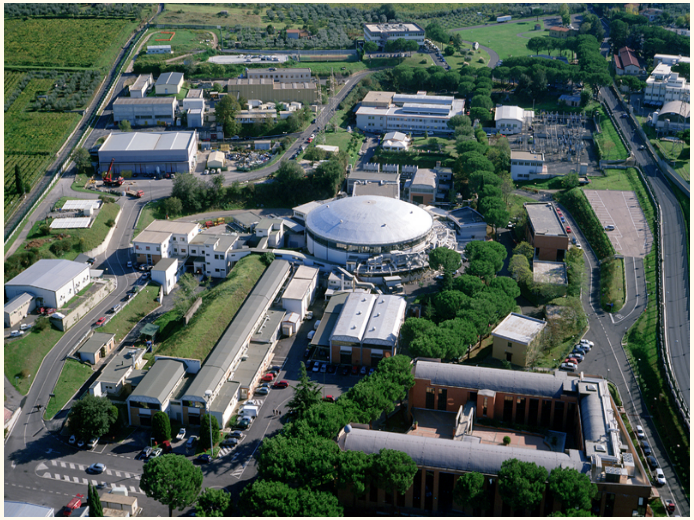
Proposal of an experimental test at DAFNE for LEMMA



M. Boscolo (LNF)

for the Lemma team

ICFA Mini-Workshop on DAFNE as Open Accelerator Test Facility in year 2020

LNF, 17 December 2018

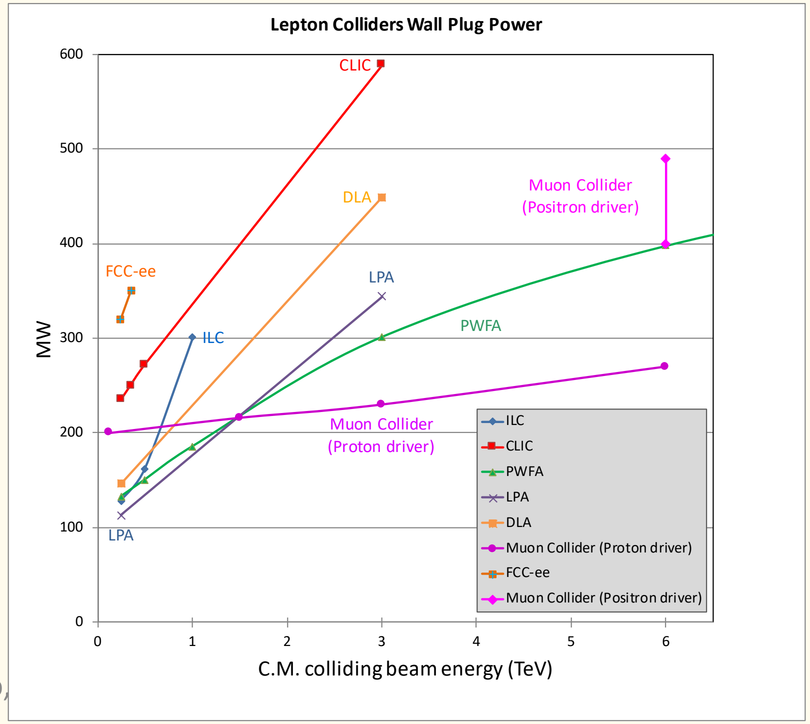
Outline

- **Introduction**
- **The Muon Collider LEMMA**
- **Lemma test beam at DAFNE**
- **Conclusion**

Introduction:
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
- **Great potentiality if the technology proves its feasibility**

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



M. Boscolo, J.P.Delahaye, M.A.Palmer, "The Future Prospects of Muon Colliders and Neutrino Factories," arXiv:1808.01858 and to appear in RAST vol 10, 2018.

Muon Source

Proton driven

Tertiary production from **protons on target:** p + target→ $\pi/K \rightarrow \mu$
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 → **cooling needed**
production Rate > $10^{13}\mu$/sec $N_\mu = 2\cdot10^{12}$/bunch

MAP

Positron driven

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^-)
e^+e^- annihilation: **e+ beam on target**
→ **cooled muon** beam with **low emittance** at production
Goal: production Rate ≈ 10^{11} μ/sec $N_\mu \approx 6\cdot10^9$/bunch

LEMMA

↓

Low **EM**ittance **M**uon **A**ccelerator

Muons are produced in positron annihilation on e^- at rest → e^+ beam impinging on target

It is a low emittance muon source

Low emittance concept:
- **overcomes muon cooling**
- **allows operation in the Multi-TeV range**

LEMMA concept was proposed at Snowmass 2013 by M. Antonelli and P. Raimondi: "*Ideas for muon production from positron beam interaction on a plasma target*", INFN-13-22/LNF Note, M. Antonelli and P. Raimondi, Snowmass Report (2013)

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

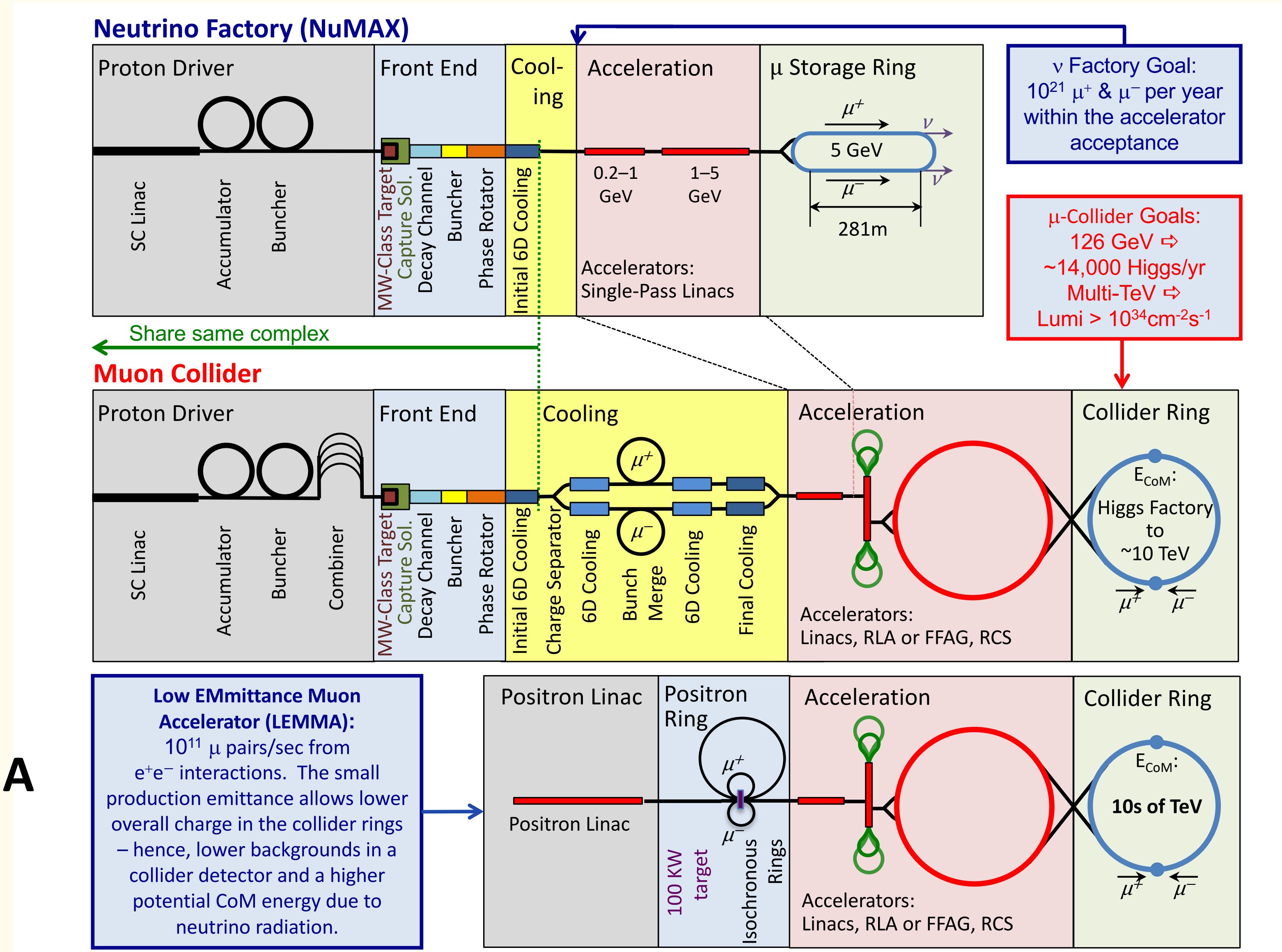
Disadvantages:

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

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

MAP

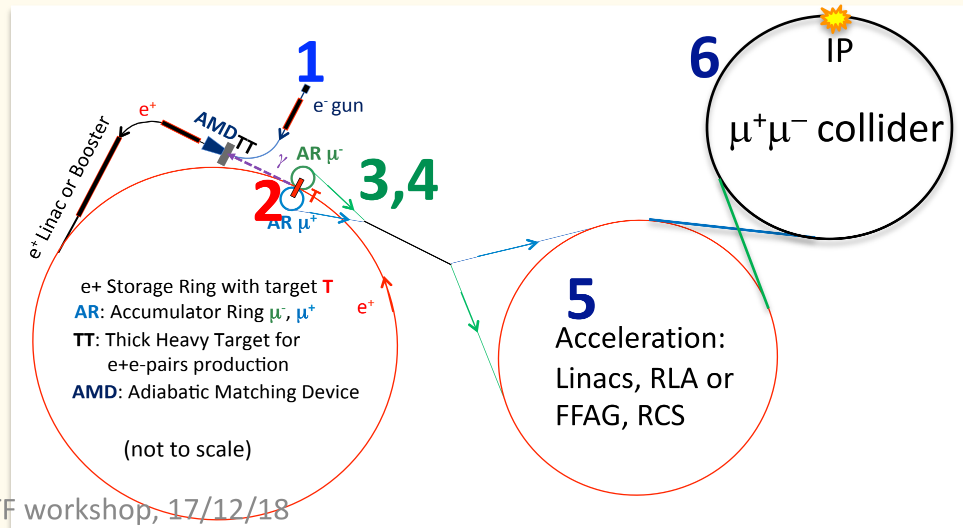
LEMMA



in: "The Future Prospects of Muon Colliders and Neutrino Factories," M. Boscolo, J.P.Delahaye, M.A.Palmer, to appear in RAST vol 10, 2018.

LEMMA Key steps and challenges

1. **e^+ source / e^+ beam** → goal: maximize rate at muon target
2. **$\mu^{+/-}$ production target** → goal: reach limit for PEDD and thermo-mechanical stress (to produce the best possible muon beam emittance and intensity)
3. **Muon Accumulator Rings** → goal: preserve muon emittance and maximize bunch intensity
4. **Muon Recombination scheme and injection scheme** → enhancement factor needed to maximize lumi
5. **Fast acceleration**
6. **Muon Collider**



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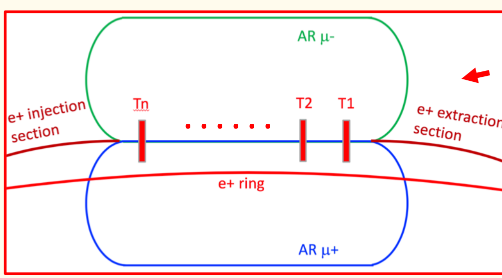
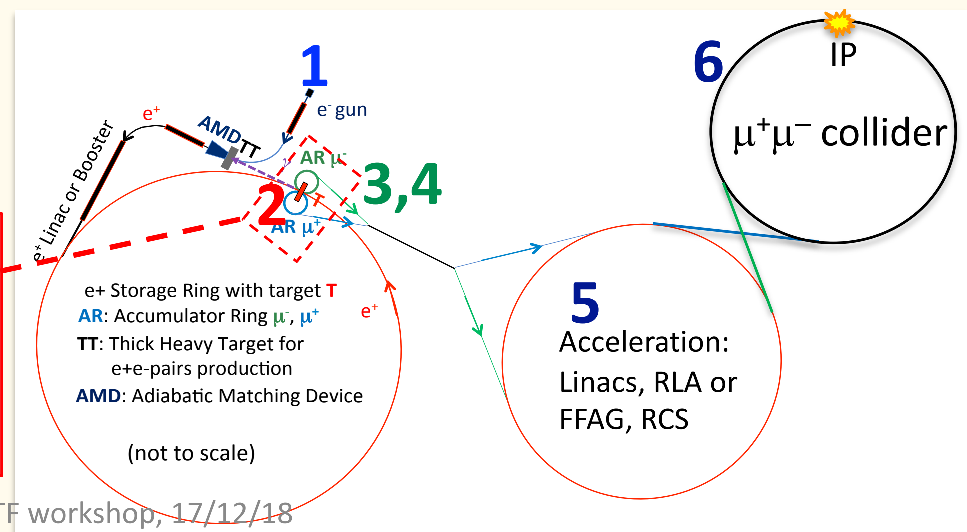
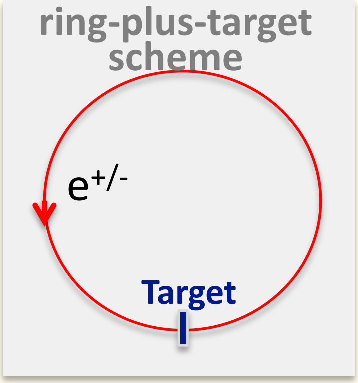
To **increase the bunch population** and to **reduce target thermomechanical stress** a positron ring followed by a **multi-target system** is being considered.





Two key aspects of the LEMMA concept can be studied with the test at DAFNE

- ✓ **Emittance evolution due to target interaction**
  - multi-passage through single target
  - multi-target passage

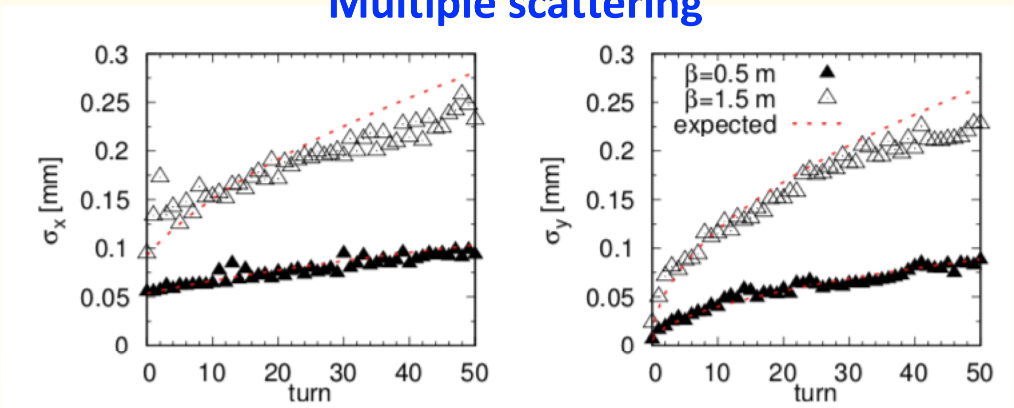


- ✓ **Target thermo-mechanical stress**
  - Simulation studies are on-going for the LEMMA case
  - Dedicated studies also for the DAFNE case

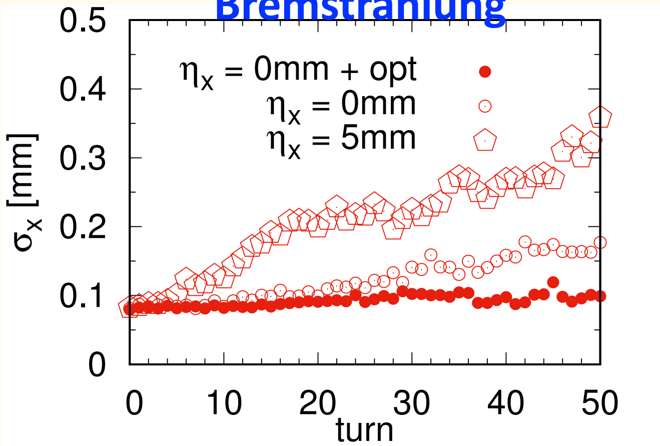
Beam dynamics e^+ beam in ring-with-target

e^+ emittance growth controlled with proper β and D values @ target

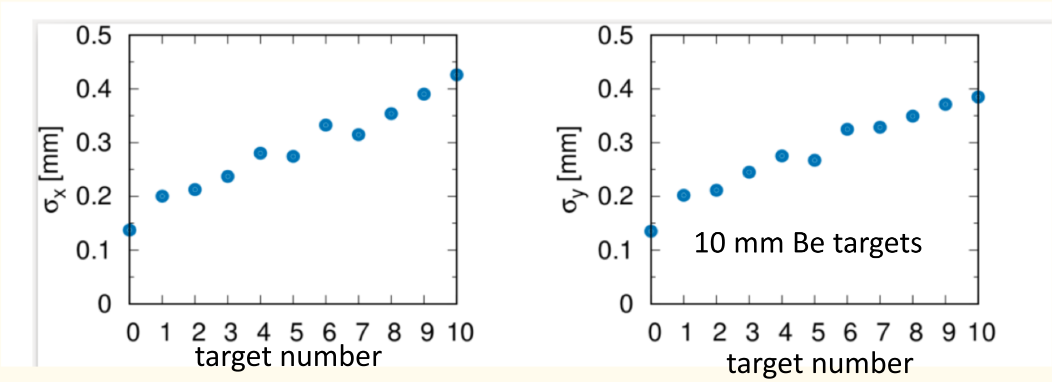
Multiple scattering



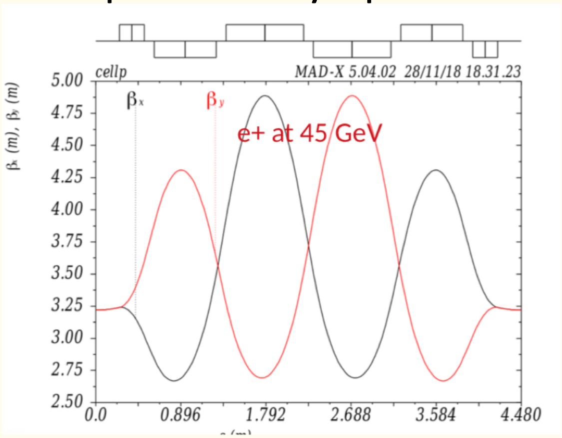
Bremstrahlung



analogous problem with multi-target system



preliminary optics



Muon production target: constraint (solid)

