# Muon production and accumulation from positrons on target

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In this paper we investigate the production of a muon beam by positrons on target. We describe the characteristics of the muon beam as produced by different target configurations. We present an optics for the muon accumulator ring, discussing how it fulfils the large energy acceptance requirement and the high order chromaticity correction at the target, as well as other parameters relevant to enhance the muon bunch quality. We discuss the muon beam dynamics through the ring for the configuration of the single-pass LEMMA scheme, and the optimization study performed with the goals of maximizing the muon bunch population and minimizing its emittance.

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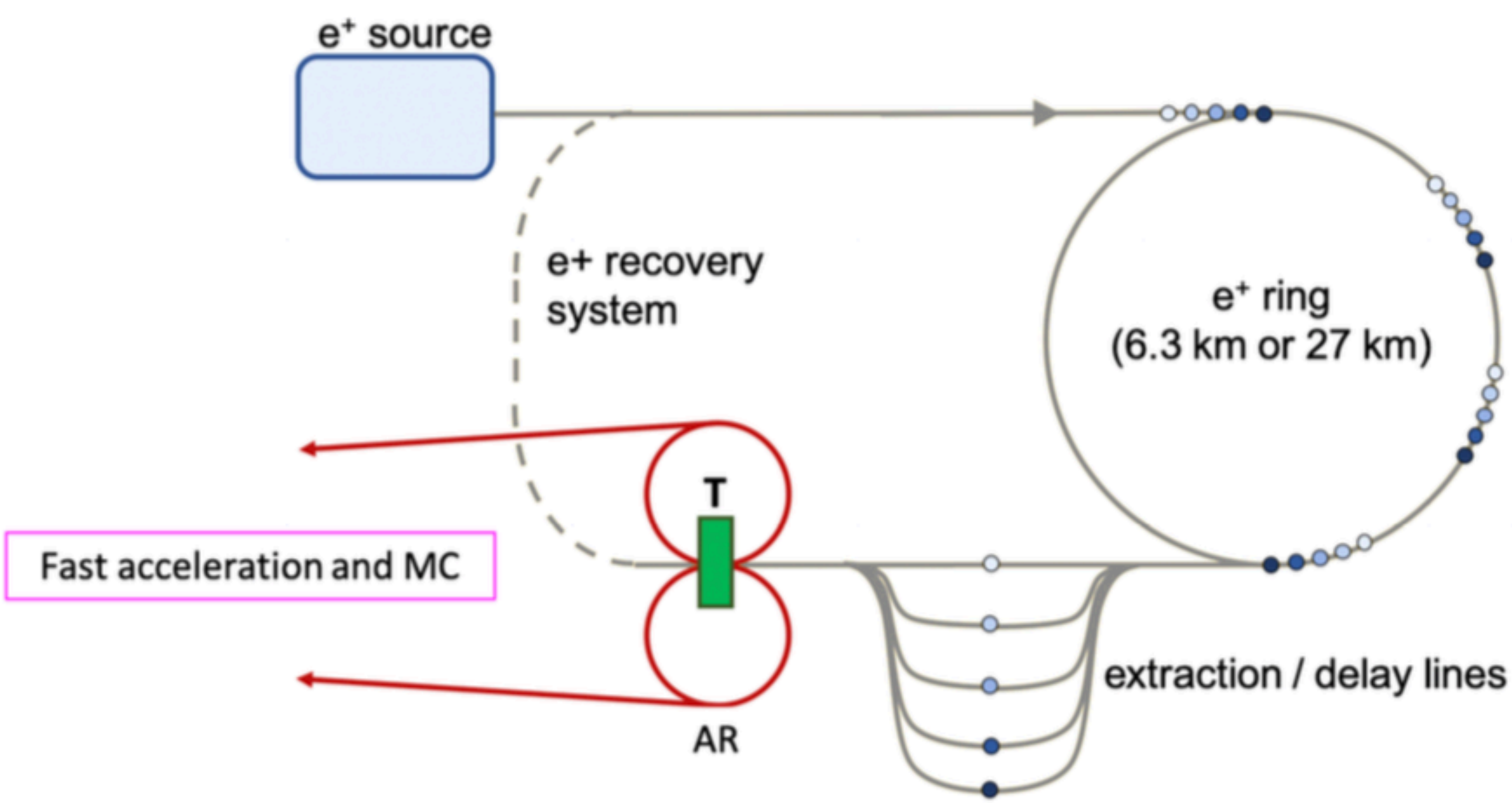
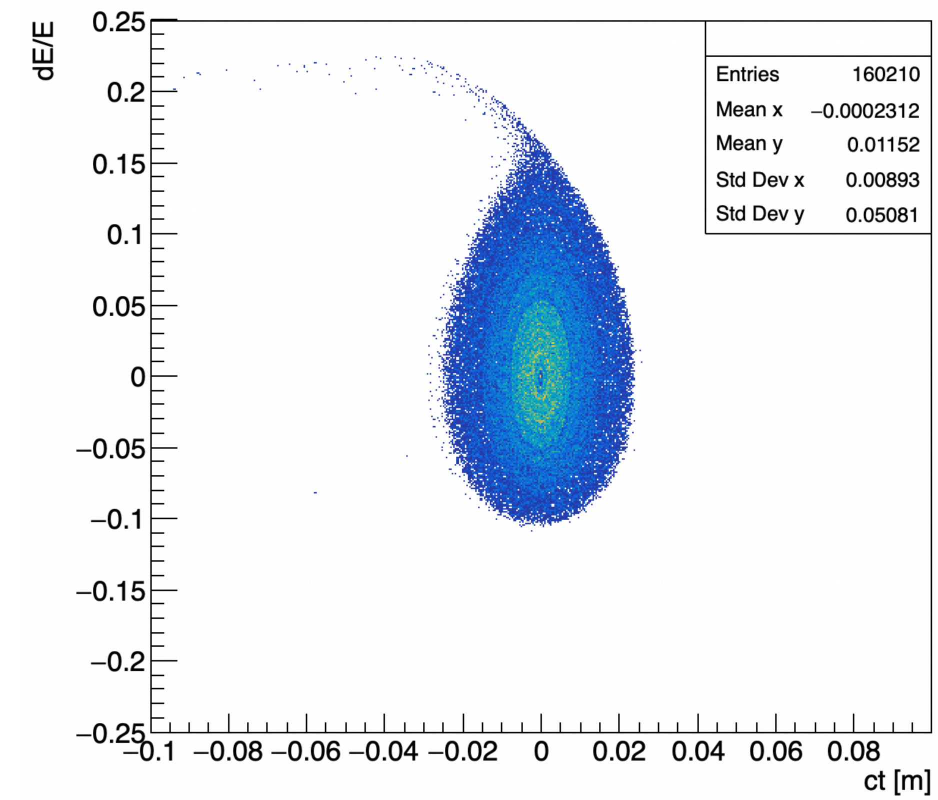
# Dedicated study on the muon production in the LEMMA "single-pass" scheme




- Muon accumulator rings design **very large energy acceptance** (-10%/+15%)
- Full simulation of the accumulation process allowing targets optimisation:
  - Solid target
  - Liquid jet film
  - Compound target

# Muon Accumulator Ring Optics

A novel design for the Muon Accumulators has been developed. The **140m compact circumference** is obtained with **15T** dipoles

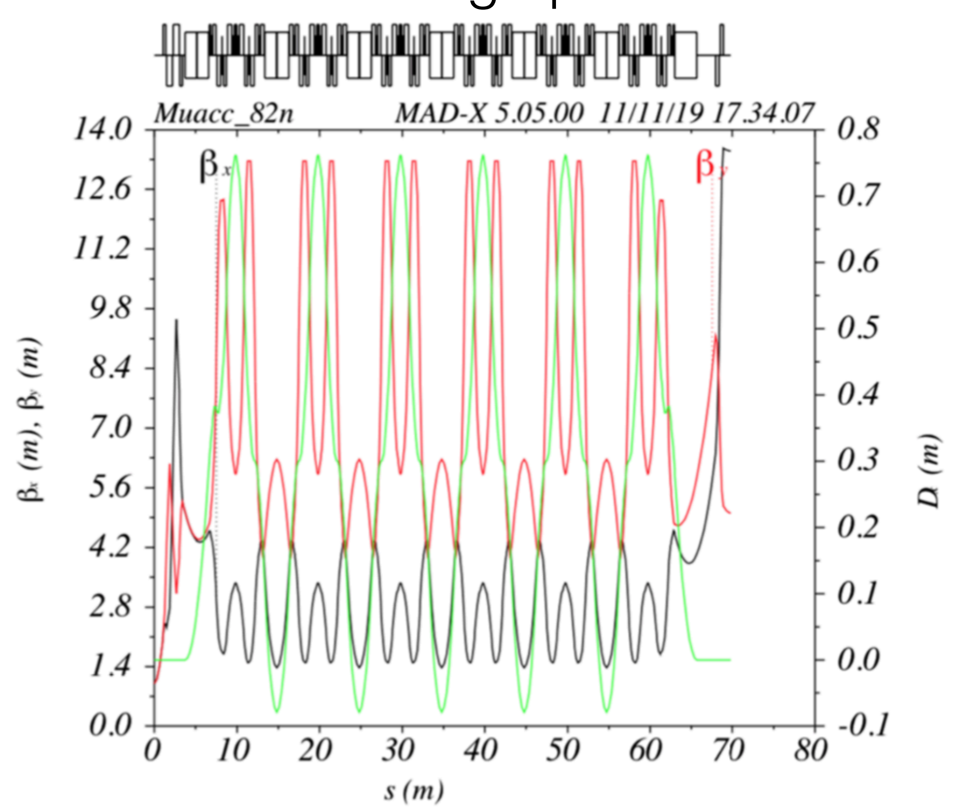
Chromaticity and high order momentum compaction correction is achieved by dedicated families of sextupoles, resulting in a **very large energy acceptance** of **-10%/+15%**

