Low Emittance Muon Collider (LEMMA)

M. Antonelli (INFN-LNF)

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→ $\pi/K \to \mu$
typically **$P_\mu \approx$ 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 $N_\mu = 2\cdot10^{12}$/bunch

MAP

Positron driven

from **direct μ pair production**:
muons produced from **$e^+e^-\to\mu^+\mu^-$** at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold
($\sqrt{s} \approx$ 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 $N_\mu \approx 6\cdot10^9$/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

Muon source Comparison

	Physical process	**Rate μ/s**	**normalized emittance e_N [μm-rad]**
e+ on target	**e+e-→ μ+μ-**	**0.9×10^{11}**	**0.04**
Protons on target	p N→ πX, kX→ μ X’	10^{13}	25
Compton γ on target	γ N→ μ+μ- N	5×10^{10}	2

Exploring the potential for a
Low Emittance Muon Collider

some <u>References:</u>

- M. Boscolo *et al.*, **"***Studies of a scheme for low emittance muon beam production from positrons on target", ***IPAC17 (2017)***
- M.Antonelli, *"Very Low Emittance Muon Beam using Positron Beam on Target"*, **ICHEP (2016)**
- M.Antonelli *et al.* , *"Very Low Emittance Muon Beam using Positron Beam on Target"*, **IPAC (2016)**
- M. Antonelli, *"Performance estimate of a FCC-ee-based muon collider"*, **FCC-WEEK 2016**
- M. Antonelli, *"Low-emittance muon collider from positrons on target"*, **FCC-WEEK 2016**
- M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, *"Novel proposal for a low emittance muon beam using positron beam on target"*, **NIM A 807 101-107 (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 by SLAC team:

L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:

- *"Luminosity Estimate in a Multi-TeV Muon Collider using $e^+e^- \rightarrow \mu^+\mu^-$ as the Muon Source"*, MAP 2014 Spring workshop, Fermilab (USA) May '14
- Advanced Accelerator Concepts Workshop, San Jose (USA), July '14

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 $e^+e^- \rightarrow \mu^+\mu^-$

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

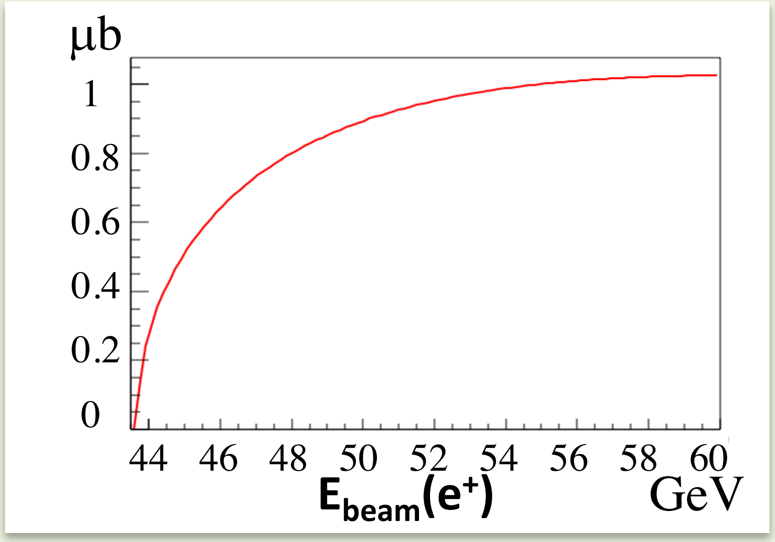
$\sigma(e^+e^-\rightarrow\mu^+\mu^-) \approx$ **1 μb** at most wrt σ(from p)$\approx$ **mb**

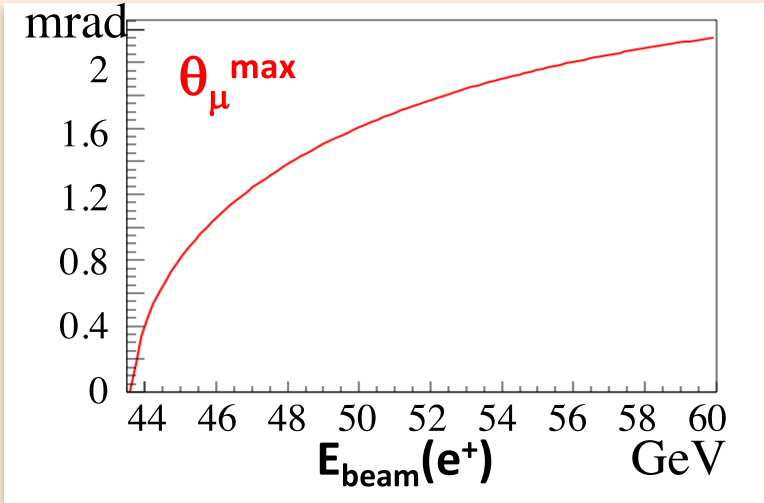
Pro LEMMA:

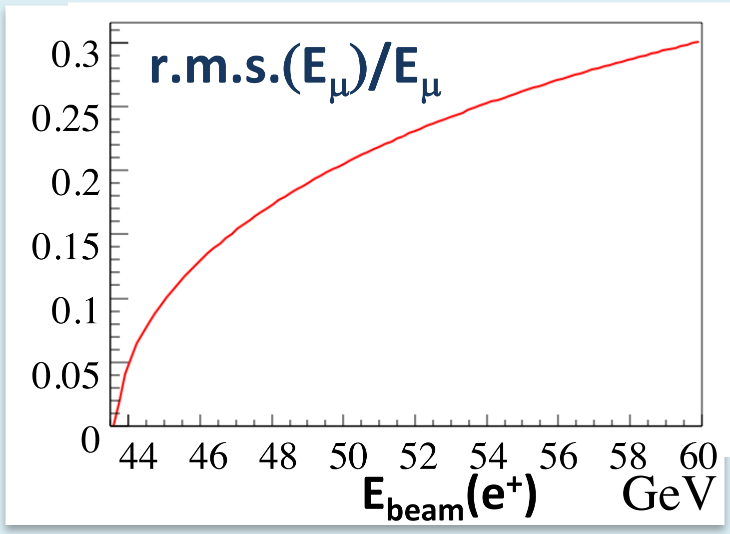
- Reduced losses from decay: **high collection efficiency**
- Low background: **Luminosity at low emittance will allow low background and low neutrino radiation → easier experimental conditions & can go to higher energies**
- Energy spread: muon energy spread might be **also small at threshold**, it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

Cross-section, muons beam divergence and energy spread as a function of the e+ beam energy

$\sigma(e^+e^- \rightarrow \mu^+\mu^-)$







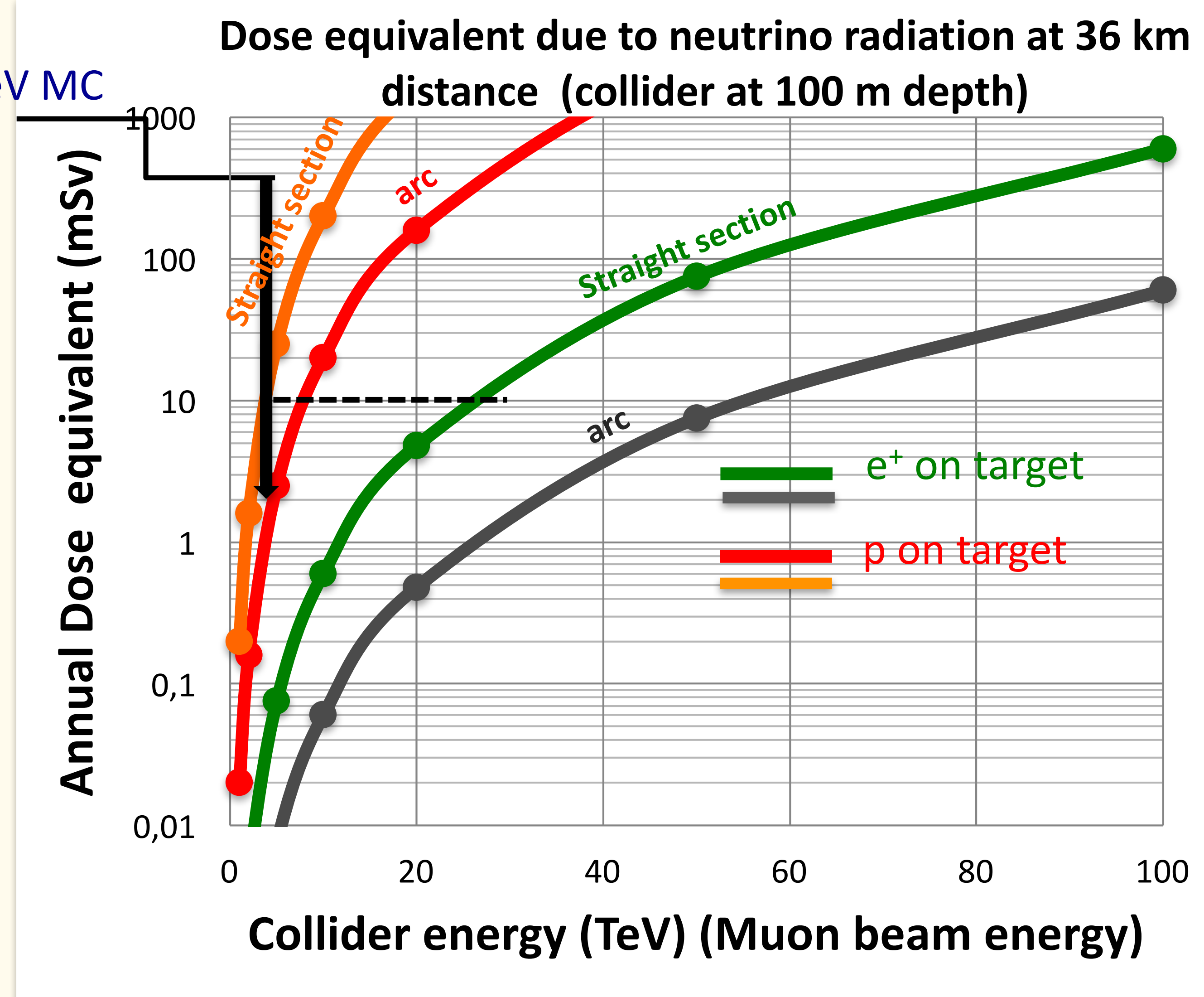
The value of sqrt(s) (*i.e.* $E(e^+)$ for atomic e^- in target) has to maximize the muons production and minimize the beam angular divergence and energy spread

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
$3 \times 10^{13}\ \mu/s$
e^+ on target option
$9 \times 10^{10}\ \mu/s$



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

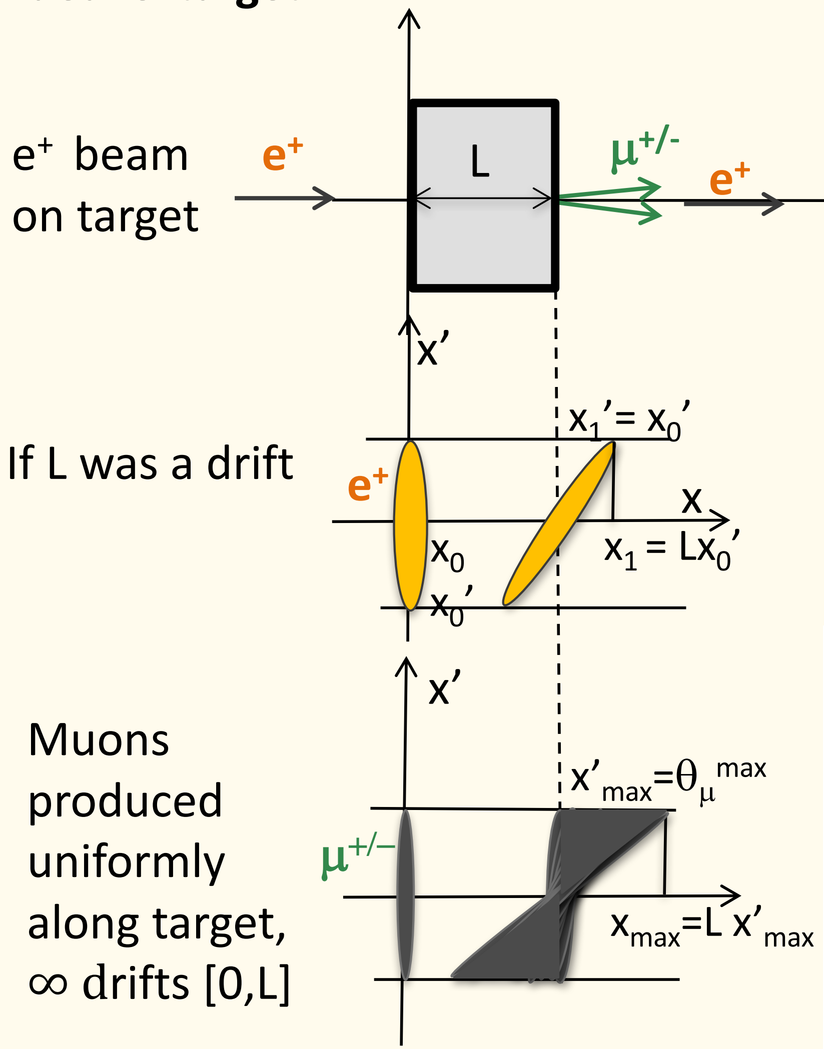
Possible Schemes

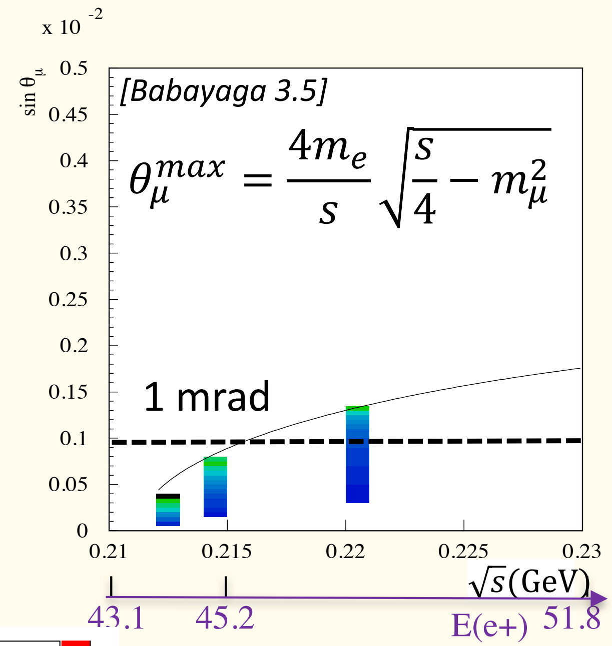
- **Low energy collider with e^+/e^- beam (e$^+$ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity $\approx 10^{40}$ is beyond present capability)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^3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

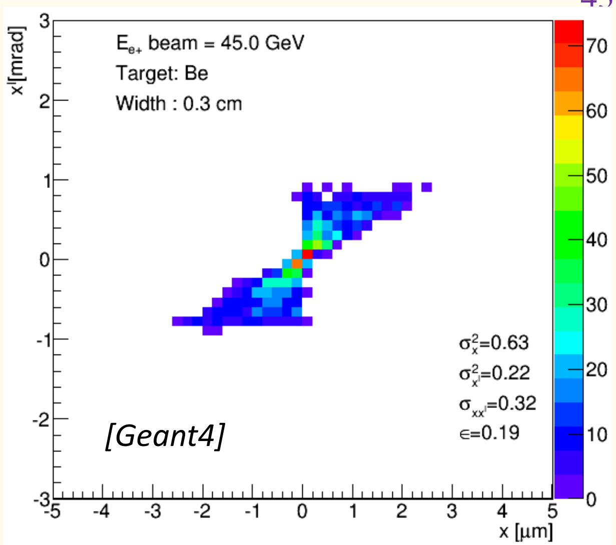
Ideally muons will *copy* the positron beam

