

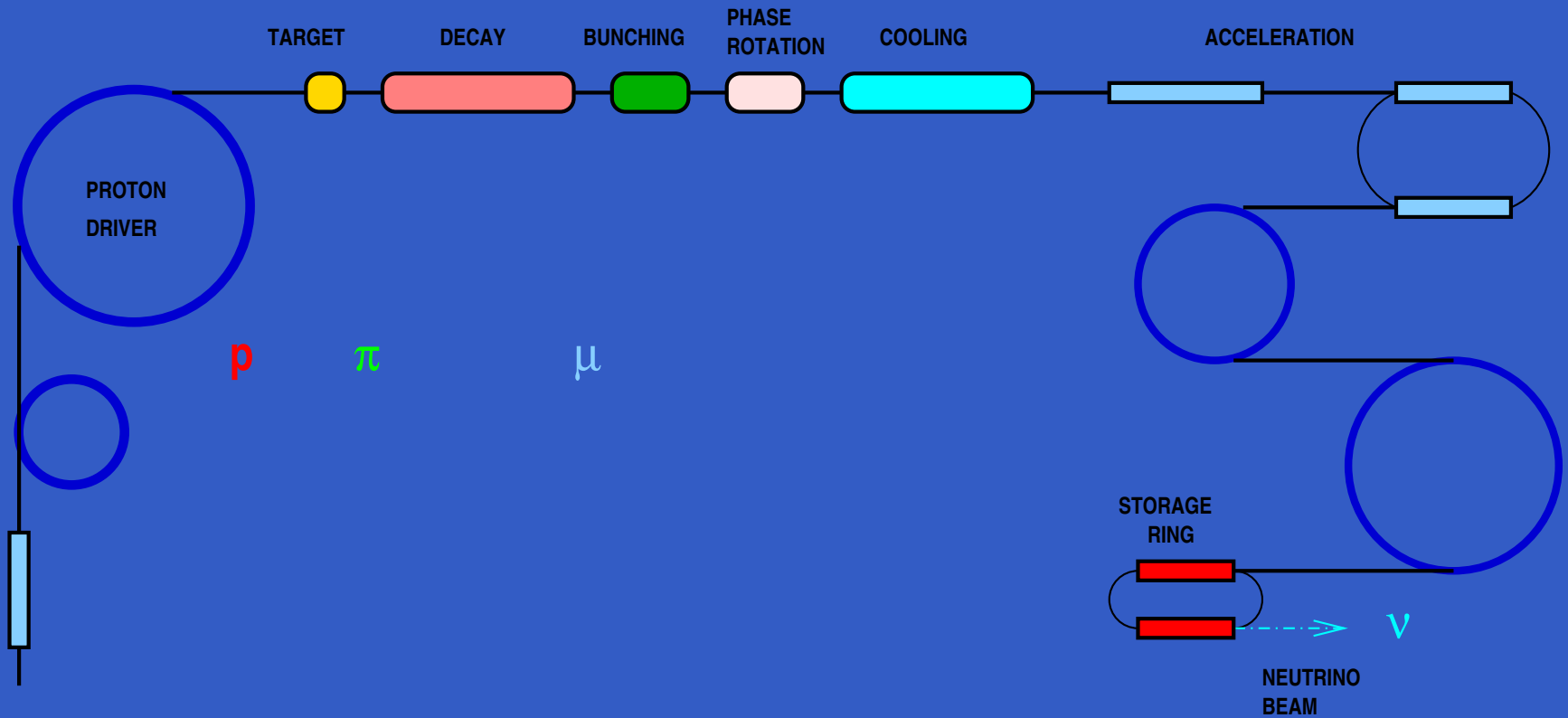
NEUTRINO FACTORY DESIGN AND ISSUES

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Machine Layout



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.:

	BNL	FNAL	
Power	1	1.2	MW
Energy	24	16	GeV
Rep rate	2.5	15	Hz
Bunches/fill	$6 \times (1.7 \cdot 10^{13})$	$18 \times (1.7 \cdot 10^{12})$	
Bunch spacing	20	13	ms
Bunch length	3	1	ns (rms)

