Neutrino Factory Accelerator R&D

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Outline

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- Technical Challenges
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  - system tests (MERIT, MICE, EMMA)
- Remaining R&D Issues
- Summary

Introduction

- Discovery of neutrino oscillations led to strong interest in providing intense beams of accelerator-produced neutrinos
  - such a facility may be able to observe CP violation in the lepton sector
    - the reason we're all here

- Two ideas have been proposed for producing the required neutrino beams
  - a Neutrino Factory based on the decays of a stored muon beam
  - a Beta Beam facility based on decays of a stored beam of beta-unstable ions

- Both approaches are challenging!

Physics Context

- **Neutrino oscillation parameters are within reach of future accelerator experiments**

- **Neutrino Factory beam properties**

$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \overline{\nu}_\mu$$

$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu \Rightarrow 50\% \overline{\nu}_e + 50\% \nu_\mu$$

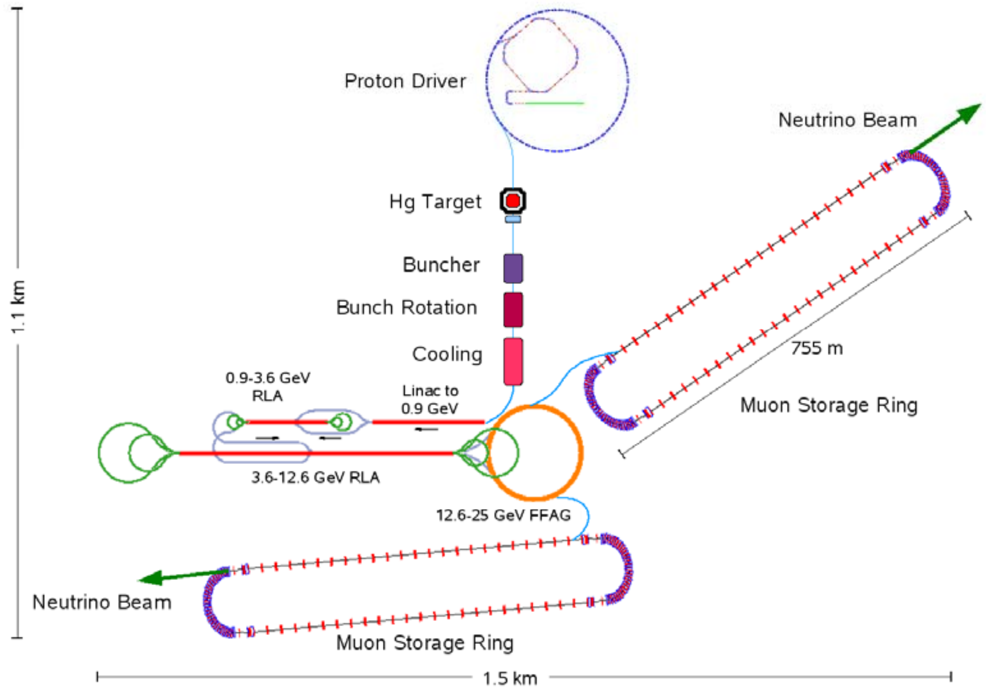
Produces high energy neutrinos

- **Decay kinematics well known**
  - **minimal hadronic uncertainties in the spectrum and flux**

- **$\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable "wrong-sign" μ**

Neutrino Factory

- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into $\mu \Rightarrow$ **MERIT**
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance $\Rightarrow$ **MICE**
  - Acceleration
    - 130 MeV $\rightarrow$ 20-40 GeV with RLAs or FFAGs
  - Decay Ring
    - store for ~500 turns; long straight(s)



ISS design

Technical Challenges

- Constructing muon-based Neutrino Factory is challenging
  - muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
    - low production rate
      - need target that can tolerate multi-MW beam
    - large energy spread and transverse phase space
      - need emittance cooling
      - high-acceptance acceleration system and decay ring
  - muons have short lifetime (2.2 μs at rest)
    - puts premium on rapid beam manipulations
      - high-gradient RF cavities (in magnetic field) for cooling
      - presently untested ionization cooling technique
      - fast acceleration system
    - must accommodate heat load from decay products

- Challenges require solutions well beyond standard machines
  - developing and demonstrating these requires a substantial R&D effort

R&D Mission

- To make Neutrino Factory a worthwhile option for HEP community, we must address the technical challenges
  - an informed decision will require knowledge (for *all* approaches) of
    - expected performance
    - technical feasibility/risk
    - approximate cost

- Neutrino Factory R&D mission
  - develop conceptual solutions to produce, condition, accelerate and store intense muon beams
    - seamlessly integrate solutions into an overall facility concept
      - and estimate its performance (ν_e per year)
  - demonstrate technical viability of critical components
    - and verify performance of key subsystems
  - estimate overall cost of facility

R&D Approaches

- There are three prongs in the R&D program
  - simulations (£)
    - develop and validate required tools
      - simulation codes, FEA approaches
    - carry out design studies for subsystems and overall facility
      - feasibility studies, ISS → IDS
  - component development (££)
    - build and test critical devices in the lab
  - system tests (£££)
    - validate performance of key systems (e.g., target, cooling) to ensure they perform as predicted
      - engineering demonstration
      - design will continue to evolve, so "calibrating" simulation tools is a main deliverable

R&D Participants (1)

- Program began with separate efforts in different regions
  - has evolved into a highly international effort
    - but maintains aspects of "intelligent design" ☺
  - NuFact workshops were an important mechanism in this evolution
- Europe
  - ECFA CARE (BENE working group)
  - UK Neutrino Factory (UKNF) collaboration (large overlap in constituency)
- Japan
  - NuFact-J Working Group (Osaka, Kyoto, KEK)
- US
  - Neutrino Factory and Muon Collider Collaboration

R&D Participants (2)

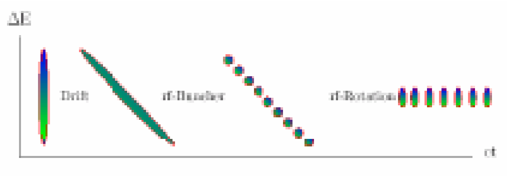
- **Jointly coordinated programs becoming increasingly common**
  - **coordination happening at the working level, not dictated externally by funding agencies or Lab directors**
    - **such "natural" collaboration is by far the most effective kind**
      - **driven by scientific goals, not politics or money**
  - **examples**
    - **MICE, MERIT, EMMA, ISS, IDS, MuCool, APS Neutrino Physics study**

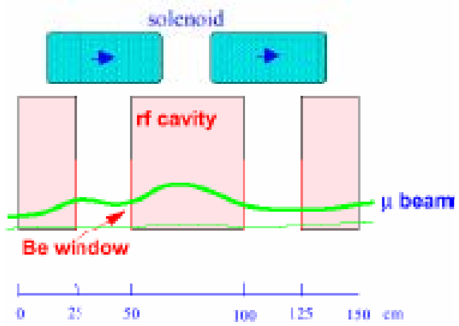
Design Simulations (1)

- To date, four NF feasibility studies have been carried out
  - 2 in US, 1 in Japan, 1 in Europe
- US Study 2 was updated ("2a") as part of APS Neutrino Physics Study
  - maintained Study 2 performance
  - provided possibility to use both μ^+ and μ^- simultaneously
  - reduced hardware costs

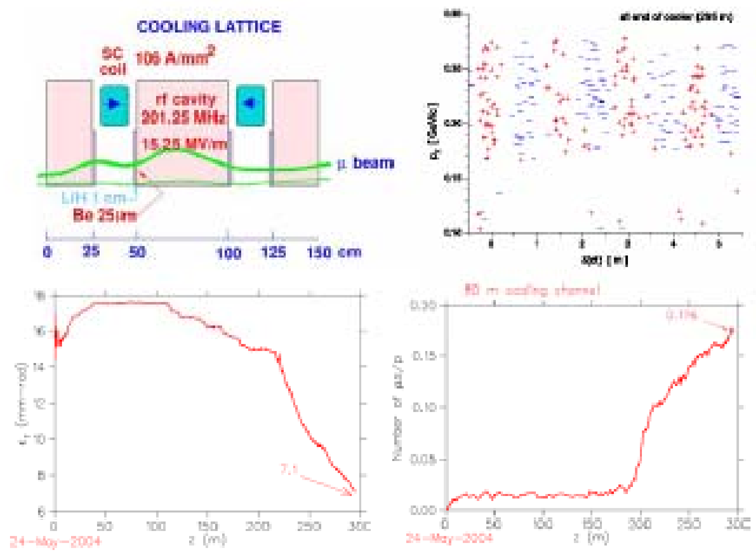
	All ($M)	No PD ($M)	No PD & Tgt. ($M)
FS2	1832	1641	1538
FS2a-scaled (%)	67	63	60

