Neutrino Factory and Muon Collider R&D

Muon Production, Capture and Acceleration R&D directed at Physics with Intense Muon Beams

The Neutrino Factory and Muon Collider Collaboration

A Bit of History

Since 1995 the Neutrino Factory and Muon Collider Collaboration (a.k.a. Muon Collaboration) has pursued an active R&D program that has focused on muon production, capture and acceleration. Initially the physics emphasis was on muon colliders (both a Higgs Factory and an energy frontier machine). By 2000 the focus of the collaboration had shifted to studying the feasibility of a Neutrino Factory. Recently new ideas in muon ionization cooling have reinvigorated the collaboration's efforts on the investigation of energy frontier muon colliders. I will:

1. Review the physics motivation for our activities
2. Describe the Collaboration's program
3. Explore the synergy between Neutrino Factory and Muon Collider facilities both from the point of view of the physics program and the accelerator complex

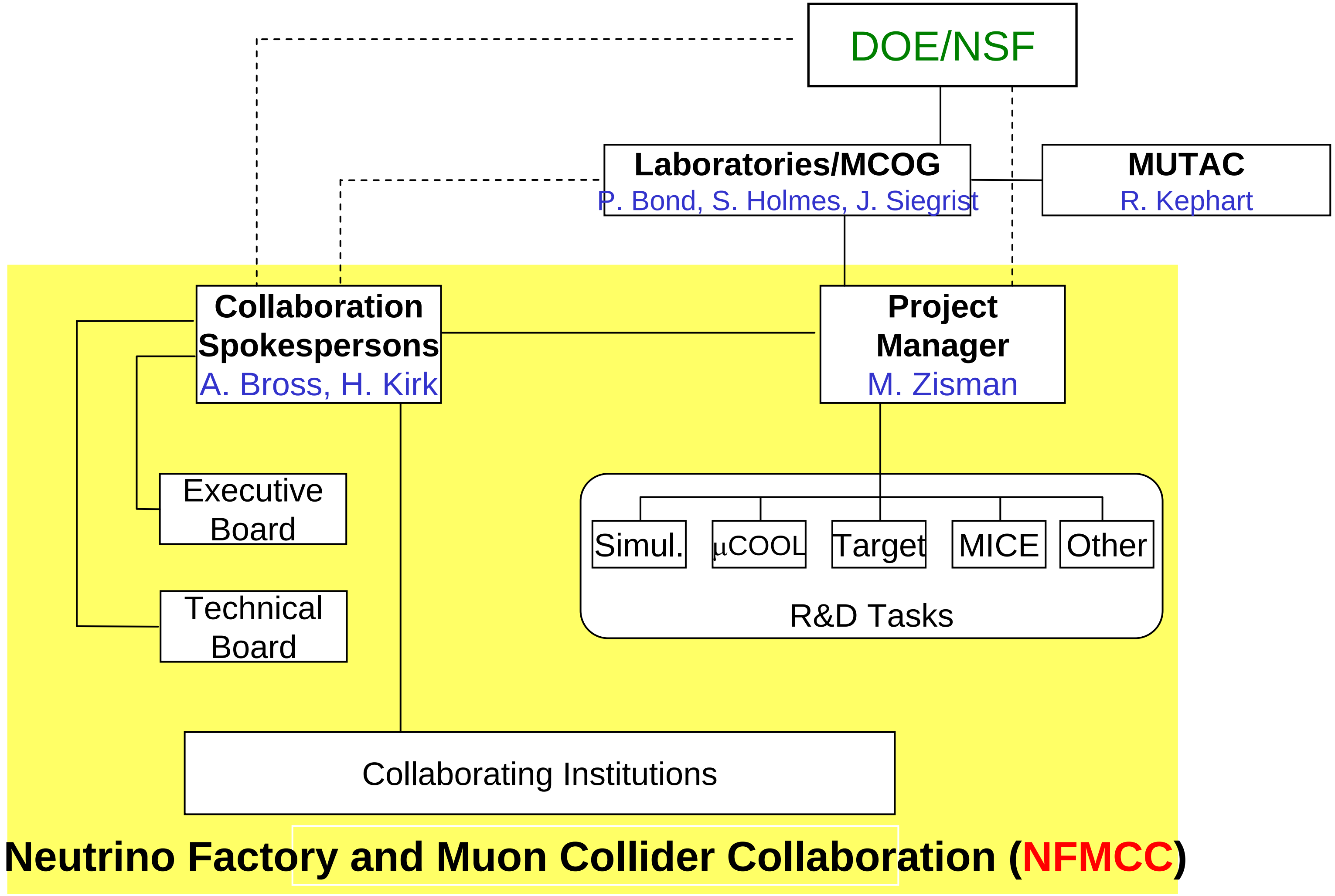
NFMCC Mission

To study and develop the theoretical tools, the software simulation tools, and to carry out R&D on the hardware that is unique to the design of Neutrino Factories and Muon Colliders

- **Extensive experimental program to verify the theoretical and simulation predictions**

NFMCC WEB site: http://www.cap.bnl.gov/mumu/

Current Organization



Collaborating Institutions

US

National Labs
Argonne
BNL
Fermilab
LBNL
Oak Ridge
Thomas Jefferson

Universities
Columbia
Cornell
IIT
Indiana
Michigan State
Mississippi
Northern Illinois
Princeton
UC-Berkeley
UC-Davis
UC-Los Angeles
UC-Riverside
University of Chicago

International

National Labs
Budker
DESY
INFN
JINR, Dubna
KEK
RAL
TRIUMF

Universities
Karlsruhe
Imperial College
Lancaster
Osaka
Oxford
Pohang
Tel Aviv

Corporate Partners
Muons Inc*
Tech-X Corporation

*SBIR Funding
9 Phase I
6 Phase II
Currently 8 FT Ph.D.

Core Program

Targetry R&D: Mercury Intense Target Experiment (MERIT)

Co-Spokesperson: Kirk McDonald
Co-Spokesperson & PM: Harold Kirk

Ionization Cooling R&D: MuCool and MICE

MuCool Spokesperson: Alan Bross
MICE Deputy Spokesperson: Mike Zisman
US MICE Leader: Dan Kaplan

Simulations & Theory

Coordinator: Rick Fernow

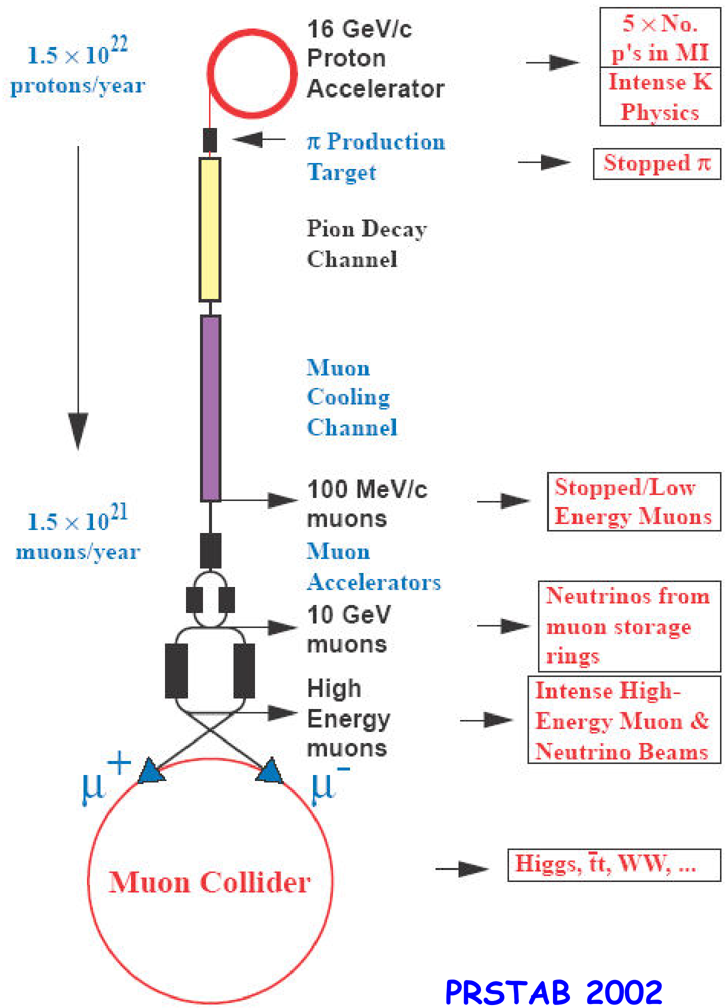
Muon Collider Task Force*

*@ Fermilab

Physics Motivation

Is Muon Production, Capture and Acceleration R&D worth the investment?

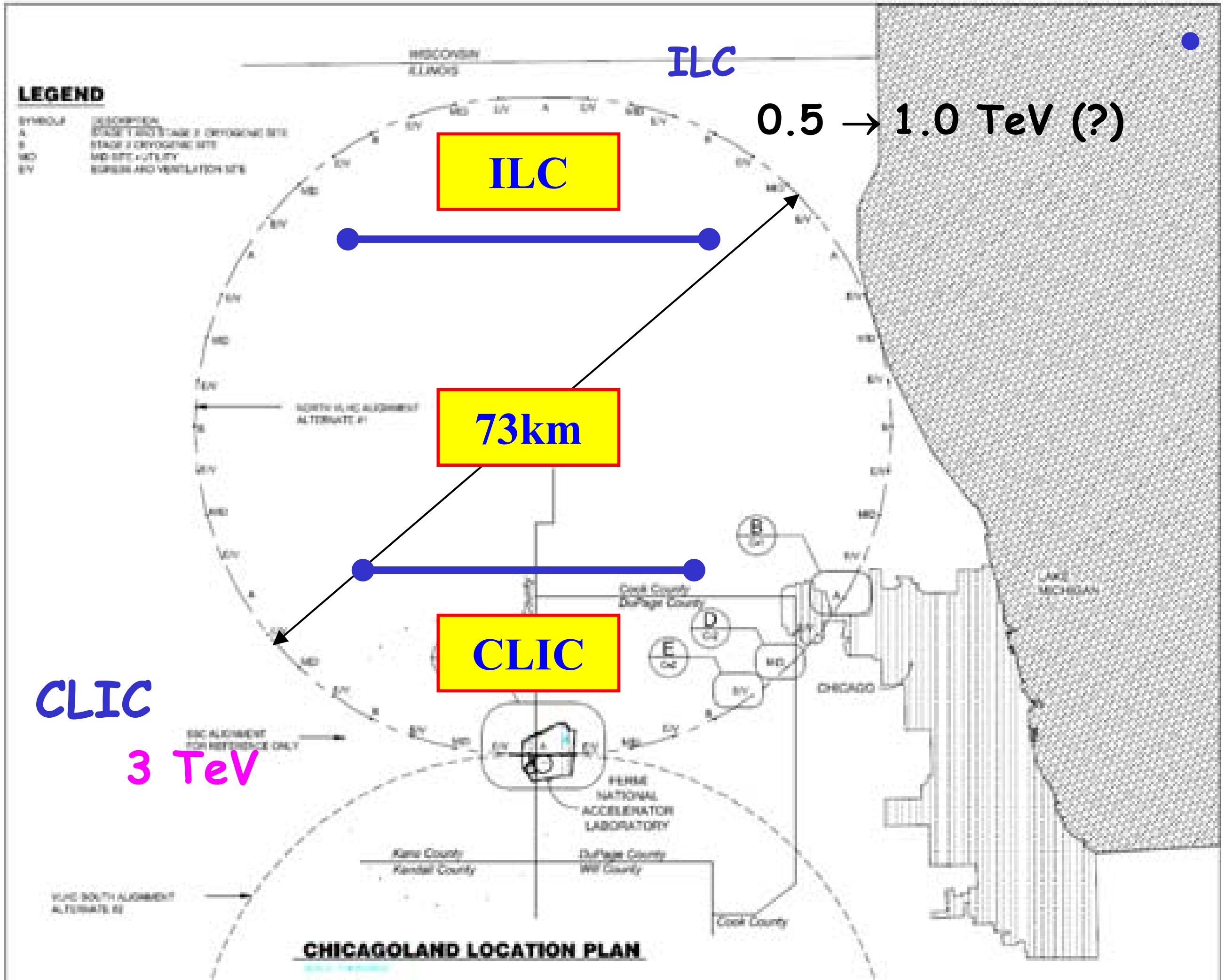
Evolution of a Physics Program



PRSTAB 2002

1. Intense Low-energy muon physics
   - μ e conversion experiment
2. Neutrino Factory
   - High Energy 10-20 GeV
     - Possible Low Energy 4 GeV option
3. Energy Frontier Muon Collider
   - 1.5 - 4 TeV+

Footprint and the Energy Frontier

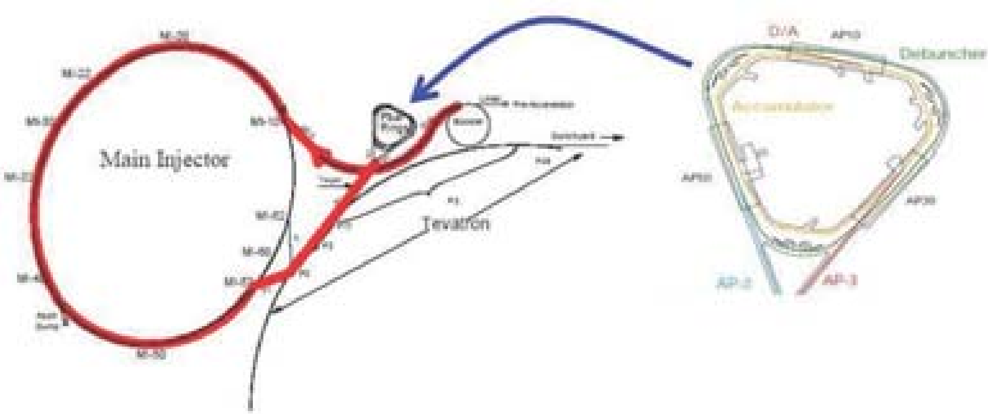


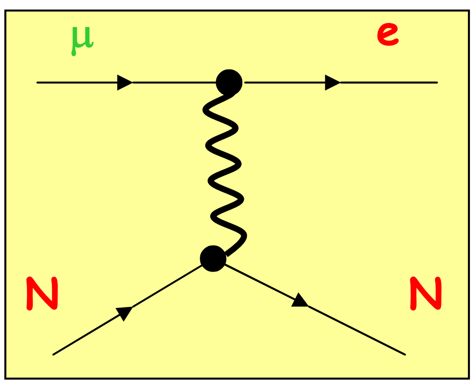
- The VLHC is the largest machine to be seriously considered to date
  - Stage 1 – 40 TeV
    - > 2 TeV
  - Stage 2 – 200 TeV
    - > 10 TeV

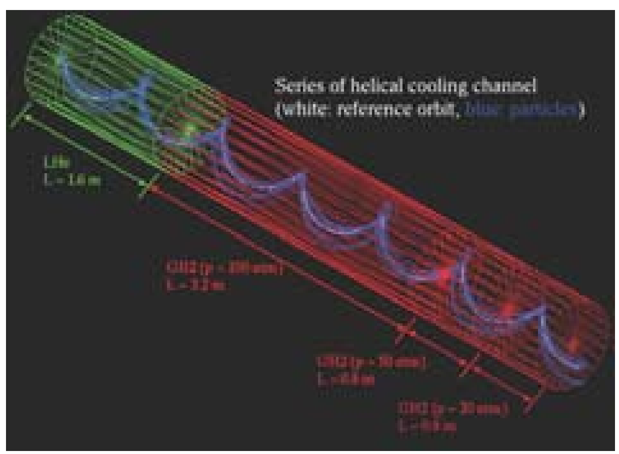
Muon Facilities are different

Compact Lepton Machine
CLEM (2 TeV)

