Neutrino Factories and Beta Beams: Concepts, Challenges, and R&D

Michael S. Zisman
Center for Beam Physics
Lawrence Berkeley National Laboratory

EPAC06-Edinburgh
June 30, 2006

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 Factory beam properties**

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

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

Produces high energy neutrinos

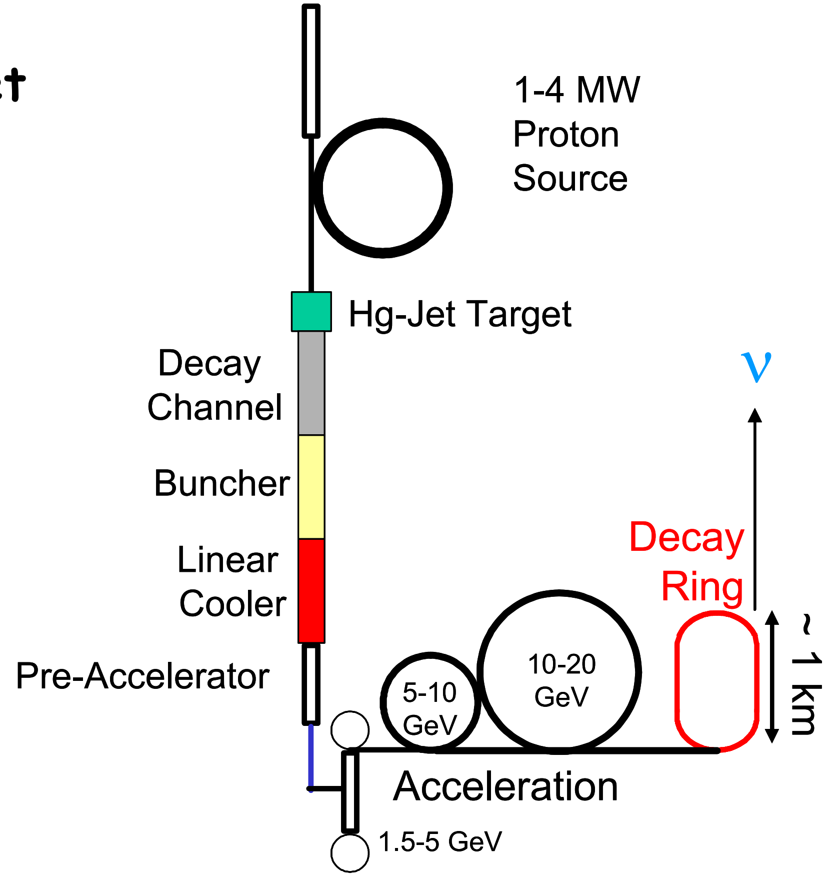
- **Beta beam properties**
  - $^6He \rightarrow {}^6Li + e^- + \overline{\nu}_e$
  - $^{18}Ne \rightarrow {}^{18}F + e^+ + \nu_e$

Produces low energy neutrinos

- **Decay kinematics well known**
  - **minimal hadronic uncertainties in the spectrum and flux**
- **Electron neutrinos are most favorable to do the science**
  - **$\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable "wrong-sign" μ**
    - **do not get ν_e from "conventional" neutrino beam line ($\pi \rightarrow \mu + \nu_\mu$)**

Neutrino Factory

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



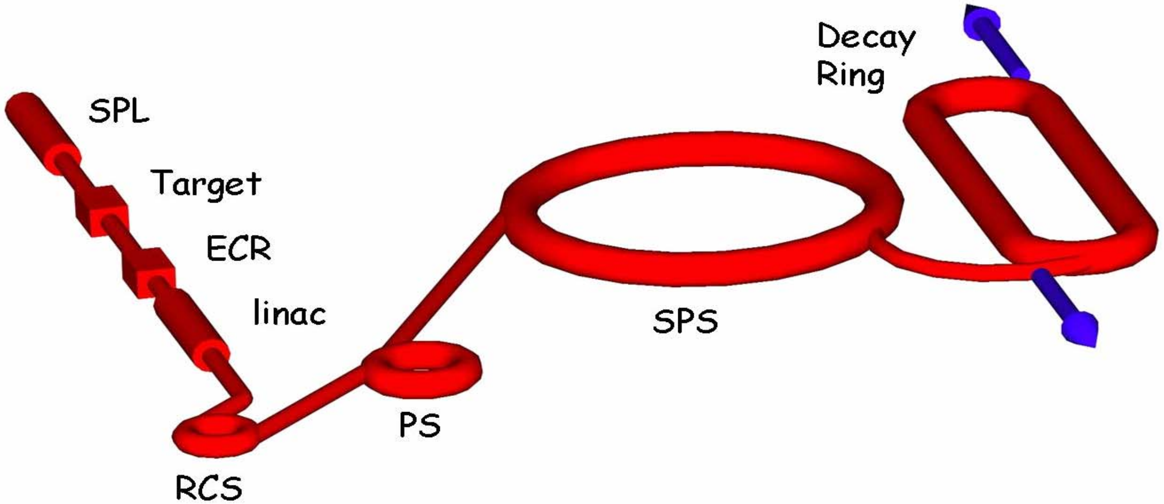
U.S. design (schematic)

Beta Beam

- Baseline Beta Beam facility comprises these sections
  - Proton Driver
    - SPL (≈4 GeV)
  - ISOL Target
    - spallation neutrons or direct protons
  - Ion Source
    - pulsed ECR
  - Acceleration
    - linac, RCS, PS, SPS
  - Decay Ring
    - 7000 m; 2500 m straight

Baseline concept assumes CERN PS, SPS

Use of Tevatron also being considered

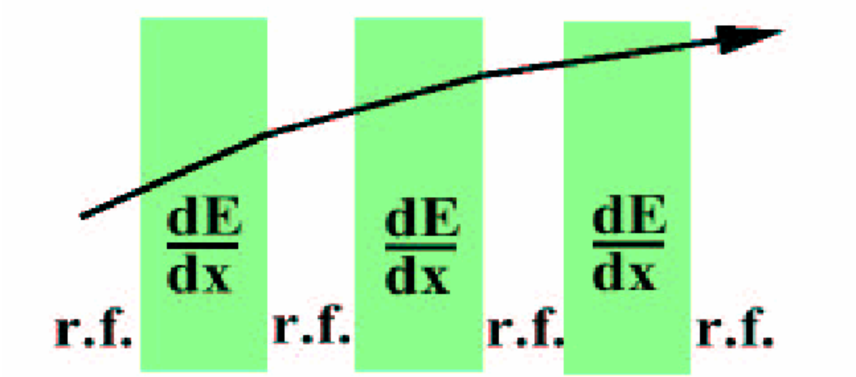


Technical Challenges-NF

- **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

Ionization Cooling (1)

- **Ionization cooling analogous to familiar SR damping process in electron storage rings**
  - energy loss (SR or *dE/dx*) reduces p_x, p_y, p_z
  - energy gain (RF cavities) restores only p_z
  - repeating this reduces $p_{x,y}/p_z$



