Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Low Emittance Muon Accelerator: stato e prospettive

M. Antonelli for the LEMMA Team

Tonelli Guido	10 PI
Benato Lisa	15 PD
Bertolin Alessandro	5 PD
Checchia Paolo	10 PD
Lucchesi Donatella	30 PD
Lujan Paul	15 PD
Lupato Anna	10 PD
Morandin Mauro	5 PD
Rossin Roberto	10 PD
Sestini Lorenzo	30 PD
Zanetti Marco	25 PD
Gonella Franco	20 PD
Anulli Fabio	20 RM1
Collamati Francesco	40 RM1
Migliorati Mauro	15 RM1
Palumbo Luigi	20 RM1
Camattari Riccardo	30 FE
Guidi Vincenzo	10 FE
Vallazza Erik	50 TS
Antonelli Mario	20 LNF
Blanco Garcia Oscar	30 LNF
Guiducci Susanna	20 LNF
Iafrati Matteo	100 LNF
Rotondo Marcello	20 LNF
Biagini Maria	20 LNF
Boscolo Manuela	60 LNF
Pellegrino Luigi	10 LNF

Low EMittance Muon Accelerator team

Additional national

- M. Ricci **(Uni. Marconi, INFN-LNF),** G. Cavoto **(La Sapienza),** E. Bagli **(INFN-Fe),** M. Prest, M. Soldani, **(Uni-Insubria&INFN), A. Lorenzon (Uni. Padova)**

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)**

Collaboration in **ARIES for WP 6 (**improving Accelerator PErformance and new Concepts), **WP 17** (PowerMat)

- Participation to WP8 with alternative option: L. Serafini, C. Curatolo

Idea for low emittance μ beam

Conventional production: from **proton on target**

π, K decays from proton on target have typical **P_μ~ 100 MeV/c** (π, K rest frame)

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

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

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

very small emittance at μ production point → **no cooling** needed!

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 ($\approx$ mb)

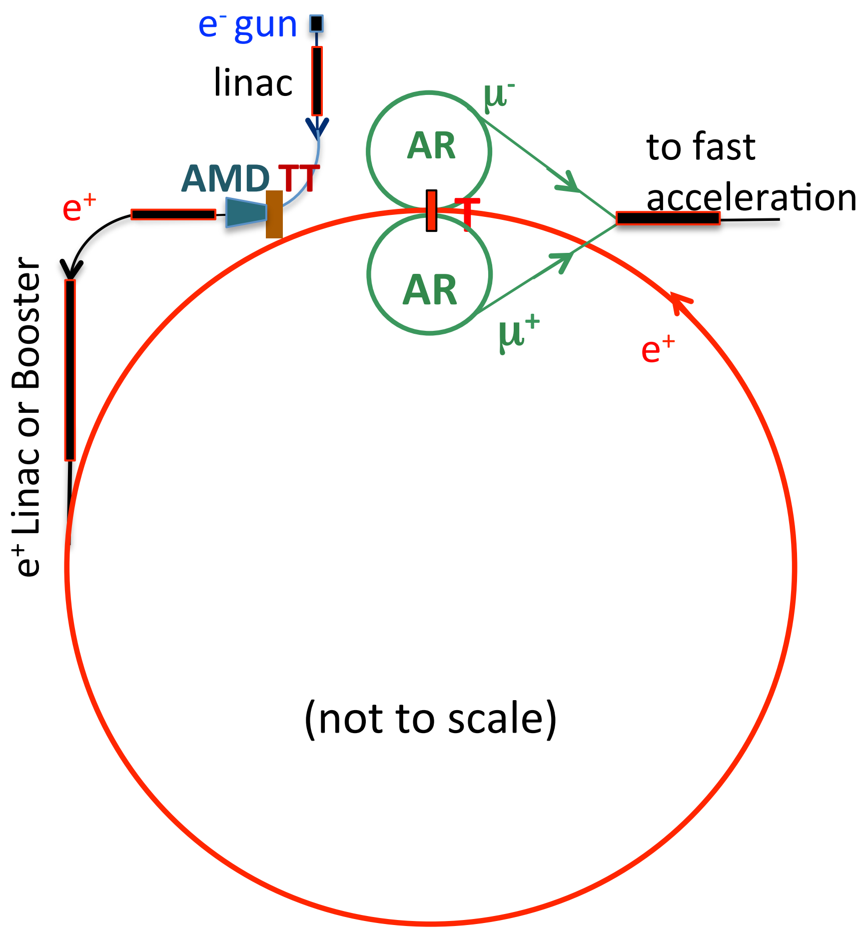
  $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1\ \mu b$ at most

Addressing Key topics for this scheme

- **Low emittance and high momentum acceptance 45 GeV e^+ ring: heavy activity in 2017**
- **O(100 kW) class target in the e^+ ring for $\mu^+ \mu^-$ production: activity just started**
- **High rate positron source: ongoing activity**
- **High momentum acceptance muon accumulator rings: some item has been studied**
- **Validate with experimental test**
  - **Muon production: experiment @ H4 (1week July/August), continue next year**
  - **Target thermo-mechanical stresses: to start next year?**
  - **Beam recirculation in storage ring: proposal in progress**

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

ε_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

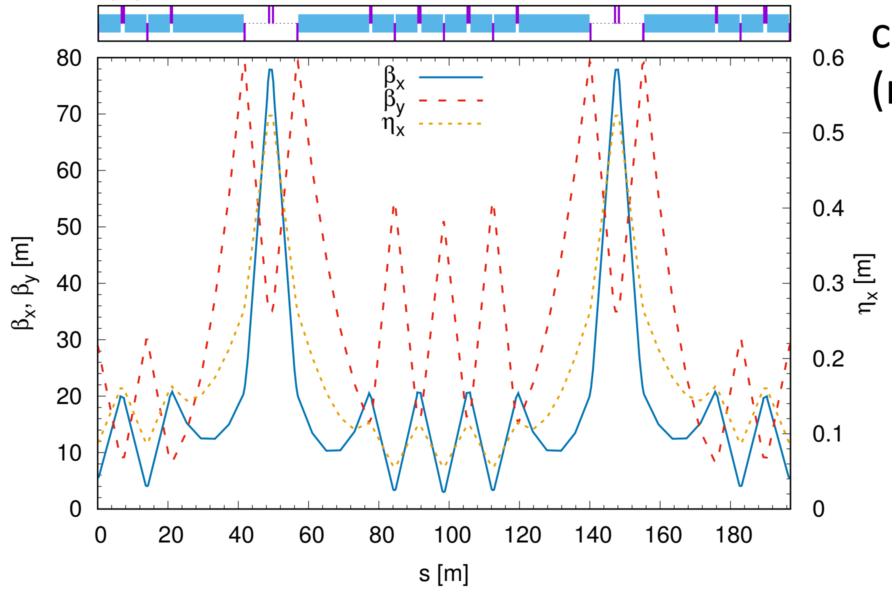
thanks to very small emittance (and lower beta*) comparable luminosity with lower Nμ/bunch
(→ lower background)

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
β_x @ IP	m	0.0002
β_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
σ_x @ IP	micron	1.68E-02
σ_y @ IP	micron	1.68E-02
$\sigma_{x'}$ @ IP	rad	8.39E-05
$\sigma_{y'}$ @ IP	rad	8.39E-05