Since the **target region is in common** for the positrons and the two muon beams, a septum in the first bending magnet is used to separate the beams

The ring is composed by two symmetric arcs and two straight sections, one for the **target insertion** and one for the **RF**

| | | |
|---|---|---|
| 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 | | $-7.12 \times 10^{-5}$ |
| Natural horizontal chromaticity | | −8.28 |
| Natural vertical chromaticity | | −10.37 |
| Bunch length | cm | 0.9 |
| Ring energy acceptance | | −10%, +15% |

Half ring optics



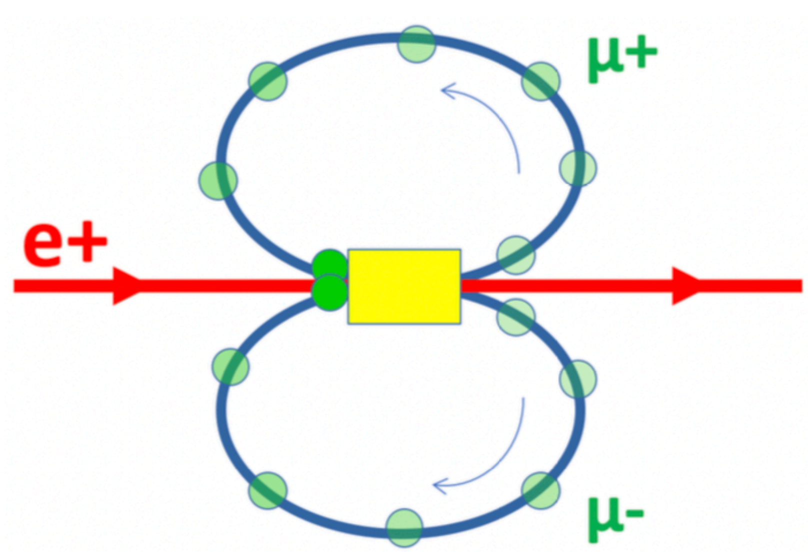
# Muon Production and Accumulation Simulation with MUFASA

The design of a realistic optics for the muon accumulator allowed for a full study on the **muon beam dynamics** during the accumulation process. To this extent a dedicated simulation tool named **MUFASA** has been developed.

This tool is a C++ based **MonteCarlo** which includes the most relevant processes of muon and electron interaction with matter, and it is interfaced with **MADX** for the 6D particle tracking.

This code is essential for a **start-to-end simulation** and to determine the best target for LEMMA, allowing the study of the **dynamics of the stored beam** passing hundreds of times through the target during the accumulation process.

We found that the optimised positron beam energy is **45GeV** and the low-Z targets thickness is **~0.3 radiation lengths ($X_0$)**

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**MUFASA: MUon FAst Simulation Algorithm**

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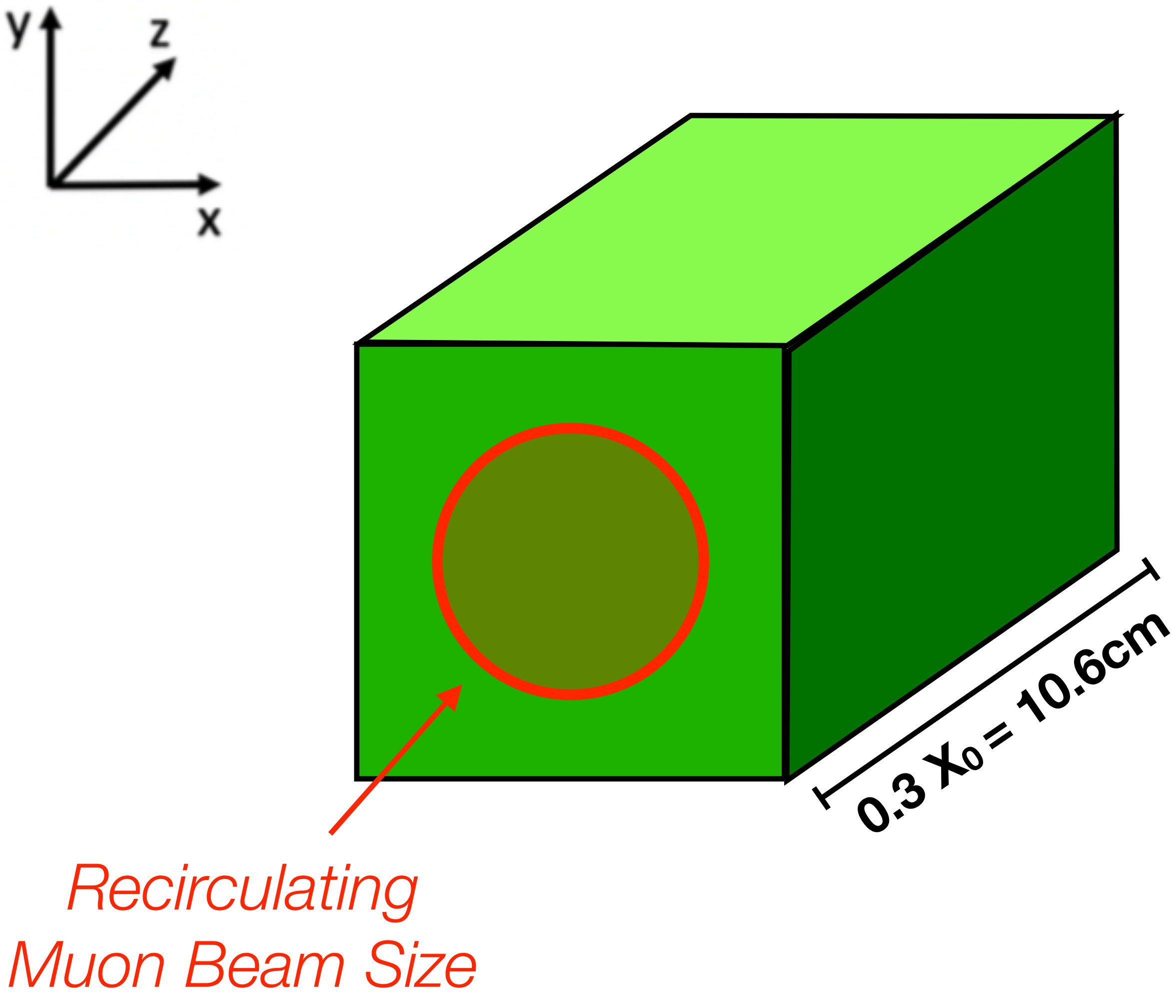
*This note contains the description of the code and the results of its Benchmark against Geant4*

