Bersagli cristallini per muon collider - LEMMA

M. Antonelli (LNF)

INFN
LNF
Istituto Nazionale di Fisica Nucleare

Low EMittance Muon Accelerator team:

INFN institutions involved: LNF, Roma1, Pd, Pi, Ts, Fe

Universities: Sapienza, Padova, Insubria

Contributions from: CERN, ESRF, LAL, SLAC

This new proposal covers different areas of research:
accelerator physics, high energy, theory, engineering material science, …

Many colleagues are interested to collaborate,
informal contacts with international experts has started

We believe in the potential of this idea, but key challenges need to be demonstrated to prove its feasibility.
I will show the work done up to now that may lead to a Conceptual Design Report

Low EMittance Muon Accelerator team

Tonelli Guido	10 PI
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Bertolin Alessandro	5 PD
Checchia Paolo	10 PD
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Sestini Lorenzo	30 PD
Zanetti Marco	25 PD
Gonella Franco	20 PD
Anulli Fabio	20 RM1
Collamati Francesco	40 RM1
Palumbo Luigi	20 RM1
Camattari Riccardo	30 FE
Guidi Vincenzo	10 FE
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Rotondo Marcello	20 LNF
Biagini Maria	20 LNF
Boscolo Manuela	60 LNF
Pellegrino Luigi	10 LNF

← CSN1 team

Additional national

- M. Ricci **(Uni. Marconi, INFN-LNF)** A. Stella **(LNF),** G. Cavoto **(La Sapienza),** E. Bagli **(INFN-Fe),** M. Prest, M. Soldani, C. Brizzolari **(Uni-Insubria&INFN),** A. Lorenzon, S. Vanini, S. Ventura, D. Dattola**(INFN-Uni. Padova),** A. Wulzer **(Uni. Pd & EPFL)**

Additional international

- P. Raimondi, S. Liuzzo, N. Carmignani **(ESRF)**
- R. Di Nardo, P. Sievers, M. Calviani, S. Gilardoni **(CERN)**
- I. Chaikovska, R. Chehab **(LAL-Orsay)**
- L. Keller, T. Markiewicz **(SLAC)**

ARIES WP6: improving Accelerator PErformance and new Concepts task for muon collider
Task 6.6 Assessment of advanced muon-collider concepts without ionization cooling

Muon based Colliders

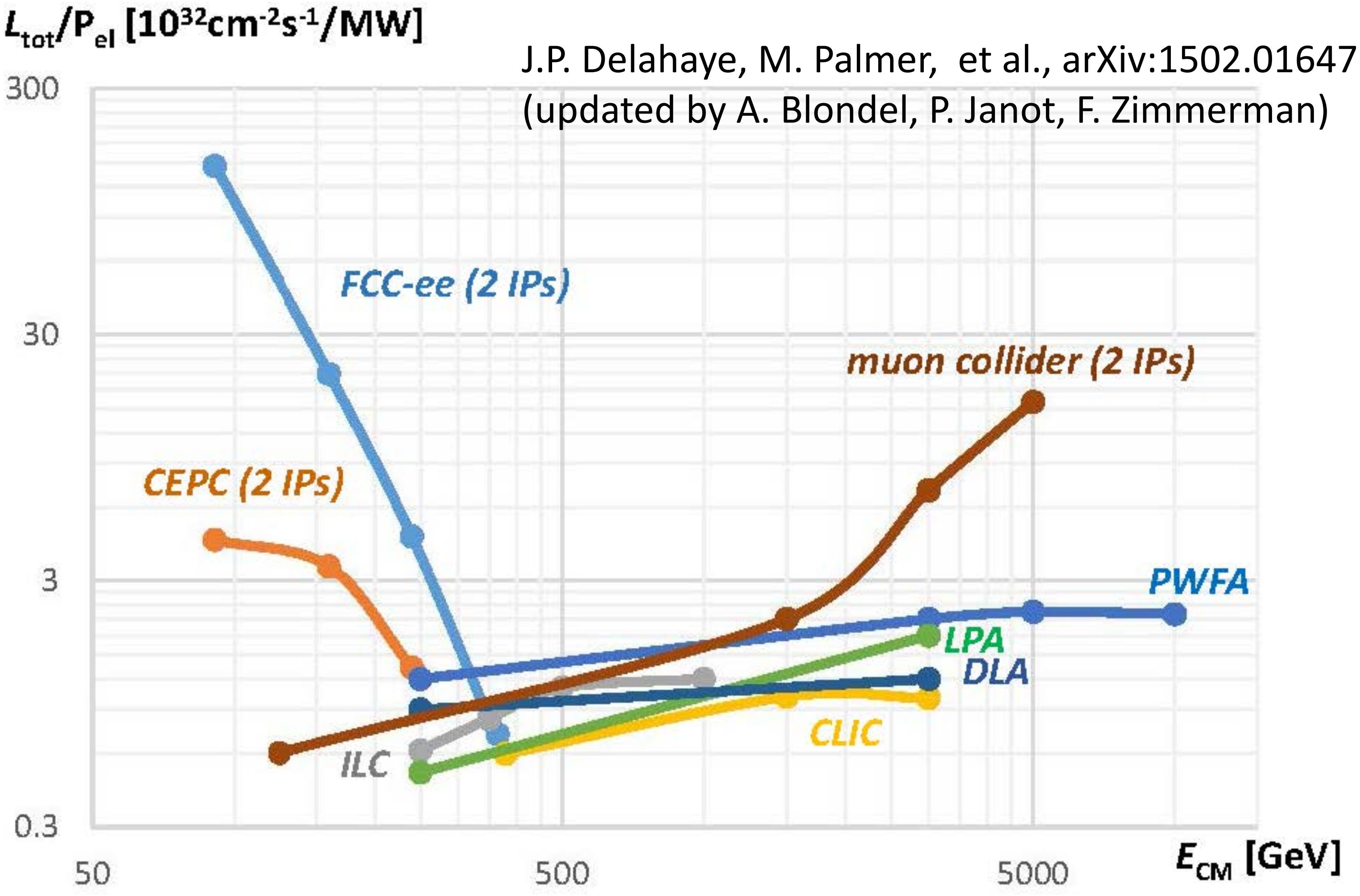
- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in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

- Great potentiality if the technology proves its feasibility:
  - cooled muon source
  - fast acceleration
  - μ Collider
  - radiation Safety (muon decay in accelerator and detector)

Muon Colliders potential of extending leptons high energy frontier with high performance

luminosity per wall-plug power vs c.m. energy

J.P. Delahaye, M. Palmer, et al., arXiv:1502.01647
(updated by A. Blondel, P. Janot, F. Zimmerman)



Muon Source

Goals

- **Neutrino Factories**: Rate > 10^{14} μ/sec within the acceptance of a μ ring
- **Muon Collider**: luminosities >10^{34}/$cm^{-2}s^{-1}$ at TeV-scale ($\approx N_\mu^2 \; 1/\varepsilon_\mu$)

Options

- Tertiary production through **proton on target:** cooling needed, baseline for Fermilab design study
  production Rate > $10^{13}\mu$/sec $N_\mu = 2\cdot 10^{12}$/bunch ($5\;10^8$ μ/sec today @PSI)

- **e^+e^- annihilation**: **positron beam on target**: very low emittance and no cooling needed, baseline for our proposal here
  production Rate $\approx 10^{11}$ μ/sec $N_\mu \approx 6\cdot 10^9$/bunch

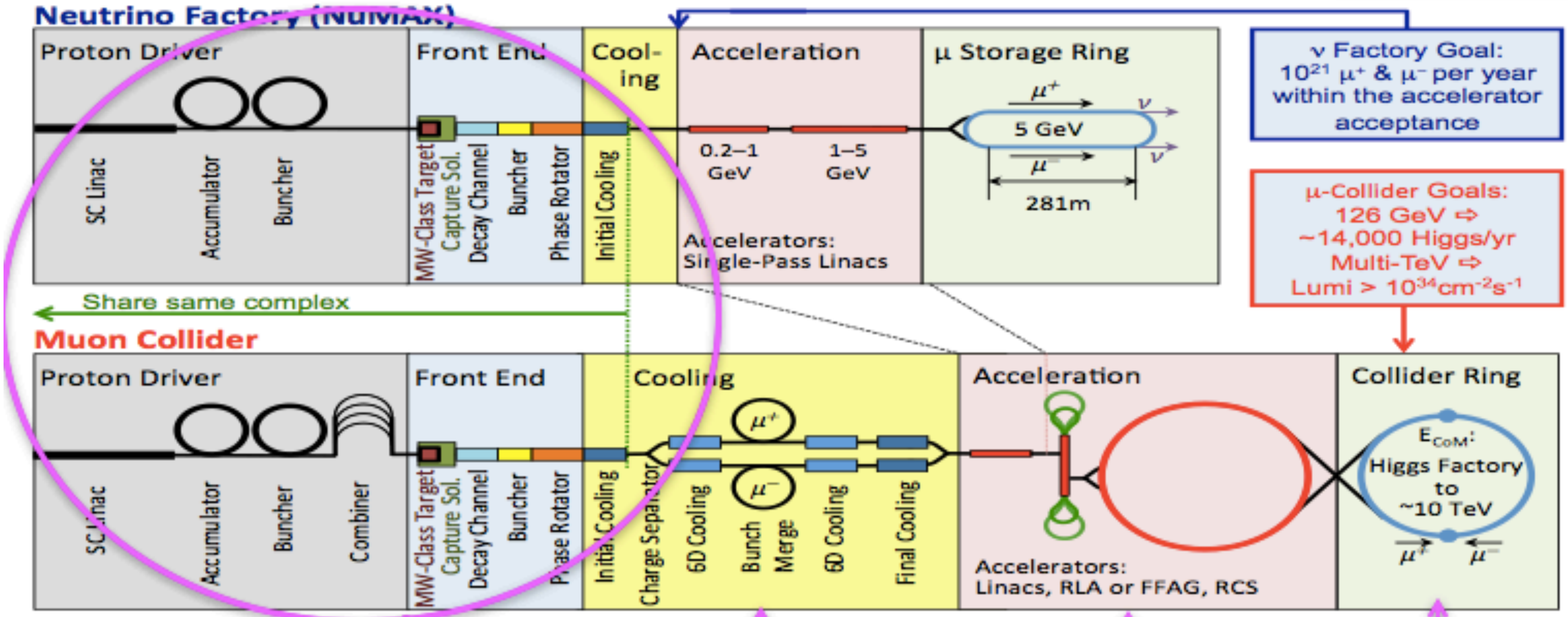
- **by Gammas** ($\gamma N \rightarrow \mu^+\mu^- N$)**: GeV-scale Compton γs** not discussed here
  production Rate $\approx 5\cdot 10^{10}$ μ/sec $N_\mu \approx 10^6$ (Pulsed Linac)
  production Rate >10^{13} μ/sec $N_\mu \approx$ few$\cdot 10^4$ (High Current ERL)
  see also: W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44 ($e^- N \rightarrow \mu^+\mu^- e^- N$)

Muon source Comparison

	Physical process	**Rate μ/s**	**normalized emittance e_N [μm-rad]**
e+ on target	**$e^+e^- \rightarrow \mu^+\mu^-$**	**0.9×10^{11}**	**0.04**
Protons on target	$p\,N \rightarrow \pi X,\ kX \rightarrow \mu\,X'$	10^{13}	25
Compton γ on target	$\gamma\ N \rightarrow \mu^+\mu^-\,N$	5×10^{10}	2

Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



ν Factory Goal:
10^{21} μ^+ & μ^- per year
within the accelerator
acceptance

μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

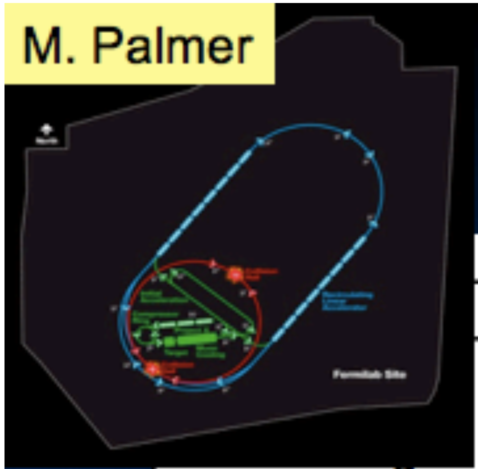
Key Challenges

- ~10^{13}-10^{14} μ / sec Tertiary particle $p \to \pi \to \mu$:
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key R&D

- MW proton driver
  MW class target
  NCRF in magnetic field
- Ionization cooling
  High field solenoids (30T)
  High Temp Superconductor
- Cost eff. low RF SC
  Fast pulsed magnet
  (1kHz)
- Detector/
  machine
  interface

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}]

‘novel’ muon production concept:
e^+ on target

low emittance concept
overcomes cooling

Exploring the potential for a Low Emittance Muon Collider

some <u>References:</u>

- M. Boscolo *et al.*, **"***Studies of a scheme for low emittance muon beam production from positrons on target",* **IPAC17 (2017)**
- M.Antonelli, *"Very Low Emittance Muon Beam using Positron Beam on Target"*, **ICHEP (2016)**
- M.Antonelli *et al.* , *"Very Low Emittance Muon Beam using Positron Beam on Target"*, **IPAC (2016)**
- M. Antonelli, *"Performance estimate of a FCC-ee-based muon collider"*, **FCC-WEEK 2016**
- M. Antonelli, *"Low-emittance muon collider from positrons on target"*, **FCC-WEEK 2016**
- M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, *"Novel proposal for a low emittance muon beam using positron beam on target"*, **NIM A 807 101-107 (2016)**
- P. Raimondi, *"Exploring the potential for a Low Emittance Muon Collider"*, in **Discussion of the scientific potential of muon beams workshop**, CERN, Nov. 18th 2015
- M. Antonelli, **Presentation Snowmass 2013**, Minneapolis (USA) July 2013, [M. Antonelli and P. Raimondi, Snowmass Report (2013) also INFN-13-22/LNF Note

Also investigated by SLAC team:

L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:

- *"Luminosity Estimate in a Multi-TeV Muon Collider using* $e^+e^- \rightarrow \mu^+\mu^-$ *as the Muon Source"*, MAP 2014 Spring workshop, Fermilab (USA) May '14
- Advanced Accelerator Concepts Workshop, San Jose (USA), July '14

Idea for low emittance μ beam

from **proton on target:** $p+\text{target}\rightarrow\pi/K \rightarrow \mu$

typically **$P_\mu \approx$ 100 MeV/c** (π, K rest frame)

whatever is the boost P_T will stay in Lab frame →

very high emittance at production point → **cooling needed**!

from **direct μ pair production**:

Muons produced from **$e^+e^-\rightarrow\mu^+\mu^-$** at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold **($\sqrt{s} \approx$ 0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

NIM A Reviewer: ***"A major advantage of this proposal is the lack of cooling of the muons…. the idea presented in this paper may truly revolutionise the design of muon colliders … "***

Advantages:

1. **Low emittance possible:** θ_μ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$
   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

Disadvantages:

- Rate: much smaller cross section wrt protons (≈ mb)

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

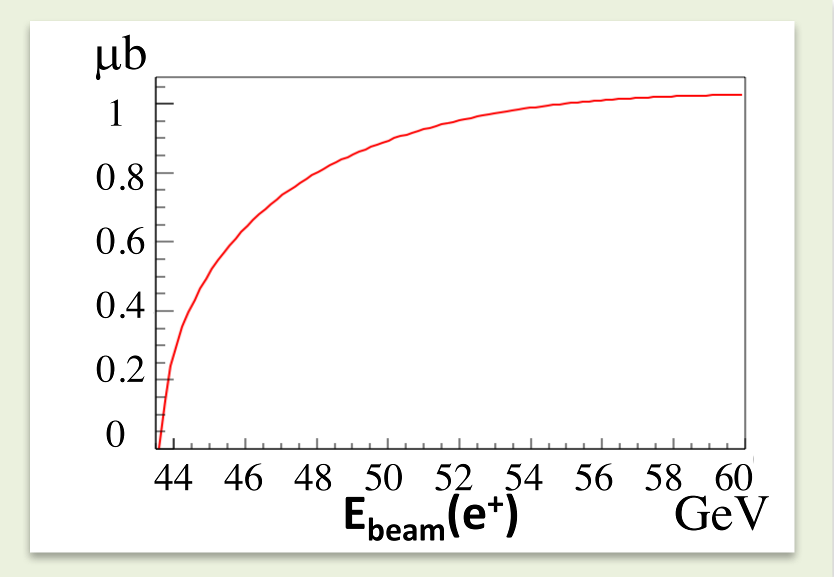
Possible Schemes

- **Low energy collider with e^+/e^- beam (e$^+$ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity $\approx 10^{40}$ is beyond present capability)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^3 needed to obtain a reasonable conversion efficiency to muons)
- **Electrons at rest (seems more feasible):**
  3. e$^+$ on Plasma target
  4. **e$^+$ on standard target** (eventually crystals in channeling)
  - **Need Positrons of ≈ 45 GeV**
  - $\gamma(\mu)\approx 200$ and μ laboratory lifetime of about 500 μs

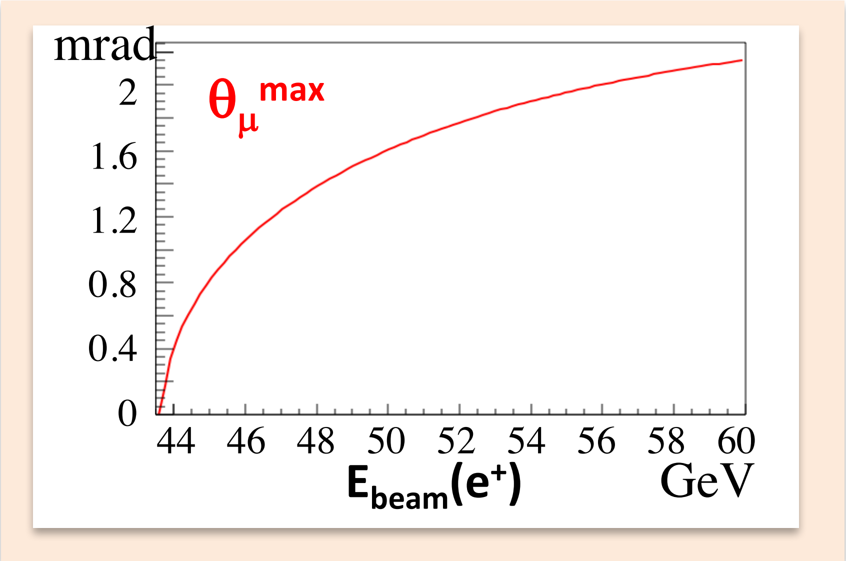
Ideally muons will *copy* the positron beam

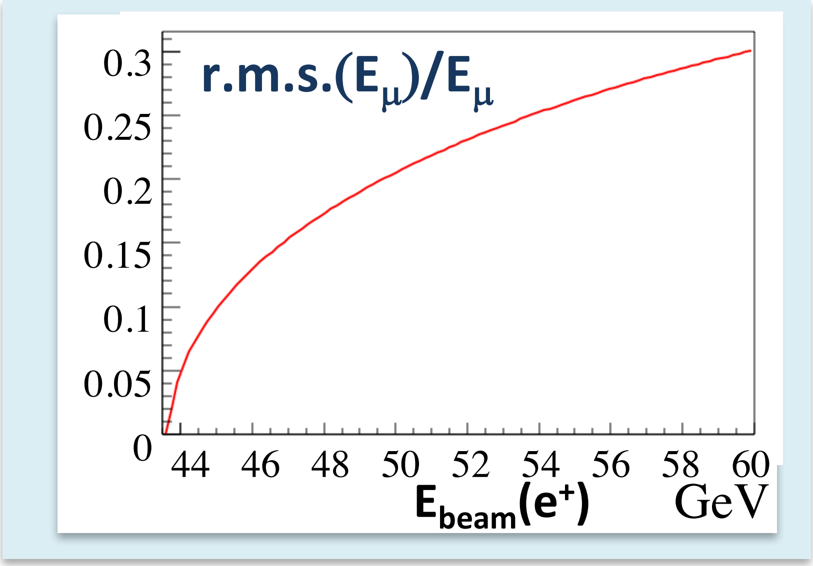
Cross-section, muons beam divergence and energy spread as a function of the e+ beam energy

