Design Studies

- **95-98:** Muon Collider
  Much smaller than Linear Collider
  Hard Problem - Only conceptual studies done

- **99-04:** Neutrino Factories
  Similar technologies
  Only way to study leptonic CP violation if $\sin^2(2\theta_{13}) < 0.01$
  Detailed Studies including cost and performance

- **05–:** Returning to Collider

Technology R&D

- Hg Target Experiments
- Cooling Components and MICE Experiment
- 200 MHz SC RF, and FFAG Studies
Collaborators

- **US Collaboration**  > 100 members
  BNL, Cornell, Fermi, LBNL, US Universities (including MSU)
  - 2 Spokespersons: S. Geer, Bob Palmer
  - Project manager: Mike Zisman
  - MCOG Steve Holmes Jim Siegrist, Tom Kirk
  - MUTAC Helen Edwards chair

- **European Groups**
  CERN, RAL (UK), INFN (Italy), Universities

- **Japanese Groups**
  KEK, Osaka, other Universities

- **Russia**
  BINP (including Skrinski, who started all this)
MUON COLLIDER

• Energy advantage over p’s (same as for e⁺ e⁻ Linear Collider)

• Suppressed Synchrotron Radiation \( \propto \gamma^4 \propto m^{-4} \)
  
  – Circular
    
    * Smaller because acceleration over many turns
    * \( \approx 1000 \) turns cf 1 collision for Linear Collider
  
  – no ”beamstrahlung”
    
    * \( \frac{dE}{E} \ll 1\% \) eg for Higgs mass determination
      (cf 30% for 3 TeV Linear)
    * allows larger \( N_\mu \) per bunch (Helps Luminisity)

  – larger spot size & emittance (For same Luminosity)
    * Easier Final Focus Tolerances

• Direct Higgs Production
  
  \[ \mu^+ \mu^- \rightarrow h, A, H \quad (\sigma \propto m^2) \]
But: $\mu$’s in diffuse phase space and $\mu$’s Decay

- **Requires Efficient $\mu$ Production**
  - 20 T Solenoid to capture $\pi$’s
  - RF Phase Rotation to reduce $dE/E$

- **Requires Rapid Cooling (Beam size reduction)**
  - ionization cooling certain
  - study optical and other exotics

- **Requires Rapid Acceleration**
  - Recirculating Linear Acceleration (RLA) or FFAG

- **Must Shield Ring Magnets from Muon Decay Electrons**
  - 3-6 cm Tungsten Shield

- **Must Shield Detector from Decay Electron Background**
  - Loss of Forward Cone

- **Must be Deep to Avoid Serious Neutrino Radiation**
  - Limits Energy to 3-10 TeV
Neutrino Radiation Limits Maximum Energy

- Radiation $\propto \frac{E^3}{\text{length}^2} \propto \frac{E^3}{\text{depth}}$
- Use: 1/10 Federal limit = 10 mR/year
- Negligible problem at 1.5 TeV
- $E = 3$ TeV ok at 300 m depth
  - $\approx 10$ mR/year
- $E > 3$ TeV Requires:
  - Beam wobbles, and/or
  - Special Locations (eg an island), and/or
  - Better Cooling (Optical Stochastic?)
Schematic of Muon Collider (not to scale)

Injection in both directions in all rings (not shown)

Proton driver
Target & Capture
Phase Rotate (Reduces dp/p)

Cool (Reduce Emittance by 1000,000)

Linac
FFAG/RLA
FFAG/RLA

Acceleration (.2 GeV - 1.5 T)

Synchrotron

Collider Ring (High Ave, Bending Field)
3 TeV Muon Collider (drawn to scale)
Compare sizes for 3 TeV Physics

14 TeV LHC pp (1.5 TeV)

5T 25+25 TeV pp
(≈ 3 TeV)

CLIC ee (3 TeV)

MuMu (3 TeV)

10 km

FNAL

BNL
NEUTRINO FACTORY

- Uses similar technologies as Collider, but
- Simpler than Collider

Flux Required for the Physics
Neutrino Factory Studies in the US

• 99-00  Neutrino Factory Feasibility Study I
  – Emphasized Feasibility, with complete Simulation
  – ”Entry Level Performance” ($\approx 0.2 \times 10^{20} \mu/\text{yearsec at 1 MW}$)