- To permit use of both signs, Study 2a developed **RF bunching and phase rotation** system





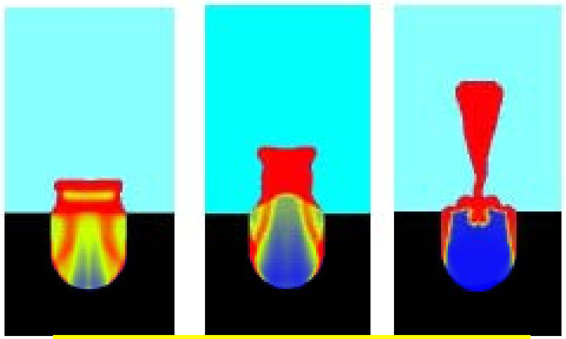
– also a simplified cooling channel



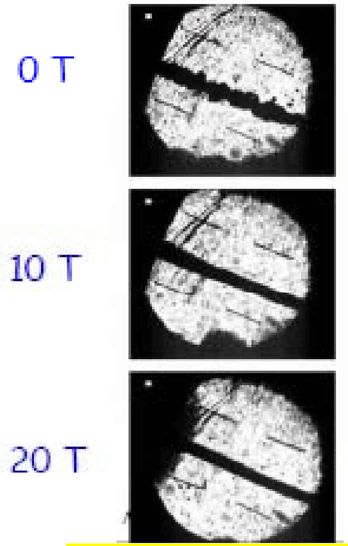
Target Simulations (1)

- **Target simulations have reached a high degree of sophistication**
  - **will be useful to interpret MERIT experiment data**

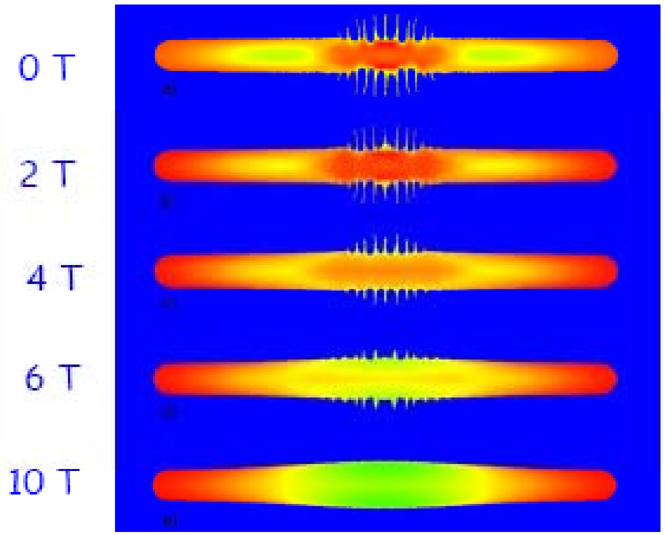
Experiment
(McDonald; Kirk)



MHD simulation
(Samulyak)



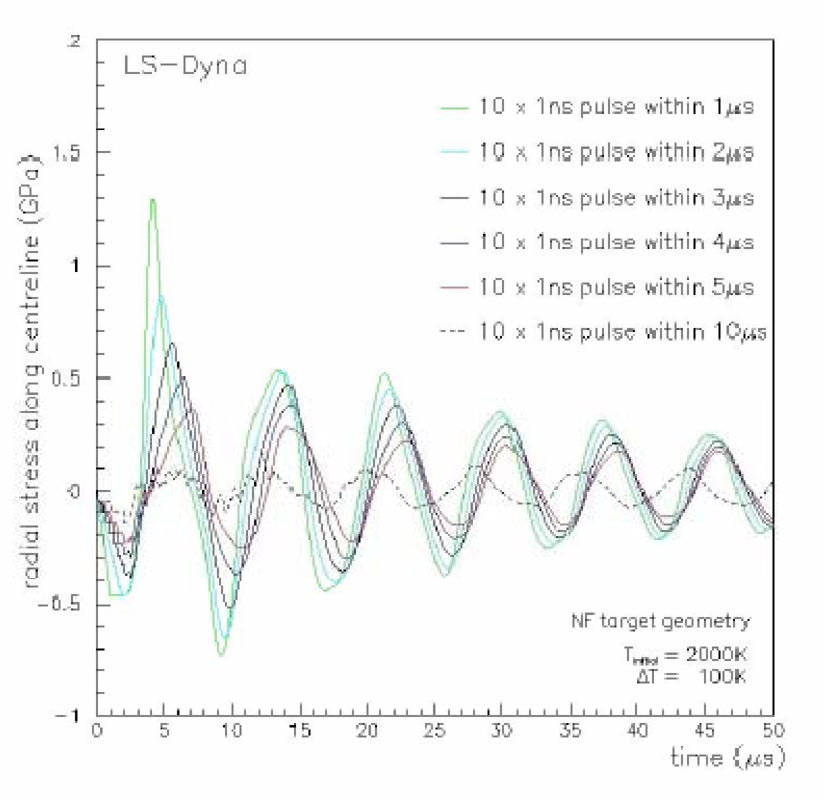
Experiment
(Fabich)



MHD simulation
(Samulyak)

Target Simulations (2)

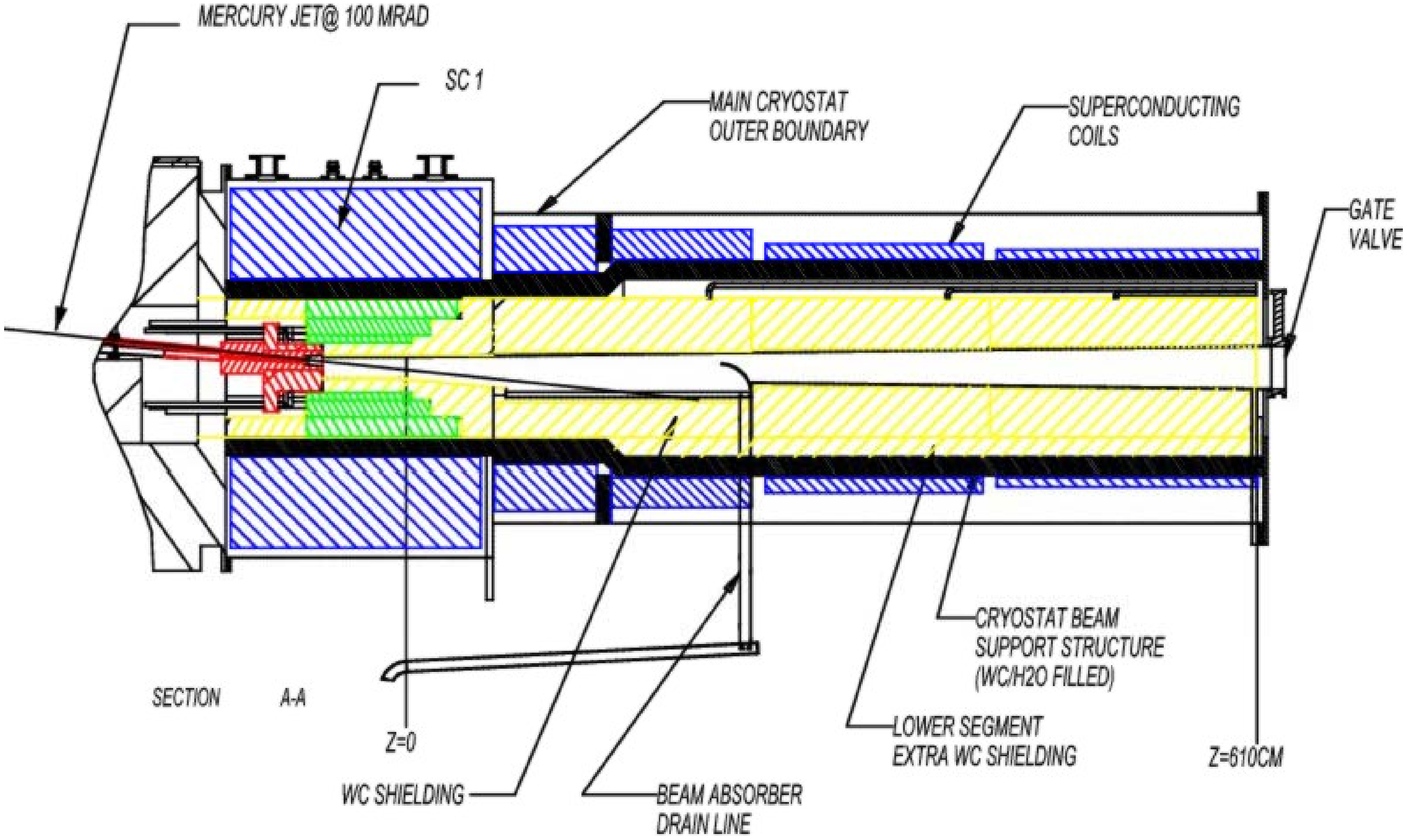
- **Solid target simulations provide guidance on acceptable pulse structure of beam**
  - **pulses more than ~1 μs apart are becoming independent**



