Machine Layout

PROTON DRIVER

TARGET

DECAY

BUNCHING

PHASE ROTATION

COOLING

ACCELERATION

RING

STORAGE

NEUTRINO BEAM

p π µ ν
Machine Layout

- Front end
  - short, intense pion pulse into diffuse phase space
  - captured in tapered high-field solenoidal channel
  - decay to muons, exchange energy spread for time
  - chop into bunch train in time
- Cooling to reduce transverse phase space volume
- Accelerate cooled muon beam
- Store in ring to produce "lighthouse" neutrino beam
Challenges

- Proton driver: high power (MW), short pulses (ns)
- Target: needs to survive fraction of beam power/pulse
- Decay channel: high field in high radiation environment
- Phase rotation: high efficiency over wide energy range
- Cooling: high-gradient cavities in high magnetic field, liquid hydrogen, thin windows
- Acceleration: large acceptance, complex design
- Storage ring: shape and orientation to aim neutrinos at detector sites
### Proton Driver

Upgrade paths exist for several existing facilities, eg.:

<table>
<thead>
<tr>
<th></th>
<th>BNL</th>
<th>FNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>Energy</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Rep rate</td>
<td>2.5</td>
<td>15</td>
</tr>
<tr>
<td>Bunches/fill</td>
<td>$6 \times (1.7 \cdot 10^{13})$</td>
<td>$18 \times (1.7 \cdot 10^{12})$</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Bunch length</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Other possibilities at CERN, KEK ...
Target

• Long, thin, skew target geometry favored for high yield
• Optimal pion yields at high energy from high-Z materials
• At low energy (few GeV), C composites might withstand the load and provide comparable yield
Target

- Solid cylinders melt or break from thermal shock with high energy beams
- Granular solids or rotating bands possible but less efficient
- Liquid mercury jets look promising, but require nozzles in high radiation environment, have other complications from motion in magnetic field and shot-to-shot stability with shock waves
Transverse momentum in pA interactions

\[
\frac{1}{m_t} \frac{dN}{dm_t} \sim e^{-m_t/m_\pi}, \quad m_t = \sqrt{p_\perp^2 + m^2}
\]

A solenoid with field B and radius R can trap

\[
p_\perp = \left( \frac{3}{4} \frac{MeV/c}{T \text{ cm}} \right) BR
\]
Phase Rotation and Bunching

- At target, the pion bunch is narrow in $t$, $z$, and $p_{\perp}$ but has large spread in $p_z$
- After drift in decay channel, this shows as correlation between muon $E$ and $t$ (and $z$)
- Properly phased rf can reduce energy spread
- Induction linacs or cavities
- Resulting muon beam still has large spread in $t$ and $z$
- For cooling and acceleration, the muon beam needs to be sliced into small bunches in time
Cooling Channel

- After phase rotation, transverse emittance of beam still too large to fit in a conventional accelerator
- Short muon lifetime (2.2 $\mu$s) rules out slow techniques
- Linear ionization cooling should work but still to be demonstrated
- Cooling rings show promise although not obviously applicable to current Neutrino Factory designs
Ionization Cooling

- Evolution of normalized transverse emittance $\varepsilon$ along absorber axis in solenoidal field
  \[
  \frac{d\varepsilon}{ds} \approx -\frac{1}{\beta^2 E} \langle \frac{dE}{ds} \rangle (\varepsilon - \varepsilon_0), \quad \varepsilon_0 \approx \frac{\beta_\perp}{2\beta m \langle \frac{dE}{ds} \rangle X_0}
  \]

- For minimum equilibrium emittance $\varepsilon_0$, we need
  - strong focusing (small $\beta_\perp$)
  - material with large $\langle \frac{dE}{ds} \rangle X_0$ (hydrogen)

- Need large rf gradient to replace lost energy (30 MeV/m in liquid hydrogen)
Ionization Cooling

Many technical challenges:

- High-gradient normal-conducting rf cavities in high magnetic field with Be foil (or Al grid) windows
- Liquid hydrogen vessels with thin windows
- Superconducting solenoids
- Very tight packing
- Possibly tricky diagnostics

Hardware R&D in progress by MuCool Collaboration

http://fnal.gov/projects/muon_collider/cool/
Ionization Cooling

Need experience with the technology and accurate simulation and test of channel dynamics ⇒ MICE (http://mice.iit.edu)

Muon Ionization Cooling Experiment

Approved for running at RAL, detailed engineering in progress.
Acceleration

- Need to accelerate muons after cooling (~ 200 MeV/c) to final storage energy (20-50 GeV/c)
- RLAs are efficient but complex, various options (racetrack, dogbone)
- FFAGs have high acceptance, still in development
- Superconducting cavities for power efficiency
• Includes long straight section(s) for focused neutrino beam from muon decay

• Clean neutrino beam with well-defined flavor content

\[ \mu^+ \rightarrow \bar{\nu}_\mu + \nu_e \]
\[ \mu^- \rightarrow \nu_\mu + \bar{\nu}_e \]

• Angular divergence \( \sim \frac{1}{\gamma_\mu} \)
Storage Ring

Ring can be shaped/oriented to support multiple experiments
General Issues

- Cost vs performance, staging
- Performance needs to be optimized as a whole (amount of cooling vs acceptance of acceleration, etc.). Various switches and knobs:
  - Target and capture: solid vs liquid, target shape, horn vs solenoid, jet design, field profile, magnets, shielding
  - Phase rotation: induction linacs vs rf cavities
  - Cooling: absorber material (solid/liquid/gas), windows, rf cavities, magnets, linear vs ring
  - Acceleration: RLA vs FFAG, magnet and cavity design
  - Storage ring: shielding/cooling, size, acceptance vs momentum compaction
Several studies have been done at various levels of detail:

- **CERN**: 2.2 GeV linac (SPL) + accumulator ring, up to 4 MW, horn focusing, 44 MHz phase rotation, 44/88 MHz cooling, bowtie storage ring
- **KEK**: 4 MW 50 GeV synchtotron (JHF upgrade), no phase rotation or cooling, FFAG acceleration
- **FNAL**: new booster, C target, induction linacs, 50 GeV ring
- **BNL**: AGS upgrade, Hg jet target, 20 GeV ring
- Iteration of US design in progress here
- A global study originating in the UK in planning
Outlook

- Still exciting possibilities in neutrino physics
- Neutrino Factory design concepts quite mature
- Various options available in rich configuration space
- R&D on technology issues in progress
- Cost vs performance optimization now appropriate