Muon Collider based on positron-driven source: the LEMMA proposal

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Outline

• Introduction
• Positron driven source
• LEMMA scheme
• Status
• Further studies on key topics
• Conclusion
Concept based on a positron driven source for muon beams

\[ \mu^+ \mu^- \] are produced in positron annihilation on \( e^- \) at rest

\[ \rightarrow \sim 45 \text{ GeV} \] e\(^+\) beam impinging on target

- Low emittance overcomes muon cooling
- Low emittance allows operations at very high c.o.m. energy
  (lower neutrino radiation hazard)

LEMMA deals with low muon rates
Muon production

from **proton on target**: $p + \text{target} \rightarrow \pi/K \rightarrow \mu$

typically $P_{\mu} \approx 100 \text{ MeV/c}$ ($\pi$, $K$ rest frame)

whatever is the boost $P_T$ will stay in Lab frame $\rightarrow$

**very high emittance** at production point $\rightarrow$ **cooling needed**!

from **direct $\mu$ pair production**:

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

NIM A Reviewer: “A major advantage of this proposal is the lack of cooling of the muons.... the idea presented in this paper may truly revolutionise the design of muon colliders ...”
Low EMittance Muon Accelerator (LEemma): 10^{11} \mu pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.


Not really a fair comparison: MAP studies much more advanced LEMMA much simpler in principle but still many key aspects to be fully studied (this talk)

New tunnels and/or new high field magnets (e.g. HTS) and/or new acceleration could provide large benefits to both options
LEMMA & MAP

Proton Driver
- SC Linac
- Accumulator
- Buncher
- Combiner

Front End
- Charge Separator
- Capture Sol.
- Decay Channel
- Buncher
- Phase Rotator

Cooling
- Initial 6D Cooling
- 6D Cooling
- Bunch Merge
- 6D Cooling
- Final Cooling

Acceleration
- Accelerators: Linacs, RLA or FFAG, RCS

Collider Ring
- $E_{\text{CoM}}$: Higgs Factory to $\sim 10$ TeV
- $\mu^+ \mu^-$

Combiner is needed to simultaneously deliver multiple proton beams on pion target to provide the required production rates.

Bunch merging needed to increase $N(\mu)/\text{bunch}$

Goal $\sim 4 \times 10^{12} \mu/\text{bunch}$

Huge 6D cooling factor

MC with proton-driven source deals both with emittance cooling & muon rate.
MICE selected Result

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude

Noticeable reduction of 9% emittance

But still some way to go
• 6D cooling
• Stages
• Small emittances
Advantages:

1. **Low emittance possible:** $\theta_\mu$ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$. $\theta_\mu$ 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.

Disadvantages:

- **Rate:** much smaller cross section wrt protons ($\approx$ mb)
  
  \[ \sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1 \text{ } \mu\text{b} \text{ at most} \]
Possible implementation

• **Low energy collider with e\(^+\)/e\(^-\) beam (e\(^+\) in the GeV range):**
  
  1. Conventional asymmetric collisions (but required luminosity \(\approx 10^{40}\) is beyond present capability)
  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 (eventually crystals in channeling)
    - Need Positrons of \(\approx 45\) GeV
    - \(\gamma(\mu)\approx200\) and \(\mu\) laboratory lifetime of about 500 \(\mu s\)

*Ideally muons will *copy* the positron beam*
Contribution to $\mu$ beam size due to finite target length

If $L$ was a drift

Muons produced uniformly along target, $\infty$ drifts $[0,L]$

The emittance contributions due to muon production angle: $\varepsilon_\mu = x x_{max}' / 12 = L (\theta_{\mu \text{max}})^2 / 12$

$\varepsilon_\mu$ completely determined by $L$ and $s$ -by target thickness and c.o.m. energy
Criteria for target design

Luminosity is proportional to $N_\mu^2 \cdot 1/\varepsilon_\mu$

optimal target: minimizes $\mu$ emittance with highest $\mu$ rate

• **Heavy materials, thin target**
  - to minimize $\varepsilon_\mu$: thin target ($\varepsilon_\mu \propto L$) with high density $\rho$
  - Copper: MS and $\mu^+\mu^-$ production give about same contribution to $\varepsilon_\mu$
    - BUT high $e^+$ loss (Bremsstrahlung is dominant) so
      $$\sigma(e^+\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(\text{Bhabha}) \rightarrow$$
      $$N(\mu^+\mu^-)/N(e^+) \approx \sigma_\mu/[(Z+1)\sigma(\text{Bhabha})] \approx 10^{-7}$$

