LEMMA, a novel scheme for producing low-emittance muon beams

S. Guiducci (LNF)

POSIPOL Workshop 2018

CERN 5/9/2018

Bibliography

- M. Antonelli, P. Raimondi, "*Snowmass Report: Ideas for muon production from positron beam interaction on a plasma target,*" INFN-13-22/LNF, 2013
- M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, "*Novel proposal for a low emittance muon beam using positron beam on target,"* NIM in Physics Research A, vol. 807, pp. 101-107, 2016
- M. Boscolo, M. Antonelli, M.E. Biagini, O.R. Blanco-Garcia, F. Collamati, S. Liuzzo, P. Raimondi, *"Studies of a scheme for low emittance muon beam production from positrons on targe*t," Proc. of IPAC17, Copenhagen, 2017
- M. Boscolo, M. Antonelli, O.R. Blanco-Garcia, S. Guiducci, S. Liuzzo, P. Raimondi, F. Collamati, "*Low EMittance Muon Accelerator Studies with Production from Positrons on Target*," Phys. Rev. Accel. and Beams, vol. 21, p. 061005, 2018
- M. Boscolo, M. Antonelli, O.R. Blanco-Garcia, S. Guiducci, F. Collamati, S. Liuzzo, P. Raimondi, L.Keller, D. Schulte, "*Muon Accumulator ring requirements for a low emittance muon collider from positrons on target,*" Proc. of IPAC18, Vancouver, 2018
- M. Boscolo et al., "*Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target*," Proc. of IPAC18, Vancouver, 2018
- ARIES Muon Collider Workshop, Padova, Italy, 2-3 July 2018, https://indico.cern.ch/event/719240/ : ***LEMMA***, M. Boscolo, INFN/LNF, ***Positron Source Options***, S. Guiducci, , INFN/LNF , ***Positron regeneration***, F. Collamati, , INFN/Roma I, ***Muon Accumulator Ring***, O. Blanco Garcia, INFN/LNF, ***Positron Ring***, S. Liuzzo, ESRF, ***Overview of Requirements on targets***, M. Iafrati

