Muon Collider (Accelerator Strategy)

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Many thanks to Mark Palmer, Vladimir Shiltsev and the MAP and LEMMA teams

Also to Christian Carli, Alexej Grudiev, Alessandra Lombardi, Gijs De Rijk, Mauricio Vretenar

Introduction

Last year a working group, chaired by Nadia Pastrone, has been set up to provide input to the European Strategy Update regarding a potential muon collider and submitted a paper to the Strategy Process.
The working group performed a first, high-level review of two muon collider schemes, one base on protons to produce muons and one on positrons. The focus has been on the positron-based scheme, which has been found to require consolidation. This year a more in depth investigation also of the proton-driver scheme can provide a better assessment for the European Strategy Process about the potential value of the technology for a collider and the R&D programme that would be required. Also work is being carried out on the positron scheme

Note:
We did not make a conceptual design
At least my knowledge is much less than about projects, I seriously worked on
In case we want to pursue muon colliders, it should actually be part of the future R&D effort to take ownership of a conceptual design or develop it

Spoiler

We will have to answer three main questions:

- **Can muon colliders at this moment be considered for the next project?**
  - No, no serious conceptual design of a facility exists and it there is quite a way to go
- **Is it worthwhile to do muon collider R&D?**
  - Yes, it seems to have promises that make it worthwhile to attempt to overcome the obstacles
- **What needs to be done?**
  - The muon production and cooling is key. A new test facility is required.
  - A conceptual design of the collider has to be made.
  - Many components need R&D
    - e.g. fast ramping magnets
    - background in the detector
  - Site-dependent studies have to be performed to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source

Goal of the Meeting

Help to sharpen the answers to the questions:
- No, muon collider collider technology is not yet ready for the next project
- Yes, it is worthwhile to perform muon collider R&D because of the promise at high energies
- But in particular we need to better define the R&D required

The results will be presented in Granada
- In the plenary by Vladimir
- In the accelerator session by me
- and also in the physics

Particle Type and Luminosity Goal

Lepton colliders offer the potential of precision measurements

- Well defined initial conditions
- Low background levels
- …

To investigate s-channel processes, luminosities have to increase quadratically with energy

- From the physics a luminosity goal is defined as

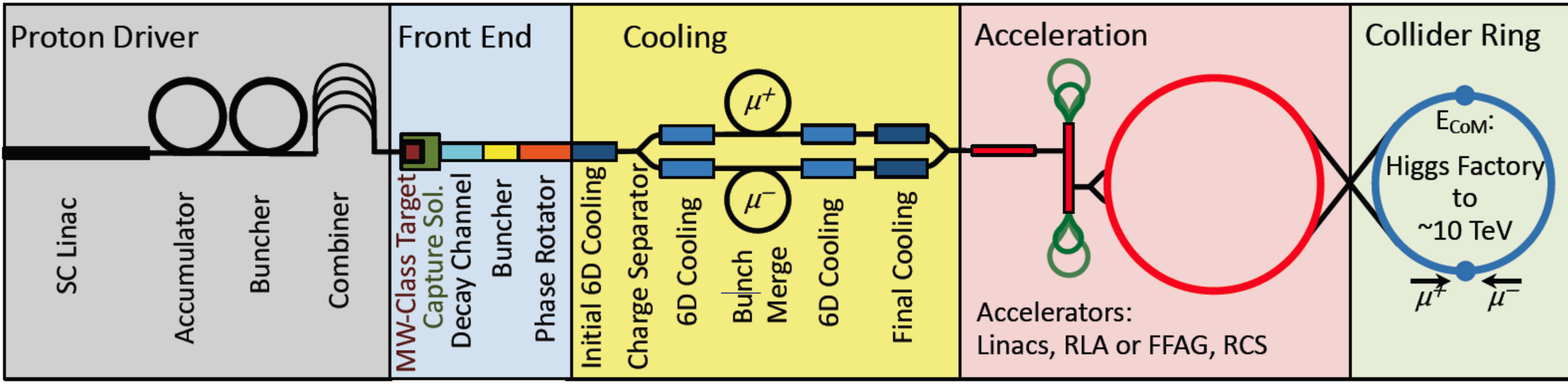
$$L \gtrsim \frac{5\,\mathrm{years}}{\mathrm{time}} \left(\frac{\sqrt{s_\mu}}{10\,\mathrm{TeV}} \right)^2 2 \cdot 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