Constraints

- Very high Peak Energy Density Deposition (PEDD) with high local temperature rise (limit on beam spot ~10μm for solid target from single bunch simulations)
- High deposited power (~100kW, to be distributed on a large surface)

Knobs

- To contrast high PEDD and distribute deposited power:
  - Fast rotating wheel (20000 rpm) (for free with liquid jet)
  - multiple targets and reduced angular velocity
  - e^+ beam bump every 1 bunch muon accumulation

Next steps

R&D experimental tests & engineering simulations required to find the optimal target material considering the mechanical stress and heat load resistance

Muon production target

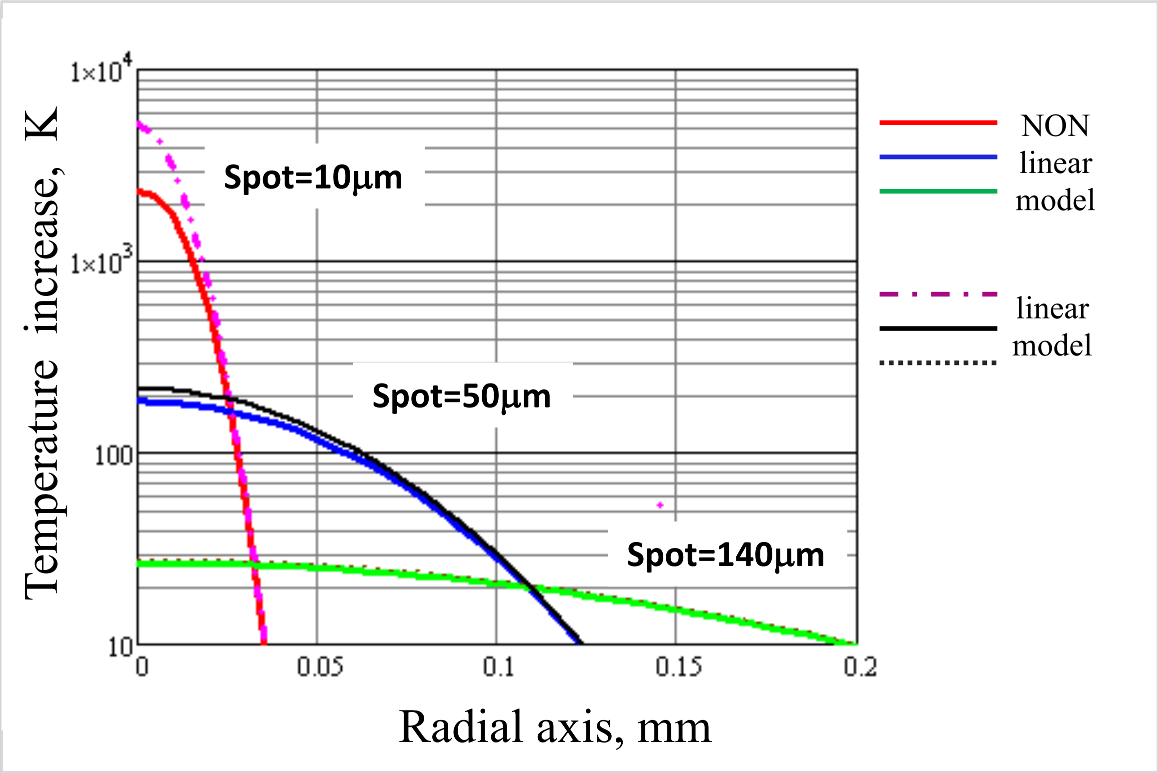
We are considering:

- Beryllium
- Carbon composites
- Liquid Lithium
- Hydrogen pellet

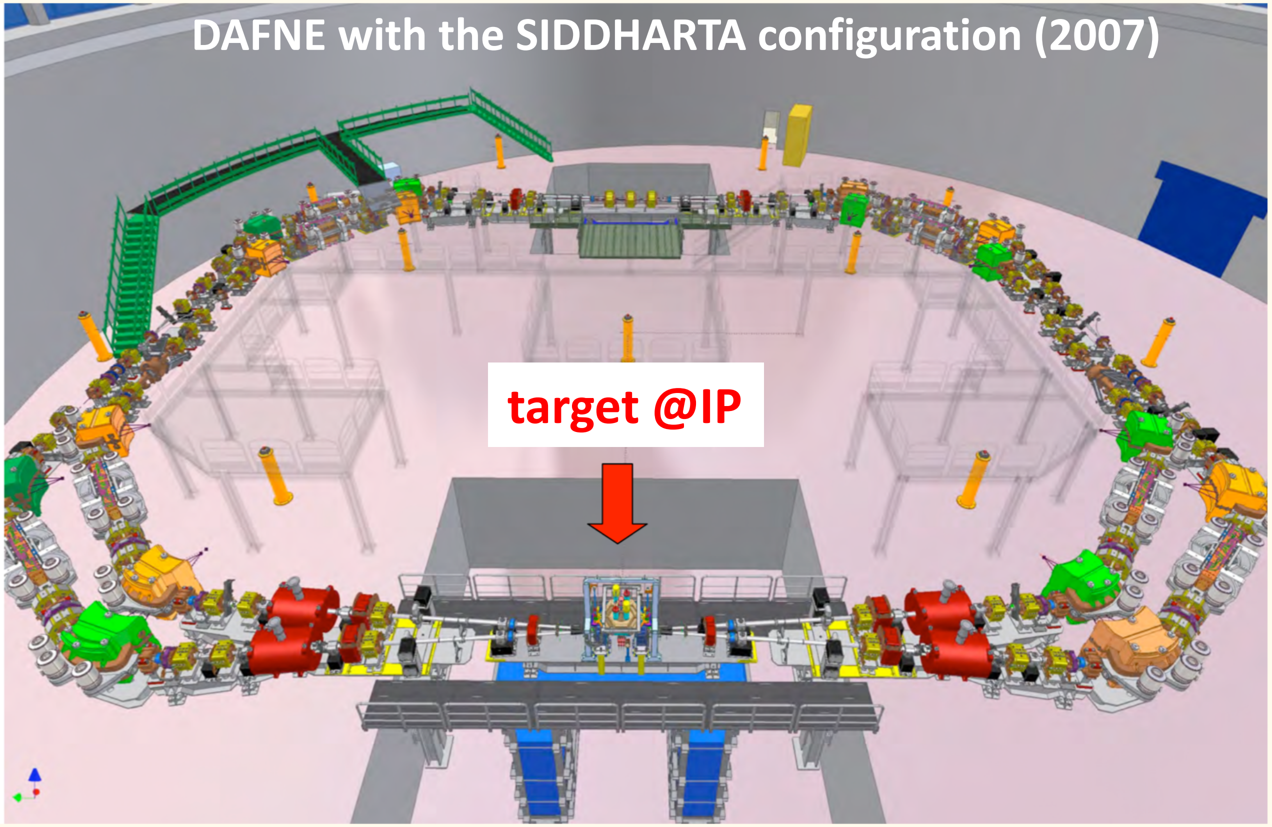
need material characterization to tune Finite Element Analysis simulations

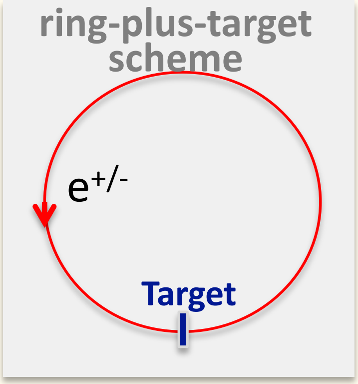
beam experimental tests are best probe for target design

Engineering simulations and **experimental tests** are required to find the optimal target material, considering **mechanical stress** and **heat load resistance** properties.



