Positron-based muon collider: overview, issues and R&D needs

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Gratefully acknowledging input from all contributors

Istituto Nazionale di Fisica Nucleare

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STFC, Rutherford Appleton Laboratory, UK

Outline

- Overview: LEMMA concept & scheme
- LEMMA issues
- R&D needs
- Outlook

Muon Source

Proton driven

Tertiary production from **protons on target:** p + target→ $\pi/K \rightarrow \mu$
typically **$P_\mu \approx$ 100 MeV/c** (π, K rest frame)
whatever is the boost P_T will stay in Lab frame
→ **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 **$e^+e^-\rightarrow\mu^+\mu^-$** 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 $N_\mu \approx 6\cdot10^9$/bunch

LEMMA

⬇

Low **EM**ittance **M**uon **A**ccelerator

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**
- **allows operation in the Multi-TeV range**

LEMMA concept was proposed at Snowmass 2013 by M. Antonelli and P. Raimondi: *"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)

Advantages:

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

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

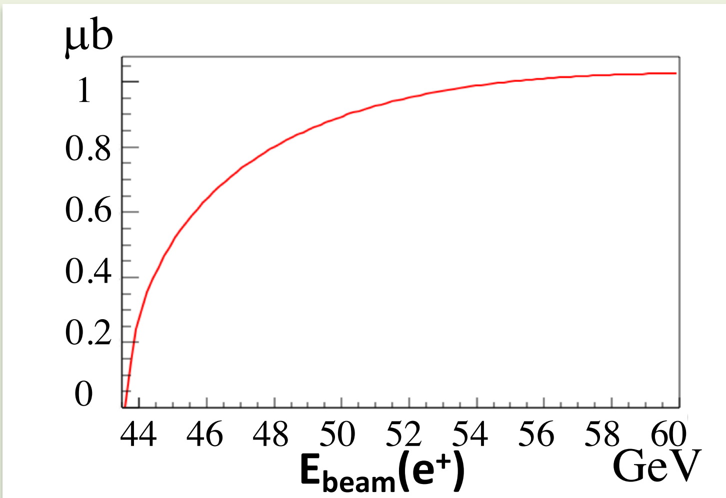
Possible Schemes

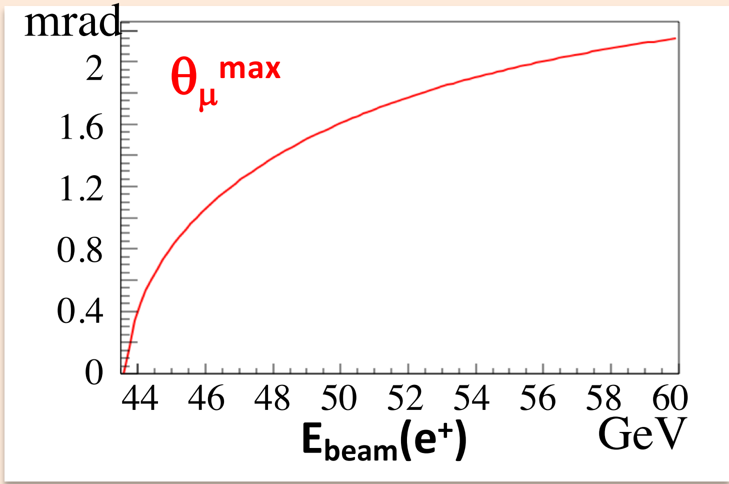
- **Low energy collider with e^+/e^- beam (e$^+$ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity $\approx 10^{40}$ is beyond present capability)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^3 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**
  - $\gamma(\mu)\approx200$ and μ laboratory lifetime of about 500 μs

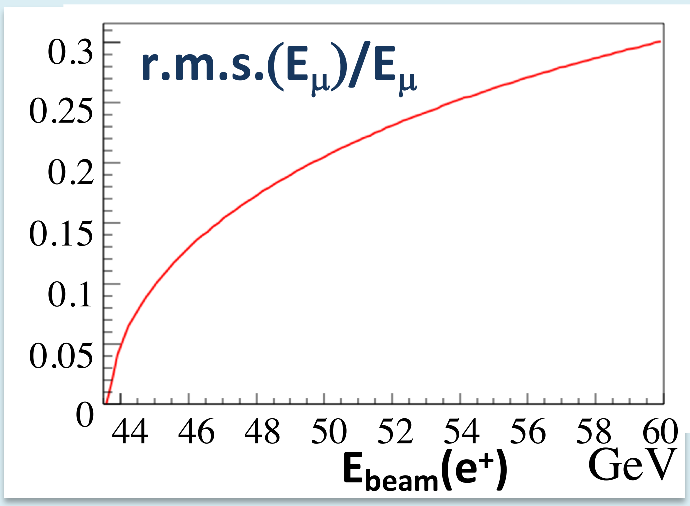
Ideally muons will *copy* the positron beam

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 the 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
- J.D. Cossairt, N.L. Grossman and E.T . Marshall, Health Phys. 73 (1997), 894-898 (on neutrino dose equivalent/fluence)
- see also D. Neuffer, MC workshop, Padova. 2-3 July 18 sl.9-10

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

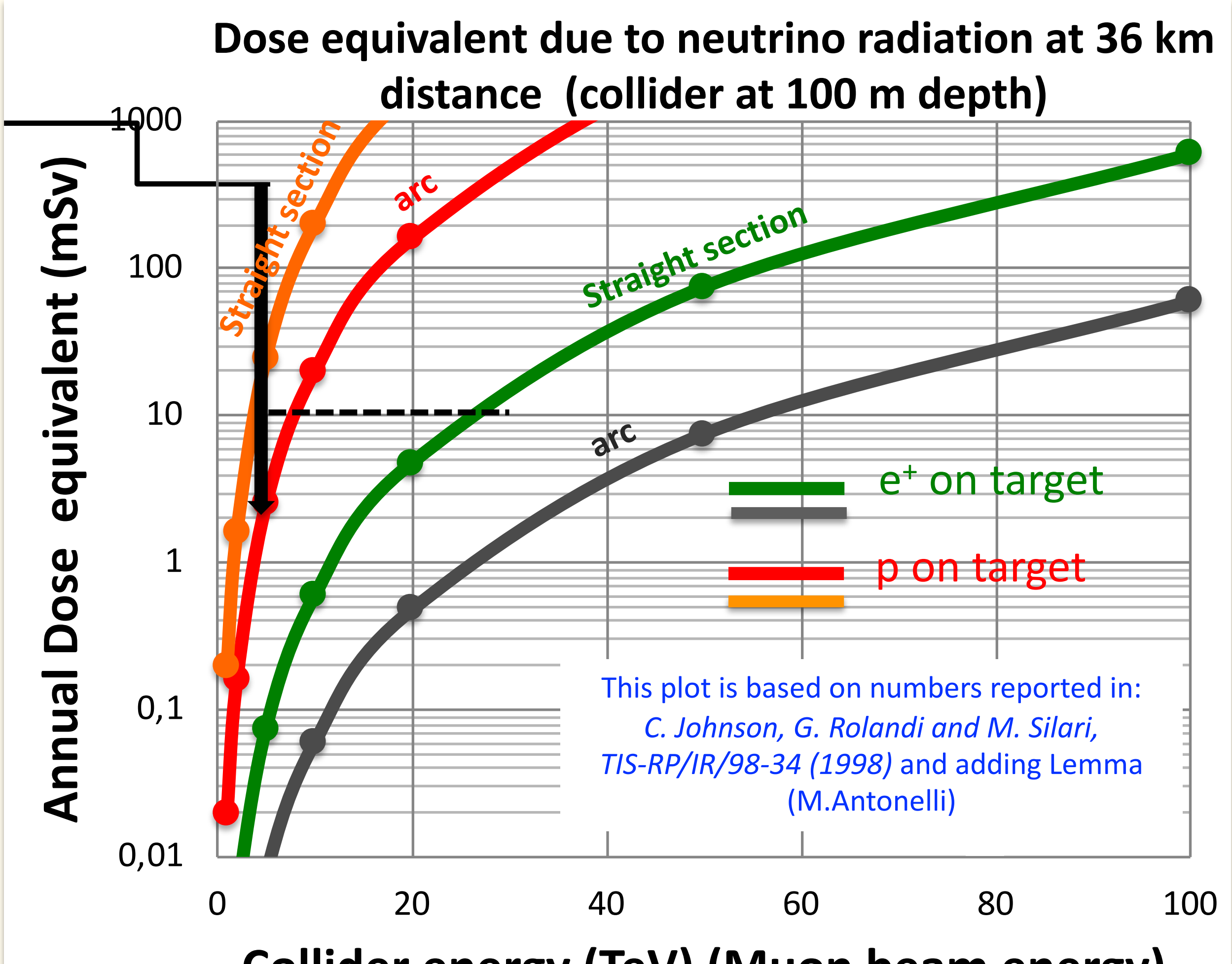
muon rate:

p on target option

3×10^{13} μ/s

e^+ on target option

9×10^{10} μ/s



Time steps in the Lemma study

2013: Snowmass — concept of low emittance muon beam $e^+e^- \rightarrow \mu^+\mu^-$

2016: NIM A 807 101-107 — first scheme for a muon beam suitable for HE muon collider

2016: IPAC16 — Luminosity table with ideal parameters

2017: IPAC17 contributed **oral** — first positron ring optics & studies of e+ ring-with-target insertion

Oct-2017: LEMMA presented at the **INFN M**achine **A**dvisory **C**ommittee, M. B.