Low-Energy Muon Physics
μ to e conversion - *Mu2e*



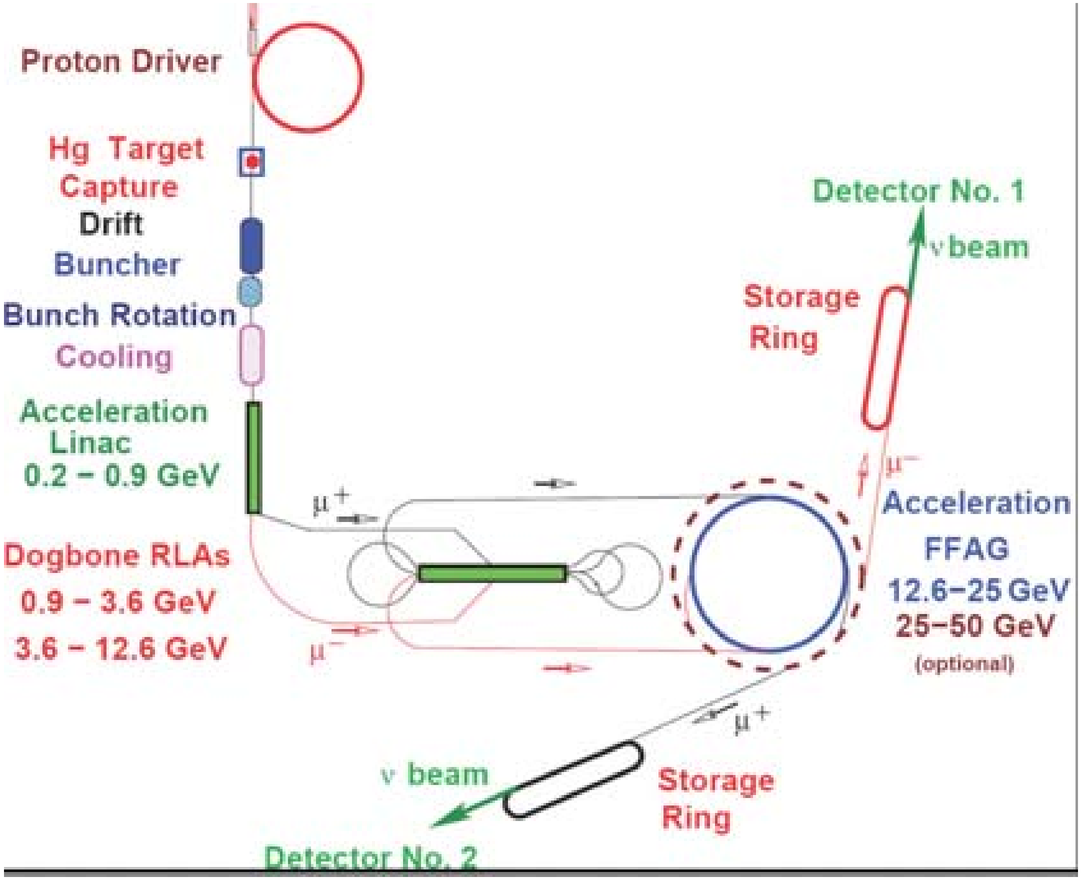




- Sensitive tests of Lepton Flavor Violation (LFV)
  - In SM occurs via ν mixing
    - Rate well below what is experimentally accessible
  - Places stringent constraints on physics beyond SM
    - Supersymmetry
      - Predictions at 10^{-15}
- Requirement – Intense low energy μ beam
  - Cooling improves stopping efficiency in target of experiment
    - Might be an appropriate option for a Mu2e expert.
      - Time Scale is issue
  - Test bed for Muon Ionization Cooling for NF and MC with intense μ beam

Neutrino Factories

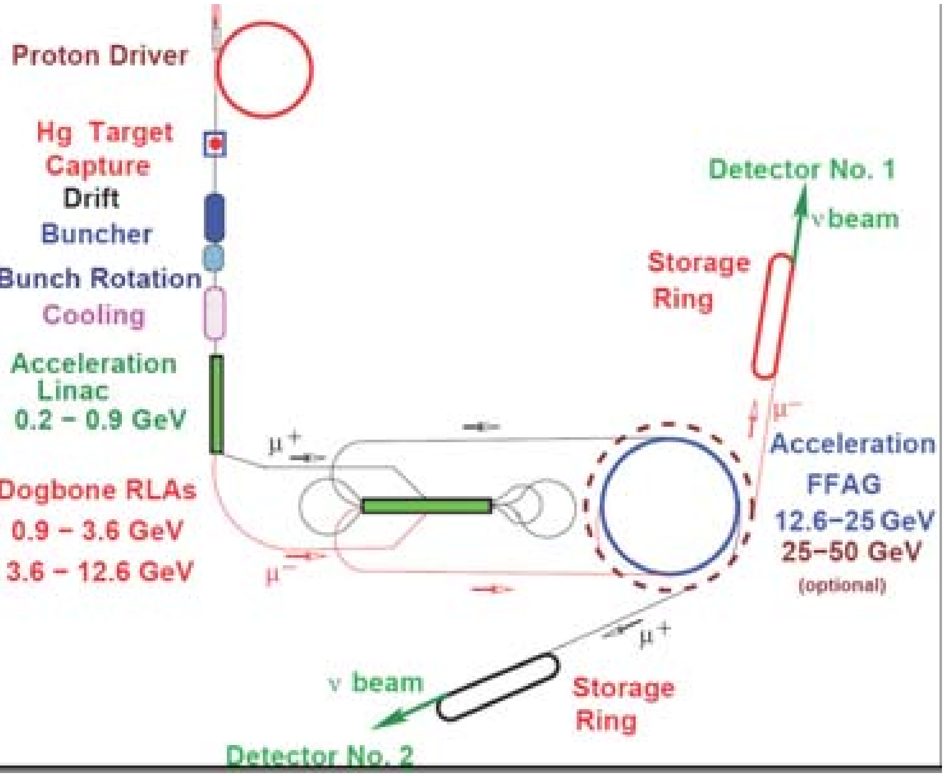
Preliminary Design From the International Scoping Study



- Why a Neutrino Factory?
  - Strong case for precision neutrino program
    - Very Rich Experimental Program
- Want Very Intense ν beam with well-understood systematics

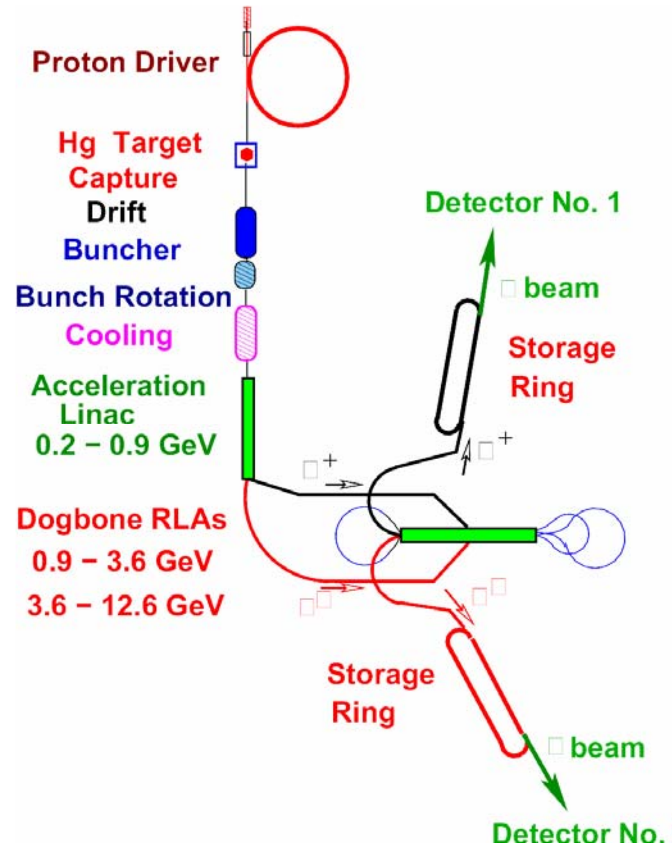
Low-Energy NF
Neutrino Factory Lite

25-50 GeV



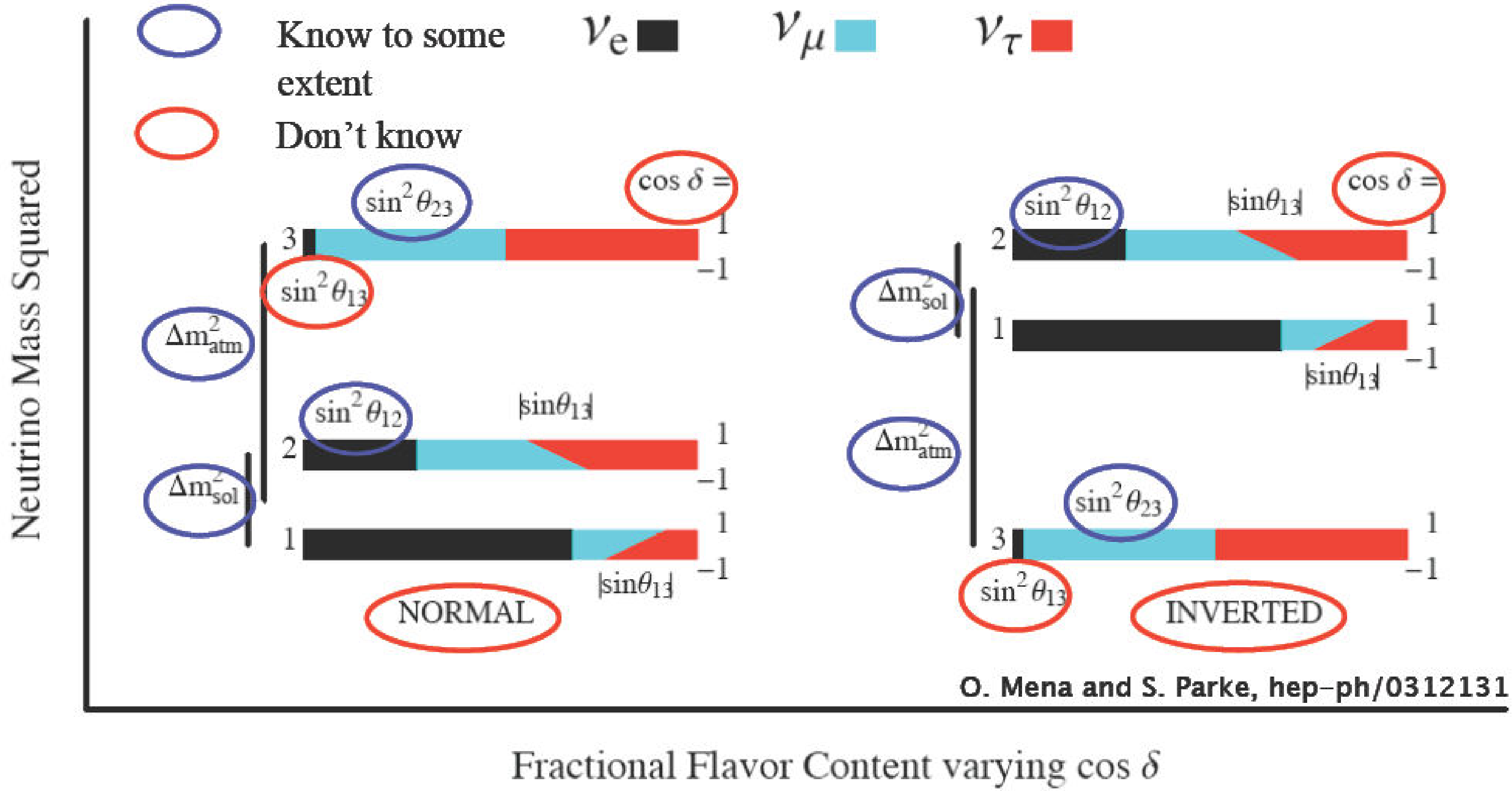
ISS Preliminary Design

4 GeV



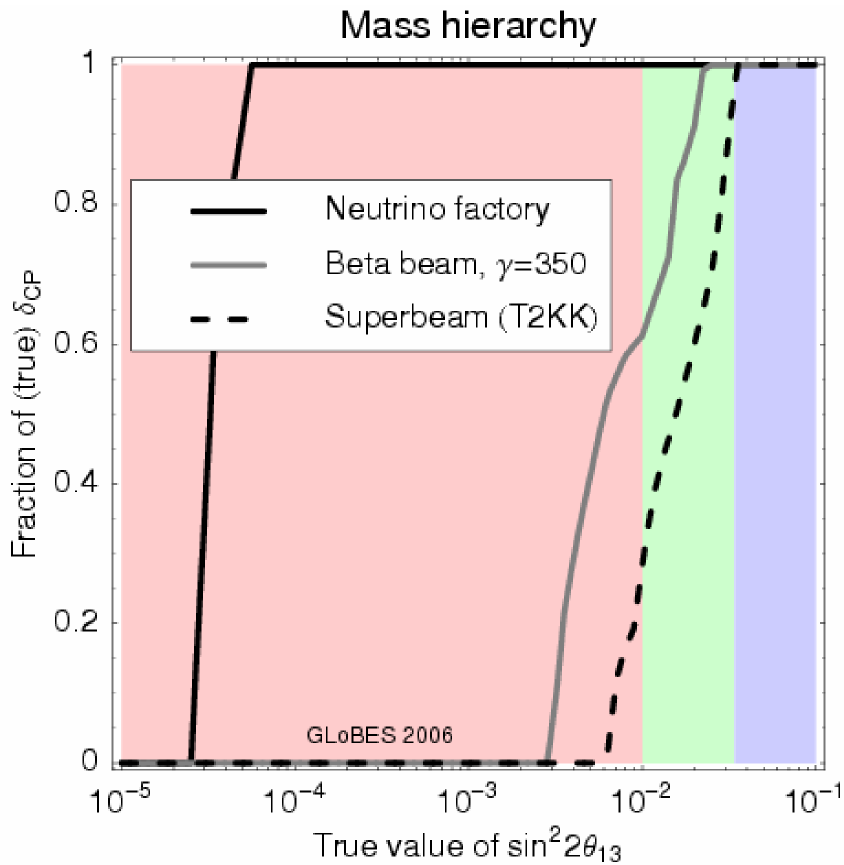
40% Cost Reduction

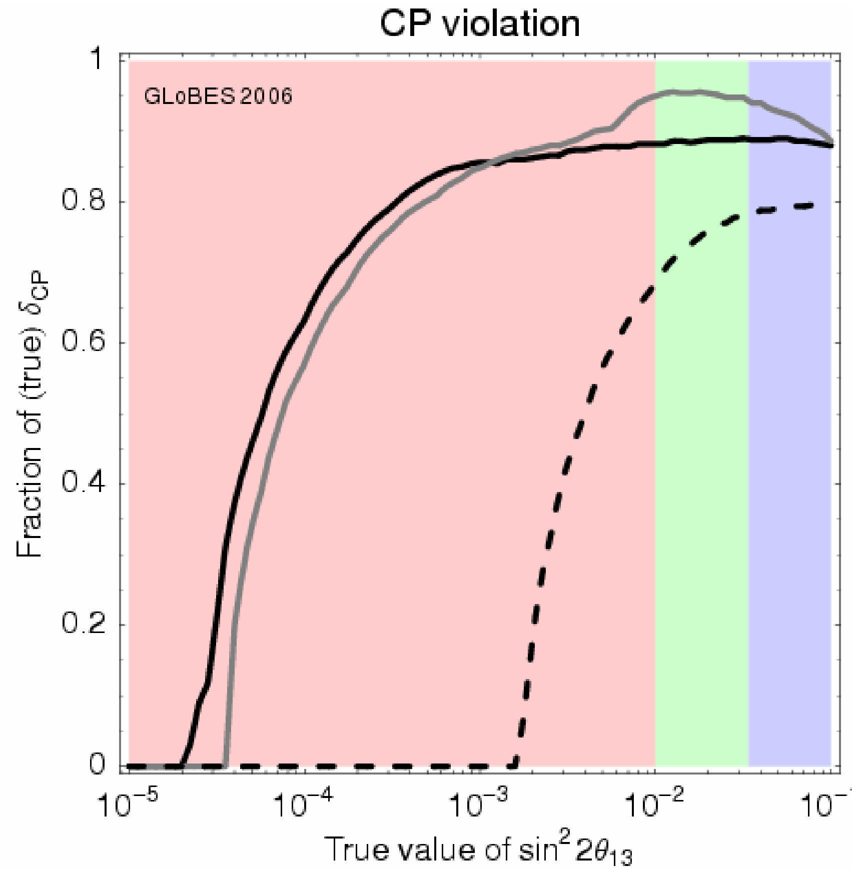
3 ν Mixing Model



Is a Neutrino Factory needed in order to fill in the blanks?

