INFN LNF
Istituto Nazionale di Fisica Nucleare

Low emittance muon accelerator studies

M. Boscolo (INFN-LNF),
M. Antonelli, O. R. Blanco-Garcia, S. Guiducci (INFN-LNF),
S. Liuzzo, P. Raimondi (ESRF), F. Collamati (INFN-Rm1)

gratefully acknowledging input from all contributors

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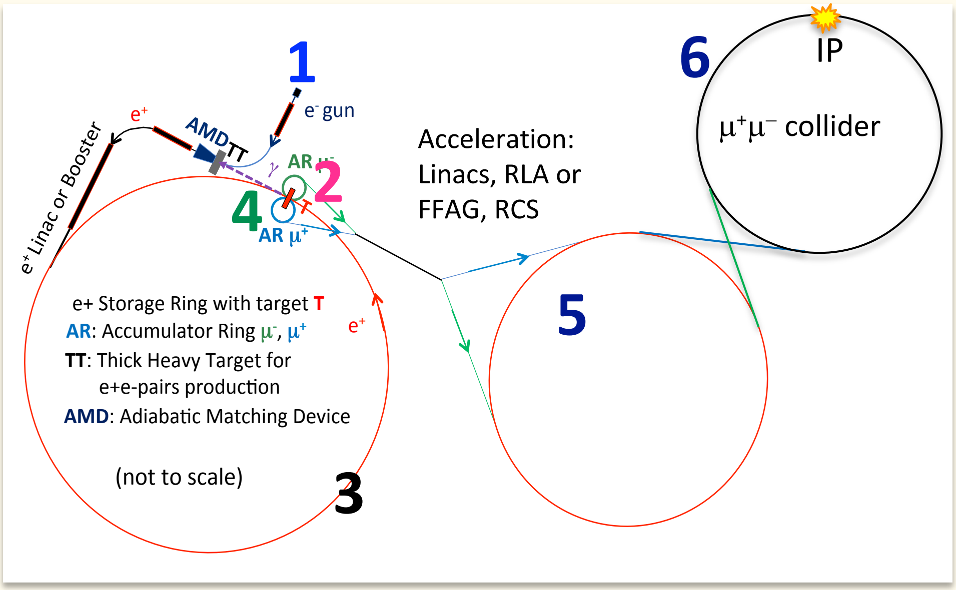
Outline

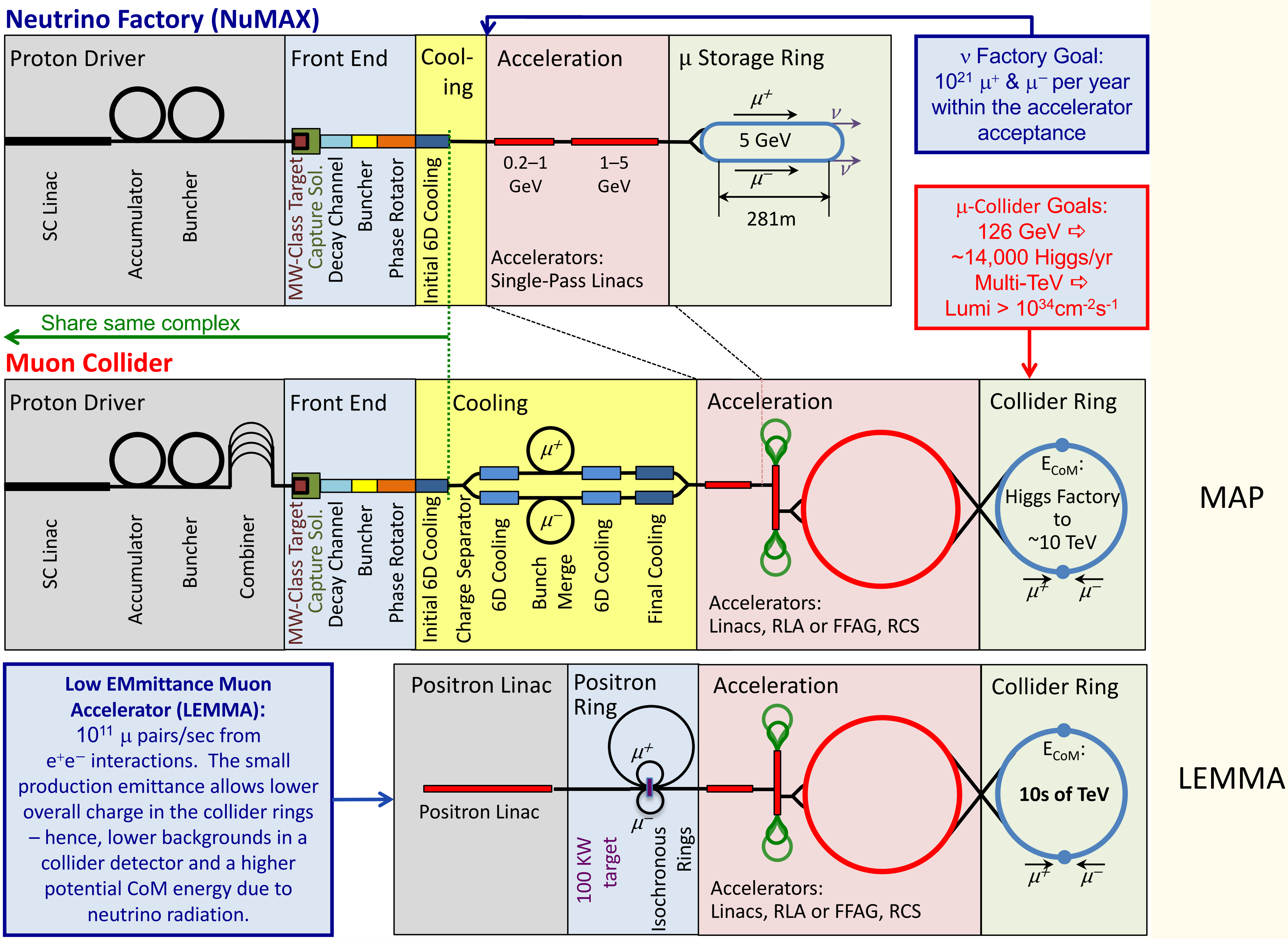
Status of the accelerator studies for LEMMA following the key steps of the scheme

1. High rate **e^+ source**
2. **$\mu^{+/-}$ production target**
3. **e^+ ring**
4. **Muon Accumulator Rings**
5. **Fast acceleration**
6. **Muon Collider**



Main Refs:

- MB *et al.* Phys. Rev. Accel. and Beams 21, 061005, June 2018
- ARIES Muon Collider workshop, Padova, 2-3 July 2018
- MB, J.P. Delahaye and M. Palmer ArXiv:1808.01858



