Positron driven muon source for a muon collider (LEMMA): recent developments

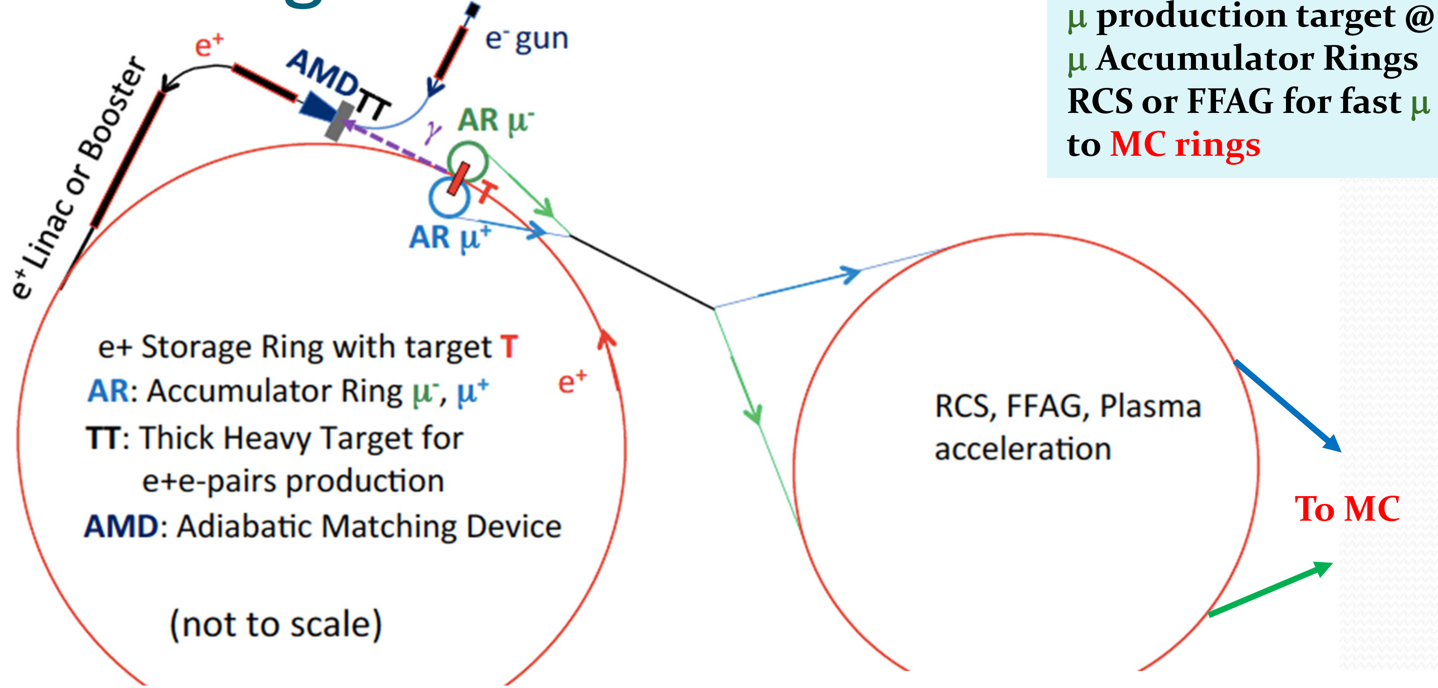
M.E. Biagini, INFN-LNF, IPAC19, Melbourne, May 2019
On behalf of the LEMMA Team

Low EMittance Muon Accelerator

- A Muon Collider is the only cost-effective opportunity for lepton colliders to go to **$E_{cm} > 3$ TeV**
- LEMMA concept (P. Raimondi & M. Antonelli, first presented at Snowmass 2013):
  - $\mu^\pm$ produced by **e^+** beam interacting with **e^-** in a target in a ring → small $\mu^\pm$ beam emittance and long laboratory lifetime due to the $\mu^\pm$ boost in the laboratory frame
  - average $\mu^\pm$ energy **22 GeV** (average laboratory lifetime of **~500 μs**) eases the acceleration scheme
  - Aimed at obtaining high luminosity with relatively small $\mu^\pm$ fluxes thus reducing background rates and activation problems due to high energy $\mu^\pm$ decays
- Advantages: final state $\mu^\pm$ highly collimated and with small emittance → muon cooling not required

