Explore feasibility and limiting factors of large-acceptance Recirculating Linear Accelerators (RLAs) based on Superconducting RF

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Outline

- Design of multi-GeV muon accelerator complex for future Neutrino Factory – International Design Study
- TeV-scale muon acceleration for future Muon Collider
- Extreme muon cooling schemes for Low Emittance Muon Collider
- Collaborations & Partnerships
- Summary
Motivation – Scientific Case

- Muon Colliders and Neutrino Factories are attractive options for future facilities aimed at achieving the highest lepton-antilepton collision energies (e.g. to mass-produce Higgs bosons in s-channel) and precision measurements of parameters of the neutrino mixing matrix with intense \(10^{14}\) \(\mu/\text{sec}\), small divergence neutrino beams with well-understood systematics.

- Their performance and feasibility depend strongly on how well a muon beam can be cooled and accelerated to multi-GeV and TeV energies.

- Recent progress in muon cooling and acceleration (International Design Study and prototype tests) encourages the hope that such facilities can be built during the next decade…

- Funding for these studies provided by: HEP and SBIR/STTR grants
Opportunities and Challenges

• Future Muon facilities based on muon storage rings will require innovative SRF linacs to:
  • Longitudinally compress and ‘shape’ them into a beam
    • μs are produced in a tertiary process into a large emittance (p + A → π → μ)
  • Rapidly accelerate them to multi-GeV (NF) and TeV (MC) energies
    • it has a short life time (2.2 μsec) in its own rest frame
    • high gradient, fixed field accelerator

• Why Recirculating Linear Accelerators based on SRF?
  • RLAs are possible because muons do not generate significant synchrotron radiation
    • high energies and in strong magnetic fields (m_μ = 105 MeV/c^2)
  • Huge initial phase-space requires large acceptances (both trans/longit)
  • Large intensities call for RF operating at stored energy
Design of multi-GeV muon accelerator complex for future Neutrino Factory – International Design Study
Multi-GeV muon RLAs for Neutrino Factory

- Conceptual design of an RLA based Muon Accelerator Complex
  (as part of NF International Design Study)

- 200 MHz SRF Linac (0.3 to 0.9 GeV)
  - Rapid acceleration of short lived muons, high gradient SRF
  - ‘Full bucket’ acceleration and longitudinal bunch compression
  - Two-step, vertically stacked ‘dogbone’ RLAs (0.9 to 12.6 GeV)
  - phase slippage, RF cavities synchronized for a speed of light particle
  - simultaneous acceleration of $\mu^+$ and $\mu^-$ charge species
‘Dogbone’ vs ‘Racetrack’ RLA (both $\mu^+$ and $\mu^-$)

- better orbit separation at linac’s end ~ energy difference between consecutive passes ($2\Delta E$)
- allows both charges to traverse the linac in the same direction (more uniform focusing profile)
Linear Pre-accelerator – 240 to 900 MeV

Transverse acceptance (normalized): $(2.5)^2 \varepsilon_N = 30$ mm rad

Longitudinal acceptance: $(2.5)^2 \sigma_\Delta p \sigma_z / m_\mu c = 150$ mm

SRF linac with individually phased RF cavities; far off-crest at the beginning of the linac and gradually brought on-crest by the linac end. Induced synchrotron motion is allowing for longitudinal bunch compression in both length and momentum spread.
Pre-accelerator – Longitudinal compression

Transverse acceptance (normalized): $(2.5)^2 \varepsilon_N = 30 \text{ mm rad}$

Longitudinal acceptance: $(2.5)^2 \sigma_{\Delta p} \sigma_z / m_i c = 150 \text{ mm}$

Longitudinal phase-space $(s, \Delta p/p)$ axis range: $s = \pm 25 \text{ cm}$, $\Delta p/p = \pm 0.2$
Multi-pass linac Optics

‘half pass’, 900-1200 MeV

initial phase adv/cell 90 deg. scaling quads with energy

1-pass, 1200-1800 MeV

mirror symmetric quads in the linac
Multi-pass linac Optics

4-pass, 3000-3600 MeV

phase adv. still larger then 180 deg. in both planes

5-pass, 3600-4200 MeV
Mirror-symmetric ‘Droplet’ Arc – Optics

E = 1.2 GeV

\( \beta_{\text{out}} = \beta_{\text{in}} \) and \( \alpha_{\text{out}} = -\alpha_{\text{in}} \), matched to the linacs

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**Diagram: mirror-symmetric arc optics**

- **Input Parameters:**
  - Energy: 1.2 GeV
  - Beta: \( \beta_{\text{in}}, \beta_{\text{out}} \)
  - Alpha: \( \alpha_{\text{in}}, -\alpha_{\text{out}} \)

- **Optics Layout:**
  - 10 Cells in
  - Transition sections
  - 2 Cells Out

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**Legend:**

- **View:** At the lattice end
- **Footprint:**

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**Graphs:**

- Betas and Dispersions
- Trajectory plots
TeV-scale muon acceleration for future Muon Collider
Low Emittance Muon Collider Scenario