Low emittance 45 GeV positron ring

cell

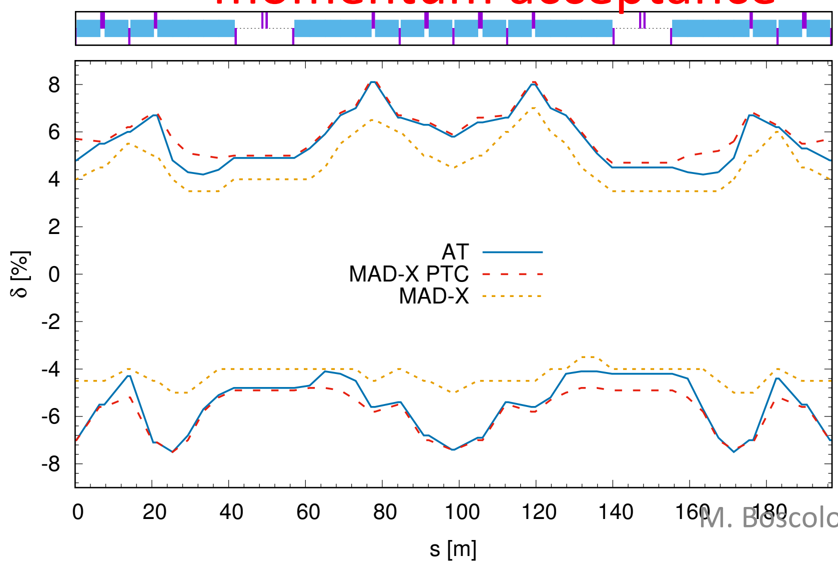


circumference 6.3 km: 197 m x 32 cells
(no injection section yet)

Table e+ ring parameters

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

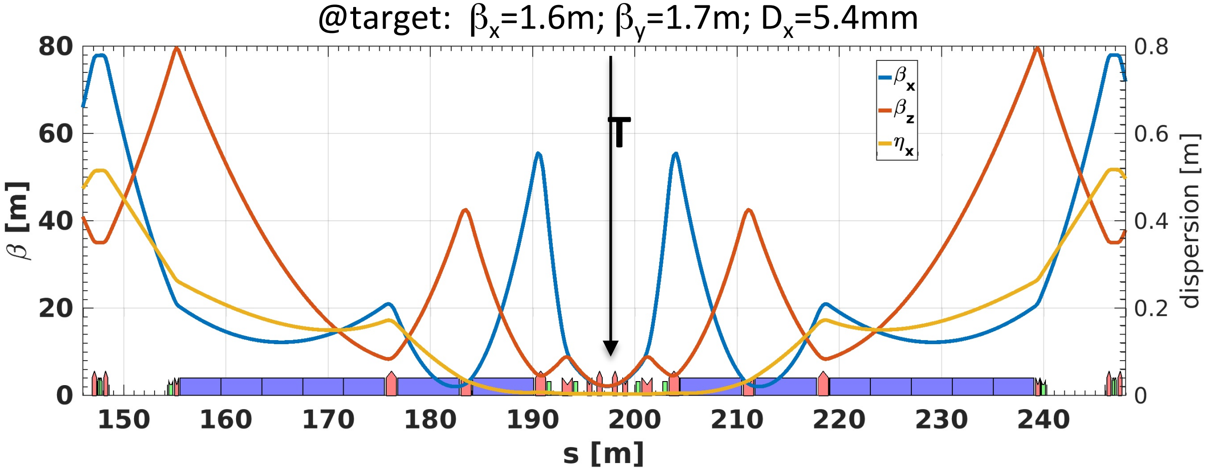
momentum acceptance

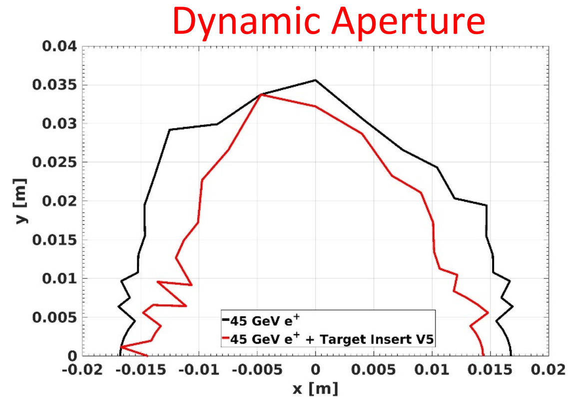


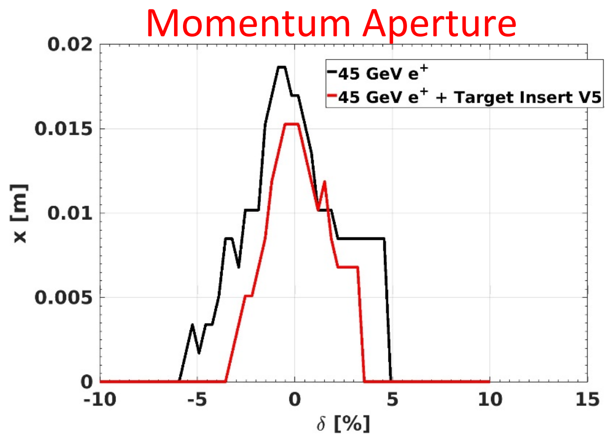
Physical aperture=5 cm constant
no errors

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

Preliminary low-β IR for muon target insertion

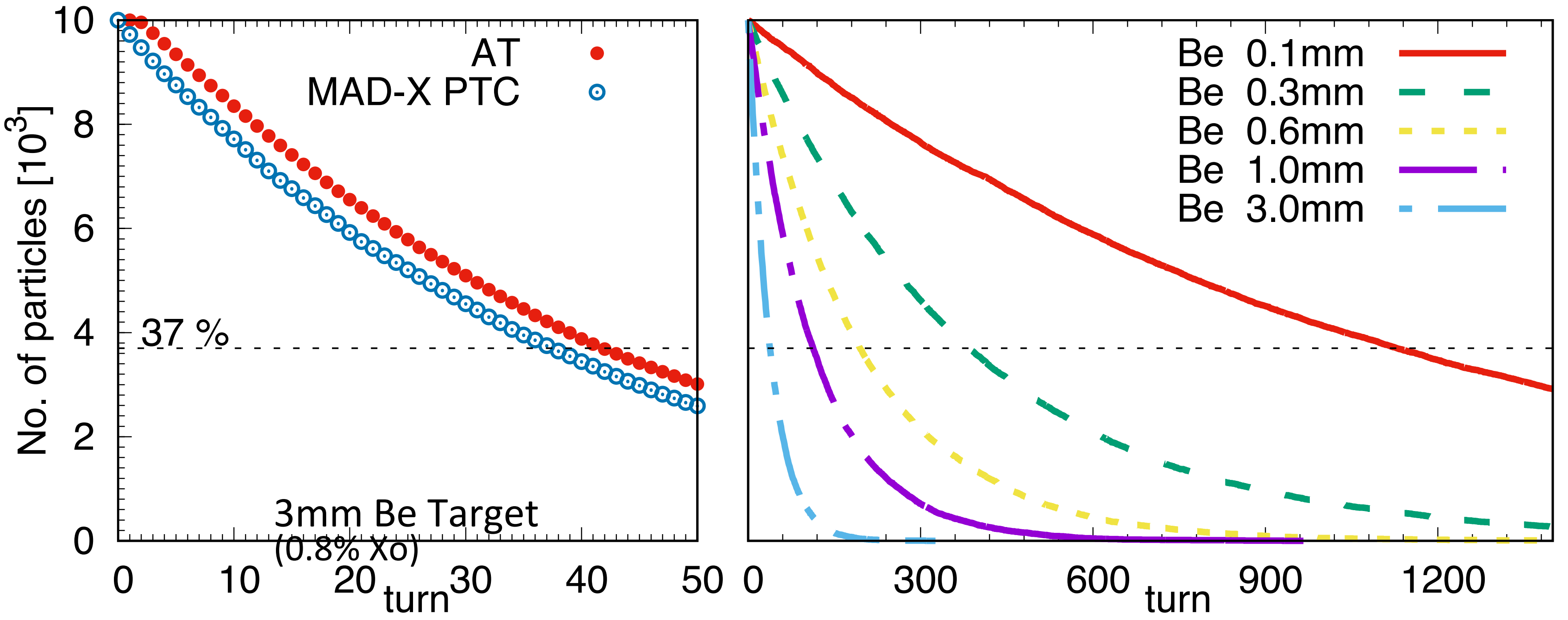






- **@target location:**
  - **$D_x \approx 0$**
  - **low-β**
- Further optimizations are underway:
  - match the transverse minimum beam size with constraints of target thermo-mechanical stress
  - match with other contributions to muon emittance (production, accumulation)
  - dynamic and momentum aperture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

