High Energy Muon Collider and Neutrino Factory:

A Staged Pathway to Discovery

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30 October 2008
with input from:

Big Picture Since ICFA-2005

- LHC is built and will run in 2009:
  - confidence in getting new physics insight ~2012-13
- Growing consensus on the next machine (P5)
  - should be lepton-lepton collider
  - ILC energy reach may not be enough → multi-TeV
  - very serious attention to alternatives (P5 report)
- Alternative schemes:
  - CLIC e+e- linear collider (CDR by ~2010)
  - plasma-wake e+e- linear colliders (emerging)
  - muon collider (aims for DFSR by 2013) - advantages
Negligible synchrotron radiation

- Acceleration in rings rather than linear
- Less RF, very high energy reach >4TeV

Collider as a Ring

- Collisions over ~1000 turns of muon lifetime
- Larger spot, easier tolerances, 2 detector

LHC

- $p+p$ (1.5 TeV)

ILC

- $e^+e^-$ (0.5 TeV)

CLIC

- $e^+e^-$ (3 TeV)

$\mu^+\mu^-$ (4 TeV)
Superb Energy Resolution

100% luminosity in $dE/E \sim 0.1\%$

Beamstrahlung in any $e^+e^-$ collider

$\delta E/E \propto \gamma^2$
Other Changes Since 2005

- Rapid development of plans for multi-MW proton facilities:
  - FNAL: Project-X
  - CERN: Linac 4, PS Upgrade, SPL
  - RAL: ISIS upgrade to 3-5 MW
  - Europe: ESS

- This is exactly what’s needed for a Neutrino Factory or a Muon Collider:
  - thus, Muon Collider/Neutrino Factory offer a natural continuation of the near-future programs
Technical Progress Since 2005

- Successful completion of multi-MW liquid Hg-target experiment MERIT
- Start-up of ionization cooling experiment MICE (1st beam)
- Development of Muon Cooling components (absorbers, coils, RF cavities)
- Revealing results of RF studies (~20MV/m in 201MHz cavity, ~35MV/m in 805MHz, 60MV/m HP RF, in B-field, ionizing beam studies coming)
- SC coils for helical cooling designed and built
- NF Int’l Scoping Study report delivered
- Progress in MC design (ring lattice, RLA, cool)
Muon Collider Scheme

4D cooling
Phase rotation to 12 bunches
20T capture
Hg target
Buncher
Multi-MW Proton Driver
SC linac
Synchrotron both

