Accelerator Challenges and Opportunities for Future Neutrino Experiments

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Introduction

- Discovery of neutrino oscillations led to strong interest in providing intense beams of accelerator-produced neutrinos
  - such facilities may be able to observe CP violation in the lepton sector
    - possibly the reason we're all here
- Several ideas have been proposed for producing the required neutrino beams
  - a Beta Beam facility based on decays of a stored beam of beta-unstable ions
  - a Neutrino Factory based on the decays of a stored muon beam
    - could serve as precursor to eventual Muon Collider
  - a Superbeam facility based on the decays of an intense pion beam
- All approaches have their advantages and disadvantages
  - all are challenging…and all will be expensive
  - EUROnu program attempting to compare all options on an equal footing

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

Baseline scenario 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 ($\pi \rightarrow \mu + \nu_\mu$)**

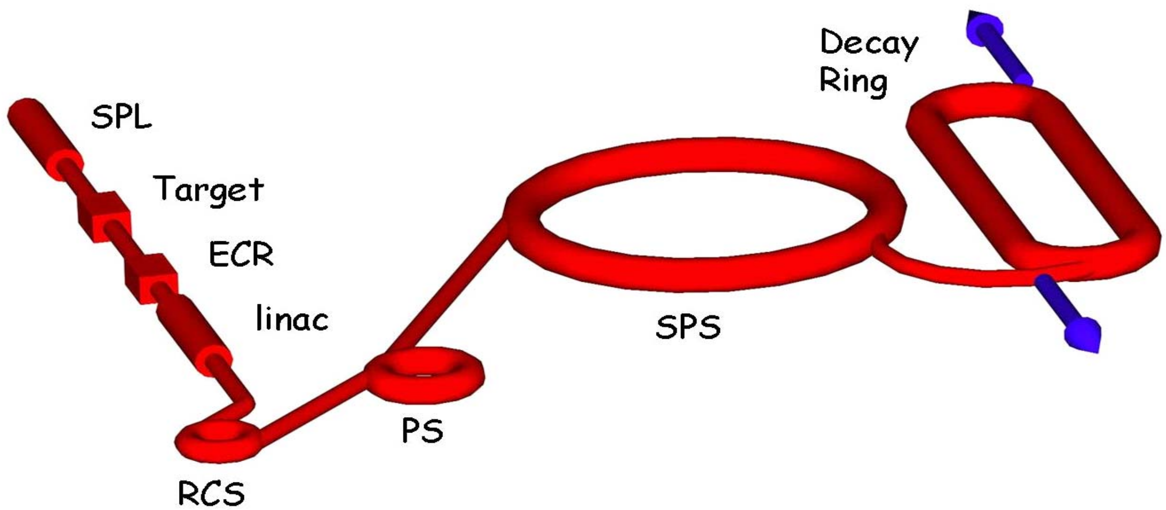
Beta Beam

- **Baseline Beta Beam facility comprises these sections**
  - **Proton Driver**
    - **"light" SPL (≈4 GeV) and upgraded Linac 4**
  - **ISOL Target**
    - **spallation neutrons or direct protons**
  - **Ion Source**
    - **pulsed ECR**
  - **Acceleration**
    - **linac, RCS, PS, SPS**
  - **Decay Ring**
    - **6900 m; 2500 m straight**

Two concepts being explored:

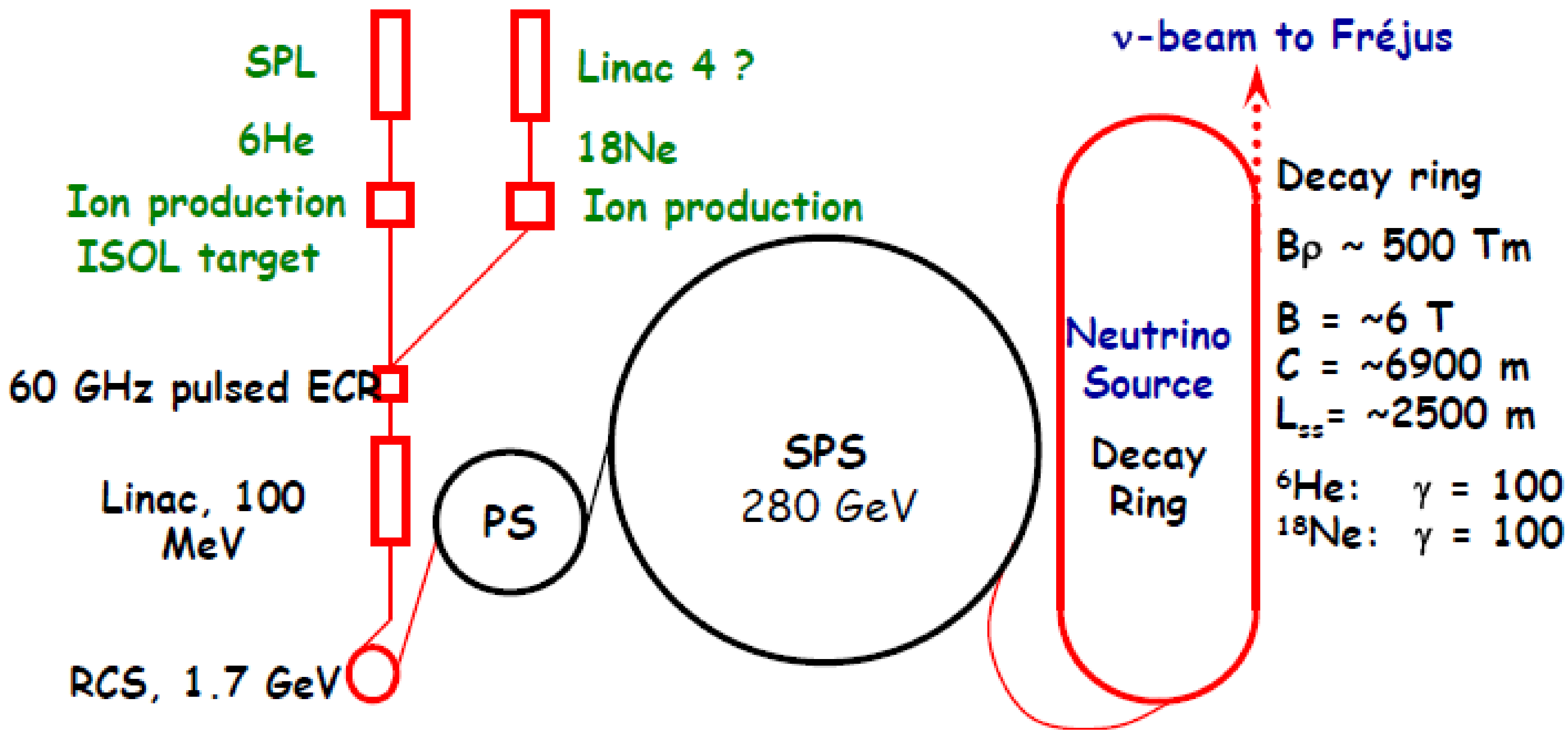
Low-*Q* version (^{6}He, ^{18}Ne)

High-*Q* version (^{8}Li,^{8}B)



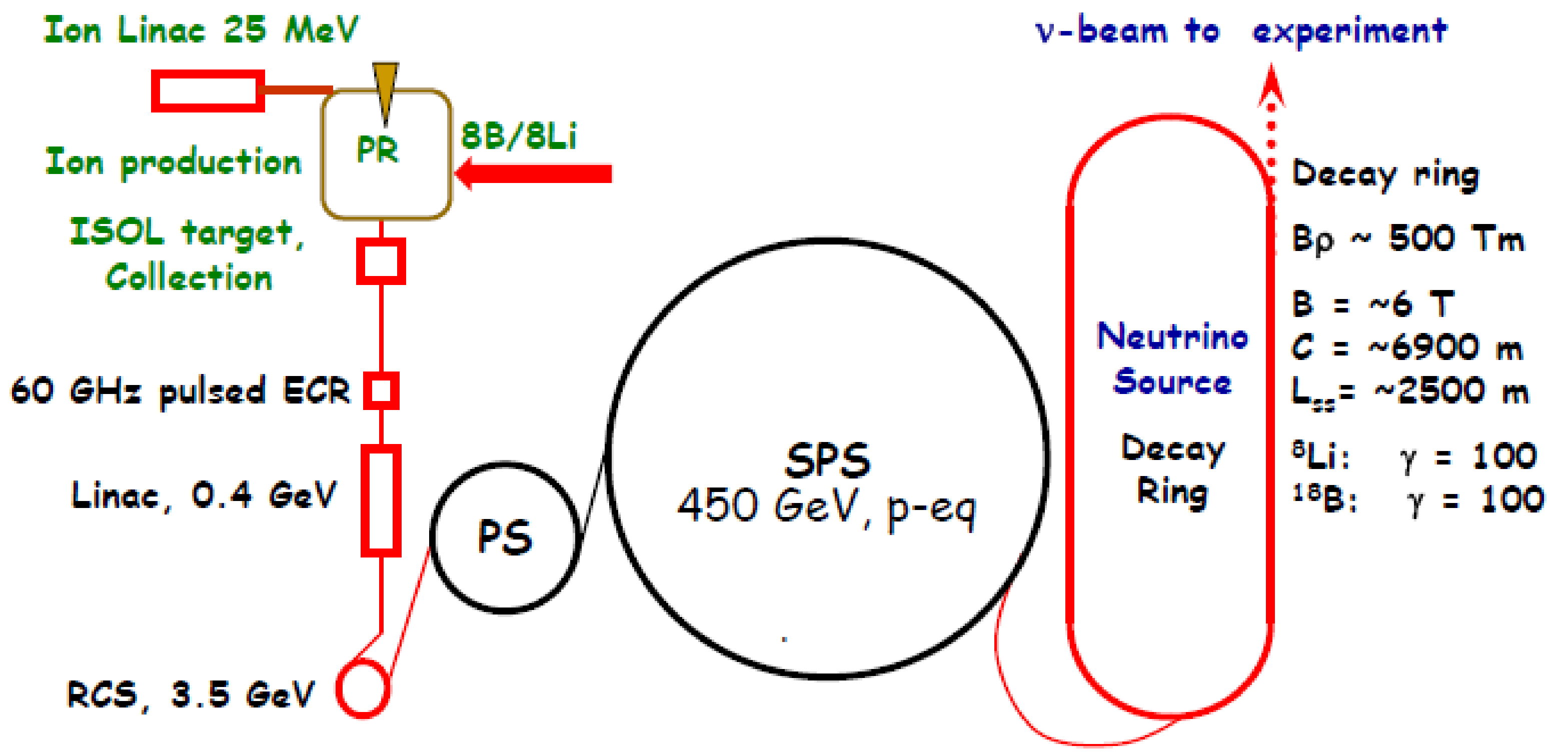
Beta Beam (Low-Q)