e+ lifetime

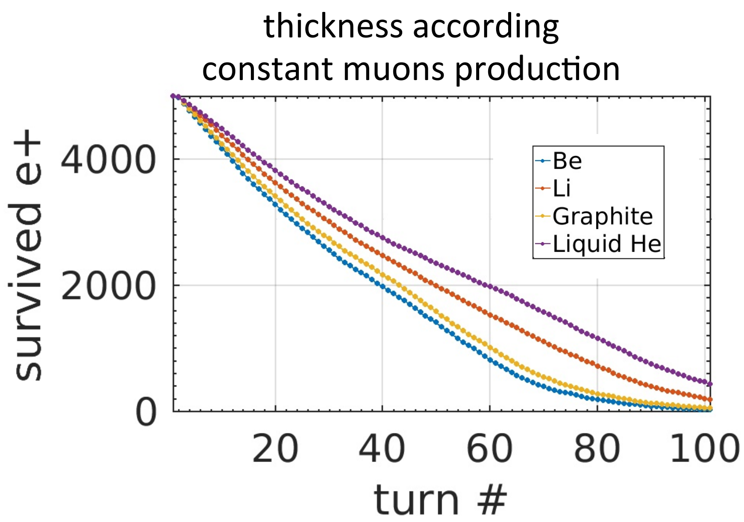


determined by **bremsstrahlung and momentum acceptance**

Lifetime with ~ 40 turns

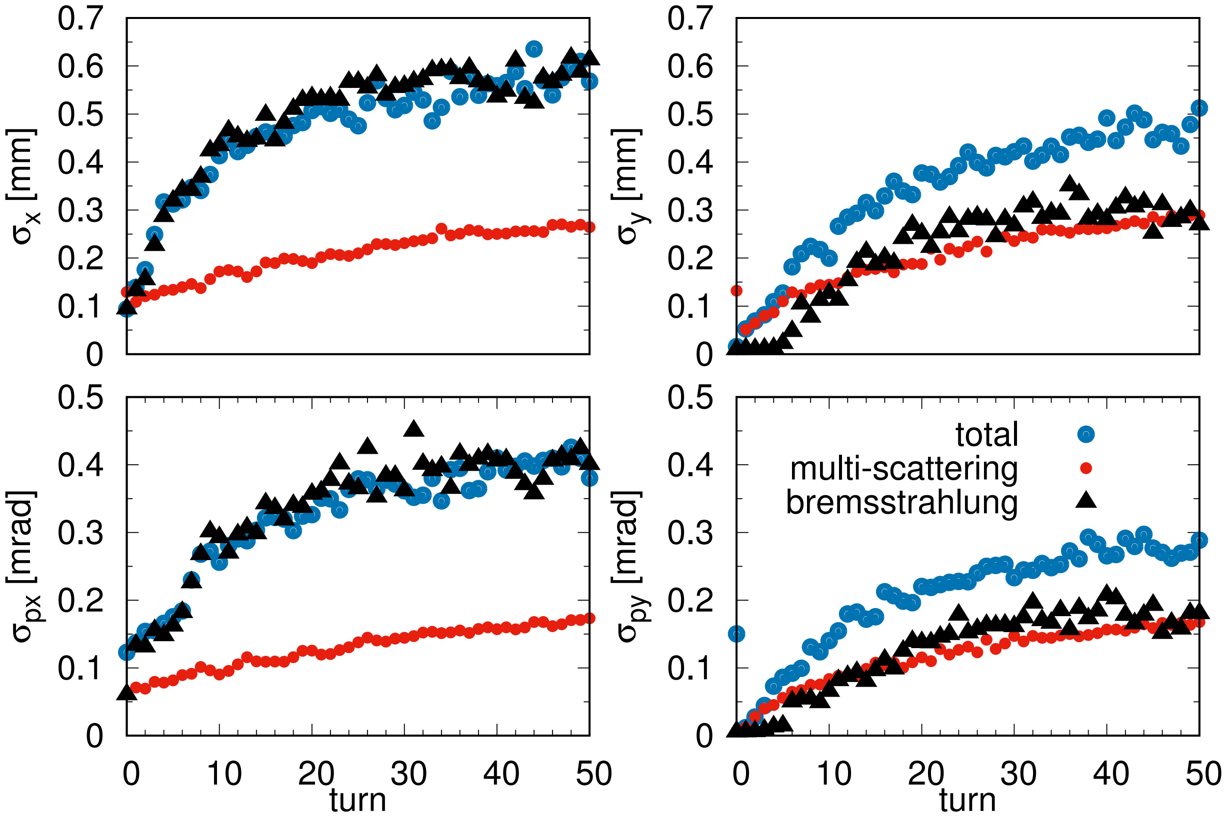
agreement within 10%

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



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)

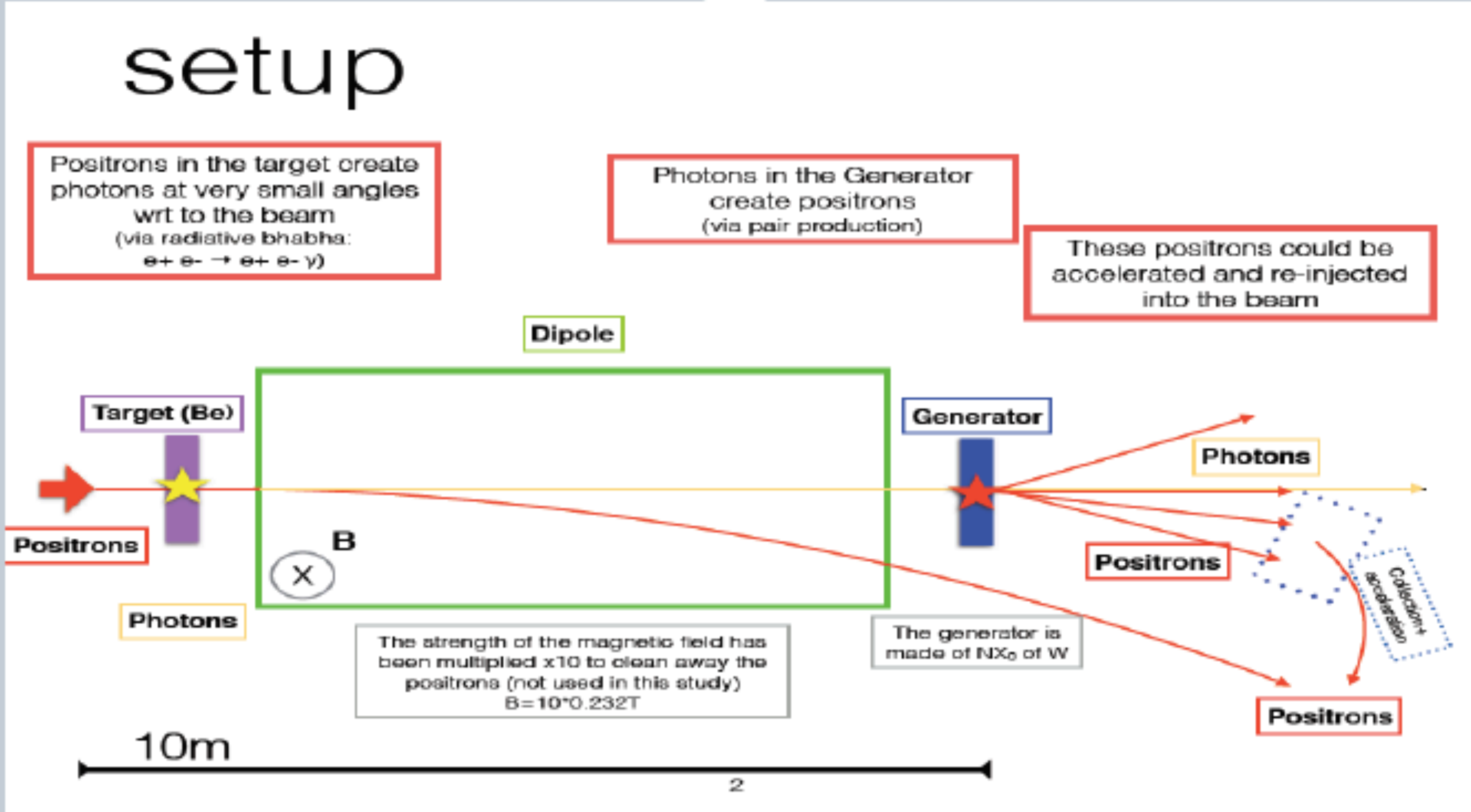
Some bremsstrahlung contribution due to residual dispersion at target

