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

LEMMA

(Low EMittance Muon Accelerator)

Concept based on a positron driven source for muon beams

$\mu^+ \mu^-$ are produced in positron annihilation on e^- at rest

→ ~45 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+target$\rightarrow \pi/K \rightarrow \mu$

typically **$P_\mu \approx$ 100 MeV/c** (π, K rest frame)

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

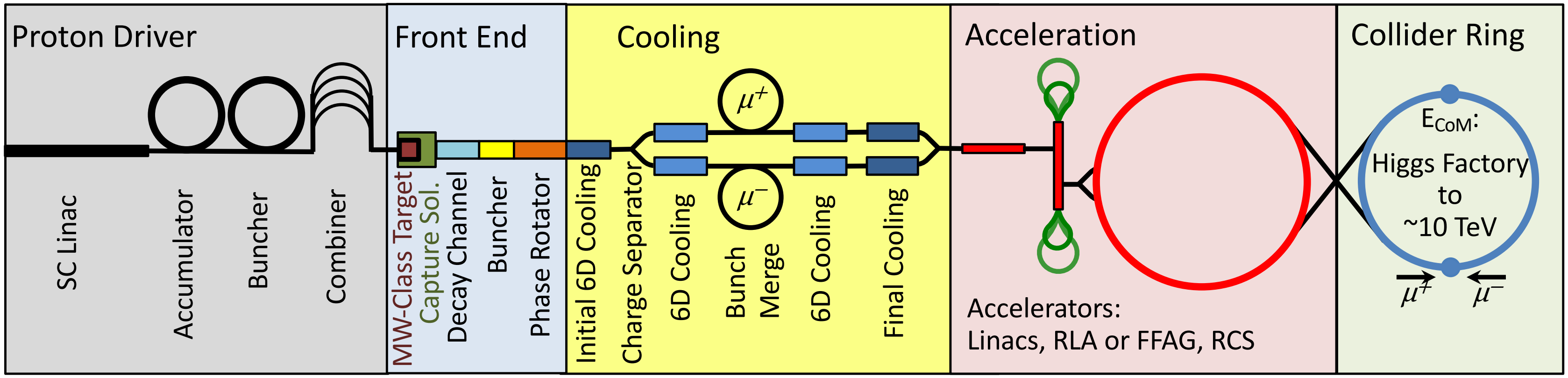
very high emittance at production point $\rightarrow$ **cooling needed**!

from **direct μ pair production**:

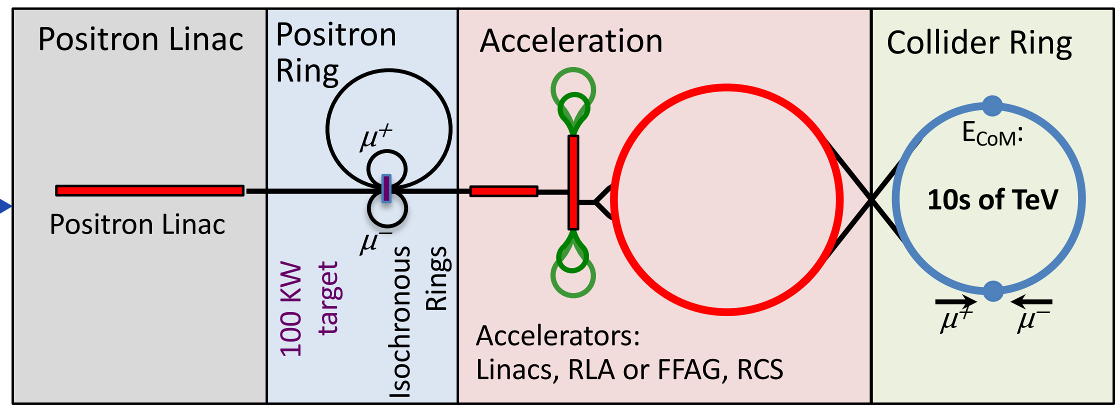
Muons produced from **$e^+e^- \rightarrow \mu^+\mu^-$** at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold **($\sqrt{s} \approx$ 0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

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 … "***

LEMMA & MAP



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ 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.

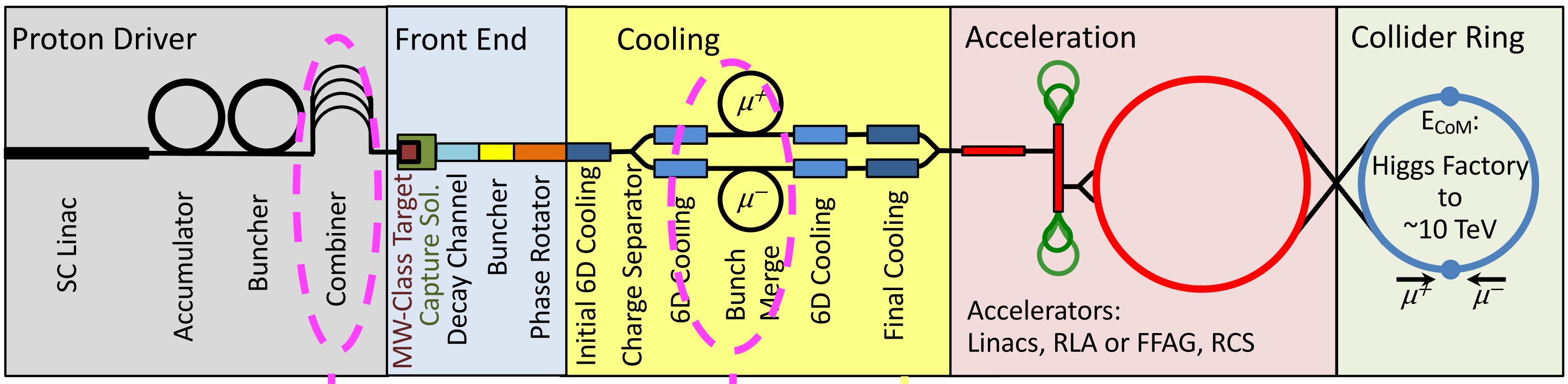


Ref. M. Boscolo et al., "*The future prospects of muon colliders and neutrino factories*", RAST 10 (2019) 189-214 ArXiv.1808.01858