The main difficulty of electron-positron colliders is to provide the luminosity at high energies

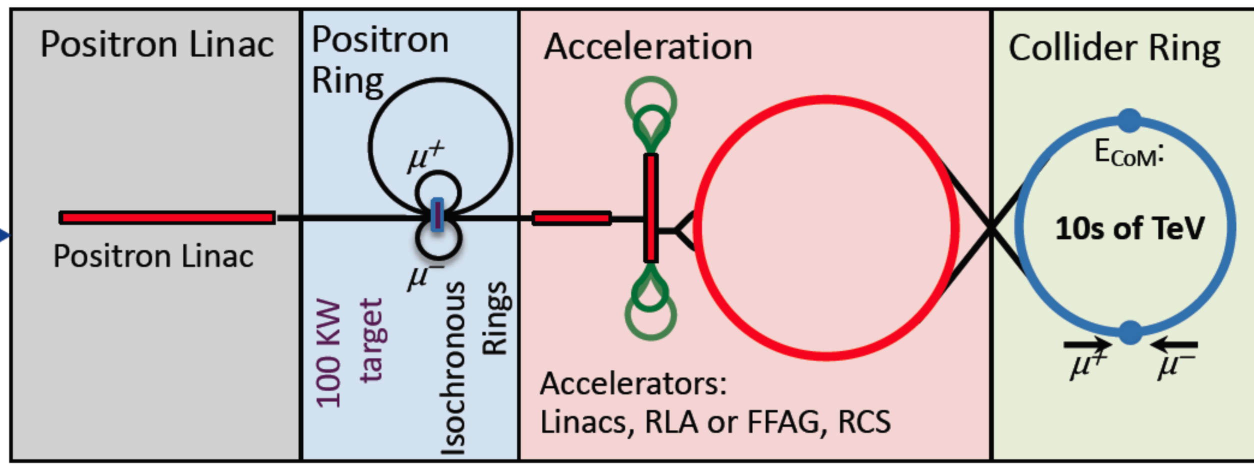
- Circular collider lose dramatically with energy
- Linear colliders can provide linear increase of luminosity for constant beam current
- Or a constant luminosity per beam power

A muon collider might break this limit and provide a luminosity that increases linearly with energy for constant beam power

Muon Collider Concepts



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Collider Parameter Examples

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.			
Goal			0.45	1.8	7.2
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
b*	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, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_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
Beam power	MW		7.2	11.5	11.5

Key to Luminosity

Integrated luminosity of one bunch

$$\Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \frac{\left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2}{4\pi\sigma_x\sigma_y}$$

High bunch charge

High energy

$$\mathcal{L} \propto B \frac{N_0}{\epsilon} \gamma P_{beam}$$

High field in collider ring

Small emittance

High beam power

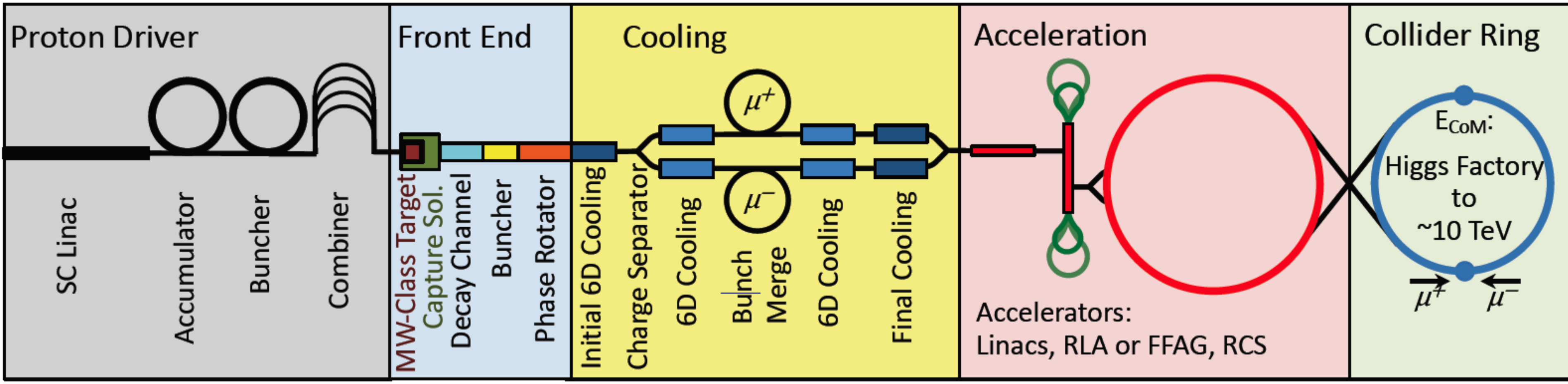
Win luminosity per power as the energy increases

