Neutrino Factory and Beta Beam

Experiments and Development

“Study IIa” Status Report

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CENTER FOR BEAM PHYSICS

MICE Collaboration Meeting–CERN
March 29, 2004
Outline

• Introduction
• Previous Neutrino Factory studies
• Neutrino Factory ingredients
• Beta beam ingredients
• Progress and plans: Neutrino Factory
• Progress and plans: Beta Beams
• Possibilities for next meeting
• Summary
**Introduction**

- APS Neutrino Study grew from desire to make the case for neutrino science in the broadest terms
  
  - mission: identify key scientific questions driving the field; analyze the most promising experimental approaches to answering them

- Sponsored by four APS Divisions (DPF, DPB, DNP, DAP)
  - reflects inherent interdisciplinary nature of neutrino physics

- Physics issues
  
  - neutrino mass and mixing, no. and types of neutrinos, assets as probes of hadron structure, roles in astrophysics and cosmology

- Experimental approaches
  
  - long and short baseline accelerator experiments, reactor experiments, nuclear $\beta$ decay and $2\beta$ decay experiments, cosmic rays and cosmological and astrophysical observations

- Theoretical connections
  
  - neutrino sector to extra dimensions and higher energy scales
Introduction

• “The overarching purpose of the Study is for a diverse community of scientists to examine the broad sweep of neutrino physics, and if possible, to move towards agreement on the next steps towards answering the questions that drive the field. The Study will lay scientific groundwork for the choices that must be made during the next few years.”

• Organized into working groups

  Solar and atmospheric neutrino experiments (J. Bahcall, J. Klein)
  Reactor neutrino experiments (G. Barenboim, E. Blucher)
  Superbeam experiments and development (W. Marciano, D. Michael)
  Neutrino factory and beta beam experiments and development (S. Geer, M. Zisman)
  Neutrinoless double beta decay and direct searches for neutrino mass (S. Elliott, P. Vogel)
  What cosmology/astrophysics and neutrino physics can teach each other (S. Barwick, J. Beacom)
Introduction

• Study organizing committee

  Stuart Freedman (co-chair)
  Boris Kayser (co-chair)
  Janet Conrad
  Guido Drexlin
  Belen Gavela
  Takaaki Kajita
  Paul Langacker
  Keith Olive
  Bob Palmer
  Georg Raffelt
  Hamish Robertson
  Stan Wojcicki
  Lincoln Wolfenstein

• Report writing (tentatively) scheduled for June 26–27 in Aspen

• URL for Study is http://www.interactions.org/neutrinostudy/

• URL for March 3–4 meeting talks is http://www.neutrinooscillation.org/studyaps/neutrinofactoryworkshop.html
Introduction

• For Neutrino Factory design and R&D, strong and active groups already exist
  — Neutrino Factory and Muon Collider Collaboration (U.S.)
  — European Neutrino Group (EU)
  — Japanese Neutrino Group (Japan)

• Our goal is to build on that work and document it for the broader U.S. neutrino-science community
  — progress toward a more cost-effective implementation is particularly important

• Work on beta beams centered at CERN
  — they are happy to work with us to provide information on what has been done and what remains to be done

• Our goals are to understand the CERN work, to evaluate the R&D program required to realize a beta beam facility, and to consider a possible U.S. implementation of such a machine
Previous Neutrino Factory Studies

- Study I (1999–2000) instigated by the Fermilab Director
  - MC invited to participate
  - basic organization and decision-making done by Fermilab editors (Holtkamp and Finley)

- Focus on feasibility
  - first attempt to specify a Neutrino Factory from end to end
  - approach: base design on (reasonably) well-understood technologies
  - no attempt made to optimize either costs or overall performance

- Proper approach at that time, as feasibility itself was most at issue

- Led to predictable result: feasibility established, performance poor, and costs relatively high

- In large measure results were generic; not dominated by site-specific parameters
Previous Neutrino Factory Studies

- **Study II (2000–2001)** done as collaboration between **MC** and BNL as sponsoring laboratory
  - co-led by **S. Ozaki (BNL)**, **R. Palmer (BNL–MC)**, **M. Zisman (MC)**

- **Goal**: maintain convincing feasibility, improve performance substantially
  - minimizing costs was again given lower priority

- **Results:**
  - performance 5x that of Study I
    - $1.2 \times 10^{20}$ vs. $2.5 \times 10^{19}$ $\nu_e$ per year ($10^7$ s) per MW
  - cost about 75% of Study I
    - mainly due to using **20 GeV** rather than **50 GeV**, saving one RLA
  - performance scalable with proton power, if target does not limit this parameter
    - should be able to operate at 4 MW
Previous Neutrino Factory Studies

