Overview of Muon Cooling

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Outline

• Brief Motivation
• Muon Collider and Neutrino Factory concepts
• Need for muon cooling
• Ionization cooling
• Rubbia’s vision
• Frictional cooling
• R&D overview
• Summary
Thank you!

• to the organizers

• and

  Yuri Alexahin, Chuck Ankenbrandt, Valeri Balbekov, Alain Blondel, Dave Cline, J-P Delahaye, Slava Derbenev, Rick Fernow, Juan Gallardo, Steve Geer, Gail Hanson, Rol Johnson, Yoshi Kuno, Ken Long, Yoshi Mori, Dave Neuffer, Bob Palmer, Mark Palmer, Tom Roberts, Carlo Rubbia, Andy Sessler, Sasha Skrinsky, Pavel Snopok, Diktys Stratakis, Don Summers, Yagmur Torun, Katsuya Yonehara, Mike Zisman…

• and, of course,

  - DOE, NSF, STFC…
Muon Accelerators in a Nutshell

As the first speaker on muon cooling, let me briefly summarize its motivation:

- High-energy $e^+e^-$ colliders radiatively limited $\propto m^{-4}$
  - need heavier fundamental fermions — i.e., muons
    - and an effective cooling scheme for them

- Muon storage rings could then serve as uniquely powerful $\ell^+\ell^-$ colliders
  - e.g., for sensitive Higgs studies

- And neutrino sources

- And potentially, improved low-energy muon experiments

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C. Rubbia, “A Complete Demonstrator of a Cooled-Muon Higgs Factory,”
https://indico.fnal.gov/conferenceDisplay.py?confId=9752

- Only a muon collider can definitively investigate Higgs physics
Some History

Late 1970s – early 1980s: Muon Collider concepts proposed (Skrinsky, Parkhomchuk, Neuffer)

1995: Muon Collider Collaboration (later, NFMCC) formed (Snowmass96)
- comprising over 140 scientists at labs and universities in U.S. and abroad

1998 – 2004: CERN muon cooling studies

1999: Neutrino Factory Feasibility Study I

2001: Neutrino Factory Feasibility Study II

2003: MICE approved

2004: Neutrino Factory Feasibility Study 2a

2006: Fermilab Muon Collider Task Force formed to study site-specific MC design

2010: (On DOE initiative) NFMCC and MCTF join forces → interim MAP & proposal to DOE

2011: MAP formally approved

2014: Start of MAP rampdown in response to P5 advice
νF and μC

- Recent MAP designs:

  ![Diagram of Neutrino Factory (NuMAX) and Muon Collider](image)

  **Neutrino Factory (NuMAX)**
  - Proton Driver
  - Front End
  - Cooling
  - Acceleration
  - μ Storage Ring

  **Muon Collider**
  - Proton Driver
  - Front End
  - Cooling
  - Acceleration
  - Collider Ring

  **ν Factory Goal:**
  \[ O(10^{21}) \ μ/\text{year} \text{ within the accelerator acceptance} \]

  **μ-Collider Goals:**
  - \( 126 \text{ GeV} \Rightarrow \sim 14,000 \text{ Higgs/yr} \)
  - Multi-TeV \( \Rightarrow \text{Lumi} > 10^{34}\text{cm}^{-2}\text{s}^{-1} \)

- Note strong similarities! (Front ends very similar)
  - both start with \( \sim \text{MW} \ p \text{ beam on high-power tgt} \Rightarrow π \Rightarrow μ \),
  then cool, accelerate, & store

See M. & R. Palmer talks (this PM)
Muon Cooling

- Desired evolution of $\epsilon_n$:
- Physics of multi-TeV lepton collisions calls for $\mathcal{L} > 10^{34}$ cm$^{-2}$ s$^{-1}$
  \(\Rightarrow\) must cool both $\epsilon_\perp$ & $\epsilon_\parallel$
  - need factor $\sim 10^6$ in total 6D emittance reduction:
    $\epsilon_\perp \approx 25$ µm, $\epsilon_\parallel \approx 60$ mm

- Higgs physics requires $\mathcal{L} \sim 10^{32}$ and $\Delta p/p \sim 10^{-5}$
  - $\epsilon_\perp \leq 200$ µm, $\epsilon_\parallel \approx 1.5$ mm

- Neutrino factory (with “dual-use” linac) requires more modest, $\sim 10$ 6D cooling factor

Suggests staging plan!
The Challenge:

\[ \tau_\mu = 2.2 \, \mu s! \]

**Q:** What cooling technique works in microseconds?

**A:** There is only one, and it works only for muons:

**Ionization Cooling**


*A brilliantly simple idea!*
Ionization Cooling:

- **Two competing effects**
  - (cf. synch. rad. damping, opposed by quantum fluctuations)

- **How it works:**
  - Absorbers reduce $\vec{p}_\mu$
  - RF cavities replace $p_\parallel$
  - Reduction in muon $p_\perp$ at constant $p_\parallel$ is transverse cooling:

$$
\frac{d\epsilon}{ds} = -\frac{1}{\beta^2} \left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}
$$

(emittance change per unit length)

**Note:** It’s “just Maxwell’s equations,” so in principle it *has* to work!

But in practice it’s subtle and complicated...

