Istituto Nazionale di Fisica Nucleare

Low Emittance Muon Collider (LEMMA)

M. Antonelli (INFN-LNF)

For the LEMMA team

Outline

- Introduction
- Positron driven source
- LEMMA scheme
- Optics & Beam dynamics
- R&D on key topics
- Goal parameter table for Multi-TeV MC
- Conclusion

Muon based Colliders

- **A $\mu^+\mu^-$ 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 μs at rest
- **Great potentiality if the technology proves its feasibility**
- **Best performances in terms of luminosity and power consumption**

Recent review paper: M.Boscolo, J. P. Delahaye and M. Palmer, ``The future prospects of muon colliders and neutrino factories,'' in publication by Rev.Accel.Sci.Tech. arXiv:1808.01858

Muon Source

Proton driven

Tertiary production from **protons on target:** p + target→ π/K → μ
typically **P_μ ≈ 100 MeV/c** (π, K rest frame)
whatever is the boost P_T will stay in Lab frame
→ **very high emittance** at production → **cooling needed**
production Rate > $10^{13}\mu$/sec $N_\mu = 2 \cdot 10^{12}$/bunch

MAP

Positron driven

from **direct μ pair production**:
muons produced from **$e^+e^- \to \mu^+\mu^-$** at √s around the $\mu^+\mu^-$ threshold
(√s ≈ 0.212GeV) in asymmetric collisions (to collect μ^+ and μ^-)
e^+e^- annihilation: **e+ beam on target**
→ **cooled muon** beam with **low emittance** at production
Goal: production Rate ≈ 10^{11} μ/sec $N_\mu \approx 6 \cdot 10^9$/bunch

LEMMA

by Gammas (γ Nuclei→$\mu^+\mu^-$ Nuclei)**: GeV-scale Compton γs** [V. Yakimenko (SLAC)]

also: (**e^-Nuclei→$\mu^+\mu^-$ e^- Nuclei**) W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44

LEMMA:

Low EMittance Muon Accelerator

Concept based on a positron driven source

It opens the perspective to a Multi-TeV Muon Collider

- Muons are produced in positron annihilation on e^- at rest
  → e^+ beam impinging on target
- It is a low emittance muon source

- **Low emittance concept overcomes muon cooling**
- **Low emittance allows operations at very high c.o.m. energy**

LEMMA concept was proposed at Snowmass 2013 by M. Antonelli and P. Raimondi:
M. Antonelli, "*Ideas for muon production from positron beam interaction on a plasma target*", INFN-13-22/LNF Note, M. Antonelli and P. Raimondi, Snowmass Report (2013)

Summary of LEMMA pro&cons features

Pro LEMMA:

θ_μ is tunable with $\sqrt{s}$ in $e^+e^- \to \mu^+\mu^-$

μ **beam divergence** can be **very small** close to the $\mu^+\mu^-$ threshold

Cons LEMMA: Low μ prod. Rate

much smaller cross section. wrt proton-driven-source

$\sigma(e^+e^- \to \mu^+\mu^-) \approx$ **1 μb** at most wrt σ(from p)$\approx$ **mb**

Pro LEMMA:

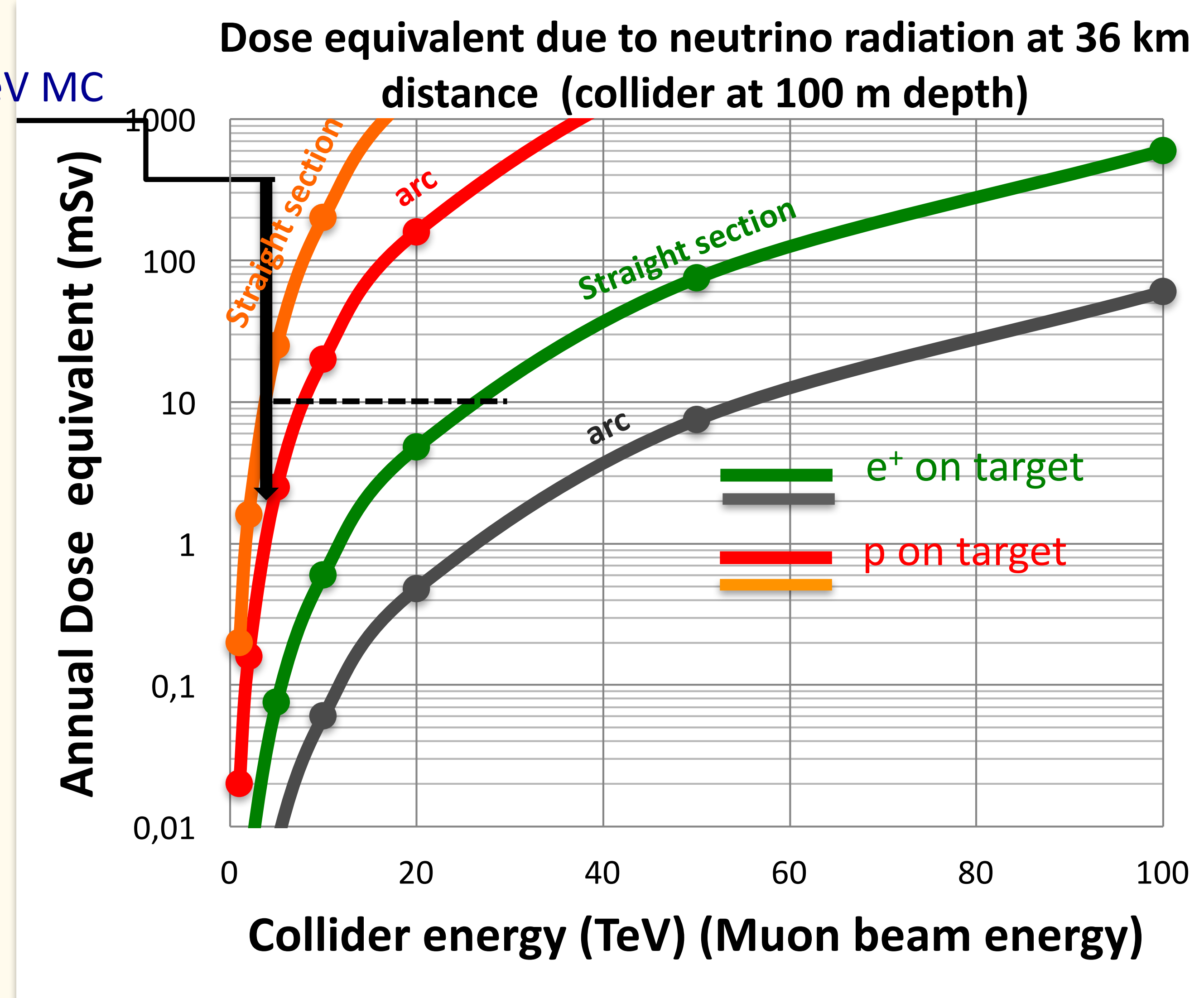
- Reduced losses from decay: **high collection efficiency**
- Low background: **Luminosity at low emittance will allow low background and low neutrino radiation → easier experimental conditions & can go to higher energies**
- Energy spread: muon energy spread might be **also small at threshold**, it gets larger as $\sqrt{s}$ increases

Radiological hazard due to neutrinos from a MC

- First studies by B.J.King in Proc. EPAC98, p. 841-843 and Proc. 1999 PAC p. 319
- C. Johnson, G. Rolandi and M. Silari, TIS-RP/IR/98-34 (1998)
- J.D. Cossairt, N.L. Grossman and E.T . Marshall, Health Phys. 73 (1997), 894-898 (on neutrino dose equivalent/fluence)

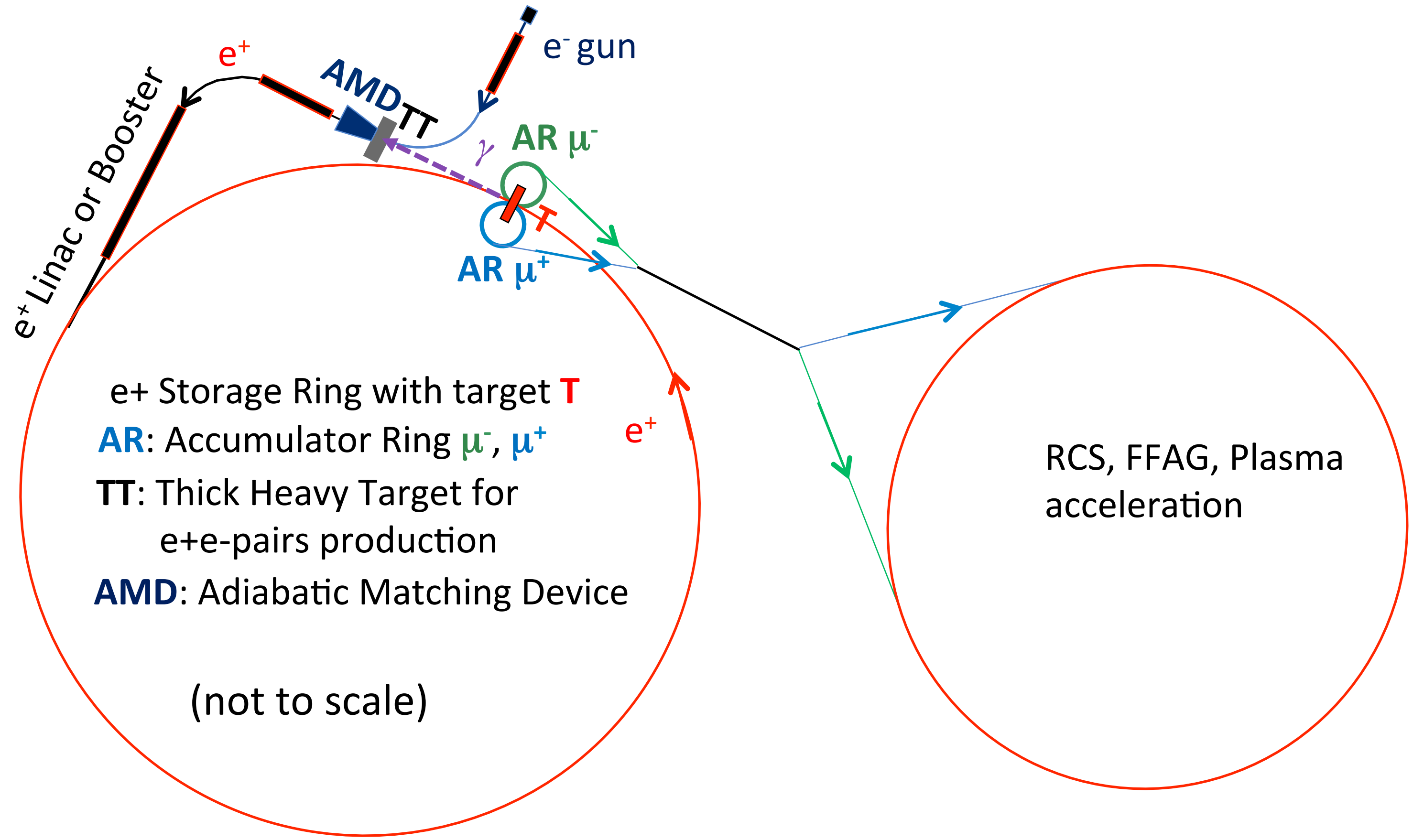
MAP design for a 6 TeV MC
(500 m depth)