Skoro

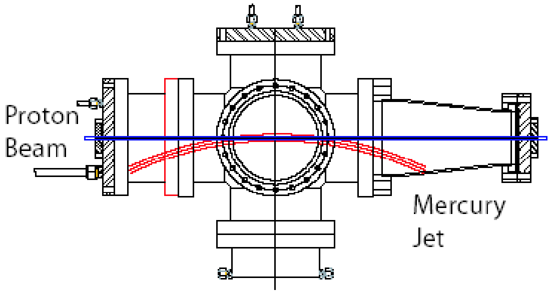
Target Concept

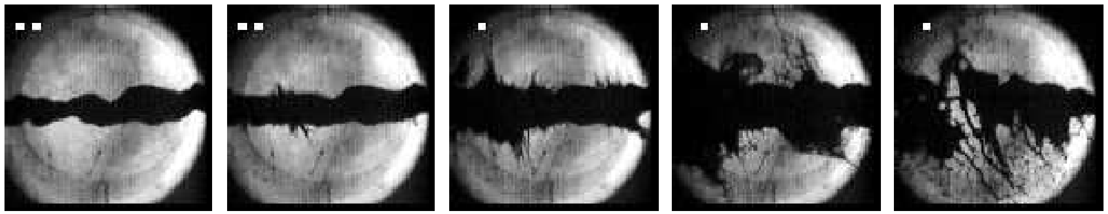
- **Favored target concept based on Hg jet in 20-T solenoid**
  - **jet velocity of 20 m/s establishes "new" target each beam pulse**



Target R&D

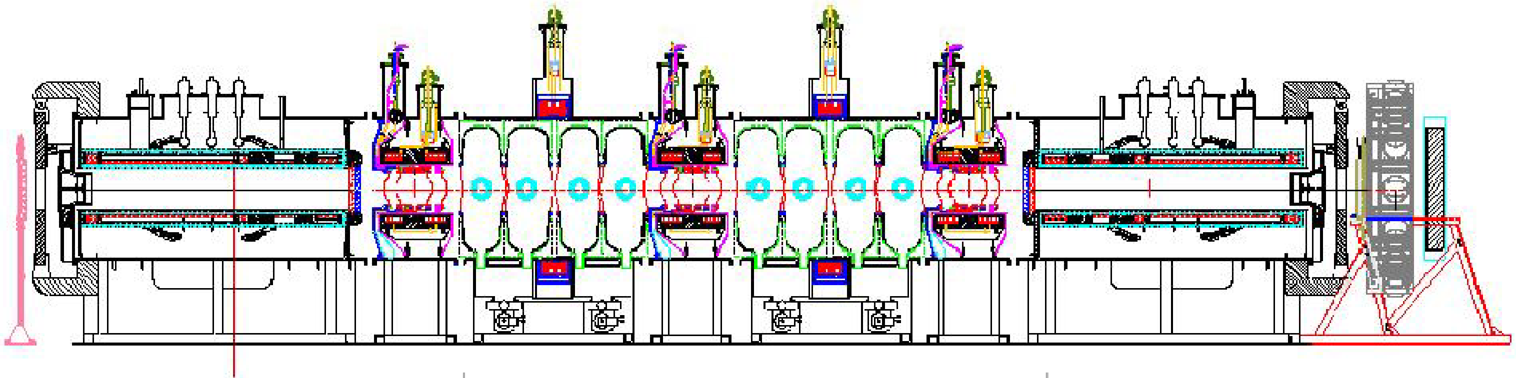
- **Disruption at moderate intensity (4 Tp) demonstrated in BNL E951**
  - ***what happens at higher intensity and with strong solenoid? (MERIT)***

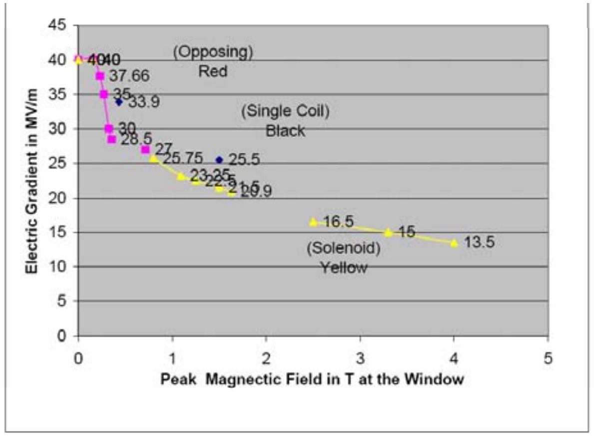




RF Concept

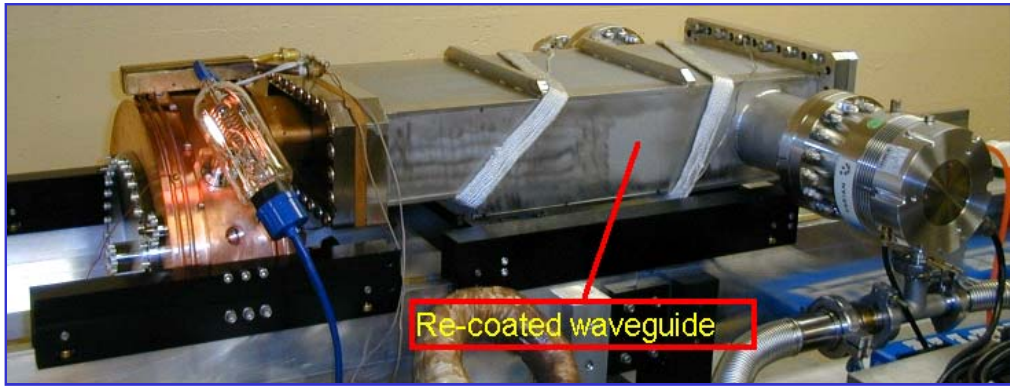
- Cooling channel requires high-gradient RF in a strong magnetic field
  - 805 MHz experiments indicate substantial degradation of gradient in such conditions

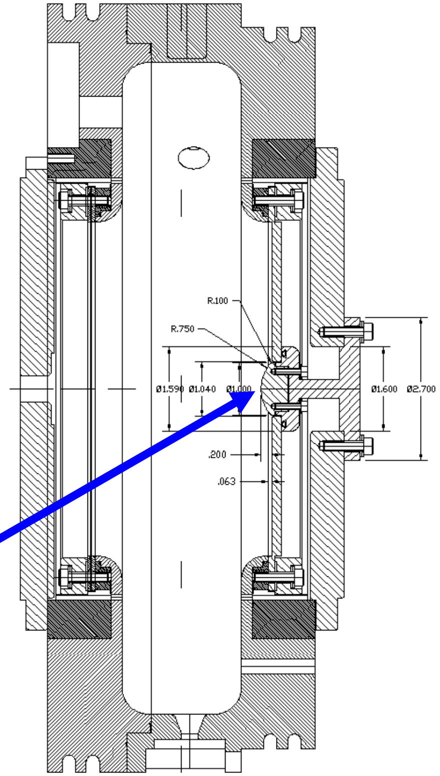




RF R&D (1)

- Using 805 MHz pillbox cavity to study effects of different materials and coatings
  - cavity fits in bore of 5 T solenoid at Fermilab MTA
    - low stored energy is a drawback





