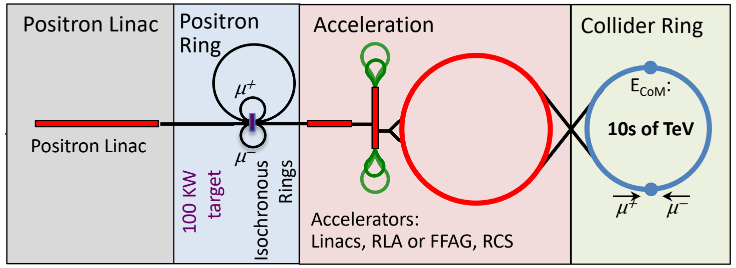
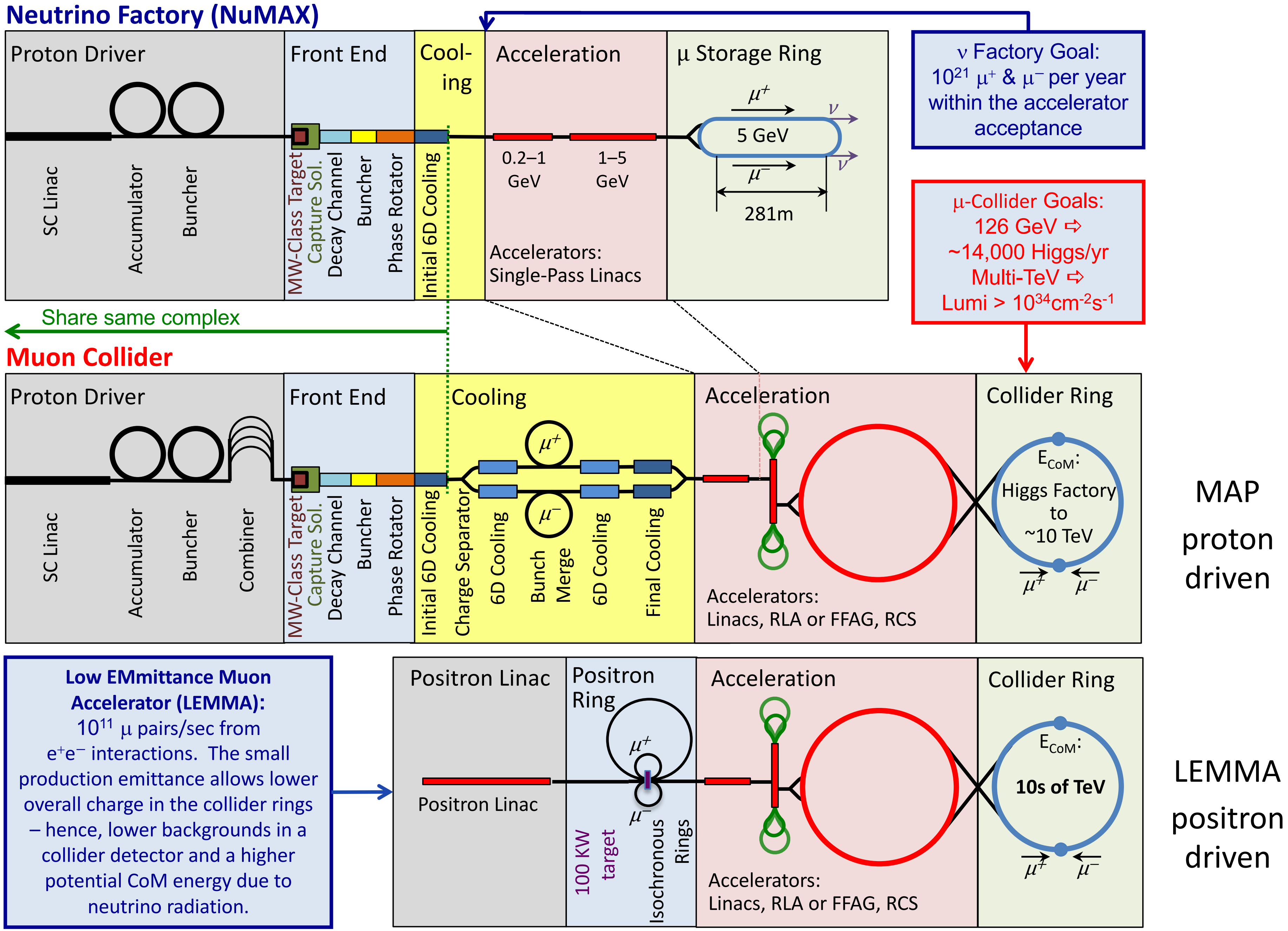


Accumulator studies for LEMMA source

M. Boscolo (INFN-LNF)

New Muon Collaboration Leader meets INFN-Accelerator Community

12 October 2020



Ref. M. Boscolo, J.-P. Delahaye, M. Palmer, "*The future prospects of muon colliders and neutrino factories*", Review of Accelerators Science and Technology, Vol. 10 (2019) 189-214 ArXiv.1808.01858

LEMMA 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

LEMMA Disadvantages:

- Rate: much smaller cross section wrt protons ($\approx$ mb)

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

Time steps of the Lemma study

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

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

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

Oct 2017: LEMMA presented at the **INFN Machine Advisory Committee**

June 2018: PR-AB 21, 061005 — multi-pass scheme: dedicated optics study to cope with target perturbation

2018: IPAC18 link

- definition of accumulator rings requirements
- Proposal for experimental test at DAFNE R&D on target & beam dynamics

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

2019/2020: Preparation for the EPPSU

- Preparatory meeting for the ESPPU, April 10-11, 2019 CERN link
- Muon Collider workshop, October 2019 CERN link
- Muon Collider meeting, April 2020, CERN link
- Muon Collider Collaboration Meeting , 3/7/20 link

