

Studies of a scheme for low emittance muon beam production from positrons on target

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Outline

- Introduction: Muons case
- Proposal for a novel technique for muon production
- e⁺ ring with target
- Multi-turn simulations
- Conclusion and Perspectives

Muon based Colliders

- A μ⁺μ⁻ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
 - No synchrotron radiation (limit of e⁺e⁻ circular colliders)
 - No beamstrahlung (limit of e⁺e⁻ linear colliders)
 - but muon lifetime is 2.2 μ s (at rest)
- Best performances in terms of luminosity and power consumption
- Great potentiality if the technology proves its feasibility:
 - Muon source
 - Fast muon cooling
 - Fast acceleration
 - $-\mu$ Collider
 - Radiation Safety (muon decay in accelerator and detector)

Idea for low emittance μ beam

Conventional production: from **proton on target**

 π , K decays from proton on target have typical **P**_µ~ **100 MeV/c** (π , K rest frame)

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

Novel proposal: direct μ pair production: $e^+e^- \rightarrow \mu^+\mu^-$

just above the $\mu^+\mu^-$ production threshold ($\sqrt{s} \approx 0.212$ GeV) with minimal muon energy spread, with direct annihilation of ≈ 45 GeV e⁺ with atomic e⁻ in a thin target O(0.01 radiation length)

very small emittance at μ production point \rightarrow **no cooling** needed!

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 v 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) $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1 \ \mu b$ at most

Parametric behaviours

M. Boscolo, IPAC17







Criteria for target design

minimize emittance maximize rate minimize positron loss \rightarrow thin target

 \rightarrow maximize density (high Z)

minimize positron loss (brem.) \rightarrow low Z

Heavy materials, thin target

- to minimize ε_{μ} : thin target ($\varepsilon_{\mu} \propto \text{length}$) with high density ρ Copper: MS and $\mu^{+}\mu^{-}$ production give about same contribution to ε_{μ} BUT high e⁺ loss (Bremsstrahlung is dominant) so $\sigma(e^{+}\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(Bhabha) \rightarrow$ low maximimal $\mu^{+}\mu^{-}$ production efficiency (infinite length target) Eff_{max} $\approx \sigma_{\mu}/[(Z+1)\sigma(Bhabha)] \sim 10^{-7}$

- Very light materials, thick target
 - maximize $\mu^+\mu^-$ production efficiency ~10⁻⁵ (enters quad) \rightarrow H₂ Even for liquid targets O(1m) needed $\rightarrow \epsilon_{\mu}$ increase
- Not too heavy materials (Be, C, Li)
 - Allow low ϵ_{μ} with small e^+ loss $\text{Eff}_{\text{max}} \approx 10^{\text{-6}}$

not too heavy and thin in combination with stored positron beam to reduce the requests on positron source

$\begin{array}{l} \mbox{Preliminary scheme for} \\ \mbox{low emittance } \mu \mbox{ beam production} \end{array}$

<u>Goal:</u>

@T ≈ $10^{11} \mu/s$ Efficiency ≈ 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] \rightarrow n(µ)/n(e⁺ source) \approx 10⁻⁵



Preliminary scheme for low emittance μ beam production



Preliminary scheme for low emittance μ beam production



$\begin{array}{l} \mbox{Preliminary scheme for} \\ \mbox{low emittance } \mu \mbox{ beam production} \end{array}$

e+ ring parameter	unit	
Circumference	km	6.3
Energy	GeV	45
bunches	#	100
e⁺ bunch spacing = T _{rev} (AR)	ns	200
Beam current	mA	240
N(e⁺)/bunch	#	$3\cdot10^{11}$
U ₀	GeV	0.51
SR power	MW	120

(also 28 km foreseen to be studied as an option)



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Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari



Key topics for this scheme

- Low emittance and high momentum acceptance 45 GeV e⁺ ring
- O(100 kW) class target in the e⁺ ring for $\mu^+ \mu^-$ production
- High rate positron source
- High momentum acceptance muon accumulator rings

"Low emittance 45 GeV positron ring



120

100

s [m]

140

160

180

-6

-8

0

20

40

60

80

circumference 6.3 km: 197 m x 32 cells (no injection section yet)

Parameter	Units	
Energy	GeV	45
Circumference	m	6300
Coupling(full current)	%	1
Emittance x	m	5.73×10^{-9}
Emittance y	m	5.73×10^{-1}
Bunch length	mm	3
Beam current	mA	240
RF frequency	MHz	500
RF voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
N. particles/bunch	#	3.15×10^{11}
Synchrotron tune		0.068
Transverse damping time	turns	175
Longitudinal damping time	turns	87.5
Energy loss/turn	GeV	0.511
Momentum compaction		1.1×10^{-4}
RF acceptance	%	± 7.2
Energy spread	dE/E	1×10^{-3}
SR power	MW	120