Ionization Cooling (2)

- There is also a heating term
  - for SR it is quantum excitation
  - for ionization cooling it is multiple scattering

- Balance between heating and cooling gives equilibrium emittance

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left|\frac{dE_\mu}{ds}\right|\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\text{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

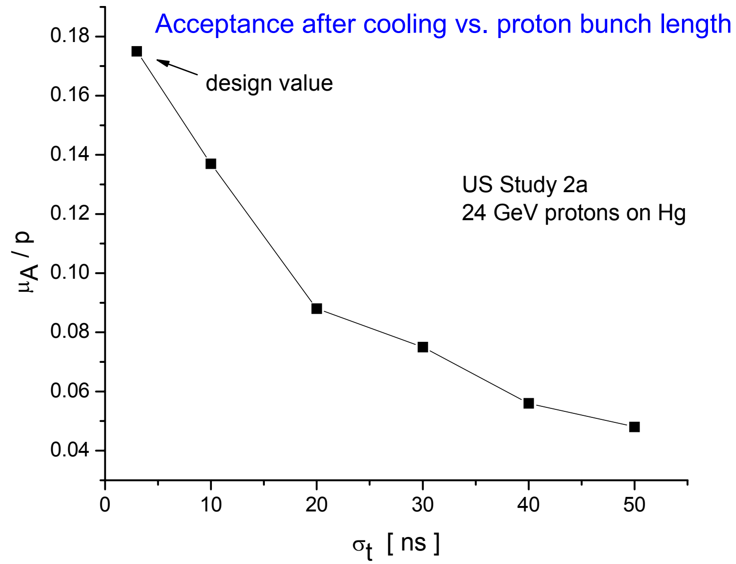
Cooling Heating

$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\,\text{GeV})^2}{2\beta m_\mu X_0 \left|\frac{dE_\mu}{ds}\right|}$$

- prefer low $\beta_\perp$ (strong focusing), large X_0 and *dE/ds* (H_2 is best)

Proton Parameters

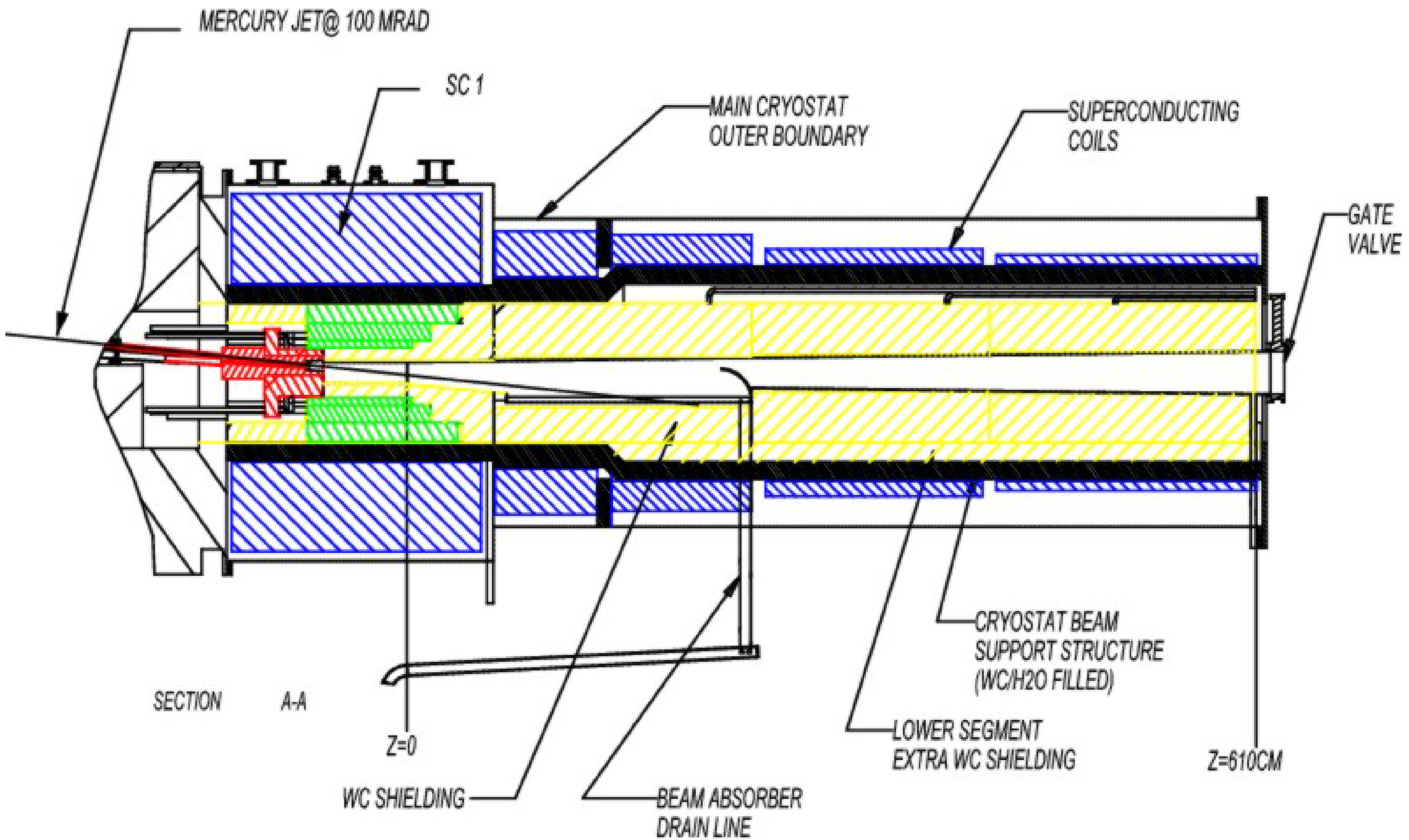
- **Desired proton intensity for Neutrino Factory is 4 MW**
  - e.g., 2.5 x 10^{15} p/s at 10 GeV or 5 x 10^{13} p/pulse at 50 Hz
- **Desired bunch length is 1-3 ns to minimize intensity loss**
  - not easily done at high intensity and moderate energy