- **Baseline scenario from EUROnu study based on ^{6}He and ^{18}Ne at γ = 100**
  - **beam to Fréjus**



Beta Beam (High-*Q*)

- **Looking at option of higher *Q* decays to boost neutrino energy**
  - ^{8}Li and ^{8}B at γ = 100 aimed at Gran Sasso

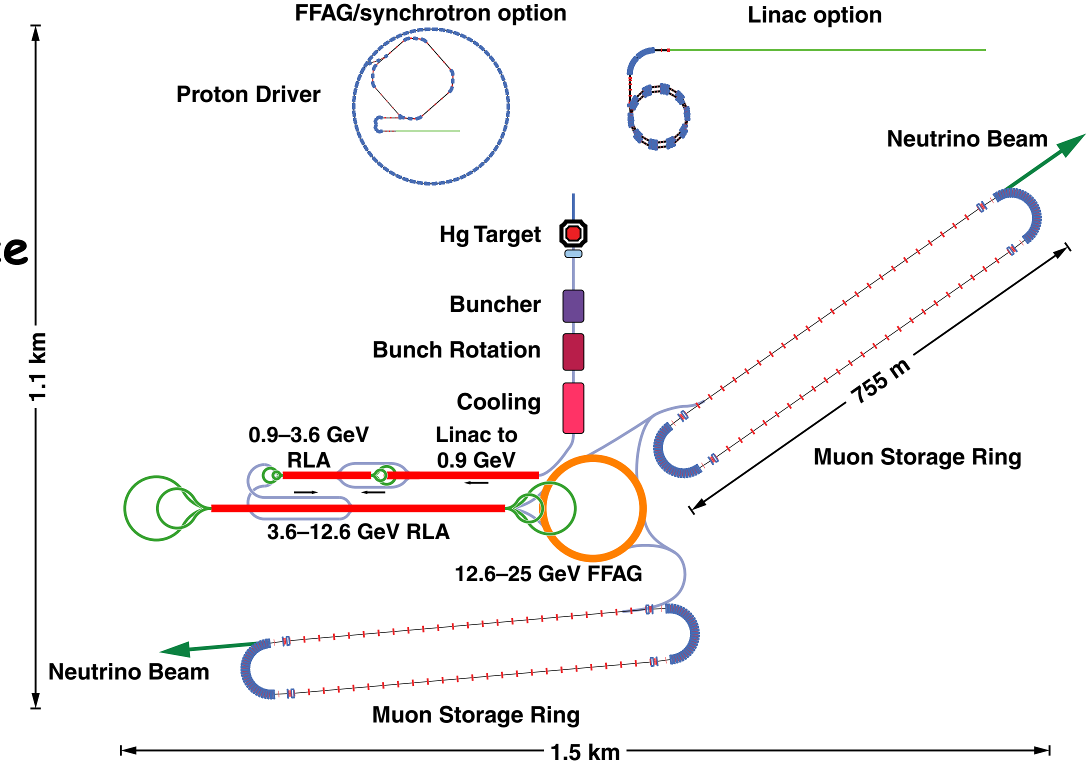


Detector Gran Sasso (~ 5 times higher Q)

Neutrino Factory

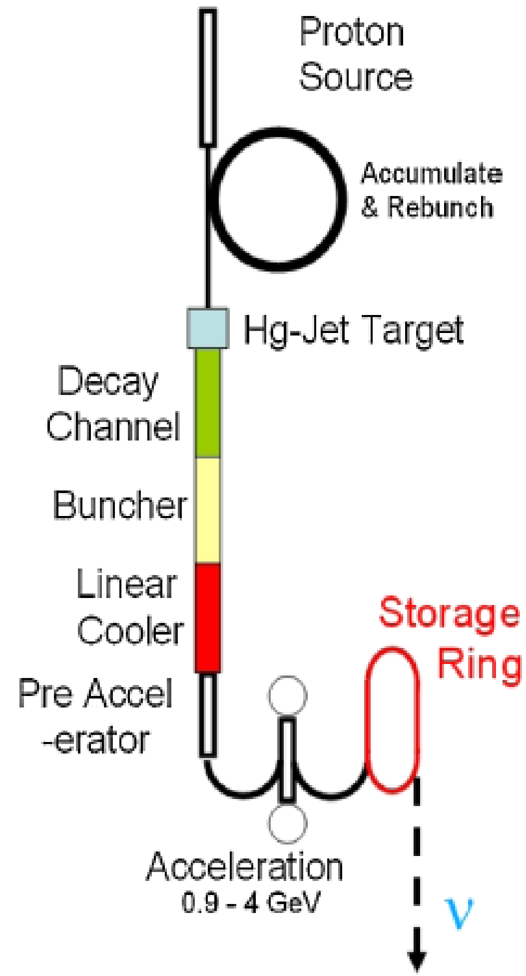
- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into μ ⇒ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance ⇒ MICE
  - Acceleration
    - 130 MeV → 20-40 GeV with RLAs or FFAGs
  - Decay Ring
    - store for ~1000 turns; long straights

IDS-NF baseline design



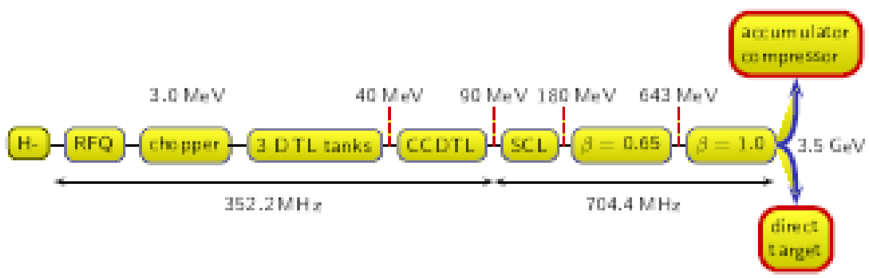
Low Energy Neutrino Factory

- **Alternative 4 GeV NF design being explored at Fermilab**
  - motivated by
    - expectation of reduced facility cost
    - energy well matched to Fermilab-DUSEL baseline
    - detector concept (magnetized TASD) capable of required performance at chosen energy
  - ingredients same as IDS-NF design…but fewer of them
    - less acceleration
    - smaller decay ring
    - single baseline

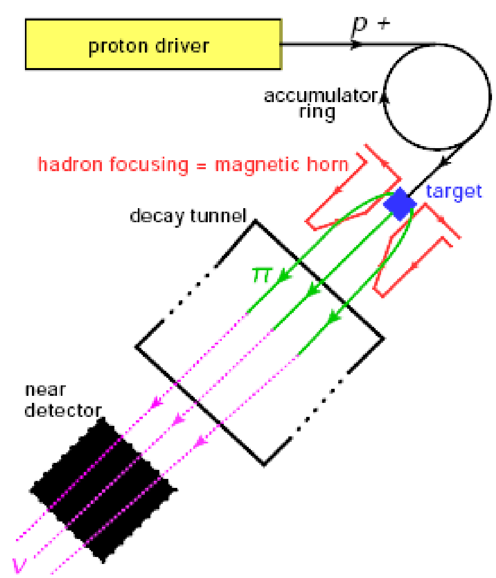


Superbeam

- **Superbeam facility is a higher-power version of today's neutrino beam facilities**
  - **approach is evolutionary rather than revolutionary**
    - **but nonetheless a big step forward**
      - **EUROnu version shown here**
        - **CERN to Fréjus**



"High-power" SPL (CERN)



4 MW, 5 GeV proton beam

130 km baseline

Commonality

- A common feature of all future neutrino facilities is the requirement for substantially increased intensity
  - all current approaches to produce the requisite number of neutrinos rely on production of secondary, or even tertiary, beam
    - ⇒ need for intense particle sources
    - ⇒ need for very large detectors

- Both features represent major technical challenges
  - must extend today's state-of-the-art by factor of 5-10

