Muon Collider
Status and Plans

UPHUK8

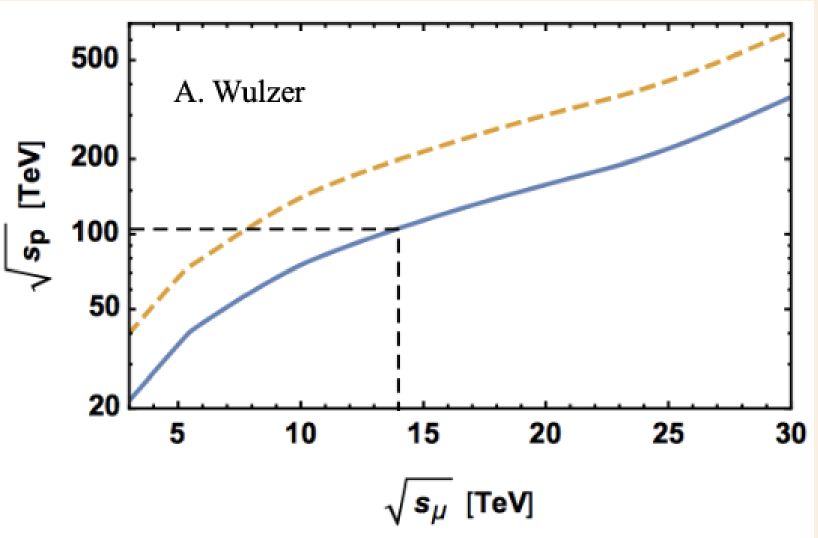
Bodrum, 5th September 2022

Christian Carli on behalf of the International Muon Collider Collaboration (IMCC)

Present status of ideas on muon colliders based on several studies in the past and, in particular, the MAP study. Many of the images taken from MAP publications.

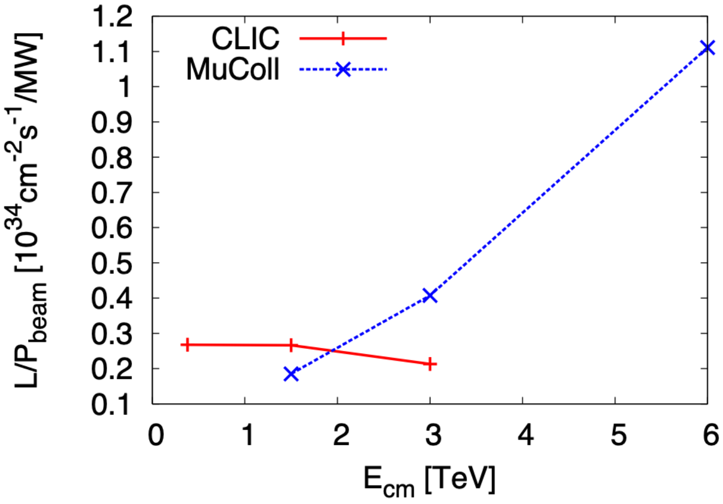
Content

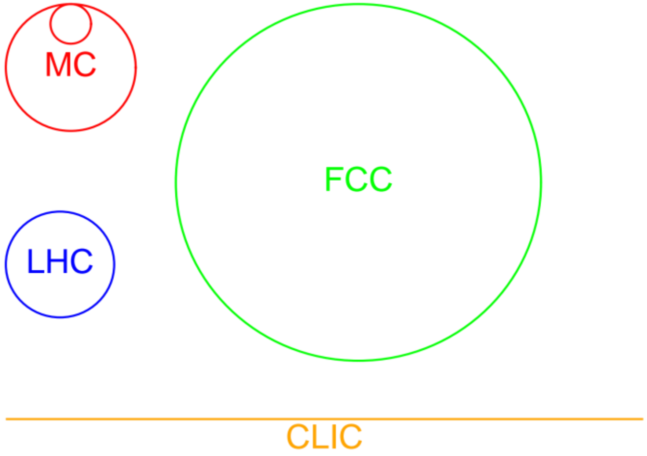
Introduction



- High energy lepton colliders precision and discovery machines
  - Given physics reach with at lower energies than for proton colliders
- Electron-positron colliders limited by low particle mass
  - Energy loss from synchrotron radiation for circular colliders
  - Length for linear colliders
- Collide muons – leptons with mass ~105 MeV
    - Feasible lepton circular collider
    - Same (higher) physics reach at lower beam energy than hadron collider
  - Drawbacks and limitations
    - Effort to generate useful muon beams, still resulting in large emittance
    - Low life-time of ~2.2 us in muon rest frame
      => Fast (ionization) cooling and acceleration (e.g., by pulsed synchrotrons)

Introduction



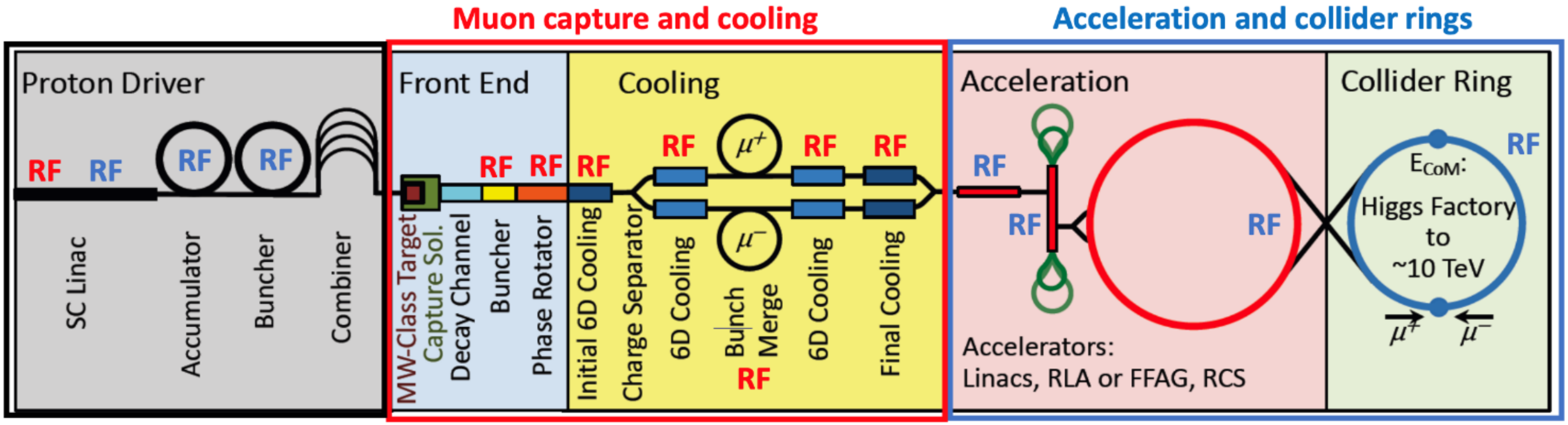


- Luminosity per beam power as function of beam energy
  - Ratio of luminosity to beam power increases with beam energy
  - Muon collider attractive in particular for high energies

- Facility footprints for different high energy physics projects
- 10 TeV muon collider
  - Footprint comparable to 3 TeV CLIC …
  - … with physics potential comparable to FCC-pp

Introduction

- Muon collider studies exist since decades
  - First proposal about 50 years ago, concepts with ionization cooling in the 80ies
  - Studies in US and Russia in the 90ies, later at CERN
- Muon Accelerator program
  - US initiative launched in 2011