April 2019: ArXiv:1905.05747

May 2020: PR-AB 23, 051001 link

LEMMA

NIMA 807 (2016) 101-107 “*Novel proposal for a low emittance muon beam using positron beam on target*”, M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, link

- Paragraph 5.1: **SINGLE PASS** scheme
- Paragraph 5.2: **MULTI PASS** scheme

SINGLE PASS (ArXiv:1905.05747)

Muon production target OUTSIDE e^+ ring:

e+ beam passes once through thick target

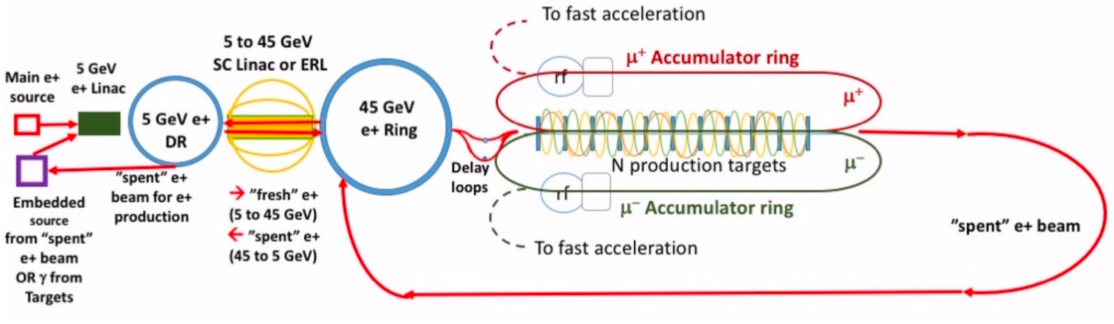
Target length ≈ $0.3X_0$

😀 **Higher number of muons/bunch**

😀 **Low total power deposited on target for energy loss**

😀 **Compliant with standard muon acceleration schemes**

☹️ **Emittance increases sizeably with such a thickness in light materials, may be solved with channeling (crystal target) [Ref. NIMA 807]**



evolved scheme [IPAC19-MOZZPLS2]

MULTI PASS (PR-AB 21)

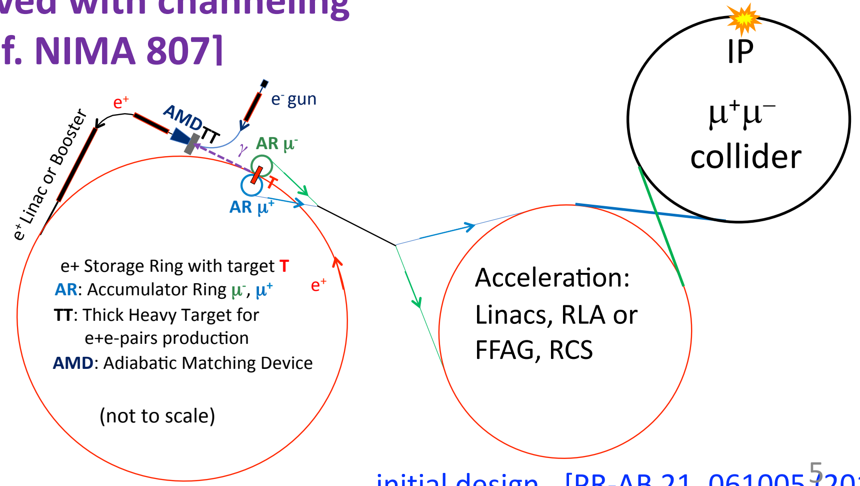
Muon production target INSIDE e^+ ring:

e^+ beam passes multiple times through thin target

Target length ≈ $0.01 X_0$

😀 **Small emittance increase with thin target**

☹️ **High total power deposited on target for energy loss**



initial design [PR-AB 21, 061005 (2018)]

Muon production and accumulation from positrons on target

with the LEMMA **single-pass** scheme

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23**, 051001 (2020)

Muon production and accumulation from positrons on target

M. Boscolo,[1,*] M. Antonelli,[1] A. Ciarma,[1] and P. Raimondi[2]
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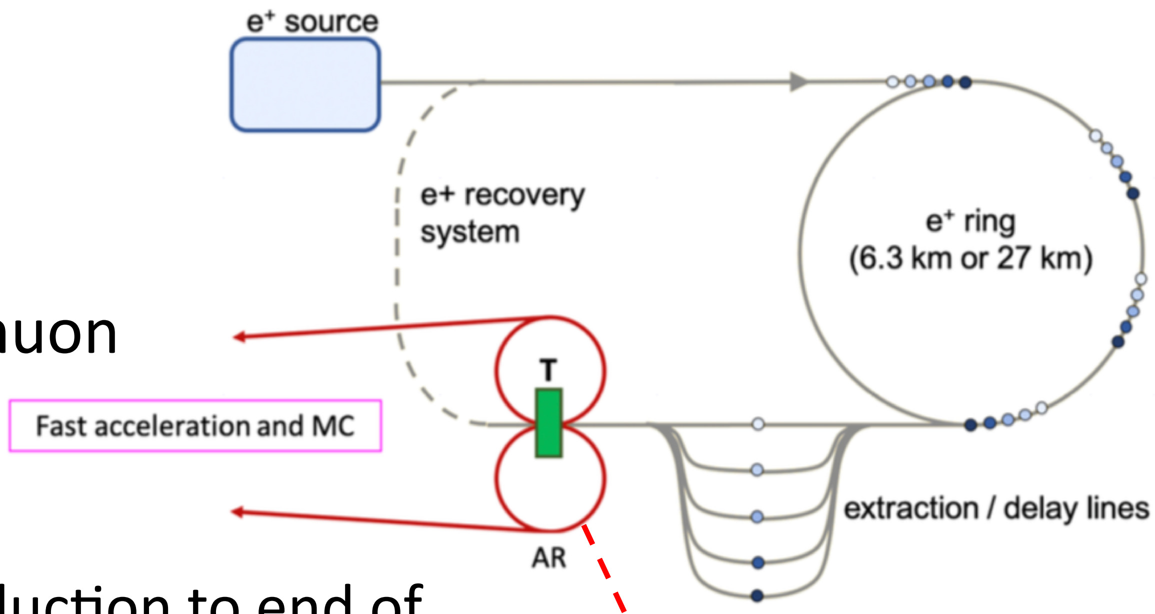
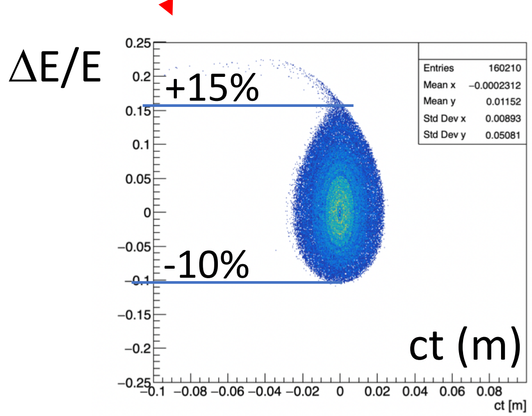
(Received 30 January 2020; accepted 15 April 2020; published 8 May 2020)