• **Very light materials, thick target**
  - maximize $\mu^+\mu^-$ conversion efficiency $\approx 10^{-5}$ (enters quad) $\rightarrow$ $H_2$
    - Even for liquid targets O(1m) needed $\rightarrow$ $\varepsilon_\mu \propto L$ increase

• **Not too heavy materials (Li, Be, C)**
  - Allow low $\varepsilon_\mu$ with small $e^+$ loss
    $$N(\mu^+\mu^-)/N(e^+) \approx 10^{-6}$$
Possible schemes for muon production

Multi-pass scheme

- e^- gun
- e^+ Linac
- Ramping e+ storage ring
- μ^-
- μ^+
- e^+
- Muons acceleration

Single-pass scheme

- e^- gun
- e^+ Linac
- Muons acceleration
- Recovery system or secondary e+ source
- Ramping e+ storage ring or recirculating linac
Multi-pass scheme

**Goal:**
\[ @T \approx 10^{11} \mu/s \]

Efficiency \( \approx 10^{-7} \) (with Be 3mm) → 
\( 10^{18} \) e\(^+\)/s needed @T →

\( e^+ \) "stored" beam with T

need the largest possible lifetime
to minimize positron source rate

LHeC like e+ source required rate
with lifetime(e+) \( \approx 250 \) turns [i.e.
25% momentum aperture →
\( n(\mu)/n(e^+ \text{ source}) \approx 10^{-5} \)

- Low emittance and high momentum acceptance
  45 GeV e\(^+\) ring
- O(100 kW) class target in the e\(^+\) ring for \( \mu^+ \mu^- \) production

and, in common with single-pass scheme:

- High-rate positron source
- High momentum acceptance
muon accumulator rings
Low emittance 45 GeV positron ring

cell

Table e+ ring parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0.7 nm</th>
<th>6 nm</th>
<th>10 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [km]</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>N. cells</td>
<td>64</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>(I_b) [A]</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>(N_{part}/\text{bunch})</td>
<td>(5 \times 10^{11})</td>
<td>(5 \times 10^{11})</td>
<td>(5 \times 10^{11})</td>
</tr>
<tr>
<td>N. bunches</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>(E_{loss/\text{turn}}) [GeV]</td>
<td>0.12</td>
<td>0.12</td>
<td>0.19</td>
</tr>
<tr>
<td>Nat. (\sigma_z) [mm]</td>
<td>1.9</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td>(\alpha_c)</td>
<td>(2.9 \times 10^{-5})</td>
<td>(1 \times 10^{-4})</td>
<td>(1.1 \times 10^{-4})</td>
</tr>
<tr>
<td>Energy spread</td>
<td>(7 \times 10^{-4})</td>
<td>(7 \times 10^{-4})</td>
<td>(9 \times 10^{-4})</td>
</tr>
<tr>
<td>(\tau_{x,y}) [ms]</td>
<td>68</td>
<td>66</td>
<td>42</td>
</tr>
<tr>
<td>Energy acceptance [%]</td>
<td>±8</td>
<td>±6</td>
<td>±2</td>
</tr>
<tr>
<td>SR power [MW]</td>
<td>106</td>
<td>109</td>
<td>170</td>
</tr>
</tbody>
</table>

Physical aperture = 5 cm constant
no errors

Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies
Beam dynamics e\(^+\) beam in ring-with-target

**e\(^+\) emittance growth controlled with proper \(\beta\) and D values @ target**

After 40 turns  \(\sigma'_{MS} = 25 \ \mu\text{rad}\)
Comments on multi-pass scheme

**CONS**

- High power on target
- Low number of muons per bunch: do not have a realistic scheme for recombination at high energy
- Muon beam almost in CW, not compatible with acceleration by synchrotron
- The same is true for positron beam replacement (source + acceleration + injection)

**PROS**

✓ muon emittance is small
Single-pass scheme

positron beam passes only once through a $\sim \chi_0$

- **More muons** produced per bunch
- **Power can be distributed** over a long target

Very large **energy acceptance** muon accumulator rings [-10%; +15%] have been designed

- Start-to-end muon particle tracking from production to end of accumulation process performed allowing a realistic estimate of emittance and number of muons/bunch
- Targets considered: solid, liquid jet and compound liquid/solid target

PR-AB 23, 051001 (2020)
Considerations on $\mu$ accumulation

Accumulation must be performed in $\tau_{lab} \sim 500\mu s$
Ring must be as short as possible with the largest possible E acceptance

Number of muons increases by using a thick target

- $\times$ drift contribution on beamsize ($\propto L_T$)
- $\times$ MS contribution on emittance ($\propto \sqrt{X_0 N_T}$)