muon rate:
p on target option
3×10^{13} μ/s
e^+ on target option
9×10^{10} μ/s



This plot is based on numbers reported in C. Jonhson et al adding Lemma, M.Antonelli

LEMMA scheme



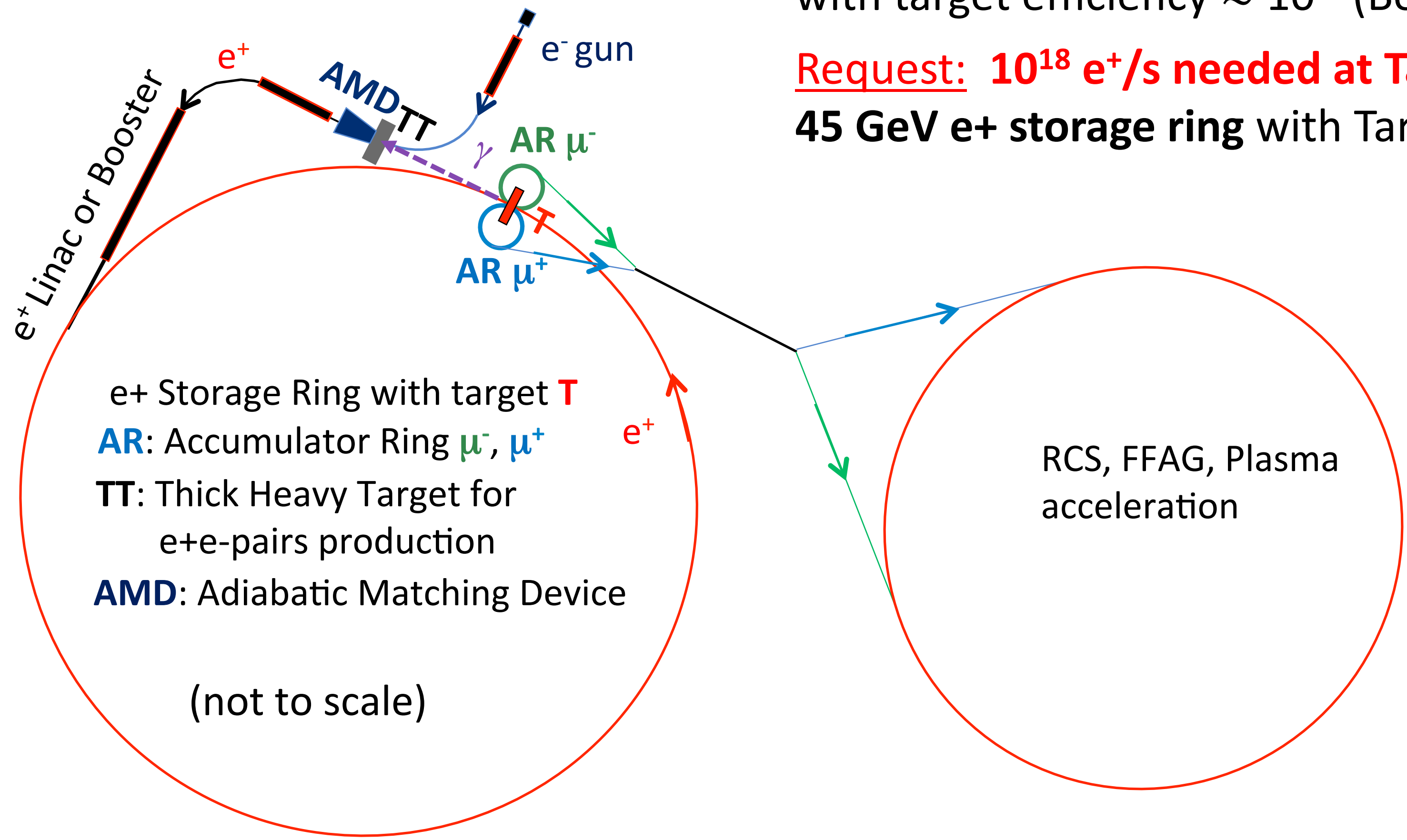
LEMMA scheme

Goal: ≈ **10^{11} μ/s** produced at Target

with target efficiency ≈ 10^{-7} (Be 3mm)