1.5 TeV LEMC

4 km ILC linac
103 GeV/pass

30 GeV Coalescing ring

30 GeV RLA

μ⁻ cool/accel
μ⁺ cool/accel

μ⁻ cap/cool
Target
μ⁺ cap/cool

HρD Linac

8 GeV proton accumulator and buncher rings
‘Pulsed’ linac Dogbone RLA

• Design of a muon RLA based on ILC linac (solicited by Muon Collider Task Force at Fermilab)

• Multi-pass linac optics with pulsed quads – newly awarded SBIR with Muons Inc
  • Quad pulse would assume 500 Hz cycle ramp with the top pole field of 1 Tesla.
  • Mitigation of focusing deficiency - larger number of passes
‘Pulsed’ vs ‘Fixed’ Dogbone RLA

**Pulsed**

![Graph showing pulsing effects](image1)

- Phase advance diminishes down to 180°
- 8-pass, 28-32 GeV

**Fixed**

![Graph showing fixed effects](image2)
‘Pulsed’ vs ‘Fixed’ Dogbone RLA

- Pulsed
  - phase adv. diminishes down to 180°
  - 12-pass, 47-51 GeV

- Fixed
  - no phase adv. across the linac
  - beam envelopes not confined
Large momentum acceptance multi-pass Arc

- Non Scaling FFAG Optics
  - Compact triplet cells based on opposed bend combined function magnets

For different energies self-similar beta functions in a periodic cell
MADX- Polymorphic Tracking Code. Energy acceptance: -30% to 90%
NS-FFAG multi-pass ‘Droplet’ Arc

- MADX-PT – Polymorphic Tracking Code is used to study multi-pass beam dynamics for different pass beams: path length difference, optics mismatch between linac and arcs, orbit offset and tune change is being studied.
Extreme muon cooling schemes for Low Emittance Muon Collider
Muon Ionization Cooling

Absorber
Momentum loss is opposite to motion, \( p_x, p_y, \Delta E \) decrease

Accelerator
Momentum gain is purely longitudinal

\( \Delta \rho_{ds} \times \rho_{in} \)

Absorber Plate

Transverse cooling

Dipole (bend)
Wedge Absorber reduces energy spread

Longitudinal Emittance Exchange

\( x \rightarrow x_0 + \eta \frac{dp}{\rho} \)
Helical Cooling Channel

A linac filled with high pressure hydrogen gas and imbedded in strong magnetic fields has been proposed to rapidly cool muon beams

Combined function magnet (invisible in this picture)
Solenoid + Helical dipole + Helical Quadrupole

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

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

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

\[ f_{\text{central}} = \frac{e}{m} (b_\varphi \cdot p_z - b_z \cdot p_\varphi) \]

Both terms have opposite signs.
Parametric Resonance Cooling

- Transport channel (between consecutive absorbers) designed to replenish large angular component, \( x' \), sector of the phase-space, ‘mined’ by ionization cooling process.

- Normal elliptical motion of a particle’s transverse coordinate in phase space becomes hyperbolic (half-integer resonance) – resulting beam emittance has a wide spread in \( x' \) and very narrow spread in \( x \).
Epicyclic Helical Solenoid

\[ B_T = |B_1|e^{ik_1z} + |B_2|e^{ik_2z} \]

- Superimposed transverse magnetic fields with two spatial periods
- Variable dispersion function

\[ k_1 = -2k_2 \]
\[ B_1 = 2B_2 \]
Collaborations & Partnerships
### Monday, 15 December 2008

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Speaker(s)</th>
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| 09:00-12:30| Front end session - cooling and end2end simulation                       | All
|            | Discussion of ICOOL, GEANT4 Material Model                               |                             |
|            | Alternate lattices; optimisation algorithms                              | Chris Rogers                |
| 09:00-12:30| Acceleration session - FFAG                                              | (JPa obo) Shinji Machida    |
|            | FFAG lattice with chromaticity correction                                |                             |
| 12:30-13:30| Lunch                                                                    | Scott Berg                  |
| 13:30-16:00| Joint front end and acceleration session                                 | Fernow/Rogers               |
|            | Front end - plans and schedule                                          |                             |
|            | Acceleration - plans and schedule                                       | Bogacz/Pozimski             |
SBIR/STTR Grants

Muons, Inc.
Summary

- Muon Colliders & Neutrino Factories will require innovative SRF linacs to: cool/compress and ‘shape’ them into a beam and finally to rapidly accelerate them to multi – GeV (NF) & TeV (MC) energies

- Large acceptance Recirculating Linacs – rapid acceleration and effective longitudinal bunch compression

- ‘Dogbone’ (Single Linac) RLA has advantages over the ‘Racetrack’
  - better orbit separation for higher passes
  - offers symmetric solution for simultaneous acceleration of $\mu^+$ and $\mu^-$

- Pulsed linac multi-pass Optics….even larger number of passes is possible if the quadrupole focusing can be increased as the beam energy increases

- Extreme Cooling – A linac filled with high pressure hydrogen gas and imbedded in strong magnetic fields has been proposed to rapidly cool muon beams
  - Helical Cooling channel
  - Parametric Resonance – Epicyclic channels