International MUON Collider Collaboration

The Muon Collider

Daniel Schulte

Introduction

Muon collider had been studied mainly in the US (MAP), effort reduced after P5

Other activities mainly in UK (demonstration of ionisation cooling) and at INFN (alternative muon production scheme)

The Laboratory Directors Group (LDG) appointed a working group (chair N. Pastrone) to review the muon collider for the European Strategy Update

- The report was favorable

The updated strategy recommends R&D on muon beams

The LDG initiated an international muon collider collaboration

- kick-off meeting July 3rd, 272 participants

CERN will host the study, we are finalising a Memorandum of Cooperation

High-energy Frontier Proposals

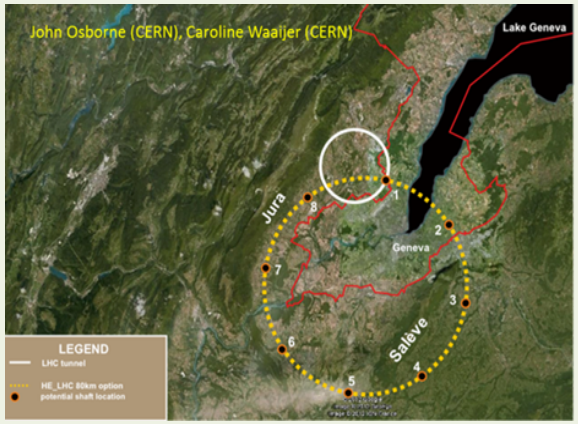
European Strategy Process just finished

Four main high-energy facilities proposed
- two at CERN
- two in Asia

FCC (Future Circular Collider):
FCC-hh
- pp collider with 100 TeV cms
- ion option

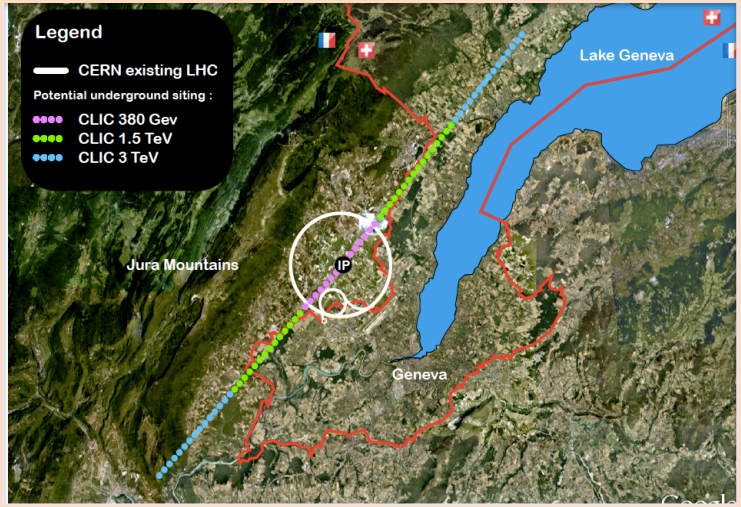
FCC-ee
- Potential e^+e^- first stage

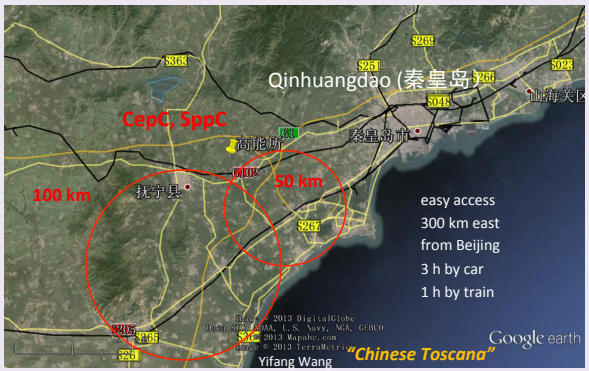
FCC-eh
- additional option



ILC
- 250 GeV electron-positron linear collider
- Japan might host
- limited in energy reach