• Lessons learned from the two Studies

  — necessary to **optimize the “front end”** (decay, bunching, phase rotation, cooling) as one system to get high performance

  — necessary to **simulate entire concept before starting detailed engineering** (self-consistent solution)

  — necessary to **work as partners with engineers** to converge on buildable design

  — facility as conceived was **costly, O($2B)**

  — increasing proton driver power is cost-effective way to get higher performance

    ◦ it also tends to mesh well with other programs, e.g. **Superbeams**
Previous Neutrino Factory Studies

• For Neutrino Factory, we have already studied those portions of “design space” representing
  — low performance, high cost
  — high performance, high cost

• What’s left?
  — high performance, optimized cost
    • note that I resisted temptation to say “low” cost

• Based on previous work, we have some ideas where to begin:
  — replace induction linacs with RF bunching and phase rotation scheme
  — replace RLA with FFAG ring or very fast cycling synchrotron
  — examine trade-off between amount of cooling and acceleration system/storage ring acceptance
    • and between beam intensity and detector size
Neutrino Factory Ingredients

- Neutrino Factory comprises these sections
  - **Proton Driver**
    (primary beam on production target)
  - **Target and Capture**
    (create π's; capture into decay channel)
  - **Phase Rotation**
    (reduce ∆E of bunch)
  - **Cooling**
    (reduce transverse emittance of beam)
    ⇒ **Muon Ionization Cooling Experiment**
  - **Acceleration**
    (130 MeV → 20–50 GeV with RLAs)
  - **Storage Ring**
    (store muon beam for ≈500 turns; optimize yield with long straight section aimed in desired direction)

Feasibility Study II version
Beta Beam Ingredients

- **CERN scheme**
  - one extra step compared with Neutrino Factory: ionization of beta unstable isotopes
    - also one step less: no cooling of beam
  - premium on rapid acceleration, but less so than for muon beams
Progress and Plans: Neutrino Factory

- Starting place for Neutrino Factory design is Palmer’s updated version of “Study-II” design (Gallardo talk)
  - uses RF sections for both bunching and phase rotation
  - uses new cost-optimized cooling channel
  - uses acceleration scheme based on FFAGs
Progress and Plans: Neutrino Factory

- These changes should markedly reduce cost of the facility
  - RF bunching and phase rotation section shorter than induction linac version, and uses less expensive components
    - original scheme took 25% of total cost
    - new scheme can keep both $\mu^-$ and $\mu^+$ simultaneously
  - RLA was major cost in Study II Neutrino Factory design (23%)
    - large aperture FFAG magnets accommodate the large energy change per turn without requiring separate arcs
      - avoids large aperture splitter-recombiner magnets
    - increased acceptance downstream allows reduction in required cooling (20% of facility cost)
Progress and Plans: Neutrino Factory

- Buncher and rotator concept due to Neuffer
- Overall layout more compact than Study II version

- RF buncher and rotator
Progress and Plans: Neutrino Factory

110.7 m End of drift

161.7 m End of bunch

215.63 m End of rotate

265.9 m 50 m of cooling
Progress and Plans: Neutrino Factory

- New design (Palmer) uses less cooling than Study II version
  - 50 m vs. 108 m
  - weaker focusing, $\beta_\perp = 70 \text{ cm} \text{ vs.} 40 \text{ cm}$
  - fewer solenoids and RF cavities
  - solid (Li or LiH) vs. liquid-hydrogen absorbers
    - no performance difference in a short channel
Progress and Plans: Neutrino Factory

- performance is acceptable (yield better than Study II if larger downstream acceptance is realized)

  - must verify this when more realism is added to simulation model

\[
\begin{align*}
\varepsilon_T &= 30 \text{ mm-rad}; \varepsilon_L = 150 \text{ mm} \\
\varepsilon_T &= 15 \text{ mm-rad}; \varepsilon_L = 150 \text{ mm}
\end{align*}
\]
Progress and Plans: Neutrino Factory

- But, much work to be done to make initial simulations more realistic (Fernow talk)
  - must produce lattice for entire front end
    - replace constant buncher and rotator fields with periodic solenoids
      - join all separately-calculated regions into one continuous lattice
      - carry out proper matching between regions
    - add beam-pipe constraints in capture section
    - add realistic RF windows in all cavities
    - implement discrete RF frequencies for buncher and rotator
    - use MARS to make sure radiation levels in capture and decay region are acceptable
    - do GEANT simulation of final configuration
Progress and Plans: Neutrino Factory