Pulse structure is also important—target issue

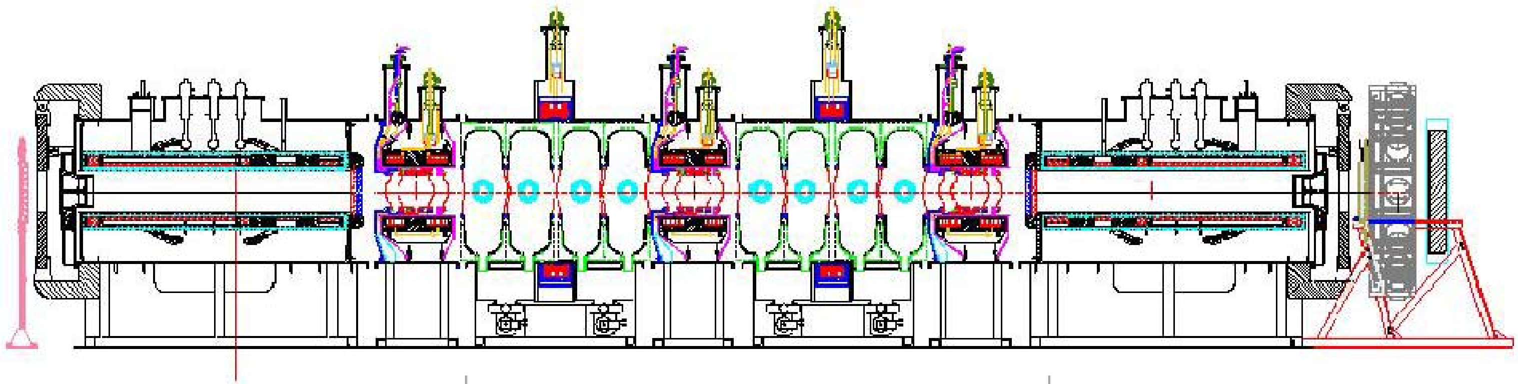
NF Target

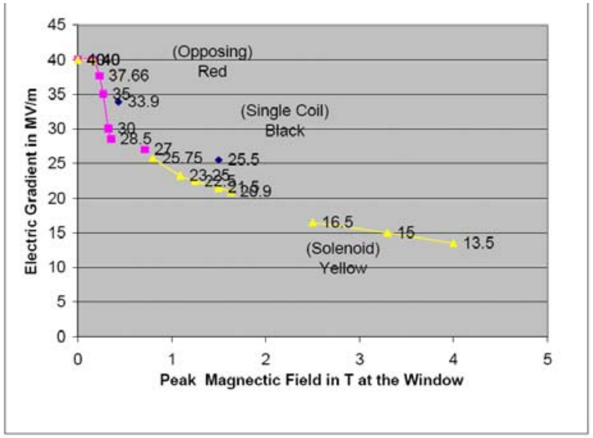
- **Favored target concept based on Hg jet in 20-T solenoid**
  - **jet velocity of 20 m/s establishes "new" target each beam pulse**



NF RF

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





BB Technical Challenges (1)

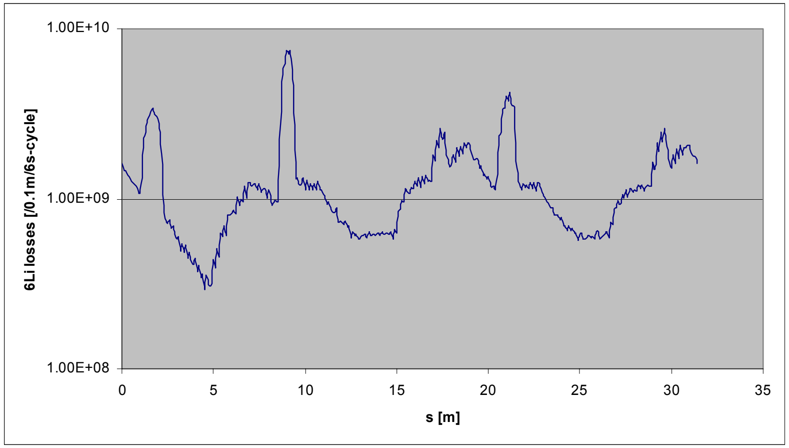
- Production of the required ion species at the required intensity
  - requires production, transport to ion source, ionization, bunching
    - target's ability to accommodate primary beam is sometimes limited to a few hundred kW
  - looks okay for ^{6}He but ^{18}Ne is presently estimated at about 4% of desired intensity level
    - higher *Z* atoms are produced in multiple charge states, with the peak at 25-30% of the total intensity

	Nominal production rate [ions/s]	Required production rate [ions/s]	Missing factor
6He	2×10^{13}	2×10^{13}	1
18Ne	8×10^{11}	1.9×10^{13}	24

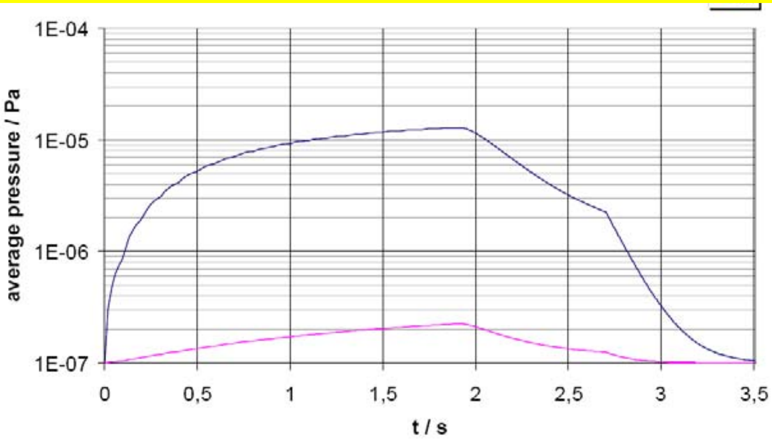
BB Technical Challenges (2)

- **RF manipulations in transfers**
  - ion source → RCS → PS → SPS → decay ring
  - process is not 100% efficient
    - beam losses represent vacuum challenge in PS
      - optimized lattice with collimation system could improve vacuum x100

Predicted ^{6}Li losses in PS lattice



Pressure degrades to 75 ntorr from ^{6}He losses



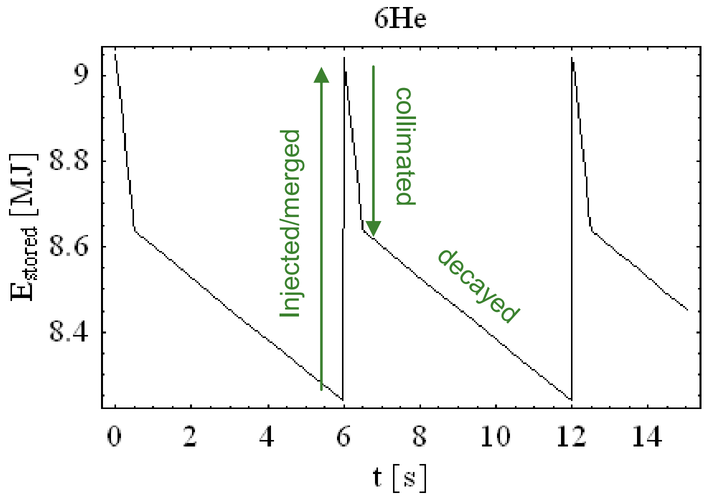
BB Technical Challenges (3)

- RF stacking in decay ring
  - need to stack beam in decay ring to get acceptable decay rate
    - after 15-20 merges, about 50% of the beam is pushed outside the acceptance
  - need substantial momentum collimation scheme
    - beam losses represent 150 kW average power load on collimators
      - peak load during bunch compression process (few 100 ms) will be at MW level