CLIC
- 380 GeV, 1.5 TeV and 3 TeV electron positron collider





CEPC / SppC
CEPC
- e^+e^- collider 90-240 GeV

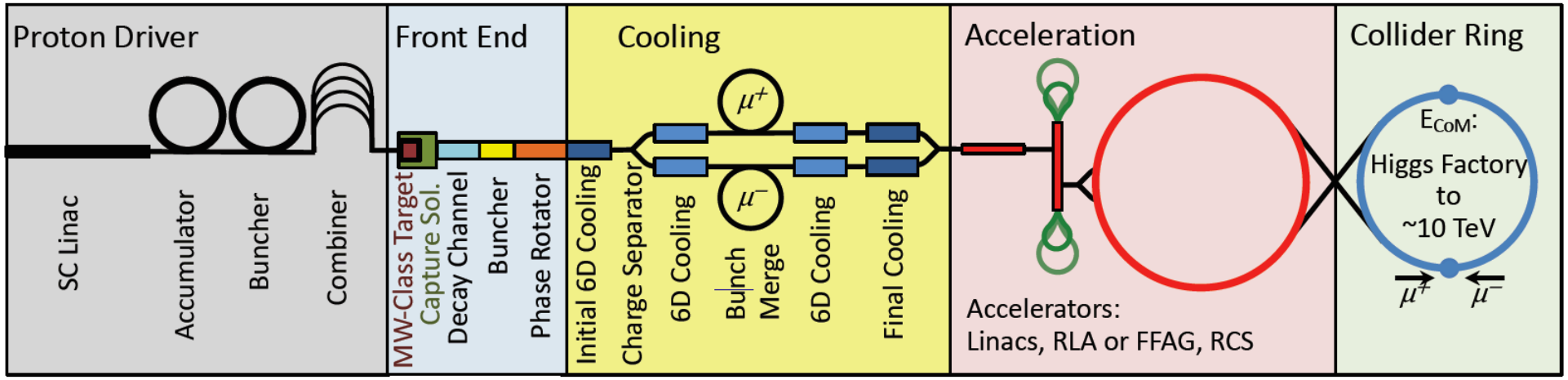
SppC
- 75-150 TeV hadron collider later in the same tunnel

Proposed Projects (ESU)

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Proton-driven Muon Collider Concept

MAP collaboration



Acceleration to collision energy

Collision

Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

Pions decay into muons that can be captured

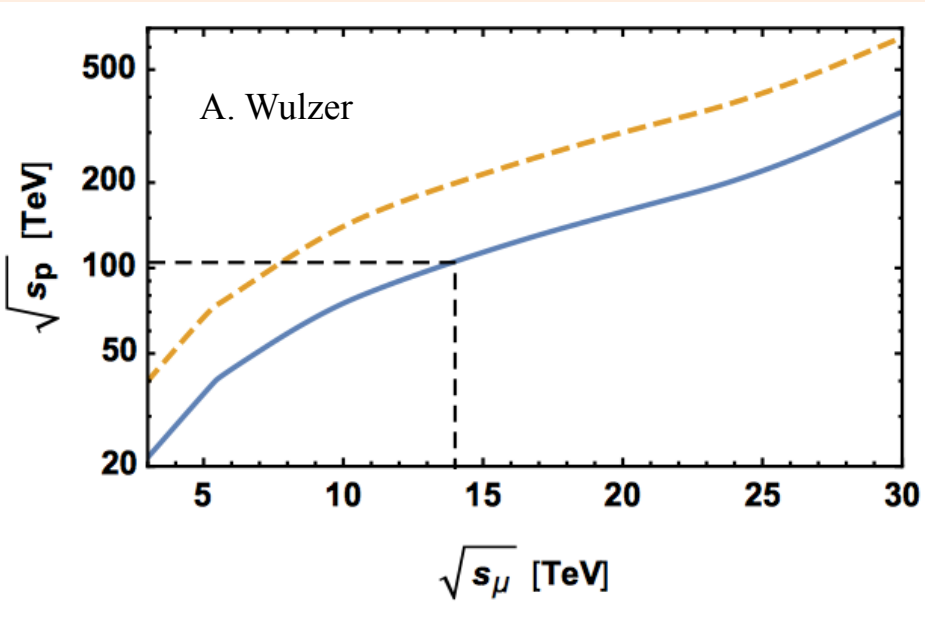
No CDR exists, no coherent baseline of machine
No cost estimate
Need to extend to higher energies (10+ TeV)
But did not find something that does not work

Lepton Physics at High Energy

High energy lepton colliders are precision and discovery machines

$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao
Muon Collider - Preparatory Meeting