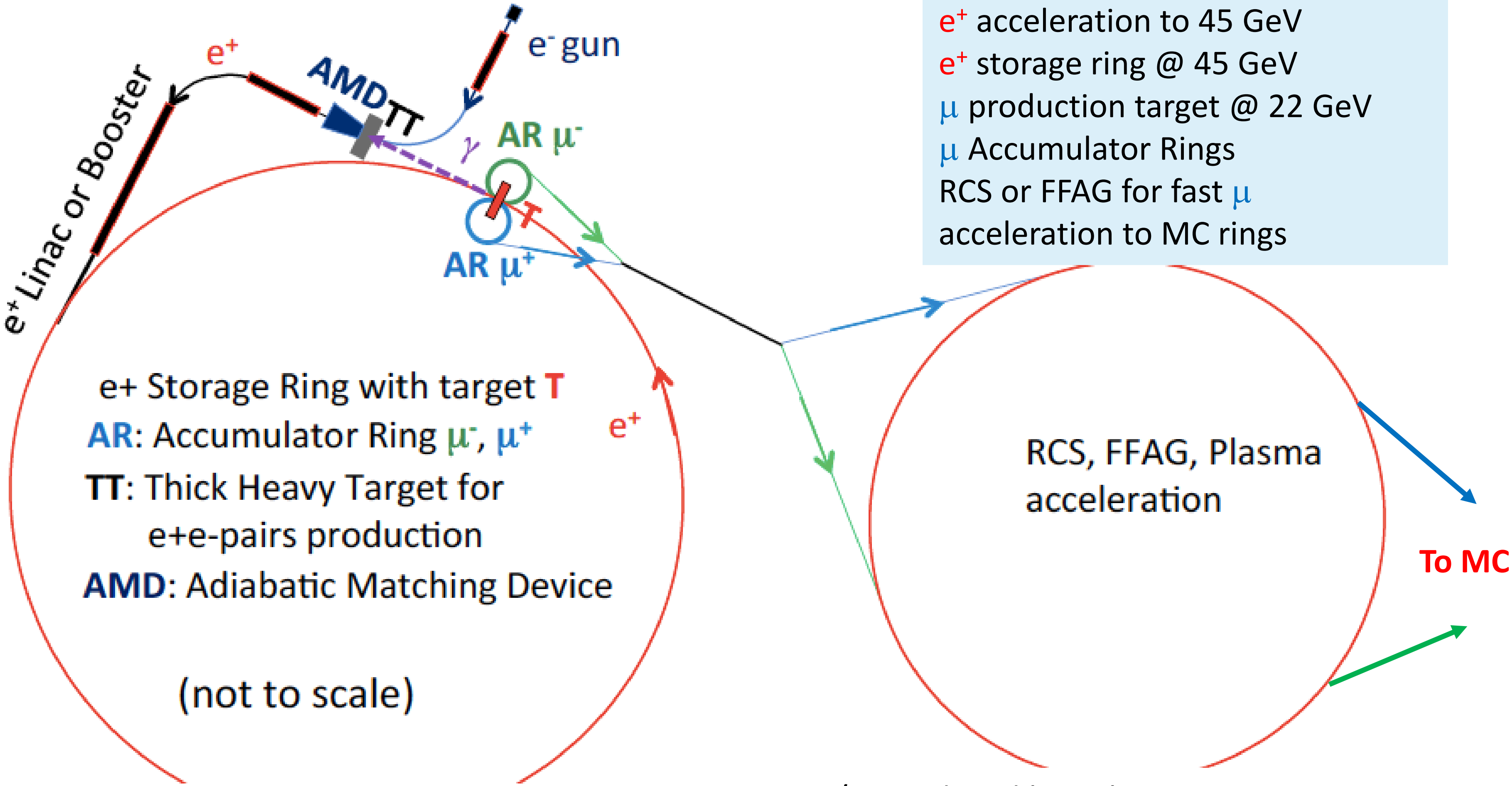
LEMMA proposal

- Alternative concept (first presented at Snowmass 2013): muons produced in e^+e^- interactions close to threshold are constrained to occupy a small region in phase-space → muon beam with a small emittance, comparable to that typically achieved with electron beams, and long laboratory-lifetime due to the boost of the muons in the laboratory frame
- Most important properties of the muons produced by positrons on target are:
  - low and tunable muon momentum in the center of mass frame
  - large boost of $\gamma\sim200$
- Advantages: final state muons highly collimated and with very small emittance → cooling not required
- Muons are produced with average energy of 22 GeV corresponding to an average laboratory lifetime of ~500 μs, which also eases the acceleration scheme
- Possibility of obtaining high luminosity with relatively small muon fluxes thus reducing background rates and activation problems due to high energy muon decays
- While this scheme is appealing for >TeV collisions, its luminosity and energy spread are not suitable for a Higgs Factory

LEMMA ingredients

M. Boscolo

- e^+ high intensity source
- e^+ acceleration to 45 GeV
- e^+ storage ring @ 45 GeV
- μ production target @ 22 GeV
- μ Accumulator Rings
- RCS or FFAG for fast μ acceleration to MC rings



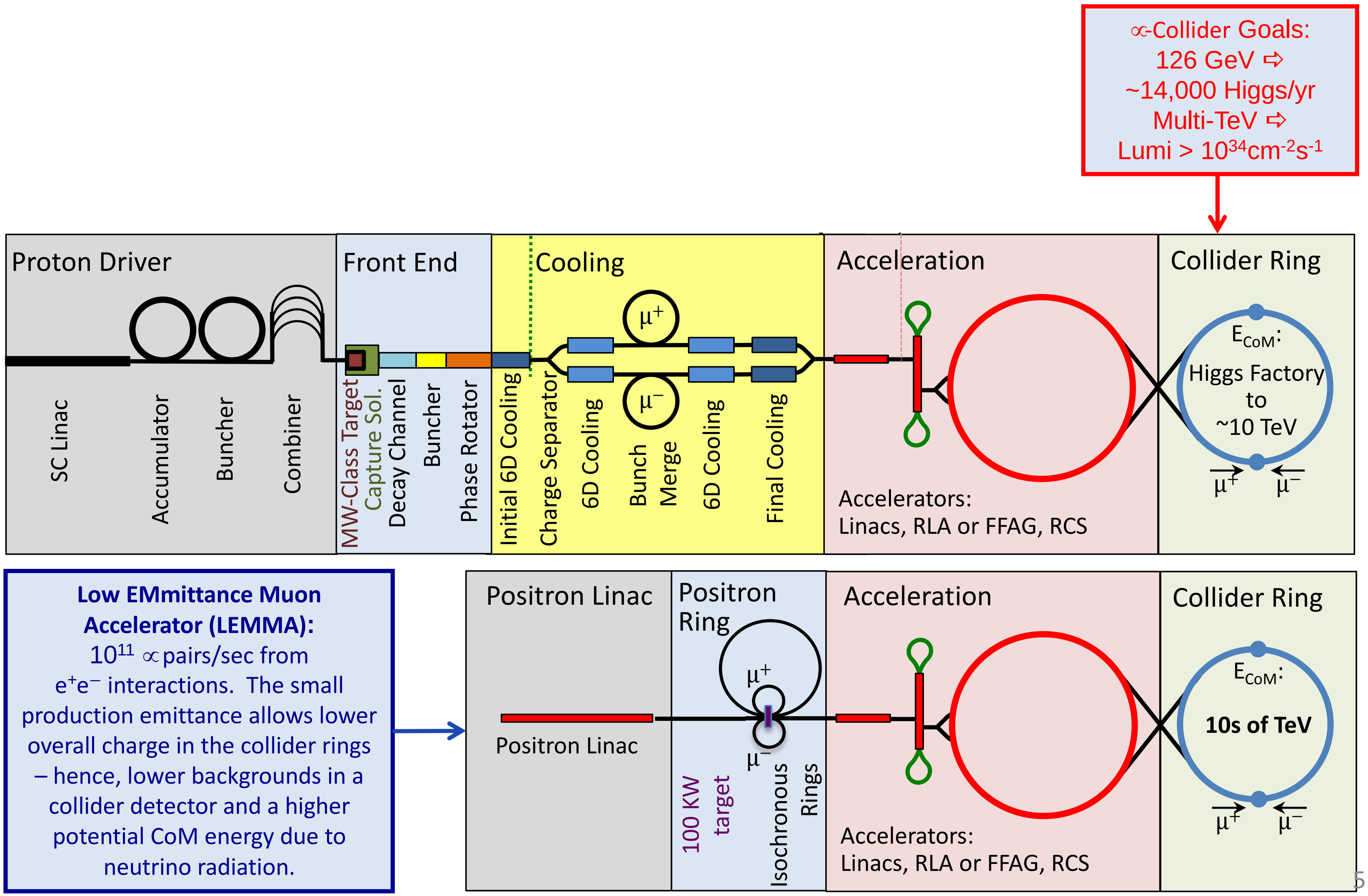
<u>Goal:</u> $\approx 10^{11}$ μ/s produced at target