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

FOCUSING SYSTEMS FOR POSITRON SOURCES



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

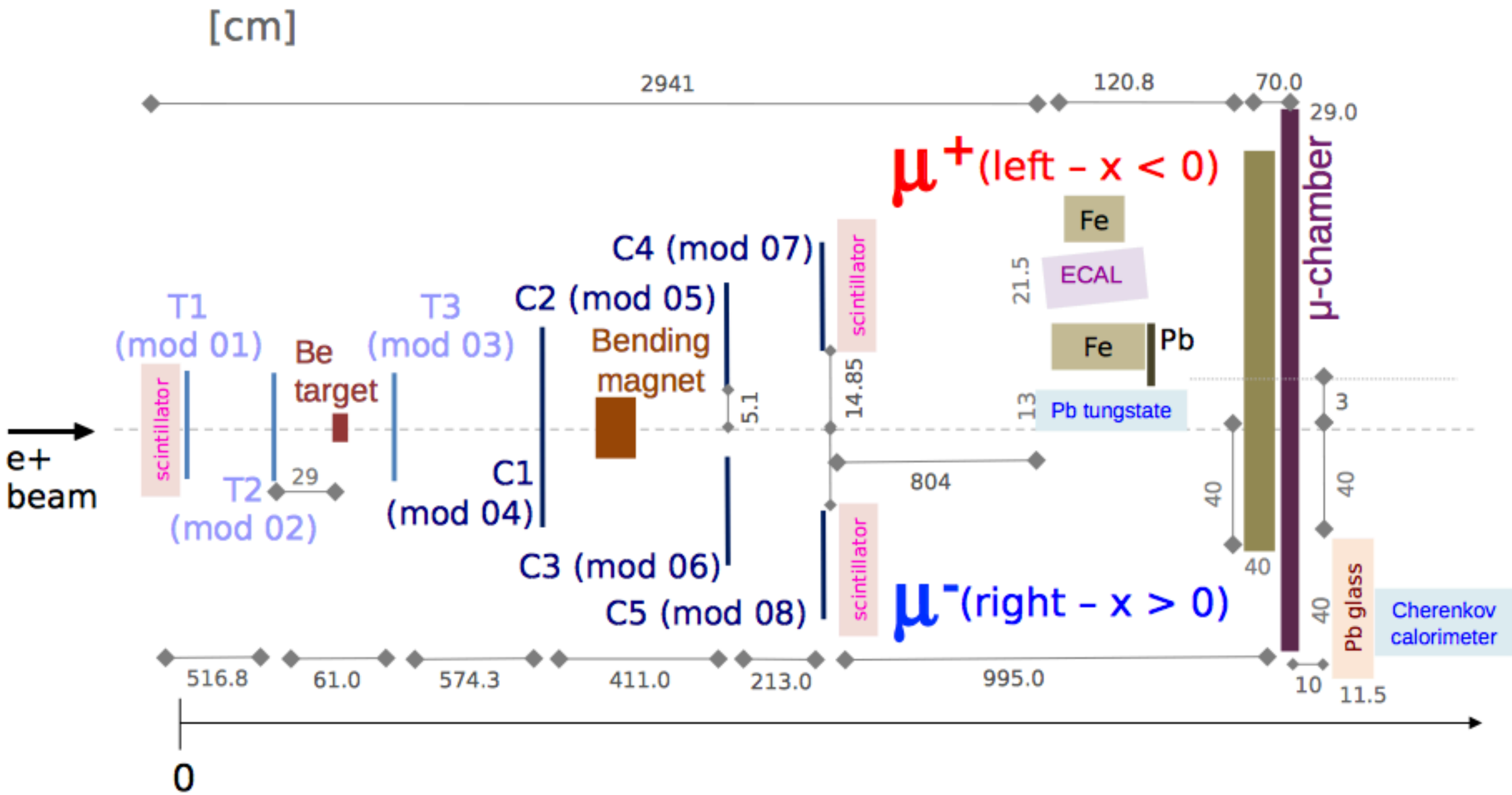
- **Solid target**: simpler and better wrt temperature rise
  - Be, C [Kavin Ammigan 6th High Power Targetry Workshop]
    - Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, N=1.7x10^{11} p/bunch, up to 288 bunches in one shot
- **Liquid** target: better wrt power removal (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

H4 Experiment

- First experimental verification of positron induced low emittance muon beam
- Test mu pair production at threshold with e+ beam on target
  - Beam test in H4 (North Area) with a low intensity 45 GeV ($\sqrt{s}$~0.215 GeV) e+ beam
- Goals:
  - Measure emittance of outcoming muon pairs
  - Measure production cross section as a function of $\sqrt{s}$ and other properties of the production process

