Very low Emittance Muon Beam using positron beam on target

M. Antonelli (INFN-LNF)
Chicago (USA), ICHEP 2016

References:

- P. Raimondi, “Exploring the potential for a Low Emittance Muon Collider”, in Discussion of the scientific potential of muon beams workshop, CERN, Nov. 18th 2015

Also investigated SLAC team:
L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:
  - “Luminosity Estimate in a Multi-TeV Muon Collider using e⁺e⁻ → μ⁺μ⁻ as the Muon Source”, MAP 2014 Spring workshop, Fermilab (USA) May ’14
  - Advanced Accelerator Concepts Workshop, San Jose (USA), July ‘14
Involved persons:

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- M. Prest \textit{(Uni-Insubria & INFN)}
- P. Raimondi \textit{(ESRF)}
- J. P. Delahaye, P. Sievers, R. Di Nardo \textit{(CERN)}
- I. Chaikovska, R. Chehab \textit{(LAL-Orsay)}
- L. Keller, T. Markiewicz \textit{(SLAC)}
Idea for low emittance $\mu$ beam

Conventional production: from **proton on target**

$\pi$, K decays from proton on target have typical $P_\mu \sim 100$ MeV/c ($\pi$, K rest frame)

whatever is the boost $P_T$ will stay in Lab frame $\rightarrow$ **very high emittance** at production point $\rightarrow$ **cooling needed**!

Direct $\mu$ pair production:

Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold ($\sqrt{s} \sim 0.212$ GeV) in asymmetric collisions (to collect $\mu^+$ and $\mu^-$)
Advantages:

1. **Low emittance possible:** $P\mu$ is tunable with $\sqrt{s}$ in $e^+e^-\rightarrow\mu^+\mu^-$. $P\mu$ can be very small close to the $\mu^+\mu^-$ threshold.

2. **Low background:** Luminosity at low emittance will allow low background and low $\nu$ radiation (easier experimental conditions, can go up in energy).

3. **Reduced losses from decay:** Muons can be produced with a relatively high boost in asymmetric collisions.

4. **Energy spread:** Muon Energy spread also small at threshold, it gets larger as $\sqrt{s}$ increases, one can use correlation with emission angle (eventually it can be reduced with short bunches).

Disadvantages:

- **Rate:** much smaller cross section wrt protons
  
  $\sigma(e^+e^-\rightarrow\mu^+\mu^-) \sim 1 \, \mu b$ at most

  *i.e.* Luminosity$(e^+e^-)= 10^{40} \, \text{cm}^{-2} \, \text{s}^{-1}$ → gives $\mu$ rates $10^{10} \, \text{Hz}$
Possible Schemes

• **Low energy collider with e+/e- beam (e+ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity is beyond current knowledge)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, $10^{20}$ electrons/cm$^3$ needed to obtain a reasonable conversion efficiency to muons)

• **Electrons at rest (seems more feasible):**
  3. e+ on Plasma target
  4. e+ on standard target
     – Need Positrons of $\sim 45$ GeV
     – $\gamma(\mu) \sim 200$ and $\mu$ laboratory lifetime of about 500 $\mu$s

Ideally muons will *copy* the positron beam
Muons angle contribution to $\mu$ beam emittance

The target thickness and c.o.m. energy completely determine the emittance contributions due to muon production angle

$$\theta_{\mu}^{\text{max}} = 4 m_{\mu} \frac{(s/4-m_{\mu}^2)^{1/2}}{s}$$

$$\varepsilon_{\mu} = x \times'_{\text{max}} / 12 = L \left( \theta_{\mu}^{\text{max}} \right)^2 / 12$$

[Babayaga 3.5]
Criteria for target design

- **Number of $\mu^+\mu^-$ pairs produced per interaction:**

  \[
  n(\mu^+\mu^-) = n^+ \rho^- L \sigma(\mu^+\mu^-)
  \]

  \(n^+\) = number of $e^+$
  \(\rho^-\) = target electron density
  \(L\) = target length