- Other studies undertaken to see how well optimized the design is with regard to cost-performance trade-offs
  - optimize magnetic channel for capture and decay region
  - compare alternative window and absorber materials
  - attempt to shorten phase rotator section
  - evaluate dependence of performance on RF gradient

- Present assignments (abridged)*
  - Gallardo: periodic transport solenoids, buncher windows
  - Fernow: design capture solenoids, match into cooling section
  - Kirk: develop MARS radiation map and new particle distribution
  - Paul: optimize field profile for capture and decay section
  - Neuffer: study material effects and optimize rotator length
  - Fukui: study performance effect of reduced gradients

*additional volunteers welcome
Progress and Plans: Neutrino Factory

• Studying variants permits understanding of cost-performance trade-offs (Neuffer talk)
  
  — things to examine: energy of cooling channel, buncher and phase rotator parameters, absorber materials

• Looked at replacing LiH absorbers with Be absorbers
  
  — we have Be foils anyway for terminating the RF cavity fields
  
  — find cooling somewhat worse $\varepsilon_\perp = 9.3$ mm (vs. 7.3 mm for LiH)
    
    o get $\mu/p = 0.21$ at 80 m (vs. 0.25 at 100 m for LiH)

• Need to look at $H_2$ gas-filled cavity performance also
Progress and Plans: Neutrino Factory

• Looking at performance of shorter bunch rotator

Palmer scheme

— gives $\mu/p = 0.22$ (vs. 0.24 for Palmer scheme)

• Need to assess how many discrete frequencies are needed for adequate implementation of buncher

— previous work showed that 10-20 frequencies will suffice
— tried buncher with 11 frequencies, rotator with 6 frequencies
— results in $\mu/p = 0.2$ (vs. 0.22 for continuous frequency scheme)

• While these simulations done without fully realistic windows and magnetic fields, results expected to scale to fully realistic case

Accelerator and Fusion Research Division
Progress and Plans: Neutrino Factory

- Optimization of capture and decay region (Paul’s talk)
  - goals: maximize muon yield, evaluate cost-optimization
  - start from Study II configuration
    - 24 GeV p incident at 67 mrad from solenoid axis
    - Hg jet, 1-cm diameter, at 100 mrad from solenoid axis
    - tapered solenoidal matching section (≈20 T at target to ≈1 T in decay channel)
    - uniform solenoidal decay channel
Progress and Plans: Neutrino Factory

- Present results favor long taper (20 m); 1.25 T and 2 T decay channels similar
  
  — crude cost optimization (based on yield per unit of stored energy in magnets relative to that in Study II) favors 1.25 T field

  \[\text{Yield} \quad \text{Relative "Cost"}\]

  \[\begin{array}{|c|}
  \hline
  \text{1.25 T} \\
  \hline
  \end{array}\]

  \[\begin{array}{|c|}
  \hline
  \text{One sign only} \\
  \hline
  \end{array}\]

  \[\begin{array}{|c|}
  \hline
  \text{1.25 T} \\
  \hline
  \end{array}\]

  \[\begin{array}{|c|}
  \hline
  \text{One sign only} \\
  \hline
  \end{array}\]

- looks like 10 m drift is a sensible compromise

- need to evaluate with same energy cuts as downstream channel (100–300 MeV/c)
Progress and Plans: Neutrino Factory

• High-power proton drivers are a key ingredient for a Neutrino Factory, a Beta Beam facility, a Superbeam
  — also important for neutron spallation, kaon or muon beam facilities

• There are many proposals for proton drivers (Kirk talk)

<table>
<thead>
<tr>
<th>Facility</th>
<th>Power 1</th>
<th>Power 2</th>
<th>Power 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNS</td>
<td>1.2 MW</td>
<td>2.0 MW</td>
<td></td>
</tr>
<tr>
<td>JPARC</td>
<td>0.7 MW</td>
<td>4.0 MW</td>
<td></td>
</tr>
<tr>
<td>FNAL</td>
<td>0.4 MW</td>
<td>1.2 MW</td>
<td>2.0 MW</td>
</tr>
<tr>
<td>BNL</td>
<td>0.14 MW</td>
<td>1.0 MW</td>
<td>4.0 MW</td>
</tr>
<tr>
<td>CERN(PS)</td>
<td>0.1 MW</td>
<td></td>
<td>SPL 4.0</td>
</tr>
</tbody>
</table>

— we need to compare the needs of the various users to assess how well the proposed projects fulfill them

• Fermilab proposing Proton Driver project (CD-0 by end of year) to
  — replace 400 MeV linac
  — develop new 8 GeV proton driver (0.5 MW)
  — upgrade MI to 2 MW
Progress and Plans: Neutrino Factory