EXPERIMENTAL SETUP

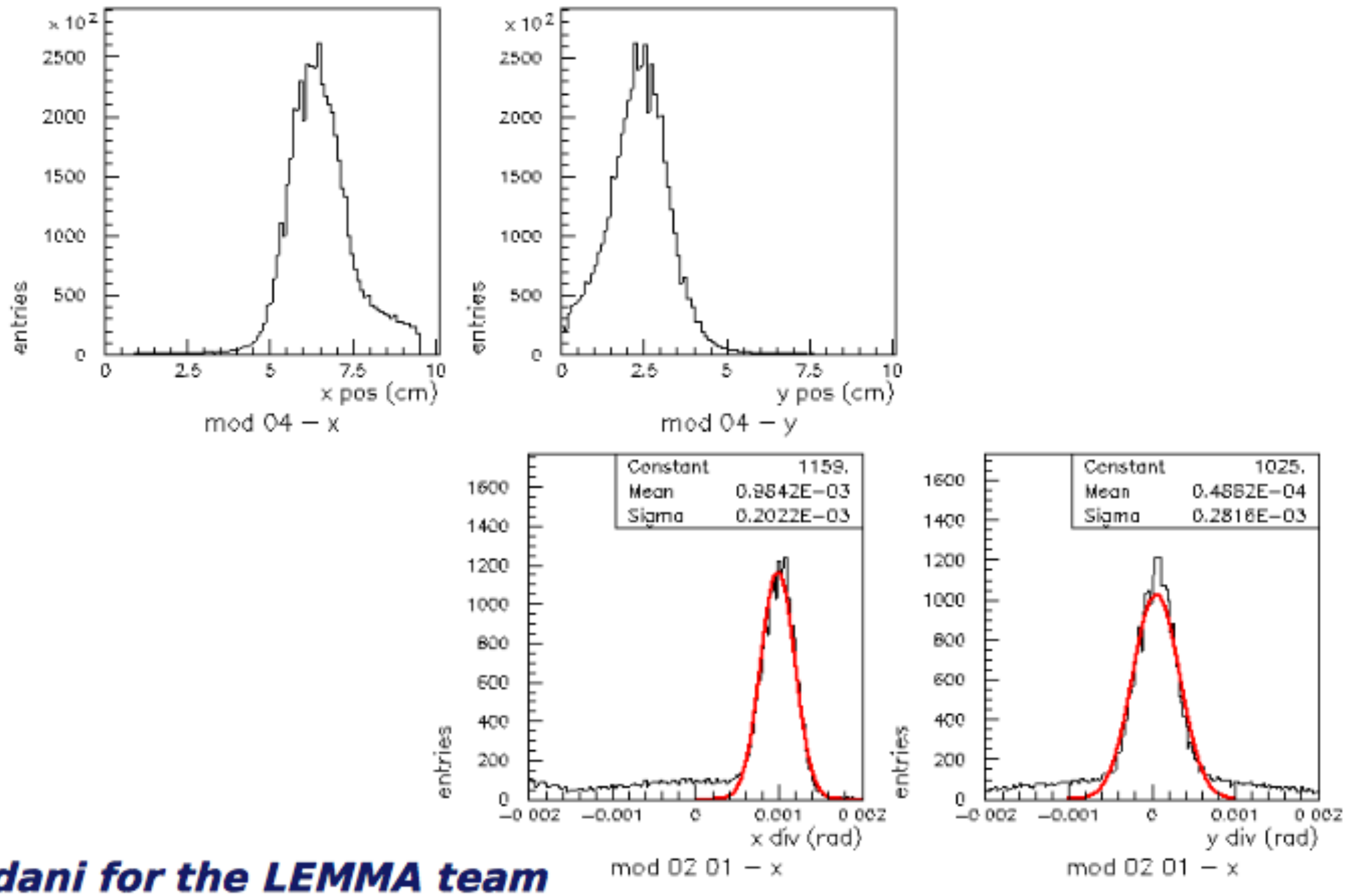


Mattia Soldani for the LEMMA team
CERN PS/SPS User Meeting, August 3rd 2017

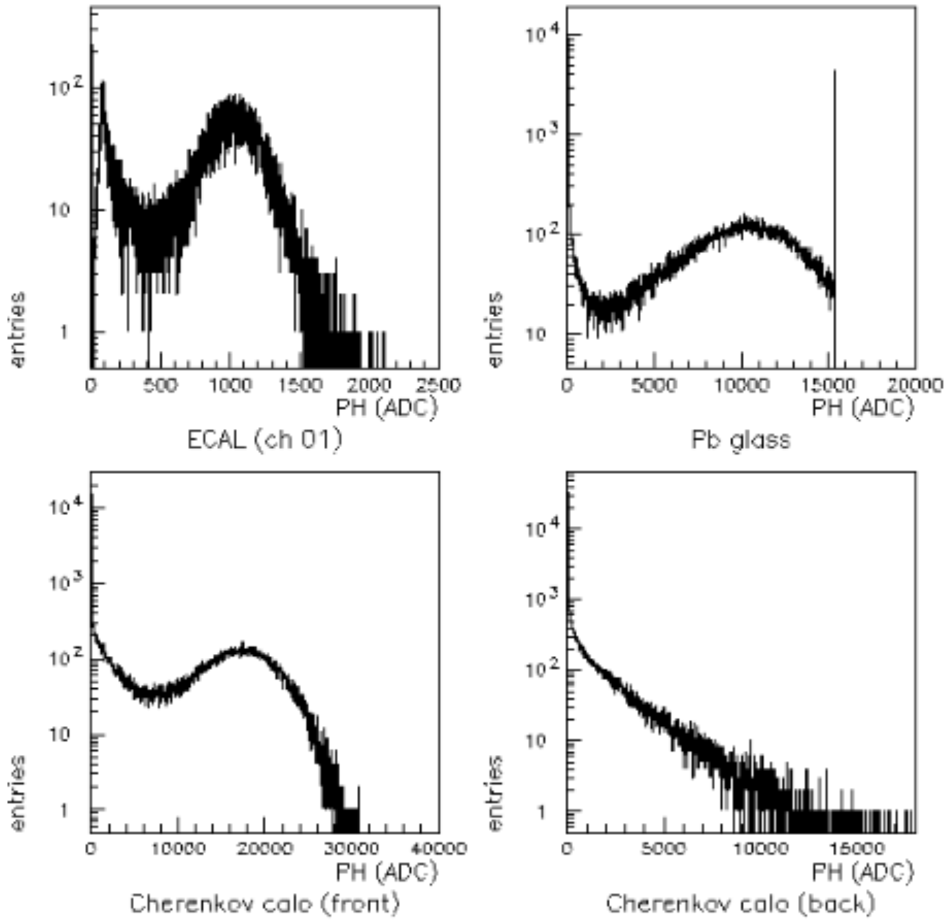
EXPERIMENTAL SETUP

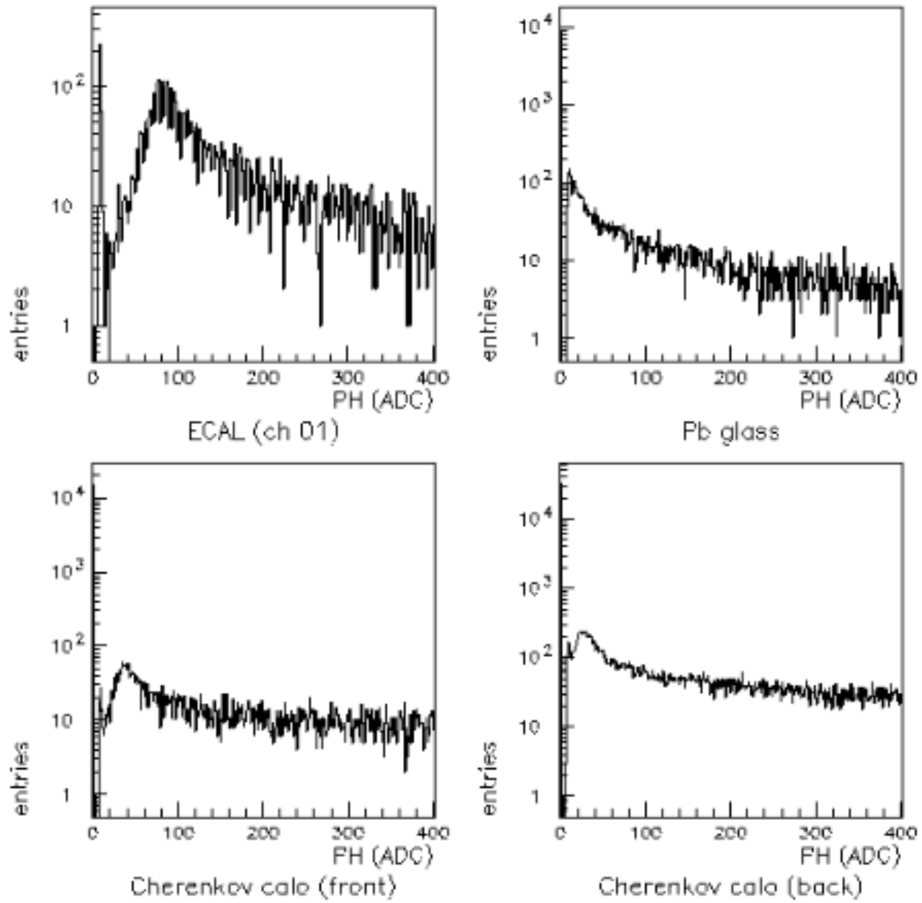
INCIDENT BEAM IN THE SILICON DETECTORS

- Tracking systems installation on July 26th (Wed)
- Completion of the setup with calorimeters on July 28th (Fri)
- Very high intensity e^+ beam (~ 4-5x10^6 spill^{-1} - great job by Nikos!) from July 29th (Sat)