June-2018: PRAB 21, 061005 — dedicated optics study to cope with target perturbation

2018: IPAC18
- definition of accumulator rings requirements
- Proposal for exp. test at DAFNE on beam dynamics&target

2-3 July 2018: ARIES Workshop on Future Muon Colliders

NEXT

Introduction

- Lemma is not an approved design study project, no CDR has started
- I believe in the potential of this idea, but key challenges need to be demonstrated to prove its feasibility, I will discuss these issues.
- I will show the work done up to now that may lead to a Conceptual Design Report

General criteria for the design study

Need to set our constraints:

- Multi-TeV **energy range**: maximize energy / luminosity at a specific energy
- Use **existing infrastructure** (i.e. **CERN**?) / best solution in terms of L/power?
- B **dipole field** (i.e. **B=16 T**?) -> HTS would give large benefits
- **Solid / Liquid target**?

As a start, we decided to compare the LEMMA potentiality with MAP:
we set the μ collider at 6 km and 6 TeV c.m. energy, and found the requirements for LEMMA to get a comparable luminosity ($5 \times 10^{34} cm^{-2} s^{-1}$),
and we used a solid target (3 mm Be) for beam dynamics studies

Year of the Strategy Input

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

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

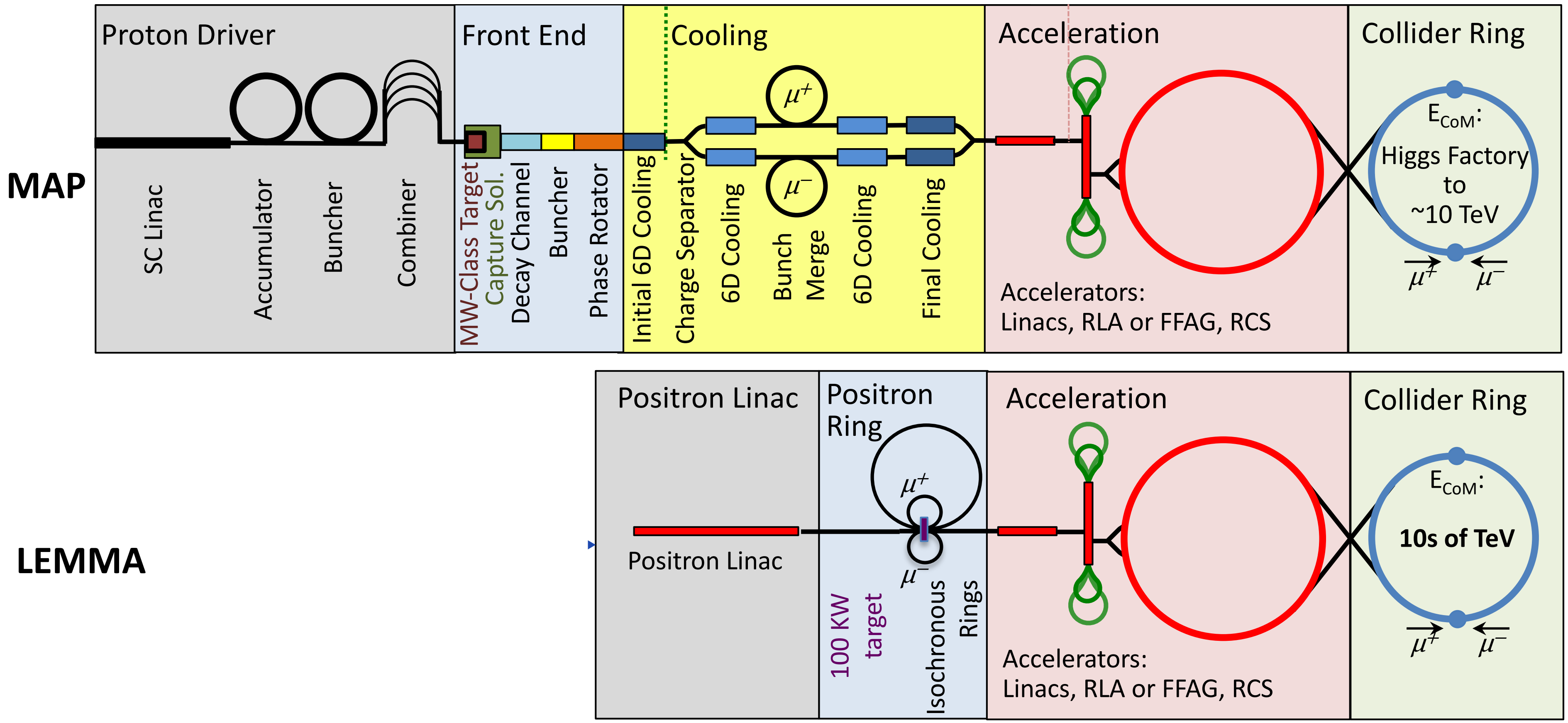
- LHC tunnel ideal to house 45 GeV positron ring
- SPS requires much more installed voltage and power
- SPS tunnel can house 3+3 TeV muon collider
- LHC tunnel can house 7+7 or 14+14 TeV muon collider
- LEP3 collider in LHC tunnel is consistent with doing muon production studies, spot on for Z production

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

D. Schulte, ARIES MC Workshop, Padua, 2-3 July 2018

MAP & LEMMA



[M. B., 2017 EuCard-2 XBEAM Strategy Workshop, Valencia, 13-17 Febr. 2017]