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



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

bunch merging needed to increase N(μ)/bunch

Goal~ $4x10^{12}$ μ/bunch

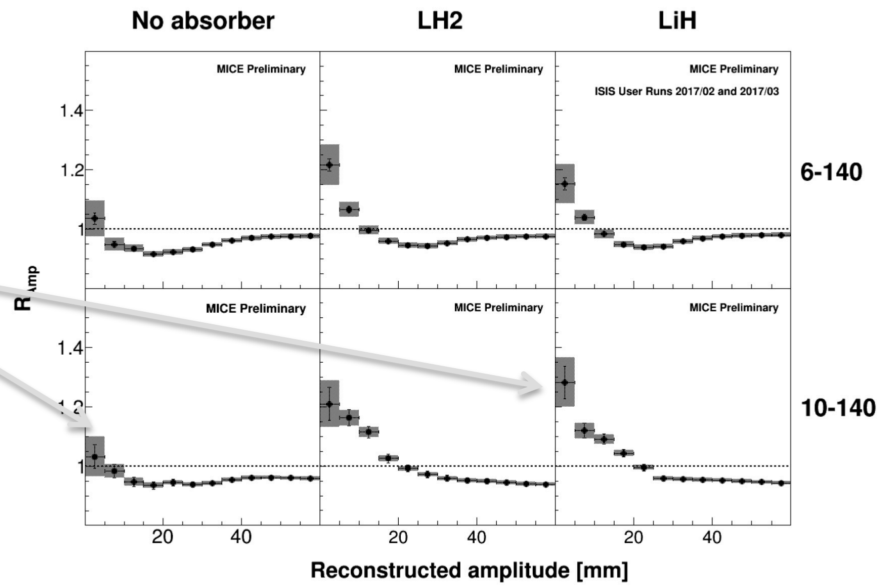
huge 6D cooling factor

MC with proton-driven source deals both with
emittance cooling & muon rate

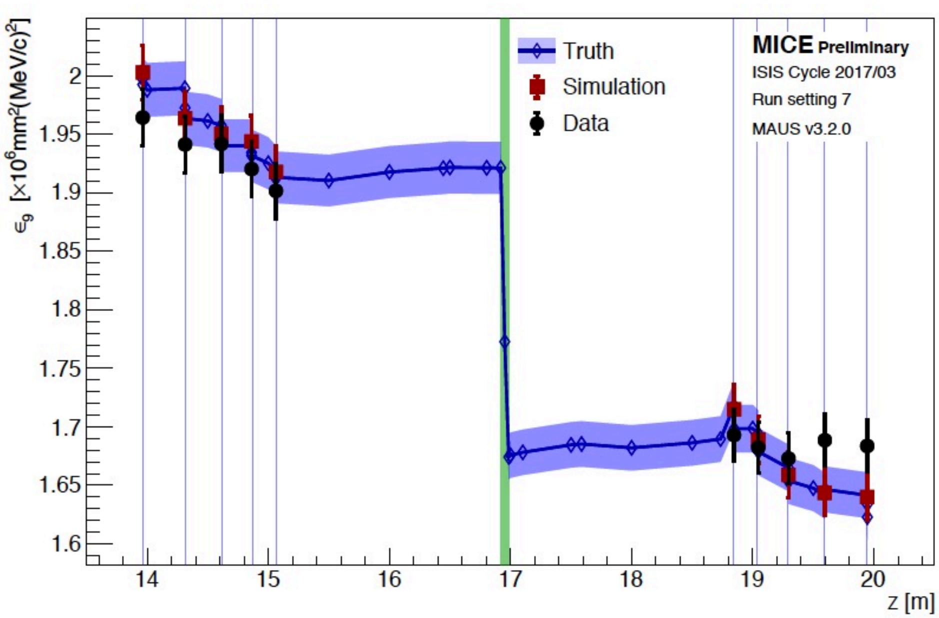
MICE selected Result

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:** θ_μ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$
   θ_μ can be **very small** close to the $\mu^+\mu^-$ threshold
2. **Low background:** Luminosity at low emittance will allow low background and low ν 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)

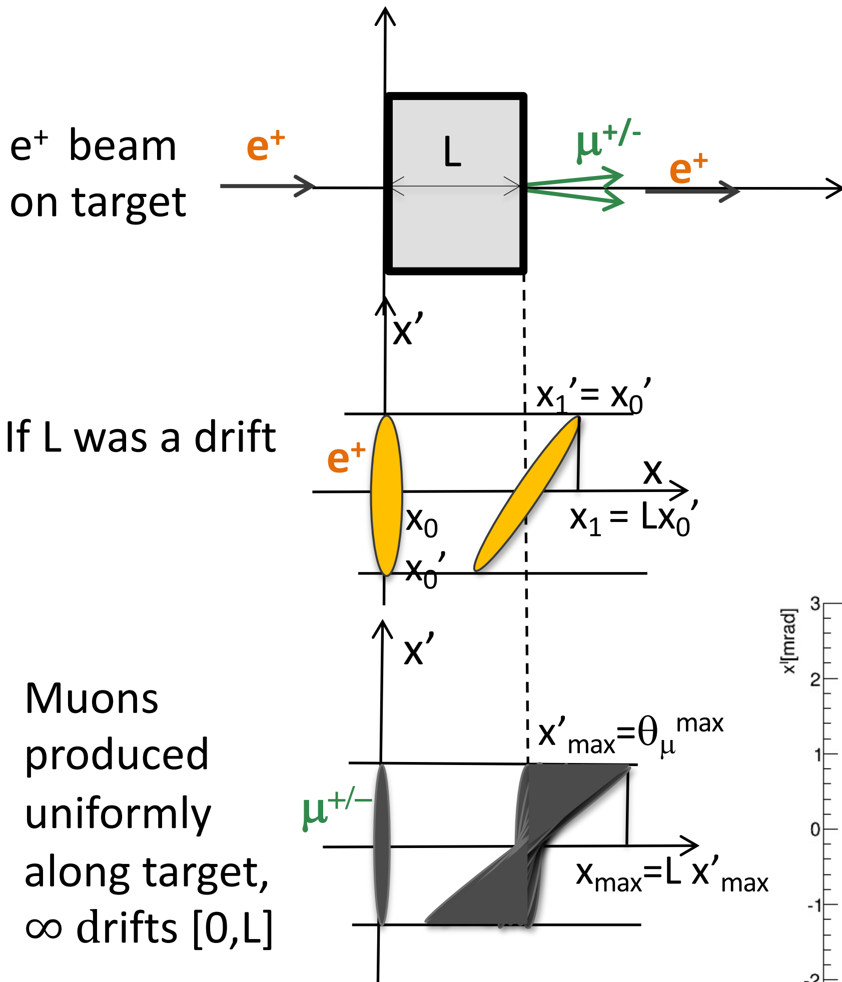
  $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1\ \mu b$ at most

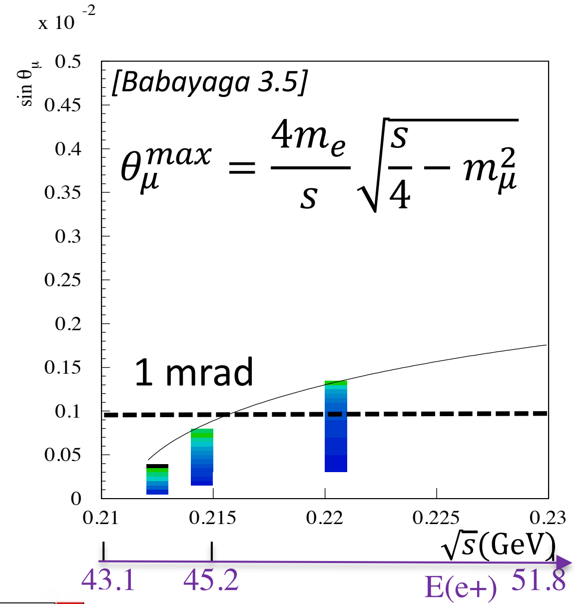
Possible implementation

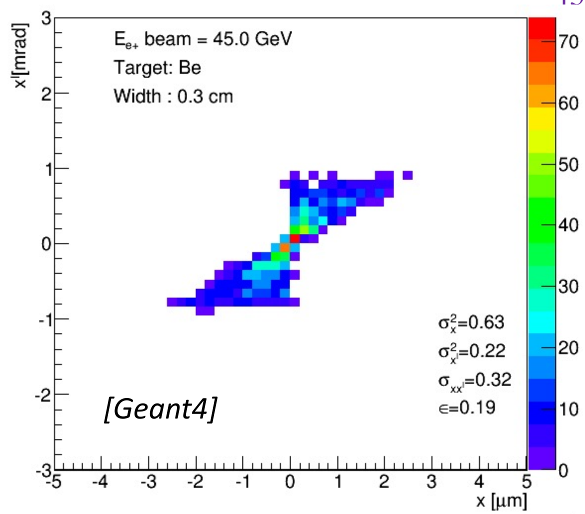
- **Low energy collider with e^+/e^- beam (e$^+$ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity $\approx 10^{40}$ is beyond present capability)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^3 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**
  - $\gamma(\mu)\approx 200$ and μ laboratory lifetime of about 500 μs

Ideally muons will *copy* the positron beam

Contribution to μ beam size due to finite target length







Muon beam at the exit of a 3 mm Be target
ε_μ=0.19 nm
(45 GeV e+ beam)

thin light materials targets have negligible multiple scattering contribution

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

ε_μ completely determined by L and s -by target thickness and c.o.m. energy

Criteria for target design

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

optimal target: minimizes μ emittance with highest μ rate

- **Heavy materials, thin target**
  - to minimize ε_μ : thin target ($\varepsilon_\mu \propto L$) 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

$\sigma(e^+\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(\text{Bhabha}) \rightarrow$

$N(\mu^+\mu^-)/N(e^+) \approx \sigma_\mu/[(Z+1)\sigma(\text{Bhabha})] \approx 10^{-7}$

