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# Studies of a scheme for low emittance muon beam production from positrons on target


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# Outline

- Introduction: Muons case
- Proposal for a novel technique for muon production
- $e^+$ ring with target
- Multi-turn simulations
- Conclusion and Perspectives

# Muon based Colliders

- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of $e^+e^-$ circular colliders)
  - No beamstrahlung (limit of $e^+e^-$ linear colliders)
  - but muon lifetime is 2.2 $\mu$s (at rest)
- Best performances in terms of luminosity and power consumption

- Great potentiality if the technology proves its feasibility:
  - Muon source
  - Fast muon cooling
  - Fast acceleration
  - $\mu$ Collider
  - Radiation Safety (muon decay in accelerator and detector)

# Idea for low emittance $\mu$ beam

Conventional production: from **proton on target**

$\pi$, K decays from proton on target have typical **$P_\mu$~ 100 MeV/c** ($\pi$, K rest frame)

whatever is the boost, $P_T$ will stay in Lab frame →
**very high emittance** at $\mu$ production point → **cooling** needed!

Novel proposal: **direct $\mu$ pair production: $e^+e^- \rightarrow \mu^+\mu^-$**

just above the $\mu^+\mu^-$ production threshold ($\sqrt{s}$ ≈0.212 GeV) with minimal muon energy spread, with direct annihilation of ≈ 45GeV $e^+$ with atomic $e^-$ in a thin target O(0.01 radiation length)

**very small emittance** at $\mu$ production point→ **no cooling** needed!

## Advantages:

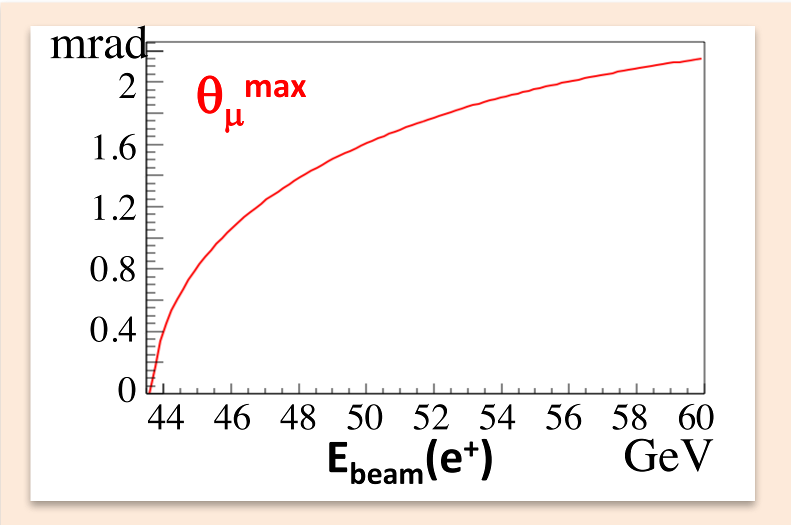
1. **Low emittance possible:** $\theta\mu$ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$
   $\theta\mu$ can be **very small** close to the $\mu^+\mu^-$ threshold
2. **Low background:** Luminosity at low emittance will allow low background and low $\nu$ radiation (easier experimental conditions, 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

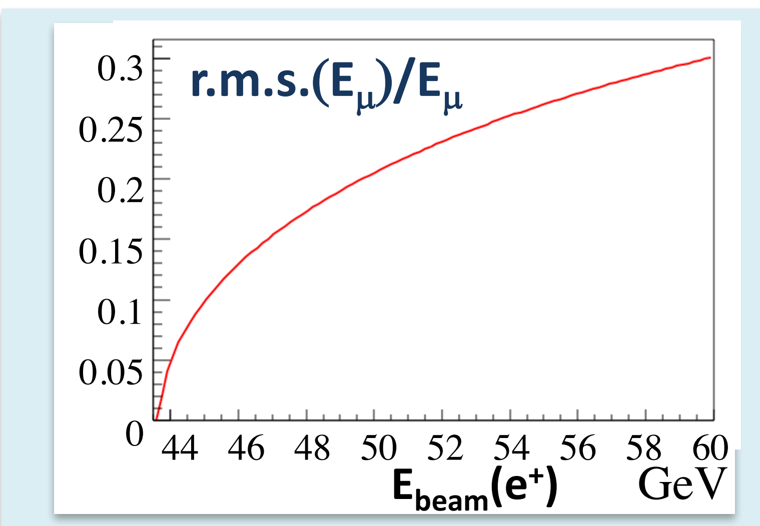
## Disadvantages:

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

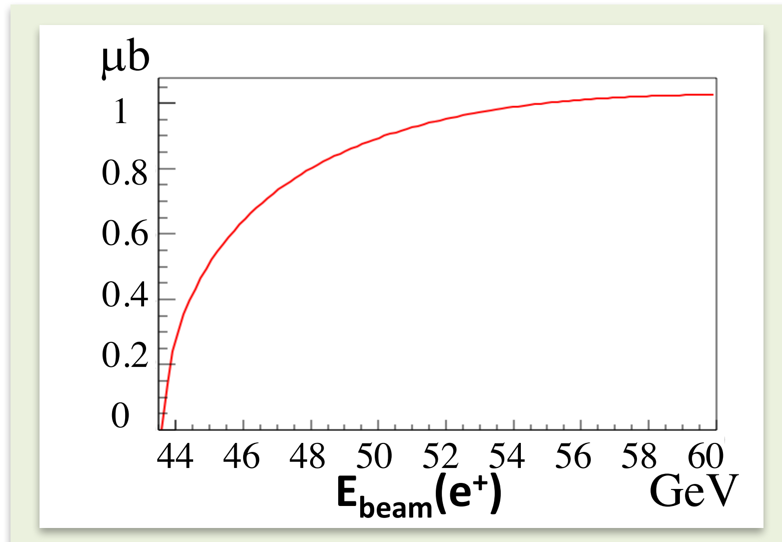
  $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1\ \mu b$ at most

# Parametric behaviours




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



# Criteria for target design

**minimize emittance** → **thin target**
**maximize rate** → **maximize density (high Z)**
**minimize positron loss (brem.)** → **low Z**

- **Heavy materials, thin target**
  - to minimize $\varepsilon_\mu$ : thin target ($\varepsilon_\mu \propto$ length ) with high density $\rho$

  Copper: MS and $\mu^+\mu^-$ production give about same contribution to $\varepsilon_\mu$
  BUT high $e^+$ loss (Bremsstrahlung is dominant) so
  $\sigma(e^+loss) \approx \sigma(Brem+bhabha) \approx (Z+1)\sigma(Bhabha) \rightarrow$
  low maximimal $\mu^+\mu^-$ production efficiency (infinite length target)
  $Eff_{max} \approx \sigma_\mu/[(Z+1)\sigma(Bhabha)] \sim 10^{-7}$
- **Very light materials, thick target**
  - maximize $\mu^+\mu^-$ production efficiency $\sim 10^{-5}$ (enters quad) → $H_2$