- **$\rho^- L$ constraints**
  - Ideal target ($e^-\) dominated)
    \((\rho^- L)_{\text{max}} = 1/\sigma(\text{radiative bhabha}) \approx 10^{25}\ cm^{-2}\)
    (beam lifetime determined by radiative Bhabha)
  - With \((\rho^- L)_{\text{max}}\) one has a maximal $\mu^+\mu^-$ production efficiency $\sim 10^{-5}$
  - Muon beam emittance increases with \(L\) (in absence of intrinsic focusing effects) \(\Rightarrow\) increase \(\rho^-\)
  - Conventional target \((\rho^- L)_{\text{max}}\) depends on material (see next slides)
Criteria for target design

Bremsstrahlung on nuclei and multiple scattering (MS) are the dominant effects in real life... Xo and electron density will matter:

• **Heavy materials**
  - minimize emittance (enters linearly) ➔ Copper has about same contributions to emittance from MS and $\mu^+\mu^-$ production
  - high $e^+$ loss (Bremsstrahlung is dominant)

• **Very light materials**
  - maximize production efficiency (enters quad) ➔ $H_2$
  - even for liquid need $O(1m)$ target ➔ emittance increase

• **Not too heavy materials**(Be, C )
  - Allow low emittance with small $e^+$ loss

  **optimal: not too heavy and thin**
Application for Multi-TeV Muon Collider as an example

- Use thin target with high efficiency and small $e^+$ loss
- Positrons in storage ring with high momentum acceptance
- No need of extreme beam energy spread
Possible target: 3 mm Be

45 GeV $e^+$ impinging beam

- Emittance at $E_\mu = 22$ GeV:
  \[ \varepsilon_x = 0.19 \times 10^{-9} \text{ m-rad} \]

  **Multiple Scattering contribution is negligible**

  -> $\mu$ after production is not affected by nuclei in target
  -> $e^+$ beam emittance is preserved, not being affected by nuclei in target (see also next slide)

- Conversion efficiency: $10^{-7}$
- Muons beam energy spread: 9%

*~1 mm diamond target works with similar performances (more resistant to PEDD)*
Positrons Storage Ring Requirements

- Transverse phase space almost not affected by target
- Most of positrons experience a small energy deviation:
  A large fraction of $e^+$ can be stored (depending on the momentum acceptance)
  - 10% momentum acceptance will increase the effective muon conversion efficiency (produced muon pairs/produced positrons) by factor 100

![Graphs and diagrams showing positrons at the target exit surface and muon beam loss distribution.](image-url)
Schematic Layout for muon source from e+

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>6 km</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.6 km</td>
</tr>
<tr>
<td>number e+ bunches</td>
<td>100</td>
</tr>
<tr>
<td>e+ bunch spacing</td>
<td>200 ns</td>
</tr>
<tr>
<td>Beam current</td>
<td>240 mA</td>
</tr>
<tr>
<td>e+ Particles/bunch</td>
<td>$3 \cdot 10^{11}$</td>
</tr>
<tr>
<td>Rate e+ on target</td>
<td>$1.5 \cdot 10^{18} \text{ e}^+/s$</td>
</tr>
<tr>
<td>$U_0$</td>
<td>0.58 GeV</td>
</tr>
<tr>
<td>$P_{\text{tot}}$</td>
<td>139 MW</td>
</tr>
<tr>
<td>B</td>
<td>0.245 T</td>
</tr>
</tbody>
</table>

Key point:
Positron source requirements strictly related to the e$^+$ ring momentum acceptance

$n_b = \sum_{i=1}^{N_T} e^{-\Delta t(N_T-i)/\tau_{\mu}^{\text{lab}}}$

60 m isochronous rings recombine bunches for $\sim 1 \tau_{\mu}^{\text{lab}} \sim 2500$ turns
Muon beam parameters

Assuming

- a positron ring with a total 25% momentum acceptance
- $\sim 3 \times$ FCC-he positron source rate

- push on mom. acceptance and $e^+$ source performances
- improve target performances