Decay losses also an issue:

SC dipoles require 16 cm aperture and suffer ≈10 W/m heat load

Predicted ^6He losses in decay ring



NF R&D

- R&D program has three main thrusts
  - simulation and theory (ongoing effort as part of ISS)
  - development of high-power target technology
  - development of cooling channel and rapid acceleration technology

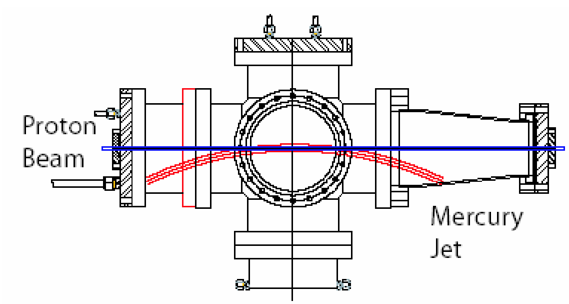
- Recent simulation effort has focused on simplifying NF design to reduce costs
  - replaced induction linacs with RF bunching and phase rotation scheme
    - this permitted simultaneous use of muons of both signs
  - improved acceleration system (RLAs → non-scaling FFAGs)
    - larger acceptance 15π mm-rad → 30π mm-rad
  - increased downstream acceptance permitted simplified cooling channel
    - fewer solenoids, fewer RF cavities, simpler absorbers (LH_2 → LiH)

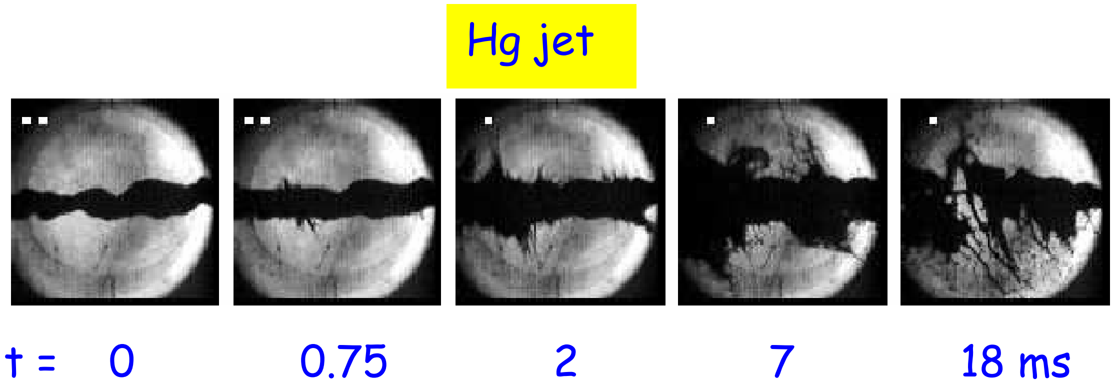
- Together, improvements doubled intensity (2 signs) and reduced cost of facility by 35%

NF Target R&D (1)

- **Disruption at moderate intensity (4 Tp) demonstrated in BNL E951**
  - **no solenoidal field**

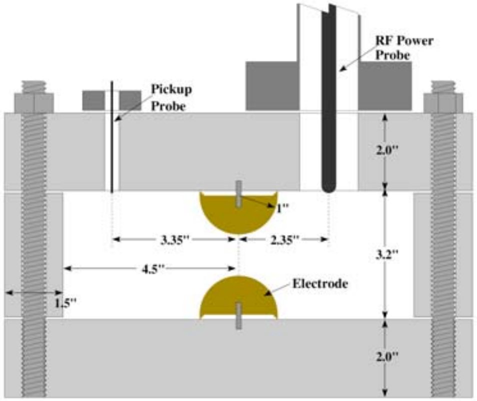
- **What happens at higher intensity and with strong solenoid? (MERIT)**





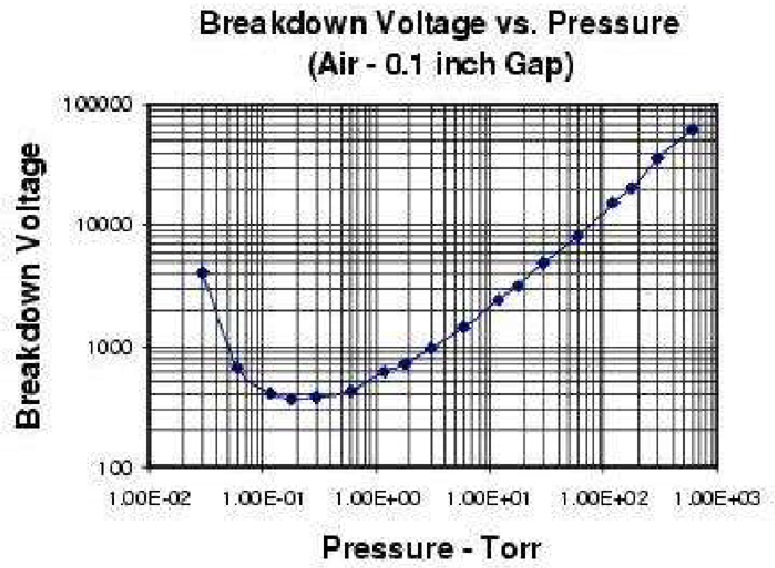
NF RF R&D (1)

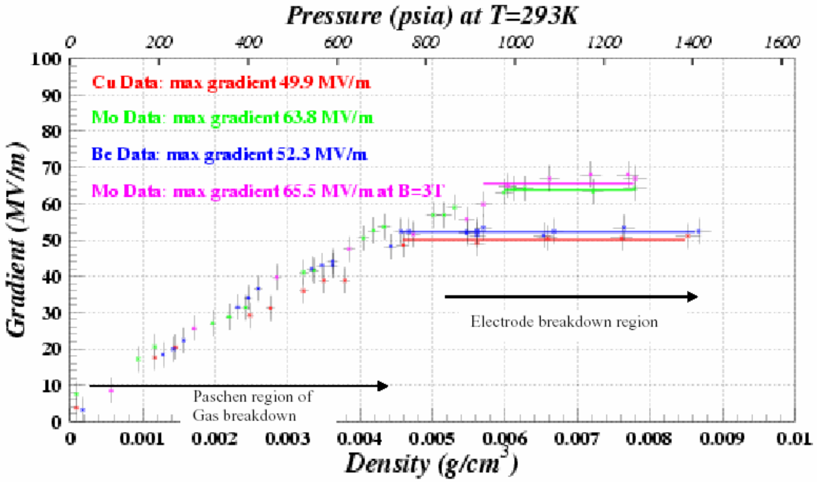
- Testing pressurized version of button cavity
  - use high-pressure H_2 gas to limit breakdown



Muons, Inc.

