Accelerator Options
for
Possible 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 Superbeam facility based on the decays of an intense pion beam
  - 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*
- 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
    - a real service to our community!

Physics Context

- Superbeam gives ~98% muon neutrinos ($\pi \rightarrow \mu + \nu_\mu$)
- Beta beam gives only electron neutrinos
  - $^6He \rightarrow {}^6Li + e^- + \bar{\nu}_e$
  - $^{18}Ne \rightarrow {}^{18}F + e^+ + \nu_e$

Baseline scenario produces low energy neutrinos

- Neutrino Factory beam gives both electron and muon neutrinos

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

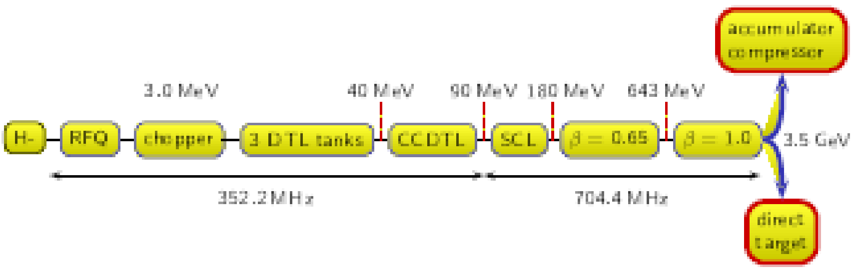
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

Produces high energy neutrinos, above τ threshold

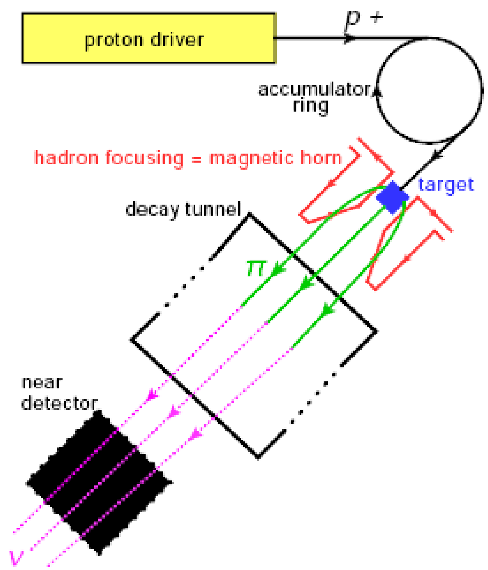
- Electron neutrinos are most favorable to do the science
  - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable "wrong-sign" μ
    - do not get ν_e from "conventional" neutrino beam line

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

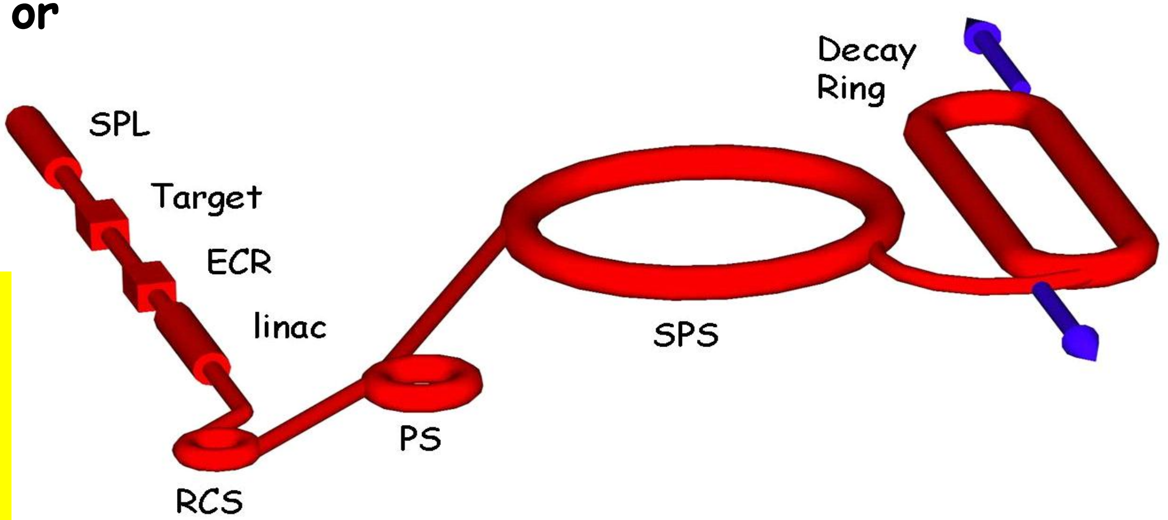
Beta Beam

- 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)