In linear colliders, luminosity per power tends to be energy independent

- except if one changes technology (very short bunches, smaller vertical emittance)

In circular electron-positron colliders luminosity drops rapidly with energy (power ≈3.5)

Source and Cooling Overview



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled

Acceleration to collision energy

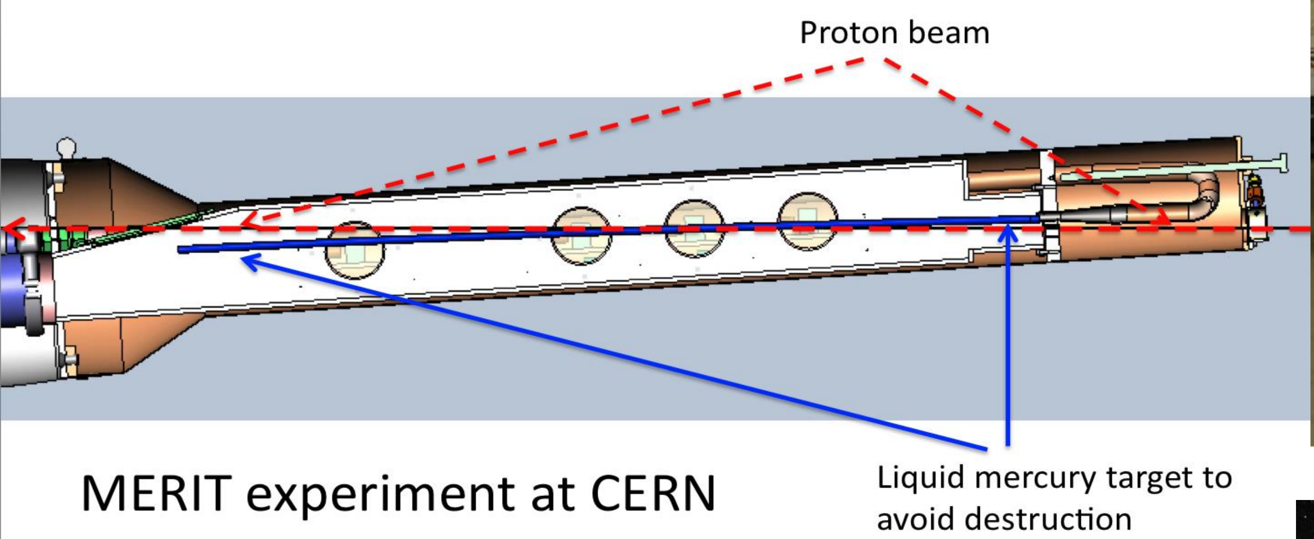
Collision