Viewpoint

- For this talk, I will take the point of view that

Challenges ≡ Opportunities

↑

R&D

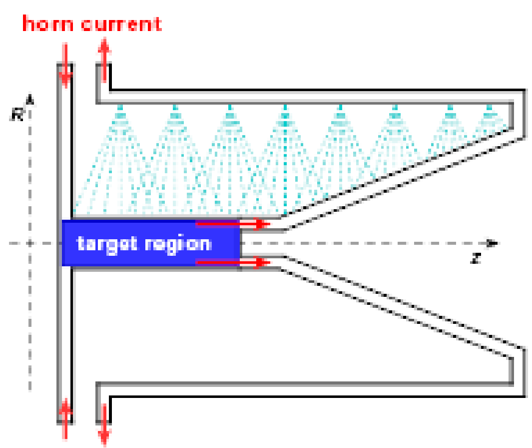
Technical Challenges-SB

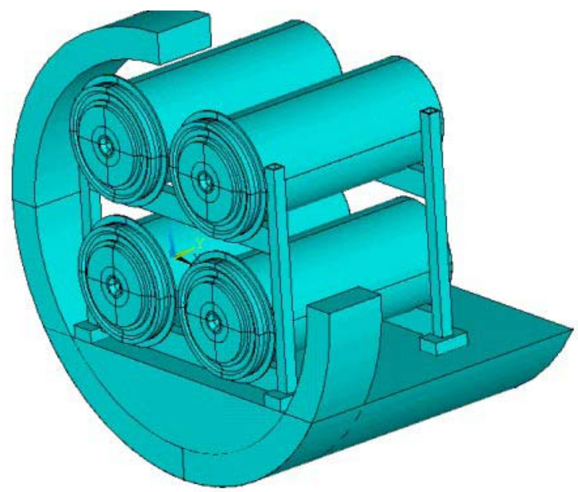
- **Challenges related mainly to intensity requirement**
  - target capable of handling 4 MW of protons
  - horn capable of handling 4 MW of protons
    - and operating at high repetition rate (50 Hz)
  - good charge selection (beam purity)

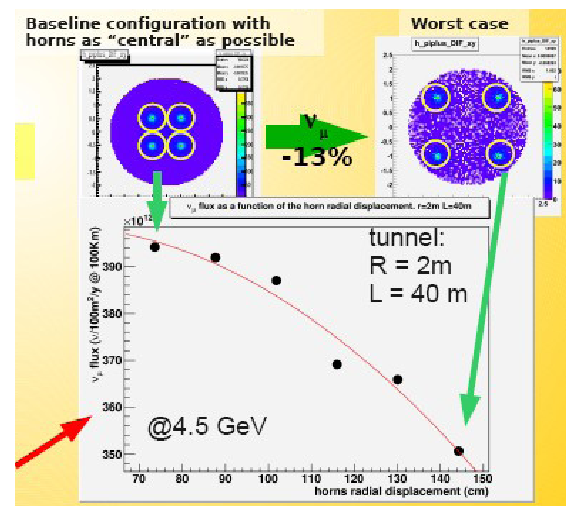
- **Target resides in close proximity to horn**
  - spatial constraints favor solid, or perhaps "contained" powder target
    - materials compatibility issues make Hg target impractical
  - cooling is difficult
  - high radiation environment
    - *need* to repair is inevitable
      - hands-on repair will not be possible

Proposed Approach-SB

- **Recent studies (Zito *et al.*, EUROnu WP2) based on**
  - low-Z target
  - multiple targets + horns
    - reduces power deposition
      - 4 MW → 4 x 1 MW
    - reduces repetition-rate requirement
      - 50 Hz → 4 x 12.5 Hz
  - single-horn optics (no reflector)
  - optimized horn shape





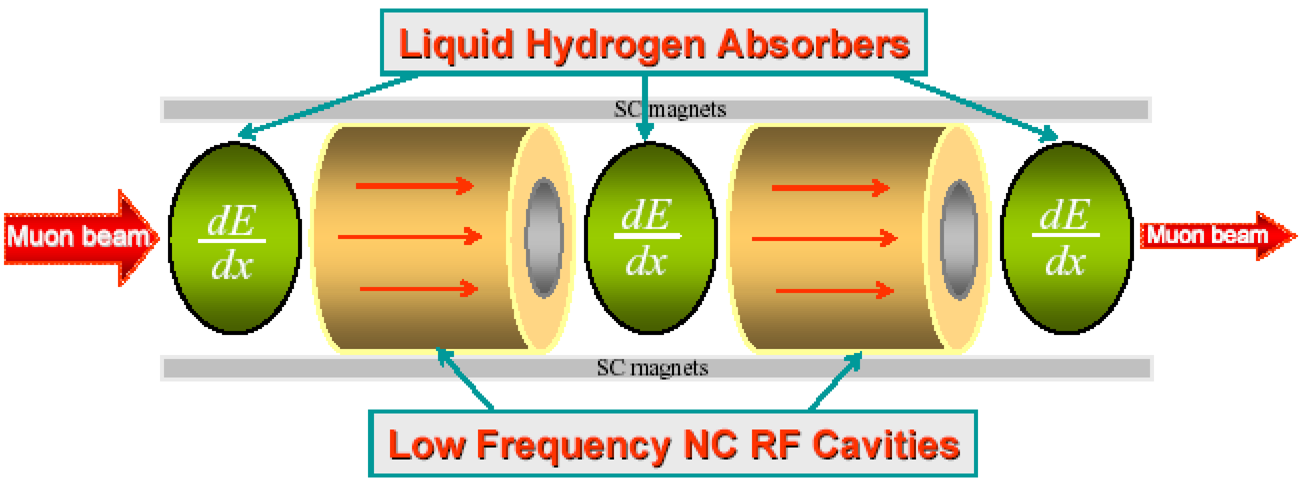


Technical Challenges-NF

- **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
- **Proposed approaches will be described**

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

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

Cooling   Heating

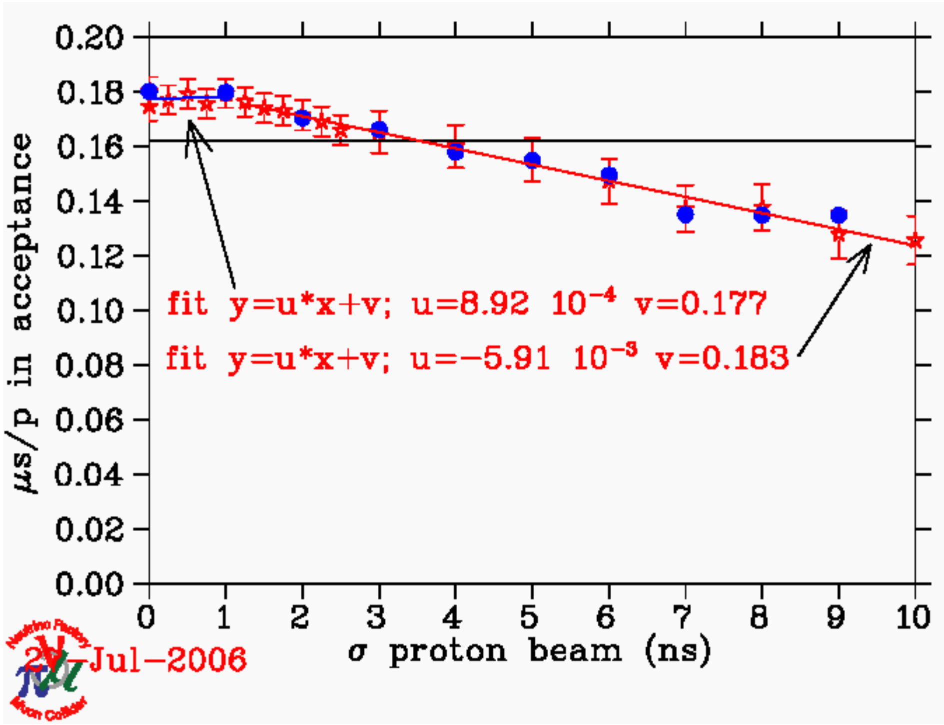
$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta m_\mu X_0 \left|\frac{dE_\mu}{ds}\right|}$$