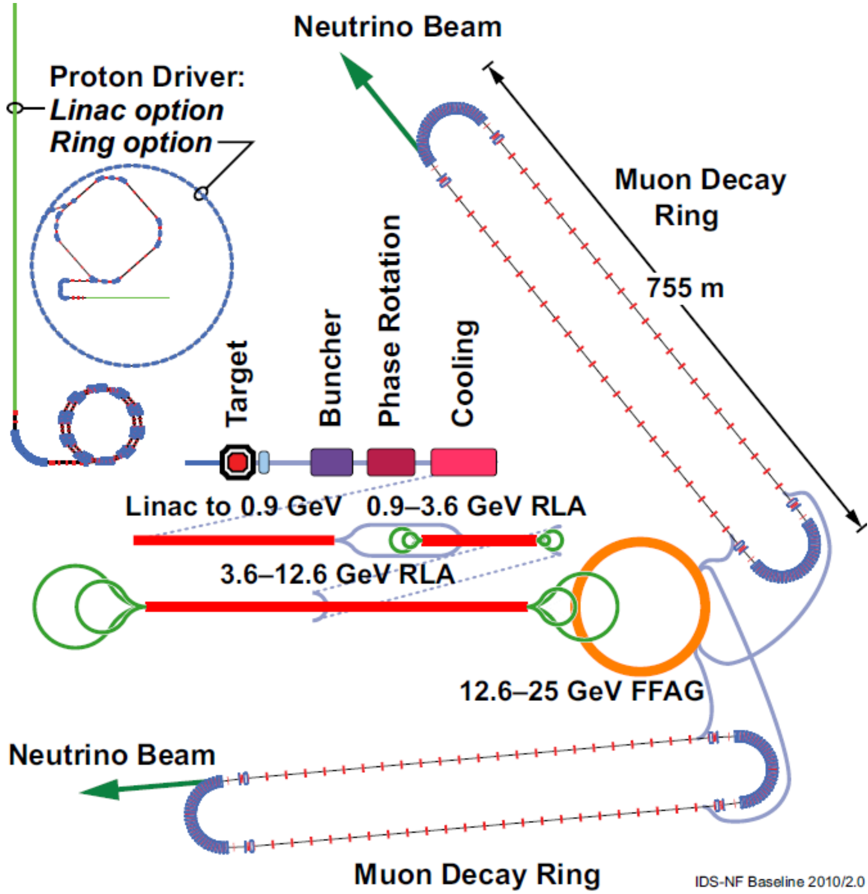
High-*Q* version (^{8}Li,^{8}B)



Neutrino Factory

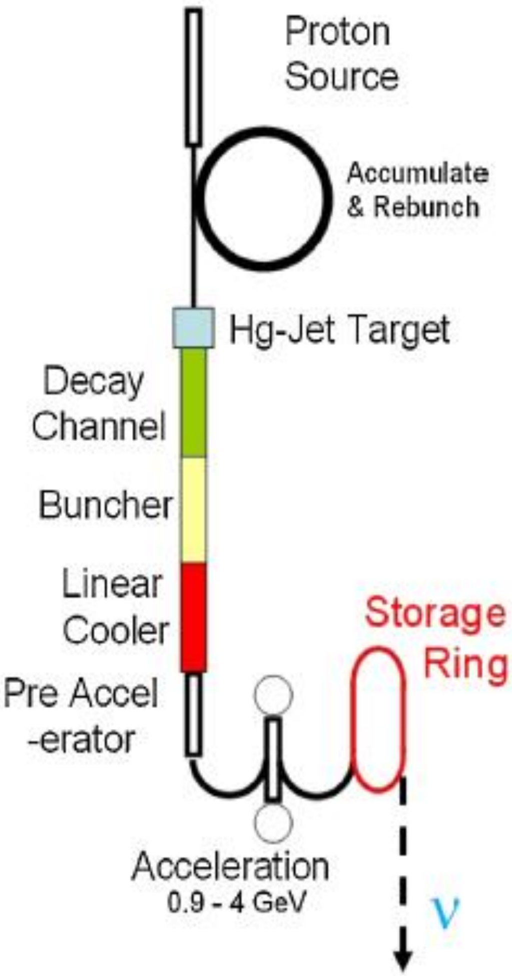
- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target ⇒ HARP
  - Target, Capture, and Decay
    - create π; decay into μ ⇒ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance ⇒ MICE
  - Acceleration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



Commonality

- A common feature of *all* future neutrino facilities is the requirement for substantially increased quantity of data
  - ⇒ need for intense particle sources
  - ⇒ need for very large detectors

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

- All current approaches to giving the requisite number of neutrinos rely on production of secondary, or even tertiary, beam