Pions decay into muons that can be captured

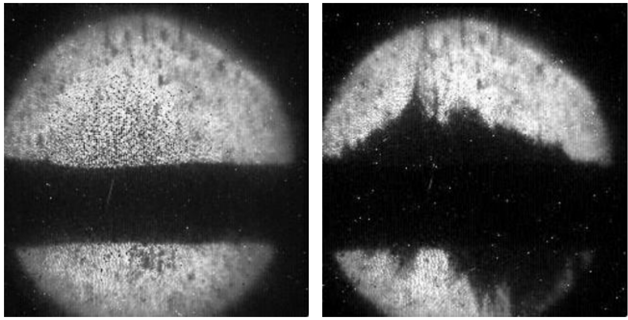
80 GeV proton energy per muon

Source

Protons → Target → Pions → Muons



MERIT experiment at CERN



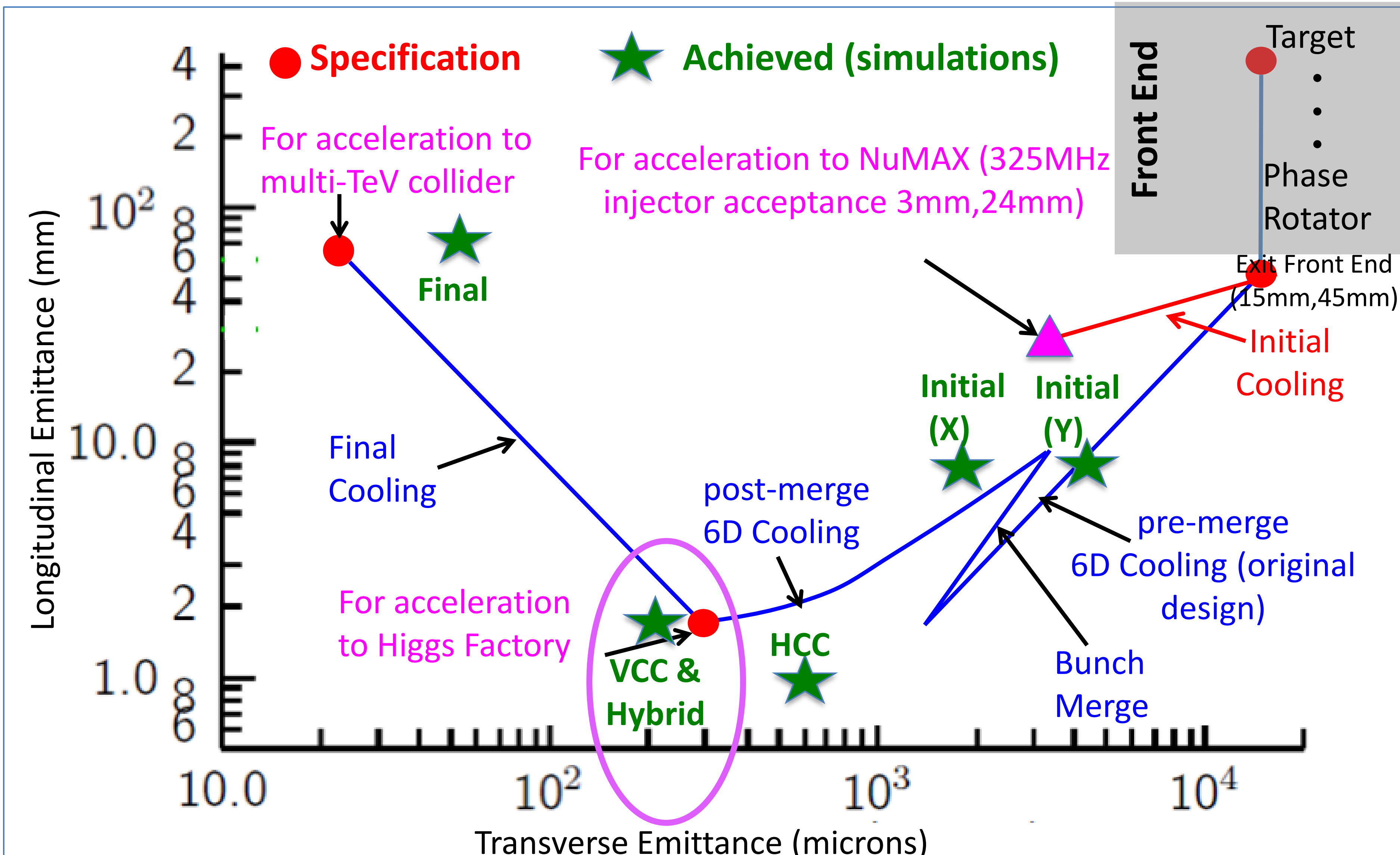
High power target (8MW) has been demonstrated

Maximum of 30×10^{12} protons with 24 GeV

But radiation issues?

What could be made available at CERN (or elsewhere) as a proton driver for a potential test facility?