Production contribution to μ beam emittance

ideal e^- target







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

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

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

$N(e^+)$ 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 $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \longrightarrow \mu^+\mu^-)/\sigma_{brem}$

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**
  - **minimize emittance** (enters linearly) → Copper has about same contributions to emittance from MS and $\mu^{+}\mu^{-}$ production
  - high e^{+} loss, Bremsstrahlung is dominant, **not optimal μ rate**
- **Very light materials**
  - **maximize conversion efficiency** (enters quad) → H_2
  - even for liquid need O(1m) target, $\varepsilon_{\mu} \propto L$ → **μ emittance increase**
- **Not too heavy materials (Be, C)**
  - Allow **low emittance with small e^{+} loss**

optimal: not too heavy and thin

Criteria for target design

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

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

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

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

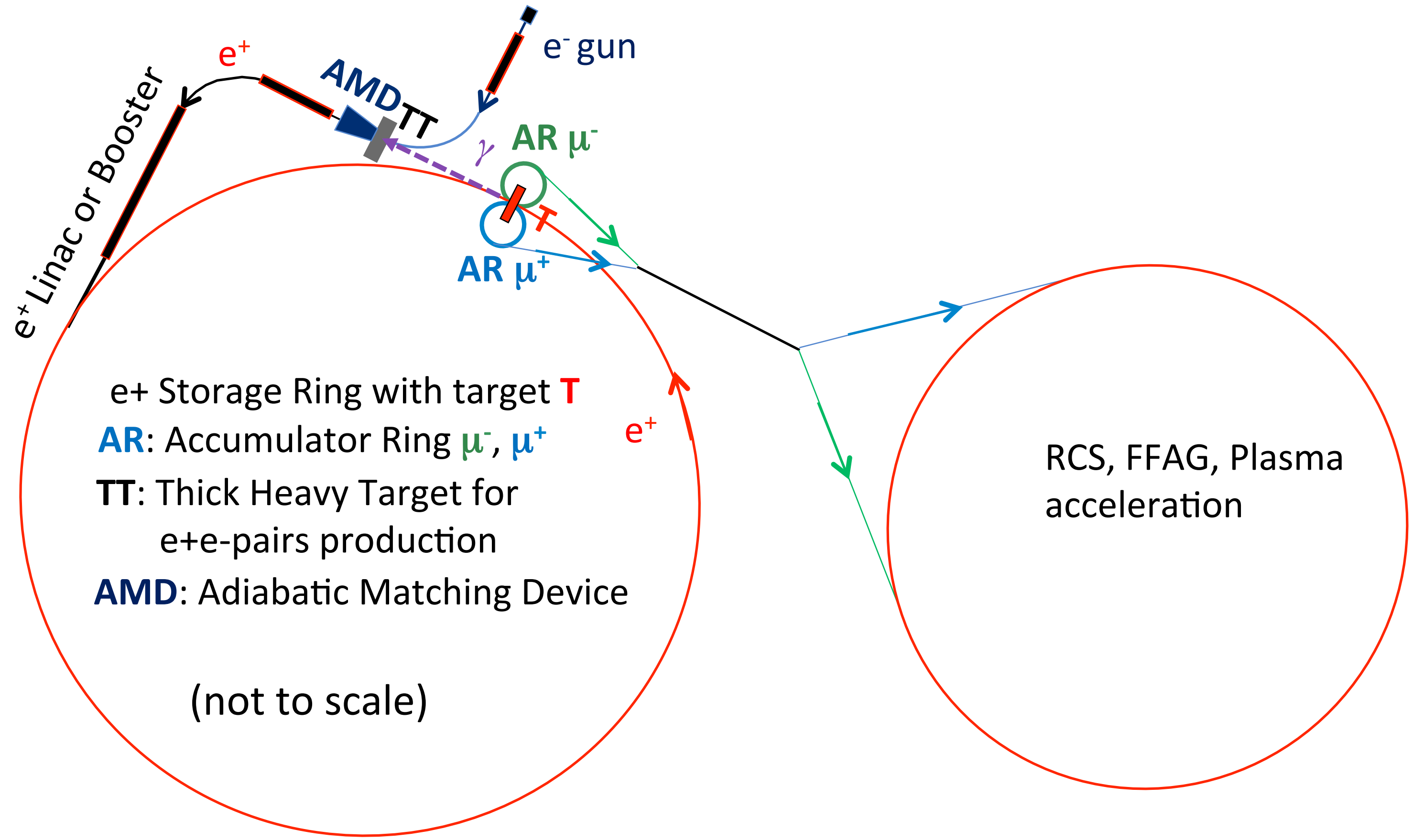
- **Very light materials, thick target**
  - **maximize $\mu^+\mu^-$ conversion efficiency $\approx 10^{-5}$** (enters quad) $\rightarrow$ H_2

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

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

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

LEMMA scheme



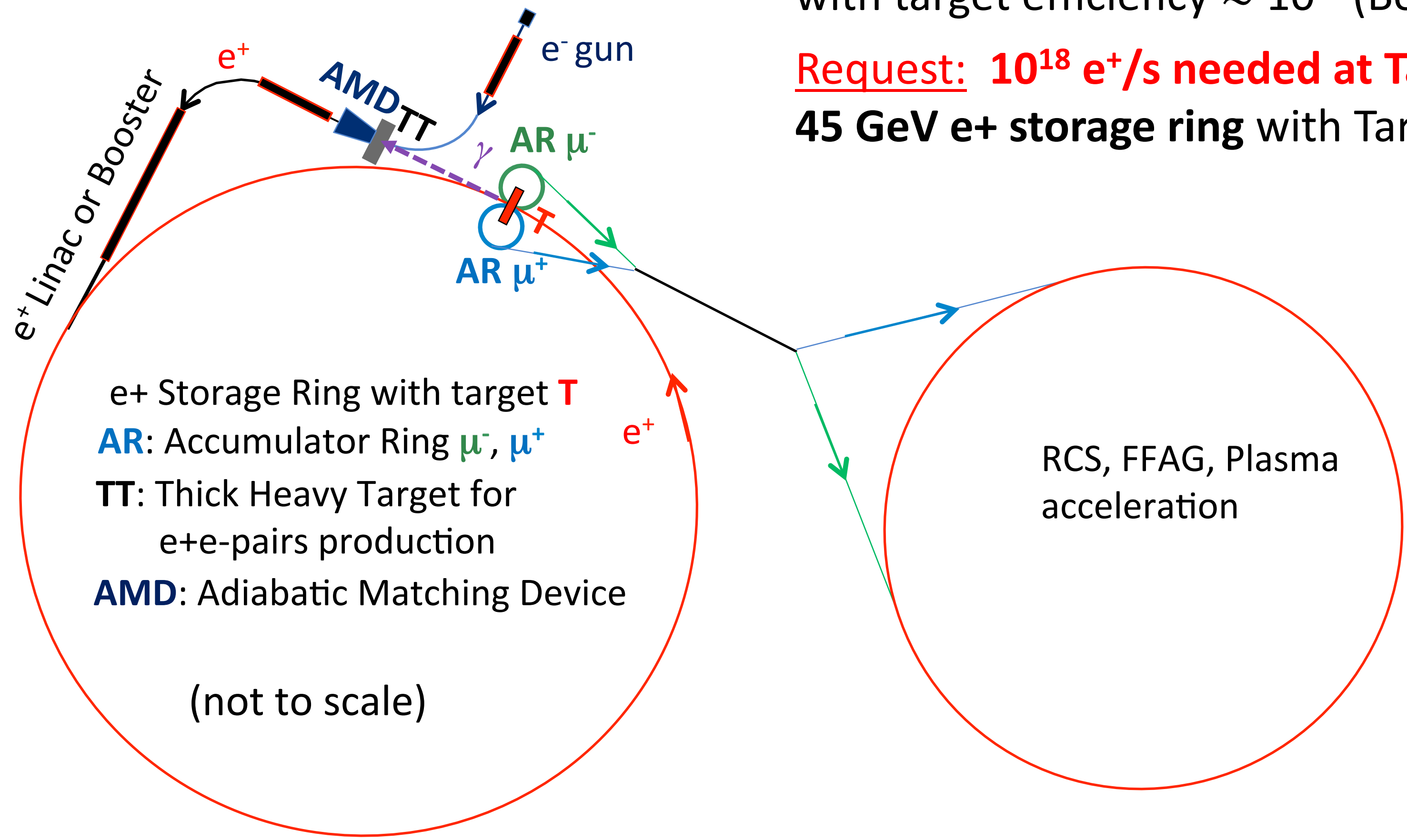
LEMMA scheme

Goal: $\approx$ **10^{11} μ/s** produced at Target

with target efficiency $\approx 10^{-7}$ (Be 3mm)

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

45 GeV e+ storage ring with Target insertion



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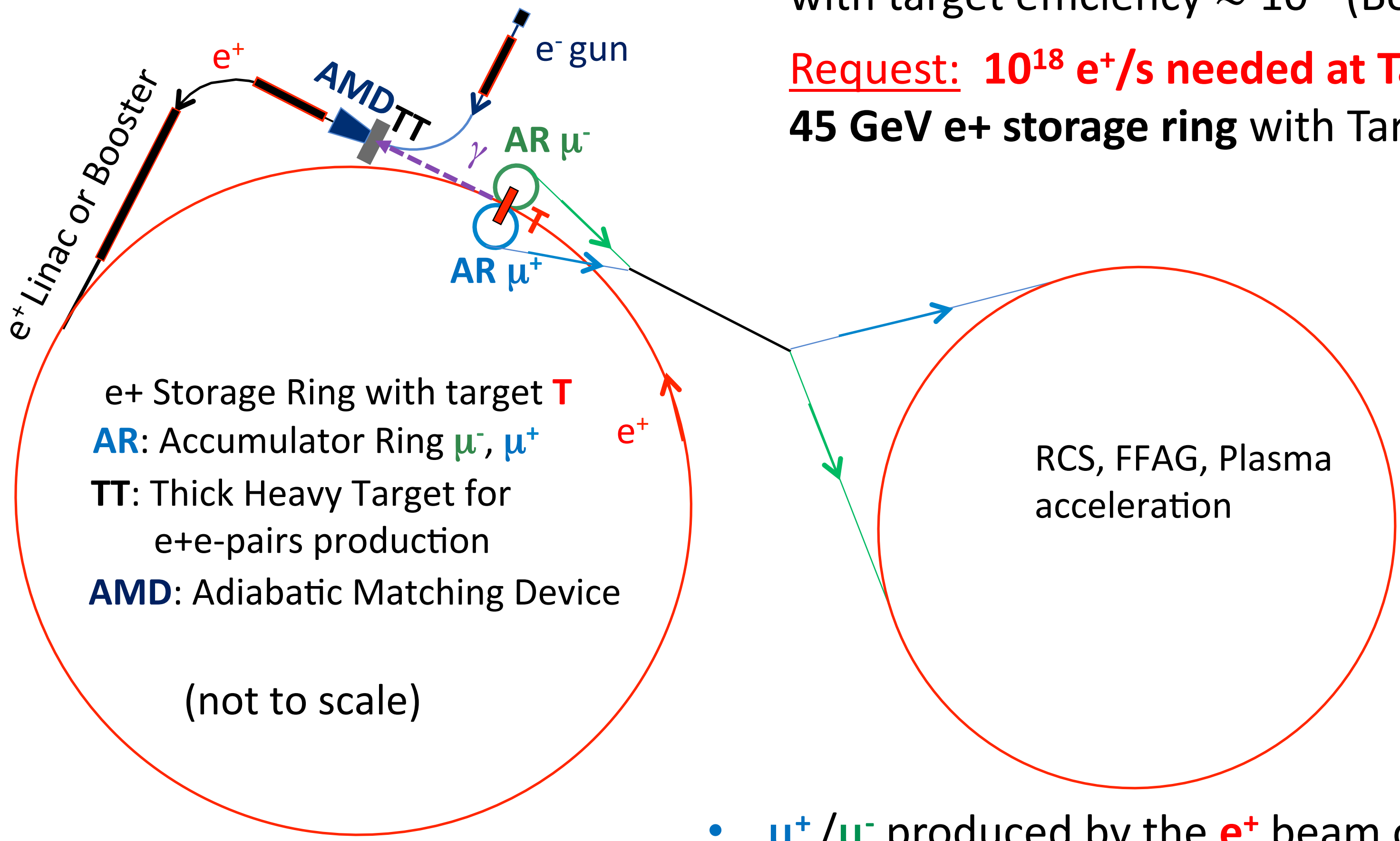
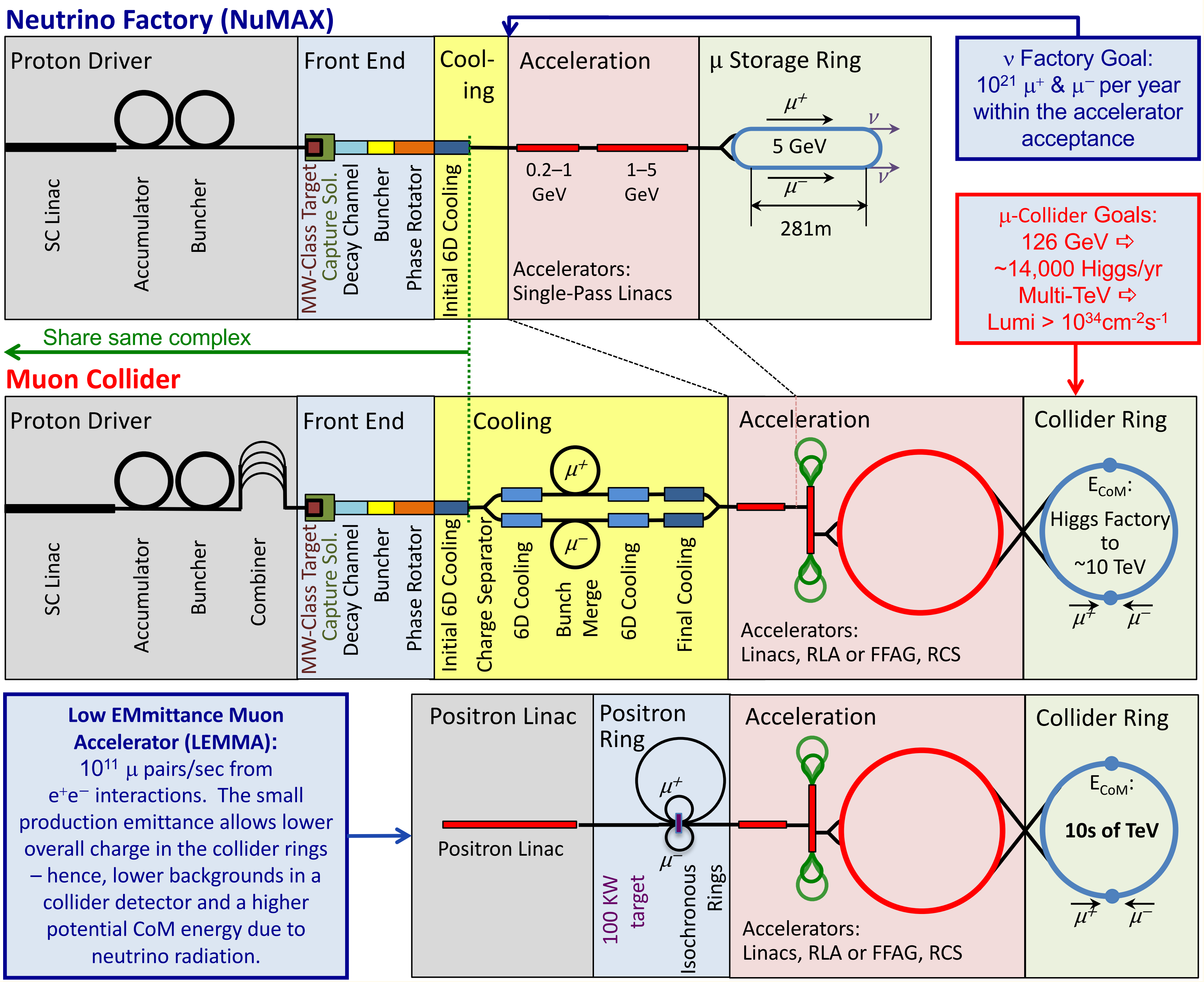