Strengths

- Superbeam
  - closest to today's technology
  - likely to be the least expensive (≠ inexpensive!)
- Beta Beam
  - ability to make use of CERN infrastructure
  - potential synergy with nuclear physics interests on isotope production
  - clean beam (only electron neutrinos)
    - requires combination with Superbeam to fully extract the physics
- Neutrino Factory
  - best sensitivity (⇒ best physics reach)
  - both electron and muon neutrino beams available simultaneously
  - synergy with intense muon and/or muon collider programs (staging possible)

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)

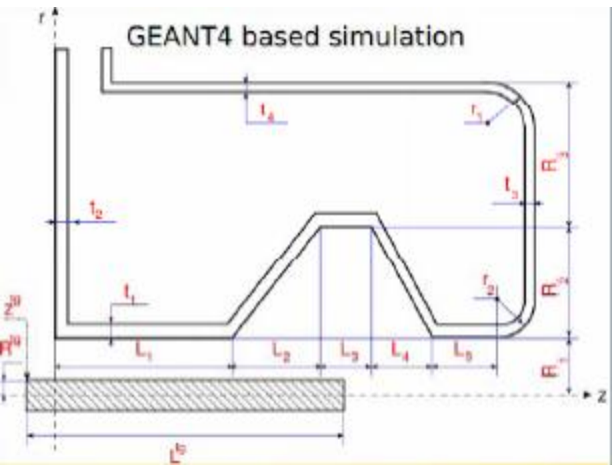
- Target resides in close proximity to horn
  - spatial constraints favor solid, or perhaps powder target
    - materials compatibility issues make Hg target impractical
  - cooling is difficult
  - high radiation environment
    - *need* to repair is inevitable
      - hands-on repair will not be possible

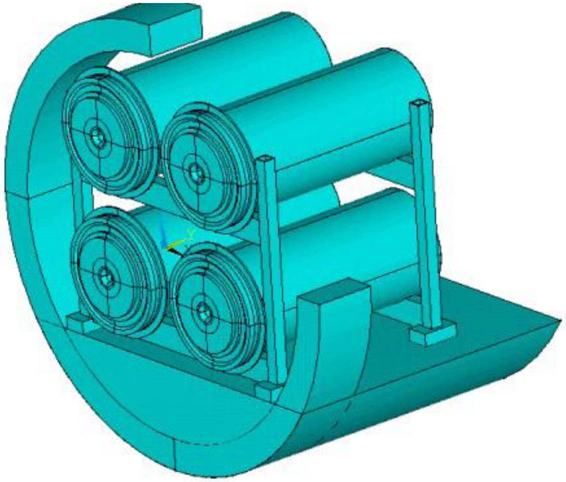
Proposed Approach-SB

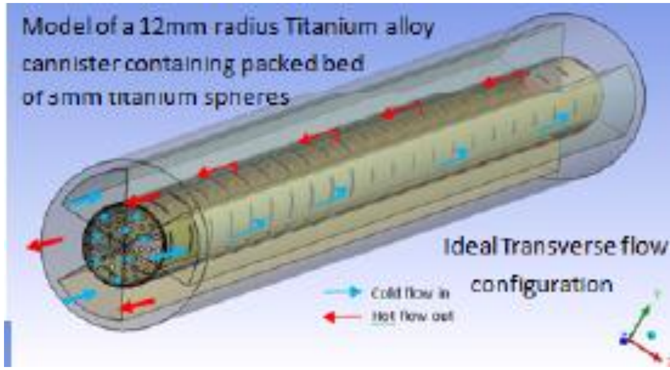
- Recent studies (Zito *et al.*, EUROnu WP2) based on
  - low- or medium-*Z* target
  - multiple targets + horns
    - reduces power deposition
      - 4 MW → 4 x 1 MW
    - reduces repetition-rate requirement
      - 50 Hz → 4 x 12.5 Hz
  - single-horn optics (no reflector)
    - optimized horn shape

Challenges of more complex proton beam optics and horn repair/replacement remain

Pebble-bed target





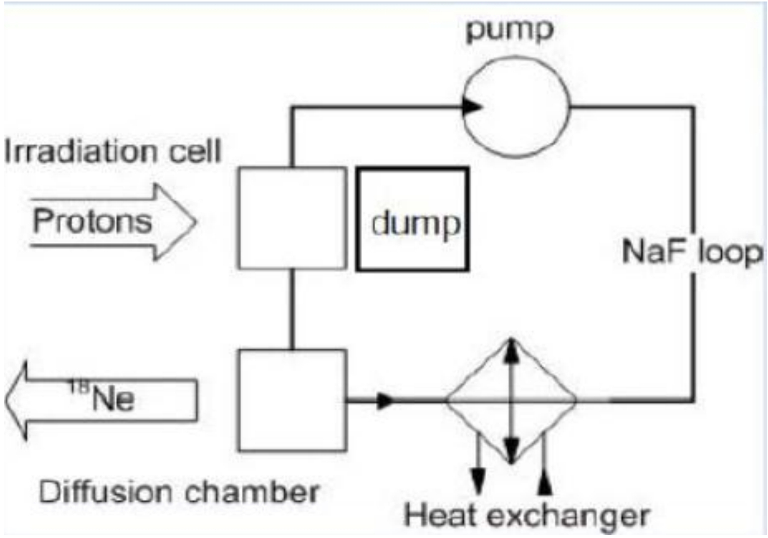


BB Technical Challenges (1)