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

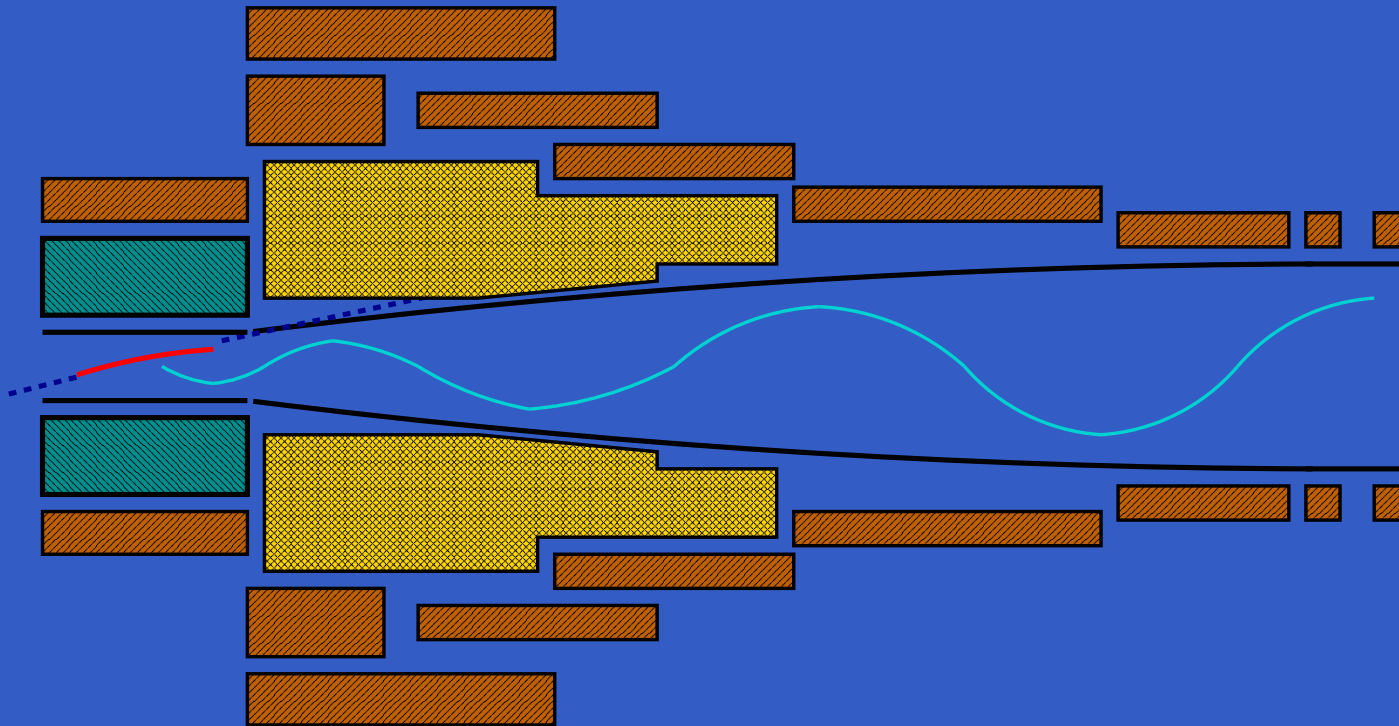
Target

- 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

Pion Capture

Transverse momentum in pA interactions $\frac{1}{m_t} \frac{dN}{dm_t} \sim e^{-m_t/m_\pi}$, $m_t = \sqrt{p_\perp^2 + m^2}$

A solenoid with field B and radius R can trap $p_\perp = \left(\frac{3}{4} \frac{MeV/c}{T cm}\right) BR$