Neutrino Factory- ISS



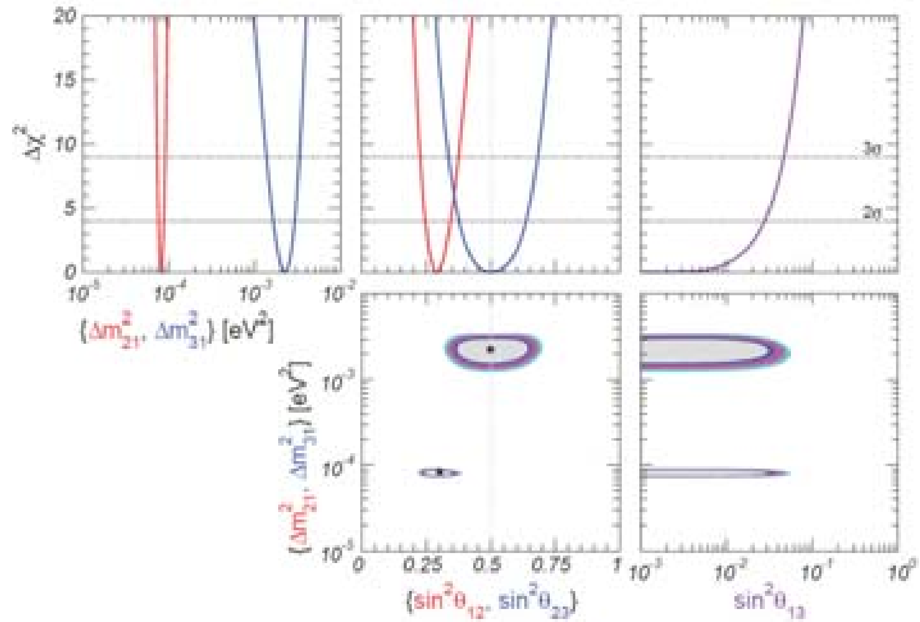


(3σ, Δm_{31}^2=0.0022 eV^2)

Best possible reach in θ_{13} for all performance indicators → Neutrino factory

Theoretical Indications That θ_{13} may be small

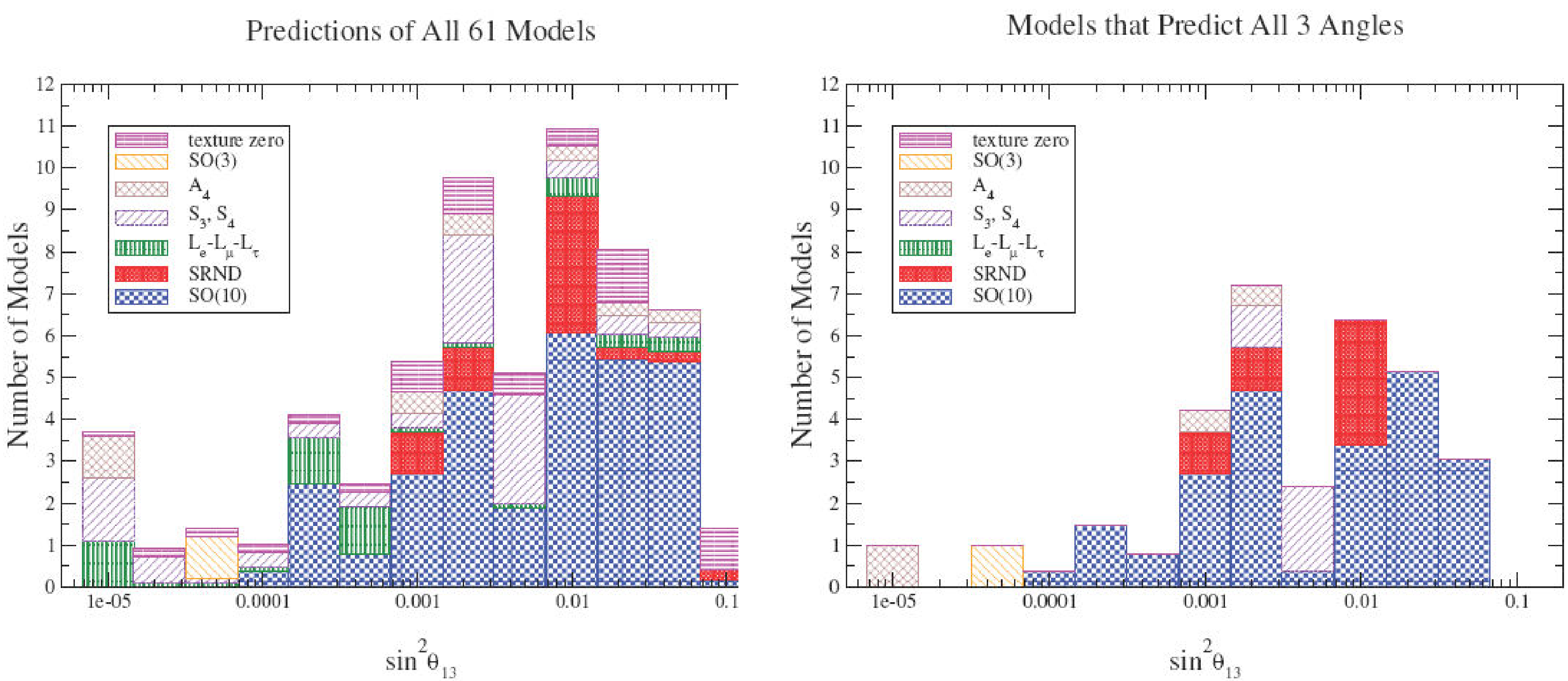
Projections of the allowed regions from the global oscillation data at 90%, 95%, 99%, and 3σ C.L.



parameter	best fit	2σ	3σ	4σ
Δm^2_{21} [10^{-5}eV^2]	8.1	7.5–8.7	7.2–9.1	7.0–9.4
Δm^2_{31} [10^{-3}eV^2]	2.2	1.7–2.9	1.4–3.3	1.1–3.7
$\sin^2\theta_{12}$	0.30	0.25–0.34	0.23–0.38	0.21–0.41
$\sin^2\theta_{23}$	0.50	0.38–0.64	0.34–0.68	0.30–0.72
$\sin^2\theta_{13}$	0.000	≤ 0.028	≤ 0.047	≤ 0.068

Maltoni et. al. hep-ph/0405172 June 2006

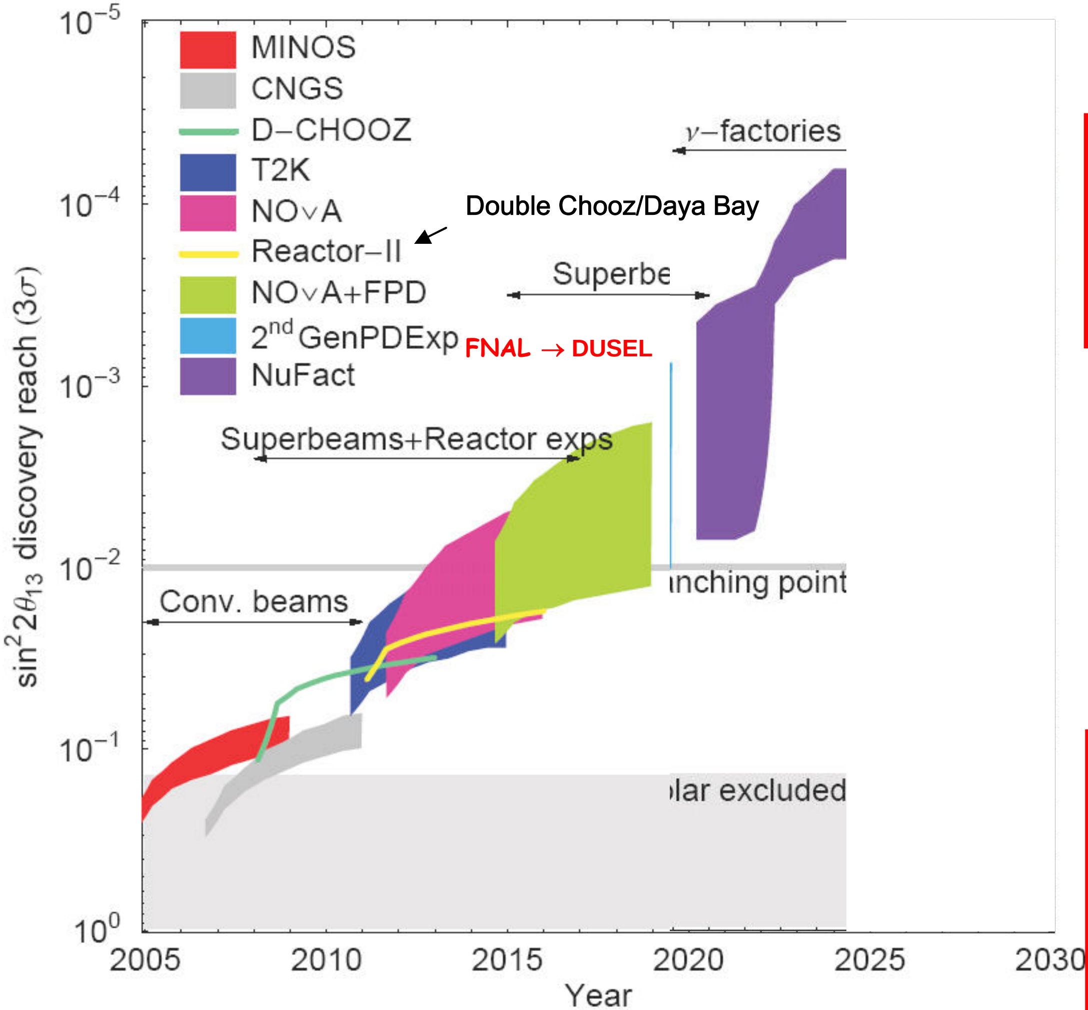
$\sin^2\theta_{13}$ Model Predictions



Histogram of the number of models for each $\sin^2\theta_{13}$ bin.

Albright and Chen, hep-ph/0608137 August 2006

Neutrino Factory
To Build or Not to Build



We Don't Know –
But
There is a Natural Decision Point
≈ 2012

After NOvA and T2K
If θ_{13} not seen
or
seen at 3σ
Consider Major Upgrades or New Facility

In order to make an informed decision about a New Facility and if the NF plays a role – Will need a RDR ready at this time (IDS)
This defines the R&D Program

Muon Collider - Motivation

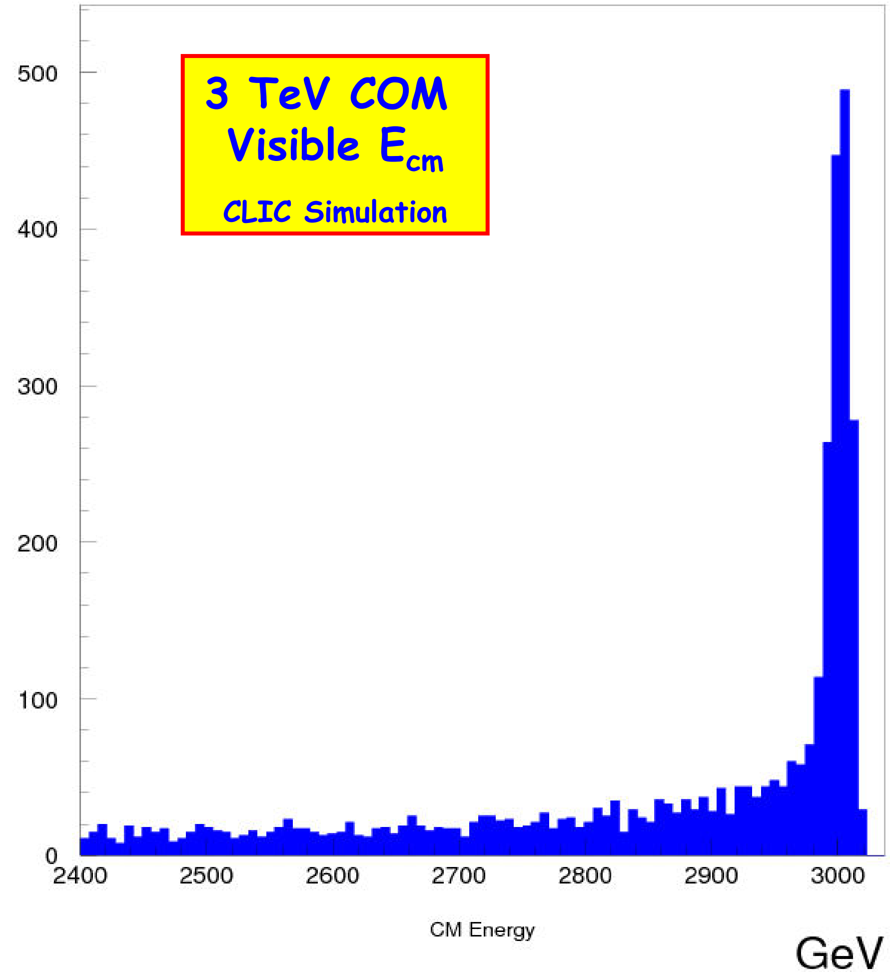
Reach Multi-TeV Lepton-Lepton Collisions at High Luminosity

Muon Colliders may have special role for precision measurements.
Small ΔE beam spread - Precise energy scans