- Design of very large **energy acceptance** muon accumulator rings [-10%; +15%]

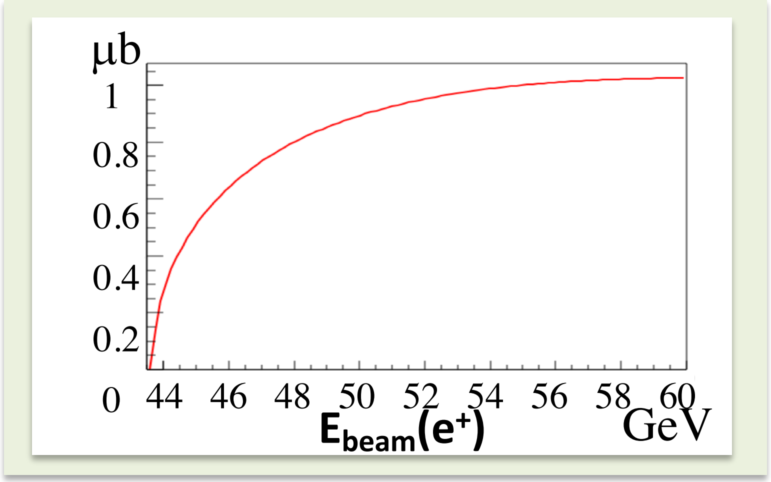


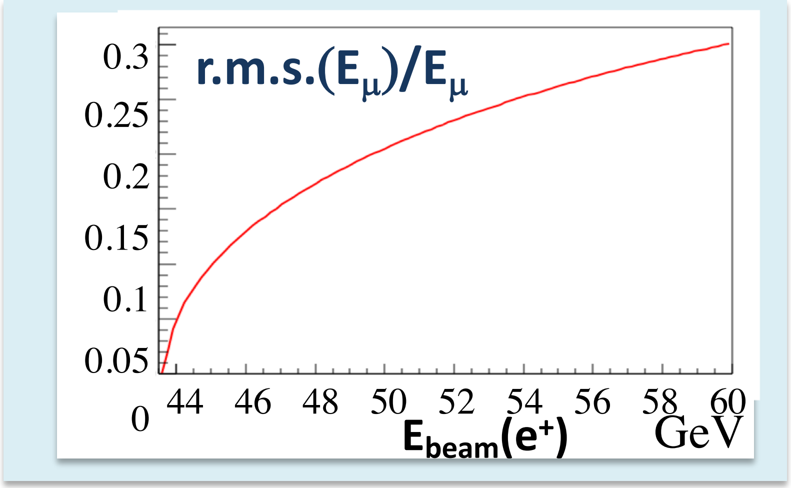
- Start-to-end muon particle tracking from production to end of accumulation process: simulation tool developed on purpose (MUFASA)
- Realistic estimate of emittance and number of muons/bunch
- Targets considered
  - solid
  - liquid jet
  - compound liquid/solid target

Large momentum acceptance ring

- Key topic for LEMMA to increase the muon production rate

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





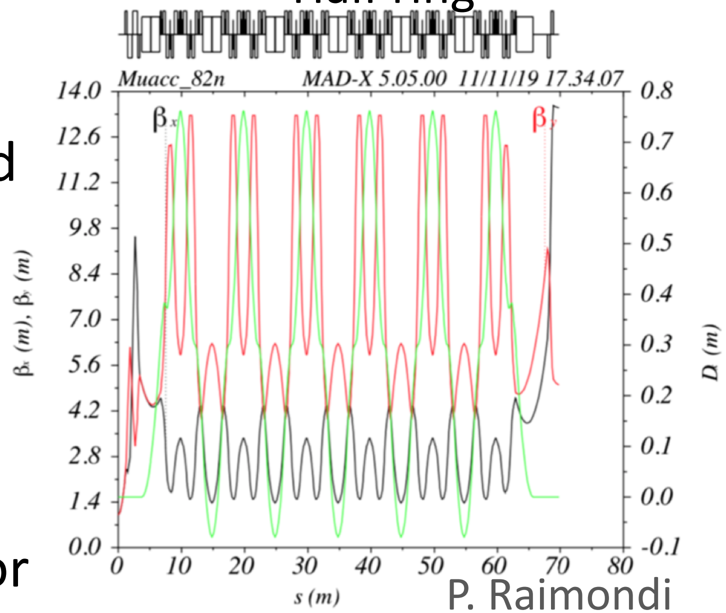
large momentum acceptance allows to work with large production efficiency

- Also very important for fast acceleration using FFA
  See for example Scott Berg, Padova, 2/7/18: link
  FFA in RLA arcs or directly in a ring