Request: **10^{18} e^+/s needed at Target** →

45 GeV e+ storage ring with Target insertion



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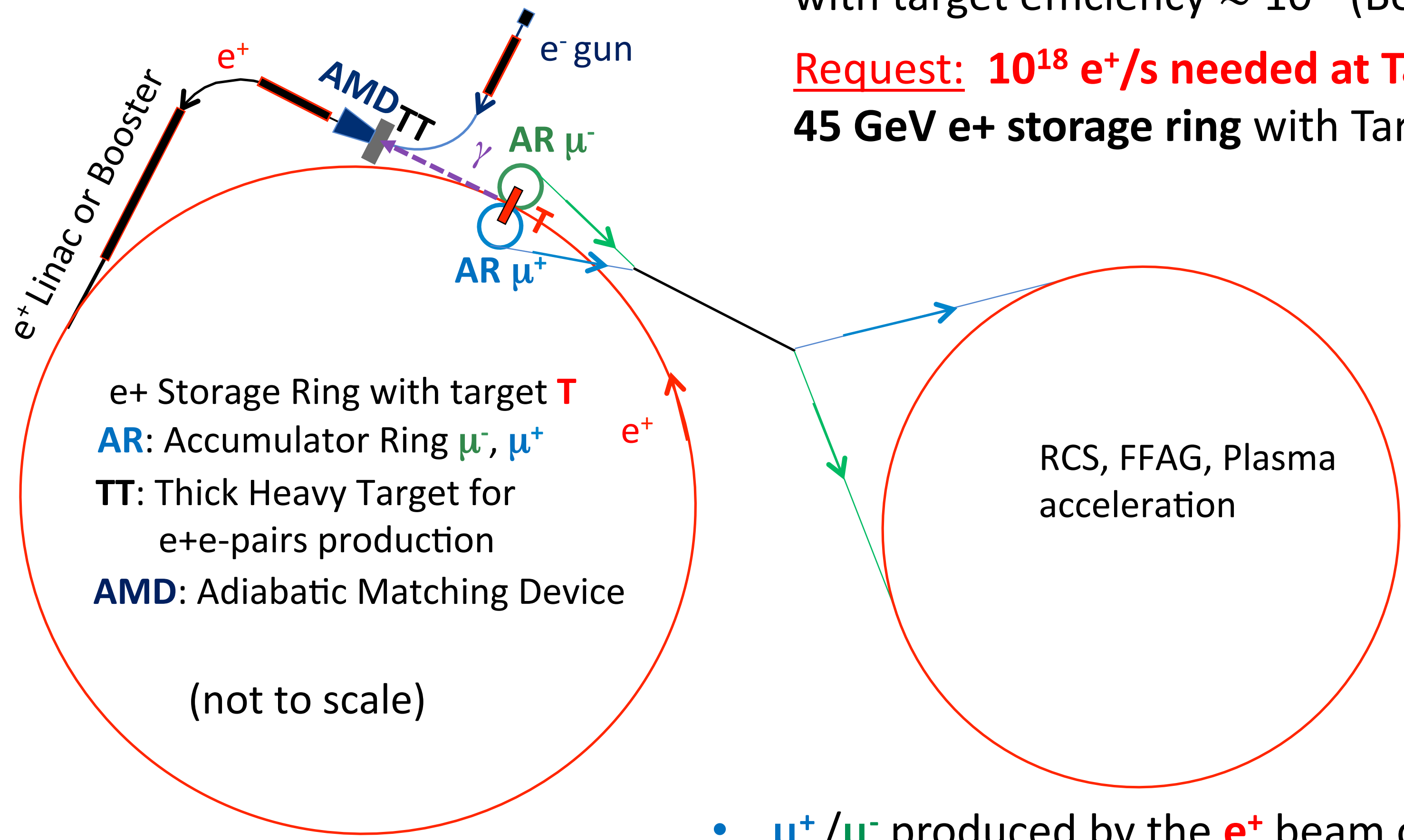
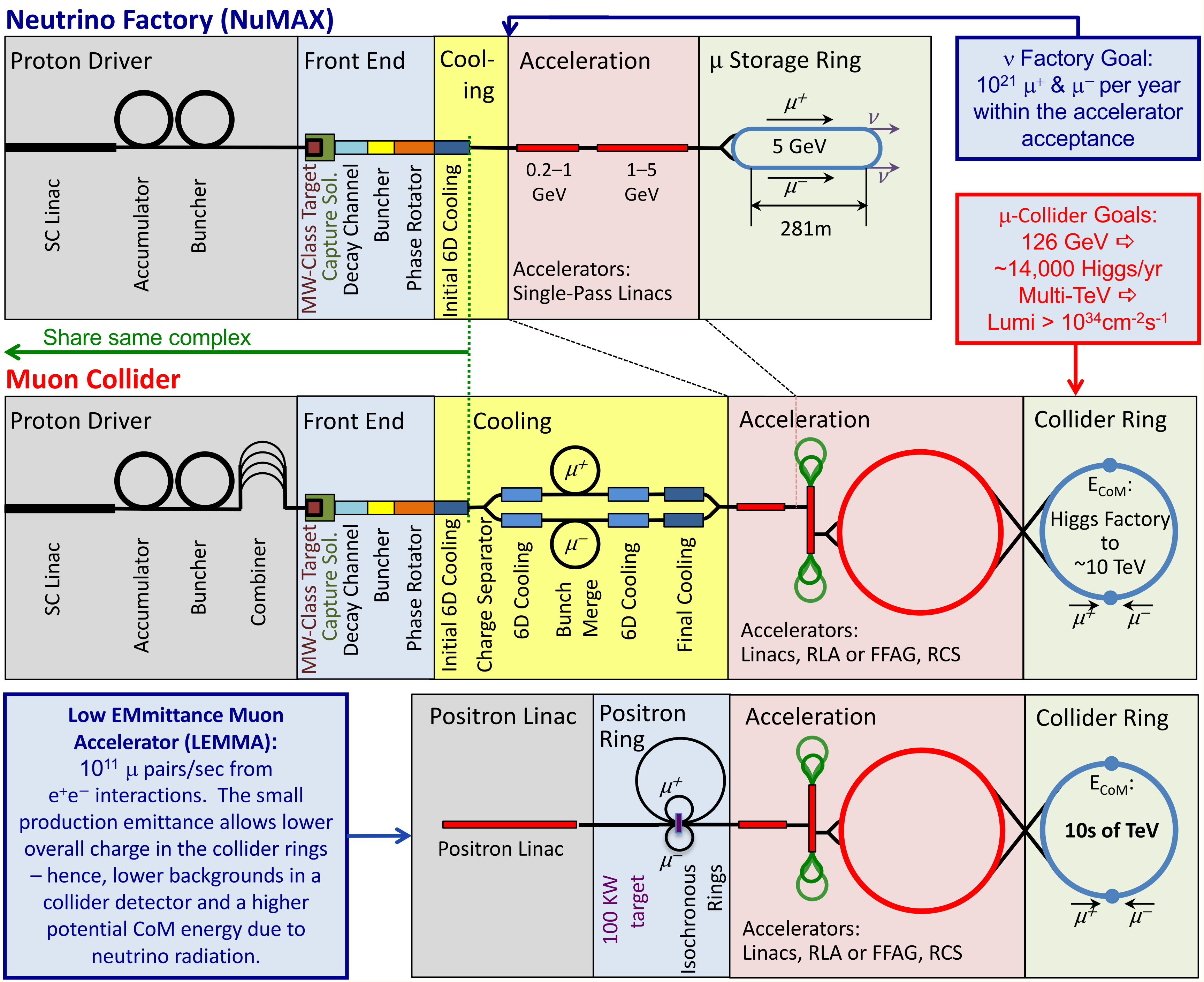


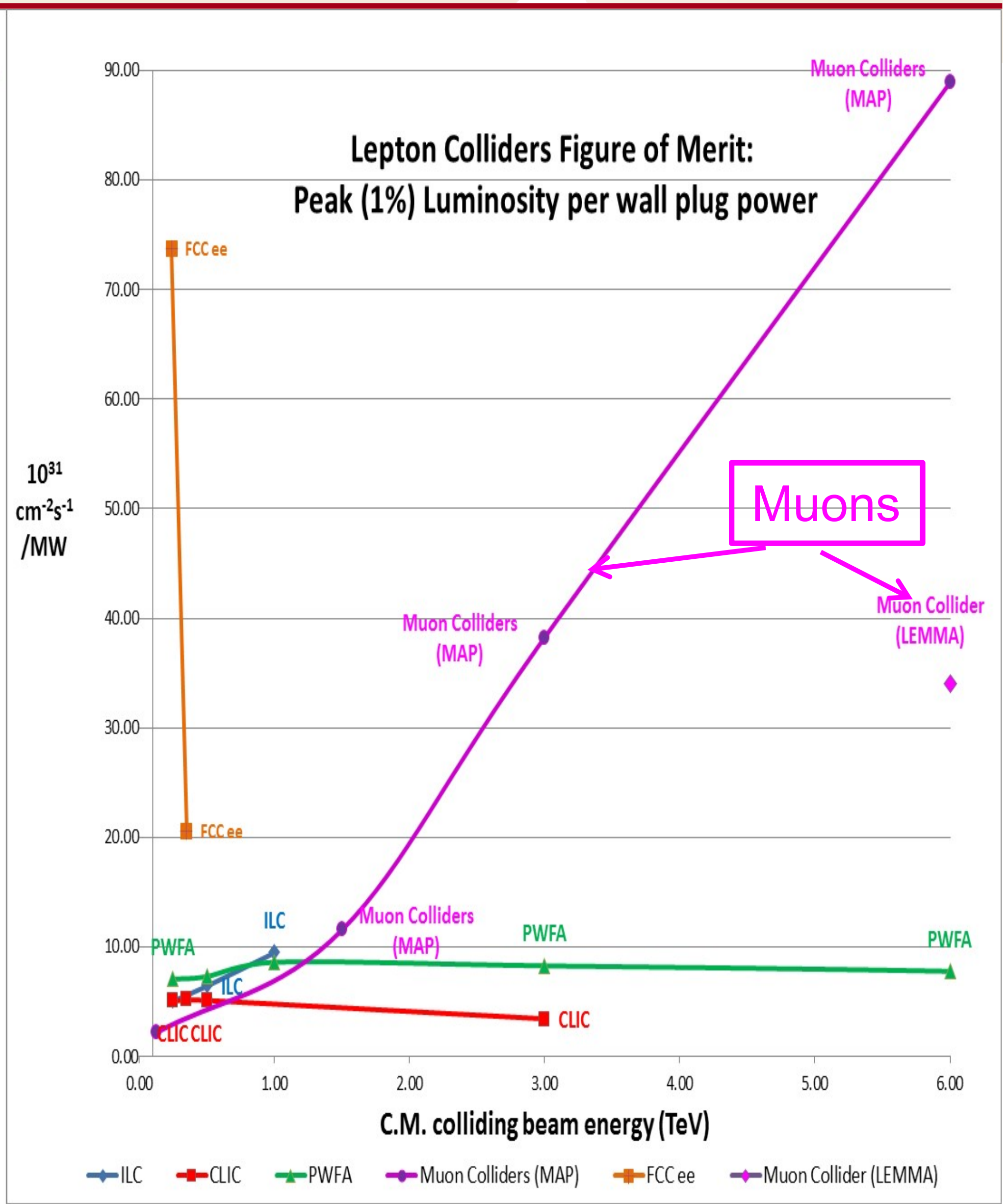
<u>from μ^+ μ^- production to collider</u>

- μ^+ / μ^- produced by the e^+ beam on target **T** at about **22 GeV** → $\tau_{lab}(\mu)$ ≈ **500μs** ($\gamma(\mu) \approx 200$)
- Accumulator Rings (**AR**) isochronous with high momentum acceptance, they recombine μ bunches for ~ 1 τ_μ^{lab} ≈ 2500 turns
- fast acceleration and to collider



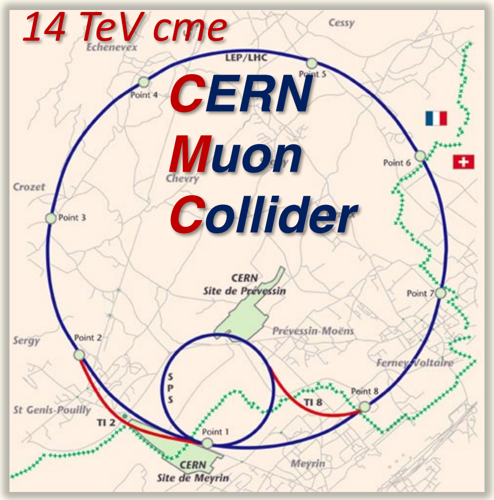
http://arxiv.org/abs/1808.01858

Figure of merit: Luminosity per wall plug power

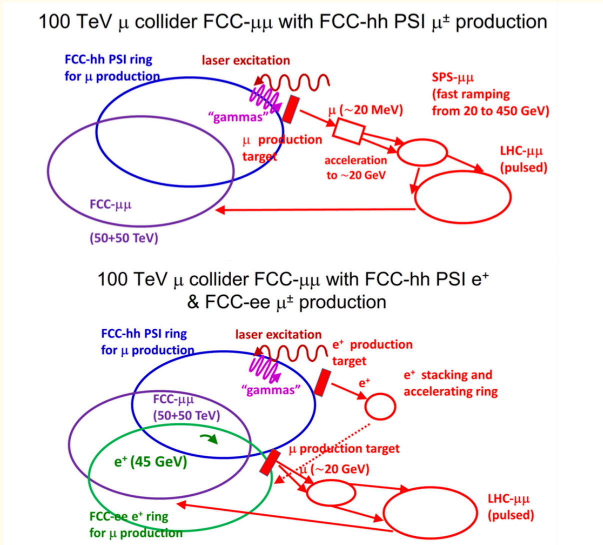


LEMMA concept and MC prospects

- The LEMMA concept renewed the interest and extended the reach of Multi-TeV Muon Colliders
- Two interesting recent proposals:
  - **CERN Muon Collider @14 TeV** [V. Shiltzev and D. Neuffer, MOPMF072, IPAC18]
  - **LHC/FCC based MC** [F. Zimmermann, MOPMF065, IPAC18]