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



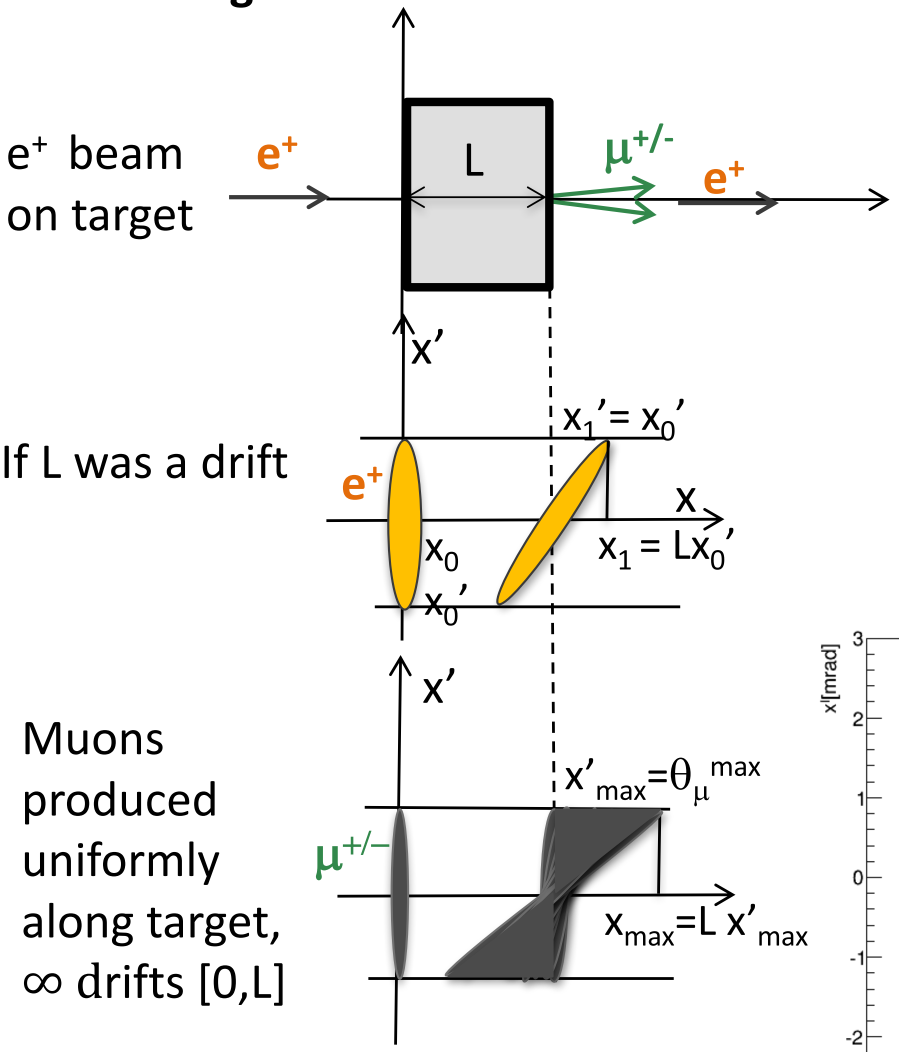
The value of sqrt(s) (*i.e.* E(e^+) for atomic e^- in target) has to maximize the muons production and minimize the beam angular divergence and energy spread

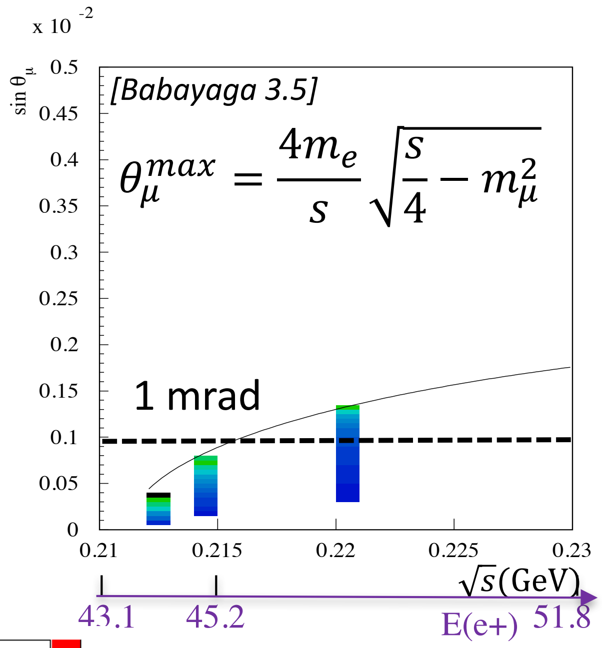


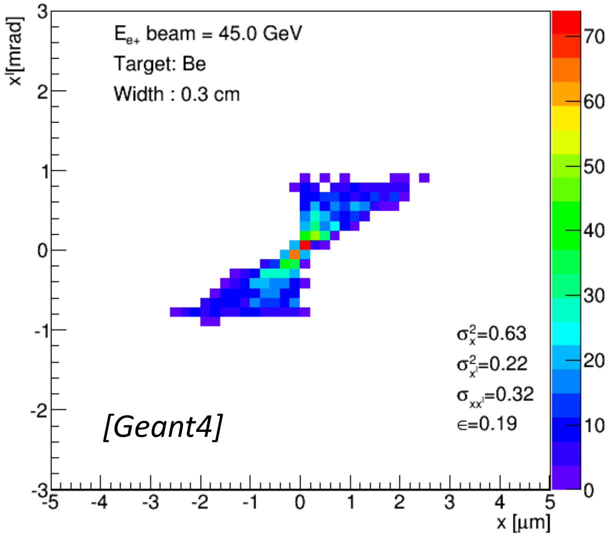


Production contribution to μ beam emittance

ideal e$^-$ target







Muon beam at the exit of a 3 mm Be target

ε_μ=0.19 nm

(45 GeV e+ beam)

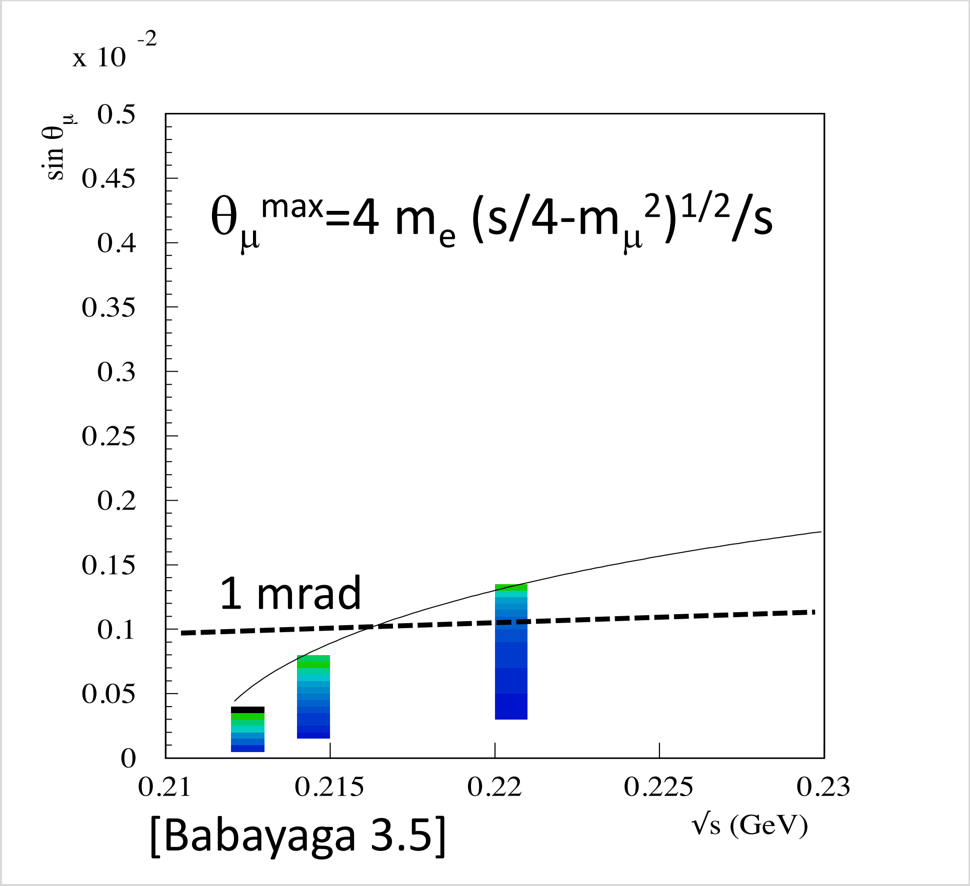
thin light materials targets have negligible multiple scattering contribution

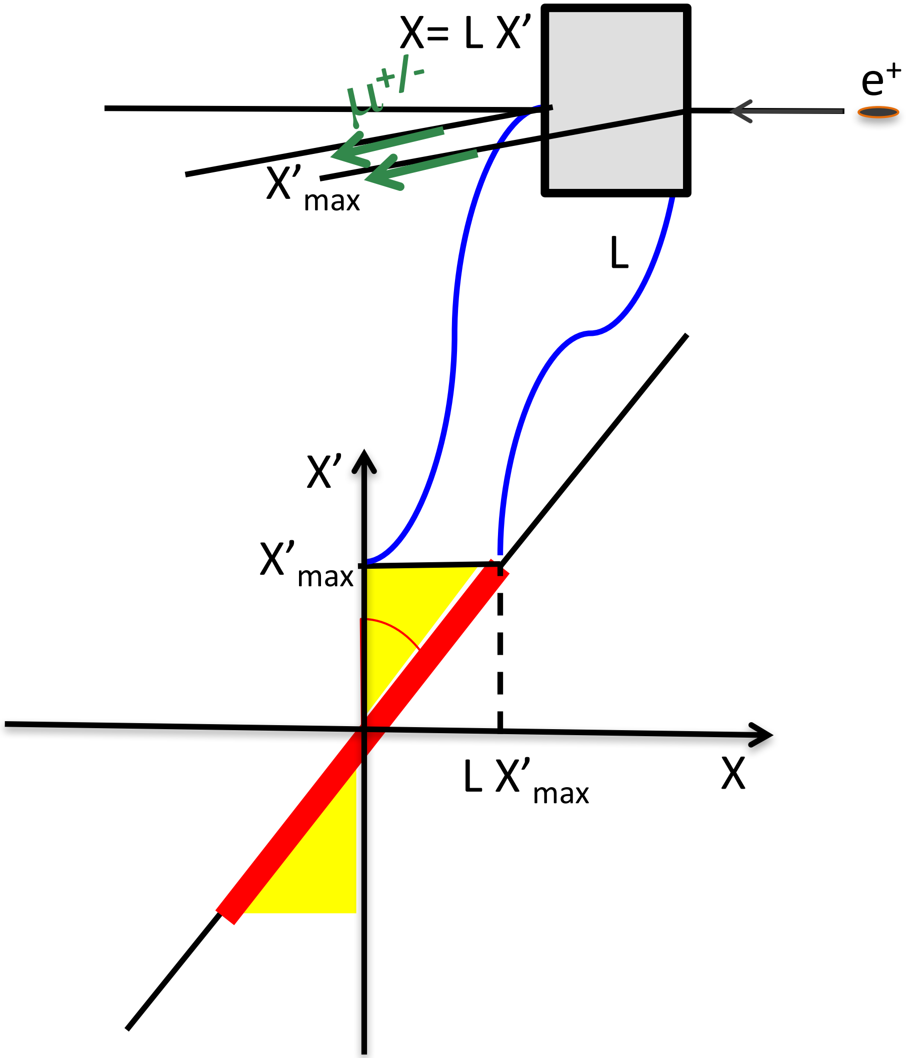
The emittance contributions due to muon production angle: $\varepsilon_\mu = x\, x'_{max}/12 = L\, (\theta_\mu^{max})^2/12$

→ ε_μ completely determined by L and s -by target thickness and c.o.m. energy

Muons angle contribution to μ beam emittance

The target thickness and c.o.m. energy completely determine the emittance contributions due to muon production angle





$$\varepsilon_\mu = x\, x'_{max}/12 = L\, (\theta_\mu^{max})^2/12$$

Criteria for target design

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

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

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

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**
  - **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

  $\sigma(e^+\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(\text{Bhabha}) \rightarrow$

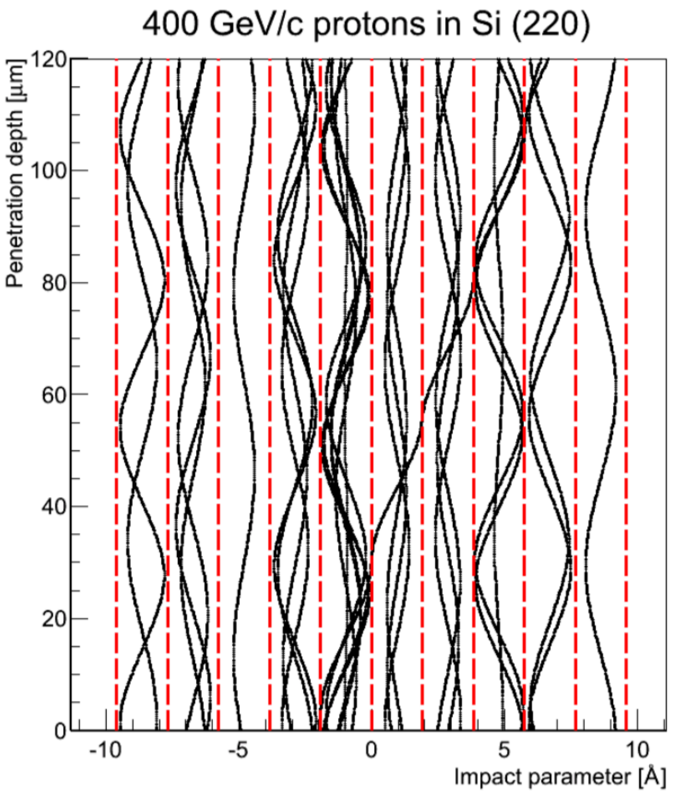
  $N(\mu^+\mu^-)/N(e^+) \approx \sigma_\mu/[(Z+1)\sigma(\text{Bhabha})] \approx 10^{-7}$
- **Very light materials, thick target**
  - **maximize $\mu^+\mu^-$ conversion efficiency $\approx 10^{-5}$** (enters quad) → H_2

  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

Crystals as a target?

- No emittance increase with the target length in channeling regime
  - Ordered pattern of atoms.
  - Aligned atoms can be seen as planes or axes.
  - Strong electromagnetic field between planes and between axes (GeV/cm).
  - Particle direction aligned with planes or axes

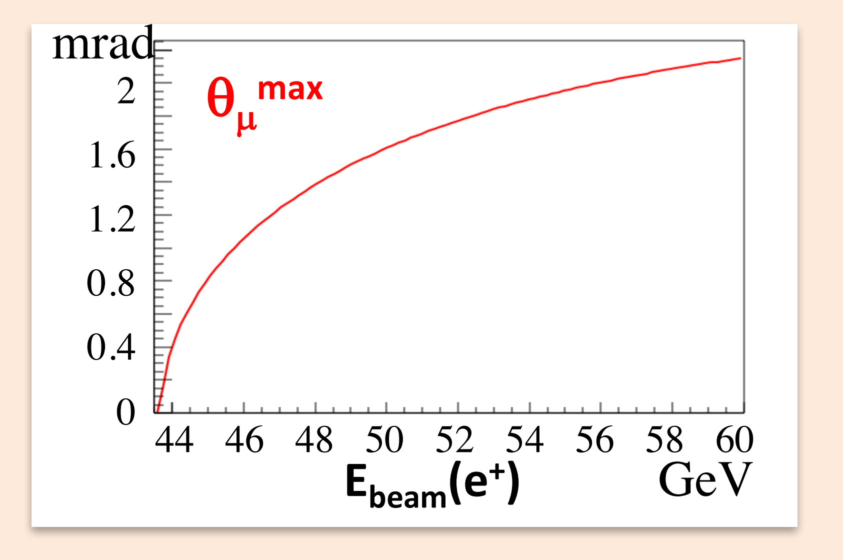


DYNECHARM++ - E. Bagli, V. Guidi, NIMB 309, 124 (2013)

Extreme low emittances: Higgs factory case

Muon channeling

- To have muon channeling both the positron incident angle and the muon production angle < critical angle
- Use diamond -> low Z(minimize brems.) + thermo-mechanical stresses
  - critical angle 0.1 mrad @ 22 GeV



Extreme low emittance Muon beams

- Channeling for e+ energies <44 GeV
- production cross section is slightly above 0.1 μb
- muon energy spread at 22 GeV 1.5%
- Good option for an Higgs factory
  - Possible implementation with an ERL at 43.8 GeV on ~1 X_0 diamond target
  - Positron rate on target $4x10^{15}$e+/s
  - Very similar to LHeC parameters
- No much done up to now just an option for Higgs factory (see NIMA 807 (2016) 101–107)
- First guess luminosity around 10^{31} $cm^{-2}s^{-1}$

low emittances:
Multi TeV case

Preliminary scheme for low emittance μ beam production

Goal:

$@T \approx 10^{11}\ \mu/s$

Efficiency $\approx 10^{-7}$ (with Be 3mm)→

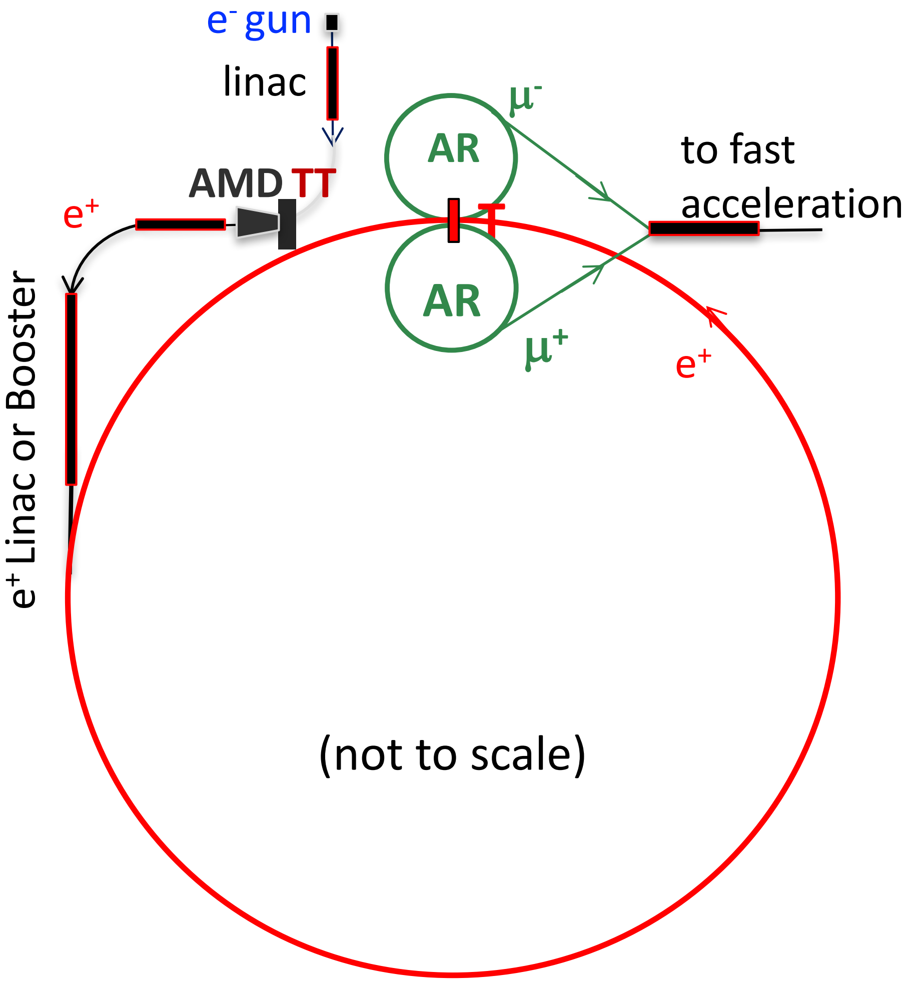
$10^{18}\ e^+/s$ needed @T →

e^+ stored beam with T

need the largest possible lifetime to minimize positron source rate

LHeC like e+ source required rate with lifetime(e+) $\approx$ 250 turns [i.e. 25% momentum aperture (+/-12%)]

→ $n(\mu)/n(e^+ \text{ source}) \approx 10^{-5}$



Preliminary scheme for low emittance μ beam production

from e^+ SOURCE to RING:

