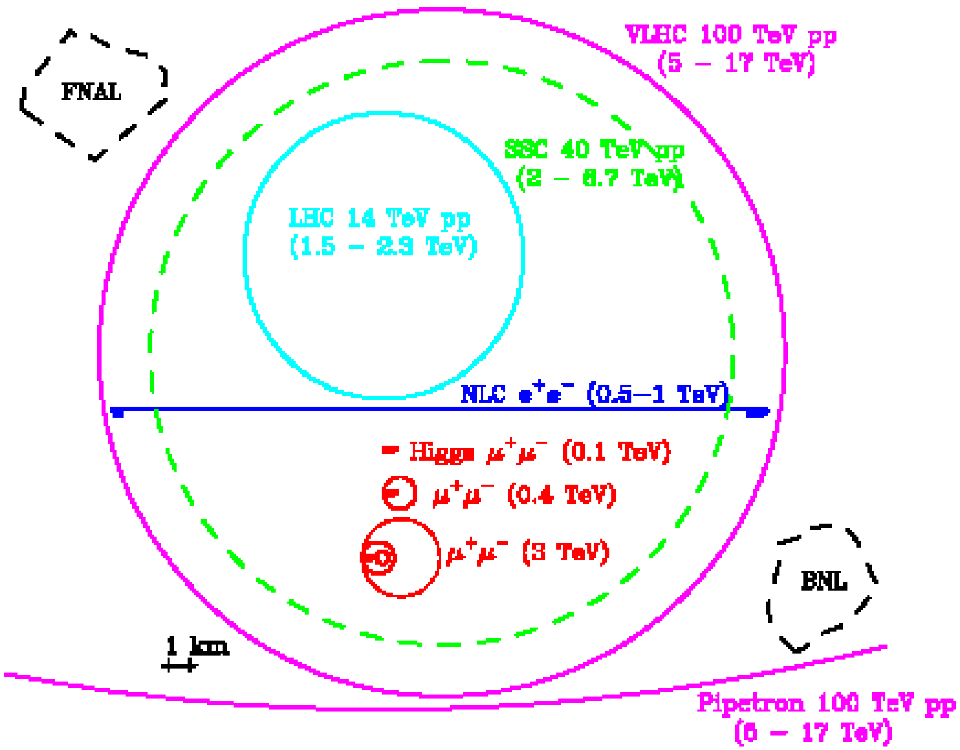


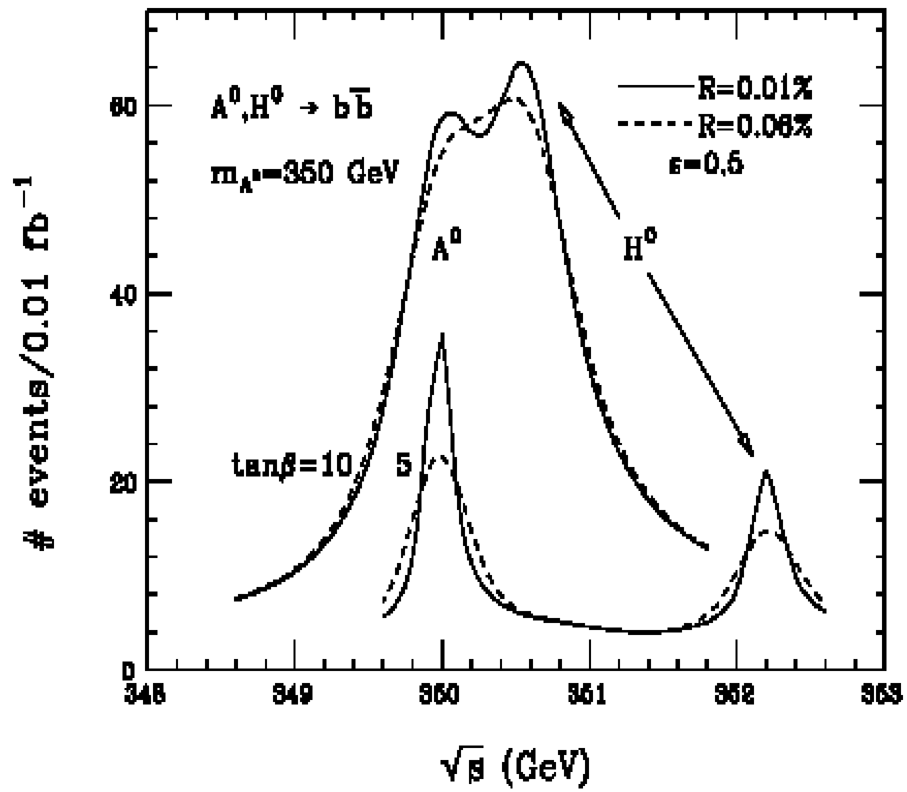
- For LMA, 10^{20} decays with 50-kT detector will see δ down to 8° $\Rightarrow$ flux is crucual!
- Note: SNO now favors LMA at 99% CL (VAC and SMA ruled out @ >3σ)

Motivation: Muon Collider

- A pathway to *high-energy* lepton colliders
  - unlike e^+e^-, $\sqrt{s}$ not limited by radiative effects
  - a muon collider can fit on existing laboratory sites even for $\sqrt{s}$ > 3 TeV

- *s*-channel coupling of Higgs to lepton pairs $\propto m^2_{\text{lepton}}$





- E.g., μμ-collider resolution can separate near-degenerate scalar and pseudo-scalar Higgs states of minimal SUSY

“A Brief History of Muons”

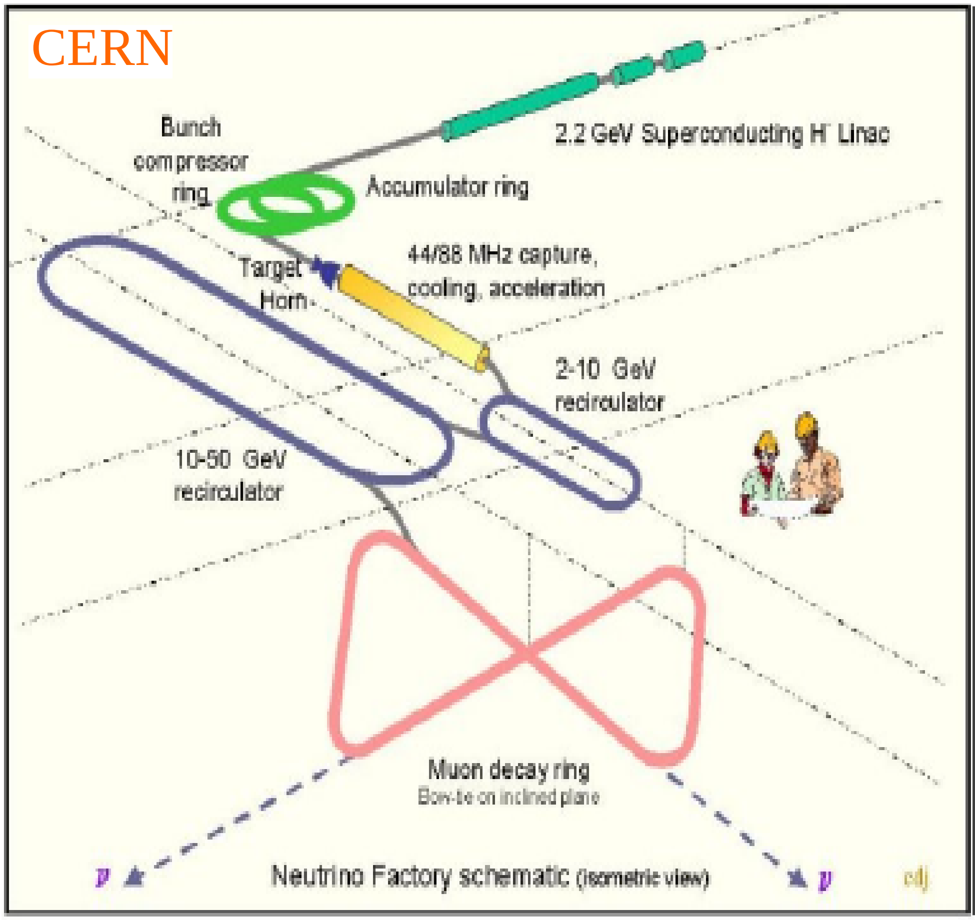
- Muon storage rings are an old idea:
  - Charpak *et al.* ($g-2$) (1960), Tinlot & Green (1960), Melissinos (1960)
- Muon colliders suggested by Tikhonin (1968)
- But no concept for achieving high luminosity until ionization cooling
  - O’Neill (1956), Lichtenberg *et al.* (1956),

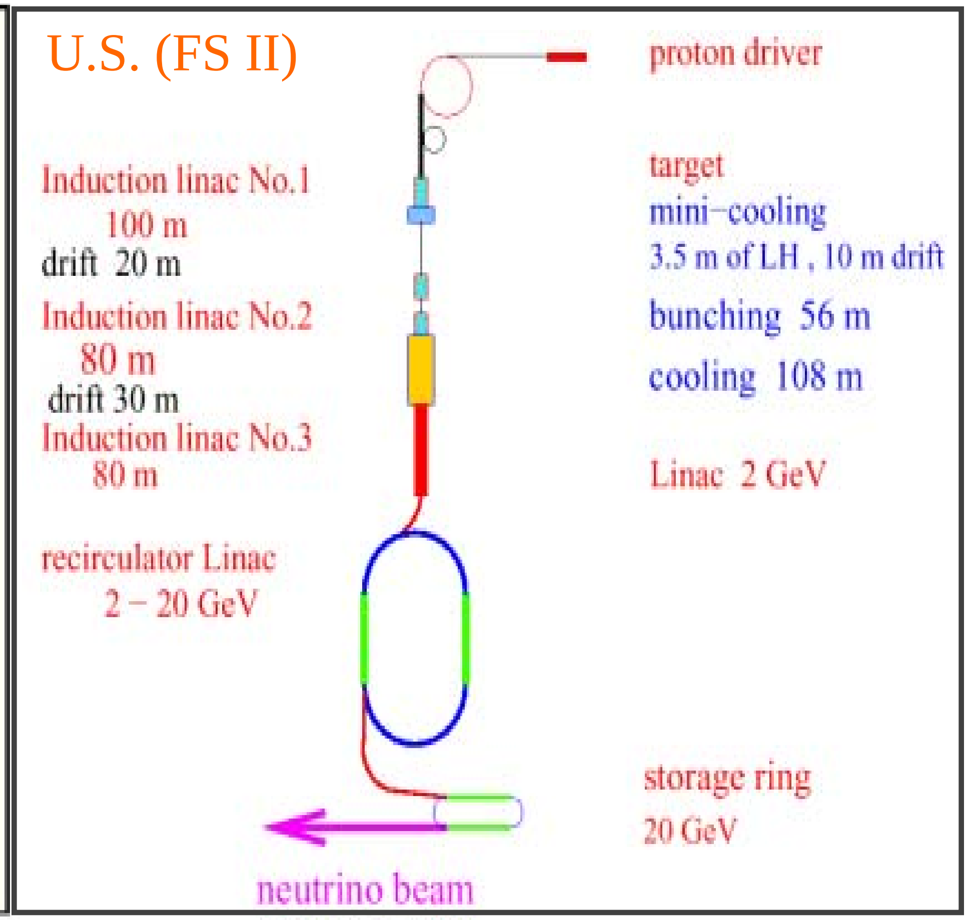
  applied to muon cooling by Skrinsky & Parkhomchuk (1981) and Neuffer (1979, 1983)
- The realization (Neuffer and Palmer) that a high-luminosity muon collider might be feasible stimulated a series of workshops & formation (1995) of the Muon Collaboration
  - has since grown to 26 institutions and >100 physicists
- Snowmass Summer Study (1996)
  - study of feasibility of a 2+2 TeV Muon Collider [Fermilab-conf-96/092]
- Neutrino Factory suggested by Geer (1997) at the Workshop on Physics at the First Muon Collider and the Front End of the Muon Collider [AIP Conf. Proc. **435**]; also CERN yellow report (1999) [CERN 99-02, ECFA 99-197]

See also “Status of Muon Collider Research and Future Plans” [PRSTAB **2**:081001 (1999)]; Neutrino Factory Feasibility Study I (2000) and II (2001) reports; “The Program in Muon and Neutrino Physics” [hep-ex/0108041]; http://www.fnal.gov/projects/muon_collider

νFac Overview

- Only way to produce intense beam of high-energy electron neutrinos: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$
- 2 schemes with cooling:

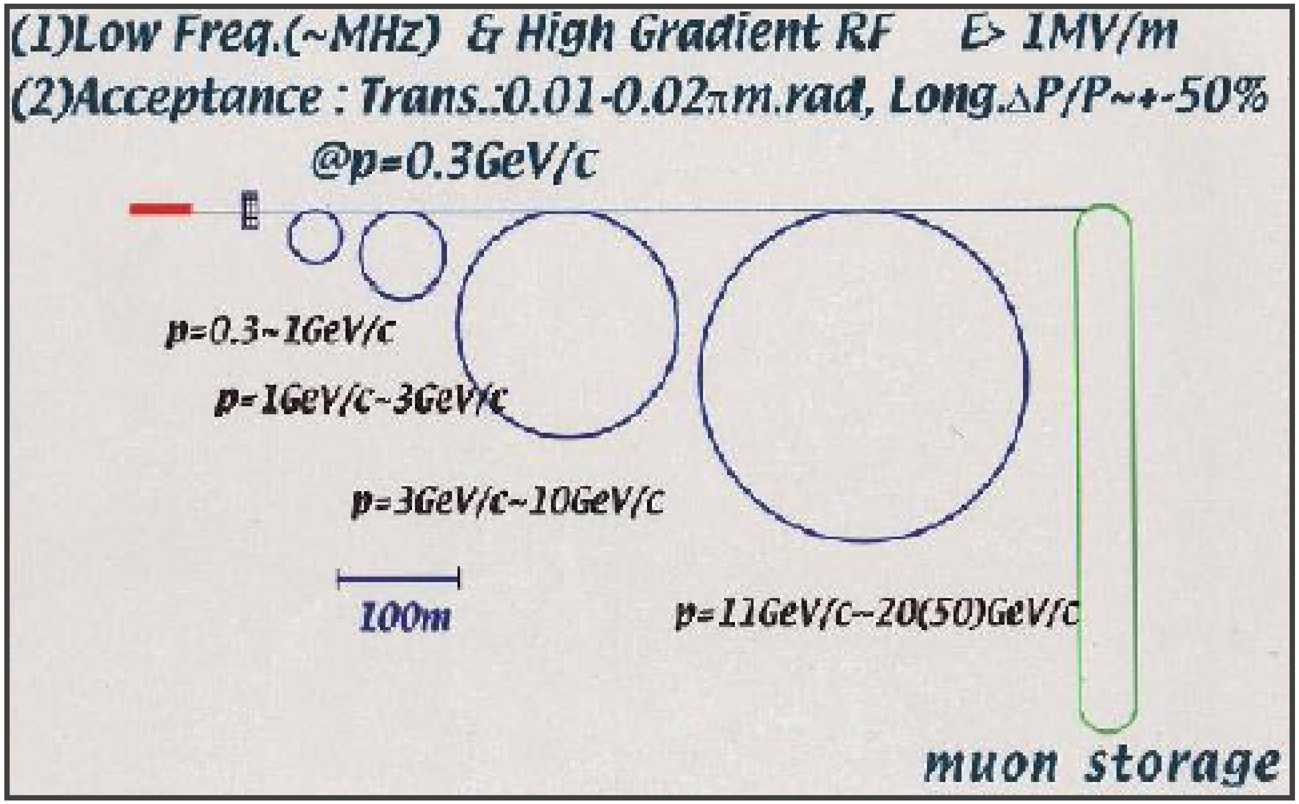




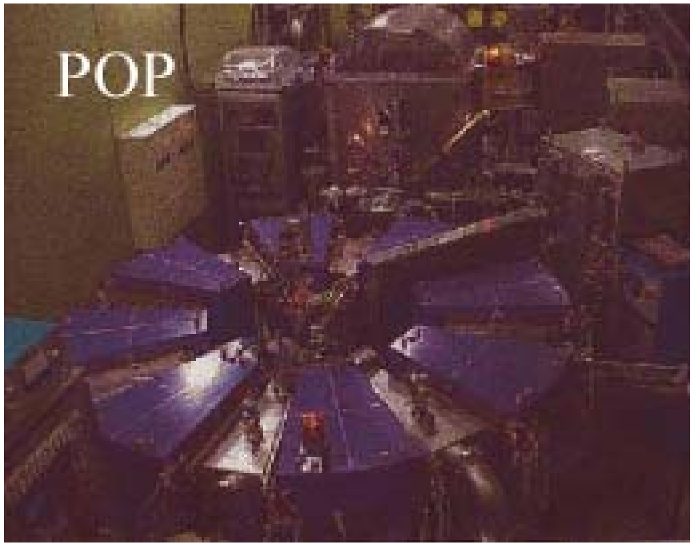
- Both designs feature MW proton beams on high-power target, with pion collection & decay in focusing channel
- Decay muons undergo phase-space manipulations, cooling, acceleration, and storage in decay ring

νFac Overview (cont'd)

- 1 scheme without cooling (KEK):



  - Based on large-acceptance FFAGs
  - No phase rotation or cooling
  - Exploring possibility of adding cooling
  - R&D Issues: RF, injection/extraction, magnet design, dynamic aperture



"Proof of Principle" FFAG tested successfully at KEK in June

→ 3 world regions cooperatively exploring complementary technical approaches, but all have similar goal:

