Very low Emittance Muon Beam using positron beam on target

M. Antonelli (INFN-LNF)

Chicago (USA), ICHEP 2016

References:

• M. Antonelli, “Low-emittance muon collider from positrons on target”, FCC-WEEK 2016
• 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
• M. Antonelli, Presentation Snowmass 2013, Minneapolis (USA) July 2013, [M. Antonelli and P. Raimondi, Snowmass Report (2013) also INFN-13-22/LNF Note

Also investigated SLAC team:
L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:
  o “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
  o Advanced Accelerator Concepts Workshop, San Jose (USA), July ‘14
Involved persons:

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- F. Bedeschi, F. Cervelli, R. Tenchini (INFN-Pi), G. Tonelli (Univ. & INFN-Pi)
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- E. Bagli, V. Guidi, A. Mazzolari (INFN-Fe)
- M. Prest (Uni-Insubria & INFN)
- P. Raimondi (ESRF)
- J. P. Delahaye, P. Sievers, R. Di Nardo (CERN)
- I. Chaikovska, R. Chehab (LAL-Orsay)
- L. Keller, T. Markiewicz (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 $(\sqrt{s} \sim 0.212 \text{GeV})$ 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

  $$\sigma(e^+e^-\rightarrow\mu^+\mu^-) \sim 1 \, \mu b \text{ at most}$$

  *i.e. Luminosity(e+e-)= $10^{40}$ cm$^{-2}$ s$^{-1}$ $\rightarrow$ gives $\mu$ rates $10^{10}$ 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 an 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.

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

$\epsilon_\mu = x x'_\text{max} / 12 = L (\theta_{\mu}^{\text{max}})^2/12$

The target thickness and c.o.m. energy completely determine the emittance contributions due to muon production angle.
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)
    
    $$(\rho^- L)_{\text{max}} = 1/\sigma(\text{radiative bhabha}) \approx 10^{25} \text{ cm}^{-2}$$
    
    (beam lifetime determined by radiative Bhabha)
  
  - With $(\rho^- L)_{\text{max}}$ one has a maximal $\mu^+\mu^-$ production efficiency $\approx 10^{-5}$
  
  - 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:
  $\varepsilon_x = 0.19 \cdot 10^{-9}$ 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%

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Image showing the emittance distribution of muons at the target exit surface. The emittance is shown in a plot with $\varepsilon_x$ values and a scale indicating the intensity of the beam. The target is Be with a width of 0.3 cm. The plot also includes parameters such as $\sigma_x$, $\sigma_y$, and $\varepsilon$.

~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

![Graph](image1)

**$E_{e^+}$ beam = 45.0 GeV**
Target: Be
Width : 0.3 cm

**Graph 1:** 3 mm Berillium
Positrons at the target exit surface

**Graph 2:**
$e^+$ beam loss [%]
Target: Be
Width : 0.3 cm

[Geant4]
**Key point:**
Positron source requirements strictly related to the e⁺ ring momentum acceptance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>6 km</td>
</tr>
<tr>
<td>ρ</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 \times 10^{11}</td>
</tr>
<tr>
<td>Rate e⁺ on target</td>
<td>1.5 \times 10^{18} e⁺/s</td>
</tr>
<tr>
<td>U₀</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>

60 m isochronous rings recombine bunches for \( \sim 1 \tau_{\mu}^{\text{lab}} \sim 2500 \) turns

\[
\begin{align*}
\text{n}_b &= \sum_{i=1}^{N_T} e^{-\Delta t(N_T-i)/\tau_{\mu}^{\text{lab}}} \\
\end{align*}
\]
Muon beam parameters

Assuming

- a positron ring with a total 25% momentum acceptance
- \( \sim 3 \times \text{FCC-he positron source rate} \)

<table>
<thead>
<tr>
<th></th>
<th>positron source</th>
<th>proton source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu ) rate [Hz]</td>
<td>( 9 \cdot 10^{10} )</td>
<td>( 2 \cdot 10^{13} )</td>
</tr>
<tr>
<td>( \mu / \text{bunch} )</td>
<td>( 4.5 \cdot 10^{7} )</td>
<td>( 2 \cdot 10^{12} )</td>
</tr>
<tr>
<td>normalised ( \epsilon ) [( \mu \text{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 \( \mu / \text{bunch} \) in the muon collider can be larger by a factor \( \sim \tau_{\mu}^{\text{lab(HE)}}/500 \mu s \) (\( \sim 100 \) @6 TeV) by topping up.