Precision potential

Measure k_4 to some 10%
With 14 TeV, 20 ab^{-1}

Discovery reach

14 TeV lepton collisions are comparable to 100 TeV proton collisions for production of heavy particle pairs

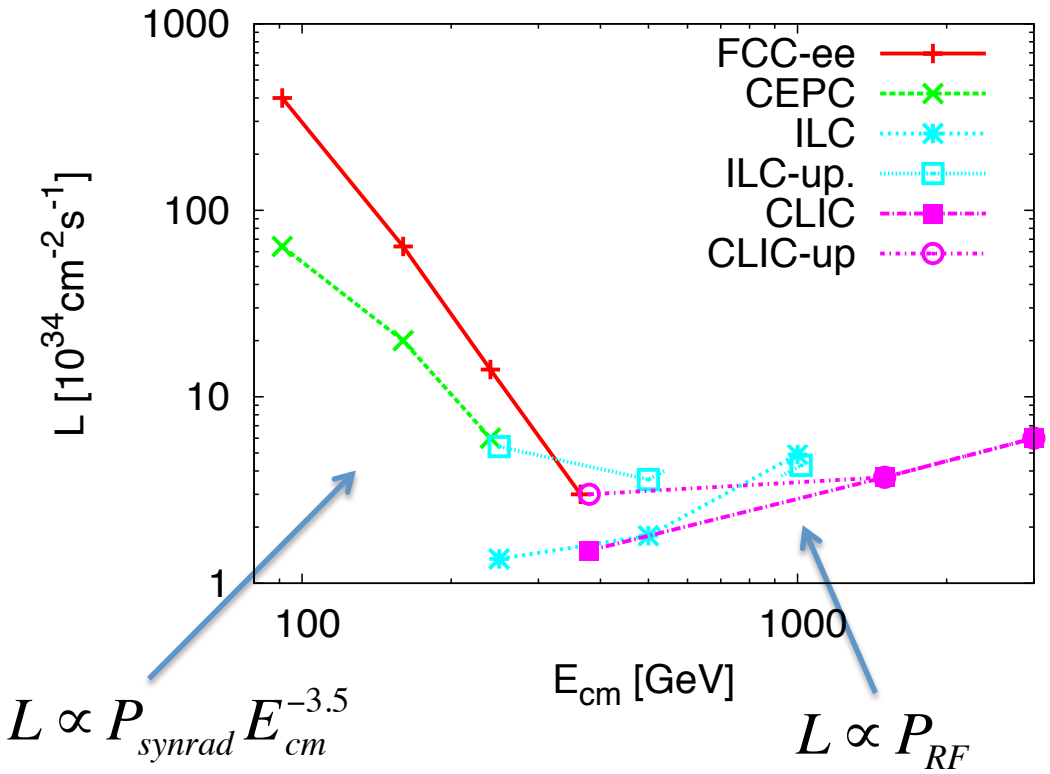
Luminosity goal

(Factor O(3) less than CLIC at 3 TeV)
4×10^{35} $cm^{-2}s^{-1}$ at 14 TeV

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

Proposed Lepton Colliders (ESU)

Luminosity per facility



Maximum proposed energy CLIC 3 TeV

- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy

But is it affordable?

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

Cost roughly is linear with energy

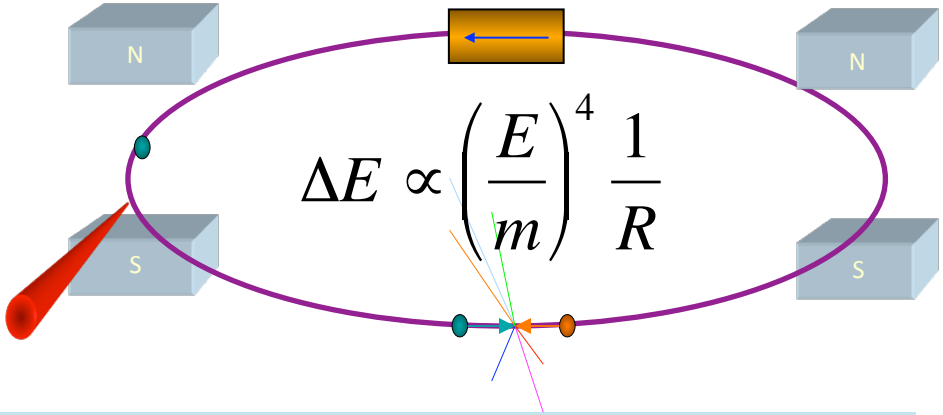
Power consumption roughly goes with the square of energy

Energy Limit

Electron-positron rings are **multi-pass** colliders limited by synchrotron radiation

Strong dependence on particle mass

Hence **proton rings** are energy frontier

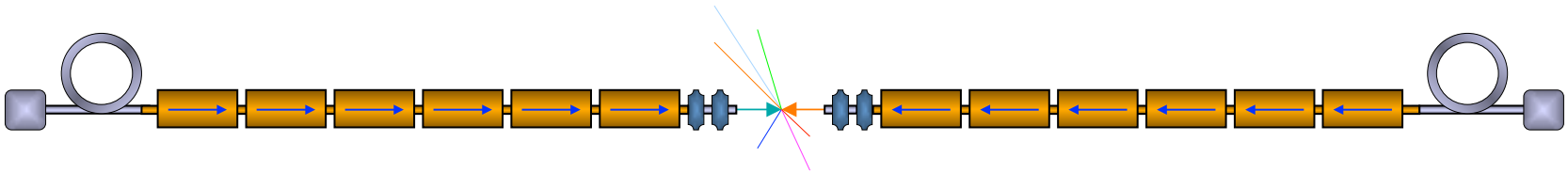


$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electron-positron linear colliders avoid synchrotron radiation, but **single pass**