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

<u>Request:</u> 10^{18} e^+/s needed at target →
45 GeV e+ storage ring with target insertion

- μ^+/μ^- produced by e^+ beam on target **T** @ ~ **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

LEMMA vs Proton Driver

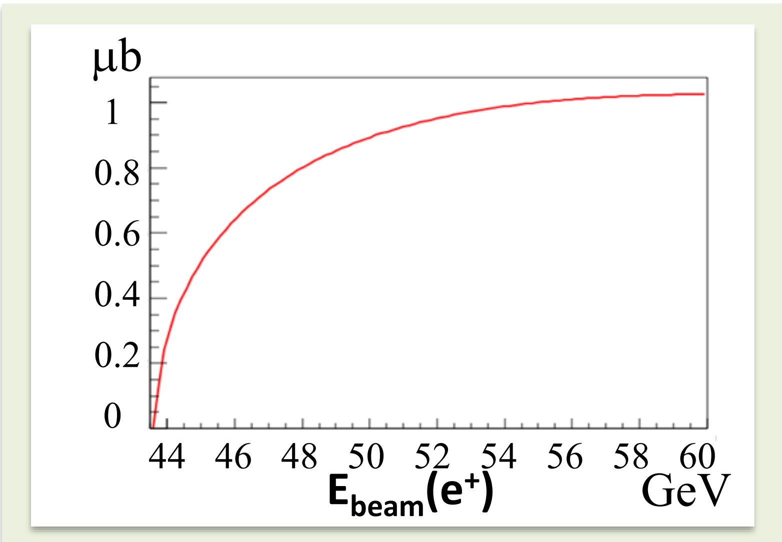


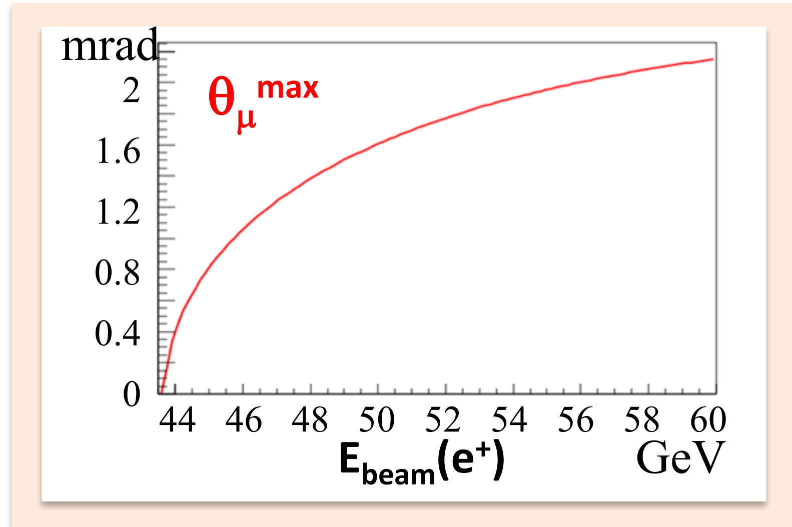
LEMMA pros & cons

- **Pros:**
  - Small emittance muon beam → no cooling needed
    - θ_μ is tunable with √s in $e^+e^- \to \mu^+\mu^-$
    - μ beam divergence can be very small close to the $\mu^+\mu^-$ threshold
  - Lower charge → lower backgrounds in MC
  - Less boundary radiation limitations (neutrinos) from muons decay
  - Possibility of higher c.o.m. energies (>TeV)
- **Cons:**
  - Energy spread too large for a Higgs Factory
  - Lower muon production rate
    - much smaller cross section wrt proton-driven-source
    - $\sigma(e^+e^-\to\mu^+\mu^-) \approx 1\ \mu b$ at most wrt σ(from p)$\approx$ mb
  - Technical challenges