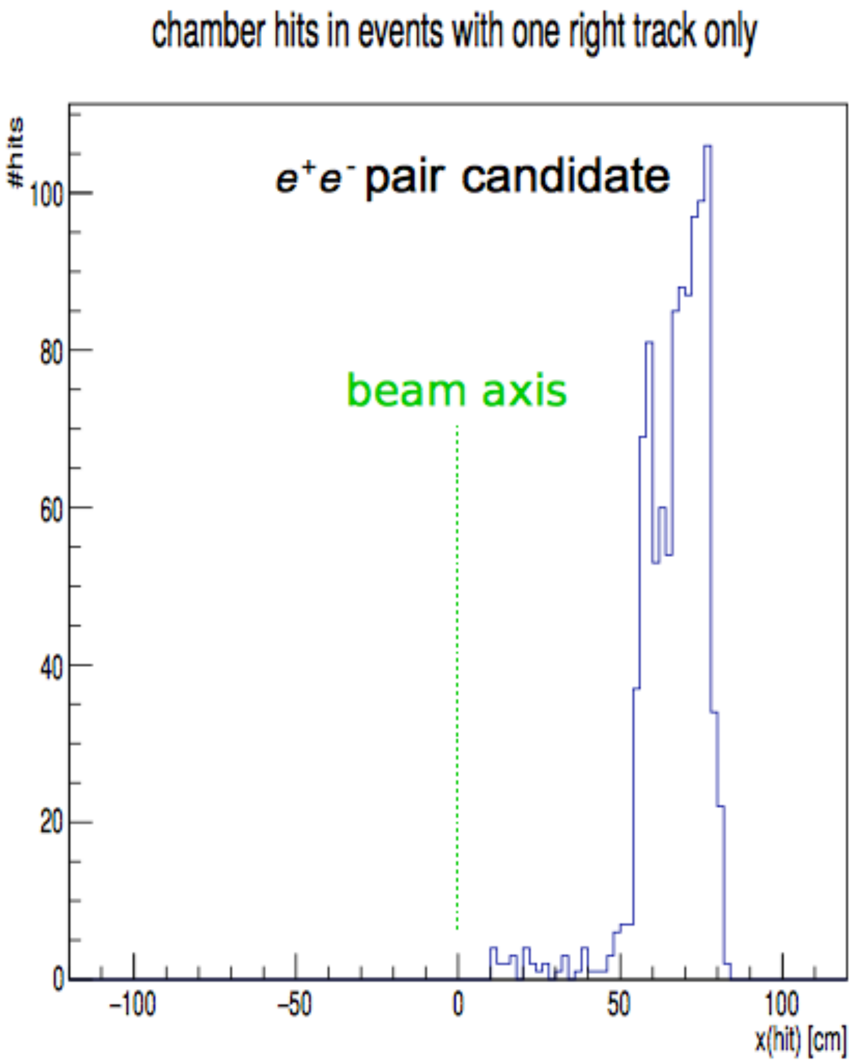


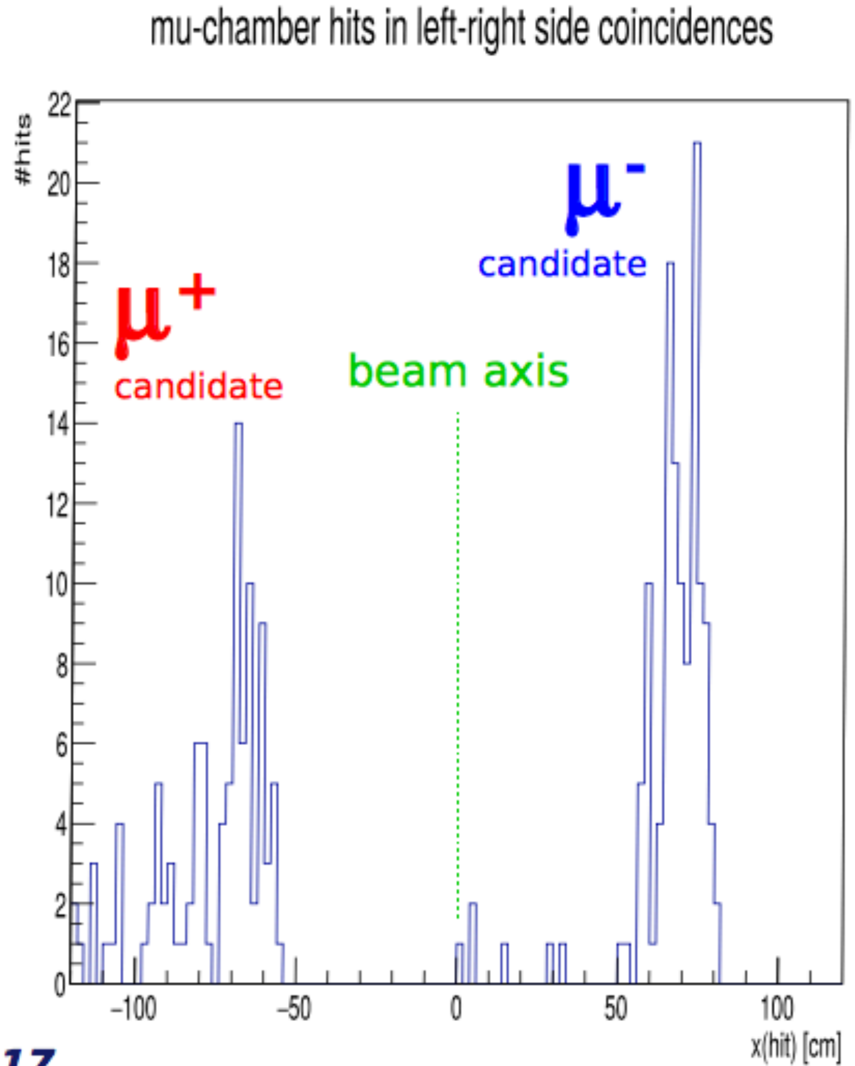
PULSE HEIGHT IN THE CALORIMETERS





CANDIDATE EVENTS IN THE μ-CHAMBER...





Mattia Soldani for the LEMMA team
CERN PS/SPS User Meeting, August 3rd 2017

2018 activities

- **Experiments in H4**: 1 week assigned out of 2 requested for 2017
  - **High intensity** (up to 5 x 10^6 /spill) with amorphous targets
  - measure muon production rate and muons kinematic properties
  - **Low intensity**
  - measure beam degradation (emittance energy spectrum)
  - measure produced photons flux and spectrum
- Priority to High intensity
- **Request 1-(2) weeks in 2018** for:
  - Complete original program of the 2017 experiment
  - Attempt muon production on crystals (see this year results)
- **Exploring the possibility to perform tests at Fermilab**

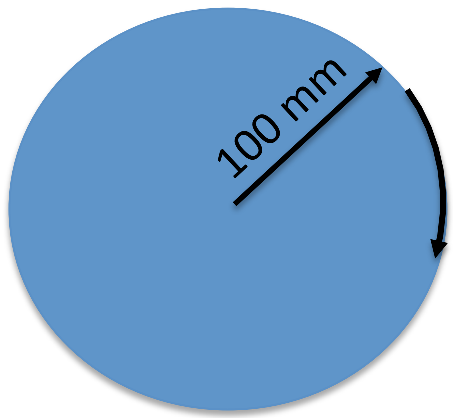
Target design

- Started informal collaboration with CERN STI group
- 2 meetings to discuss technical and political items

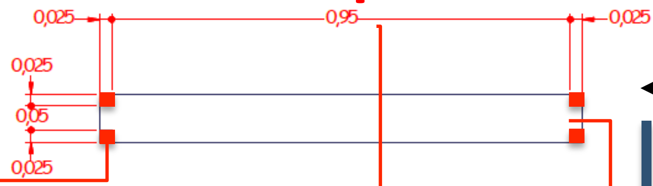
Solid Moving target

- Rotating disc
  - 24000 rpm
- Bunch spacing of ΔT=200ns
  - Bunch separation on target L = 50 μm
  - 12500 bunches in 1 turn