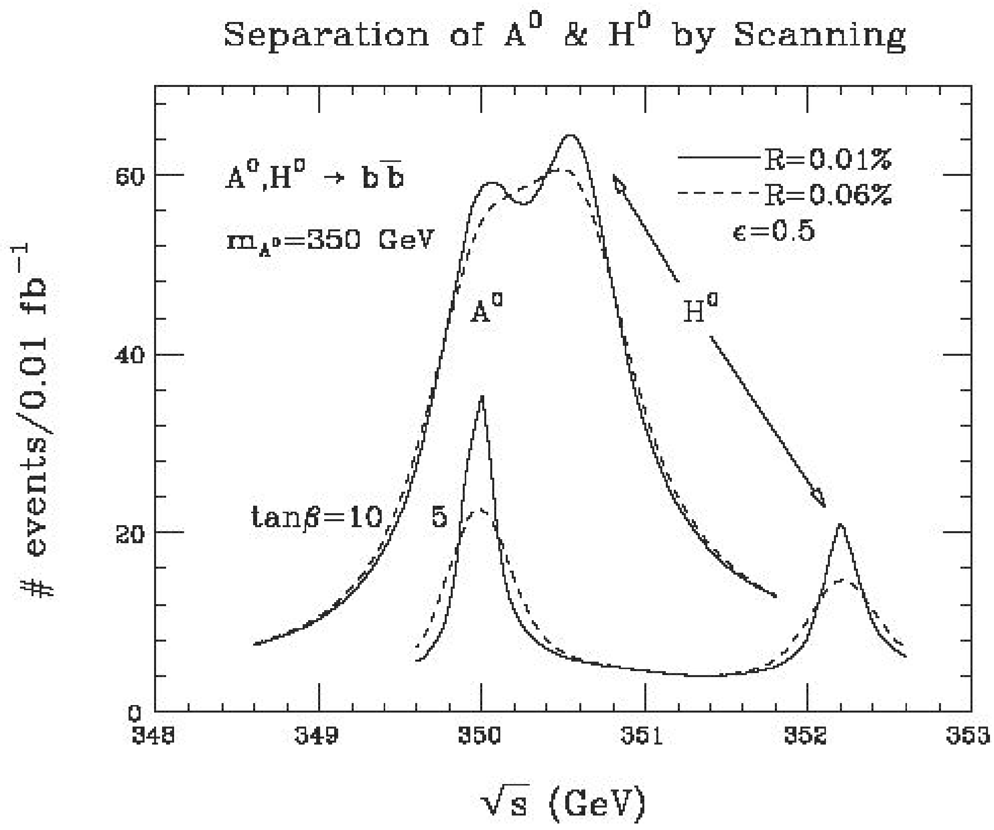
Small Footprint - Could Fit on Existing Laboratory Site

Muon Collider at the Energy Frontier

- Comparisons with Energy Frontier e^+e^- Collider
  - For many processes - Similar cross sections
  - Advantage in s-channel scalar production
    - Cross section enhancement of $(m_\mu/m_e)^2$
      - $\approx$ 40,000
  - Beam polarization also possible
    - Polarization likely easier in e^+e^- machine
  - More precise energy scan capability
    - Beam energy spread and Beamstrahlhung limits precision of energy frontier (3TeV) e^+e^- machines
  - Muon decay backgrounds in MC do have detector implications, however

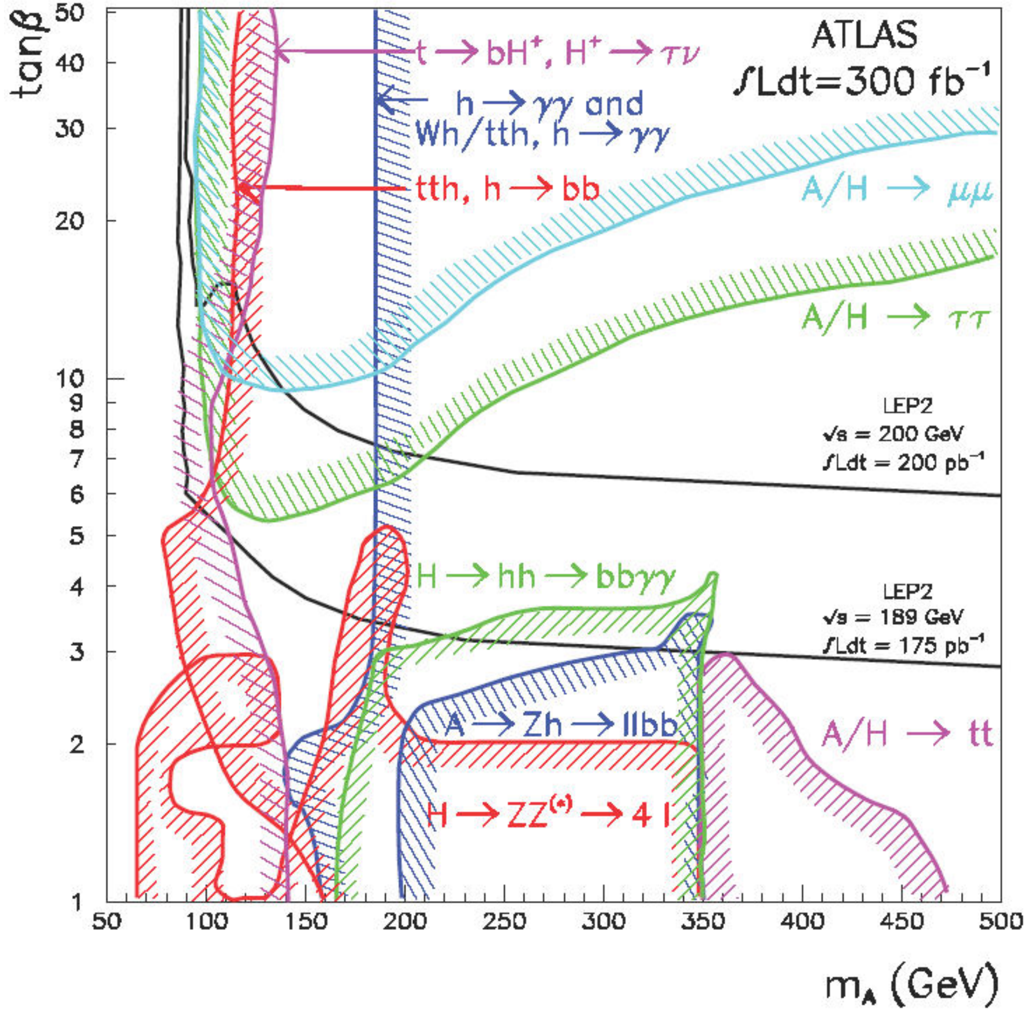


MC Physics - Resolving degenerate Higgs



Precision Energy Scan Capability of Muon Collider

For larger values of tanβ there is a range of heavy Higgs boson masses (H_0, A_0) for which discovery at LHC or *e+e-* linear collider may not be possible due to suppression of coupling to gauge bosons



Davide Costanzo
hep-ex/0105033v2

Key Ingredients of the Facilities

Needs Common to NF and MC Facility

- Proton Driver
  - primary beam on production target
- Target, Capture, and Decay
  - create π's; decay into μ's
- Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce emittance of the muons
    - Cost-effective for NF
    - Essential for MC
- Acceleration
  - Accelerate the Muons
- Storage Ring
  - store for ~1000 turns

But there are Key Differences

Neutrino Factory

- Cooling
  - Reduce transverse emittance
    - $\varepsilon_\perp$ ~ 7 mm
- Acceleration
  - Accelerate to 20-40 GeV
    - May be as low as 5-7 GeV
- Storage Ring
  - No intersecting beams

Muon Collider

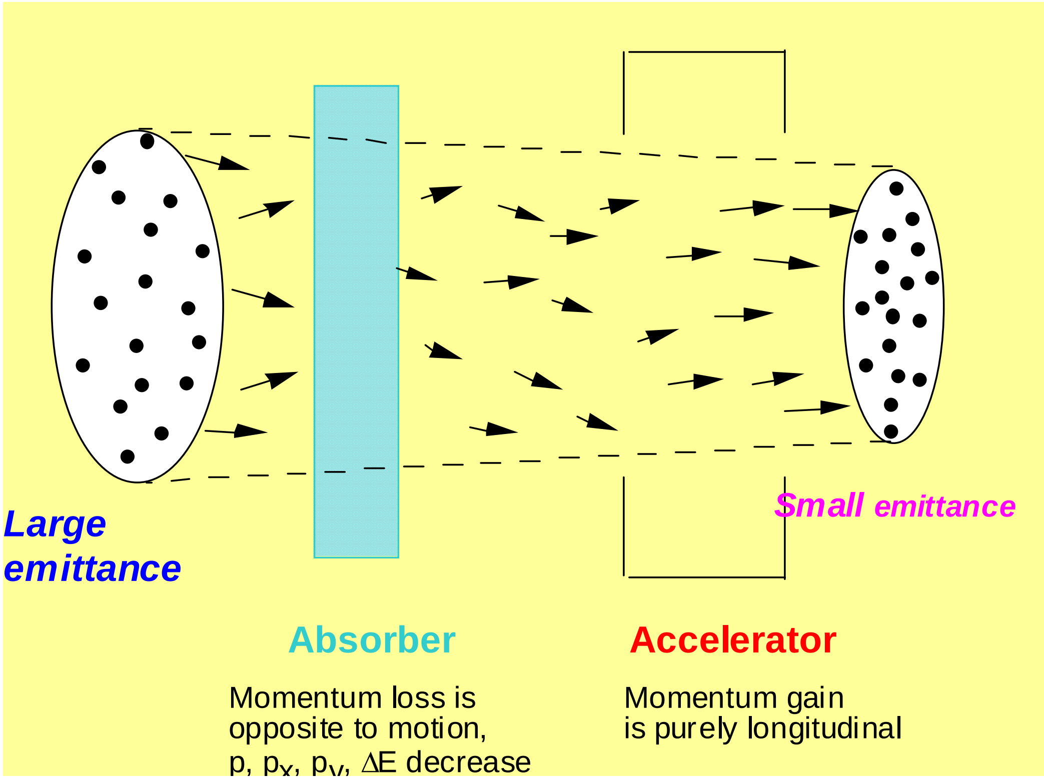
- Bunch Merging
- Cooling
  - Reduce 6D emittance
    - $\varepsilon_\perp$ ~ 3-25 μm
    - ε_L ~ 70 mm
- Acceleration
  - Accelerate to 1-2 TeV
- Storage Ring
  - Intersecting beams

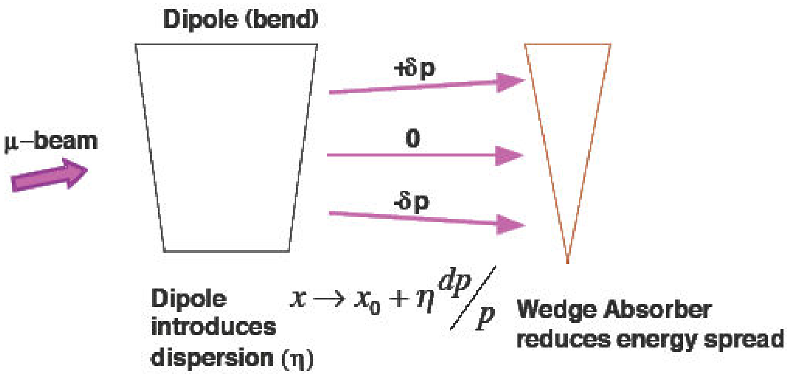
Key R&D Issues

- High Power Targetry – NF & MC *(MERIT Experiment)*
- Initial Cooling – NF & MC *(MICE (4D Cooling))*
- 200 MHz RF - NF & MC *(MuCool and Muon's Inc)*
  - Investigate operation of vacuum RF cavities in presence of high magnetic fields
  - Investigate Gas-Filled RF cavities
    - Operation in B field and Beam-Induced Effects
  - While obtaining high accelerating gradients (~16MV/m)
- Intense 6D Cooling – MC
  - RFOFO "Guggenheim"
  - Helical Channel Cooling *(MANX Proposal)*
  - Parametric Resonance Ionization Cooling
- Bunch Recombination
- Acceleration– A cost driver for both NF & MC, but in very different ways
  - FFAG's – *(Electron Model Muon Accelerator - EMMA Demonstration)*
  - Multi-turn RLA's
- Storage Ring(s) – NF & MC
- Theoretical Studies NF & MC
  - Analytic Calculations
  - Lattice Designs
  - Numeric Simulations

Note: Almost all R&D Issues for a NF are currently under theoretical and experimental study