LEMMA Test beam at DAΦNE





Add a single target in a low-β and dispersion-free location (Interaction Point)

Goals of the test: two-fold Experiment

1. **Validation LEMMA beam dynamics studies**

2. **Test thermo-mechanical stress of different targets**

Goals of the test: two-fold Experiment

1. **Validation LEMMA beam dynamics studies**

   benchmark beam dynamics simulations of the multi-passage through target measuring

   - ✓ transverse beam size
   - ✓ beam current
   - ✓ beam lifetime

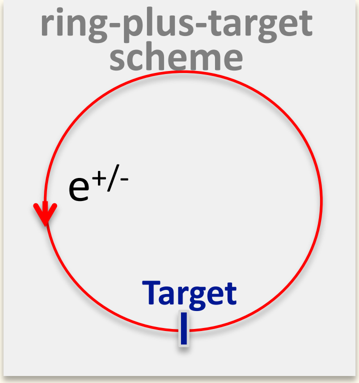
2. **Test thermo-mechanical stress of different targets** (various materials and thickness) after multi-passage of beam measuring

   - ✓ temperature
   - ✓ surface deformation

Light targets (Be, C) with thickness in the range ≈ 100 μm

Liquid Lithium and H_2 targets can be foreseen too in a second phase

DAFNE configuration for the test



- **Add a single target in a low-β and dispersion-free location**
  - *i.e.* Interaction Point

  Possible different locations for the target can be studied

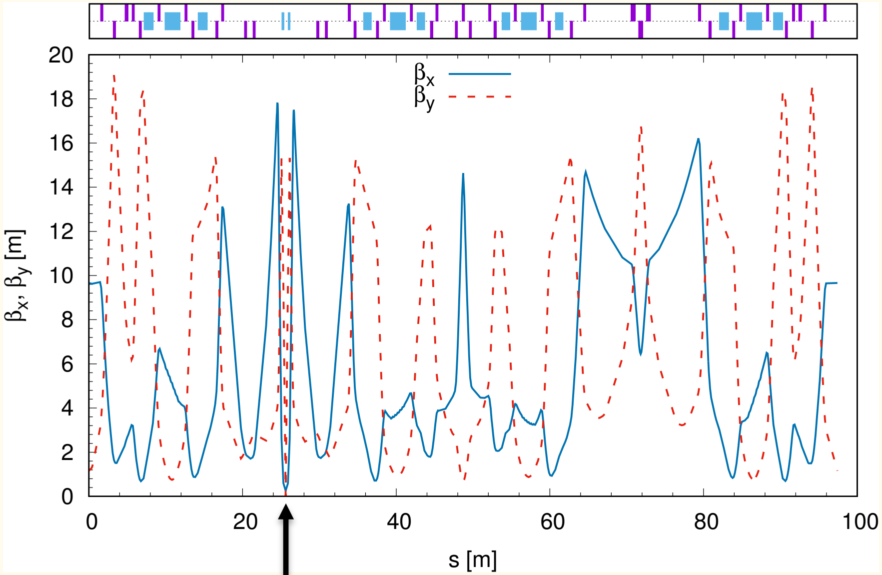
- **Single beam, single bunch** (positrons or electrons)
- The use of positrons would allow to measure annihilation products ($\gamma\gamma$, e^+e^-,..)

- First studies with the SIDDHARTA optics and target placed at the IP performed

Ref. **M. Boscolo, M. Antonelli, O. Blanco, S. Guiducci, A. Stella, F. Collamati, S. Liuzzo, P.Raimondi, R. Li Voti** ***"Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target"*****,**
2018 J. Phys.: Conf. Ser. 1067 022013 (IPAC18)

Siddharta Optics

SIDDHARTA 2008 optics



IP, target

β_x^*=26 cm; β_y^*=0.9 cm

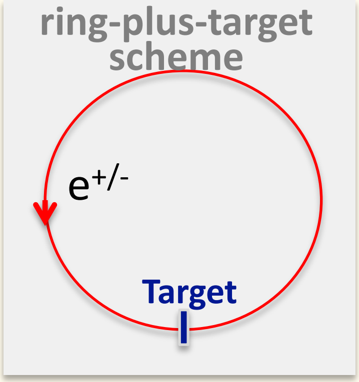
σ_x^*=0.27mm; σ_y^*=4.4μm

ε_x = 0.28 μm

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

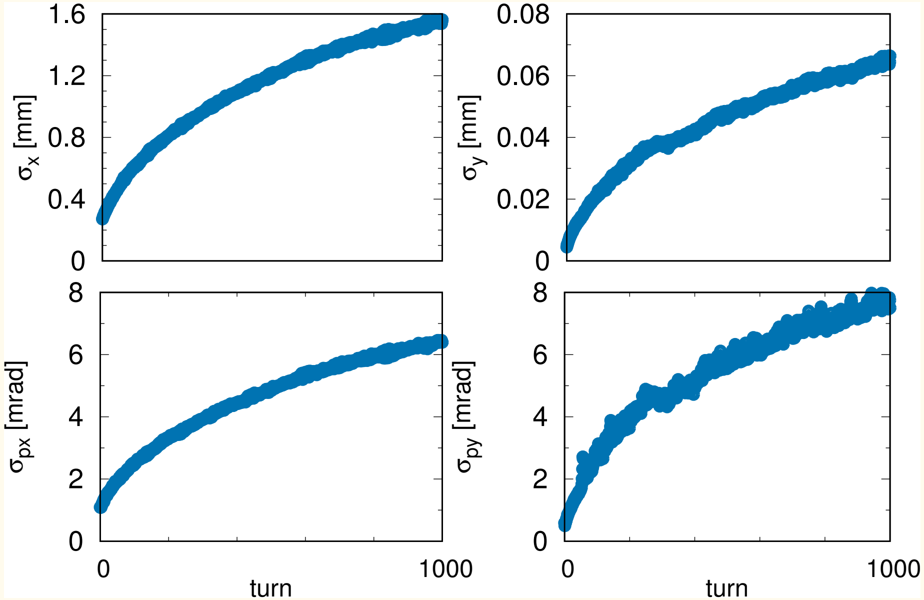
Parameter	Units	
Energy	GeV	0.51
Circumference	m	97.422
Coupling(full current)	%	1
Emittance x	m	0.28×10^{-6}
Emittance y	m	0.21×10^{-8}
Bunch length	mm	15
Beam current	mA	5
Number of bunches	#	1
RF frequency	MHz	368.366
RF voltage	kV	150
N. particles/bunch	#	1×10^{10}
Horizontal Transverse damping time	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

We checked with particle tracking simulations what happens placing a thin Be target at the Siddharta IP without any optics change



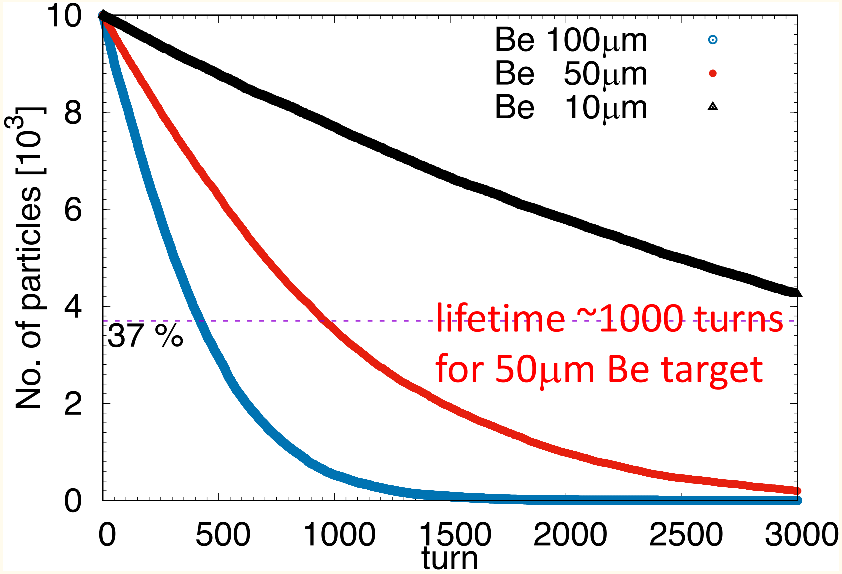
Particle tracking simulations to benchmark with measurements