Energy challenge
Need full voltage in main linac which is costly

Luminosity challenge
Need very small beam size at collision is required, leads to strong beam-beam effects, requires extremely tight tolerances



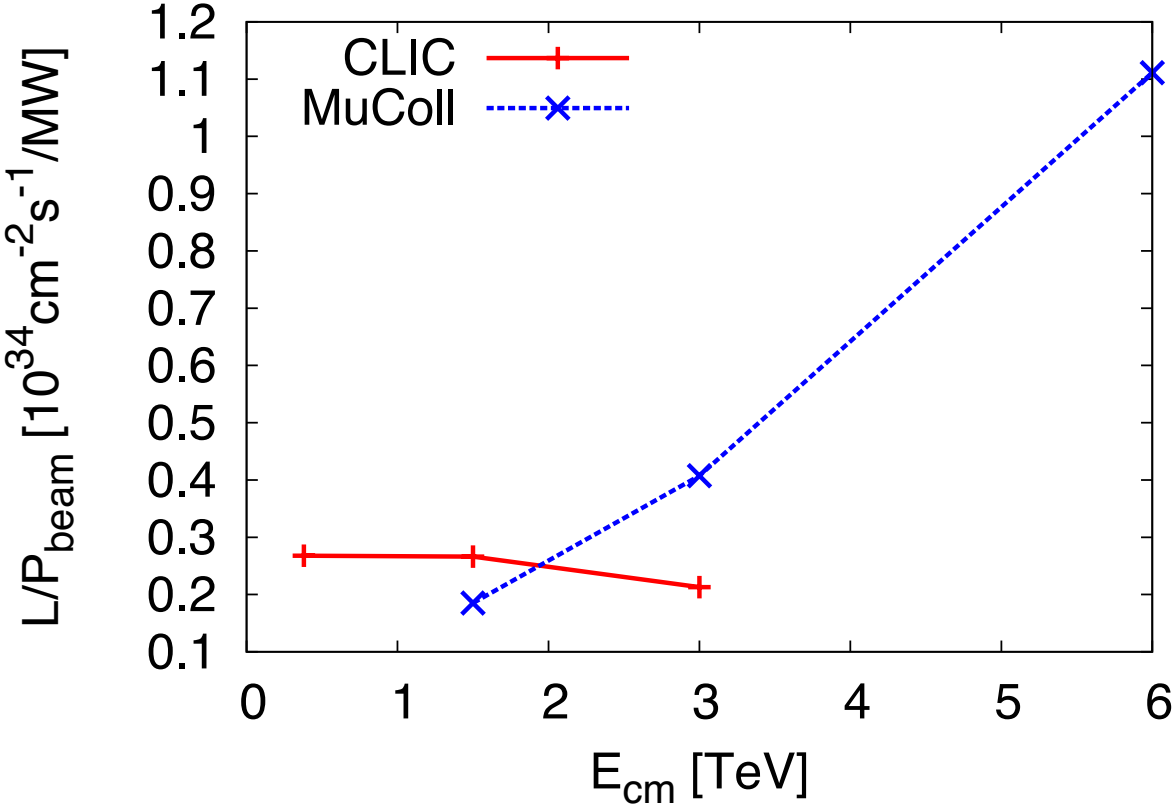
Comparing Luminosity in MAP vs. CLIC

In linear colliders luminosity per beam power is independent of collision energy for same technology

CLIC is at the limit of what one can do (decades of R&D)

No obvious way to improve

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$



Luminosity per beam power increases with energy in muon collider

Muon colliders have the potential for high energies

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

Luminosity Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Note: currently no staging
Would only do 10 or 14 TeV

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

Now study if these parameters lead to realistic design with acceptable cost and power

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

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

Target Parameter Scaling

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
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ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Scaled from MAP parameters

Emittance is constant

$$\sigma_E \sigma_z = \text{const}$$

Collider ring acceptance is constant

$$\frac{\sigma_E}{E} = \text{const}$$

Bunch length decreases

$$\sigma_z \propto \frac{1}{\gamma}$$

Betafunction decreases

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

International Muon Collider Collaboration

Objective:

In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.