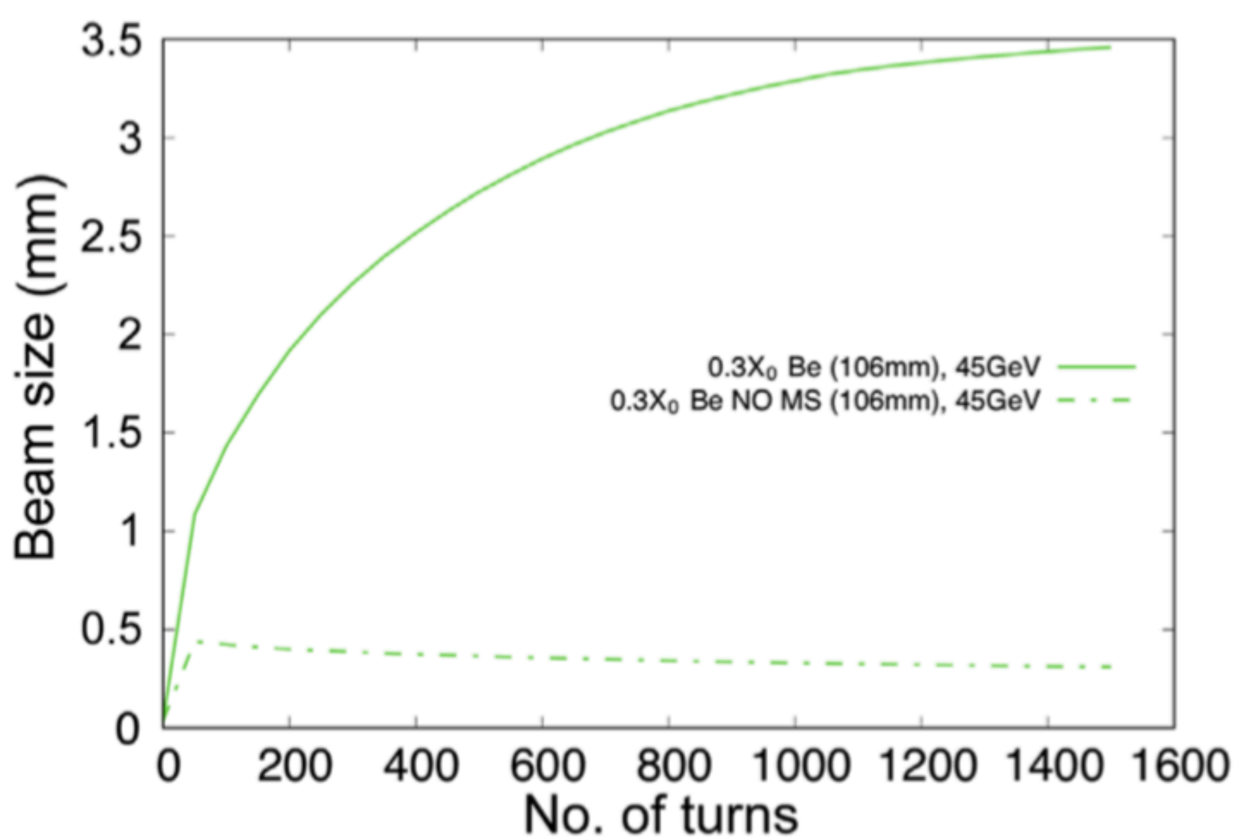
# **Be**ryllium Target

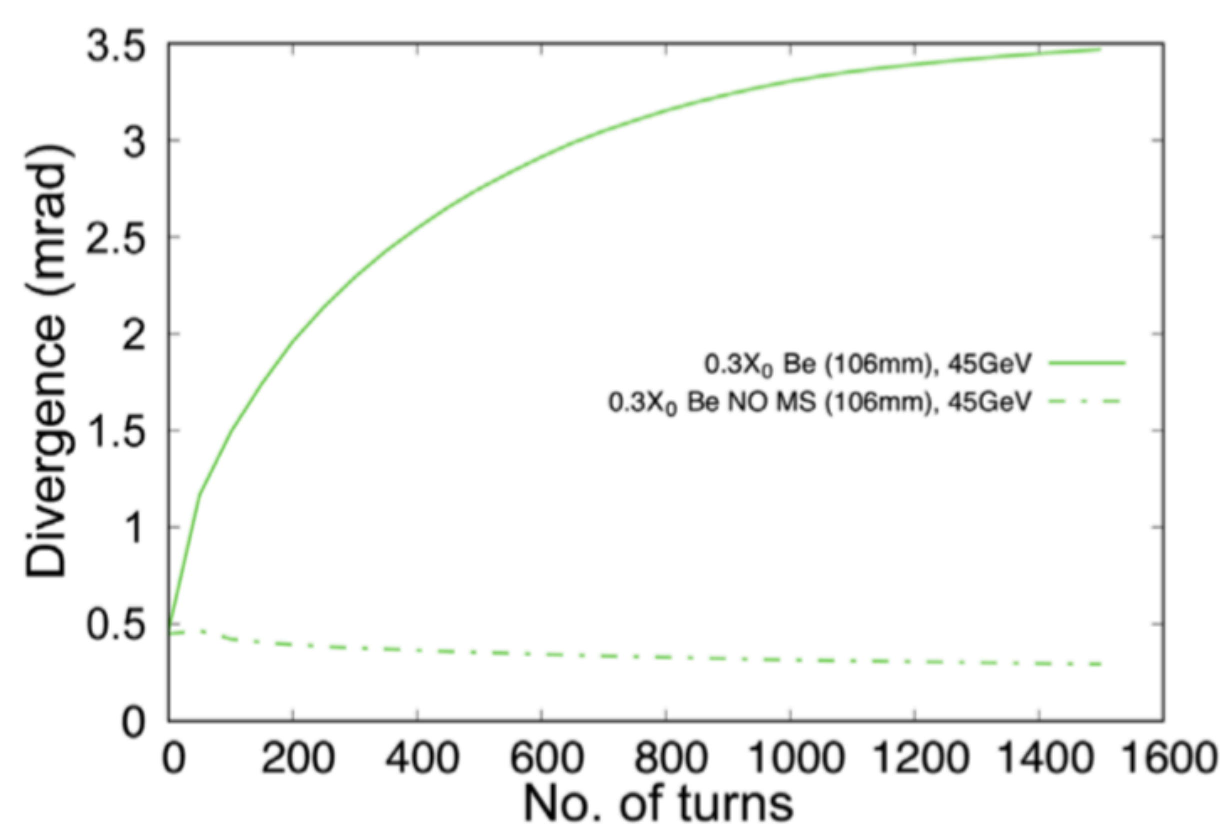



Beryllium is the **most efficient solid target** for muon pair production.

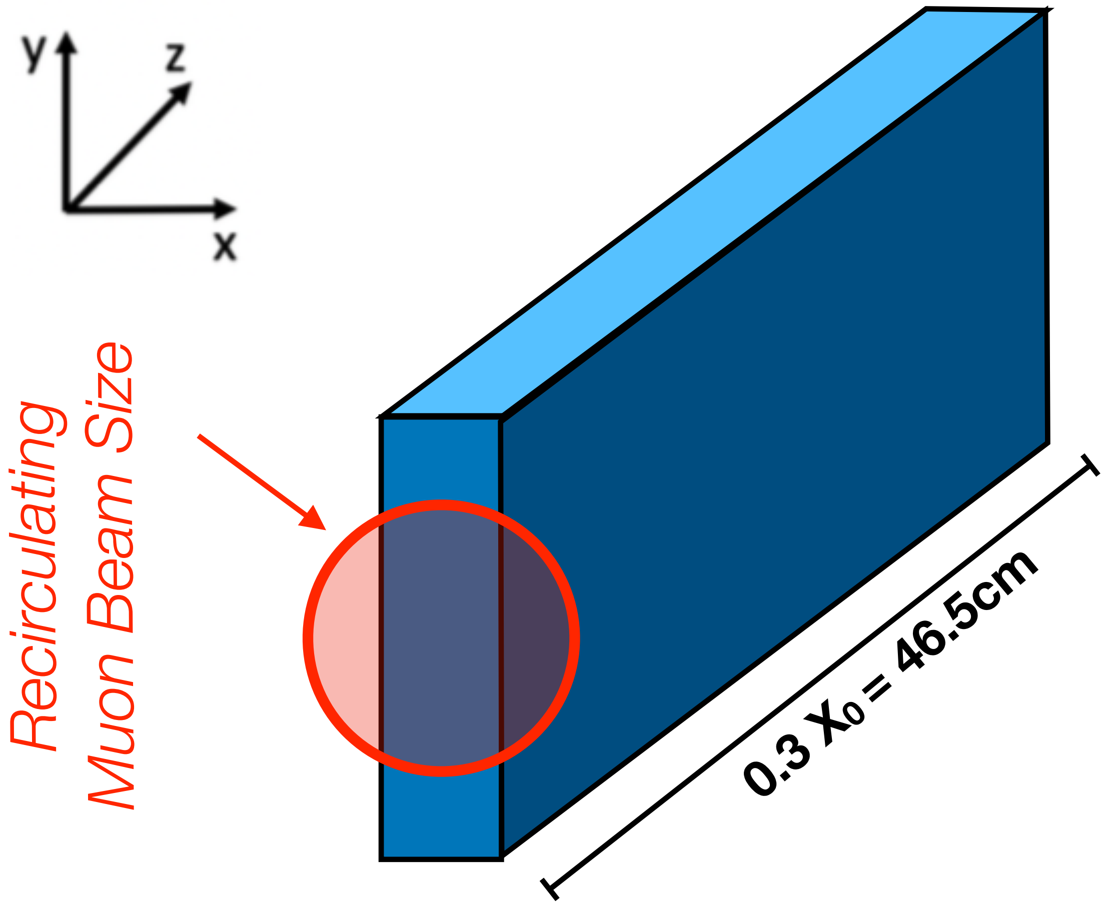
After 1500 turns (~1.5 lifetimes), **$3.5 \times 10^8$ muon pairs** accumulated considering 1500 impinging positron bunches of $5 \times 10^{11}$ positrons per bunch.