Cooling: The Emittance Path



Emittance

- Emittance cooling due to ionisation and limited by multiple scattering

$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

- Equilibrium depends on the material properties and on the local beta-function

$$\epsilon_{eq} = \frac{1}{v/c}\frac{(14\,\mathrm{MeV})^2}{m_\mu c^2}\frac{1}{L_R\frac{dE}{ds}}\beta$$

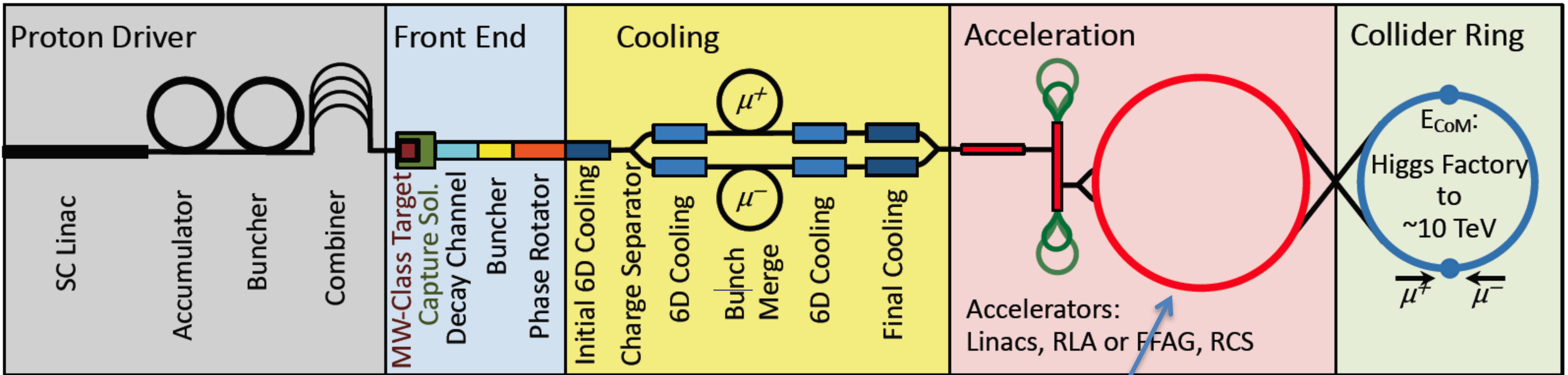
- Material with maximum energy loss per radiation length
- Small beta-function is achieved using strong solenoids
  - Alternative is to use short waists
  - Parametric cooling is doing this in a special fashion
- Developing energy spread needs to be removed with chromatic/dispersive lattice and wedges

Key Issues

- The theoretically predicted emittance is larger than the target value
  - need to make new designs, also taking advantage of hardware improvements
- MICE focused on the larger emittance end of the cooling, how important is the small emittance end ?
  - I think it is important
  - How close to the target value do we have to demonstrate?
- What remains to be done to fully validate the hardware?
  - MICE performance values vs. requirements for collider
  - High radiation environment
  - …
- 6D cooling remains to be demonstrated
- Parametric ionisation cooling remains to be demonstrated
  - I still need to understand how this differs from a sequence of waists with decreasing beta-functions

- A new test facility could address these issues
  - What would be required?
  - Which proton source would be available?
  - Which infrastructures are available?
  - What would need to be added?

Beam Acceleration



Had some difficulty finding detailed information

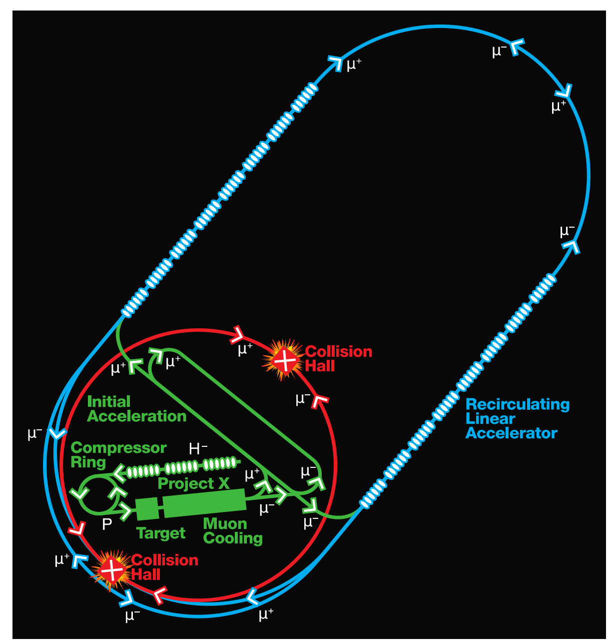
A trade-off between cost and muon survival