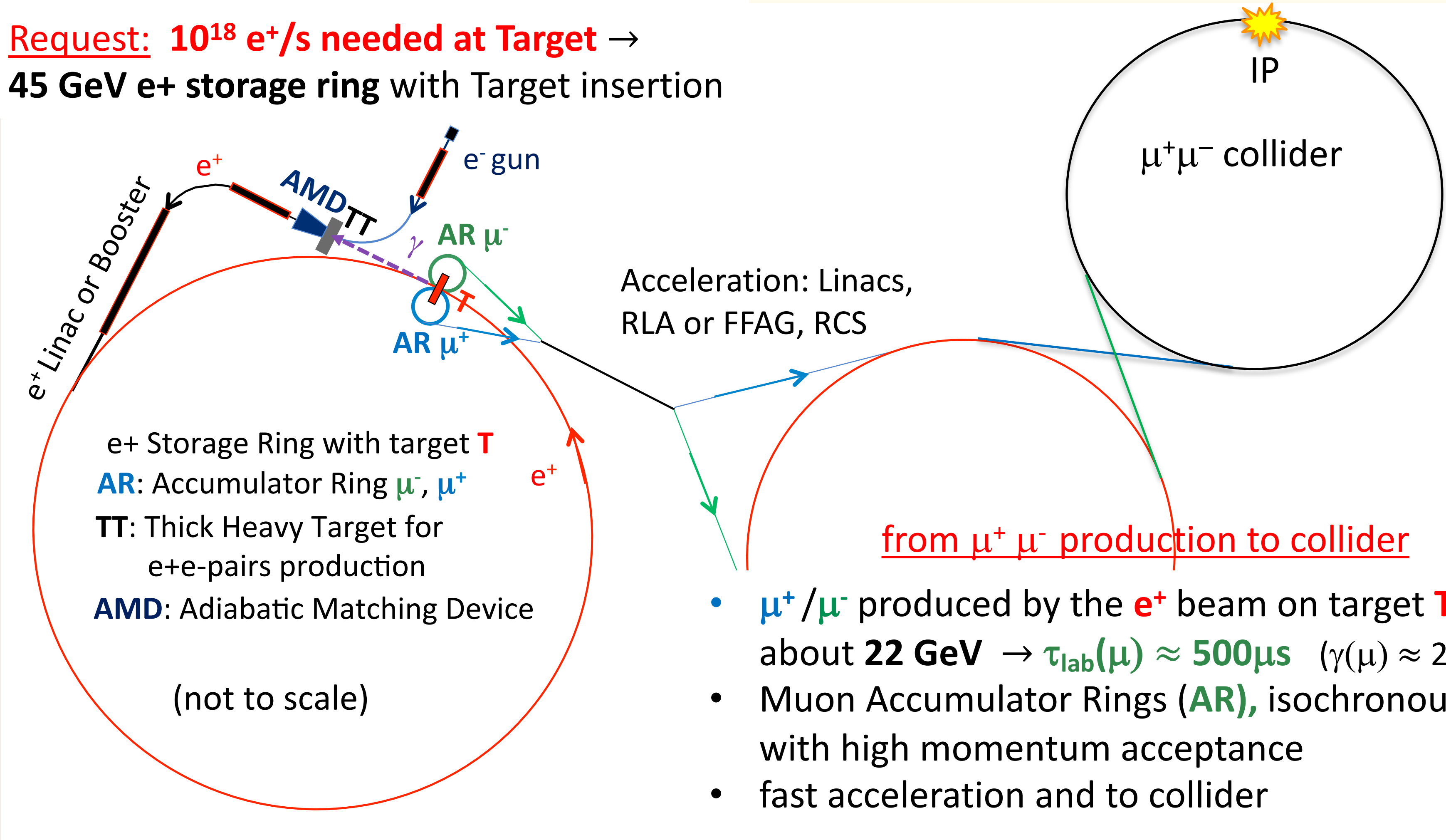
LEMMA scheme

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

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

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

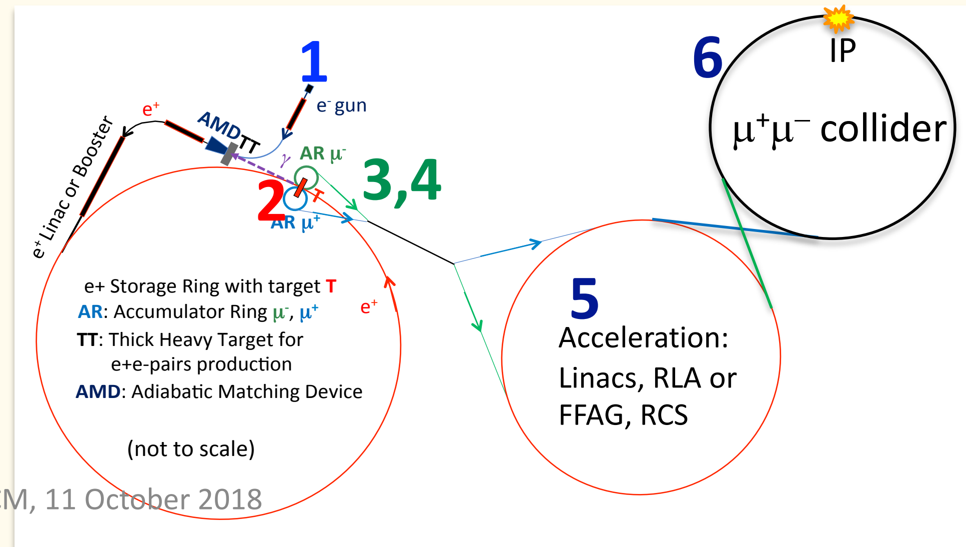
45 GeV e+ storage ring with Target insertion



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

LEMMA Key steps

1. **e^+ source / e^+ beam** → goal: maximize rate at muon target
2. **$\mu^{+/-}$ production target** → goal: reach limit for PEDD and thermo-mechanical stress (to produce the best possible muon beam emittance and intensity)
3. **Muon Accumulator Rings** → goal: preserve muon emittance and maximize bunch intensity
4. **Muon Recombination scheme and injection scheme** → enhancement factor needed to maximize lumi
5. **Fast acceleration**
6. **Muon Collider**



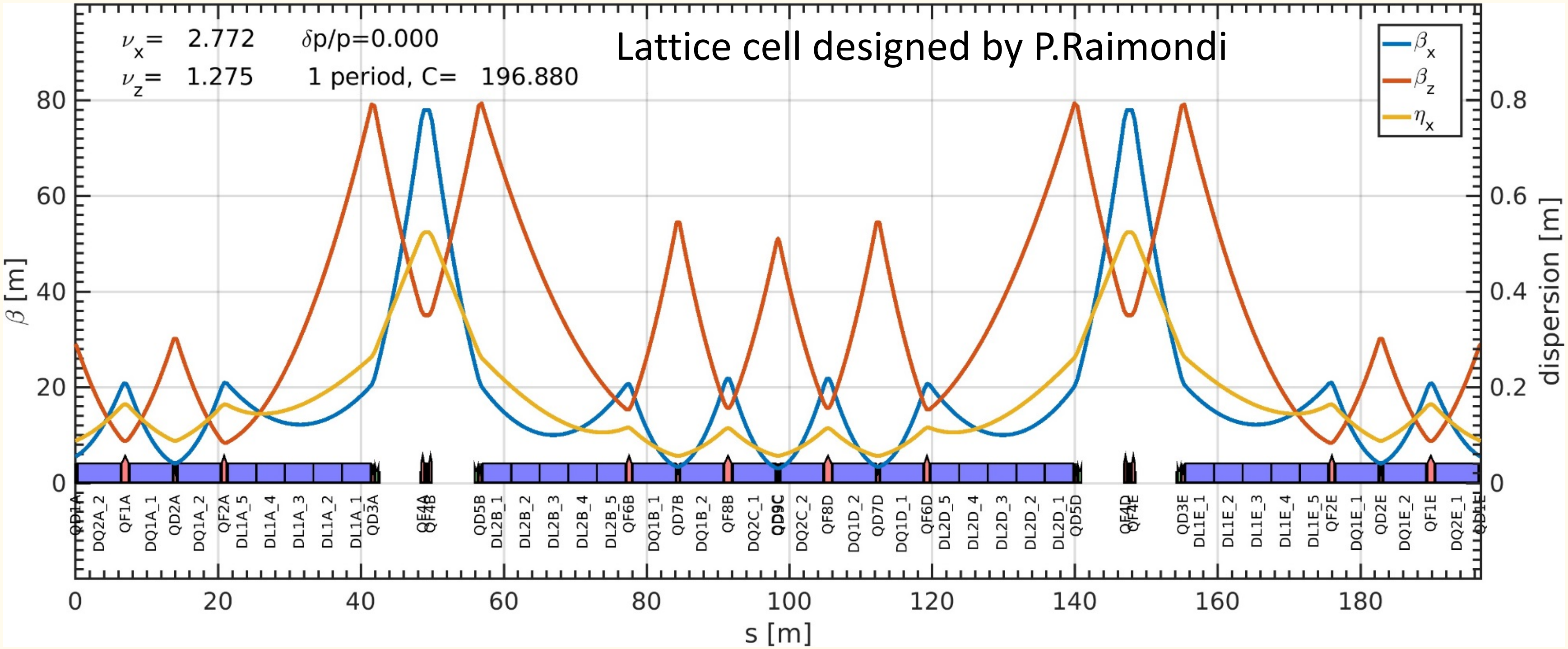
e+ ring-plus-target:
beam optics & beam dynamics studies

- existing **SPS**, **LHC** or **FCC** tunnels can be foreseen
- We started from the **SPS** case (used for the studies in PRAB 21, 061005 (2018)):
- **LHC** tunnel studied (see Padua workshop)
- [SPS: it minimizes the cost of the infrastructure but it also maximizes the beam plug power (120 MW)]

Low-ε 45 GeV positron ring

Parameter	Units	
Energy	GeV	45
Circumference (32 ARCs, no IR)	m	6300.960
Geometrical emittance x, y	m	5.73×10^{-9}
Bunch length	mm	3
Beam current	mA	240
rf frequency	MHz	500
rf voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
No. of 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