ω = 24000 rpm



Power dissipation



- beam spot of σ=20 μm
- radiation in vacuum to cool down

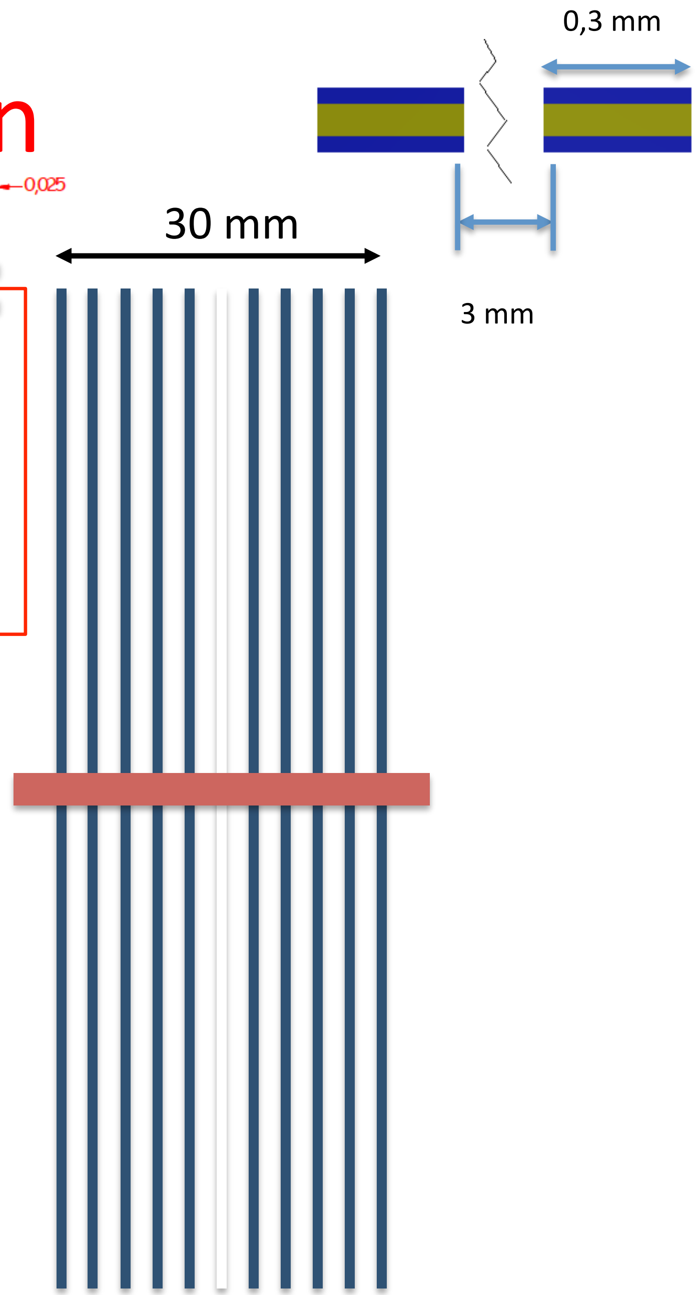
Distribute bunches in 10 rotating disks

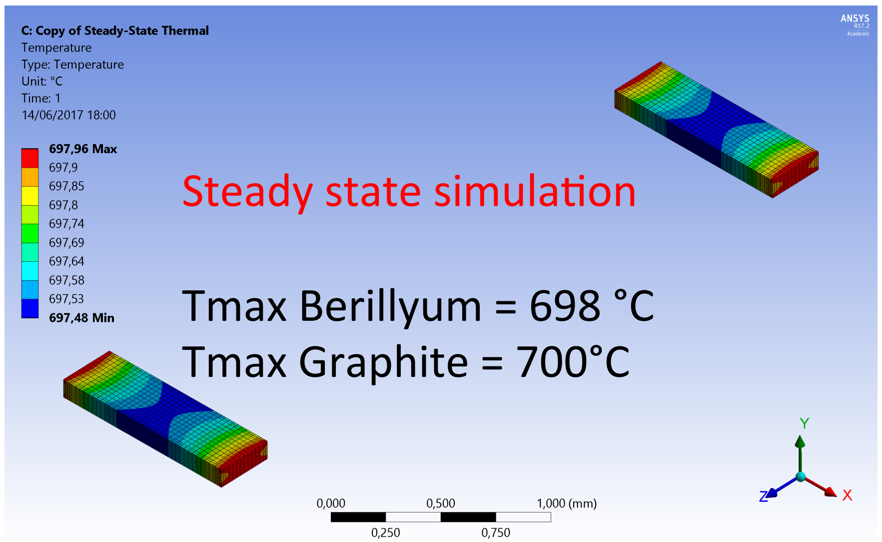
400k beam spots:

1 mm (beam bump) in

50 μm space (disk rotation) in rϕ

100 kW distributed in 400k spots and 10 disks



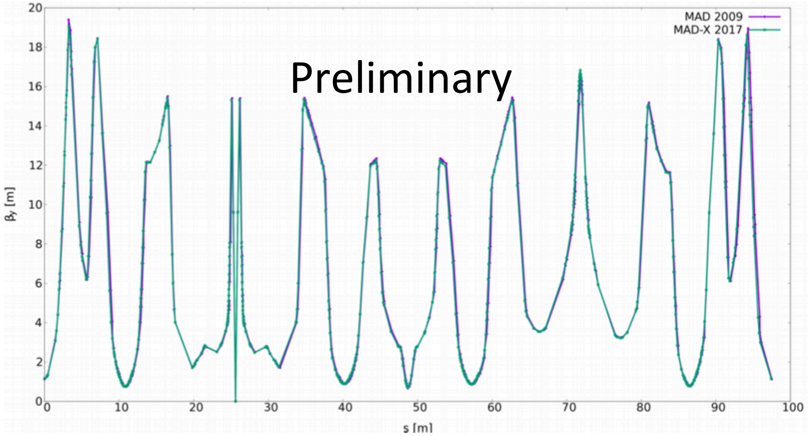


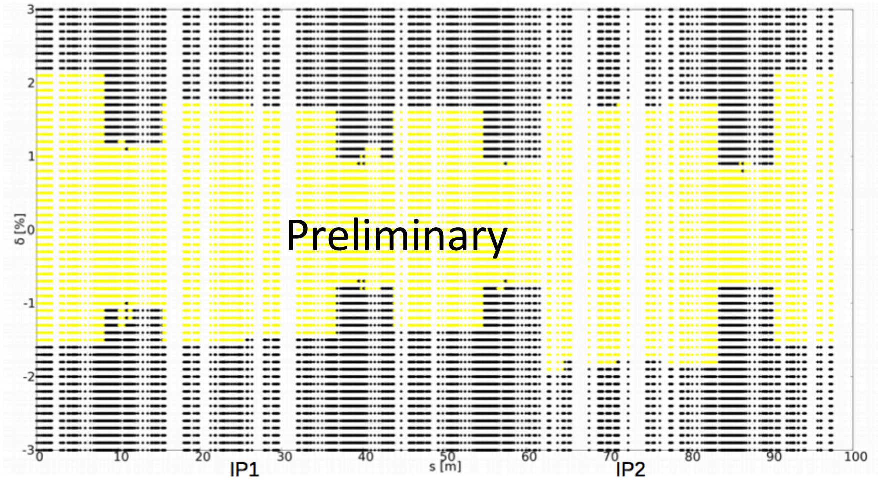
2018 activities

- **Target termo-mechanical stresses**:
  - Design and construction of target prototipe
- **Test at small spot size ~20 μm (T rise):**
  - 20 μm 10^{11} e+ /bunch 100 hz at FACET
  - Additional possibility at SLAC under investigation
  - Sps extracted beam Hi-RadMat
- **Power dissipation test**
  - Would need accumulator
  - Check with Dafne linac

Test at storage ring: DAFNE

- Measure beam properties evolution with turns
- Preliminary studies with "siddartha" optics:





- Small momentum aperture use thin target (Be ~10-100 μm)
- Possibility to inject at 2 hz