Options that are considered are

- Recirculating linac
- Rapid cycling synchrotron
- Rapid cycling synchrotron with mixed magnets
- Final acceleration in collider ring

An important cost driver

Much larger than collider ring



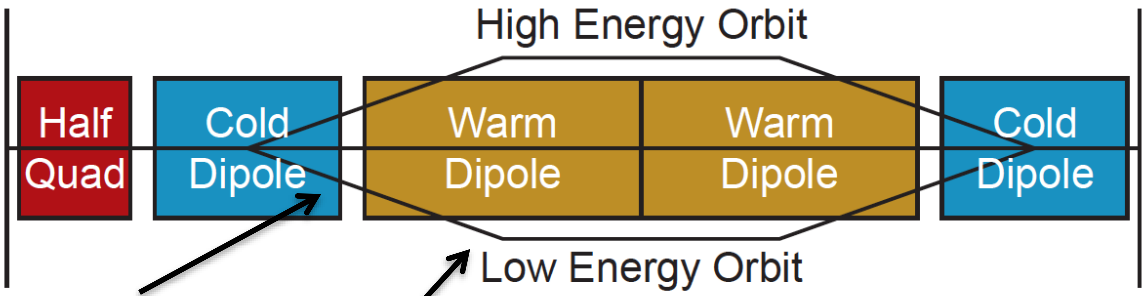
Rapid Cycling Synchrotron

Use fast ramping normal conducting magnets

- Limits field to 1.4-2 T

Use mixture of high field static magnets and fast ramping normal conducting magnets

- Normal magnets change sign
- Can about double the effective field reach



Low energy beam is bend too much

But normal magnets bend back

Significant aperture required to accommodate different beams

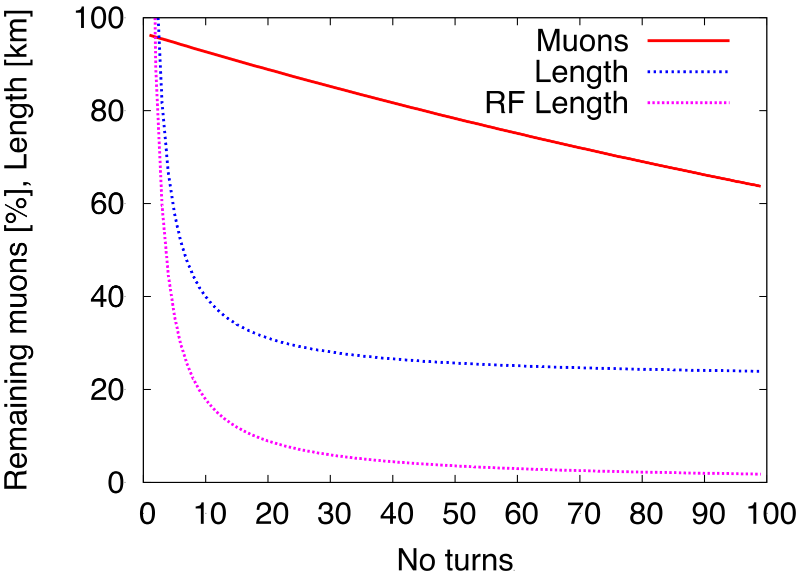
How much energy is required to ramp magnets?
Can some be recovered?