Muon Accumulator Rings: novel design

- Compact: 140 m circumference with 15 T dipoles
- Chromaticity and high order momentum compaction correction achieved by dedicated families of sextupoles, resulting in a very large energy acceptance [-10%,+15%]
- Since the target region is in common for the positron ad the two muon beams, a septum in the first bending magnet is used to separate the beams
- The ring is made by two symmetric arcs and two straight sections, one for the target insertions and one for the RF cavities

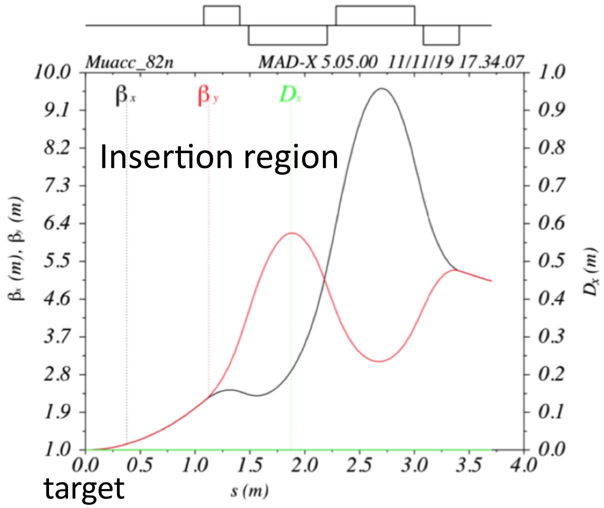
Half ring



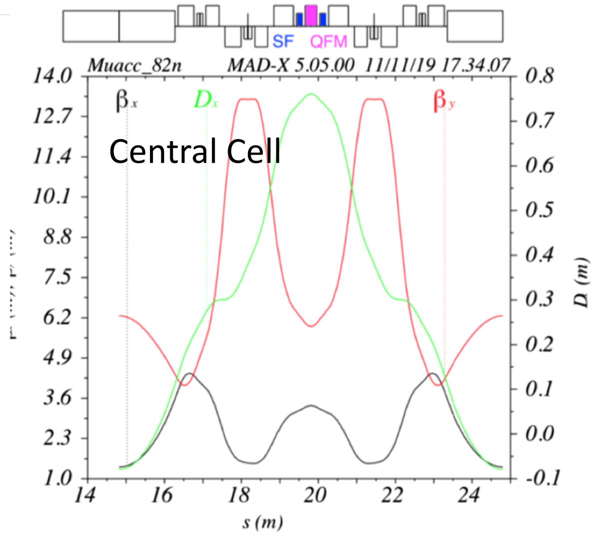
P. Raimondi

Parameters table

Muon beam energy	GeV	22.5
Circumference	m	140
Number of cells		12
rf frequency	GHz	3.9
rf voltage	MV	200
Harmonic number		2100
Number of bunches		1
Horizontal betatron tune		8.84
Vertical betatron tune		3.73
Longitudinal tune		0.015
Momentum compaction		-7.12×10^{-5}
Natural horizontal chromaticity		−8.28
Natural vertical chromaticity		−10.37
Bunch length	cm	0.9
Ring energy acceptance		−10%, +15%



target



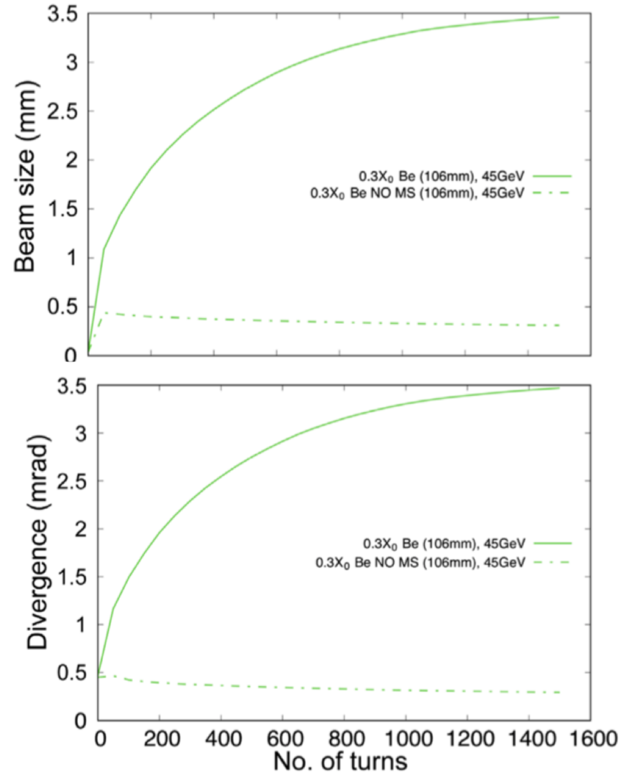
MUFASA simulation code for the Muon Production and Accumulation

- A dedicated simulation tool name MUFASA has been developed for start-to-end particle tracking simulations, essential for the muon beam dynamics study from production through the accumulation process.
- C++ MonteCarlo that includes the most relevant processes of muon and electron interaction in matter, interfaced with MADX for the 6D tracking.
- MUFASA allowes to determine the optimal parameters to maximise muon brilliance ($\propto N^2/\varepsilon$)
  - low-Z $\approx$ 0.3 X_0
  - 45 GeV e^+ beam

more details in: A. Ciarma, INFN-20-07/LNF (10/6/2020)