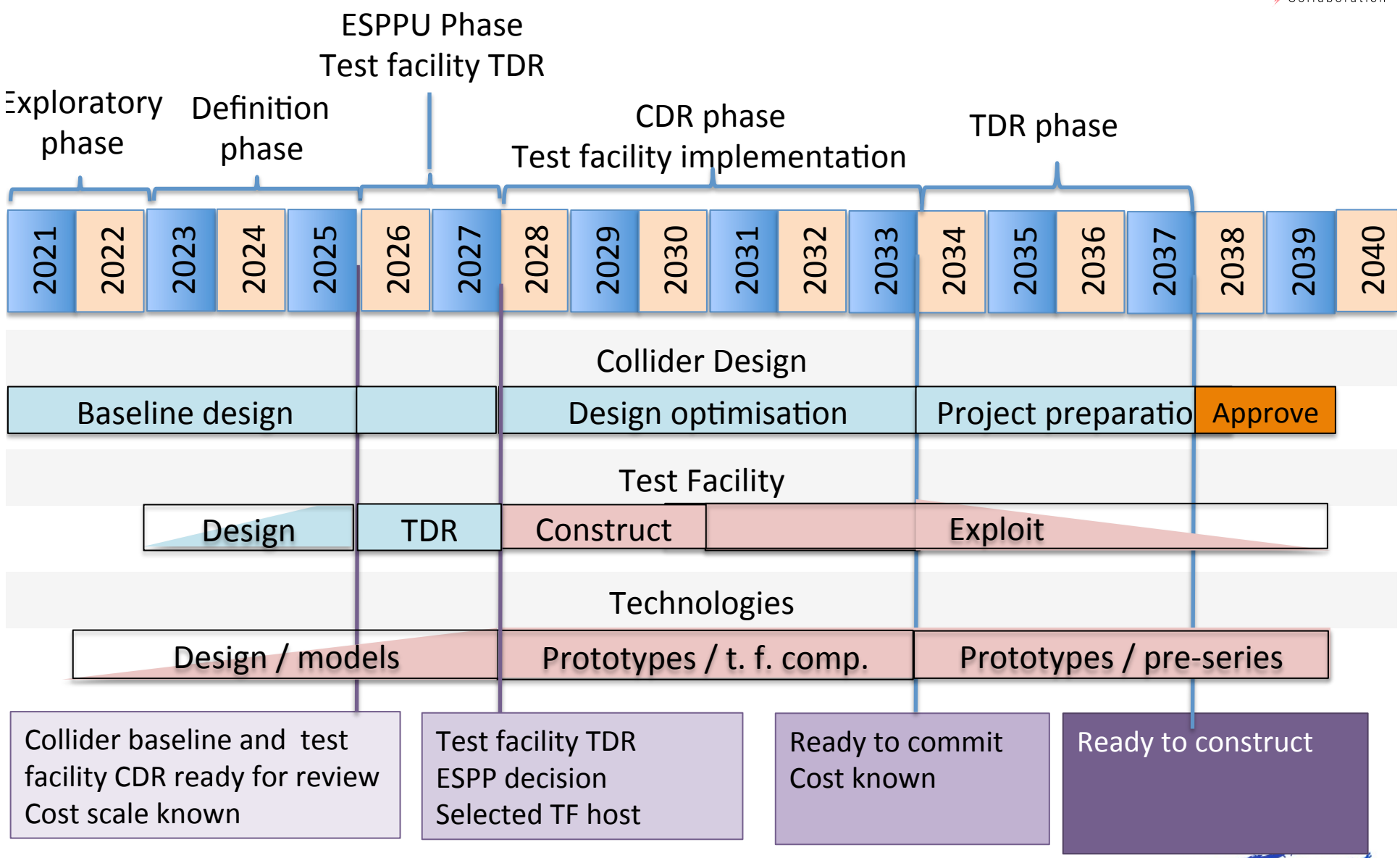
Scope:

- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 15-20 years
  - **10+ TeV**, with more advanced technology, **the reason to do muon colliders**
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

Deliverable:

- Report supporting that the muon collider is a realistic option, including description of required R&D programme to arrive at CDR
- Conceptual design report for test facility

Technically Limited Long-Term Timeline



Muon Collider Luminosity Drivers

Fundamental limitation
Requires emittance preservation and advanced lattice design

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

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

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

Luminosity per power increases with energy
Provided all technical limits can be solved