LEMMA original scheme

- e^+ high intensity source
- e^+ acceleration to 45 GeV
- e^+ storage ring @ 45 GeV
- μ production target @ 22 GeV
- μ Accumulator Rings
- RCS or FFAG for fast μ acceleration to MC rings



Goal: $\approx 10^{11}$ μ/s produced at target
with target efficiency $\approx 10^{-7}$ (Be, 3mm)
Request: 10^{18} e^+/s impinging on target →
45 GeV e^+ storage ring with target insertion

$\mu^\pm$ produced by e^+ beam on target T @ ~ 22 GeV →
$\tau_{lab}(\mu) \approx 500\mu s$ $(\gamma(\mu) \approx 200)$
Muon Accumulator Rings (MA) isochronous with high momentum acceptance, recombine $\mu^\pm$ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns

LEMMA new developments

- To overcome some technical limitations, such as:
  - Required # of **e^+** from source too large with respect to state-of-the-art (ILC, CLIC)
  - Instantaneous and average energy deposited on target too large
- 3 different accelerator complex layouts are currently being studied, in order to choose the one fulfilling all the requirements with a reasonable R&D program
- In this talk one Scheme is presented
- All have the **e^+** beam **extracted** and imping on **external** targets

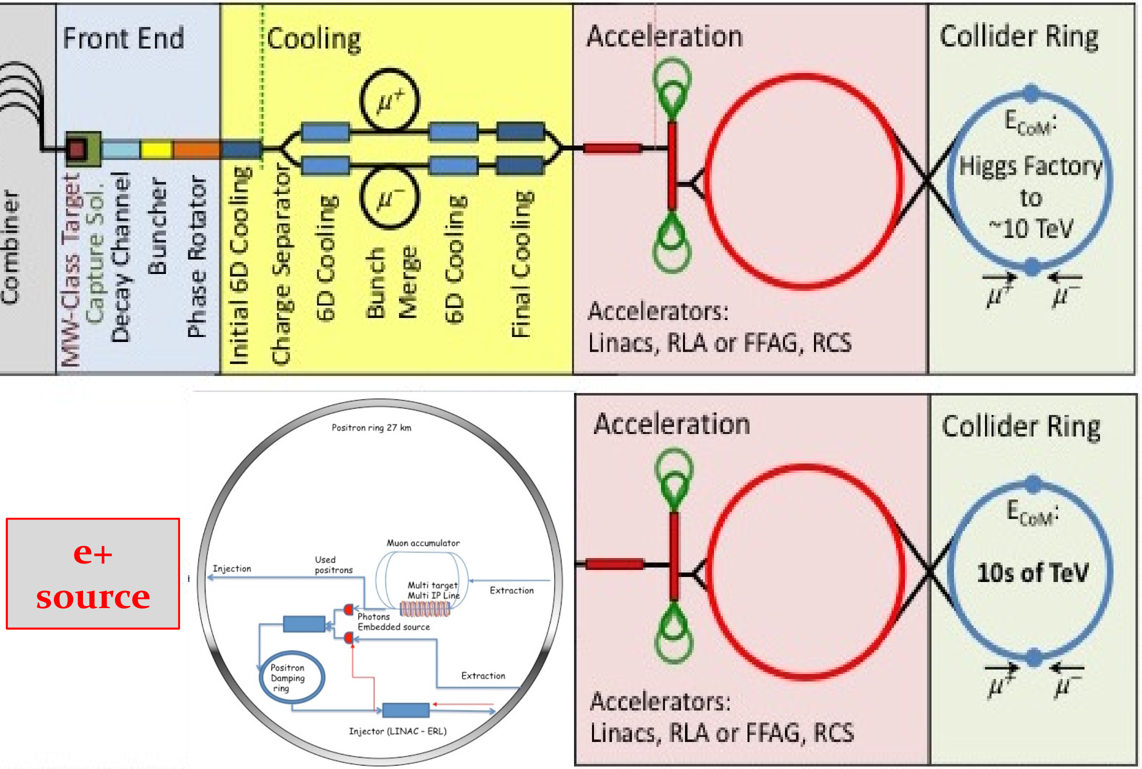
LEMMA new scheme

- Precise requirements on the muon source chain have been set:
  - complete **μ** production cycle ~410 μs (lifetime = 467 μs @ 22.5 GeV)
  - one complete cycle must last enough time for **e^+** production and damping
  - damping time must be compatible with a reasonable amount of synchrotron power emitted → Damping Ring to cool **e^+** at lower energy
  - possibility to recuperate **e^+** bunches "*spent*" after the **μ** production, to produce **e^+** ("*embedded*" **e^+** source)
  - study of different types of targets (material, thickness, resistance to heating,…)