  Even for liquid targets O(1m) needed → $\varepsilon_\mu$ increase
- **Not too heavy materials (Be, C, Li)**
  - Allow low $\varepsilon_\mu$ with small $e^+$ loss $Eff_{max} \approx 10^{-6}$

**not too heavy and thin in combination with stored positron beam to reduce the requests on positron source**

# Preliminary scheme for low emittance μ beam production

Goal:

@T ≈ $10^{11}$ μ/s

Efficiency ≈ $10^{-7}$ (with Be 3mm)→

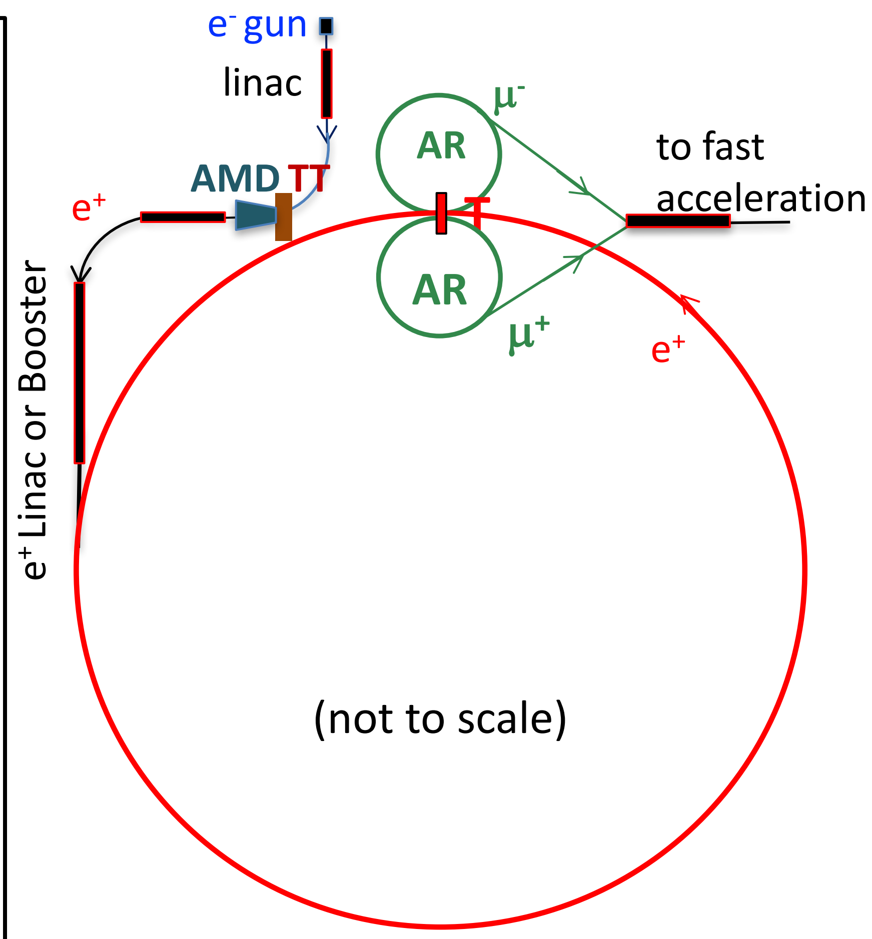
$10^{18}$ $e^+$/s needed @T →

$e^+$ stored beam with T

need the largest possible lifetime to minimize positron source rate

LHeC like e+ source required rate with lifetime(e+) ≈ 250 turns [i.e. 25% momentum aperture] →

n(μ)/n($e^+$ source) ≈ $10^{-5}$



# Preliminary scheme for low emittance μ beam production

**from e⁺ SOURCE to RING:**

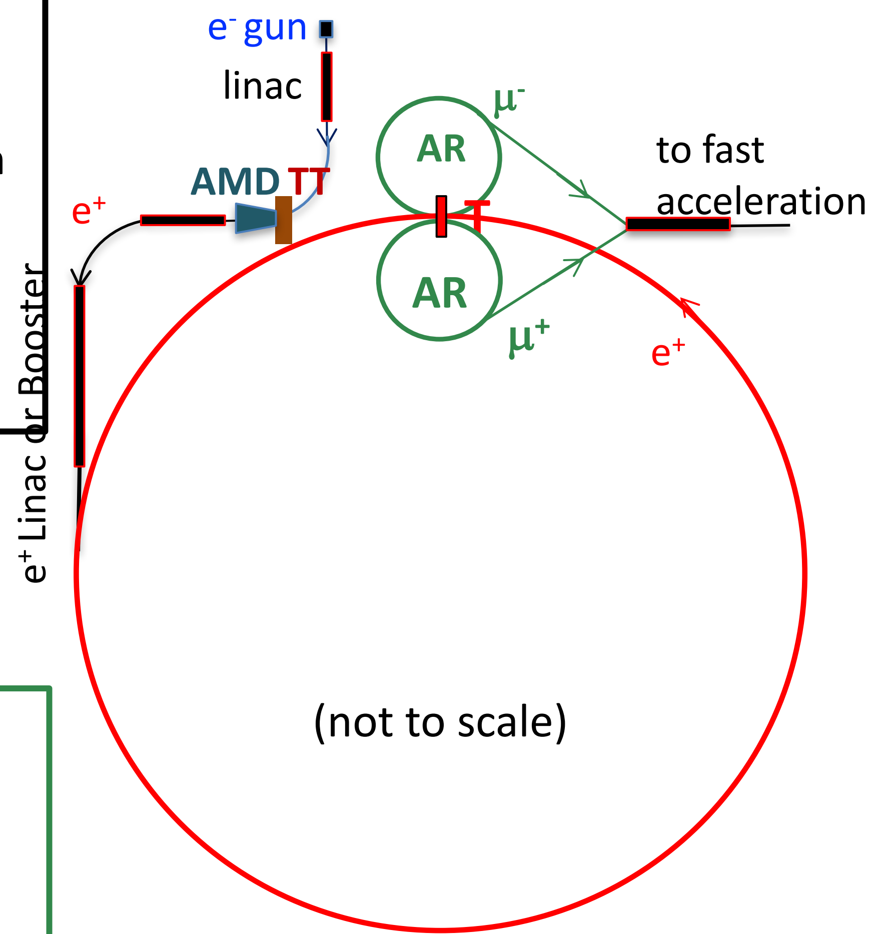
- **e⁻** on conventional Heavy Thick Target (**TT**) for e⁺e⁻ pairs production.
- possibly with γ produced by e⁺ stored beam on **T**→
- Adiabatic Matching Device (**AMD**) for **e⁺** collection →
- acceleration (linac / booster) , injection →

**e⁺ RING:**

- **6.3 km 45 GeV** storage ring with target **T** for muon production

**from μ⁺ μ⁻ production to collider**

- produced by the **e⁺** beam on target **T** with **E(μ) ≈ 22 GeV**, γ(μ) ≈ 200 → $\tau_{lab}(\mu) \approx 500\mu s$
- **AR**: **60 m** isochronous and high mom. acceptance rings will recombine μ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns
- fast acceleration
- muon collider