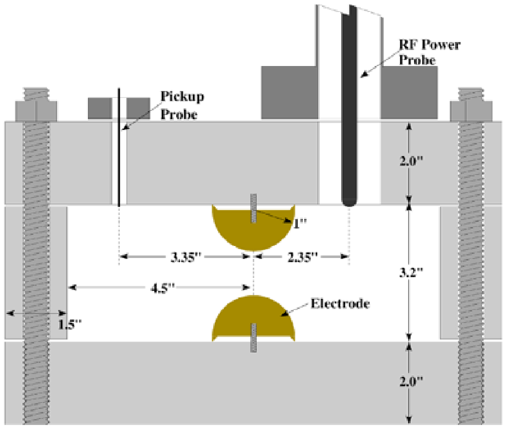
"Button" for materials tests

RF R&D (2)

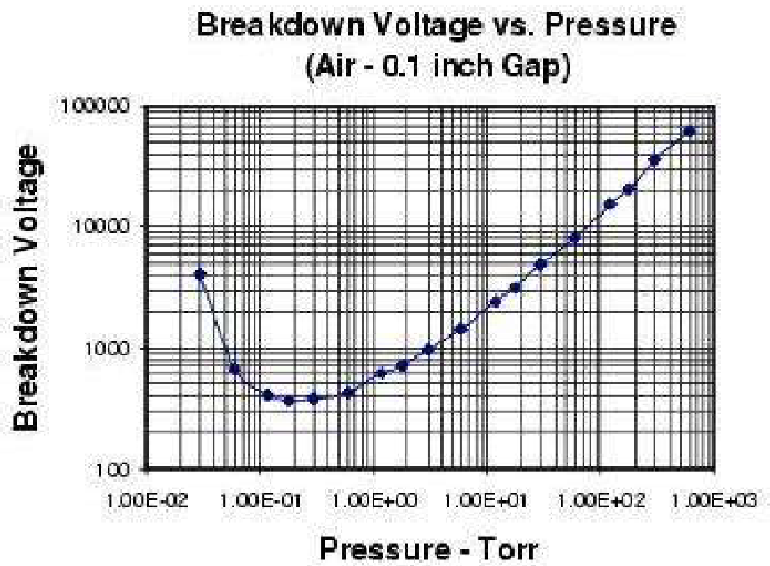
- **Tested version of button cavity pressurized with H_2 gas**
  - **limit breakdown by Paschen effect**

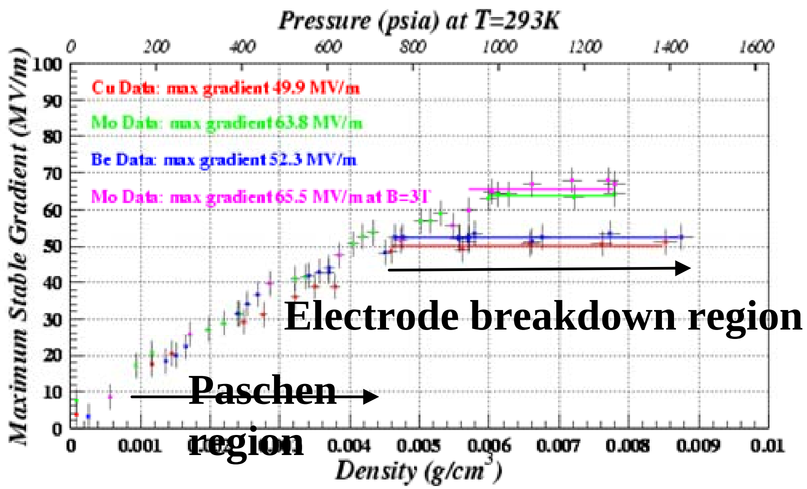
Muons, Inc.

Remaining issue:
What happens when high intensity beam traverses gas?



Breakdown limitation does *not* degrade in magnetic field

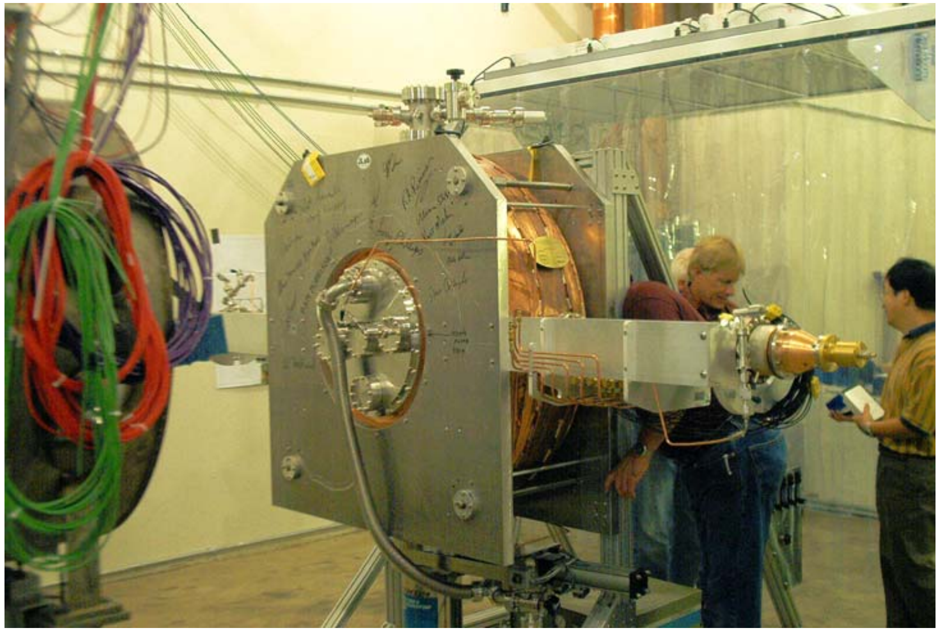


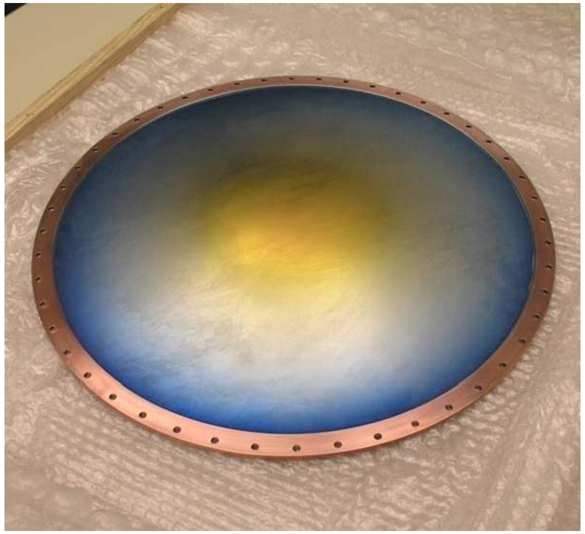


RF R&D (3)

- Initial tests of 201 MHz prototype cavity are under way
  - fabricated by collaboration of LBNL, Jlab, and U-Mississippi
  - processed as if a superconducting cavity (electropolished)

- Cavity exceeded design gradient of 16 MV/m rapidly
  - no signs of conditioning up to 4.2 MW input power

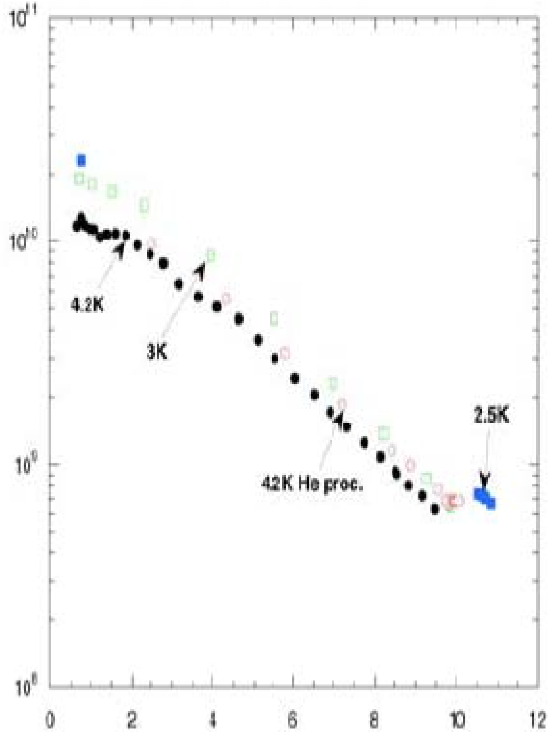




42-cm curved Be window

RF R&D (4)

