Accelerators for Future Neutrino Facilities: Strengths and Challenges

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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**

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

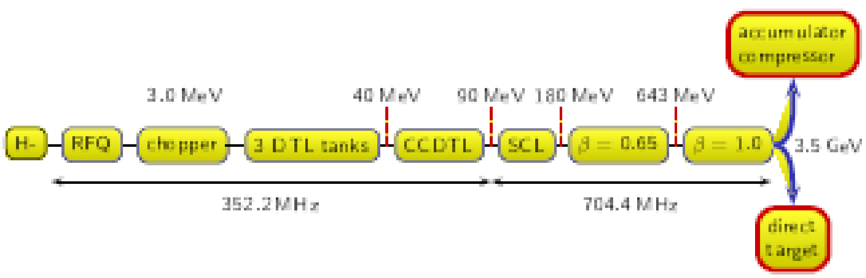
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

Baseline scenario produces high energy neutrinos, above τ threshold

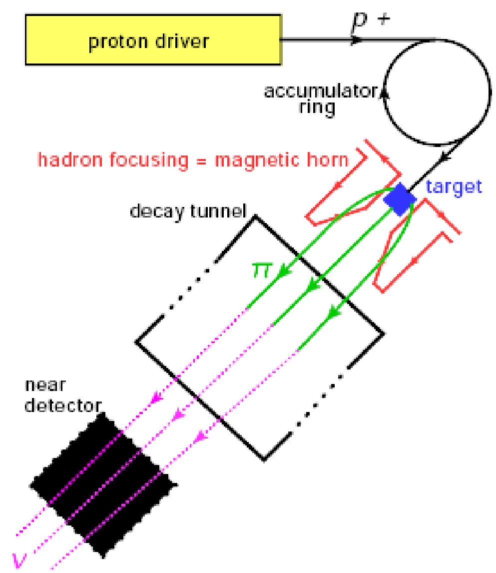
- **Electron neutrinos are most favorable to do the science**
  - **$\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable "wrong-sign" μ**
    - **do not get ν_e from "conventional" neutrino beam line**

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

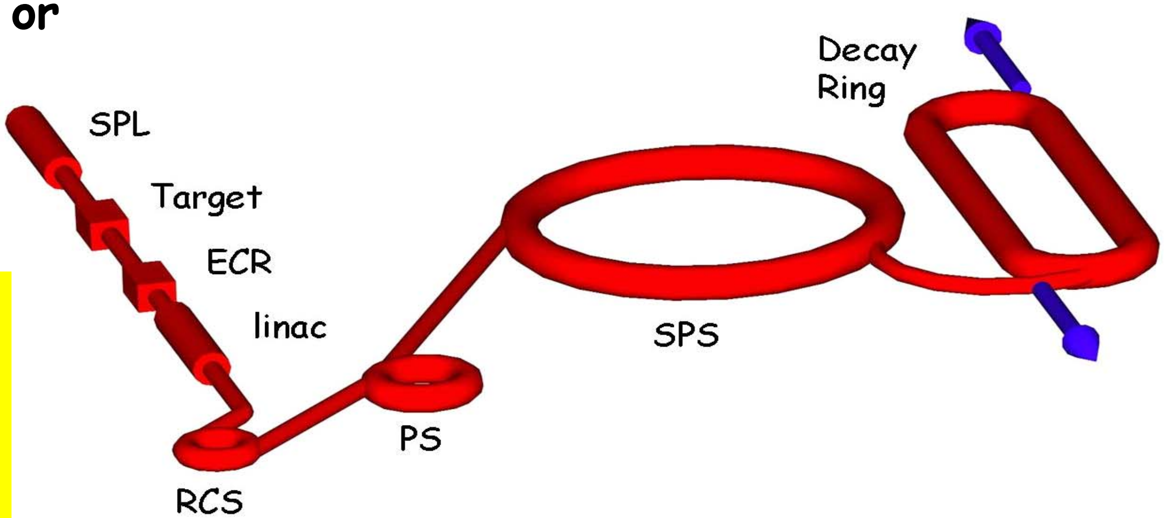
Beta Beam

- **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:

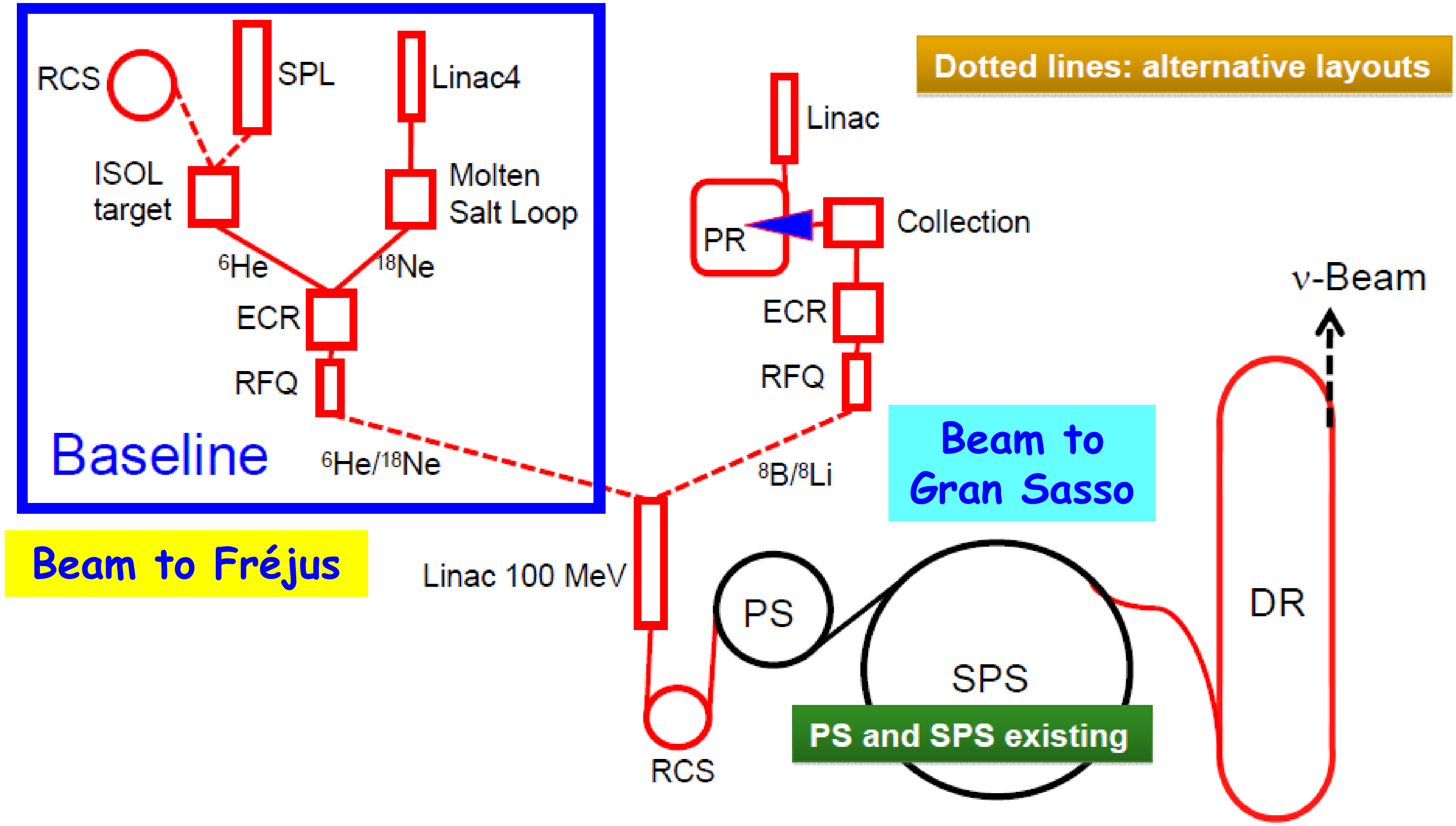
Low-*Q* version (^{6}He, ^{18}Ne)