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

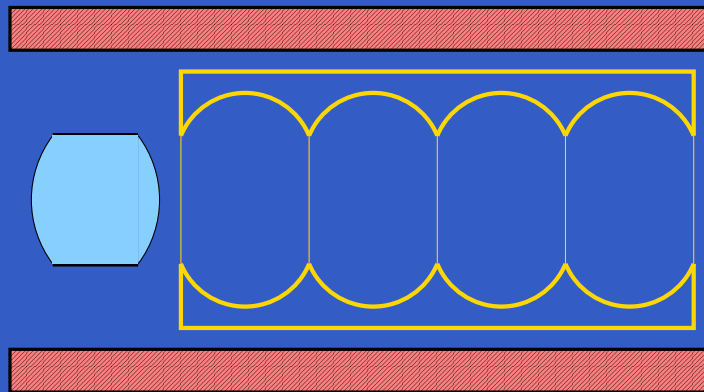
- After phase rotation, transverse emittance of beam still too large to fit in a conventional accelerator
- Short muon lifetime ($2.2 \mu s$) rules out slow techniques
- Linear ionization cooling should work but still to be demonstrated
- Cooling rings show promise although not obviously applicable to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

Ionization Cooling

- Evolution of normalized transverse emittance ε along absorber axis in solenoidal field

$$\frac{d\varepsilon}{ds} \simeq -\frac{1}{\beta^2 E} \left\langle \frac{dE}{ds} \right\rangle (\varepsilon - \varepsilon_0), \quad \varepsilon_0 \sim \frac{\beta_{\perp}}{2\beta m \left\langle \frac{dE}{ds} \right\rangle X_0}$$

- For minimum equilibrium emittance ε_0 , we need
 - strong focusing (small β_{\perp})
 - material with large $\left\langle \frac{dE}{ds} \right\rangle X_0$ (hydrogen)
- Need large rf gradient to replace lost energy (30 MeV/m in liquid hydrogen)



Ionization Cooling

Many technical challenges:

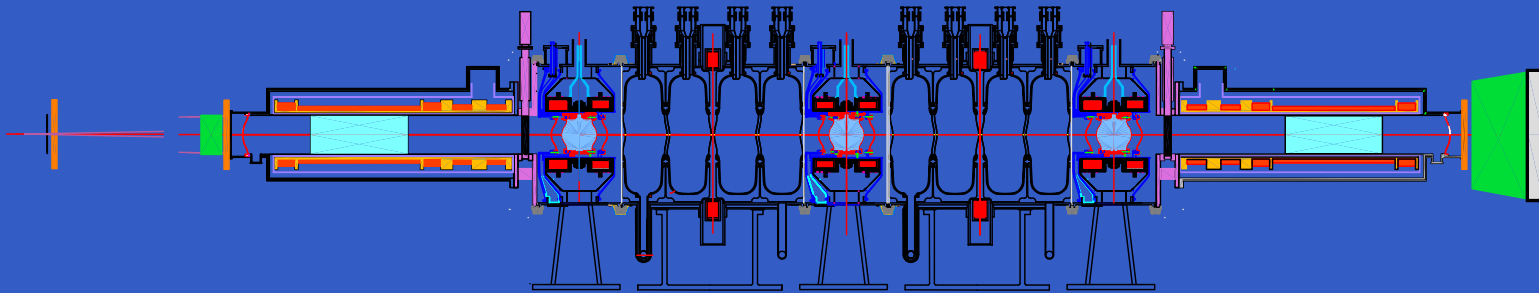
- High-gradient normal-conducting rf cavities in high magnetic field with Be foil (or Al grid) windows
- Liquid hydrogen vessels with thin windows
- Superconducting solenoids
- Very tight packing
- Possibly tricky diagnostics

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 \Rightarrow 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

