Low Emittance Muon Accelerator: stato e prospettive

M. Antonelli (LNF-INFN) for the LEMMA Team

RD_FA meeting, Bologna, 3-4 July 2017

Low EMittance Muon Accelerator team

- M. Antonelli, M. Biagini, M. Boscolo, S Dabagov, M. Dreucci, A. Ghigo, S. Guiducci, L. Pellegrino, M. Rotondo, A.Variola, O.R. Blanco-Garcia, O. Frasciello **(INFN-LNF)**
- M. Ricci **(Uni. Marconi, INFN-LNF)**
- M. Iafrati **(INFN-LNF, ENEA Frascati, & Uni. Pd)**
- F.Bedeschi, F. Cervelli, R.Tenchini **(INFN-Pi)**, G.Tonelli **(Univ.& INFN-Pi)**
- A. Bacci **(INFN-Mi)**
- A. Bertolin, U. Dosselli, L. Sestini, M. Morandin **(INFN-Pd)**
- D. Lucchesi, A. Wulzer, M. Zanetti **(Univ.& INFN-Pd)**
- F. Anulli, G. Cavoto, F. Collamati, L. Palumbo **(INFN-Roma1)**
- E. Bagli, V. Guidi, A. Mazzolari, L. Bandiera **(INFN-Fe)**
- M. Prest, E. Vallazza **(Uni-Insubria&INFN)**

- 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)

Outline

- Introduction: Muons case
- Proposal for a novel technique for muon production
- 2017 activities and directions:
  - Accelerator (e+ ring M. Boscolo and e+ source)
  - Experimental (H4 Test beam F. Anulli, M. Zanetti)
- 2018 activities proposal

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:
  - Muon source
  - Fast muon cooling
  - Fast acceleration
  - μ Collider
  - Radiation Safety (muon decay in accelerator and detector)

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 ($\sqrt{s}$ ≈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 μ 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 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

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 ε_μ : thin target ($\varepsilon_\mu \propto$ length) 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
  $\sigma(e^+\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(\text{Bhabha}) \rightarrow$
  low maximimal $\mu^+\mu^-$ production efficiency (infinite length target)
  $Eff_{max} \approx \sigma_\mu/[(Z+1)\sigma(\text{Bhabha})] \sim 10^{-7}$
- **Very light materials, thick target**
  - maximize $\mu^+\mu^-$ production efficiency $\sim 10^{-5}$ (enters quad) → H_2

  Even for liquid targets O(1m) needed → ε_μ increase
- **Not too heavy materials (Be, C, Li)**
  - Allow low ε_μ 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:

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

Efficiency ≈ 10^{-7} (with Be 3mm)→

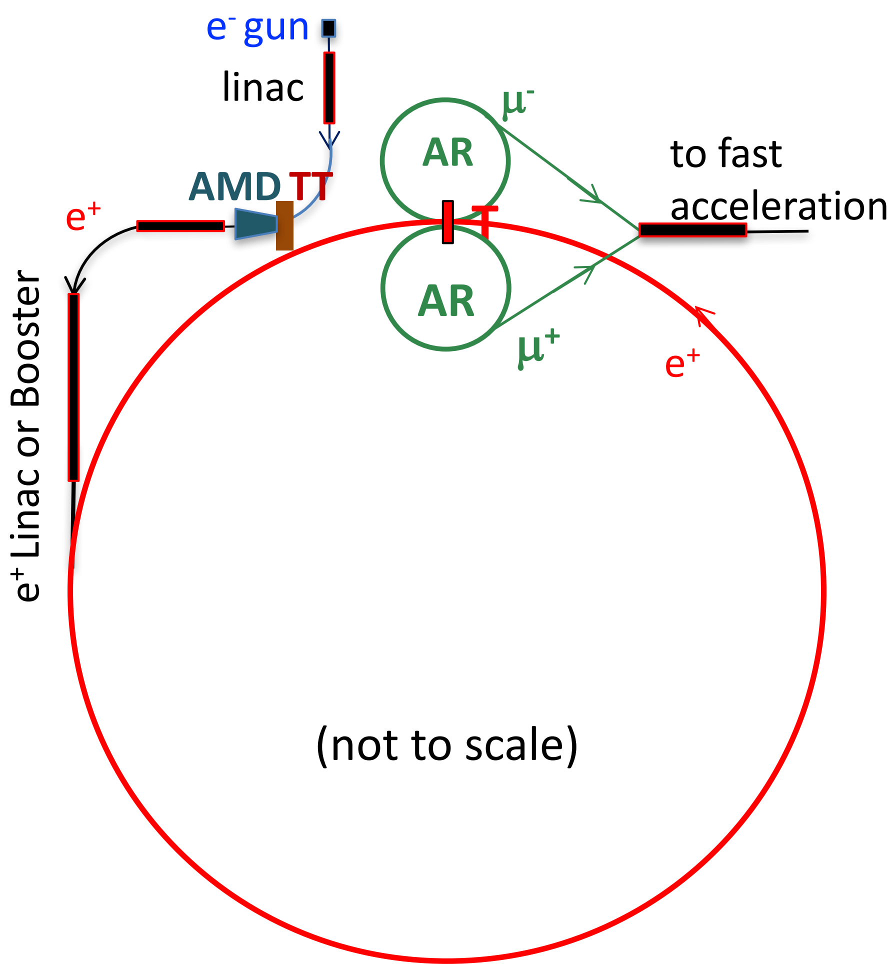
10^{18} e^+/s needed @T →

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] →

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



Preliminary scheme for low emittance μ beam production

from e^+ SOURCE to RING:

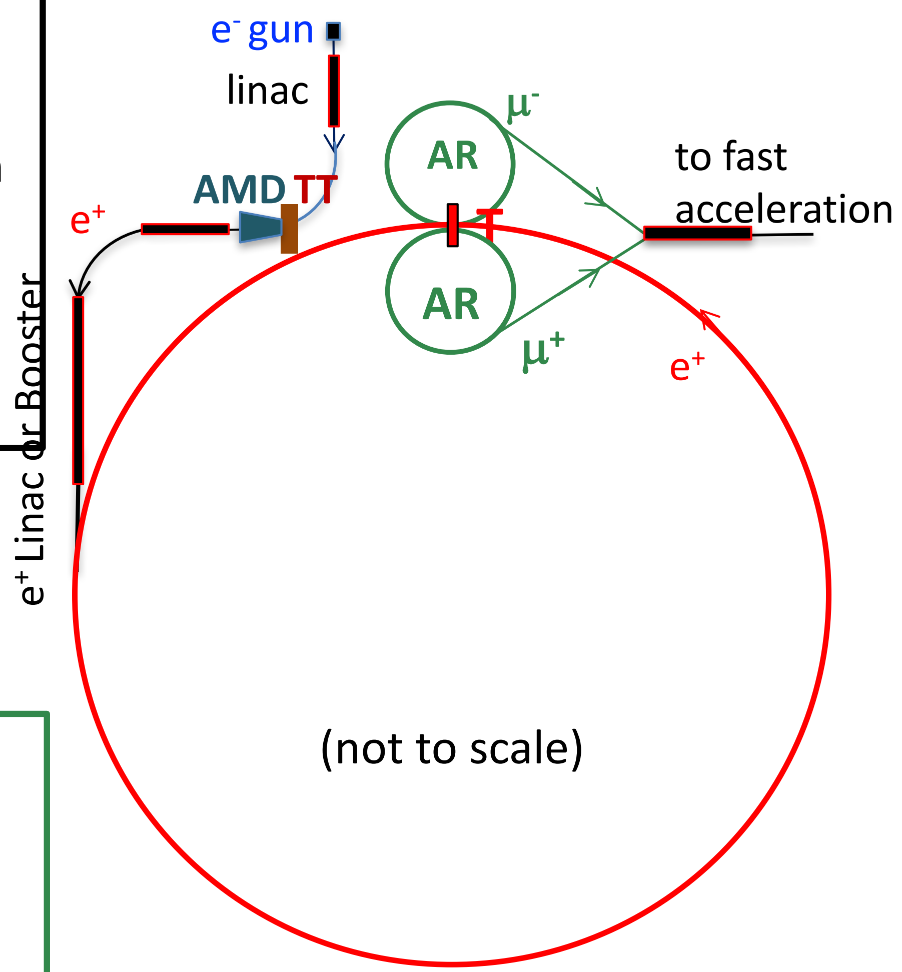
- **e^-** on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- possibly with γ produced by e^+ stored beam on **T** →
- Adiabatic Matching Device (**AMD**) for **e^+** collection →
- acceleration (linac / booster) , injection →

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**, $\gamma(\mu) \approx 200$ → $\tau_{lab}(\mu) \approx$ **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:

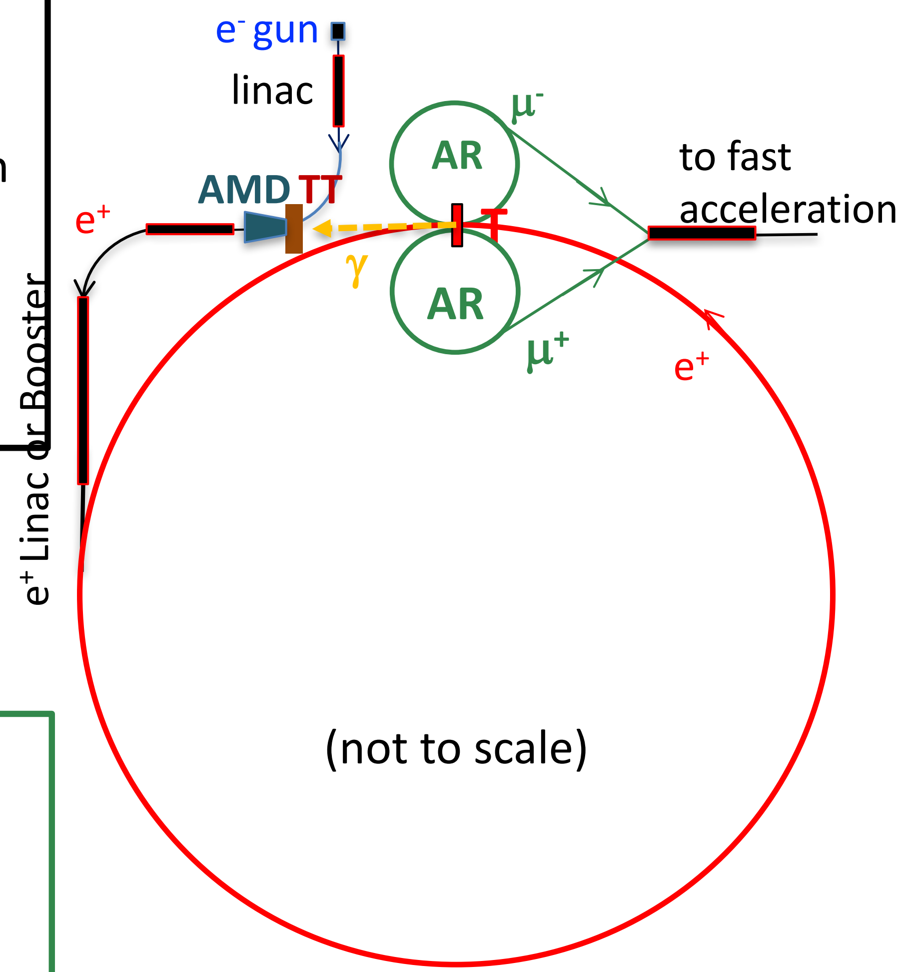
- **e^-** on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- possibly with γ produced by e^+ stored beam on **T**→
- Adiabatic Matching Device (**AMD**) for **e^+** collection →
- acceleration (linac / booster) , injection →

e^+ RING:

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

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

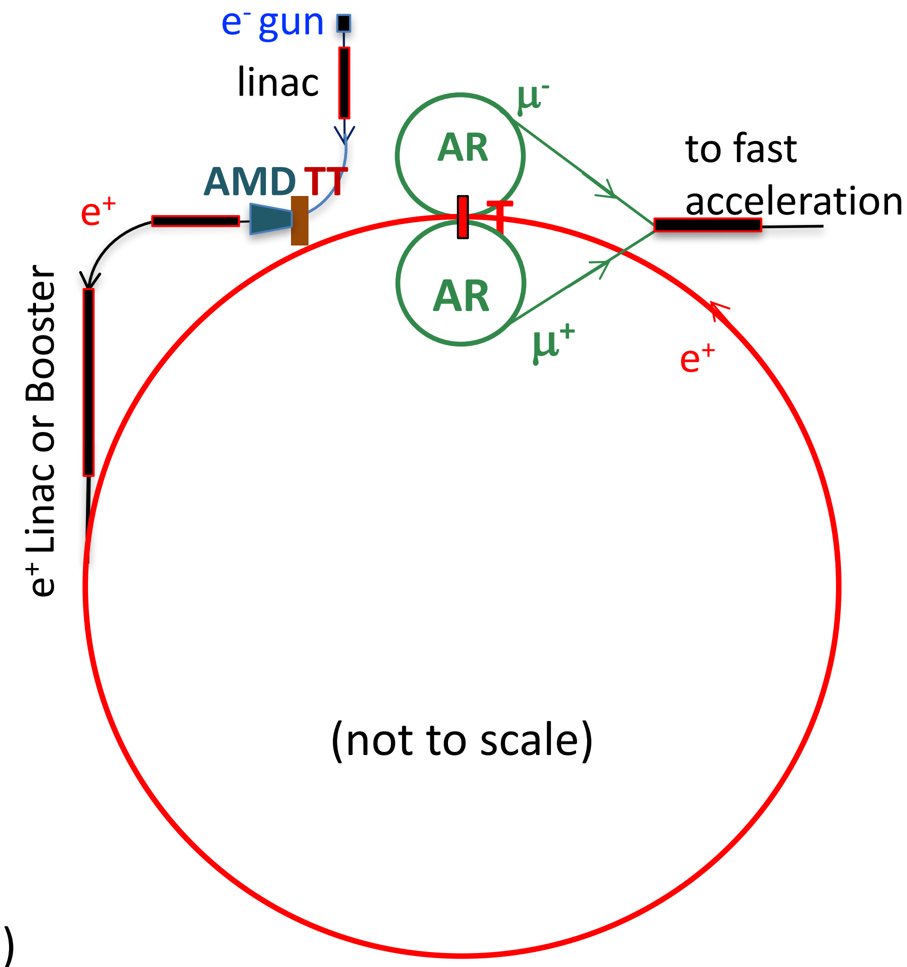
- produced by the **e^+** beam on target **T** with **E(μ) ≈ 22 GeV**, γ(μ) ≈ 200 → **$\tau_{lab}(\mu) \approx 500\mu s$**
- **AR**: **60 m** isochronous and high mom. acceptance rings will recombine μ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns
- fast acceleration
- muon collider