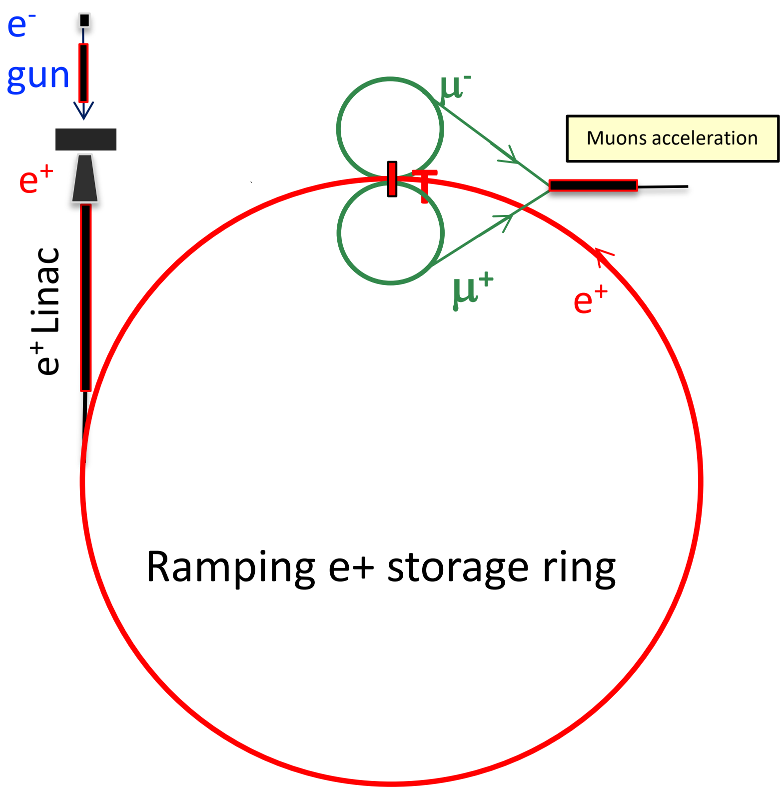
- **Very light materials, thick target**
  - **maximize $\mu^+\mu^-$ conversion efficiency $\approx 10^{-5}$** (enters quad) $\rightarrow$ H_2

Even for liquid targets O(1m) needed $\rightarrow$ $\varepsilon_\mu \propto L$ increase

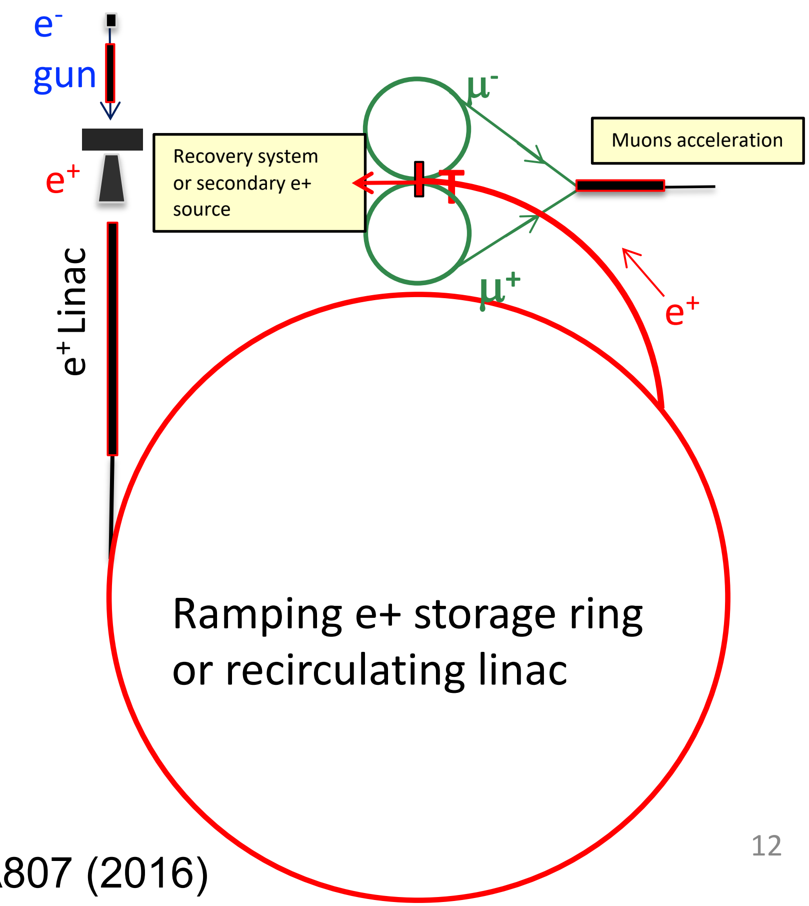
- **Not too heavy materials (Li, Be, C)**
  - Allow low ε_μ with small e^+ loss **$N(\mu^+\mu^-)/N(e^+) \approx 10^{-6}$**

Possible schemes for muon production

Multi-pass scheme



Single-pass scheme



Nucl.Instrum.Meth. A807 (2016)

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+) ≈ 250 turns [i.e. 25% momentum aperture → $n(\mu)/n(e^+ \text{ source}) \approx 10^{-5}$

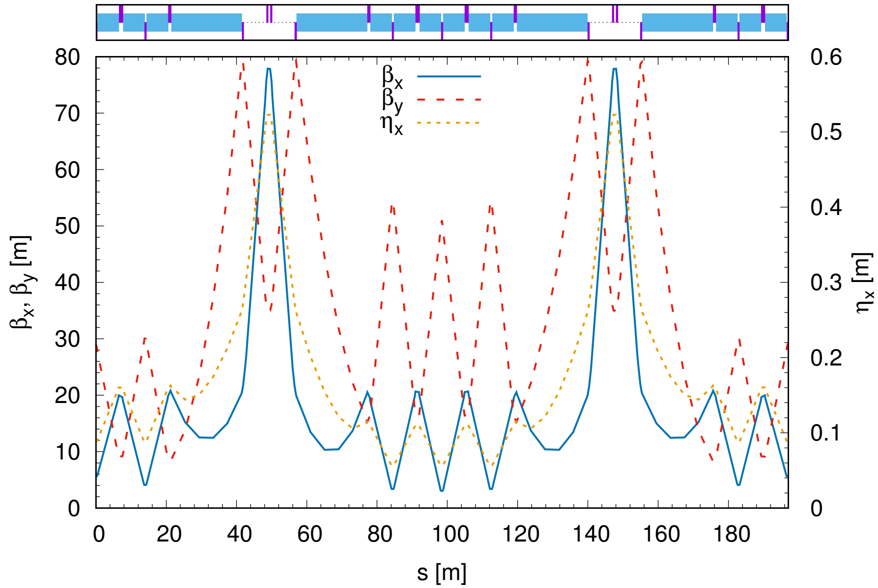
- **Low emittance and high momentum acceptance 45 GeV e^+ ring**
- **O(100 kW) class target in the e^+ ring for $\mu^+ \mu^-$ production**

and, in common with single-pass scheme:

- **High-rate positron source**
- **High momentum acceptance muon accumulator rings**

Low emittance 45 GeV positron ring

cell

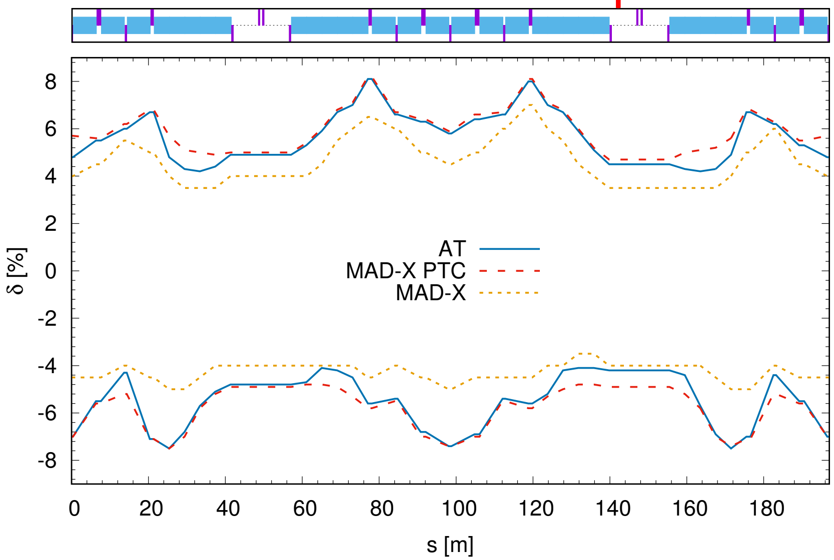


circumference 6.3/27 km: 197 m x 32 cells

Table e+ ring parameters

Parameter	0.7 nm	6 nm	10 nm
Circumference [km]	27	27	27
N. cells	64	32	32
I_b [A]	0.89	0.89	0.89
N_{part} /bunch	$5x10^{11}$	$5x10^{11}$	$5x10^{11}$
N. bunches	1000	1000	1000
E_{loss}/turn [GeV]	0.12	0.12	0.19
Nat. σ_z [mm]	1.9	3.6	3.8
α_c	$2.9x10^{-5}$	$1x10^{-4}$	$1.1x10^{-4}$
Energy spread	$7x10^{-4}$	$7x10^{-4}$	$9x10^{-4}$
$\tau_{x,y}$ [ms]	68	66	42
Energy acceptance [%]	± 8	±6	± 2
SR power [MW]	106	109	170