# Preliminary scheme for low emittance μ beam production

**from $e^+$ SOURCE to RING:**

- **$e^-$** on conventional Heavy Thick Target (**TT**) for $e^+e^-$ pairs production.
- possibly with γ produced by $e^+$ stored beam on **T**→
- Adiabatic Matching Device (**AMD**) for **$e^+$** collection →
- acceleration (linac / booster) , injection →

**$e^+$ RING:**

- **6.3 km 45 GeV** storage ring with target **T** for muon production

**from $\mu^+ \mu^-$ production to collider**

- produced by the **$e^+$** beam on target **T** with **E(μ) ≈ 22 GeV**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx 500\mu s$
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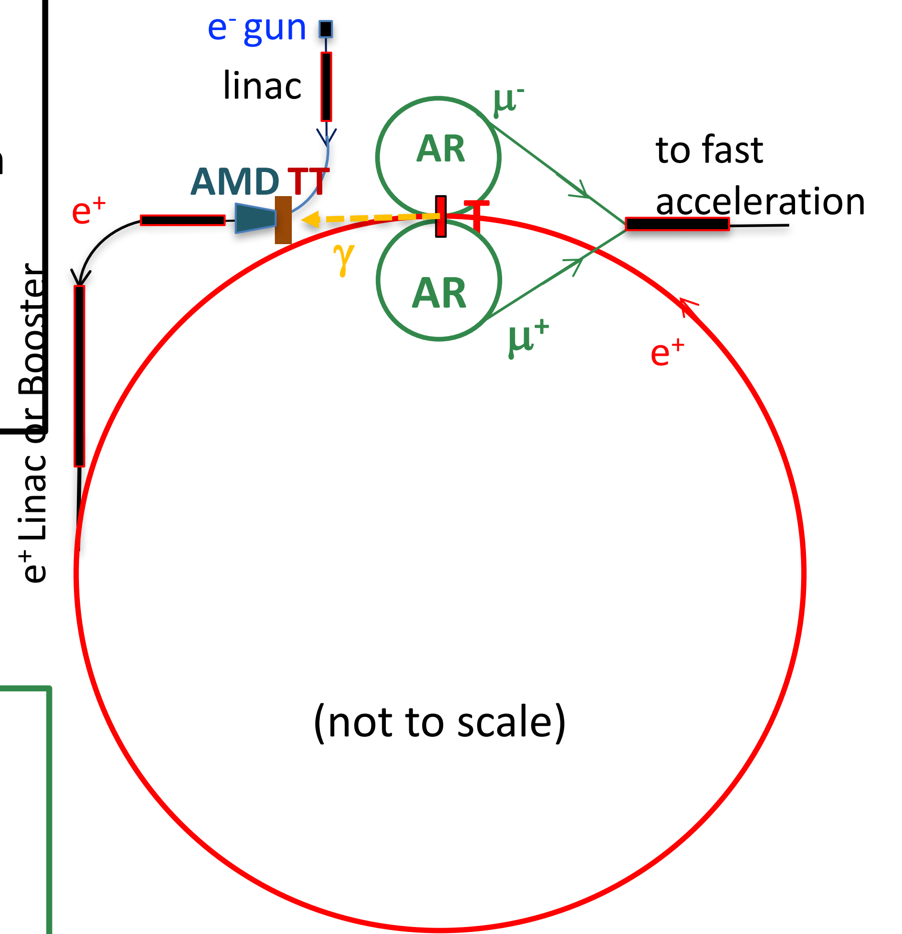
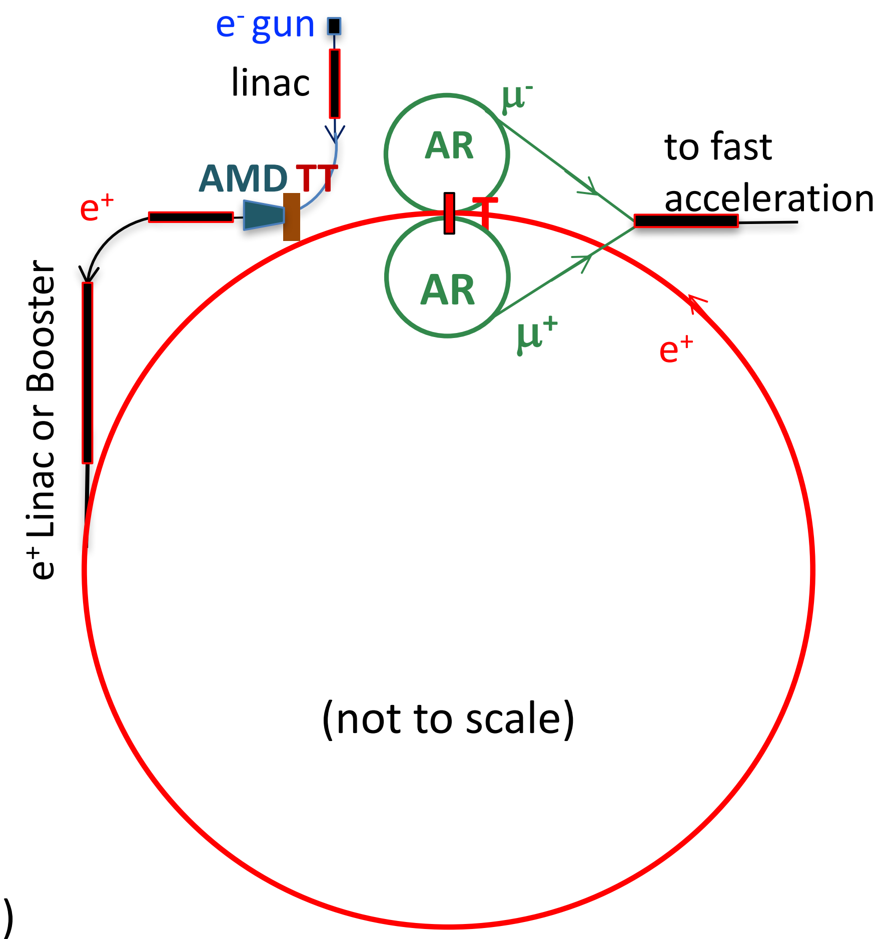



M. Boscolo, IPAC17

# Preliminary scheme for low emittance μ beam production

| e+ ring parameter | unit | |
|---|---|---|
| Circumference | km | 6.3 |
| Energy | GeV | 45 |
| bunches | # | 100 |
| $e^+$ bunch spacing = $T_{rev}$ (AR) | ns | 200 |
| Beam current | mA | 240 |
| $N(e^+)$/bunch | # | $3 \cdot 10^{11}$ |
| $U_0$ | GeV | 0.51 |
| SR power | MW | 120 |

(also 28 km foreseen to be studied as an option)



# 6 TeV μ collider draft Parameters

no lattice yet

**$\mu^+\mu^-$ rate = 9 $10^{10}$ Hz**

**$\varepsilon_N$ = 40 nm**

[ NIM A 807 101-107 (2016)]

if: LHeC like $e^+$ source
with 25% mom. accept. $e^+$ ring
and ε dominated by μ production

thanks to very small
emittance (and lower beta*)
comparable luminosity with
lower Nμ/bunch
(→ lower background)