Due to the repeated passes through the target, the accumulated muon beam size and divergence increase because of the **Multiple Scattering**.



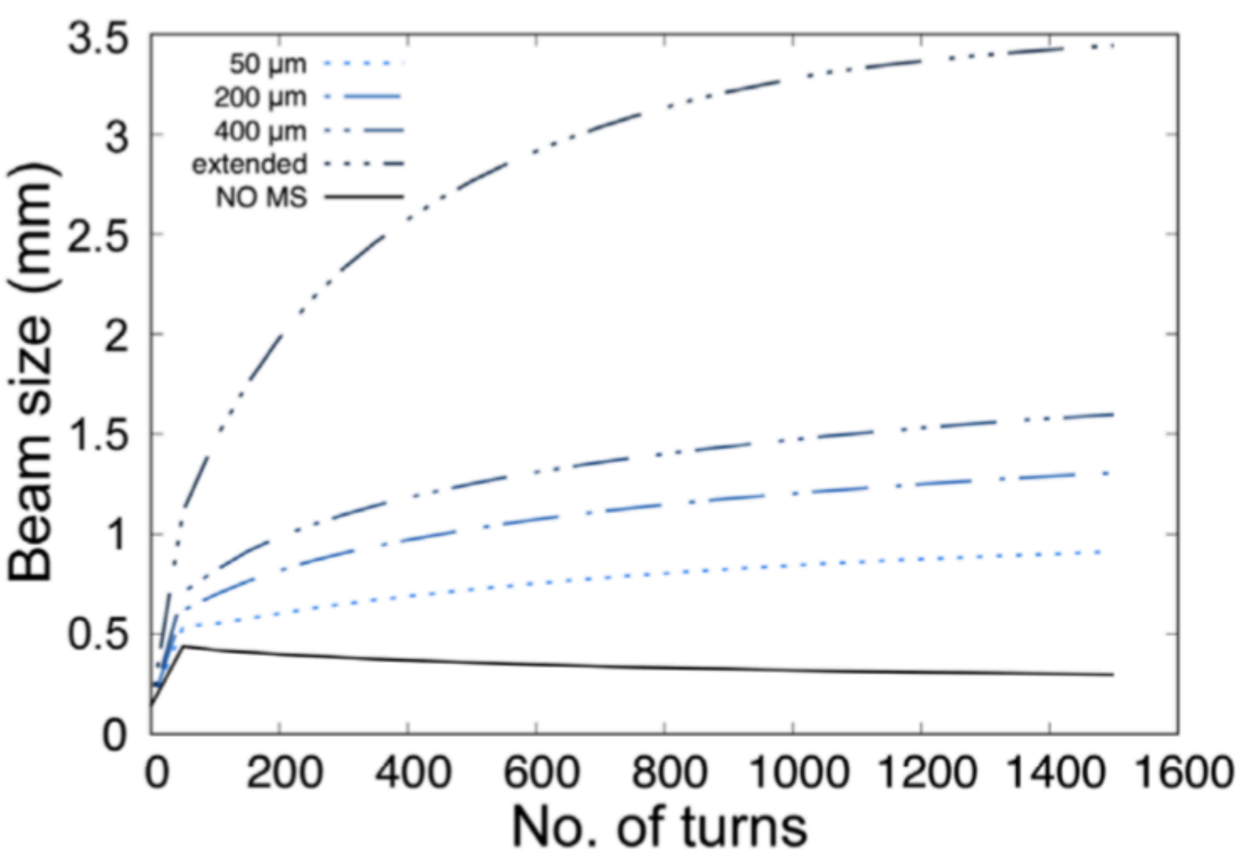
# Liquid Lithium Target

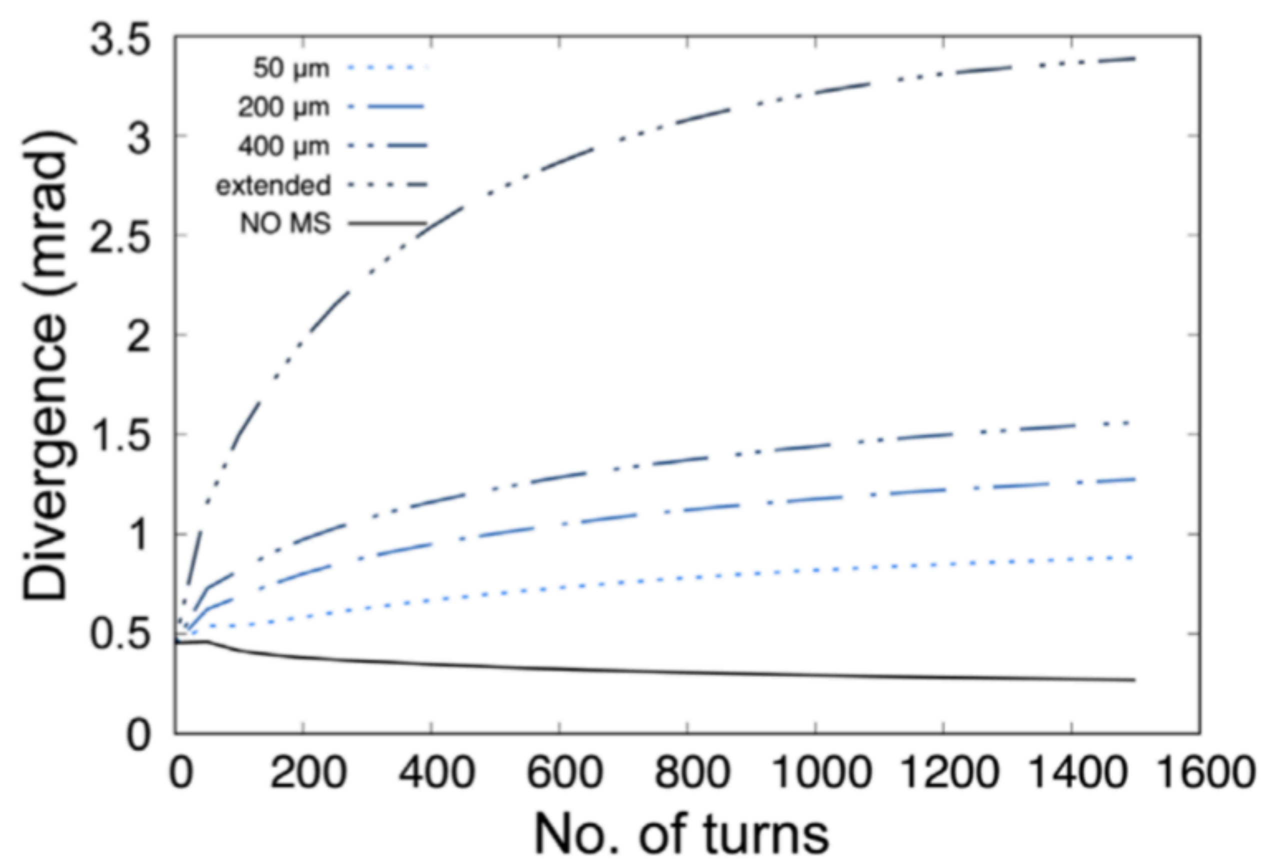



To **mitigate the effect of multiple scattering** during the accumulation a **thin film target** can be obtained using a jet of liquid Lithium.