From MAP study

- International Muon Collider Collaboration IMCC working on 10+ TeV scheme

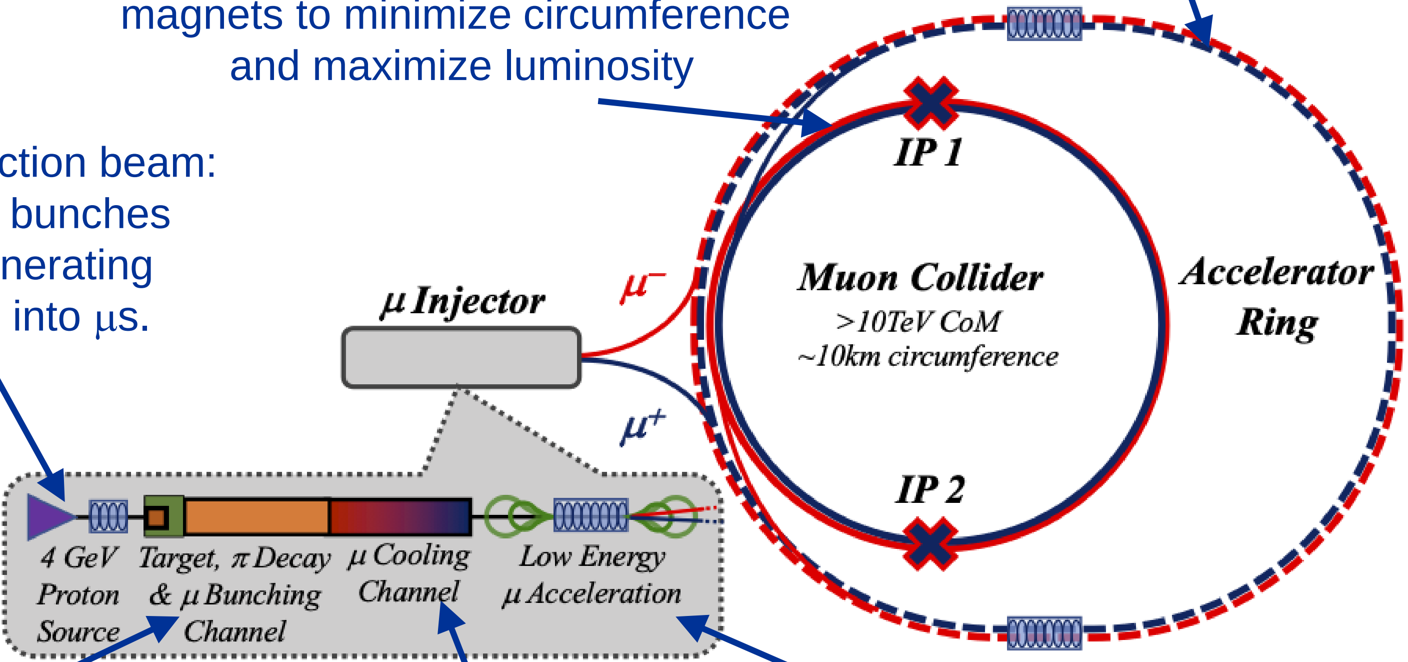
Design Baseline Overview

Short beam life-time:
=> Ionization cooling, fast acceleration,
high RF gradients and high field magnets!

Acceleration in a sequence of
pulsed synchrotrons
(last one larger than collider)

Collider: tightly packed high field
magnets to minimize circumference
and maximize luminosity

Few MW production beam:
short intense bunches
on target generating
πs decaying into μs.



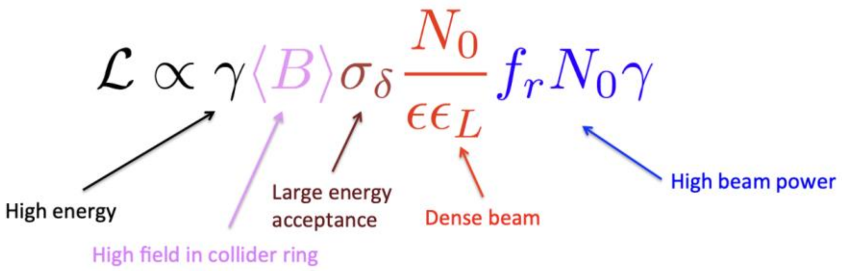
Target and capture
channel: large energy
μ beam transformed
to sequence of bunches

Cooling stages and
merging of μ bunches
into one bunch

Low energy acceleration
In recirculating Linacs

Design Baseline Overview

tentative parameter list for IMCC study



$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon\epsilon_L} f_r N_0 \gamma$$

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

High (average) magnetic field

Relative energy spread kept constant at 10^{-3}

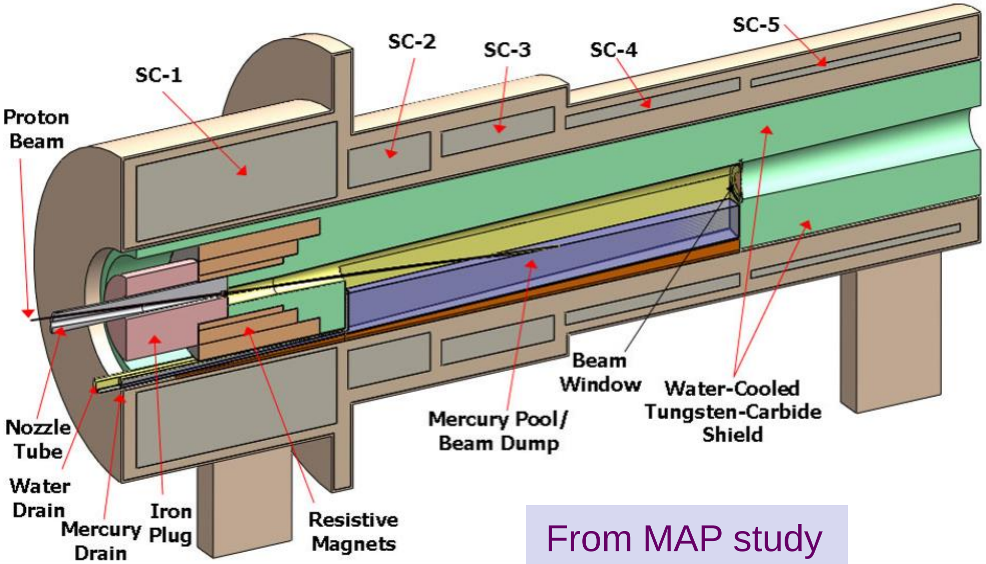
Bunch length and β^* decreasing with beam energy

Muon Production and Capture

- Production beam
  - A few (1-4) MW proton beam with a few GeV beam energy
  - Short bunch length of a few ns!
  - Could be a SC linac followed by accumulator and compressor rings

- Target
  - Options: graphite, liquid metal jet (mercury tested with MERIT experiment or powder) …
  - P+ N -> π + X followed by decay with charged πs decaying into μs
  - Large energy distribution of muons

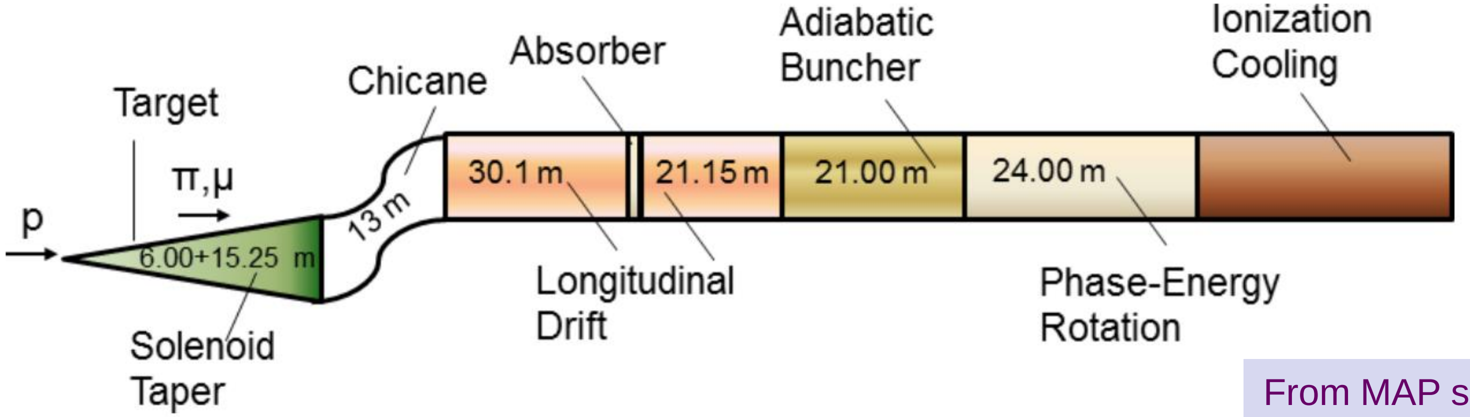
- Magnetic field taper
  - Aim: collection of muons in range 50 MeV to 400 MeV
  - Target in high field ~20 T to minimize transverse emittance
  - Reduction to ~2 T over ~10m length a compromise between transverse and long. blow-up



From MAP study

Muon Production and Capture

- Transformation of large energy spread muon beam into sequence of bunches
  - Target and drift followed by chicane to remove most unwanted particle
  - Be absorbed stopping protons in momentum range of selected muons