Cross-section, $\mu^{\pm}$ beam divergence and energy spread vs e^{+} beam E

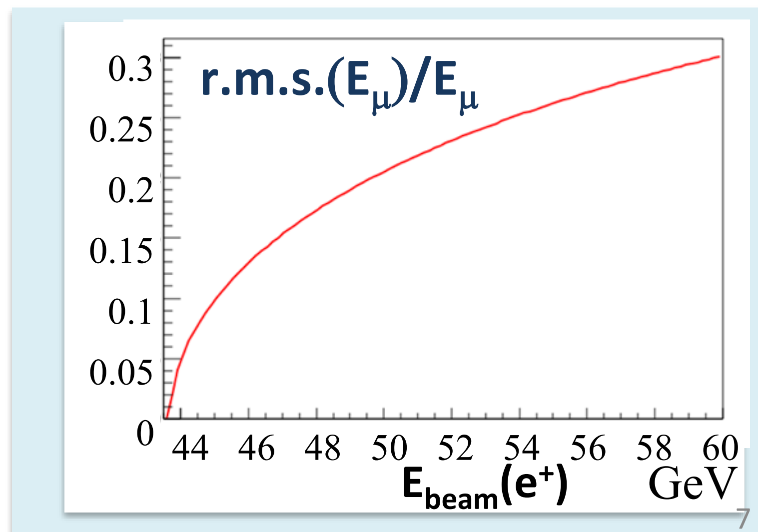
$\sigma(e^{+}e^{-} \rightarrow \mu^{+}\mu^{-})$





Value of √s (*i.e.* $E(e^{+})$ for atomic e^{-} in target) has to

- maximize muons production
- minimize beam angular divergence and energy spread



@ 50 GeV production rate increases,
but so do production angular divergence and energy spread
However since MCS (>> θ_{μ}^{rms}) dominates σ'_{μ},
50 GeV can be considered

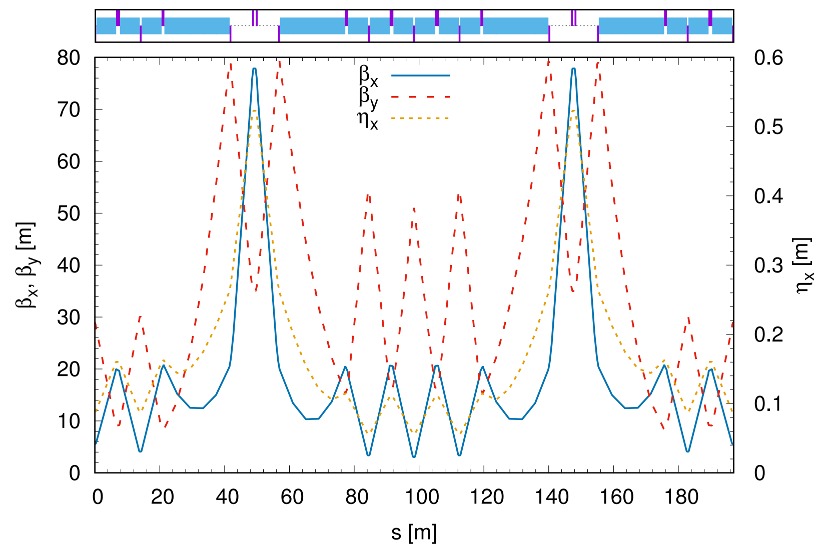
Positron ring lattice

TABLE I. Positron ring parameters.

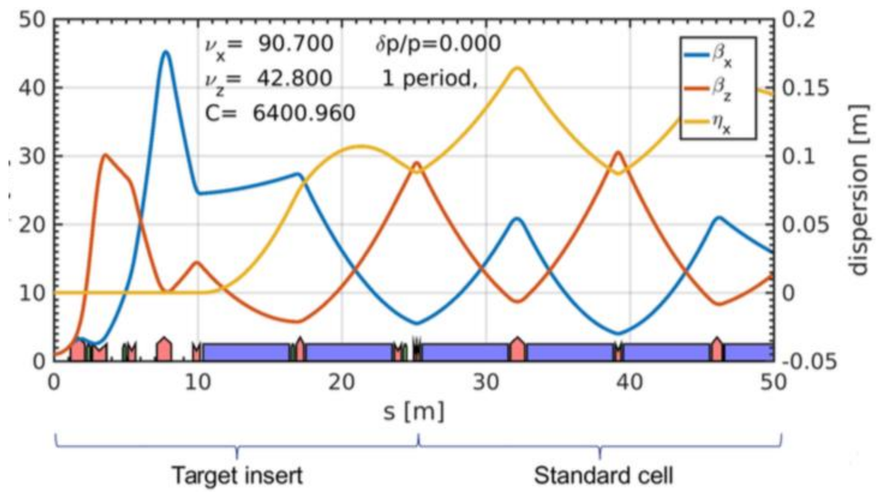
Parameter	Units	
Energy	GeV	45
Circumference (32 ARCs, no IR)	m	6300.960
Geometrical emittance x, y	m	5.73×10^{-9}
Bunch length	mm	3
Beam current	mA	240
RF frequency	MHz	500
RF voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
N. particles/bunch	#	3.15×10^{11}
Synchrotron tune		0.068
Transverse damping time	turns	175
Longitudinal damping time	turns	87.5
Energy loss/turn	GeV	0.511
Momentum compaction		1.1×10^{-4}
RF acceptance	%	$\pm$ 7.2
Energy spread	dE/E	1×10^{-3}
SR power	MW	120