$>10^{20}$ useful muon decays per year

U.S. νFac Feasibility Studies

Have established (with detailed conceptual engineering)

- that a Neutrino Factory is technically feasible
- likely performance, cost, cost drivers, needed R&D

(partial FS II author list)

Members of the Collaboration and Non-Member Participants of the Study

Maury Goodman, Ahmed Hassanein, James H. Norem, Claude B. Reed, Dale Smith, Lee C. Teng, Chun-xi Wang
Argonne National Laboratory, Argonne, IL 60439
Michael Anerella†, J. Scott Berg, Joseph M. Brennan†, Richard C. Fernow, Juan C. Gallardo, Ramesh Gupta, Michael Harrison†, Michael Hemmer†, Hsiao-C. Hseuh†, Michael A. Iarocci†, Stephen A. Kahn, Bruce J. King, Harold G. Kirk, David Lissauer, Laurence S. Littenberg, Alfredo Luccio†, Hans Ludewig†,

Peter Hwang†, Gregory Naumovich†
Everson Electric Company, Bethlehem, PA
David R. Winn
Fairfield University, Fairfield, CT 06430

Alain Blondel

Robert Shrock

Study	FS I	FS II
Requestor	Fermilab	Brookhaven
Duration	6 months	12 months
Finished	April, 2000	June, 2001
Target	C	Hg jet
Phase rotation	"distorting"	"nondistorting"
# Induction linacs	1	3
Cooling lattices (baseline)	FOFO	SFOFO
(alternate)	Single-Flip	Double-Flip
Storage-ring energy	50 GeV	20 GeV
# RLAs	2	1
ν_e / 10^7 s / straight / MW	2×10^{19}	1.2×10^{20}

Indicative (not definitive!) FS II cost estimate

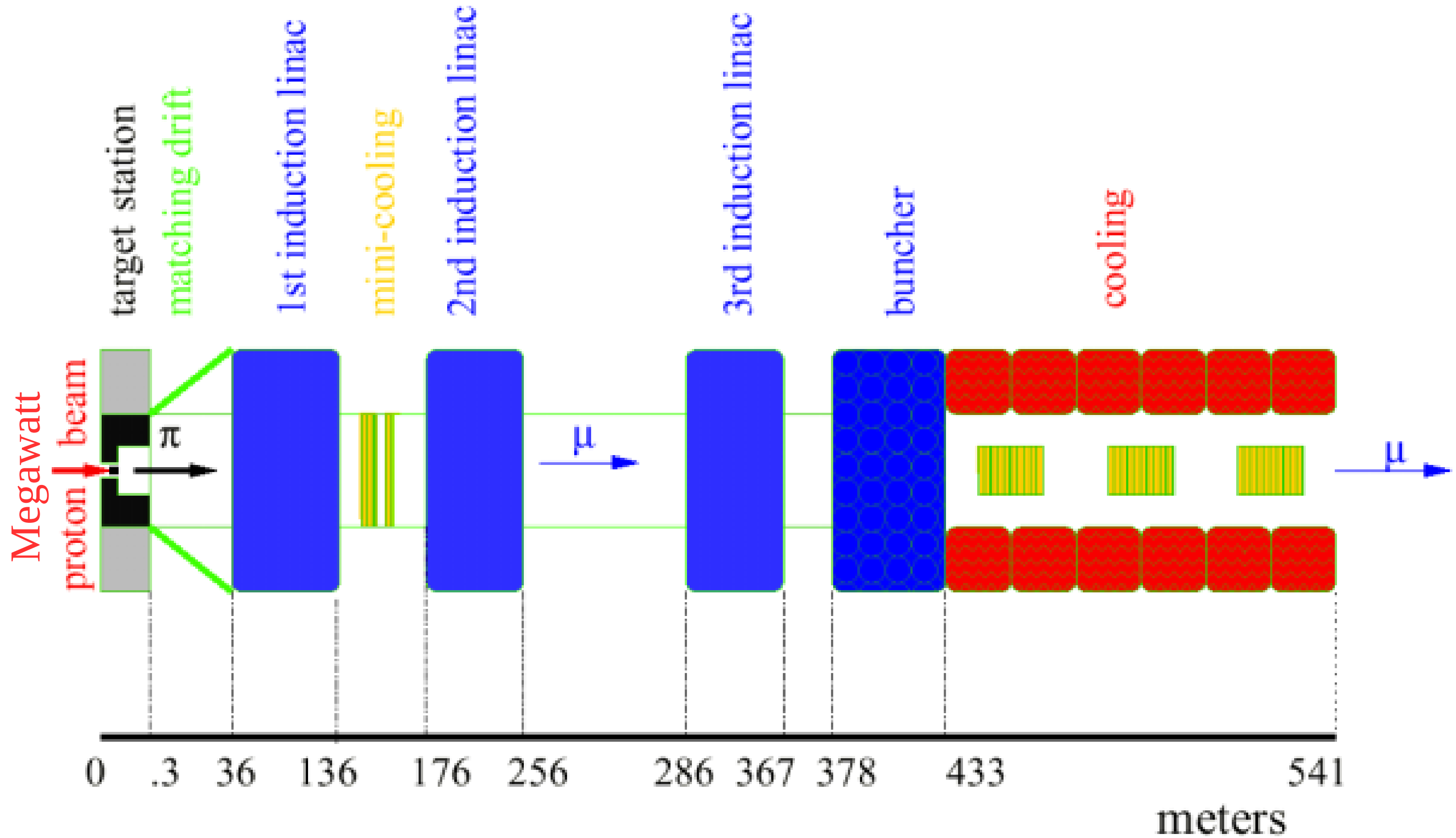
System	Sum ($M)	Others[a] ($M)	Total ($M)
Proton Driver	167.6	16.8	184.4
Target Systems	91.6	9.2	100.8
Decay Channel	4.6	0.5	5.1
Induction Linacs	319.1	31.9	351.0
Bunching	68.6	6.9	75.5
Cooling Channel	317.0	31.7	348.7
Pre-accel. linac	188.9	18.9	207.8
RLA	355.5	35.5	391.0
Storage Ring	107.4	10.7	118.1
Site Utilities	126.9	12.7	139.6
Totals	1,747.2	174.8	1,922.0

Study II design est. ~ 1/2 NLC cost

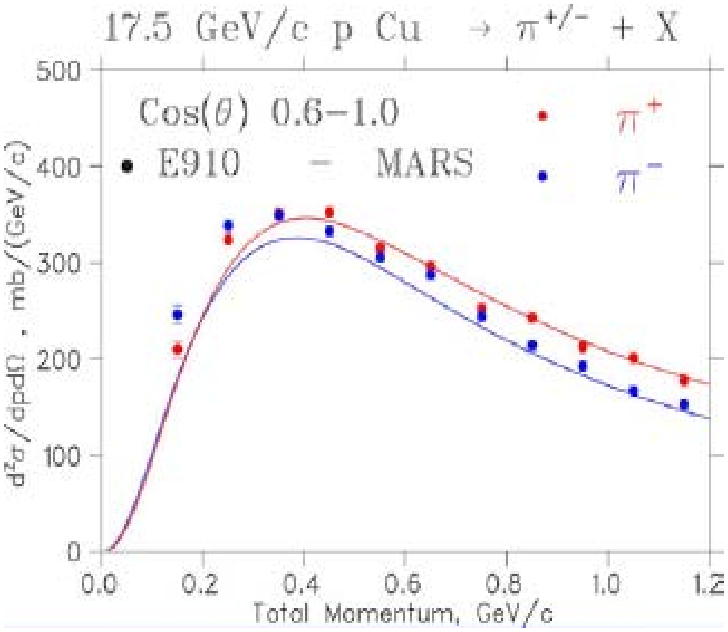
R&D now focusing on the "cost drivers"

- Good prospect for substantial cost reduction and/or performance increase via new ideas:
  - bunched-beam phase rotation, ring coolers, cheaper acceleration

FS II νFac Front End

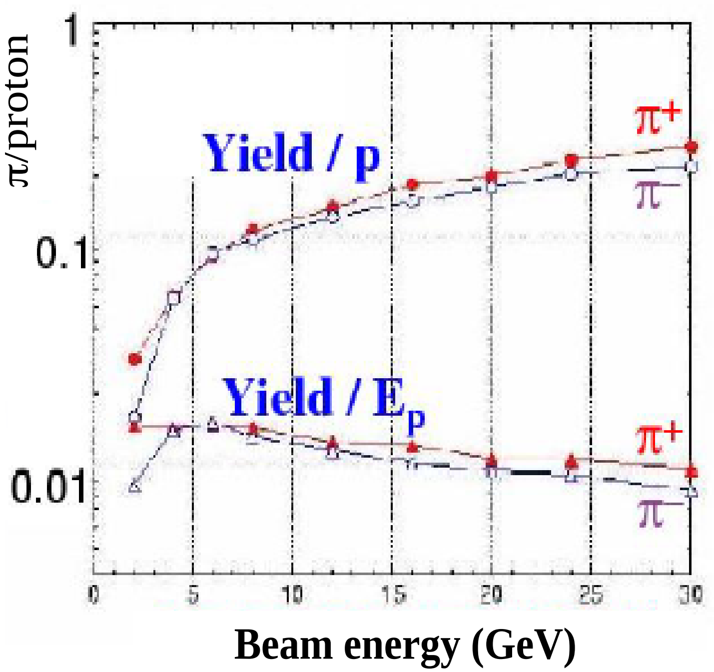


Producing Pions



- BNL E910 pion production results
  - Pion yields peak at few hundred MeV/c
  - Data in fair agreement with predictions of MARS simulation

    (yields may be slightly higher than predicted)

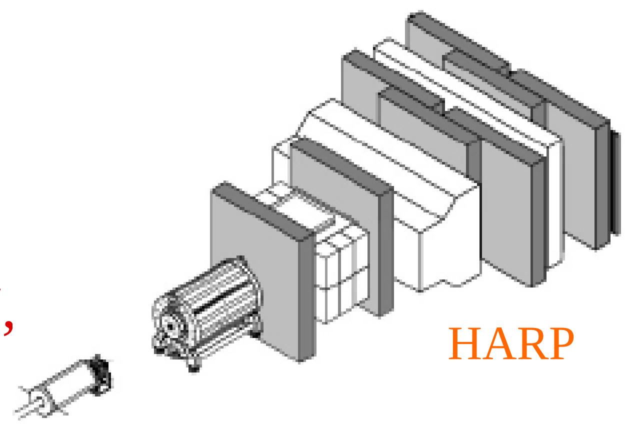


- At constant proton beam power, pion yields vary only slowly with proton energy

  >> broad range of proton driver energies can be considered:

  CERN 2.2 GeV
  FS II 24 GeV
  JHF 50 GeV

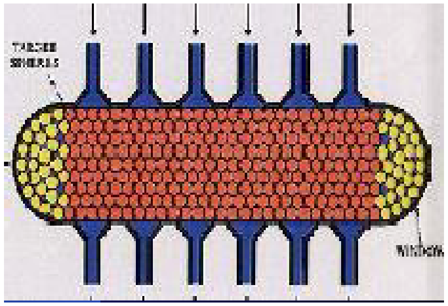
- More data to come from HARP @ CERN, FNAL E907



HARP

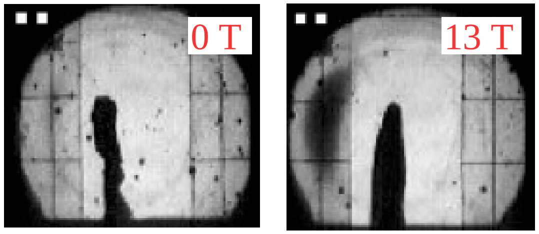
Target R&D for MW-Scale Proton Beams

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

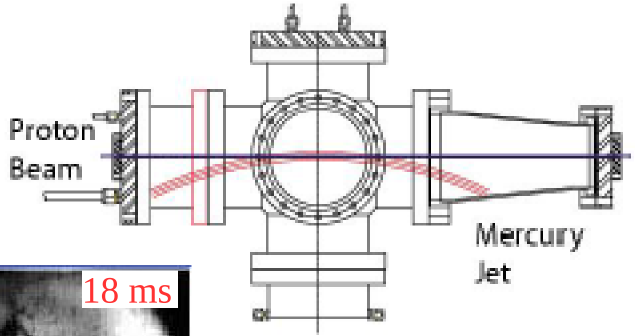


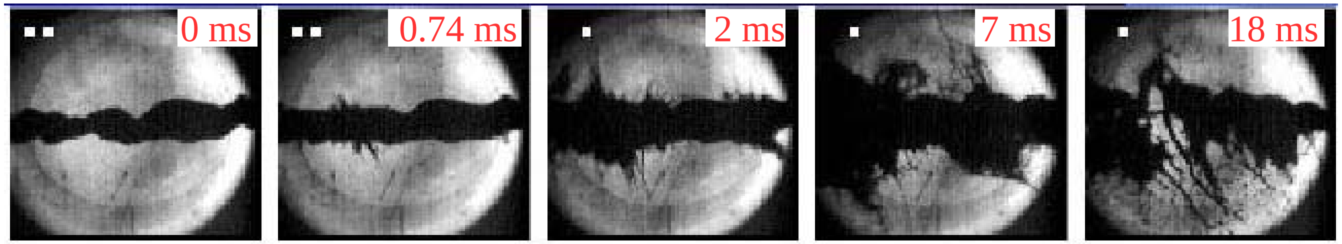
- Target ideas for 4 MW: Water-cooled Ta spheres (P. Sievers), rotating band (B. King), front-runner is Hg jet

- CERN/Grenoble Hg-jet tests in 13 T solenoid
  - Field damps surface tension waves

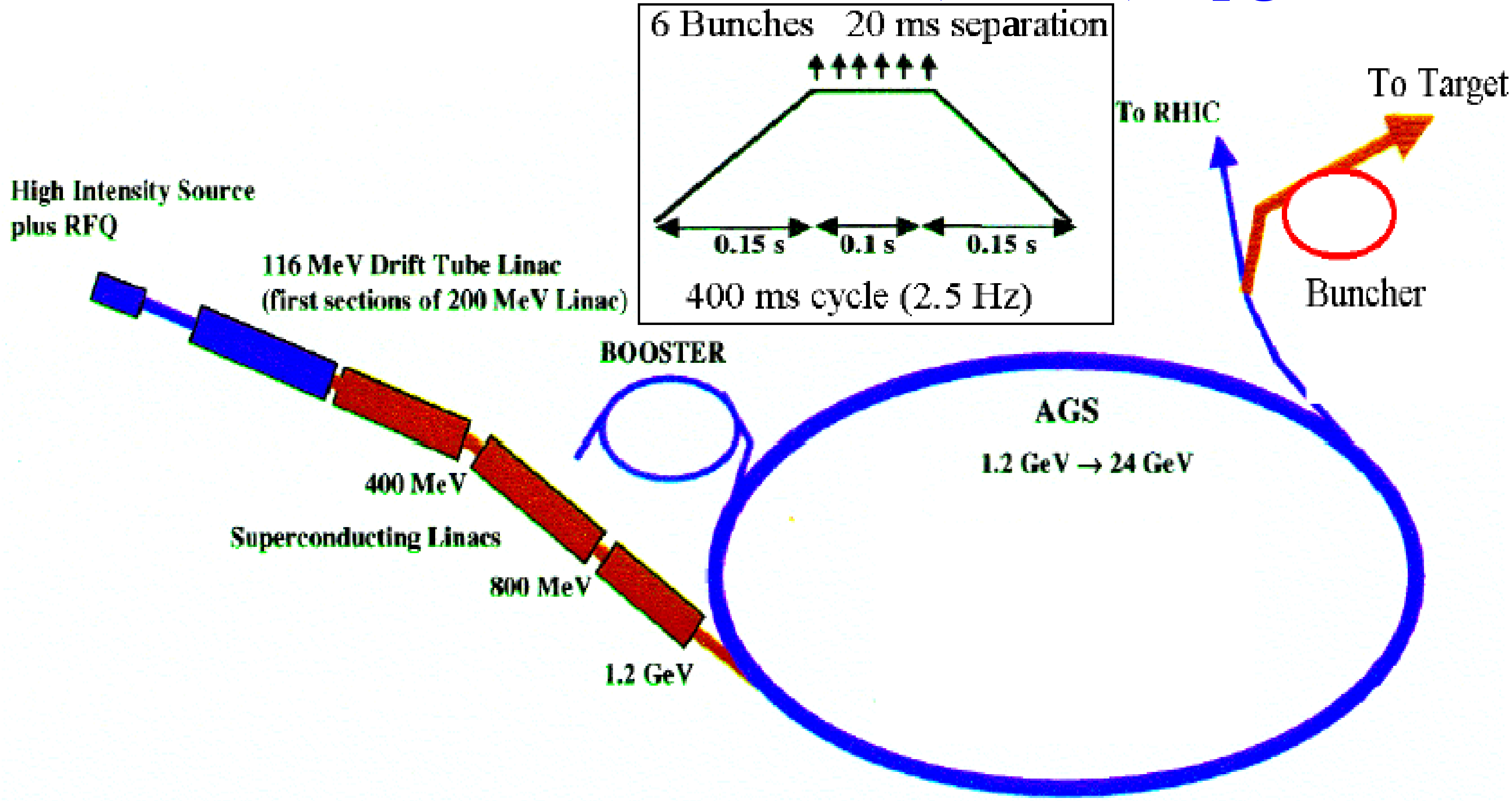


- BNL E951: Hg jet in AGS beam
  - Jet (2.5 m/s) quickly re-establishes itself
  - Plan future test in 20T solenoid