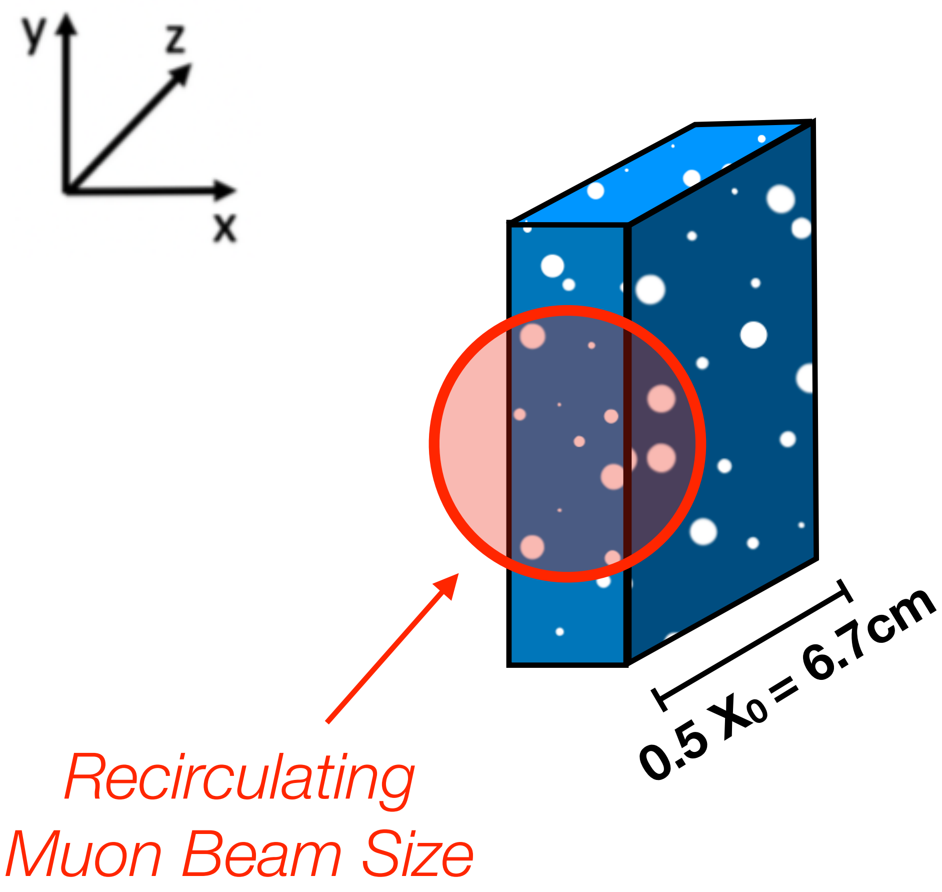
If the transverse size of the target is much **smaller than the stored beam size** (but bigger than the positron beam size!), muons will mostly not interact with matter.

On the other hand Lithium has a low $X_0$ so the target would be quite **long** and difficult to build



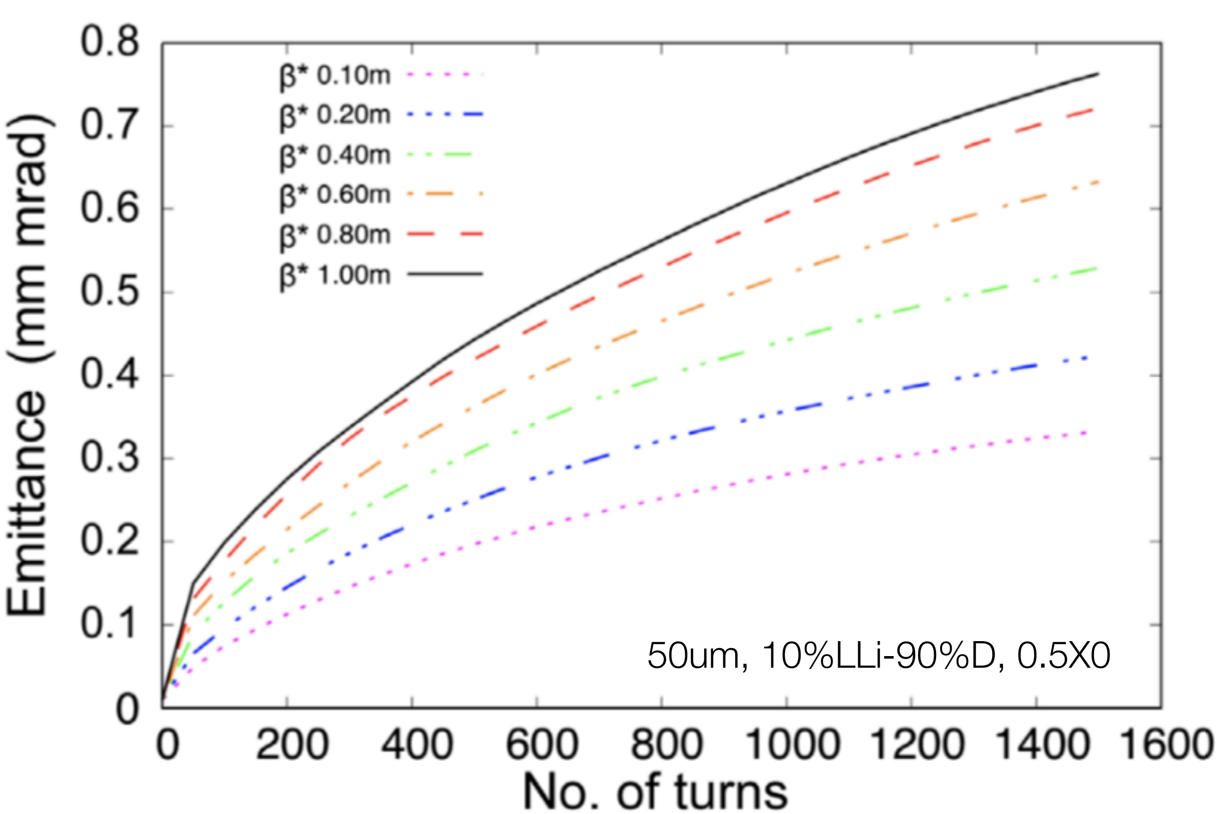
# Liquid Lithium Target with Diamond dust