$N = 5\times10^{11}$ e^+/bunch

Beryllium Target



😀 Advantage: most efficient for μ production

After 1500 turns ≈ 1.5 lifetimes, 3.5×10^8 μ are accumulated

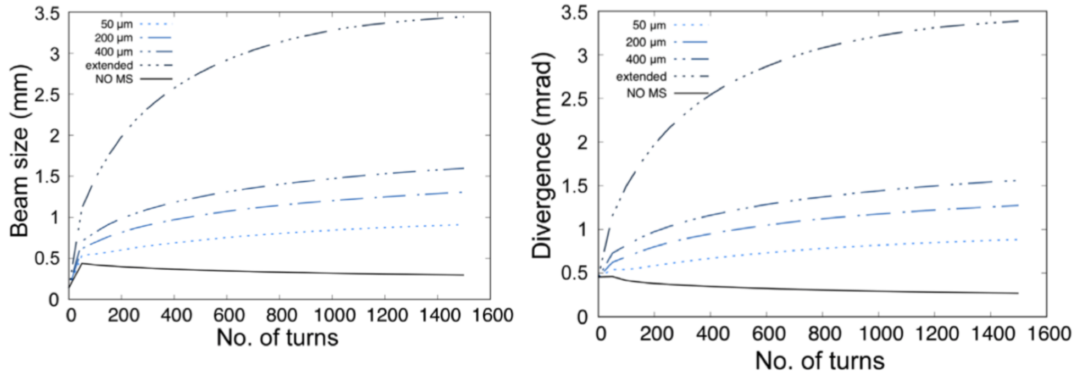
☹️ Due to the multi passages of muons through the target, the beam size and divergence of muons during the accumulation process increase (multiple scattering)

Liquid Lithium Target

- We considered the transverse size of the jet much smaller than the stored beam size to preserve muon beam emittance

😀 Jet of liquid Lithium mitigates multiple scattering

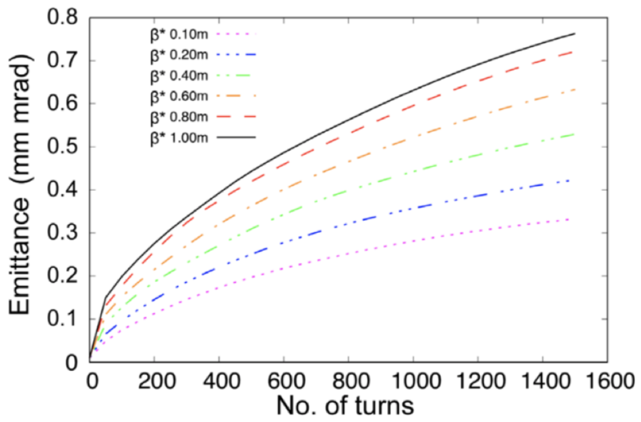
☹️ Disadvantage: low X_0 → long jet target needed



Liquid Lithium Target with Diamond dust

- Best compromise to increase efficiency of liquid Lithium allowing to reduce target length and strongly suppress multiple scattering

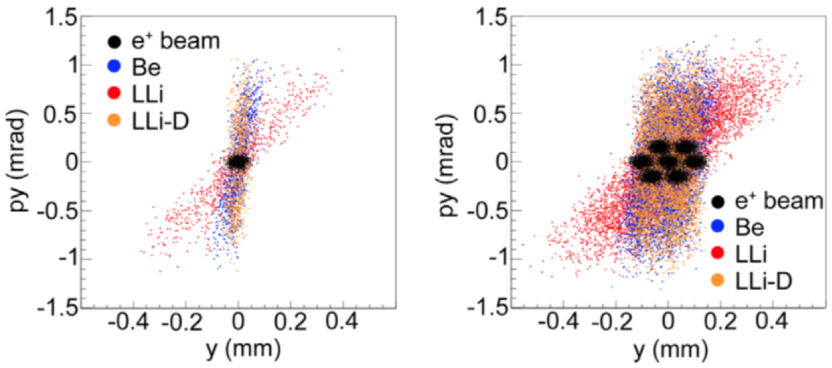
- Lowering β^* at target muon beam emittance is further reduced (as expected)

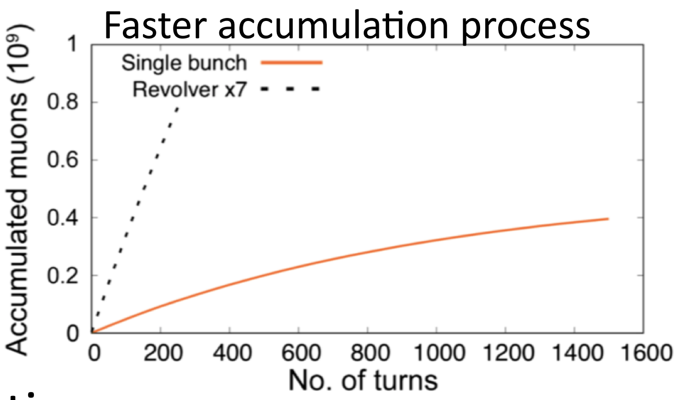


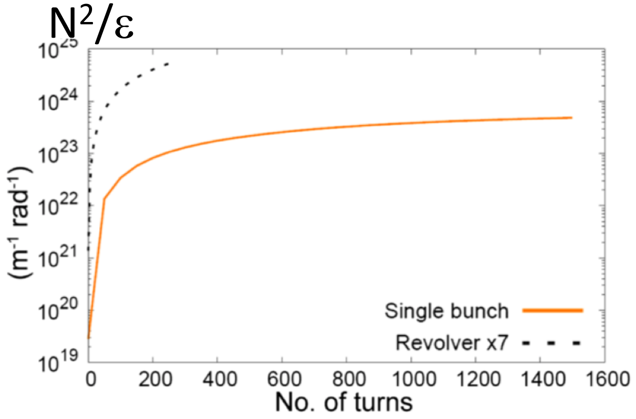
Recombination positron bunch at the target

(revolver configuration)

multiple e+ bunches on the target using the delay lines







might allow to further increase the muon production, reaching the goal value ≈ $10^9\ \mu$/bunch