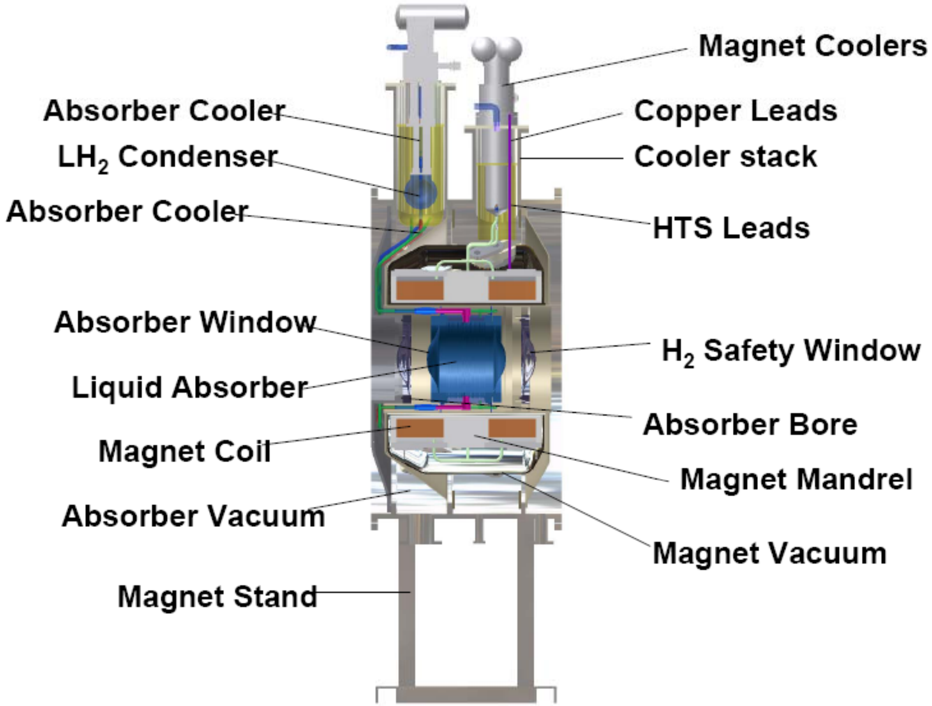
- Also studied SCRF for acceleration system (Cornell)
  - reached 11 MV/m in initial tests
  - observed substantial “Q-slope”
    - believed to be related to poor coating in cavity
      - improving this has thus far been unsuccessful



Absorber Concept

- **Baseline absorber material is LH_2**
  - *very good material, but substantial safety implications*

- **Absorber (+ safety windows) sits within superconducting focus coil**



Absorber R&D

- Test program (including safety issues) carried out jointly in Japan and US

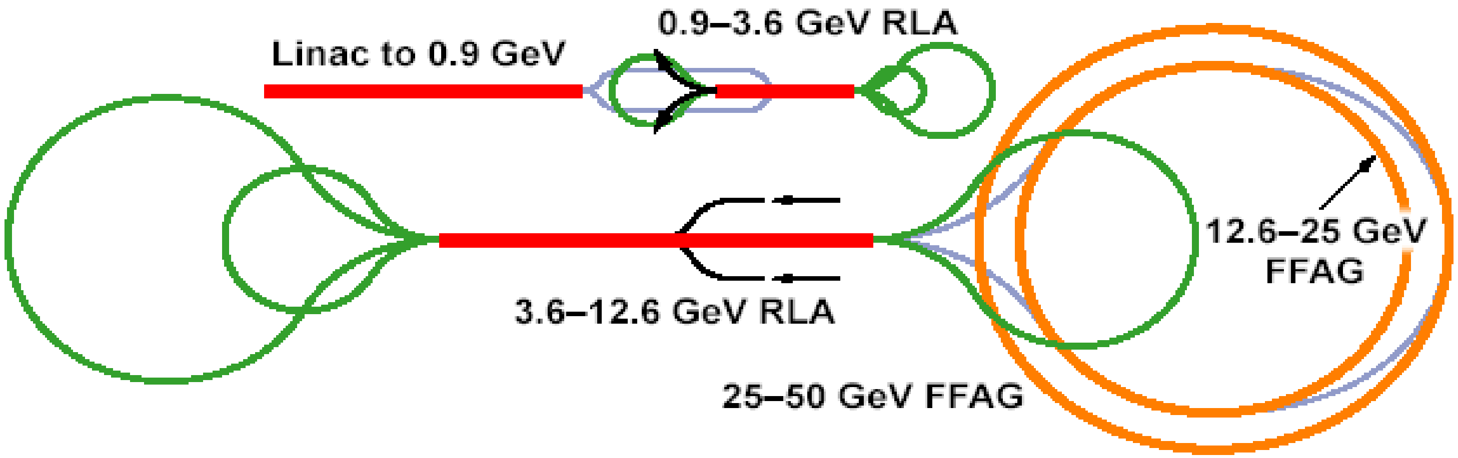
Prototype LH_2 absorber

Test cryostat at Fermilab MTA

Acceleration Concept

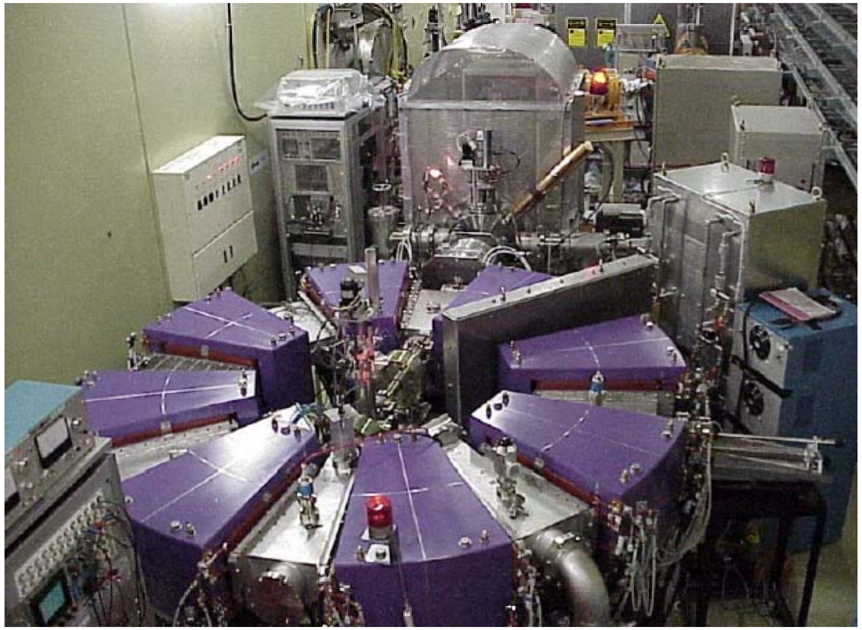
- Scheme for rapid acceleration makes use of linacs, dogbone RLA, non-scaling FFAG rings
  - "non-scaling" means that the tune and orbit change during acceleration

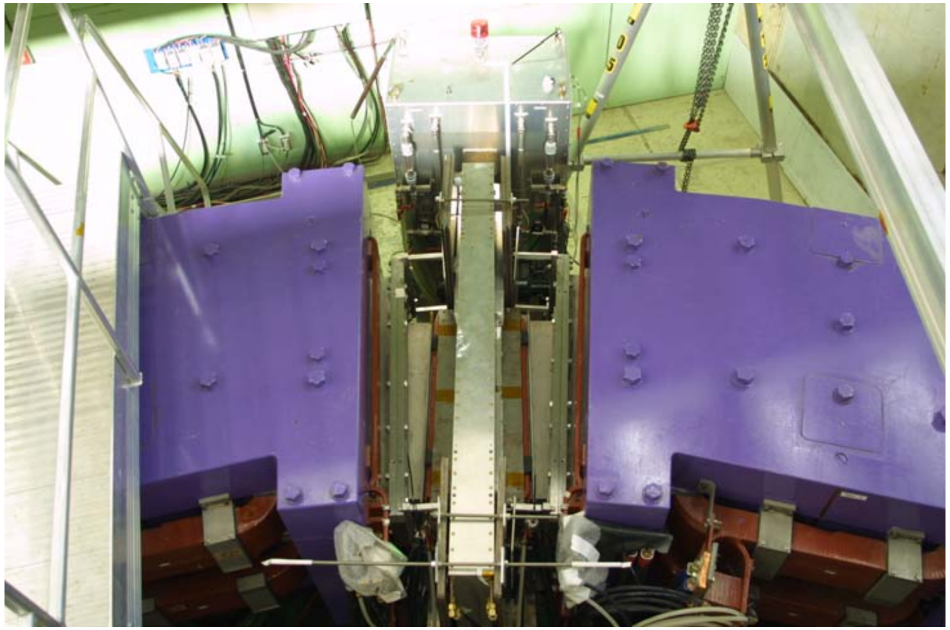
- In terms of challenges...picture is worth 1000 words