Muon Ionization Cooling



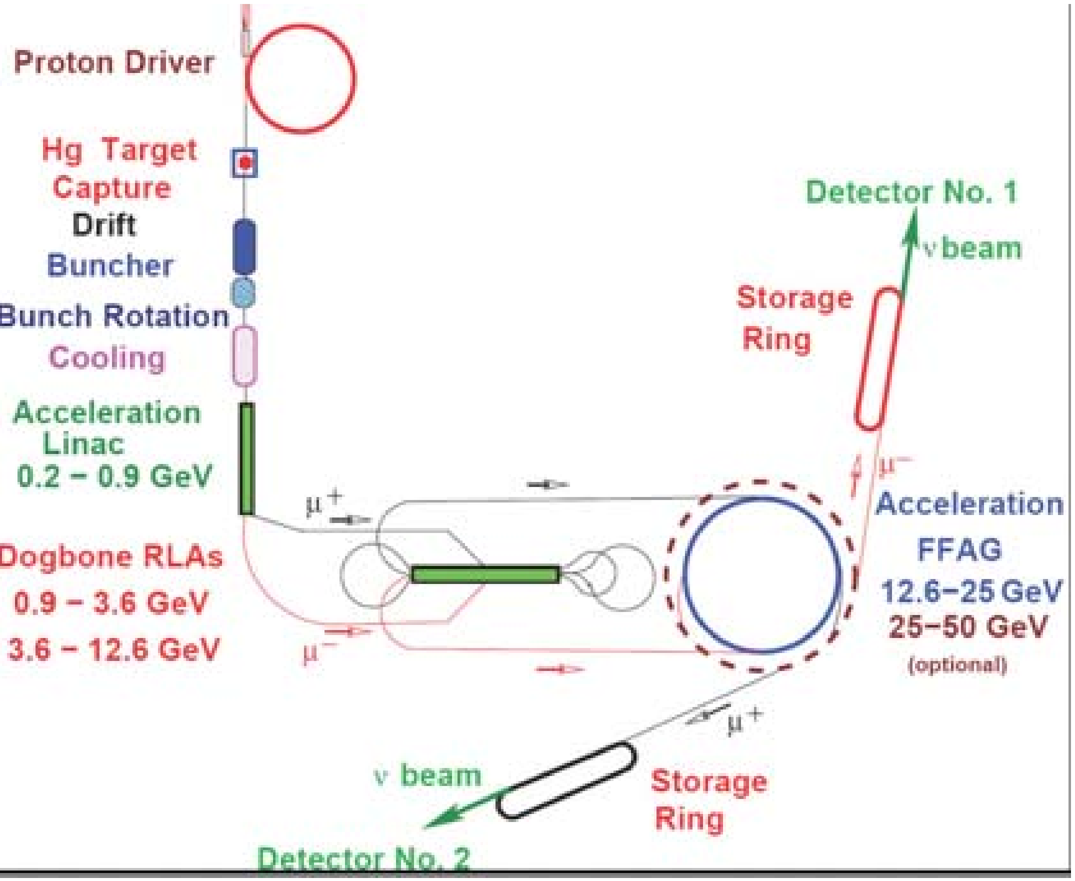


Transverse

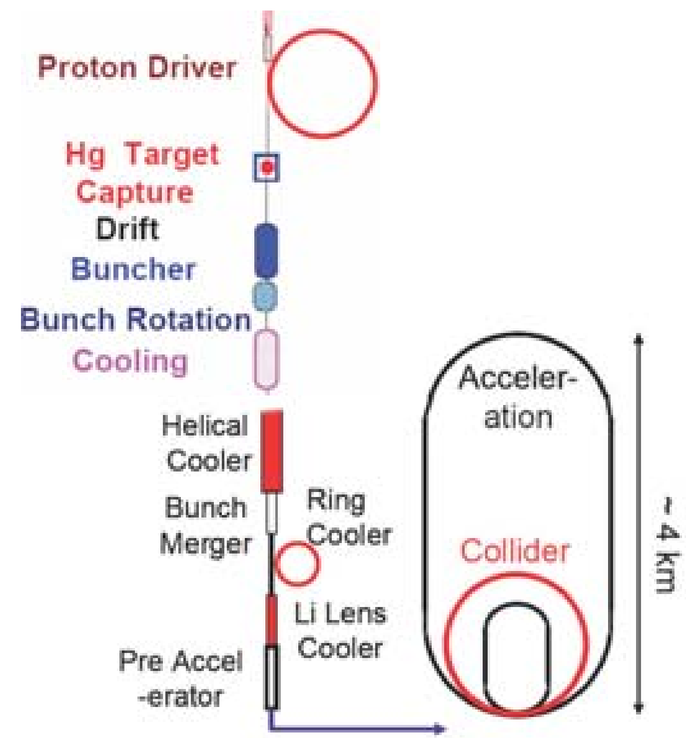
Longitudinal - Emittance Exchange

NF, Muon Collider - Synergy

Neutrino Factory –ISS Preliminary



Muon Collider Schematic



Additional Technologies Needed for a Muon Collider

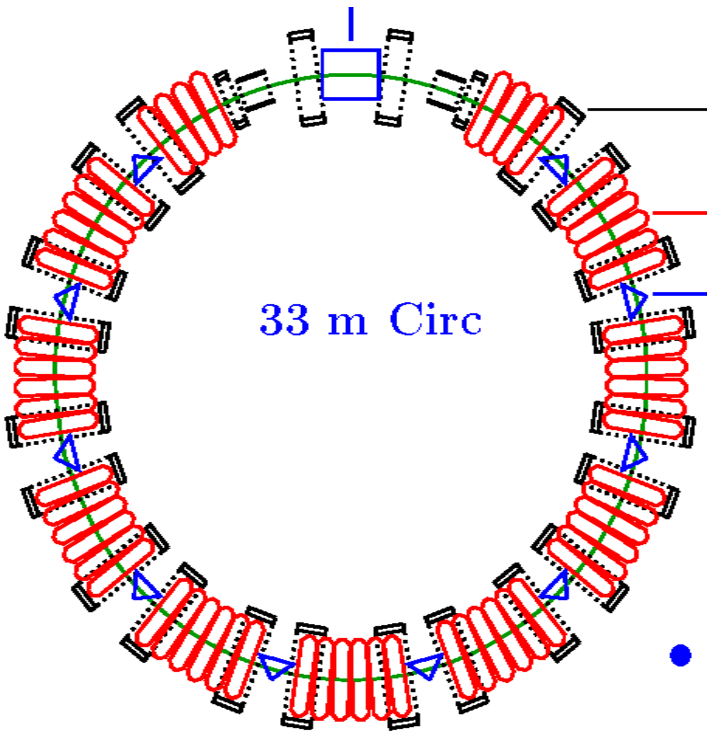
- Although a great deal of R&D has been done (or is ongoing) for a Neutrino Factory and is applicable to a MC, the Technological requirements for a Muon Collider are Much More Aggressive
  - Bunch Merging is required
  - MUCH more Cooling is required (MAKE OR BREAK FOR MC !)
    - 1000X in each transverse dimension, ≈ 10X in longitudinal

Palmer et al:
RFOFO Ring
Guggenheim
50-60T Solenoid Channel

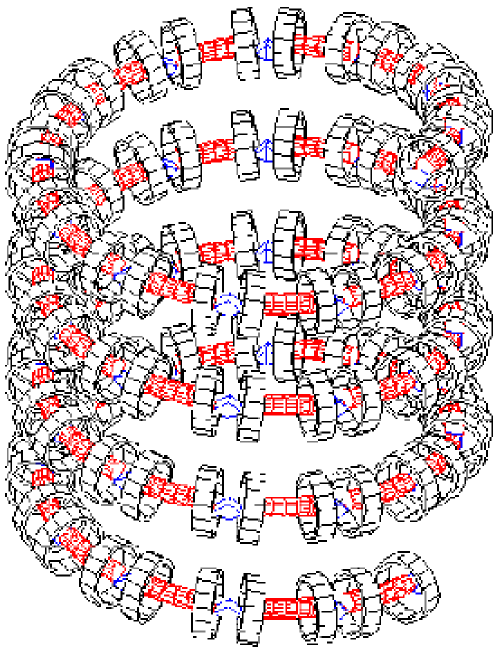
Muons Inc.
High pressure gas-filled cavities
Helical Cooling Channel
Reverse Emittance Exchange
Parametric Resonance Induced Cooling

  - Acceleration to much higher energy (20-40 GeV vs. 1.5-3 TeV)
  - Storage rings
    - Colliding beams
    - Energy loss in magnets from muon decay (electrons) is an issue

6 Dimensional Cooling



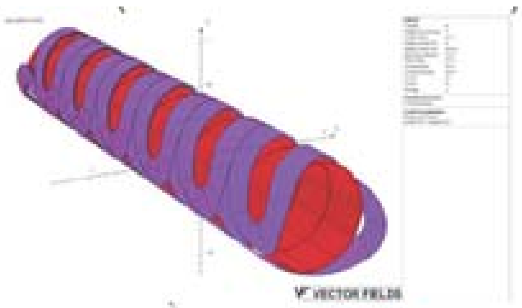
RFOFO Ring

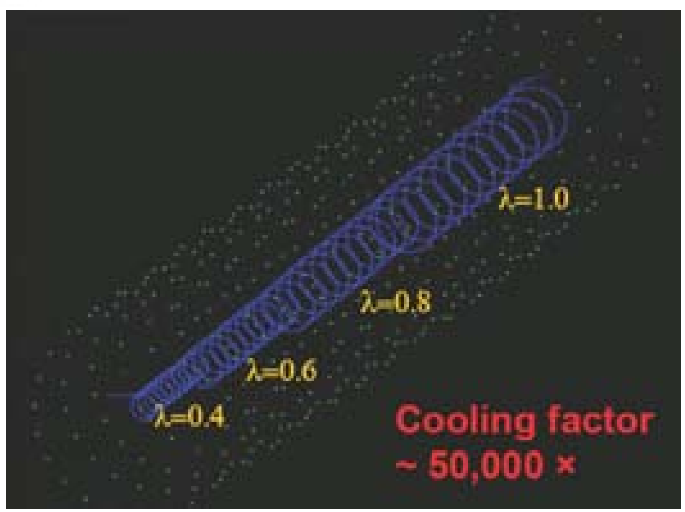


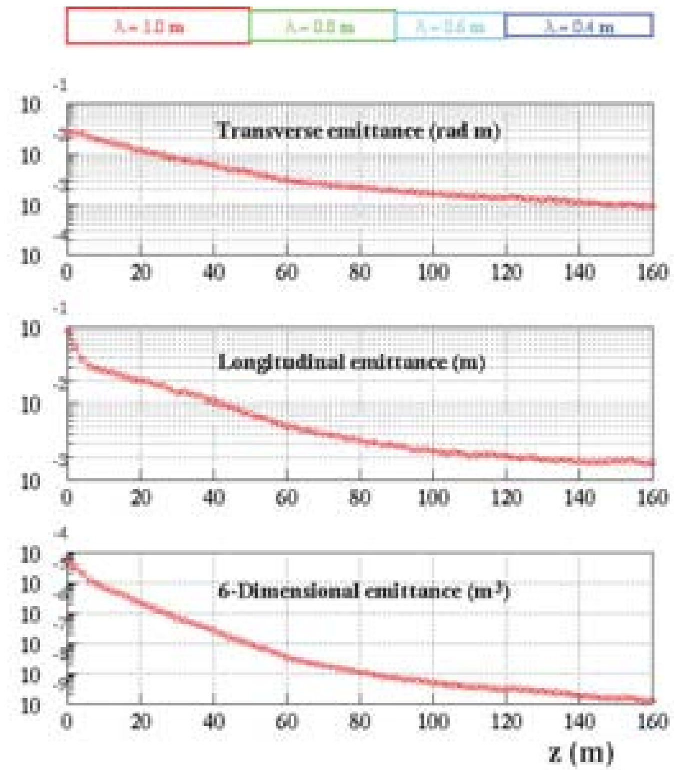
Guggenheim "Ring"

Helical Cooling Channel

- Magnetic field is solenoid B0+ dipole + quad + …
- System is filled with H2 gas, includes rf cavities
- Cools 6-D (large E means longer path length)

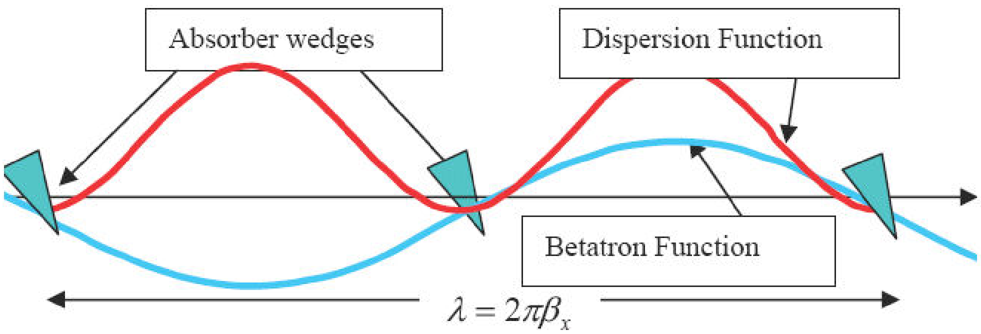


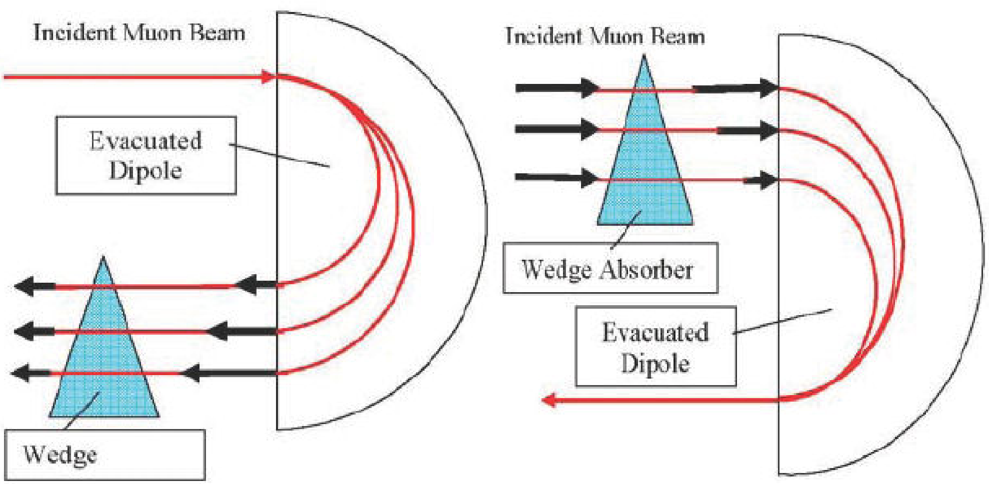




6D-MANX Experiment
To Test

Extreme μ Cooling -PIC & REMEX





- **Parametric-Resonance Ionization Cooling**
  - Drive a ½-integer parametric resonance
  - Hyperbolic Motion
    - xx'=constant
- **Reverse Emittance Exchange**
  - Increase longitudinal ε in order to decrease transverse ε

Space-Charge Effects Could be Critical

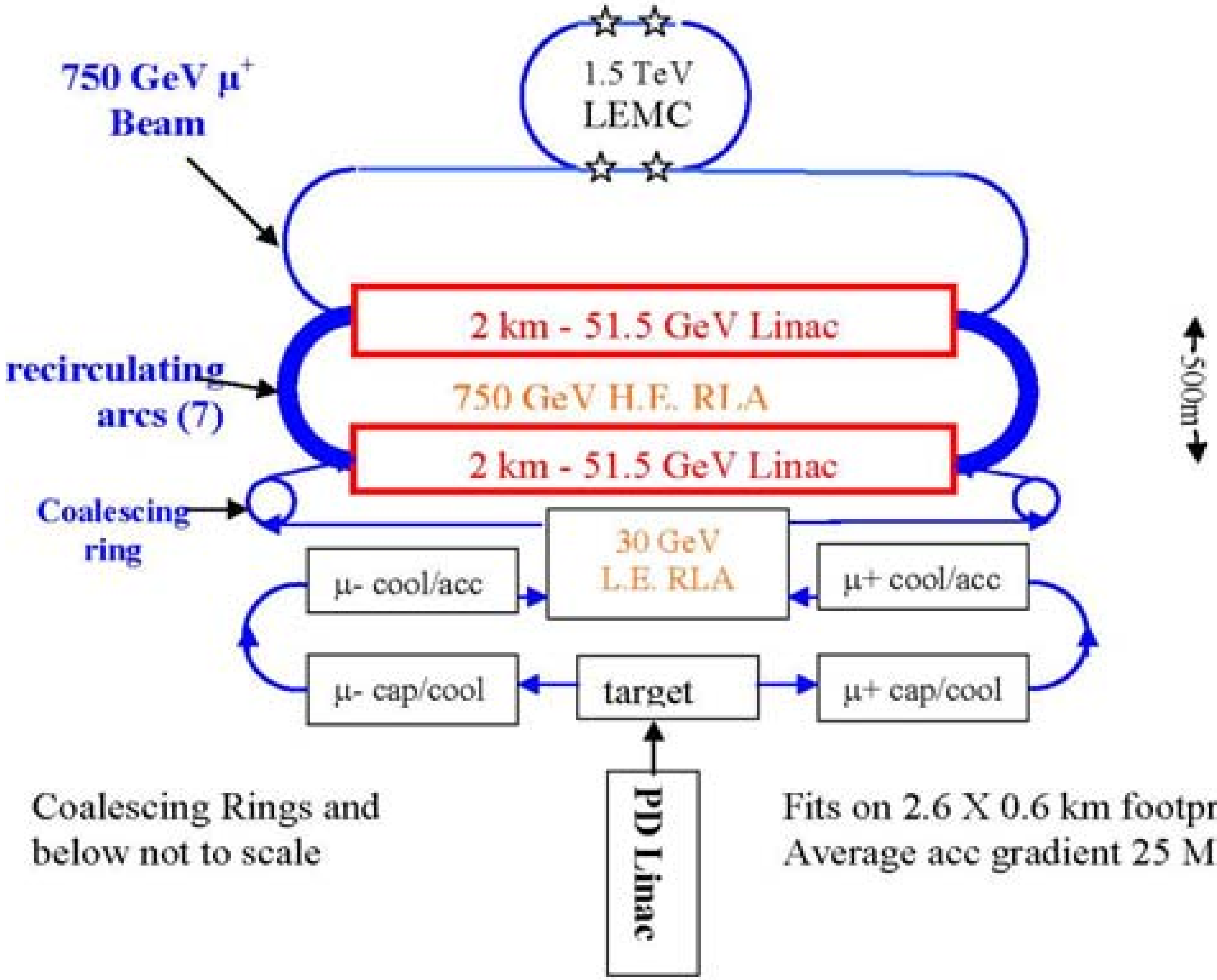
Low-Emittance Muon Collider (LEMC) Concept

Parameter List:

E_{cm} = 1.5 TeV
Peak $\mathcal{L}$ = $7X10^{34}$
#μ's/bunch = 10^{11}
Av Dipole B = 10T
δp/p = 1%
β^*(cm) = 0.5 (!)