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



Beta Beam Schematic

- **Two options: Low-*Q* (baseline) and High-*Q* (alternative)**

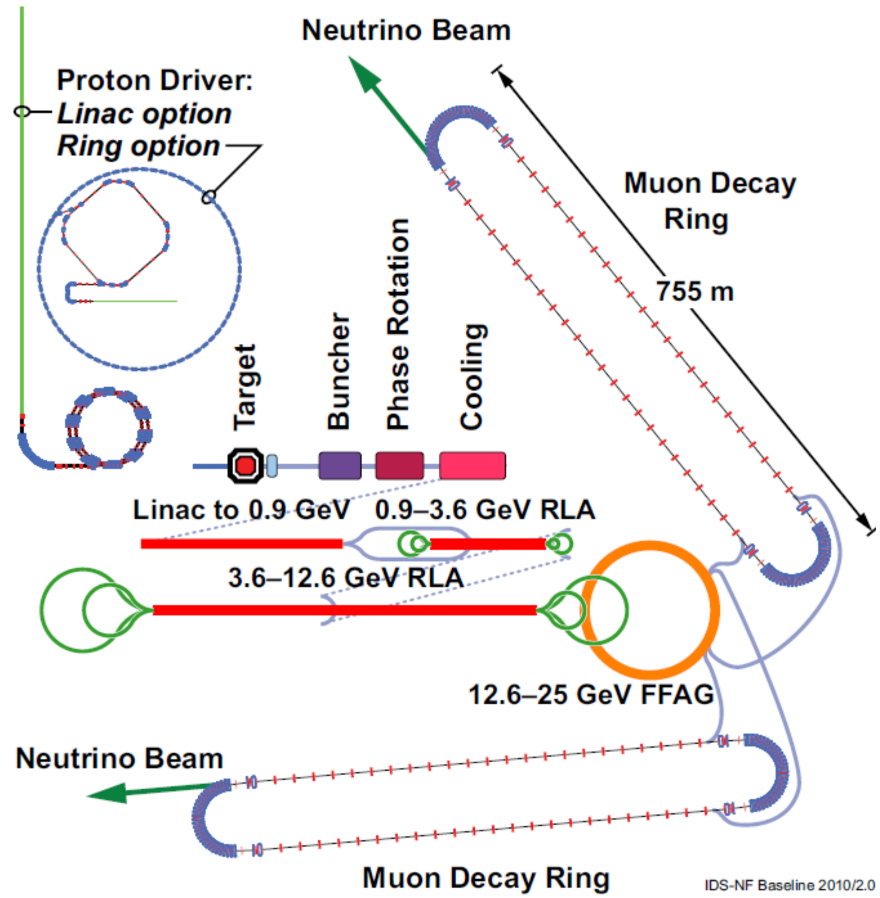


Bρ ~ 500 T-m, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

Neutrino Factory

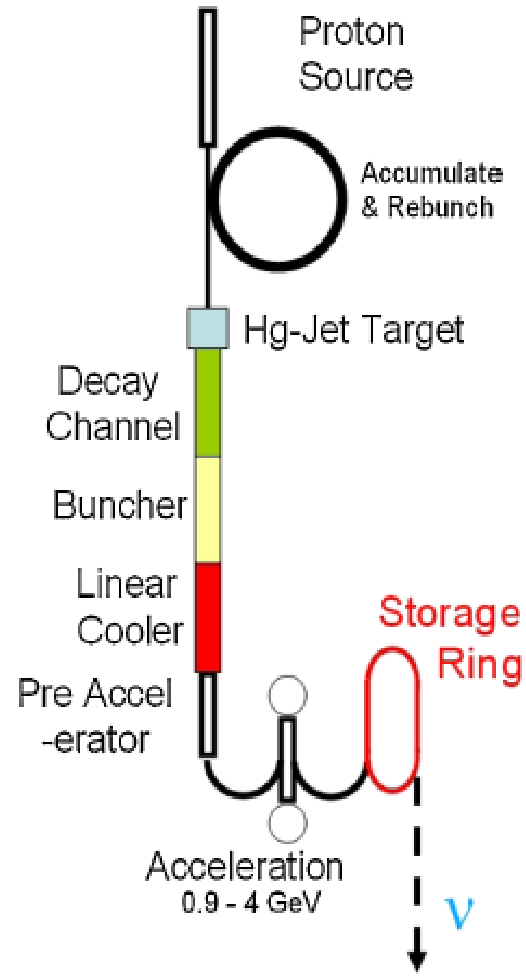
- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target ⇒ HARP
  - Target, Capture, and Decay
    - create π; decay into μ ⇒ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance ⇒ MICE
  - Acceleration
    - 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-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



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

Technical Challenges-SB

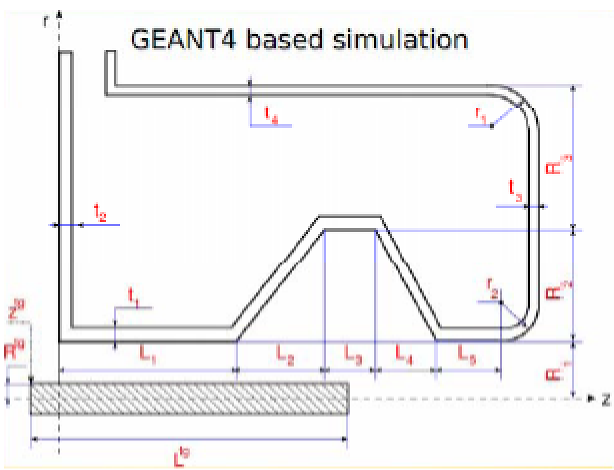
- Challenges related mainly to intensity requirement
  - target capable of handling 4 MW of protons
  - horn capable of handling 4 MW of protons
    - and operating at high repetition rate (50 Hz)
  - good charge selection (beam purity)