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

Proton Parameters-NF

- **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**

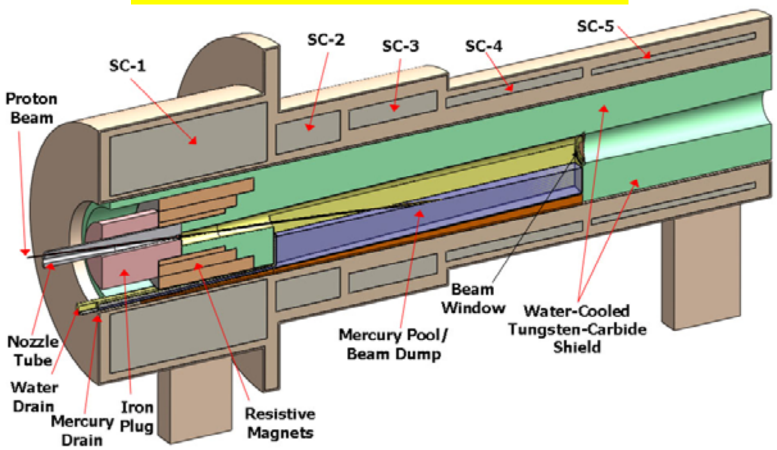


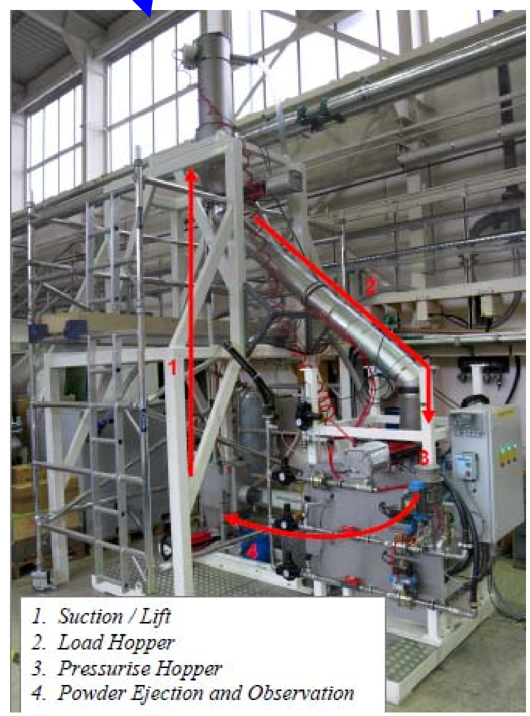
Difficult requirement at low beam energy (5-10 GeV)

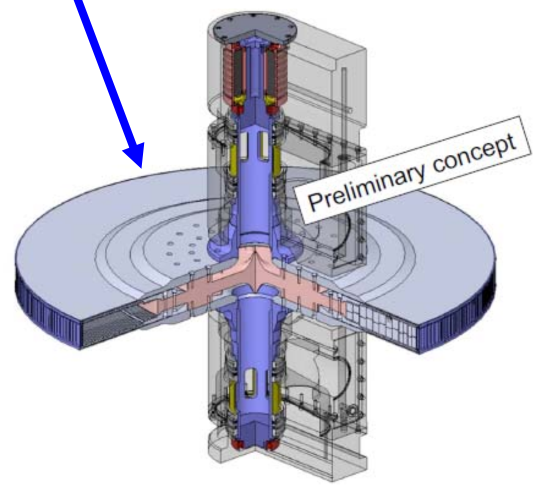
Target-NF

- **Favored target concept based on Hg jet in 20-T solenoid**
  - **jet velocity of 20 m/s establishes "new" target each beam pulse**
    - **magnet shielding remains an issue**
- **Alternatives approaches (powder or solid targets) also being pursued via EUROnu**

Hg jet target
(MERIT)

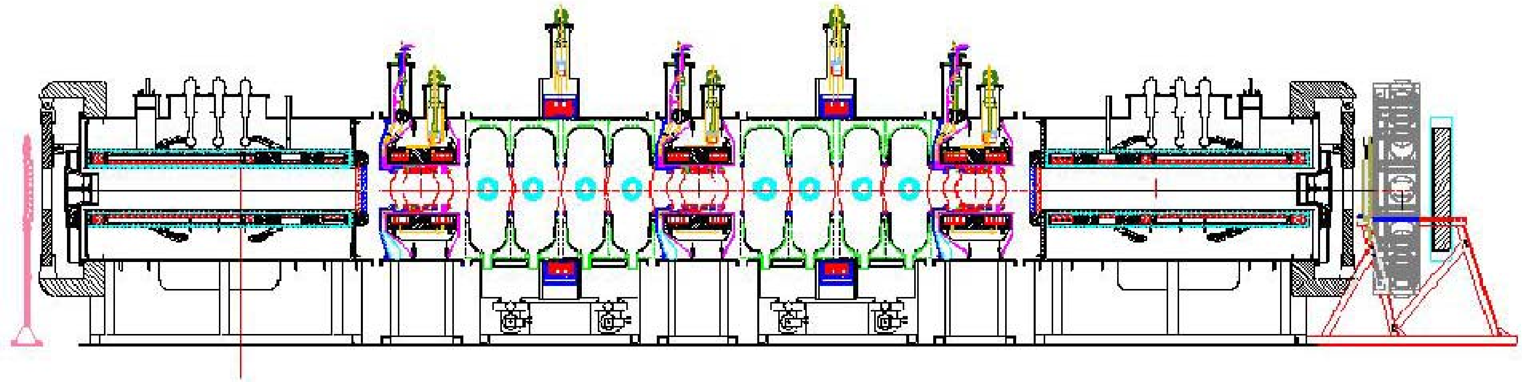


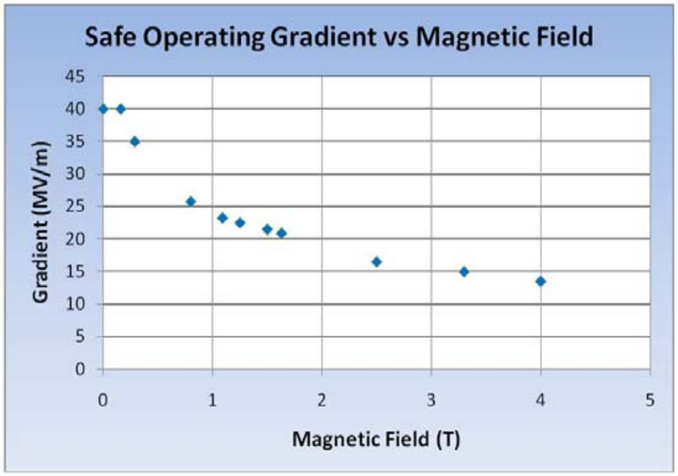




RF-NF

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

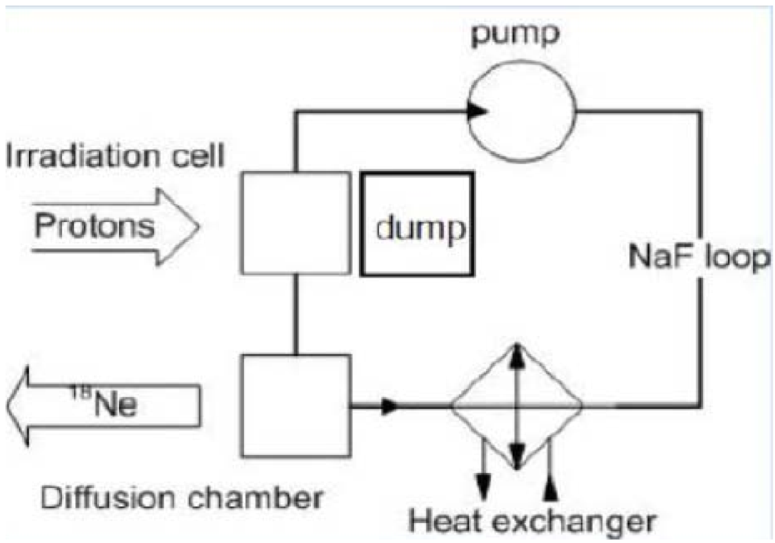




BB Technical Challenges (1)

- 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; ^{18}Ne is challenging, but appears possible with ^{19}F(p,2n)
    - higher *Z* atoms are produced in multiple charge states, with the peak at 25-30% of the total intensity

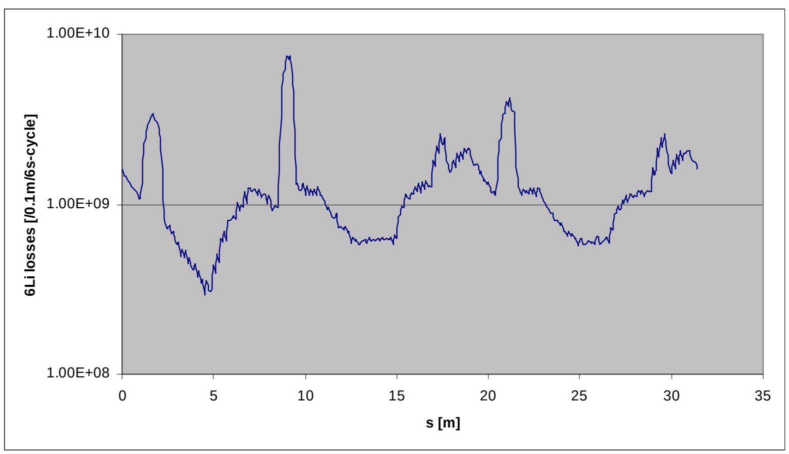
Molten NaF loop for ^{18}Ne production



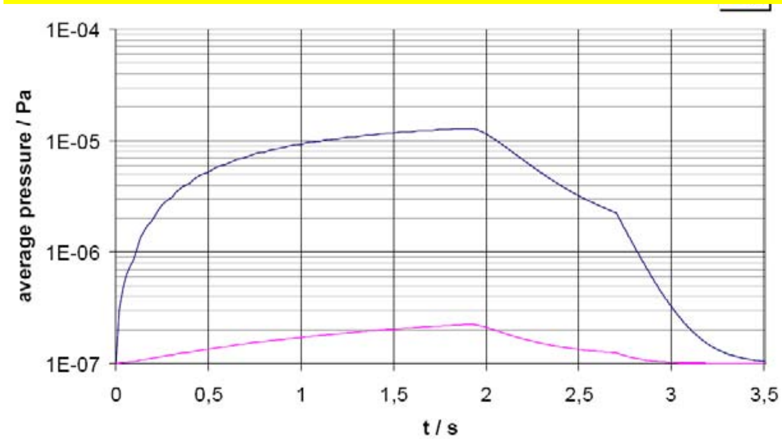
BB Technical Challenges (2)