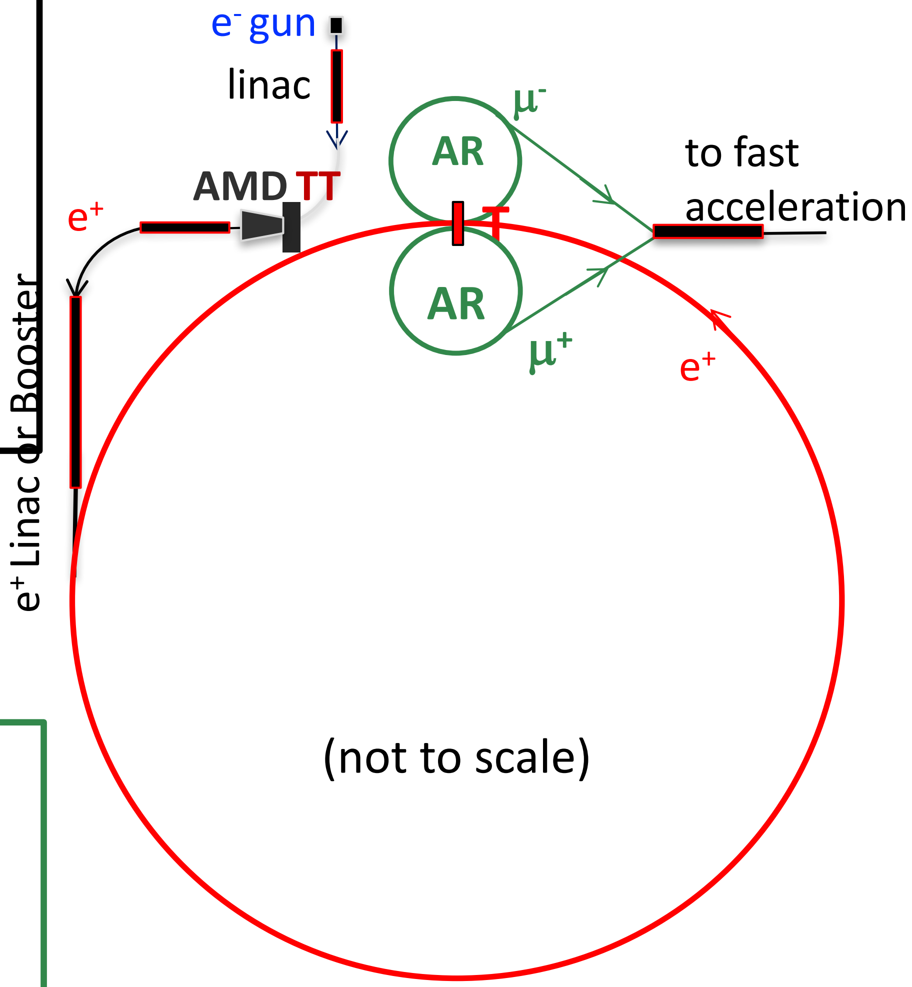
- **e^-** on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- Adiabatic Matching Device (**AMD**) for **e^+** collection →
- acceleration (linac / booster) , injection →

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**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx$ **500μs**
- **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 μ^+ μ^- production to collider

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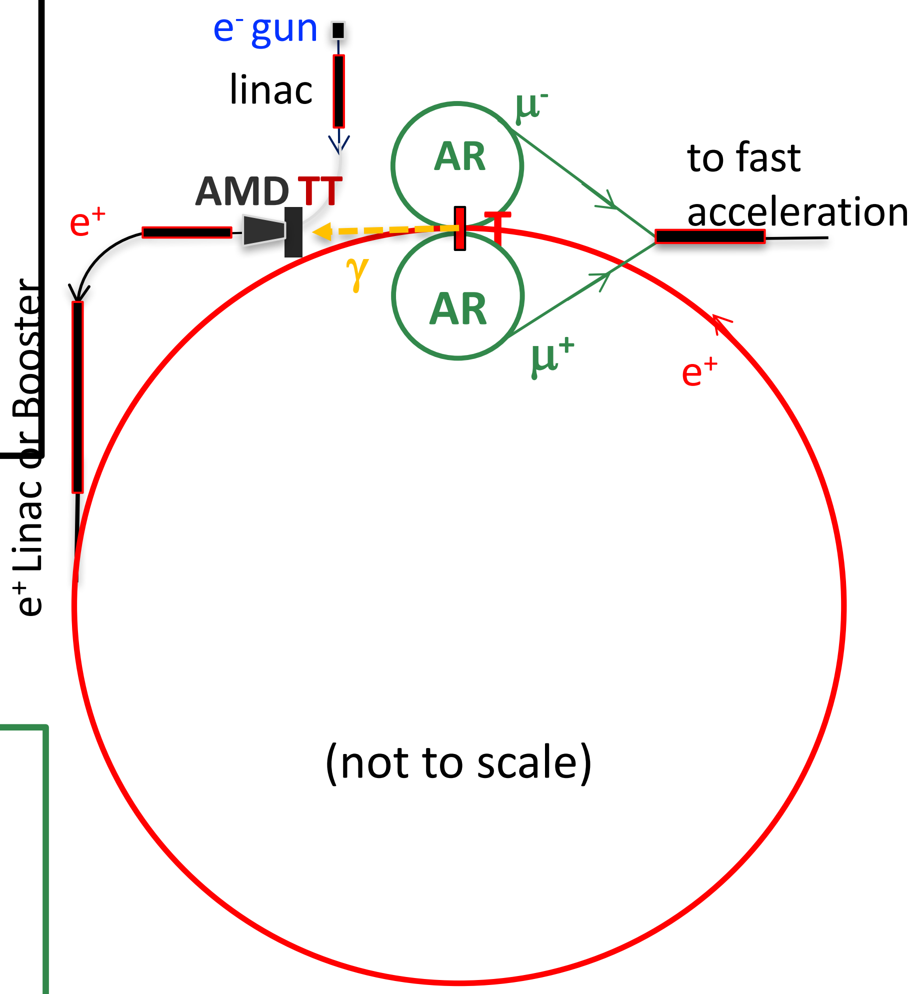


Key R&D

MW proton driver
MW class target
NCRF in magnetic field

Ionization cooling
High field solenoids (30T)
High Temp Superconductor

Cost eff. low RF SC
Fast pulsed magnet
(1kHz)

Detector/
machine
interface

Key Challenges

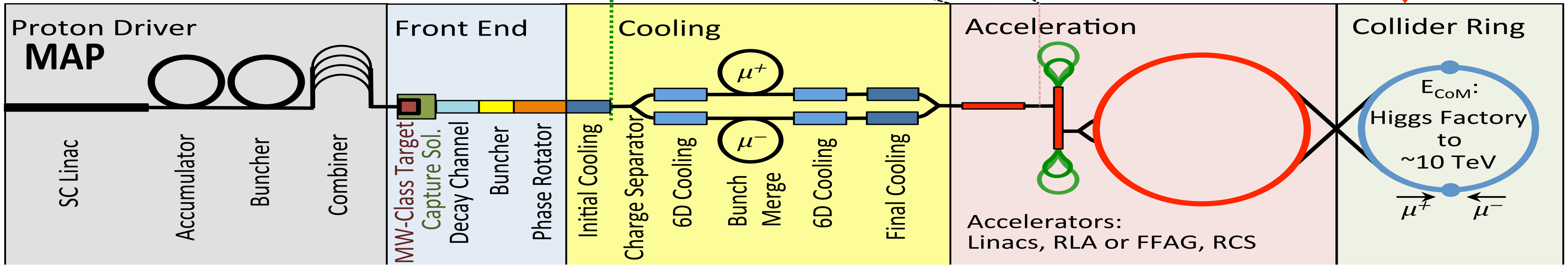
$\sim 10^{13}$-10^{14} μ / sec
Tertiary particle $p \rightarrow \pi \rightarrow \mu$:

Fast cooling
(τ=2μs) by 10^6 (6D)

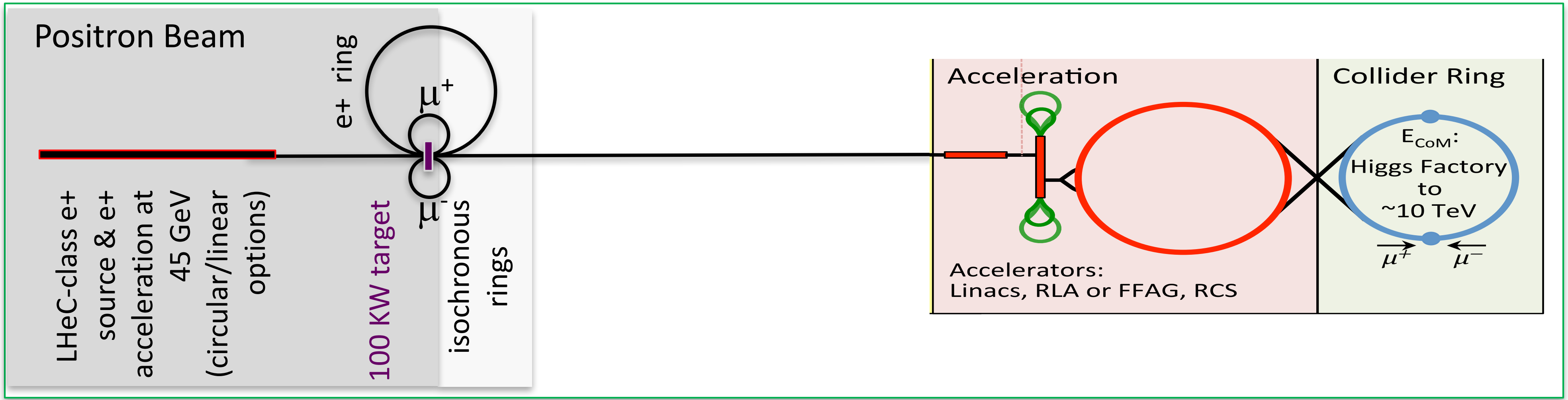
Fast acceleration
mitigating μ decay

Background
by μ decay

Muon Collider



share the same complex



Key Challenges

$\sim 10^{11}$ μ / sec from $e+e- \rightarrow \mu+\mu-$

Key R&D

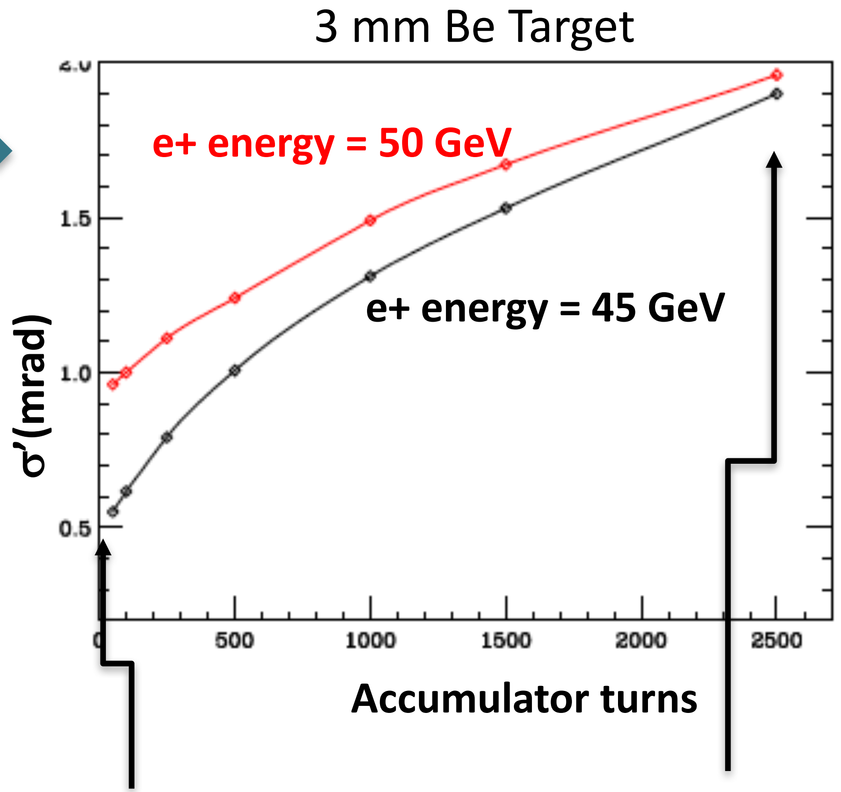
10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring

EASIER AND CHEAPER DESIGN, IF FEASIBLE

μ Accumulator Rings considerations

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

Multiple Scattering effect using one-turn matrix



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

GEANT Simulations (E. Bagli)

Geant Simulations (E. Bagli)

Initial parameters

Beam

- Particle: positron
- Momentum: 43.8 GeV/c
- Divergence: collimated
- Alignment: channeling

Crystal/Amorphous

- Material: Silicon
- Length: 4.1 mm
- Channeling plane: (110)

Muons

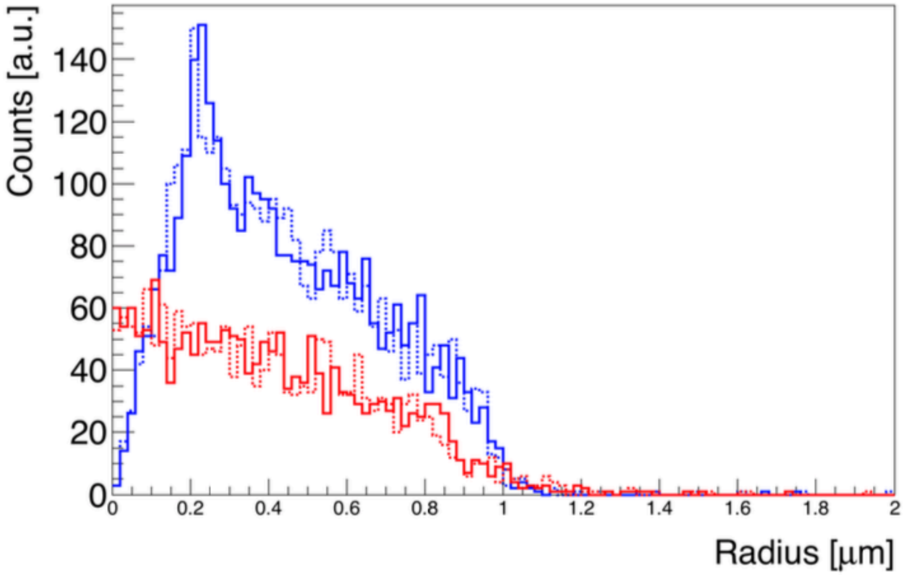
(E. Bagli)

Info

- The number of muons per particle is **lower** for channeling than for amorphous

- Muon beams also are channeled in the crystal, causing the beam shape to be different wrt amorphous material.

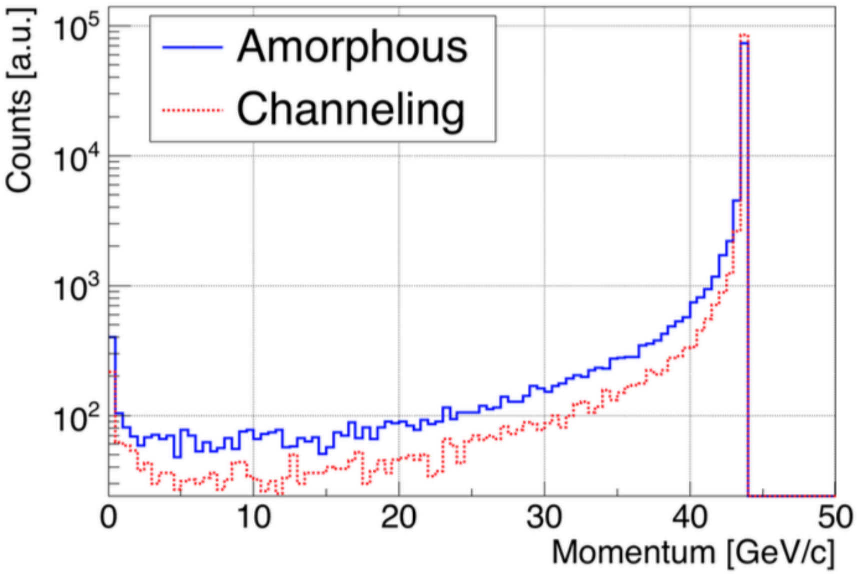
Position



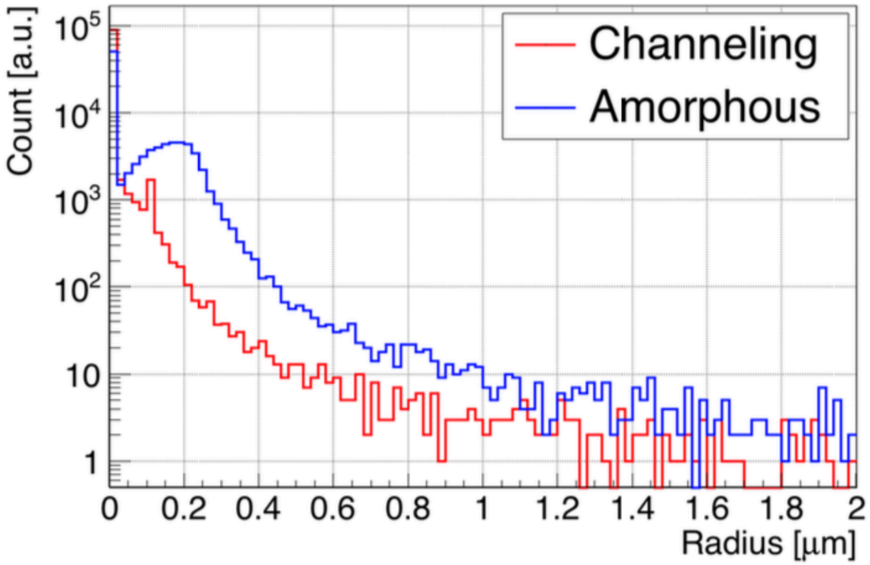
Positrons

(E. Bagli)

Momentum



Position

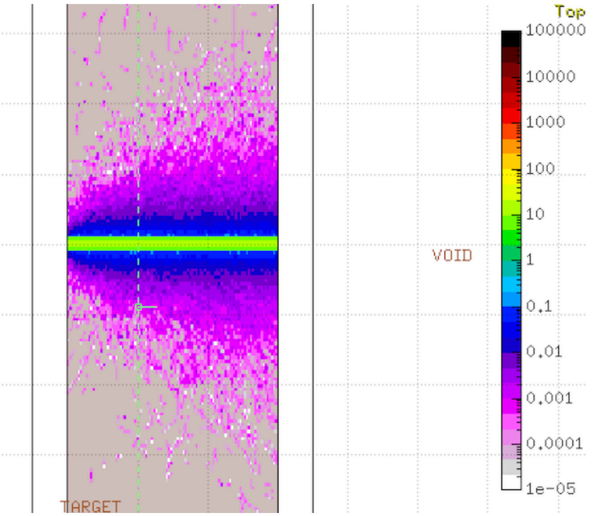


Conclusion

- in the novel scheme for the production of muons starting from e^+ beam on target channeling phenomena might help
    - No emittance increase with target length (extreme values of emittances possible)
    - Reduced MS effects (no emittance increase in muon accumulators)
    - Promising High rate positron source with hybrid schemes (KEK)
- Additional problems, crystal structure radiation damage, related to deposited power O(40-100 kW)

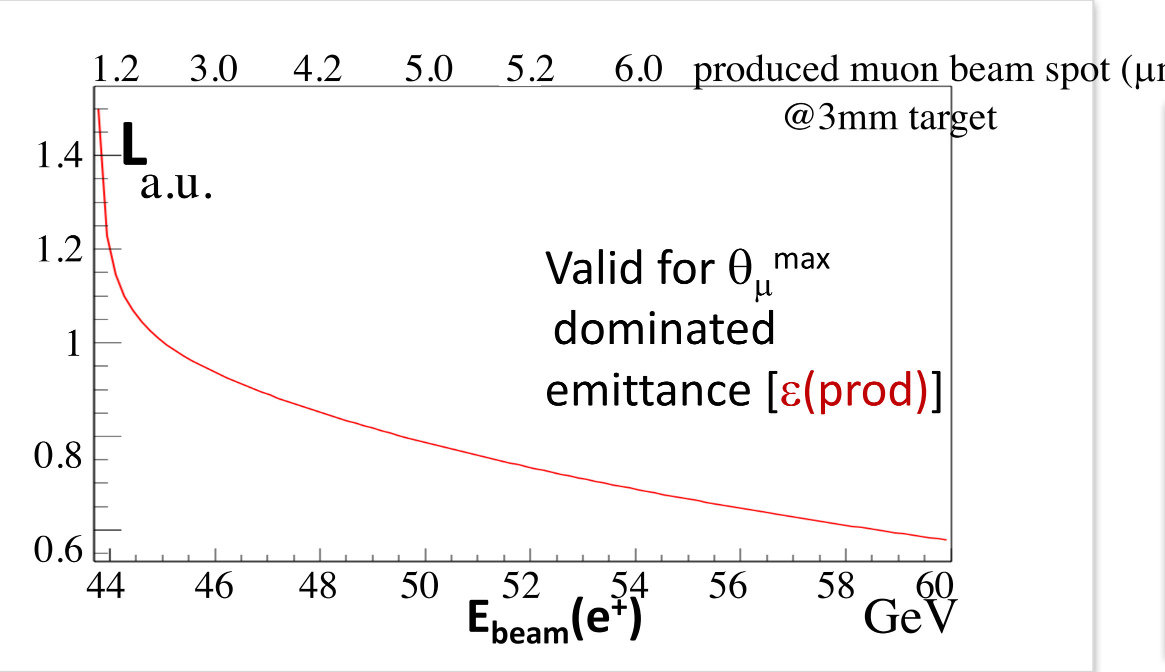
Conventional options for μ target

- Aim at bunch (3×10^{11} e^+) transverse size on the 10 μm scale: rescaled from test at HiRadMat (5×10^{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 thermo-mechanical stresses dynamics
  - Start using FLUKA + Ansys Autodyn (collaboration with CERN EN-STI)
- Experimental tests:
  - **FACET-II** available from 2019
    10^{11} e-/bunch, 10 μm spot size, 100 Hz
  - **DAFNE** available from 2020, see later