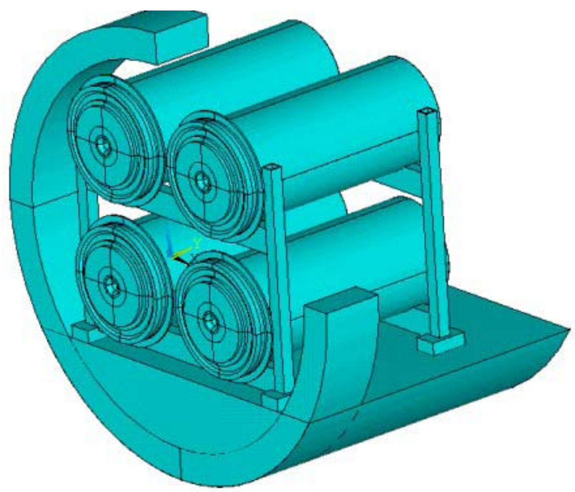
- Target resides in close proximity to horn
  - spatial constraints favor solid, or perhaps powder target
    - materials compatibility issues make Hg target impractical
  - cooling is difficult
  - high radiation environment
    - *need* to repair is inevitable
      - hands-on repair will not be possible

Proposed Approach-SB

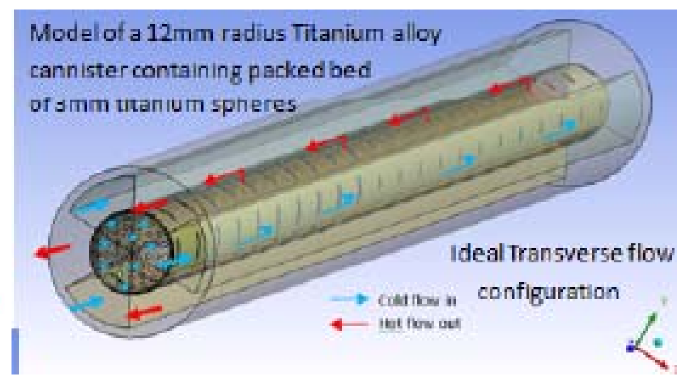
- **Recent studies (Zito *et al.*, EUROnu WP2) based on**
  - low- or medium-Z target
  - multiple targets + horns
    - reduces power deposition
      - 4 MW → 4 x 1 MW
    - reduces repetition-rate requirement
      - 50 Hz → 4 x 12.5 Hz
  - single-horn optics (no reflector)
    - optimized horn shape

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





Pebble-bed target

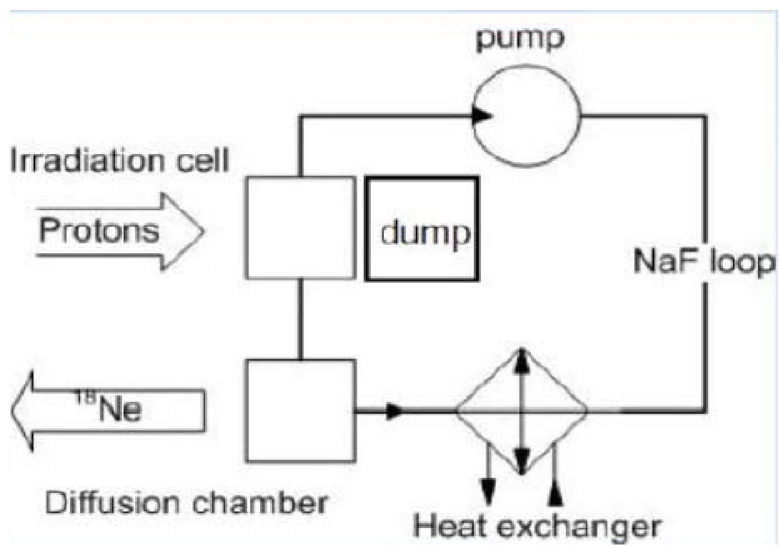


BB Technical Challenges (1)