- **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**
        - **issue considered manageable**

Predicted ^{6}Li losses in PS lattice



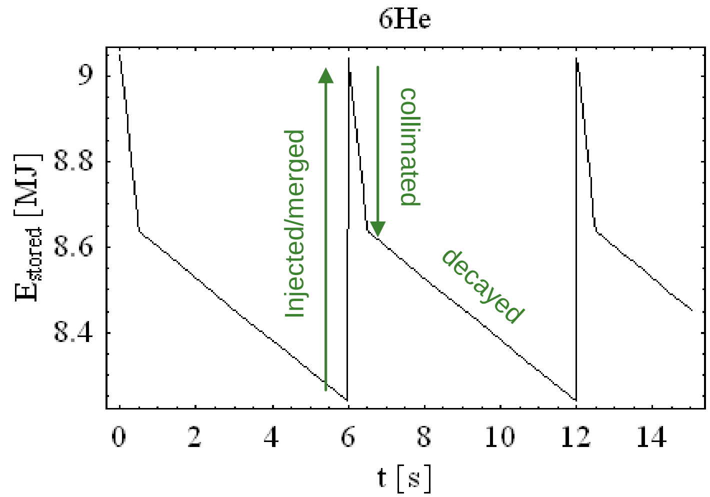
Pressure degrades to 75 ntorr from ^{6}He losses



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**

Predicted ^{6}He losses in decay ring



Decay losses also an issue:

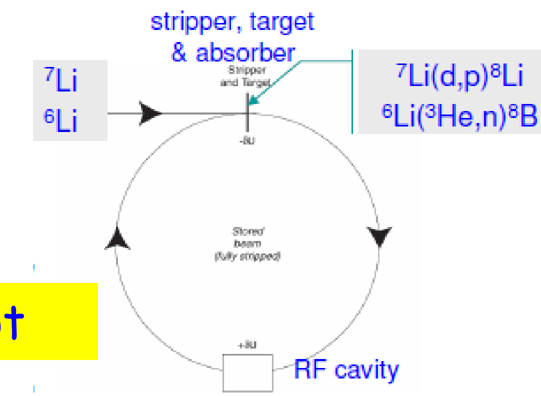
SC dipoles require 16 cm aperture and suffer ≈10 W/m heat load

R&D Activities

- To transform challenges to opportunities, worldwide R&D efforts are under way
  - of most interest here are those of EUROnu and IDS-NF
- Beta Beam
  - main items are ion production, collective effects, and RF issues
- Neutrino Factory
  - main items are target, cooling, and RF
- Superbeam
  - main items are target and horn

BB R&D (1)

- New concept for ^{8}Li, ^{8}B production proposed by **C. Rubbia *et al.***
  - based on ionization cooling of ions to maintain equilibrium emittance
  - design currently studied by Benedetto *et al.*
    - main drawback is required gas target thickness
      - 10^4 times that of existing jet targets

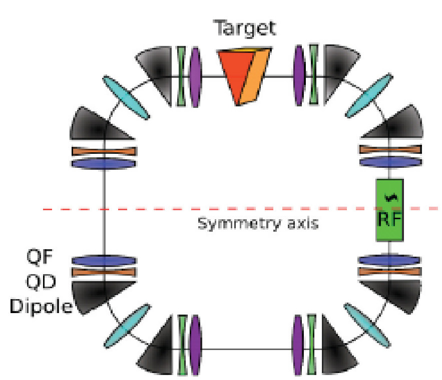


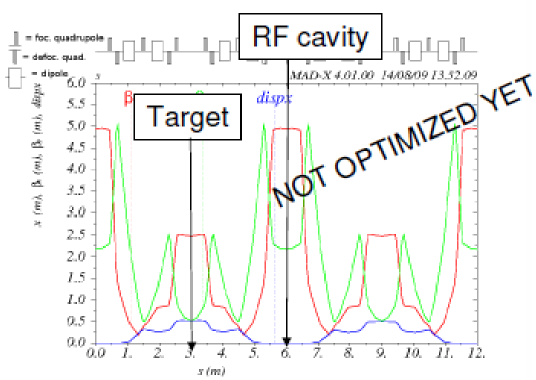
Concept

Layout

Optics

M. Schaumann, CERN-THESIS-2009-128

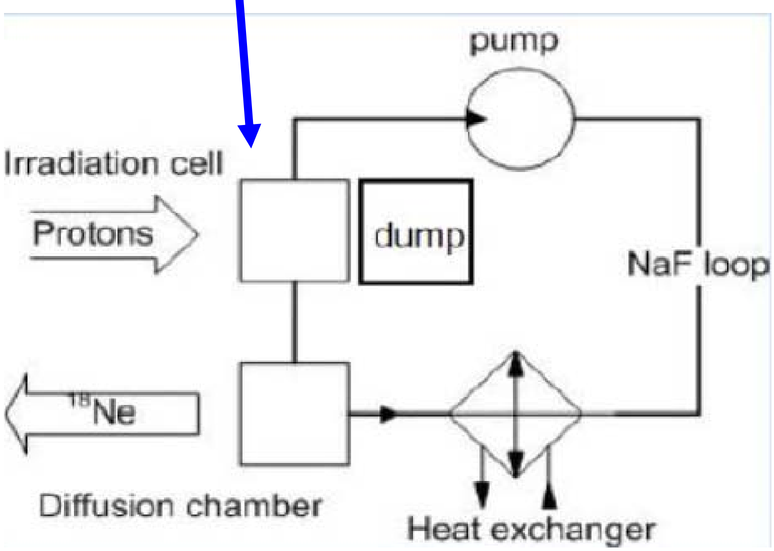


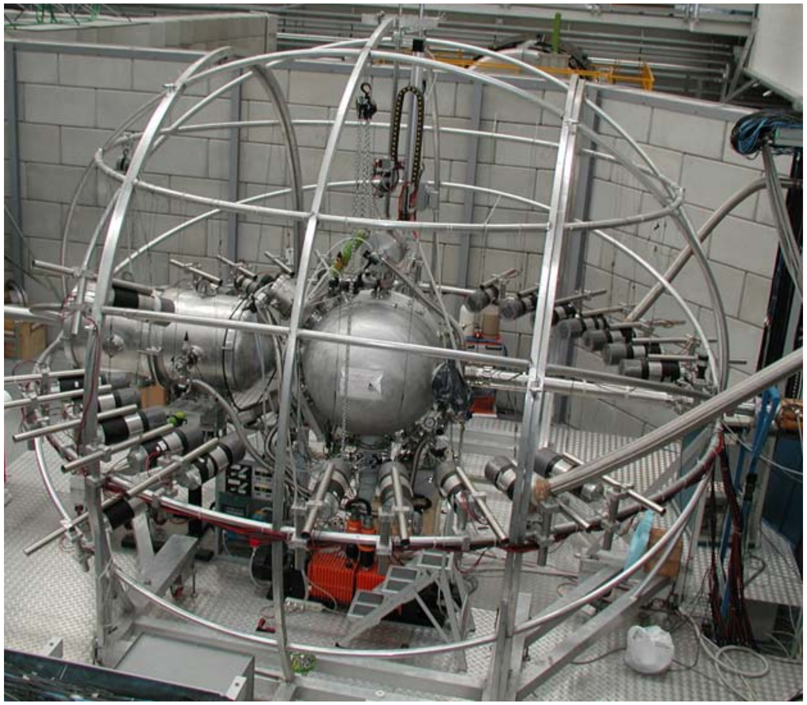


Particle		^{7}Li
Energy	E_c	25 MeV
Relativistic gamma	γ_r	1.00383
Beam rigidity	$B\rho$	0.636 T m
Transition γ	γ_t	3.58
Tune	$Q_{x,y}$	2.58, 1.63
Natural chromaticity	$Q'_{x,y}$	−3.67, −3.58
β @ target	$\beta^*_{x,y}$	2.62 m, 0.35 m
Dispersion @ target	$D^*_{x,y}$	0.523 m, 0 m
Target thickness	t_0	0.27 mg/cm^2
	n_t	10^{19} atoms/cm^2
Energy losses @ target	E_{BB}	$\sim$ 0.30 MeV

BB R&D (2)

- **Production cross sections for key reactions to be studied**
  - $^{7}Li(d,p)^{8}Li$
  - $^{6}Li(^{3}He,n)^{8}B$
  - $^{19}F(p,2n)^{18}Ne$