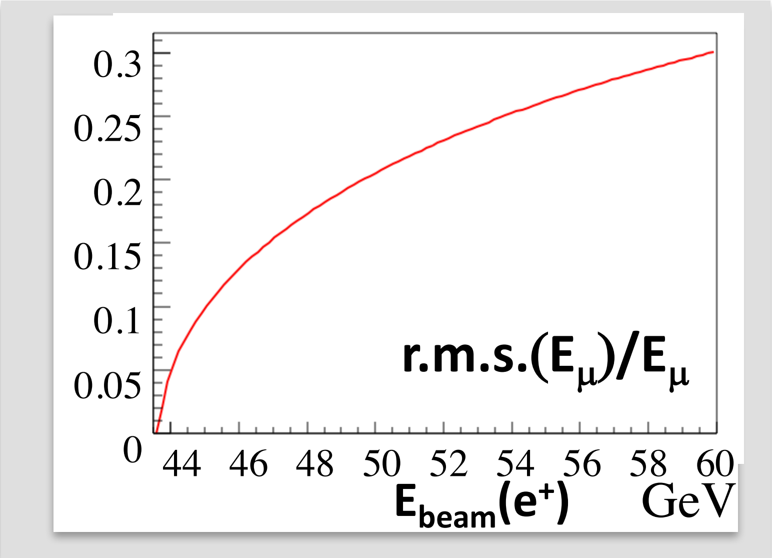


Luminosity of $\mu^+\mu^-$ Collider vs e^+ beam energy

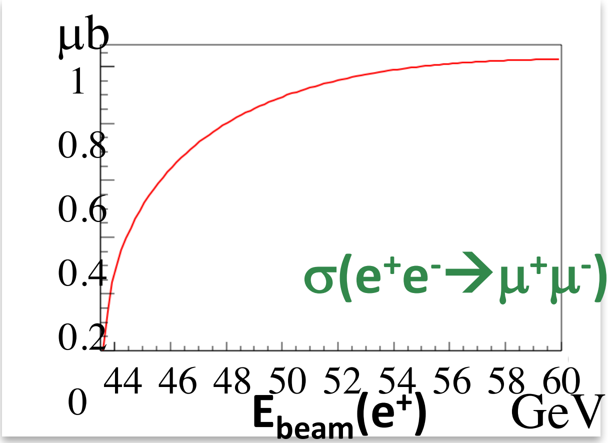
Optimal working point for $\varepsilon(e^+) \cong \varepsilon(MS) \cong \varepsilon(rad) \cong \varepsilon(prod) \cong \varepsilon(AR)$
and sustainable beam spot on target
$\varepsilon(prod)$ and μ intensity $\propto$ positron beam energy:



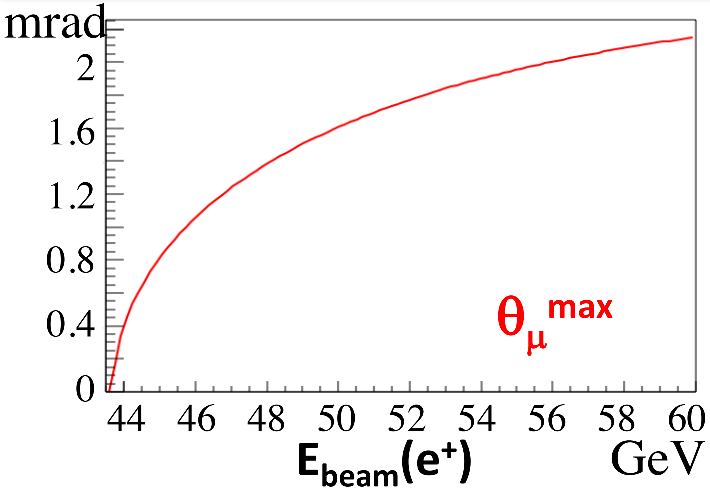
Valid for θ_μ^{max} dominated emittance [$\varepsilon(prod)$]



r.m.s.$(E_\mu)/E_\mu$



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

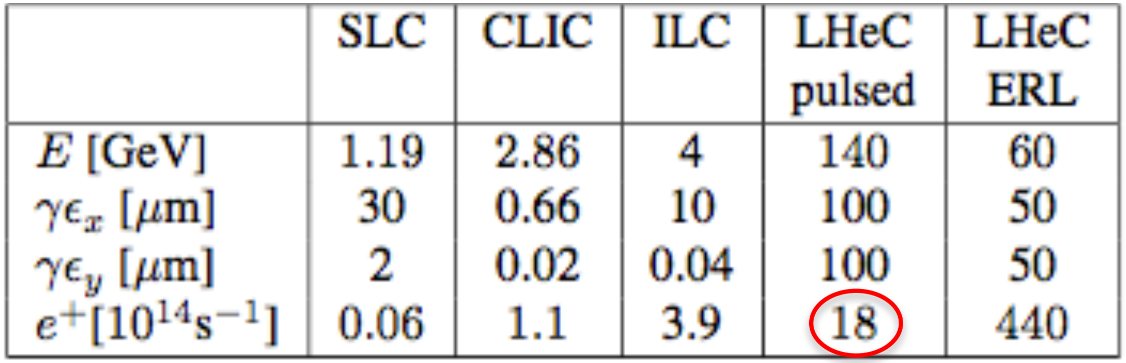


θ_μ^{max}

Positron sources: studies on the market

- Summary of e^+ sources projects (all very aggressive):

In [F. Zimmermann, et al., ‘**POSITRON OPTIONS FOR THE LINAC-RING LHEC’,** WEPPR076 Proceedings of IPAC2012, New Orleans, Louisiana, USA]



	SLC	CLIC	ILC	LHeC pulsed	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}\mathrm{s}^{-1}]$	0.06	1.1	3.9	18	440

- This is a key issue to be studied

Example of Positron Source for CLIC

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

The target represented on the figure is a conventional one.

It would be also possible to have an *hybrid positron source* using a crystal providing channeling radiation and an amorphous converter for photon conversion into e+e- pairs

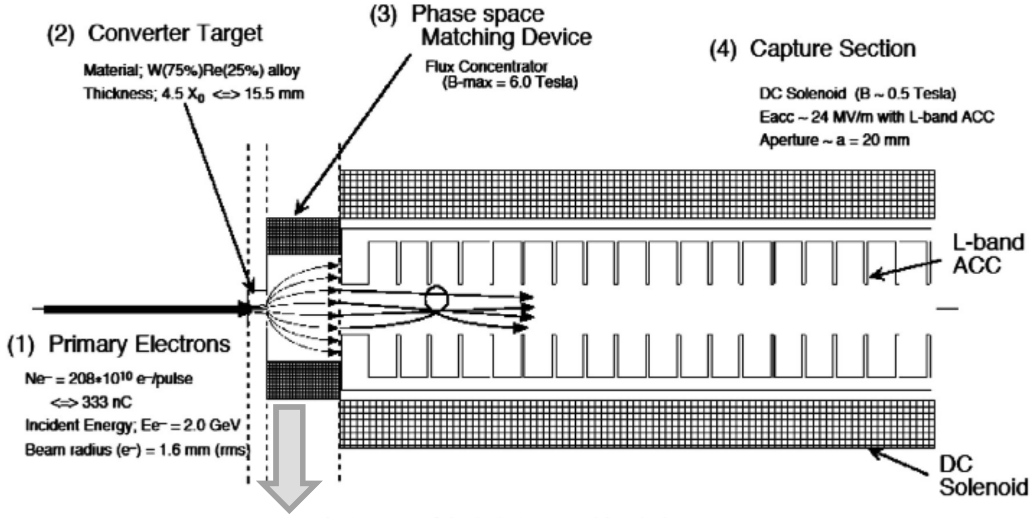
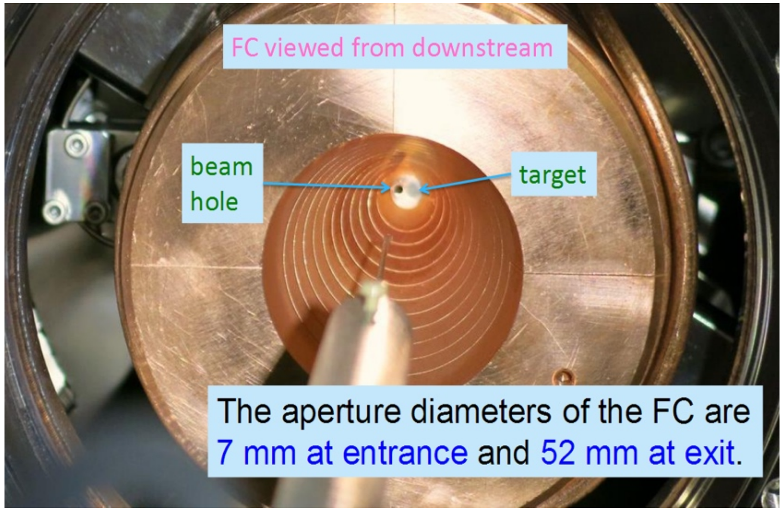


Fig. 2. Layout of the CLIC e^+ source with a single target.



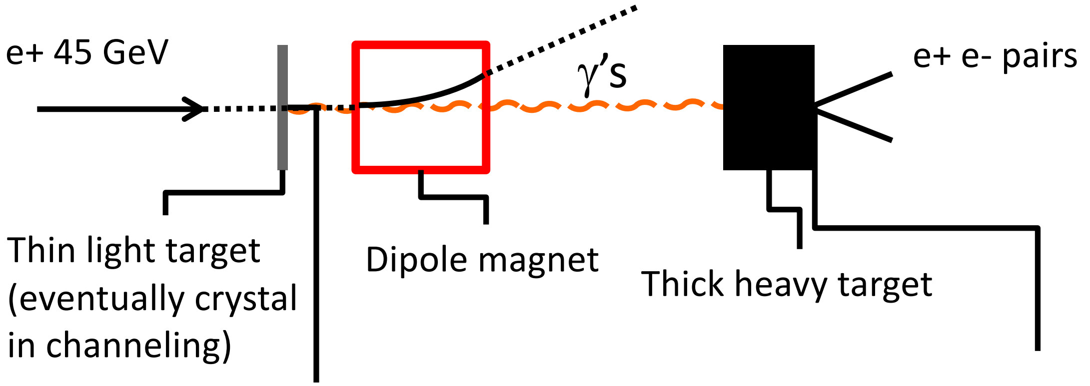
The aperture diameters of the FC are 7 mm at entrance and 52 mm at exit.

Flux concentrated used for the Adiabatic Matching Device
(from T.Kamitani, LCWS-2014,Belgrade)

Embedded positron source?

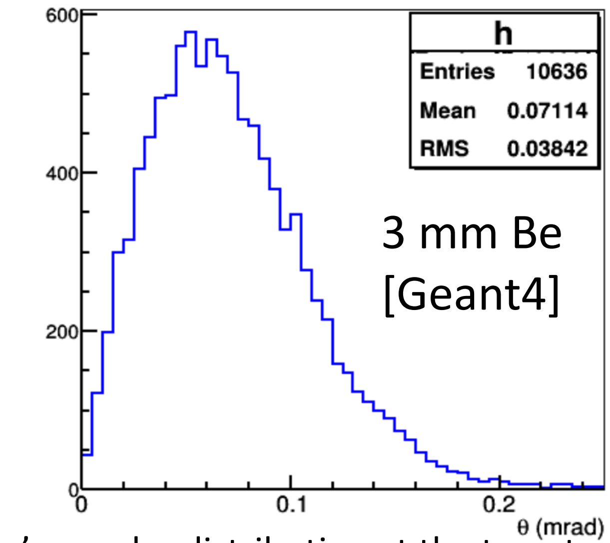
Positron source extending the target complex?
Possibility to use the γ's from the μ production target to produce e+

Focusing based on AMD under study promising preliminary results on collection efficiency

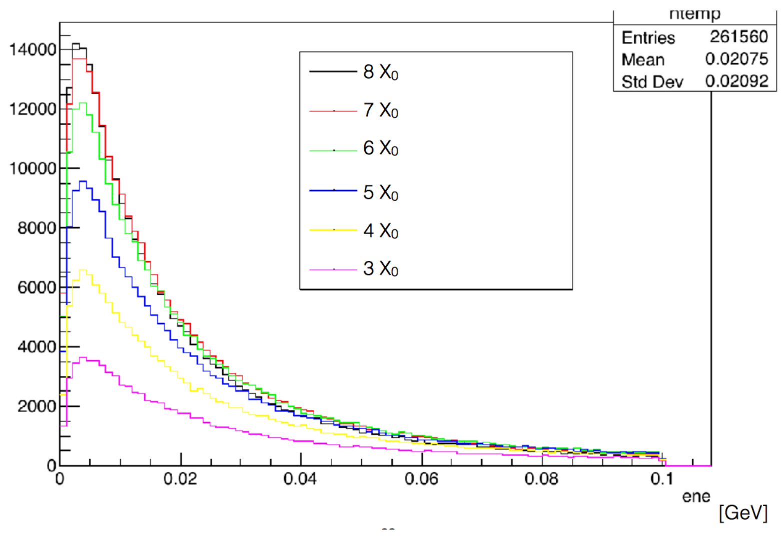


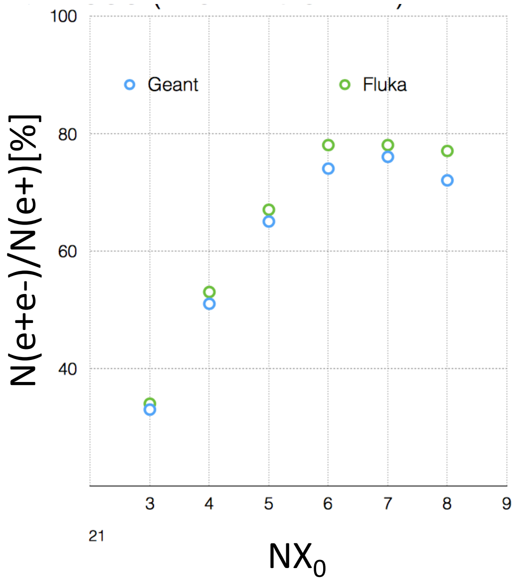
Produce a fraction of e+
of the incoming positron beam

high rate energy γ thanks to very thin target and cw structure of the stored beam



γ's angular distribution at the target exit





FOCUSING SYSTEMS FOR POSITRON BEAMS

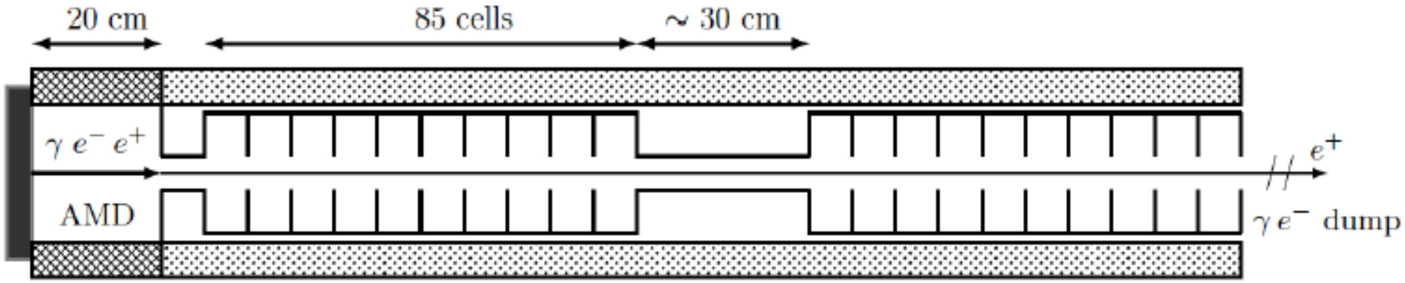
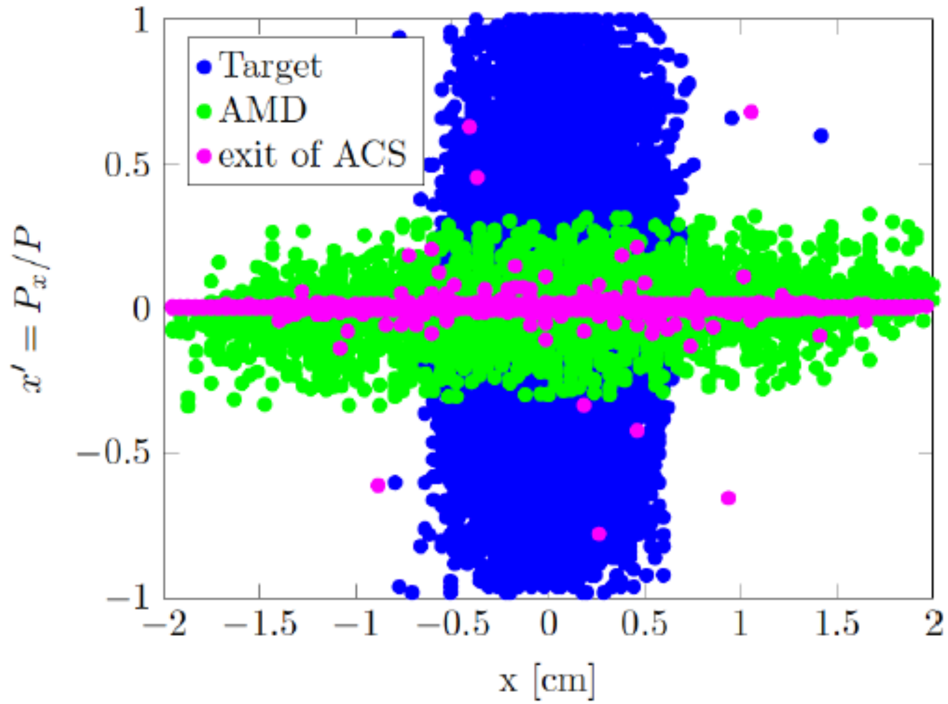


Figure 4.7: A fundamental scheme of the positron capture and primary acelerattion - A capture section based on the AMD followed by a pre-injector linac is used to capture and accelerate the positron beam up to the ~200 MeV.