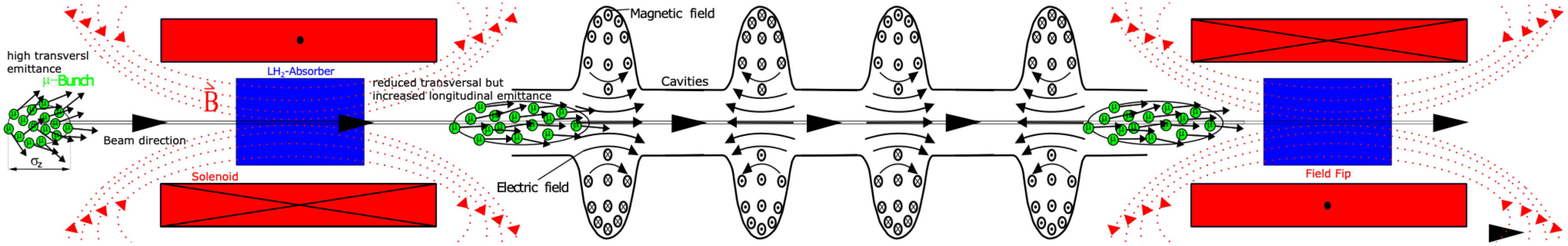
From MAP study

- Drift: generation of correlation between energy and longitudinal position
- RF cavity section to create longitudinal structure (bunches)
  - Muon distribution still becoming longer => RF frequency decreasing over buncher section
- Phase-energy rotation: accelerate low energy bunches coming late, decelerate high energy bunches coming early
  - Appropriate choice of RF frequency and phase
  - Again frequency varying over over phase-energy rotation section
- Result: train of bunches with about equal energy suitable for ionization cooling

Muon Cooling

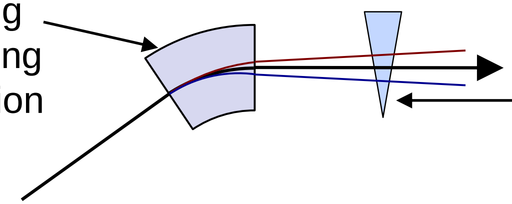
Principle

- Principle of (transverse) ionization cooling

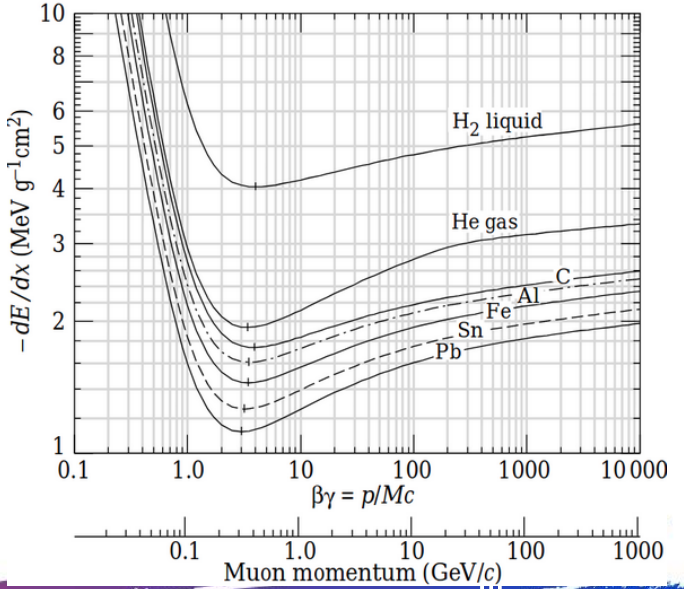


  - Absorber: reduction of both the longitudinal and transverse momentum
  - Cavities: acceleration, i.e., increase of only longitudinal momentum
  - Net effect: reduction of transverse momentum and, thus, beam cooling
  - Scattering leads to beam blow-up – need for strong focusing solenoids and low Z absorbers
- Longitudinal cooling (or heating)
  - Dependence of energy loss on energy
  - Dispersion and wedge shaped absorber

Bending generating dispersion



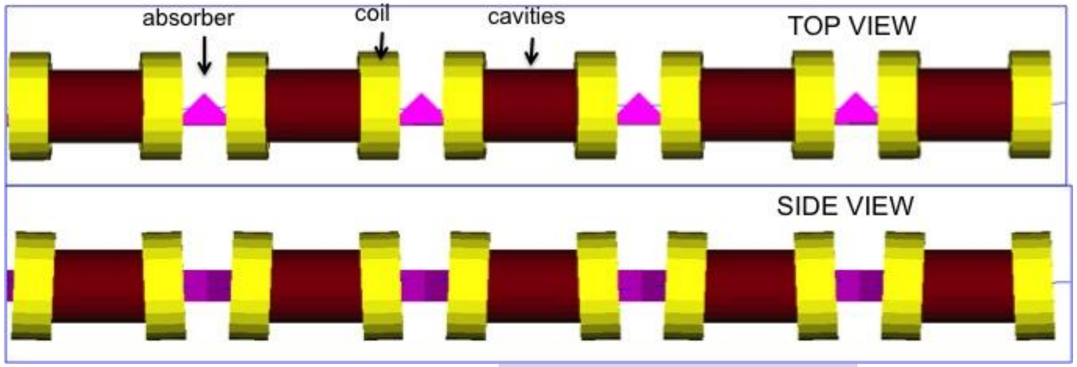
Absorber slowing down high (low) momenta more (less)



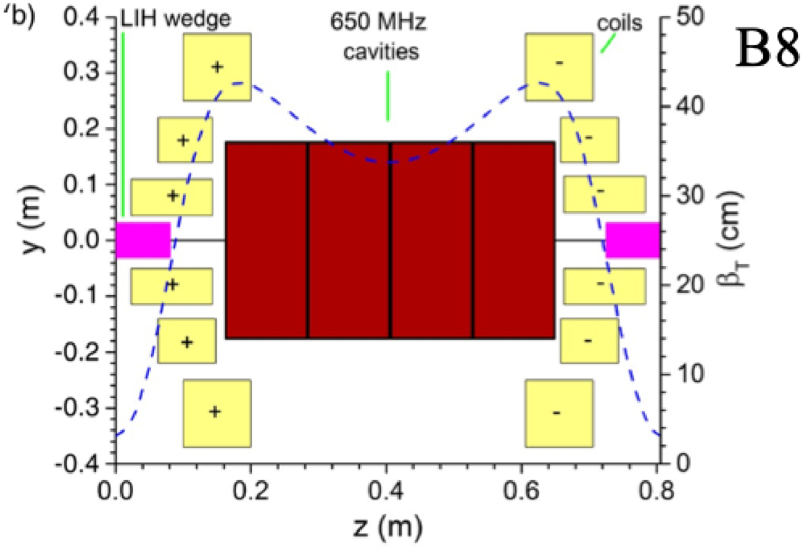
Muon Cooling

6D Cooling Channels

- First 6D cooling channel suitable for neutrino factory
- High field solenoids for focusing
  - Minimum Twiss betatron function β_T at absorber location
  - Tilting of solenoids
  - Solenoid polarity reversals
    - Dispersion from vertical magnetic field for longitudinal cooling
- Low Z absorbers: Liquid H_2 and LiH
- Cavities in high magnetic field region
- 6D cooling
  - Between muon capture and bunch merging
    - Interleaved with separation of μ^+ and μ^-
  - Between bunch merging and final cooling



From MAP study

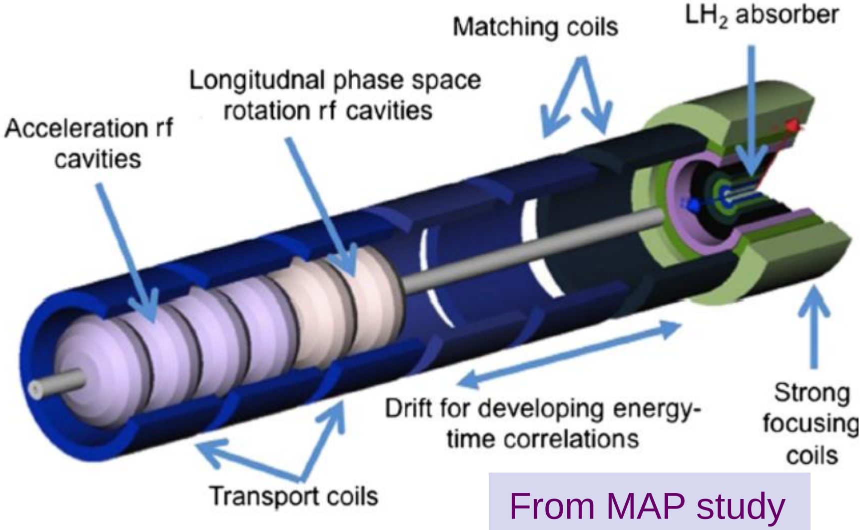


Last section of 6D cooling after bunch merge

Muon Cooling

Bunch merging and final cooling

- Bunch merging – transformation of train of 21 bunches into one bunch
  - Longitudinal gymnastics combining three bunches, resulting in 7 bunches
  - Transverse merging
- Followed by another 6D cooling channel
  - Equilibrium transverse emittances too large, small longitudinal emittance
- Final cooling channel
  - Gradually decreasing energy to reach smaller transverse emittances
  - Absorber liquid H_2
  - No longitudinal cooling resulting in significant blow-up
  - High magnetic field (~30T) at absorber location