Breakdown limitation does not degrade in magnetic field

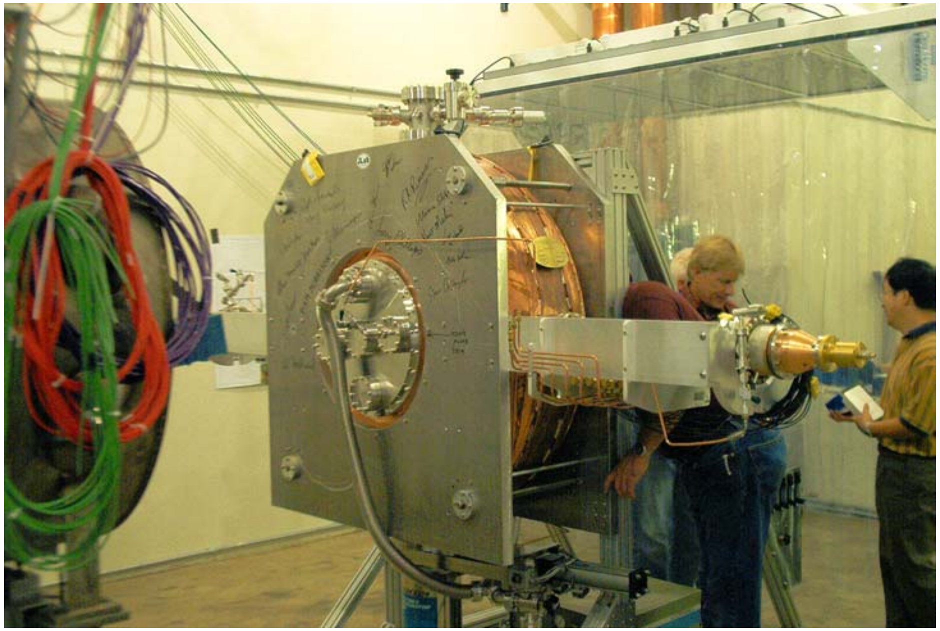


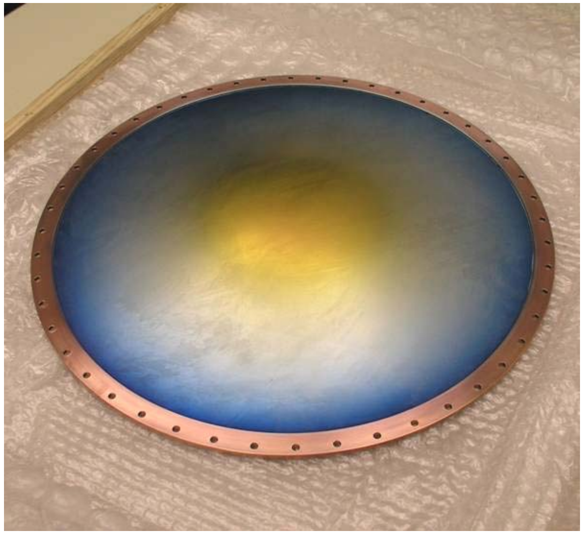


NF RF R&D (2)