Preliminary scheme for low emittance μ beam production

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

Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

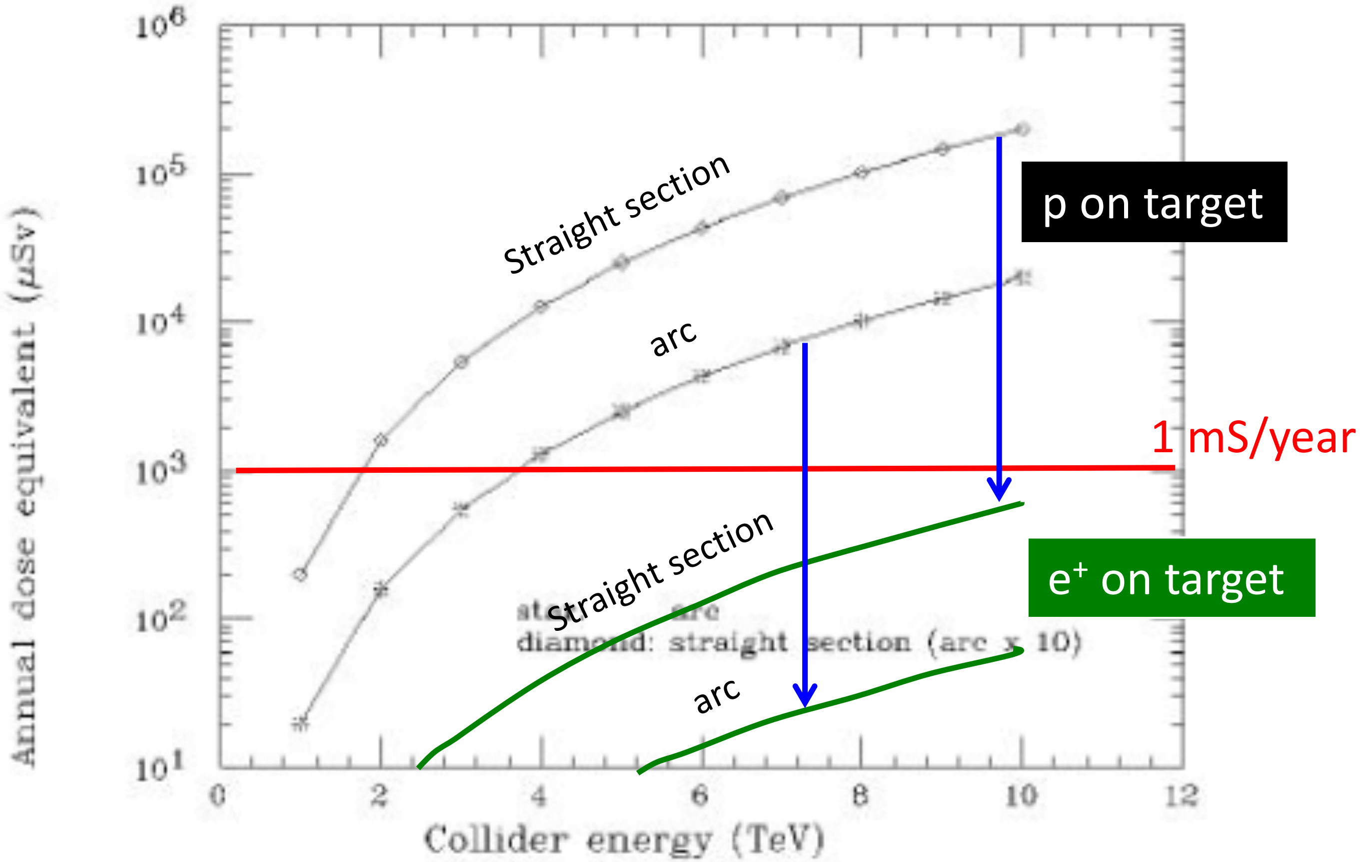


Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

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 (M. Boscolo talk)**
- **O(100 kW) class target in the e^+ ring for $\mu^+ \mu^-$ production**
- **High rate positron source (M. Boscolo talk)**
- **High momentum acceptance muon accumulator rings**
- **Validate with experimental test (F. Anulli, M. Zanetti talk)**

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

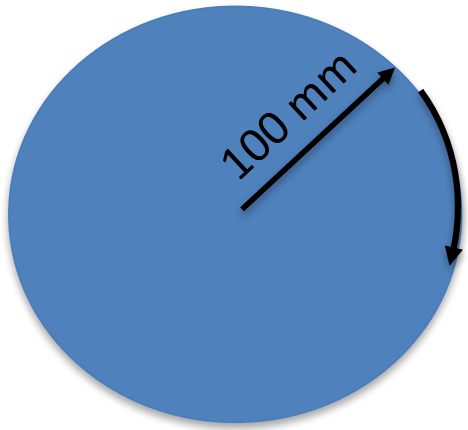
- **Solid target**: simpler and better wrt temperature rise
  - Be, C [Kavin Ammigan 6th High Power Targetry Workshop]
    - Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, N=1.7x10^{11} p/bunch, up to 288 bunches in one shot
- **Liquid** target: better wrt power removal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

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



Single bunch T rise

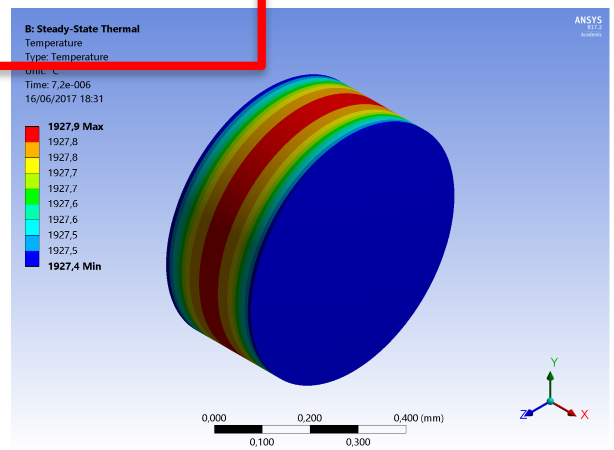
Experimental test in Hi-Rad-MAT

2D axisymmetric model showing effective total strain

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

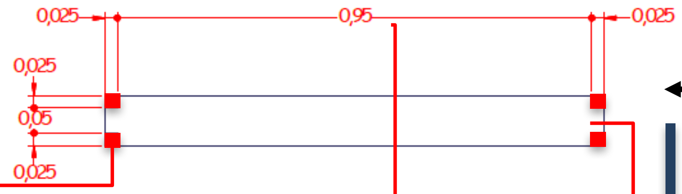
End of beam pulse

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



- Scale 4.9×10^{13} protons, σ = 0.3 mm
- for our number of e+/b = 3×10^{11}
- $\sigma^2 = (300\mu m)^2/200 = (21\mu m)^2$