Experimental Tests

Test @CERN

Experiments in H4:

45 GeV e^+ on target, beam spot 2 cm, mrad divergence

High intensity (up to 5 x 10^6 e+/spill) with 6 cm Be target (spill ~15s)

goal: measure muon production rate and muons kinematic properties

Low intensity

measure beam degradation (emittance energy spectrum)

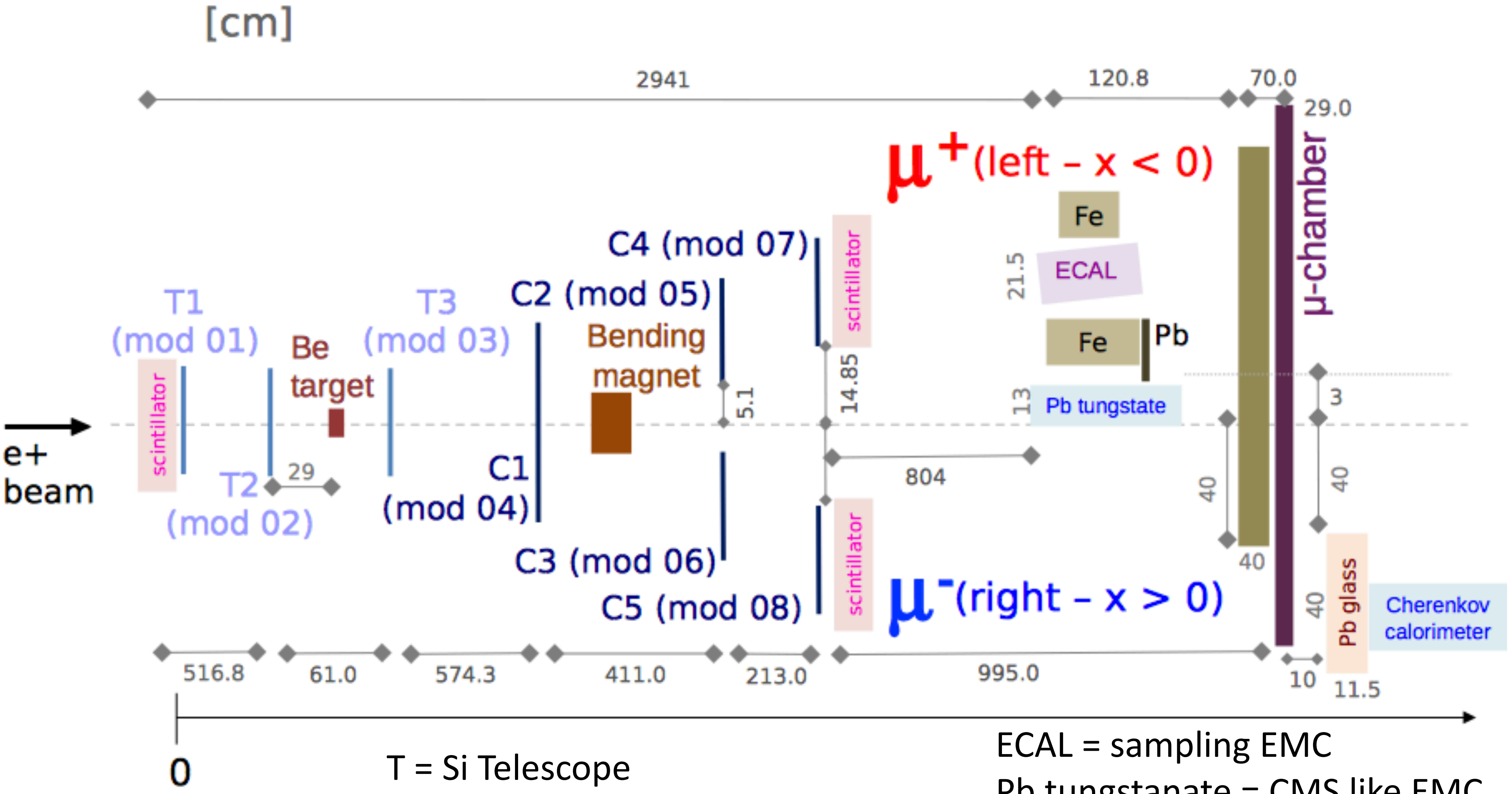
measure produced photons flux and spectrum

- 1 week assigned out of 2 requested in 2017

Priority to High intensity (had 2 days at ≈ 10^6 e^+ /spill)

- **Request 1-(2) weeks in 2018** for:
  - Complete original program of the 2017 experiment (need 2 weeks for high and low intensity runs)
  - Attempt muon production on crystals

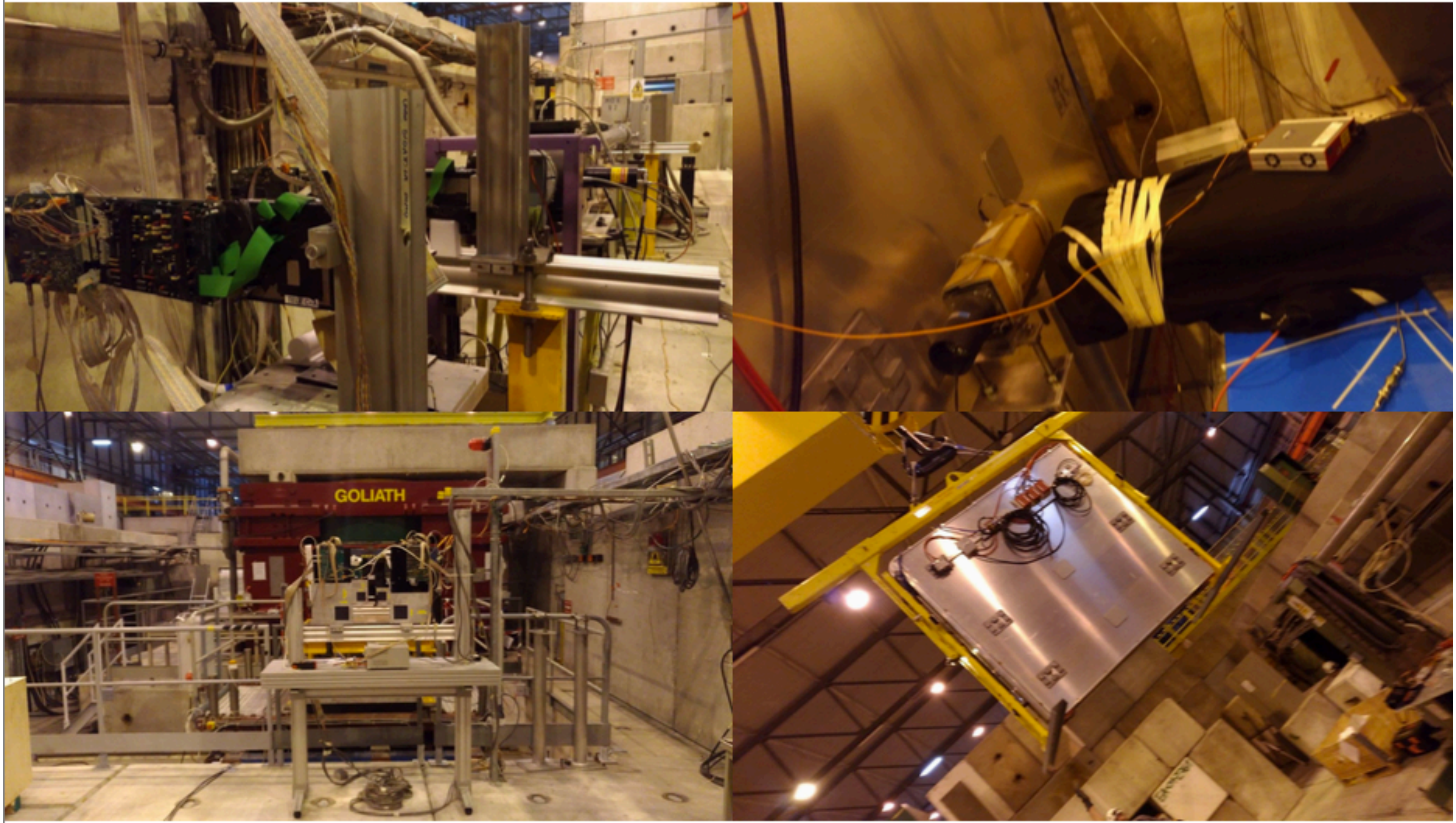
Experimental set-up



T = Si Telescope
C = Si chambers

ECAL = sampling EMC
Pb tungstanate = CMS like EMC
Pb glass = lead glass EMC

EXPERIMENTAL SETUP



Test at DAΦNE

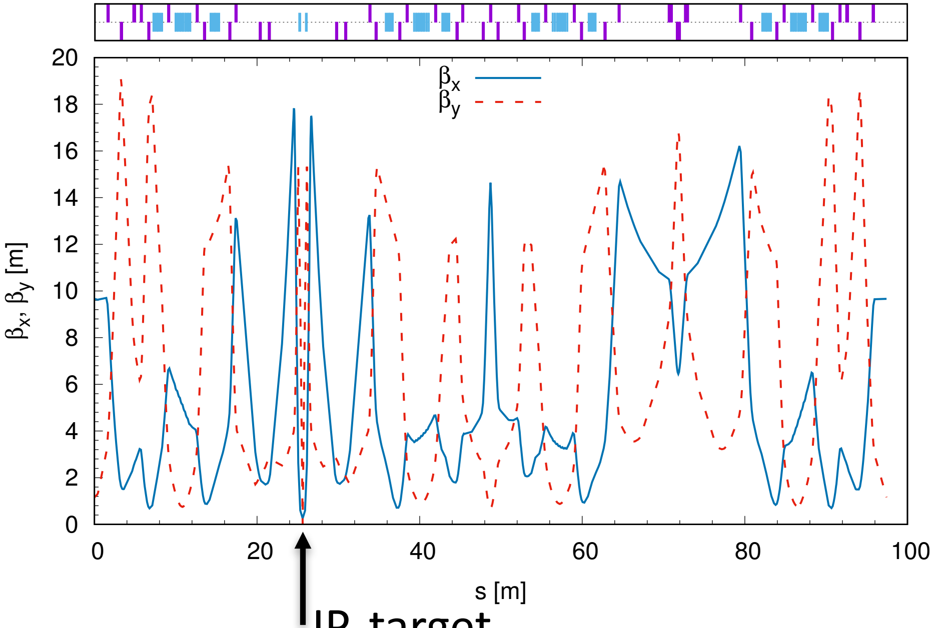
- **Test of the ring-plus-target scheme:**
    - **beam dynamics**
    - **target heat load and thermo-mechanical stress**

GOAL:

- Benchmark simulations with experimental data to validate LEMMA studies.
- Measurements on targets: various materials and thicknesses can be envisaged.
    - ➢ as validation for LEMMA studies
    - ➢ interesting in the test itself

Test at DAΦNE

- The SIDDHARTA-2 run will end on 2019
- Test proposed after this run
- The target is at the IP:
  - To minimize modifications of the existing configuration
  - low-β and D_x=0 is needed
- First studies with the SIDDHARTA optics and target placed at the IP.
- Possible different locations for the target can be studied



IP, target

SIDDHARTA 2008 optics

β_x^*=26cm; β_y^*=0.9cm

σ_x^*=0.27mm; σ_y^*=4.4μm

ε_x = 0.28 μm

Goals of the Test at DAΦNE

- Beam dynamics studies of the ring-plus-target scheme:
  - transverse beam size
  - current
  - lifetime
- Measurements on target:
  - temperature (heat load)
  - thermo—mechanical stress

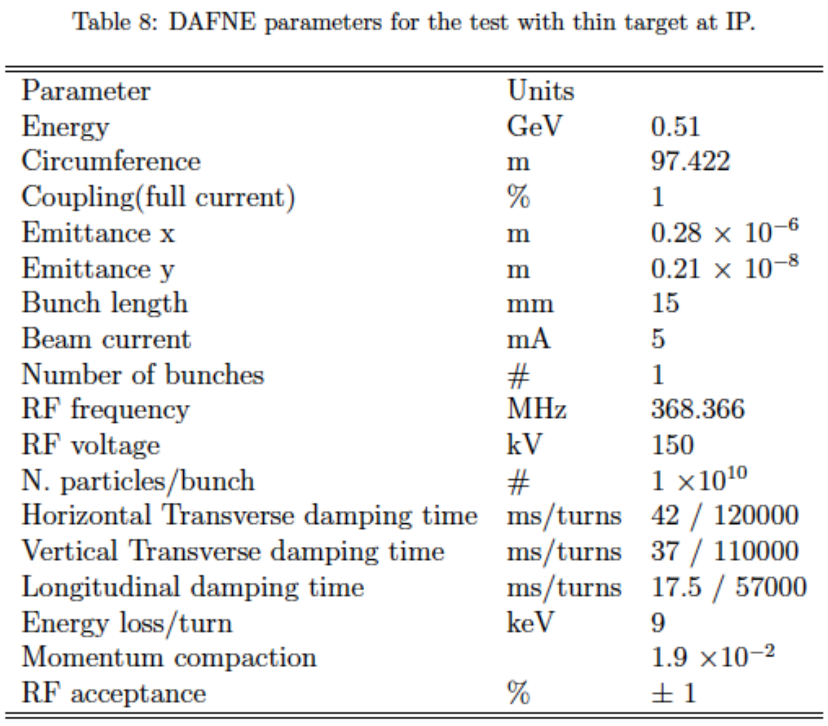


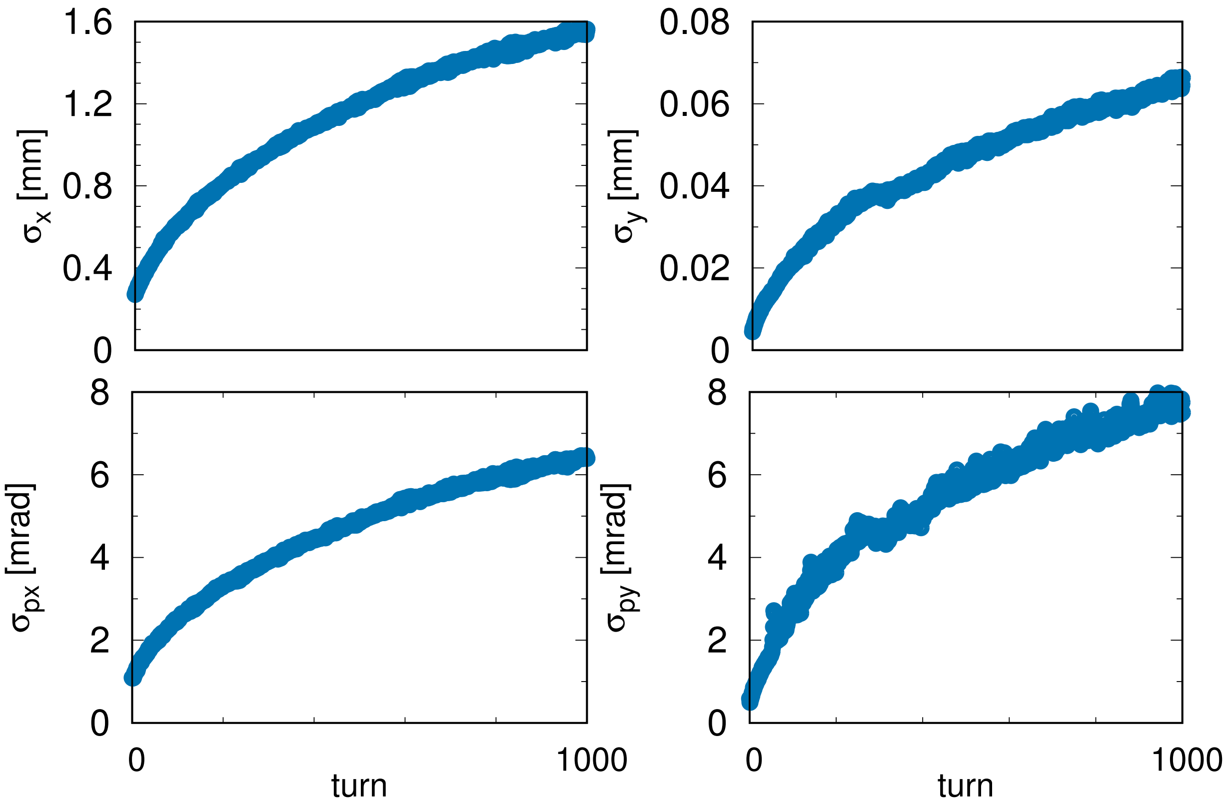
Table 8: DAFNE parameters for the test with thin target at IP.

Parameter	Units	
Energy	GeV	0.51
Circumference	m	97.422
Coupling(full current)	%	1
Emittance x	m	0.28×10^{-6}
Emittance y	m	0.21×10^{-8}
Bunch length	mm	15
Beam current	mA	5
Number of bunches	#	1
RF frequency	MHz	368.366
RF voltage	kV	150
N. particles/bunch	#	1×10^{10}
Horizontal Transverse damping time	ms/turns	42 / 120000
Vertical Transverse damping time	ms/turns	37 / 110000
Longitudinal damping time	ms/turns	17.5 / 57000
Energy loss/turn	keV	9
Momentum compaction		1.9×10^{-2}
RF acceptance	%	± 1

Given the limited energy acceptance of the ring (~1%), we plan to insert light targets (Be, C) with thickness in the range 10-100μm.
Crystal targets can be foreseen too, modified G4 tool needed for the simulation

Evolution of e+ beam size and divergence

Beam evolution in the ring with 50μm Be target at IP

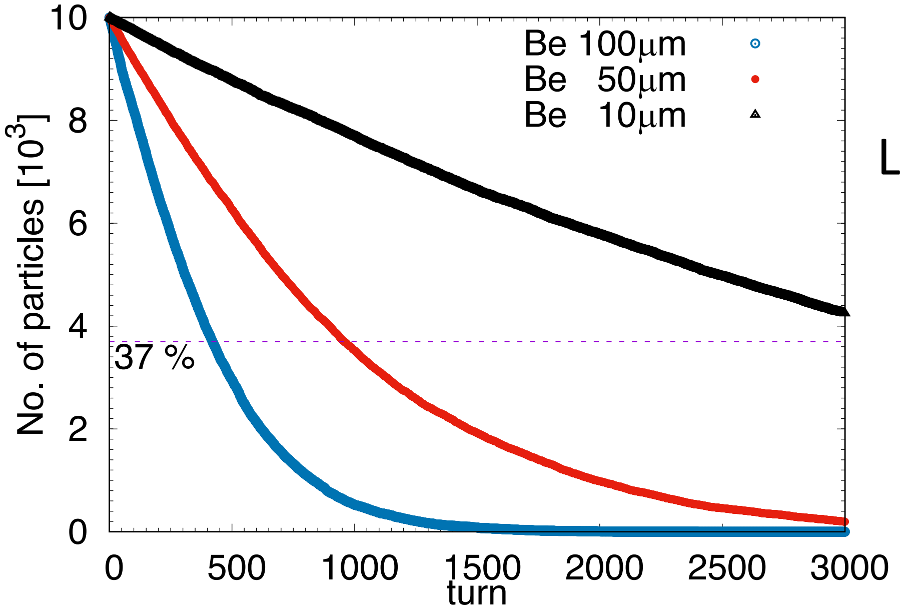


first turn, before target

$\sigma_x^* = 0.27$ mm

$\sigma_y^* = 4.4 \mu m$

e+ lifetime with Be target

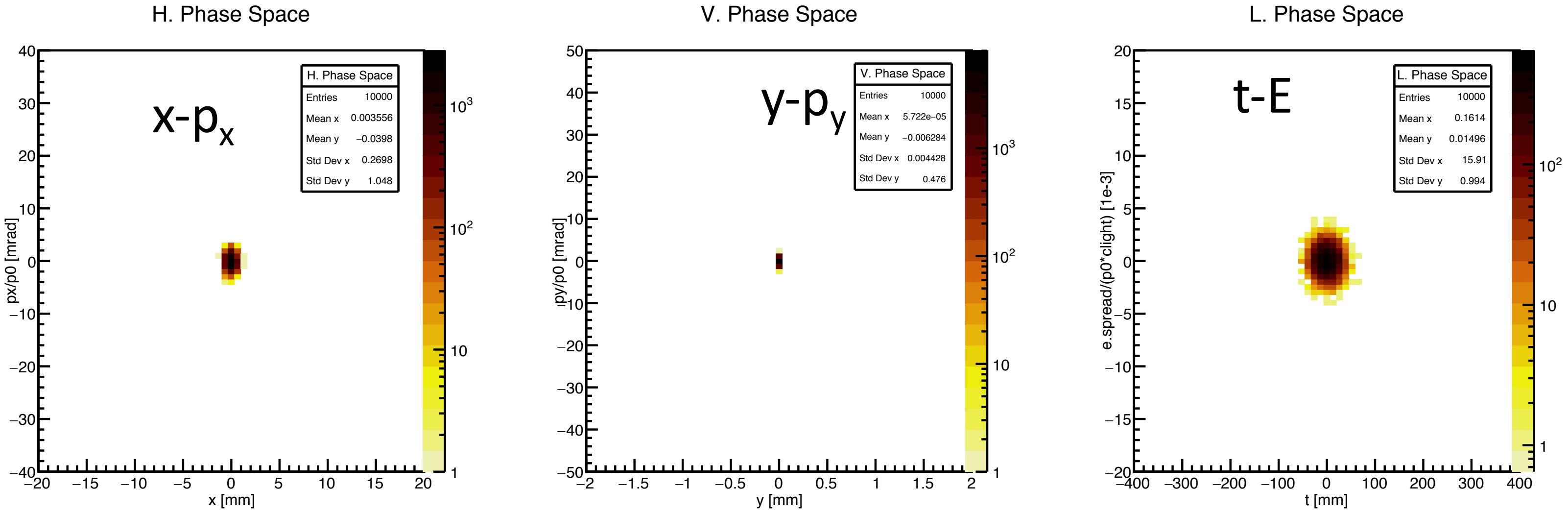


Lifetime with ~ 3500 turns for 10μm Be target
as short as 1.6 ms

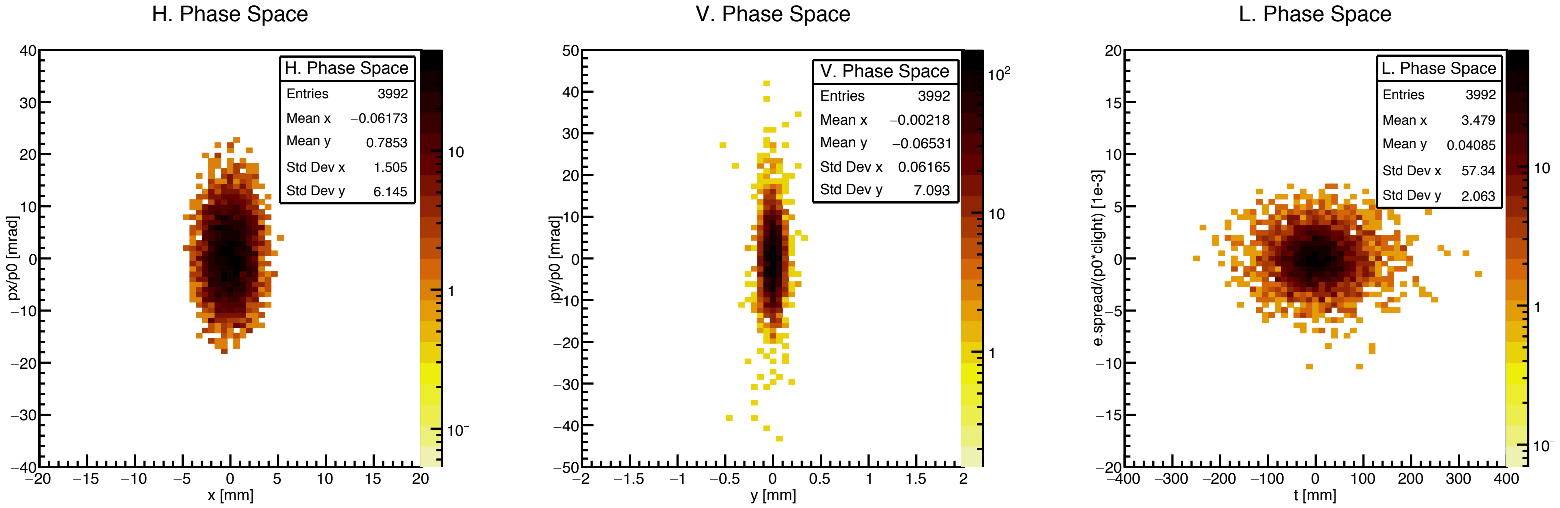
- Beam will not be stored
- Injection in single bunch mode
- turn-by-turn beam size and charge measurement