• 01-02  Neutrino Factory Feasibility Study II
  – Emphasized Performance
  – Similar Cost
  – 6 times Performance of Study I

• 03-04  Neutrino Factory Feasibility Study IIa
  – Emphasized Cost Reduction
  – Part of APS Neutrino Study  (September 04)
  – 61 % cost of Study II
  – Same flux, both charges: 12 times Performance of Study I
  – Meets original Physics Requirement
  – Small further cost reduction possible: publication this year
Comparison: Conventional vs. Factory

- **Conventional:**
  \[ p + C \rightarrow \pi_{High\ E} \rightarrow \bar{\mu} + \nu_\mu \]

- **Neutrino Factories:**
  \[ p + Hg \rightarrow \pi_{Low\ E} \rightarrow \mu_{Low\ E} \rightarrow \mu_{High\ E} \rightarrow e + \nu_\mu + \bar{\nu}_e \]

For \( \theta_{13} \) or CP

- **Conventional:** \( \nu_\mu \rightarrow \nu_e \)
  - ID: e shower and no \( \mu \)
  - Detector: water or light plates
  - Background: \( \nu_e \)’s and NC \( \pi^0 \)’s \( \approx 10^{-2} \)

- **Neutrino Factories:** \( \nu_e \rightarrow \nu_\mu \)
  - ID: wrong sign \( \mu \)
  - Detector: Thin magnetized Fe plates or Liquid A
  - Background: Misidentified sign \( \approx 10^{-4} \)
Looking for CP violation

$\bar{\nu}/\nu$

$|\Delta m^2_{32}| = 0.0035 \text{ eV}^2$
$|\Delta m^2_{21}| = 5 \times 10^{-5} \text{ eV}^2$
$\sin^2 2\theta_{13} = 0.004$

$\Delta m^2_{32} < 0$
$\Delta m^2_{32} > 0$

Baseline (km)

$\delta_{CP} = 90^\circ, 1\sigma$

CP angle error (degrees)

True value of $\sin^2 2\theta_{13}$

Combined, T2K+NOvA+Reactor–II, JPARC–HK, NuFact–II
Ambiguities

Resolution of Ambiguities
Requires two distances

Sensitivity reach in $\sin^22\theta_{13}$

- $\sin^22\theta_{13}$
  - 3000 km+
  - 3000 km
- $\text{sgn}(\Delta m^2_{31})$
  - 7500 km+
  - 7500 km
- CP viol.
  - No sensitivity

N (neutrino) vs N (anti-neutrino)

- Normal Hierarchy
  - no CP violation
  - 2 solutions
- Inverted Hierarchy
  - no CP violation
  - CP viol.
Schematic of Neutrino Factory Study IIa

Proton driver

Target & Capture 10 %

Phase Rotate 17 %

Cool (factor 1-10) 21 %

Linac

Acceleration 42 %

RLA

FFAG 1

FFAG 2

Storage Ring 9 %

Approx 1 B$

• Very similar to front end of Collider (but easier)
• Technologies for Factory also apply to Collider
TECHNOLOGIES for Factory or Collider

1) Target and Capture

- Liquid mercury Jet ‘destroyed’ on every pulse
- 20 T Solenoid captures all low momentum pions
- Field subsequently tapers down to approx 2 T
- Target tilted to maximize extraction of pions
BNL Target Experiment E951

- Single pulse 4 Tp
  But density equiv to 1 MW
- Non-Explosive Dispersion good
- But 4 MW Nu-Factory requires: 32 Tp/bunch

CERN Proposed Experiment P186

- More intensity 32 Tp as required for 4 MW
- 15 T pulsed Magnet near completion
2) Phase Rotation  (Reduce $dp/p$ prior to Cooling)

Neuffer’s Bunched Beam Rotation with 200 MHz RF

- RF frequency must vary along bunching channel
  Because High mom. bunches move faster than lower

\[ \text{d}E \]

\[ \text{Drift} \quad \text{RF Buncher} \quad \text{RF} \]

\[ \text{dt} \]
Simulation of Phase Rotation

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
3) Ionization Cooling

Electron, synchrotron, and stochastic cooling all too slow

- **TRANSVERSE**
  - Competes with Coulomb Scattering
  - Best with Hydrogen
  - and Strong Focus