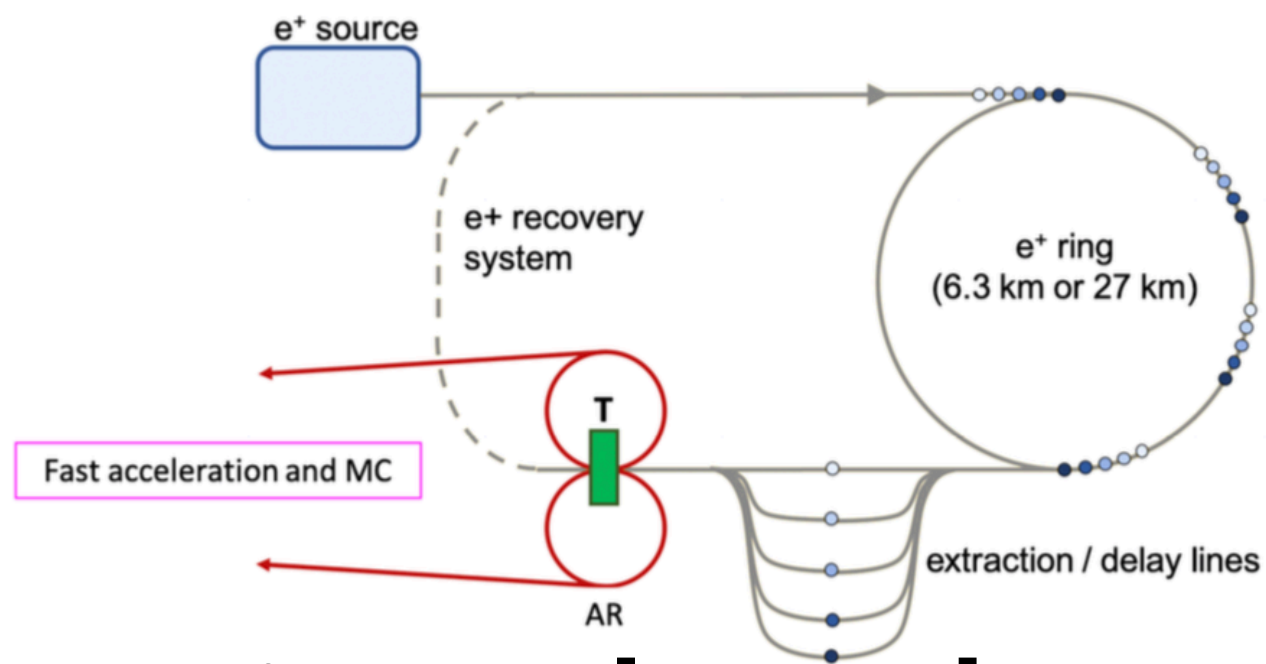


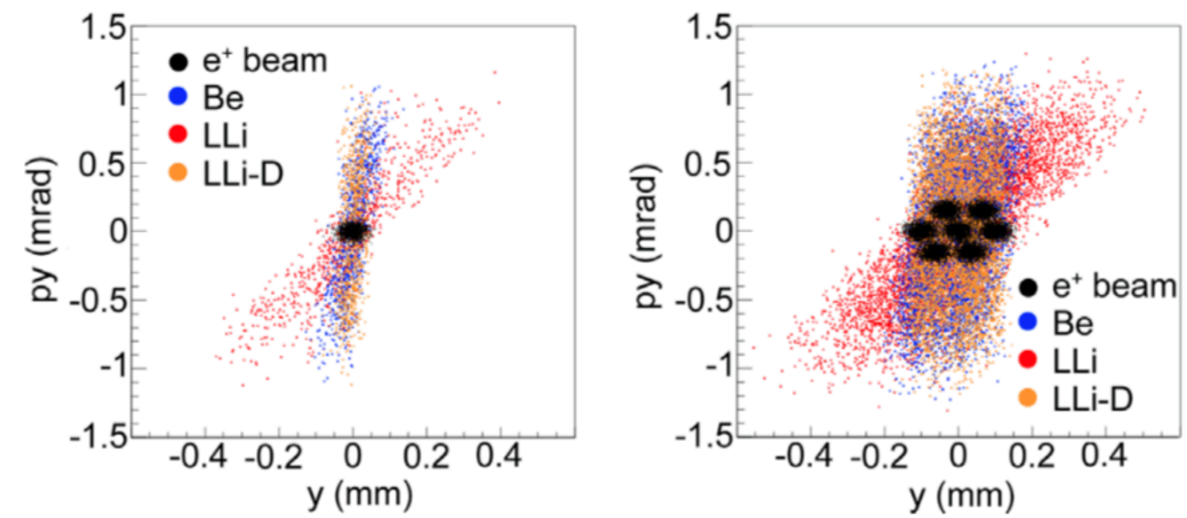

The film jet target length can be reduced by mixing **diamond powder** to the liquid Lithium.

By doing so the multiple scattering contribution to emittance is strongly suppressed, and the target has a reasonable length.

Using this target, a preliminary study on the effect of a **lower beta function** at the target location has been performed and it showed that a lower beta would **further reduce** the final muon beam emittance.



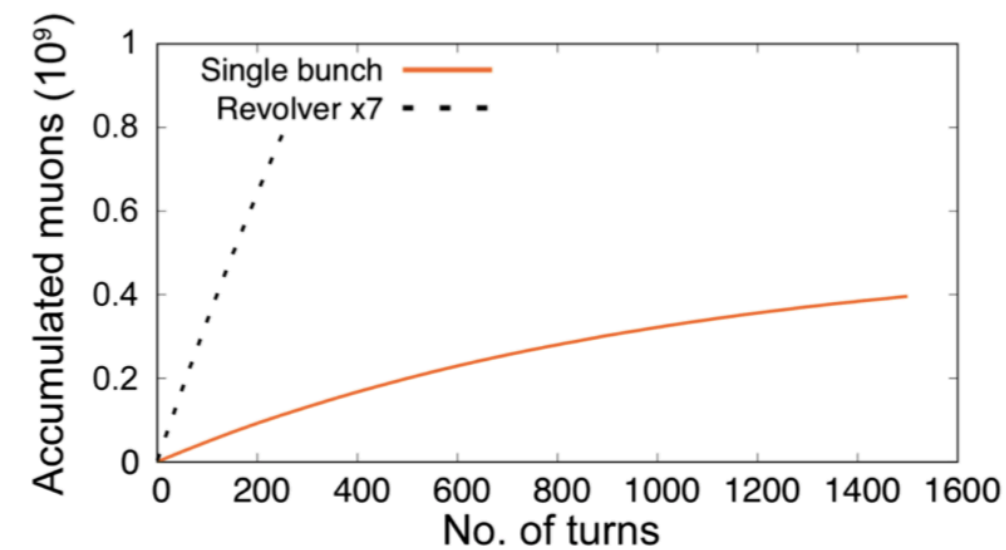


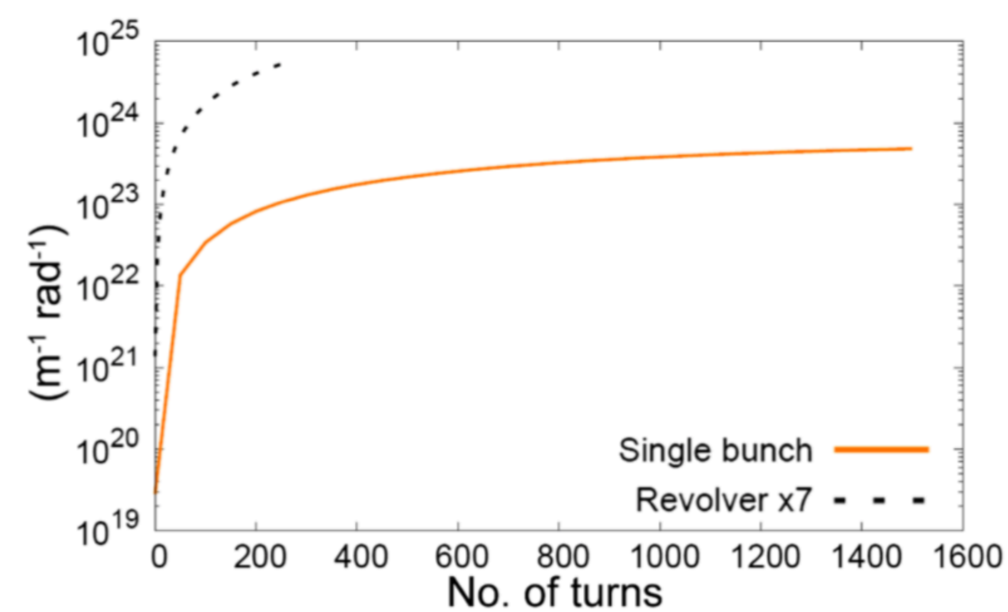




# Positron bunch recombination at the target

Thanks to the small positron emittance it could be possible to simultaneously inject **multiple positron bunches** on the target by using a dedicated system of **delay lines**, spacing them on the vertical phase space.

The advantage of this configuration is the faster accumulation process, reducing the MS contribution to emittance and also preventing a lot of muons from decaying.



# Conclusions

- Muon beams **start-to-end simulations** from production to accumulation for the LEMMA single-pass scheme have been performed

- The optics for a compact muon accumulator with **-10%/+15%** energy acceptance and a proper **low-beta interaction region** for target insertion has been presented

- Several ideas for the suppression of the multiple scattering contribution to the final emittance have been studied, the best solution being a 50$\mu m$ LLi-D film jet target of about 0.5$X_0$ using a $\beta^* = 0.1m$, producing a muon beam with **0.3x10$^{-6}$ m rad** emittance after 1000 accumulation turns with **0.4x10$^9$ muons per bunch**