- **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

Test experiment approved at CERN



BB Technical Challenges (2)

- Collective effects (Hansen, Chance)
  - transverse mode coupling in Decay Ring presently limits intensities
    - exploring modified ring designs to mitigate effect
      - low duty factor (0.5%) exacerbates this difficulty
  - SPS may also present challenges
    - work to understand this in progress

	Bunch Intensity Limit, N_b^{th}		
	[e12]	[N_b^{nom}]	[N_b^{nom}]
^{18}Ne	1.2	0.3	0.6
^{6}He	10	2.1	1.0
^{8}B	2.1	0.2	0.6
^{8}Li	5.9	0.2	0.6

A. Donini, Summary on Beta-Beams

Ions	Fluxes [10^{18}]	Years	$(\sin^2 2\theta_{13})_{min}$	NH,$(\sin^2 2\theta_{13})_{min}$
^{6}He	$\Phi_0 = 2.9$	5	5×10^{-4}	No Sensitivity
^{18}Ne	$\Phi_0 = 1.1$	5		
^{8}Li	$\bar{\Phi}_0 \times 5$	5	2×10^{-4}	8×10^{-3}
^{8}B	$\Phi_0 \times 5$	5		
^{6}He	$\bar{\Phi}_0 \times 2$	2	6×10^{-4}	No Sensitivity
^{18}Ne	$\Phi_0/2$	8		
^{8}Li	$\bar{\Phi}_0 \times 2$	5	7×10^{-4}	1.5×10^{-2}
^{8}B	$\Phi_0 \times 2$	5		

- Note; In Donini's table SF = 10^{-4} while we are using SF = $5 \cdot 10^{-3}$

NF Technical Challenges (1)

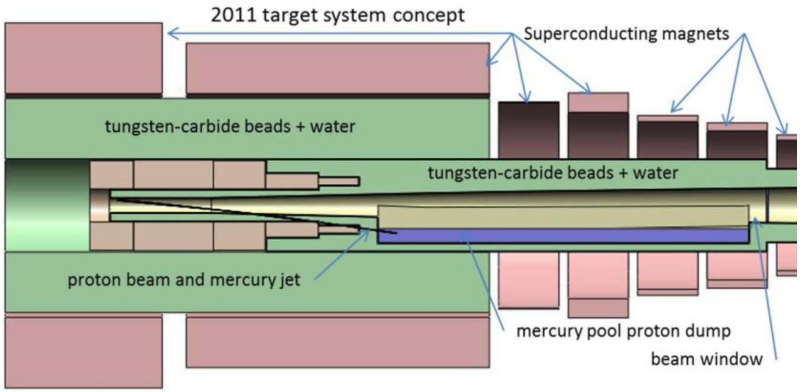
- **Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)**
  - low production rate
    - need target that can tolerate multi-MW beam
  - large energy spread and transverse phase space
    - need emittance cooling
    - high-acceptance acceleration system and decay ring

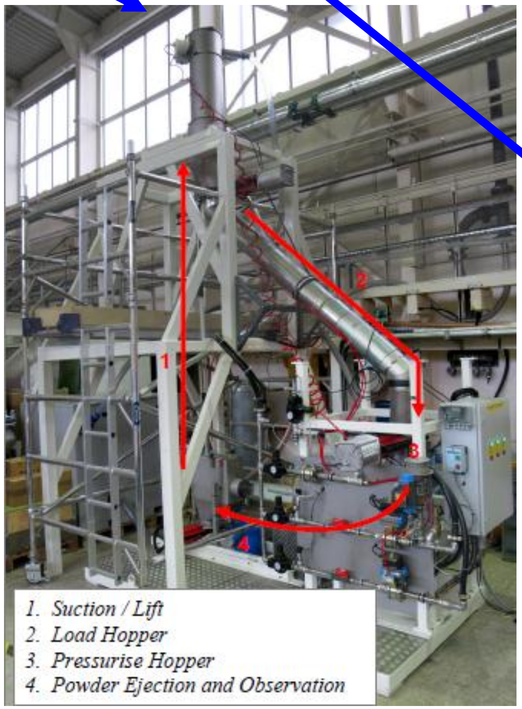
- **Muons have short lifetime (2.2 μs at rest)**
  - puts premium on rapid beam manipulations
    - high-gradient RF cavities (in magnetic field for cooling)
    - presently untested ionization cooling technique
    - fast acceleration system