2 cells out of 34 have been modified for target insertion

Optical functions in one of 32 ring cells



Target Insertion Region



At target: zero dispersion $\eta_x = 0$ and low beta $\beta_{x,y} = 0.5$ m

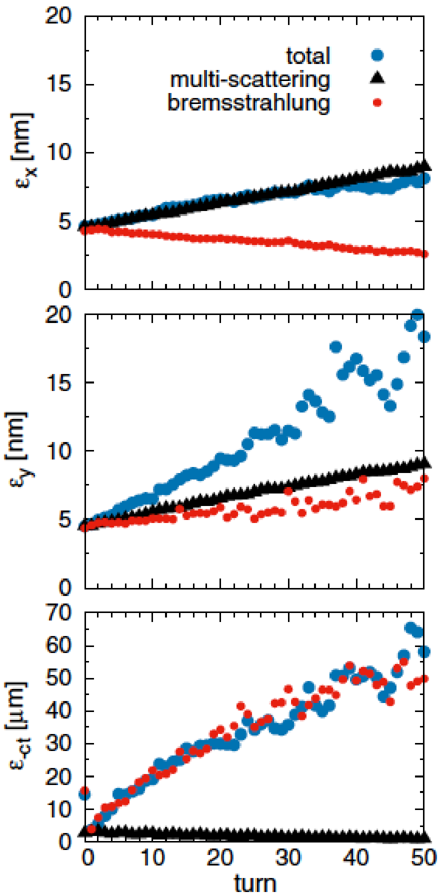
Multi-turn tracking with target insertion

1. Initial 6D distribution from the equilibrium emittances
2. 6D e^+ distribution tracking up to the target (AT and MAD-X PTC), including synchrotron oscillations and damping
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 resulting in a transverse emittance increase
- undergoes **bremsstrahlung energy loss** producing a loss of the particles with energy loss larger than the ring acceptance and transverse and longitudinal emittance increase

Multi-turn tracking with 3 mm Be target

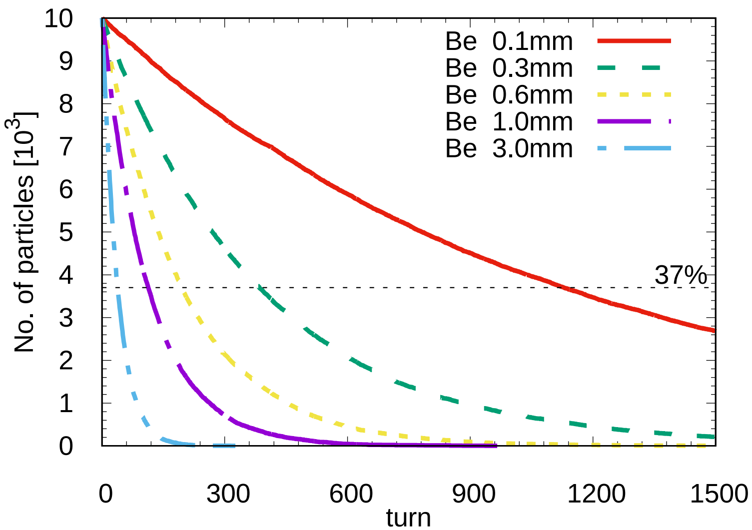


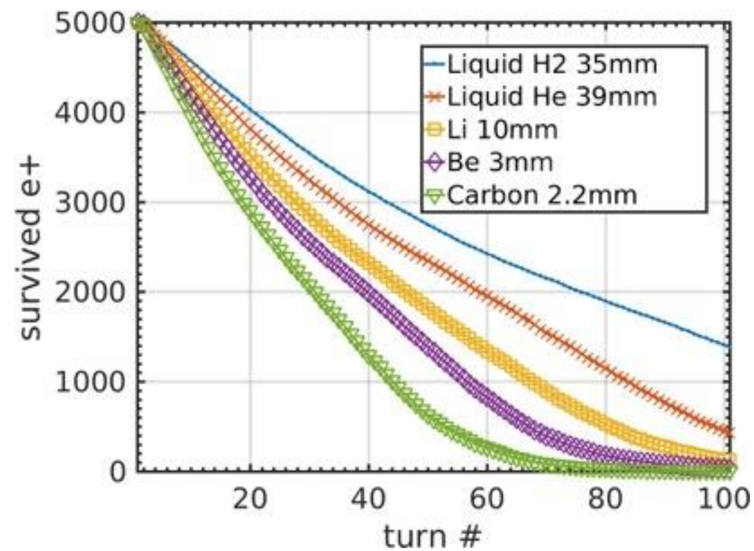
Horizontal (top), Vertical (middle) and Longitudinal (bottom) emittance degradation vs #turns