Constant current for required luminosity

Better scaling than linear colliders

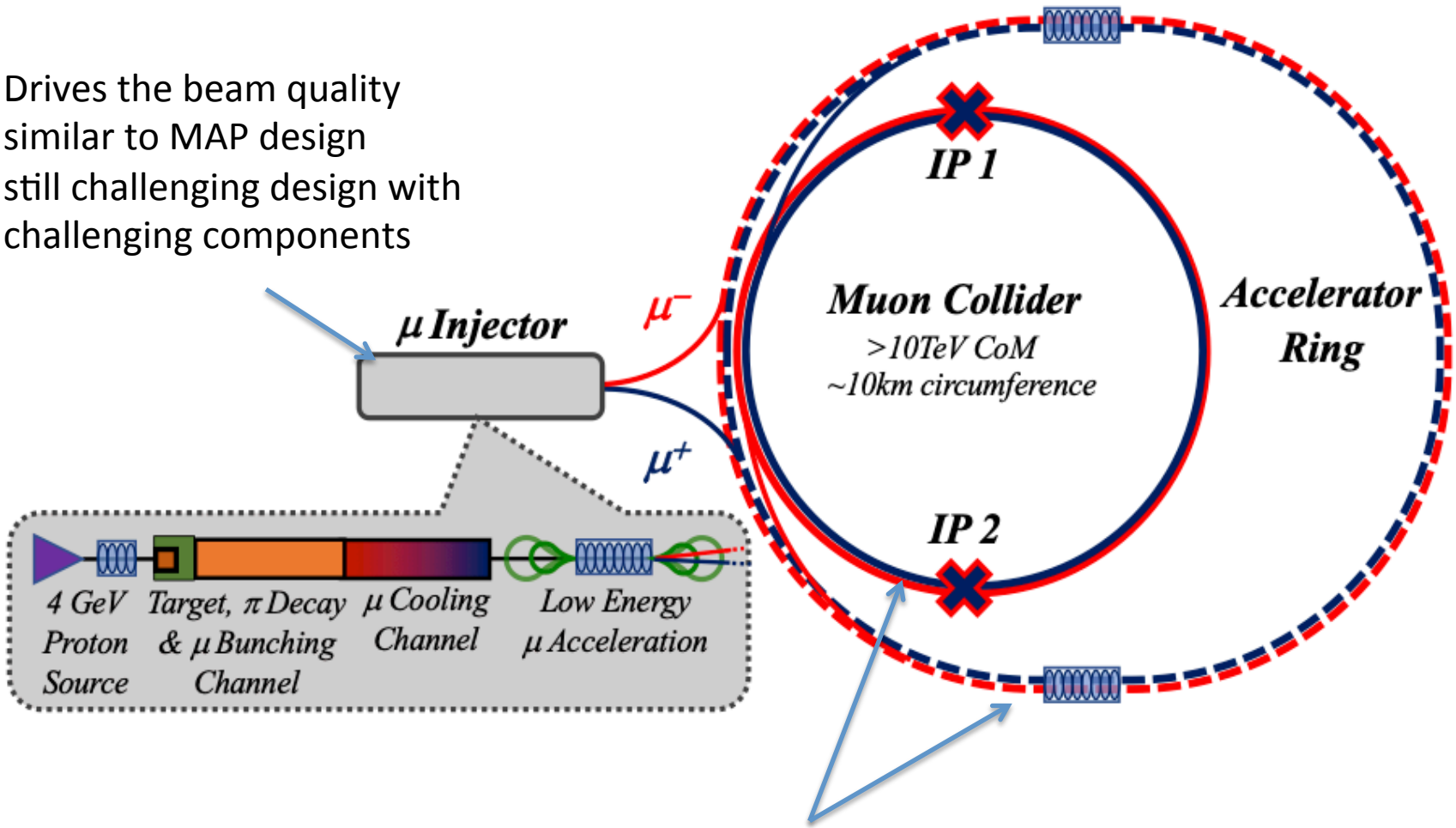
Key Challenge Areas

10+ TeV is uncharted territory

- **Physics potential** evaluation
- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site
- The impact of **machine induced background** on the detector, as it might limit the physics reach.
- **High-energy systems** after the cooling (acceleration, collision, …)
  - This can limit the energy reach via cost, power and beam quality
- **High-quality beam production** of cooled muon beam
  - MAP did study this in detail
  - First experimental verification in MICE
  - Need to optimise and prepare test facility
- **Integrated Collider Design** with choices, parameters, trade-offs
  - need to cover all accelerator areas

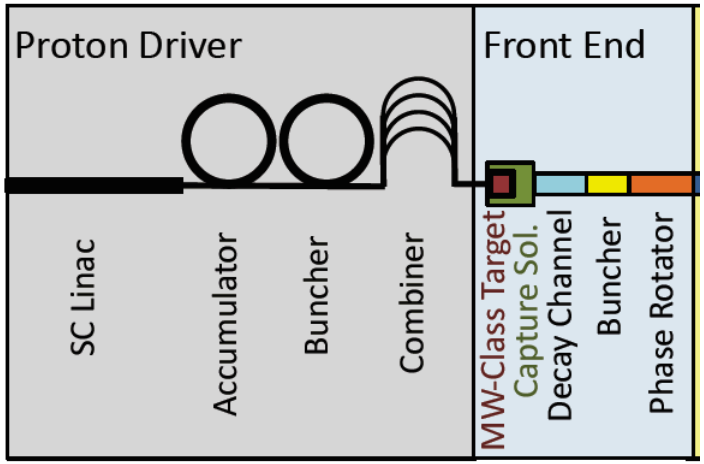
Overall Considerations

Drives the beam quality
similar to MAP design
still challenging design with
challenging components