### Table

<table>
<thead>
<tr>
<th>$\mu$ rate [Hz]</th>
<th>positron source</th>
<th>proton source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$9 \cdot 10^{10}$</td>
<td>$2 \cdot 10^{13}$</td>
<td></td>
</tr>
<tr>
<td>$\mu$/bunch</td>
<td>$4.5 \cdot 10^{7}$</td>
<td>$2 \cdot 10^{12}$</td>
</tr>
<tr>
<td>normalised $\epsilon$ [\mu m-mrad]</td>
<td>40</td>
<td>25000</td>
</tr>
</tbody>
</table>

**Very small emittance, high muon rates** but relatively small bunch population:

- The actual number of $\mu$/bunch in the muon collider can be larger by a factor $\sim \tau_\mu^{\text{lab}}(\text{HE})/500 \, \mu s$ (~100 @6 TeV) by topping up.
**Low Emittance Muon Muon Accelerator**

**Draft Parameters**

Comparable luminosity with lower Nµ/bunch (lower background) thanks to very small emittance (and lower beta*)

Of course, a design study is needed to have a reliable estimate of performances
Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

Fig. 1: Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

Muon rate: $p$ on target option 3 $10^{13} \mu/s$

$e^+$ on target option $9 \times 10^{10} \mu/s$
Muon collider reach: an example

• Study the same benchmark used for White Paper:
  – New heavy particles, both colored and EW charged (~vector like quarks) \(\Rightarrow\) xsec can be predicted
  – FCC reach stops at \(M_X = 7\) TeV

• Hadron machine pays the price of the exponentially falling PDF \(\Rightarrow\) multi-TeV muon machine can be competitive!

![Graph showing the cross-section \(\sigma\) vs. mass \(M_X\) for different collider energies and scales.](image)
Muon Collider:
Schematic Layout for positron based muon source

Key Challenges
~$10^{11}$ $\mu$ / sec from $e^+e^- \rightarrow \mu^+\mu^-$

Key R&D
$10^{15}$ $e^+/sec$, 100 kW class target, NON destructive process in $e^+$ ring

Accelerators:
Linacs, RLA or FFAG, RCS

$E_{CoM}$: Higgs Factory to ~10 TeV

Positron Beam
LHC-class $e^+$ source & $e^+$ acceleration at 45 GeV (circular/linear options)

$100$ kW target

$\mu^+$

isochronous rings

e+ ring

Acceleration

Collider Ring

Muon - $\mu^- - \mu^+$
Key Feasibility Issues

- Positron Source
  - Muon Target
  - Positron Ring

- Collider MDI
- Collider Detector
- \( \mu \) Acceleration
- Collider Ring

- NEED deep investigation (design study)
- HIGH rate
- Non destructive
- Mom. acceptance
- Targets survival

(mostly) independent on muon source
Benefit from MAP studies
First Optics for e\(^+\) ring

Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>m</td>
</tr>
<tr>
<td>Bending radius</td>
<td>m</td>
</tr>
<tr>
<td>Magnetic rigidity</td>
<td>T m</td>
</tr>
<tr>
<td>Lorentz factor</td>
<td></td>
</tr>
<tr>
<td>Coupling (full current)</td>
<td>%</td>
</tr>
<tr>
<td>Emittance x (from model)</td>
<td>m</td>
</tr>
<tr>
<td>Emittance y</td>
<td>m</td>
</tr>
<tr>
<td>Bunch length (zero current)</td>
<td>mm</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
</tr>
<tr>
<td>RF frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>RF voltage</td>
<td>GV</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>#</td>
</tr>
<tr>
<td>Revolution period</td>
<td>s</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>#</td>
</tr>
<tr>
<td>N. Particle/bunch</td>
<td>#</td>
</tr>
<tr>
<td>Synchronous phase</td>
<td></td>
</tr>
<tr>
<td>Syncrotron frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>#</td>
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<tr>
<td>synchrotron period</td>
<td>turns</td>
</tr>
<tr>
<td>Overvoltage</td>
<td></td>
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<tr>
<td>Transverse damping time</td>
<td>turns</td>
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<td>Transverse damping time</td>
<td>s</td>
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<td>Longitudinal damping time</td>
<td>turns</td>
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<tr>
<td>Longitudinal damping time</td>
<td>s</td>
</tr>
<tr>
<td>Energy Loss/turn</td>
<td>GeV</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>T</td>
</tr>
<tr>
<td>B field</td>
<td></td>
</tr>
<tr>
<td>Rf energy acceptance</td>
<td>%</td>
</tr>
<tr>
<td>Energy spread (SR)</td>
<td>dE/E</td>
</tr>
<tr>
<td>SR power loss</td>
<td>GW</td>
</tr>
<tr>
<td>SR power/Circumference</td>
<td>kW/m</td>
</tr>
</tbody>
</table>