*so a test is essential!*

⇒ MICE [C. Rogers talk (Tuesday)]
Some Ionization Cooling Details

1. Effect is transverse only
   - might hope to cool longitudinally via \( dE/dx \) curve’s slight positive slope above ionization minimum
   - but \( dE/dx \) “straggling” tail leads to heating

2. Optimal cooling requires:
   - low \( \beta_\perp \) at absorber
   - large absorber \( X_0 \) (low \( Z \))
   - low \( E_\mu \) (typ. \( 150 < p_\mu < 400 \) MeV/c)

3. Can couple cooling effect into longitudinal phase plane via emittance exchange
   - allows all 6 phase-space dimensions to be cooled

\[
\frac{d\epsilon}{ds} = -\frac{1}{\beta^2} \left( \frac{dE_\mu}{ds} \right) \frac{\epsilon_N}{E_\mu} + \frac{\beta \gamma (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}
\]

Emittance exchange example (D. Neuffer):

Dipole (bend)

\( +\delta p \)

\( 0 \)

\( -\delta p \)

Wedge Absorber reduces energy spread

Dipole introduces dispersion (\( \eta \))

\( x \to x_0 + \eta \frac{dp}{p} \)
Preparing for Ionization Cooling

Example: International Design Study (IDS) vF design [hep-ex/1112.2853]

- Ionization cooling requires bunched beam with \( dp/p \approx 10\% \)
  - \( \mu \) “born” with small \( \Delta t \) but large \( \Delta E \)
  - first, bunch, then phase-rotate:

\[ \Delta E \]

- efficient bunching via RF “vernier” [D. Neuffer]
  - uses several RF frequencies starting at \( \approx 500 \) MHz, decreasing to 325
Alternating-Gradient Lattices

R. Palmer (BNL) et al.

• With thick- or thin-solenoid focusing

Alternating Solenoid

\[ B_z(\text{max}) = 3.4 \text{ (T)} \]
\[ \frac{dB_z}{dz(\text{max})} = 15 \text{ (T/m)} \]

FOFO

\[ B_z(\text{max}) = 3.4 \text{ (T)} \]
\[ \frac{dB_z}{dz(\text{max})} = 9.4 \text{ (T/m)} \]

Super FOFO

\[ B_z(\text{max}) = 2.6 \text{ (T)} \]
\[ \frac{dB_z}{dz(\text{max})} = 7 \text{ (T/m)} \]

Resonances → low β with less superconductor

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Simple Transverse Cooling Scheme

IDS design [hep-ex/1112.2853]:

- Alternating-solenoid (“RFOFO”) focusing (Study 2a)
- Thin, Be-coated LiH absorbers double as RF-cavity windows

• Performance:
  - ≈100-m-long cooling channel
  - ≈doubles muon intensity
  - accepts and cools \( \mu^+ \) and \( \mu^- \) simultaneously, in interspersed RF buckets
6D Cooling Approaches

- Effective transverse ionization cooling designs proposed ~2000
- 6D harder – many lattices explored to find current, successful ones:

Fig. 5: Schematic of Balbekov ring cooler

Quad+Dipole Ring

Helical Solenoid (HCC)

Palmer ring

33 m Circumference
200 MeV/c
“Injection possible”

RFOFO “Guggenheim”

Injection unnecessary

K. Yonehara (FNAL), R Johnson (µ, Inc.), Ya. Derbenev (JLab)

A. Garren, D. Cline (UCLA), H. Kirk (BNL)

Helical FOFO “Snake”

Y. Alexahin (FNAL)

R. Palmer, D. Stratakis (BNL), A. Klier, G. Hanson (UCR), P. Snopok (UCR/IIT)

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Initial Cooling

- Helical (Guggenheim etc.) channels need $\mu^+/\mu^-$ charge separation – hard at large emittance

  - Y. Alexahin Helical FOFO
    “Snake” accepts both signs, via rotating, tilted solenoids giving (small) rotating dipole
      - like synchronizing traffic lights on 2-way street!
  
  - 3 120° orientation steps give isomorphic $\mu^+$ and $\mu^-$ orbits with half-period offset
Current 6D Schemes

- Guggenheim scheme neatly avoided difficult injection and allowed tailoring of $\beta_\bot$ to $\epsilon$

  but engineering looked hard!