LEMMA vs Proton Driver

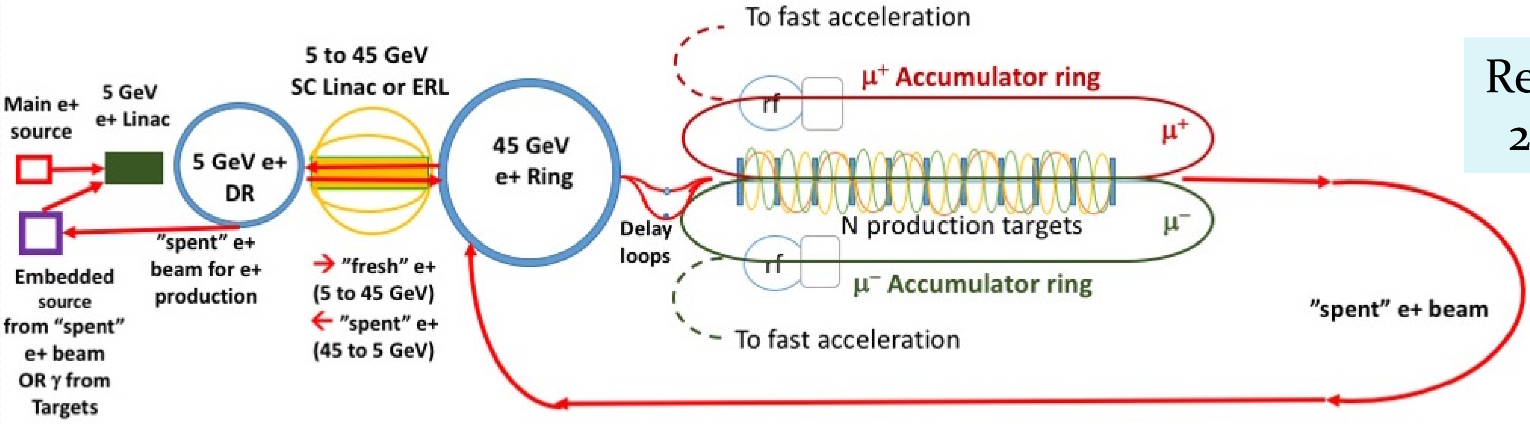
MAP

LEMMA



Complex layout

- **e^+ Source** @ 300 MeV + 5 GeV **Linac**
- **5 GeV e^+ Damping Ring** (damping ~10 ms)
- **SC Linac or ERL** from 5 to 45 GeV and from 45 to 5 GeV to cool *spent* **e^+** beam after $\mu^\pm$ production
- **45 GeV e^+ Ring** to accumulate 1000 bunches, 5x10^{11} part/bunch needed for $\mu^\pm$ production, and **e^+** *spent* beam after $\mu^\pm$ production, for slow extraction towards decelerating Linac and the DR
- **Delay loops** to synchronize **e^+** and $\mu^\pm$ bunches
- **One (or more) Target Lines** where **e^+** beam collides with targets for the direct $\mu^\pm$ production
- **2 Accumulation Rings** where $\mu^\pm$ are stored until the bunch has **~10^9** μ/bunch
- **"Embedded" e^+ source** for the production of **e^+** needed to restore the design **e^+** beam current, either using the γ coming from the $\mu^\pm$ production targets, or the 45 GeV **e^+** *spent* beam