MOPMF072, IPAC18, V. Shiltzev, D. Neuffer



MOPMF065,IPAC18, F. Zimmermann

- In view of the European Strategy Update an international WG has been established last September 2017 on MC, to prepare a document for the ESU on this subject

On going activity on the LEMMA proposal

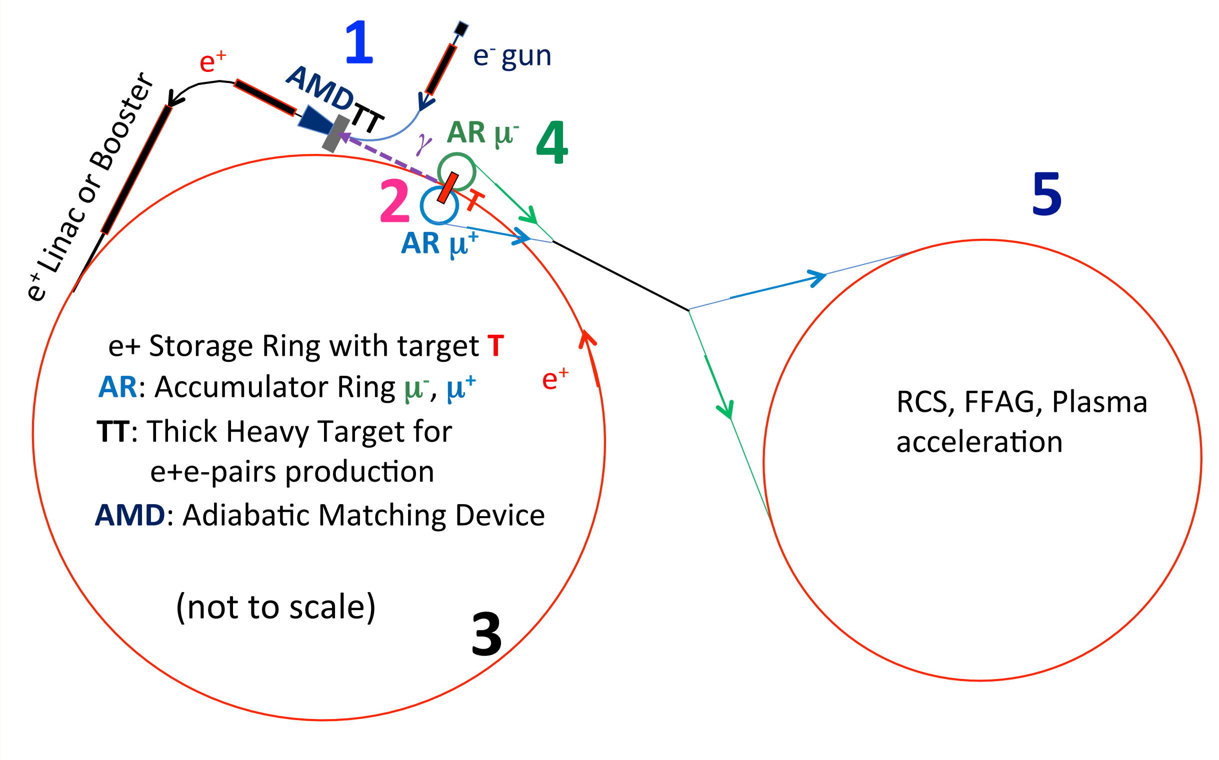
- **Our goal is to define the potentiality of this concept for a multi-TeV MC:**
  - **in terms of luminosity and beam power**
  - **design the optics for the accelerator complex**
  - **identify and possibly start with the necessary key R&D**

- **Updates** of our studies can be found in **Refs.:**
  - "***The future prospects of muon colliders and neutrino factories***", M. Boscolo, J.P.Delahaye and M. Palmer, ArXiv: 1808.01858, 6 August 2018
  - "***Low emittance muon accelerator studies with production from positrons on target***", Phys. Rev. Accel. and Beams 21, 061005 (June 2018)
  - "***Muon accumulator ring requirements for a low emittance muon collider from positrons on target***", M. Boscolo et al., in Proc. IPAC18, MOPMF087 (May 2018)
  - "***Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target***", in Proc. IPAC18, MOPMF086 (May 2018)

Key steps of the study

1. **High rate e+ source**
2. **$\mu^{+/-}$ production target** (high peak energy density deposition (PEDD), power O(100 kW))
3. **Positron ring** (low ε and high momentum acceptance)
4. **Muon Accumulator Rings** (high momentum acceptance)
5. **Fast acceleration**
6. **Muon Collider**

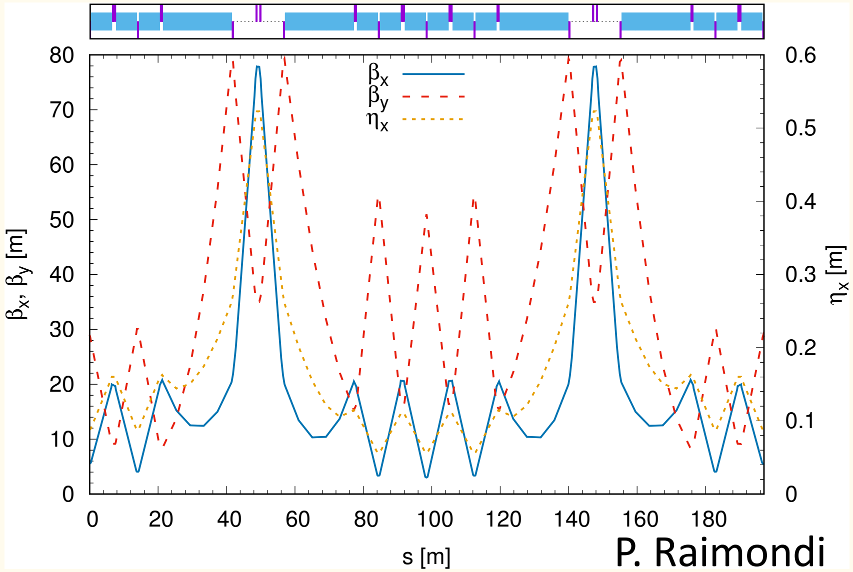
All require R&D study and present challenges



Optics design positron ring

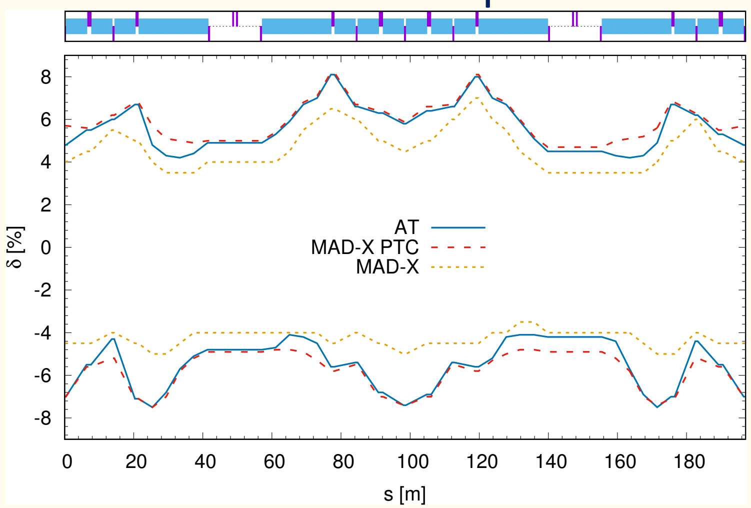
e+ ring parameter	unit	MAP option	LHC tunnel
Energy	**GeV**	**45**	**45**
Circumference	**km**	**6.3**	**27**
No.part./bunch	**#**	**$3 \cdot 10^{11}$**	
bunches	#	100	
e^{+} bunch spacing = T_{rev} (AR)	ns	200	
Beam current	mA	240	
Emittance	nm	6	0.7
U_0	GeV	0.51	0.12
SR power	**MW**	**120**	**29**