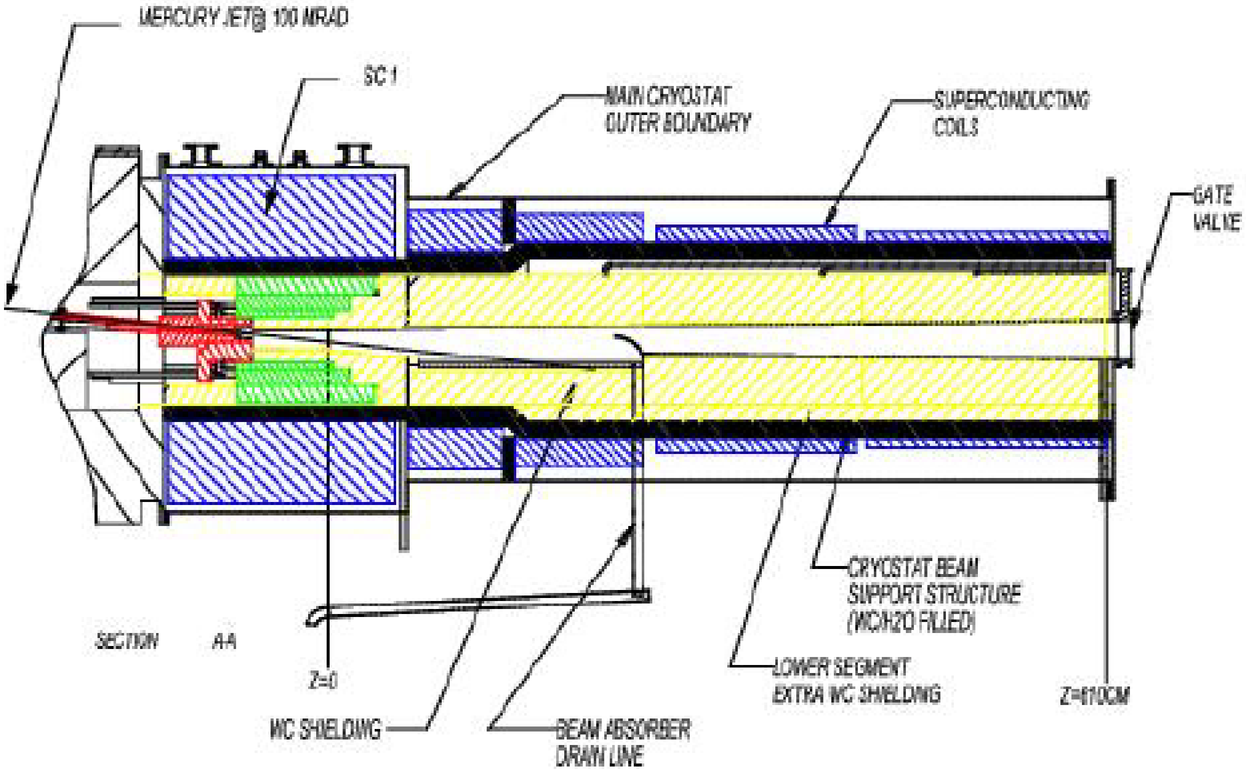


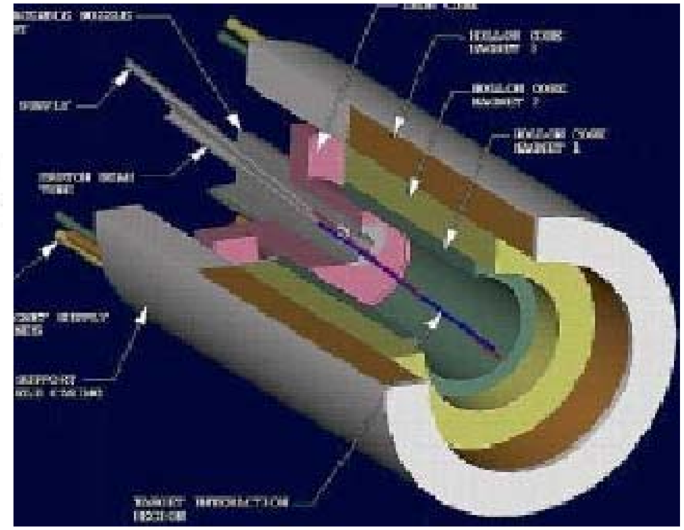
FS II Proton Driver: AGS×7 (1-MW) Upgrade

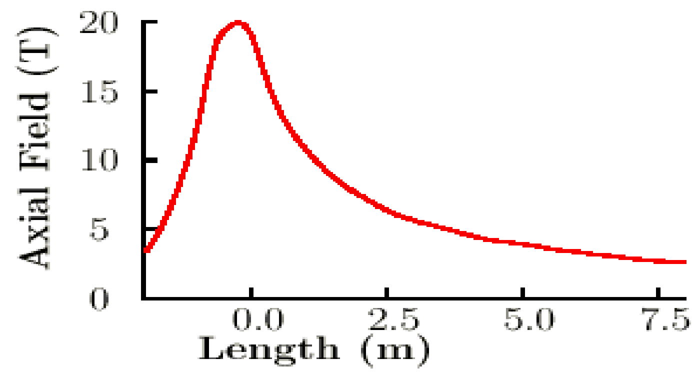


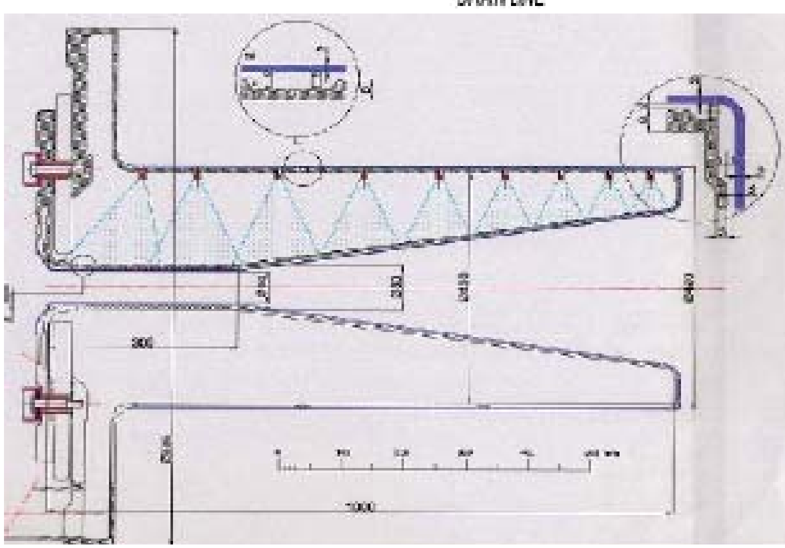
- New SC linacs bypass booster synchrotron
- 6 bunches of 1.7×10^{13} each at 2.5 Hz rep. rate → 15 Hz avg. rate, 2.5×10^{14} *p*/s
- 20 ms interbunch time allows Hg jet target to advance to undisturbed material between bunches
- Other 1-MW designs also workable (*e.g.*, JHF, new Fermilab Booster, CERN SPL)

Pion Capture









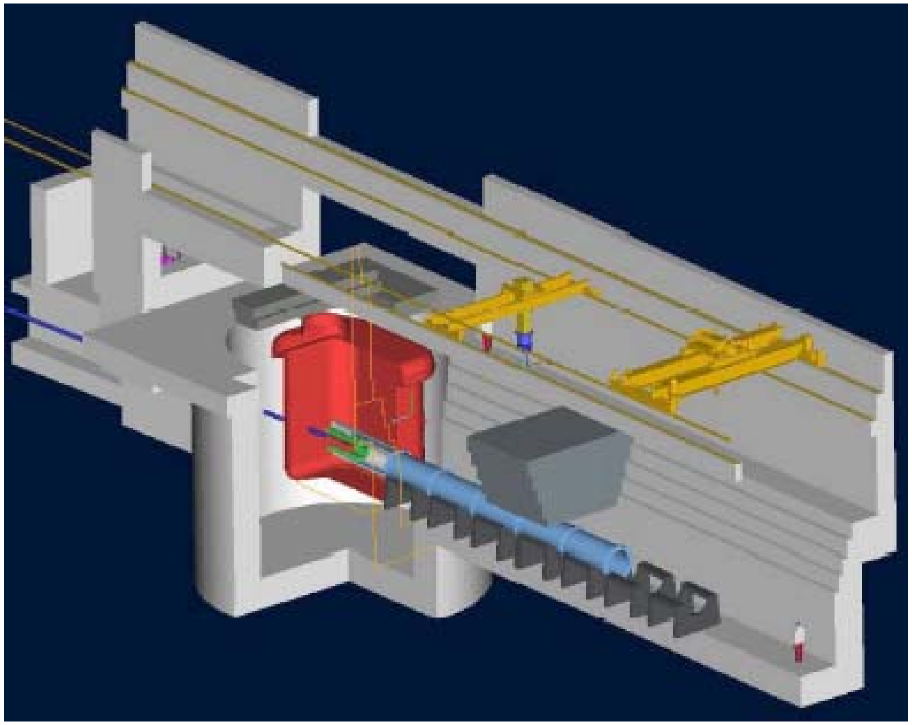
US Design: target in 20-T capture solenoid, with field tapering to 1.25 T

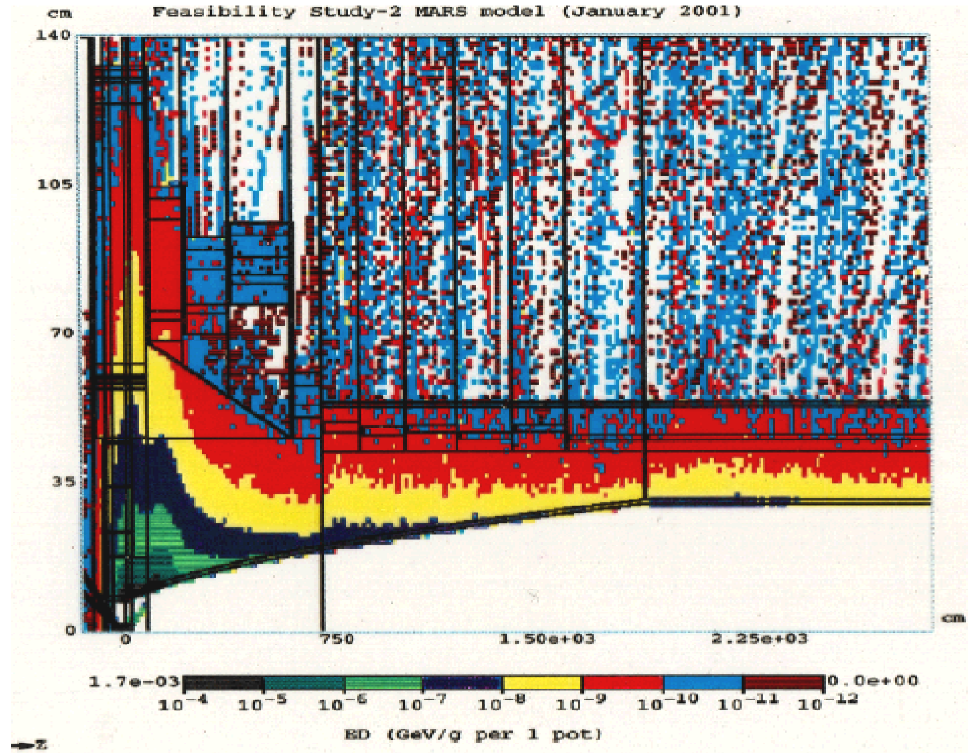
CERN Design: magnetic horn (waist radius = 4 cm, peak current = 300 kA)

Radiation Levels/Survivability

(N. Mokhov, FNAL)

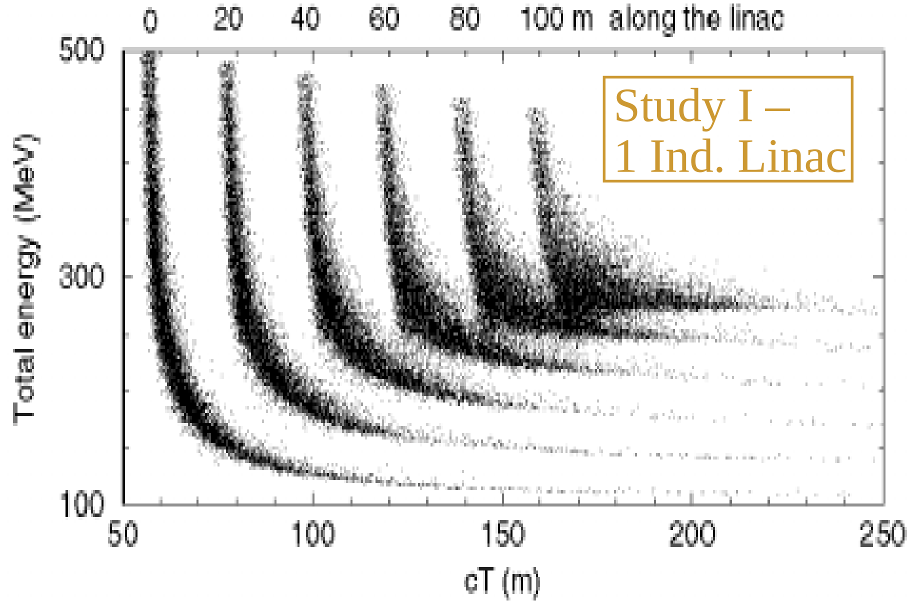
- Remote-handling-area layout (Oak Ridge)

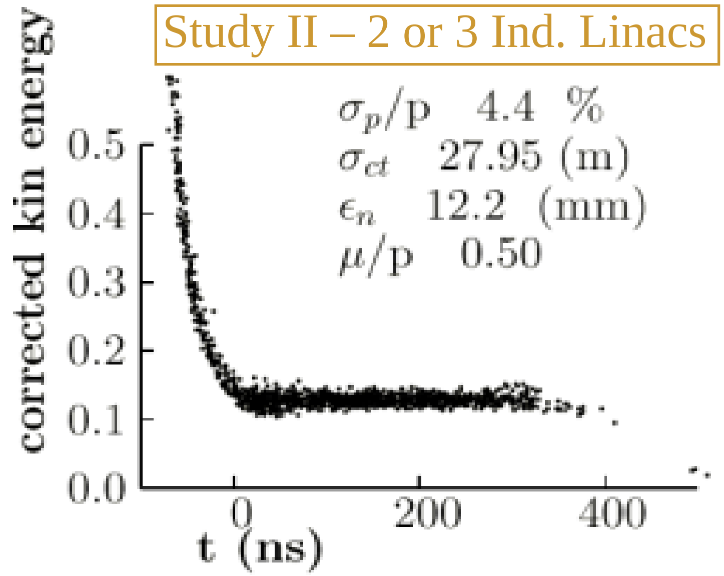




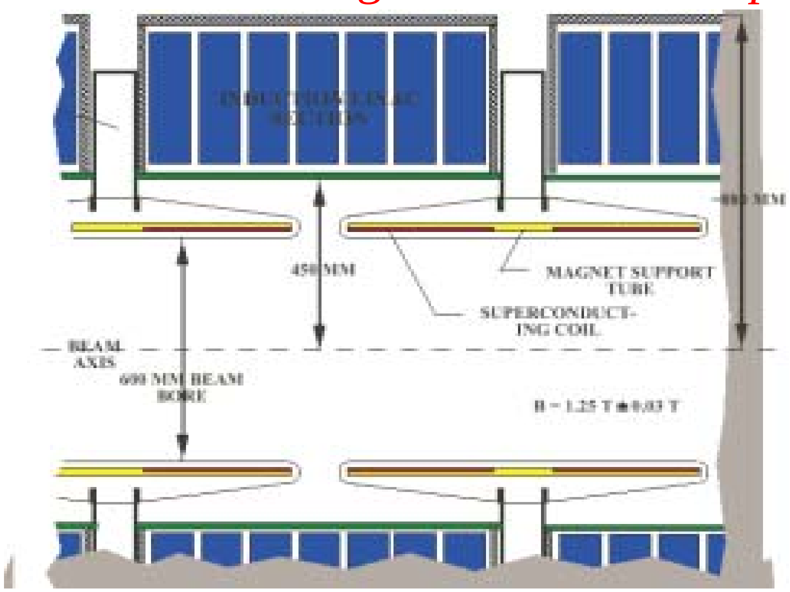
Component	1MW Life years	4 MW life years
Inner Shielding (SS)	40	10
Containment (SS)	500	125
Hollow Conductor (SS)	200	50
Superconducting Coil	100	25