Proton driver:
E = 8 GeV
Power ≈ 1 MW

ILC Accelerating Structure Envisioned



Coalescing Rings and below not to scale

Fits on 2.6 X 0.6 km footprint
Average acc gradient 25 MeV/m

Scientific Program

R&D Initiatives

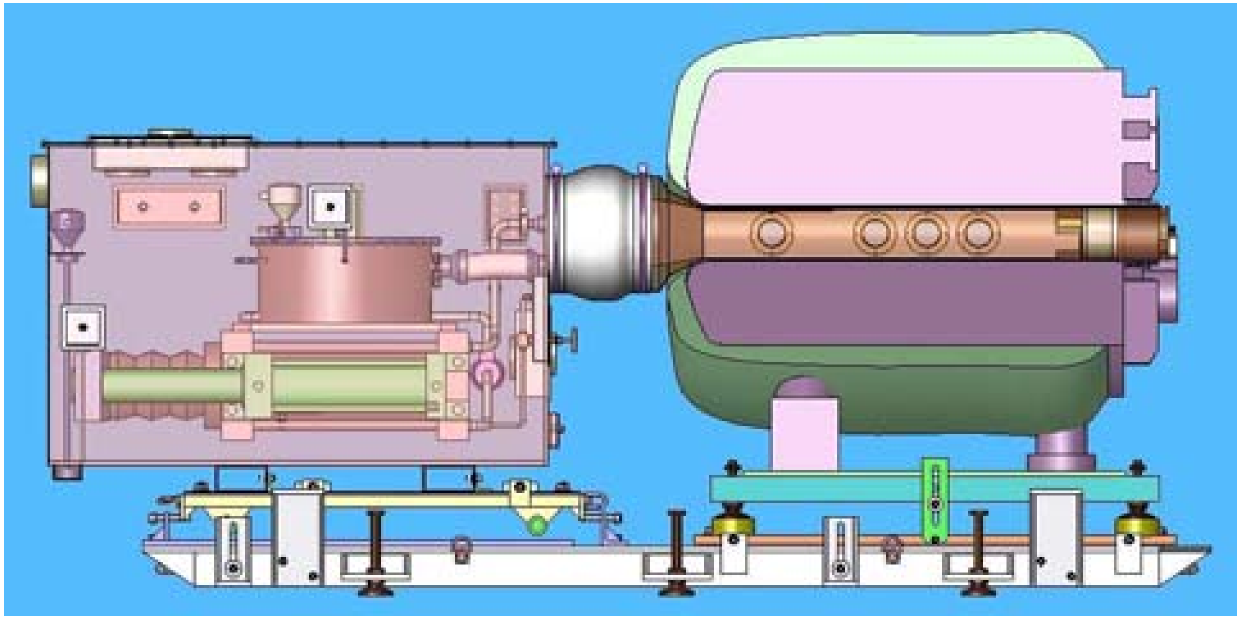
Targetry, Muon Cooling, Theory and Simulation

MERIT

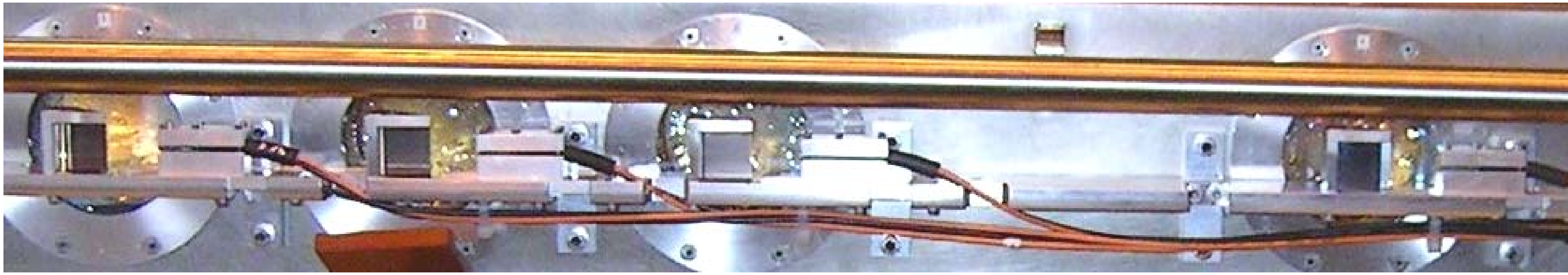
Mercury Intense Target

MERIT –Mercury Intense Target

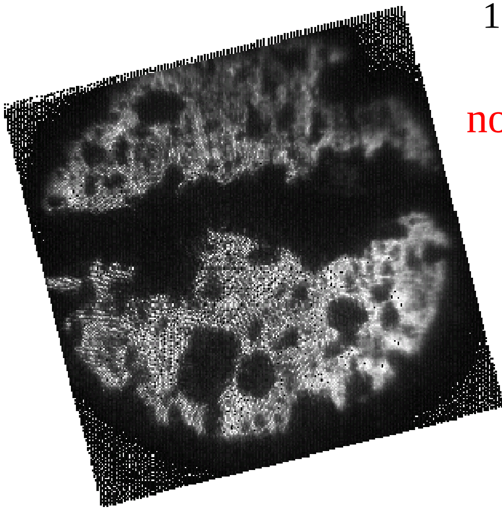
- Test of Hg-Jet target in magnetic field (15T)
- Submitted to CERN April, 2004 (approved April 2005)
- Located in TT2A tunnel to ISR, in nTOF beam line
- Physics Data Run – Oct-Nov, 2007
  - Single pulse tests equivalent to 4 MW Power On Target
    - 40 Hz @ 24 GeV



Movies of viewport #2, SMD camera, 0.1 ms/frame

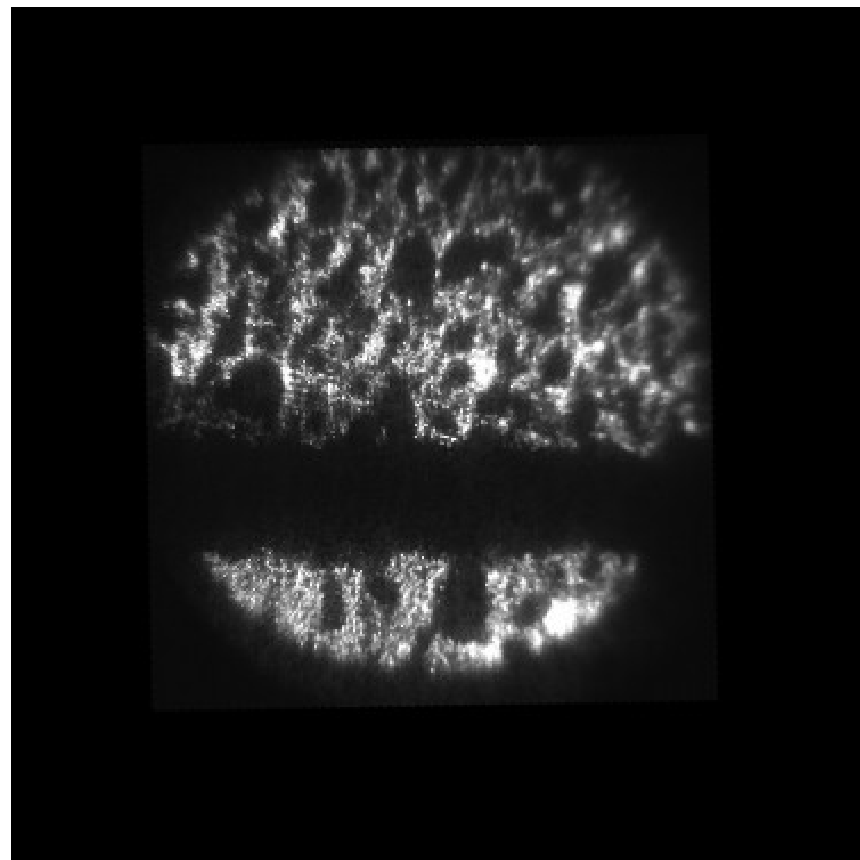


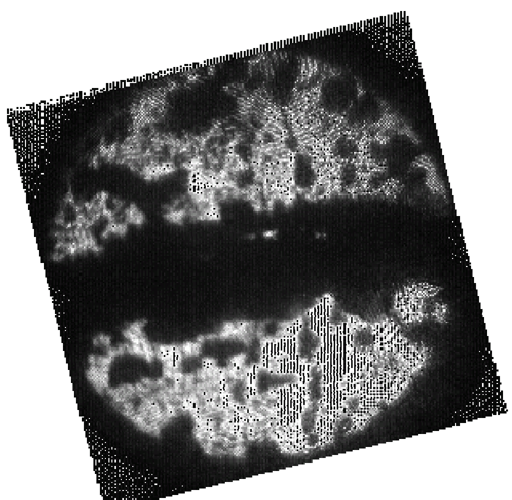
ORNL 2006 Nov 28 runs
10 m/s



nozzle A before reaming

ORNL 2006 Nov 29 run, uprighted image
Nozzle C 20 m/s





nozzle A after reaming

Magnet and Hg Jet system installed
in TT2A tunnel at CERN

MuCool

Muon Cooling: MuCool
Component R&D

- **MuCool**
  - Component testing: RF, Absorbers, Solenoids
    - RF – High Gradient Operation in High B field
  - Uses Facility @Fermilab (MuCool Test Area –MTA)
  - Supports Muon Ionization Cooling Experiment (MICE)

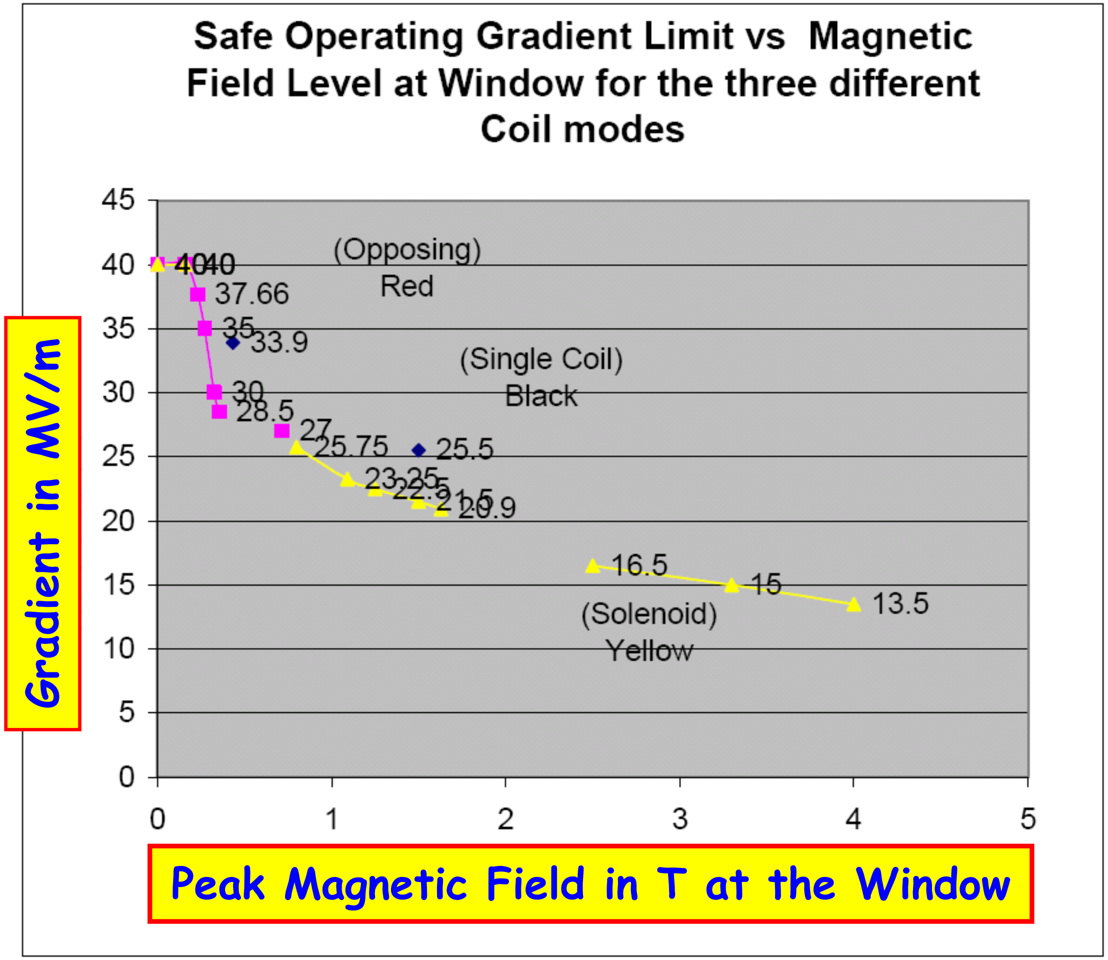
50 cm ∅ Be RF window

MuCool Test Area

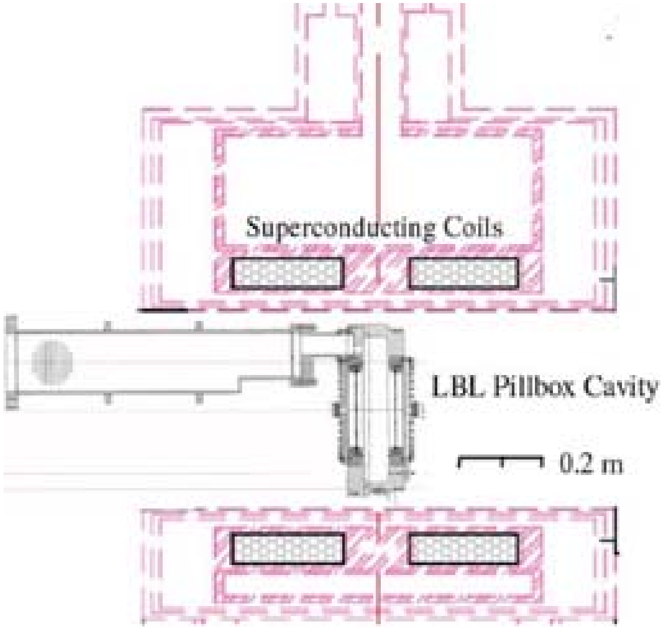
MuCool
201 MHz RF Testing

MuCool
LH_2 Absorber
Body

Phase I of RF Cavity Closed Cell Magnetic Field Studies (805 MHz)