beam spot evolution



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

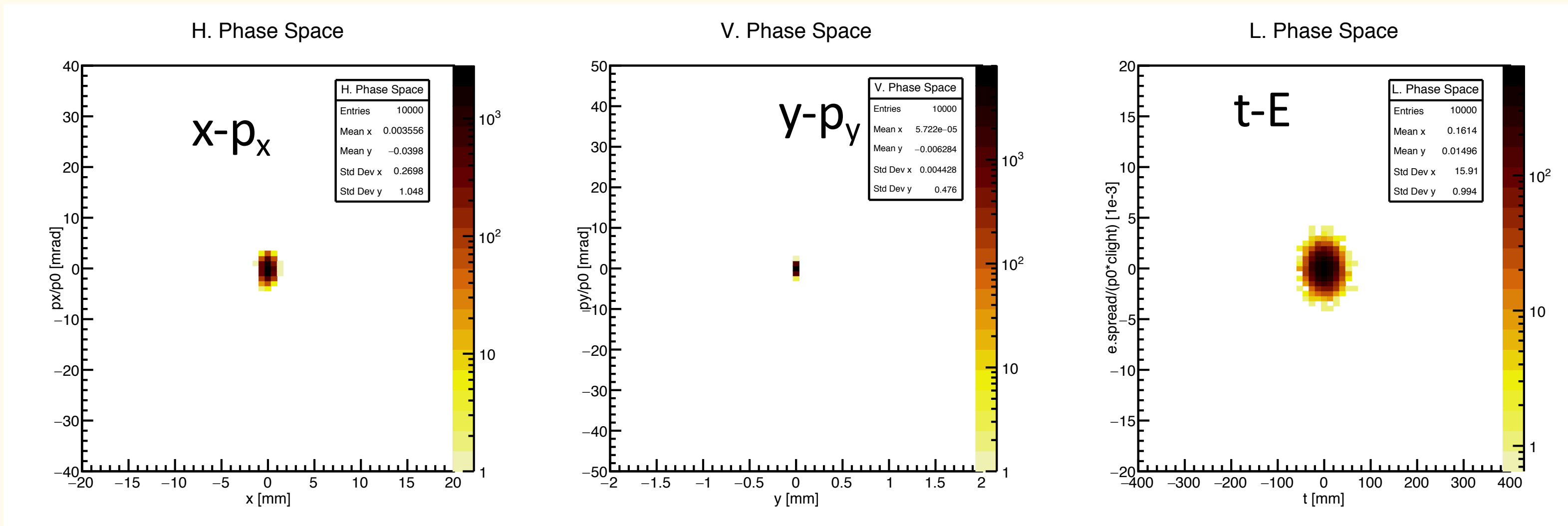
beam lifetime



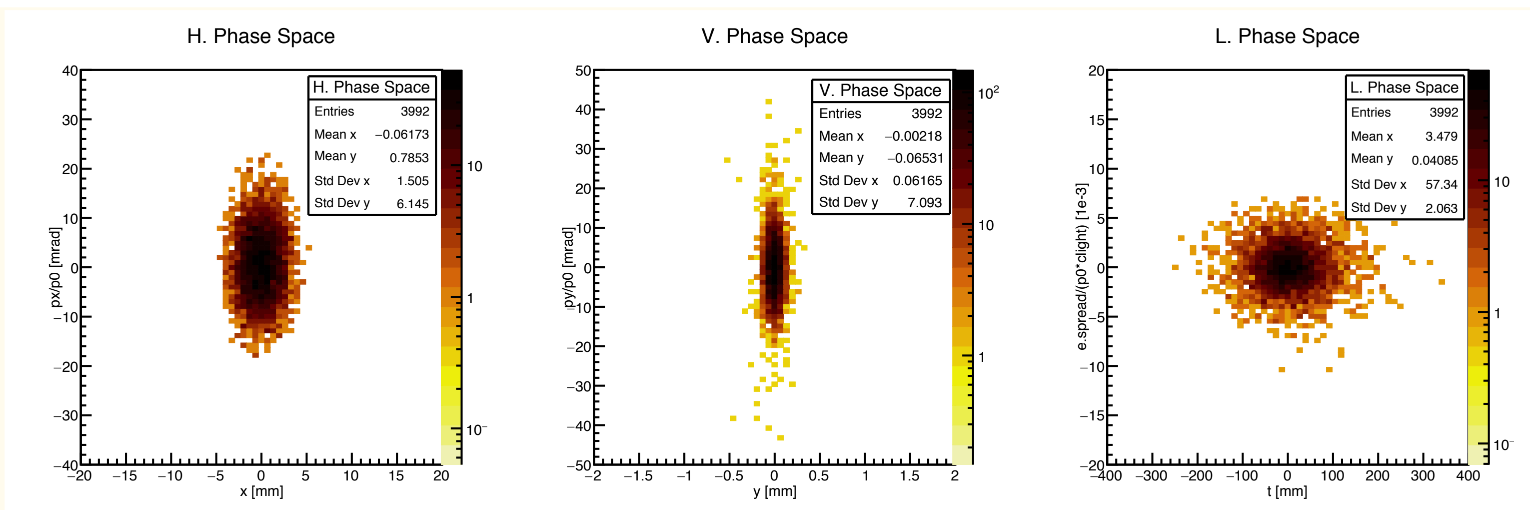
Beam will not be stored (RF off)
Injection in single bunch mode
turn-by-turn charge measurement

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

before target, starting point



after 900 turns

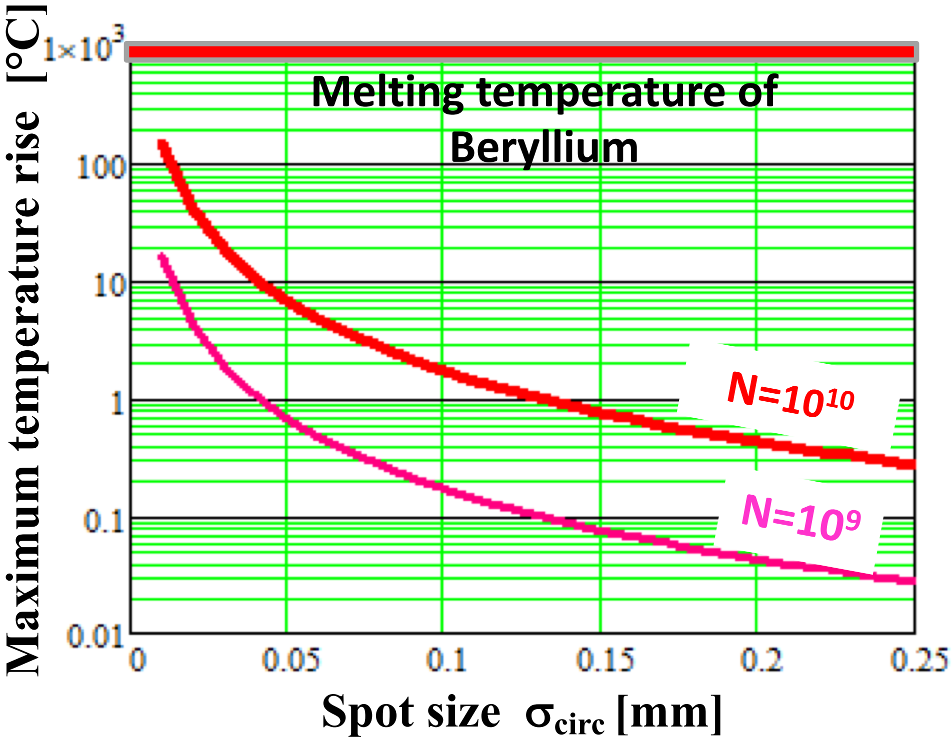


MAD-X PTC & GEANT4 6-D tracking simulation

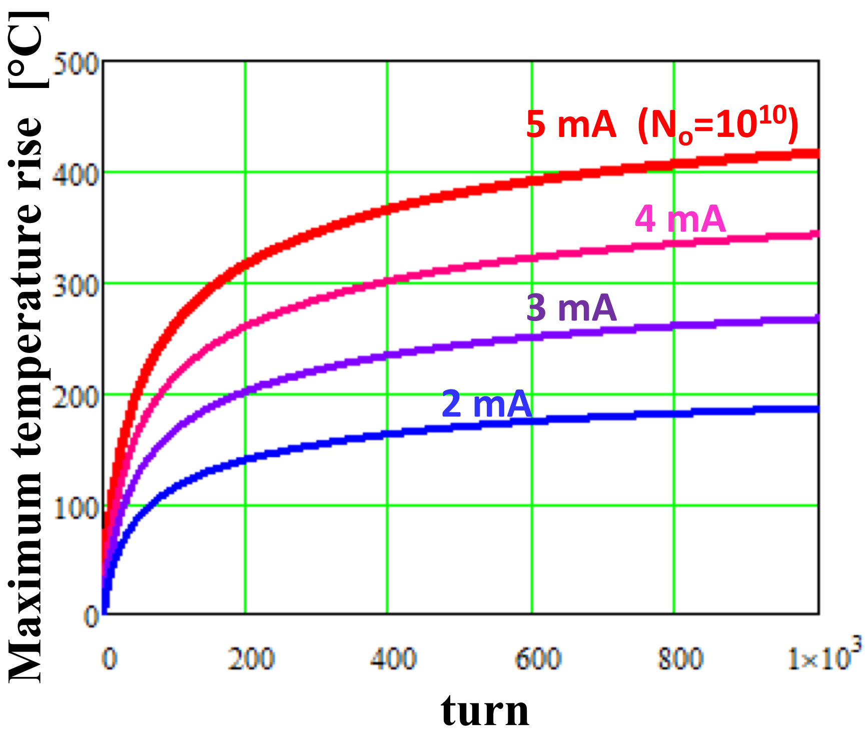
Target thermal behavior

Characterize **target thermo-mechanical properties close to the limit** by **varying bunch spot size** and **bunch intensity** able to reproduce the expected LEMMA thermo-mechanical stress

Temperature rise after 1 single turn



Analysis within 1000 turns



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.