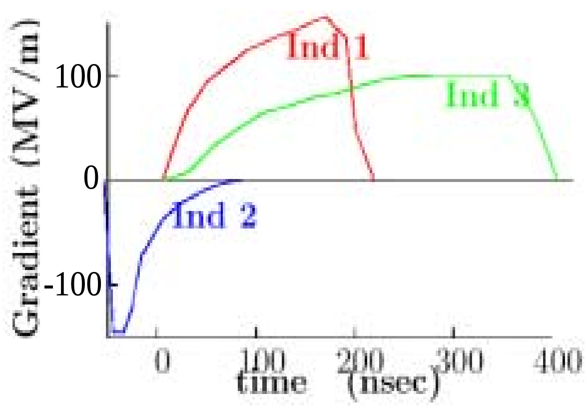
Nondistorting Phase Rotation

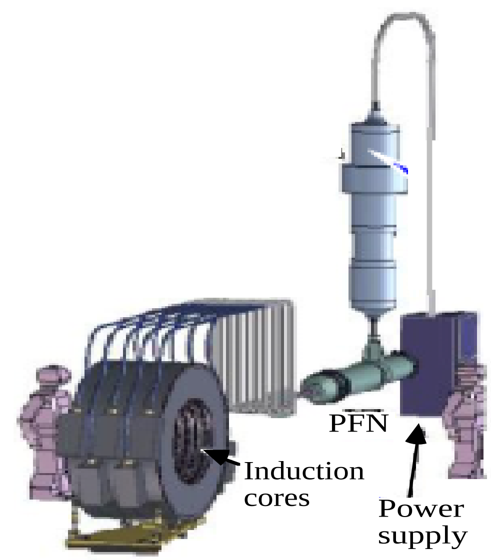




- Nondist. ϕR possible w/ 2 ind. linacs; 3 allow simpler, unipolar pulse design
- 2 “minicooling” absorbers lower *p* to 200 MeV/*c* for cooling and ε_t by ≈ 30%







Need for Muon Cooling

- Need ~ 0.1 μ/*p*-on-target ⇒ very intense muon beam from pion decay
  ⇒ must accept large (~10π mm·rad r.m.s.) beam emittance
- No acceleration system yet demonstrated with such large acceptance
  ⇒ must cool the muon beam

– **In current studies, cooling → × ~10 in accelerated muon flux**

- Only one technique fast enough to cool muons before appreciable fraction decay:

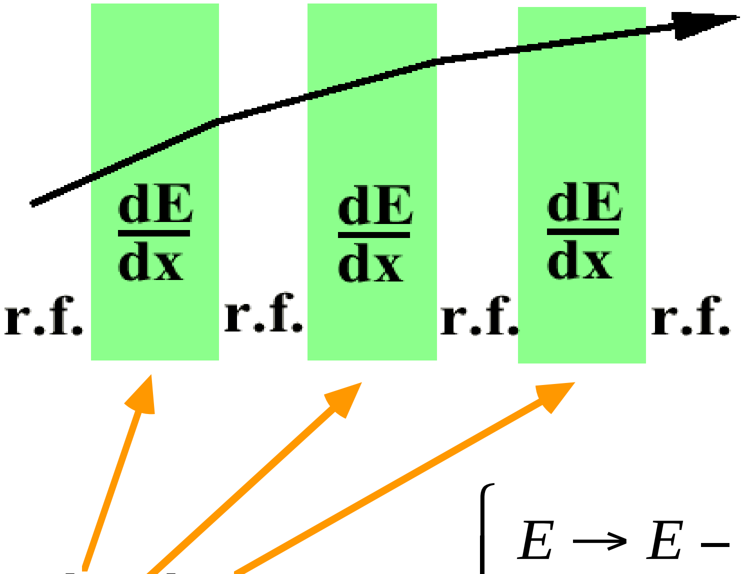
⇒ **Ionization cooling**

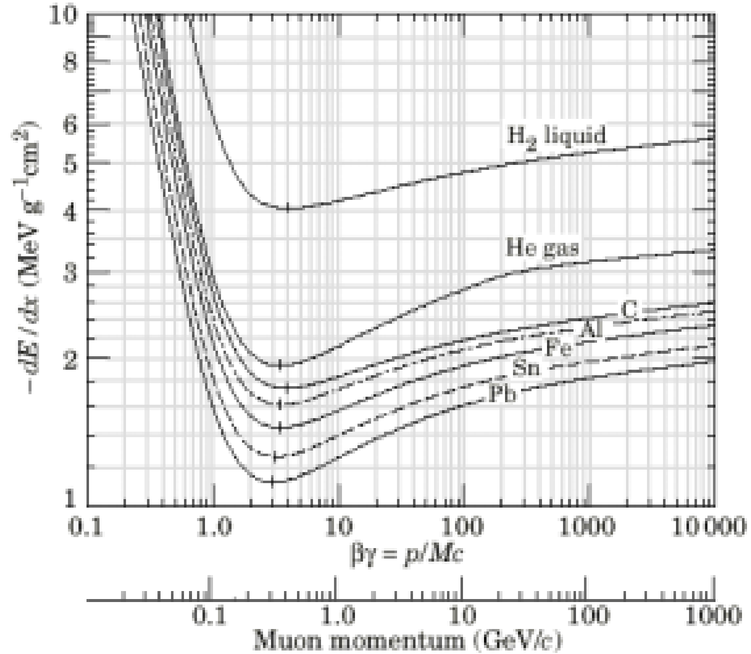
BUT:

  – It has never been observed experimentally
  – Studies show it is a delicate design and engineering problem

⇒ **Need Muon Ionization Cooling Experimental demonstration!**

Ionization Cooling: Background





- Absorbers:
$$\begin{cases} E \rightarrow E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

- RF cavities between absorbers replace ΔE
- Net effect: reduction in $p_\perp$ w.r.t. $p_\parallel$, i.e., transverse cooling:

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

$\Rightarrow$ want strong focusing, large X_0, and low E_μ

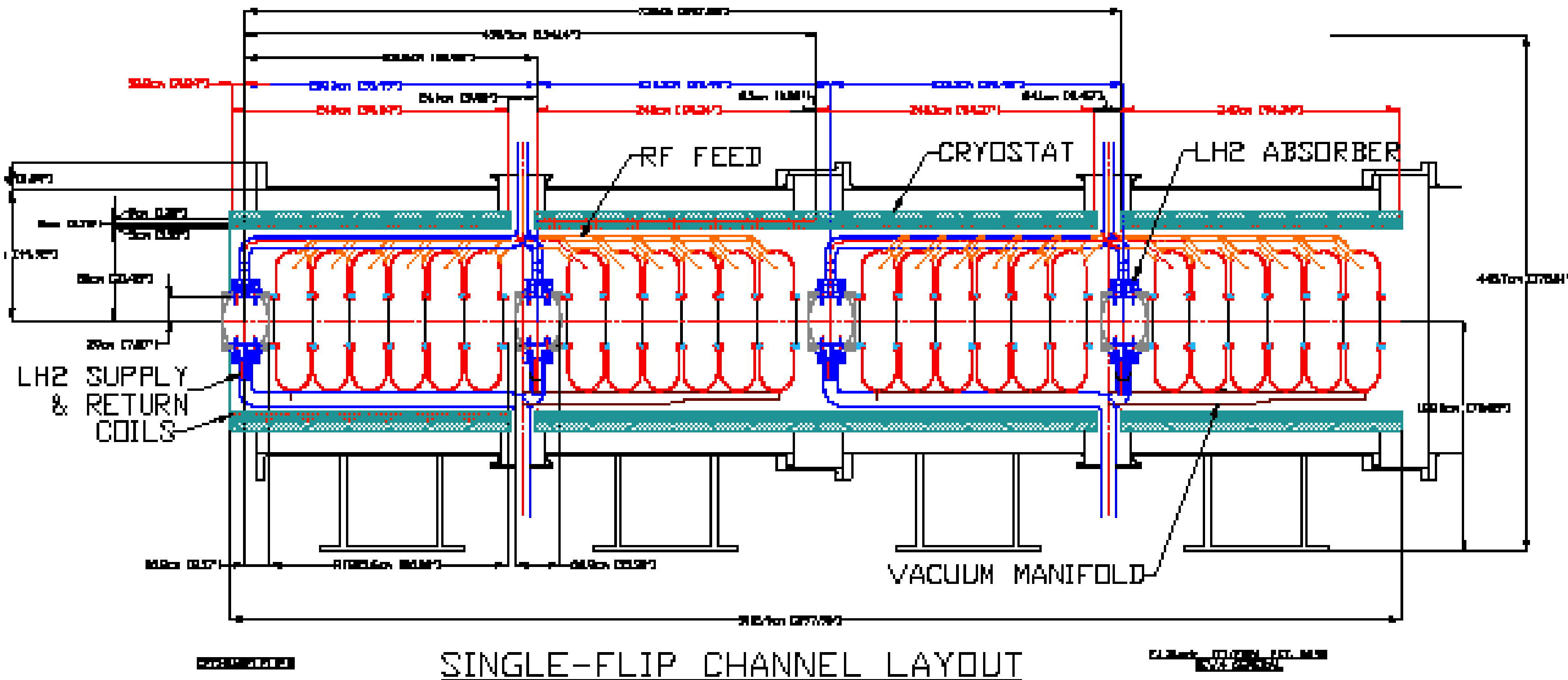
Note: The **physics** is not in doubt

$\Rightarrow$ in principle, ionization cooling **has** to work!

... but in practice it is subtle and complicated so a test is important

Simplest Conceptual Scheme

- Long SC solenoids containing LH_2 absorbers & high-field RF cavities:



Concept: V. Balbekov (FNAL)

Eng. design: E. Black (IIT), A. Moretti (FNAL), J.-M. Rey (Saclay)

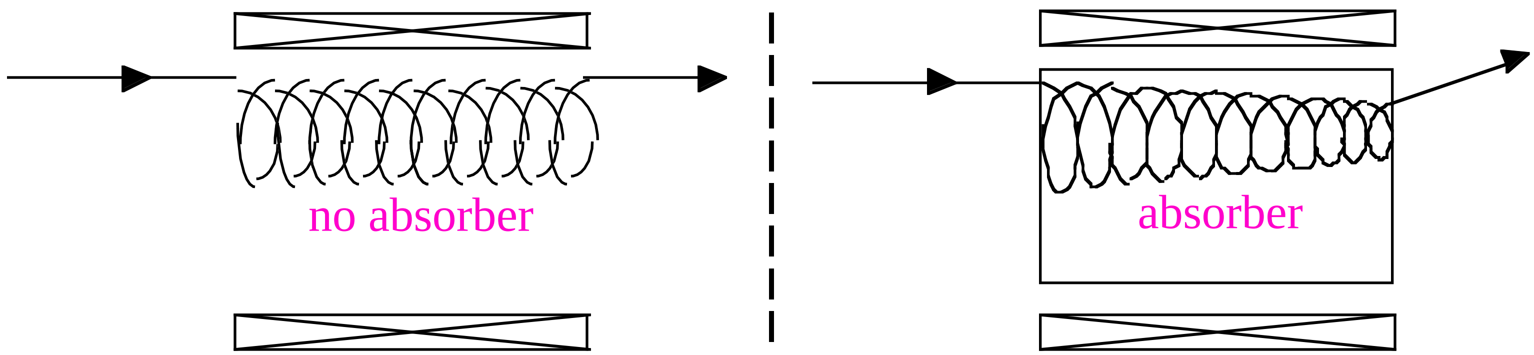
- But ∃ important subtlety:
  - Need to alternate direction of focusing field to avoid build-up of net angular momentum

Angular Momentum

- Consider particle entering long solenoid off-axis but || to axis
  - receives $p_\perp$ kick $\rightarrow$ helical motion within field
  - At end of solenoid, inverse $p_\perp$ kick restores straight trajectory
- But if particle loses momentum within solenoid, helix radius decreases

$\Rightarrow$ particle receives wrong $p_\perp$ kick at exit, emerges with net angular momentum

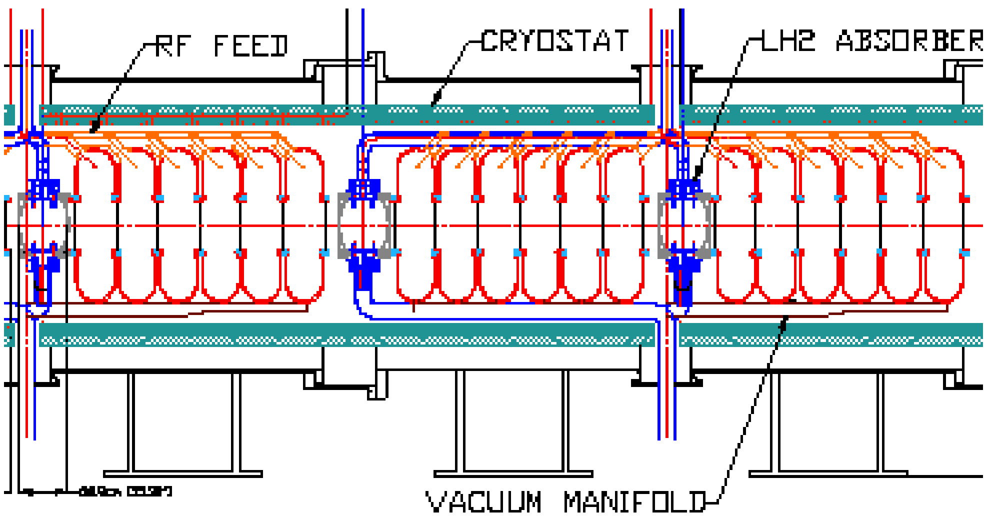
$\Rightarrow$ particle entering parallel to axis emerges at angle:

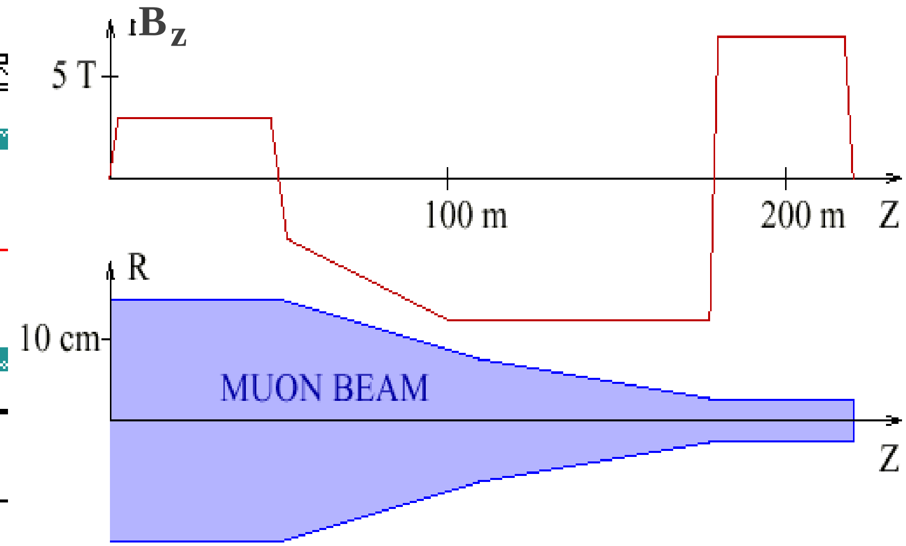


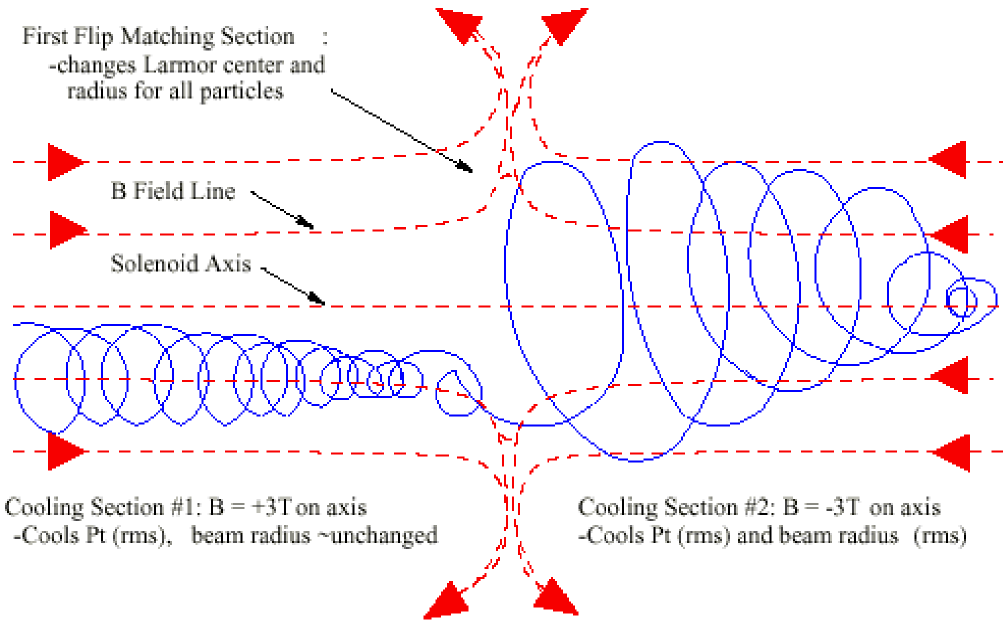
- Would disrupt beam if not handled correctly

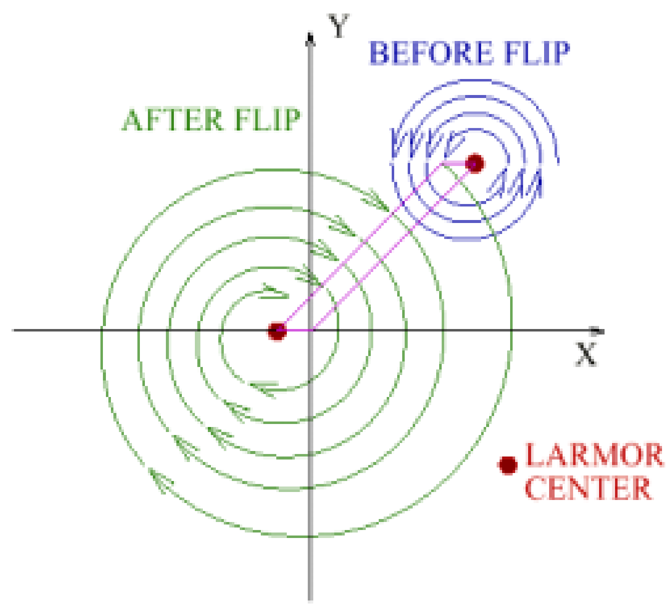
Double-Flip Cooling Channel

(V. Balbekov & D. Elvira, FNAL)