momentum acceptance



Physical aperture=5 cm constant

no errors

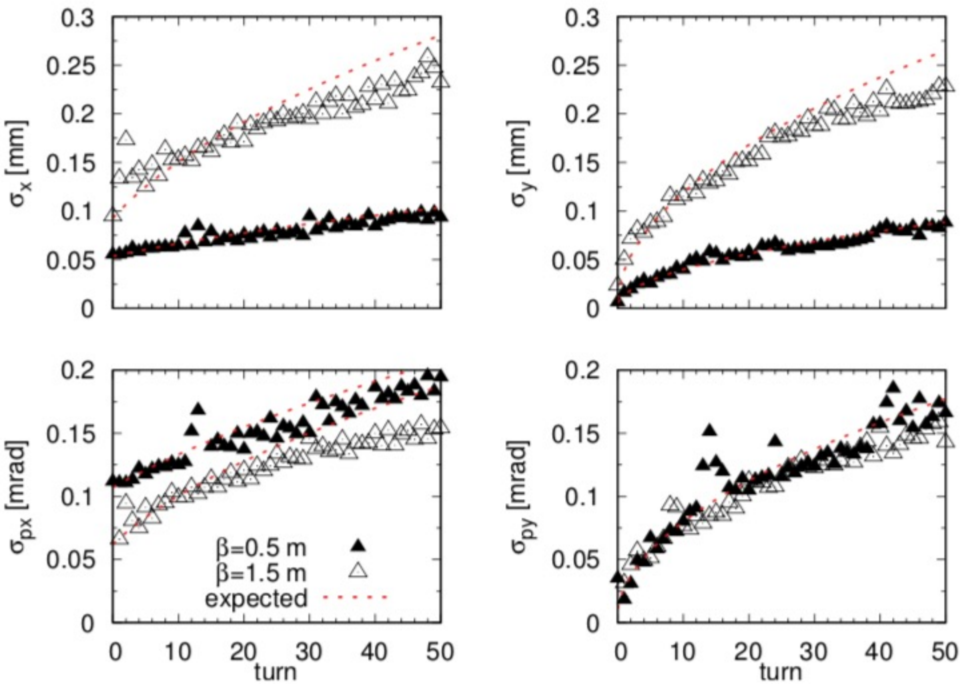
Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

Beam dynamics e^+ beam in ring-with-target

More details in: PR-AB 21, 061005 (2018)

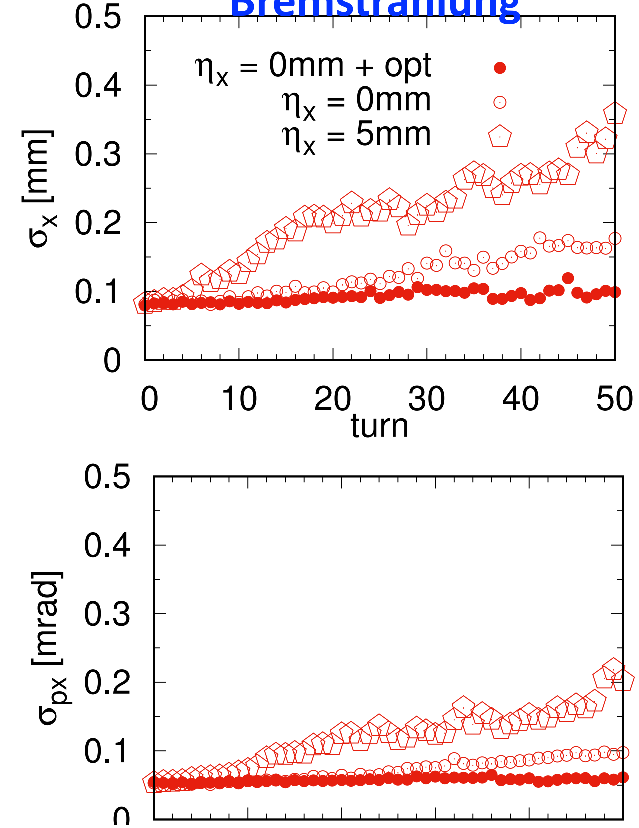
e^+ emittance growth controlled with proper β and D values @ target

Multiple scattering



After 40 turns $\sigma'_{MS} = 25\ \mu\text{rad}$

Bremstrahlung



@Target :
linear and non-linear terms
of horizontal dispersion $\eta_x = 0$

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)

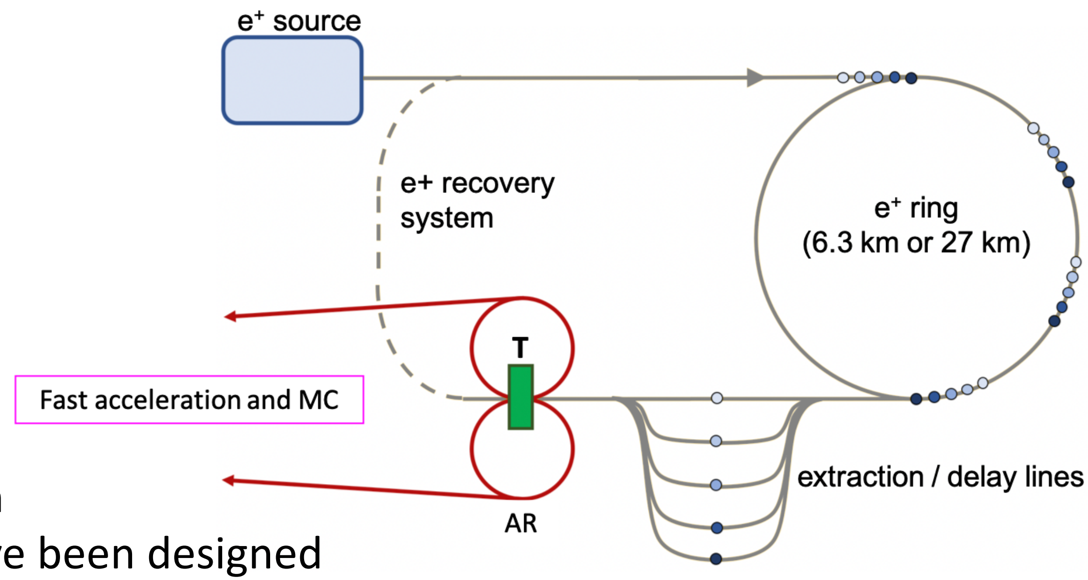
PROS

✓ muon emittance is small

Single-pass scheme

positron beam passes only once through a $\sim X_0$

- **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 μ accumulation

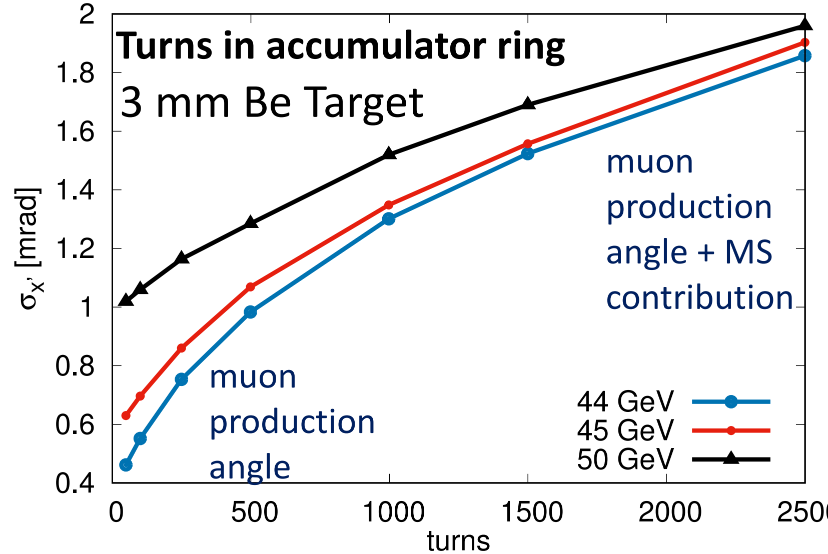
Accumulation must be performed in $\tau_{lab} \sim 500\mu s$