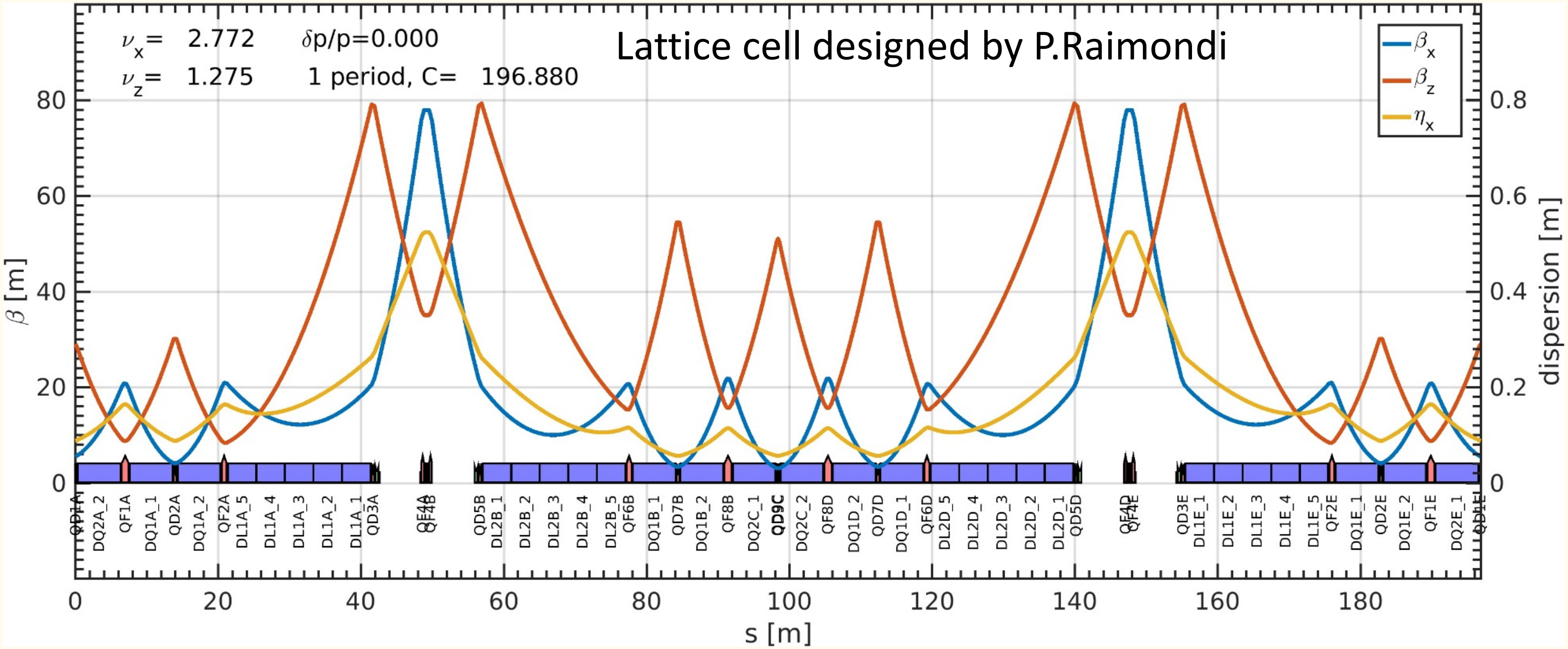
[ArXiv: 1808.01858]

Low emittance 45 GeV positron ring

Ref. PR-AB 21, 061005 (2018)

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

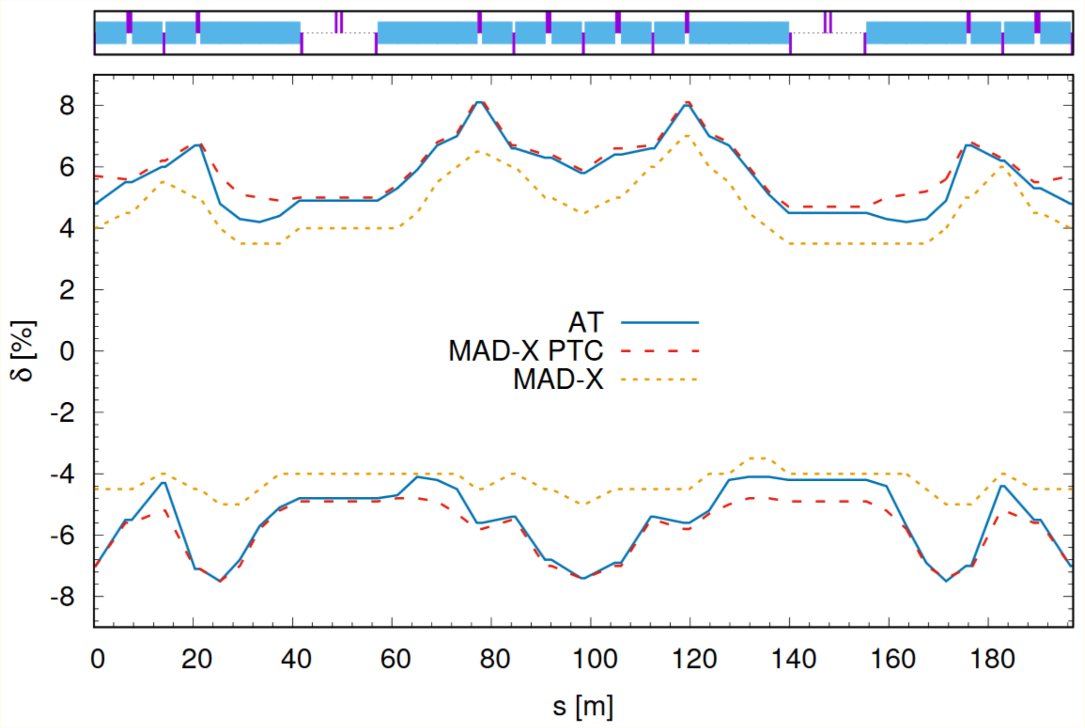


Optics Cell Based on the
Hybrid Multi Bend Achromat

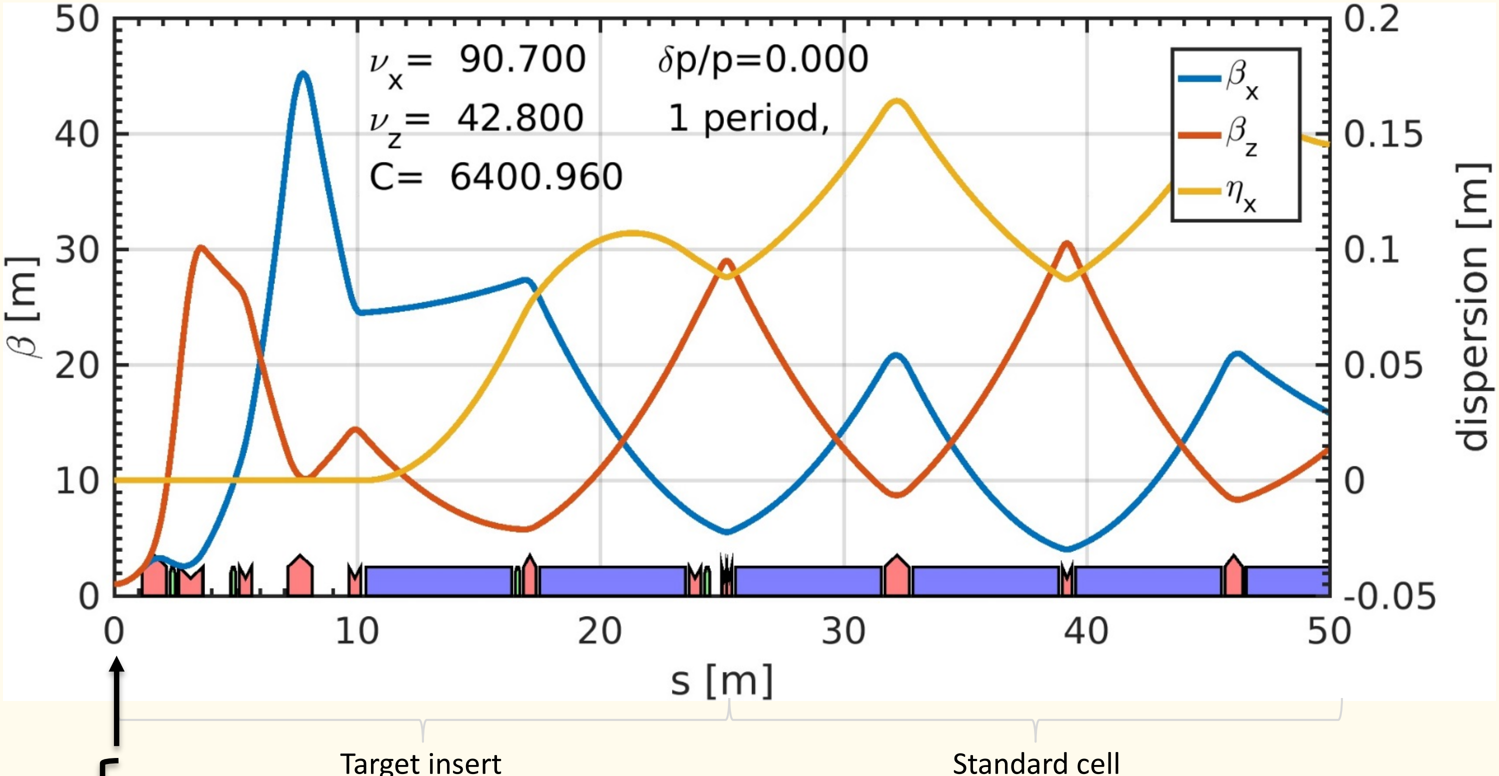
- circumference 6.3 km: 197 m x 32 cells
- Lattice includes radiation and RF
- no injection section yet
- filling factor 77%
- max dipole field 0.26 T
- 64 RF cavities, each cavity: 5.4m, 9-cells, 7 MV/m

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.