Rep rate
20 Hz

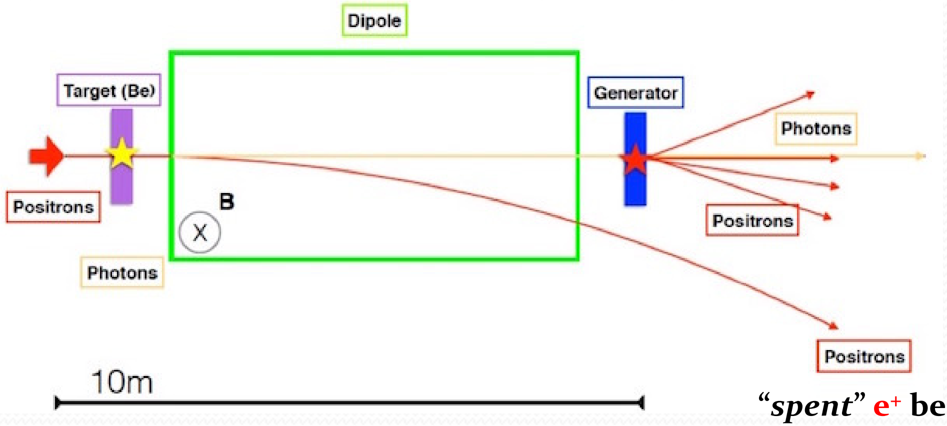
LEMMA sub-systems

Positron Source

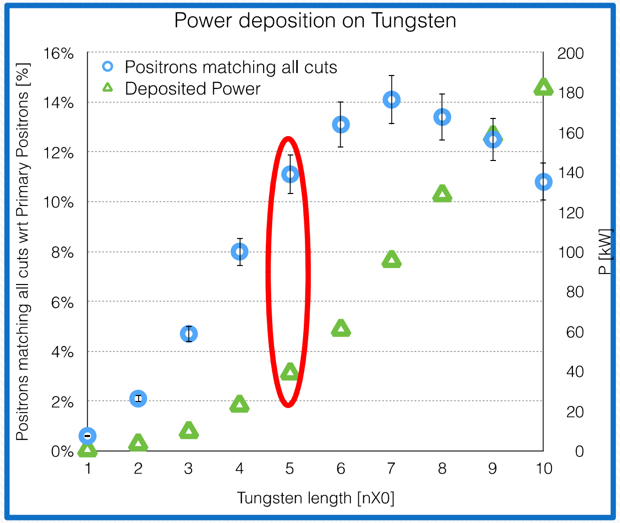
- e+ source has to provide trains of 1000 bunches with 5×10^{11} e^+/bunch
- Source needed to replace **e^+** lost in the μ production is challenging since the time available to produce, damp and accelerate the **e^+** is very short (50 ms)
- ~70% of the **e^+** after μ production can be recovered, injected in the PR, slowly (~20 ms) extracted, decelerated and injected in a DR for topping up
- Therefore only ~30% of the required **e^+** need to be produced by the source in a time cycle $t_{cycle} = 50$ ms → required **e^+** production rate is **3×10^{15} e^+/s**
- Techniques developed for the future linear colliders like hybrid targets (crystal + tungsten targets) and rotating targets will be explored and R&D on new targets will be developed

Embedded e^+ source

- To increase the number of **e^+** from the source, the high energy γ produced by the 45 GeV **e^+** beam passing through the targets can be used as an *"embedded"* **e^+** source
- Feasibility studies of γ impinging on a $5X_0$ Tungsten target were performed
- The achievable **e^+** yield will depend on the power that the target can sustain
- For each **e^+** on the primary 3 mm Be target there are:
  - 0.11 γ hitting the W generator target
  - 0.65 **e^+** coming out of the 5Xo W target
- A simulation of the **e^+** capture system has also been performed



"*spent*" e^+ beam



N. of e^+ within the parameter range that can be accepted by the capture system as a function of the target thickness

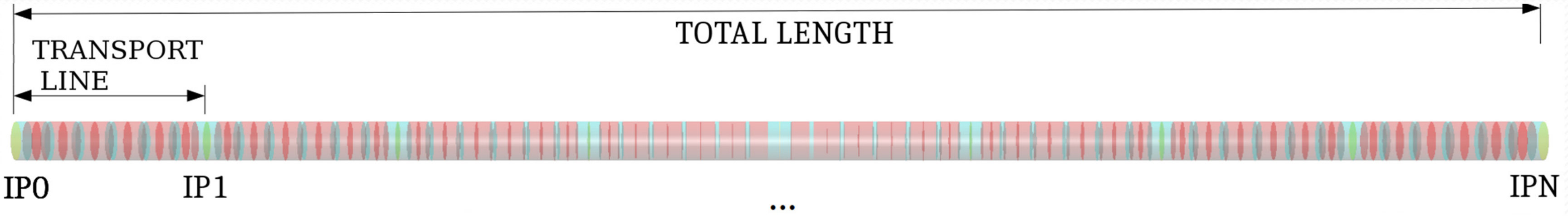
Target Line

- **e^+** bunches will be extracted from the PR and transported to one (or more) external line where μ are produced by the **e^+** impinging on targets
- Delay loops will provide the right timing between the **e^+** bunches and the μ bunches already produced
- Two designs studied up to now:
  - Multiple Interaction Points (10 IP, 10 targets)
  - Single Interaction Point (1 IP, 10 targets)
- For details see: **O.R. Blanco-Garcia, poster MOPRB003 this afternoon**