Of course, a design study
is needed to have a
reliable estimate of
performances

| Parameter | Units | LEMC-6TeV |
|---|---|---|
| LUMINOSITY/IP | $cm^{-2}$ $s^{-1}$ | 5.09E+34 |
| Beam Energy | GeV | 3000 |
| Hourglass reduction factor | | 1.000 |
| Muon mass | GeV | 0.10566 |
| Lifetime @ prod | sec | 2.20E-06 |
| Lifetime | sec | 0.06 |
| c*tau @ prod | m | 658.00 |
| c*tau | m | 1.87E+07 |
| 1/tau | Hz | 1.60E+01 |
| Circumference | m | 6000 |
| Bending Field | T | 15 |
| Bending radius | m | 667 |
| Magnetic rigidity | T m | 10000 |
| Gamma Lorentz factor | | 28392.96 |
| N turns before decay | | 3113.76 |
| $\beta_x$ @ IP | m | 0.0002 |
| $\beta_y$ @ IP | m | 0.0002 |
| Beta ratio | | 1.0 |
| Coupling (full current) | % | 100 |
| Normalised Emittance x | m | 4.00E-08 |
| Emittance x | m | 1.41E-12 |
| Emittance y | m | 1.41E-12 |
| Emittance ratio | | 1.0 |
| Bunch length (zero current) | mm | 0.1 |
| Bunch length (full current) | mm | 0.1 |
| Beam current | mA | 0.048 |
| Revolution frequency | Hz | 5.00E+04 |
| Revolution period | s | 2.00E-05 |
| Number of bunches | # | 1 |
| N. Particle/bunch | # | 6.00E+09 |
| Number of IP | # | 1.00 |
| $\sigma_x$ @ IP | micron | 1.68E-02 |
| $\sigma_y$ @ IP | micron | 1.68E-02 |
| $\sigma_{x'}$ @ IP | rad | 8.39E-05 |
| $\sigma_{y'}$ @ IP | rad | 8.39E-05 |

# Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

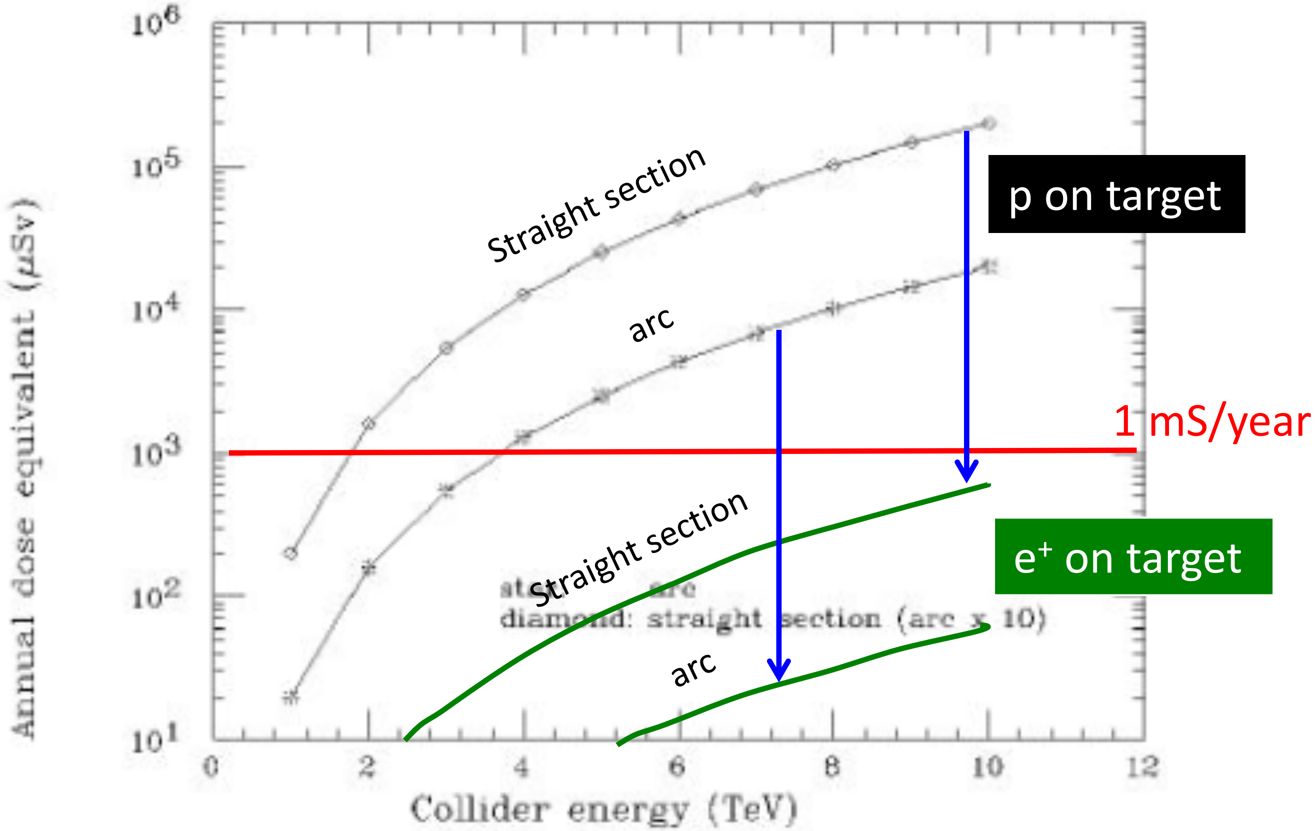



Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

muon rate: p on target option $3\ 10^{13}$ μ/s

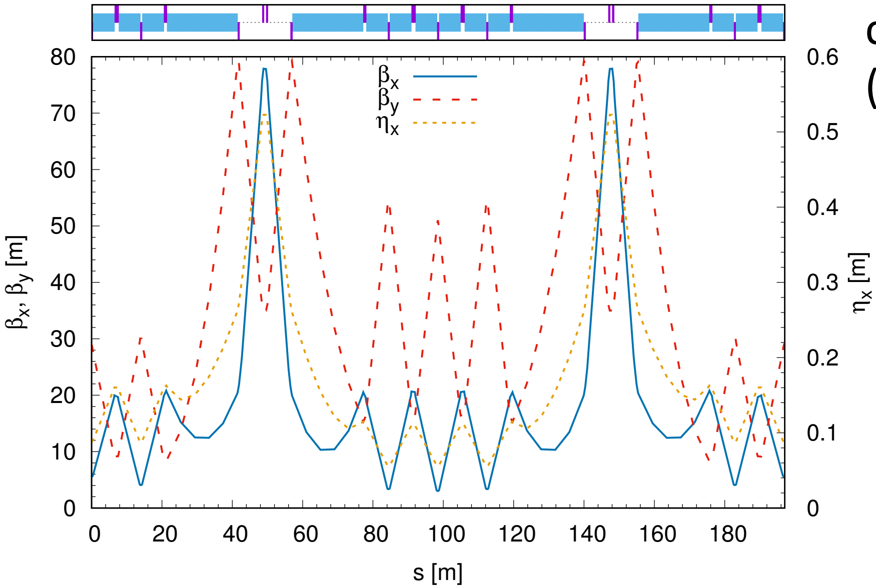
**$e^+$ on target option $9\ 10^{10}$ μ/s**