DAFNE e^+ ring with 50μm Be target: beam evolution in the 6D phase space

before target, starting point

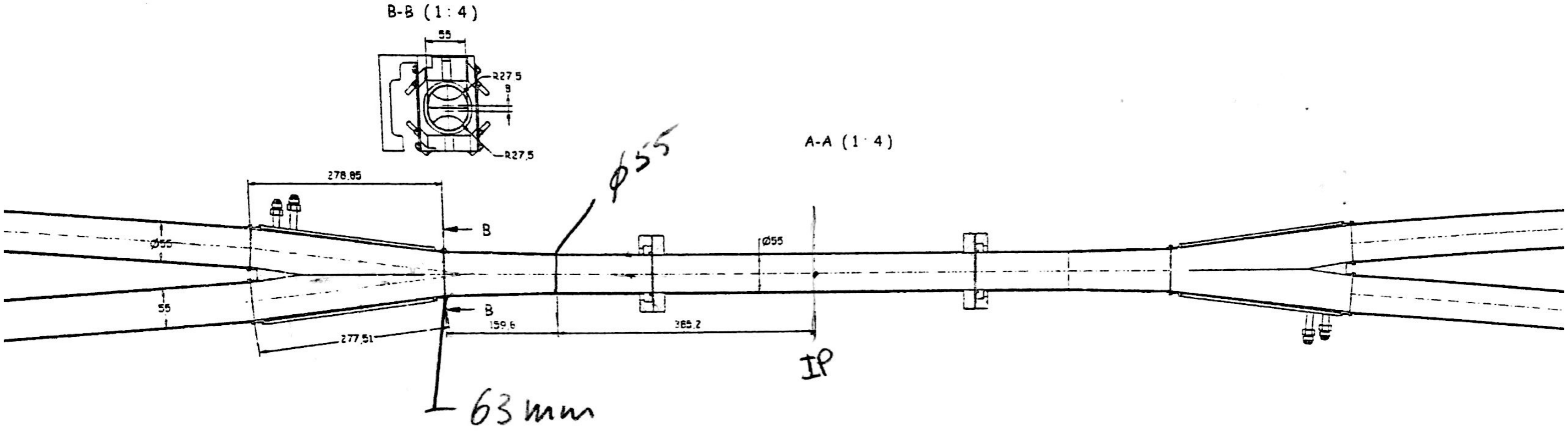


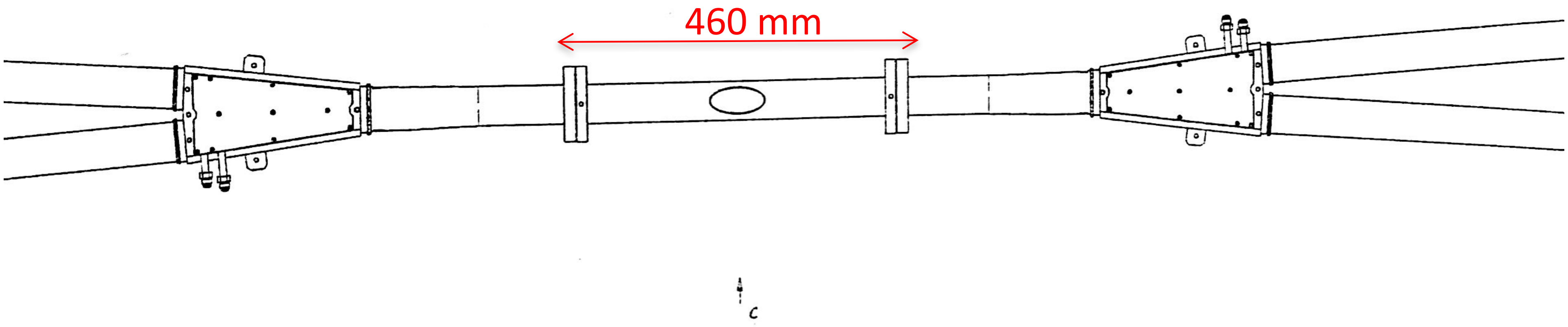
after 900 turns



MAD-X PTC & GEANT4 6-D tracking simulation

SIDDHARTA IR





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.

Back-up

Accelerator design contributors

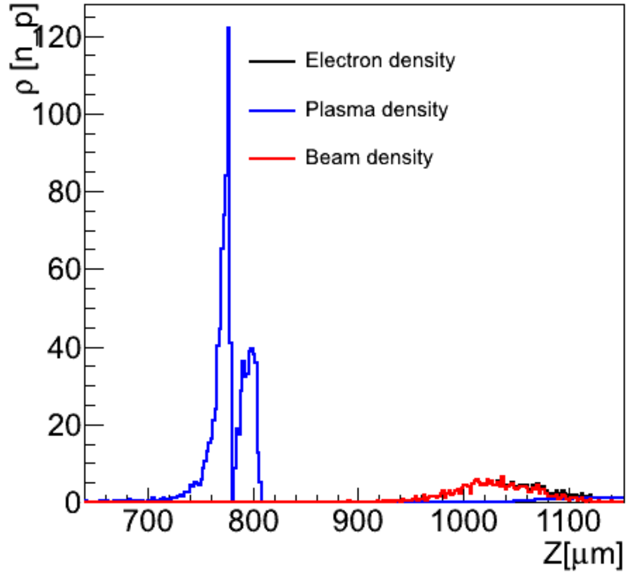
- optics and beam dynamics :
  - M. Antonelli, M. Biagini, O. Blanco, M. Boscolo, F. Collamati, S. Guiducci, L. Keller(SLAC), S. Liuzzo(ESRF), P. Raimondi(ESFR)
- positron source scheme:
  - A. Bacci, I. Chaikovska(LAL), R. Chehab(LAL), F. Collamati
- Test at DAFNE
  - D. Alesini, O. Blanco, M. Boscolo, A. Ghigo, A. Stella
- Temperature measurements of target:
  - R. Li Voti, L. Palumbo (SBAI, Sapienza)
- Target:
  - M. Iafrati, M. Ricci, L. Pellegrino,
  - M. Calviani (CERN), S. Gilardoni (CERN), P. Sievers(CERN)

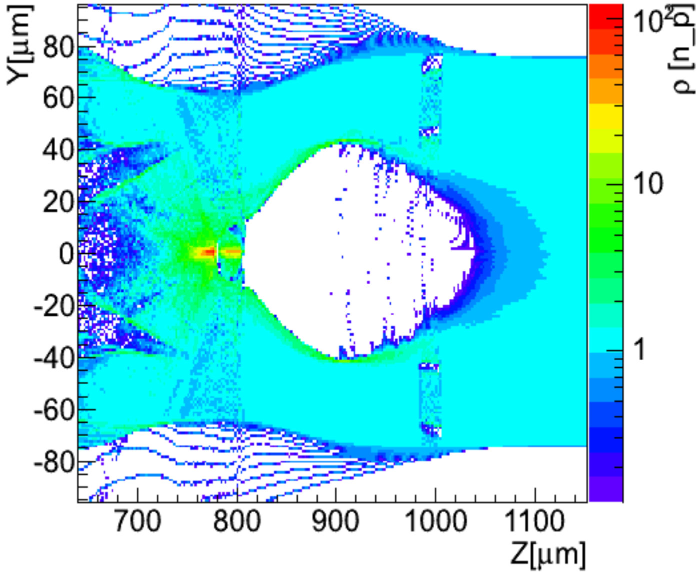
Experimental team

- experiment at H4 CERN
    - M. Antonelli, F. Anulli, A. Bertolin, M. Boscolo, C. Brizzolari, G. Cavoto, F. Collamati, R. Di Nardo, M. Dreucci, F. Gonella, F. Iacoangeli, A. Lorenzon, D. Lucchesi, M. Prest, M. Ricci, R. Rossin, M. Rotondo, L. Sestini, M.Soldani, G. Tonelli, E. Vallazza, S. Vanini, S. Ventura, M. Zanetti

Few statements on the plasma option

- Plasma would be a good approximation of an ideal electron target ++ autofocussing by Pinch effect
- enhanced electron density (up x100) can be obtained at the border of the blow-out region
- Simulations for $n_p=10^{16}$ e-/cm^3 ⇒ e- high density region ~ 100 μm (C. Gatti, P. Londrillo)
- high density region ~ $1/\sqrt{n_p}$
- In our case plasma with $n_p \sim 10^{20}$ particles/cm^3 is needed to get useful e- densities in very small region, it doesn't seem viable.



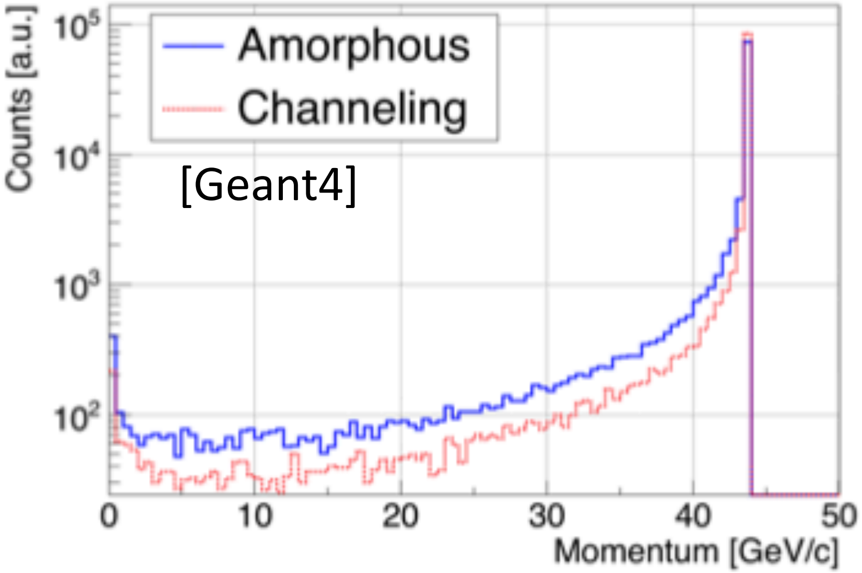


Crystals as a target ?

Positrons

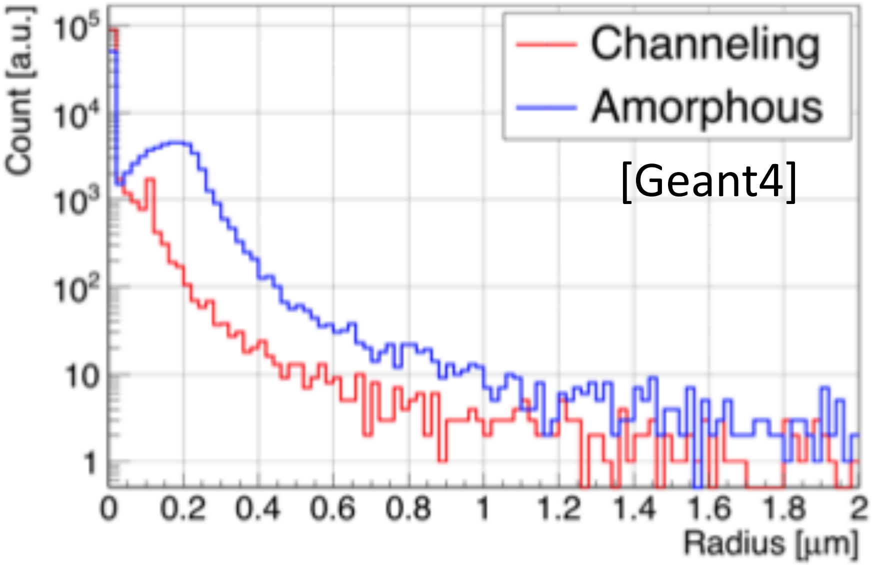
43.8 GeV e^+
4.1 mm Si Target
Channeling plane: (110)

Momentum



[Geant4]

Position

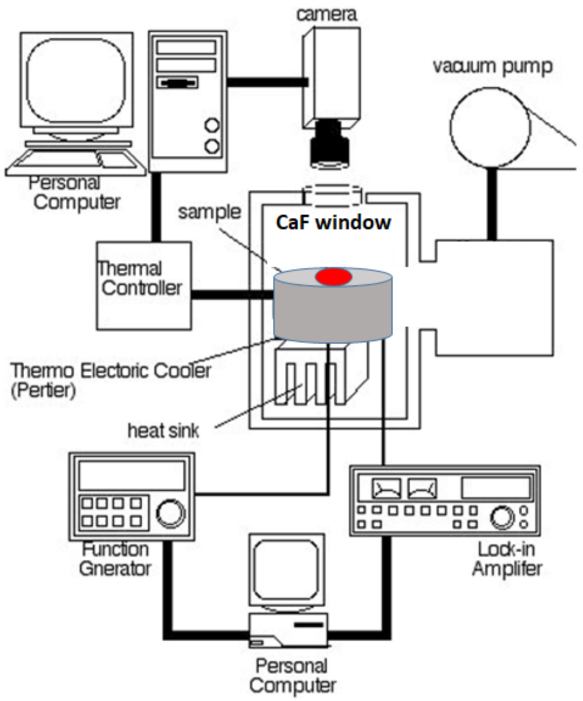


[Geant4]

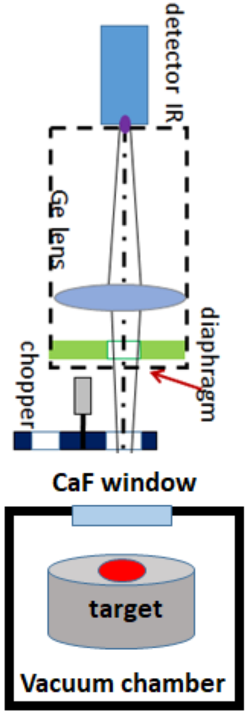
Temperature measurement in situ on the target

passive infrared:

very good spatial resolution 7.5µm~3µm/pixel. The frame rate can vary from 60Hz to 5000Hz



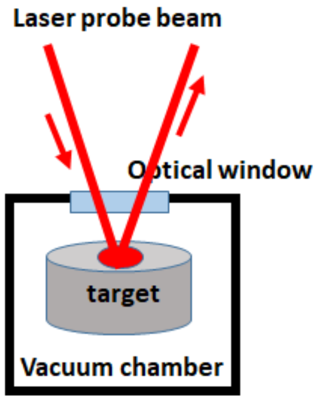
Experimental Setup - IR Emittance

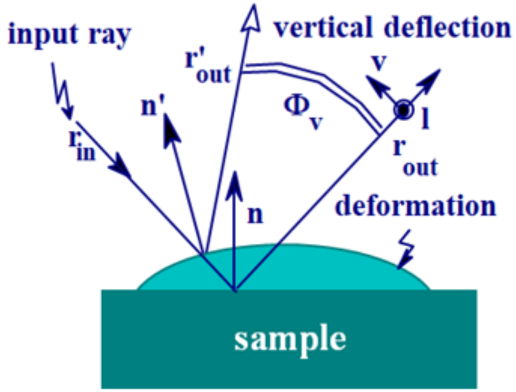


Infrared radiometry:

temperature dynamics in the microsecond range, no spatial resolution

Target deformation measurement





contactless laser technique to measure indirectly the temperature.

This technique is very sensitive and can detect very weak deformation of the order of some picometer corresponding to less than 1°C. After a proper calibration can be used to follow the ultrafast dynamic of the temperature of the target

Possible target: 3 mm Be

45 GeV e^+ impinging beam

- Emittance at E_μ = 22 GeV:

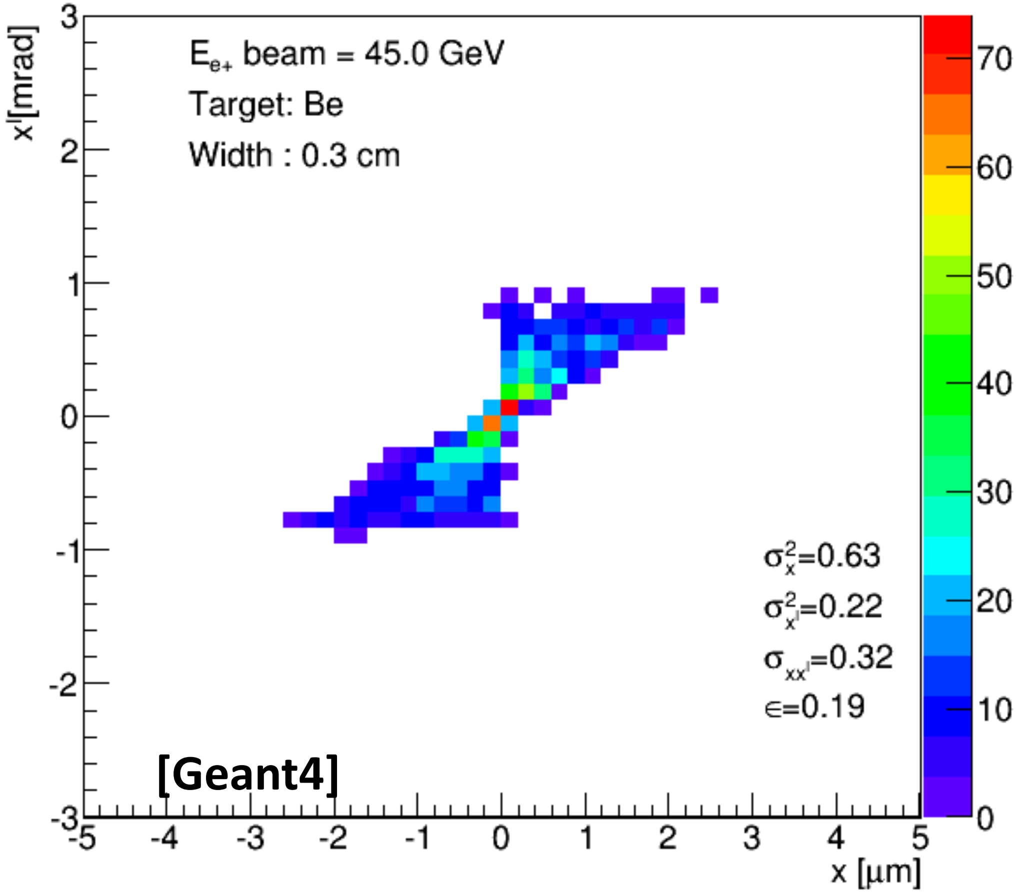
  $\varepsilon_x = 0.19 \cdot 10^{-9}$ m-rad

Multiple Scattering contribution is negligible

-> μ after production is not affected by nuclei in target
-> e+ beam emittance is preserved, not being affected by nuclei in target (see also next slide)