Cell based on the Hybrid Multi Bend Achromat



P. Raimondi

momentum acceptance



S. Liuzzo, Padova workshop, 2-3 July 2018

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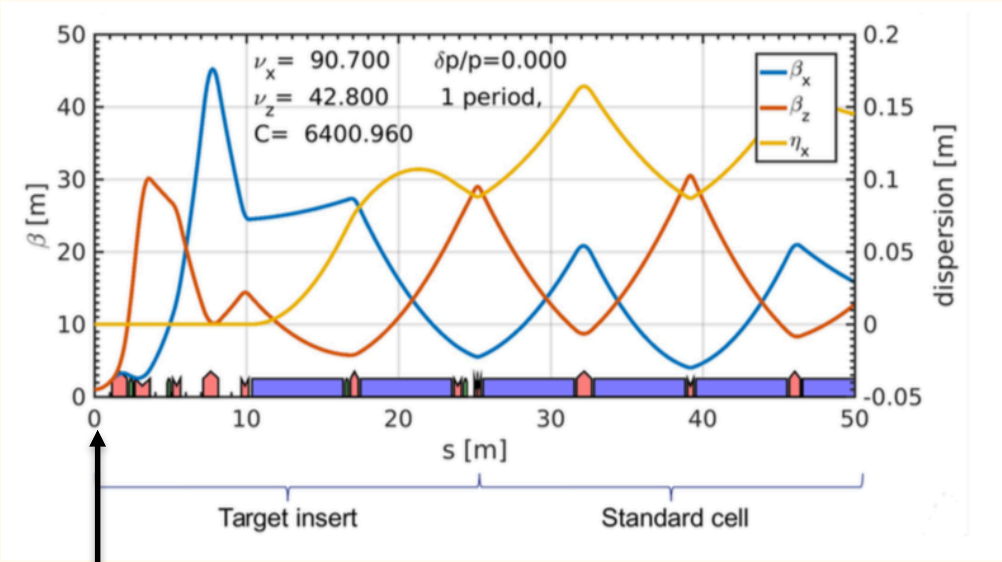
Target Insertion Region



@target $\begin{cases} D_x \approx 0 \\ \text{low-}\beta\ (\beta_{x,y} = 0.5\ \text{m}) \end{cases}$

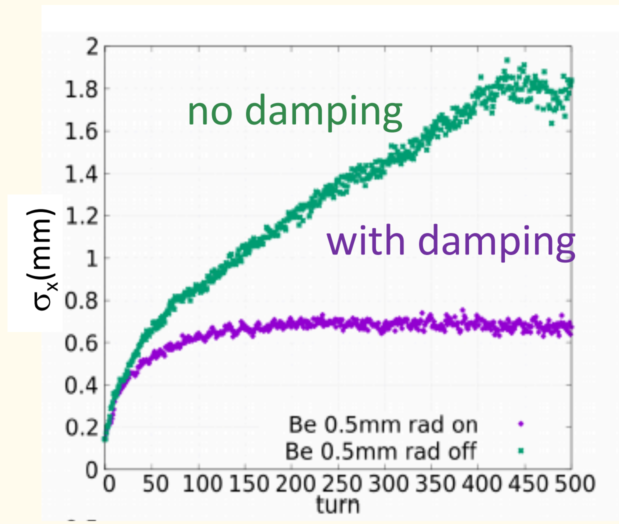
S. Liuzzo, Padova workshop, 2-3 July 2018

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)

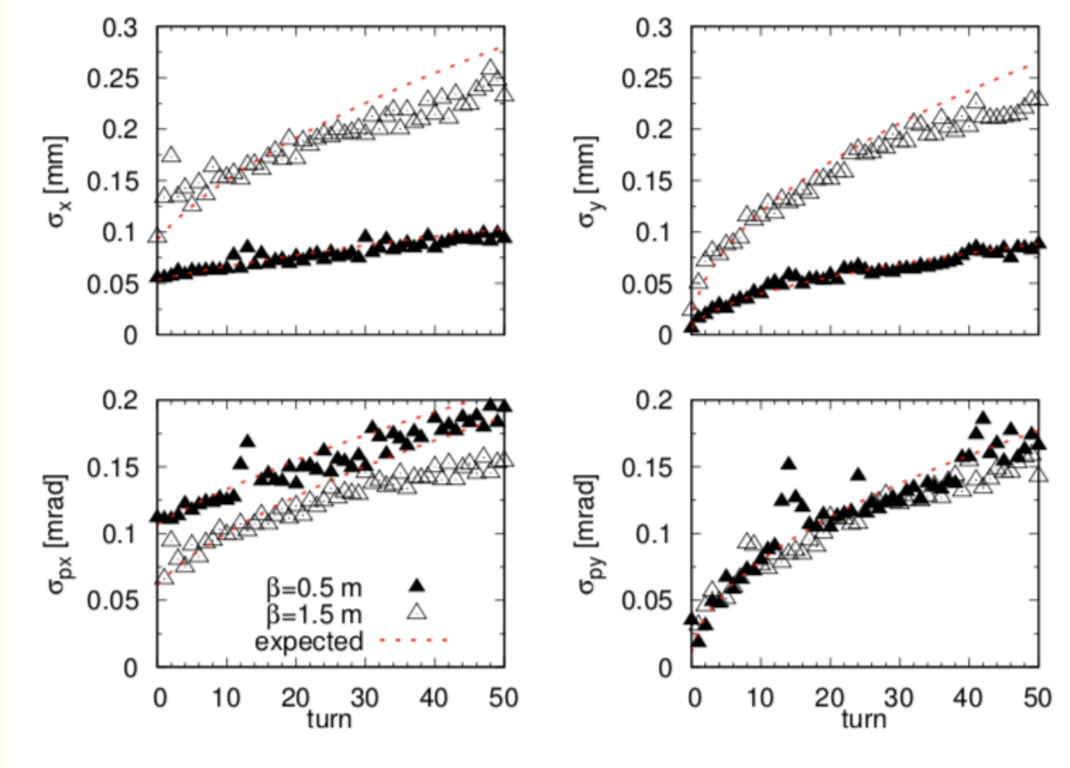


Beam dynamics e^+ beam in ring-with-target

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

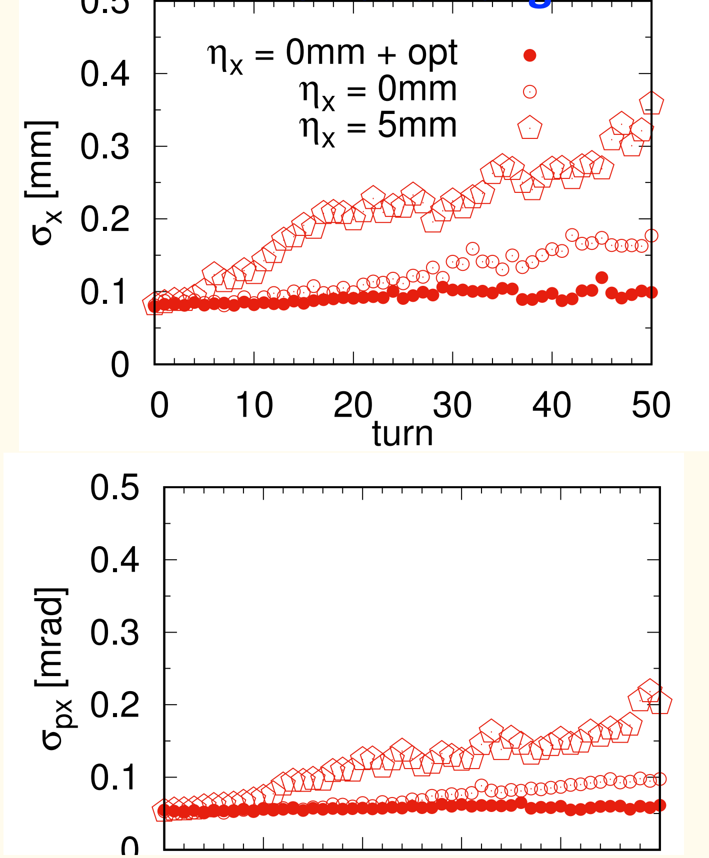
e^+ emittance growth controlled with proper β and D values @ target

Multiple scattering



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

Bremstrahlung



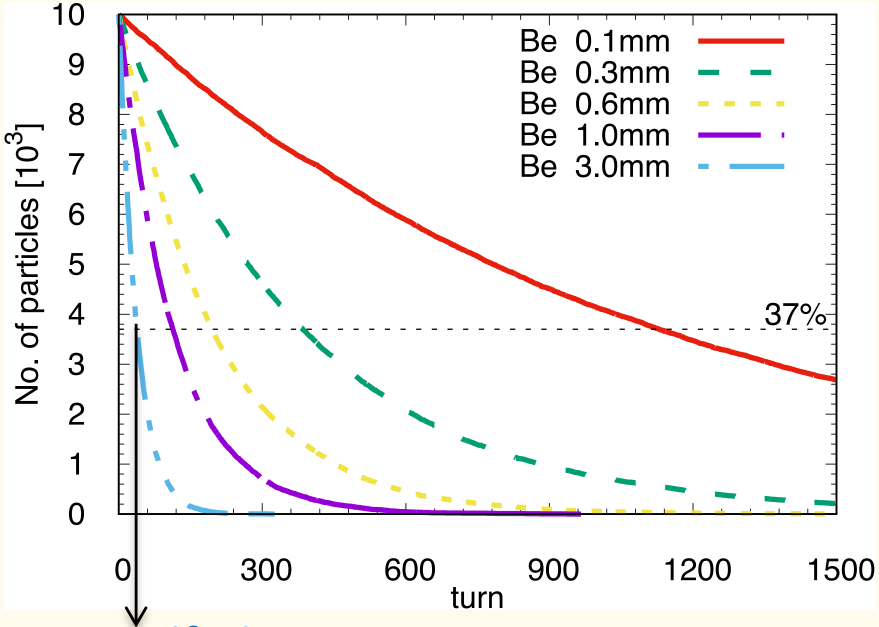
@Target :
linear and non-linear terms
of horizontal dispersion $\eta_x = 0$