Lattice cell positron ring

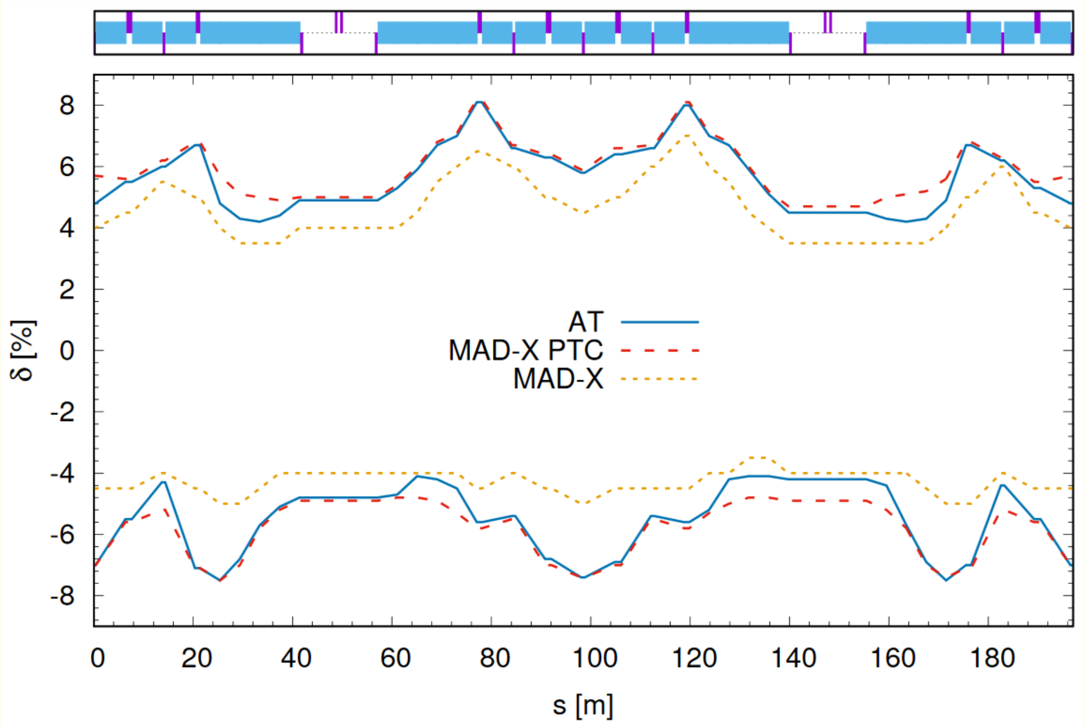


Optics Cell Based on the
Hybrid Multi Bend Achromat

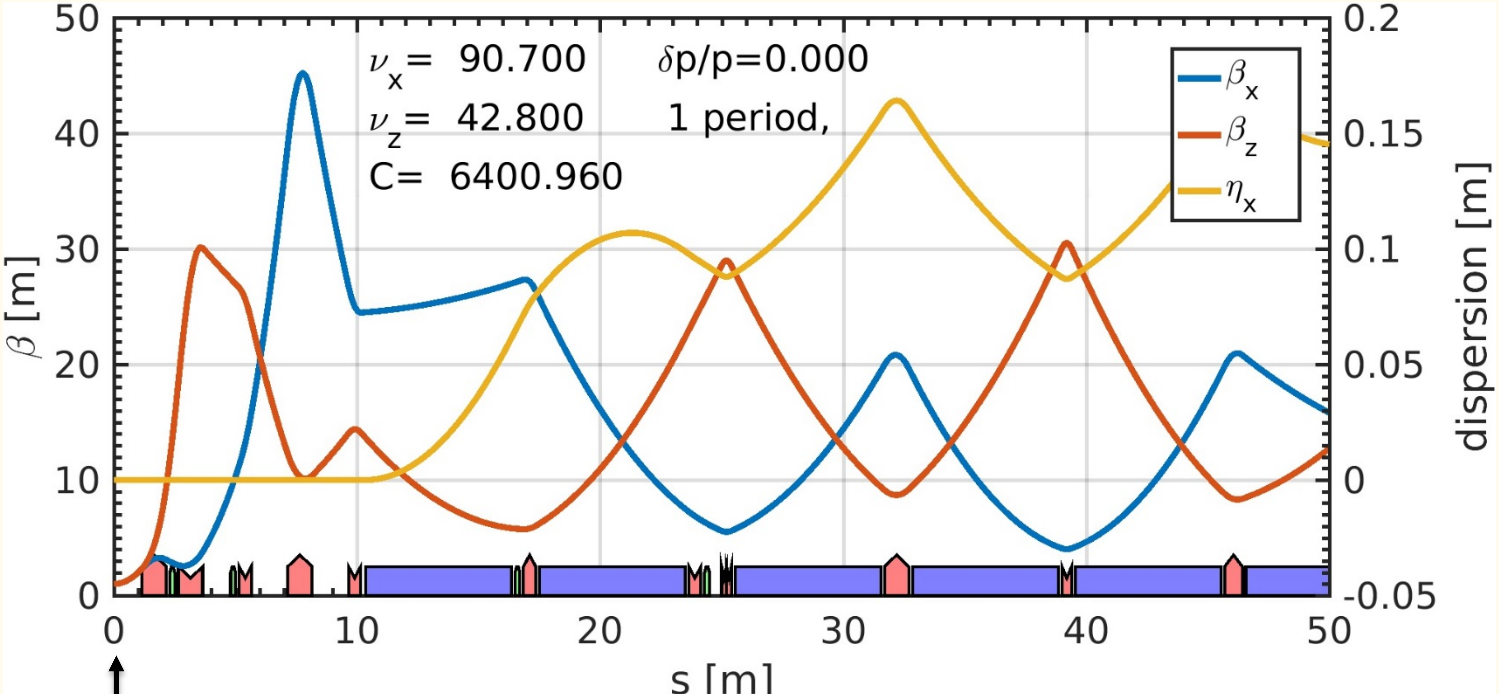
- circumference 6.3 km: 197 m x 32 cells
- Lattice includes radiation and RF
- no injection section yet
- filling factor 77%
- max dipole field 0.26 T
- 64 RF cavities, each cavity: 5.4m, 9-cells, 7 MV/m

Momentum acceptance

Positron ring design must allow for maximum energy acceptance, in order to minimize the scattered positrons lost after the interaction with the target.



Target Insertion region



Target insert

Standard cell

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

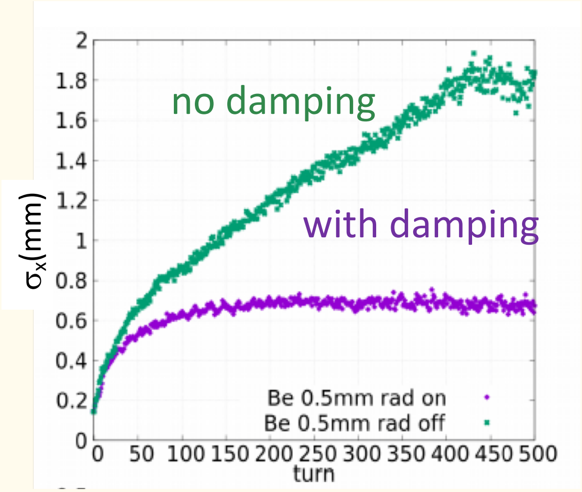
Target optics designed only to study target interaction with given optics functions.
The target interaction region optics, including dipoles for positron-muon beam separation and adequate chromaticity correction, need to be designed.

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)

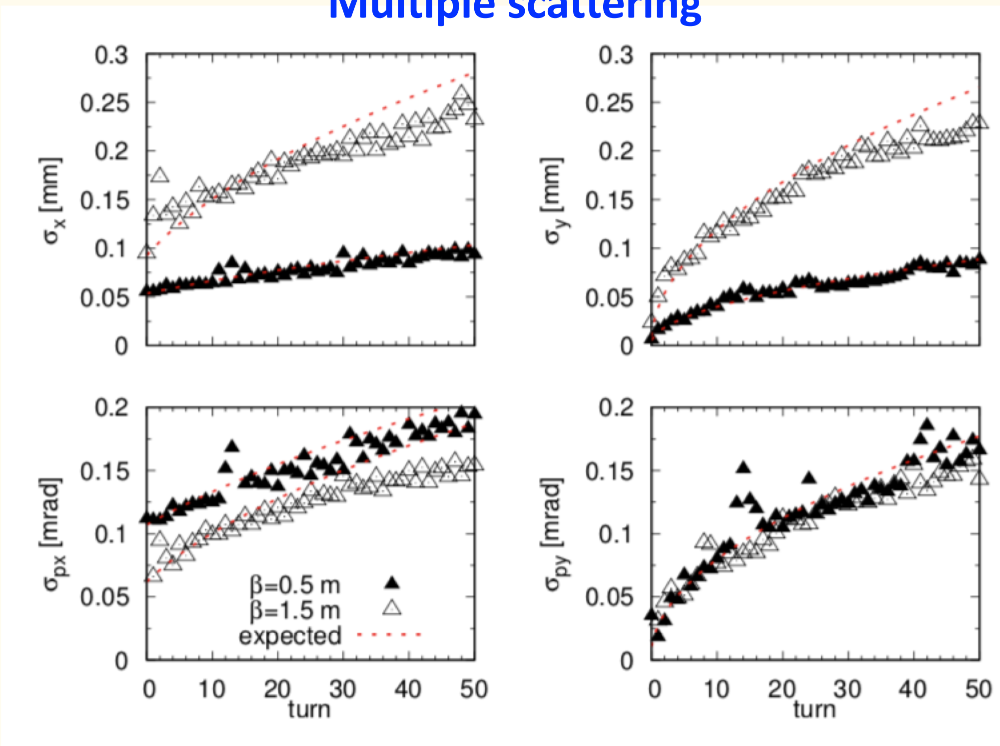


Beam dynamics e^+ beam in ring-with-target

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

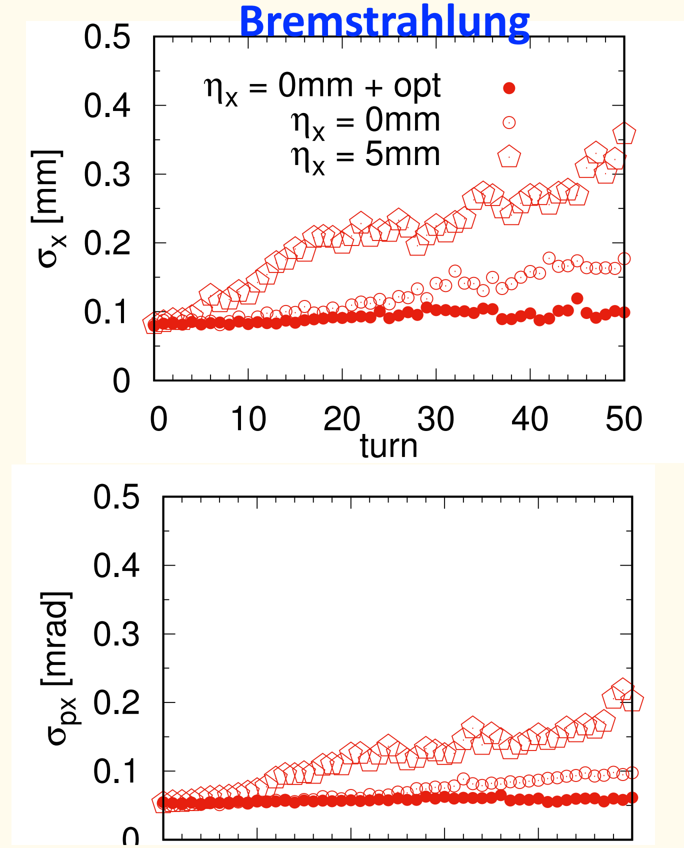
e^+ emittance growth controlled with proper β and D values @ target