# Key topics for this scheme

- **Low emittance and high momentum acceptance 45 GeV $e^+$ ring**
- **O(100 kW) class target in the $e^+$ ring for $\mu^+ \mu^-$ production**
- **High rate positron source**
- **High momentum acceptance muon accumulator rings**

# Low emittance 45 GeV positron ring

cell

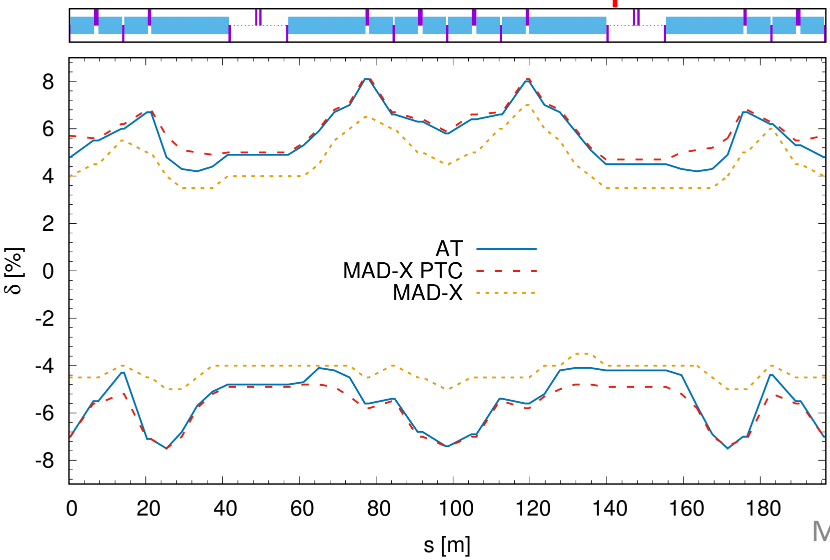



circumference 6.3 km: 197 m x 32 cells
(no injection section yet)

## Table e+ ring parameters

| Parameter | Units | |
|---|---|---|
| Energy | GeV | 45 |
| Circumference | m | 6300 |
| Coupling(full current) | % | 1 |
| Emittance x | m | $5.73 \times 10^{-9}$ |
| Emittance y | m | $5.73 \times 10^{-11}$ |
| 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 | # | $3.15 \times 10^{11}$ |
| Synchrotron tune | | 0.068 |
| Transverse damping time | turns | 175 |
| Longitudinal damping time | turns | 87.5 |
| Energy loss/turn | GeV | 0.511 |
| Momentum compaction | | $1.1 \times 10^{-4}$ |
| RF acceptance | % | $\pm$ 7.2 |
| Energy spread | dE/E | $1 \times 10^{-3}$ |
| SR power | MW | 120 |

momentum acceptance




Physical aperture=5 cm constant

no errors

Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

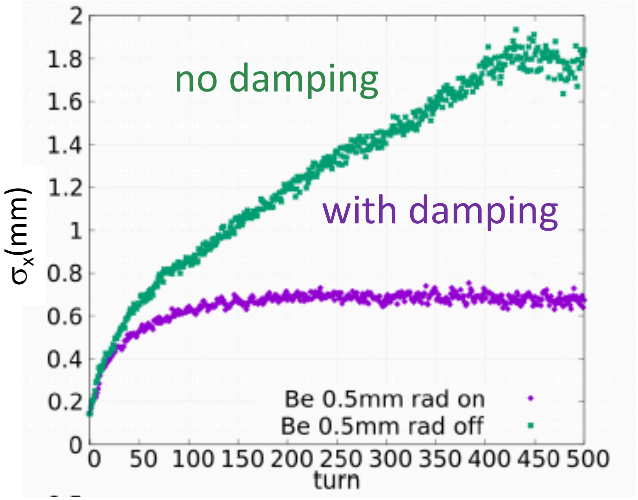
# Multi-turn simulations

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

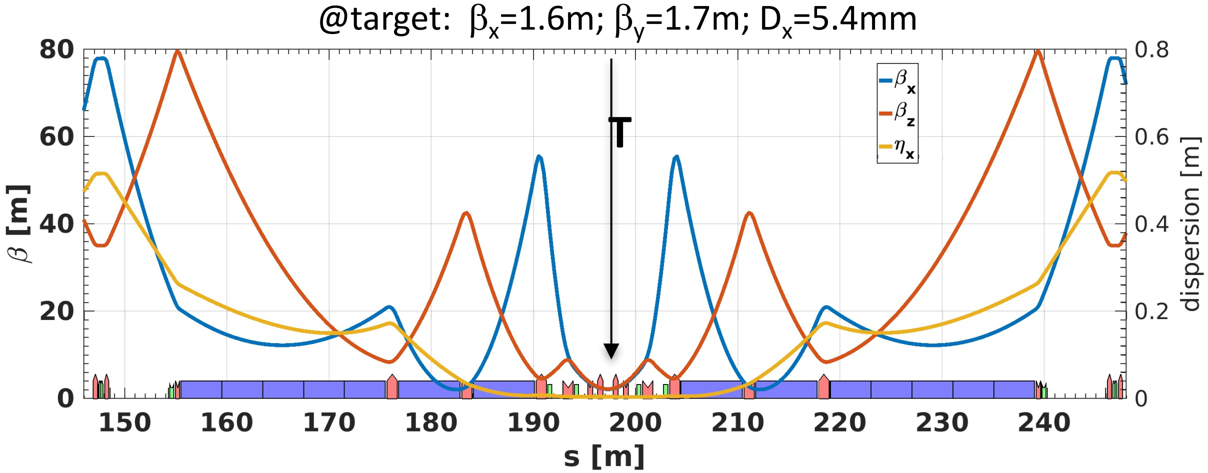
At each pass through the muon target the e+ beam

- 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

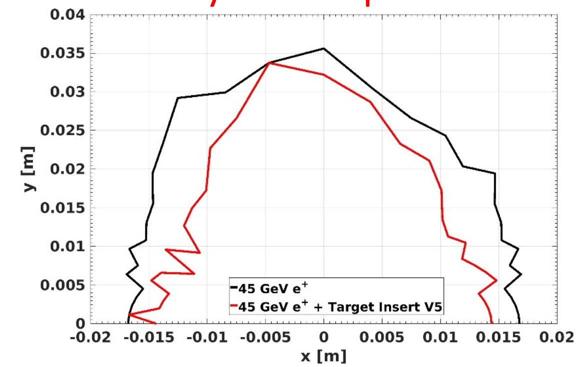
- in addition there is natural radiation **damping** **(**it prevents an indefinite beam growth)