\[
\frac{\delta v}{v_{oc}} = 0
\]
43.8 GeV e$^+$
4.1 mm Si Target
Channeling plane: (110)
Going to lighter targets for $\mu$ production

Look to light liquid targets to reduce problems of thermo-mechanical stresses

LLi might be a good option:

$< \text{factor } 4 \implies \text{increase } \rightarrow < 2 \text{ worse } \ln L$

25% gain in $e^+$ survival @ same $\mu$ production efficiency

Proposed/tested for targets for $n$ production

High Boiling point 1615 K

Mass evaporation? Safety?
Embedded positron source?

Positron source extending the target complex? Possibility to use the γ’s from the μ production target to produce e+

- e+ 45 GeV
- Thin light target (eventually crystal in channeling)
- Dipole magnet
- Thick heavy target

Proposed for example for CLIC

- Produce a fraction of 8% e+ of the incoming positron beam

Assuming a 10% collection efficiency
Need to have 45 GeV e+ loss on thin target <1%

Fast acceleration to 45 GeV (~ KHz) like μ

Target/s survival 100 KW (on the thin one) on small area

3 mm Be [Geant4]

γ’s angular distribution at the target exit

$4X_0 \ W$ [Geant4]
Embedded positron source?

+ 45 GeV

Thin light target (eventually crystal in channeling)

Dipole magnet

Thick heavy target

e+ injector

Positron ring

Collection system?
Fast acceleration:
Linac
ERL booster
Tests with e\(^+\) beam

Use tertiary 45 GeV e\(^+\) beam in CERN North area (H4) (ask for 2 weeks of beam time for next year)

- Low intensity (one by one e\(^+\) tracking) with crystals and amorphous targets:
  - measure beam degradation (emittance energy spectrum)
  - measure produced photons flux and spectrum

- High intensity (up to 5 x 10\(^6\) /spill) with amorphous targets:
  - measure muon production rate and muons kinematic properties
Conclusion

- Very low emittance muon beams can be obtained by means of positron beam on target
- High Luminosity at Multi-TeV with much reduced radiological risks
- Some synergy with future $e^+e^-$ collider parameters: beam energy, emittance, bunch structure.. But
- Competitive muon rates require:
  - Challenging positron source (FCC-eh like)
  - Positron ring with high momentum acceptance (synergy with next generation SR sources)
- Design study and tests to address Key issues
<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-ee</th>
<th>LEMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy/beam [GeV]</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>bunches/beam</td>
<td>90000</td>
<td>1700</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1450</td>
<td>240</td>
</tr>
<tr>
<td>luminosity/IP x 10^{34} cm^{-2}s^{-1}</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>energy loss/turn [GeV]</td>
<td>0.03</td>
<td>~0.4</td>
</tr>
<tr>
<td>synchrotron power [MW]</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>RF voltage [GV]</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>rms bunch length (SR,+BS) [mm]</td>
<td>1.6, 3.8</td>
<td></td>
</tr>
<tr>
<td>rms emittance $\varepsilon_{x,y}$ [nm, pm]</td>
<td>0.09, 1</td>
<td>&gt;0.1,&gt;100</td>
</tr>
<tr>
<td>longit. damping time [turns]</td>
<td>1320</td>
<td></td>
</tr>
<tr>
<td>crossing angle [mrad]</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>beam lifetime [min]</td>
<td>251</td>
<td>&gt;&gt;1s</td>
</tr>
</tbody>
</table>
Channeling of produced muons

43.8 GeV e⁺
4.1 mm Si Target
Channeling plane: (110)

Crystal  amorphous

[Geant4]