Multiple scattering



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

Bremstrahlung

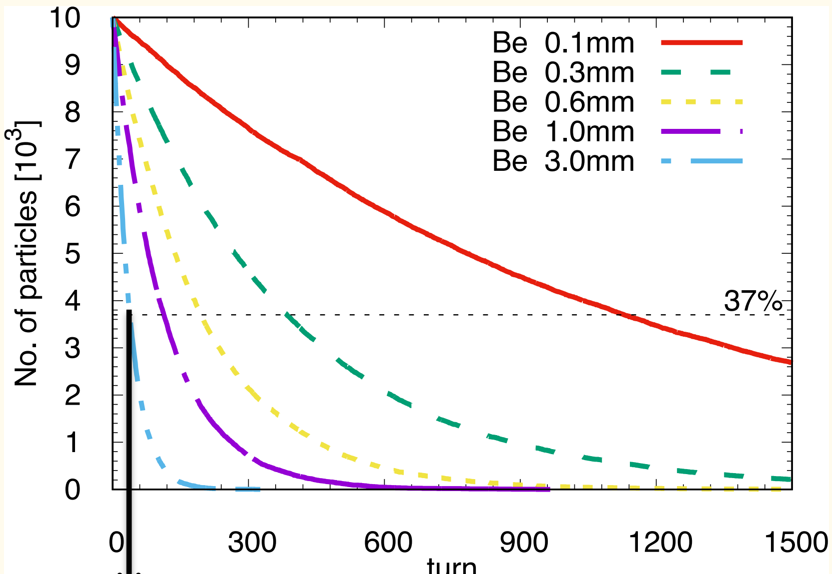


@Target :
linear and non-linear terms
of horizontal dispersion η_x =0

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

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

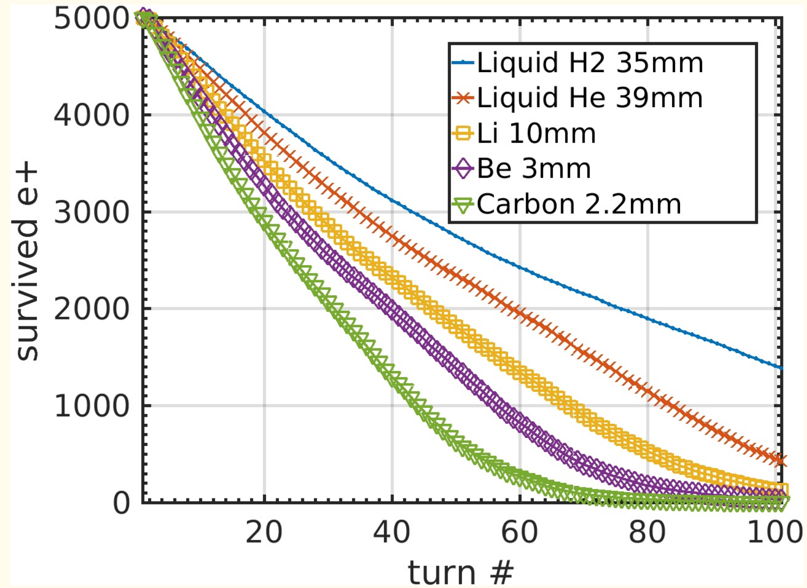
Lifetime ∝ 1/thickness as expected



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

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

knobs:

$\varepsilon(e^+)$	= e^+ emittance	
$\varepsilon(MS)$	= multiple scattering contribution	β_x β_y @target & target material
$\varepsilon(rad)$	= energy loss (brem.) contribution	β_x β_y D_x @target & target material
$\varepsilon(prod)$	= muon production contribution	$E(e^+)$ & target thickness
$\varepsilon(AR)$	= accumulator ring contribution	AR optics & target

with **constraints** from **target survival**

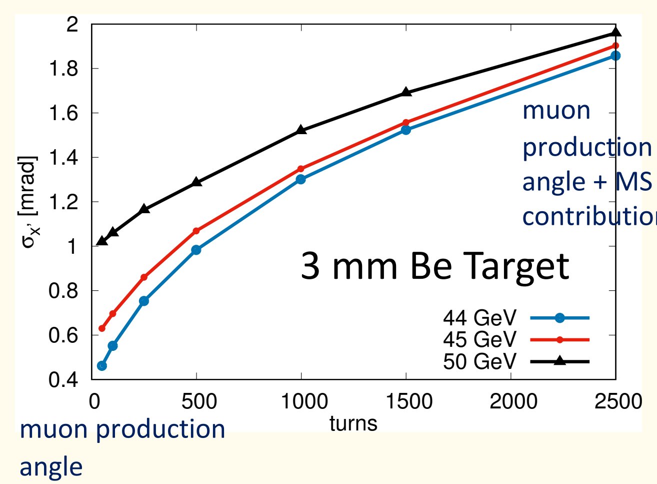
now: $\varepsilon(\mu)$ dominated by $\varepsilon(MS) \oplus \varepsilon(rad)$ -> lower dispersion & lower β-functions at target with beam spot at the limit of the target survival

[Proc. of IPAC18, Vancouver, MOPMF087]

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

45 GeV e+ beam, 3 mm Be, after 2500 turns:
$\sigma_{x'}$ = 1.85 mrad -> norm. emittance **0.6 µm**

Multiple scattering contribution can be reduced in lighter material



Muon Accumulator Rings Outlook

The estimate of the multiple scattering with the solid target has been essential to determine handles and next steps.

- Knobs to reduce multiple scattering:
  - **<~ 1000 turns in AR ($\Delta\varepsilon$ < factor 2)**
  - lighter target (i.e. 35 mm H pellet gives equivalent muon yield)

Next steps

- **Optics design**, challenges:
  - high momentum acceptance
  - Extraction section from production target into muon rings
- **Full particle tracking with lighter target (H)**
- **Study how to increase the muon bunches intensity into the μ collider (from the AR now we have $4.5\text{x}10^7$ μ/bunch)**

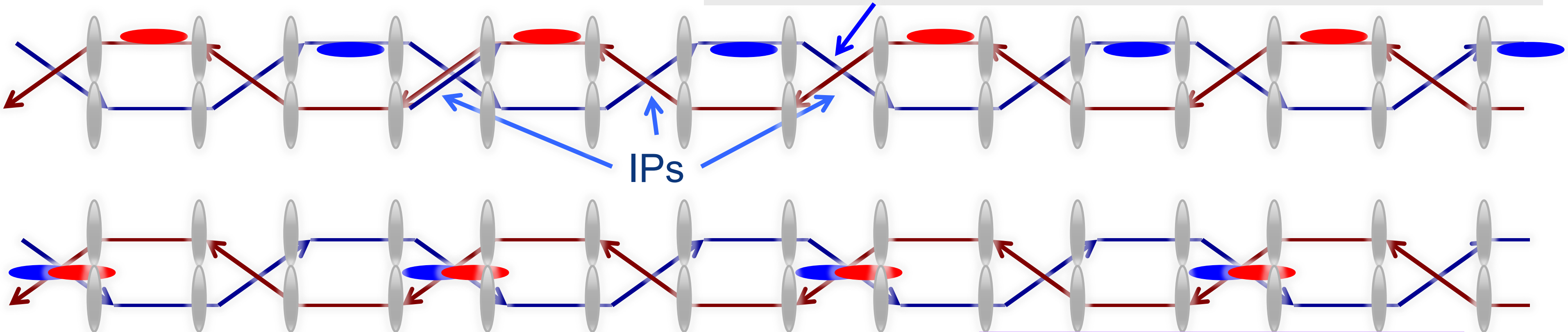
⇨ Key point to assess a luminosity

Consideration

Potential approach: combine bunches to train not single bunch

- Very short bunch spacing (mm) due to ultra-fast kicker (to be developed)
- Multi-interaction point in stretch-limousine detector
- All bunches collide with all
- Betafunction can be small

At least few mm distance to increase beta-function to level that it is channeled
e.g. in diamond β>2cm for ε=40 nm @ 7 TeV



Very short focusing systems are required

- Crystals, beams, plasma could be options
- But need strong focusing, maybe not possible

But few points of collision would already help

Is this insane?
Very well possible

Note scheme could also improve production
Few thinner targets in a row

Muon production target

Criteria for target design: maximise the brightness

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

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

Muon production target: constraint (solid)

Constraints

- Very high Peak Energy Density Deposition with high local temperature rise (limit on beam spot ~10μm for solid target from single bunch simulations)
- High deposited power (~100kW, to be distributed on a large surface)

Knobs

- To contrast high PEDD and distribute deposited power:
  - Fast rotating wheel (20000 rpm) (for free with liquid jet)
  - multiple targets and reduced angular velocity
  - e^+ beam bump every 1 bunch muon accumulation

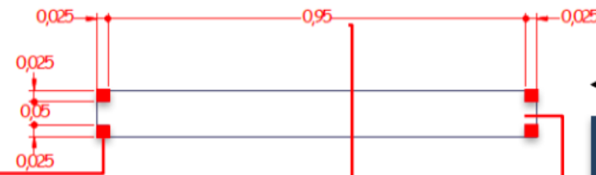
Next steps

R&D experimental tests & engineering simulations required to find the optimal target material considering the mechanical stress and heat load resistance