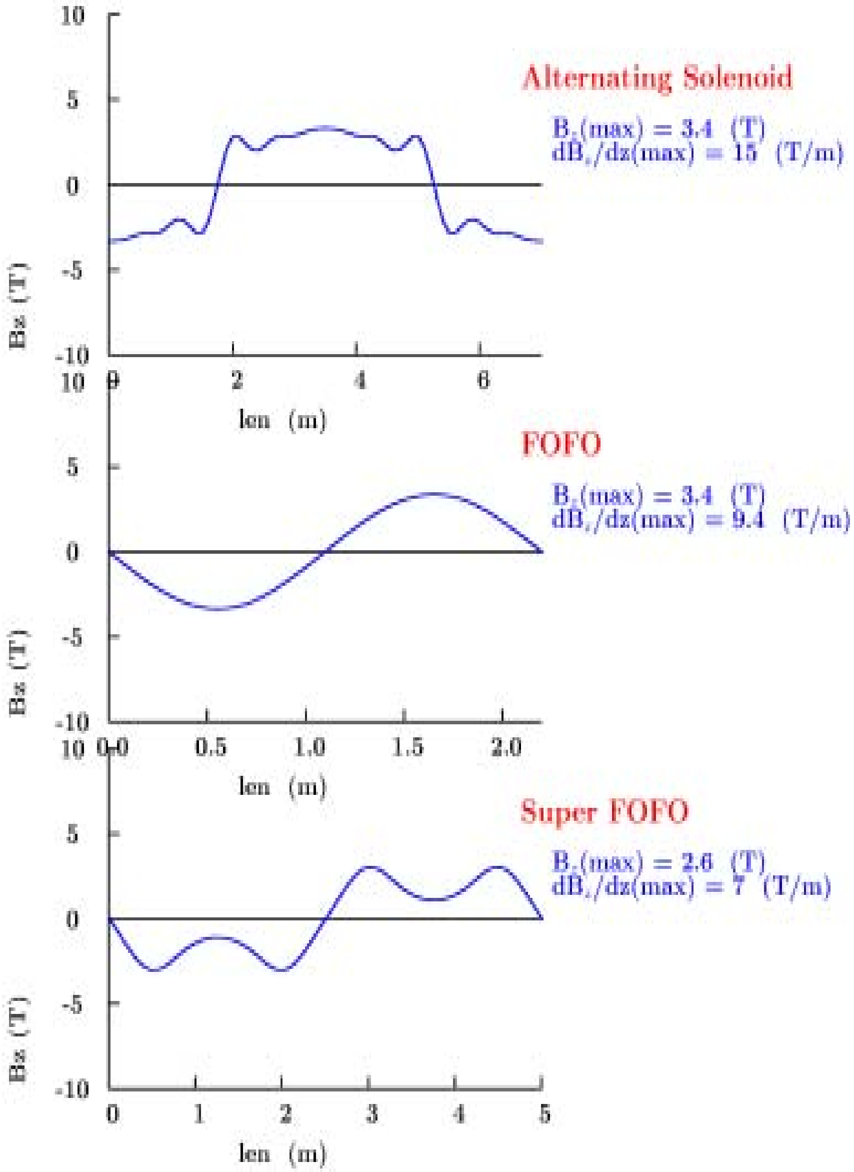


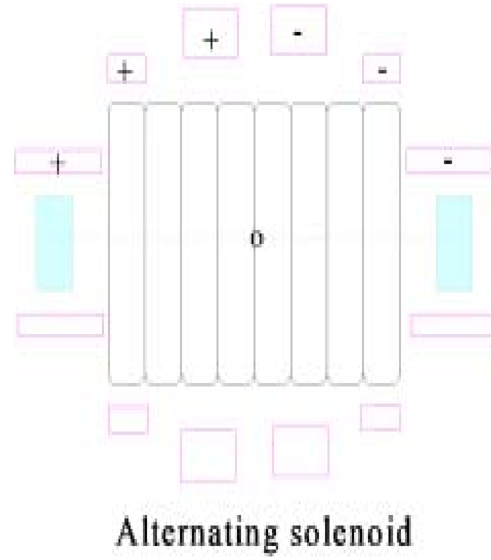


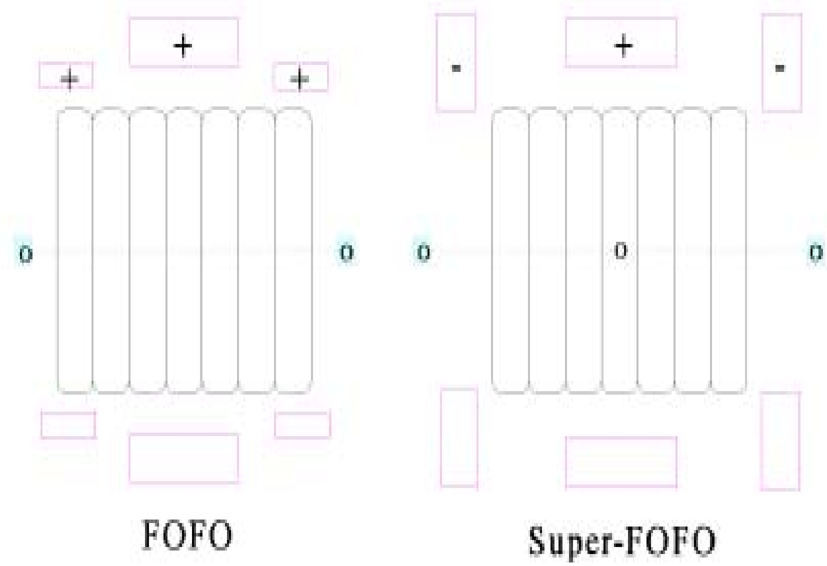


Periodic Cooling Lattices

- Various lattice designs have been studied:



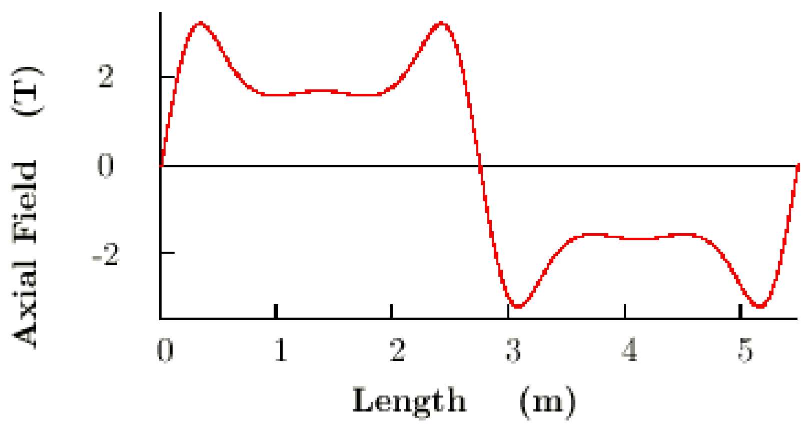


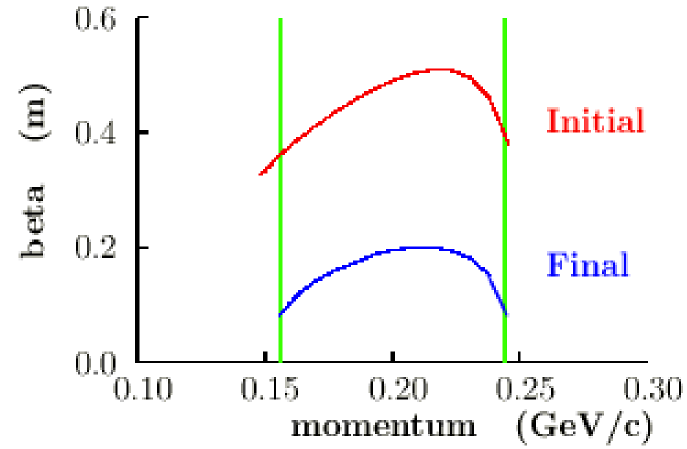


(+ RFOFO, DFOFO, Single-Flip, Double-Flip)

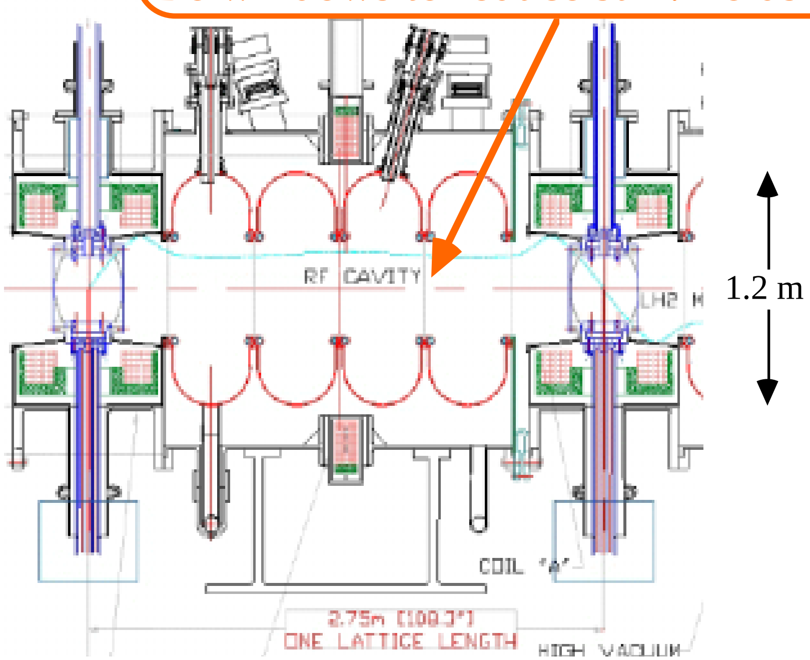
Tapered-SFOFO Cooling Lattice:

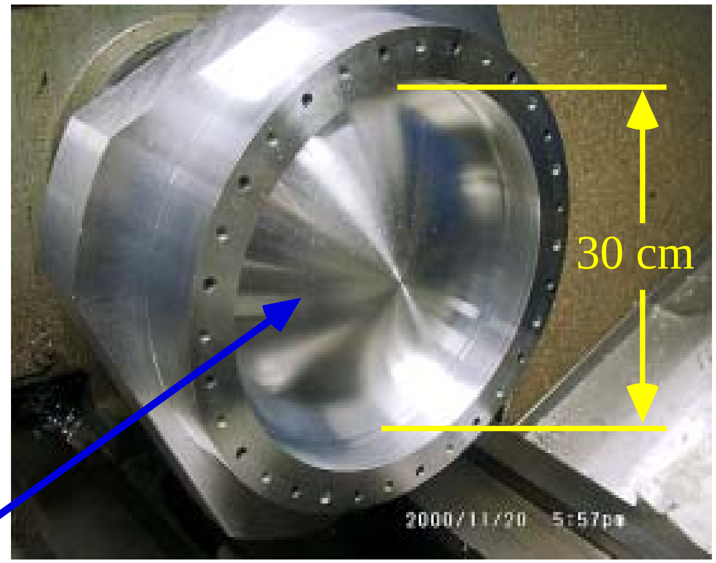
(R. Palmer, BNL)





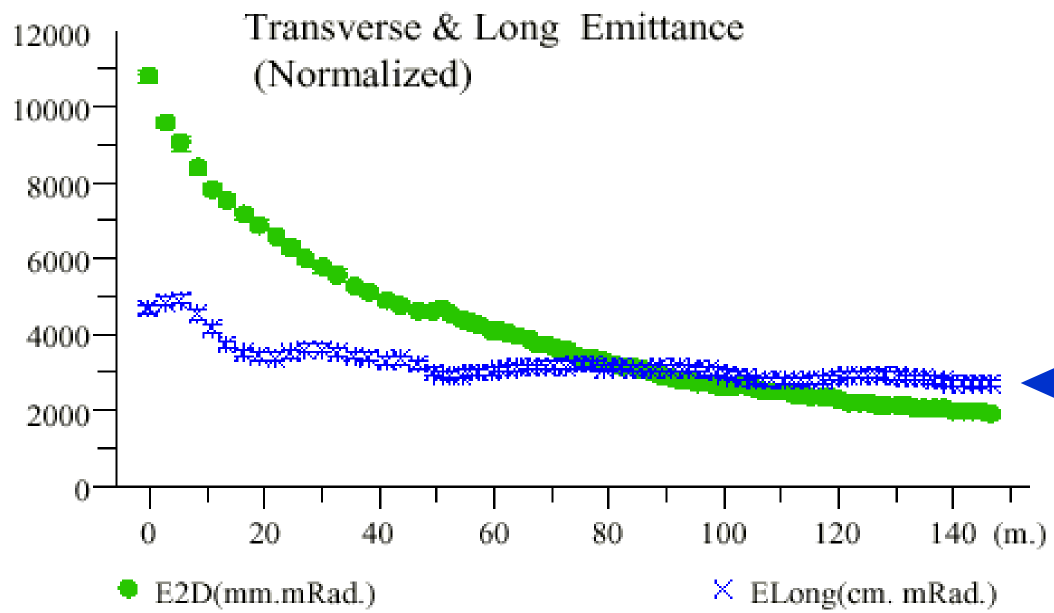
Cavities have thin (≈0.5–1-mm) stepped
Be windows to reduce surf. fields and RF power



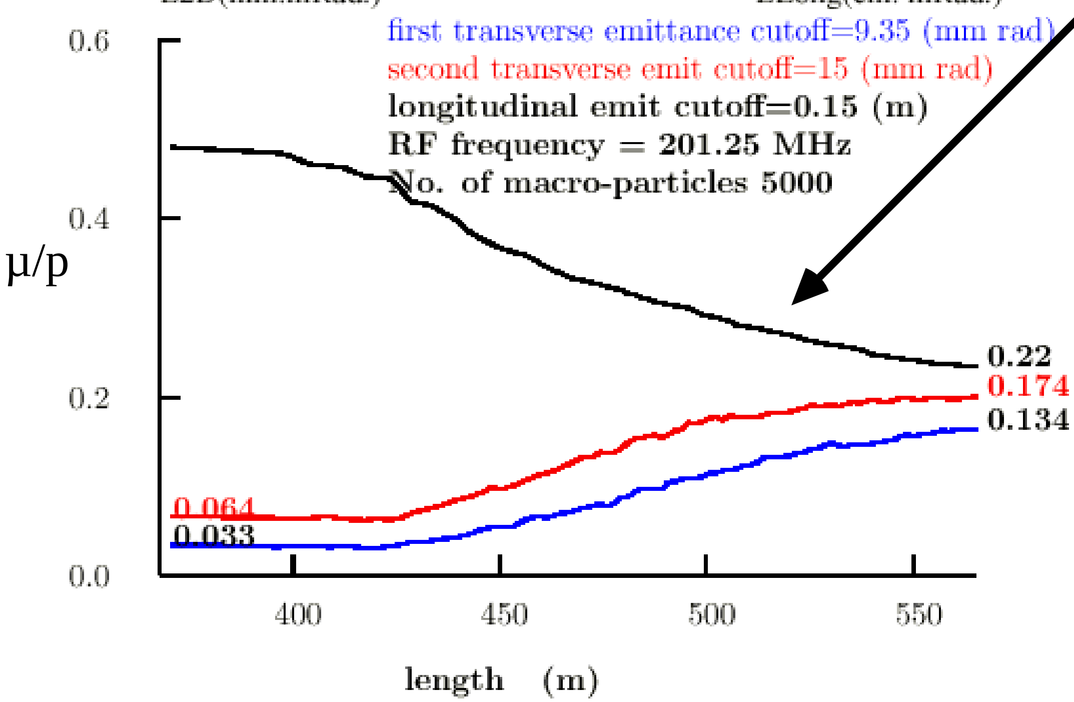


Absorbers have thin (330-µm) tapered
Al windows to minimize muon scattering

Tapered-SFOFO Cooling Performance



- Transverse emittance damps ≈exponentially
- Longitudinal emittance growth with scraping of tails gives ≈constant longitudinal beam size due to losses