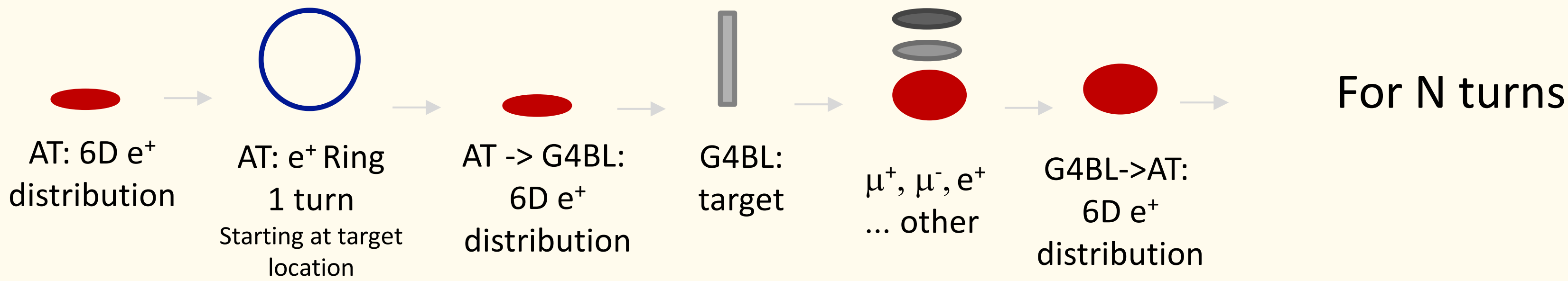
Target Insertion region



@target $\left\{ \begin{array}{l} \mathbf{D_x \approx 0} \\ \textbf{low-}\boldsymbol{\beta}\ (\boldsymbol{\beta_{x,y}} \mathbf{=0.5\ m}) \end{array} \right.$

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.

Including the target effect in AT



At each turn:

1. Accelerator Toolbox (AT, matlab) tracks any 6D e+ distribution
2. The 6D e+ distribution is converted to Geant4BeamLine* (G4BL) units
3. The 6D distribution is tracked trough the target in G4BL
4. The G4BL output 6D positron distribution is converted back to AT

The initial 6D distribution is obtained using the equilibrium emittances in AT

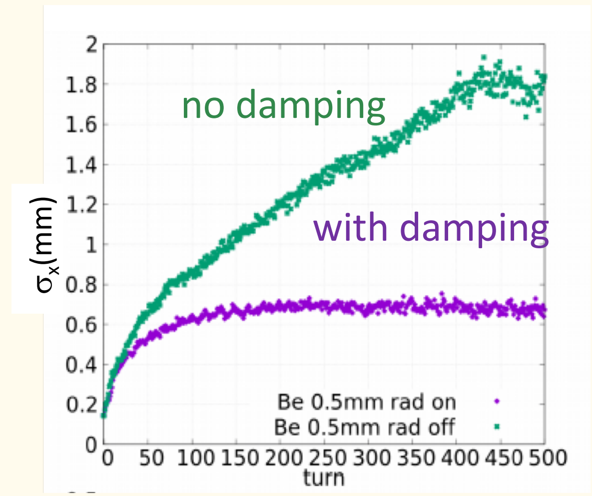
* Gean4BeamLine, Muons Inc.
http://muonsinc.com/muons3/g4beamline/G4beamlineUsersGuide.pdf

Multi-turn simulations

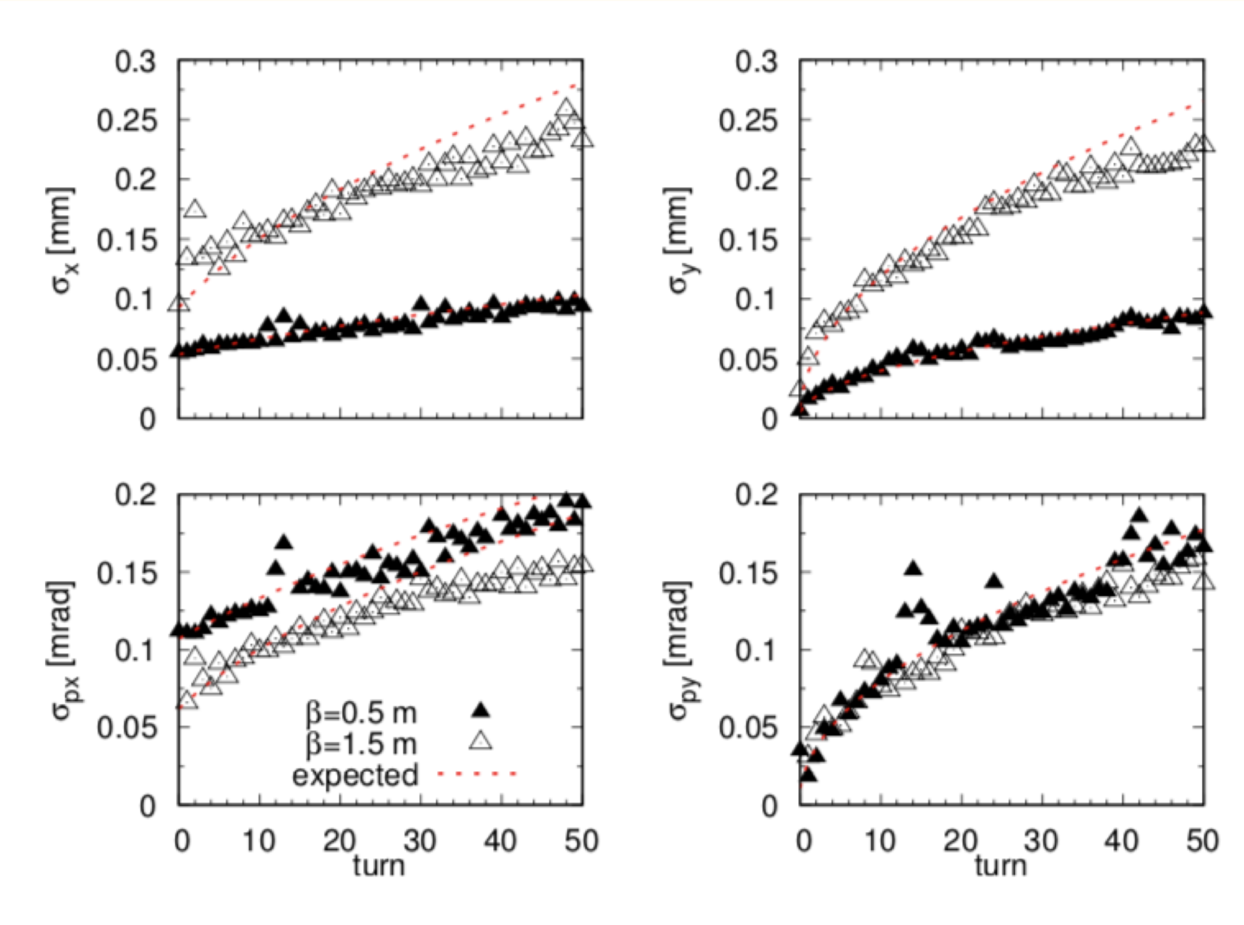
1. Initial 6D distribution from the equilibrium emittances
2. 6D e^+ distribution tracking up to the target (AT and MAD-X PTC)
3. tracking through the target (with Geant4beamline and FLUKA and GEANT4)
4. back to tracking code