Ring must be as short as possible with the largest possible E acceptance

Number of muons increases by using a thick target

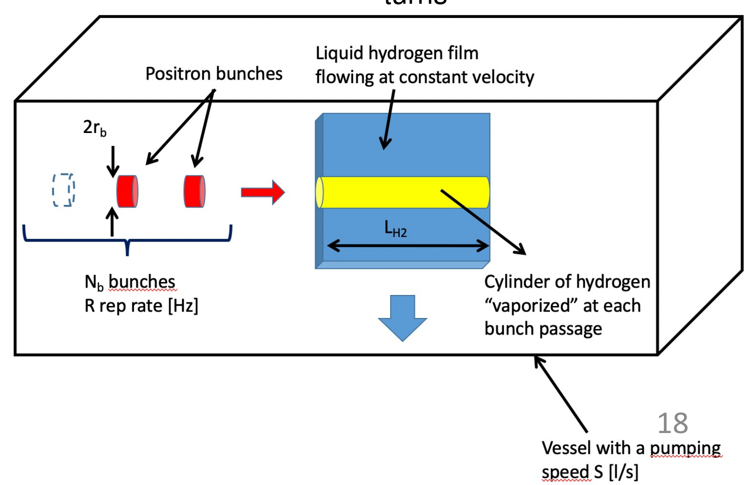
- ✗ drift contribution on beamsize ($\propto L_T$)
- ✗ MS contribution on emittance($\propto \sqrt{X_0 N_T}$)

Proc. of IPAC18, Vancouver, MOPMF087



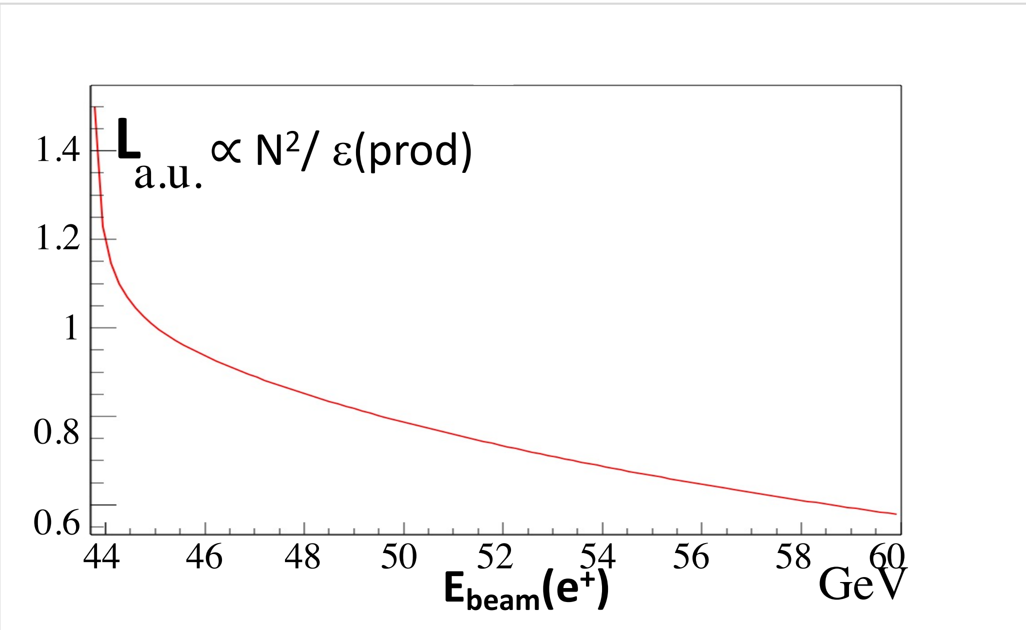
Possible solutions:

- ✓ Multiple IP
- ✓ **Spaghetti/film-like targets** or channeling in crystals

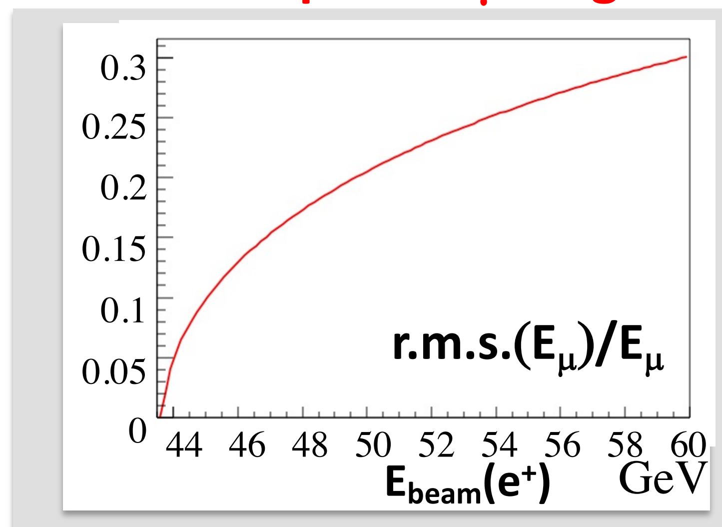


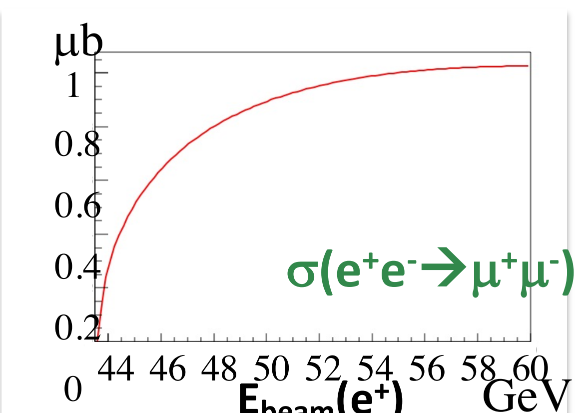
Luminosity of $\mu^+\mu^-$ Collider vs e^+ beam energy

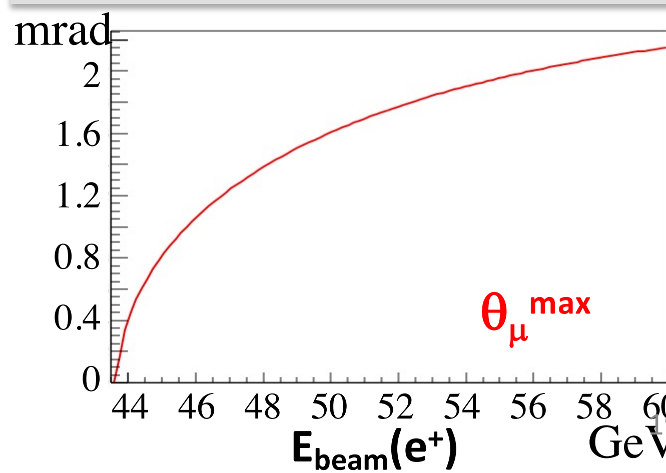
Optimal working point for $\varepsilon(e^+) \cong \varepsilon(MS) \cong \varepsilon(rad) \cong \varepsilon(prod) \cong \varepsilon(AR)$
and sustainable beam spot on target
$\varepsilon(prod)$ and μ intensity $\propto$ positron beam energy:



Need of high energy acceptance μ ring

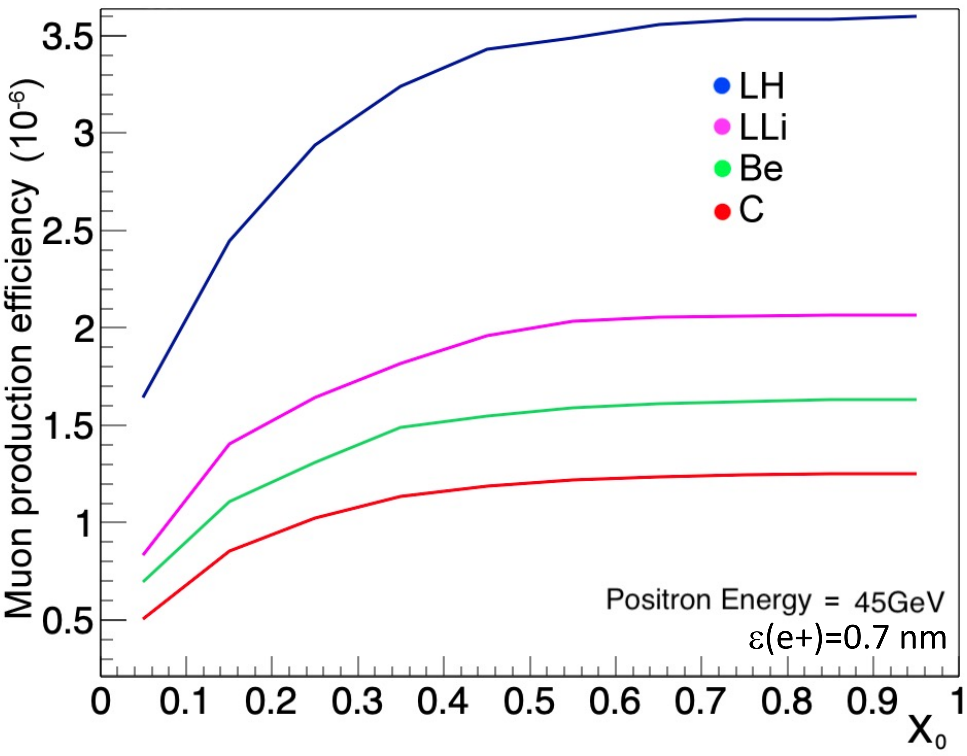






Target options for best production efficiency

Target material plays a crucial role

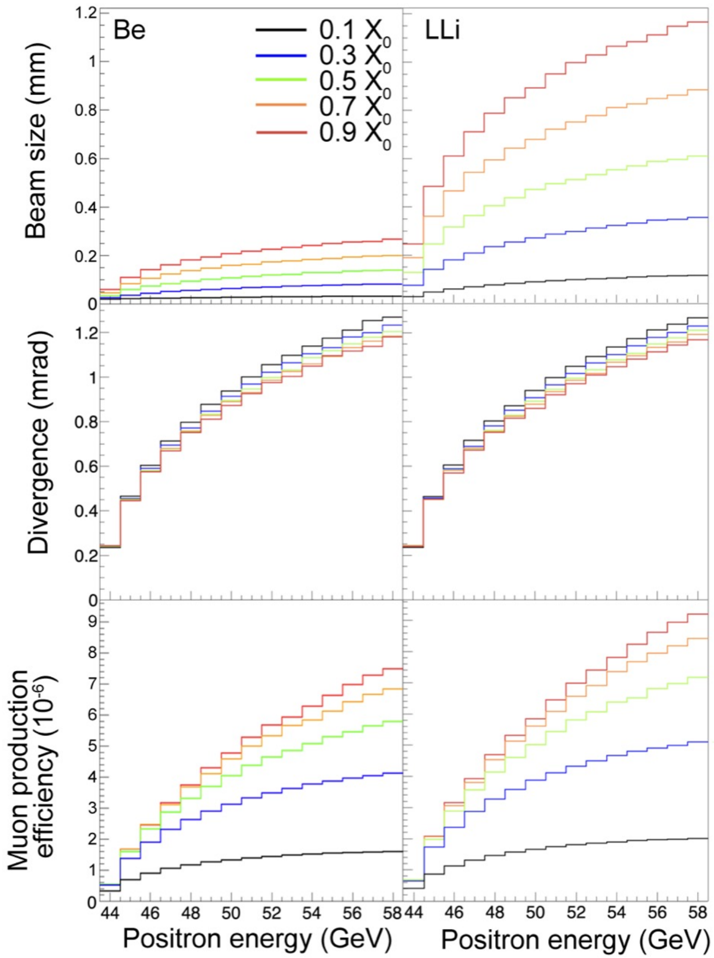


The lighter the material,
the higher the production efficiency

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

3e11 e+ @45GeV
10 x $0.1X_0$

Comparison solid and liquid target



Beam size is proportional to target thickness

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

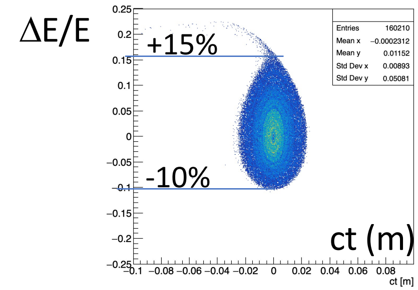
Production efficiency

We also need to optimize the target choice wrt the muon beam quality after the accumulation process (muons/bunch <u>and</u> muon emittance)

Muon Accumulator Rings

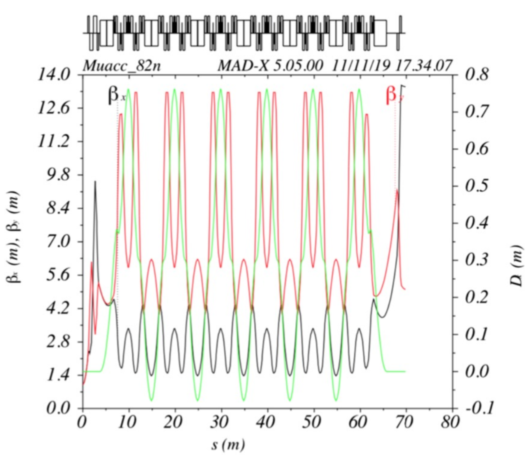
P. Raimondi

- 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

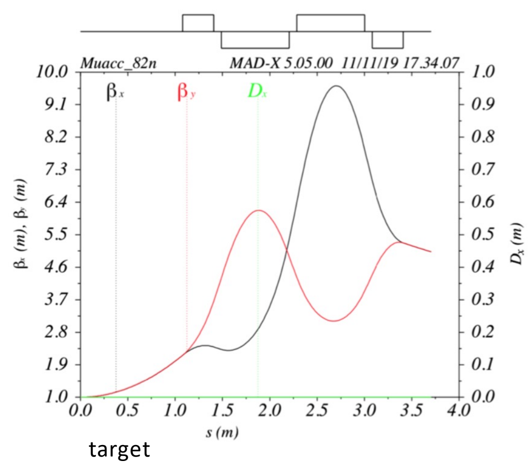


energy acceptance accumulator rings

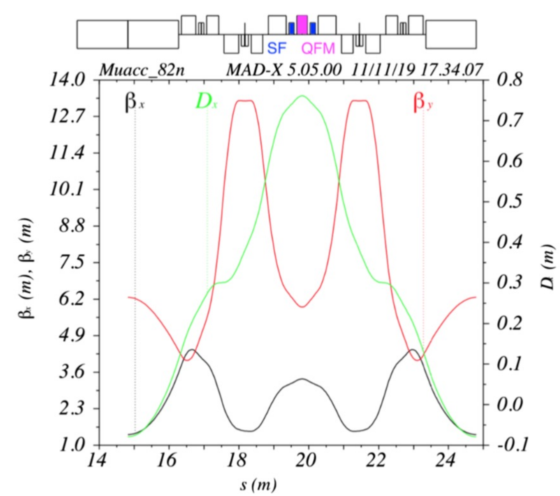
- The ring is made by two symmetric arcs and two straight sections, one for the target insertions and one for the RF cavities



Half ring



Insertion region



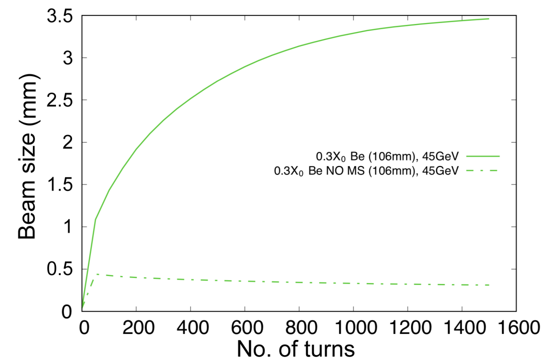
Central Cell

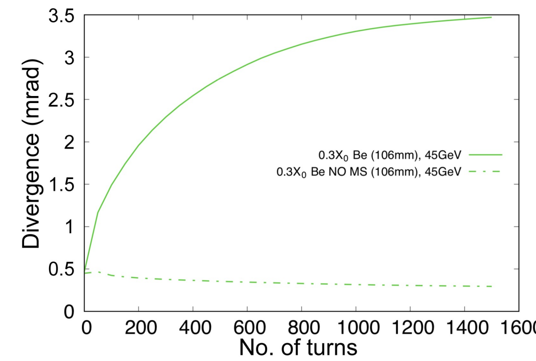
Muon accumulation vs solid and liquid target

N = 5×10^{11} e^+/bunch, 1500 bunches
$\sigma(e+)=20\mu m$ @Target
$\varepsilon(e+)=0.7nm$

Beryllium Target

$0.3X_0Be = 0.106$ m





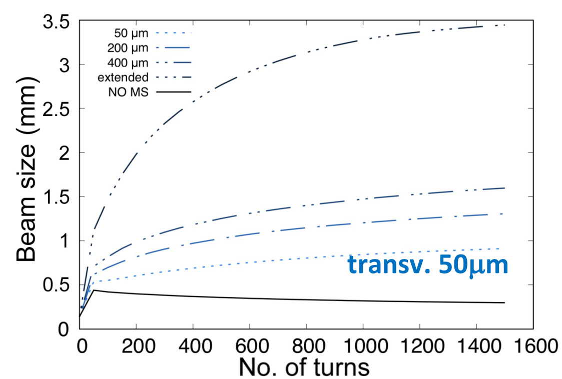
😀 Advantage: most efficient for μ production: After 1500 turns ≈ 1.5 lifetimes, accumulated 3.5×10^8 μ