- dE/E Reduced by Emit Exchange (Not needed for Factory)
  - Competes with Straggling
  - Best with strong RF
  - \( \longrightarrow \) large \( \frac{dp}{p} \)
  - Also works with material in bend
Study IIa Cooling Channel

- ≤ 200 MHz RF for required aperture
- LiH instead of Liquid Hydrogen (as in Study II)
- Simpler focus system than Study II (see MICE Exp. below)
Cooling Performance in Study IIa

![Graph showing cooling performance in Study IIa with data points and labels.]
Cooling with Emittance Exchange in a Ring

- Bending and wedge absorbers: Cooling also in longitudinal
- Many turns gives more cooling at lower cost
- Needed for a Muon Collider
- e.g RFOFO Ring  Now fully simulated

- 6D emittance down by 300 (cf 1000,000 req for Collider)
R&D on Ionization Cooling Components
MUCCOL Collaborative  Lead by Fermilab (A. Bross)

- Design, Build, Absorbers
- Design, Build, and Test Absorber Windows
- High Gradient RF Studies at 805 MHz (Lab G FNAL)
- Design & Start Const. of 201 MHz Cavities
- Experiment with High Pressure Hydrogen STTR
- Test area at FNAL
MUON IONIZATION COOLING EXPERIMENT (MICE)

- Solid Design based on Study-2 channel (Similar components to RFOFO cooling ring)
- International Collaboration: (US, Europe, Japan)
- Funding proposal sent to NSF, (& in Europe & Japan)
- Proposal has Scientific Approval at RAL
4) R&D ON ACCELERATION
SC Cavity work for Acceleration (Cornell NSF)

- Built new test pit
- Design, build, and test 201 MHz SC cavities
  11 MV/m achieved
  limited by drop in Q  c.f. FS2 spec = 16 MV/m
- Cavity returned to CERN for re-coating
ACCELERATION

- Must be fast: Muon lifetime = 2 micro sec
- Synchrotron much too slow Except above 500 GeV for collider
- Use initial SC Linac
- Then Recirculating Linear Collider (RLA)

Dog-bone and Racetrack RLA’s, with same number of passes through the Linac, have:
- slightly less total arc length
- much easier switch-yards

- Followed by FFAG’s (see below)
Scaling FFAG MURA & KEK (Japan)

\[ p \propto r^{n+1} \]

- Drift for rf
- Bend outward
- Bend inward

\[ B \propto r^n \]

Low Momentum
Mid Momentum
High Momentum

- Eliminates multiple arcs of RLA
- Allows more turns \( \rightarrow \) less RF
- \( \Delta p \) limited only by aperture
  but only 1:2 for Japan 20 GeV
- Tune independent of momentum
  i.e. Chromaticity=0

**BUT**

- Large magnet apertures
- Non-isochronous
  \( \rightarrow \) Low Frequency RF
  \( \rightarrow \) Non-superconducting RF

- Studies in Collaboration with Japan
  2-3 Workshops per year
Non-Scaling FFAG (Proposed by Carol Johnstone)

Combined function strongly focusing lattices without sextupoles e.g. from Dejan Trbojevic

- Orbits are not similar, as in scaling
- They are closer together than in scaling
  → smaller apertures
  → more isochronous
More Isochronous than Scaling  Allows use of SC RF

Design can be isochronous at center of momentum range:

- Less path length difference for same energy range
- Non-monotonic
- Allows 200 MHz (vs. 25 MHz for scaling)
But huge chromaticity

→ Tunes cross many integer resonances (right scale)

But if

1. All cells essentially identical
2. Reasonably small magnet errors
3. Rapid acceleration

Initial simulations indicate negligible emittance growth
Conclusion

• Muon Collider
  – Interesting for physics & Smaller than Linear Collider
  – Difficult technically
  – Neutrino Radiation limits Maximum Energy
  – Now returning to its study

• Neutrino Factory
  – If $\theta_{13} < 10^{-2}$ Factory is only hope to see CP
  – If $\theta_{13} > 10^{-2}$ Factory perhaps not needed
  – Will not know for 5-10 years
  – Neutrino Factory Design in good shape

• Sound R&D Program in Progress
  – Hg Jet Target for 4 MW (CERN Exp)
  – Cooling Components (MUCOOL)
  – SC RF at 200 MHz (Cornell)
  – Cooling Experiment (MICE)

• Interesting Spin-Offs: Hg Target, Non-Scaling FFAG’s

• US Funding a problem for MICE