Power dissipation



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

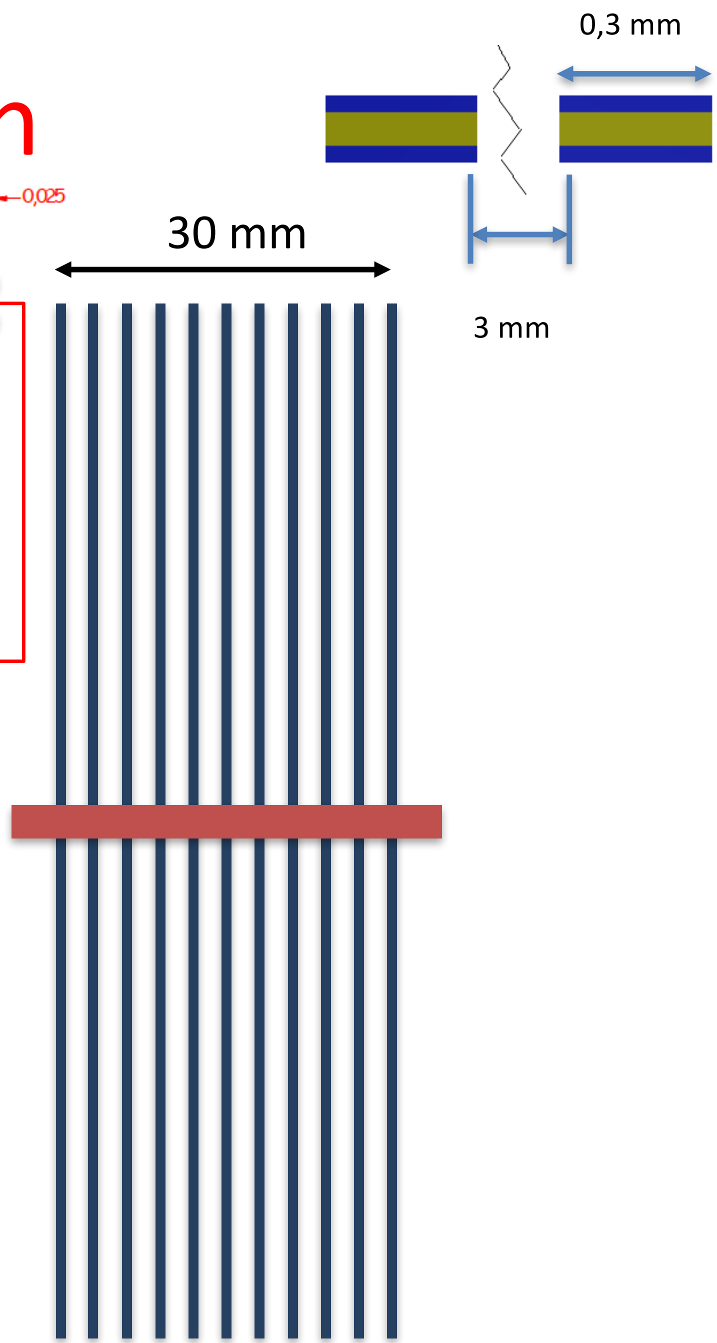
Distribute bunches in 10 rotating disks

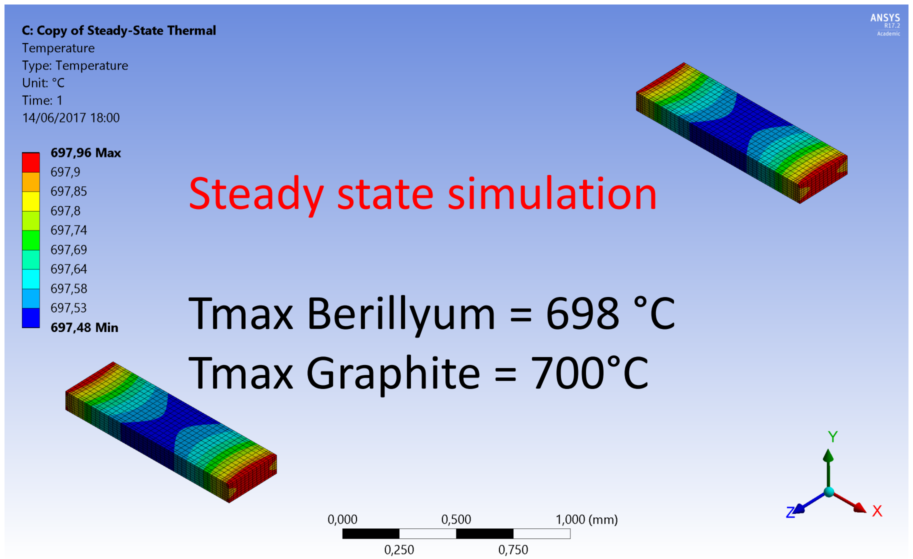
400k beam spots:

1 mm (beam bump) in

50 μm space (disk rotation) in rϕ

100 kW distributed in 400k spots and 10 disks

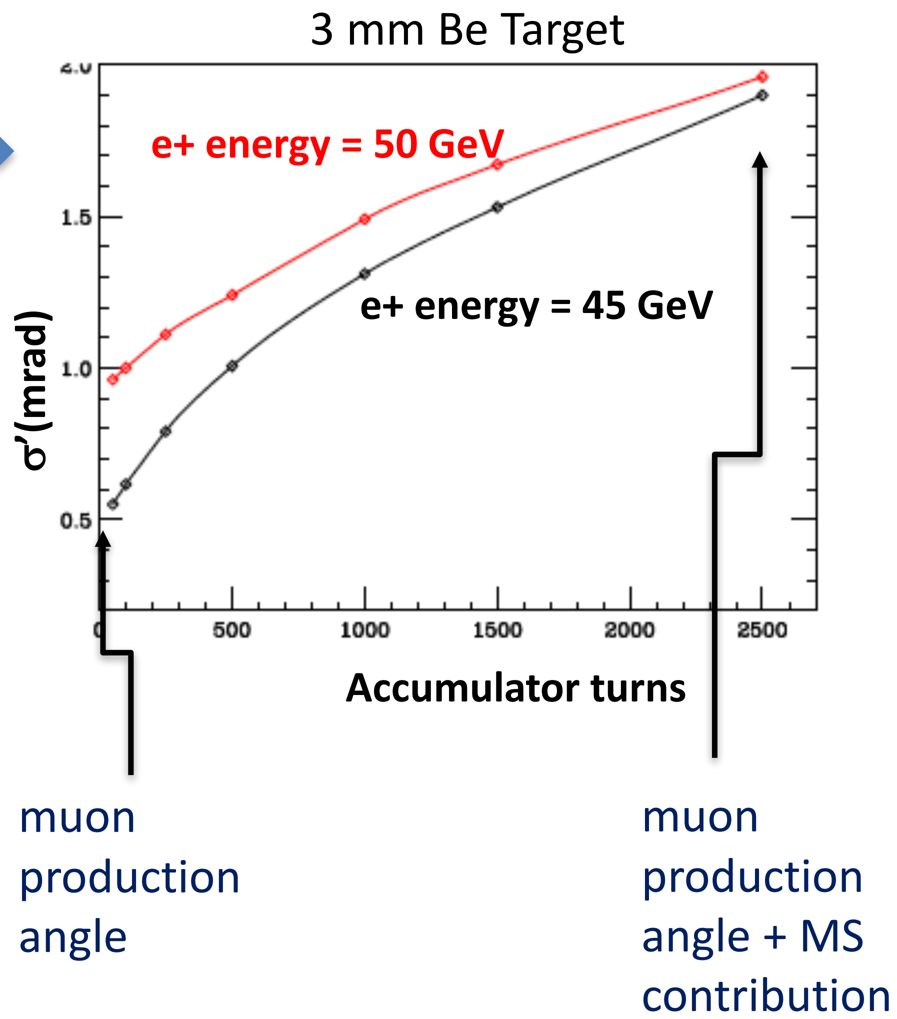




μ Accumulator Rings considerations

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

Multiple Scattering effect using one-turn matrix

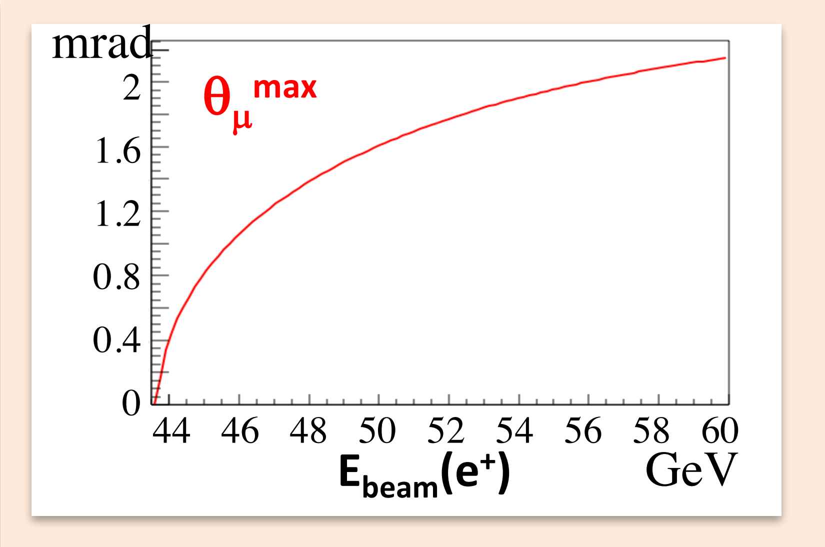


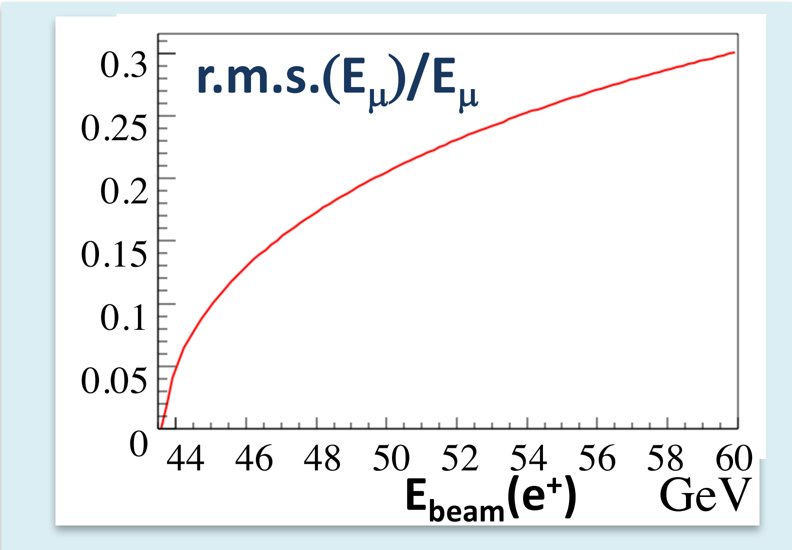
beam divergence:
a factor 3-2 increase at 45-50 GeV w.r.t. muon production angle contribution
beam size:
depends on optics need low-β to suppress size increase

this contribution can be strongly reduced with crystals in channeling

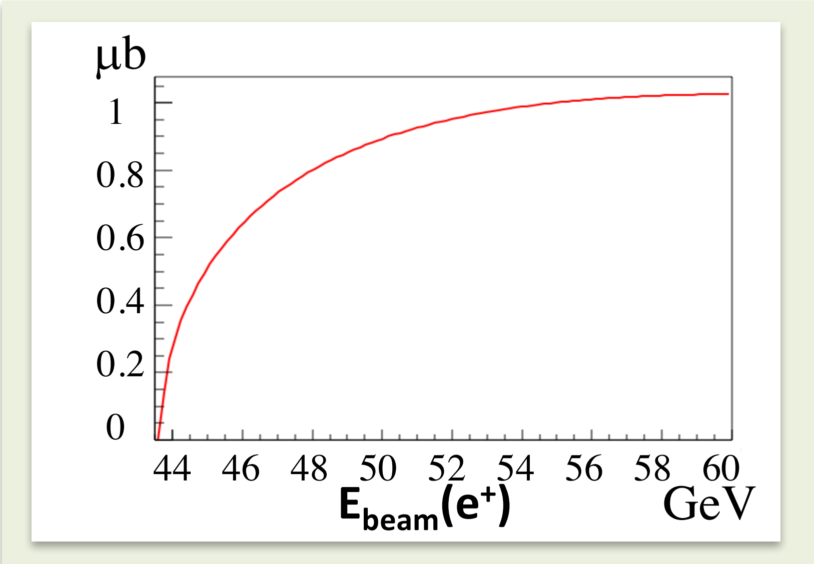
better performances at 50 GeV provided >15% momentum acceptance **(FFAG for numax has 19 %)**

Parametric behaviours





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



2018 possible 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 (see next talk)
- **Request 1-(2) weeks in 2018** for:
  - Complete original program of the 2017 experiment
  - Attempt muon production on crystals (depending on beam quality….. see this year)

2018 possible 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 (check if it is available)
  - Sps extracted beam Hi-RadMat
- **Power dissipation test**
  - Would need accumulator
  - Check with Dafne linac

Funding requests

- **Missioni:**
  - Test beam H4 **20 Keuro**
  - Contatti per disegno targhette **2 Keuro**
  - Riunioni e conf. **3 Keuro** x sezione
  - Test tenuta targhette **10 Keuro (SJ)**
- **Consumo:**
  - Targhetta (indicativo) **10 Keuro**
  - Cristalli. (indicativo) **10 Keuro (SJ)**

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**
    - Detailed study of experiment layout
    - Muon production experiment ready
- **Many ideas for 2018…**
  - H4 test beam run-2
  - Attempt to test target termo-mechanical stresses