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

Power dissipation



- beam spot of σ=20 μm
- radiation in vacuum to cool down

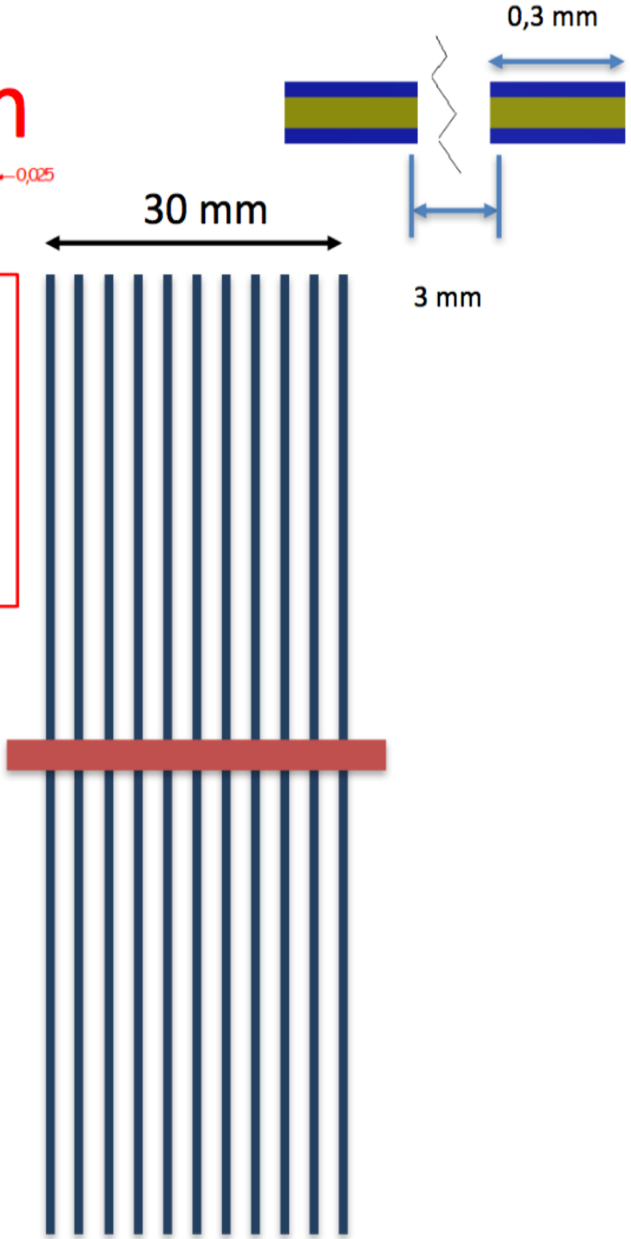
Distribute bunches in 10 rotating disks

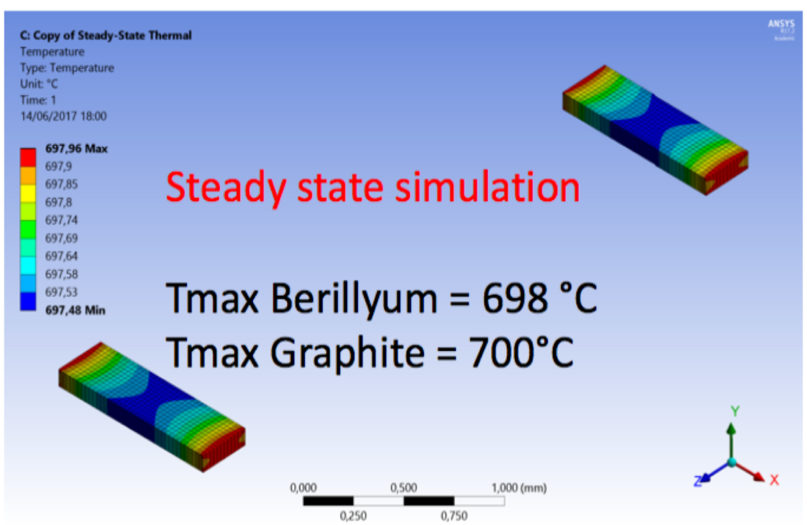
400k beam spots:

1 mm (beam bump) in

50 μm space (disk rotation) in rϕ

100 kW distributed in 400k spots and 10 disks





Plan & achieved performances

- **Limit of PEDD not straightforward to assess, detailed studies and measurements are needed**
- **We plan to start engineering simulations with Ansys Autodyn and LS-DYNA**
- **R&D test at DAFNE to benchmark and validate simulation extremely helpful**

- F.L. Maciariello *et al.*, TUPMB052, IPAC2016: scale test for HL-LHC at HiRadMat, 5.8×10^{13}p on 100μm, C-based targets, goal: validate a material with the capability to withstand intense particle beam impacts lasting very short time and reaching temperatures >1000°C
  -> used as ref. for our aim:$3\times10^{11}e^{+}$ bunch on the 10 μm scale

- Kavin Ammigan 6th High Power Targetry Workshop: experiment at HiRadMat, safe operation with 1.7×10^{11} p/bunch, up to 288 bunches in one shot beam size 300 μm, thin Be target
  -> Be target was the starting point for our studies
- A. Knecht, NuFact17: Power removal by radiation cooling, PSI muon beam upgrade project HiMB, C-based target at 60kW at 1700 °C

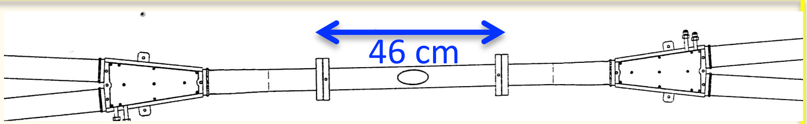
LEMMA Test beam at DAΦNE

- **Beam dynamics study of the ring-plus-target scheme:**
  - transverse beam size / current / lifetime
- **Measurements on target:**
  - temperature (heat load) / thermo—mechanical stress

GOAL of the experiment:

- **Validation LEMMA studies**, benchmarking data/expectations
- **Target Tests**: various targets (materials and thicknesses)

After SIDDHARTA-2 run, possibly in 2020



SIDDHARTA-1 IR

The target will be placed at the SIDDHARTA IP because:

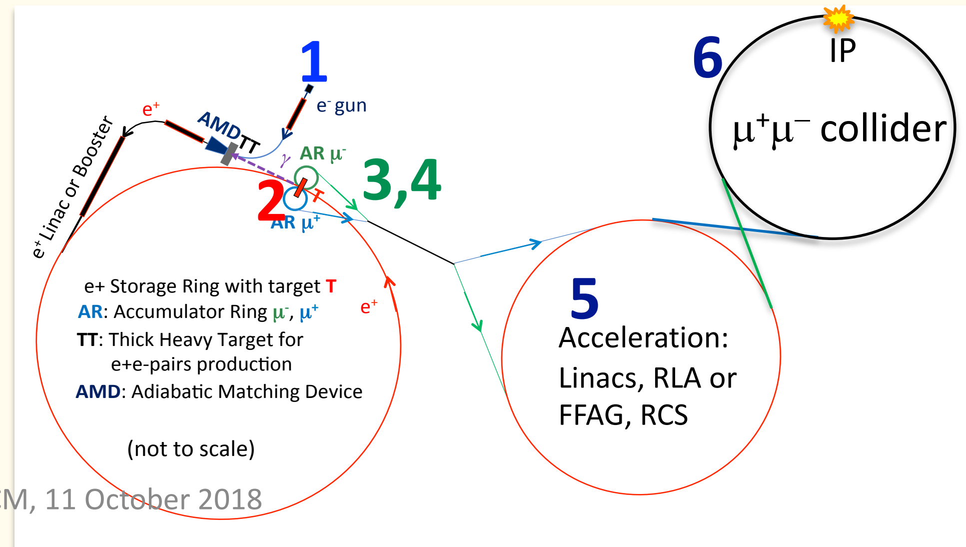
- low-β and D_x=0 is needed (similarly to IP requirements)
- to minimize modifications of the existing configuration

Possible different locations for the target can be studied

Ref. M. Boscolo *et al.*, "*Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target,* MOPMF086, IPAC18

LEMMA Key steps

1. **e^+ source / e^+ beam** → goal: maximize rate at muon target
2. **$\mu^{+/-}$ production target** → goal: reach limit for PEDD and thermo-mechanical stress (to produce the best possible muon beam emittance and intensity)
3. **Muon Accumulator Rings** → goal: preserve muon emittance and maximize bunch intensity
4. **Muon Recombination scheme and injection scheme** → enhancement factor needed to maximize lumi
5. **Fast acceleration**
6. **Muon Collider**



R&D on high rate positron source

- R&D on this topic can take advantage of **significant synergies with future e+e- 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.
- Optimization of the **e+ ring** automatically relaxes the e+ source requirements.

e^+ production rates achieved (SLC) or needed

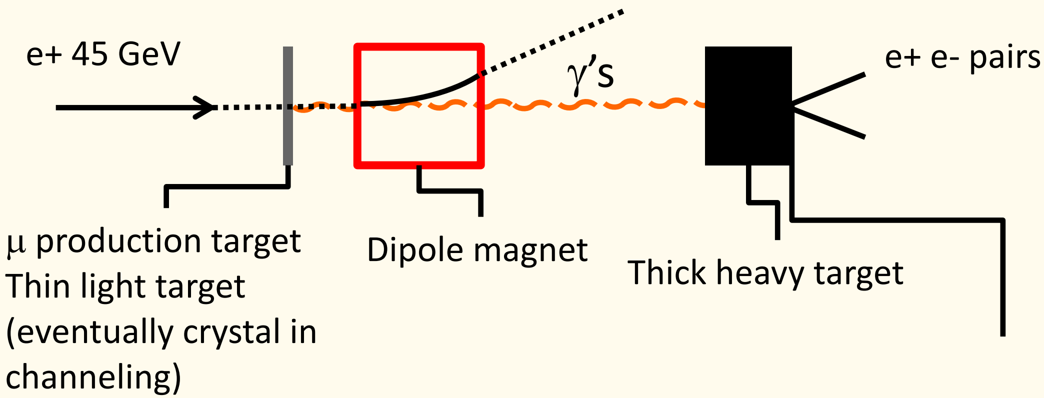
	S-KEKB	SLC	CLIC (3 TeV)	ILC (*H*)	FCC-ee (*Z*)	LEMMA
10^{14} e^+ / s	**0.025**	**0.06**	**1.1**	**2**	**0.05**	**100**