Multiple IPs Target Line

MOPRB003

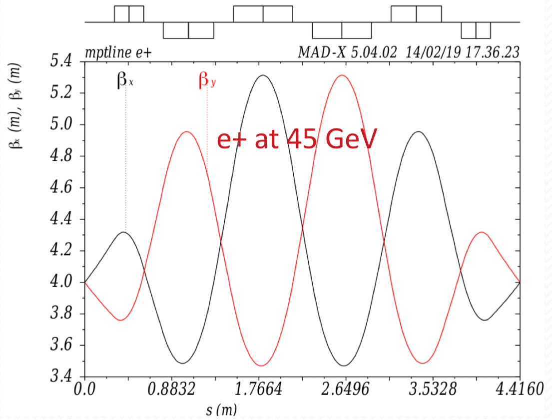
- Targets are separated by a transport line with magnets common to 3 beams (**e^+**, **μ^+**, **μ^-**)
- Line must focus (low β) the beams at each IP to achieve the production of new **μ** with minimal growth of the final **μ** beam emittance
- Length should be as small as possible in order to minimize **μ** decay issues
- Chromaticity cannot be corrected with standard method, because this would split the 3 beams → other method used to mitigate the chromatic effect

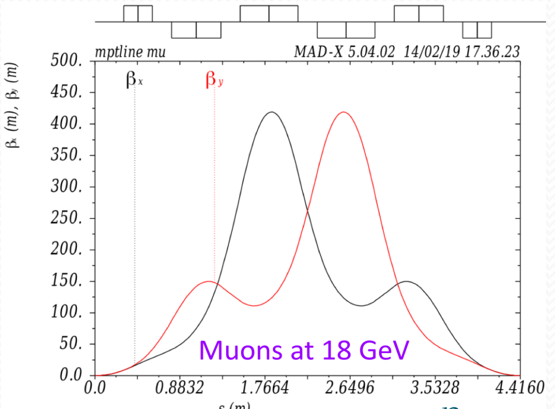


Multiple IPs transport line optics

MOPRB003

- Two asymmetric triplets, in order to partially cancel chromaticity at 45 GeV as in the *apochromatic design* (*C. A. Lindström, E. Adli, PRAB 19, 2016*) used to focus beams at 45 GeV and 18 GeV on both transverse planes
- Between 1st and 2nd IP the μ emittance grows due to combination of chromaticity of the μ beam not being completely corrected and of the large energy spread (±18%) of the produced μ
- For an **e⁺** beam spot at the first target of $\sigma_{e+} = 150\ \mu m$ and 6 nm **e⁺** beam emittance, the produced μ emittance is 70 nm (see next slide, magenta line) and grows up to 200 nm, a factor two with respect to the initial μ emittance