- **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

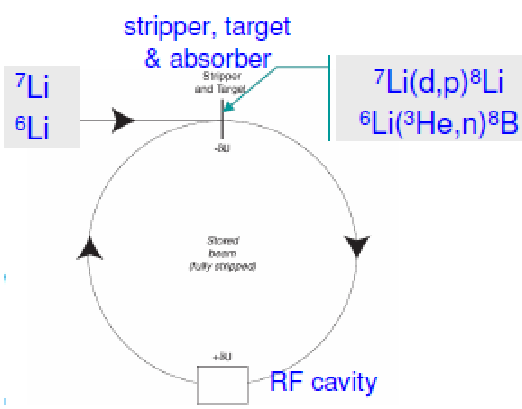
Test experiment approved at CERN



BB Technical Challenges (2)

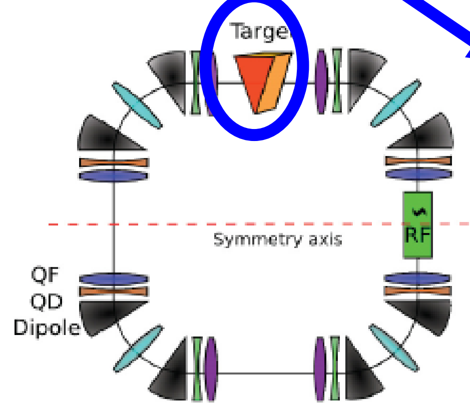
- **For high-*Q* isotopes (^{8}Li, ^{8}B) exploring new production concept proposed by C. Rubbia *et al.***
  - **based on ionization cooling of ions to maintain equilibrium emittance**
  - **design currently studied by Benedetto *et al.***
    - **main drawback is required gas target thickness**
      - **10^4 times that of existing jet targets**
        - **need 5x more ions than for ^{6}He, ^{18}Ne**
    - ***possible* workaround is forward kinematics with liquid-film target**

Concept

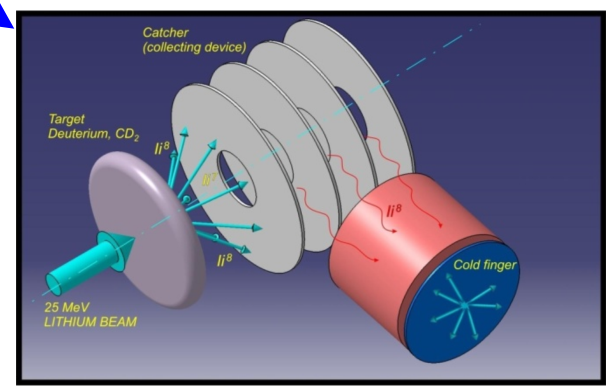


Layout

M. Schaumann, CERN-THESIS-2009-128



Collector



BB Technical Challenges (3)