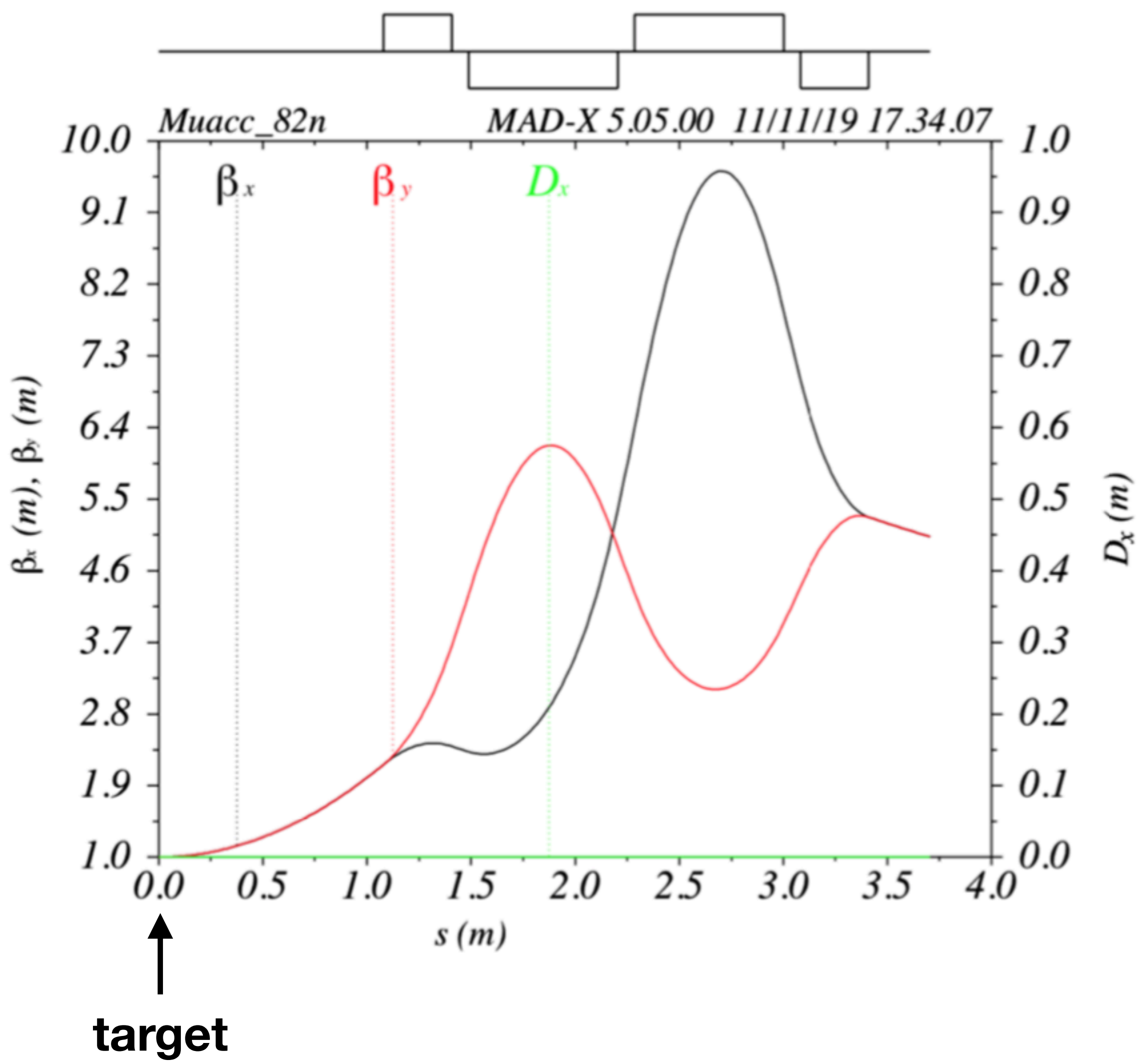
- It was also shown that the number of turns in the accumulator can be reduced using the **Revolver Configuration** resulting in an increase of the muons survival with smaller muon bunch perturbation. In this case an emittance of about **0.1x10$^{-6}$ m rad** and a number of muons per bunch of about **10$^9$** have been obtained

- The further increase of the ring energy acceptance would allow operation at higher positron energy thus increasing the production efficiency. Also further reduction of the beta* will bring a smaller emittance.

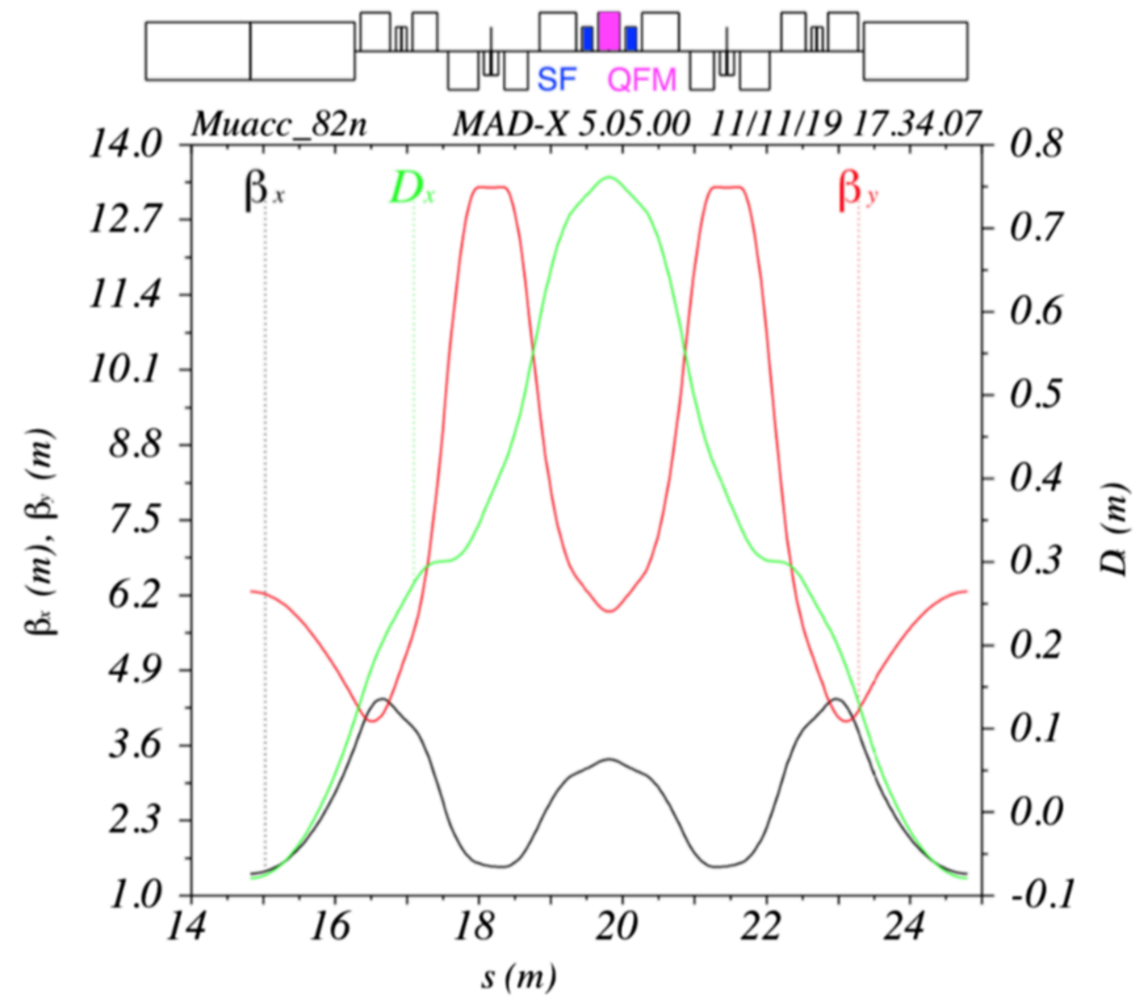
- Once the beam will be accelerated at the multi-TeV regime at the muon collider ring (i.e. FCC tunnel), the final muon emittance will be reduced by the synchrotron radiation **damping.**