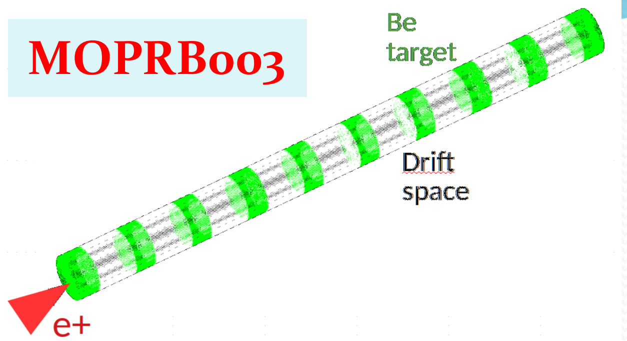


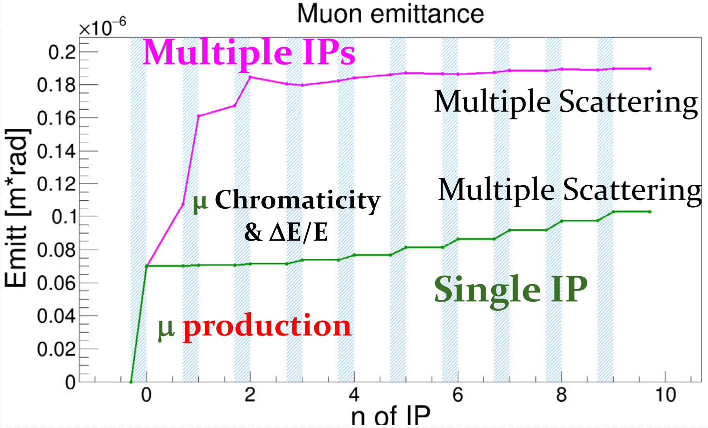


Single IP Target Line

- One target is cut in **10 thin slices**, each one separated by short drifts in order to give space for power dissipation on target
- For an **e^+** beam spot at the first target of $\sigma_{e+} = 150$ μm and 6 nm emittance the produced μ emittance is 70 nm (green line) and grows up to 110 nm
- A smaller **e^+** beam spot σ_{e+} (smaller β^*) at the target gives smaller μ emittance, the limit is the target resistance to temperature and stresses
- Different σ_{e+} on target are being studied, as well as different target materials, since this parameter is crucial both for the final μ emittance and for the amount of deposited energy and temperature rise of the target

MOPRB003



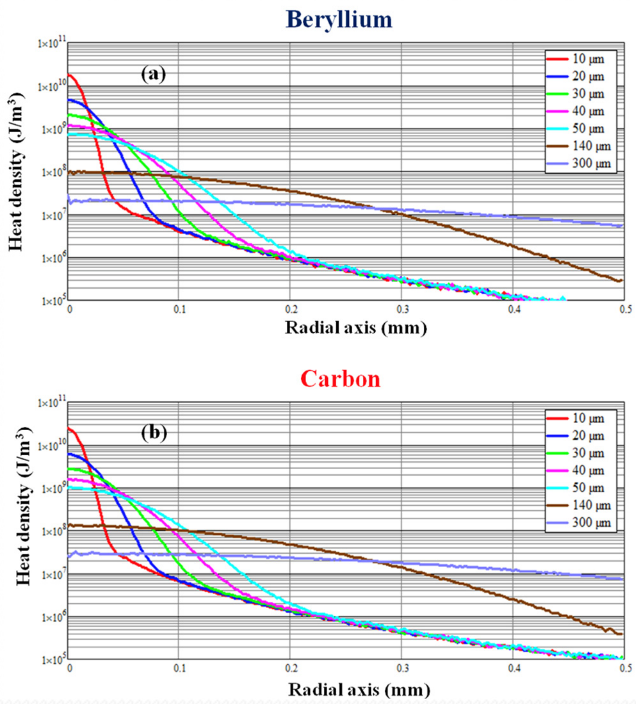


Comparison of μ emittance growth for the Multiple IPs (magenta) and Single IP (green) for same e^+ spot on target (150 μm) vs target number