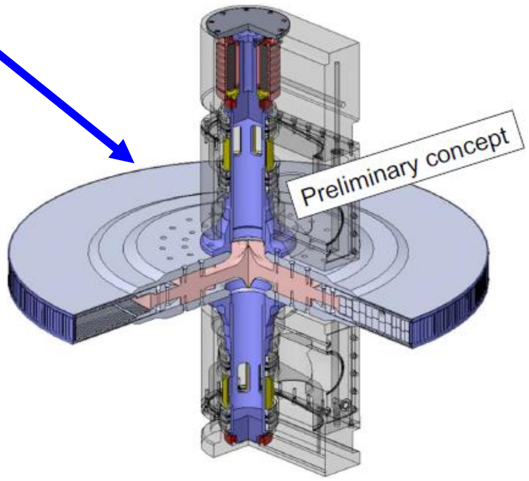
NF Technical Challenges (2)

- Target
  - 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 is daunting, but appears manageable
  - alternative approaches (powder or solid targets) also being pursued within EUROnu

Hg-jet target (MERIT)

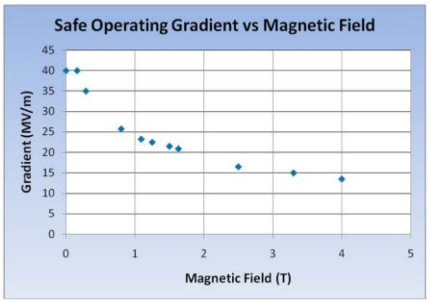






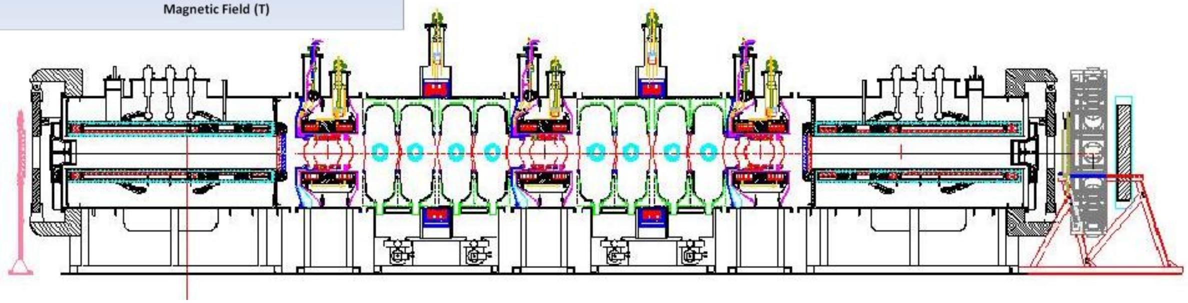
NF Technical Challenges (3)

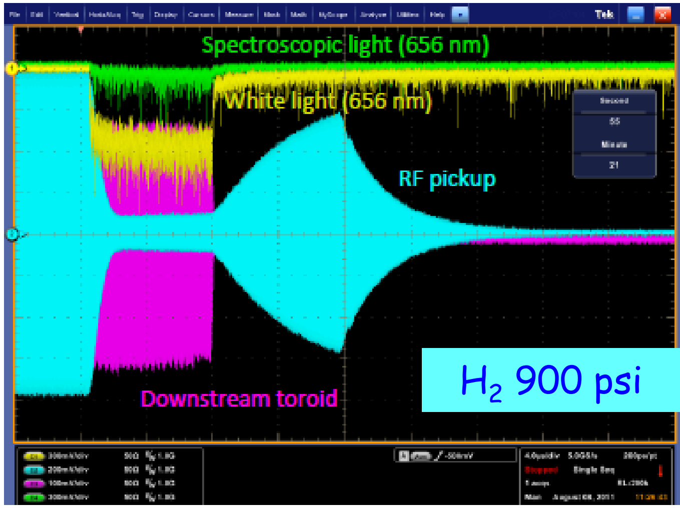
- Normal conducting RF in magnetic field
  - cooling channel requires this
    - 805-MHz experiments indicate substantial degradation of gradient in such conditions
      - initial 201-MHz tests show similar behavior (coupler issue?)
    - gas-filled cavities avoid performance degradation in magnetic field
      - effects of intense ionizing radiation traversing gas now under study
        - first indications are that beam loading is severe