“Front End”~ same as for Neutrino Factory → Idea of staging

μ⁺ μ⁻

6D cooling
Merge 12 to 1 bunch
6D cooling

Guggenheim*
HCC
FOFO Snake

50T solenoids*
REMEX
Li lenses

Final cooling
Linac
RLA(s)
High Energy Acceleration
Collider Ring

RLA
Pulsed synchrotron*
FFAG

* favored now

Shiltsev: μ+μ- Collider and ν-Factory
Stage I: Neutrino Factory

ν DUSEL

H-Stripping & Proton Accumulation

4 or 25 GeV ν-Fact

8 GeV H- Linac

μ Capture Bunching Cooling Acceleration

Bunching Targeting
Stage II: Muon Collider

Collider and \( \mu^- \) Factory

\( \mu \) Acceleration

\( \mu \mu \) Collisions
### Muon Collider Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>TeV/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CM Energy</strong></td>
<td>1.5 TeV</td>
<td>4 TeV</td>
<td>10^34 cm^-2 s^-1</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>1</td>
<td>4</td>
<td>10^12 cm^-2 s^-1</td>
</tr>
<tr>
<td>Muons/bunch</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Ring circumf.</td>
<td>3 km</td>
<td>8.1 km</td>
<td></td>
</tr>
<tr>
<td>Beta at IP β* = σ_z</td>
<td>10 mm</td>
<td>3 mm</td>
<td></td>
</tr>
<tr>
<td>dp/p (rms)</td>
<td>0.1 %</td>
<td>0.12 %</td>
<td></td>
</tr>
<tr>
<td>Ring depth*</td>
<td>13 m</td>
<td>135 m</td>
<td></td>
</tr>
<tr>
<td>PD Rep rate</td>
<td>12 Hz</td>
<td>6 Hz</td>
<td></td>
</tr>
<tr>
<td><strong>PD Power</strong></td>
<td>≈4 MW</td>
<td>≈2 MW</td>
<td></td>
</tr>
<tr>
<td><strong>Transv.emm. ε_T</strong></td>
<td>25 π mm mrad</td>
<td>25 π mm mrad</td>
<td></td>
</tr>
<tr>
<td>Long. emm. ε_L</td>
<td>72,000 π mm mrad</td>
<td>72,000 π mm mrad</td>
<td></td>
</tr>
</tbody>
</table>

*Based on real designs; depth for ν radiation keeps off site dose <1 mrem/yr

** low emittance options are under consideration (discussion below)
MC/NF Target

MERIT experiment

- Demonstration at CERN of 1 cm dia 20 m/s Hg jet target in 15 T & 3e13 24 GeV protons
- Target concept has been validated for 4MW 50Hz
Emittances vs Stage

- **Initial**
- **Final**

- Phase rotate to 12 bunches
- Merge to single bunch
- 4D cooling
- Final Transv Cooling in 50T solenoids
- 6D cooling before merge after merge

**Graph Details:**
- **Y-axis:** Longitudinal Emittance (mm rad)
- **X-axis:** Transverse Emittance (mm rad)

**Axis Scale:**
- Y-axis: From 0.01 to 100
- X-axis: From 0.01 to 10

**Note:**
- The graph illustrates the changes in emittance and cooling stages throughout the process.
Ionization Cooling is the Key

- Absorbers (Liquid H2, LiH)
- SC magnets
- RF Cavities (NC, Low→High Frequency)

- There is no “mystery” in the ionization cooling
  - single particle physics well understood to simulate
  - seen in low-\(E_p\)-rings (Novosibirsk 60’s, Osaka ERIT ‘08)
  - experiment(s) are to address technical challenges
4D-Cooling

will be demonstrated (2011) at RAL

International
Muon
Ionization
Cooling
Experiment

ISIS accelerator

MICE experimental hall
Muon Ionization Cooling Experiment

Status:
First beam, μ’s: Mar’30, 2008
Funded in: UK, CH, JP, NL, US

Challenges:
201MHz RF in 3T field
0.1% meas. of emittance
LH2 safety issues

Some prototyping:
- Scintillating-fiber tracker
- MUCOOL Liquid-hydrogen absorber
- MUCOOL 201 MHz RF cavity with beryllium windows

MUCOOL 201 MHz RF cavity with beryllium windows
6D- Cooling: Baseline

- **Guggenheim lattice** - as for slide 1:
  - lattice arranged as helix
  - bending gives dispersion
  - higher $p = \text{longer path in wedge absorbers} \Rightarrow \text{giving long. cooling}$

  **Q:** RF breakdown in 3-10 T field
“Final-” Transverse Cooling

High Field Solenoids:

- low momenta and strong focusing allow low transverse emittance
- longitudinal emittance rises

40/50 T solenoids:

- 45T hybrid at NHMFL, but 30MW
- 30T all HTS under construction
- Conductor → Magnet R&D: HTS Collab.
Alternatives Under Study

- **6D Cooling:**
  - Helical Cooling Channel (HCC)
  - Tilted Coils channel (FOFO Snake)
  - Both allow to cool both signs $\mu^+\mu^-$

- **Final Transverse Cooling:**
  - Resonant Lattice (low-$\beta$ PIC)
  - Liquid Li Lenses (0.5Hz $\rightarrow$ 5-10Hz)
Alternatives Under Study