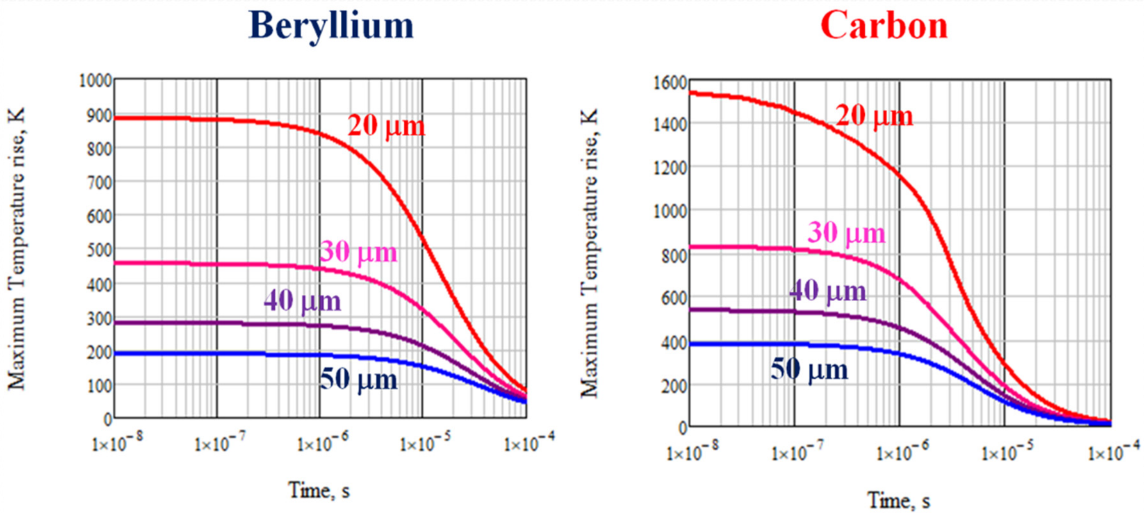
Target studies

- Both temperature rise and thermal shock are related to the **e^+** beam spot on target
- For a given material the lower limit on the beam size is obtained when there is no pile-up of bunches on the same target position → ideal: both target and **e^+** beam move
- Fast moving targets can be obtained with rotating disks for solid targets or high velocity jets for liquids
- A power deposition of about 30 kW is expected for a 0.3X0 target. The target has to be therefore sliced in many thin targets to easy the power removal
- Recently developed Carbon based materials with excellent thermo-mechanical properties are under study for the LHC upgrade collimators
- First study of thermal behavior performed both for 3 mm Be and 1 mm C targets → an ILC-like rotating system could be used
- Future R&D on Liquid jet target, H_2 pellet/spaghetti (twice more μ, less multiple scattering, but difficult to realize) and crystals

Target studies



Deposited Energy Density of 1 e⁺ bunch for Be (top) and C (bottom) for different e⁺ spot sizes



Temperature increase for Be (3 mm) and C (1 mm) targets as a function of time, for different incident e⁺ beam spots

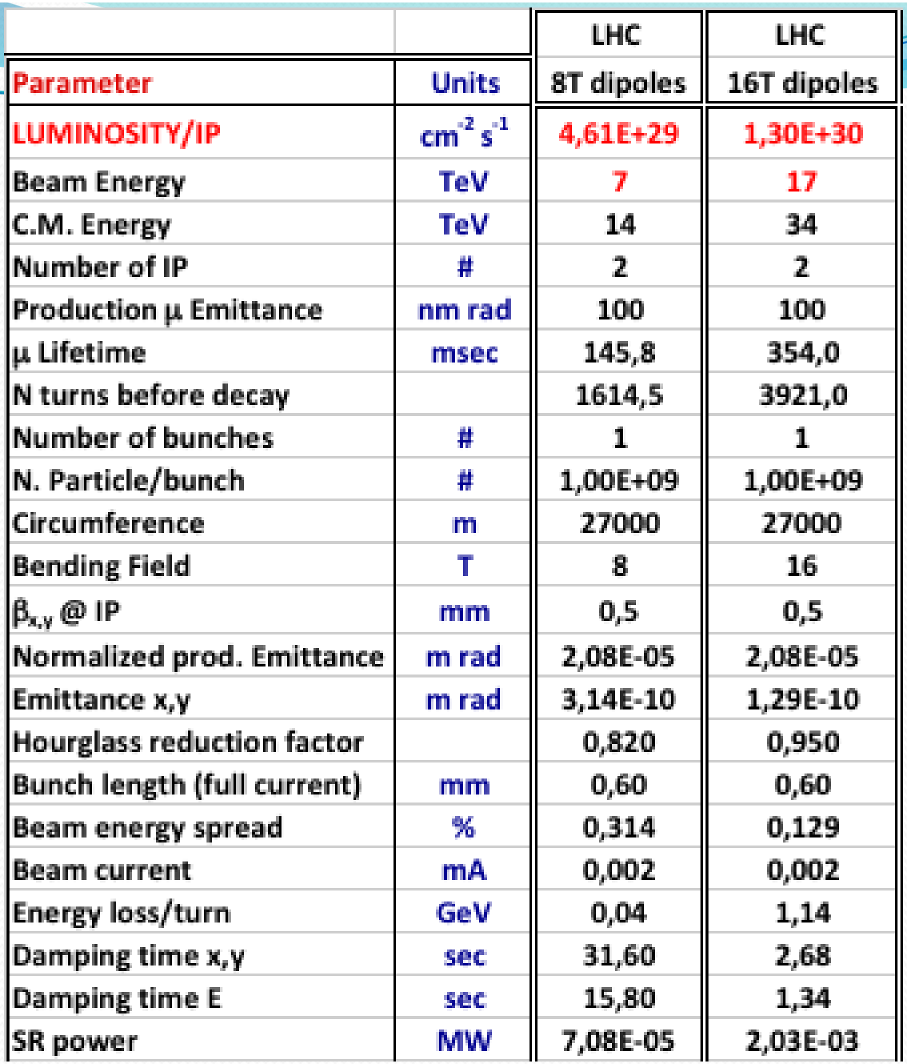
While Beryllium has a higher $\mu^{\pm}$ production efficiency, Carbon can sustain a higher energy deposition and temperature raise