(Bad) Example Parameters

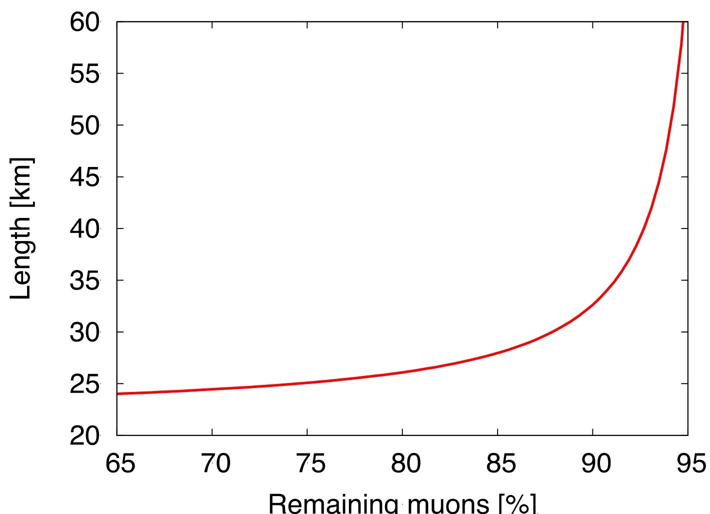
Assuming

- Injection at 100 GeV
- Acceleration to 3 TeV
- Magnet field of 2 T for warm and 16 T for cold magnets (effective maximum field 3.5 T)
- Filling factor 80% for magnets
- Accelerating gradient of 25 MV/m with filling factor 65%

Just a first try to start thinking



44 turns correspond to 80% survival
I.e. luminosity reduction to 64%
26.2 km long ring
22.1 km of magnets
4.1 km of RF
3.8 ms to ramp



40mm aperture allows for 12 sigma at injection
100m beta-function assumed
Beam larger than in LHC at injection
Need higher injection energy and additional ring

Some Key Issues

Magnets

- Minimisation of energy lost per ramp
  - Minimise power consumption and peak power
- Maximisation of field that can be achieved
  - Reduces accelerator and collider size and hopefully cost
- Control of field level during ramp
  - Maintain muon beam quality

RF systems

- Wakefields
- Power systems
- Cavities and gradient control

Beam dynamics

- Beam stability, wakefields
- Control of beam path length and RF phase and amplitude

Overall design and optimisation

- Also tolerances

Radiation Considerations

- Production of muons
  - Hadronic showers and radiation for equipment and public

- Decay of muons (mainly, but not only in collider ring)
  - Background for the detector
  - Irradiates machine
  - Can produce radiation hazard for the public

- Neutrino radiation is important for site
  - Existing tunnels have straights, which can concentrate radiation at one point
  - Except if we develop a special optics to dilute the radiation (opening cone O(0.1mrad))

- Detector background
  - Actually LEMMA would shine here, integrated study with detector expert

- Collimation and beam dumps

- Detailed study is important
  - FLUKA team, detector experts, radiation experts, civil engineering, beamline design, system experts, …

The LEMMA Scheme

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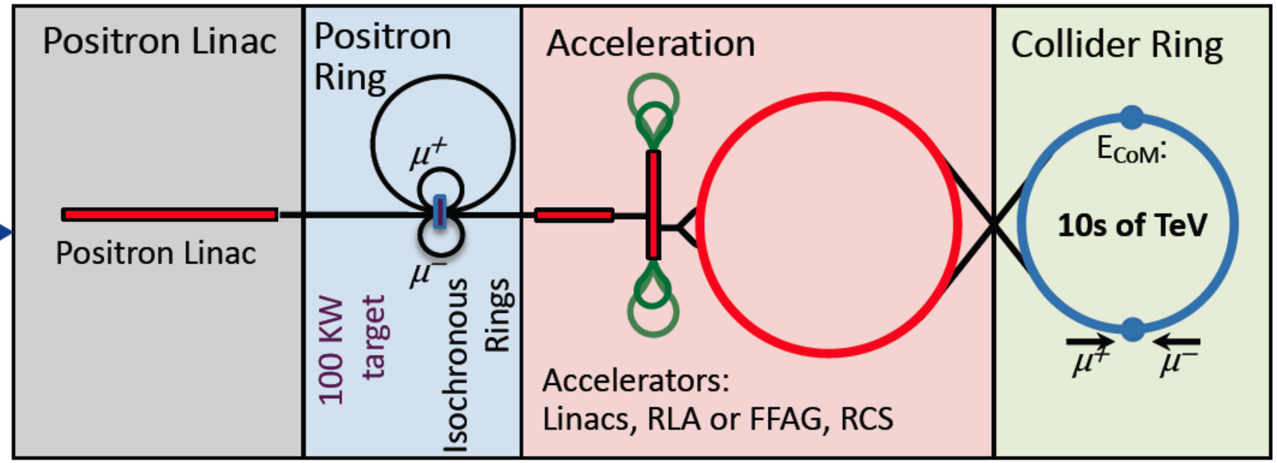