- The effects of MCS (black) and Bremsstrahlung (red) are considered separately and combined (blue)
- MCS dominates H emittance. With Bremsstrahlung only the H emittance is not increased since dispersion and its nonlinear terms are zero. Moreover damping and particle losses decrease the emittance
- For the V emittance the MCS contribution is the same as the H one. The Bremsstrahlung contribution is higher due to dispersion nonlinear terms
- L emittance increase is dominated by Bremsstrahlung

Bremsstrahlung can be controlled with zero dispersion (and its derivatives) in the transverse plane, by very small momentum compaction in the longitudinal plane, MCB needs a low β

e^+ ring beam lifetime studies





Number of e^+ vs #turns for different thickness of Berillium target
Lifetime ∝ 1/thickness as expected

Number of e^+ vs #turns for different target materials - Target thickness chosen for constant muon yield

Lifetime is determined by the number of particles with bremsstrahlung energy loss larger than momentum acceptance

Beam lifetimes are in agreement with calculations for 6% ring energy acceptance
For 3 mm Be target the percentage of particles with > 6% energy loss per turn is 2.5% corresponding to 39 turns beam lifetime

e^+ ring lattice with 26.7 km circumference

- Two designs for 6.3 Km and 26.7 Km, with same Hybrid Multi Bend Achromat cell, derived from ESRF Upgrade design (to be installed next year @ Grenoble)
- 27 km lattice has much smaller emittance and about the same energy acceptance
- 27 km lattice gives potentially equivalent μ beams with the same e+ current and the same e+ production rate
- Synchrotron radiation losses much more sustainable in longer ring

e^+ 45 GeV	Units	e+ ring parameters	
C	Km	6.3	27
N cells	#	32	**64**
n_e (bunches)	#	100	428
n_μ (bunches)	#	1	1
ε_x	nm	6	0.7
Current	A	0.24	0.24
$C_{m,acc}$	m	63	63
Turns for accumulation	#	25	6
N_{e+} / bunch	e+11	3	3
N_μ / bunch	e+7	4.5*	4.5*
U_0	GeV	0.51	0.12
Synch. power	MW	122	29

* 3mm Be @ 45GeV

Muon emittance contributions

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

$\varepsilon(e^+)$ = e^+ emittance
ε(prod)= muon production contribution
ε(AR) = MCS contribution in accumulator ring

e^+ and μ optics parameters at target

θ_μ mrad	ϵ_{e^+} nm	$\beta^*_{e^+}$ m	σ_{e^+} μ m	σ'_{e^+} mrad	σ'_μ mrad	ϵ_{μ^+} nm
1	10	0.01	10	1	1.41	14.1
1	10	1.00	100	0.10	1.0	100
0.5	10	0.01	10	1	1.12	11.2
0.5	10	1.00	100	0.1	0.51	51.4

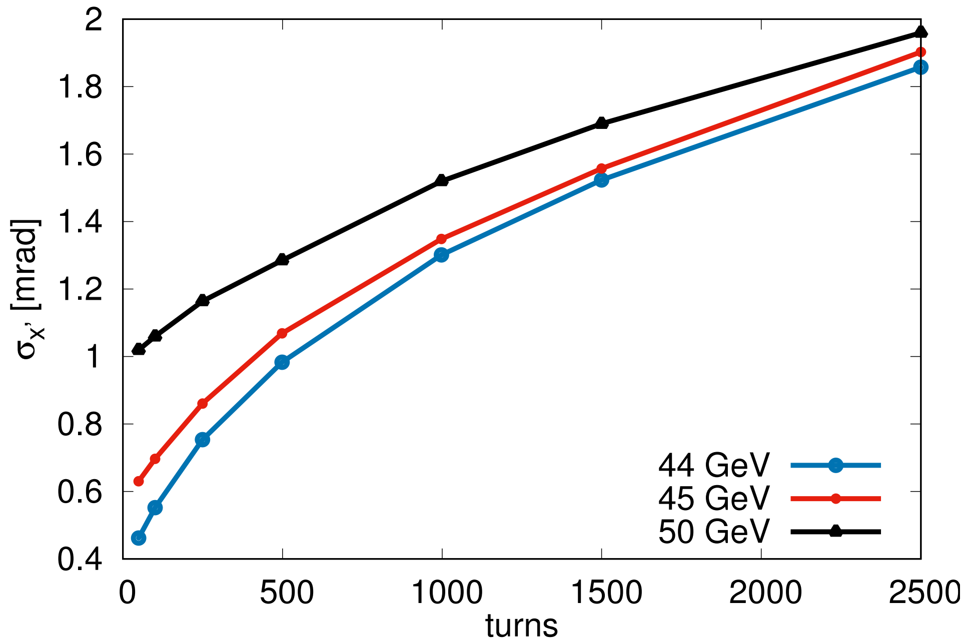
θ_μ = rms muon production angle
For 3mm Be target at 45 GeV it is θ_μ = 0.47 mrad and the muon production beam size is σ_x = 0.79 μm (negligible with respect to e^+ beam size)
Muon emittance is estimated by quadratic combination of positron and muon beam sizes and angles
and it is essentially given by the positron beam spot and the muon production angle
The $\beta *_{e+}$ value is chosen to get a given e^+ beam spot at the target