FFAG R&D

- NuFact-J group has now built and commissioned world's first 150 MeV proton FFAG ring
  - experimental results in good agreement with design predictions
    - fast cycling (100 Hz) demonstrated
- Non-scaling FFAG to be tested in EMMA experiment

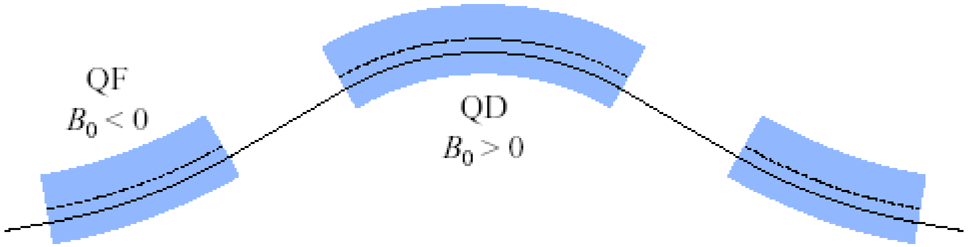


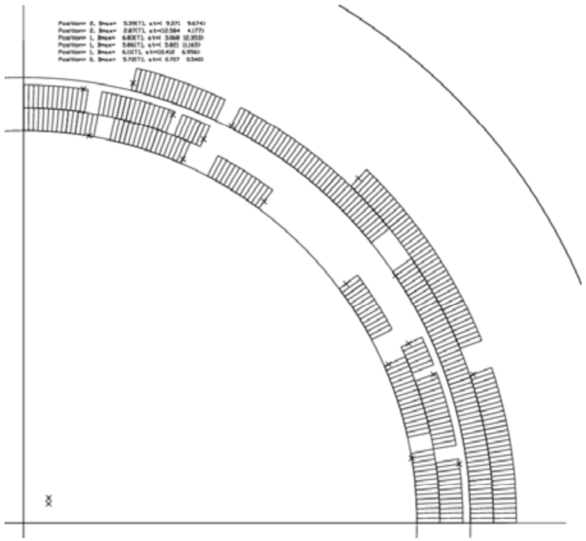


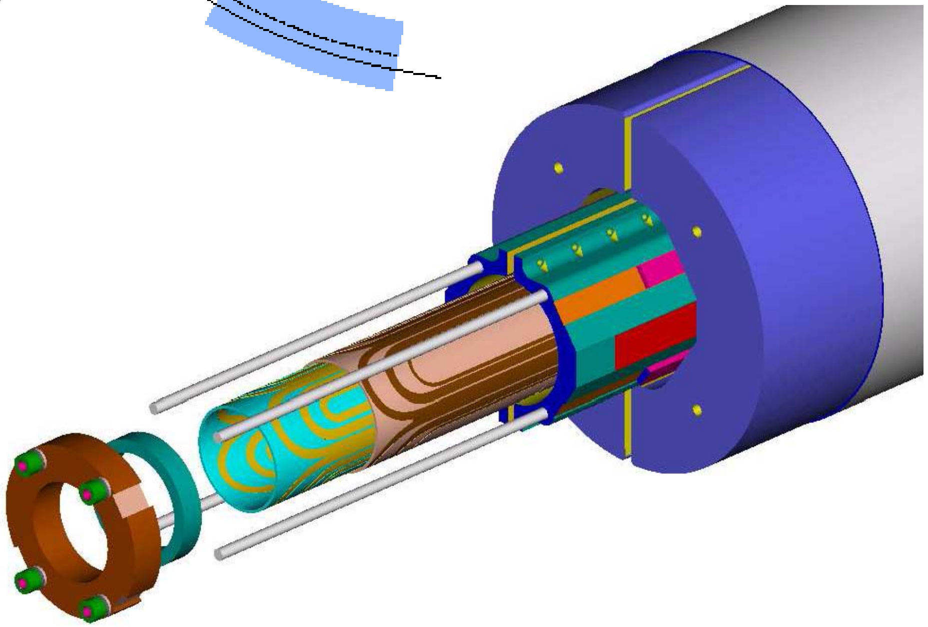
RF cavity

Acceleration R&D

- **For later stages of acceleration, propose FFAG ring with combined function SC magnets (Berg, Machida)**
  - **initial design carried out (Caspi) but not optimized**
    - **nested quadrupole and dipole coils**