Target diagnostics

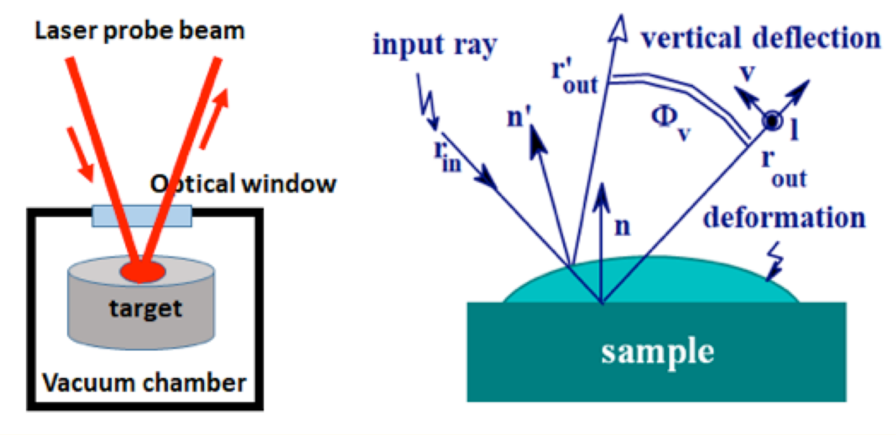
Target surface temperature measurement:

- HIGH-SPEED HD MWIR INSB CAMERA
  - e.g. FLIR X8500sc

Target surface deformation measurement:

A contactless measurement of the surface deformation can be performed with **laser technique**.

The probe laser beam enters the vacuum chamber and is reflected back by the target surface. When the target surface is subjected to a thermoelastic deformation the probe beam changes its direction of reflection. This change is measured by a position sensor. This technique is very sensitive and can detect very weak deformation of the order of some pm



Activity needed for the experiment:

- ✓ **Optics design**
- ✓ **Beam dynamics studies**

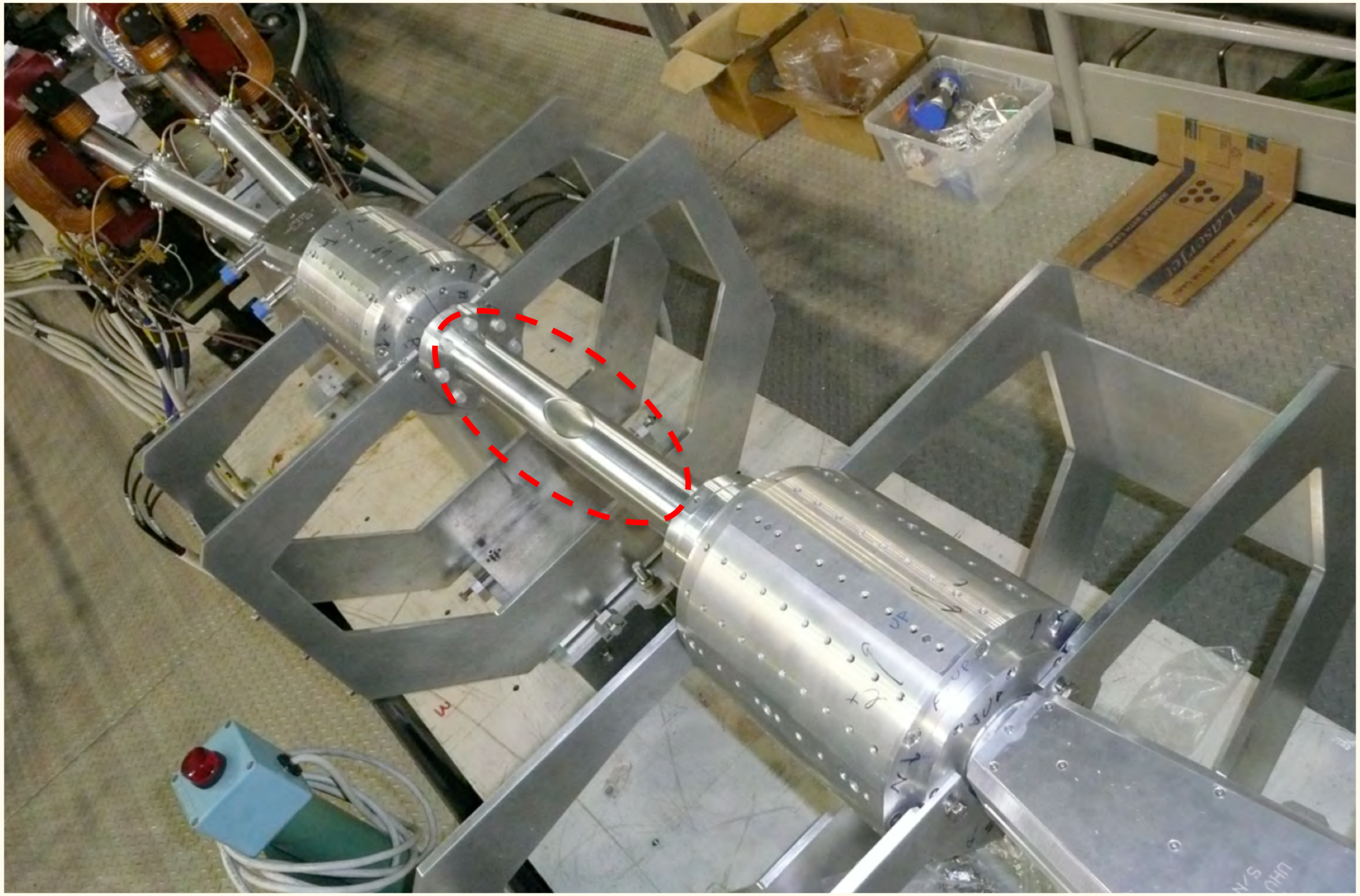
- ✓ On-axis injection scheme

- ✓ **Target thermo-mechanical stress:** simulations & test

- ✓ **Vacuum chamber** for the target Insertion Region
- ✓ **Target insertion section**

- ✓ **Target diagnostics**
- ✓ **Beam diagnostics**

SIDDHARTA IR (2007)



Conclusion

This test at DAFNE would be a key aspect of the LEMMA project:

- for the beam dynamics behaviour studies
- for the target design
- for operation with the ring and target system

Mandatory test for a realistic LEMMA design

LEMMA is a novel concept -conceaved at LNF- for muon production that renewed the interest and extended the reach of Multi-TeV Muon Colliders

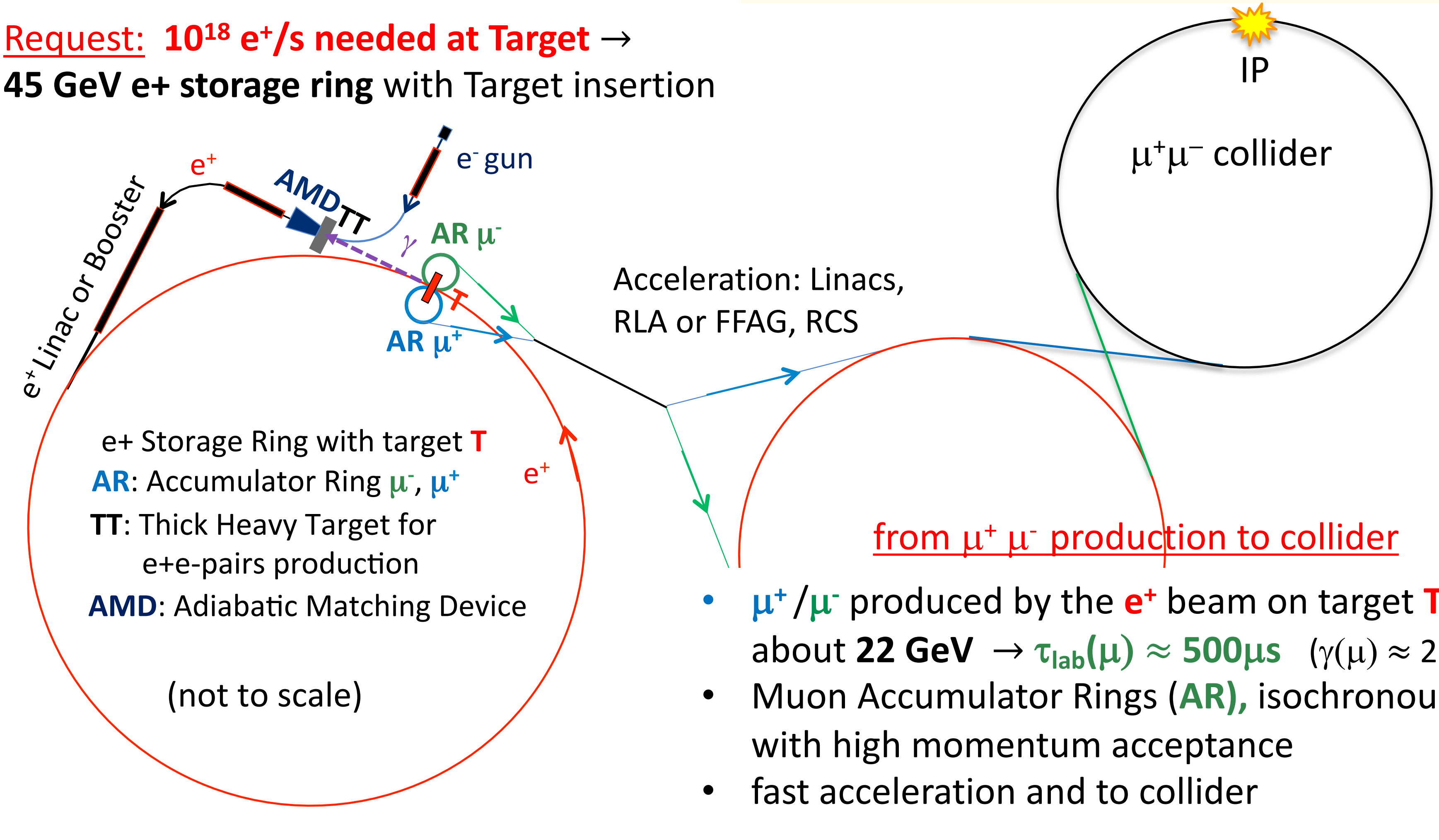
LEMMA scheme

Goal: ≈ **10^{11} μ/s** produced at Target

with target efficiency ≈ 10^{-7} (Be 3mm)