- **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

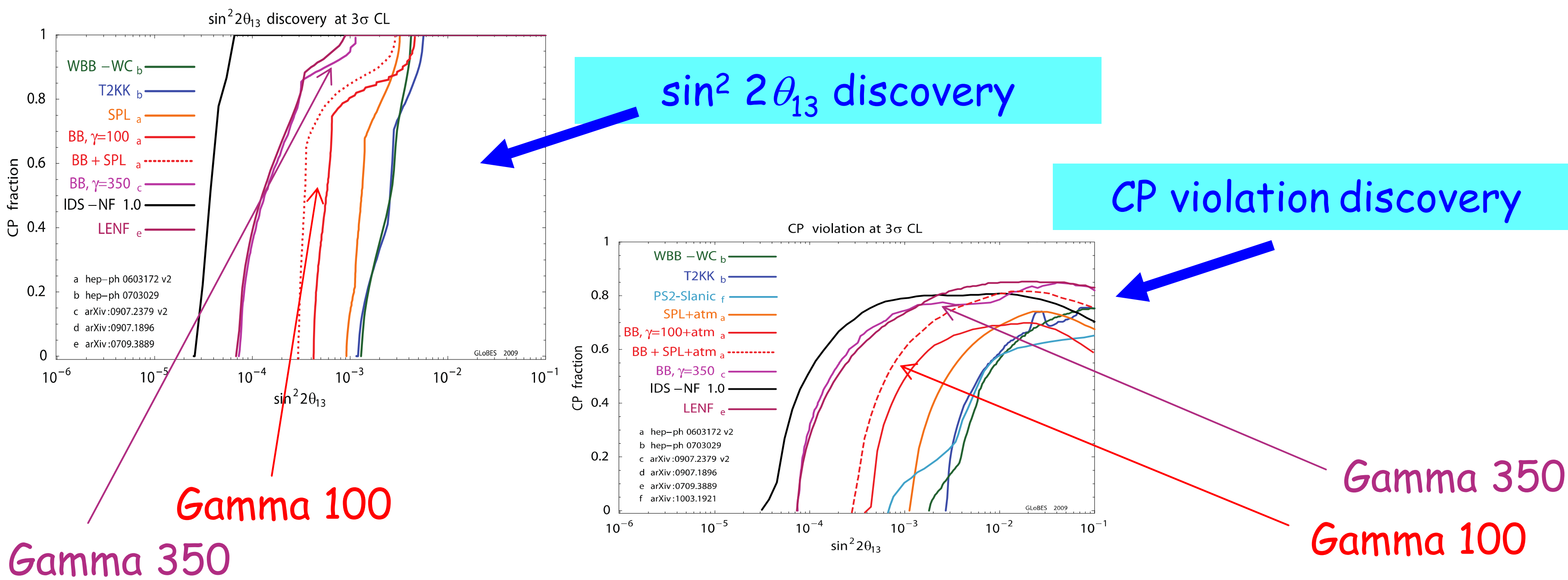
A. Donini, Summary on Beta-Beams

Ions	Fluxes [10^{18}]	Years	$(\sin^2 2\theta_{13})_{min}$	NH,$(\sin^2 2\theta_{13})_{min}$
^{6}He	$\bar{\Phi}_0 = 2.9$	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 = $5 \cdot 10^{-3}$*

BB Technical Challenges (4)

- **Baseline energy (γ = 100) too low for optimal physics reach**
  - **γ = 350 preferred**
    - **implies very high-field dipoles in decay ring (>20 T)**
    - **requires energy upgrade of SPS**
      - **no current CERN plans for this**



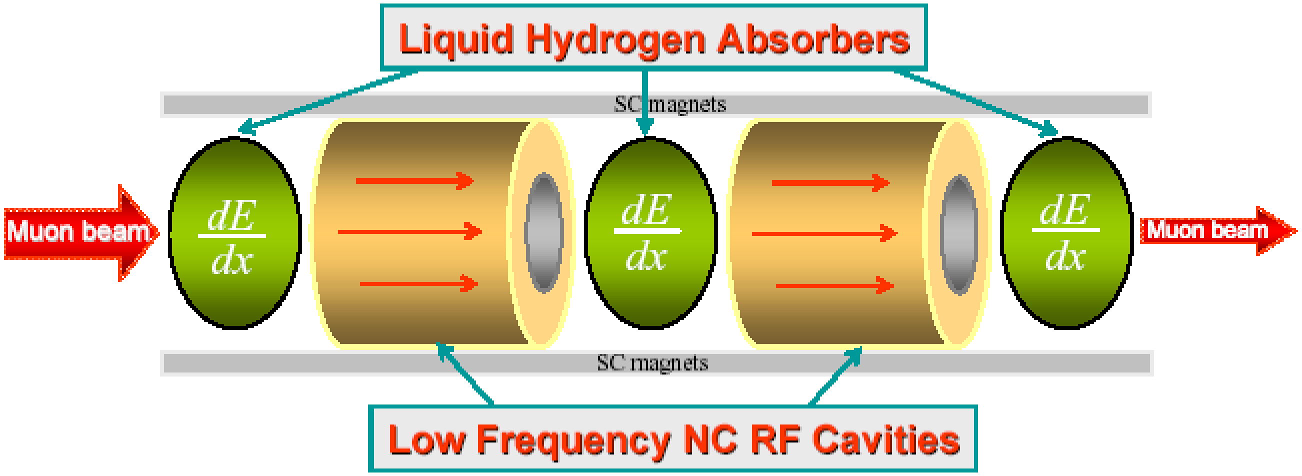
NF Technical Challenges (1)

- **Muons created as tertiary beam ($p \to \pi \to \mu$)**
  - **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**