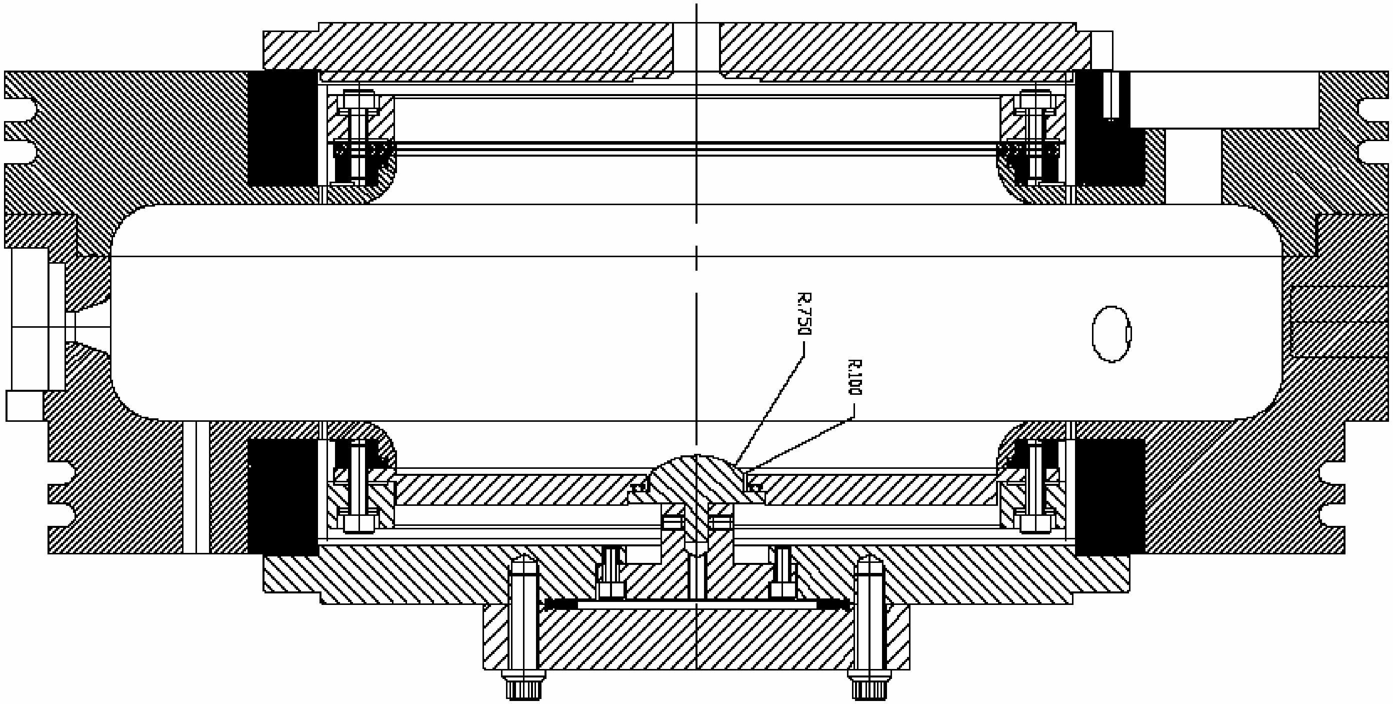


- Data seem to follow universal curve
  - Max stable gradient degrades quickly with B field
- Sparking limits max gradient
- Copper surfaces the problem



Next 805 MHz study - Buttons

- Button test
  - Evaluate various materials and coatings
  - Quick Change over



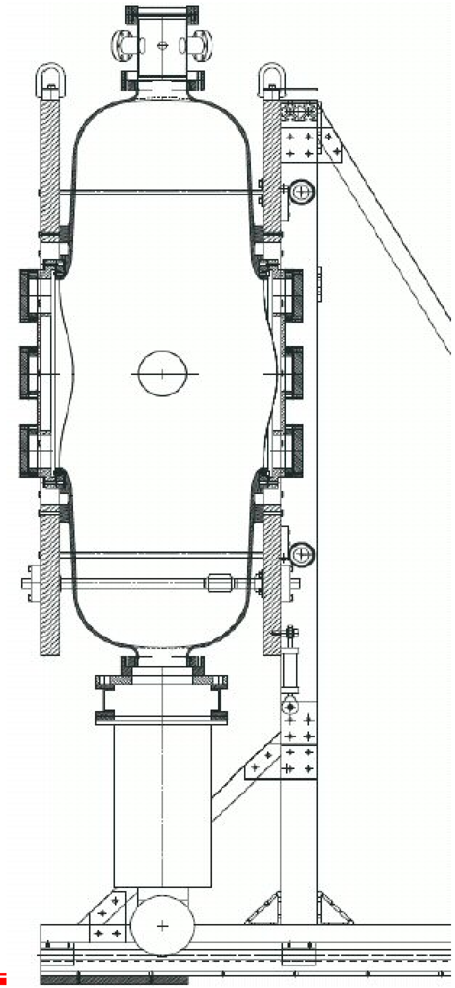
Tantalum
Tungsten
Molybdenum-zirconium alloy
Niobium
Niobium-titanium alloy
Stainless steel

RF R&D – 201 MHz Cavity Design

- The 201 MHz Cavity is now operating tested to design gradient – 16MV/m at B=0 and at B= a few hundred Gauss

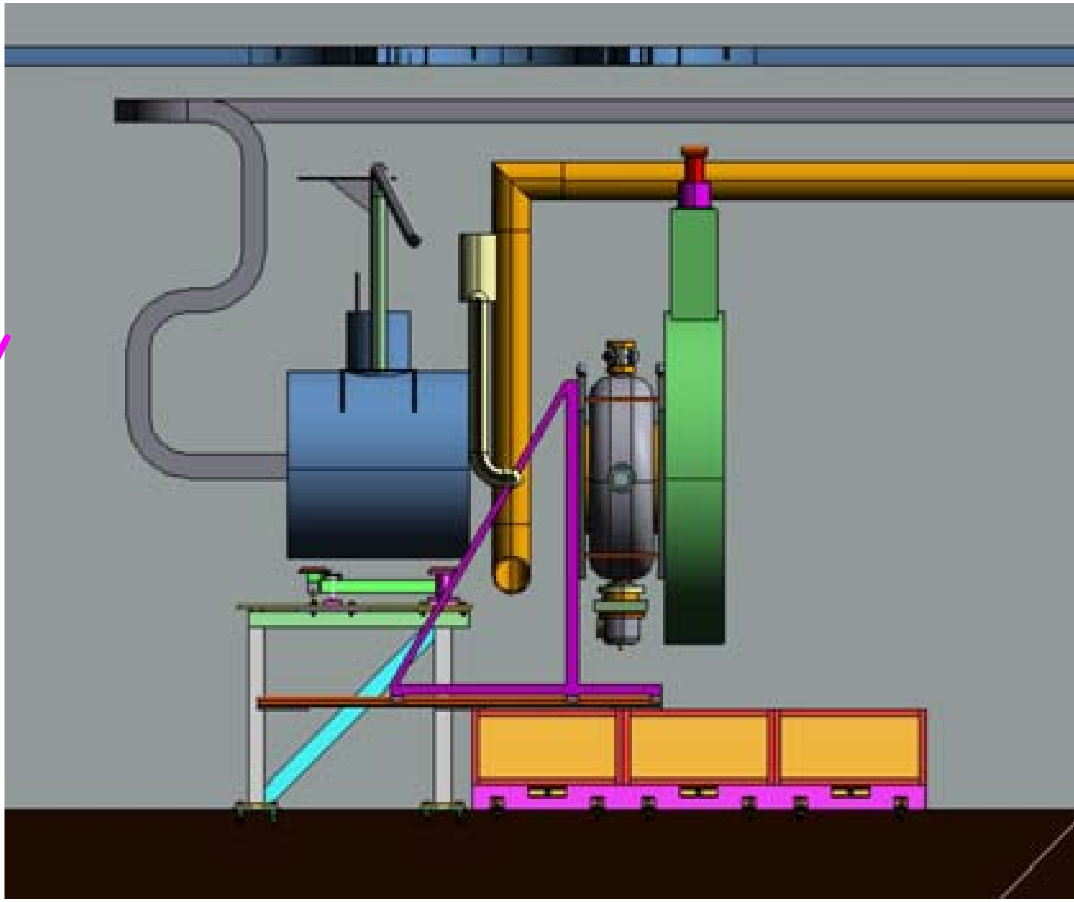
Did Not Condition!

Note: This cavity was assembled at TJNL using techniques/procedures used for SCRF

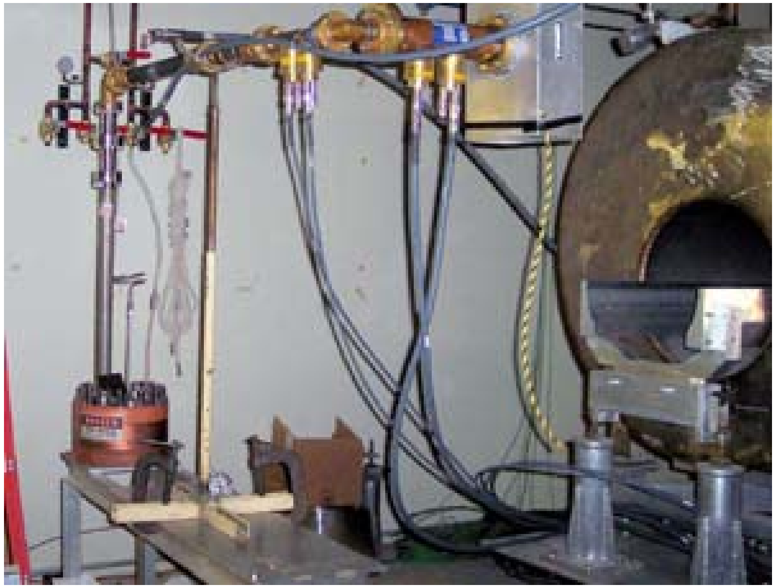


Future Tests of 201 MHz Cavity Operation in Magnetic Field

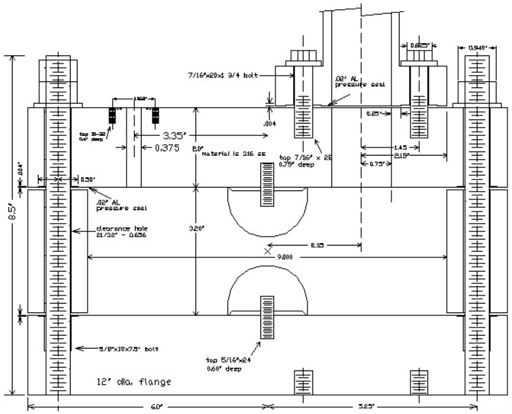
- Need Coupling Coil (2.5T) MICE design
  - Shown in green schematically
  - THIS IS A CRUCIAL TEST FOR MICE AND FOR NF & MC in general
    - High Gradient RF operation in a magnetic field

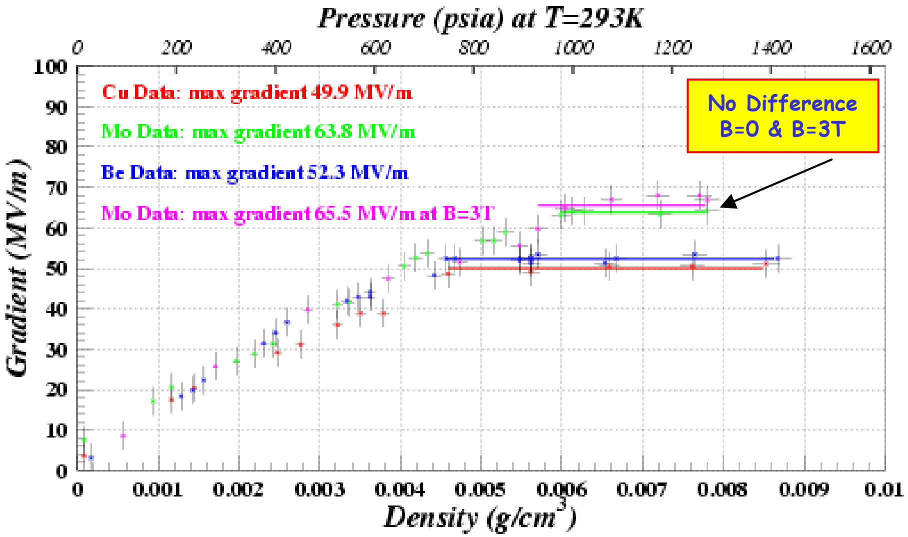


High Pressure H_2 Filled Cavity Work
Muon's Inc



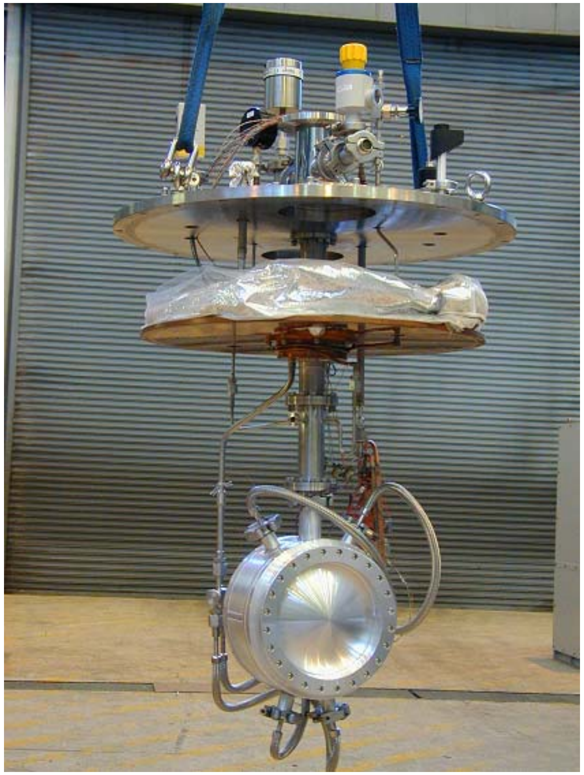
- High Pressure Test Cell
- Study breakdown properties of materials in H_2 gas
- Operation in B field
  - No degradation in M.S.O.G. up to ≈ 3.5T

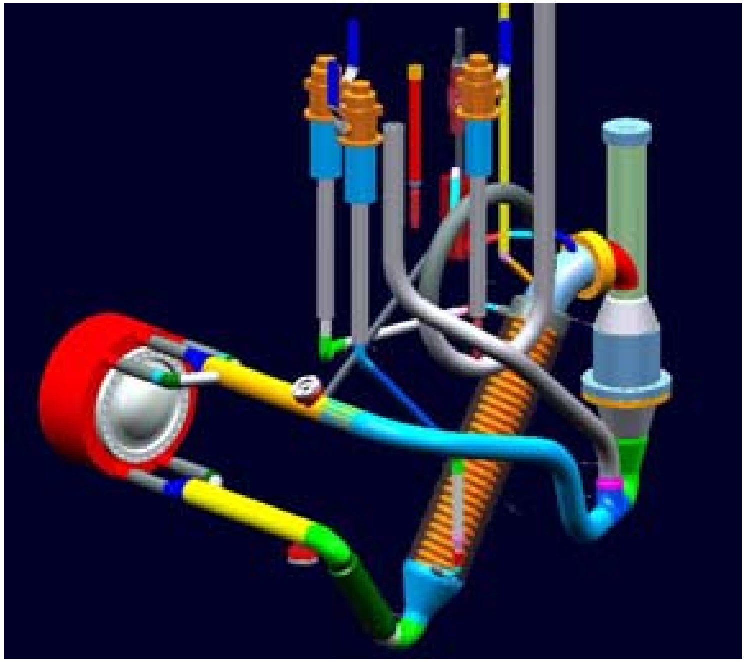




Absorber R&D

- Two LH_2 absorber designs are being studied
  - Handle the power load differently
- Also considering LiH (solid) for NF Cooling