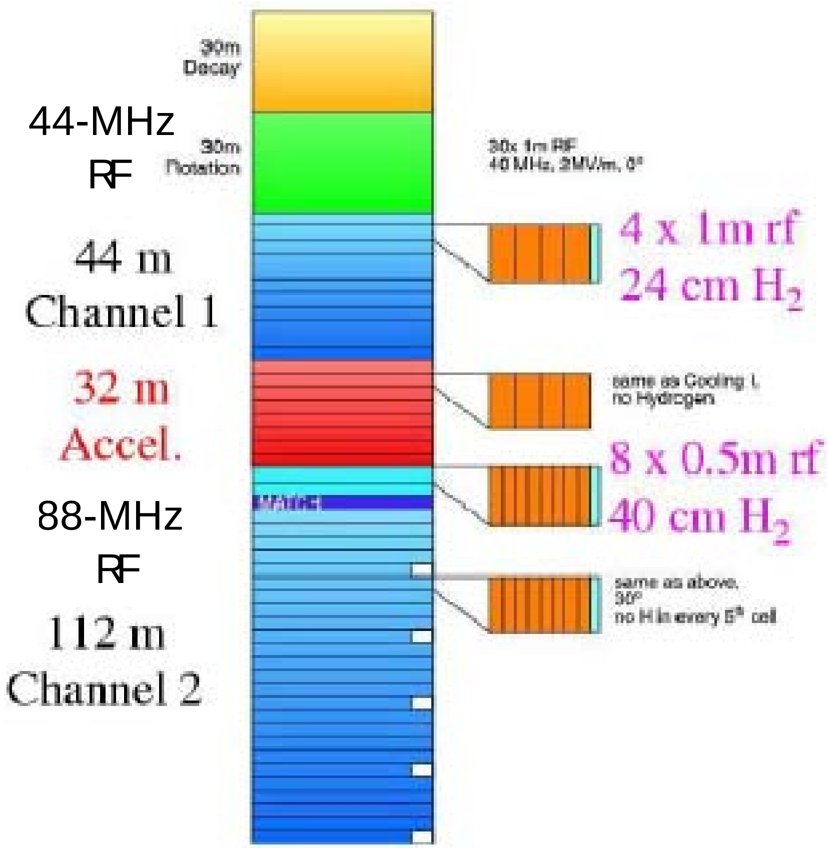
- Two indep. codes used for these sims, GEANT and ICOOL
- Codes agree on emittance decrease & beam transmission within ≈10%, as well as with analytic calculations

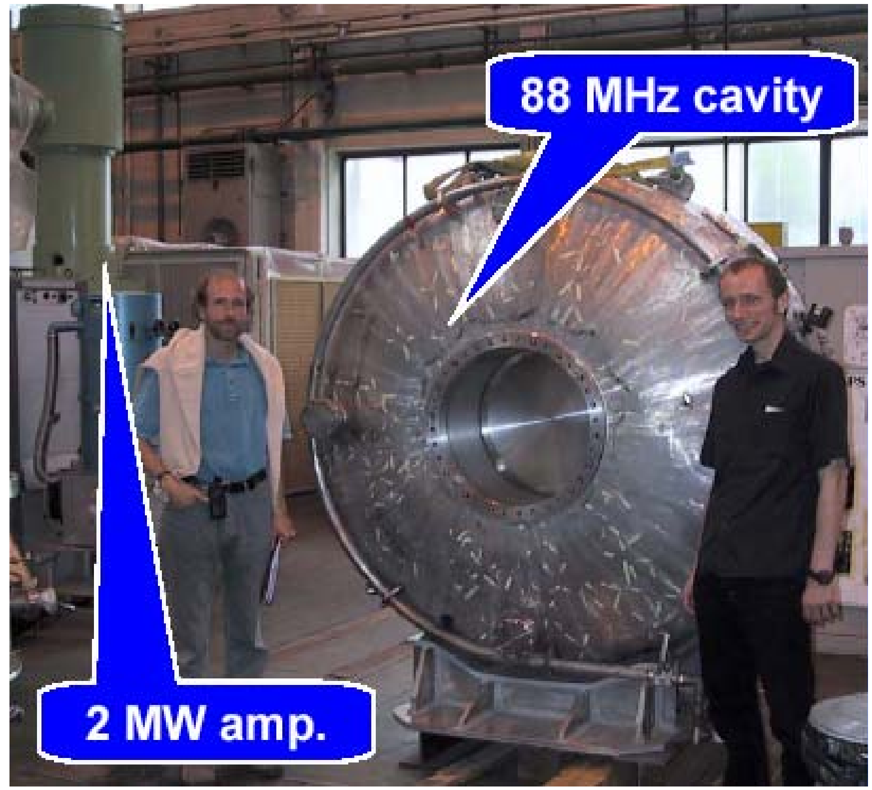
Assuming 15mm trans. acceptance
9.5mm

CERN Cooling Channel Design

(A. Lombardi, CERN, Neutrino Factory Note NF-34)

- Uses lower-frequency RF (44 & 88 MHz)
- Coils "tucked into" cavities to reduce solenoid cost





High-power test planned for later this year

- Perfomance simulated using PATH – comparable to that of US design

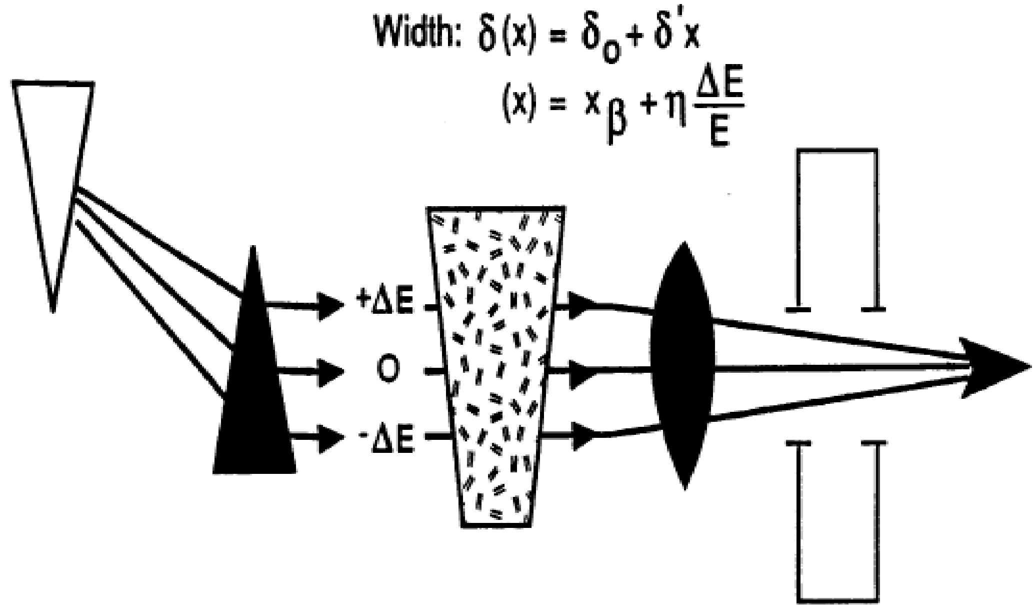
Longitudinal Cooling

- Transverse ionization cooling self-limiting due to longitudinal-emittance growth

  ⇒ need longitudinal cooling for muon collider; could also help for νFac

- Possible in principle by ionization above ionization minimum, but inefficient due to small slope *d(dE/dx)/dE* and straggling

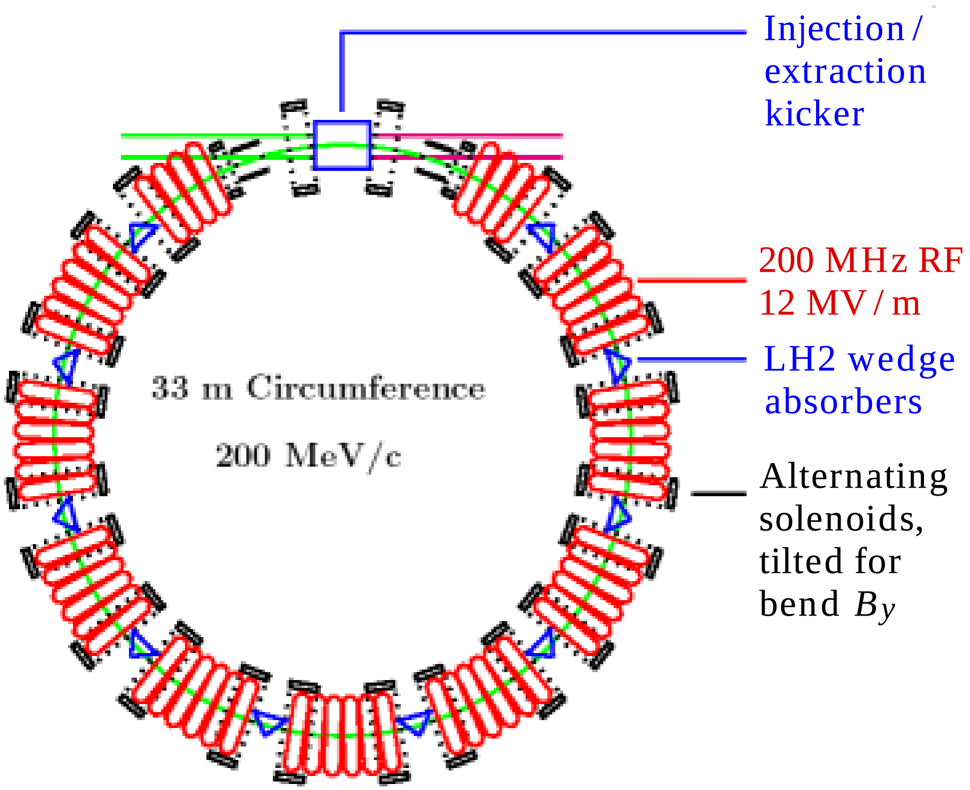
  → Emittance-*exchange* concept:

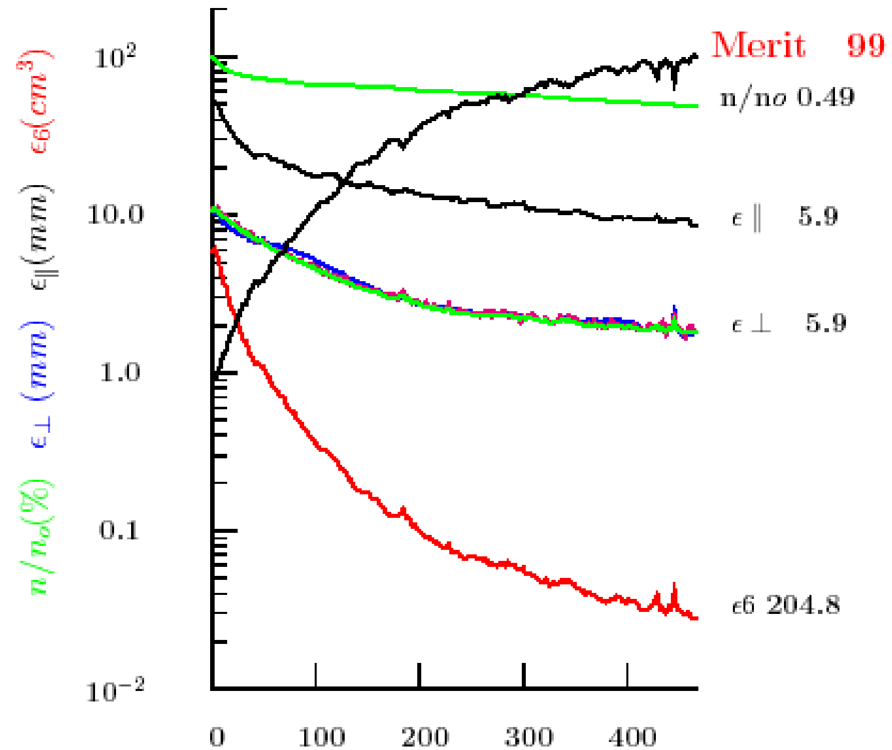


- Several promising designs under exploration

Ring Coolers

- Combine transverse cooling with emittance exchange:





- Injection & extraction appear soluble but require very fast kicker
- Could lead to νFac that is both cheaper and higher-performance

Cooling Experiment

The aims of the muon ionization cooling experiment are:

- to show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory;
- to place it in a muon beam and measure its performance in a variety of modes of operation and beam conditions.

As stated in the 2001 review of Muon Collaboration activities by the U.S. Muon Technical Advisory Committee (MUTAC):

⇒ The "cooling demonstration" is the key systems test for the Neutrino Factory.

- Much work over many years has established the components needed for muon cooling: SC solenoids, absorbers, RF cavities

It is time to start assembling a realistic cooling cell and carry out the test

Design Choices & Issues

Which design to test?

- All have common hardware elements: absorbers & cavities in strong solenoidal fields
- Choice constrained by availability of infrastructure (esp. low-frequency RF sources)

⇒ Choose 201-MHz SFOFO cell as baseline:

→ smaller and less expensive installation

– RF power supply components available

(But illustrate dynamics today with both 88- and 201-MHz simulations)

– anticipate future upgrades as more resources available (*e.g.*, adding more cooling cells) or to test new ideas (*e.g.*, emittance exchange)

Multi-particle *vs.* single-particle emittance measurement:

Multi-particle	single-particle
traditional beam-physics approach • based on multiple beam-profile measurements • compute emittance using known transfer matrices detector resolution and knowledge of transfer matrices limits precision to 10%	traditional HEP techniques • measure trajectory of each muon (x,y,z,x',y',z',t) • collect statistics • form "virtual bunch" off line and compute emittances should be capable of 0.1% precision; "software collimation" cut outs e.g. decay

Our choice

Important further issues

- Detectors must operate in strong solenoidal fields & intense RF-cavity backgrounds & contribute negligible emittance degradation

  $\Rightarrow$ *e.g.*, scint. fibers, SiPix detectors, He TPC $\rightarrow$ $\delta\varepsilon_{out}/\varepsilon_{in} \sim 10^{-3}$

- FNAL/MUCOOL tests of 805-MHz prototype cavity up to $E_{surf} \approx 53$ MV/m show high dark current (>100 mA inst.) and X-ray emission

  $\Rightarrow$ LH_2 absorbers must shield detectors from cavities

  R&D to reduce cavity discharge rate starting @ FNAL

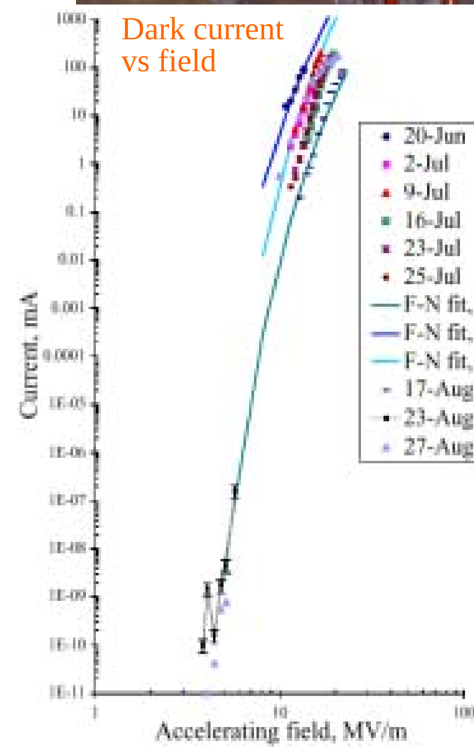
  – will explore surface treatments & coatings

  – closed-cell cavities under development have ≈1/2 the surface field for same gradient (rate ~ $E^{10} \Rightarrow \sim 10^{-3}$ in dark current)

- μ-cooling channel puts hydrogen flasks with thin windows in close proximity to possible ignition sources!

  $\Rightarrow$ working out safe design and operating approaches is a crucial & challenging part of the FNAL/MUCOOL R&D effort

805-MHz cavity in SC solenoid in Lab G



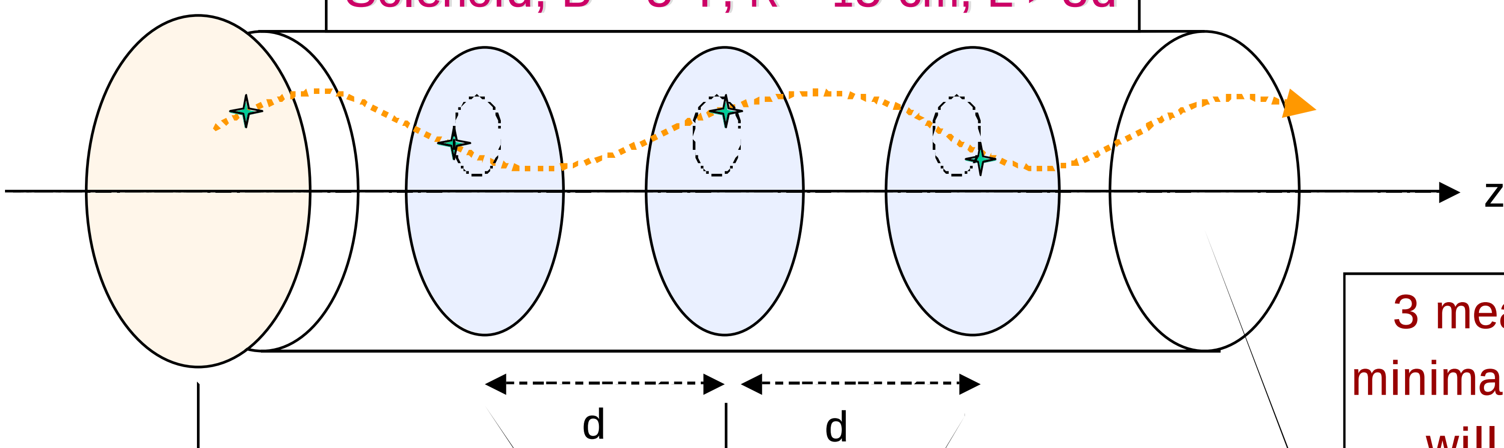
Single-Particle Emittance Measurement

(P. Janot, CERN)

- **Principle:** Measure each muon precisely before and after cooling cell
  Off-line, form "virtual bunch" and compute emittances in and out

⇒ Need to determine, for each muon, x,y,t, and x',y',t' (=p_x/p_z, p_y/p_z, E/p_z)
at entrance and exit of the cooling channel:

Solenoid, B = 5 T, R = 15 cm, L > 3d (to keep B uniform on the plates)



3 measurements is minimal set but 4 or 5 will be used for pattern-recognition redundancy

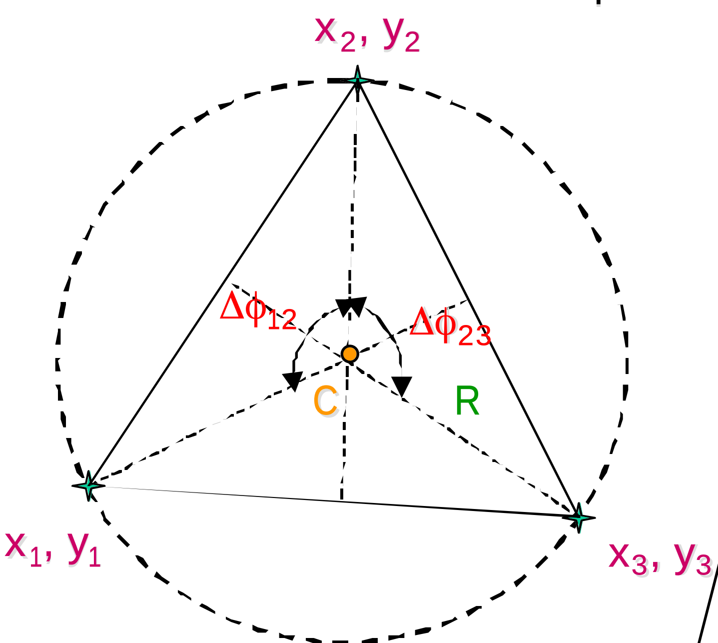
T.O.F.
Measure t
With σ_t ~ 70 ps

Three plates of, e.g., three layers of sc. fibres (diameter 0.5 mm)
Measure x_1, y_1, x_2, y_2, x_3, y_3 with precision 0.5mm/√12

Extrapolate x,y,t,p_x,p_y,p_z, at entrance of the channel. Make it symmetric at exit.