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 size degradation vs β@target, Fixed dispersion



e^+ emittance growth controlled with proper β @ target

multiple scattering contribution also explained analytically:

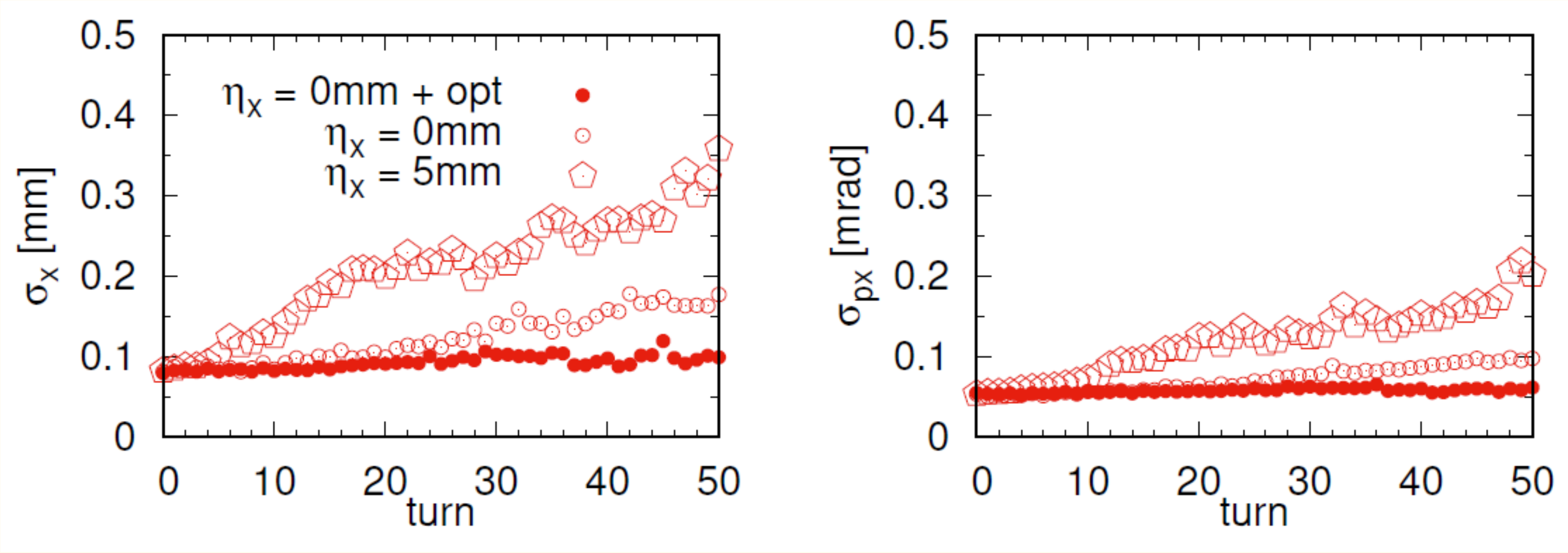
one pass contribution due to the target:

After 40 turns $\sigma'_{MS} = 25$ μrad

$$\sigma_{MS} = \frac{1}{2}\sqrt{n}\,\sigma'_{MS}\,\beta$$

n number of turns

Beam size degradation vs dispersion@target, Fixed β @target

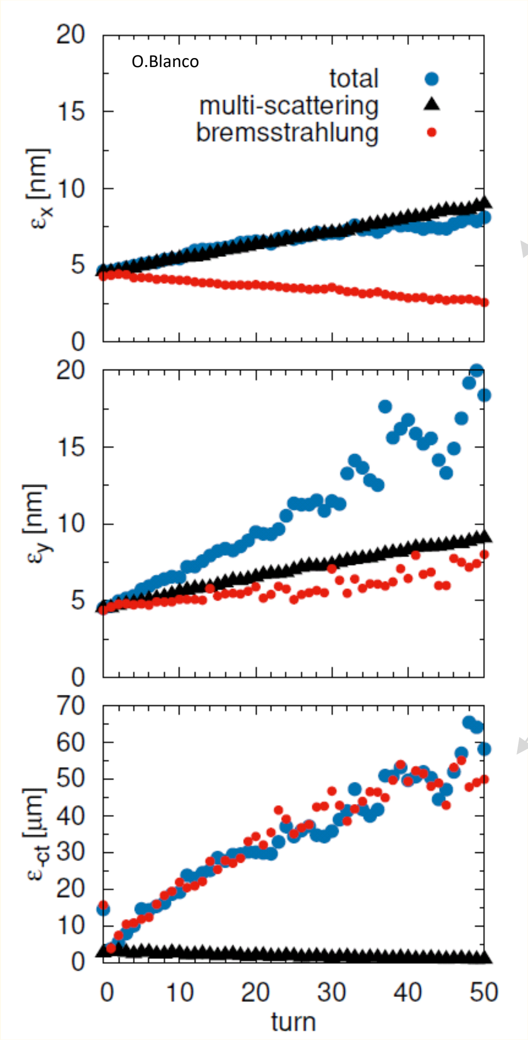


Bremstrahlung

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

Tracking simulations confirm that the small beta functions and zero dispersion at the IP cancel the degradation of the positron beam size due to the interaction with the target.

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

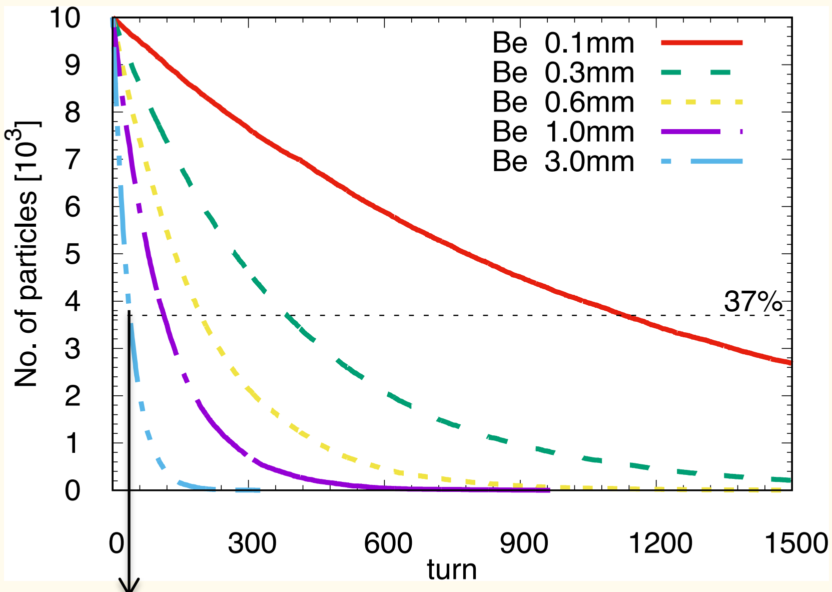
The longitudinal emittance increase is dominated by bremsstrahlung

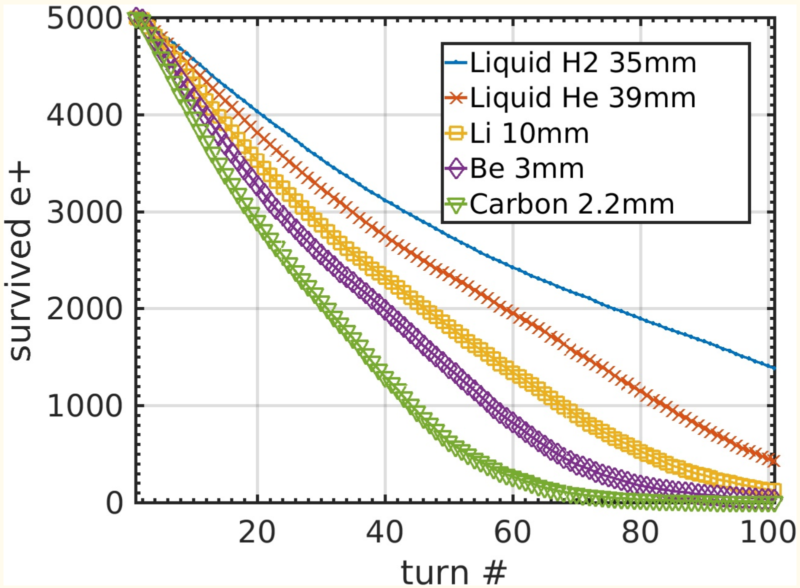
Target optics $\beta_{x,y}$ = 0.5m, η_x = 0.0m