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

More details in:
Arxiv. 1803.06696

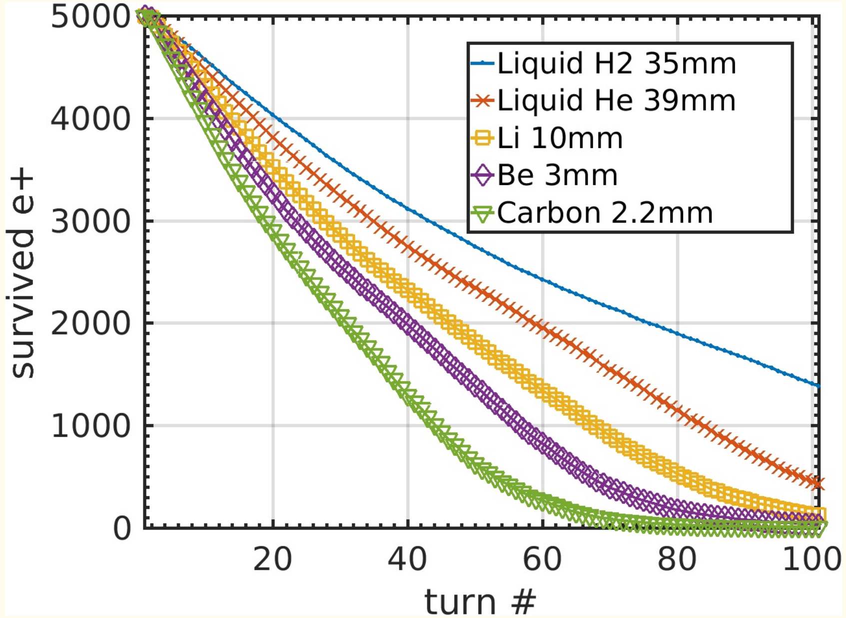
Particle tracking with: MADX/ PTC/GEANT4/FLUKA & Accelerator Toolbox/G4-Beamline

Lifetime $\propto$ 1/thickness as expected



Lifetime ~ 40 turns for Be 3 mm

Lifetime determined by bremsstrahlung and momentum acceptance
2-3% e+ losses in the first turn

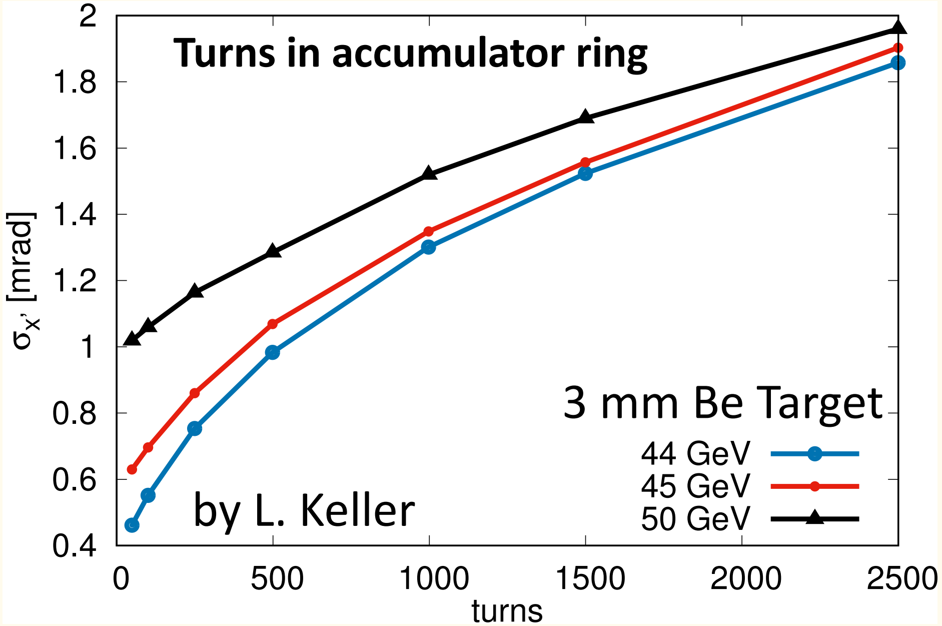


Number of e+ vs turns for different target materials.
Target thickness gives constant muon yield.

Muon emittance contributions

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

$\varepsilon(e^+)$ = e^+ emittance
$\varepsilon(MS)$ = multiple scattering contribution
$\varepsilon(rad)$ = energy loss (brem.) contribution
$\varepsilon(prod)$ = muon production contribution
$\varepsilon(AR)$ = accumulator ring contribution



muon production angle

muon production angle + MS contribution

All these values need to be matched to minimize emittance growth
due to beam filamentation.

σ_x and $\sigma_{x'}$ and correlations of e^+ and μ beams have to be similar

Proc. of IPAC18, Vancouver, MOPMF087

R&D for the muon production target

- This is the core topic of LEMMA feasibility.
- Thermo-mechanical stress is the main issue (very high Peak Energy Density Deposition)
- Engineering simulations and experimental tests will be required to find the optimal target material, considering mechanical stress and heat load resistance properties.
- We are considering now:
  - Beryllium seemed optimal from first MADX-/Geant-4 simulations
  - Carbon composites
  - Liquid Lithium
  - Hydrogen pellet
  - Crystals or more exotic targets

Target: thermo-mechanical stresses considerations

Beam size as small as possible (matching various emittance contributions), 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

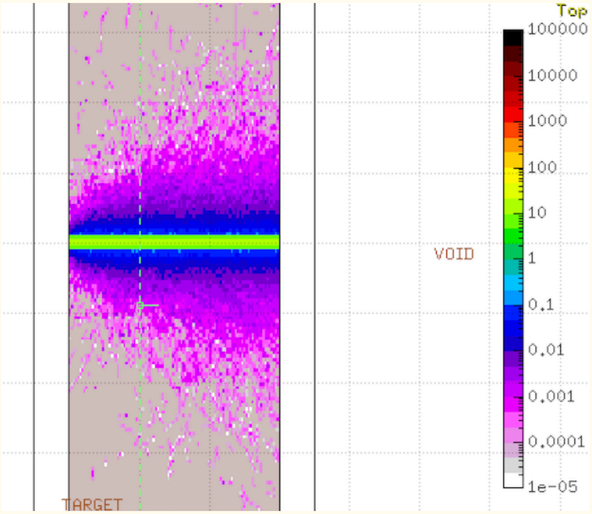
- **Solid target**: simpler and better wrt temperature rise
  - Be, C

  Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, $N=1.7 \times 10^{11}$ p/bunch, up to 288 bunches in one shot [Kavin Ammigan 6th High Power Targetry Workshop]
- **Liquid** target: better wrt power removal
  - Li, difficult to handle lighter materials, like H, He
    - LLi jets examples from neutron production, Tokamak divertor

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

Conventional options for μ target

- Aim at bunch ($3x10^{11}$ e^{+}) transverse size on the 10 μm scale: rescaled from test at HiRadMat ($5x10^{13}$p on 100μm) with **Be-based** targets and **C-based** (HL-LHC) [F. Maciariello *et al.*, IPAC2016]
- No bunch pileup ⟶ Fast rotating wheel (20000 rpm)
- Power removal by radiation cooling (see for instance PSI muon beam upgrade project HiMB) [A. Knecht, NuFact17]]
- Need detailed simulation of thermo-mechanical stresses dynamics
  - Start using FLUKA + Ansys Autodyn (collaboration with CERN EN-STI)
- Experimental tests:
  - **DAFNE** available from 2020



Alternative options like H pellet, crystals or more exotic targets are under consideration

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**

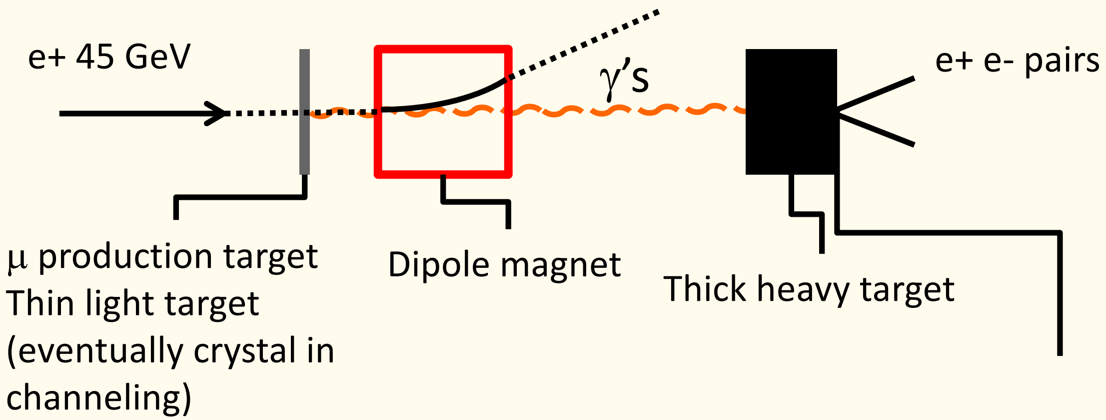
Present: 3 mm Be, 40 turns lifetime(DP/P<6%), ΔN/N=2.5%, P= 247 MW
35 mm LH2, 100 turns lifetime(DP/P<6%), ΔN/N=1%, P= 98 MW

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<6%), ΔN/N=0.1%, P= 16 MW

R&D on high rate positron source

Embedded e+ source to relax e+ source requirement

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



About 0.6 new e^+ produced per e^+ on thin target
Required collection efficiency feasible with standard design
not yet found a system able to transform the temporal structure of the produced positrons to one that is compatible with the requirement of a standard positron injection chain