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

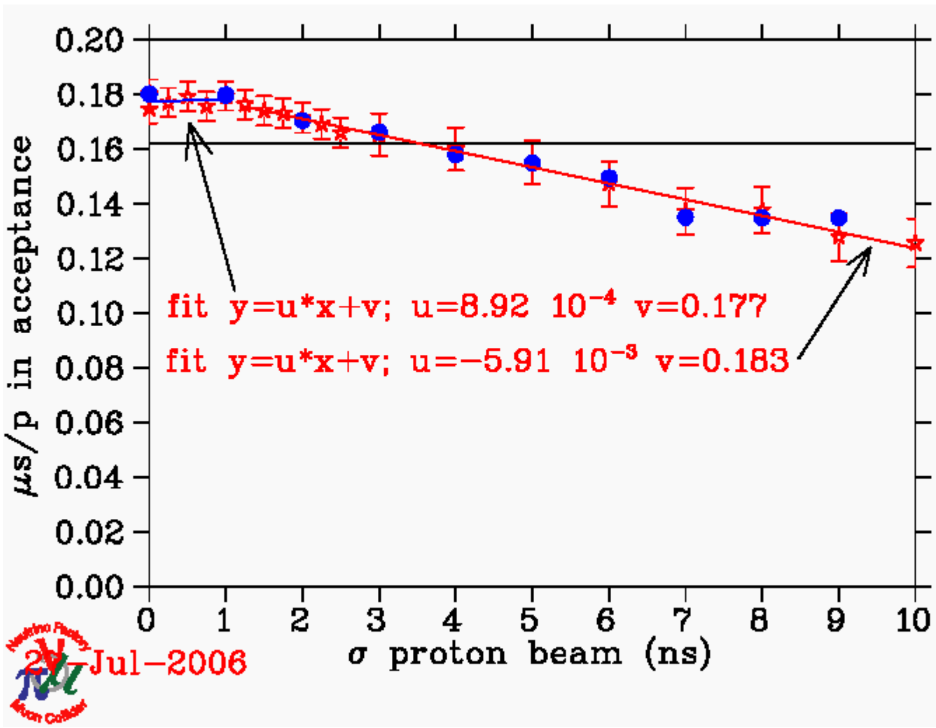
Cooling   Heating

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

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

NF Technical Challenges (2)

- **Proton beam parameters**
  - **desired proton intensity for Neutrino Factory is 4 MW**
    - **e.g., 3.1 × 10^{15} p/s at 8 GeV or 6.2 × 10^{13} p/pulse at 50 Hz**
  - **desired rms bunch length is 1-3 ns to minimize intensity loss**
    - **not easily done at high intensity and moderate energy**

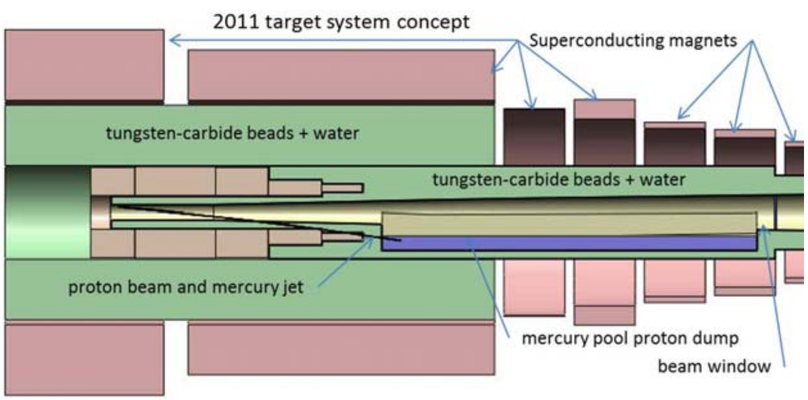


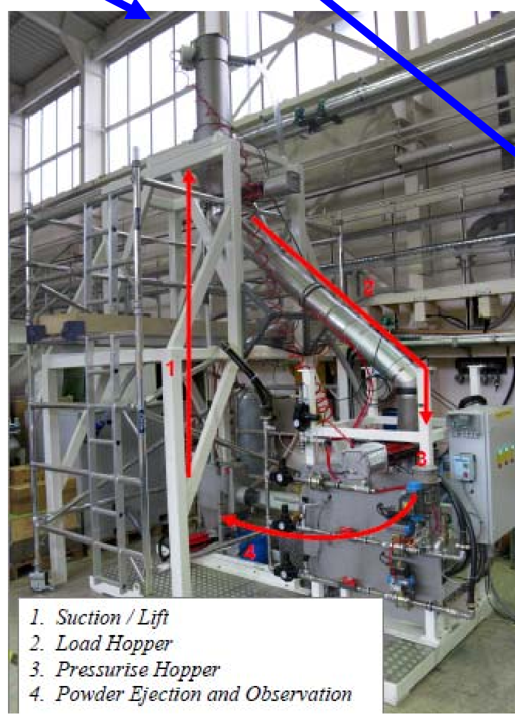
Difficult requirement at low beam energy (5-10 GeV)