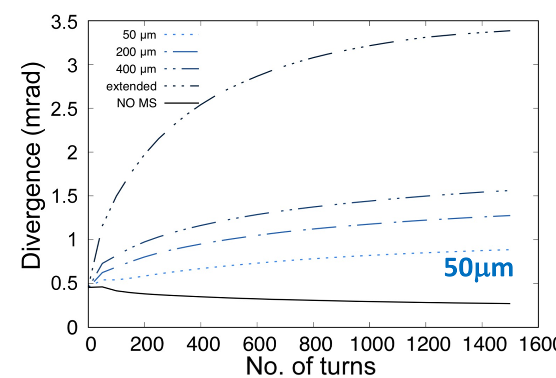
☹ muon beam size and divergence increase in the accumulation process due to the multi passages of muons through the target (multiple scattering)

Liquid Lithium Target

$0.3X_0LLi = 0.465$ m longit. length

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





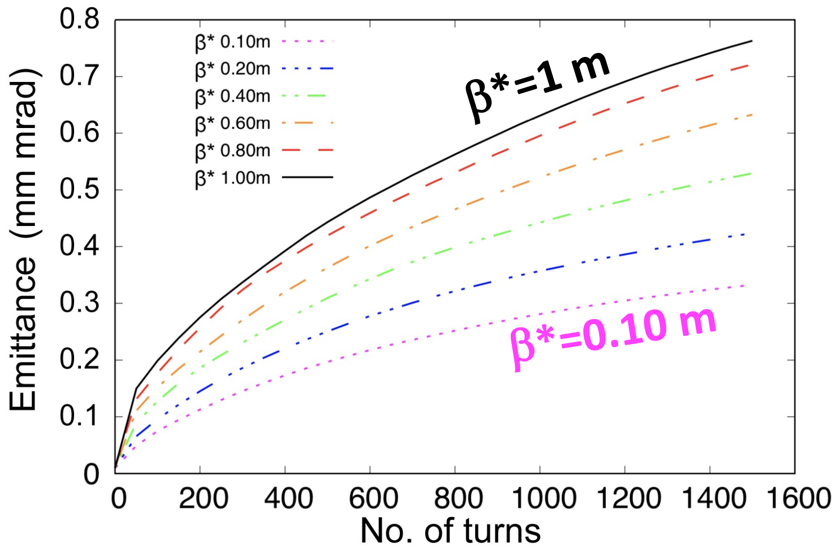
😀 Jet of liquid Lithium mitigates multiple scattering (N^2/ε higher by a factor 30 wrt to Be)
☹ Disadvantage: low X_0 → long jet target needed

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 β^* at target muon beam emittance is further reduced. (as expected)



Best solution: 50μm LLi-D film jet target ≈ 0.5 X_0 (6.7 cm) with β^*=10 cm →
$N = 0.4\times10^9 \mu$/bunch, $\varepsilon(\mu)$=0.3 μm-rad after 1000 turns

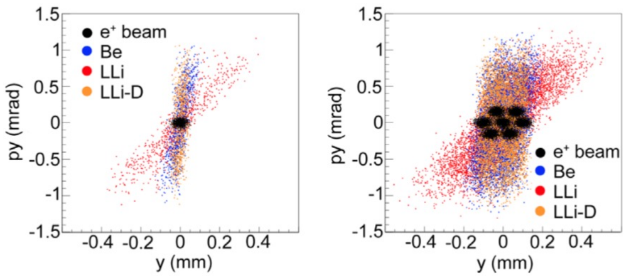
Further optimization

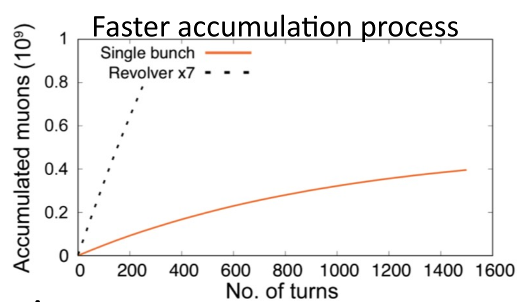
- **Further increase of AR energy acceptance would allow higher e^+ energy, increasing muon production (E^+=50 GeV × 2 in N_μ)**
- **Further reduction of β^* would reduce muon final emittance.**
- With Recombination positron bunch at the target (revolver configuration):

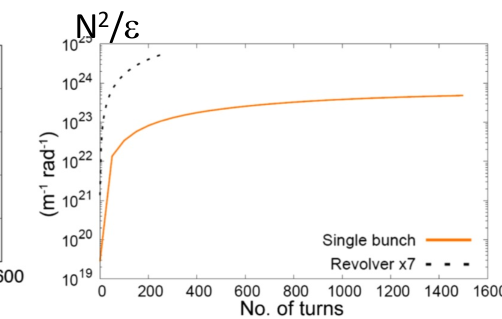
$N = 10^9 \mu$/bunch, $\varepsilon(\mu)$=0.1 μm-rad after 200 turns

revolver configuration

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



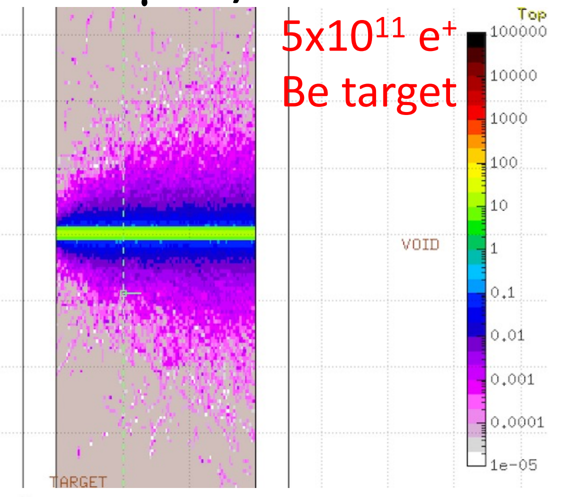




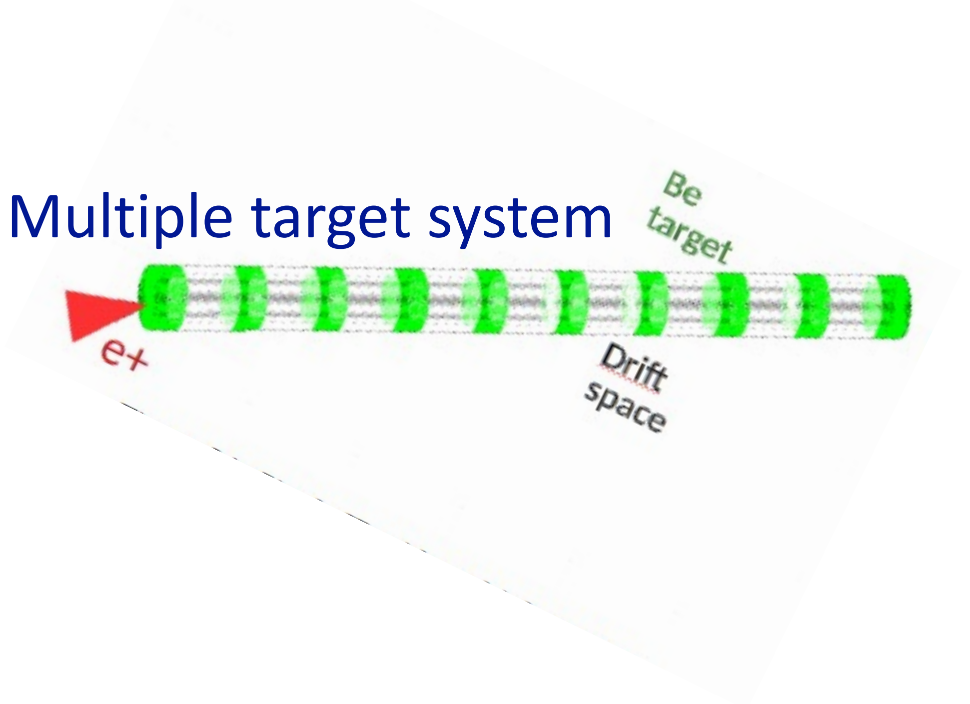
might allow to further increase the muon production, reaching the goal value ≈ 10^9 μ/bunch