Request: **10^{18} e^+/s needed at Target** →

45 GeV e+ storage ring with Target insertion



from μ+ μ- production to collider

- μ^+/μ^- produced by the e^+ beam on target **T** at about **22 GeV** → $\tau_{lab}(\mu) \approx$ **500μs** ($\gamma(\mu) \approx 200$)
- Muon Accumulator Rings (**AR**), isochronous with high momentum acceptance
- fast acceleration and to collider

M. Palmer

Proton driven source

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}]

Fermilab

Optics design positron ring

More details in:
Arxiv. 1803.06696

optics cell

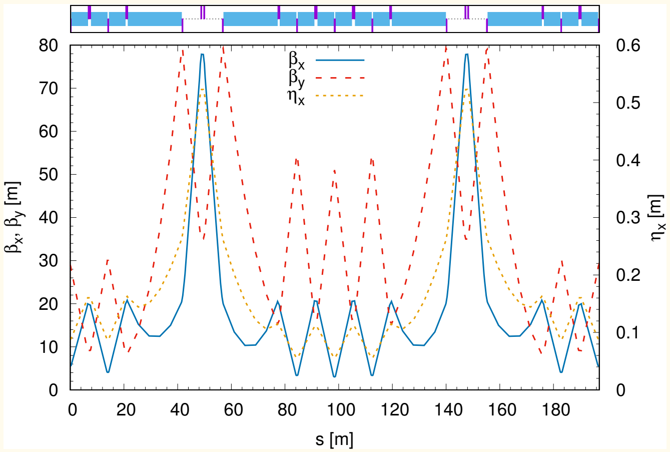
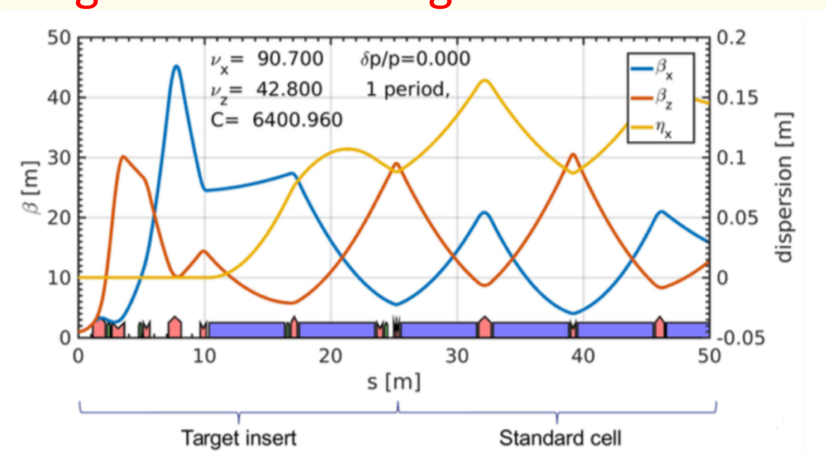


Table e+ ring parameters

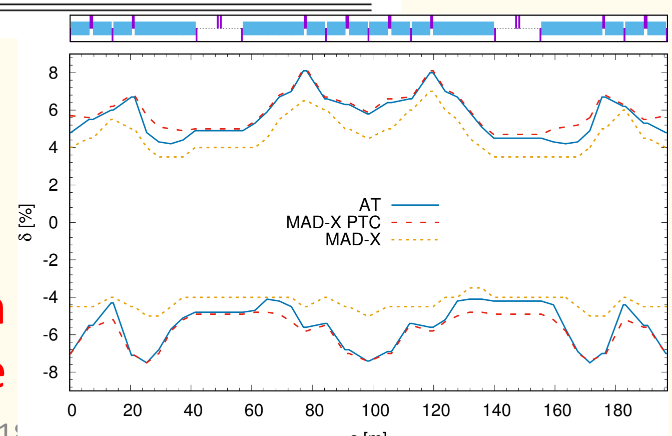
Parameter	Units	
Energy	GeV	45
Circumference	m	6300
Coupling(full current)	%	1
Emittance x	m	5.73×10^{-9}
Emittance y	m	5.73×10^{-11}
Bunch length	mm	3
Beam current	mA	240
RF frequency	MHz	500
RF voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
N. particles/bunch	#	3.15×10^{11}
Synchrotron 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	%	± 7.2
Energy spread	dE/E	1×10^{-3}
SR power	MW	120

Target Insertion Region



@target { $D_x \approx 0$
low-β ($\beta_{x,y}$=0.5 m)

momentum acceptance

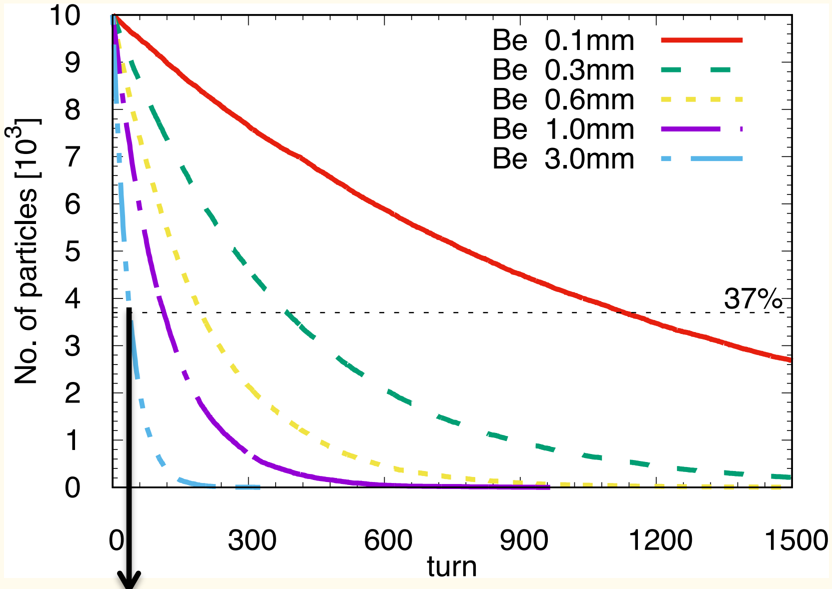


Beam dynamics e^+ beam in ring-with-target

More details in:
Arxiv. 1803.06696

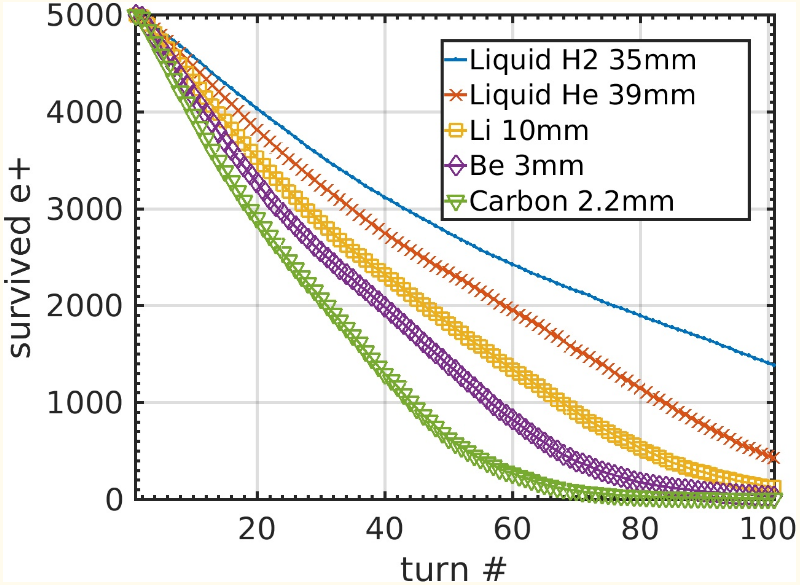
Particle tracking with: MADX/ PTC/GEANT4/FLUKA & Accelerator Toolbox/G4-Beamline

Lifetime ∝ 1/thickness as expected



Lifetime ~ 40 turns for Be 3 mm

Lifetime determined by bremsstrahlung and momentum acceptance
2-3% e+ losses in the first turn