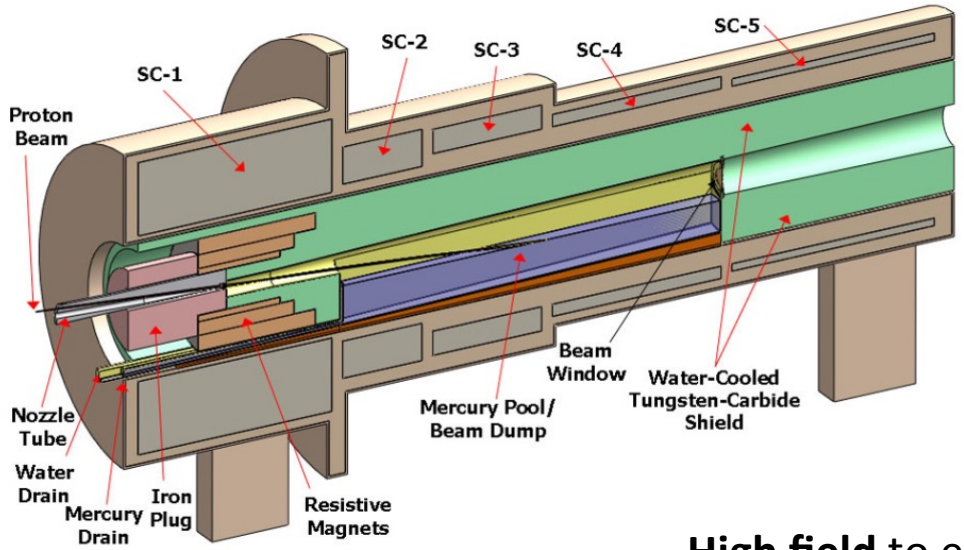
Cost and power consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts beam quality
Drives neutrino radiation and beam induced background

Proton Complex and Target Area



Proton beam power is no issue, some look required at
H- source and **accumulator complex**

2 MW proton beam
requires radiation protection

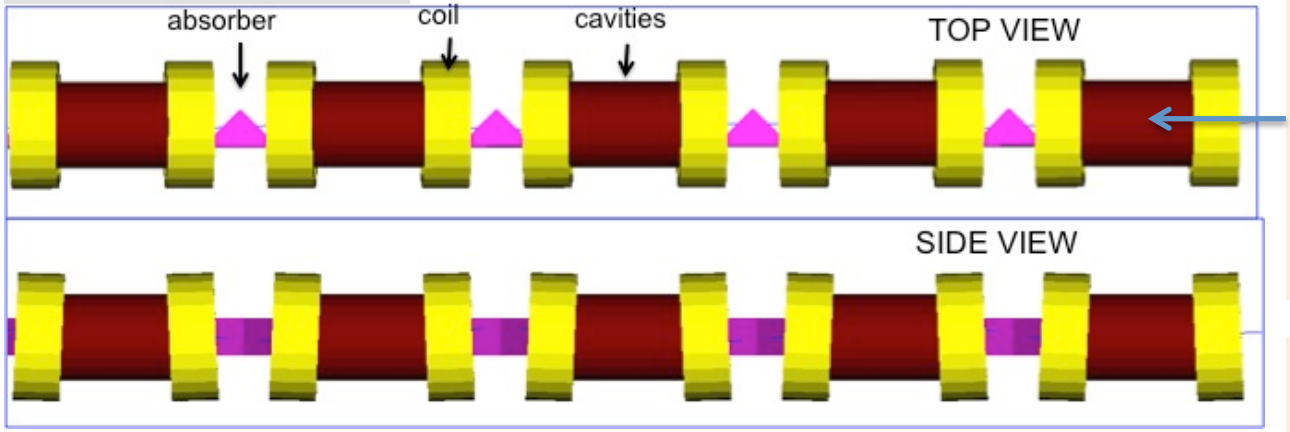


Large aperture O(1m)
to allow shielding

High field to efficiently collect pions/muons:
20 T then tapering

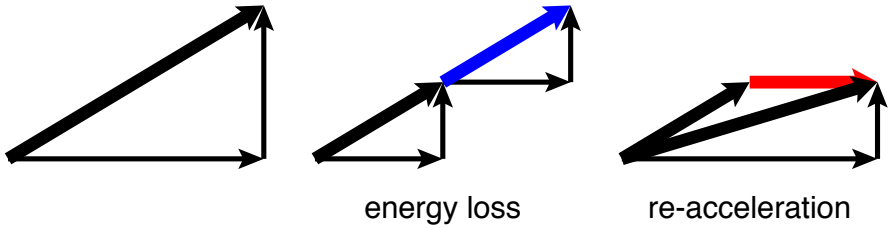
Cooling Concept

MAP collaboration



Limit muon decay, cavities with **high gradient in a magnetic field**
tests much better than design values but need to develop