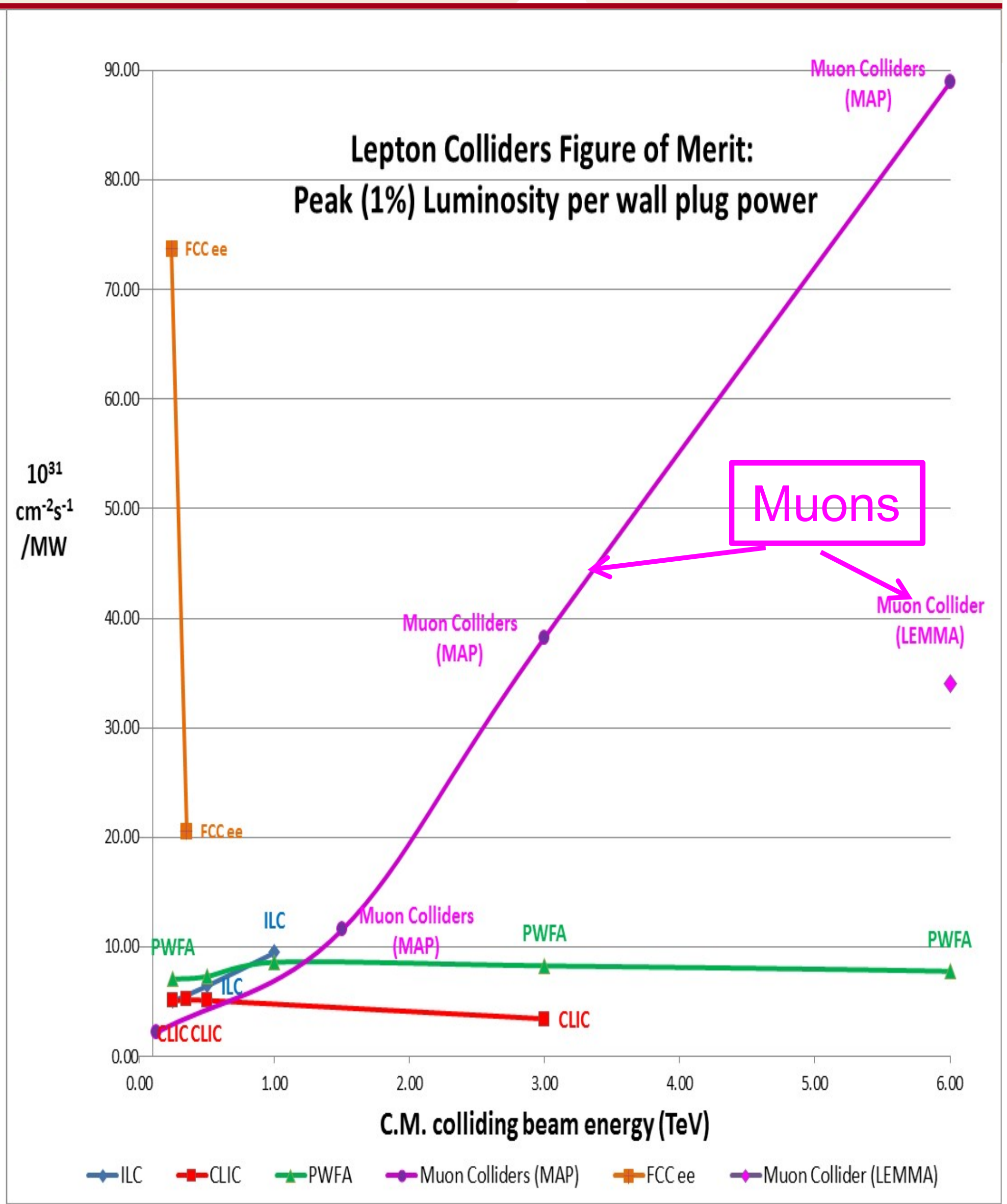
- μ^+/μ^- produced by the e^+ beam on target **T** at about **22 GeV** → $\tau_{lab}(\mu) \approx$ **500μs** ($\gamma(\mu) \approx 200$)
- Accumulator Rings (**AR**) isochronous with high momentum acceptance, they recombine μ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns
- fast acceleration and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

from μ^+ μ^- production to collider



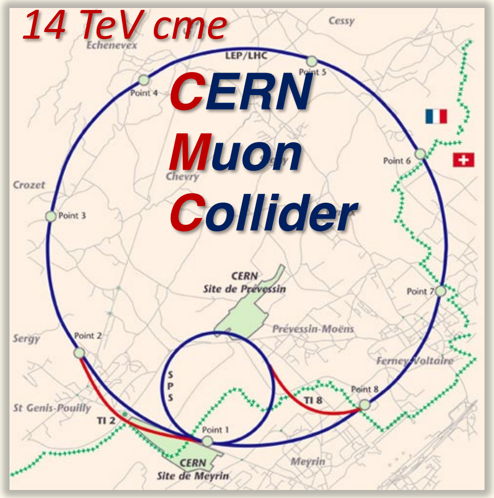
http://arxiv.org/abs/1808.01858

Figure of merit: Luminosity per wall plug power

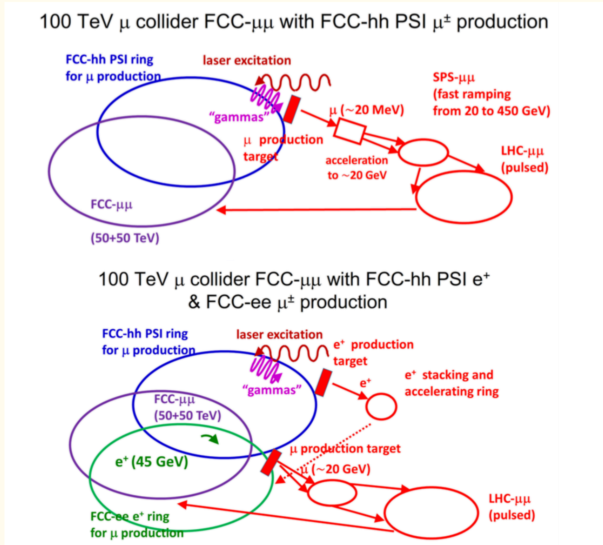


LEMMA concept and MC prospects

- 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

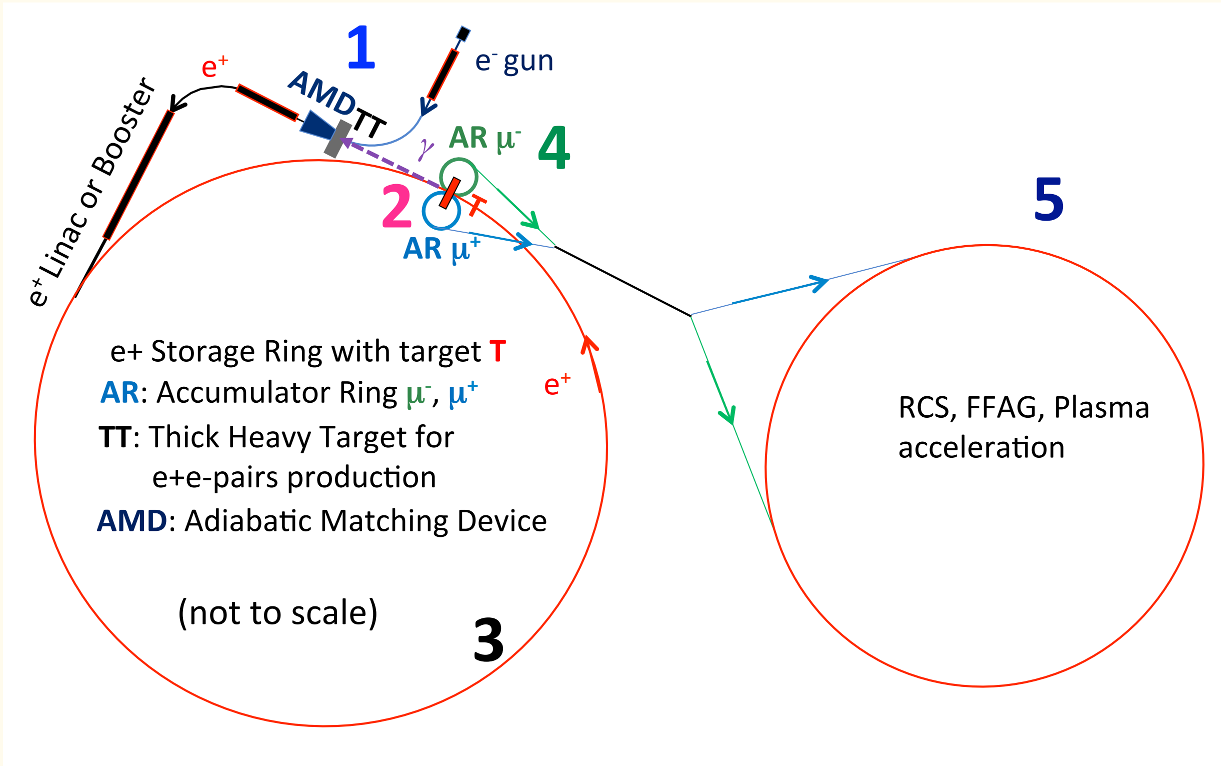
- **Our goal is to define the potentiality of this concept for a multi-TeV MC:**
  - **in terms of luminosity and beam power**
  - **design the optics for the accelerator complex**
  - **identify and possibly start with the necessary key R&D**

- **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**

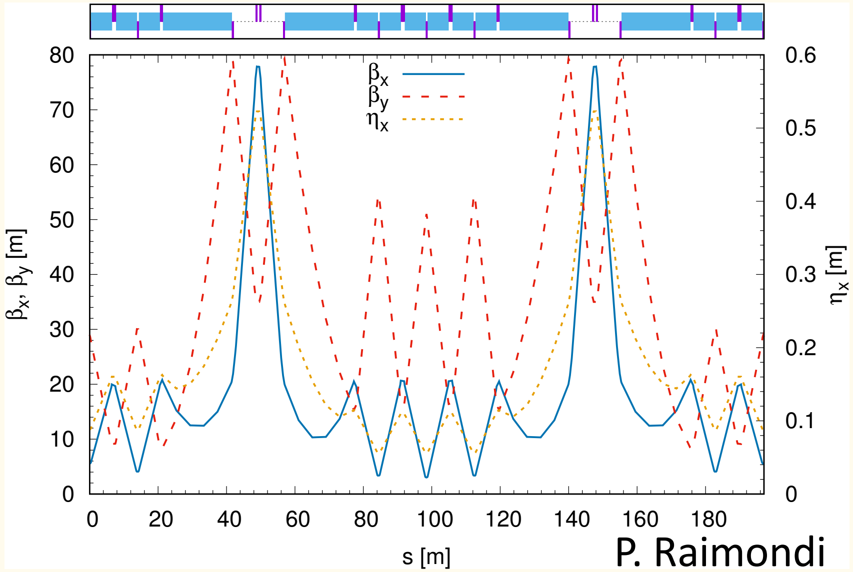
All require R&D study and present challenges



Optics design positron ring

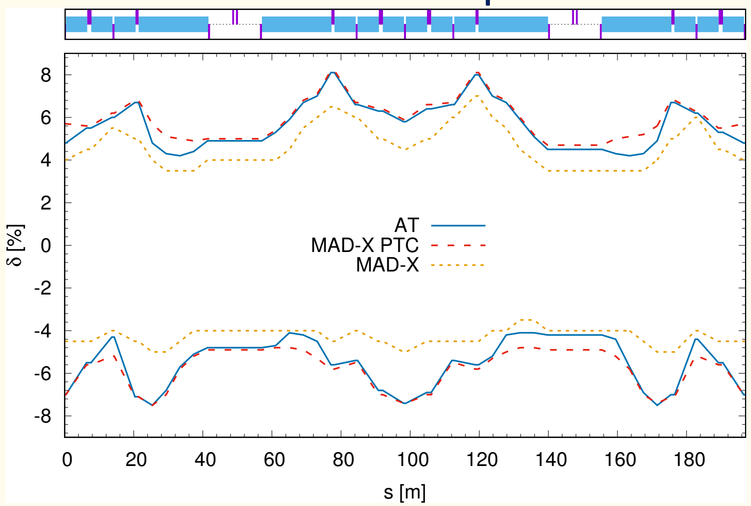
e+ ring parameter	unit	MAP option	LHC tunnel
Energy	**GeV**	**45**	**45**
Circumference	**km**	**6.3**	**27**
No.part./bunch	**#**	**$3 \cdot 10^{11}$**	
bunches	#	100	
e^+ bunch spacing = T_{rev} (AR)	ns	200	
Beam current	mA	240	
Emittance	nm	6	0.7
U_0	GeV	0.51	0.12
SR power	**MW**	**120**	**29**

Cell based on the Hybrid Multi Bend Achromat



P. Raimondi

momentum acceptance



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

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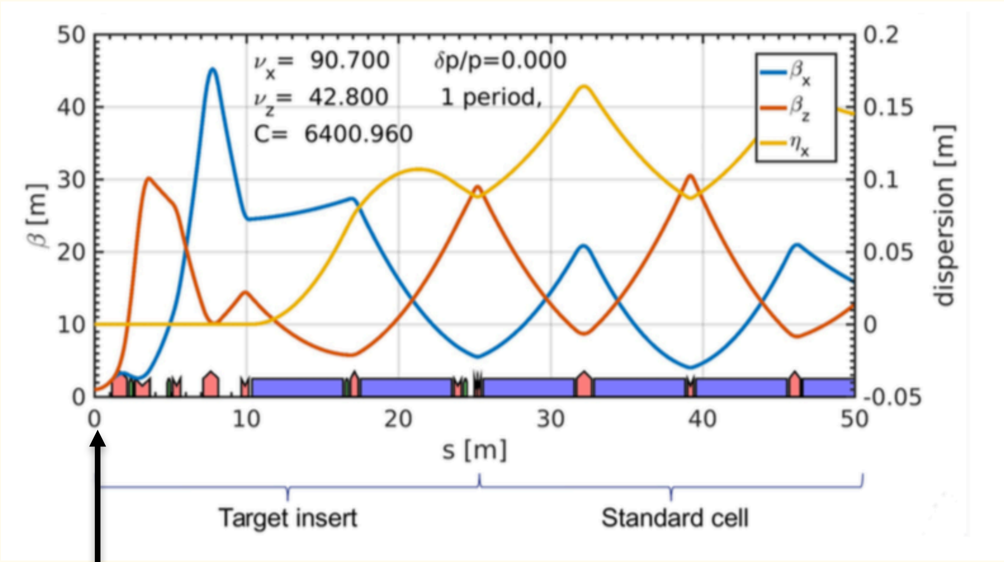
Target Insertion Region