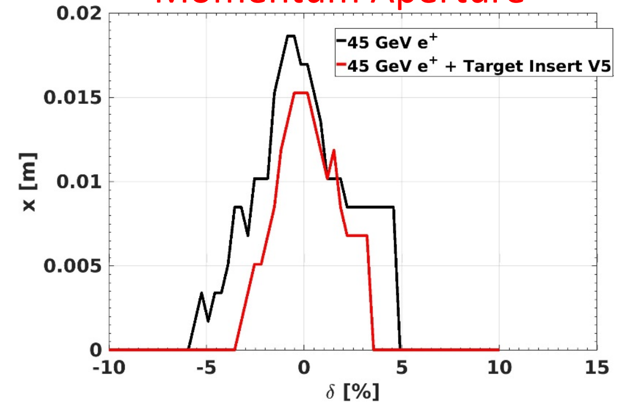
# Preliminary low-β IR for muon target insertion




Dynamic Aperture

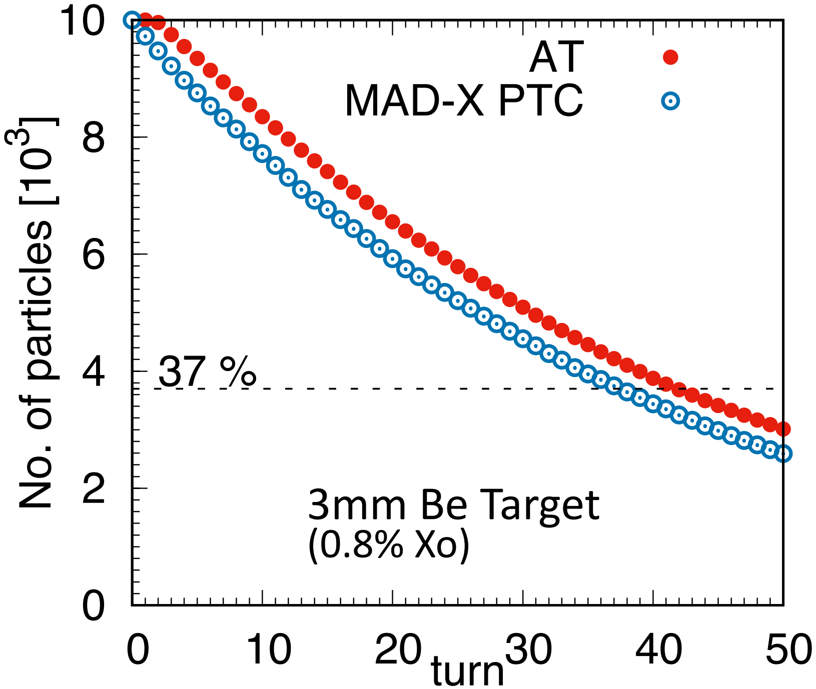


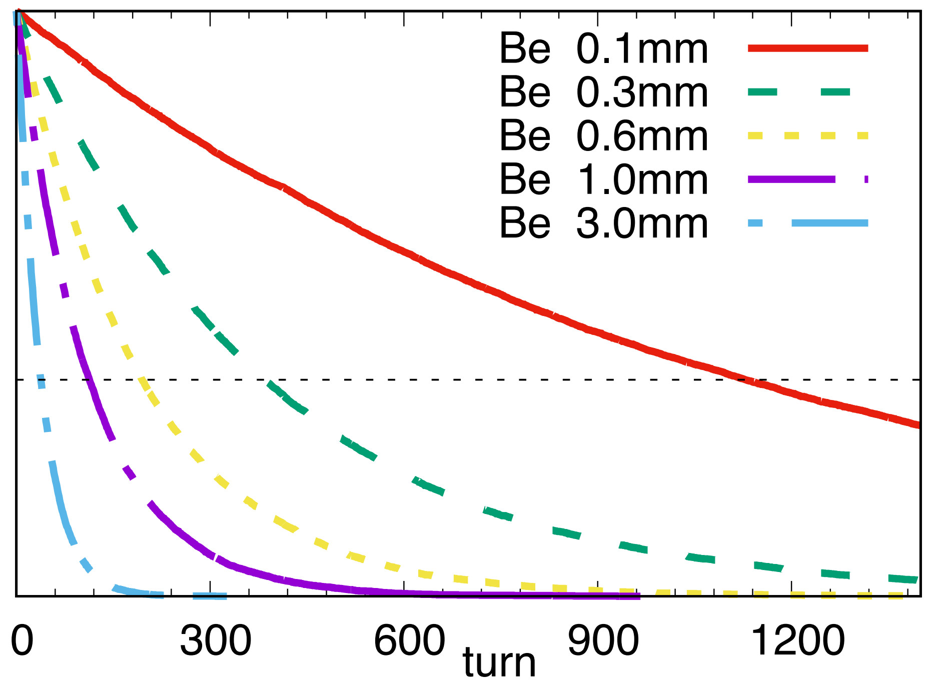

Momentum Aperture




- **@target location:**
  - **$D_x \approx 0$**
  - **low-β**
- Further optimizations are underway:
  - match the transverse minimum beam size with constraints of target thermo-mechanical stress
  - match with other contributions to muon emittance (production, accumulation)
  - dynamic and momentum aperture can be optimized