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

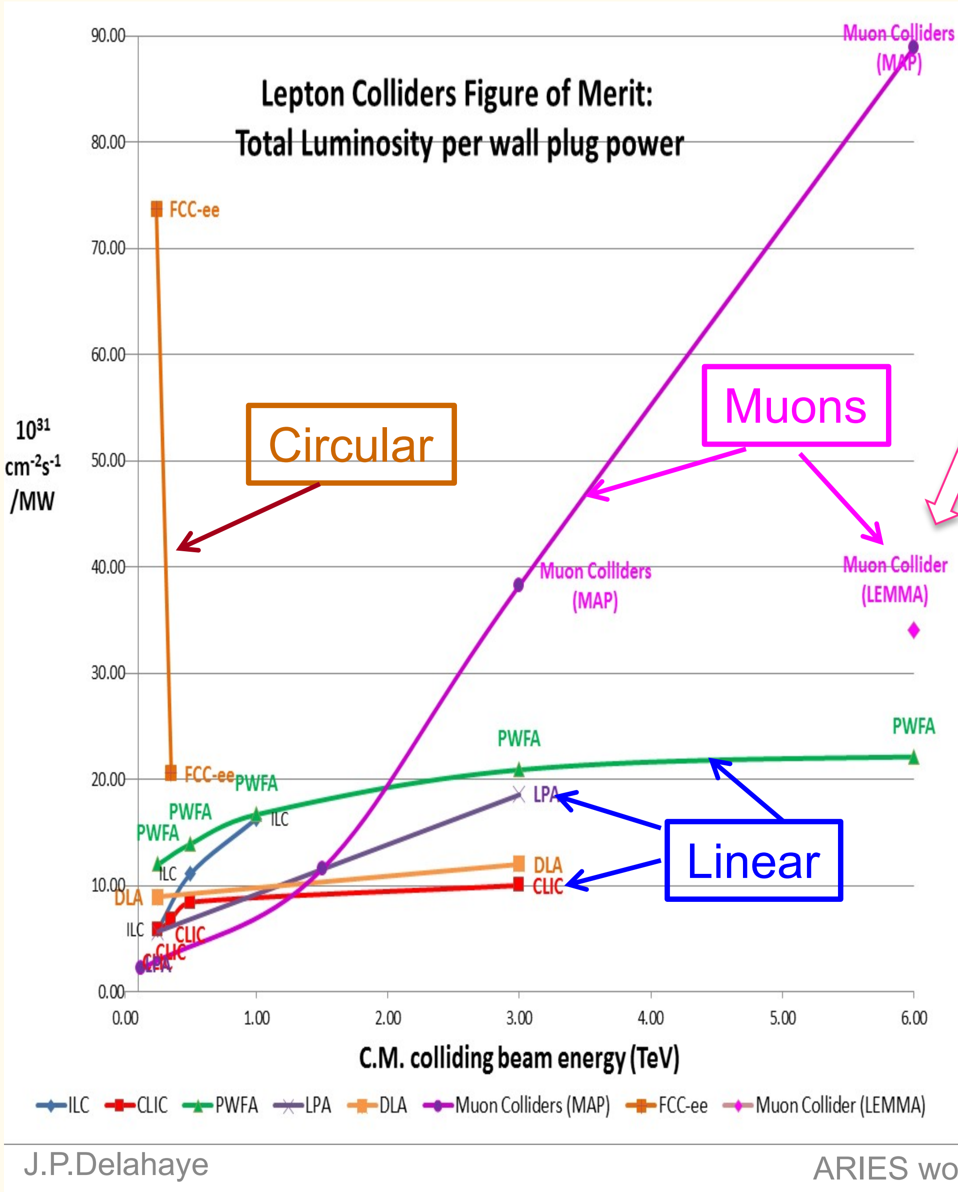
Lifetime determined by bremsstrahlung and momentum acceptance

2-3% e+ losses in the first turn

Number of e+ vs turns for different target materials.

Target thickness gives constant muon yield.

Power and e+ circumference



This value for LEMMA is dominated by the beam power required for the high rate 45GeV e^+ beam.
This value is maximized lowering the P(MW), with different handles:

- **increase circumference of the e+ ring**
- **increase energy acceptance of the e+ ring**
- **optimize muon target material**

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**

4. Muon emittance contributions

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

Multiple scattering contribution in the target

In agreement with analytical estimate (D. Schulte)

$$\sigma_x \approx \frac{L}{\sqrt{12}}\sigma_\theta$$

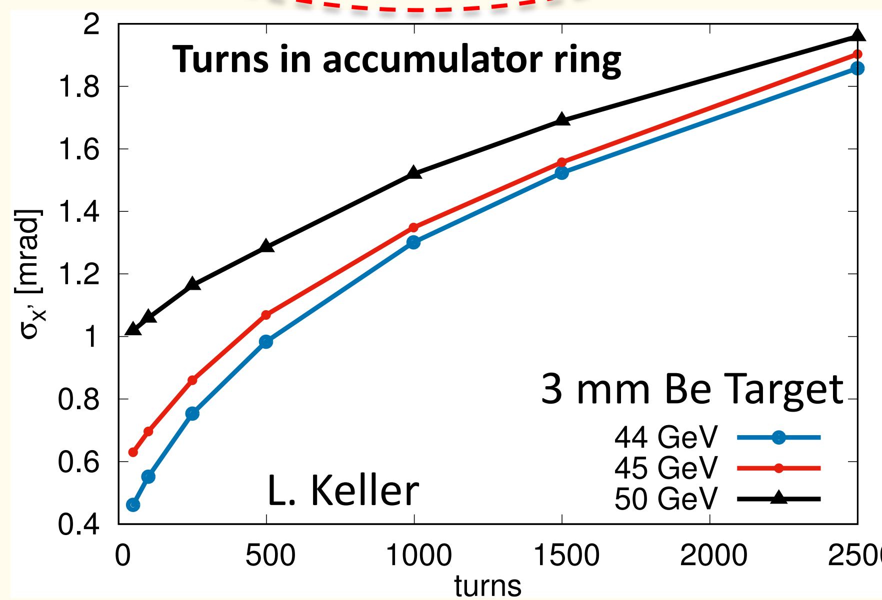
L is the target length

$$\Delta\epsilon = \sigma_\theta^2 \frac{L}{\sqrt{12}} \times \frac{E}{m_\mu c^2}$$