• Acceleration goal is to replace Study II RLAs with (hopefully) less expensive system based on FFAG rings (Berg talk)
  
  — limited FFAG energy swing (2:1) means that linac and RLA probably cannot be avoided

• Plan is as follows
  
  — base FFAGs on cost-optimized parameter sets (5–10 GeV and 10–20 GeV) [Berg]
  
  — develop rough magnet design to get end fields [Kahn]
  
  — track beam with ICOOL [Palmer] (start with 5–10 GeV; hardest)
    
    o validate with another code [Berg]
  
  — design linac and RLA for low energy acceleration [Bogacz]
  
  — specify kicker parameters [Palmer]
  
  — produce realistic FFAG magnet design for costing [BNL/LBNL] (start with 10–20 GeV; most expensive)
**Progress and Plans: Neutrino Factory**

- Tentative FFAG parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Value</th>
<th>Parameter</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{min}}$ (GeV)</td>
<td>5</td>
<td>$E_{\text{max}}$ (GeV)</td>
<td>10</td>
</tr>
<tr>
<td>$V/\omega \Delta T \Delta E$</td>
<td>1/8</td>
<td>$V/\omega \Delta T \Delta E$</td>
<td>1/12</td>
</tr>
<tr>
<td>$A_{\perp n}$ (mm)</td>
<td>30</td>
<td>$L_0$ (m)</td>
<td>2</td>
</tr>
<tr>
<td>$L_Q$ (m)</td>
<td>0.5</td>
<td>$V$ per cell (MV)</td>
<td>7.5</td>
</tr>
<tr>
<td>Empty cells</td>
<td>8</td>
<td>$v_x, v_y$ at $E_{\text{min}}$</td>
<td>0.35</td>
</tr>
<tr>
<td>$n$</td>
<td>90</td>
<td>$C$ (m)</td>
<td>606.918</td>
</tr>
<tr>
<td>$V$ total (MV)</td>
<td>675.0</td>
<td>$V$ total (MV)</td>
<td>767.953</td>
</tr>
<tr>
<td>$L$ (m)</td>
<td>1.612338</td>
<td>$\rho$ (m)</td>
<td>15.2740</td>
</tr>
<tr>
<td>$s_0$ (mm)</td>
<td>-1.573</td>
<td>$r$ (cm)</td>
<td>14.0916</td>
</tr>
<tr>
<td>$B_0$ (T)</td>
<td>1.63774</td>
<td>$B_1$ (T/m)</td>
<td>-9.1883</td>
</tr>
<tr>
<td>$B_1$ (T/m)</td>
<td>8.1768</td>
<td>$Q$</td>
<td>-15.4948</td>
</tr>
</tbody>
</table>
Progress and Plans: Neutrino Factory

- Low energy system will start with linac to 1.5 GeV, followed by “dogbone” or racetrack RLA

- Hope to provide sufficient detail for a crude cost estimate
- Will track the favored design
• Discussion issues

— use of \(\mu^+\) and \(\mu^-\) beams simultaneously needs to be worked out, including detector implications

— we presently are designing for 1 MW proton driver
  
  ◦ should we be optimizing for 2 MW instead?
    
    - has implications for cooling and/or acceleration design and costs
    
    - if Superbeams use 2 MW, shouldn't we?

  ◦ related question: is \(1 \times 10^{20} \nu_e\) per year enough?  
    \textit{(Answer: prefer twice this!)}

— is there agreement that 20 GeV beam energy will suffice?
  
  ◦ we still hear mention of 50 GeV sometimes

— all our work to date assumes proton driver energy of 8-24 GeV
  
  ◦ we should acknowledge possibility of 120 GeV beam from MI
Progress and Plans: Beta Beams

- Beta beam work presently centered at CERN (Blondel talk)
  - based on acceleration and storage of light beta-unstable isotopes
    - use $^6$He for $\beta^-$ ($t_{1/2} = 0.8$ s)
    - use $^{18}$Ne for $\beta^+$ ($t_{1/2} = 1.7$ s)

- Current scheme involves SPL, ISOL target, pulsed ECR source, 50 MeV linac, pulsed synchrotron (300 MeV/u), PS (to $\gamma = 9.2$), SPS (to $\gamma \approx 100$), decay ring with long straight section pointed toward detector
Progress and Plans: Beta Beams

- There are many technical challenges of beta beams
  - production target and ion source to give required intensity
Progress and Plans: Beta Beams