@target { $D_x \approx 0$; low-β ($\beta_{x,y}$ =0.5 m) }

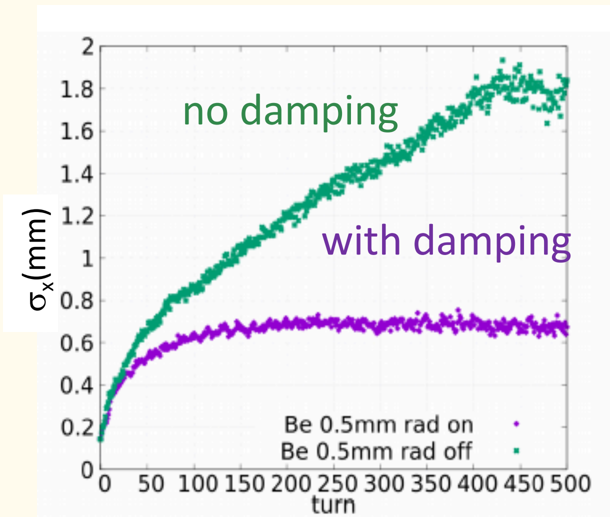
S. Liuzzo, Padova workshop, 2-3 July 2018

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

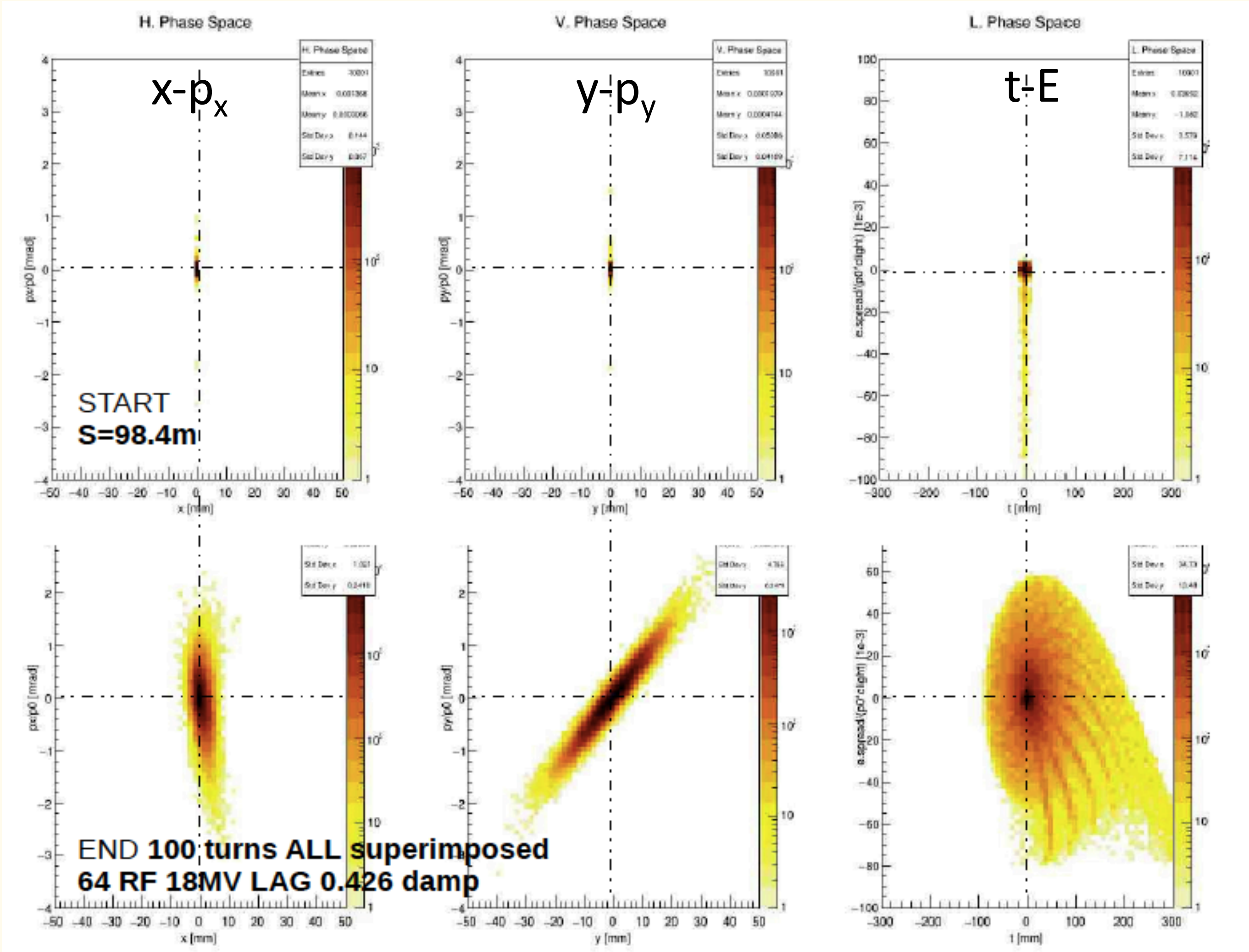
At each pass through the muon target the e+ beam

- 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)



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

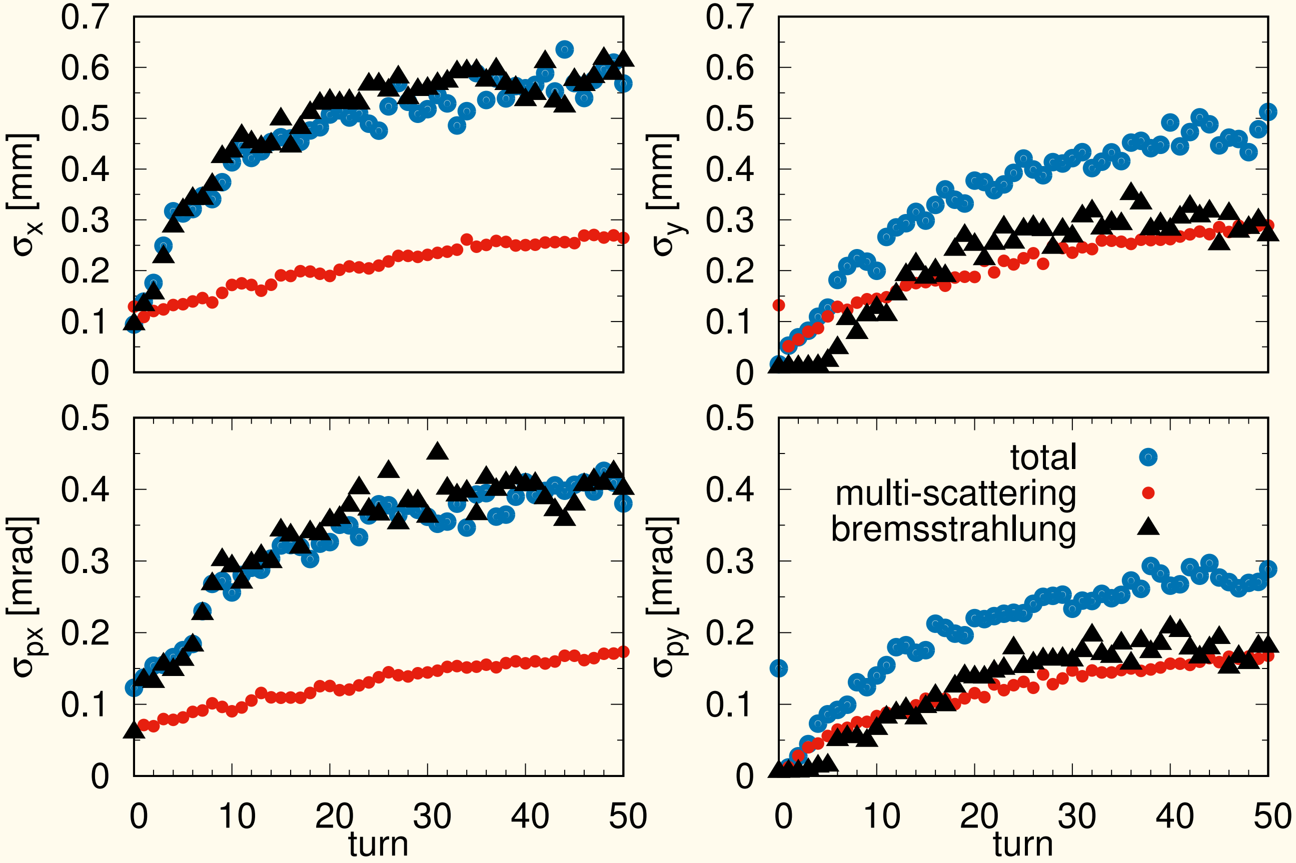
before target,
starting point



MAD-X PTC & GEANT4 6-D tracking simulation of
e+ beam with 3 mm Be target along the ring (not at IR center in this example)

Evolution of e+ beam size and divergence

3mm Be Target (0.8% Xo) at center of IR



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: $\sigma'_{MS} = 25\ \mu rad$

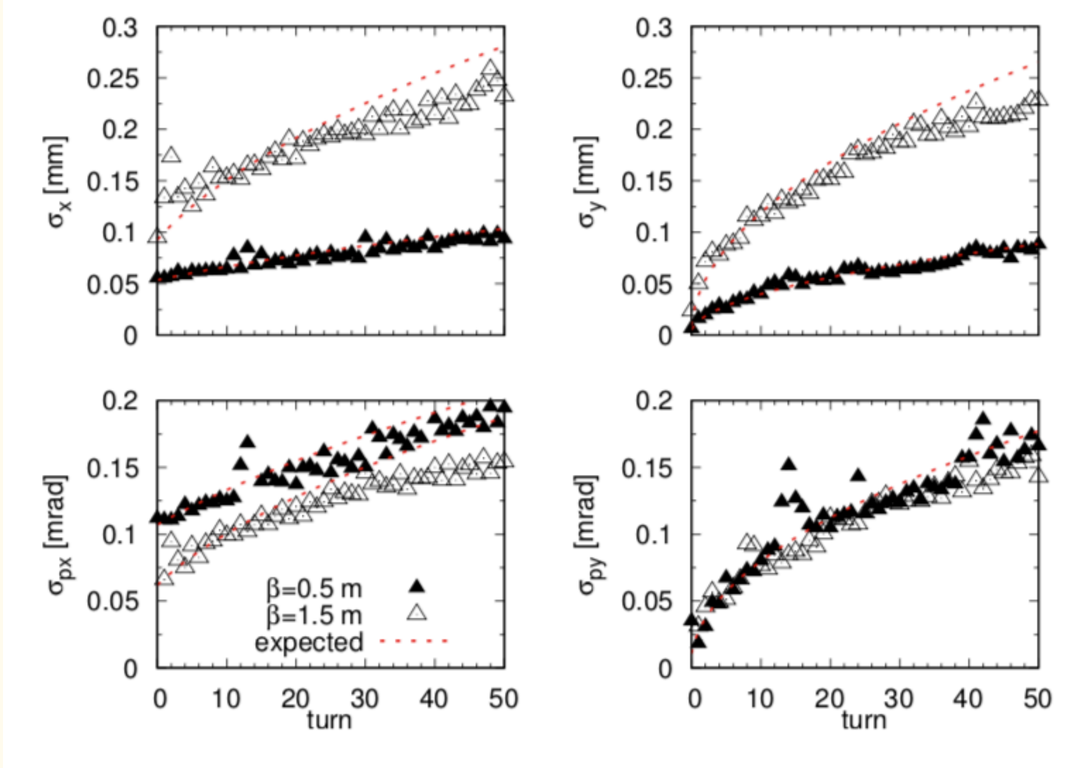
n_D number of damping turns

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

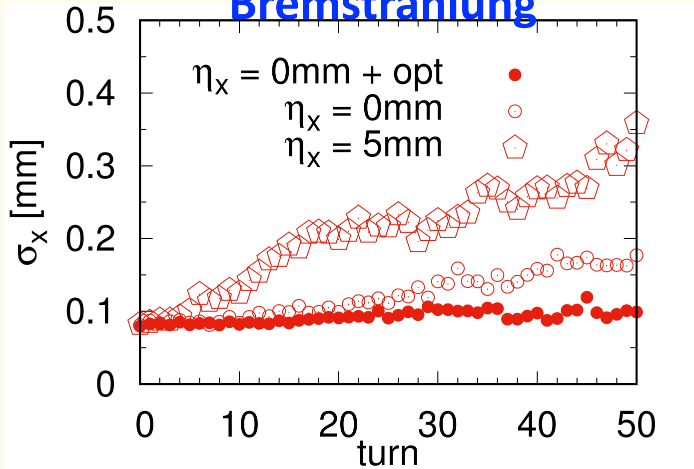
More details in: PR-AB 21, 061005 (2018)

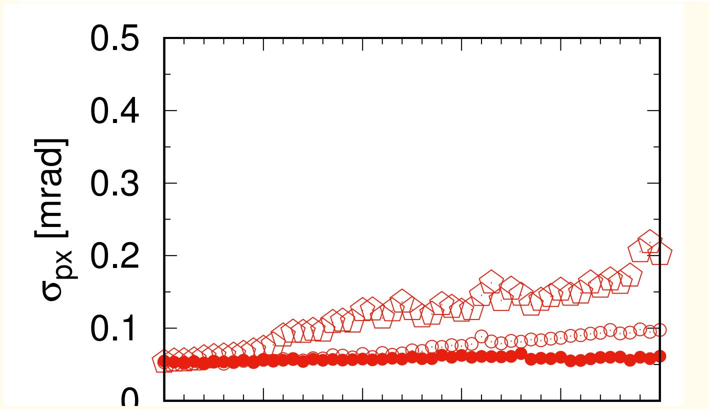
e^+ emittance growth controlled with proper β and D values @ target

Multiple scattering



Bremstrahlung





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

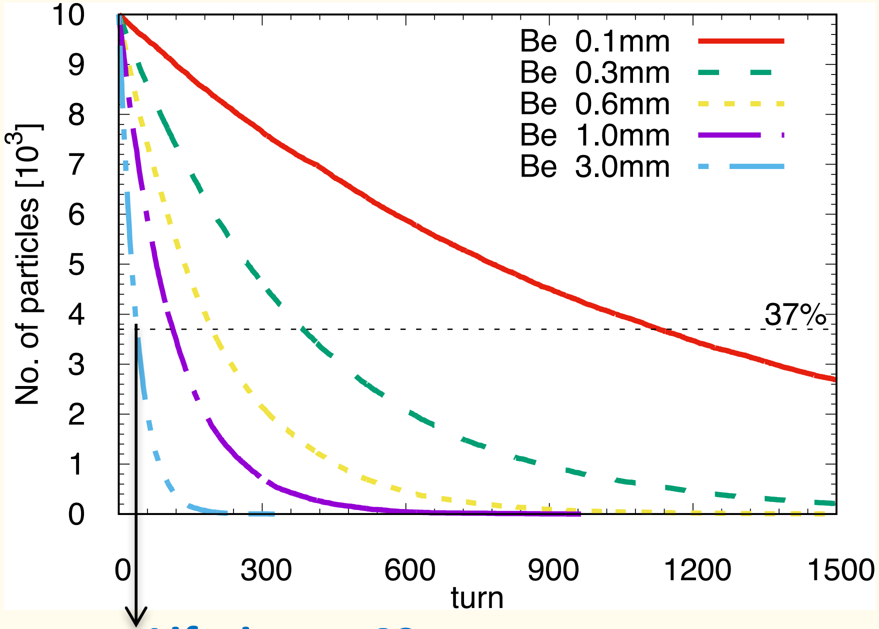
@Target :
linear and non-linear terms
of horizontal dispersion η_x =0