- Conversion efficiency: 10^{-7}
- Muons beam energy spread: 9%

Muons at the target exit surface



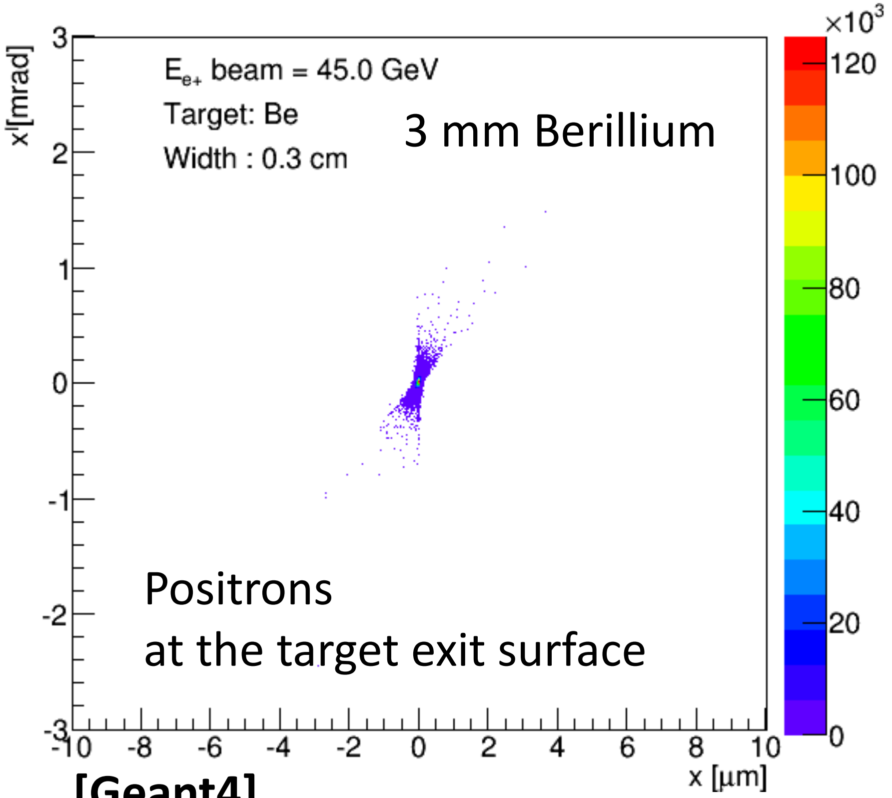
[Geant4]

Positrons Storage Ring Requirements

- Transverse phase space almost not affected by target
- Most of positrons experience a small energy deviation:

  A large fraction of e^+ can be stored (depending on the momentum acceptance)

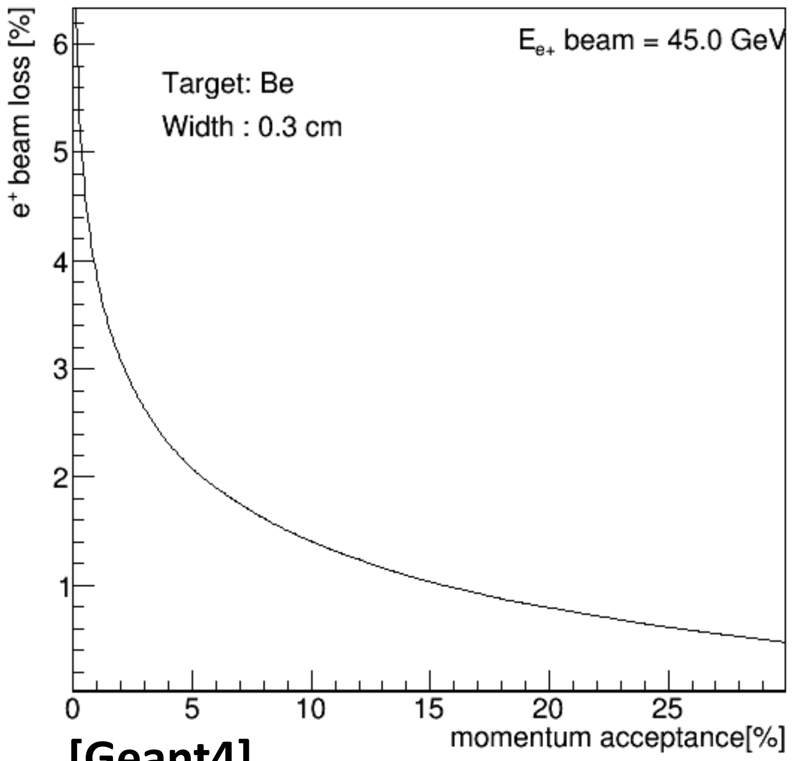
  - 10% momentum acceptance will increase the effective muon conversion efficiency (produced muon pairs/produced positrons) by factor 100



3 mm Berillium

Positrons
at the target exit surface

[Geant4]

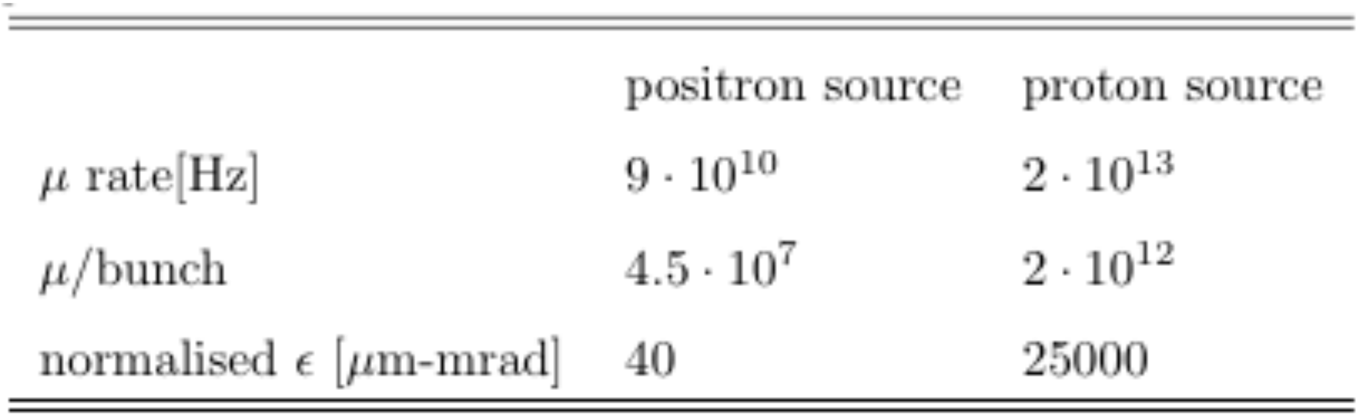


[Geant4]

Muon beam parameters

Assuming

- a positron ring with a total 25% momentum acceptance (10% easily achieved) and
- ~3 × LHeC positron source rate



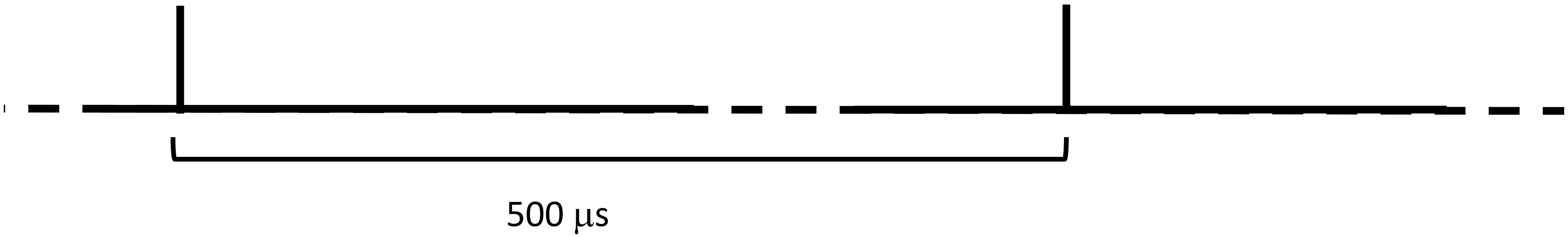
	positron source	proton source
μ rate[Hz]	$9 \cdot 10^{10}$	$2 \cdot 10^{13}$
μ/bunch	$4.5 \cdot 10^{7}$	$2 \cdot 10^{12}$
normalised ϵ [μm-mrad]	40	25000

Very small emittance, **high muon rates** but relatively small bunch population:

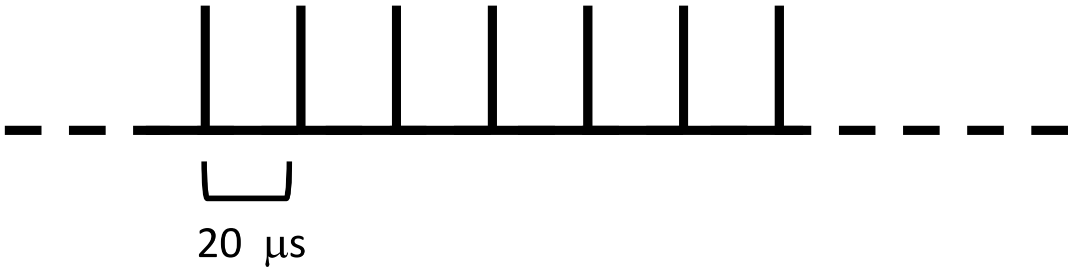
- ➢ The actual number of μ/bunch in the muon collider can be larger by a factor ~ τ_{μ}^{lab}(HE)/500 μs (~100 @6 TeV) by topping up.

rebunching at 6 TeV

bunch structure from production



bunch structure at collider

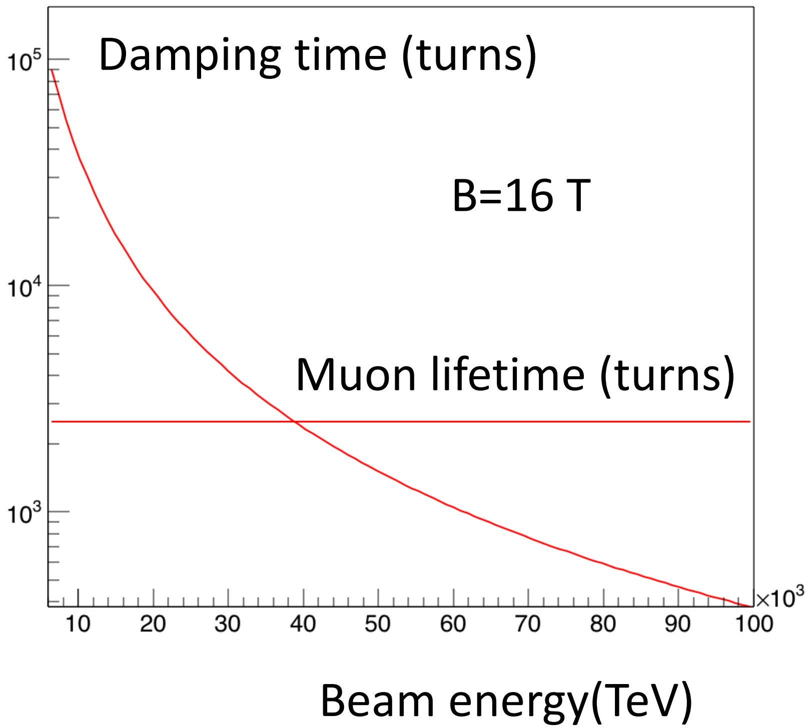


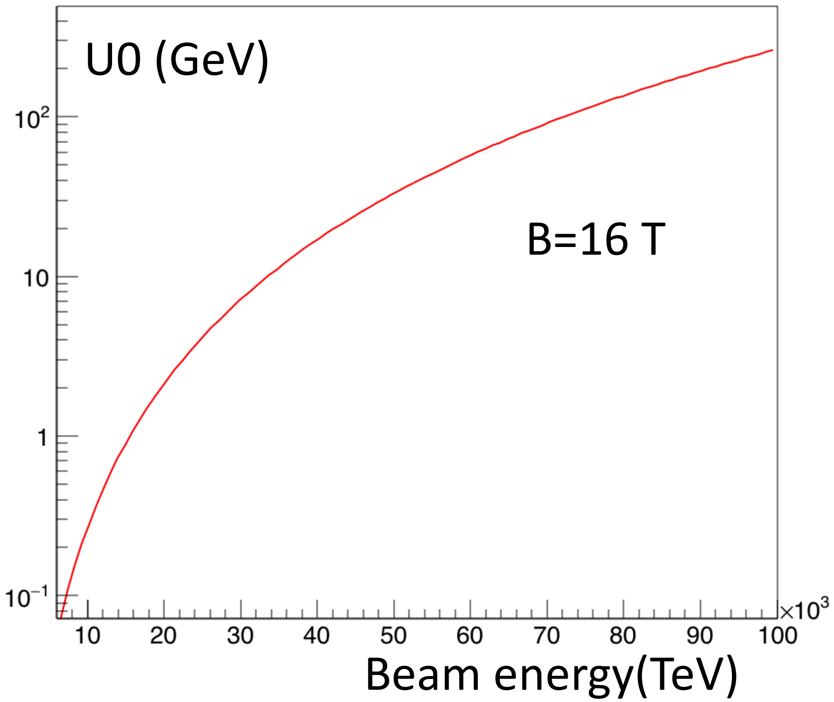
perform continuous injection every 500 μs

rebunch effective for ~ 1 muon lifetime 66 ms (factor 66/0.5)

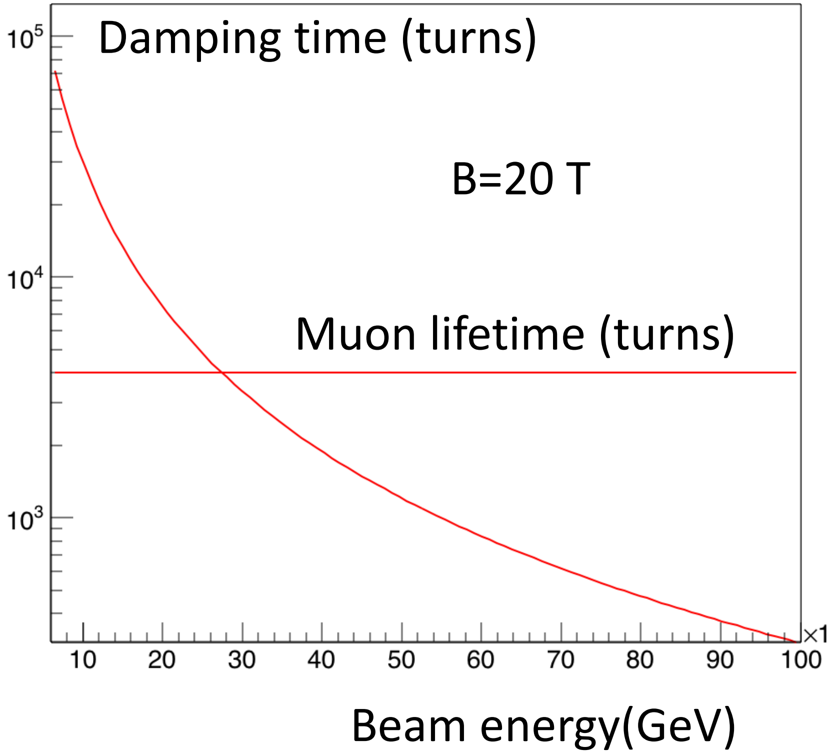
no damping -> fill transverse phase space maintaining lumi increase

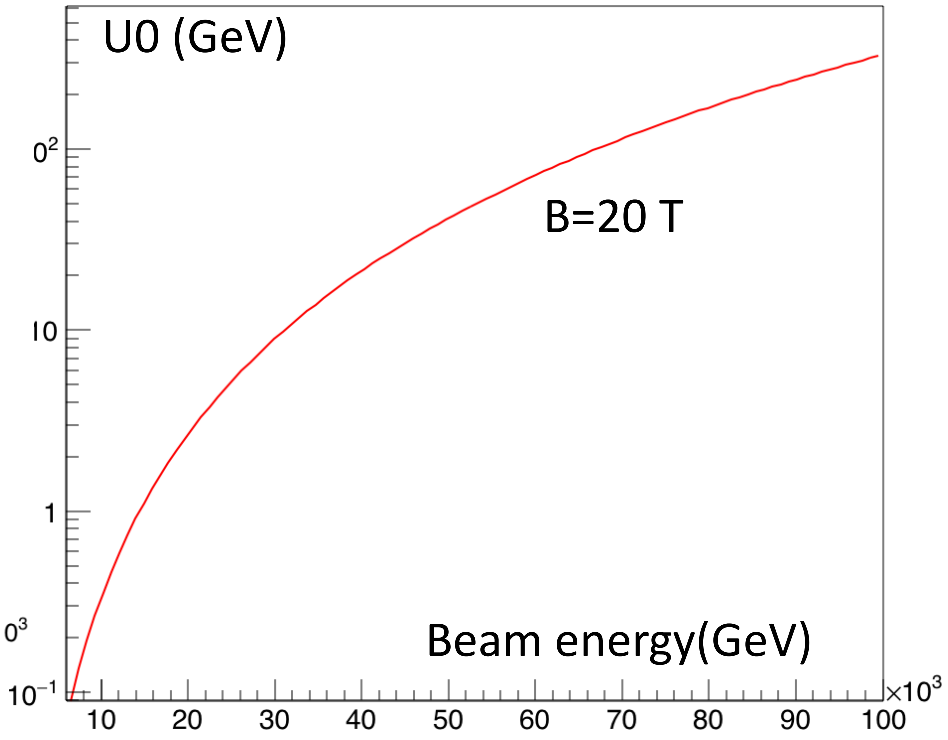
SR and damping in μ collider





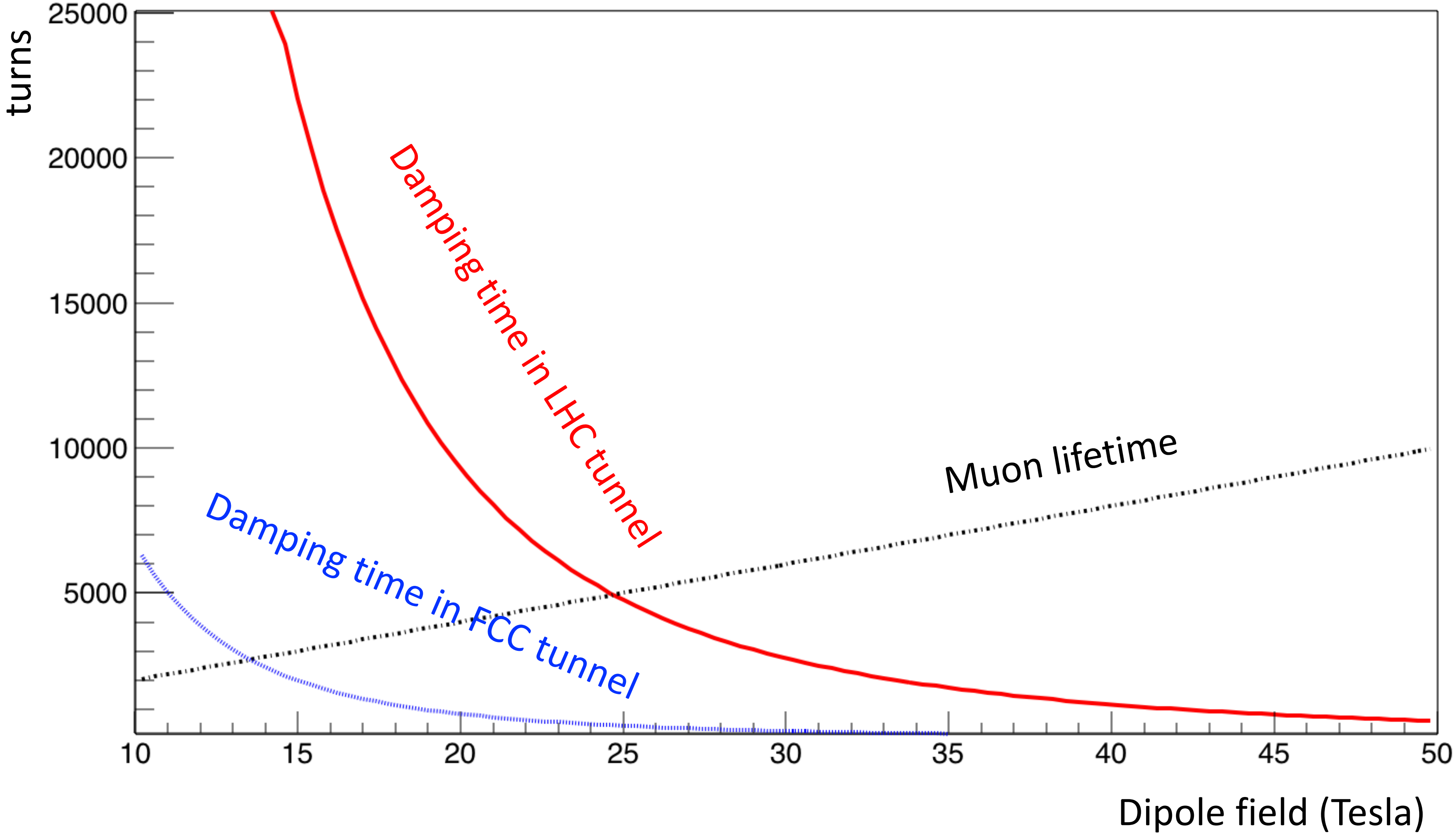
SR and damping in μ collider



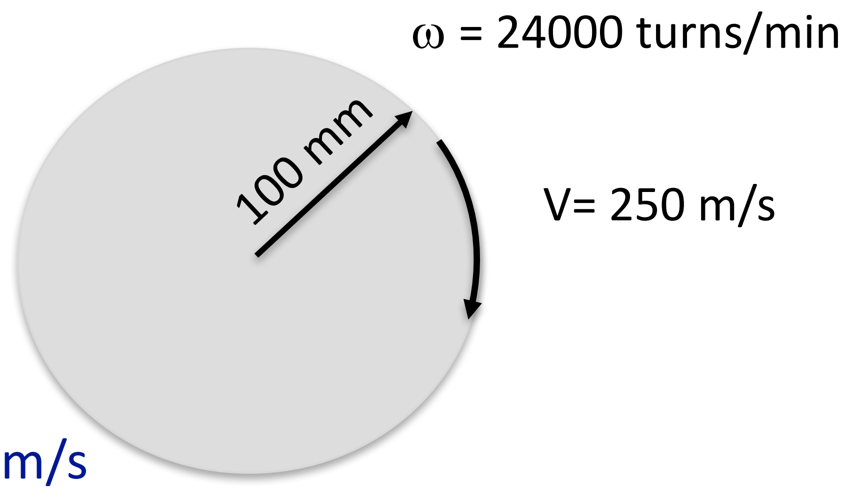


$U_o = 5.5 \times 10^{-18}\, \gamma^4/\rho$

Damping time & muon lifetime



Solid target



- Rotating disc
  - 24000 turns/min
  - Radial velocity $V= 2\,\pi\,\omega$(in turns) $r=250$ m/s
- Bunch spacing of ΔT=200ns
  - Bunch separation on target $L = V\,\Delta T= 50\ \mu m$
  - 12500 bunches in 1 turn