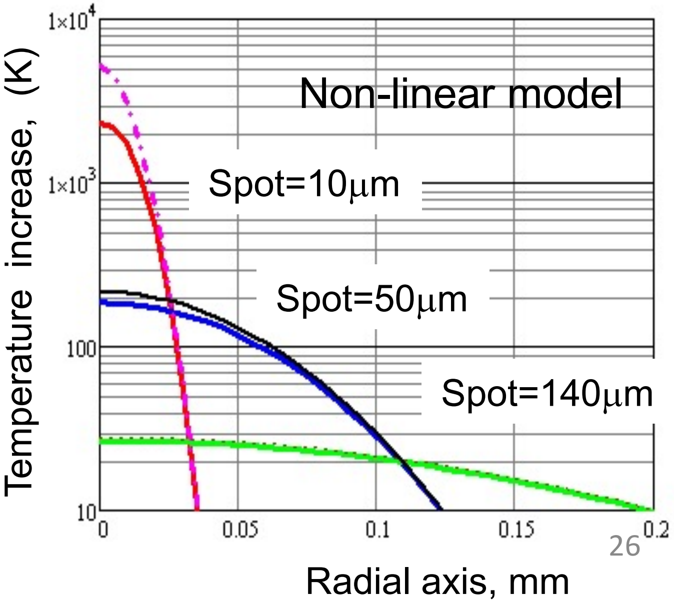
Thermo-mechanical issues – solid targets

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



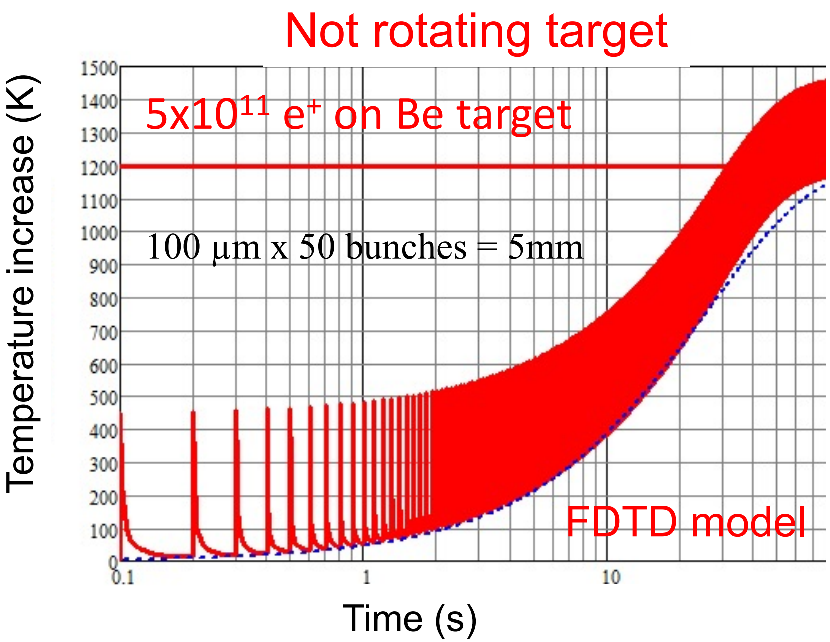
- Multiple target system

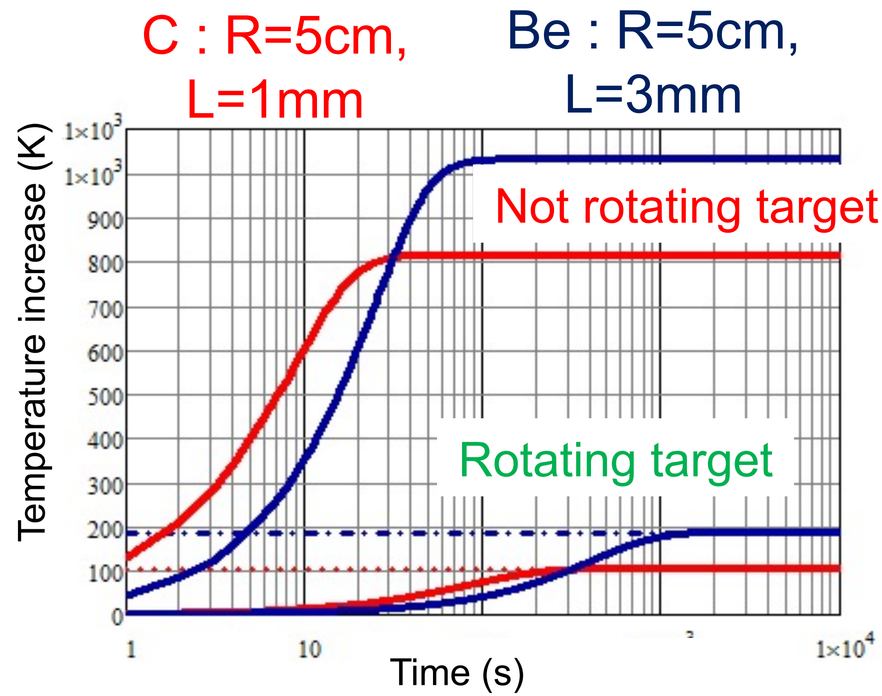




https://doi.org/10.1007/s10765-021-02913-x

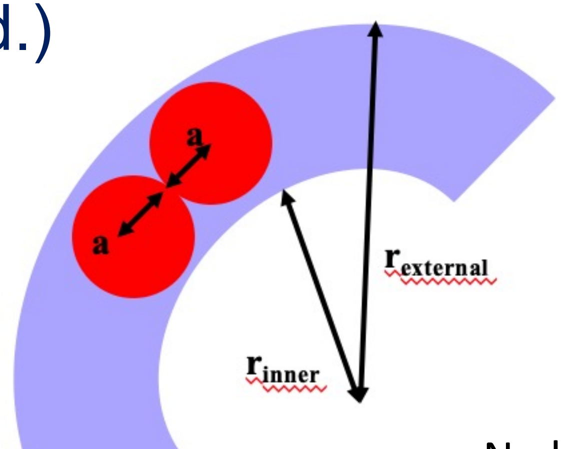
Thermal Study



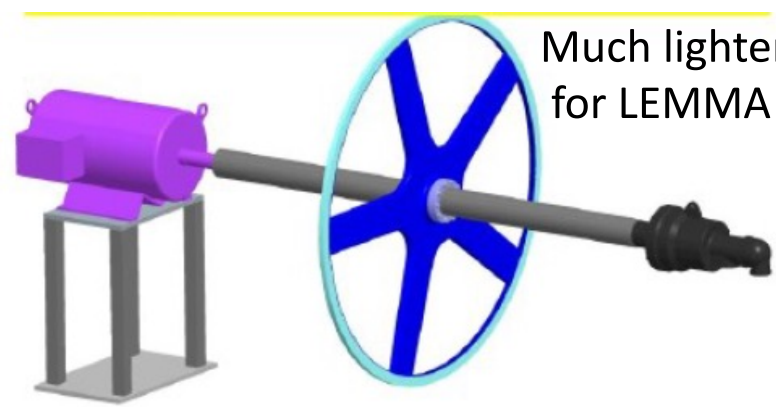


ILC(e^+ prod.) like target

- Radius 50 cm
- N ~ 2000 rpm



- Wheel rim speed 100 m/s
- Wheel diameter ~ 1 m



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

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

	Be 0.106m		LH2 2.66m		LLi 0.45m	
Energy acceptance %	ΔN/sec	Power [MW]	ΔN/sec	Power [MW]	ΔN/sec	Power [MW]
5	4,89E+15	41,43	4,99E+15	42,28	4,82E+15	40,9
10	4,11E+15	34,88	4,22E+15	35,79	4,06E+15	34,4
20	3,22E+15	27,33	3,33E+15	28,24	3,23E+15	27,4

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

	SLC	CLIC	ILC	LHeC pulsed	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}s^{-1}]$	0.06	1.1	3.9	18	440

Summary of e^+ sources projects (<u>all very aggressive</u>):
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-$\mu\mu$, 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.

e^+ production rates achieved (SLC) or needed

	S-KEKB	SLC	CLIC (3 TeV)	ILC (*H*)	FCC-ee (*Z*)	LEMMA(Be)	LEMMA(LH2)
10^{14} e^+ / s	0.025	0.06	1.1	2	0.05	100	40

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

Goal: 3 mm Be, 240 turns lifetime(DP/P<25%), , ΔN/N=0.4%, P=39 MW
35 mm LH2, 625 turns lifetime(DP/P<25%), ΔN/N=0.1%, P= 16 MW

Criteria for target design

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

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

$N(e^+)$ 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 ρ values giving total e^+ beam loss
  - **e^- dominated target:** radiative Bhabha is the dominant e^+ loss effect, giving a maximal $\mu^+\mu^-$ conversion efficiency $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \longrightarrow \mu^+\mu^-)/\sigma_{rb} \approx 10^{-5}$
  - **standard target:** Bremsstrahlung on nuclei and multiple scattering are the dominant effects, Xo and electron density will matter $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \longrightarrow \mu^+\mu^-)/\sigma_{brem}$