R&D on Fast Acceleration for LEMMA

- Muon beams must be accelerated to high energy in a very short period of time to account for their short lifetime.
- Synchrotron radiation is not a limiting factor in accelerating muons at the TeV-scale, so multi-pass acceleration is preferred for cost considerations.
- LEMMA scheme utilizes a **natural cycle time of 2.2 KHz and cannot be matched to** the slower ramp rate of the MAP hybrid **Rapid Cycling Synchrotron**.
- For LEMMA two acceleration options to study are:
  - the Recirculating Linear Accelerator (**RLA**)
  - fixed-field alternating gradient (**FFAG**) machines with large energy acceptance
- Also accelerator technologies developed for the e+e- linear collider could be of benefit. Muon beams with low emittance and low current allow the use of novel acceleration technologies like X-band cavities

Muon collider at 6 TeV com energy

Values considered for this table:

- **$\mu^+\mu^-$ rate = 0.9 10^{11} Hz**
- **ε_N = 40 nm (as ultimate goal)**
- **3 mm Beryllium target**

Comparison with MAP:

muon source	Rate μ/s	ε_{norm} μm
MAP	10^{13}	25
LEMMA	0.9×10^{11}	0.04

Same L thanks to lower β^* (nanobeam scheme)

no lattice for the muon collider yet

This table summarizes the goals of the LEMMA design study

Parameter	unit	LEMMA-6 TeV
Beam energy	Tev	3
Luminosity	$cm^{-2}s^{-1}$	5.1×10^{34}
Circumference	km	6
Bending field	T	15
N particles/bunch	#	6×10^{9}
N bunches	#	1
Beam current	mA	0.048
Emittance x,y (geo)	m-rad	1.4×10^{-12}
$\beta_{x,y}$ @IP	mm	0.2
$\sigma_{x,y}$ @IP	m	1.7×10^{-8}
$\sigma_{x',y'}$ @IP	rad	8.4×10^{-5}
Bunch length	mm	0.1
Turns before decay	#	3114
muon lifetime	ms	60

Comment on the parameters table

- **Low Emittance:** is the core of LEMMA idea, the greatest benefit of the positron driven source. The ultimate value has to be determined by R&D studies, we know that it will be given by the convolution of different contributions. Our goal is to reduce multiple scattering to a negligible value and have the best possible matching at target [with 3 mm Be target the multiple scattering contributes for a factor 15 in emittance increase]

- **Bunch intensity $6\text{x}10^9$:** a muon bunch charge of $4.5\text{x}10^7$ is provided by the AR, an enhancement by a factor 120 can be obtained by a combination scheme either in the longitudinal [D. Schulte] or in the transverse [P.Raimondi] plane. Feasibility needs to be studied, also to verify impact on emittance. Alternatively at very high energy use SR damping

- **β^*=0.2 mm:** aim is nano-beam scheme, final focus lattice not designed yet, permanent quads might be used.

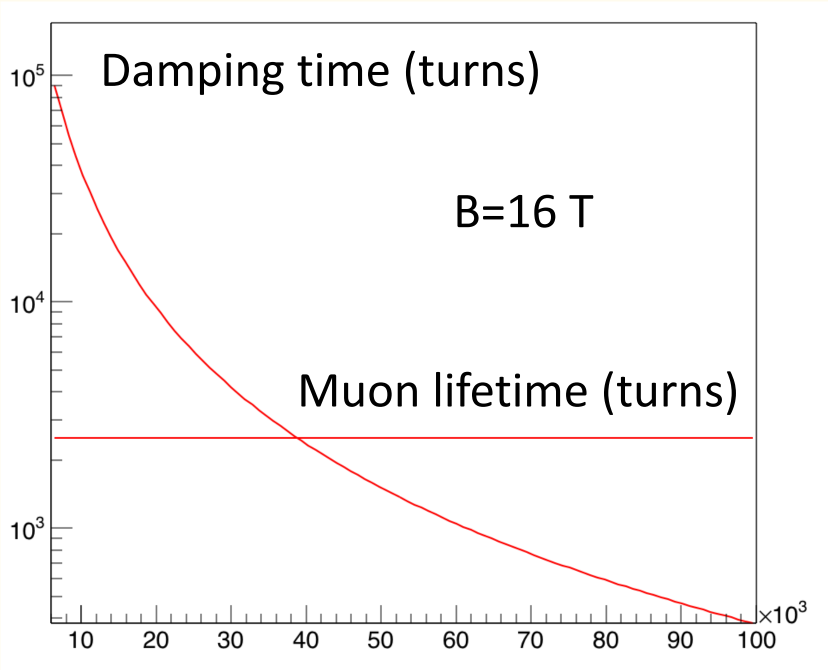
Conclusion

- **LEMMA is a novel concept for muon production, that renewed the interest and extended the reach of Multi-TeV Muon Colliders**

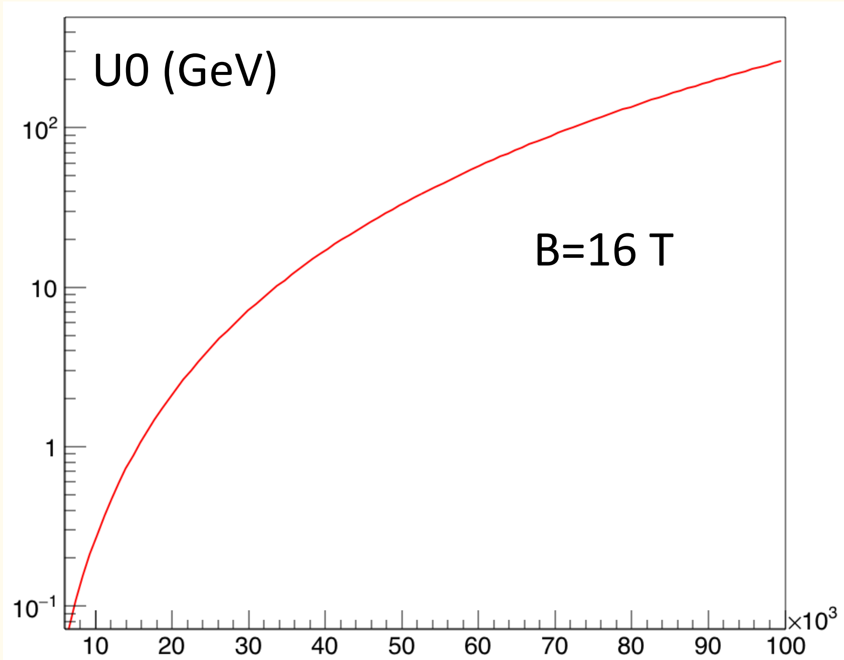
- Key topics for the LEMMA feasibility validation:
  - **Positron ring-with-target: low emittance and high momentum acceptance**
  - **Muon Accumulator Rings: compact, isochronous and high $(\Delta p/p)_{accept}$**
  - **Muon production target: extreme Peak Energy Density Deposition**
  - **High positron source rate**
  - **Fast acceleration**
  - **Final focus at MC**

- Preliminary studies pioneered by the INFN-LNF group are promising, progresses require to continue the design study of the accelerator complex.
- Experimental tests at DAFNE&CERN-NA for validation of some fundamental topics LEMMA are fundamental opportunities.

SR and damping in μ collider



Beam energy(GeV)