Multiple thin targets – under study

- Ideally β* cannot be smaller than target (hourglass effect limits the β^* reduction) →
- One way to overcome this effect is to use **multiple thin targets** and design a **transport line with multiple IPs**
- Pros: This scheme allows **small emittance** and better handling of termo-mechanical stresses
- Cons: longer ring
- More details in: Nanometric muon beam emittance from e^+ annihilation on multiple thin targets, O. Blanco and A. Ciarma, PR-AB 23,091601 (2020) link
  - Transport line length= 256 m
  - N(e+)= $5x10^{11}$ at E+=43.8 GeV
  - 20 Be targets 0.01 X_0
  - e^+ Energy acceptance ≈ 5%
  - $N_\mu = 10^5$ μ/bunch
  - $\varepsilon(\mu)$=20μm-rad
- Still limited energy acceptance (5%) no improvement with present accumulator

Conclusions

- A compact muon accumulator ring with very high energy acceptance designed
- Muon beam dynamics from production to accumulation through this ring optics performed thanks to a new particle tracking simulation code interfaced with MADX
- Best solution: **50μm LLi-D film jet target ≈ 0.5 X_0 with β*=10 cm →**

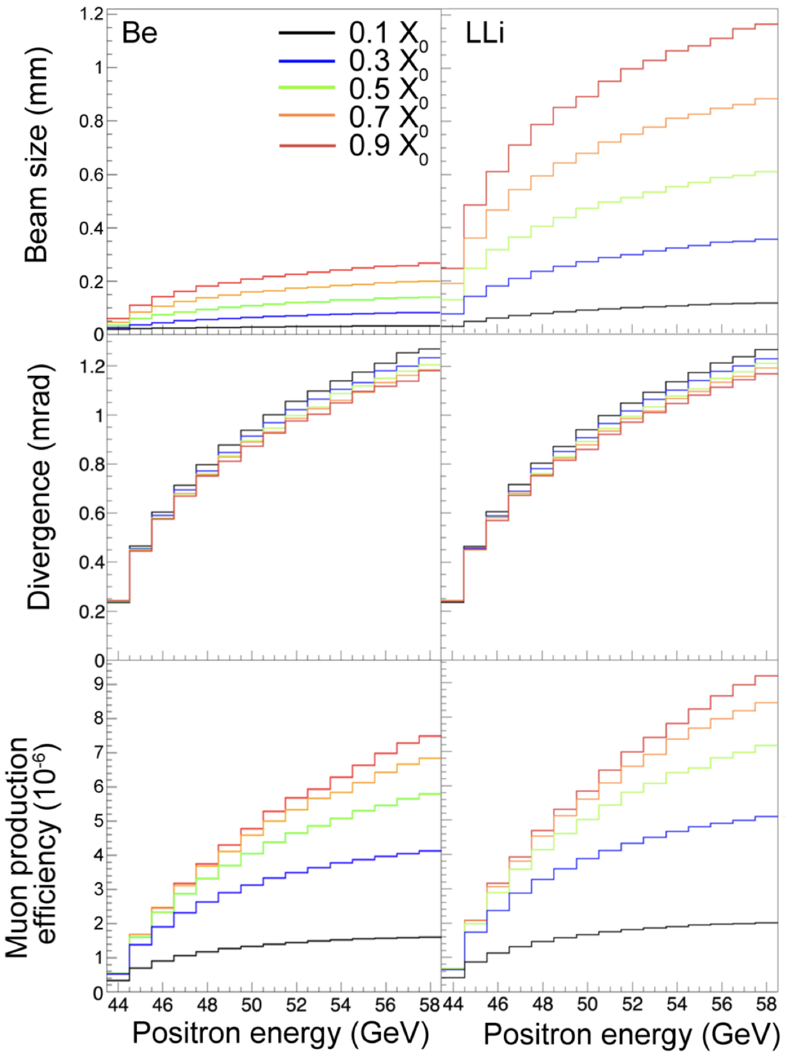
  $N=0.4\times10^{9}$ μ/bunch, ε(μ)=0.3 μm-rad after 1000 turns

- Further optimization allowed with revolver configuration :

  $N=10^{9}$ μ/bunch, ε(μ)=0.1 μm-rad after 200 turns

- **Further increase of AR energy acceptance would allow higher e^+ energy, increasing muon production (E^+=50 GeV × 2 in N_μ)**
- **Further reduction of β* would reduce muon final emittance.**