- FNAL
- Pbar lens

H2 gas
SC Coils
rf cavities

Absorber plates
Parametric resonance lenses

$\lambda/8$
$\lambda$

Shiltsev: $\mu+\mu-$ Collider and $\nu$-Factory
**Acceleration and Collider**

**Acceleration**
- rapid acceleration in linacs and RLAs, <90MW wall plug for 3TeV
- lower cost – pulsed synchrotrons prototyping needed
- FFAGs can also play a role

**Collider Ring**
- 1.5 TeV designed
- to be studied: Detector background with early dipole scheme
NF International Scoping Study (ISS-NF, 2005-2008) is finished, reports published (arXive \(\rightarrow\) JINST):

- Physics
- Accelerator
- Detector
<table>
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<th>Parameter</th>
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</thead>
<tbody>
<tr>
<td># of $\mu$ decays/yr/baseline</td>
<td>$5 \times 10^{20}$</td>
</tr>
<tr>
<td>Number of rings (baselines)</td>
<td>2 (3000 &amp; 7000 km)</td>
</tr>
<tr>
<td>Stored $\mu$ energy</td>
<td>25 GeV</td>
</tr>
<tr>
<td>Mean proton beam power</td>
<td>4 MW</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Proton kinetic energy</td>
<td>5-10-15 GeV</td>
</tr>
<tr>
<td>Bunch duration at target</td>
<td>1-3 ns rms</td>
</tr>
<tr>
<td>Number of bunches per pulse</td>
<td>1-3</td>
</tr>
<tr>
<td>Sequential extraction delay</td>
<td>$\geq 17 \mu$s</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>$\leq 40 \mu$s</td>
</tr>
</tbody>
</table>
Similarly, NF gives the best Physics Reach for studies of mass hierarchy and in the $\sin^2(2\theta_{13})$ measurements:

SPL: 4MW, 1MT $\text{H}_2\text{OC}$, 130 km BL
T2HK: 4 MW, 1MT $\text{H}_2\text{OC}$, 295 km BL
WBB: 2MW, 1MT $\text{H}_2\text{OC}$, 1300 km BL
NF: 4MW, 100KT MIND, 4000 & 7500 BL
BB350: $\gamma$=350, 1MT $\text{H}_2\text{OC}$, 730 km BL
Global Strategy

2012-13 Decision Point

- LHC results establish $E_{cm}$ and $L$ of next lepton collider

Muon Collider development plan:

- a study to demonstrate feasibility by 2013 (DFSR)
- $\mu$-beam demonstration experiments (next 7-10 yr)
- start of MC construction in early to mid-2020’s

Neutrino Factory plan:

- complete MICE experiment by ~2011
- carry out International Design Study (IDS-NF) to deliver NF-RDR in 2012
- preconstruction R&D $\rightarrow$ construction start in late 2010’s

Shiltsev: $\mu+\mu$- Collider and $\nu$-Factory
Neutrino Factory development plan:

- Collider and Muon Collider development plan:
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- 2012-13 Decision Point
  - LHC results establish Ecm and L of next lepton collider

Neutrino Factory roadmap:

- MERIT
- MICE
- EMMA
- Detector and diagnostic systems development
- International Design Study
- Interim Design Report
- Reference Design Report

Timeline:

- FY08 to FY20
- Design and Simulations
- MERIT Tgt. R&D
- MICE (4D cooling)
- Component R&D (NCRF, SRF, magnets, ...)
- Feasibility Study
- Demonstration experiments
- RDR
- CDR
- Component prototyping
- Construction (through 2028)
Activities and Resources

- **US activities with overlapping memberships**
  - Neutrino Factory & Muon Collider Collab. (NFMCC)
  - Fermilab’s Muon Collider Task Force (MCTF)
  - Experiments MICE, MERIT, EMMA (all - int’l)
  - SBIR funded companies Muons Inc, Tech-X, PBL

- Guided by “Coordinating Group”