Multiple Coulomb Scattering in the Accumulator Ring

The circulating muons undergo multiple Coulomb scattering in the target at each accumulator revolution

The turn by turn effect on the muon beam divergence is shown in the picture for three e^+ beam energies The contribution from the muon production angle is also included

The the final angular spread is almost independent on the e^+ beam energy, this suggests to increase the e^+ beam energy to benefit of the larger production cross section



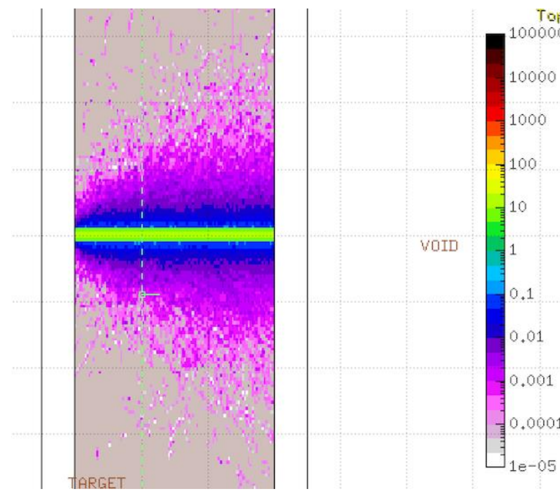
Muons beam angle due to multiple scattering in the AR as a function of turns for a 3 mm Be target

Muon production target studies

- Core topic for LEMMA success
- Thermo-mechanical stress is the main issue due to the very high Peak Energy Density Deposition
- 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
- Experimental tests at @CERN-North Area in 2017 and 2018
- Tests proposed for DAΦNE ring after 2020

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 mechanical stresses dynamics
  - Start using FLUKA + Ansys Autodyn (collaboration with CERN EN-STI)
- Experimental tests:
  - **DAΦNE** available from 2020



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

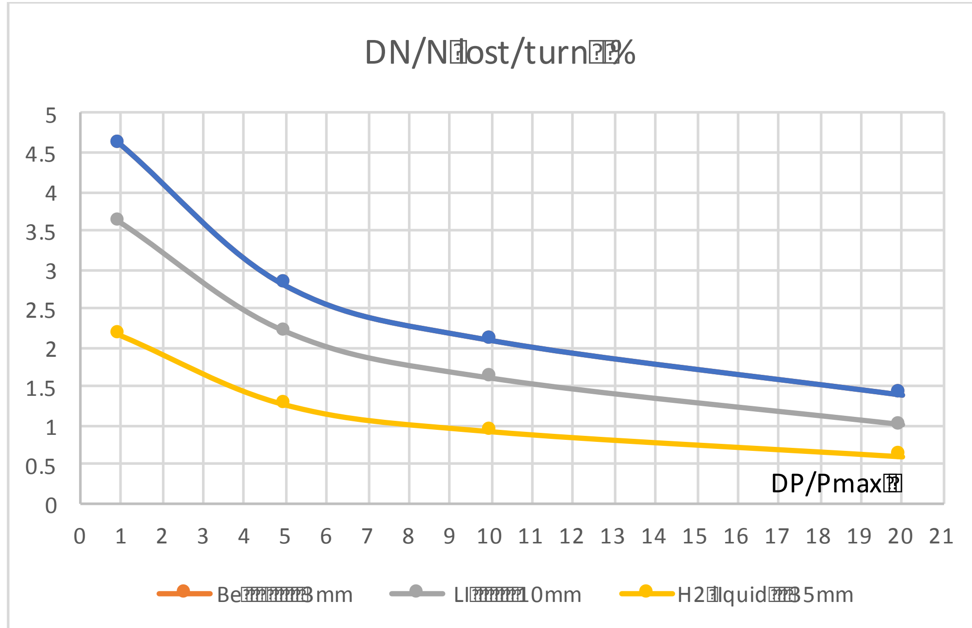
Positron source requirements for LEMMA

- Positrons stored in the LEMMA ring lose energy for bremsstrahlung at each passage in the target
- When the energy loss is larger than the ring acceptance the positrons get lost
- For a given type of target (length and material) it has been evaluated with a FLUKA simulation the percentage of particles with an energy loss larger than the ring acceptance
- The percentage of particles lost per turn gives the beam lifetime and the requirements for the positron source