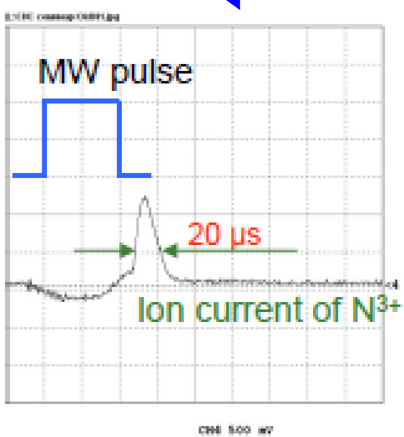


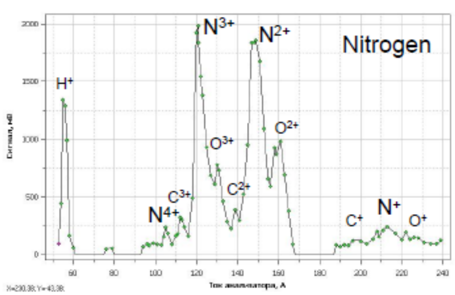
RipeN @ Legnaro

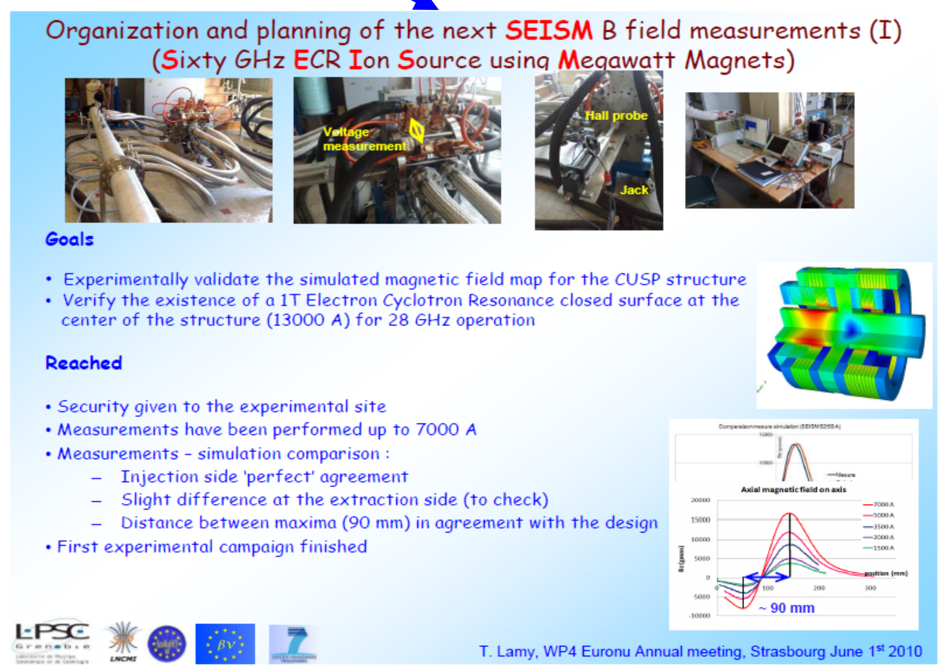
BB R&D (3)

- Ion source technology for re-ionizing secondary beam is being pursued
  - SEISM (Sixty GHz ECR Ion Source using Megawatt Magnets)
  - 37 GHz Gyrotron

V. Zorin

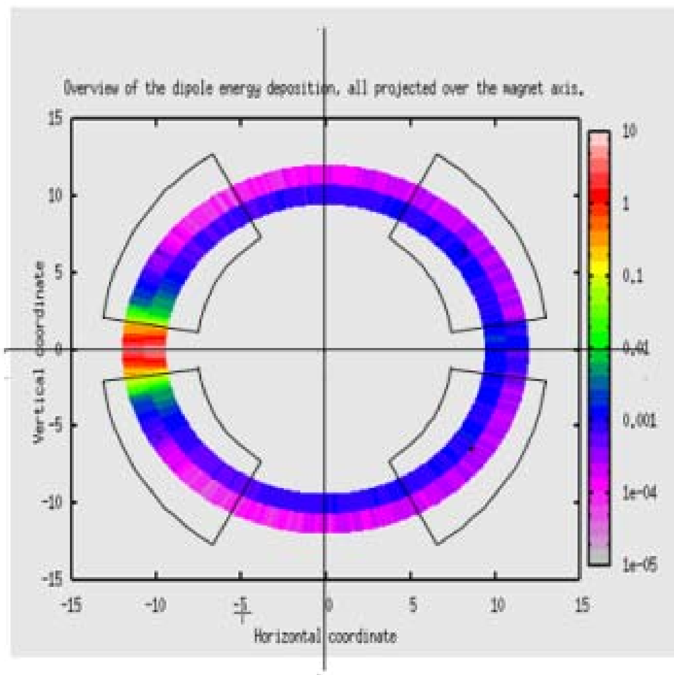






BB R&D (4)

- Radiation effects from ion decays in Decay Ring have been studied
  - magnet solutions exist
    - open mid-plane designs
    - thick liners
- Collimation not yet studied

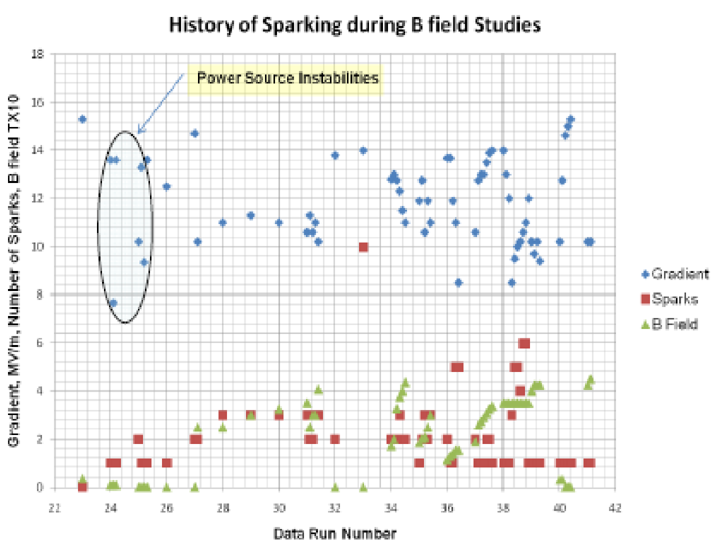


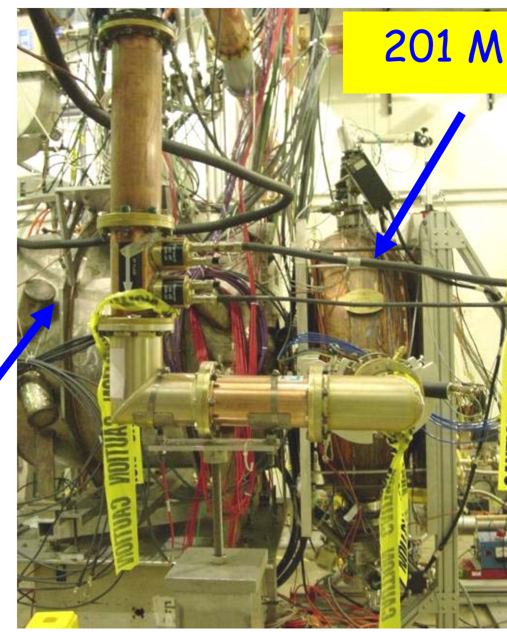
NF R&D

- R&D program has three main thrusts
  - simulation and theory
  - technology development
    - high-power target, cooling channel and acceleration system
  - system tests of target (MERIT) and cooling (MICE)
- Recent simulation effort has focused on simplifying NF design to optimize performance and reduce costs
  - work done in conjunction with IDS-NF (and EUROnu WP3)
- Technology development challenge is RF in magnetic field
- System test work focused on MICE
  - involves many international partners

MuCool R&D (1)

- **MuCool program does R&D on cooling channel components in MuCool Test Area at Fermilab**
  - RF cavities, absorbers
- **Motivation for cavity test program: observed degradation in cavity performance when strong magnetic field present**
  - 201 MHz cavity easily reached 21 MV/m without magnetic field
  - initial tests in fringe field of Lab G solenoid show some degradation
    - and lots of scatter