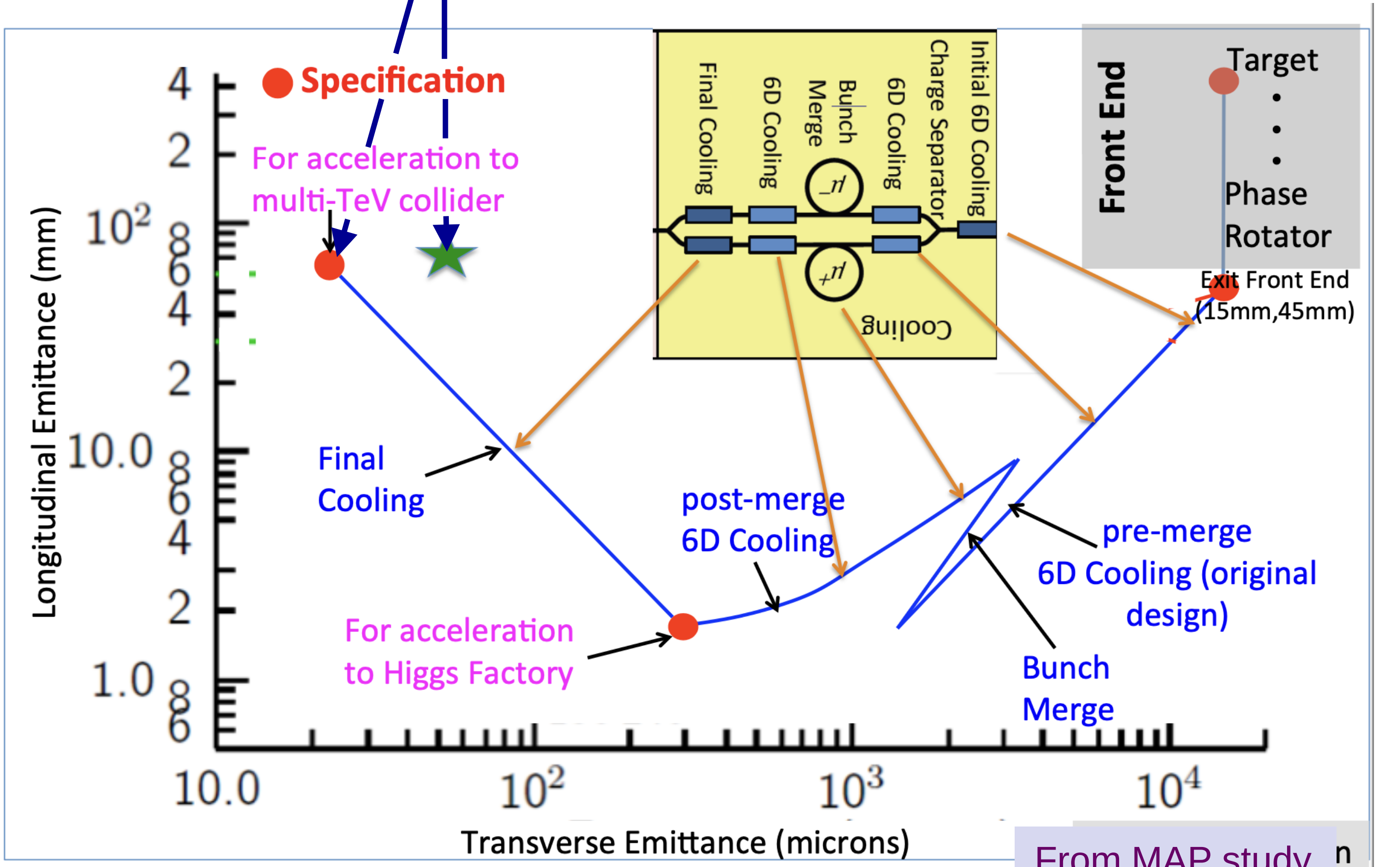


From MAP study

Muon Cooling

Emittance evolution

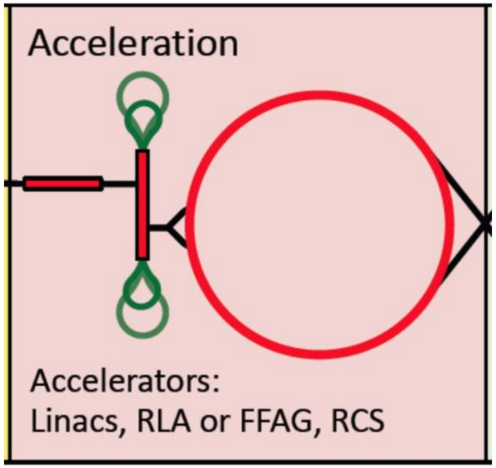
Missing factor 2 between emittances
obtained in simulations and expected for collider
to be gained by optimized final cooling design

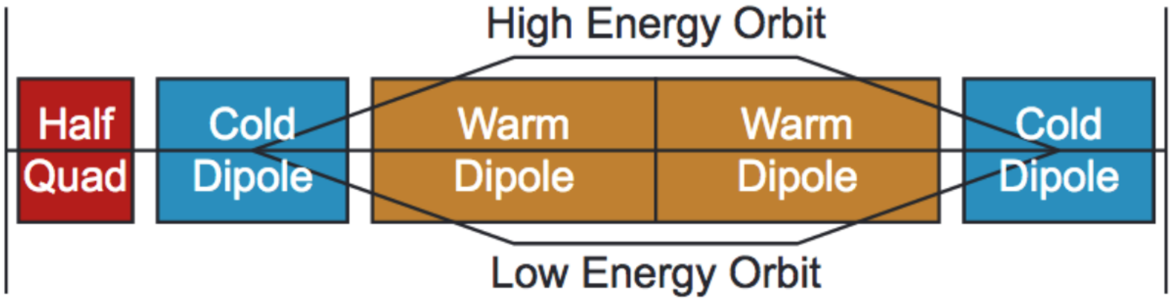


From MAP study

Acceleration

- Fast acceleration and high (average) RF gradients needed to avoid muon losses due to decay
- Starting with (re-circulating) Linacs
- Followed by “pulsed synchrotrons”
  - Acceleration within few tens of turns!
  - Combination of static SC bends and pulsed conventional bends (changing polarity)



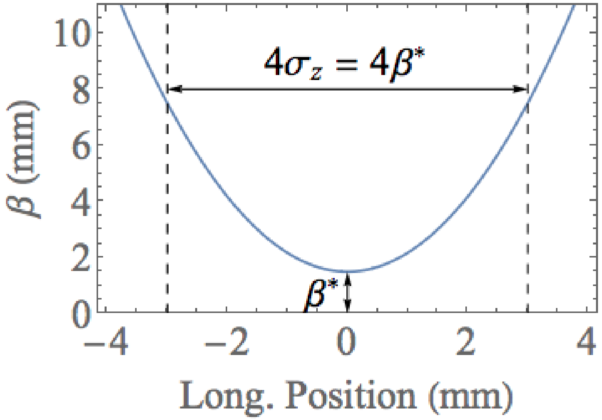


  - Ongoing work:
    - ☐ Orbit excursions – minimization of resulting circumference variation for RF
    - ☐ Magnet powering and Eddy currents a challenge, in particular, for lower energy rings
  - FFAs a possible alternative

Muon Collider Ring

- Assumptions and parameters
  - Lattice study concentrating on 10 TeV com collider => beam E = 5000 MeV
    - Increase in energy compared to previous studies
  - High magnetic fields and ≈10 km circumference for high luminosity
  - Longitudinal (rms) emittance ε_L = 7.5 MeV m, transv. emittance ε_T = 25 μm
  - Maximum acceptable rms momentum spread σ_δ R = ≈ 10^{-3}
    - Gives bunch length $\sigma_z = \varepsilon_l/(\sigma_\delta\ E)$ = 1.5 mm