- push on mom. acceptance and \( e^+ \) source performances
- improve target performances
**Low Emittance Muon Muon Accelerator**

**Draft Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>LEMC-6TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUMINOSITY/IP</td>
<td>cm⁻² s⁻¹</td>
<td>5.09E+34</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>GeV</td>
<td>3000</td>
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<tr>
<td>Hourglass reduction factor</td>
<td></td>
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<tr>
<td>Muon mass</td>
<td>GeV</td>
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</tr>
<tr>
<td>Lifetime @ prod</td>
<td>sec</td>
<td>2.20E-06</td>
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<tr>
<td>Lifetime</td>
<td>sec</td>
<td>0.06</td>
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<tr>
<td>c*tau @ prod</td>
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<td>658.00</td>
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<tr>
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<td>m</td>
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<tr>
<td>1/tau</td>
<td>Hz</td>
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<tr>
<td>Circumference</td>
<td>m</td>
<td>6000</td>
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<tr>
<td>Bending Field</td>
<td>T</td>
<td>15</td>
</tr>
<tr>
<td>Bending radius</td>
<td>m</td>
<td>667</td>
</tr>
<tr>
<td>Magnetic rigidity</td>
<td>T m</td>
<td>10000</td>
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<tr>
<td>Gamma Lorentz factor</td>
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<td>N turns before decay</td>
<td></td>
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<tr>
<td>βₓ @ IP</td>
<td>m</td>
<td>0.00002</td>
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<tr>
<td>βᵧ @ IP</td>
<td>m</td>
<td>0.00002</td>
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<tr>
<td>Beta ratio</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Coupling (full current)</td>
<td>%</td>
<td>100</td>
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<tr>
<td>Normalised Emittance x</td>
<td>m</td>
<td>4.00E-08</td>
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<tr>
<td>Emittance x</td>
<td>m</td>
<td>1.41E-12</td>
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<tr>
<td>Emittance y</td>
<td>m</td>
<td>1.41E-12</td>
</tr>
<tr>
<td>Emittance ratio</td>
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<td>1.0</td>
</tr>
<tr>
<td>Bunch length (zero current)</td>
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<td>0.1</td>
</tr>
<tr>
<td>Bunch length (full current)</td>
<td>mm</td>
<td>0.1</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td>0.048</td>
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<tr>
<td>Revolution frequency</td>
<td>Hz</td>
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</tr>
<tr>
<td>Revolution period</td>
<td>s</td>
<td>2.00E-05</td>
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<tr>
<td>Number of bunches</td>
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<td>1</td>
</tr>
<tr>
<td>N. Particle/bunch</td>
<td>#</td>
<td>6.00E+09</td>
</tr>
<tr>
<td>Number of IP</td>
<td>#</td>
<td>1.00</td>
</tr>
<tr>
<td>σₓ @ IP</td>
<td>micron</td>
<td>1.68E-02</td>
</tr>
<tr>
<td>σᵧ @ IP</td>
<td>micron</td>
<td>1.68E-02</td>
</tr>
<tr>
<td>σₓ' @ IP</td>
<td>rad</td>
<td>8.39E-05</td>
</tr>
<tr>
<td>σᵧ' @ IP</td>
<td>rad</td>
<td>8.39E-05</td>
</tr>
</tbody>
</table>

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 $3 \times 10^{13} \mu/s$

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 (\sim\text{vector like quarks}) \Rightarrow \text{xsec can be predicted}
  - FCC reach stops at \( M_X = 7 \text{ TeV} \)

- Hadron machine pays the price of the exponentially falling PDF \Rightarrow \text{multi-TeV muon machine can be competitive!}
Muon Collider: Schematic Layout for positron based muon source

Key Challenges

- $\sim 10^{11}\mu$ / sec from $e^+e^-\rightarrow\mu^+\mu^-$

Key R&D

- $10^{15}$ e+/sec, 100 kW class target, NON destructive process in e+ ring
$\sim 10^{13}$-$10^{14} \mu / \text{sec}$

Tertiary particle $p \rightarrow \pi \rightarrow \mu$:

Fast cooling $(\tau=2\mu s)$ by $10^6$ (6D)

Fast acceleration mitigating $\mu$ decay

Background by $\mu$ decay

$\sim 10^{11} \mu / \text{sec from } e^+e^- \rightarrow \mu^+\mu^-$

$10^{15} \text{ e+/sec}, 100 \text{ kW class target, NON distructive process in e+ ring}$
Key Feasibility Issues

Positron Source
  - Muon Target
  - Positron Ring

HIGH rate
  - Non destructive
  - Mom. acceptance
  - Targets survival

NEED deep investigation (design study)

- μ Acceleration
- Collider Ring
- Collider MDI
- Collider Detector

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

\[ \delta_s / \rho \sigma_c = 0. \]
43.8 GeV $e^+$
4.1 mm Si Target
Channeling plane: (110)

[Geant4]
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:

- <factor 4 $\varepsilon$ increase ➔
- <2 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 $\gamma$'s from the $\mu$ production target to produce $e^+$

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 $\mu$

Target/s survival 100 KW (on the thin one) on small area
Embedded positron source?

- **e+ 45 GeV**
- Thin light target (eventually crystal in channeling)
- Dipole magnet
- Thick heavy target
- γ’s
- Positron ring
- e+ injector
- Collection system?
- Fast acceleration: Linac ERL booster
- μ+
- e+
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 $5 \times 10^6$ /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 $\epsilon_{x,y}$ [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>

Next slides
Channeling of produced muons

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

Crystal

Amorphous

[Geant4]

[Geant4]