Back-up



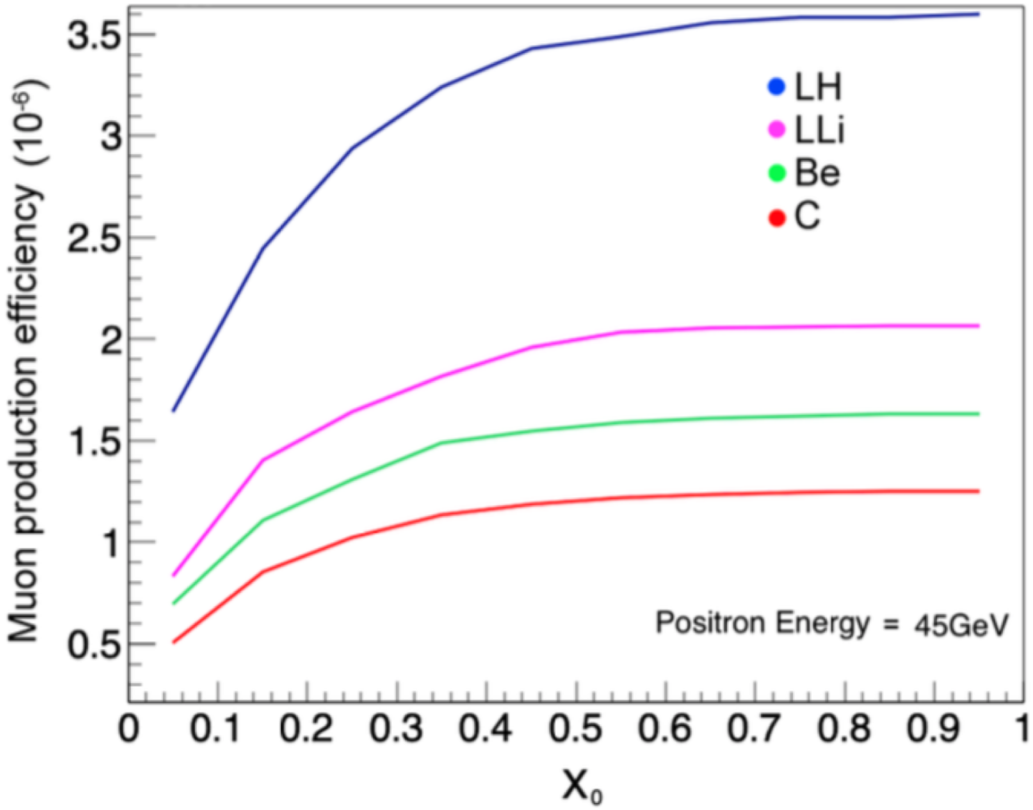
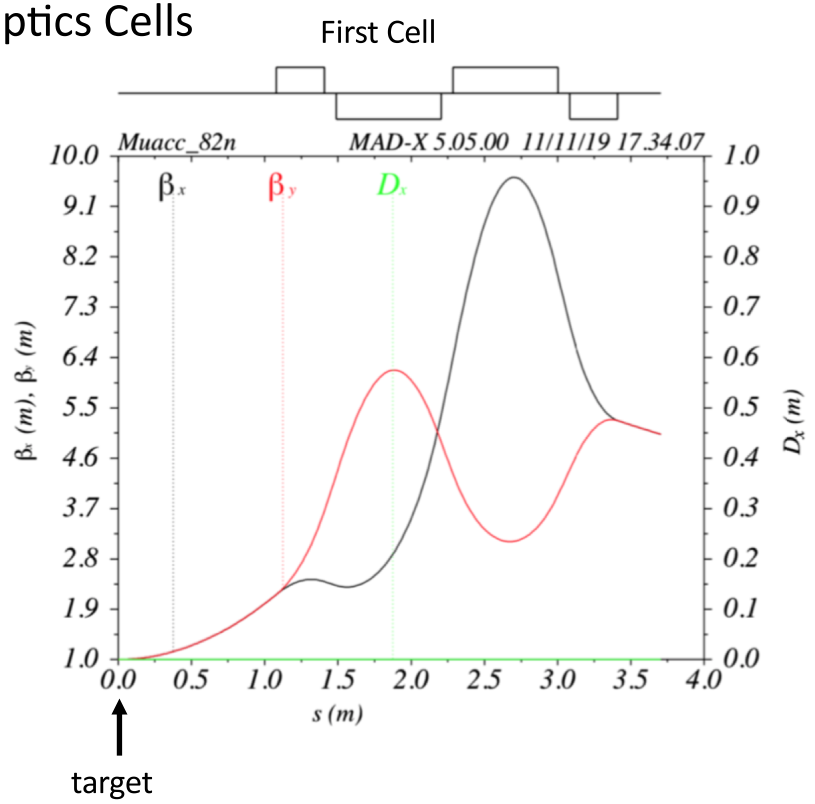


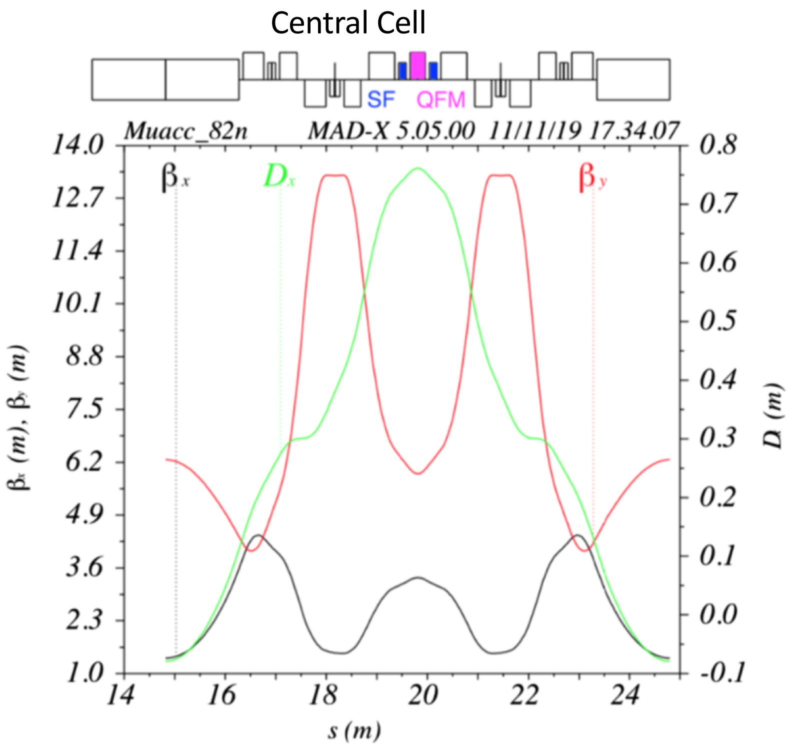
TABLE III. Properties of LLi–D compounds, for different fractions of liquid lithium $f(\mathrm{LLi})$, and diamond powder $f(\mathrm{D})$.