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

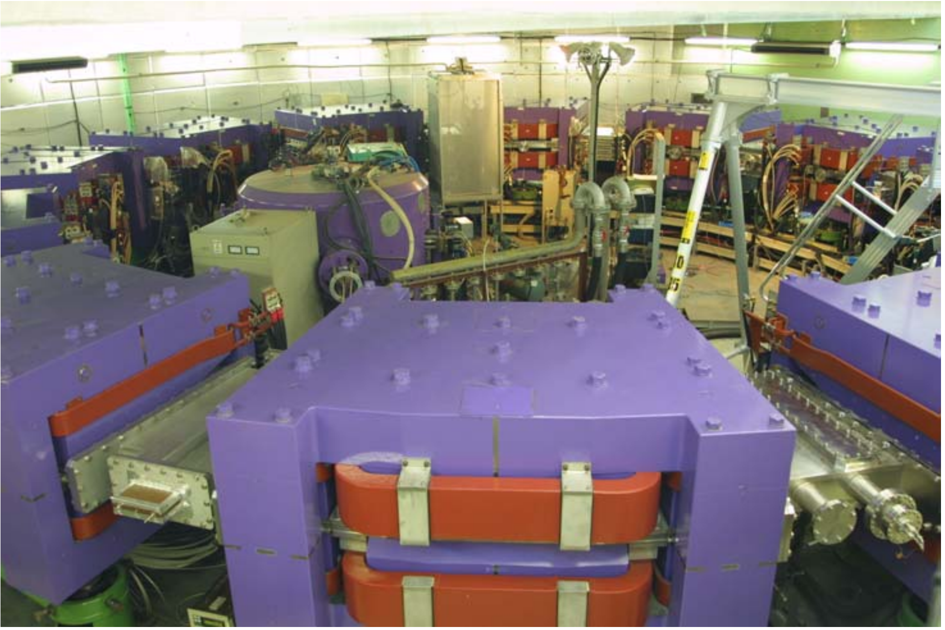


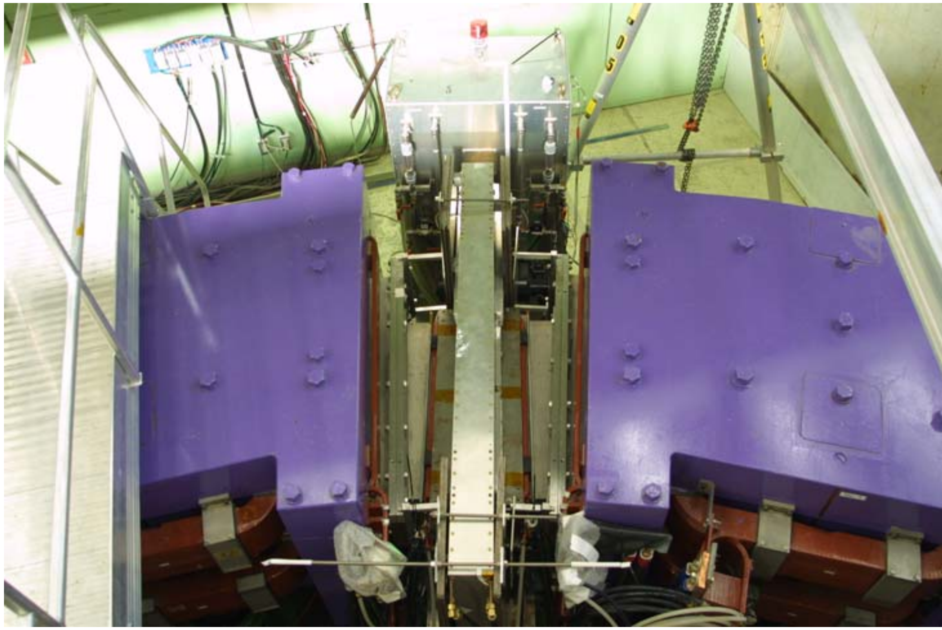


42-cm curved Be window

NF 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

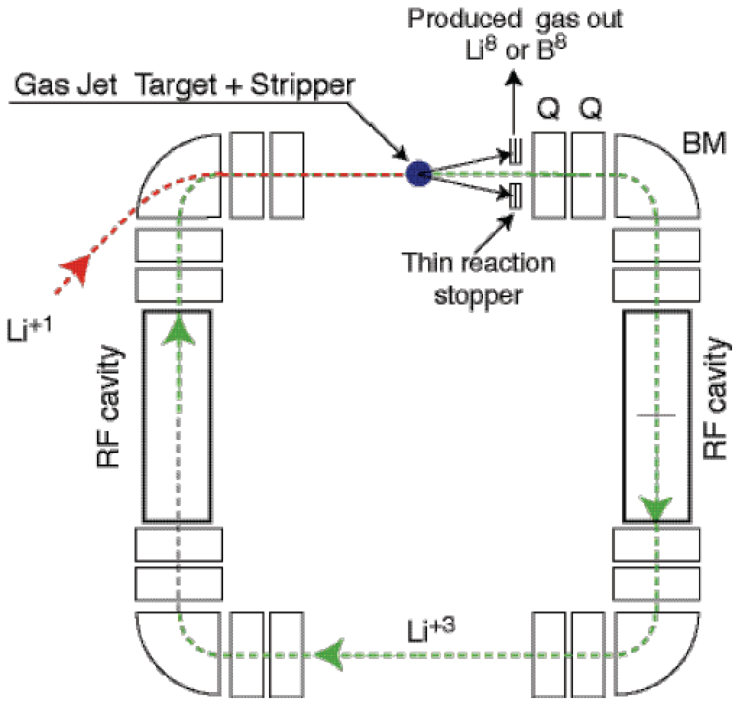


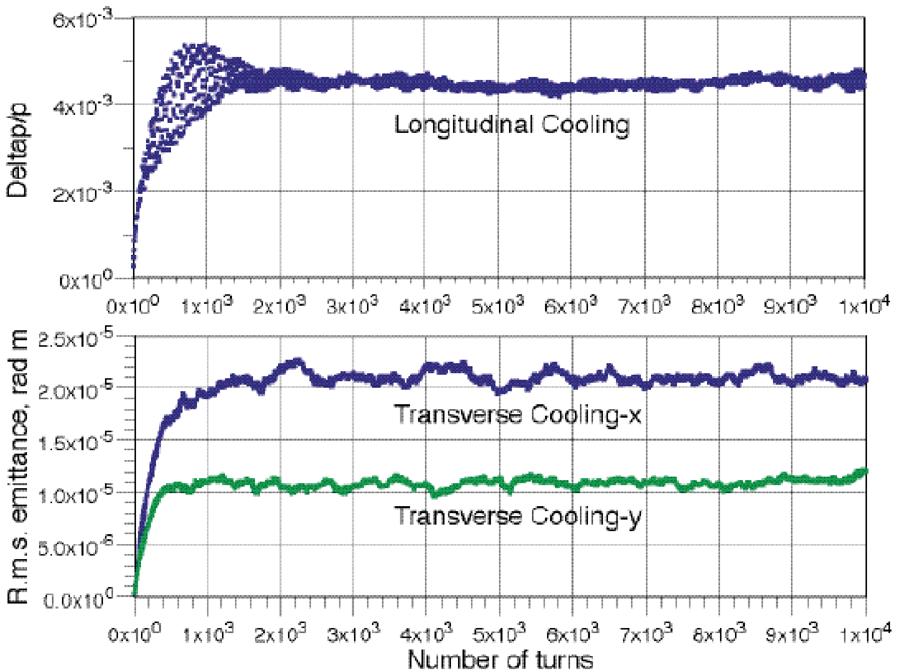


RF cavity

BB R&D (1)

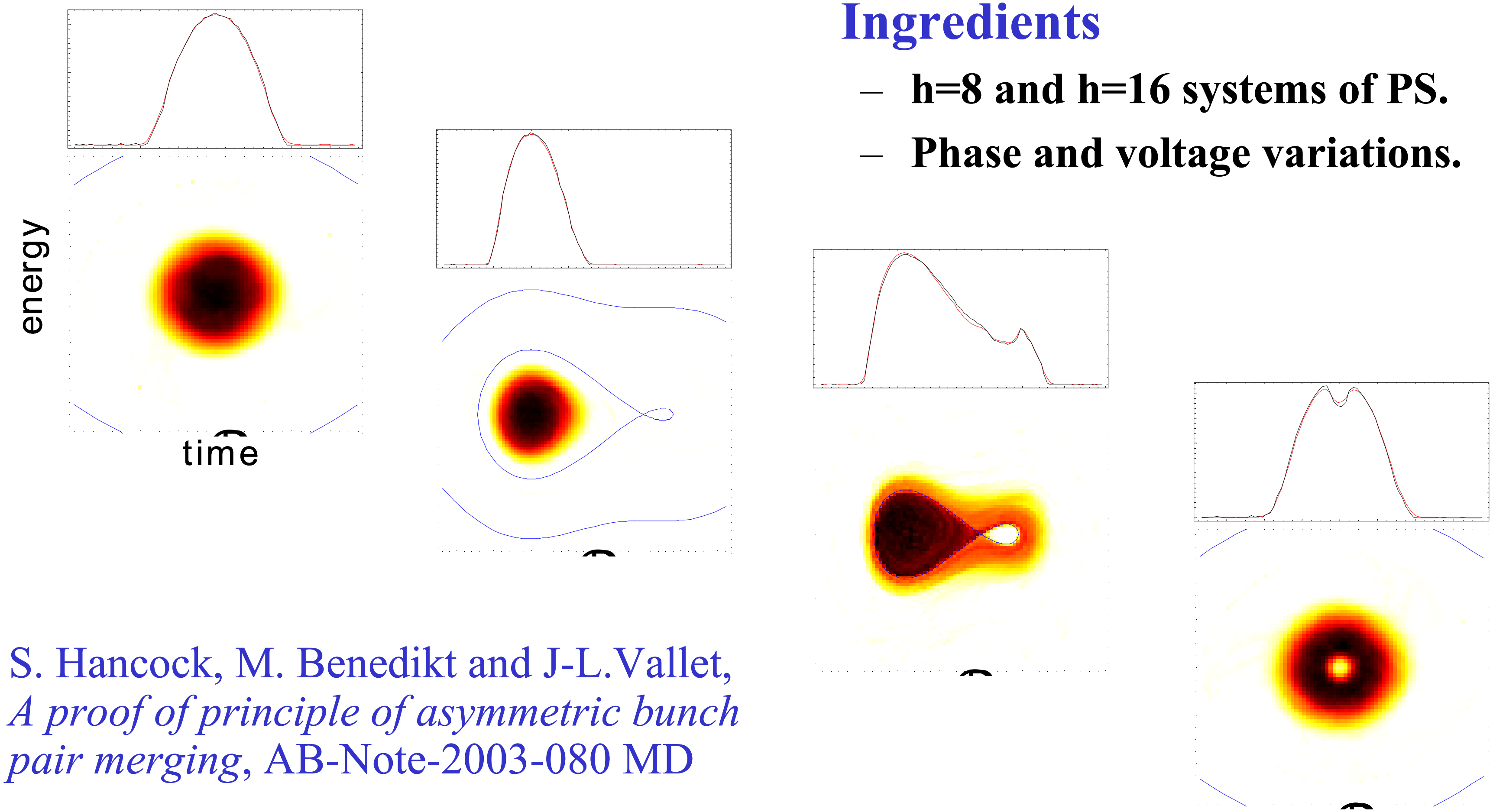
- Beta Beam work to date mostly "paper studies"
  - funded for system design, not hardware development
- New concept for production proposed by C. Rubbia *et al.*
  - based on ionization "cooling" of ions to maintain equilibrium emittance