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

More details in:
Arxiv. 1803.06696

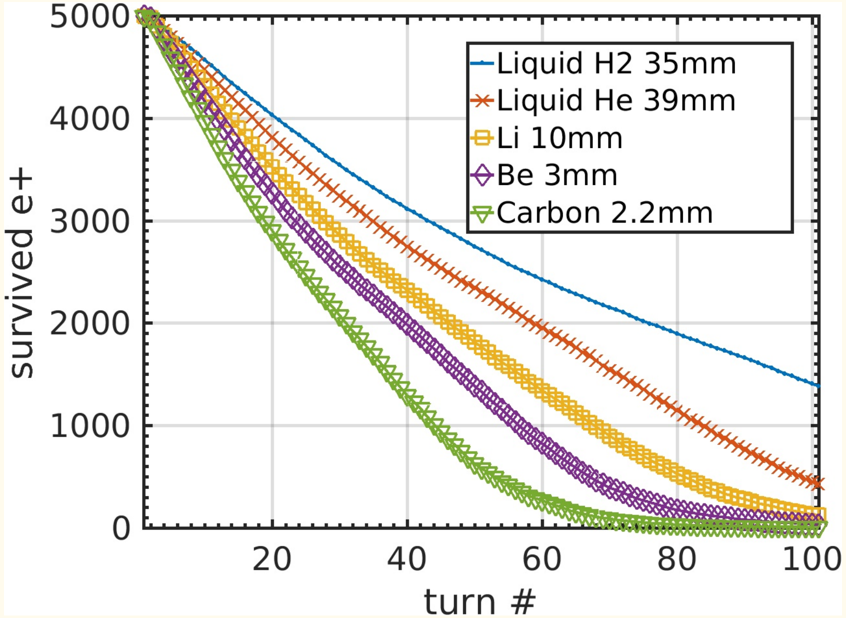
Particle tracking with: MADX/ PTC/GEANT4/FLUKA & Accelerator Toolbox/G4-Beamline

Lifetime ∝ 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

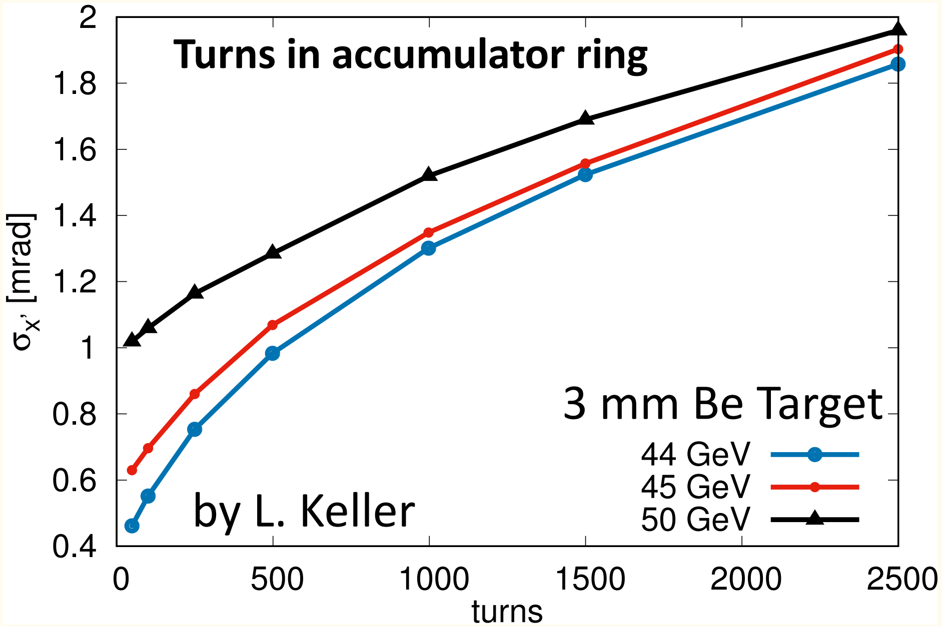


Number of e+ vs turns for different target materials.
Target thickness gives constant muon yield.

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

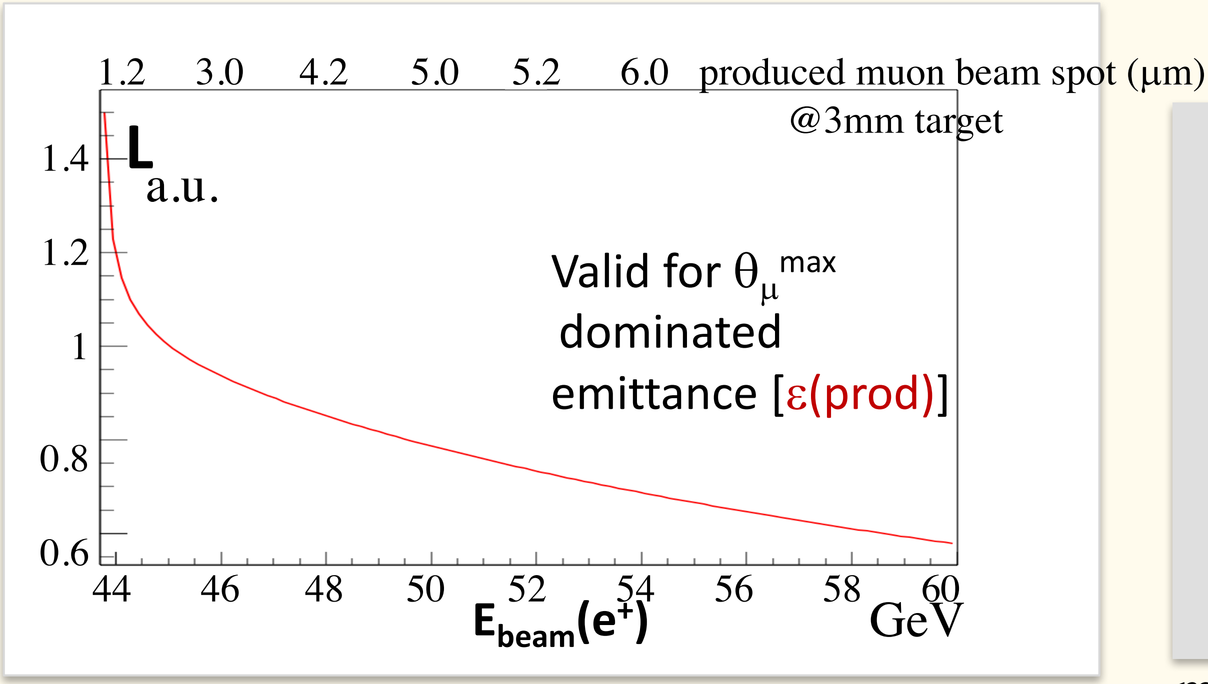
Proc. of IPAC18, Vancouver, MOPMF087

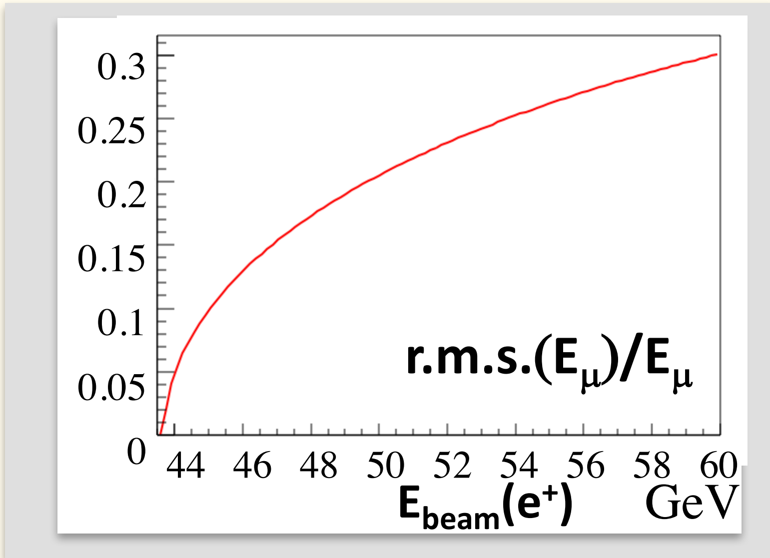
All these values need to be matched to minimize emittance growth
due to beam filamentation.

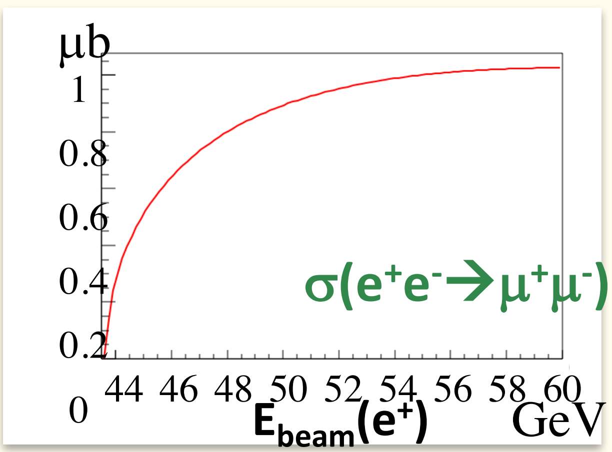
σ_x and $\sigma_{x'}$ and correlations of e^+ and μ beams have to be similar

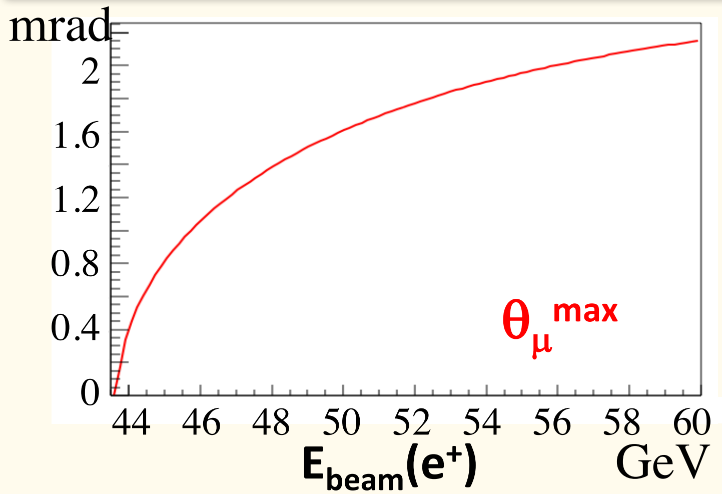
Luminosity of $\mu^+\mu^-$ Collider vs e^+ beam energy

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:







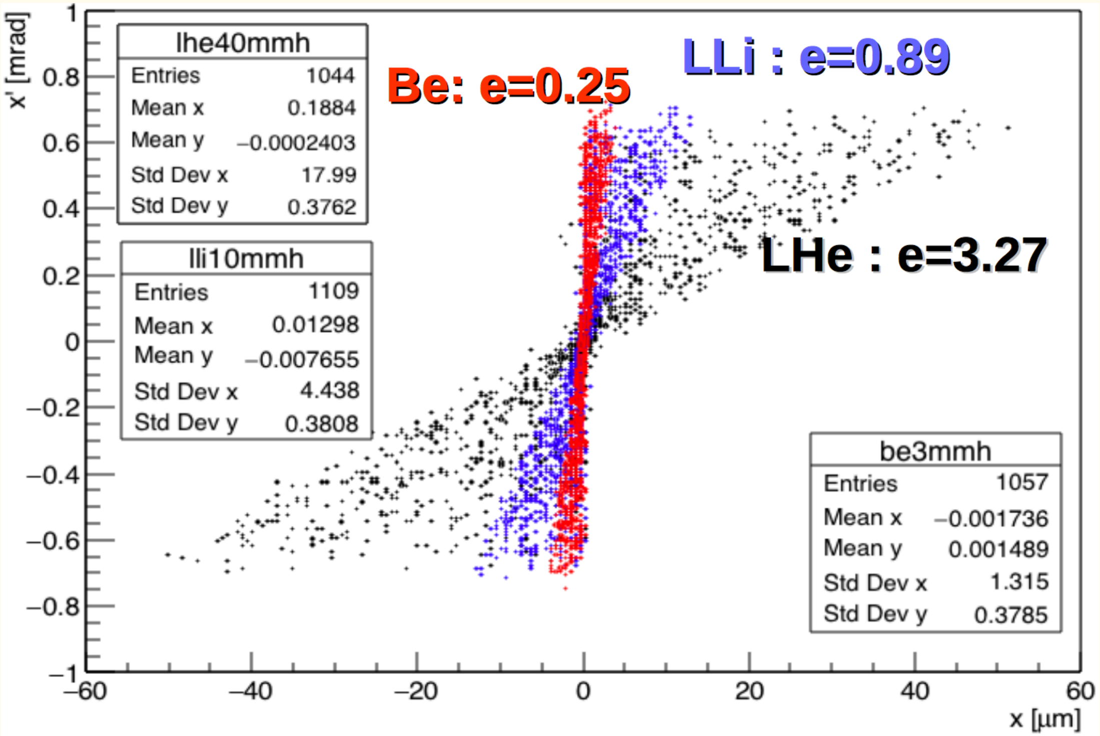


Going to lighter targets for μ production

Be Beryllium

LLi Liquid Lithium, might be a good option (Proposed/tested for targets for n production)

LHe Liquid Helium



also test different material

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

also gain in lifetime & target power removal

e = muon emittance at production [10^{-9}m-rad]

$E(e^+)$=45 GeV

Look to light liquid targets to reduce problems of thermo-mechanical stresses

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

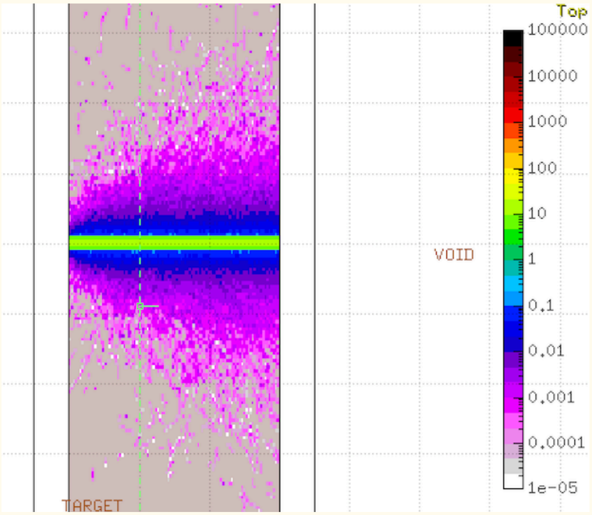
- **Solid target**: simpler and better wrt temperature rise
  - Be, C

  Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, N=1.7x10^{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 (3×10^{11} e^+) transverse size on the 10 μm scale: rescaled from test at HiRadMat (5×10^{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

Positron sources: studies on the market

- 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]

	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
$e^+[10^{14}\text{s}^{-1}]$	0.06	1.1	3.9	18	440

➢ This is a key issue to be studied

Example of Positron Source for CLIC

[L.Rinolfi *et al.* NIM B **309** (2013)50-55]

The target represented on the figure is a conventional one.