Norm. emittance growth for a single passage

45 GeV e+ beam, 3 mm Be, after 2500 turns:

$\sigma_{x'}$ = 1.85 mrad -> norm. emittance **0.6 μm**



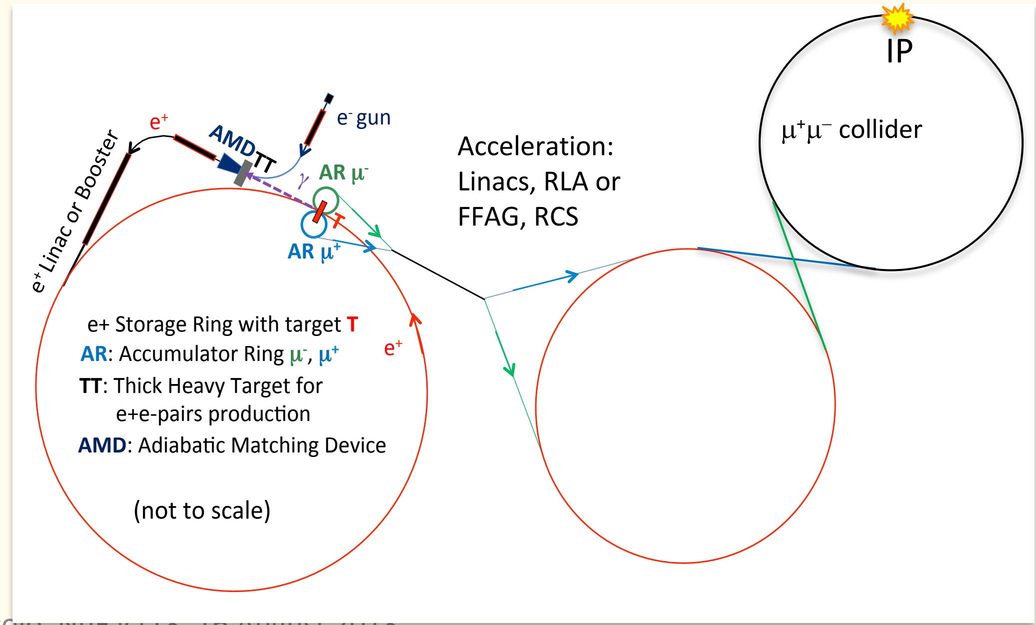
muon production angle

muon production angle + MS contribution

Multiple scattering contribution can be strongly reduced with crystals in channeling

Muon accumulator rings

- The large momentum optics needs to be designed
- The design of the target Insertion Region is challenging, due to space constraints also with the e^+ IR
- We need to find the best trade-off between muon production efficiency and multiple scattering



Muon Production target: criteria for best material

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

$$\boxed{N(\mu^+\mu^-) = \sigma(e^+e^- \to \mu^+\mu^-)\, N(e^+)\, \rho(e^-)\, L}$$

$N(e^+)$ 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 $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e^- \to \mu^+\mu^-)/\sigma_{rb} \approx 10^{-5}$
  - **standard target:** Bremsstrahlung on nuclei and multiple scattering are the dominant effects, Xo and electron density will matter $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e^- \to \mu^+\mu^-)/\sigma_{brem}$

Criteria for target design

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

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) → H_2

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

Muon production target

Activity

- Started a collaboration with ARIES PowerMat work package WP17 at CERN and Polit. Torino for their expertize on material termo-mechanical characterization, simulations and experimental validation

- Contact with CERN-STI (Sources Targets Interaction) group, S. Gilardoni, M. Calviani
- Collaboration with Sapienza SBAI, R. Li Voti for their expertize on thermo-mechanical measurements
- Collaboration with Brasimone Expertize on Liquid Lithium, A. Del Nevo, M. Iafrati

Positron source requirements for LEMMA

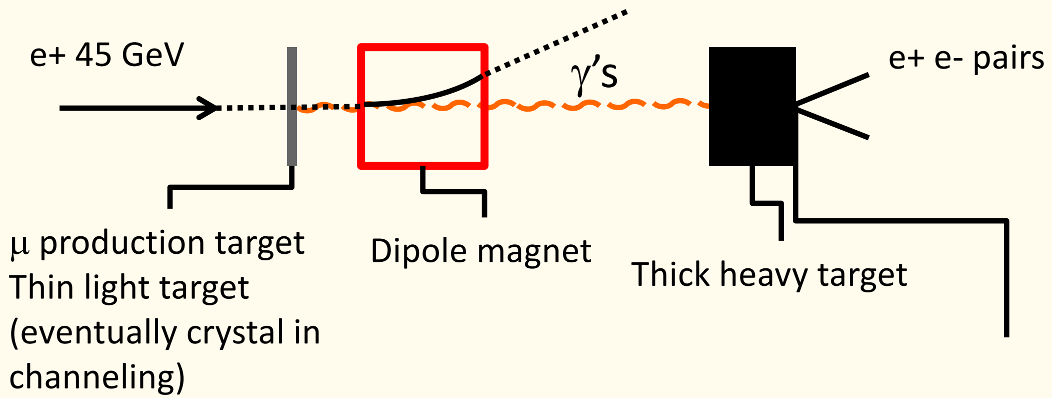
	Be 3mm			LI 10mm			H2 lIquid 35mm		
Ring energy acceptance %	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)
5	35	2.69E+16	277	45	2.11E+16	217	78	1.21E+16	125
10	47	2.01E+16	207	62	1.53E+16	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 e^+ ring: $\Delta p/p$ = 6%, tau = 40 turns, e^+/s = 2.4e16, P= 250 MW
Goal target: tau> 100 turns, e^+/s < 1e16, P < 100 MW

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

Embedded positron source
to relax e+ source requirement

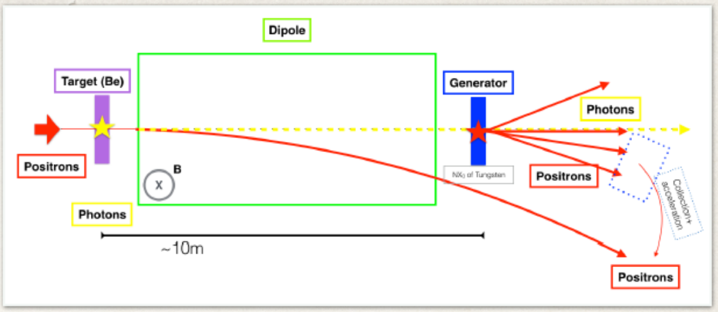
Positron source extending the target complex
Possibility to use the γ's from the μ production target to produce e+

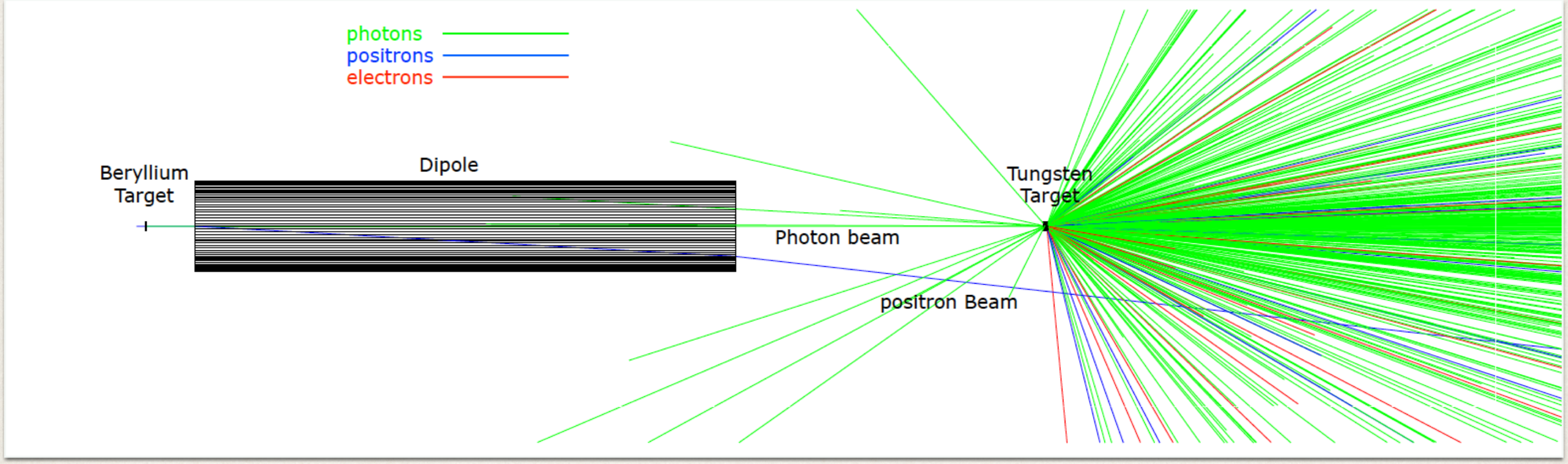


About 0.6 new e^+ produced per e^+ on thin target
Required collection efficiency feasible with standard design