BB R&D (2)

- **Experimentally demonstrated key bunch merging technique in PS**

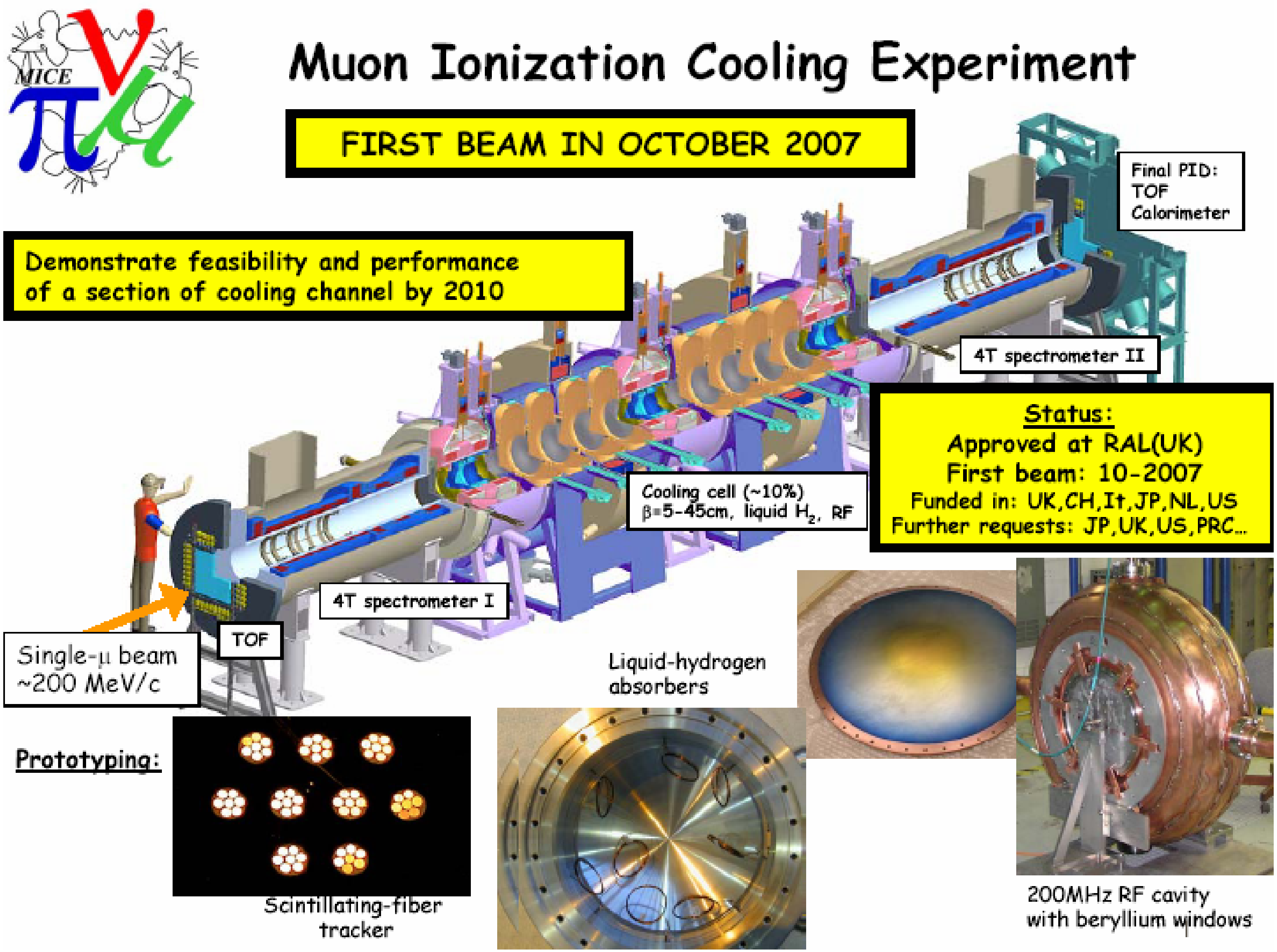


Ingredients

- h=8 and h=16 systems of PS.
- Phase and voltage variations.

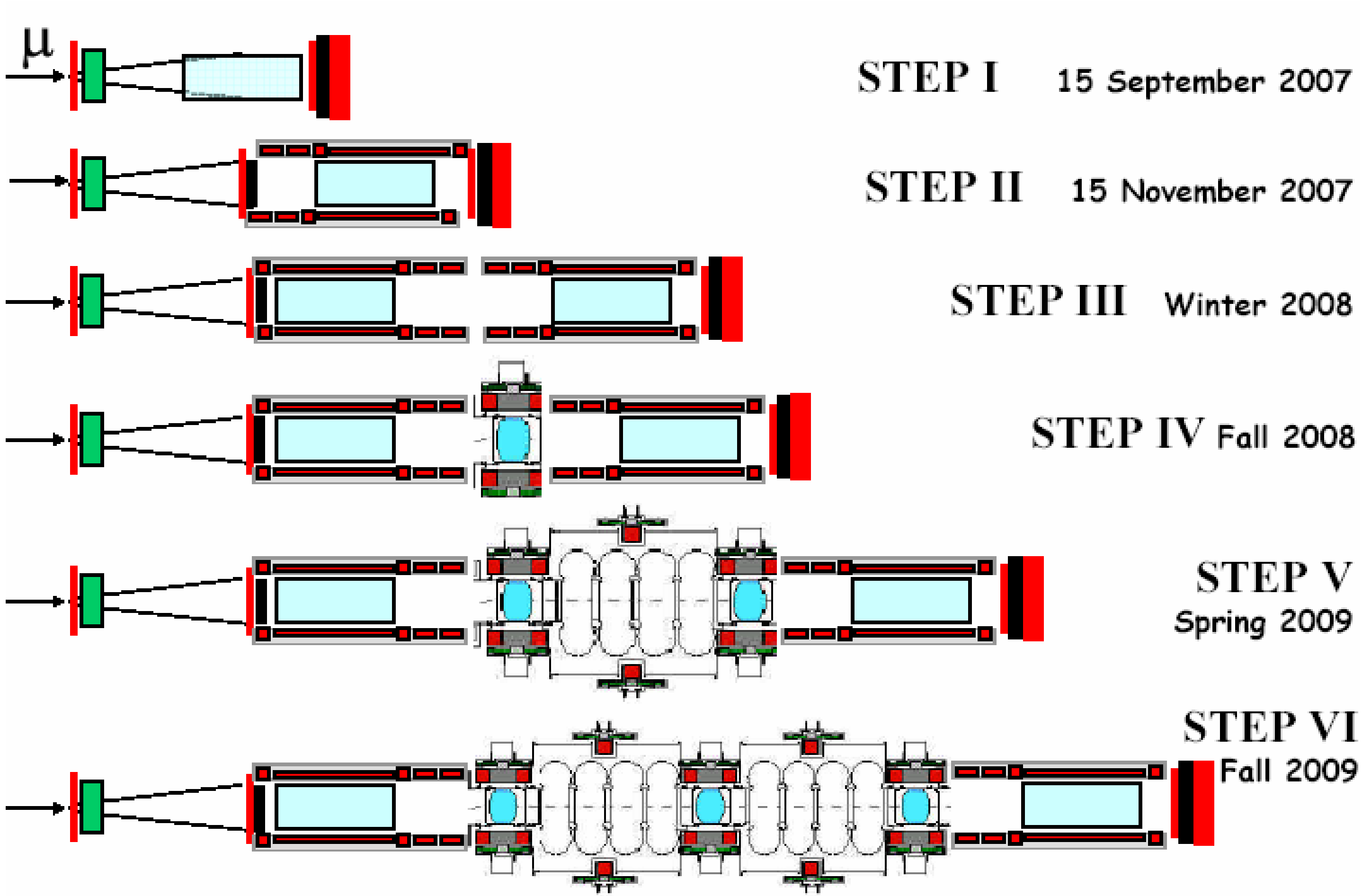
S. Hancock, M. Benedikt and J-L.Vallet, *A proof of principle of asymmetric bunch pair merging*, AB-Note-2003-080 MD