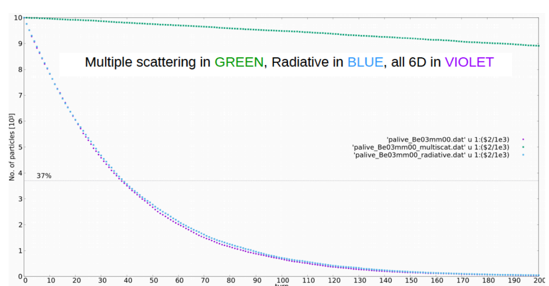
# e+ lifetime with Be target



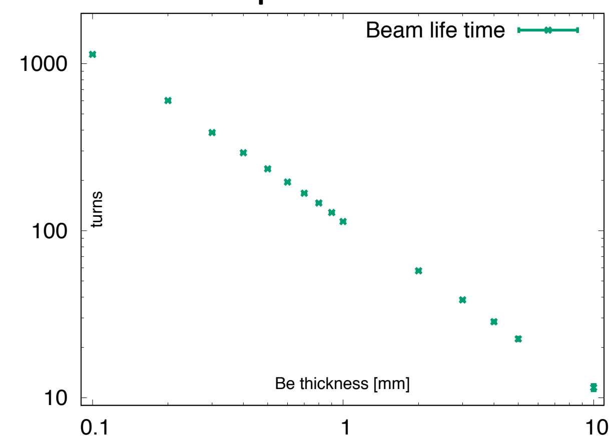




determined by **bremsstrahlung and momentum acceptance**

Lifetime with ~ 40 turns agreement within 10%




Lifetime $\propto$ 1/thickness as expected

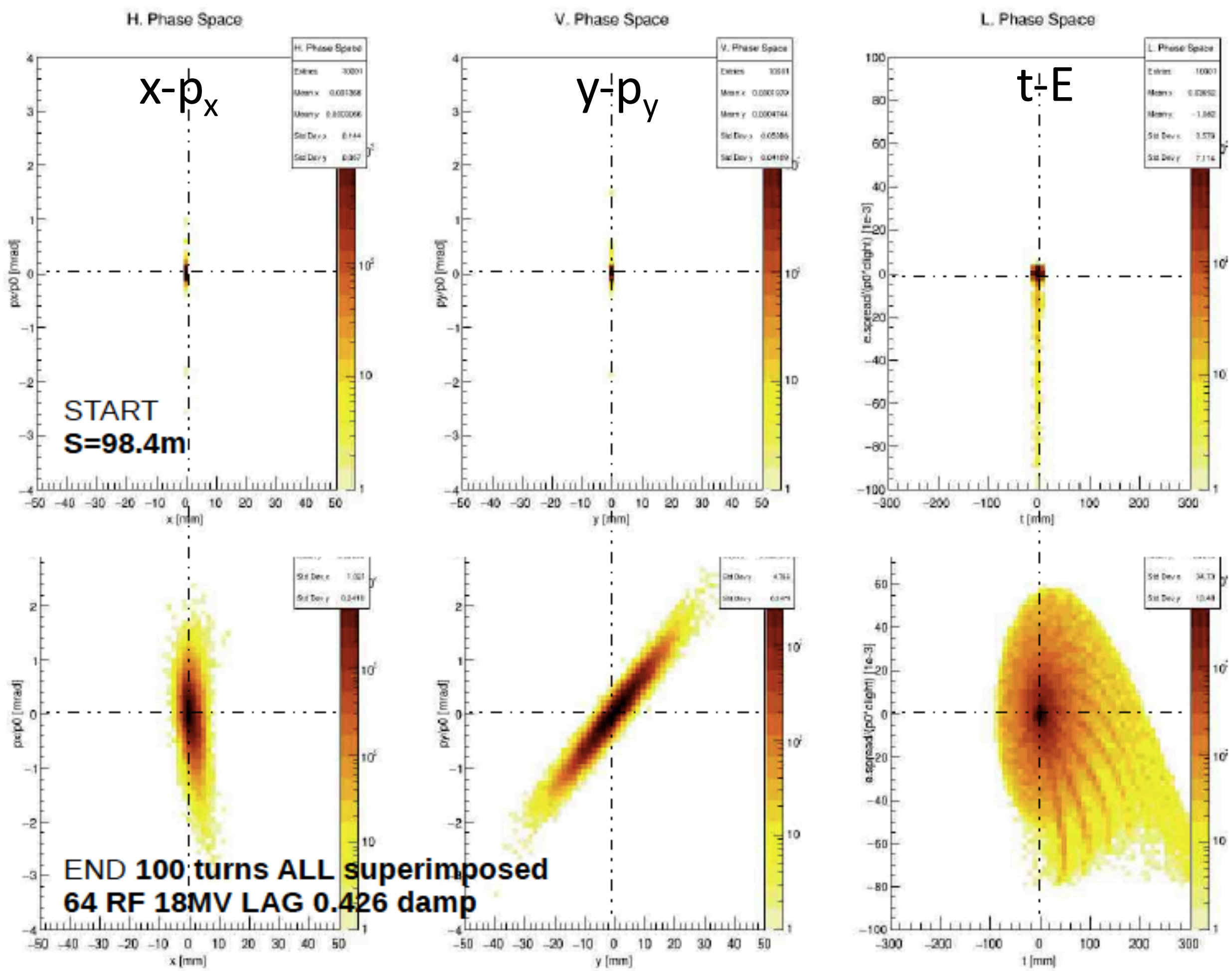



2-3% e+ losses happen in the first turn

# e+ ring with target: beam evolution in the 6D phase space

before target, starting point

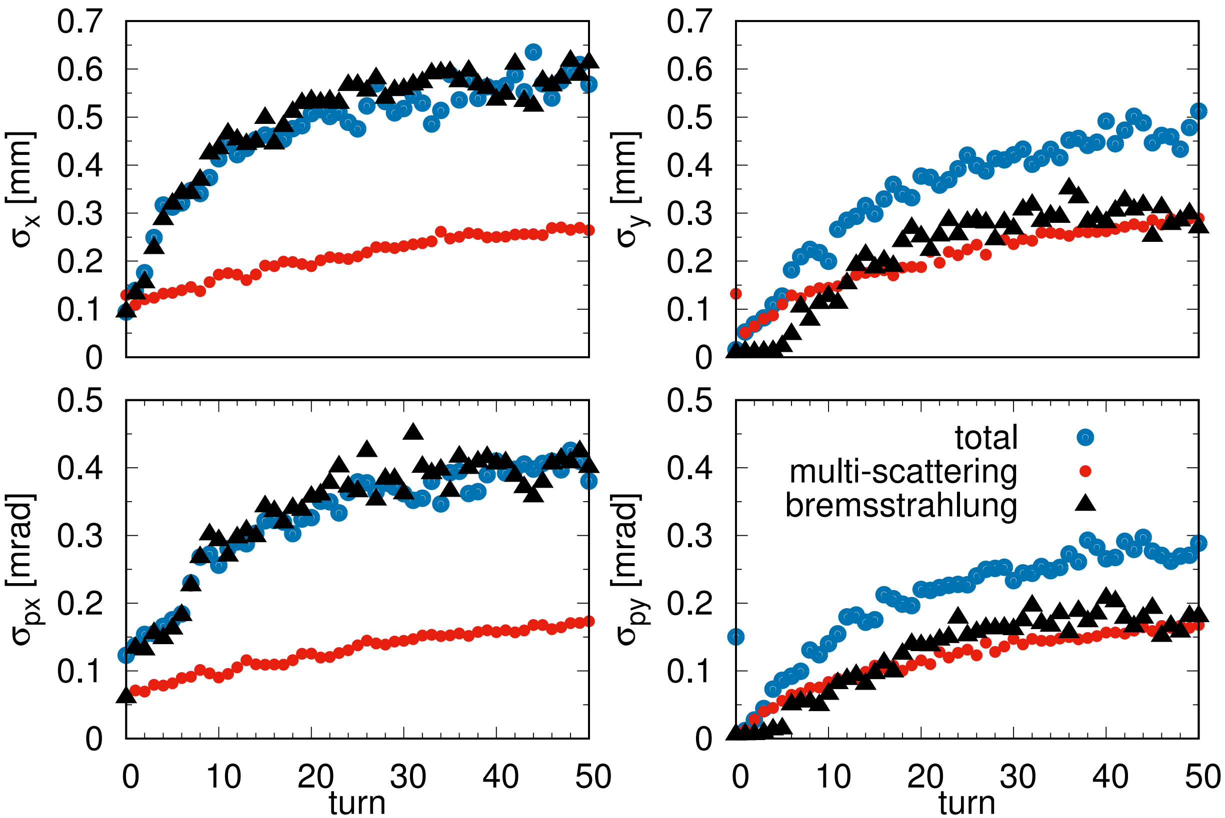
after 40 turns




MAD-X PTC & GEANT4 6-D tracking simulation of
e+ beam with 3 mm Be target along the ring (not at IR center in this example)