Track Reconstruction

In the transverse view, determine a circle from the three measured points:



$$\left.\begin{array}{l} d = p_z/E \times c\Delta t \\ R\Delta\phi_{12} = p_T/E \times c\Delta t \end{array}\right\} \; p_z/d = p_T/R\Delta\phi_{12}$$

- Compute the transverse momentum from the circle radius:

$$p_T = 0.3\,B\,R$$
$$p_x = p_T \sin\phi$$
$$p_y = -p_T \cos\phi$$

- Compute the longitudinal momentum from the number of turns

$$p_Z = 0.3\,B\,d\ /\ \Delta\phi_{12}$$
$$= 0.3\,B\,d\ /\ \Delta\phi_{23}$$
$$= 0.3\,B\,2d\ /\ \Delta\phi_{13}$$

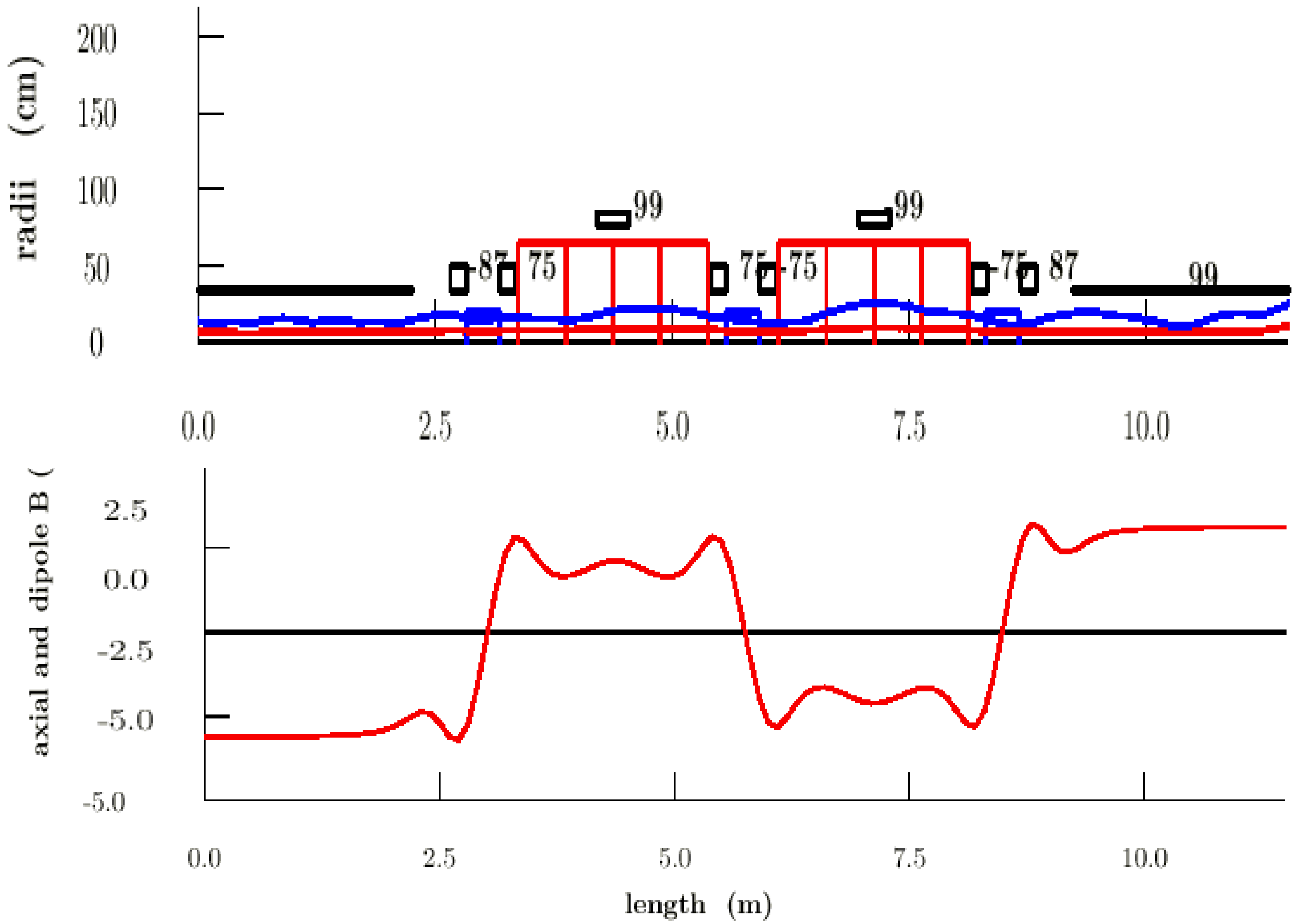
(provides constraints for alignment)

- Adjust d to make 1/3 of a turn between two plates (d = 40 cm for B = 5 T and p_Z = 260 MeV/c) on average

- Determine E from $(p^2 + m^2)^{1/2}$

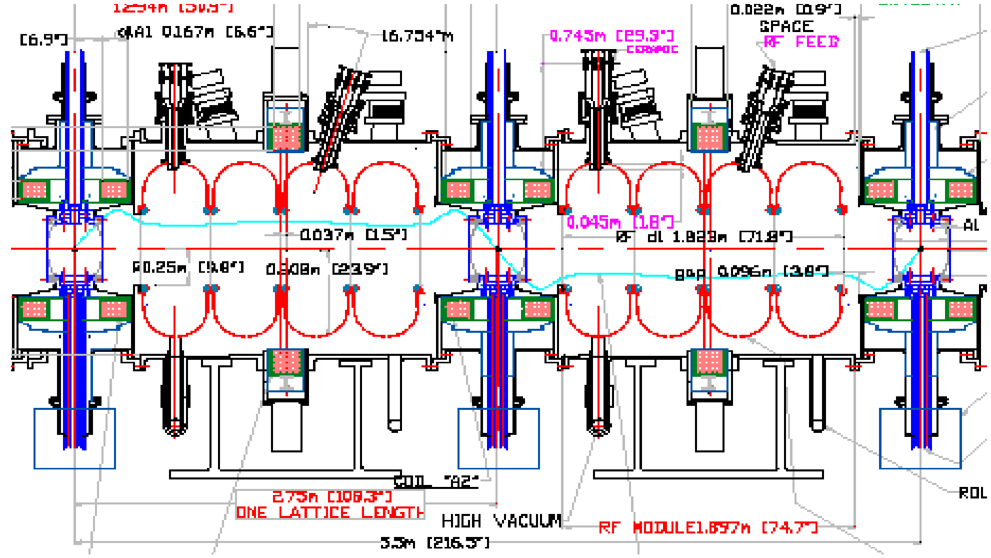
Baseline 201-MHz Cooling Experiment

(R. Palmer & R. Fernow, BNL)

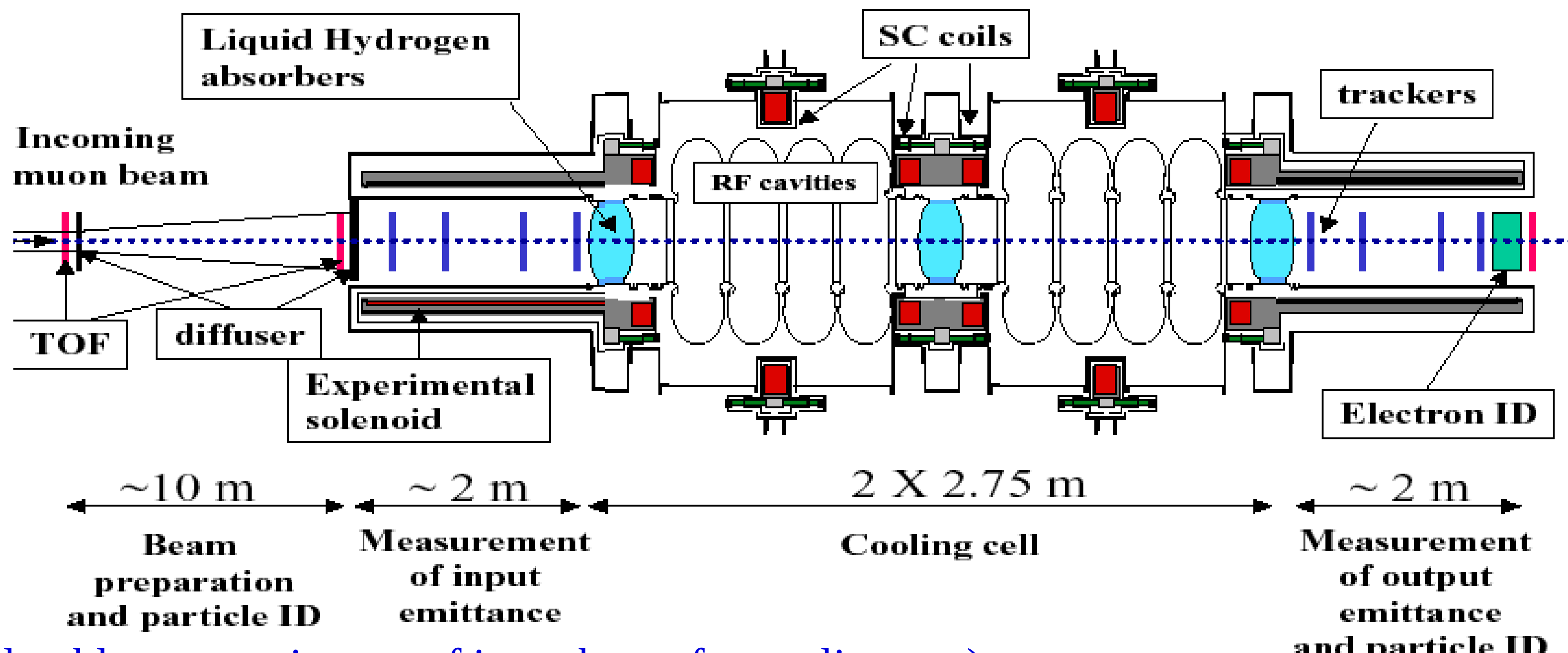


Experiment Layout

- Based on 2 cells of 2.75m SFOFO (3 absorbers, 2 4-cell 201-MHz cavities):

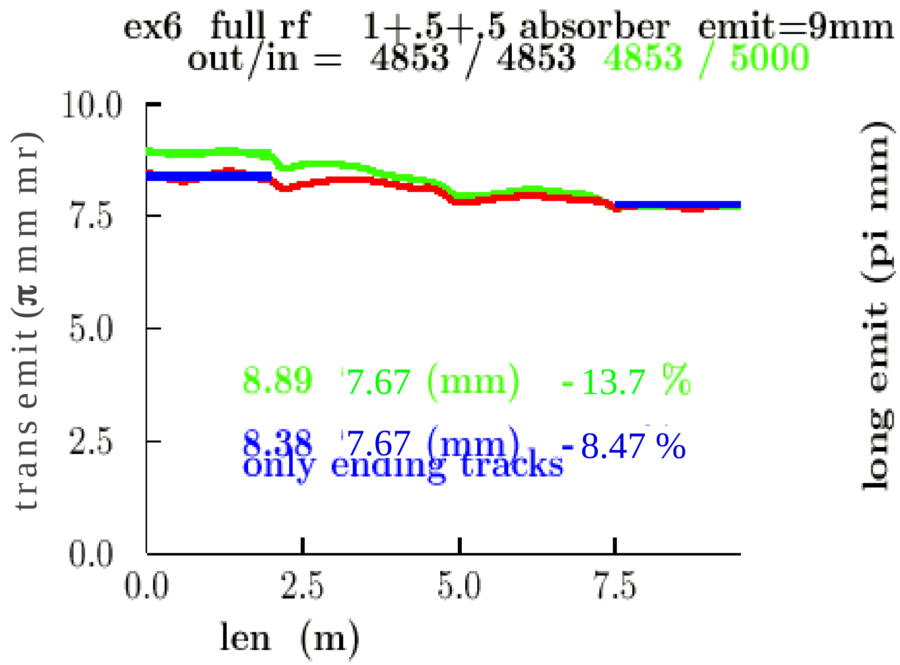


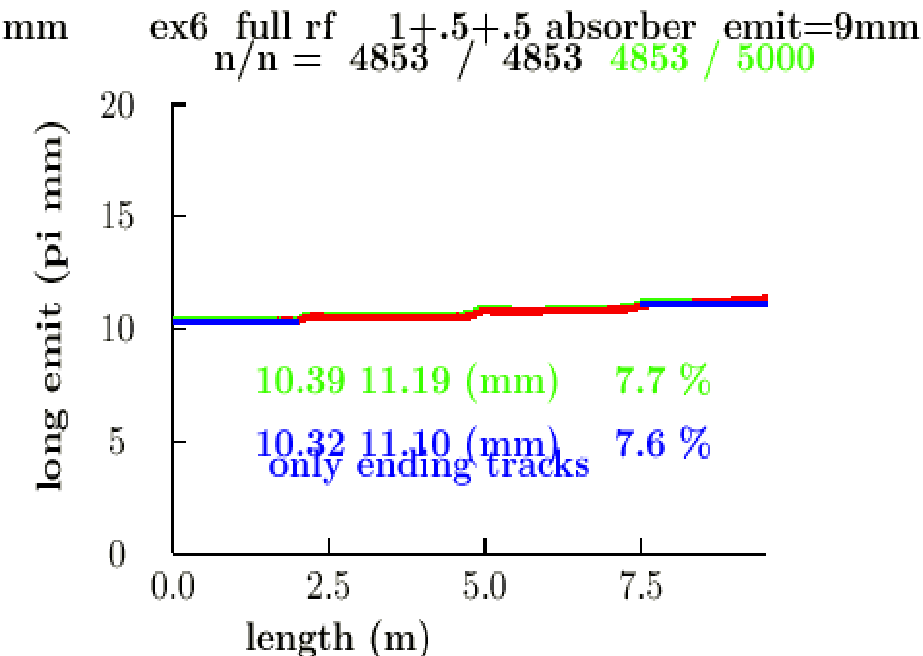
...with input & output spectrometers & beam preparation section added:

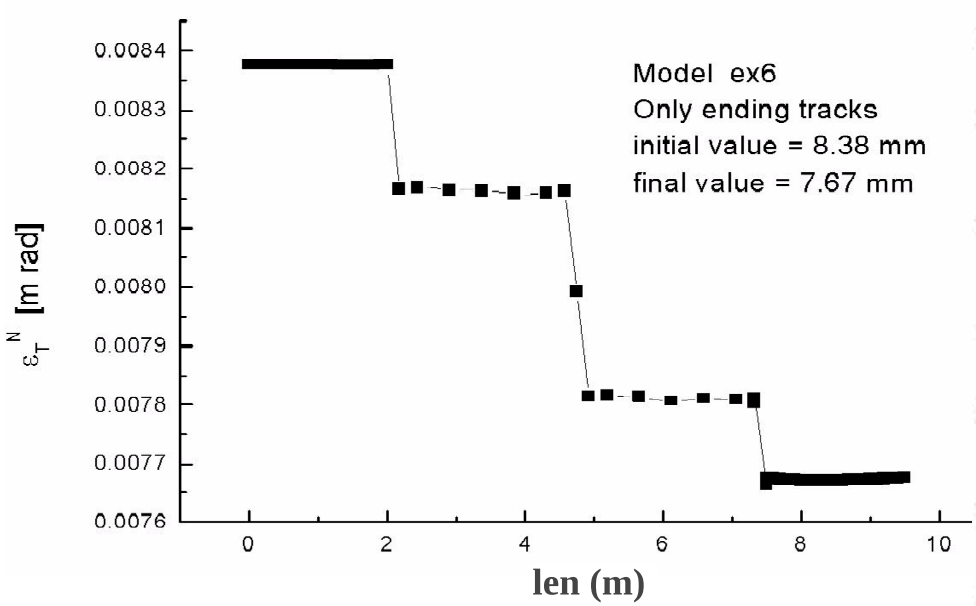


(Need to blow up emittance of input beam for cooling test)