Possible solutions:
- ✔ Multiple IP
- ✔ Spaghetti/film-like targets or channeling in crystals

![Graph showing turns in accumulator ring](image_url)
Luminosity of $\mu^+\mu^-$ Collider vs $e^+$ beam energy

Optimal working point for $\varepsilon(e^+) \approx \varepsilon(\text{MS}) \approx \varepsilon(\text{rad}) \approx \varepsilon(\text{prod}) \approx \varepsilon(\text{AR})$

and sustainable beam spot on target $\varepsilon(\text{prod})$ and $\mu$ intensity $\propto$ positron beam energy:

Need of high energy acceptance $\mu$ ring
Target options for best production efficiency

Target material plays a crucial role

The lighter the material, the higher the production efficiency

Most of the muons are produced in the first 3 targets = 0.3X₀

3e¹¹ e⁺ @45GeV
10 x 0.1X₀
Comparison solid and liquid target

Beam size is proportional to target thickness

Divergence depends mainly on e+ beam energy, dominated by the production kinematics

Production efficiency

We also need to optimize the target choice wrt the muon beam quality after the accumulation process (muons/bunch and muon emittance)
Muon Accumulator Rings

- Compact: 140 m circumference with 15 T dipoles
- Chromaticity and high order momentum compaction correction achieved by dedicated families of sextupoles, resulting in a very large energy acceptance [-10%,+15%]
- Since the target region is in common for the positron ad the two muon beams, a septum in the first bending magnet is used to separate the beams
- The ring is made by two symmetric arcs and two straight sections, one for the target insertions and one for the RF cavities
Muon accumulation vs solid and liquid target

Beryllium Target

0.3X₀Be = 0.106 m

😀 Advantage: most efficient for $\mu$ production: After 1500 turns ≈ 1.5 lifetimes, accumulated $3.5 \times 10^8 \mu$

😢 muon beam size and divergence increase in the accumulation process due to the multi passages of muons through the target (multiple scattering)

Liquid Lithium Target

0.3X₀LLi = 0.465 m longit. length

We considered the transverse size of the jet much smaller than the stored beam size to preserve muon beam emittance

😊 Jet of liquid Lithium mitigates multiple scattering ( $N^2/\varepsilon$ higher by a factor 30 wrt to Be)

😢 Disadvantage: low $X_0$ → long jet target needed
Liquid Lithium Target with Diamond dust

Best compromise to increase efficiency of liquid Lithium allowing to reduce target length and strongly suppress multiple scattering

10%LLi+90%D: $X_0$ reduced by a factor 10 wrt Li, but in liquid state and suitable to be film jet

Lowering $\beta^*$ at target muon beam emittance is further reduced. (as expected)

Best solution: 50$\mu$m LLI-D film jet target $\approx 0.5\ X_0$ (6.7 cm) with $\beta^*=10$ cm $\rightarrow$ $N = 0.4 \times 10^9 \mu$/bunch, $\varepsilon(\mu)=0.3 \ \mu$m-rad after 1000 turns
Further optimization

- Further increase of AR energy acceptance would allow higher $e^+$ energy, increasing muon production ($E^+$=50 GeV × 2 in $N_{\mu}$).
- Further reduction of $\beta^*$ would reduce muon final emittance.
- With Recombination positron bunch at the target (revolver configuration):

  \[ N = 10^9 \mu/\text{bunch}, \ \varepsilon(\mu)=0.1 \ \mu\text{m-rad after 200 turns} \]

revolver configuration

multiple $e^+$ bunches on the target using the delay lines

might allow to further increase the muon production, reaching the goal value $\approx 10^9 \mu/\text{bunch}$
Thermo-mechanical issues – solid targets

- Aim at bunch \(5 \times 10^{11} \text{ e}^+\) transverse size on the 10-20 µm scale: rescaled from test at HiRadMat \(5 \times 10^{13} \text{p on 100µm}\) with Be-based targets and C-based (HL-LHC)
- Detailed simulation of thermo-mechanical stresses dynamics
  - FLUKA + FTDT

- Multiple target system

https://doi.org/10.1007/s10765-021-02913-x
Thermal Study

5x10^{11} e^+ on Be target

100 \mu m \times 50 \text{ bunches} = 5 \text{ mm}

FDTD model

C : R=5\text{ cm}, L=1\text{ mm}

Be : R=5\text{ cm}, L=3\text{ mm}

Not rotating target

Rotating target

ILC(e^+ prod.) like target

• Radius 50 cm
• N \sim 2000 \text{ rpm}
• Wheel rim speed 100 m/s
• Wheel diameter \sim 1 \text{ m}