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

Geant4 simulation

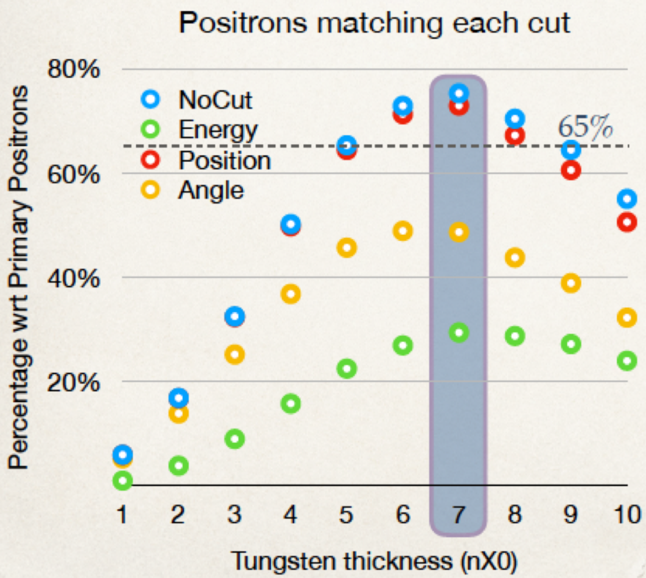


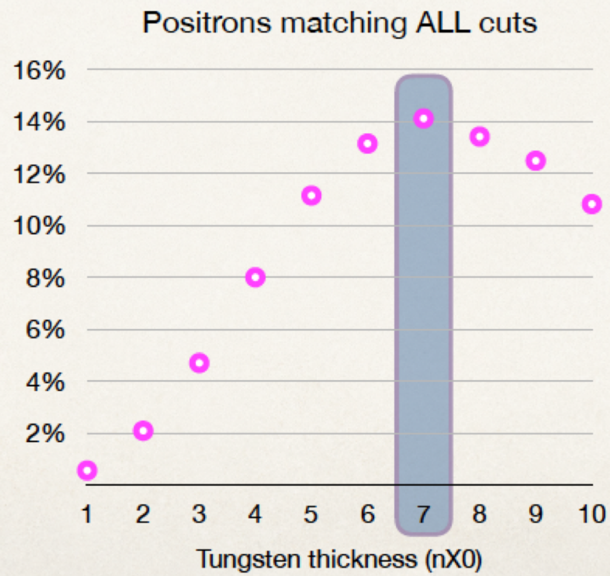


F. Collamati, "Positron regeneration", Muon Collider Workshop, Padova 2 July 2018

Collection efficiency maximization (II)

- The **Geant4** simulation was performed variating the Tungsten thickness from *1* to *10* X_0
- For each configuration the **fraction of positrons matching** each **requirement** was evaluated





Quality cuts:
- Energy in (5-20) MeV
- Emission pos. <0.5 cm
- Emission angle <0.5 rad

$7X_0$ (2.45cm) of Tungsten seems to **maximize both** the absolute **number** and the **quality** of produced positrons

However for $7X_0$ the power load is 30 MW, **$3X_0$** is a better compromise, as P= **3 MW**

- Start-to-end simulations from the generation point in the thick target up to e+ ring with ASTRA (or equivalent) foreseen.
- Crucial for the feasibility of this scheme is to find a solution to give the temporal structure required to re-inject e+ into the ring

Muon collider at 6 TeV com energy

Values considered for this table:

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

Comparison with MAP:

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

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

no lattice for the muon collider yet

This table summarizes the goals of the LEMMA design study

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

Comment on the parameters table

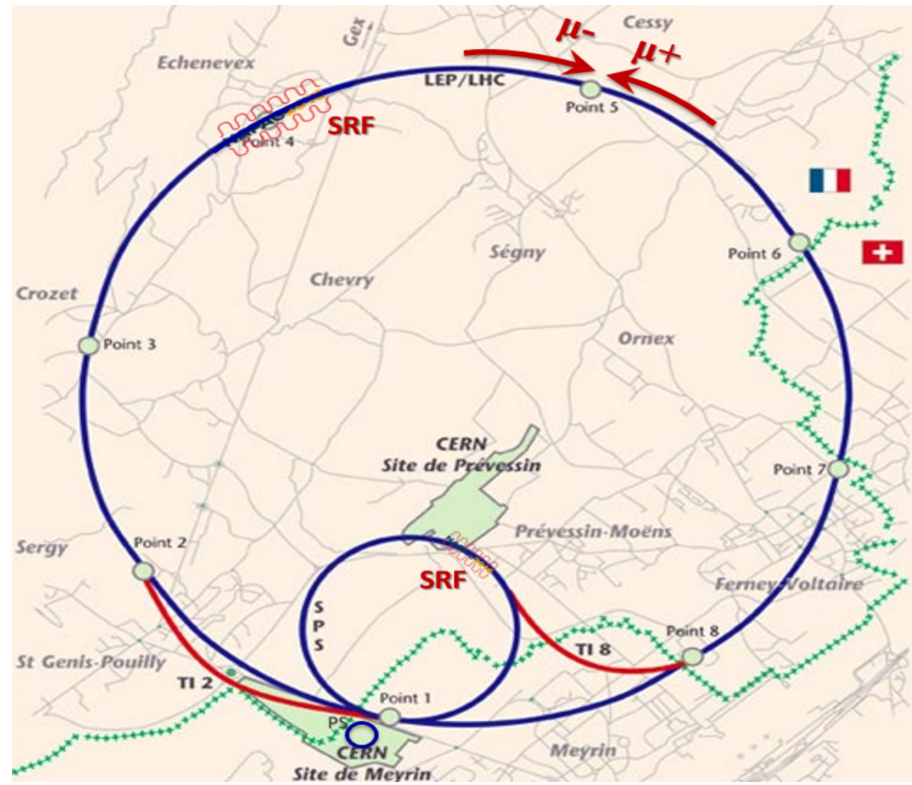
- **Low Emittance:** is the core of LEMMA idea, the greatest benefit of the positron driven source. The ultimate value has to be determined by R&D studies, we know that it will be given by the convolution of different contributions. Our goal is to reduce multiple scattering to a negligible value and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

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

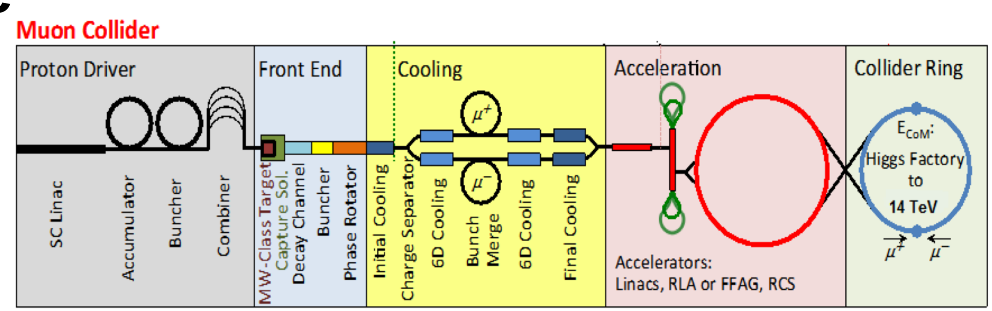
- **β^*=0.2 mm:** aim is nano-beam scheme, final focus lattice not designed yet, permanent quads might be used.