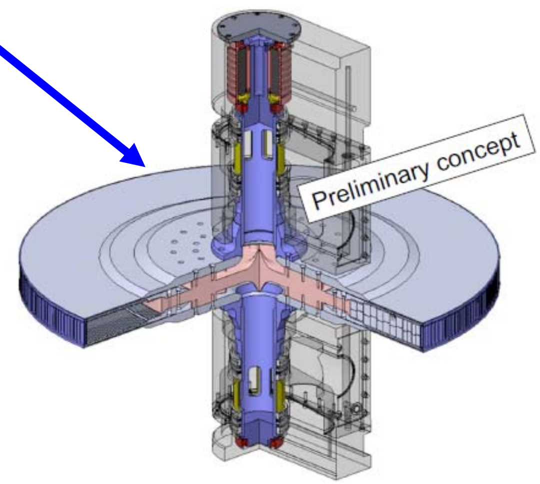
NF Technical Challenges (3)

- **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)

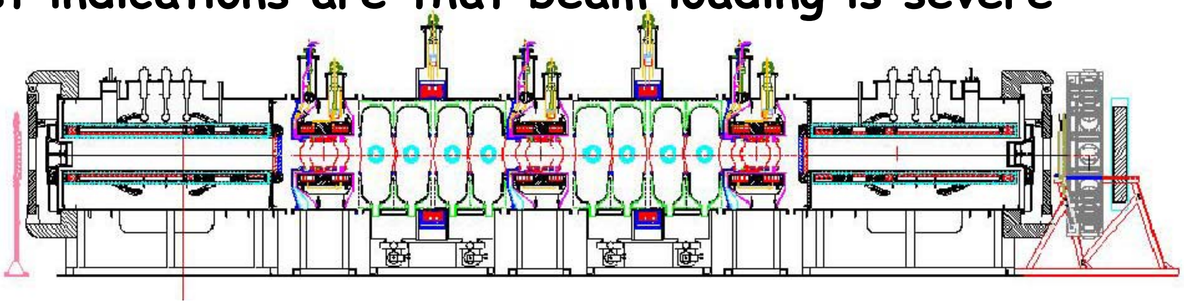


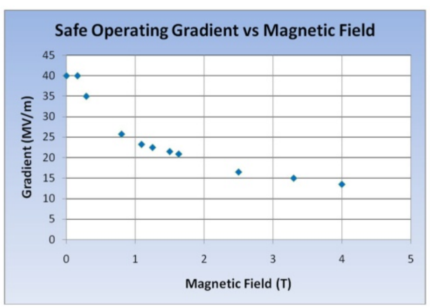




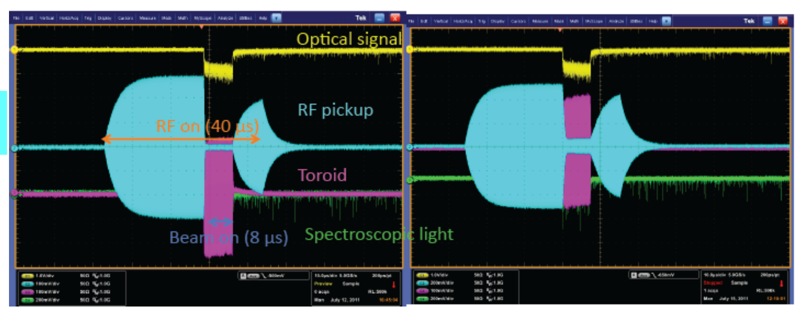
NF Technical Challenges (4)

- **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
    - 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





N_2 500 psi



H_2 900 psi

Viewpoint

- I hold the view that

Challenges → Opportunities

↑

R&D

Unfortunately, the process is reversible

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
    - 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)

Questions to Address

NOTE: only my personal view

- Superbeam
  - Is the layout of the proton beam transport compatible with horn repair or replacement?
- Beta Beam
  - Given the complications of producing and capturing ^{8}Li and ^{8}B, and the need for 5x higher intensity, is the cost-benefit ratio for this option really favorable?
  - Are there limitations (operational or technical) in the baseline CERN-based scenario that are severe enough to justify consideration of a "green-field" site?
- Neutrino Factory
  - What combination of proton beam energy and bunch length is the best compromise for integrated muon beam intensity?
  - Is the RF R&D plan well-focused or too broad?
- All
  - What time frame is needed for a funding proposal?

Summary

- Substantial progress being made toward design of accelerator-based neutrino facilities to study CP violation in the lepton sector
  - challenges are being understood and overcome
    - experiments play a critical role in this task
- Work extends state-of-the-art in accelerator science
  - high-power targets, new cooling techniques, ion source development, rapid acceleration techniques,...
- Thanks to all my accelerator colleagues for sharing both their expertise and their enthusiasm