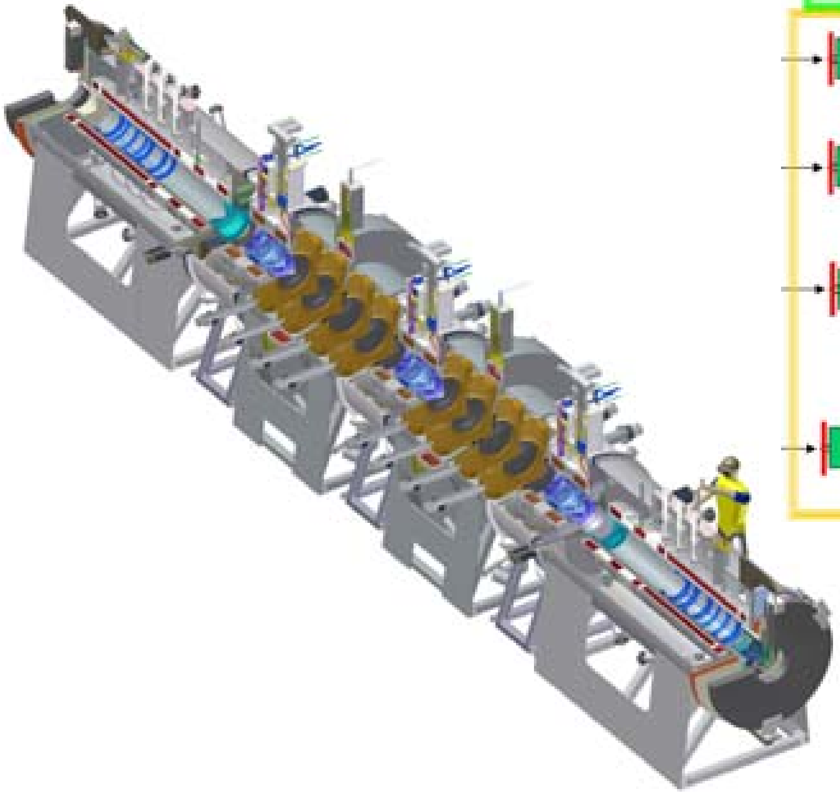
Forced-Convection-cooled. Has internal heat exchanger (LHe) and heater - KEK System
Tested @MTA to 25W → 100W

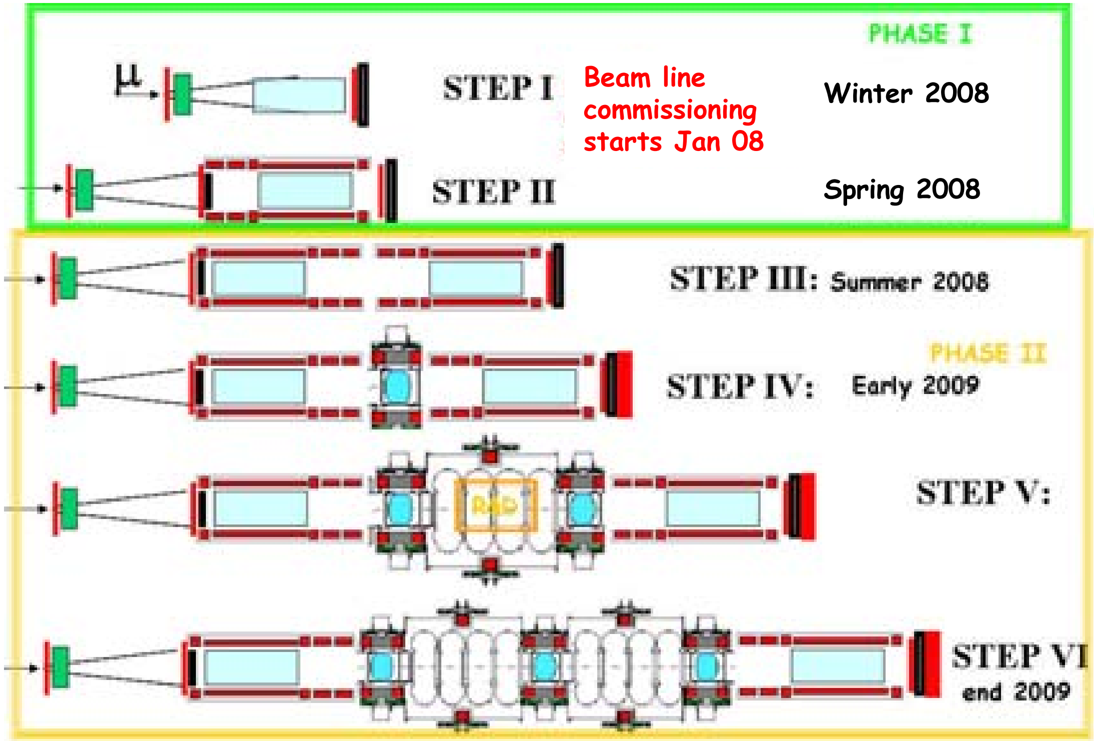
Forced-Flow with external cooling loop
Muon Collider

MICE

Muon Ionization Cooling Experiment (MICE)

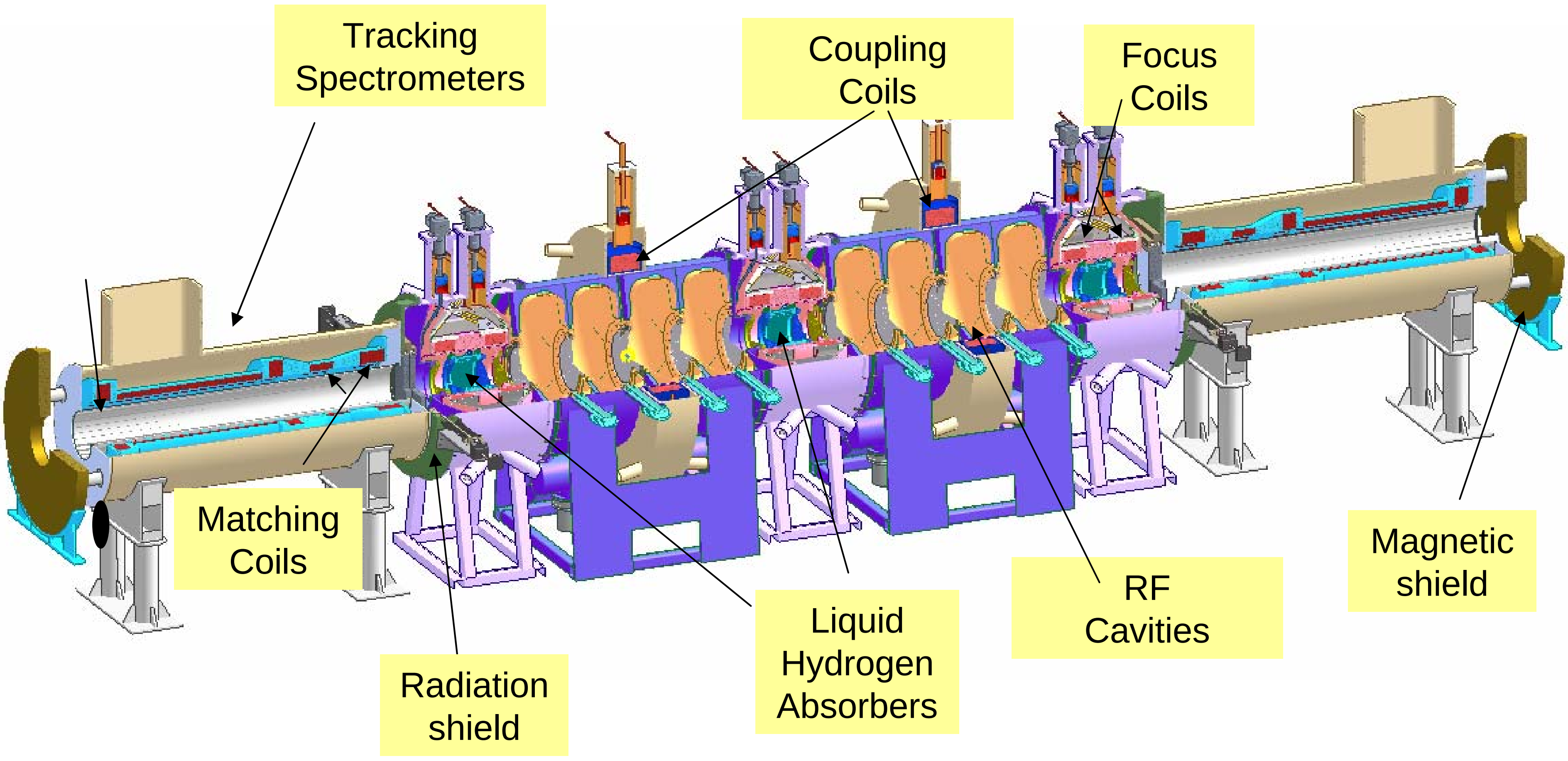
MICE
Measurement of Muon Cooling
Emittance Measurement @ 10^{-3}
First Beam January 2008





Neutrino Factory Decision Point ≈ 2012

Muon Ionization Cooling Experiment MICE



US MICE

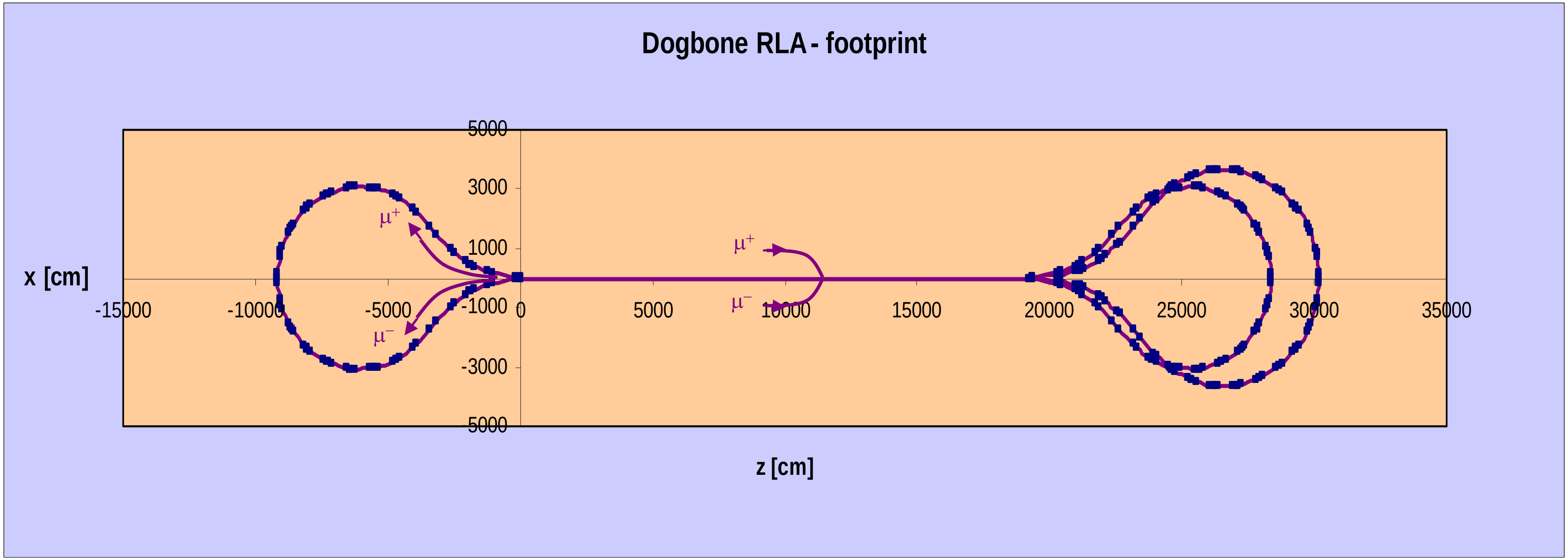
- Tracker Module
  - Solenoids
  - Fiber ribbons
  - VLPC System
    - VLPCs, Cryostats and cryo-support equipment, AFEIIt (front-end readout board), VME memory modules, power supplies, cables, etc
- Absorber Focus Coil Module
  - LH_2 and vacuum safety windows
- RF Module
  - Coupling Coils (with ICST of Harbin University, China)
  - RF Cavities
- Particle ID
  - Cerenkov

Design and Simulation

Key Simulation Studies

- Muon Capture and Bunch Rotation
  - Uses "standard" cooling components
  - Keeps both μ^+ and μ^-
- Performance of Open Cell RF lattice
  - Might mitigate problems with high-gradient RF in B field if not solved in RF R&D program
- Full optimization of acceleration scheme for NF
  - Past year spent on International Scoping Study → International Design Study for a NF
    - Arrive at Reference Design Report
- Full simulation and performance evaluation of PIC and REMEX
- Complete baseline cooling scheme for a Muon Collider
- Acceleration scheme for a Muon Collider
- Design of low-beta collider ring

Acceleration



NFMCC 5 Year Budget Plan

- Summary of baseline (flat-flat) case is

Activity	FY05	FY06	FY07	FY08	FY09	FY10
Cooling	492	345	345	705	615	225
Targetry	713	640	625	100	100	100
System Studies	195	195	195	295	295	195
MICE	300	620	635	700	790	1280
TOTAL	1700	1800	1800	1800	1800	1800

Base Program funds: remain as in FY06: BNL ($0.9M); Fermilab ($0.6M); LBNL ($0.3M)

Including Base: About $3.6M per year plus supplemental ($400k in FY06)

Conclusions

- Neutrino Factory
  - Compelling case for a precision neutrino program exists
    - With present assumptions Neutrino Factory out-performs other options. However, more is needed before concluding this is the right path
      - What the on-going Neutrino Physics program tells us (θ_{13})
      - Cost and schedule considerations
  - The collaboration is making excellent progress on R&D on the major sub-systems
    - Targetry – MERIT
    - Muon Cooling – MuCool and MICE
    - Acceleration Design Studies
      - FFAG
        - Also participating in the EMMA experiment in the UK
      - RLA
  - Strong Participation in the recently completed International Scoping Study
    - Move on to the International Design Study
      - Goal is to deliver a RDR by 2012

Conclusions II

- Muon Collider
  - New concepts in muon cooling improve the prospects for a multi-TeV Muon Collider
    - Many new ideas emerging
  - Front-end is the same or similar as that for a Neutrino Factory
  - First end-to-end muon cooling scenario for a Muon Collider has been developed
- Much more to do
  - Detailed simulation and analysis of cooling designs
    - Space charge and loading effects particularly important in final stages
    - 6D Cooling experiment(s)
      - Converge on a preferred cooling scheme
  - Acceleration
  - Collider ring
- The NFMCC will work closely with the Fermilab MCTF
  - Muon Collider Coordination Group
    - Kirk, Bross, Zisman, Shiltsev, Geer