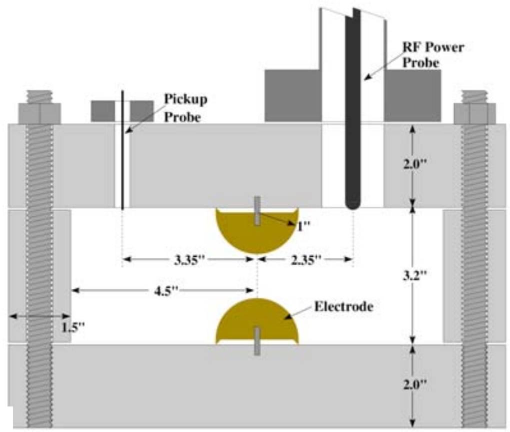


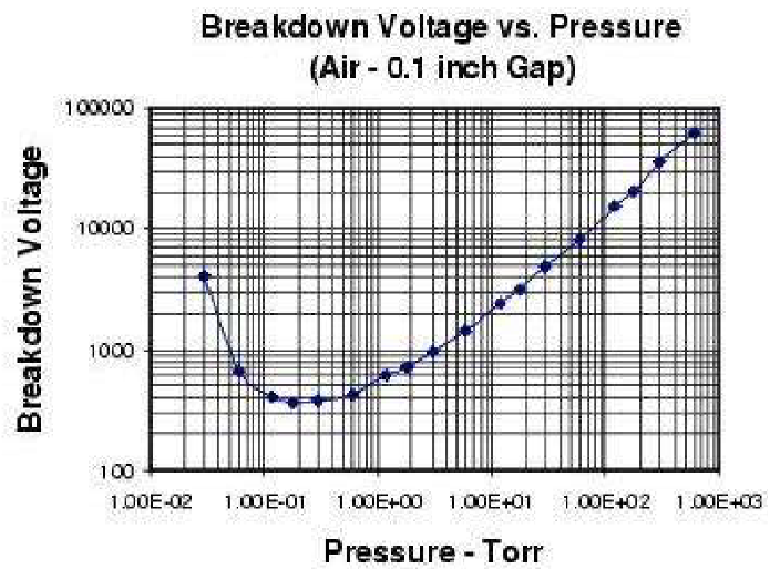


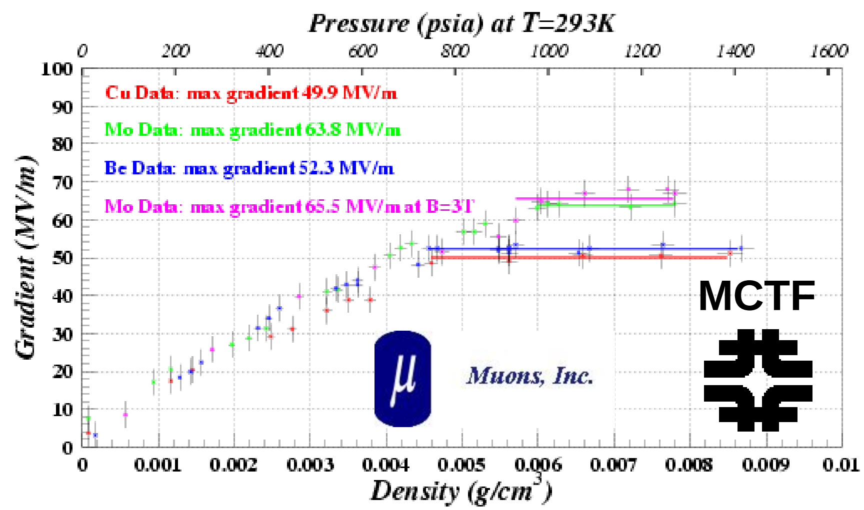
MuCool R&D (2)

- **Tested pressurized button cavity at MTA** FNAL + Muons, Inc.
  - **use high-pressure H_2 gas to limit breakdown (⇒ no magnetic field effect)**

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







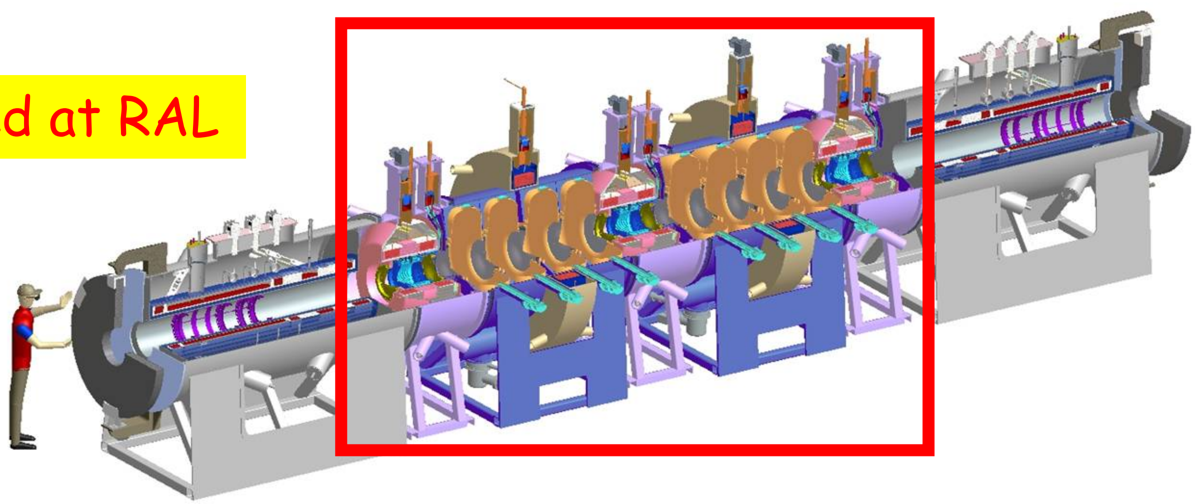
MICE

- Neutrino Factory (≈10^{21} ν_e aimed at far detector per 10^7-s year) or Muon Collider depends on ionization cooling
  - straightforward physics but not experimentally demonstrated
  - facility will be expensive (O(1B$)), so prudence dictates a demonstration of the key principle
- Cooling demonstration aims to:
  - design, engineer, and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
  - place this apparatus in a muon beam and measure its performance in a variety of modes of operation and beam conditions
- Another key aim:
  - show that design tools (simulation codes) agree with experiment
    - gives confidence that we can optimize design of an actual facility
- Getting the components fabricated and operating properly is teaching us a lot about both the cost and complexity of a muon cooling channel
  - measuring the "expected" cooling will serve as a proof of principle for the ionization cooling technique

System Description

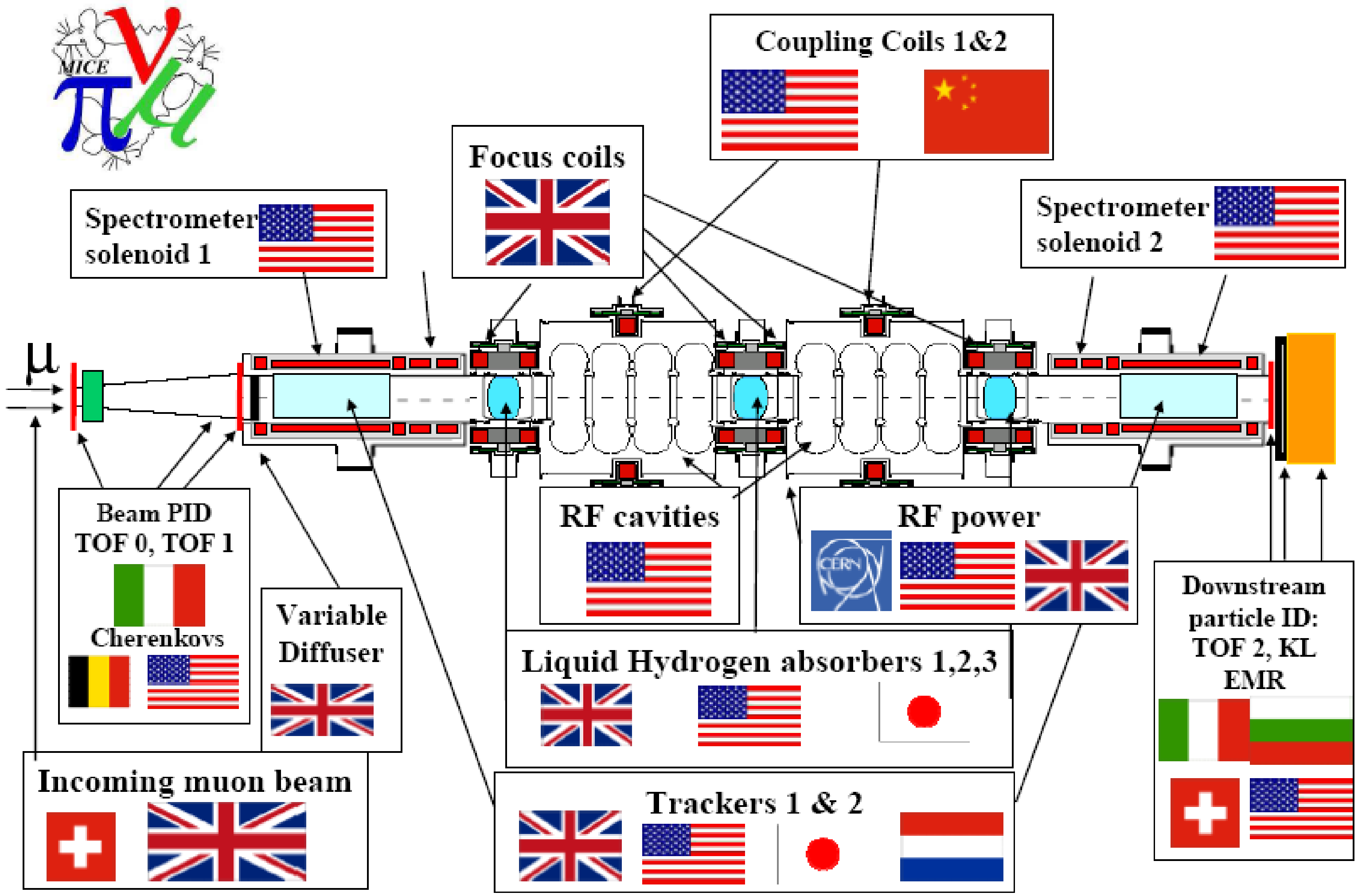
- **MICE includes one cell of the FS2 cooling channel**
  - three Focus Coil (FC) modules with absorbers (LH_2 or solid)
  - two RF-Coupling Coil (RFCC) modules (4 cavities per module)
- **Along with two Spectrometer Solenoids with scintillating fiber tracking detectors**
  - plus other detectors for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

Experiment sited at RAL



MICE Contributors

- Many international partners contributing



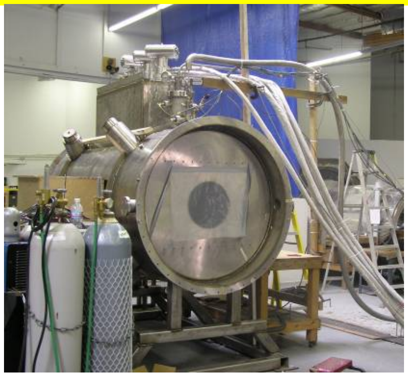
Status of MICE

- **Civil engineering nearly completed**
  - **main "missing piece" is RF infrastructure for Steps 5 and 6**
    - **installation of RF power sources and connection of RF power to cavities**

Cooling Channel Components

- **All cooling channel components are now in production**

Spectrometer Solenoid (Wang NMR)

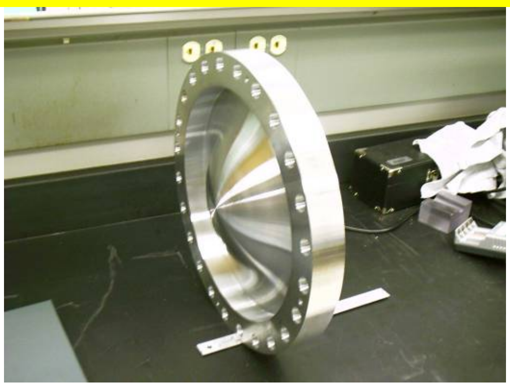


CC large test coil (HIT)

CC winding (Qi Huan Co.)