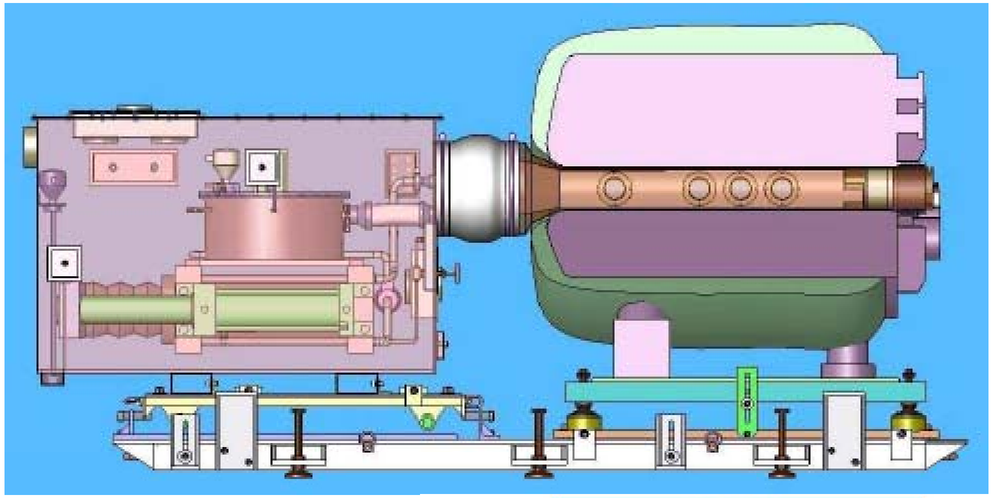


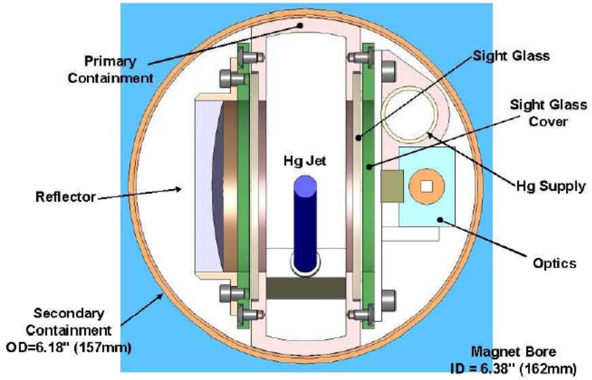


MERIT

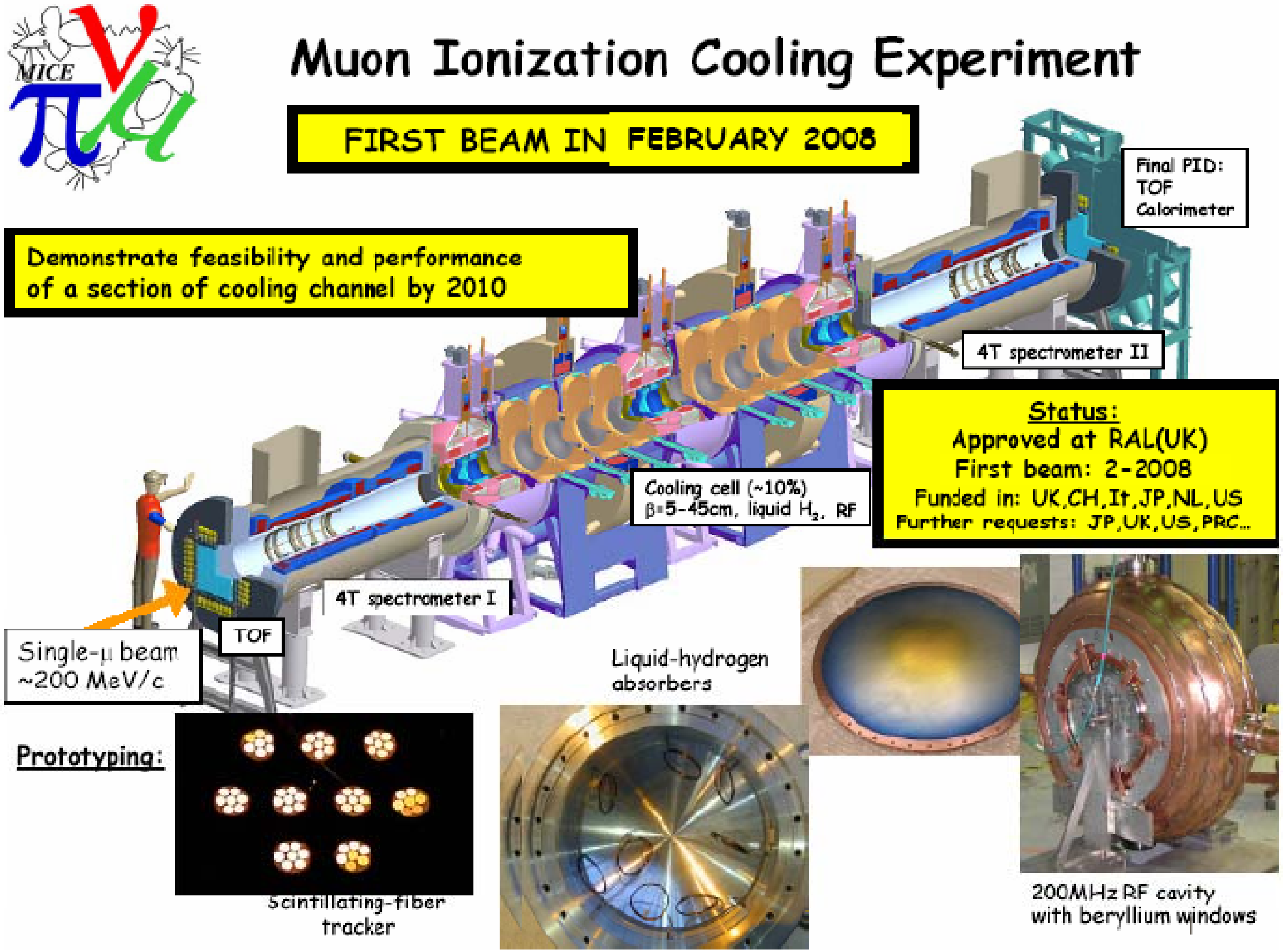
- MERIT experiment will test Hg jet in 15-T solenoid (Kirk, McDonald, Efthymiopoulos)
  - 24 GeV proton beam from CERN PS
    - started October 2007

15-T solenoid and Hg jet installed in TT2A tunnel at CERN





MICE

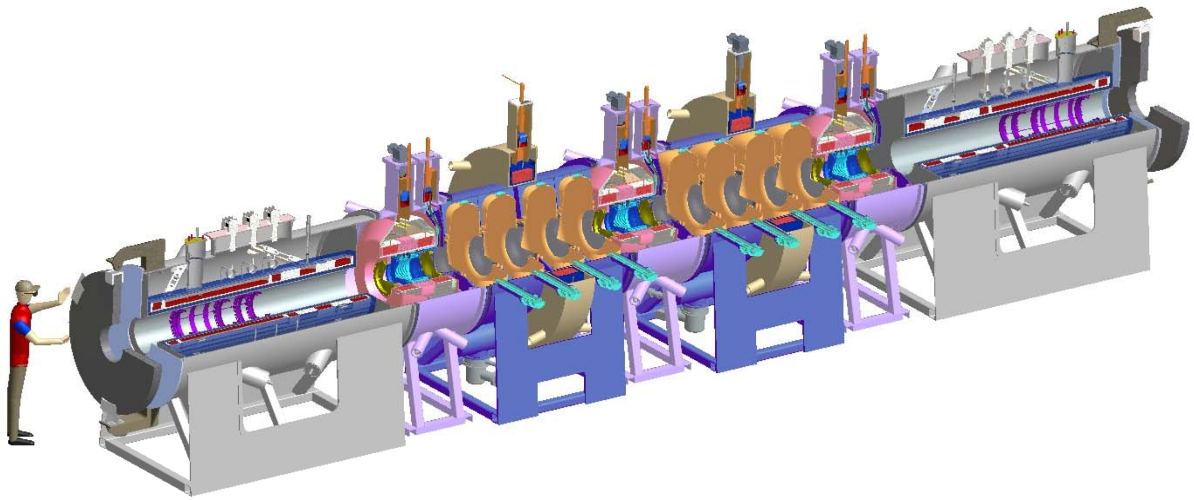

MICE
Muon Ionization Cooling Experiment
FIRST BEAM IN FEBRUARY 2008
Demonstrate feasibility and performance
of a section of cooling channel by 2010
Final PID:
TOF
Calorimeter
4T spectrometer II
Status:
Approved at RAL(UK)
First beam: 2-2008
Funded in: UK,CH,It,JP,NL,US
Further requests: JP,UK,US,PRC...
Cooling cell (~10%)
β=5-45cm, liquid H_2, RF
4T spectrometer I
TOF
Single-μ beam
~200 MeV/c
Liquid-hydrogen
absorbers
Prototyping:
Scintillating-fiber
tracker
200MHz RF cavity
with beryllium windows

MICE Goals

- To design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
- To place this in a muon beam and measure its performance in various modes of operation and beam conditions
  - and reproduce the results with a simulation code!
- Challenges
  - operating high-gradient RF cavities in solenoidal field
  - operating LH_2 absorbers with thin windows in accord with safety needs
  - integrating cooling channel components while maintaining operational functionality
  - measuring small emittance reduction (~10%) to level of 10^{-3}

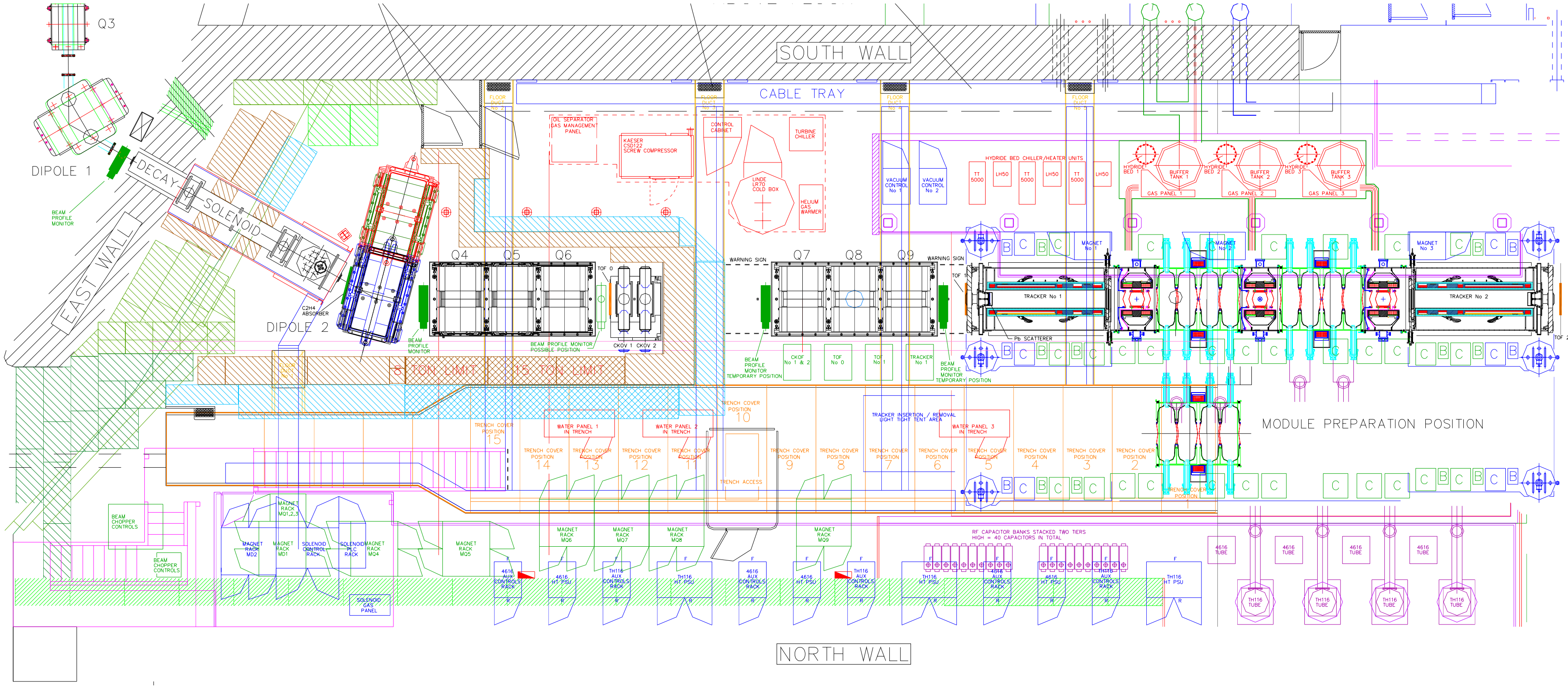
MICE Description

- MICE includes one cell of the FS2 cooling channel
  - three Focus Coil modules with absorbers (LH_2 or solid)
  - two RF-Coupling Coil modules (4 cavities per module)
- Along with two Spectrometer Solenoids with scintillating fiber tracking detectors
  - plus other detectors for confirming particle ID and timing (determining phase wrt RF and measuring longitudinal emittance)
    - TOF, Cherenkov, Calorimeter