Muon Accumulators

- 2 Muon Accumulator Rings (MA) will store the μ produced over several passages of the e^+ beam → their length must match the timing between e^+ bunch passages, i.e. new $\mu^\pm$ are created at the moment of passage of the stored μ → increase μ bunch intensity
- MA must be short in order to complete a large number of turns before $\mu^\pm$ decay
- Preliminary compact design (C=123 m) done, optimized to get small momentum compaction factor, allowing the recirculation of the $\mu^\pm$ beam every 410 ns, to complete 1000 turns in one $\mu^\pm$ lifetime at 22.5 GeV
- A preliminary "separation" region after production, common to e^+, μ^+ and μ^- for the 3 beams was designed

MC Luminosity

- Estimate of collider luminosity with new LEMMA parameters
- 2 examples: LHC tunnel with 8T dipoles, LHC With the present design performances, excluding the recombination of bunches or other exotic scheme, peak luminosity/IP with 1 bunch is in the **10^{29}-10^{30} cm^{-2} s^{-1}** range
- Future R&D aiming at improving these values (ex. more bunches, cooler μ bunches) will be carried out (see next slide)



		LHC	LHC
Parameter	Units	8T dipoles	16T dipoles
LUMINOSITY/IP	cm^{-2} s^{-1}	4,61E+29	1,30E+30
Beam Energy	TeV	7	17
C.M. Energy	TeV	14	34
Number of IP	#	2	2
Production μ Emittance	nm rad	100	100
μ Lifetime	msec	145,8	354,0
N turns before decay		1614,5	3921,0
Number of bunches	#	1	1
N. Particle/bunch	#	1,00E+09	1,00E+09
Circumference	m	27000	27000
Bending Field	T	8	16
$\beta_{x,y}$ @ IP	mm	0,5	0,5
Normalized prod. Emittance	m rad	2,08E-05	2,08E-05
Emittance x,y	m rad	3,14E-10	1,29E-10
Hourglass reduction factor		0,820	0,950
Bunch length (full current)	mm	0,60	0,60
Beam energy spread	%	0,314	0,129
Beam current	mA	0,002	0,002
Energy loss/turn	GeV	0,04	1,14
Damping time x,y	sec	31,60	2,68
Damping time E	sec	15,80	1,34
SR power	MW	7,08E-05	2,03E-03

Future R&D

- A solid R&D program can increase the **μ** beams quality and the final luminosity
- H2 targets could improve the integrated thickness, reducing the number of passages and increasing the rate of "*fresh*" bunches/passage → with a linear dependence on the **μ**/bunch number, a quadratic increase of the final luminosity can be expected, a simple scaling with Z gives a factor 15 increase of the luminosity
- Rotating target conceived for ILC and the possibility to develop immersed **e^+** capture systems with very high peak B field in the AMD (20 T as in MAP), could increase the efficiency of the **e^+** source and the repetition rate of a factor 5-10, with a linear dependence on the luminosity
- To reduce the **μ** production emittance, a moderate cooling mechanism, such as stochastic, optical stochastic, and crystal cooling can be envisaged. A full evaluation of these mechanisms is needed, targeting at a reduction of the **μ** emittance by 1-2 order of magnitude, with a linear impact on the final luminosity

Conclusions

- LEMMA is an alternative μ source complex, using small emittance 45 GeV **e^+** bunches to produce collimated μ
- Three different complex schemes, taking into account the full μ production cycle, are being studied
- Some simulations of the sub–systems operating in the schemes were done to evaluate their final performances, more are in progress
- This activity will allow to assess LEMMA conceptual feasibility and to identify the R&D path and the design development directions to be followed to achieve the required collider luminosity
- A more detailed description of this work is available at https://arxiv.org/abs/1905.05747

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