- V. Balbekov (2013): “R FOFO snake channel for 6D muon cooling,”
  http://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4365

![Diagram of Guggenheim scheme](image)

Rectilinear FOFO

![Diagram of rectilinear FOFO](image)

~ 20 m

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Current 6D Schemes

- **R_FOFO performance:**
  - 12 stages → $\times 10^{-5}$ in 6D emittance in 500 m
  - reaches $\epsilon_\perp \approx 280 \ \mu\text{m}$, $\epsilon_\parallel \approx 1.6 \ \text{mm}$

[D. Stratakis, R. Palmer, PRSTAB 18, 031003 (2015)]
Helical-Channel Dynamics

[Ya. Derbenev, R. Johnson, PRSTAB 8, 041002 (2005)]

Solenoid + Helical dipole + Helical Quadrupole

Dispersive component makes longer path length for higher momentum particle and shorter path length for lower momentum particle.

- Continuous focusing &
  (high-pressure-gas) absorber

\[ f_{\uparrow} \propto b_\phi \cdot p_z \text{ Repulsive force} \]
\[ f_{\downarrow} \propto -b_z \cdot p_\phi \text{ Attractive force} \]

- HCC performance:
  - reaches \( \epsilon_\perp \approx 600 \text{ \( \mu \)m}, \epsilon_{||} \approx 0.9 \text{ mm} \)
    [K. Yonehara, ICFA BD Newslett. 65, 63 (2015)]

\[ \kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z} \]

Simulated 6D evolution in HCC
But we have a different “last mile” problem

- we’ve shown how to get within an order of magnitude of the desired 6D emittance!

- what about that last factor of 10???
“Beyond” 6D Cooling

Ya. Derbenev (JLab), R. Johnson (Muons), R. Palmer, H Sayed (BNL)

- Can cool beam yet further with new approaches:
  - Parametric-resonance Ionization Cooling (PIC)...
  - Reverse Emittance Exchange (REMEX):

- or with ~30 T HTS solenoids and $dE/dx$ at low energy (~5 MeV)

R. Palmer talk (this PM)

Acosta & Neuffer posters (this PM)
“Rubbia Vision”

[see e.g. C. Rubbia, “A complete demonstrator of a muon cooled Higgs factory,” arXiv:1308.6612; http://tinyurl.com/oe9yesf]

- Higgs physics is best done at muon collider!
  - scan Higgs resonance with precision and precisely (≤1%) measure branching ratios
    ⇒ s-channel $\mu^+\mu^-$ Higgs Factory: $E = 126$ GeV ± ε
    - want $\mathcal{L} > 10^{32} \rightarrow \sim 50,000$ Higgs/yr/detector
      ⇒ need new (“beyond 6D”) cooling technique
  - must also go above 2-Higgs production threshold and measure Higgs self-coupling
    ⇒ TeV muon collider upgrade
  - “no other” approach is as capable!

necessary in order to rule out, or confirm, alternatives to SM Higgs

need to reinforce R&D effort (CERN?)
Frictional Cooling

- Conventional ionization cooling works at the ionization minimum!
- Why not work where $dE/dx$ is 2 orders of magnitude larger, and → – feedback?
  - answer: momentum acceptance $\lesssim 10$ keV
  - but still of interest for low-energy applications
Frictional Cooling

• Can use foil stacks (or gas, but sparks)

• Idea to increase momentum acceptance: “Particle Refrigerator” (possible use: cooled-muon cargo-container scanning?)

• Planned surface-muon-beam application:
  - increase phase-space density of stopping muon beam @ PSI
Muon Cooling R&D

• MICE: build and test a section of cooling channel

• Efficient ionization-cooling channel requires high-gradient RF cavities in strong focusing fields

→ high-gradient NC cavity studies at Fermilab

- large beam ⇒ low RF freq. (now 325/650 MHz)

MuCool Test Area

Prototype MICE 201-MHz cavity

Freemire talk (Thursday)

Rogers talk (Tuesday)
RF Cavity R&D

- Early work showed strong spark-probability increase with B-field
  - suppressed by high-pressure H₂ fill

• Newer vacuum cavities perform better

Freemire talk (Thursday)
and M. Palmer talk (this PM)
Summary

• Muon cooling looks feasible
• Promising facility designs conceived
• Neutrino Factory: best future ν facility
• “Heavier electron” colliders remain compelling
• Appealing solutions to “last mile” problem proposed
• See coming talks…
In Memoriam

- We lost three pioneering leaders this year

Andy Sessler, 1928–2015

Dave Cline, 1933–2015

Mike Zisman 1944–2015

- All made important contributions to muon collider R&D

- We will miss them!