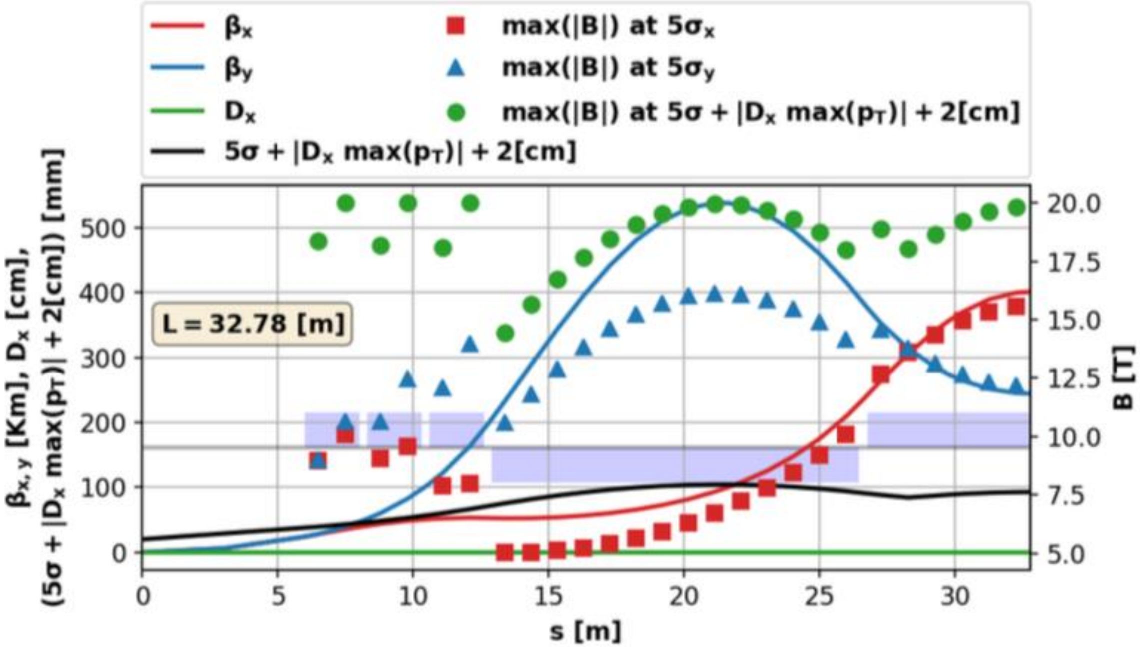
    => Challenging, short bunch length needed over ≈1000 turns
    => linear and non-linear momentum compaction, path length increase due to divergence
  - Twiss beta function at IR $\beta^{*=}\sigma_z = \varepsilon_l/(\sigma_\delta\ E)$ = 1.5 mm
    - "Hour glass" effect f_{hg} describes luminosity reduction if bunch length is not negligible (collisions at different longitudinal positions with different Twiss β)
    - For $\beta^{*=}\sigma_z$ one gets f_{hg} $(\beta^* = \sigma_z) \approx 0.76$, little gain by going to $\beta^{*=}$smaller than σ_z
    - Energy increase results in higher beam rigidity, but unchanged divergence at IP
    - Larger maximum Twiss β–functions around IP



- Challenging conditions for collider lattice design!

Muon Collider Ring

- Interaction region
  - Small β^* and high beam rigidity (energy)
    - Lead to long quadrupole triplet and large maximum β
    - Despite large maximum magnetic field (or quadrupole gradient) assumed
    - Different versions without or with dipolar (bending) field components to remove decay products

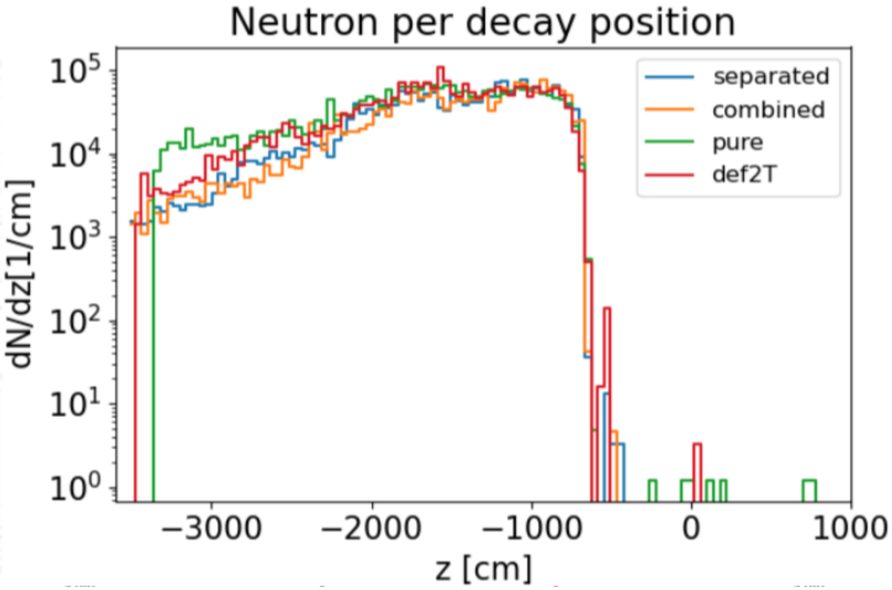


From K. Skoufaris

    - Version here without dipolar fields

Muon Collider Ring

- Interaction region
  - Beam Induced Background (BIB): particles from decays seen by detector and perturbing data taking an issue
  - MAP study (lower energy) concluded that dipolar fields mitigate

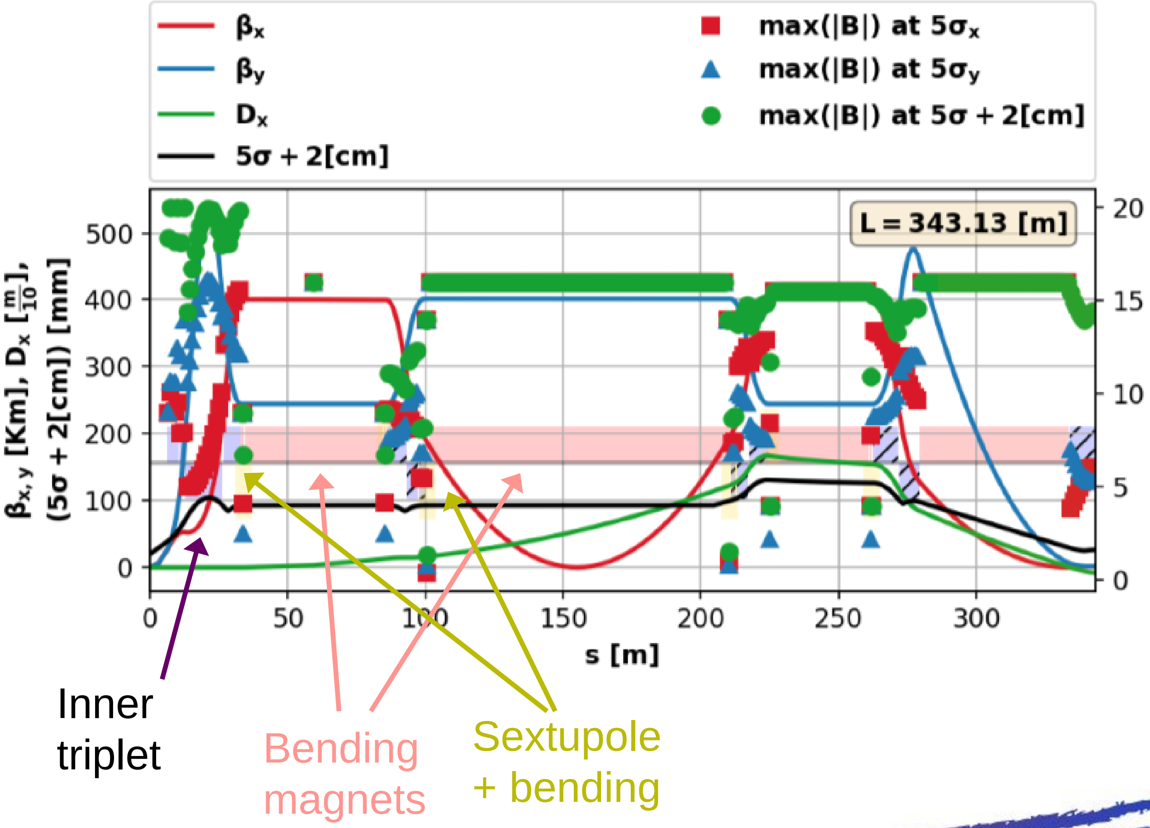


From D. Calzolari, A. Lechner et al.