Present: 3 mm Be, 40 turns lifetime, ΔN/N=2.5%, ΔN=2.5E+16, P= 247 MW
Goal: 3 mm Be, 240 turns lifetime, ΔN/N=0.4%, ΔN=3.8E+15, P= 39 MW

R&D on high rate positron source

Self-amplified 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 Collider

- Luminosity table depends on:
  - muon bunch intensity
  - muon emittance
  - Energy

- First step: 3 TeV beam energy to compare with MAP
- Next steps:
  - LHC tunnel
  - FCC tunnel

- Design Final Focus scheme
- Injection scheme

Conclusion

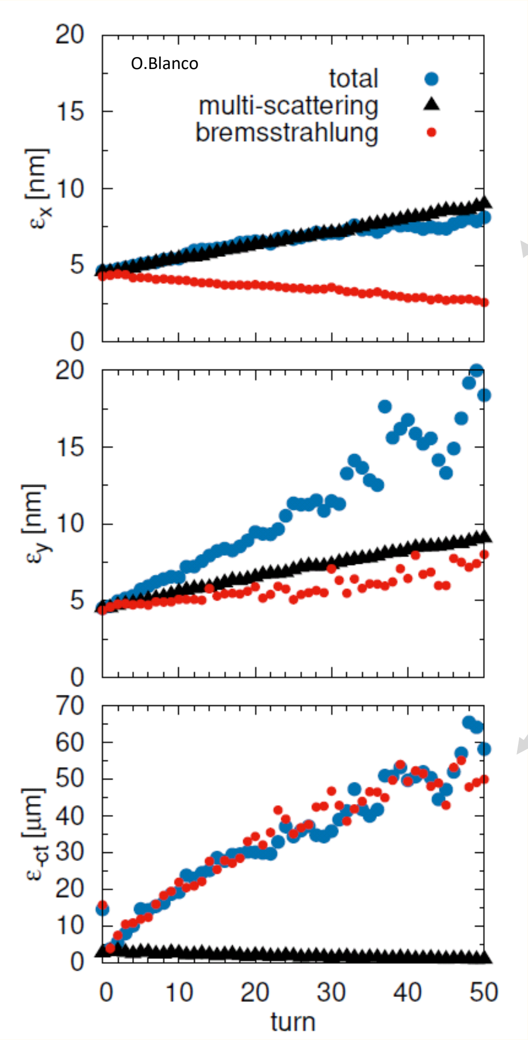
Our goal is to define the potentiality of this concept for a multi-TeV MC:

- **in terms of luminosity and beam power**
- **conceptual design of the whole the accelerator complex**
- **identify and possibly start with the necessary key R&D**

Presently we are focusing on a layout that maximises muon beam brightness considering the two options of multiple solid targets and liquid target.

Back-up

Positron emittance evolution interacting with target



Positron beam interaction with 3mm Be target: separated contributions of multiple scattering and bremsstrahlung.

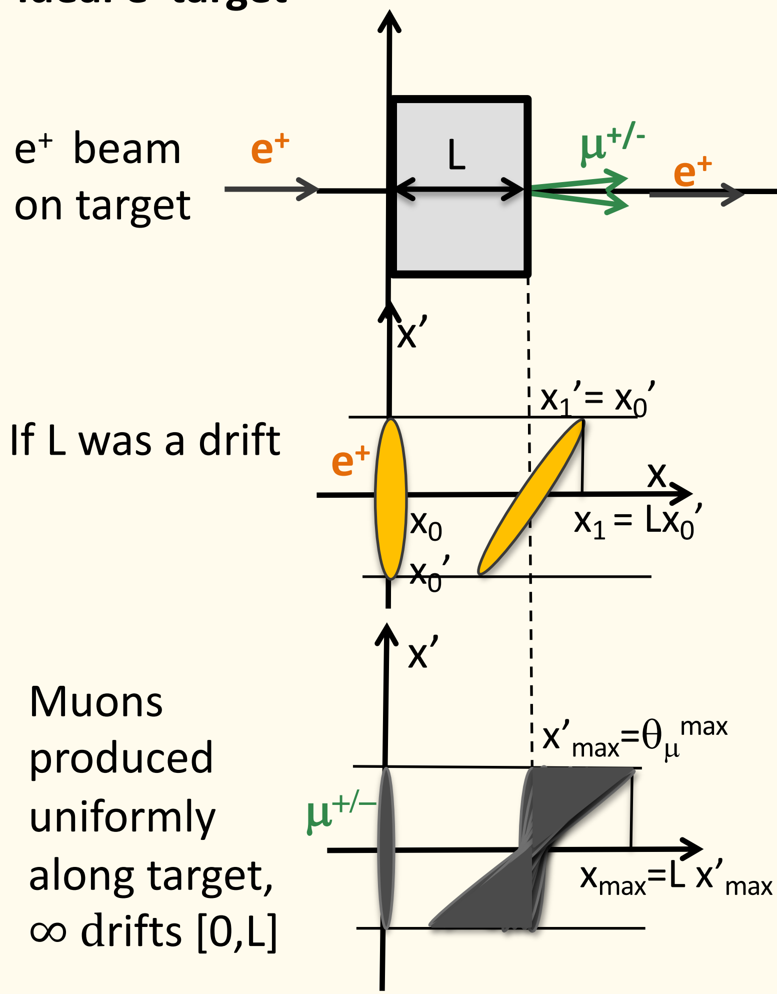
The horizontal emittance increase is dominated by multiple scattering

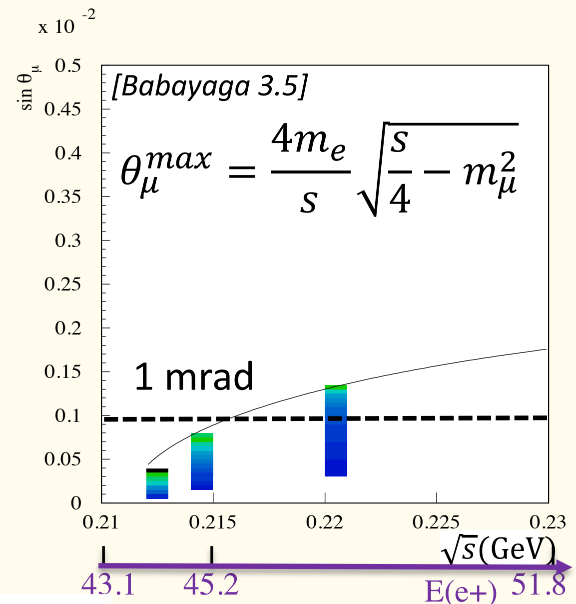
The longitudinal emittance increase is dominated by bremsstrahlung

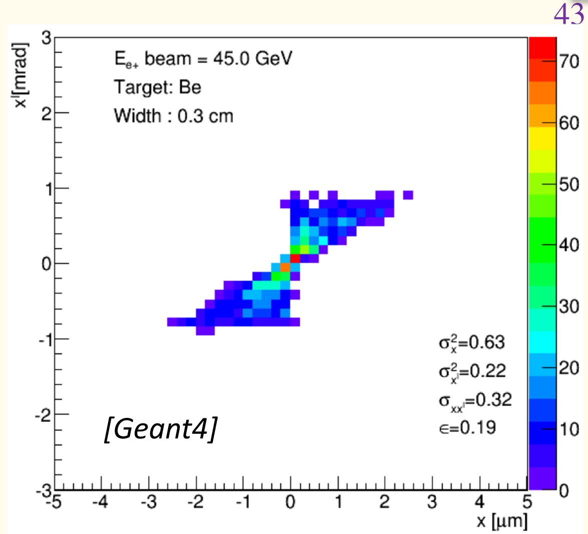
Target optics $\beta_{x,y}$ = 0.5m, η_x = 0.0m

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

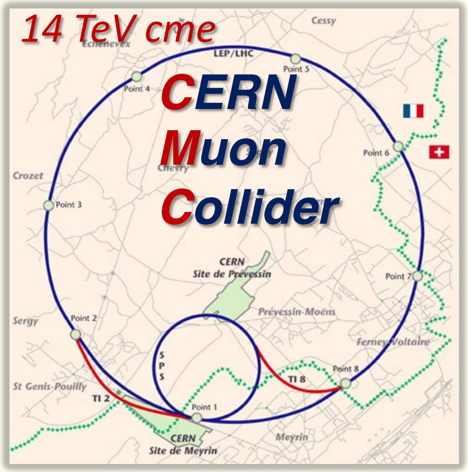
The emittance contributions due to muon production angle: $\varepsilon_\mu = x\, x'_{max}/12 = L\,(\theta_\mu^{max})^2/12$

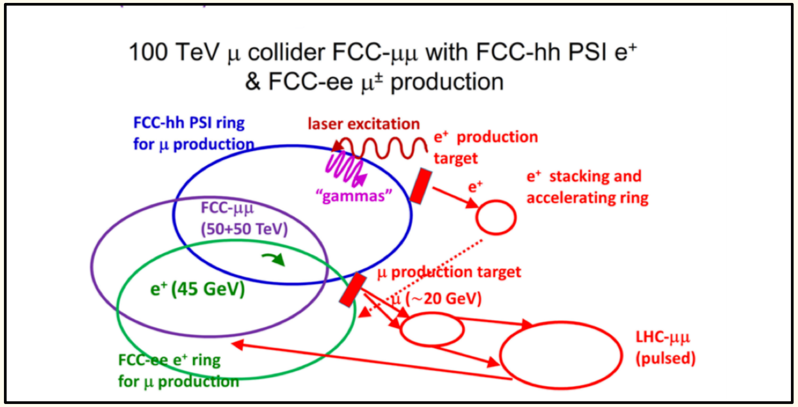
→ ε_μ completely determined by L and s -by target thickness and c.o.m. energy