Storage Ring

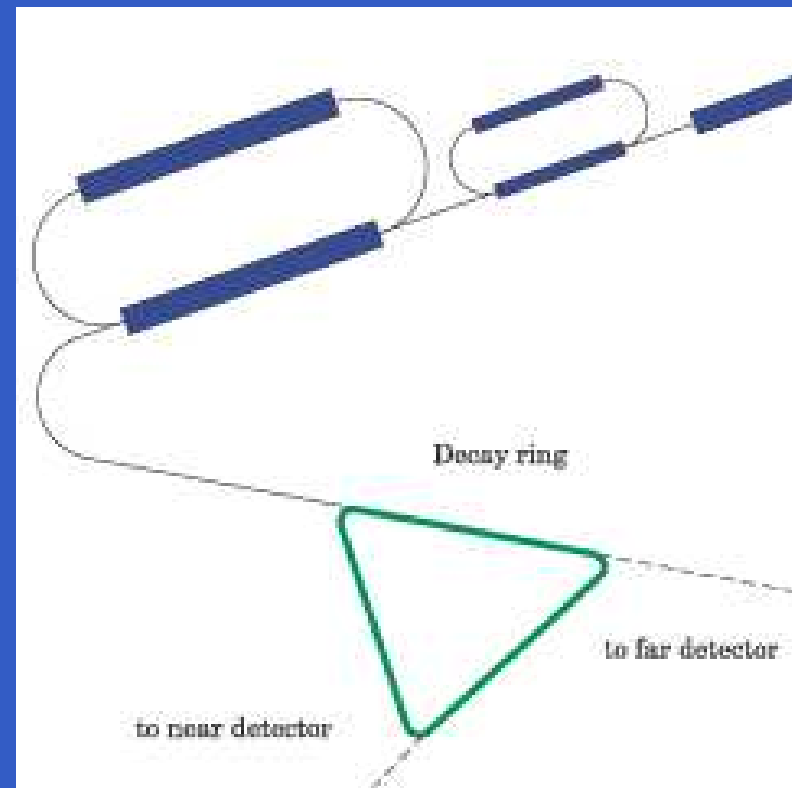
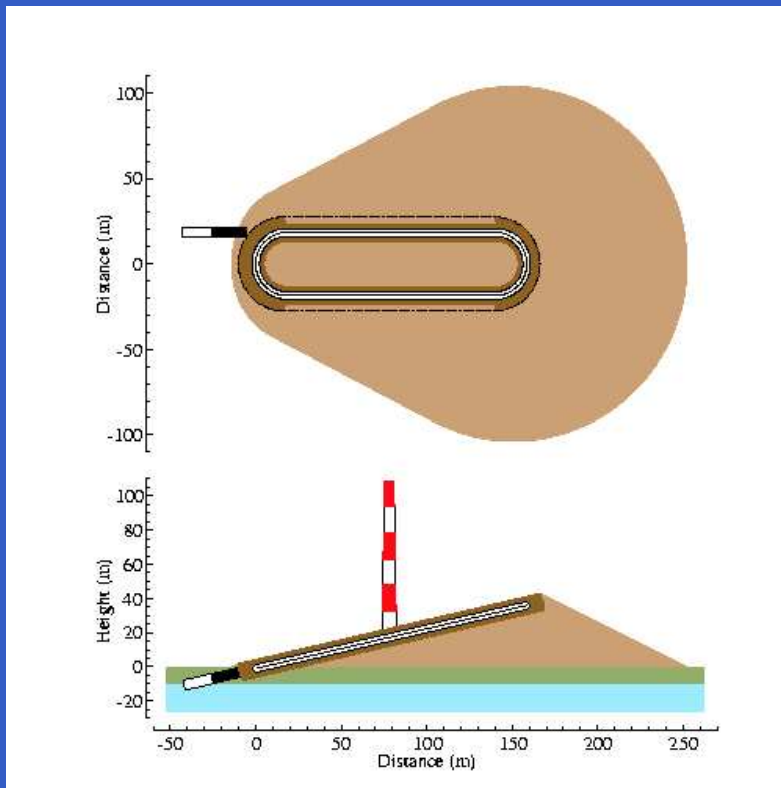
- Includes long straight section(s) for focused neutrino beam from muon decay
- Clean neutrino beam with well-defined flavor content



- Angular divergence $\sim 1/\gamma_\mu$

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

Design Work

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: 4MW 50 GeV synchrotron (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

Feasibility Study I - Fermilab



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