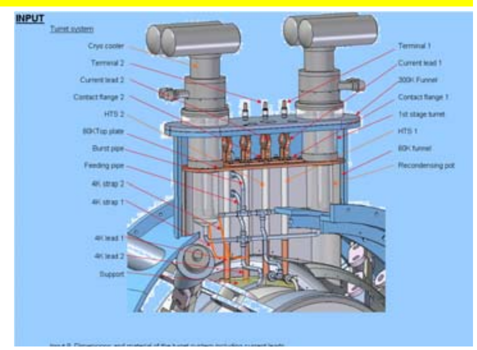
Absorber (KEK)

Absorber window (U-Miss)



Cavity at LBNL (Applied Fusion)

FC (Tesla Eng., Ltd.)



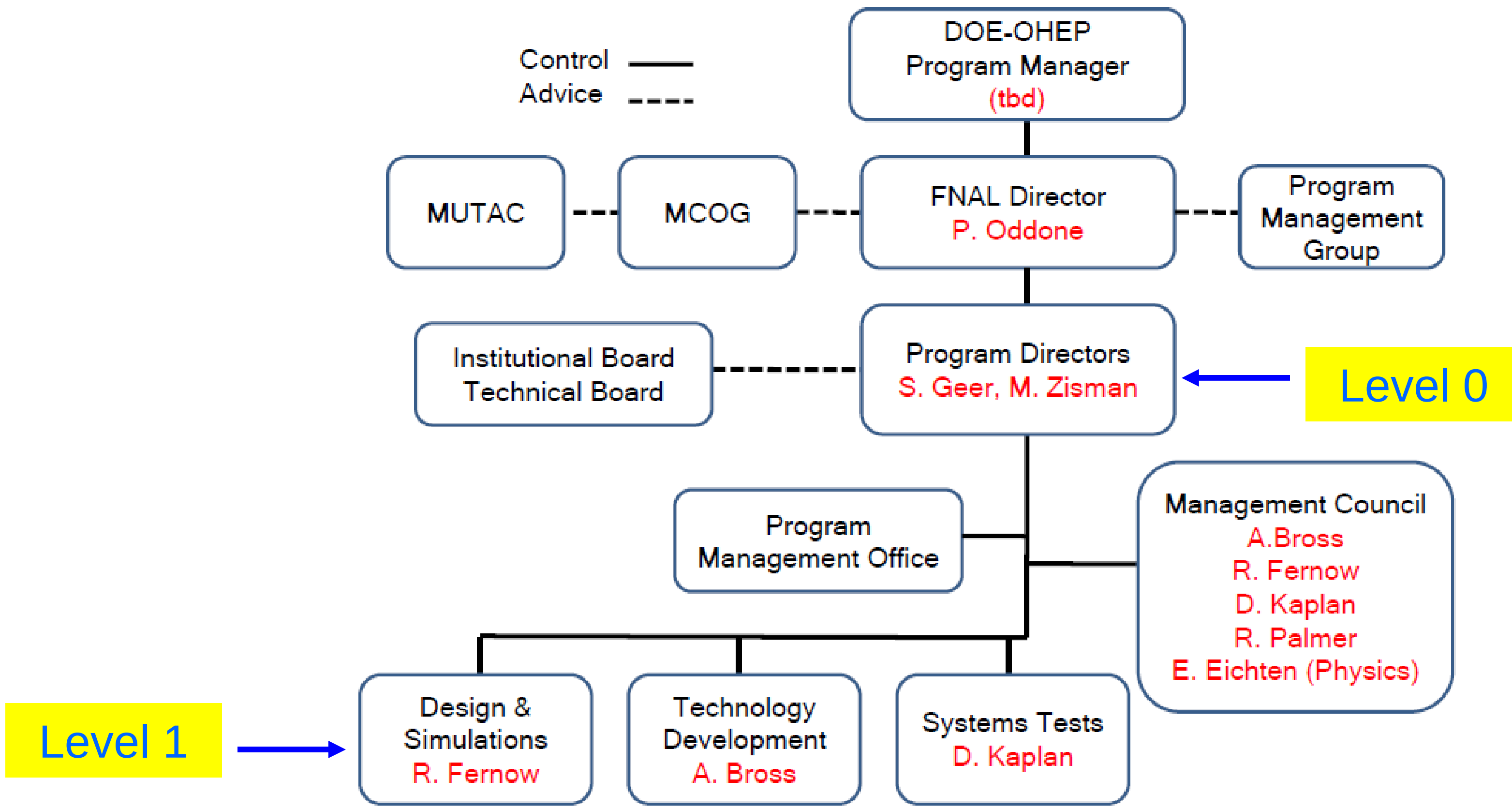
EMMA

- **EMMA testing an electron model of a non-scaling FFAG**
  - **aim:**
    - **demonstrate feasibility of non-scaling FFAG concept**
      - **investigate longitudinal dynamics, transmission, emittance growth, influence of resonances**
  - **commissioning under way at Daresbury Lab**

EMMA ring (C = 16.57 m)

Muon Accelerator Program

- **NFMCC and Fermilab MCTF jointly proposed a 7-year R&D plan to DOE**
  - *successful review took place in August 2010*



MAP R&D Plan

- Main deliverables
  - design and simulations
    - MC Design Feasibility Study (DFS)
      - intended to be a "high-end" feasibility study
        - includes associated physics and detector studies
        - engineering and costing not fully detailed
        - defines R&D program (extending beyond initial plan)
    - NF RDR (under IDS-NF auspices)
      - help with engineering and costing (select areas)
      - participate in accelerator design of various subsystems
  - component development and testing
    - demonstration of key technologies
      - sufficient to allow down-selection of cooling channel schemes
        - may not be able to pick unique optimal scheme, but will identify the most promising approaches
  - system tests of 4D and 6D cooling
    - participate in MICE and 6D "bench test" (no beam)

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,...

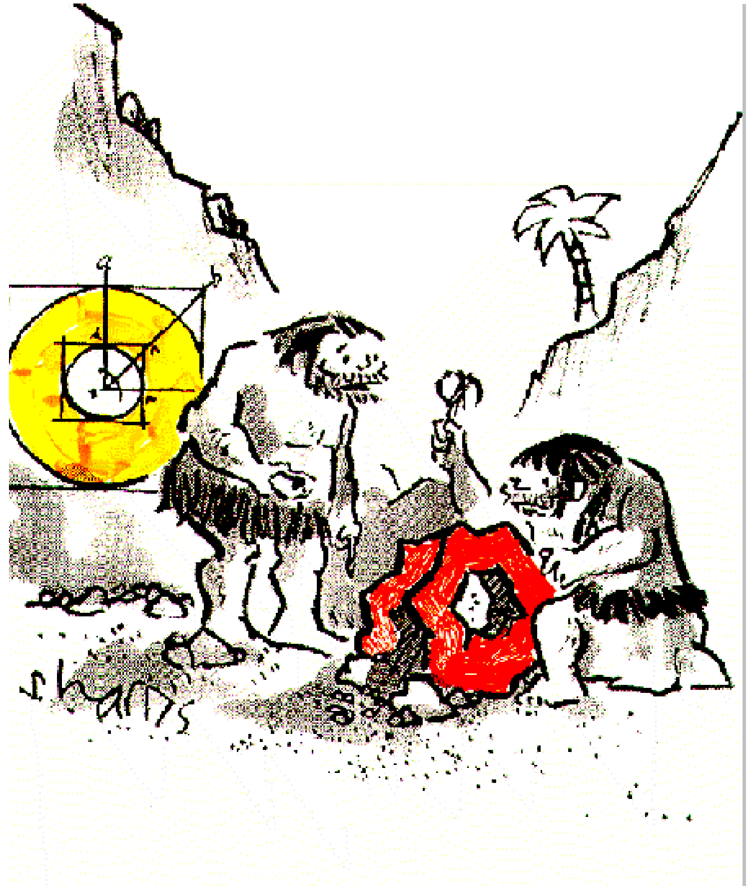
- R&D discussed here represents worldwide efforts
  - carried out in coordinated fashion internationally
    - by choice, not dictated externally

- Thanks to all my accelerator colleagues for sharing both their expertise and their enthusiasm

Final Thought

Paper studies alone are *not enough*

We need to build and test things!



"I guess there'll always be a gap between science and technology."