It would be also possible to have an *hybrid positron source* using a crystal providing channeling radiation and an amorphous converter for photon conversion into e+e- pairs

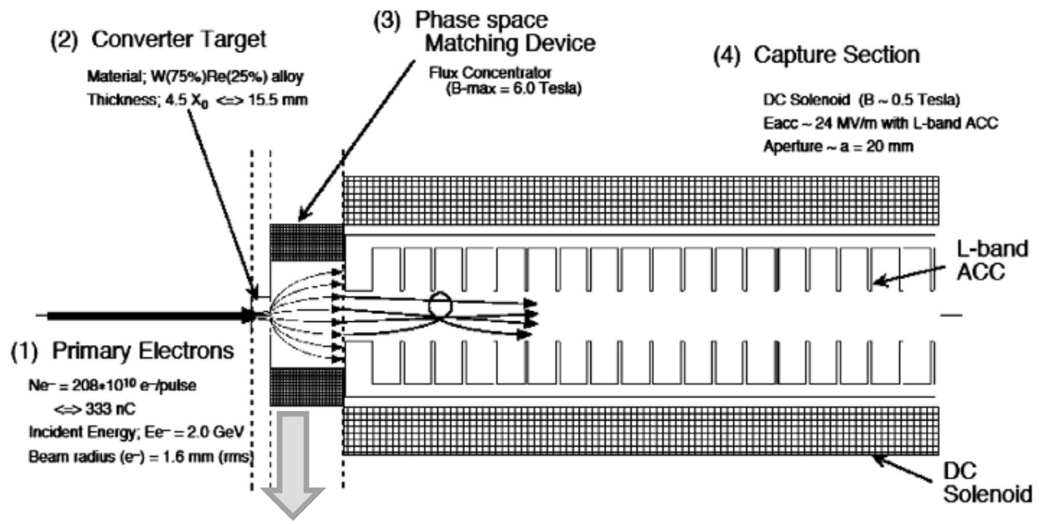
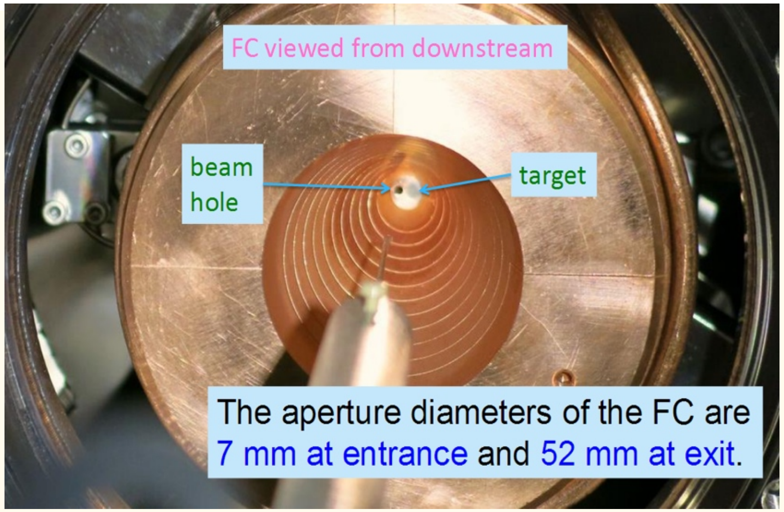


Fig. 2. Layout of the CLIC e⁺ source with a single target.



Flux concentrated used for the Adiabatic Matching Device
(from T.Kamitani, LCWS-2014,Belgrade)

FOCUSING SYSTEMS FOR POSITRON BEAMS

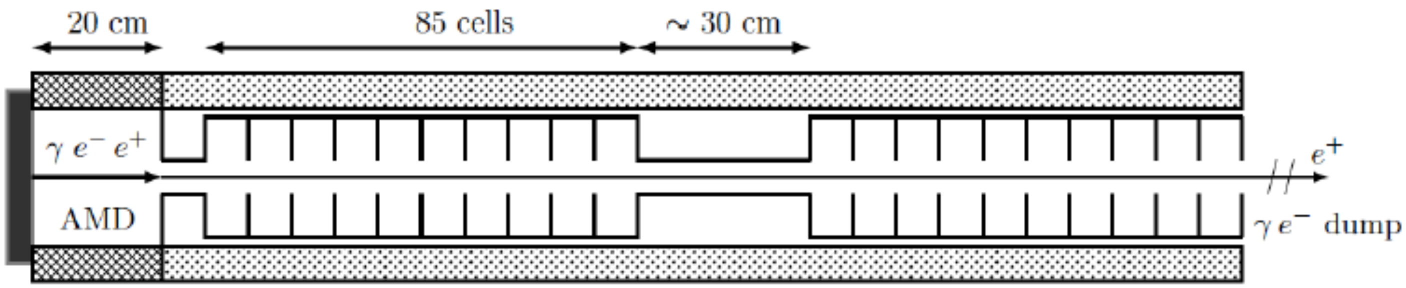
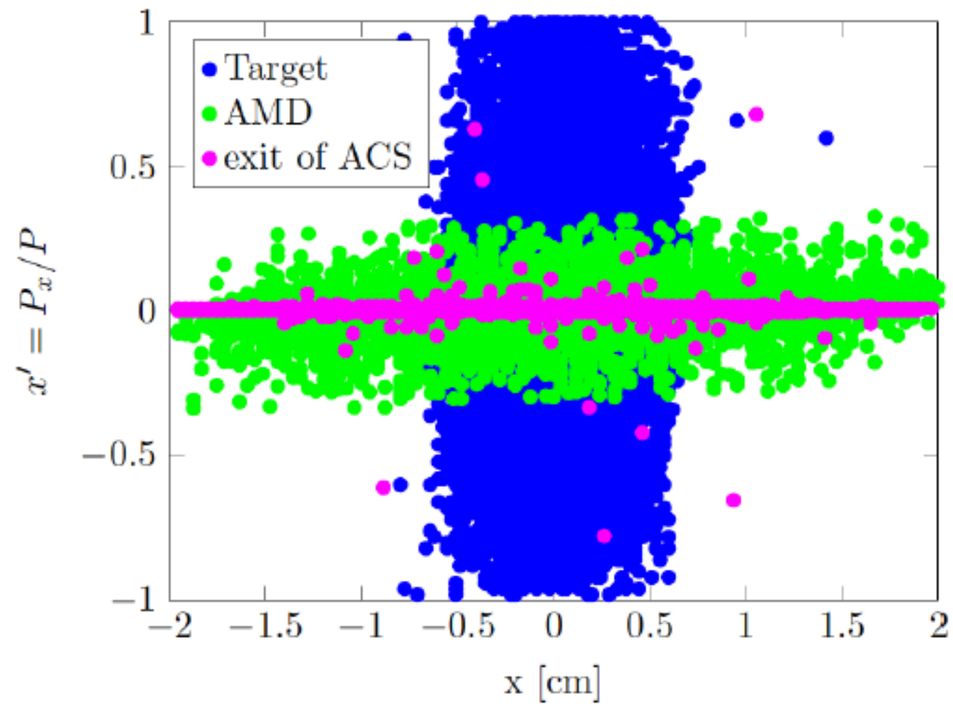


Figure 4.7: A fundamental scheme of the positron capture and primary acel-erattion - A capture section based on the AMD followed by a pre-injector linac is used to capture and accelerate the positron beam up to the ~200 MeV.



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**

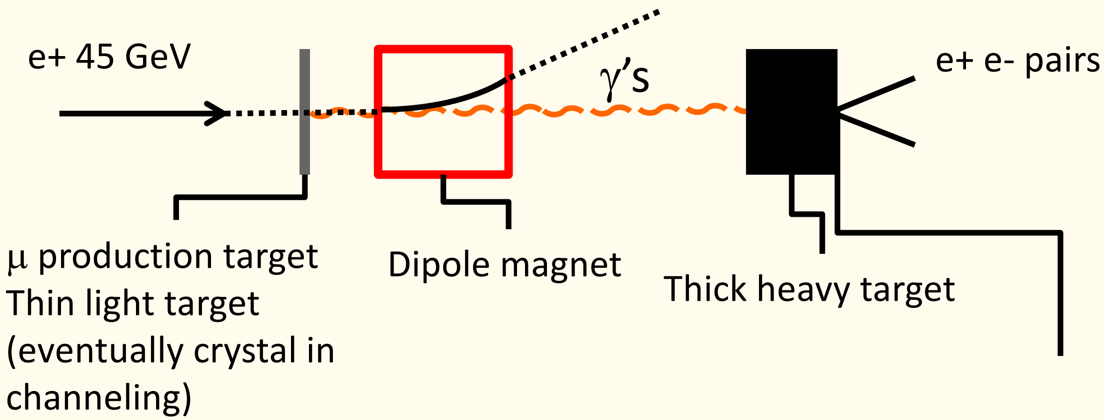
Present: 3 mm Be, 40 turns lifetime(DP/P<6%), ΔN/N=2.5%, P= 247 MW
35 mm LH2, 100 turns lifetime(DP/P<6%), ΔN/N=1%, P= 98 MW

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

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** **$6x10^9$:** a muon bunch charge of $4.5x10^7$ 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 high field quads have to be used.

Experimental Tests

Test @CERN

Experiments in H4:

45 GeV e^+ on target, beam spot 2 cm, mrad divergence

High intensity (up to 5 x 10^6 e+/spill) with 6 cm Be target (spill ~15s)

goal: measure muon production rate and muons kinematic properties

Low intensity

measure beam degradation (emittance energy spectrum)

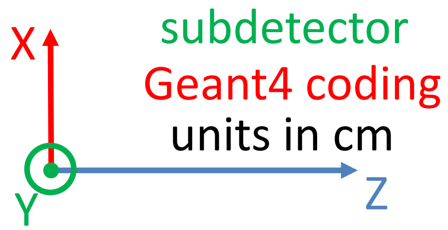
measure produced photons flux and spectrum

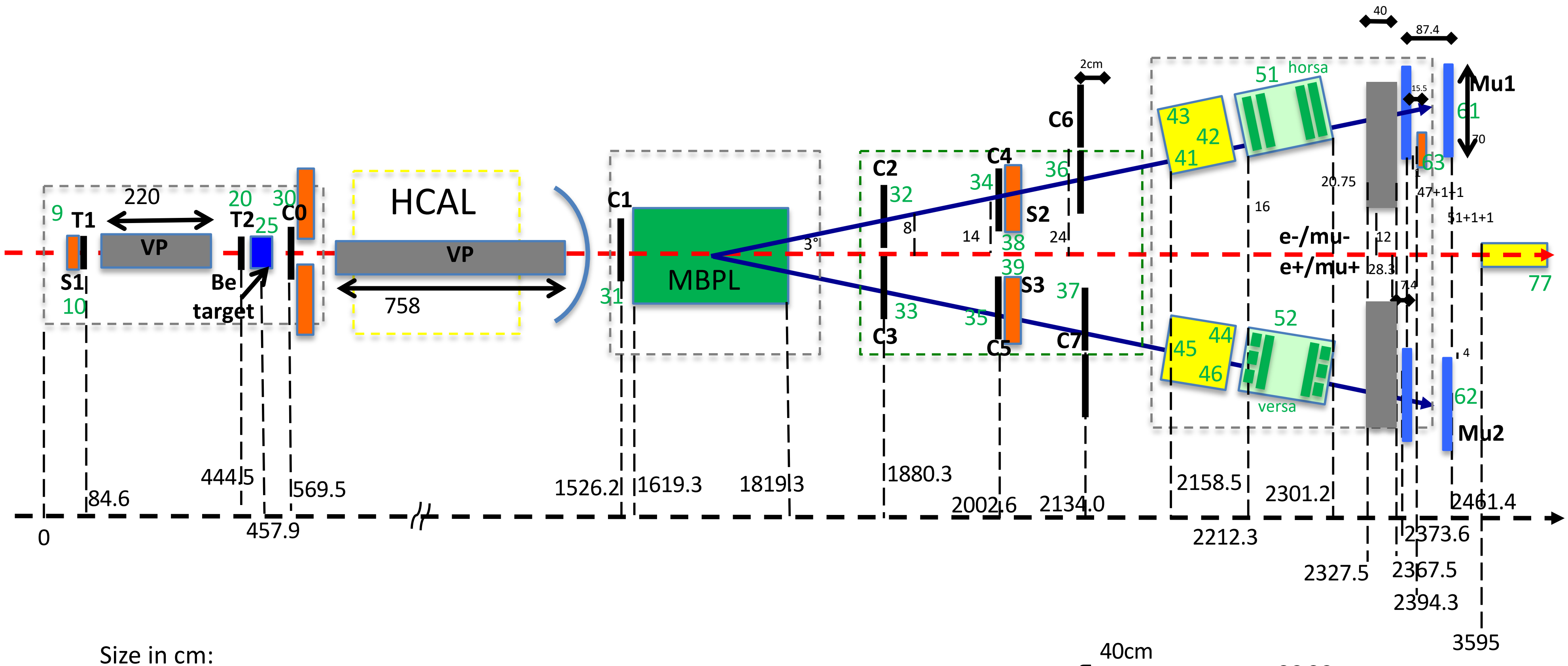
- 3 week assigned 2017/2018

Priority to High intensity (had 2 days at ≈ 10^6 e^+ /spill)

- **2018 data taking**
  - 3 positron beam energy (45 GeV, 46.5 GeV, 49 GeV)
  - 2 different targets (Be S-200-F H and C-Mo)
  - Collected few 1000 $\mu^+ \mu^-$ events

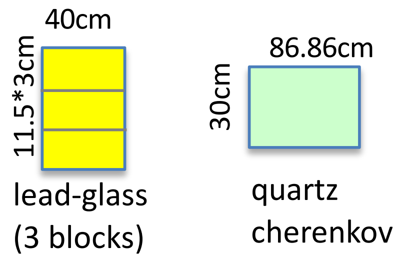
Last update: 20-aug-2018 v. 20





Size in cm:
T1-2: 1.9x1.9
C0-1,4-5: 9.3x9.3
C2-3: 8x8
C6-7: 18x18

FINAL FOR 2018a TB!!



Post Geo

Test at DAΦNE

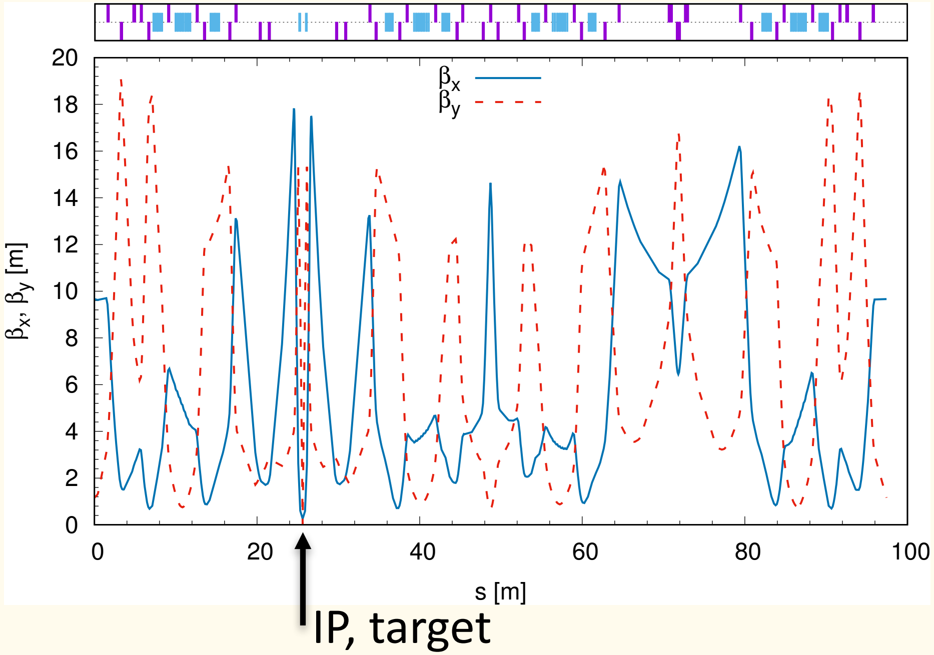
- **Test of the ring-plus-target scheme:**
  - **beam dynamics**
  - **target heat load and thermo-mechanical stress**

GOAL:

- Benchmark simulations with experimental data to validate LEMMA studies.
- Measurements on targets: various materials and thicknesses can be envisaged.
  - as validation for LEMMA studies
  - interesting in the test itself

Test at DAΦNE

- The SIDDHARTA-2 run will end on 2019
- Test proposed after this run
- The target is at the IP:
  - To minimize modifications of the existing configuration
  - low-β and D_x=0 is needed
- First studies with the SIDDHARTA optics and target placed at the IP.
- Possible different locations for the target can be studied



SIDDHARTA 2008 optics

β_x^*=26cm; β_y^*=0.9cm

σ_x^*=0.27mm; σ_y^*=4.4μm

ε_x = 0.28 μm

Goals of the Test at DAΦNE

- Beam dynamics studies of the ring-plus-target scheme:
  - transverse beam size
  - current
  - lifetime

Table 8: DAFNE parameters for the test with thin target at IP.