- **radiation losses** in various rings
  - carrying out FLUKA calculations for all stages
  - initial results
    - PS would be heavily activated (replacement needed?)
    - some issues regarding tritium and sodium
  - decay ring dipole with no midplane coil has been proposed
Progress and Plans: Beta Beams

— stacking multiple turns in decay ring without cooling the beam
Progress and Plans: Beta Beams

• Predicted intensity values:

<table>
<thead>
<tr>
<th>Stage</th>
<th>(^{6}\text{He})</th>
<th>(^{18}\text{Ne}) (single target)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From ECR source:</td>
<td>(2.0 \times 10^{13}) ions per second</td>
<td>(0.8 \times 10^{11}) ions per second</td>
</tr>
<tr>
<td>Storage ring:</td>
<td>(1.0 \times 10^{12}) ions per bunch</td>
<td>(4.1 \times 10^{10}) ions per bunch</td>
</tr>
<tr>
<td>Fast cycling synch:</td>
<td>(1.0 \times 10^{12}) ion per bunch</td>
<td>(4.1 \times 10^{10}) ion per bunch</td>
</tr>
<tr>
<td>PS after acceleration:</td>
<td>(1.0 \times 10^{13}) ions per batch</td>
<td>(5.2 \times 10^{11}) ions per batch</td>
</tr>
<tr>
<td>SPS after acceleration:</td>
<td>(0.9 \times 10^{13}) ions per batch</td>
<td>(4.9 \times 10^{11}) ions per batch</td>
</tr>
<tr>
<td>Decay ring:</td>
<td>(2.0 \times 10^{14}) ions in four 10 ns long bunch</td>
<td>(9.1 \times 10^{12}) ions in four 10 ns long bunch</td>
</tr>
</tbody>
</table>

Only β-decay losses accounted for, add efficiency losses (50%)
Progress and Plans: Beta Beams

• R&D issues
  — isotope production (GEANT simulations)
  — target design (only 100 kW proton beam is present scenario)
  — pre-bunching of high-intensity ion beams (60 GHz ECR source)
  — design of superconducting dipoles
    ▪ need ramped magnets for PS/SPS
    ▪ need high-field, rad-hard dipoles for decay ring
Progress and Plans: Beta Beams

- Scenarios for higher energy U.S. beta beam being explored (Jansson talk)
  - candidate sites are BNL and Fermilab
Progress and Plans: Beta Beams

- Comparison suggests that Fermilab is more promising candidate
  - faster ramp rate and higher $\gamma$ both favor Tevatron

<table>
<thead>
<tr>
<th>Machine</th>
<th>$\gamma^{a)}$</th>
<th>&quot;Avg.&quot; Lifetime$^{a)}$ (s)</th>
<th>Decay Loss$^{a)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS Booster</td>
<td>2.8/4.5</td>
<td>1.1/2.9</td>
<td>4%/2%</td>
</tr>
<tr>
<td>AGS</td>
<td>10/17</td>
<td>3.7/15.8</td>
<td>12%/3%</td>
</tr>
<tr>
<td>RHIC</td>
<td>83/139</td>
<td>43/183</td>
<td>70%/24%</td>
</tr>
<tr>
<td>Booster</td>
<td>2.5/3.9</td>
<td>1/3.6</td>
<td>2%/0.6%</td>
</tr>
<tr>
<td>Main Injector</td>
<td>50/83</td>
<td>13/54</td>
<td>4%/1%</td>
</tr>
<tr>
<td>Tevatron</td>
<td>326/544</td>
<td>99/423</td>
<td>13%/3%</td>
</tr>
</tbody>
</table>

$^{a)}$Values for $^{6}\text{He}^{2+}/^{18}\text{Ne}^{10+}$

- Still lots of issues to examine
  - beam losses (will SC ring quench?)
  - relatively slow ramp rate
  - activation of booster
  - longitudinal dynamics required for acceleration and transfer
Possibilities for Next Meeting

- Organizers have a mid-course meeting on April 1-2, 2004
- Expect report to be put together in late June
- It seems worthwhile to have at least one in-person meeting to present our conclusions and plan for the report writing
  - it may also be prudent to meet with the Superbeam group (since we failed badly in March)
- Possible dates (based on my schedule)
  - mid-April (12-26)
  - May (after 5/10)
    - we need to begin writing report then!
Summary

• Have a plan how to proceed on Neutrino Factory and Beta Beam study

• We still have a lot to do, and not much time to do it

• It is important that the case for continued accelerator R&D in support of the physics program be part of the roadmap

• It should be clear from the work summarized here that there’s a lot we may be able to do to make a more cost-optimized facility
  
  — it will help to get a firm idea of what performance is good enough, since, in general,

  “Good enough is best”