• No bunch pileup
• Power removal by radiation cooling (see for instance PSI muon beam upgrade project HiMB)

Much lighter for LEMMA
Positron source requirements

Positron source rate is **independent on the scheme** (multi- or single-pass)
Main dependences on **target material** and **recovery system energy acceptance**

**Single-pass scheme**

<table>
<thead>
<tr>
<th>Energy acceptance %</th>
<th>Be 0.106m</th>
<th>LH2 2.66m</th>
<th>LLi 0.45m</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.89E+15</td>
<td>41.43</td>
<td>4.99E+15</td>
</tr>
<tr>
<td>10</td>
<td>4.11E+15</td>
<td>34.88</td>
<td>4.22E+15</td>
</tr>
<tr>
<td>20</td>
<td>3.22E+15</td>
<td>27.33</td>
<td>3.33E+15</td>
</tr>
</tbody>
</table>

To evaluate the number of positrons per second required from the source we assume to have **1500 bunches** with **5 10^{11} e^+ / bunch** on target at **10Hz** (total of **7.5 10^{15} e^+/sec**)

This is a key issue to be studied

Summary of e^+ sources projects (all very aggressive):
In [F. Zimmermann, et al., ‘**POSITRON OPTIONS FOR THE LINAC-RING LHeC’**, WEPPR076 Proceedings of IPAC2012, New Orleans, Louisiana, USA]
Potential Key MC R&D items

- **Beam production** – *target complex*
- **Acceleration complex** design (important cost driver)
  - Fast ramping magnets (for RCS), magnet powering scheme
  - High-field superconducting magnets
  - Beamline design
  - Collimation
- **Collider ring** design (important parameter and cost driver)
  - High field superconducting magnets, minimal gap
  - Radiation hazard
- **Reuse of existing infrastructure or synergy with future projects** (FCC) (potential cost saving)
Conclusion

There is no easy solution to high energy and high luminosity Muon Collider

LEMMA is an elegant concept combined to state-of-the-art high energy acceptance and low emittance rings, aiming at good quality muon beams

The ultimate performance of a muon collider based on this concept is mainly dominated by the muon production target and by the quality and intensity of the positron beam. ->

R&D High power target
High-rate positron source (synergy with future e+e- colliders

An FCC-μμ, to follow FCC-ee and FCC-hh, is an attractive option worth to be investigated, see for example:

F. Zimmermann, Proc. IPAC18, MOPMF065
R&D on high rate positron source

- R&D on this topic can take advantage of significant synergies with future collider studies as FCC-ee, ILC and CLIC.
- The required intensity for LEMMA is strongly related to the beam lifetime, determined by the momentum acceptance and the target material.
- So, also optics and beam dynamics optimization is necessary.

<table>
<thead>
<tr>
<th>e(^+) production rates achieved (SLC) or needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-KEKB</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>10(^{14}) e(^+) / s</td>
</tr>
</tbody>
</table>

Present: 3 mm Be, 40 turns lifetime(DP/P<6%), \(\Delta N/N=2.5\%\), \(P=247\) MW
35 mm LH2, 100 turns lifetime(DP/P<6%), \(\Delta N/N=1\%\), \(P=98\) MW

Goal: 3 mm Be, 240 turns lifetime(DP/P<25%), \(\Delta N/N=0.4\%\), \(P=39\) MW
35 mm LH2, 625 turns lifetime(DP/P<25%), \(\Delta N/N=0.1\%\), \(P=16\) MW
Criteria for target design

Number of $\mu^+\mu^-$ pairs produced per $e^+e^-$ interaction is given by

$$N(\mu^+\mu^-) = \sigma(e^+e \rightarrow \mu^+\mu^-) \, N(e^+) \, \rho(e^-)L$$

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

To maximise $N(\mu^+\mu^-)$:
- $N(e^+)$ max rate limit set by $e^+$ source
- $\rho(e^-)L$ max occurs for $L$ or $\rho$ values giving total $e^+$ beam loss
  - **$e^-$ dominated target**: radiative Bhabha is the dominant $e^+$ loss effect, giving a maximal $\mu^+\mu^-$ conversion efficiency
    $$N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \rightarrow \mu^+\mu^-)/\sigma_{rb} \approx 10^{-5}$$
  - **standard target**: Bremsstrahlung on nuclei and multiple scattering are the dominant effects, $X\sigma$ and electron density will matter
    $$N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \rightarrow \mu^+\mu^-)/\sigma_{brem}$$