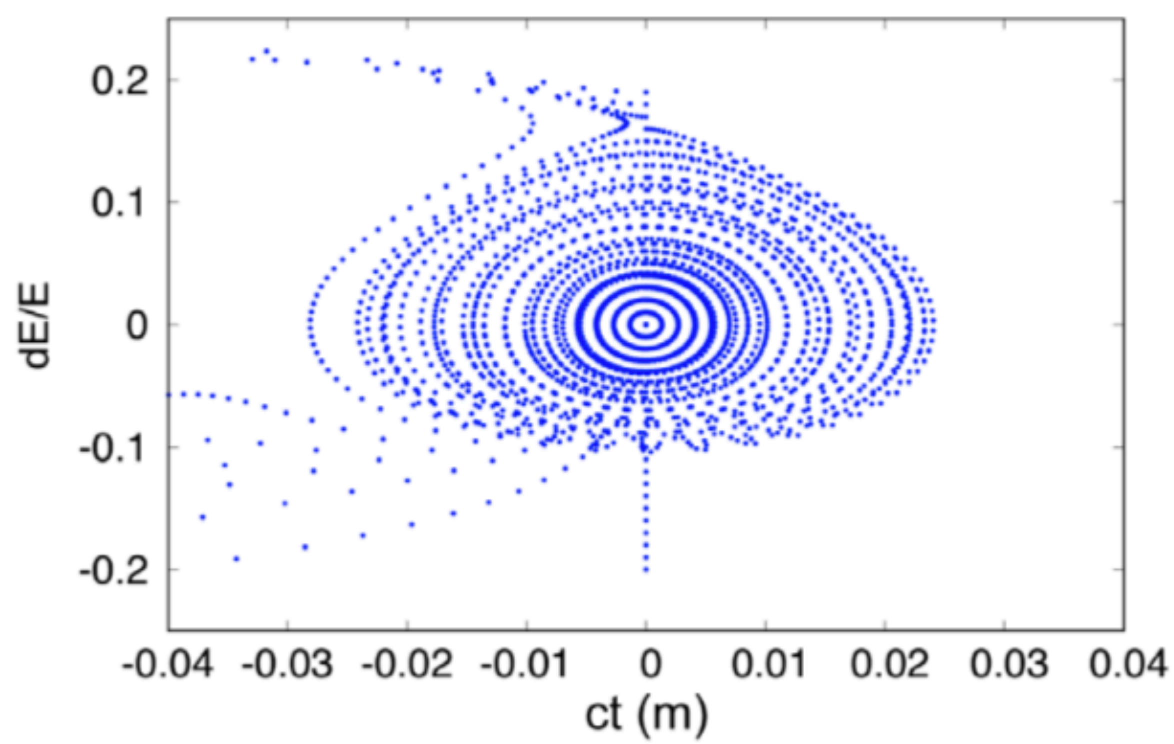
# Backup

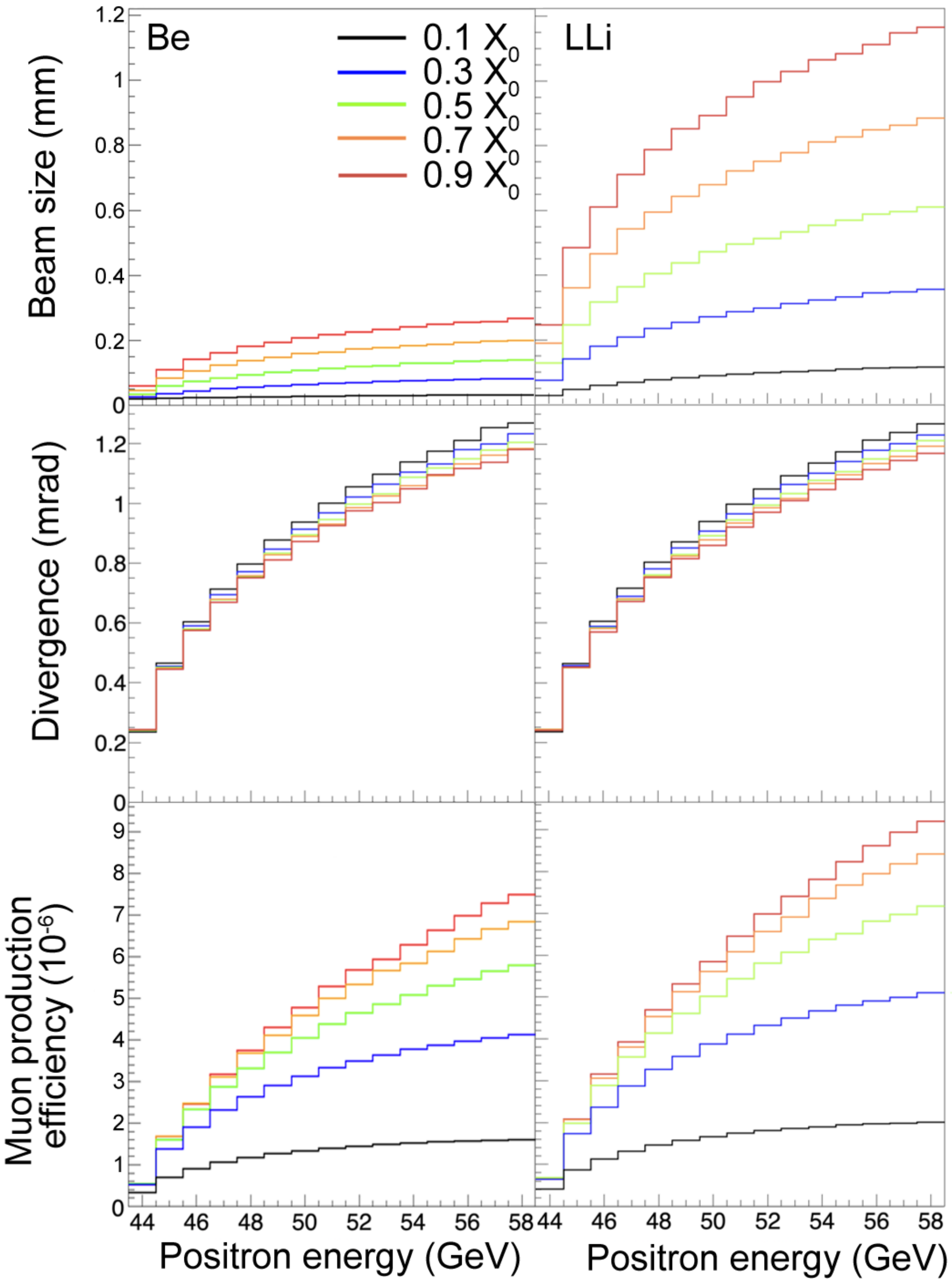
First Cell




Central Cell





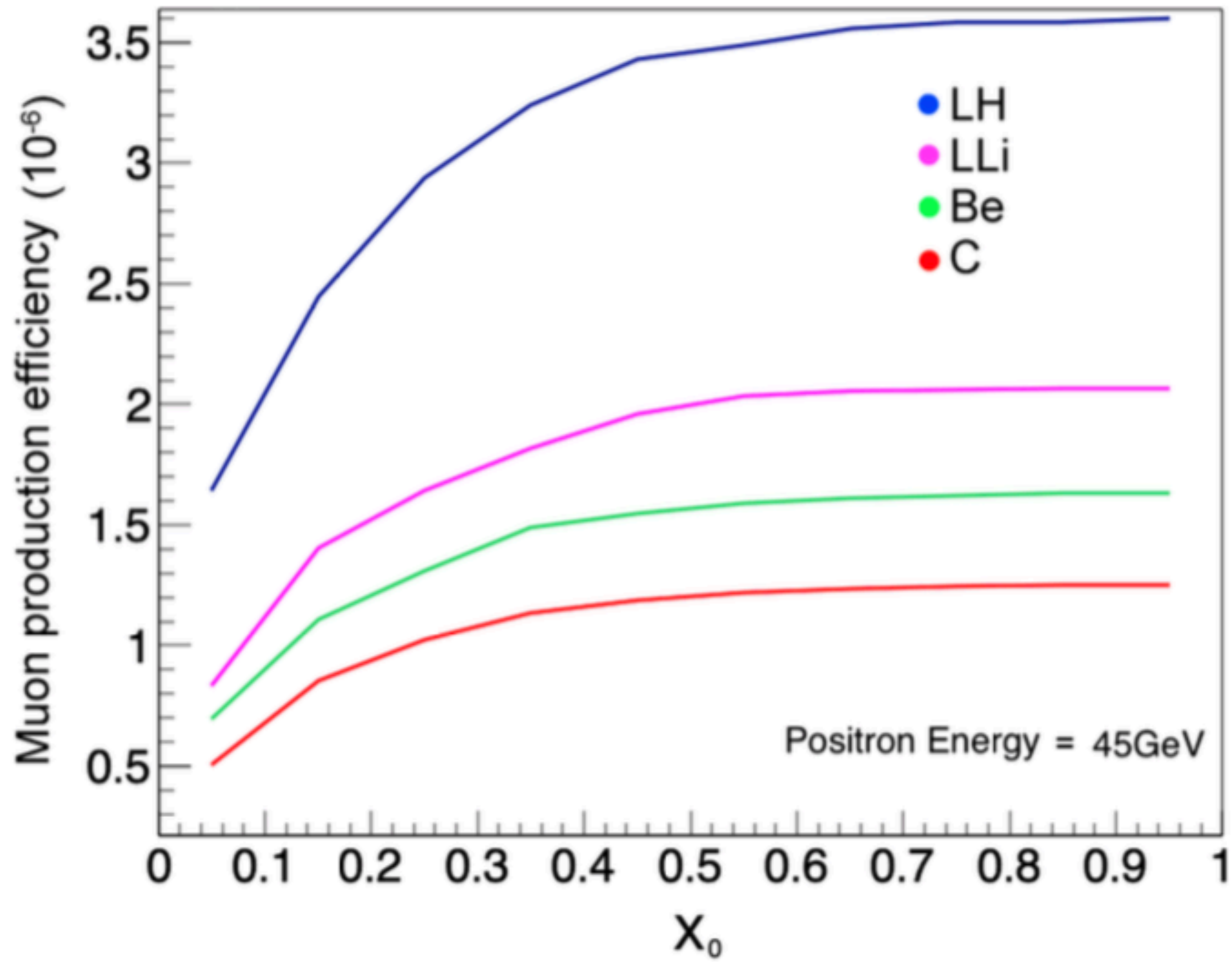




TABLE III. Properties of LLi–D compounds, for different fractions of liquid lithium $f(\mathrm{LLi})$, and diamond powder $f(\mathrm{D})$.

| $f(\mathrm{LLi})$ | $f(\mathrm{D})$ | $\rho[\mathrm{g\ cm^{-3}}]$ | $X_0\ [\mathrm{g\ cm^{-2}}]$ | $X_0$ [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 |

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