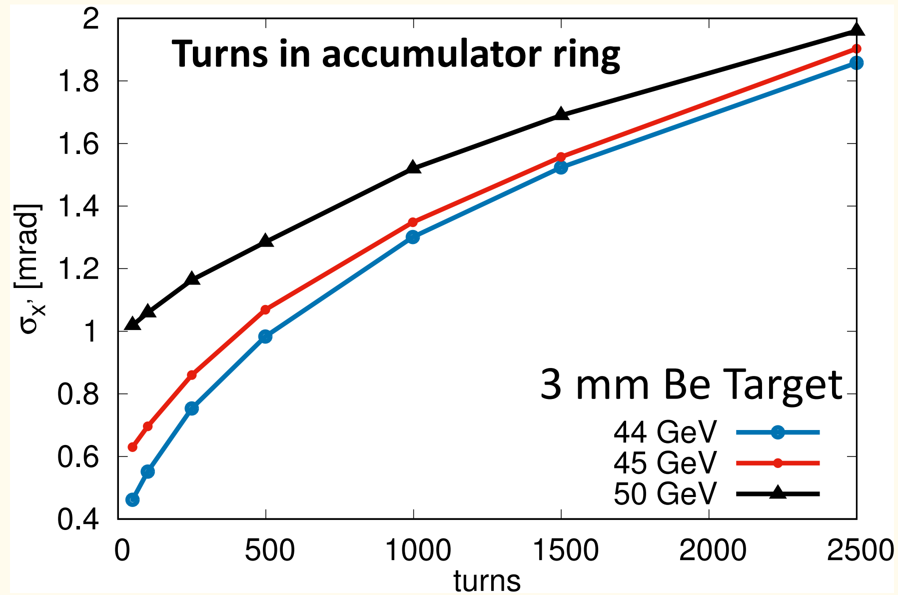


Number of e+ vs turns for different target materials.
Target thickness gives constant muon yield.

Muon emittance contributions

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

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



muon production angle

muon production angle + MS contribution

All these values need to be matched to minimize emittance growth due to beam filamentation.

σ_x and $\sigma_{x'}$ and correlations of e^+ and μ beams have to be similar

In agreement with analytical estimate

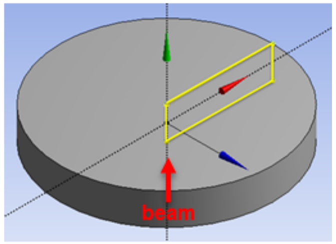
Multiple scattering contribution can be strongly reduced with crystals in channeling

More details in MOPMF087, Proc. IPAC18

Beam induced strain in thin windows

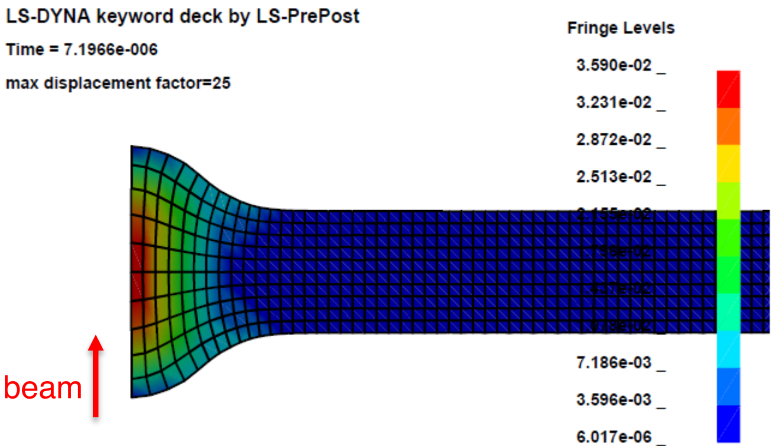
Thermo-structural FEA analyses

- Temperature and strain rate dependent Be material properties
- LS-DYNA elastic-viscoplastic material model (MAT_106)



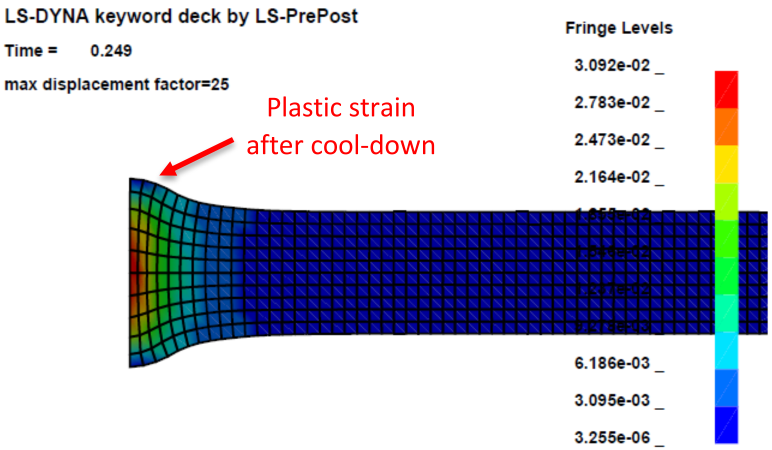
2D axisymmetric model showing effective total strain

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



End of beam pulse

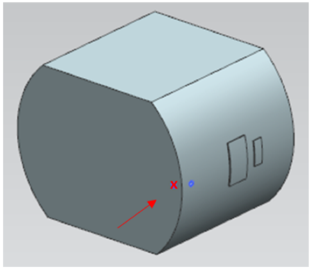
$t = 7.2\ \mu s$, $T_{max} \sim 1050\ ^{\circ}C$, $\varepsilon_{max} \sim 3.6$ %



End of cool-down

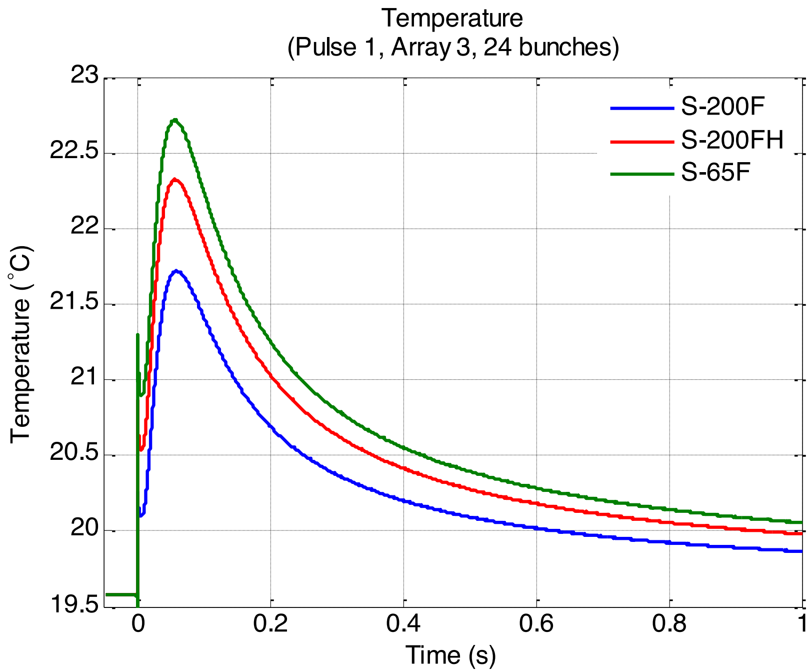
$t > 0.25$ s, $T \sim 25\ ^{\circ}C$, $\varepsilon_{max} \sim 3.1$ %

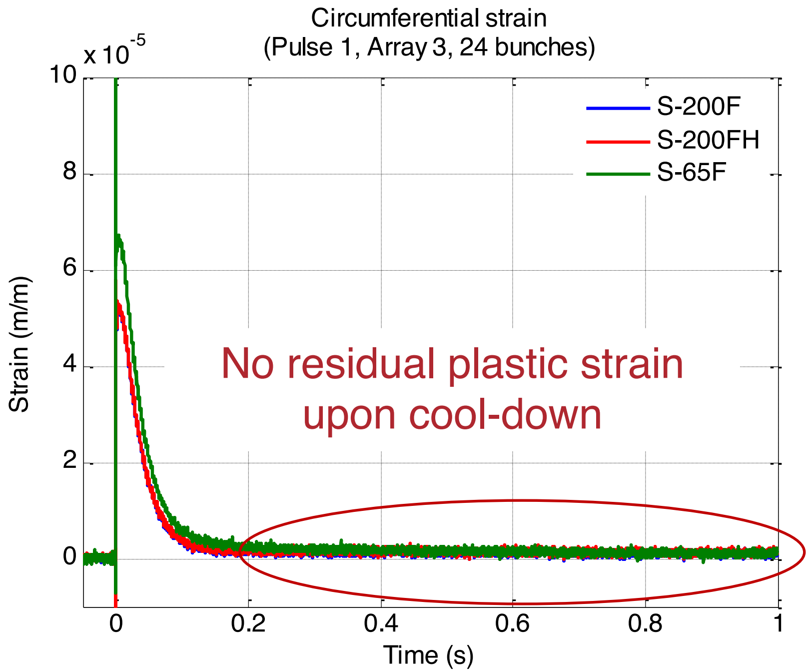
Preliminary results – Be slugs



Array 3 slugs

- 24 bunches
- 3.196 x 10^{12} POT
- Beam positioned ~ 3 mm from edge





Temperature and strain measured on circumferential surface of slug