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 c.m.e.** V. Shiltzev, D. Neuffer, Proc. IPAC18, MOPMF072
  - **LHC/FCC based MC** F. Zimmermann, Proc. IPAC18, MOPMF065





Positron source requirements for LEMMA

	Be 3mm			LI 10mm			H2 lIquid 35mm		
Ring energy acceptance %	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)
5	35	2.69E+16	277	45	2.11E+16	217	78	1.21E+16	125
10	47	2.01E+16	207	62	1.53E+16	157	107	8.86E+15	91
20	71	1.34E+16	39	99	9.53E+15	98	163	5.80E+15	60

To evaluate the number of positrons per second required from the source we assume to have **100 bunches** with **3 10^{11} e^+/ bunch** stored in the ring for one beam lifetime

The drive beam power is given by the number of positrons accelerated per second up to 45 GeV

One of the objectives of the studies on the positron ring is to increase the ring energy acceptance in order to reduce the requirements on the positron source

Present ring: Dp/p = 6%, tau = 40 turns, e^+/s = 2.4e16, P= 250 MW

Target: tau> 100 turns, e+/s < 1e16, P < 100 MW

S. Guiducci, "Positron source options", Muon Collider Workshop, Padova 2 July 2018

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	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 6×10^{9} :** a muon bunch charge of 4.5×10^{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.

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

Muon Production target: criteria for best material

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

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

$N(e^+)$ number of e^+

$\rho(e^-)$ target electron density

L target length

To maximise $N(\mu^+\mu^-)$:

- **$N(e^+)$** max rate limit set by e^+ source
- **$\rho(e^-)L$** max occurs for L or 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 $N_\mu^2 \;\; 1/\varepsilon_\mu$

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

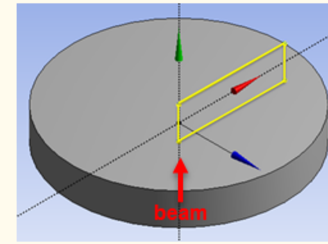
Diagnostics for the test at DAFNE

- **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.
- **Target diagnostics:**
  - Passive Infrared Thermography
  - Infrared radiometry
  - Measurement of surface deformation

A. Stella, R. Li Voti, G. Cesarini

Beam induced strain in thin windows

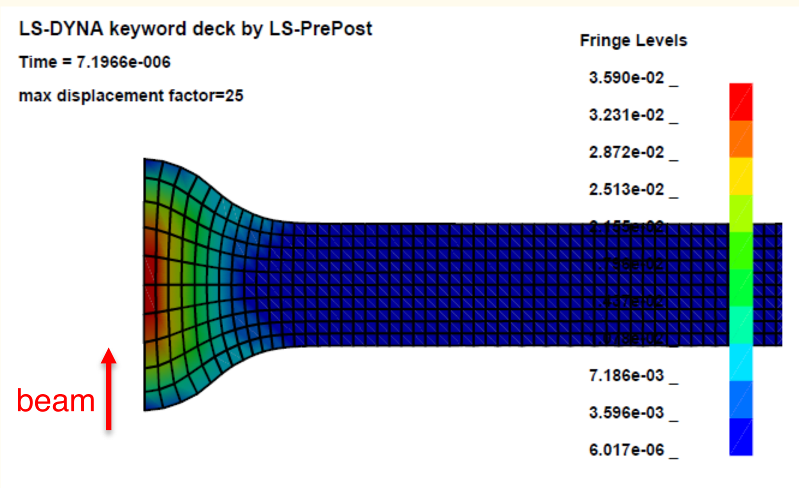
Thermo-structural FEA analyses



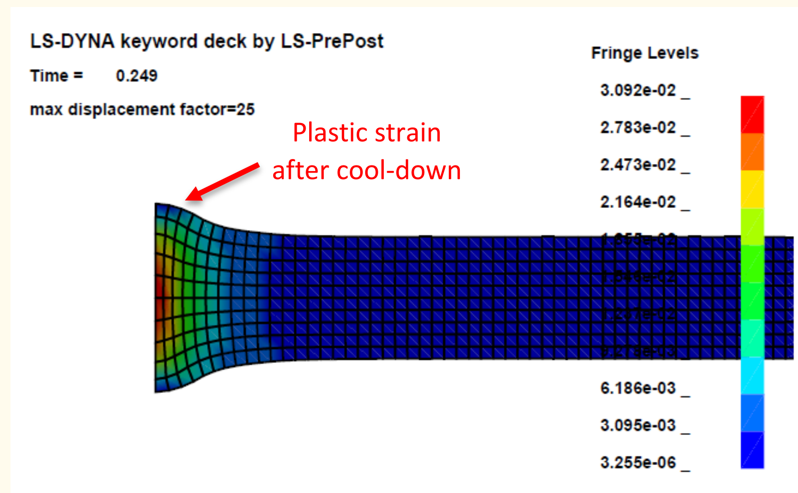
- Temperature and strain rate dependent Be material properties
- LS-DYNA elastic-viscoplastic material model (MAT_106)

2D axisymmetric model showing effective total strain

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



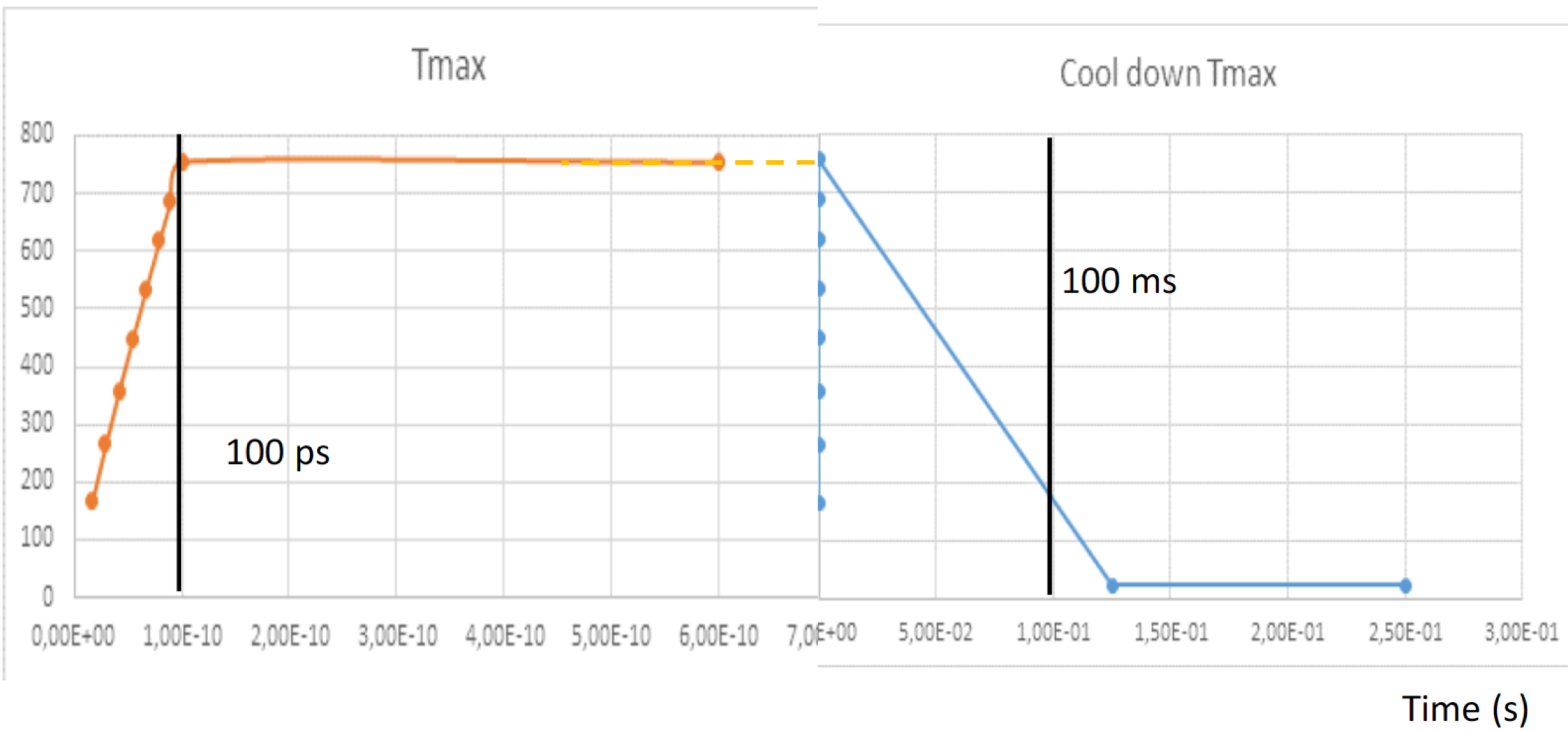
End of beam pulse
$t = 7.2\ \mu s$, $T_{max} \sim 1050$ °C, $\varepsilon_{max} \sim 3.6$ %



End of cool-down
$t > 0.25$ s, $T \sim 25$ °C, $\varepsilon_{max} \sim 3.1$ %

One bunch transient ANSYS simulations

20 μm beam spot 3×10^{11} e^+ on target



M. Antonelli, 25/10/17, Lemma general meeting