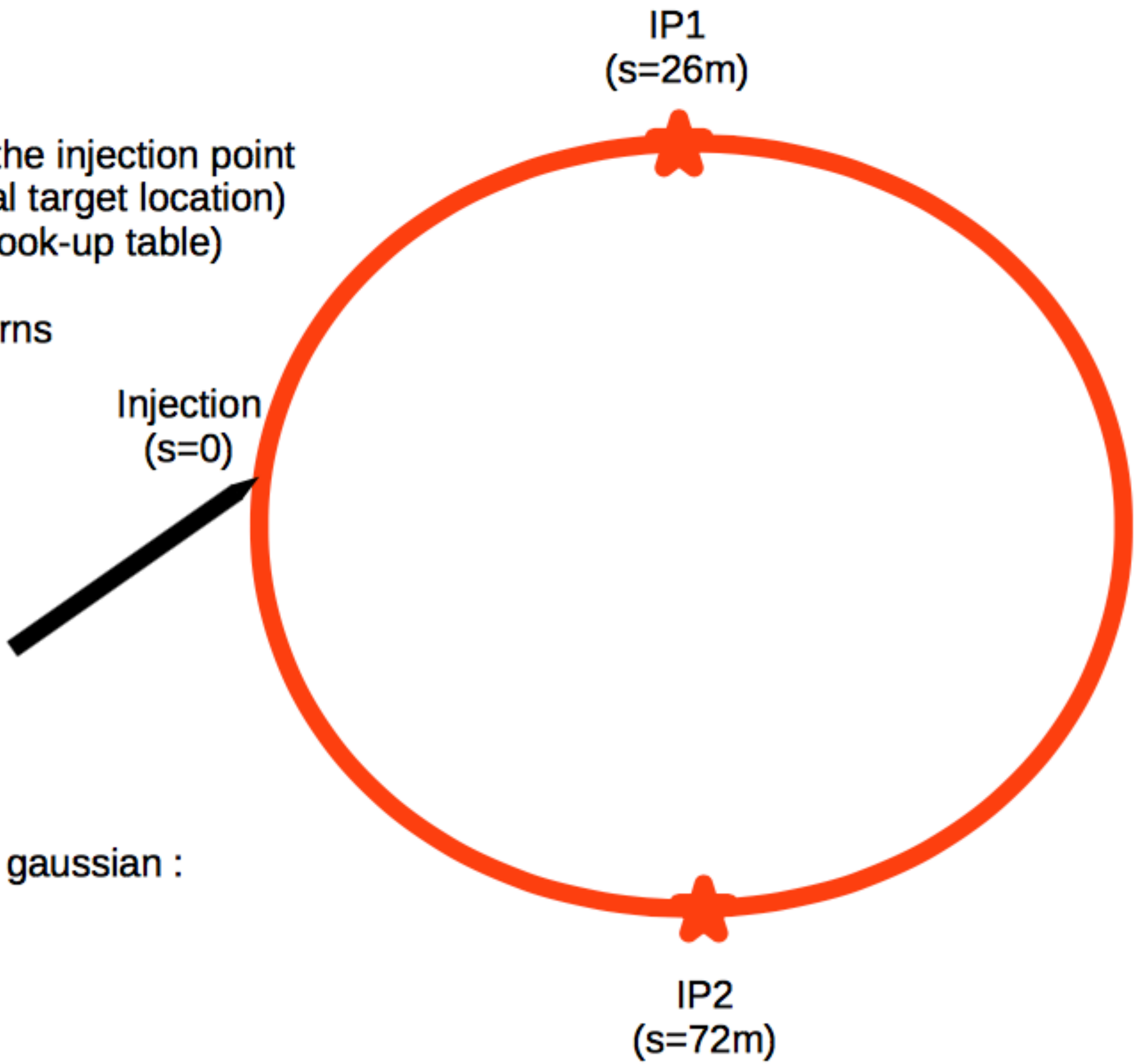
Test at storage ring: DAFNE

Tracking

1) We generate a beam at the injection point
2) We track to the IP1 (initial target location)
3) We simulate the target (look-up table)
4) We track back to the IP1
5) Repeat 3) and 4) for n turns

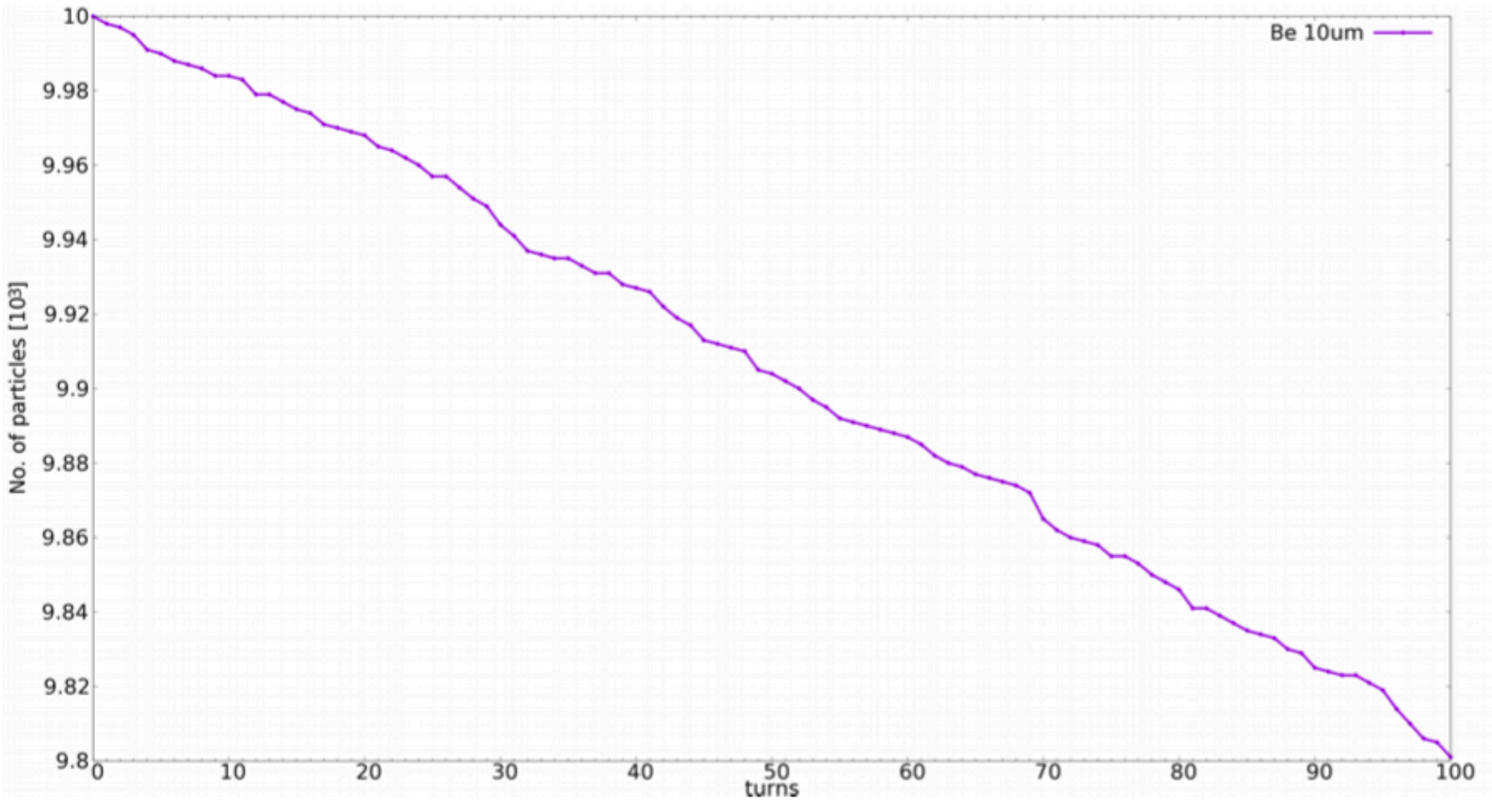
AT INJECTION :
betx 9.66173518
bety 1.159677223
dx -1.572838958

energy 0.51
ex 2.8e-07
ey 2.1e-09
et 1.6e-05
sigt 0.016
sige 0.001



At injection the beam is a gaussian :
$\sigma x = 1.6mm$
$\sigma y = 49um$
$\sigma s = 16mm$

First multi-turn simulation



Funding requests

- **Missioni:**
  - Test beam H4 **28.5 Keuro**
  - Contatti per disegno targhette **2 Keuro**
  - Riunioni e conf. **3 Keuro** x sezione
  - Test tenuta targhette **5 Keuro**
- **Consumo:**
  - Targhetta **10 Keuro**
  - Cristalli **4 Keuro**

	h4	targhette
fe	3	
lnf	9	5
pd	9	
pi	1	
rm1	5	
ts	1,5	
	28,5	5

Conclusion

- **Heavy activity on 2017:**
  - **Accelerator**
    - Accelerator complex idea
    - preliminary e+ ring design and multiturn tracking
    - First e+ source study
    - Target and mu accumulation investigations
  - **Experiments**
    - Muon production experiment performed
- **Many ideas for 2018**…
  - Continue acceleraror design
  - H4 test beam run-2
  - Attempt to test target termo-mechanical stresses
  - Study tests at DAFNE