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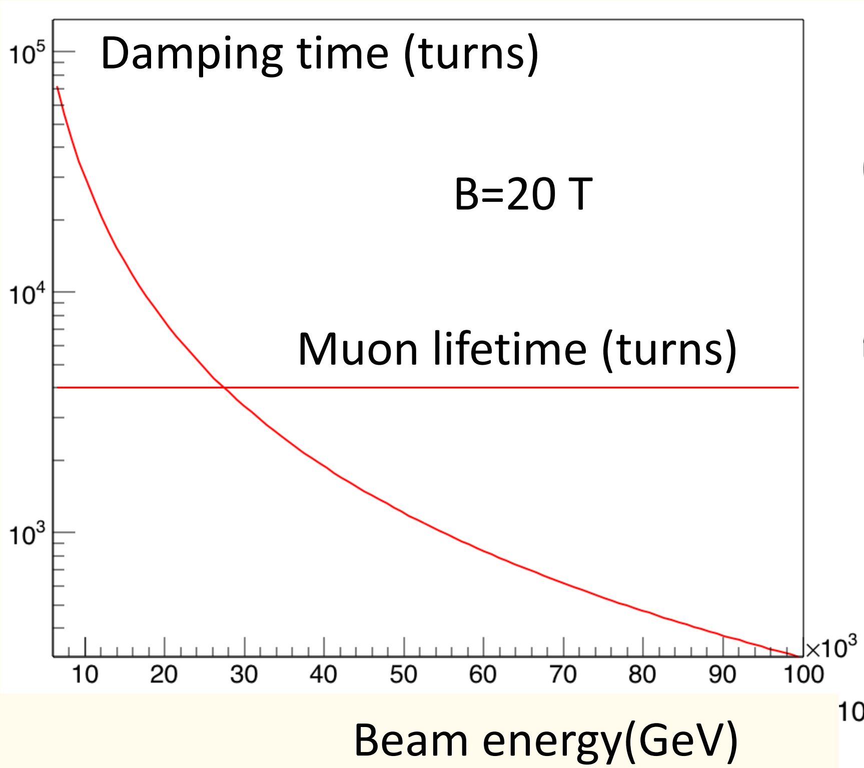
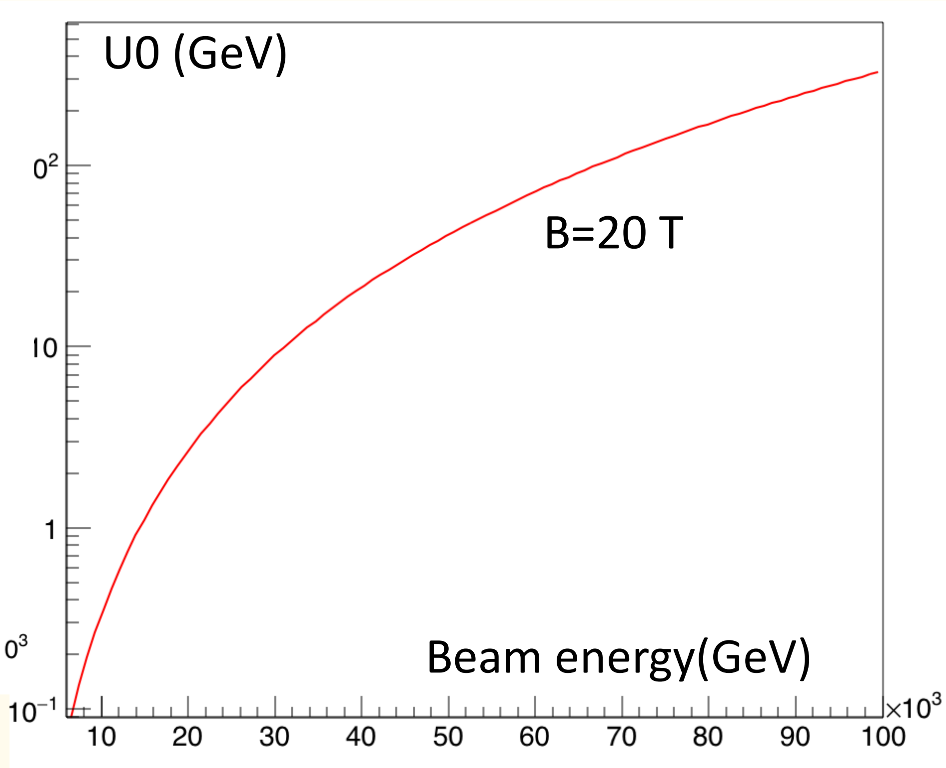
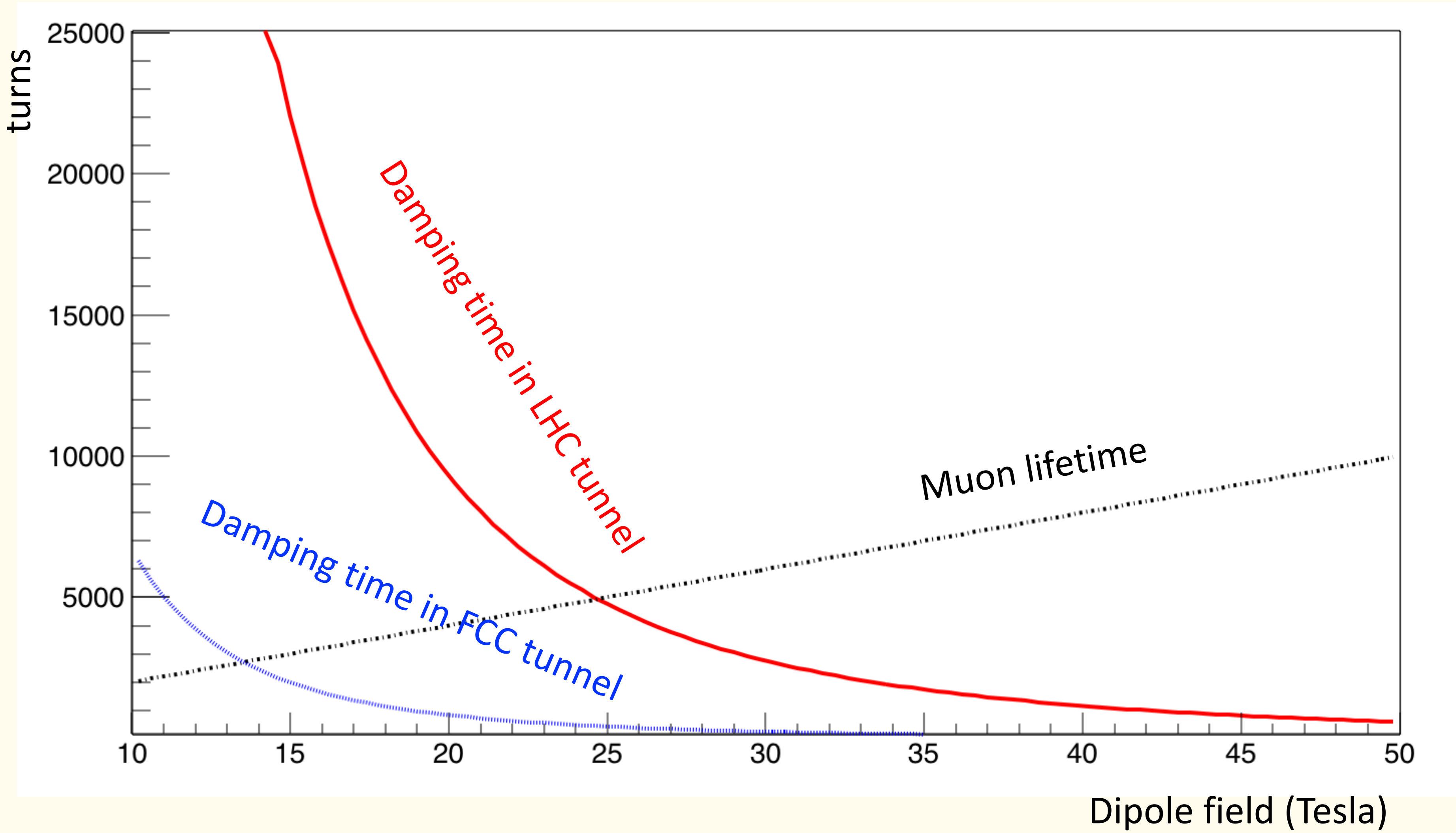


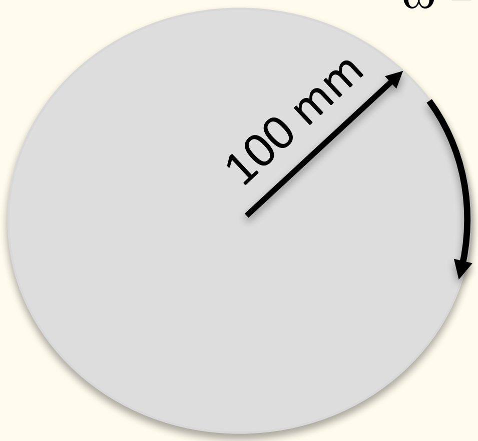


$U_o = 5.5 \times 10^{-18} \gamma^4/\rho$

Damping time & muon lifetime



Solid target



Rotating disc

- 24000 turns/min
- Radial velocity V= 2 π ω(in turns) r=250 m/s

Bunch spacing of ΔT=200ns

- Bunch separation on target L = V ΔT= 50 μm
- 12500 bunches in 1 turn

Cp = 0.97477lnT-3.6687

2D axisymmetric model showing effective total strain

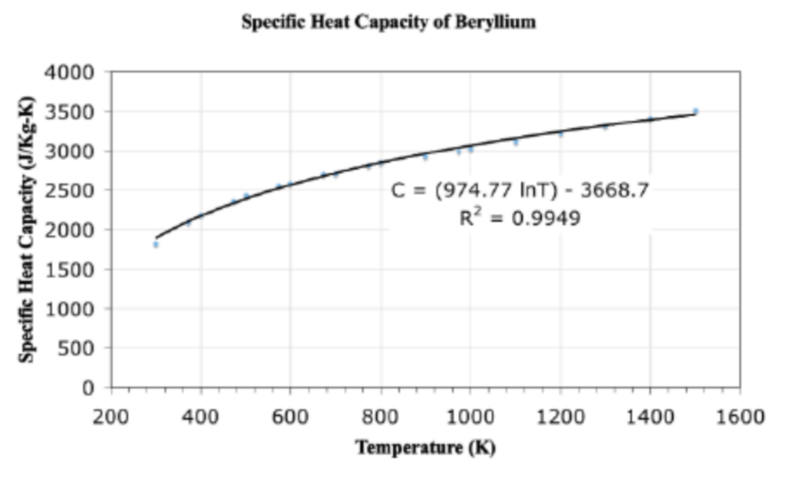
4.9×10^{13} protons, σ = 0.3 mm, $\Delta T \sim 1025$ °C, 0.25 mm thick window

End of beam pulse

$t = 7.2\ \mu s$, $T_{max} \sim 1050$ °C, $\varepsilon_{max} \sim 3.6$ %

- Use 300 µm round e+ beam, 0.25 mm Be target, 5×10^{13} e+/b
- dE/e+ = (2.0 MeV.cm2/g)(1.85 g/cm3)(0.025 cm) = 0.09 MeV/e+
- dE = 5x 10^{13} 0.09 1.6 1.6×10^{-13} j/MeV = 0.74j
- dV = pi (0.025 cm)(0.03 cm)**2 = 7×10^{-5} cm3
  m = dV ρ = 0.00013 g
  Cp = spec. heat Be = 1.8 j/g°C @ 373 K ; C = Cp m = 0.00024
- dT =dE/C = 3083 °C
- Cp = spec. heat Be = 2.8 j/g°C @ 1000 K ; C = Cp m = 0.0005
- dT =dE/C = 2000 °C
- x2 wrt LS-DYNA ?

- Scale for n= 3 x 10^{11}
- $(300\mu m)^2/200=(21\mu m)^2$



Solid target

- Use 5 µm round e+ beam, 0.3 cm Be target, 3 x 10^{11} e+/b

Cp = 0.97477lnT-3.6687

Dq = Cp DV ρ dT

Q = DV ρ [(0.97477 T(lnT-1) - 3.6687 T) - 0.97477 x 373(ln373-1) - 3.6687 x 373)]