- Reviewed by Technical Advisory Committee

- Most of the US funding from DoE OHEP:
  - ~$(7-8) \text{ M$/yr} \ (-30 \text{ FTEs})$ - at present

- About the same level in Europe:
  - mostly from UK NF and EUROnu
US Muon Accelerator R&D Program
5 yr plan (2009-2013)

Program Management

1. Design
1.1 Physics & Detector
1.2 Design & Simulations
1.3 Cost Estimate
1.4 NF IDS/RDR

2. Components and tests
2.1 MICE
2.2 Cooling Ch. RF
2.3 Magnets
2.4 6D Cooling comp & test
2.5 Other R&D

Shiltsev: $\mu^+\mu^-$ Collider and $\nu$-Factory
The 5 Year Plan

❖ Will address key R&D issues, including

❖ Study RF gradients in magnetic field (magnetic insulation)
❖ High pressure RF tests with ionizing beam
❖ 6D cooling section prototype
❖ Full start-to-end simulations
❖ Bunching ring design
❖ Magnet designs for acceleration, collider and HTS

❖ Deliverables:

❖ MC Design Feasibility Study Report and NF RDR
❖ Results of hardware R&D to make technology choice
❖ Cost estimate

❖ Funding increase needed to ~20M$/yr (about 3x present level)
**IDS-NF : EUROnu and US Plan**

- **EUROnu** is the European contribution to the IDS-NF
  - Has started (EU contract began Sep 1, 2008)
  - 1st plenary Mar 23, 2009 at CERN (all welcome!)

**EUROnu: costed performance**

**IDS-NF: RDR by 2012**
- demonstrate feasibility
  - **The Americas**
    - Canada
    - USA
  - **Asia**
    - Japan
    - India
    - (in the future: China ...)
  - **Europe**
    - EUROnu

- Part of the US 5 yr plan
R&D Facilities

For the next ~5 years – two main facilities to carry out Muon Accelerator R&D will be:

- MICE at RAL
- Mucool Test Area at Fermilab
MuCool Test Area

- Cryogenics capabilities
- RF power at 201 MHz & 805 MHz
- Liquid $\text{H}_2$ absorber filling capability
- 5 T SC Solenoid with 30 cm bore (805 MHz Cavity fits inside)
- 400 MeV/c protons
R&D Facilities: after 2012

- 6D cooling and other full scale tests will require a high intensity beam of muons = a new R&D facility:
  - could be synergetic to a muon experiment, e.g., $\mu2e$
  - or be part of a new high-intensity Proton Driver facility
Muon Complex Evolution

PROTON SOURCE = SITE SPECIFIC

1 8 GeV SC Linac

PROJECT X

0 Recycler  Main Injector

EXISTING FACILITIES

2 Muon Collider
Rebunch  R&D Hall

Decay  Cool

Target  Phase Rot. & Bunch

MUON COLLIDER TEST FACILITY

3 6D Cooling

Final Cooling

Muon Acc

Collider Ring

1.5 TeV MUON COLLIDER

4 More Acc
Larger ring

4 TeV MUON COLLIDER

β

NEUTRINO FACTORY PROJECT

α

Pre-Accel

RLA (1–4 GeV)

4 GeV NF

25 GeV NF

PRESENTED TO:
-Fermilab long range planning group (SG)
-Recent HEPAP (P5) subpanel

Shiltsev: $\mu+\mu$- Collider and $\nu$-Factory
Summary

- A broad and significant R&D programs are already underway in the US, Europe and Japan

- Focus of the programs over the next 5 years:
  - establish feasibility of a Muon Collider by 2012-13
  - deliver MC DFSR by 2013 and NF-RDR by 2012
  - greatly narrow technology options, end-end simul’s
  - give cost estimates for MC and NF

- Staged approach: PD $\rightarrow$ MCTF $\rightarrow$ NF $\rightarrow$ MC

- To be realistic option in 2012-13, increased support for $\mu$-Collider R&D is needed now
What’s Missing?