Operating at lower gradient reduces intensity gradually

$\Rightarrow$ not a "show-stopper"





R&D Activities

- To transform challenges to opportunities, worldwide R&D efforts are under way
  - of most interest in this context are those of EUROnu and IDS-NF
    - U.S. contributions to these studies via MAP
- Superbeam
  - main items are target and horn
    - proton beam delivery also needs attention
- Beta Beam
  - main items are ion production, collective effects, and beam loss issues
- Neutrino Factory
  - main items are target, cooling (MICE), and RF (MuCool)
    - see S. Henderson talk later today

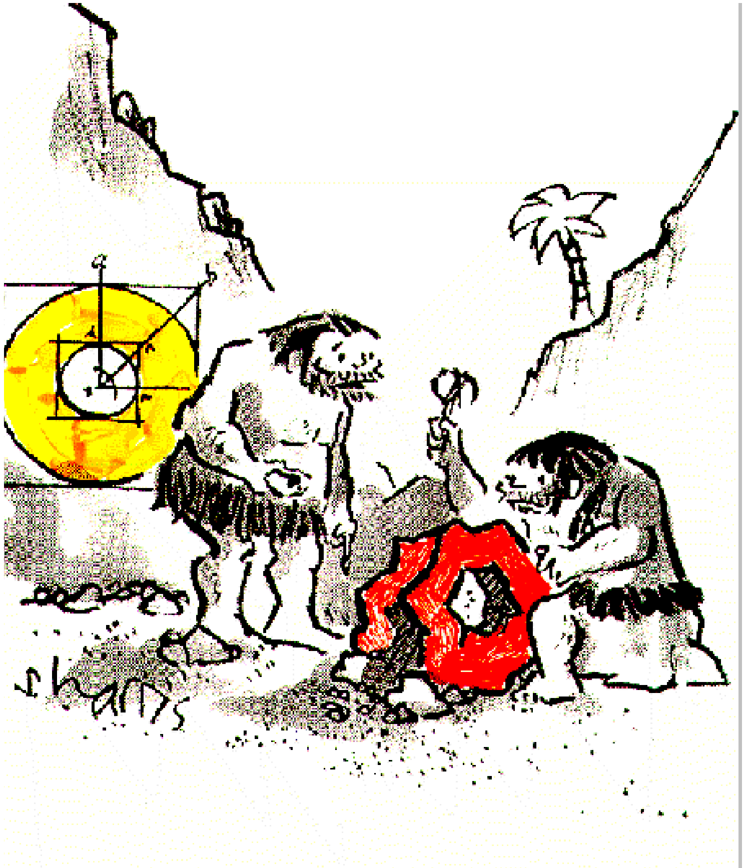
Summary

- Substantial progress being made toward designs of accelerator-based neutrino facilities to study CP violation in the lepton sector
  - challenges are understood and being overcome
- Work extends state-of-the-art in accelerator science
  - high-power targets, new cooling techniques, ion source development, rapid acceleration techniques,...
- Need to guard against putative project timescales (e.g., "far-future") becoming self-fulfilling prophecy
  - should consider merits of revolutionary *vs.* evolutionary approach
    - going slowly is *not* usually cheaper
- Thanks to all my accelerator colleagues in EUROnu, IDS-NF, MAP, and MICE for sharing both their expertise and their enthusiasm

Final Thought

Paper studies alone are *not enough*

We need to build and test things!