Physical aperture=5 cm constant

no errors

Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

M. Boscolo, IPAC17

Multi-turn simulations

- 1. Initial 6D distribution from the equilibrium emittances
- 2. 6D e⁺ distribution tracking up to the target (AT and MAD-X PTC)
- 3. tracking through the target (with Geant4beamline and FLUKA and GEANT4)
- 4. back to tracking code

At each pass through the muon target the e+ beam

- gets an angular kick due to the multiple Coulomb scattering, so at each pass changes e⁺ beam divergence and size, resulting in an emittance increase.
- undergoes bremsstrahlung energy loss: to minimize the beam degradation due to this effect, D_x=0 at target
- in addition there is natural radiation damping (it prevents an indefinite beam growth)



Preliminary low- β IR for muon target insertion



- @target location:
 - $D_x \approx 0$
 - **low**-β
- Further optimizations are underway:
 - match the transverse minimum beam size with constraints of target thermo-mechanical stress
 - match with other contributions to muon emittance (production, accumulation)
 - dynamic and momentum aperture can be optimized





e+ lifetime with Be target



Be thickness [mm]

1

10

10 <u>⊦</u>_____ 0.1

2-3% e+ losses happen in the first turn Boscolo, IPAC17

e+ ring with target: beam evolution in the 6D phase space



e+ beam with 3 mm Be target along the ring (not at IR center in this example)

Evolution of e+ beam size and divergence



bremsstrahlung and multiple scattering artificially separated by considering alternatively effects in longitudinal (dominated by **bremsstrahlung**) and transverse (dominated by **multiple scattering**) phase space due to target; in **blue** the combination of both effects (realistic target)

Some bremsstrahlung contribution due to residual dispersion at target multiple scattering contribution in line with expectation: $\sigma_{MS} = \frac{1}{2} \sqrt{n_D} \sigma'_{MS} \beta$ one pass contribution due to the target: $\sigma'_{MS} = 25 \mu rad$

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n_D number of damping turns

Muon emittance

 $\epsilon(\mu) = \epsilon(e^+) \oplus \epsilon(MS) \oplus \epsilon(rad) \oplus \epsilon(prod) \oplus \epsilon(AR)$

$ \begin{array}{l} \epsilon(e^{+}) &= e^{+} \mbox{ emittance} & \mbox{knobs:} \\ \epsilon(MS) &= \mbox{multiple scattering contribution} \\ \epsilon(rad) &= \mbox{energy loss (brem.) contribution} & \mbox{hobs:} \\ \end{array} $		would like all contributions of same size
$\epsilon(\text{prod}) = \text{muon production contribution} \\ \epsilon(\text{AR}) = \text{accumulator ring contribution} \\ \text{AR optics \& target} \\ \text{with constraints from target survival}.$	ϵ (MS) = multiple scattering contribution ϵ (rad) = energy loss (brem.) contribution ϵ (prod) = muon production contribution	knobs: n $\beta_x \beta_y$ @target & target material n $\beta_x \beta_y D_x$ @target & target material E(e ⁺) & target thickness AR optics & target

now: $\epsilon(\mu)$ dominated by $\epsilon(MS) \oplus \epsilon(rad) \rightarrow lower dispersion & lower <math>\beta$ -functions at target with beam spot at the limit of the target survival

also test different material

- crystals in channeling better: $\varepsilon(MS)$, $\varepsilon(rad)$, $\varepsilon(prod)$ (also gain in lifetime)
- light liquid jet target better: $\varepsilon(MS)$, $\varepsilon(rad)$

(also gain in lifetime & target thermo-mechanical characteristics)

μ Accumulator Rings considerations

isochronous optics with high momentum acceptance ($\delta \ge 10\%$) optics to be designed



Target considerations

Beam size as small as possible (matching various emittance contribution), but

- constraints for power removal (200 kW) and temperature rise
- to contrast the temperature rise move target (for free with liquid jet) and e⁺ beam bump every 1 bunch muon accumulation
- Solid target: simpler and better wrt temperature rise
 - Be, C
 [Kavin Ammigan 6th High Power Targetry Workshop]
 - Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, N=1.7x10¹¹ p/bunch, up to 288 bunches in one shot
- Liquid target: better wrt power removal (200kW)
 - Li, difficult to handle lighter materials (H, He)
 - LLi jets examples from neutron production, Tokamak divertor

(200 kW beam power removal seems feasible), minimum beam size to be understood

Conclusion and Perspectives

- First design of low emittance e⁺ ring with preliminary studies of beam dynamics
- Optimization requires other issues to be preliminary addressed:
 - target material & characteristics
 - e⁺ accelerator complex





muon accumulator rings design

Preliminary studies for a low emittance muon source are promising We will continue to optimize all the parameters, lattices, targets, etc. in order to assess the ultimate performances of a muon collider based on this concept M. Boscolo, IPAC17

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Tests with e⁺ beam

Use tertiary 45 GeV e⁺ beam in CERN North area (H4) (1 week of beam time July 2017, founded by CSN1-INFN)

- 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 10⁶ /spill) with amorphous targets:
 - measure muon production rate and
 - muons kinematic properties