2D axisymmetric model showing effective total strain

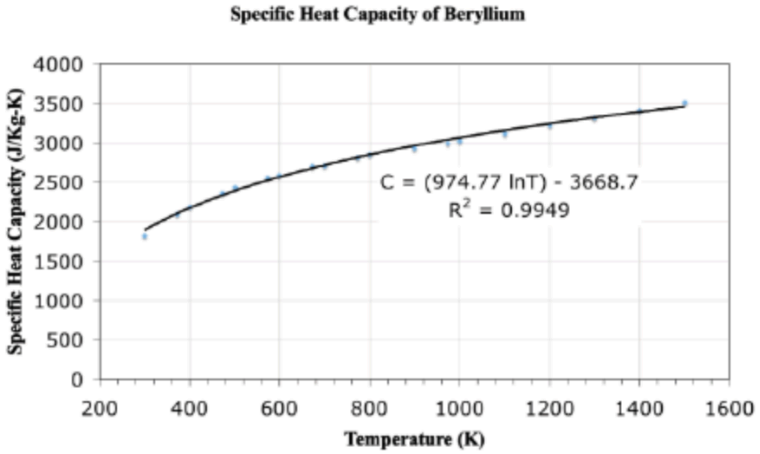
4.9 x 10^{13} protons, $\sigma = 0.3$ mm, $\Delta T \sim 1025$ °C, 0.25 mm thick window

End of beam pulse

$t = 7.2\ \mu s$, $T_{max} \sim 1050$ °C, $\varepsilon_{max} \sim 3.6$ %

- Use 300 µm round e+ beam, 0.25 mm Be target, 5 x 10^{13} e+/b
- dE/e+ = (2.0 MeV.cm2/g)(1.85 g/cm3)(0.025 cm) = 0.09 MeV/e+
- dE = 5x 10^{13} 0.09 1.6 1.6 x 10^{-13} j/MeV = 0.74j
- dV = pi (0.025 cm)(0.03 cm)**2 = 7 x 10^{-5} cm3
  m = dV ρ = 0.00013 g
  Cp = spec. heat Be = 1.8 j/g°C @ 373 K ; C = Cp m = 0.00024
- dT =dE/C = 3083 °C
- Cp = spec. heat Be = 2.8 j/g°C @ 1000 K ; C = Cp m = 0.0005
- dT =dE/C = 2000 °C
- x2 wrt LS-DYNA ?

- Scale for n= 3 x 10^{11}
- $(300\mu m)^2/200=(21\mu m)^2$



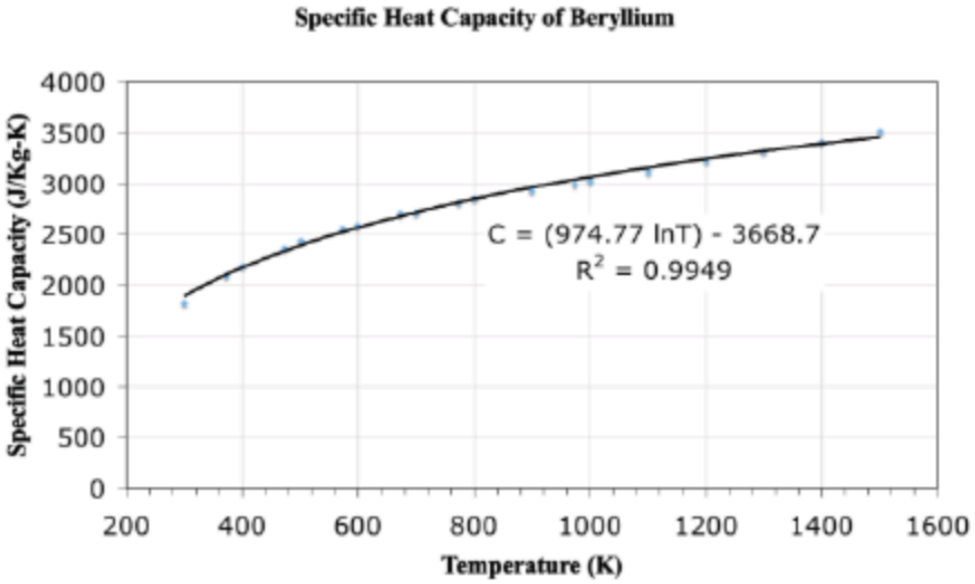
Solid target

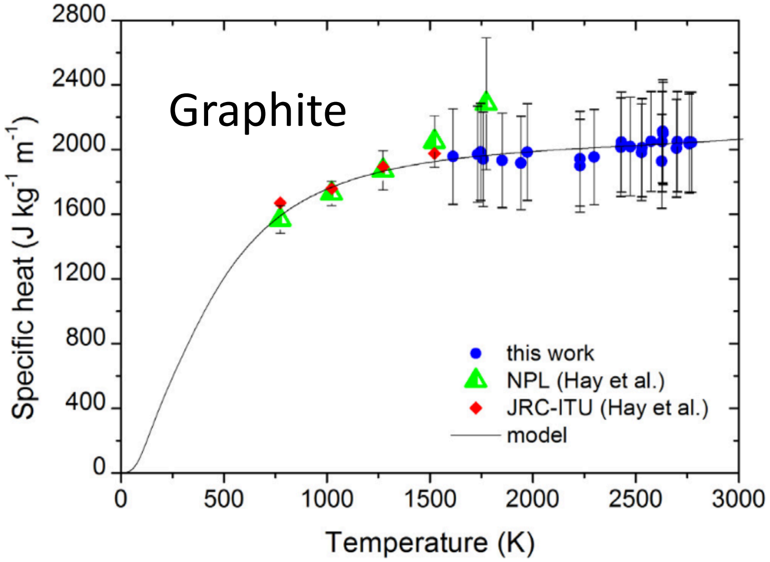
- Use 5 µm round e+ beam, 0.3 cm Be target, 3×10^{11} e+/b

$$Cp = 0.97477 \ln T - 3.6687$$

$$Dq = Cp\, DV\, \rho\, dT$$

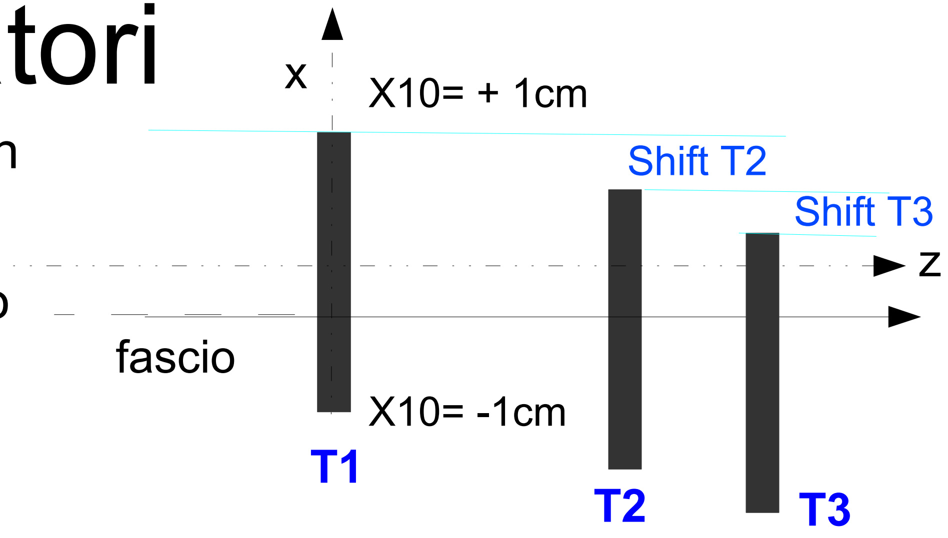
$$Q = DV\, \rho\, [(0.97477\, T(\ln T - 1) - 3.6687\, T) - 0.97477 \times 373(\ln 373 - 1) - 3.6687 \times 373)\,]$$

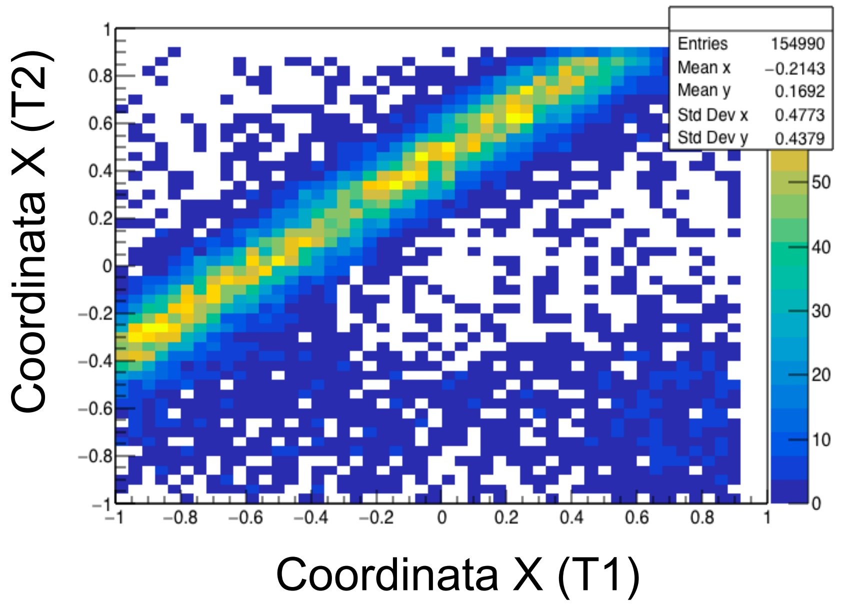


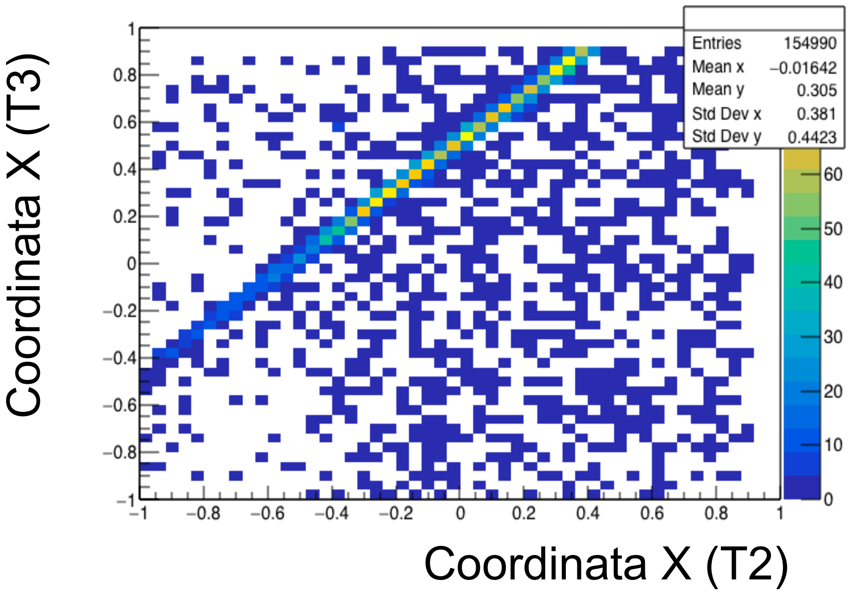


Allinemanto tracciatori

- Allineamento dei tracciatori effettuato con i run di calibrazione senza targhetta:
  - positroni da 22 GeV presi con campo magnetico diretto e invertito
  - Esempi relativi a T2 e T3 (tracciatori prima del dipolo)





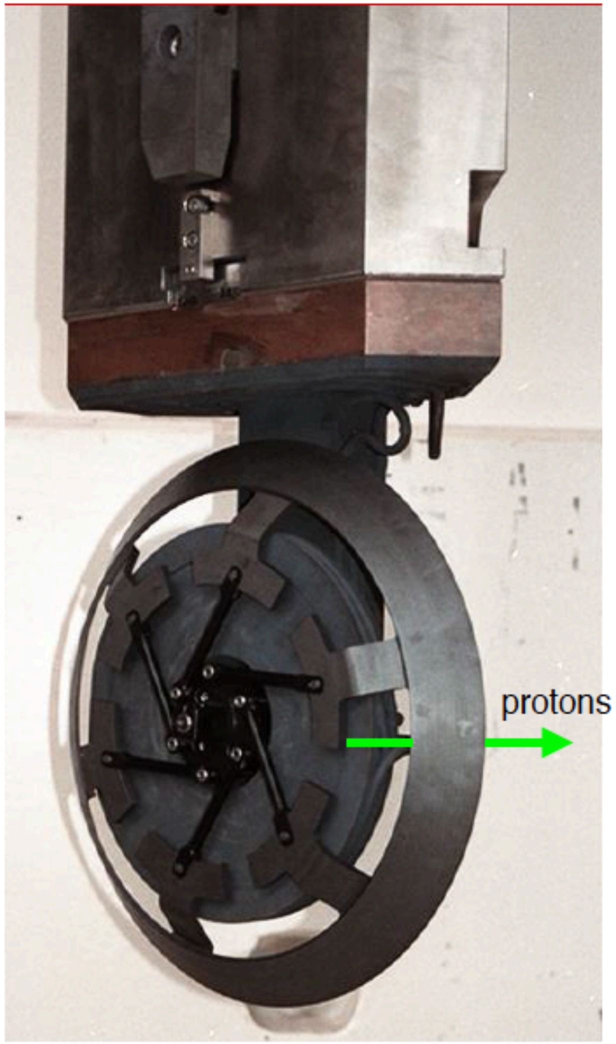


Shift relativo T2 rispetto a T1: 0.5 cm
Spread fascio in X: 0.26 mrad

In corso allineamento dei tracciatori dopo il dipolo:
- 1) misure dei geometri
- 2) confronto tra direzioni predette e posizione misurate nei due bracci dello spettrometro

Target wheel of TgE station

- 40 mm polycrystalline graphite
- ~40 kW power deposition
- Temperature 1700 K
- Radiation cooled @ 1 turn/s
- Beam loss 12% (+18% from scattering)

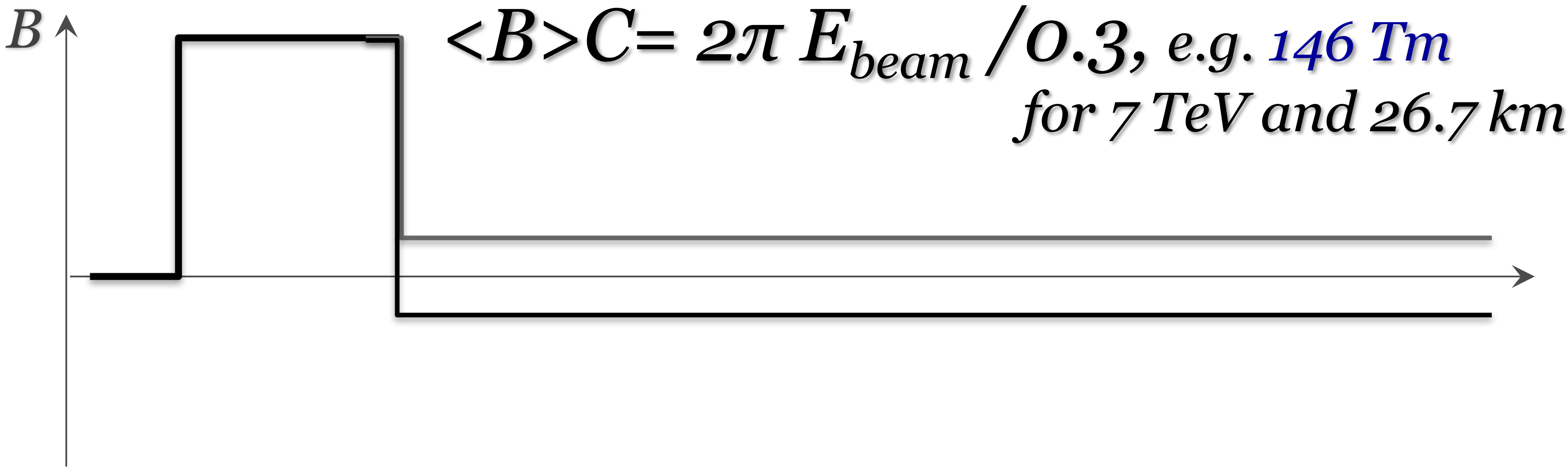


Assume RCS Acceleration

B_{max} : DC

B_{min} : pulsed from $-B_{min}$ to $+B_{min}$

Packing factor $\Pi<1$



$\langle B\rangle C = 2\pi E_{beam}/0.3$, e.g. 146 Tm for 7 TeV and 26.7 km

Example: 7 TeV, 26.7 km tunnel, 16T max

$$\frac{2\pi}{0.3}\underset{\overset{\uparrow}{146\ \mathrm{T\times km}}}{E_{max}} = \langle B \rangle \underset{\overset{\uparrow}{26.7\mathrm{km}}}{C} = \underset{\overset{\uparrow}{16\mathrm{T}}}{B_{max}}\underset{\overset{\uparrow}{0.85}}{\Pi} C \frac{2R}{R(1+\underset{\overset{\uparrow}{0.4=1/2.5}}{f)}+1-f}$$

then :

$f = \frac{B_{max}}{B_{min}}$	$R = \frac{f-1}{f-4}$	B_{min}	E_{inj}
4.2	16	3.8T	0.45TeV
4.5	7	3.5T	1TeV
5	4	3.2T	4TeV
8	1.75	2.0T	9.1TeV

Example 2: 1 TeV, 6.9km tunnel, 16T max

$$\frac{2\pi}{0.3}E_{max} =< B > C = B_{max}\Pi C\,\frac{2R}{R(1+f)+1-f}$$

20.9 T × km   6.9km   16T   0.9   0.21=1/5

then :

$f = \frac{B_{max}}{B_{min}}$	$R = \frac{f-1}{f-9}$	B_{min}	E_{inj}
10	9	1.6T	110 GeV
9.5	17	1.7T	60 GeV

To sum up: 14 TeV *CMC*

- **One can build a 14 TeV cme $\mu+\mu-$ collider at CERN if:**
  - Re-use tunnels 26.7km LHC, 6.9km SPS, 0.7km PS
  - 16 T SC magnets (DC), need ~5 km
  - Pulsed ±3.5 T magnets, with ramp ~100ms, need ~20km
  - Pulsed ±2 T magnets, with ramp ~10ms, need ~6km
  - Pulsed ±1 T magnet, with ramp ~1ms, need ~1km
- **The *αβγ*-model predicts TPC ~12B$ ±4**
  - 5B$ SC magnets, 3B$ NC magnets, 2B$ SRF, 2B$ 100MW power infrst.
  - ~ cost of LHC; ~6B$ in European accounting
- **"Free cookie" – if one has 24 T SC magnets**
  - Either 4x luminosity can be achieved with collider in SPC tunnel – that requires 7 km of 24T magnets
  - Or 7 TeV cme in the LHC tunnel with just 3T pulsed magnets