Positron loss per turn due to target interaction

DN/N lost/turn %

Ring energy acceptance %	Be 3mm	LI 10mm	H2 liquid 35mm
1	4.6	3.6	2.2
5	2.8	2.2	1.3
10	2.1	1.6	0.9
20	1.4	1.0	0.6



The percentage of particles DN/N with an energy loss larger than the ring acceptance (calculated from a FLUKA simulation) are listed in the table for different values of the ring acceptance and for 3 different targets

The target thickness has been chosen to have the same number of muons produced per incident positron

FLUKA simulation, F. Collamati

Positron drive beam power

Ring energy acceptance %	Be 3mm			Li 10mm			H2 liquid 35mm		
	e^+ beam lifetime (turns)	DN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	DN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	DN/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

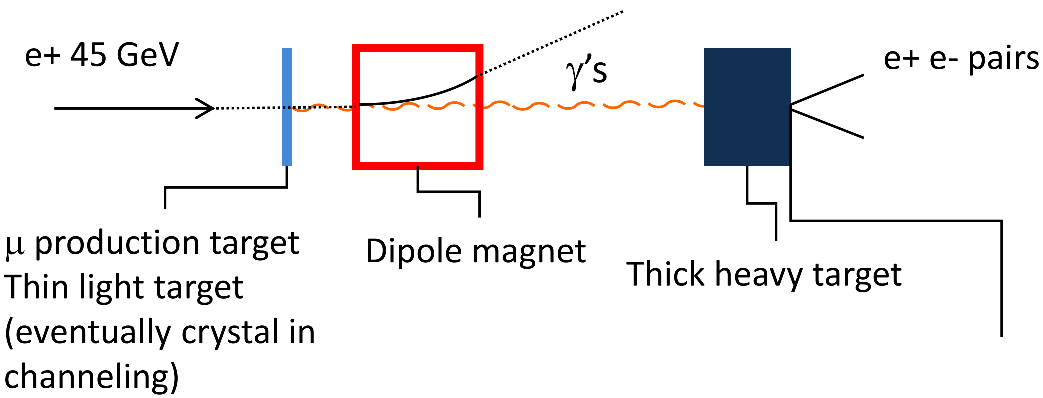
One of the objectives of the studies on the positron ring is to increase the ring energy acceptance in order to reduce the requirements on the positron source

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

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

LEMMA Proposal: embedded e+ source

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 (5 MHz CW) to one that is compatible with the requirement of a standard positron injection chain

F. Collamati presentation

LEMMA challenges

- Internal target for muon production capable of sustaining very high Peak Energy Density Deposition
- Very intense positron beams
- e^+ storage ring with low emittance, very small momentum compaction and very large energy acceptance
- Short Muons Accumulator Rings with very large energy acceptance

⬇

- Optics design for the positron storage ring
- Target definition (one of the crucial aspects for the success, R&D studies and tests)
- Positron source design and injection scheme
- Development of the required techniques for achieving and maintaining high muon rates and low emittance

LEMMA ring + target tests @ DAΦNE after SIDDHARTA-2 run

- 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)

Ref. M. Boscolo, M. Antonelli, O. Blanco, S. Guiducci, A. Stella, F. Collamati, S. Liuzzo, P. Raimondi, R. Li Voti "*Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target*", in publication in **IOP Conf. Series: Journal of Physics: Conf. Series** (IPAC18) also LNF-18/02(IR).

DAΦNE Layout for the LEMMA Test

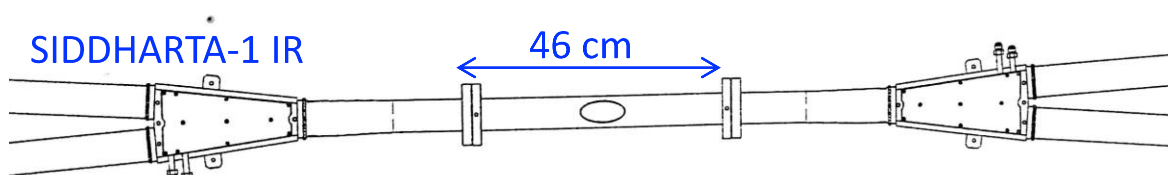
The target will be placed at the SIDDHARTA IP because:

- 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

For the preparation of this experiment we need:

1. Full design of vacuum chamber IR and target insertion system
2. Target design
3. Diagnostics for target thermo-mechanical stress measurements
4. Beam diagnostics
5. Injection scheme (on axis)
6. Optics and beam dynamics



Given the limited energy acceptance of the ring we plan to insert **light targets (Be, C)** with thickness in the range ≈ **100 μm**. Crystal targets can be foreseen too.

Conclusions

- MC studies have been carried out since many years, recently new impulse given from LEMMA idea to avoid cooling by producing μ from low emittance e^+
- Very challenging proposal
- Strong synergy with positron sources for future e^+e^- colliders
- Needs still lot of studies, R&D effort and … new ideas