System Tests-MICE (1)



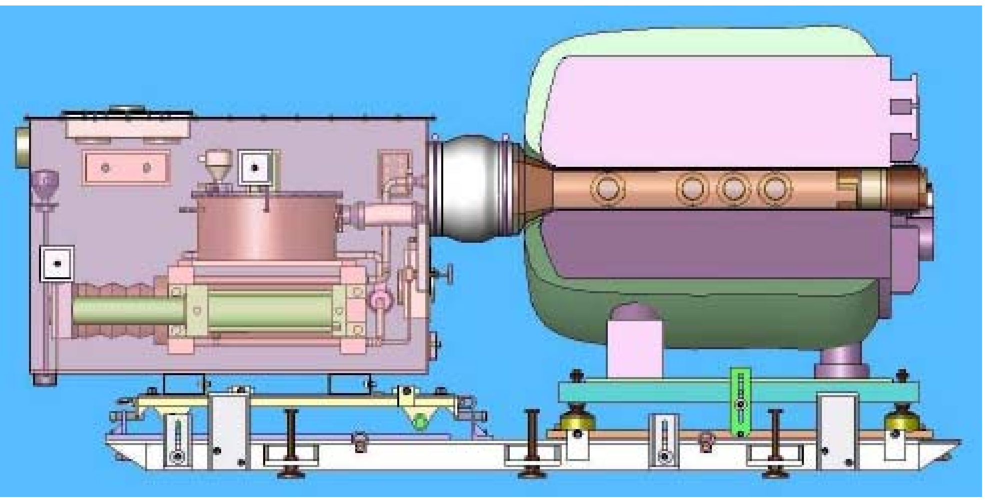
System Tests-MICE (2)

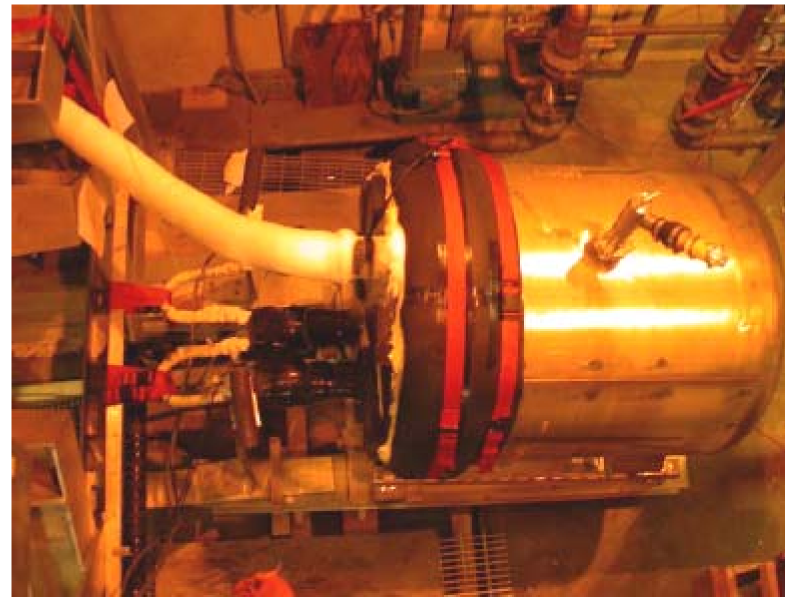
- **MICE channel at RAL will be built in steps to ensure complete understanding and control of systematic errors**



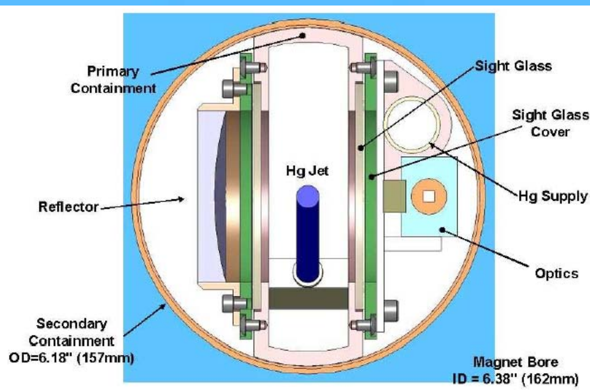
System Tests-MERIT

- **MERIT experiment will test Hg jet in 15-T solenoid**
  - 24 GeV proton beam from CERN PS
    - scheduled Spring 2007





15-T solenoid during tests at MIT



Hg delivery and containment system under construction at ORNL

Summary

- Substantial progress being made toward design of accelerator-based neutrino facilities to study CP violation in the lepton sector
- Work extending state-of-the-art in accelerator science
  - high-power targets, new cooling techniques, ion source development, rapid acceleration techniques,...
- Work shown here represents efforts in EU, Japan, U.S.
  - carried out in coordinated fashion internationally
    - by choice, not dictated externally
- Thanks to Mats Lindroos and Andreas Jansson for sharing their expertise on Beta Beams

Final Thought

Paper studies alone are *not enough*

We need to build and test things!