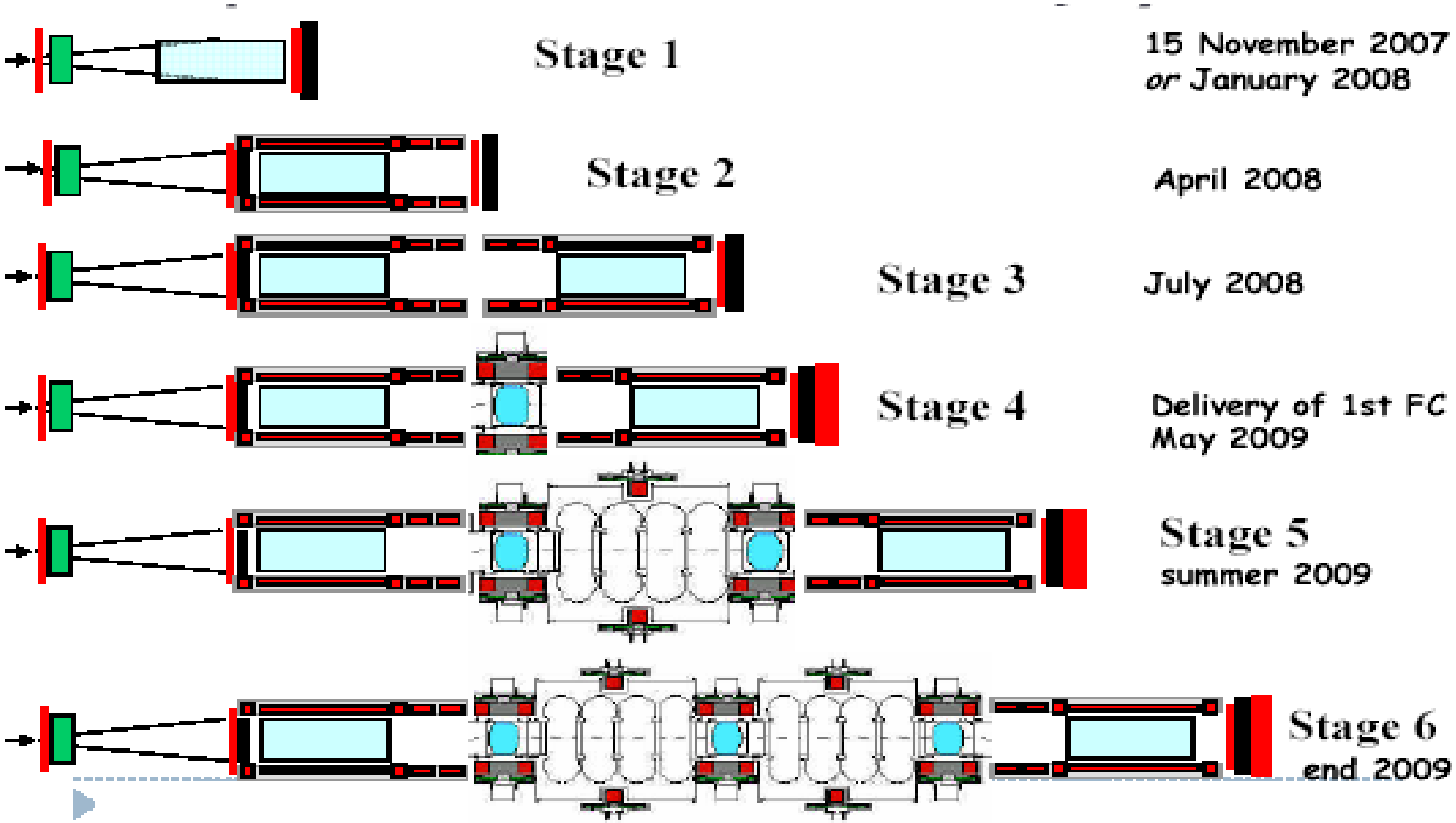
MICE Hall

- Hall will contain a *lot* of equipment



MICE Schedule

- Cooling channel will be built up in stages to ensure complete understanding and control of systematic errors

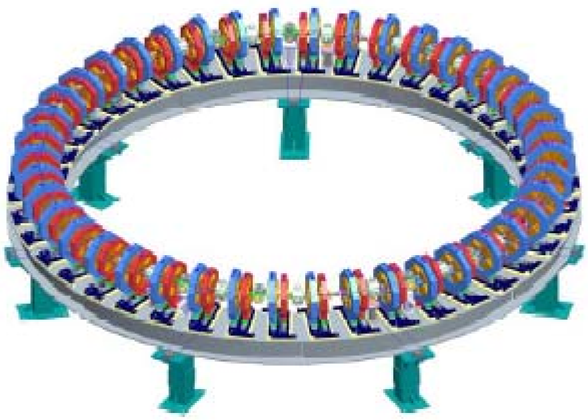


EMMA

- **EMMA will test an electron model of a non-scaling FFAG**
  - uses Daresbury ERLP as injector
  - aim:
    - demonstrate feasibility of non-scaling FFAG concept
      - investigate longitudinal dynamics, transmission, emittance growth, influence of resonances
    - *not* a hardware demonstration

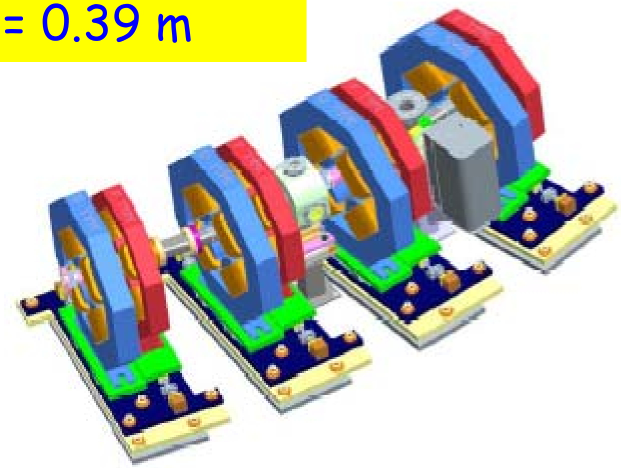
EMMA ring

C = 16.57 m



4 cells plus RF cavity

L_{cell} = 0.39 m



Remaining R&D Issues (IMHO)

- To optimize our design and narrow the range of options, cost models are required
  - more engineering is needed than has been the case heretofore
    - this implies greater R&D costs, but *it is very important*
- Some areas have not yet received adequate attention
  - design of the decay ring and acceleration system magnets
  - development of an optimized (and preferably "scalable") acceleration scheme
  - evaluation of alternative absorber materials
  - test of a solid target in a realistic Neutrino Factory configuration
    - in effect, a solid-target version of MERIT
  - cost-benefit study of using 6D cooling for a Neutrino Factory
  - possibility of staging from Neutrino Factory to Muon Collider
- Hopefully, IDS will improve the situation

Summary

- Substantial progress being made on R&D toward design of muon-based neutrino facility to study CP violation in the lepton sector

- Work extending state-of-the-art in accelerator science
  - high-power targets, new cooling techniques, rapid acceleration techniques,...
    - all of these topics are common to Muon Collider R&D as well

- Work shown here represents efforts in EU, Japan, U.S.
  - carried out in coordinated fashion internationally
    - by choice, not dictated externally

- Common goal
  - convince some Lab to identify Neutrino Factory as its next project

Final Thought

Paper studies alone are *not enough*

We need to build and test things!