14 TeV "Next Muon Collider" 7×7 TeV

- **CERN needs world-class collider**
- **Use LHC tunnel**
  - Fill with accelerator and collider ring(s)
- **Result:**
  - 7 x 7 TeV collider
- **Reuses existing infrastructure**
  - ~100 m deep tunnel
  - cost possible ?
- **Must add a muon source**
  - high intensity



Shiltsev & Neuffer, IPAC 18



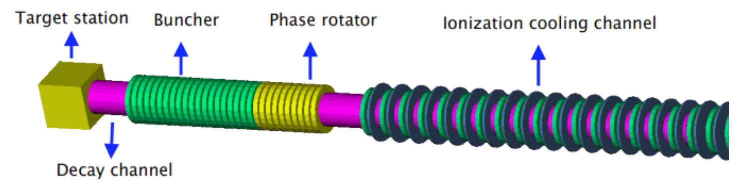
D. Neuffer, "14 TeV Muon Collider LHC, MAP, and LEMC", Muon Collider Workshop, Padova 2 July 2018

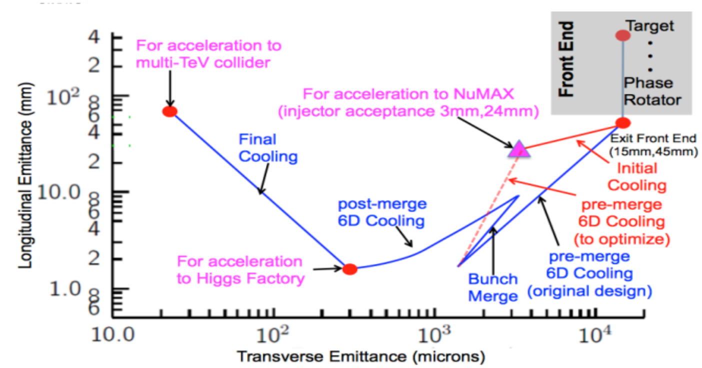
HEPAP μ+μ 2020

14 TeV machine muon sources

- Possible beam sources
  - **proton based**
  - CERN PS - ~0.13 MW
    - 24 GeV
    - 6 bunches/1.2s
      - 5Hz
  - new MW scale proton source (~MAP)
    - 5—8 GeV linac + storage ring
      - 5Hz
  - **Electron based** Boscolo et al.
  - e^+-$e^- \rightarrow \mu^+ - \mu^-$
    - 45 GeV $e^+ \rightarrow$ 22GeV $\mu^+ \mu^-$
      - 2.2 kHz
    - no cooling …

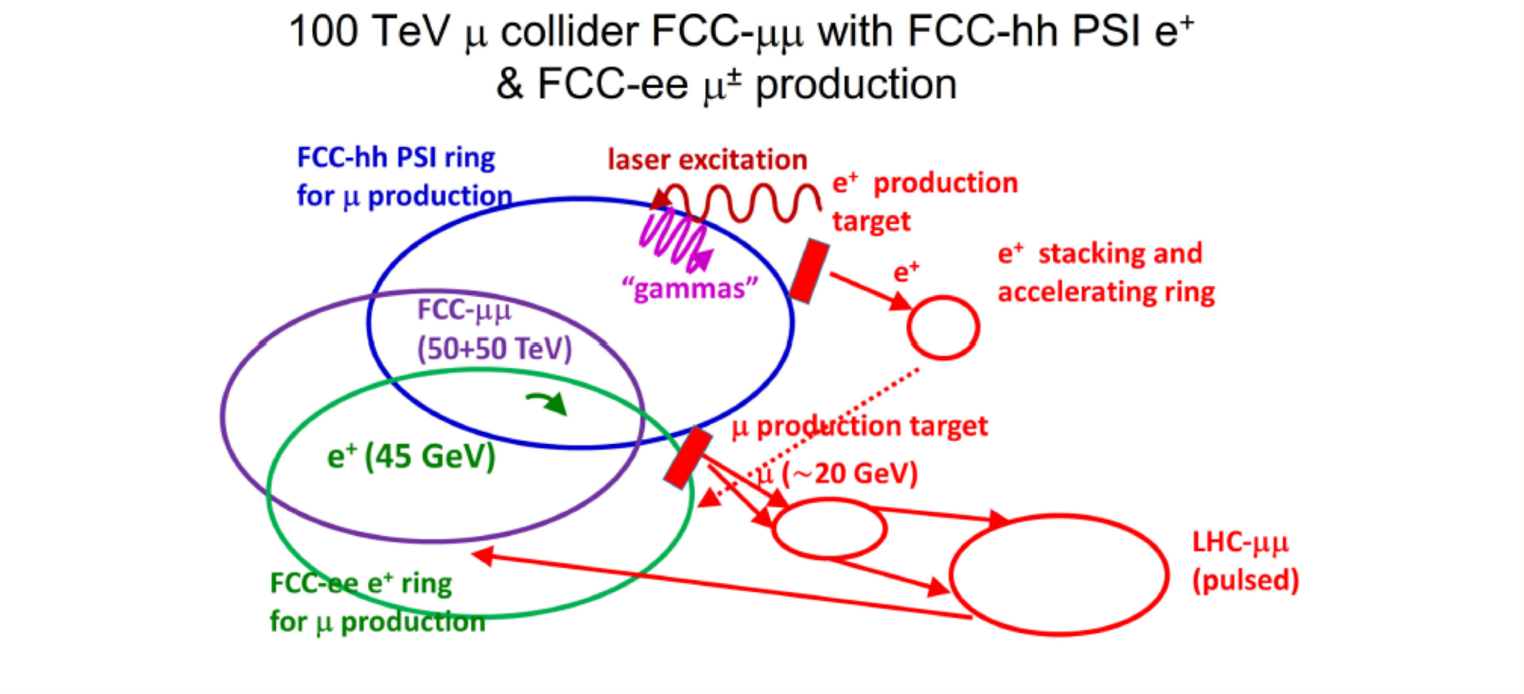
- Proton-based source uses MAP-like cooling system
  - ~1 km long single pass
    - ~1—2 G$
    - verified by simulation
  - $\varepsilon_{t,N} \rightarrow 25\ \mu$; $\varepsilon_L \rightarrow$ 60 mm





100 TeV muon collider based on the FCC complex using the LEMMA scheme

LHC/FCC based MC F. Zimmermann, Proc. IPAC18, MOPMF065



LEMMA ring-plus-target Test at 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).

DAFNE Layout for the LEMMA Test

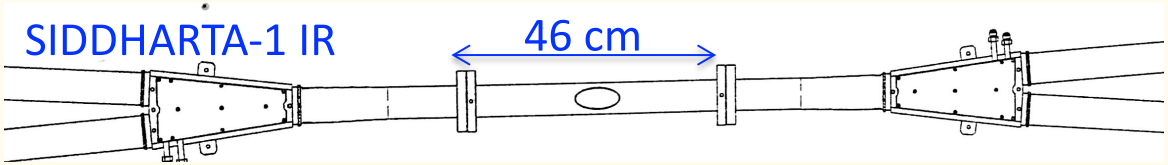
The target will be placed at the SIDDHARTA IP because:

- 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.

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

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, “Primary Electron Beam Facility at CERN”, Muon Collider Workshop, Padova 2 July 2018

Relevance of eSPS for Muon Colliders

This facility could potentially be of interest for muon collider development

Some examples, based on the LEMMA scheme

- Target
- Acceleration
- Collision
- Warning: These are fun examples made up by me to illustrate where maybe tests could help. Better examples in this workshop.

Can a muon collider with proton-based source learn something from eSPS?

D. Schulte, "Primary Electron Beam Facility at CERN", Muon Collider Workshop, Padova 2 July 2018

Conclusion

- **LEMMA is a novel concept for muon production that needs R&D study to prove its feasibility and determine its potentiality/limit**

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

- First steps to identify crucial points have been done
- There is a great amount of work needed to assess the potentiality of this scheme
- ESU is a fundamental opportunity to push forward this proposal

Back-up

M. Palmer

Muon Collider Parameters

Muon Collider Parameters					
		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts
⇨ several × 10^{32} [Rubbia proposal: 5×10^{32}]

Fermilab

Positron sources parameters for future projects

	SLC	CLIC	ILC	LHeC	LHeC	LEMMA
E [GeV]	45.6	3000	250	140	60	45
$\gamma\varepsilon_x$ [μm]	30	0.66	10	100	50	18
$\gamma\varepsilon_y$ [μm]	2	0.02	0.04	100	50	18
e^+ [10^{14} s^{-1}]	0.06	1.1	1.9	18	440	100

- The highest positron rate has been achieved at the SLAC Linear Collider more than 20 years ago
- The future Linear Colliders CLIC and ILC design foresee a positron rate higher than SLC by a factor 20 ÷ 30 and much smaller emittances
- The LHeC and LEMMA proposals aim at extremely high rates, about two order of magnitude higher than CLIC and ILC

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