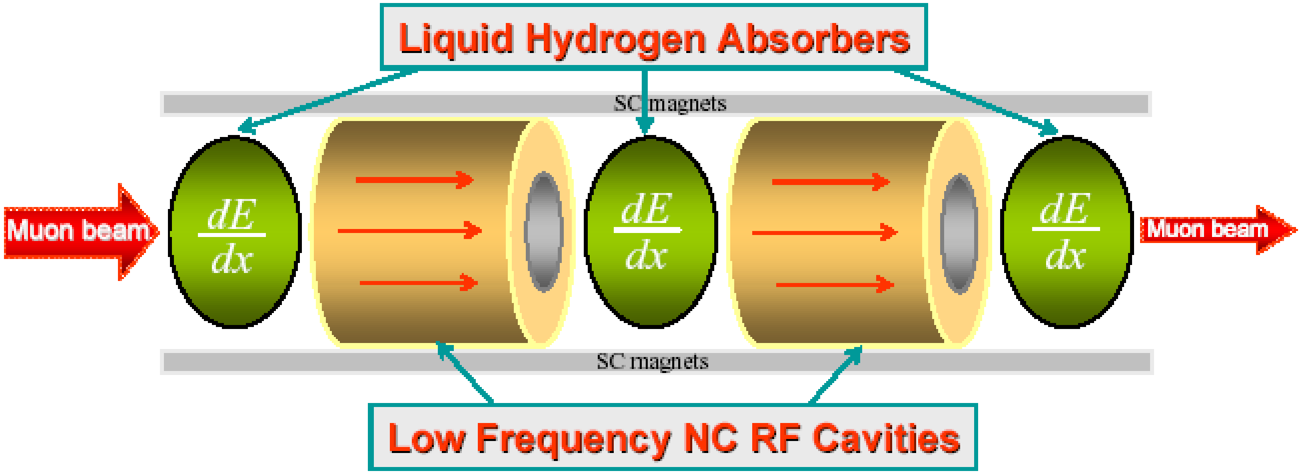


"I guess there'll always be a gap between science and technology."

Backups

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)

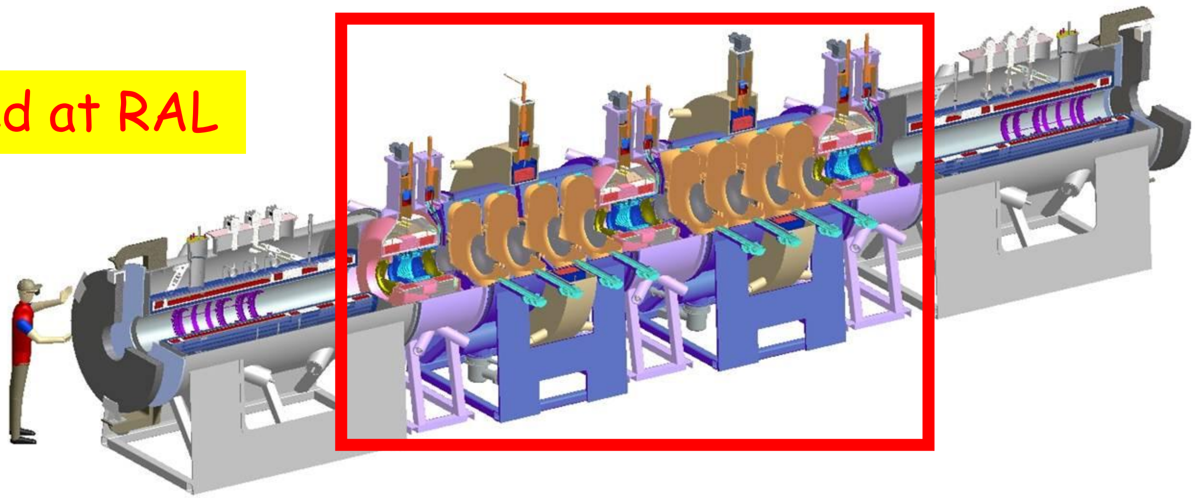
MICE

- 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 teaches us 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