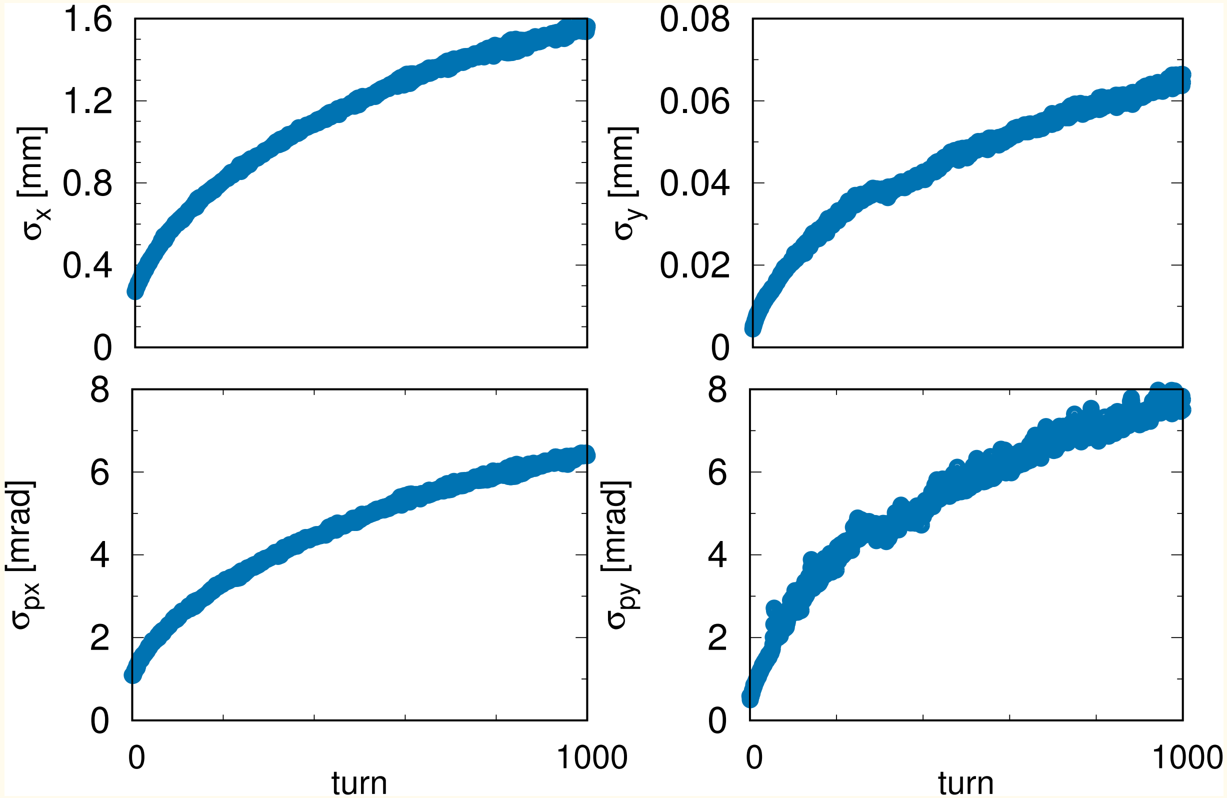
Parameter	Units	
Energy	GeV	0.51
Circumference	m	97.422
Coupling(full current)	%	1
Emittance x	m	0.28×10^{-6}
Emittance y	m	0.21×10^{-8}
Bunch length	mm	15
Beam current	mA	5
Number of bunches	#	1
RF frequency	MHz	368.366
RF voltage	kV	150
N. particles/bunch	#	1×10^{10}
Horizontal Transverse damping time	ms/turns	42 / 120000
Vertical Transverse damping time	ms/turns	37 / 110000
Longitudinal damping time	ms/turns	17.5 / 57000
Energy loss/turn	keV	9
Momentum compaction		1.9×10^{-2}
RF acceptance	%	± 1

- Measurements on target:
  - temperature (heat load)
  - thermo—mechanical stress

Given the limited energy acceptance of the ring (~1%), we plan to insert light targets (Be, C) with thickness in the range 10-100μm.
Crystal targets can be foreseen too, modified G4 tool needed for the simulation

Evolution of e+ beam size and divergence

Beam evolution in the ring with 50μm Be target at IP

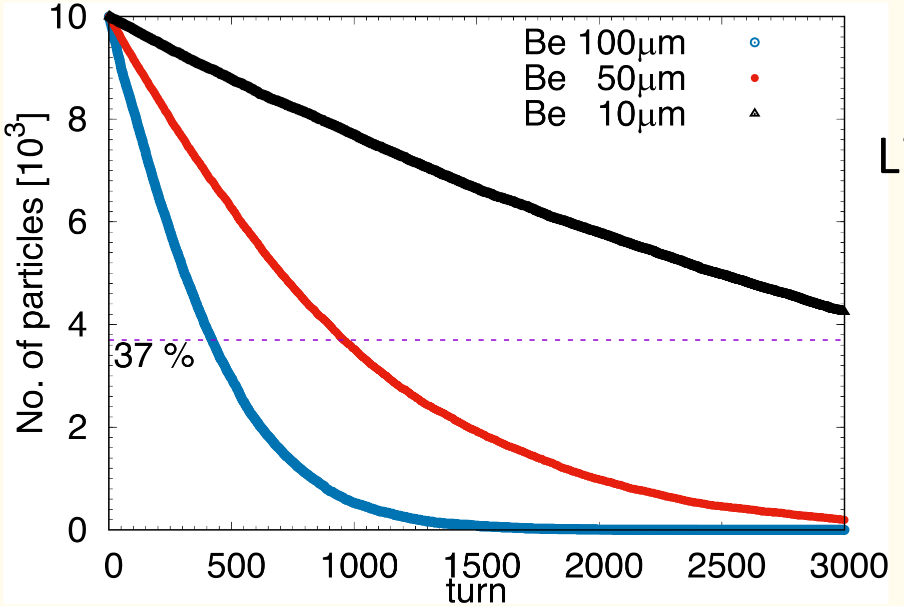


first turn, before target

$\sigma_x^* = 0.27$ mm

$\sigma_y^* = 4.4 \mu m$

e+ lifetime with Be target

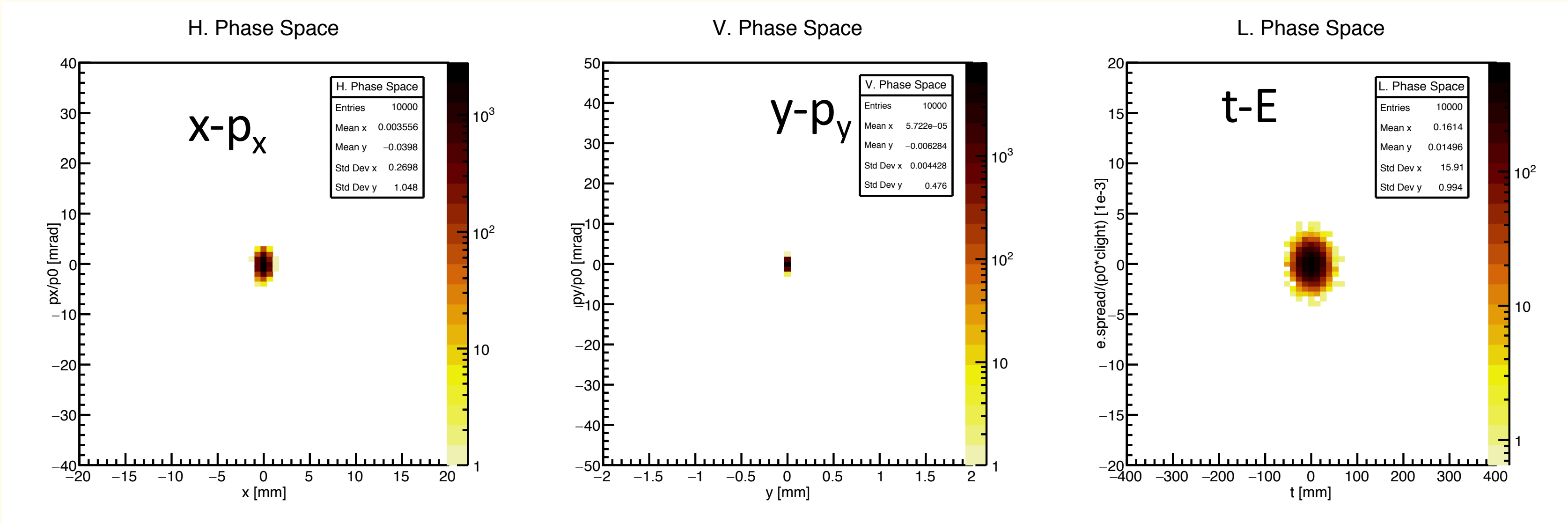


Lifetime with ~ 3500 turns for 10μm Be target as short as 1.6 ms

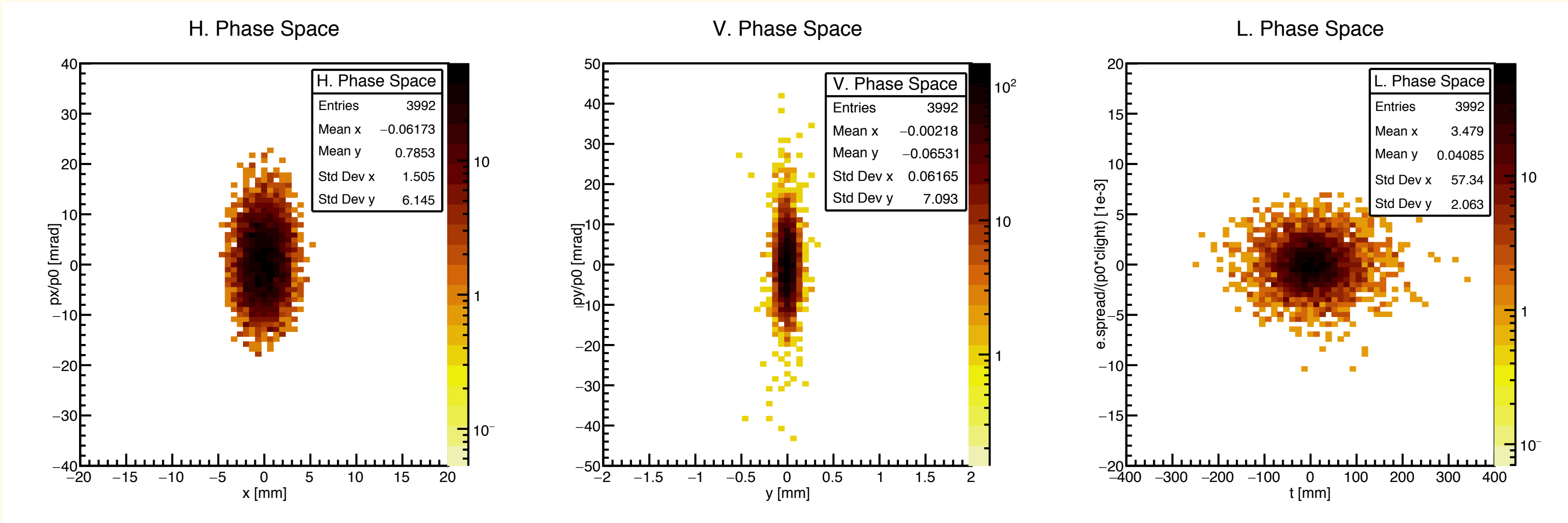
- Beam will not be stored
- Injection in single bunch mode
- turn-by-turn beam size and charge measurement

DAFNE e^+ ring with 50μm Be target: beam evolution in the 6D phase space

before target, starting point

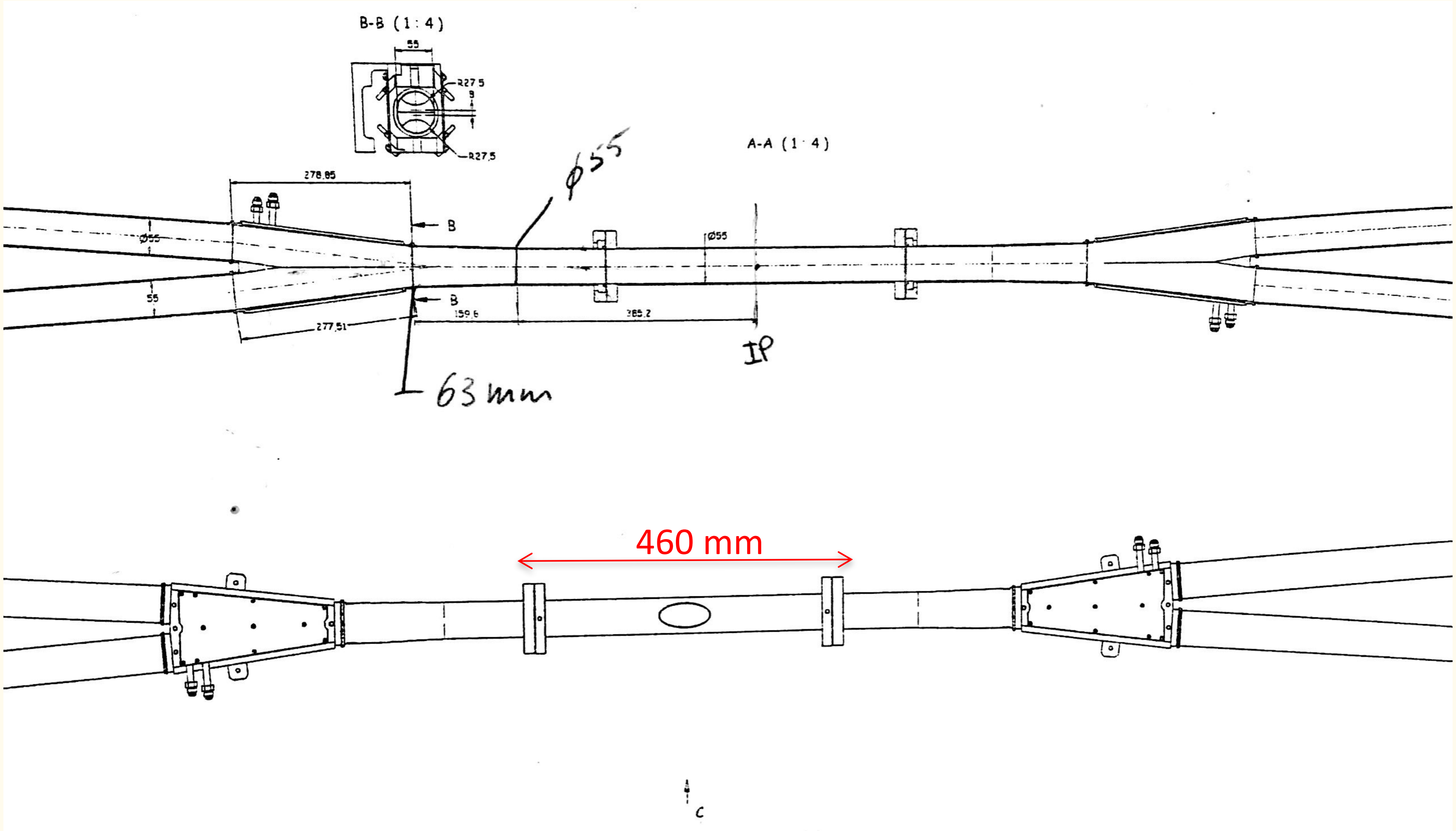


after 900 turns



MAD-X PTC & GEANT4 6-D tracking simulation

SIDDHARTA IR



Diagnostics for the test at DAFNE

beam characterization after interaction with target:

- additional beam diagnostic to be developed:
  - turn by turn charge measurement (lifetime)
    - ✓ existing diagnostic already used for stored current measurement
    - ✓ need software and timing reconfiguration
  - turn by turn beam size
    - ✓ beam imaging with synchrotron radiation
    - ✓ DAFNE CCD gated camera provides gating capabilities required to measure average beam size at each turn.
    - ✓ software modification and dedicated optics installation required.