Performance





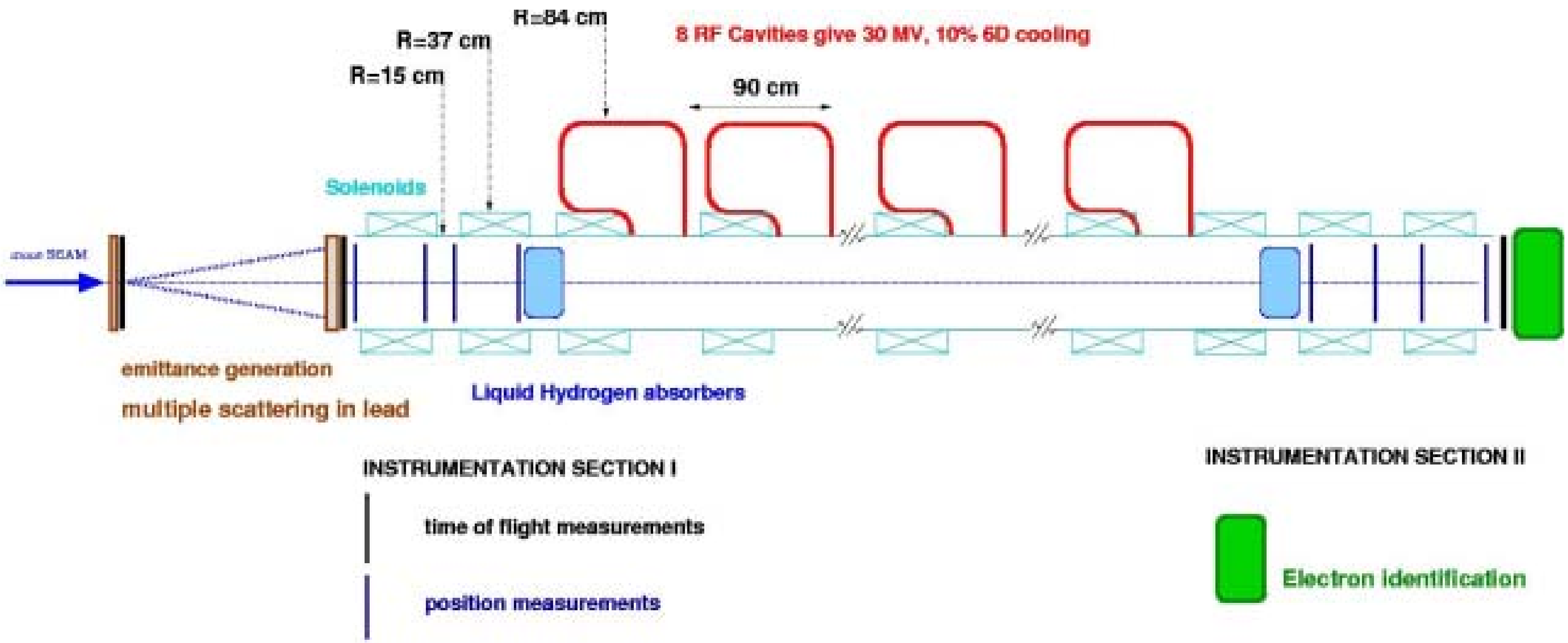


Various cases considered

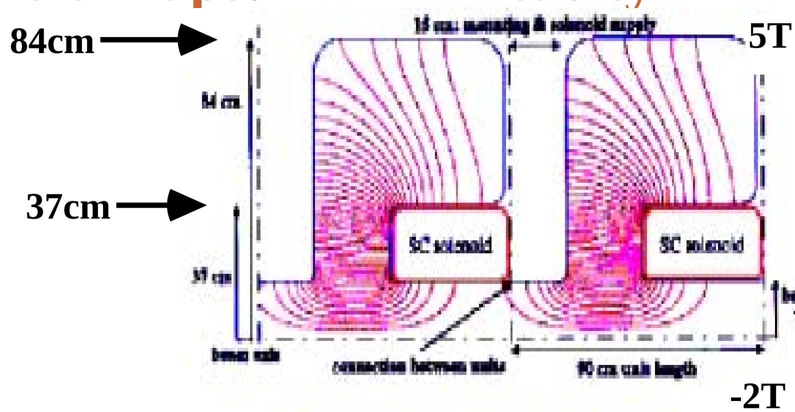
	$E_1 = E_2$?	$n_{absorbers}$	rf grad MV/m	rf phase deg	$\Delta\epsilon_\perp$ %	rf Power MW
a	yes	1/2+1+1/2	15.5	30	8	32.3
b	no	1+1+1	15.5	30	12	32.3
c	yes	1/2+1+1/2	8.7	90	2	10.3
d	no	1+1+1	8.7	90	12	10.3
e	yes	0+1+0	7.7	30	4	8.1
f	no	1+0+1	7.7	30	8	8.1
g	yes	0+1+0	4.4	90	4	2.6
h	no	1+0+1	4.4	90	8	2.6
i	no	0+1+0	0	0	4	0
j	no	1+1+1	0	0	12	0

Cooling Experiment – CERN design

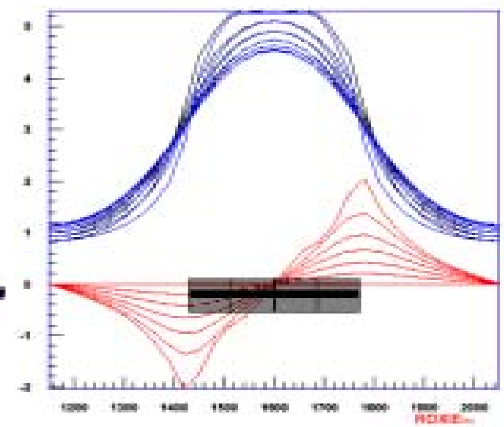
(A. Blondel, K. Hanke, H. Haseroth, et al.)



Field maps: RF cavity Solenoids



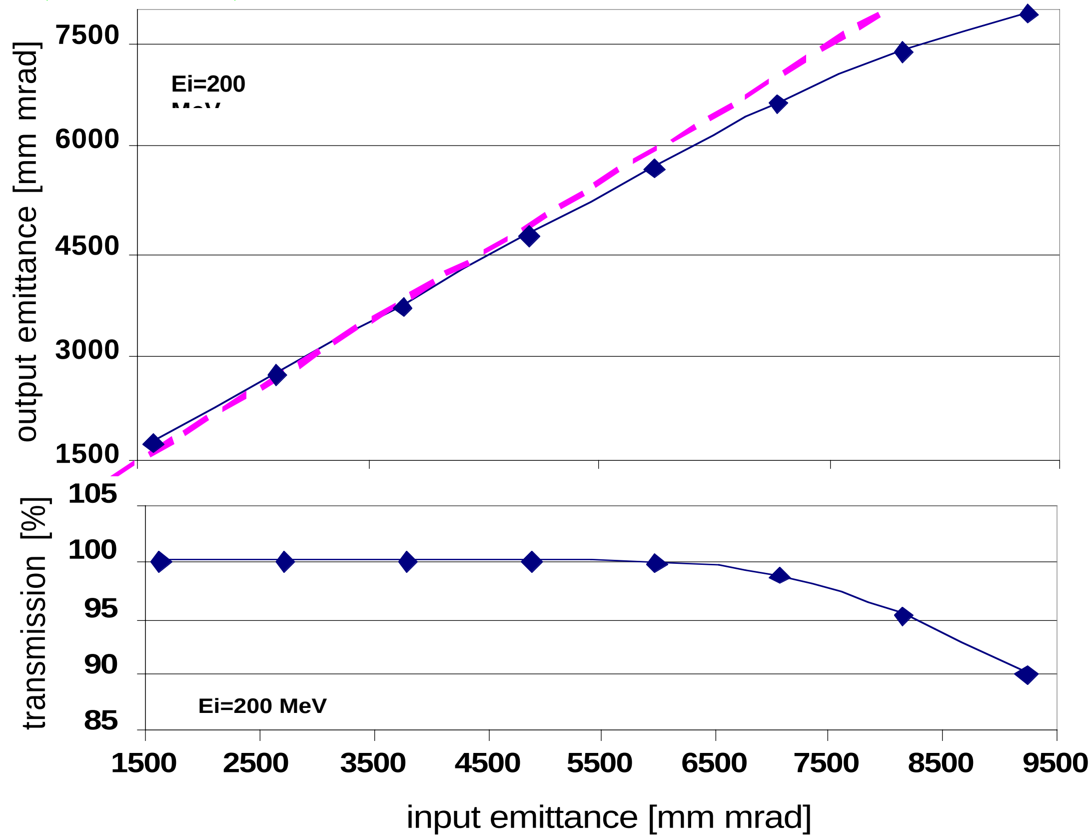
88 MHz cavities (F.Gerigk)



CERN Simulation Results

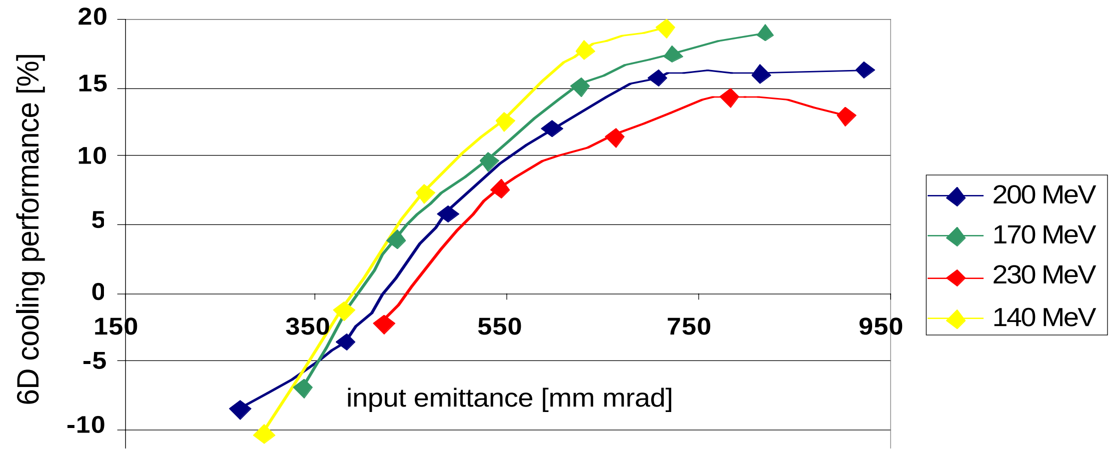
(K. Hanke)

- Experiment should verify in detail dynamics of cooling cell:
  - If input beam above equilibrium emittance, cools; if below, heats
  - Scan of input emittance reveals acceptance limits
  - Energy dependence of cooling performance



...for various cases:

- various absorbers full/empty
- various input energies
- various B-field configs
- various RF gradients & phases
- ...



Available Beams/Facilities

Comparison between beams

Single particle muon beams:

Beam	Momentum (MeV/c)	ΔP Δ(%)	Muon Intensity (during 1 s)	Area (m^2)	Exists
BNL D2	100 - 250	10	50,000 / 5 ms	5 x 3	~~Yes~~
CERN – TT1	200 - 450	?	720 / 0.1 ms	> 30 x 4	No
CERN – East Hall	200 - 450	?	1,000 / 0.5 ms	30 x 5	No
PSI – μE1	85 - 310	1 (?)	> 50,000 / 5 ms	30 x 5	Yes
RAL - ISIS	100 - 500	~ 2	20,000 / 5 ms	30 x 5	Yes
TRIUMF – M20	20 - 180	5	5,000 / 5 ms	12 x 4	Yes

Kirk McDonald
Monday, 28th May 2001

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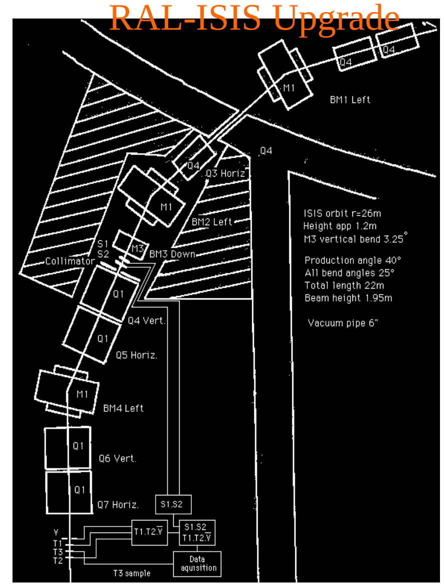
RAL-ISIS Upgrade



PSI-μE1

- We have submitted LoIs to PSI & RAL – both labs interested
- Host lab should provide beamline & infrastructure
- Natural opportunity for important European contribution

Schedule Goals & Milestones:*

Nov. '01:	Letters of Intent to PSI, RAL
Jan. '02:	Presentation to PSI
Mar. '02:	Presentation to RAL → invitation to present full proposal!
2002:	Develop detailed technical proposal; fundraising
2002–4:	Spectrometer construction
2004:	Spectrometer shakedown in muon beam
2005–6:	Assembly and shakedown of first cooling cell
2006–7:	Assembly and shakedown of second cooling cell

* This is an aggressive schedule and requires new funding sources to be found

Preliminary Cost Estimate (M$)

			1 cavity 4 MW	1 cavity 8 MW	2 cavities 4 MW	2 cavities 8 MW
cooling DE (On crest)			11.5MV	16 MV	16 MV	23 MV
Approx. $\Delta\varepsilon/\varepsilon$ (%)			5%	7%	7%	10%
Cost estimate in US$,	Fixed cost	Unit cost				
COOLING CELLS						
RF Cavities						
4 cell cavity 200 MHz	* 0.3	0.5	0.5	0.5	1	1
RF Power						
CERN-refurbish		0.2	0.2	0.2	0.2	0.2
RAL-refurbish (?)		0.2	0	0.2		0.2
Magnets						
Focus pair	* 0.55	0.45	0.9	0.9	1.35	1.35
Coupling coil	*0.4	1	1	1	2	2
Liquid H2 absorbers						
	* 0.5	0.1	0.2	0.2	0.3	0.3
LH2 plant	2		2	2	2	2
Total for cooling cell US $			4.8	5.0	6.85	7.05
SPECTROMETERS						
Solenoids	0.69	0.5	1.69	1.69	1.69	1.69
Detectors		2	2	2	2	2
Total spectrometers			3.69	3.69	3.69	3.69
Subtotal	2.69		8.49	8.69	10.54	10.74
Infrastr., extras(20%)						
TOTAL	3.23		13.4	13.7	15.9	16.1

* development costs borne by MUCOOL

cost-effective use of existing RF power sources

Organization of International Collaboration

- Starting at NuFact'01, we have formed the Muon Cooling Demonstration Experiment Steering Committee (MCDESC):

  Alain Blondel (Chair and European Spokesperson), U. Geneva
  Rob Edgecock, Rutherford
  Steve Geer, Fermilab
  Helmut Haseroth, CERN
  Daniel M. Kaplan (US Spokesperson), IIT
  Yoshitaka Kuno, Osaka U.
  Michael S. Zisman, LBNL

- We have designated the Technical Team Leaders:

  Particle detectors: A. Bross, V. Palladino
  RF radiation (dark current and X-Ray) issues: E. McKigney, J. Norem
  Magnet systems: H. Haseroth (provisional), M. Green
  RF cavities and power supplies: R. Garoby, R. Rimmer
  Hydrogen absorbers: M. A. Cummings, S. Ishimoto
  Concept development and simulations: A. Lombardi, P. Spentzouris
  Beamlines: R. Edgecock, C. Petitjean

- We have held several video meetings, several workshops (CERN, Chicago, London, CERN), and a workshop is upcoming at Rutherford Lab July 8–10

  (see http://muonstoragerings.cern.ch/October01WS/oct01ws.html,
  http://www.capp.iit.edu/~capp/workshops/mumice02/mumice02.html, and
  http://hepunx.rl.ac.uk/neutrino-factory/muons/mice-meeting.html)

Participating Institutes:

Louvain La Neuve
NESTOR Institute
Hellenic Open University
INFN LNF Frascati
INFN Milano
INFN Napoli
INFN Roma II
INFN Trieste
Osaka University
Paul Scherrer Institute
University of Zurich
Rutherford Appleton Laboratory
Brookhaven National Laboratory
Fairfield University
Illinois Institute of Technology
Michigan State University
Princeton University
University of California, Riverside
University of Chicago
University of Iowa

CERN
University of Athens
INFN Bari
INFN Legnaro
INFN Padova
INFN Roma I
INFN Roma III
KEK
ETH Zurich
University of Geneva
Imperial College London
Argonne National Laboratory
Columbia University
Fermi National Accelerator Laboratory
Lawrence Berkeley National Laboratory
Northern Illinois University
University of California Los Angeles
Indiana University
University of Illinois at Urbana-Champaign
University of Mississippi

Summary

- Muon storage rings could be a uniquely powerful option for large future facilities
- A Neutrino Factory is the best way to study neutrino mixing
- Technical feasibility has been demonstrated “on paper”
- Prerequisite to Neutrino Factory approval: experimental demonstration of muon ionization cooling
- Scope of the Muon International Cooling Experiment defined; well on the way to specifying the details
- International collaboration formed and leadership structure in place
- Scope and time scale comparable to mid-sized HEP experiment
- Need to line up necessary resources (people, equipment, funding)
- Good opportunity for new collaborators – want to join?