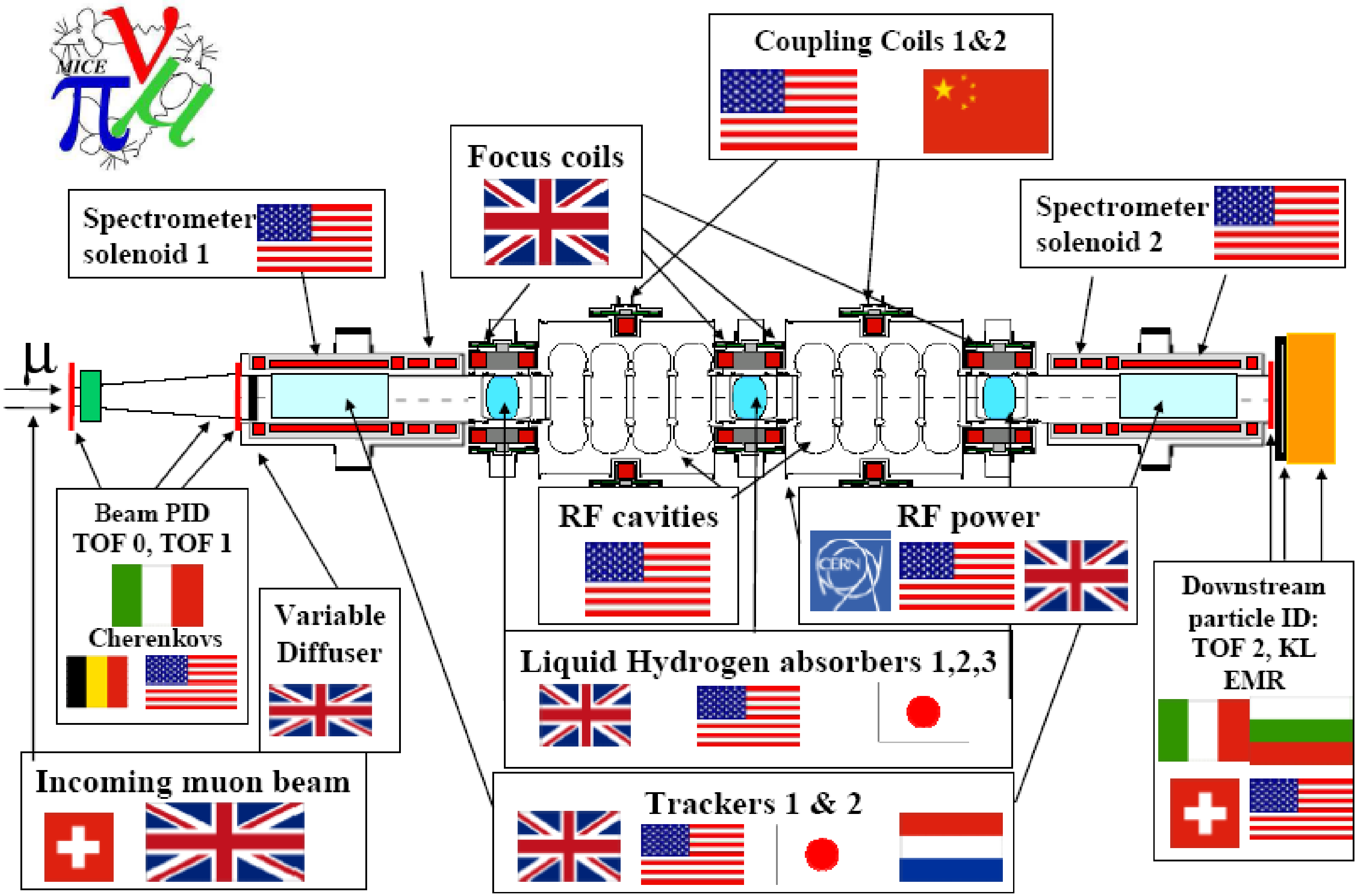
- **MICE includes one cell of the FS2 cooling channel**
  - three Focus Coil (FC) modules with absorbers (LH_2 or solid)
  - two RF-Coupling Coil (RFCC) modules (4 cavities per module)
- **Along with two Spectrometer Solenoids with scintillating fiber tracking detectors**
  - plus other detectors for 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



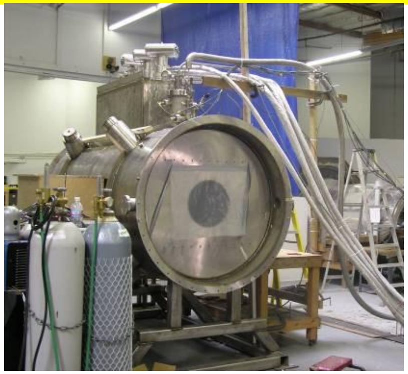
Status of MICE

- **Beam line commissioned**
  - paper describing results in preparation
- **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
- **Awaiting completion and installation of cooling channel hardware**

Cooling Channel Components

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

Spectrometer Solenoid (Wang NMR)

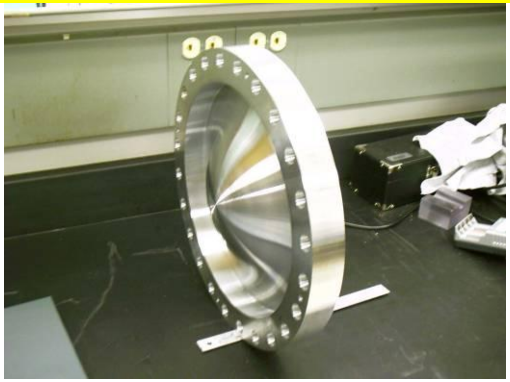


CC completed coil (Qi Huan Co.)

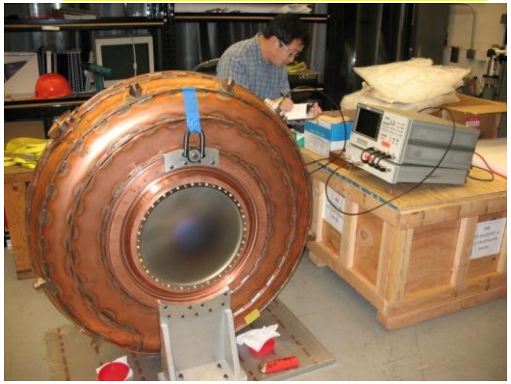
CC winding (Qi Huan Co.)

Absorber (KEK)

Absorber window (U-Miss)



Cavity at LBNL (Applied Fusion)



FC (Tesla Eng., Ltd.)