Key concept
Produce low emittance muon beam using a positron beam

- Positron beam passes through target and produces muon pairs
- Muon bunches are circulated through target many times using small rings
- Bunches are extracted and accelerated
- They are combined in the collider ring

Key Issues

Efficiency of converting positrons to muon pairs is small

- Muon pair production is only small fraction of overall cross section
- Most positrons lost with no muon produced
- Have to maintain high positron current (difficult)
- High heat load and stress in target (also difficult)

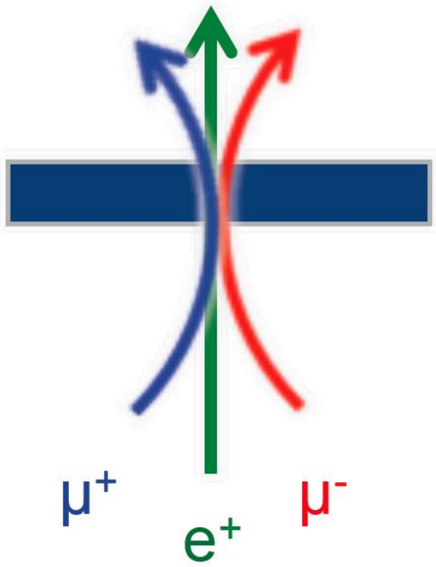
$$e^+e^- \to \mu^+\mu^- \quad O(1\mu b)$$

$$e^+e^- \to e^+e^-\gamma$$

$O(100mb)$, $E_\gamma \geq 0.01\ E_p$

Two additional severe issues were identified

- The multiple scattering of the muons in the target
  - Theoretical best emittance of 600 nm instead of assumed 40 nm
  - Reduction of luminosity by factor 15
- Small bunches were accelerated and later merged but no design exists for the merger
  - The combination factor is proportional to beam energy
  - If the combination does not work, loose a large factor of luminosity



Hope to have an update of consolidation effort this meeting

R&D Programme, First Ideas

- Parameter document
  - Specifying baseline choices and alternatives
  - Specifying relevant design parameters
  - Identify technology drivers
  - Considering LEMMA
  - 3 years to prepare

- Conceptual design of test facility
  - Design cooling test facility
  - What has to be demonstrated?
  - Ready for the next European Strategy Update

- Develop R&D programme
  - Define R&D in addition to test facility
  - E.g. magnets, RF, collimation, beam dumps, detectors
  - Identify synergies with other programmes
  - Start with R&D where affordable
  - Also for the next Strategy update

Conclusion

- The proton-driver scheme has no obvious showstoppers
  - But we do not yet have a European design to be evaluated
    - A conceptual design is needed
    - Parts are missing in the past efforts, e.g. acceleration complex
  - Key issues are
    - Muon cooling
    - Detector backgrounds
    - Acceleration cost and efficiency
    - Collider ring design
    - Neutrino radiation issues
    - Fast ramping magnets
    - …

- The LEMMA scheme would address a number of issues of the muon collider by using low emittance beams
  - E.g. reduced radiation due to lower muon current
  - Less background in the detectors
- But critical issues have been identified and need to be solved
  - An effort is ongoing

Conclusion

- Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration with leptons.

- The development of the challenging technologies for the frontier muon accelerators has shown enormous progress in addressing the feasibility of major technical issues with R&D performed by international collaborations.
- Important R&D remains to be performed to arrive at a viable conceptual muon collider design
  - Make an integrated conceptual baseline design (may contain alternatives)
    - Design and specifications that can be criticized by a variety of experts
  - Prepare a CDR for a test facility concentrating on the production and cooling
  - Development, prototyping and test of individual key components, in particular magnets and RF systems
  - Address radiation issues

- In Europe, the reuse of existing facilities and infrastructure for a muon collider is of interest. In particular the implementation of a muon collider in the LHC tunnel appears promising, but detailed studies are required to establish feasibility, performance and cost of such a project.
  - These studies are very site specific, the devil is in the detail