  - Similar shape of particle flux versus decay position for different species
  - Only week reduction of BIB seen for 10 TeV lattice with FLUKA

Muon Collider Ring

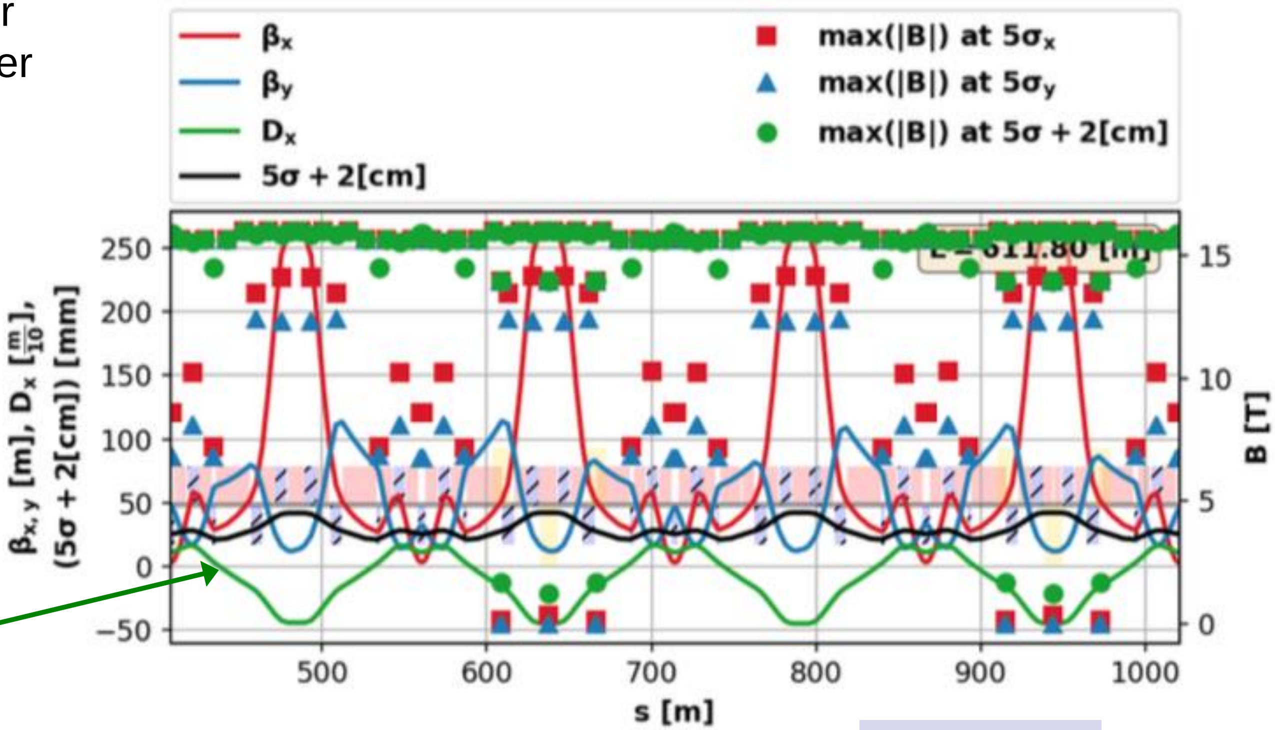
- Local chromaticity correction
  - Quadrupole strength depending on momentum
  - Needed due to strong inner triplet, large maximum Twiss β and large energy spread
  - Sextupoles in regions with dispersion to correct chromaticity …
  - … introduce non-linearities, which make the design tricky



From Skoufaris

Muon Collider Ring

- Flexible Momentum Compaction cells for arc
  - To keep short bunch length with large momentum spread
  - Good control of path length for off-momentum particles $\delta = \Delta p/p$
  - Each cells with regions with
    - positive (longer path for $\delta>0$) and
    - negative dispersion (shortcut for $\delta>0$) regions
  - In average, path shorter for $\delta>0$ to compensate for other parts of machine

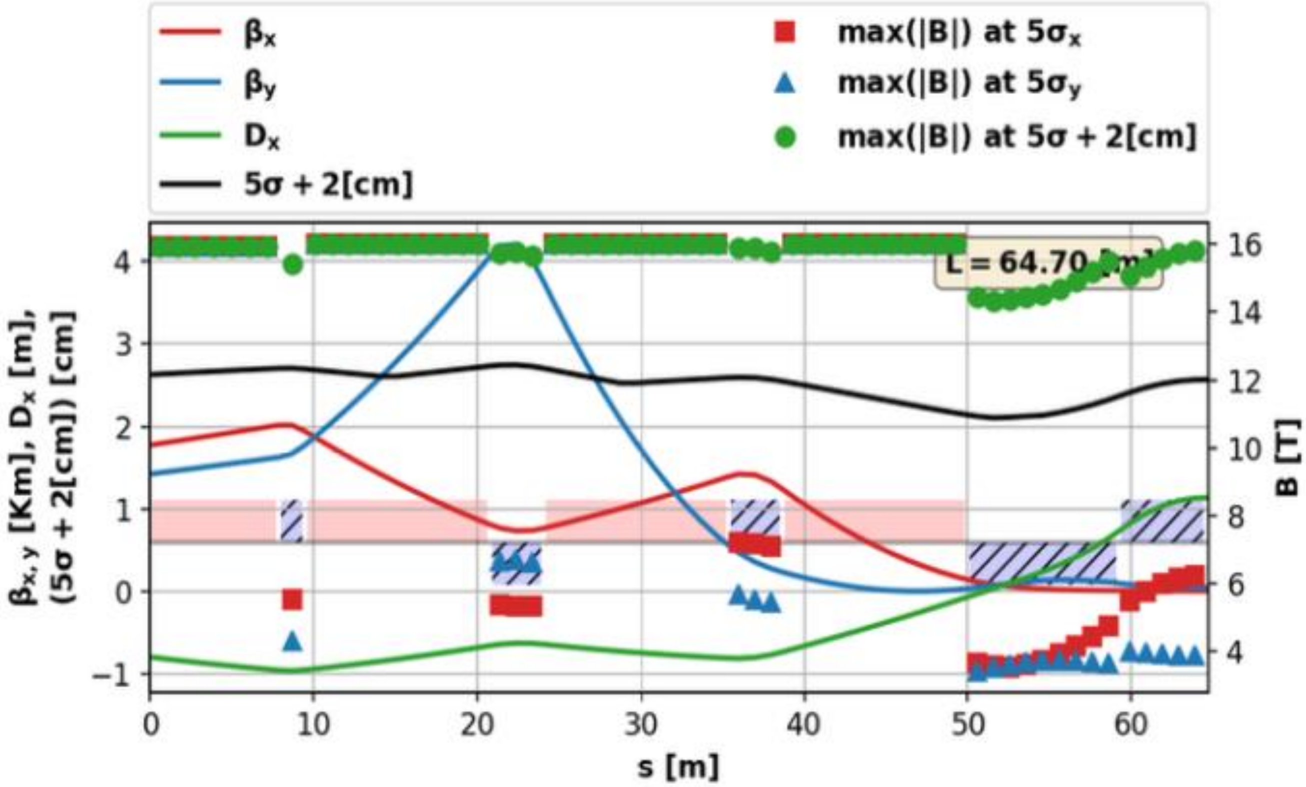


dispersion

From
K. Skoufaris

Muon Collider Ring

- Matching section
  - Linking chromatic compensation section to arc



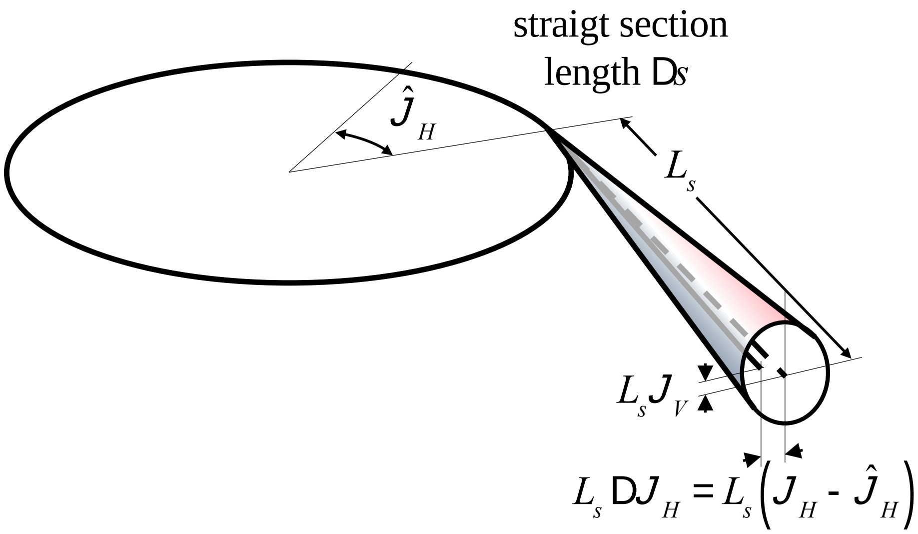
- Status
  - Full linear lattice section available and looking reasonable
    - IR, chromatic compensation, matching and arc cells
  - Study ongoing to understand and cure too small dynamic aperture – improvements expected using octupoles

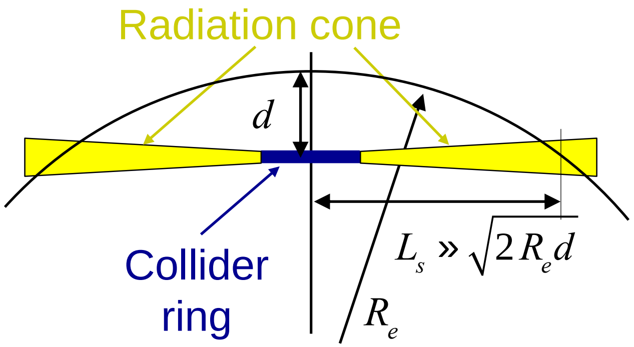
  - Work in progress!