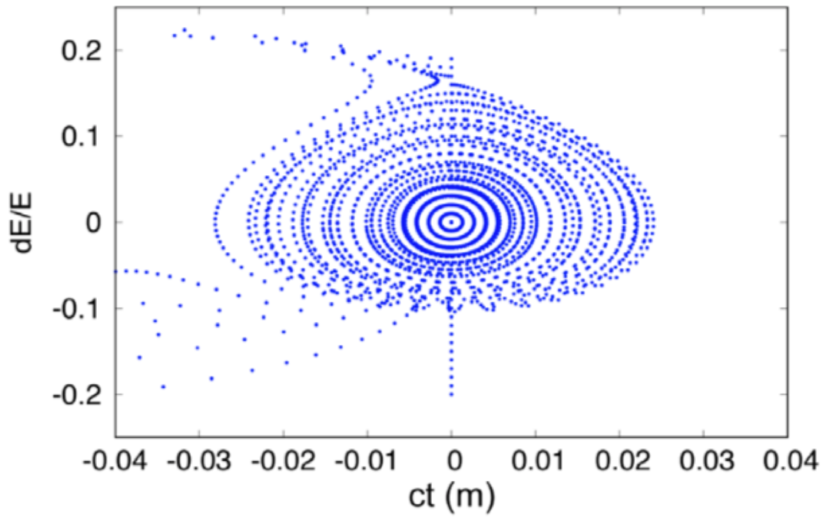
$f(\mathrm{LLi})$	$f(\mathrm{D})$	$\rho[\mathrm{g\ cm^{-3}}]$	$X_0\ [\mathrm{g\ cm^{-2}}]$	X_0 [cm]
1.0	0.0	0.534	82.78	155.02
0.9	0.1	0.833	59.26	71.18
0.7	0.3	1.430	48.89	34.19
0.5	0.5	2.027	45.61	22.50
0.3	0.7	2.624	44.00	16.77
0.1	0.9	3.221	43.04	13.36
0.0	1.0	3.520	42.70	12.13

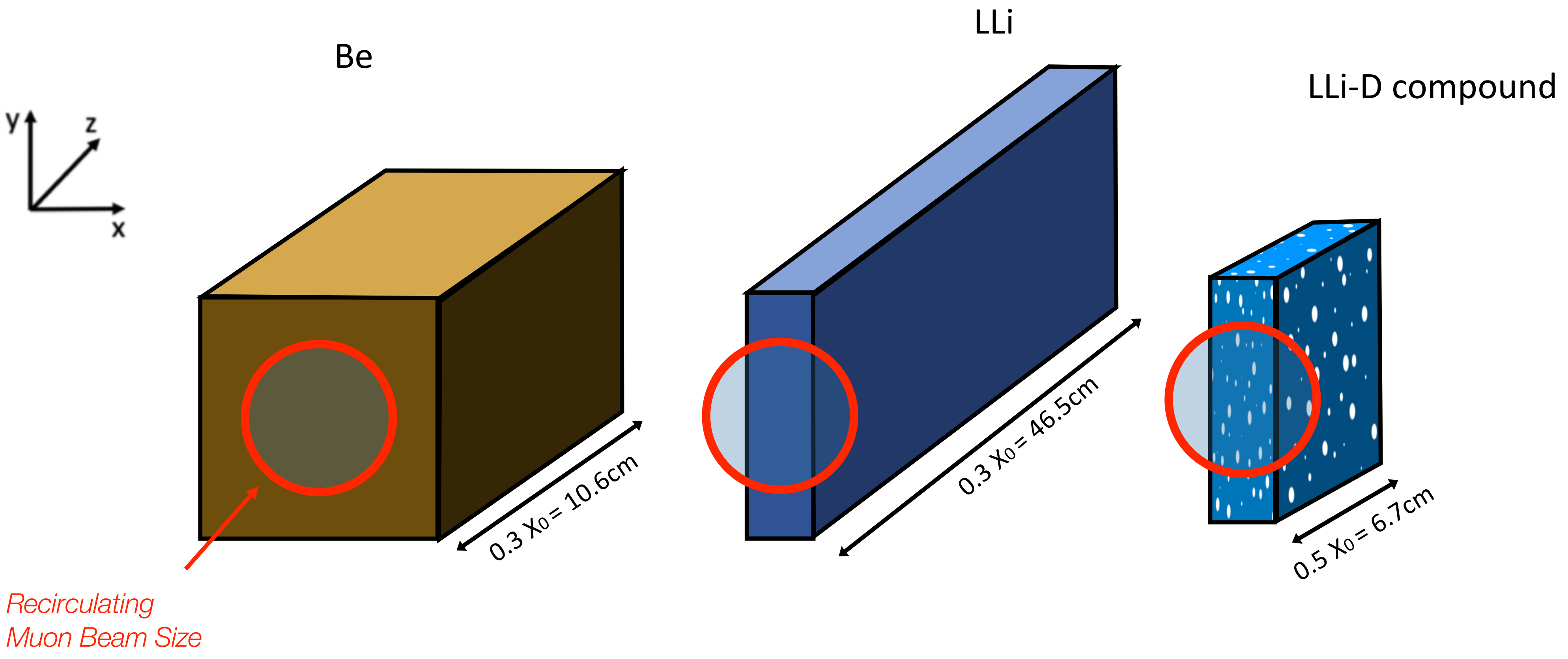
$$\frac{\rho}{X_0} = f(\mathrm{LLi})\frac{\rho\mathrm{LLi}}{X_0^{\mathrm{LLi}}} + f(\mathrm{D})\frac{\rho^{\mathrm{D}}}{X_0^{\mathrm{D}}}$$

Accumulator ring optics Cells

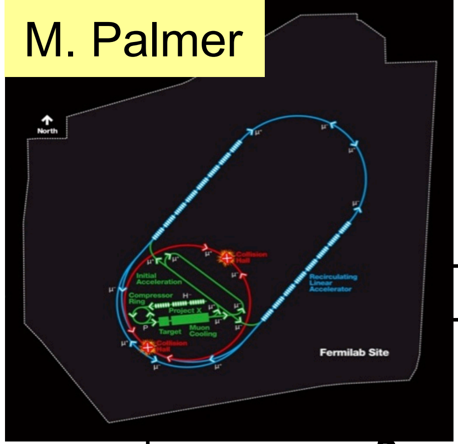








Be
LLi
LLi-D compound
y
z
x
0.3 X0 = 10.6cm
0.3 X0 = 46.5cm
0.5 X0 = 6.7cm
Recirculating
Muon Beam Size



Muon Collider Parameters

Parameter	Units	Higgs	Multi-TeV		
		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}]