Year of the Strategy Input

Observation: Existing SPS and LHC rings give long-term perspective to pursuit of LEMMA scheme

- LHC tunnel ideal to house 45 GeV positron ring
- SPS requires much more installed voltage and power
- SPS tunnel can house 3+3 TeV muon collider
- LHC tunnel can house 7+7 or 14+14 TeV muon collider
- LEP3 collider in LHC tunnel is consistent with doing muon production studies, spot on for Z production

Thinking strategy
L. Evans, S. Stapnes, D. Schulte

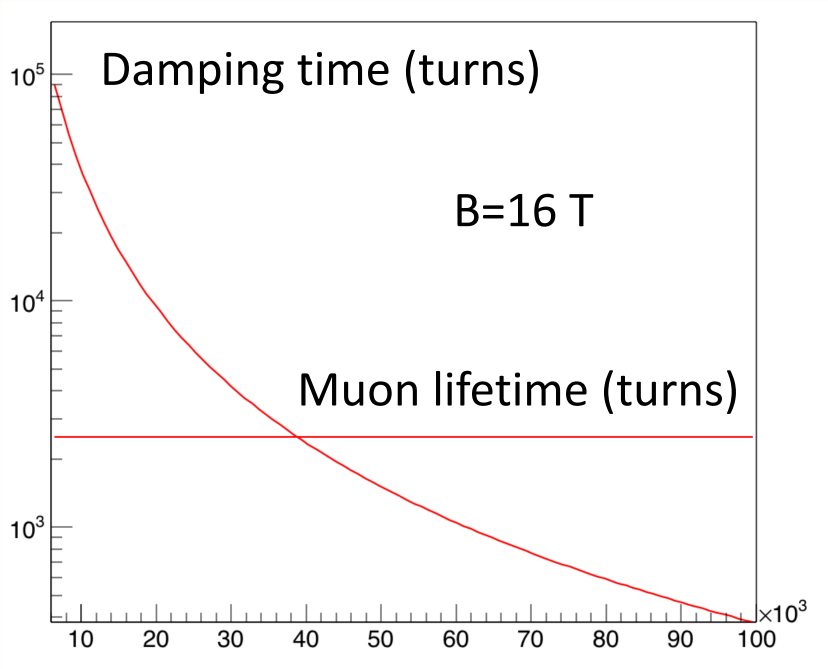
Considered phased approach:

- Phase 1: eSPS would be entry point for all options
- Phase 2: LEP3 or CLIC (use to test and develop muon production)
- Phase 3: Muon collider in SPS or LHC tunnel
- Allows to develop all technologies and wait for physics input to define energy scales and choices

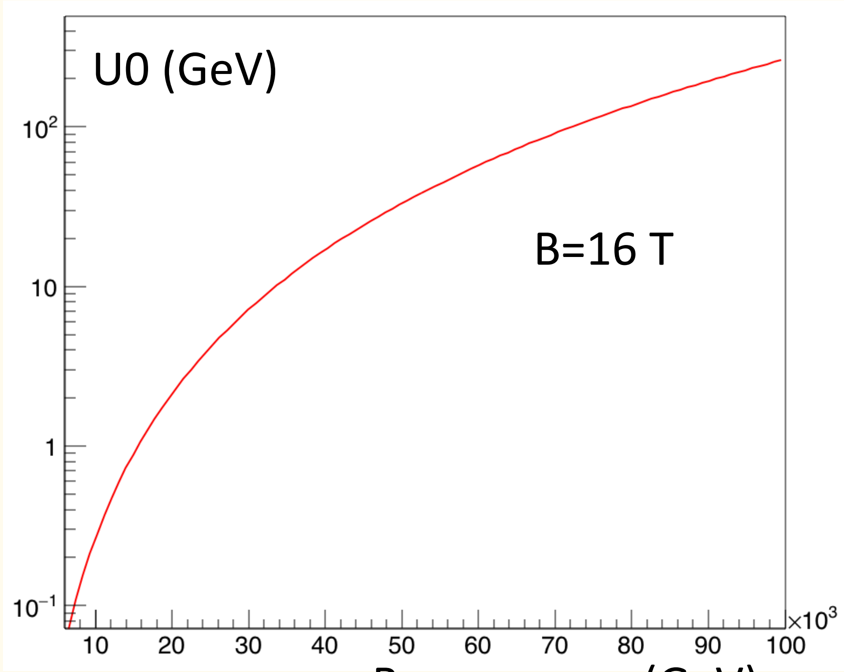
Conclusion

- **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

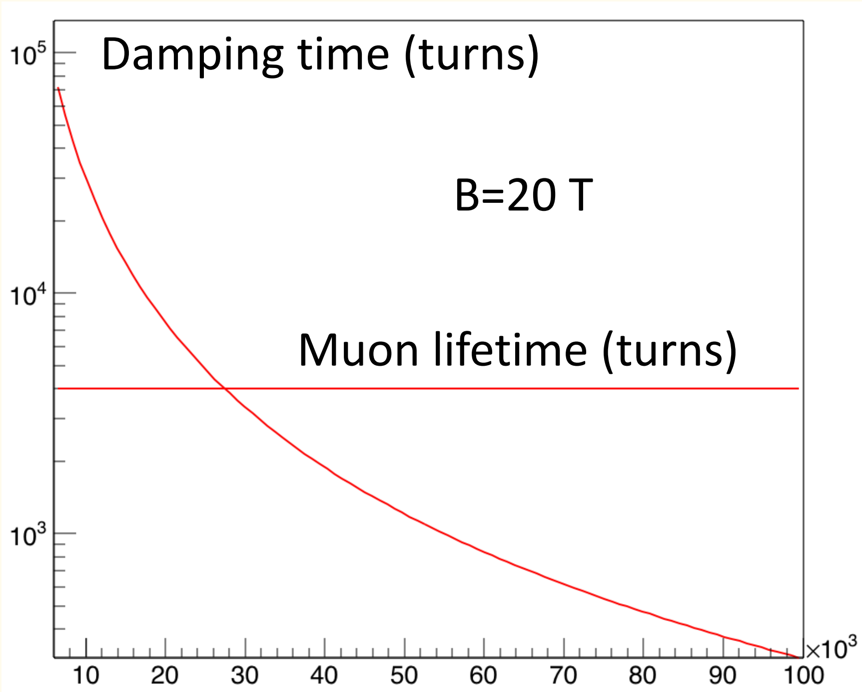


Beam energy(GeV)

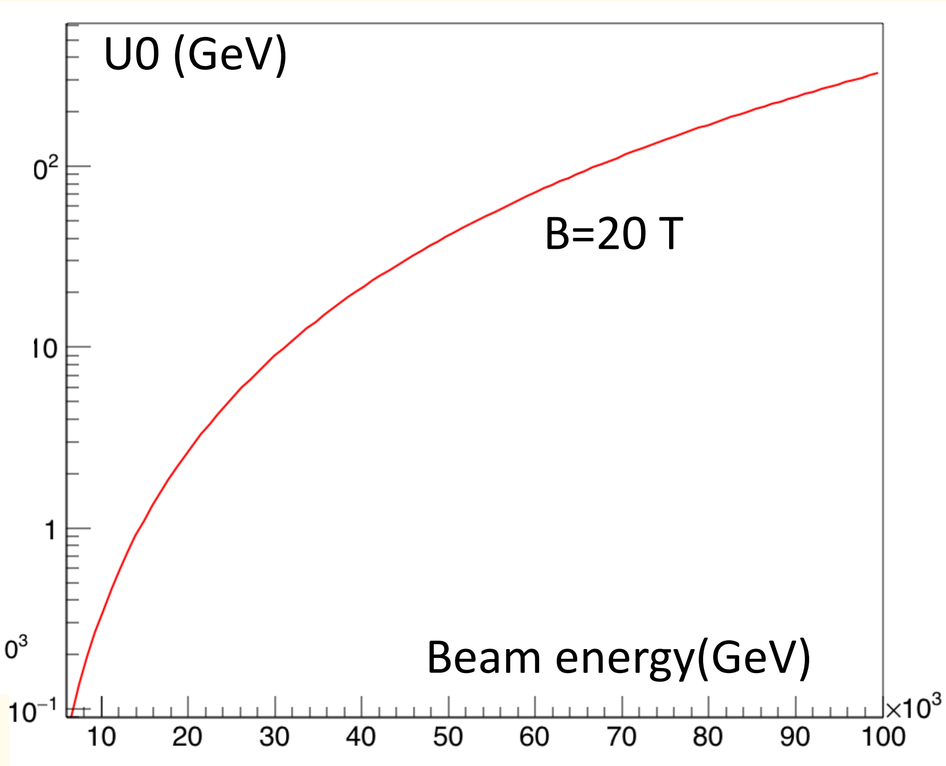


Beam energy(GeV)

SR and damping in μ collider

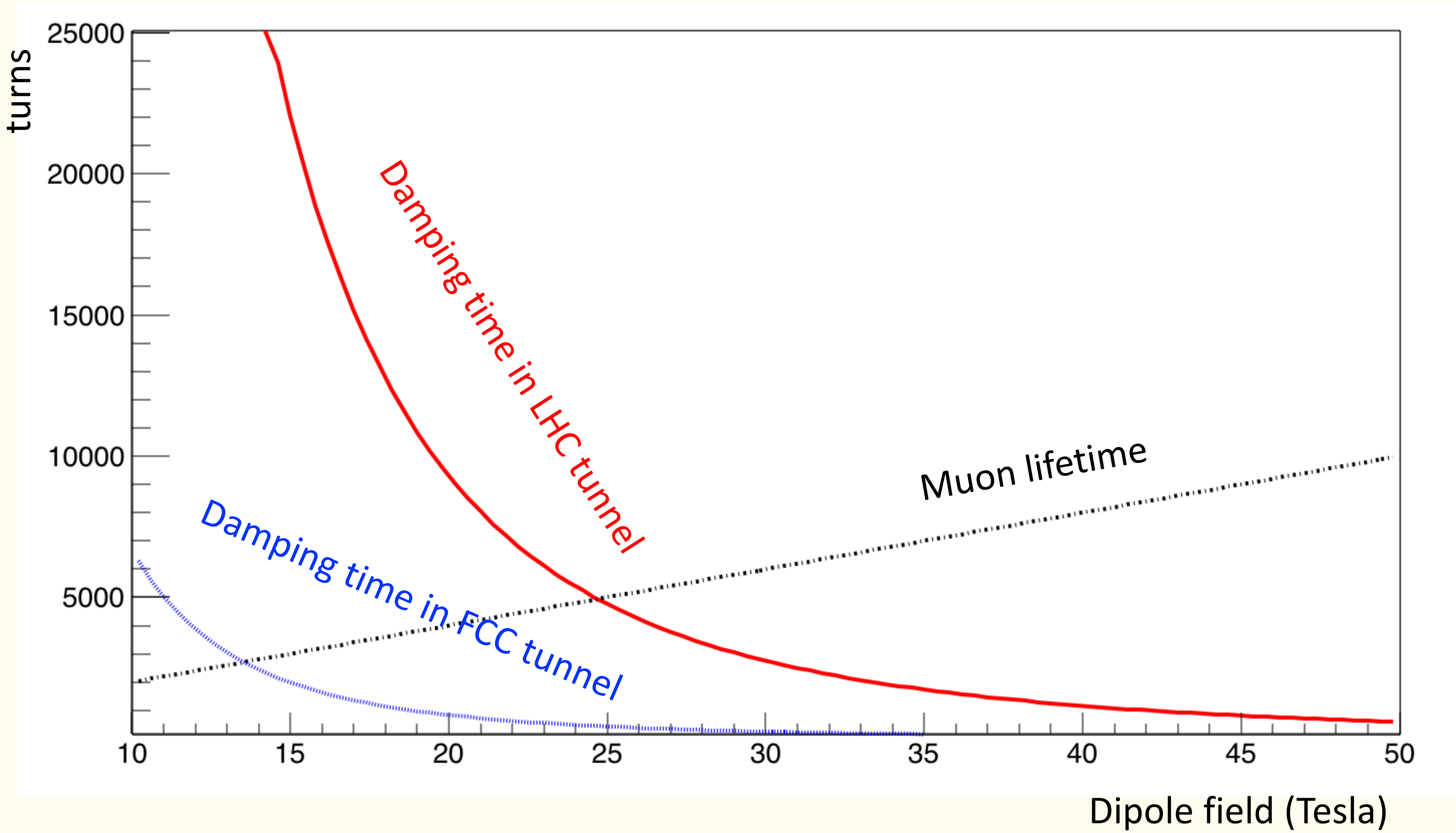


Beam energy(GeV)

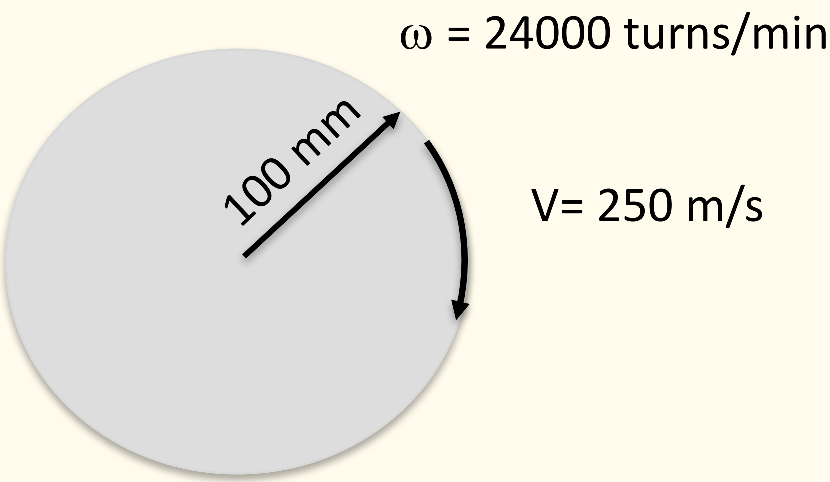


$U_o = 5.5 \times 10^{-18} \gamma^4/\rho$

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

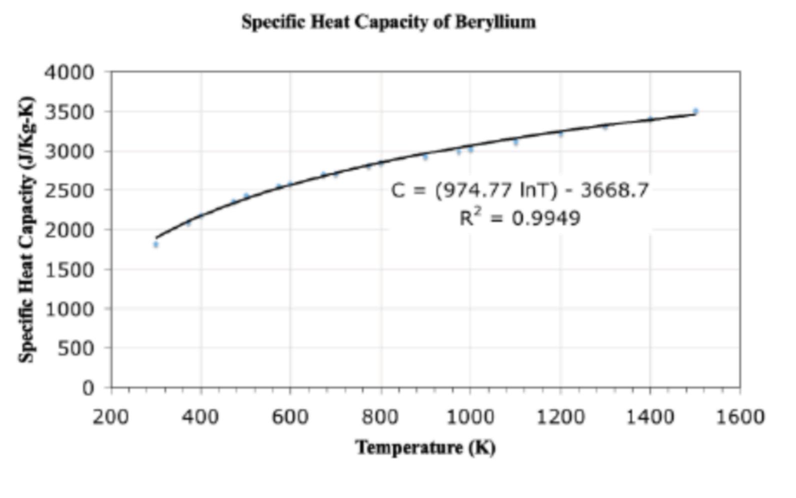
2D axisymmetric model showing effective total strain

4.9×10^{13} protons, σ = 0.3 mm, ΔT ~ 1025 ˚C, 0.25 mm thick window

End of beam pulse

$t = 7.2\ \mu s$, T_{max} ~ 1050 ˚C, ε_{max} ~ 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, 3×10^{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)]