Neutrino Radiation Issue

- Radiation due to showers generated by neutrinos reaching the earth surface
  - Matter in front (“shielding”) does not help but makes situation even worse
  - Narrow radiation “cone” for a short piece of the machine with length

- Strong increase with muon energy
  - Cross sections about proportional to energy
  - Typical energy per interaction of neutrino with matter proportional to muon energy
  - Opening of radiation inversely proportional to muon energy





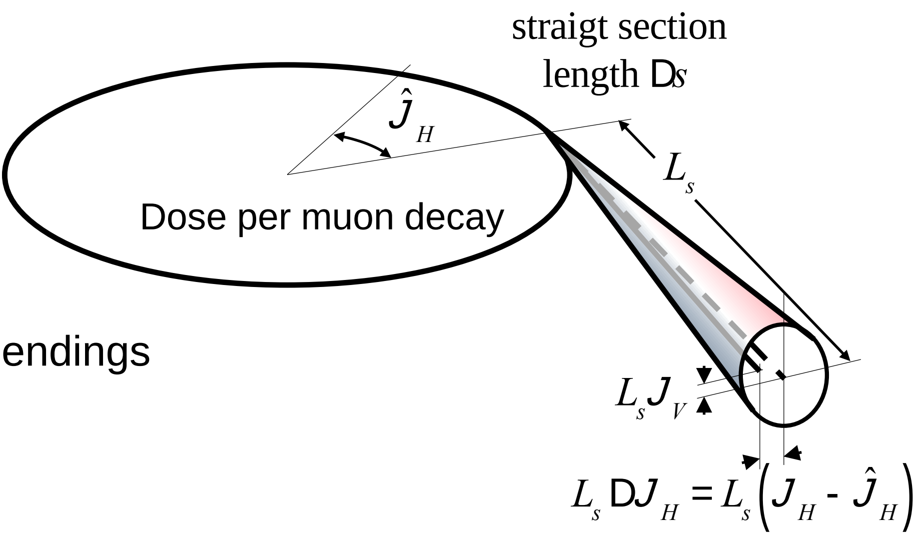
Neutrino Radiation Issue

- From analytical estimates

$$DD \approx \left(1.104\cdot 10^{-28}\ \text{Gy m}^2\right)\frac{4g^4}{p L_s^2}\frac{1}{\left(1+g^2\left(d/L_s\right)^2\right)^4}$$

$$\approx \left(1.104\cdot 10^{-28}\ \text{Gy m}^2\right)\frac{4g^4}{p L_s^2}\, e^{-3g^2\left(d/L_S\right)^2}$$

  - Narrow cone spread in horizontal plane by bendings

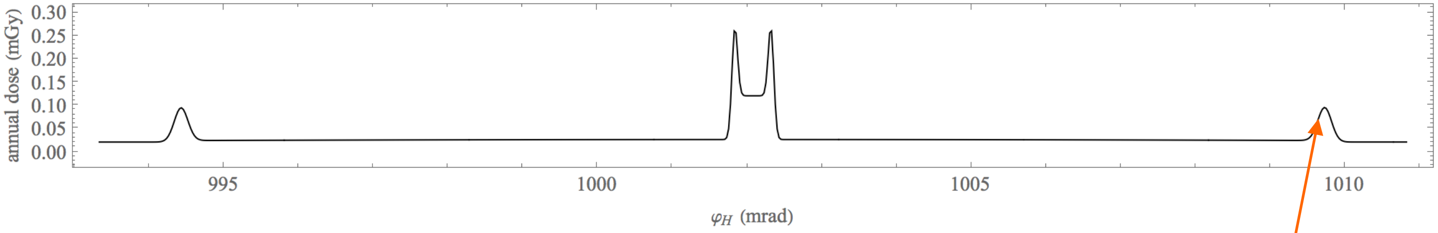


- Mitigation
  - No long straight sections other than the IR
    - Maximum straight between magnets say 0.3 m
    - Dipolar fields added to quadrupoles and sextupoles
  - Localize neutrino radiation from straight with IR in inhabited area (sea, steep mountain ..)
  - Installation deep underground
  - For high energies (say >3TeV) wobbling of collider
    - Periodic deformation of machine out of horizontal plane
    - In amplitude and phase
    - Precise movement system and horizontal B needed
    - Delicate for beam optics (vertical dispersion)

Neutrino Radiation Issue

Some Evaluations with realistic Lattice for 3 TeV

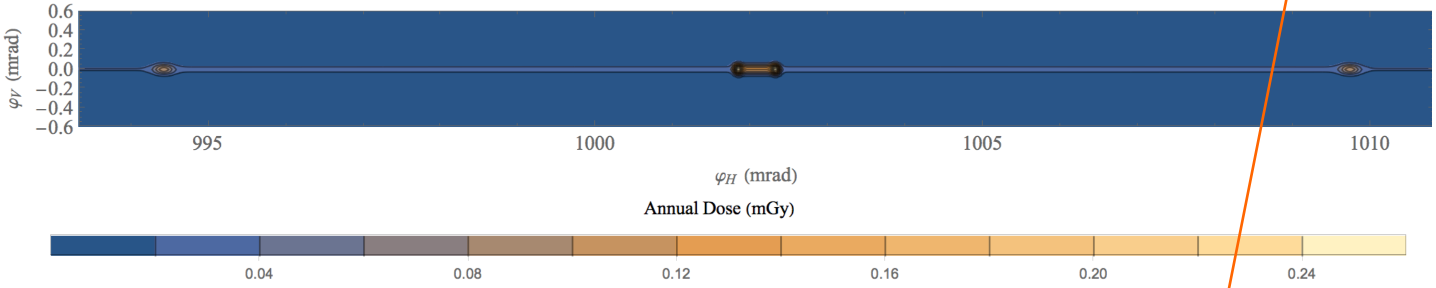
Radiation at earth surface due to neutrinos for 3 TeV collider arc cell 100 m underground



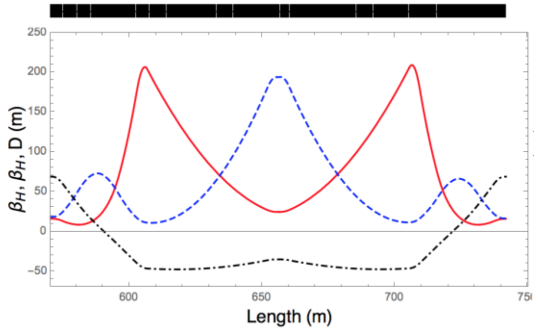
$N_m = 2\times10^{12}$

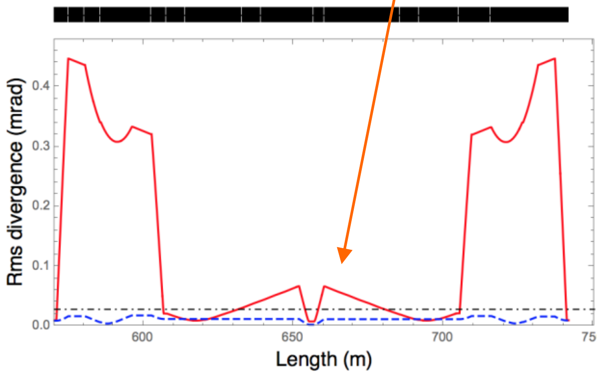
$f_r = 12$ Hz

$d = 100$ m



5000 h operation



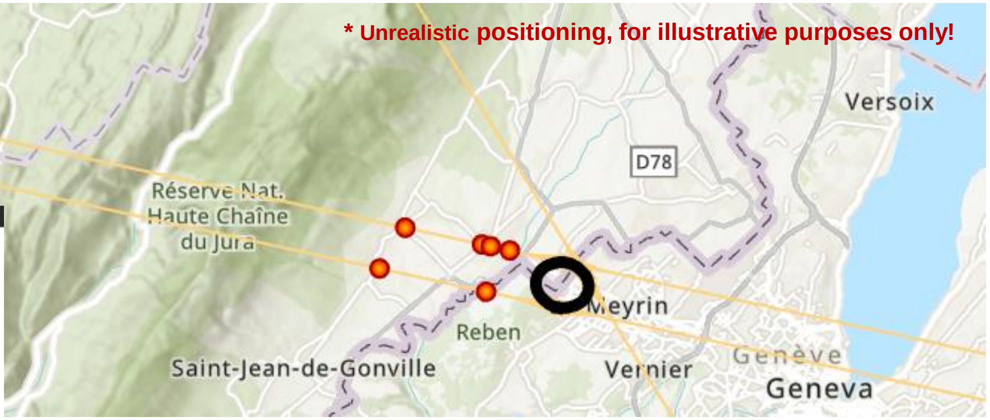


Plans:

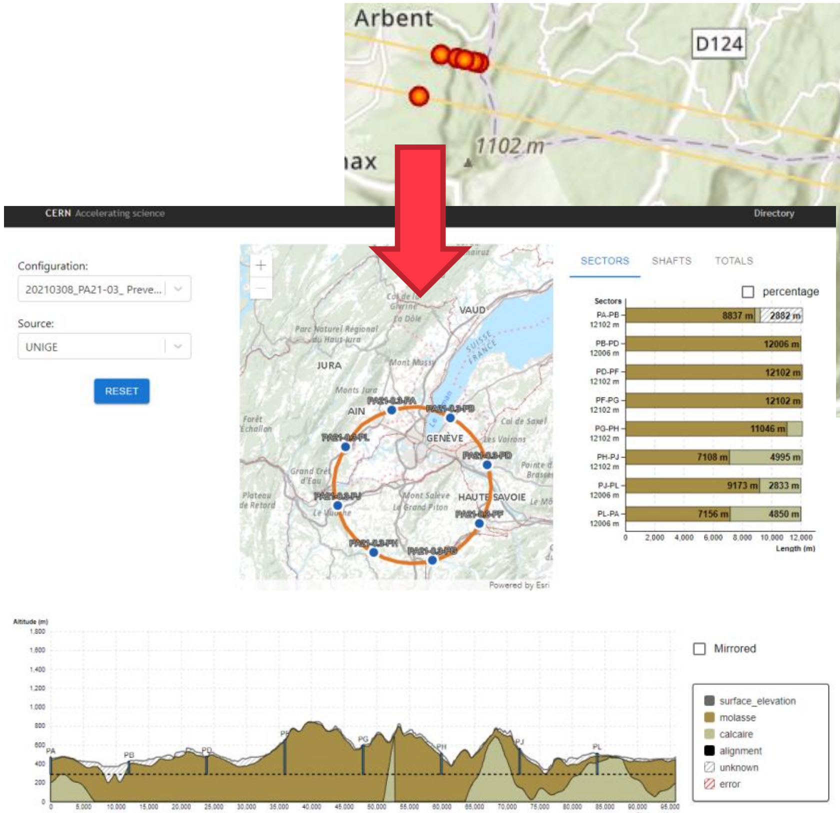
- Use FLUKA simulation results to improve precision
- Evaluation for 10 TeV collider (with wobbling)

Neutrino Radiation Issue

Geoprofiler tool for suitable collider positioning



*** Unrealistic positioning, for illustrative purposes only!**



Configuration: 20210308_PA21-03_ Preve...

Source: UNIGE

*** Prototype, for illustrative purposes only!**

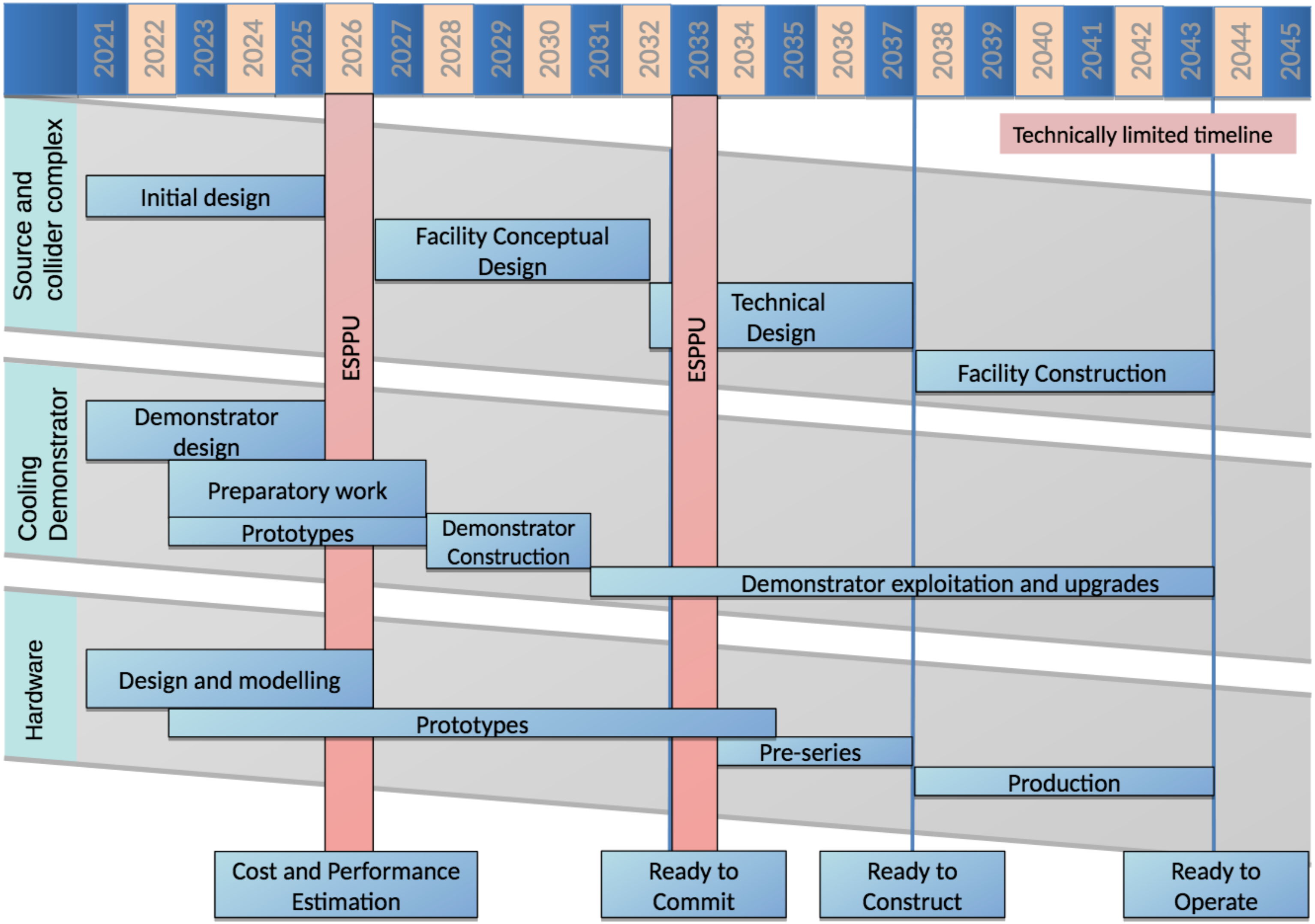
Geoprofiler Application – currently focused on geological analysis

- Edit and reposition the ring
- Detailed knowledge of shape of earth surface
- Recalculation of the geology along the tunnel
- Positions where tangential to ring reaches earth surface
- Information about impacted areas (rights, urbanization …)

From
G. Lacerda et al.

Tentative Timeline

(technically limited)



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

ESPPU

ESPPU

Source and collider complex

- Initial design
- Facility Conceptual Design
- Technical Design
- Facility Construction

Cooling Demonstrator

- Demonstrator design
- Preparatory work
- Prototypes
- Demonstrator Construction
- Demonstrator exploitation and upgrades

Hardware

- Design and modelling
- Prototypes
- Pre-series
- Production

Cost and Performance Estimation

Ready to Commit

Ready to Construct

Ready to Operate

Summary

- Muon Collider considered as future high energy project
  - Circular lepton collider not limited by beam energy loss due to synchrotron radiation
  - Very attractive option for high energy physcis
    - High precision and discovery machine equivalent to hadron collider with higher energy
  - Challenges mainly related to effort to generate muon beams and short life-time
- Not as mature as other projects as CLIC, ILC, FCC
  - Still feasibility to be shown and many R&D topics to be addressed
    - Ionization cooling to nominal emittances
    - Target, activation and damage of components, neutrino radiation, heat load
    - Fast acceleration, high field magnets, RF systems ….
    - Collider ring providing sufficient luminosity (small β^* …)
- IMCC aiming at a conceptual design of 10+ TeV com. muon collider
  - Based on several studies made over several decades and, in particular, MAP

The talk used materiel from several sources and, in particular, MAP
Special thanks to D. Schulte and E. Fol for helping with the preparation of the talk