# Evolution of e+ beam size and divergence

3mm Be Target (0.8% Xo) at center of IR




bremsstrahlung and multiple scattering artificially separated by considering alternatively effects in longitudinal (dominated by **bremsstrahlung**) and transverse (dominated by **multiple scattering**) phase space due to target; in **blue** the combination of both effects (realistic target)

Some bremsstrahlung contribution due to residual dispersion at target

multiple scattering contribution in line with expectation: $\sigma_{MS} = \frac{1}{2}\sqrt{n_D}\,\sigma'_{MS}\,\beta$

one pass contribution due to the target: $\sigma'_{MS} = 25\ \mu rad$

$n_D$ number of damping turns

# Muon emittance

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

$\varepsilon(e^+)$ = $e^+$ emittance
$\varepsilon(MS)$ = multiple scattering contribution
$\varepsilon(rad)$ = energy loss (brem.) contribution
$\varepsilon(prod)$ = muon production contribution
$\varepsilon(AR)$ = accumulator ring contribution

would like all contributions of same size

knobs:

- $\beta_x$ $\beta_y$ @target & target material
- $\beta_x$ $\beta_y$ $D_x$ @target & target material
- $E(e^+)$ & target thickness
- AR optics & target

with constraints from target survival

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

also test different material

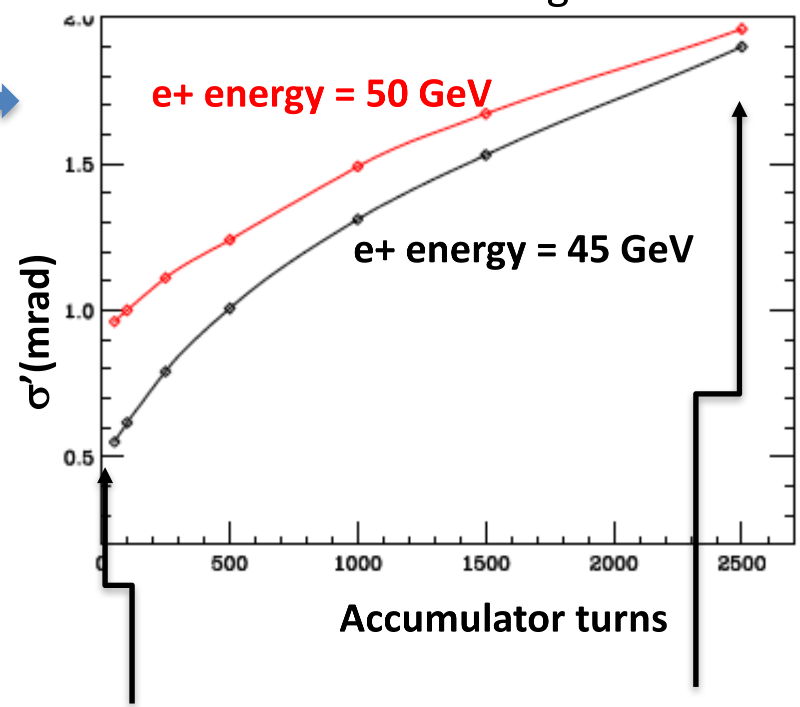
- crystals in channeling better: $\varepsilon(MS)$, $\varepsilon(rad)$, $\varepsilon(prod)$ (also gain in lifetime)
- light liquid jet target better: $\varepsilon(MS)$, $\varepsilon(rad)$
  (also gain in lifetime & target thermo-mechanical characteristics )

# μ Accumulator Rings considerations

isochronous optics with high momentum acceptance ($\delta \gtrsim 10\%$)
optics to be designed

**Multiple Scattering effect using one-turn matrix**

3 mm Be Target




muon production angle

muon production angle + MS contribution

beam divergence:
a factor 3-2 increase at 45-50 GeV w.r.t. muon production angle contribution
beam size:
depends on optics need low-β to suppress size increase

this contribution can be strongly reduced with crystals in channeling

better performances at 50 GeV provided >15% momentum acceptance

# Target considerations

Beam size as small as possible (matching various emittance contribution), 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

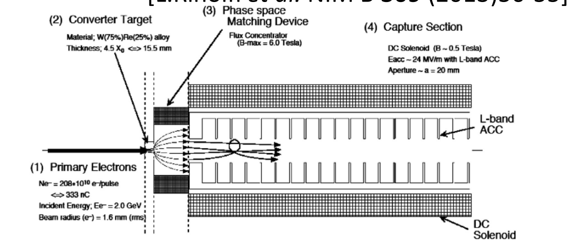
- **Solid target**: simpler and better wrt temperature rise
  - Be, C [Kavin Ammigan 6th High Power Targetry Workshop]
    - Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, N=1.7x10$^{11}$ p/bunch, up to 288 bunches in one shot
- **Liquid** target: better wrt power removal (200kW)
  - Li, difficult to handle lighter materials (H, He)
    - LLi jets examples from neutron production, Tokamak divertor

(200 kW beam power removal seems feasible) , minimum beam size to be understood

# Conclusion and Perspectives

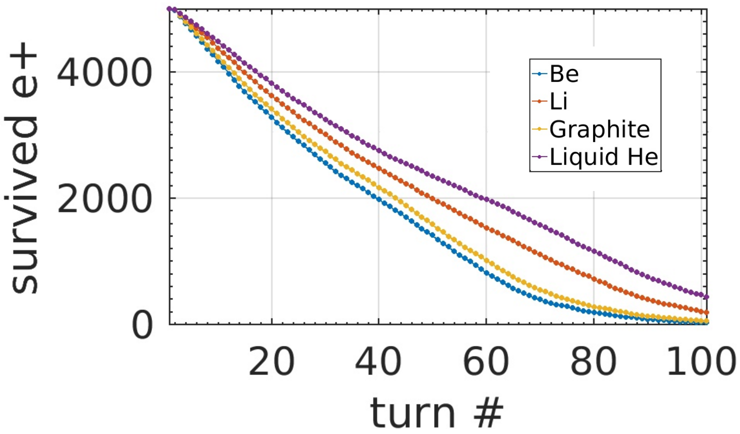
- **First design of low emittance $e^+$ ring with preliminary studies of beam dynamics**
- Optimization requires other issues to be preliminary addressed:
  - **target material & characteristics**
  - **$e^+$ accelerator complex**

[L.Rinolfi *et al.* NIM B **309** (2013)50-55]




Layout of the CLIC $e^+$ source with a single target

thickness according constant muons production




  - **muon accumulator rings design**

**Preliminary studies for a low emittance muon source are promising**

**We will continue to optimize all the parameters, lattices, targets, etc. in order to assess the ultimate performances of a muon collider based on this concept**

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# Tests with $e^+$ beam

Use tertiary 45 GeV $e^+$ beam in CERN North area (H4)
(1 week of beam time July 2017, founded by CSN1-INFN)

- **Low intensity** (one by one $e^+$ tracking) with crystals and amorphous targets:
  - measure beam degradation (emittance energy spectrum)
  - measure produced photons flux and spectrum

- **High intensity** (up to 5 x $10^6$ /spill) with amorphous targets:
  - measure muon production rate and
  - muons kinematic properties