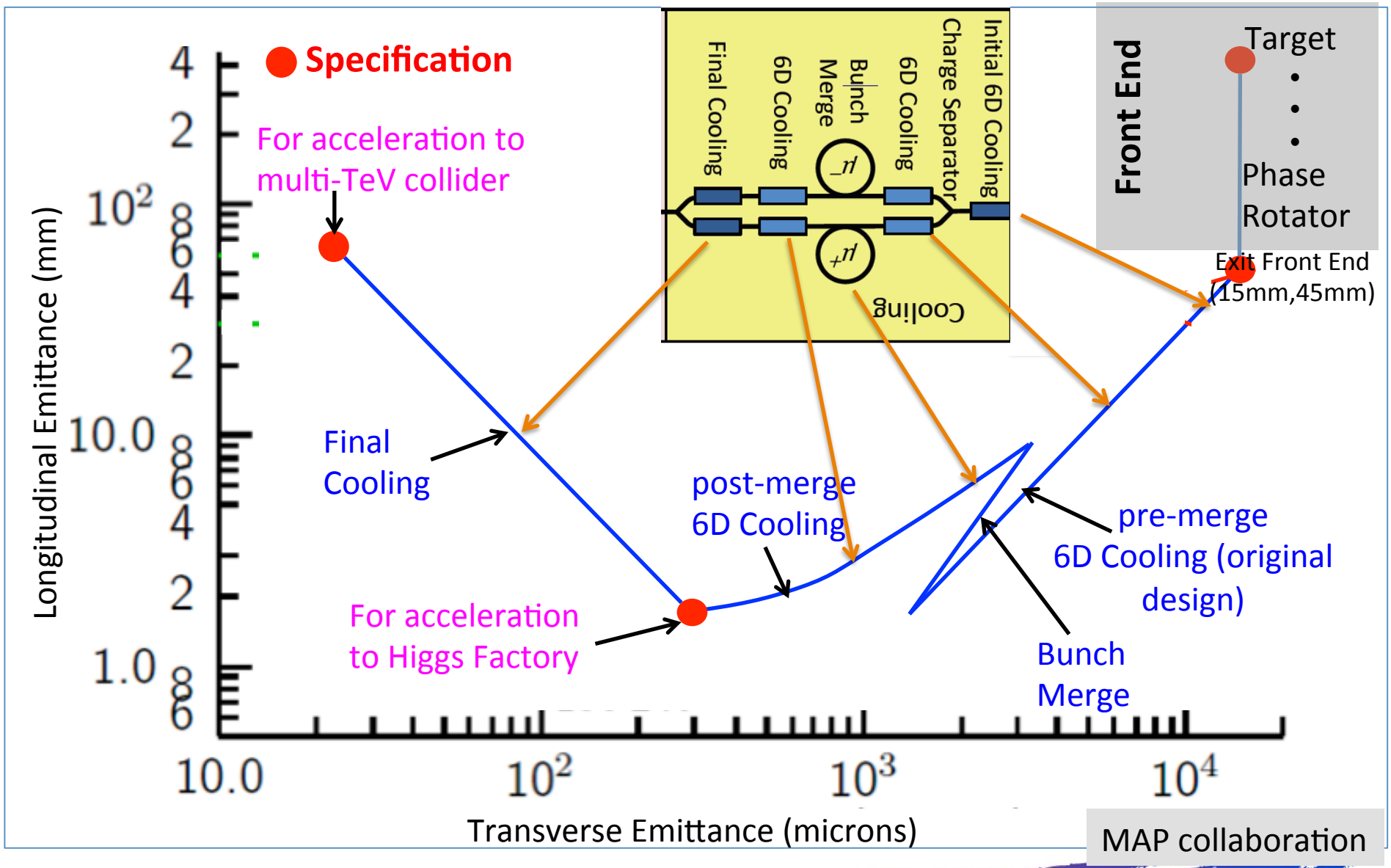
Compact integration to minimise muon loss



Minimise betafunction with **strongest solenoids (40+ T)**
32 T achieved, 40+ T planned

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

Cooling: The Emittance Path



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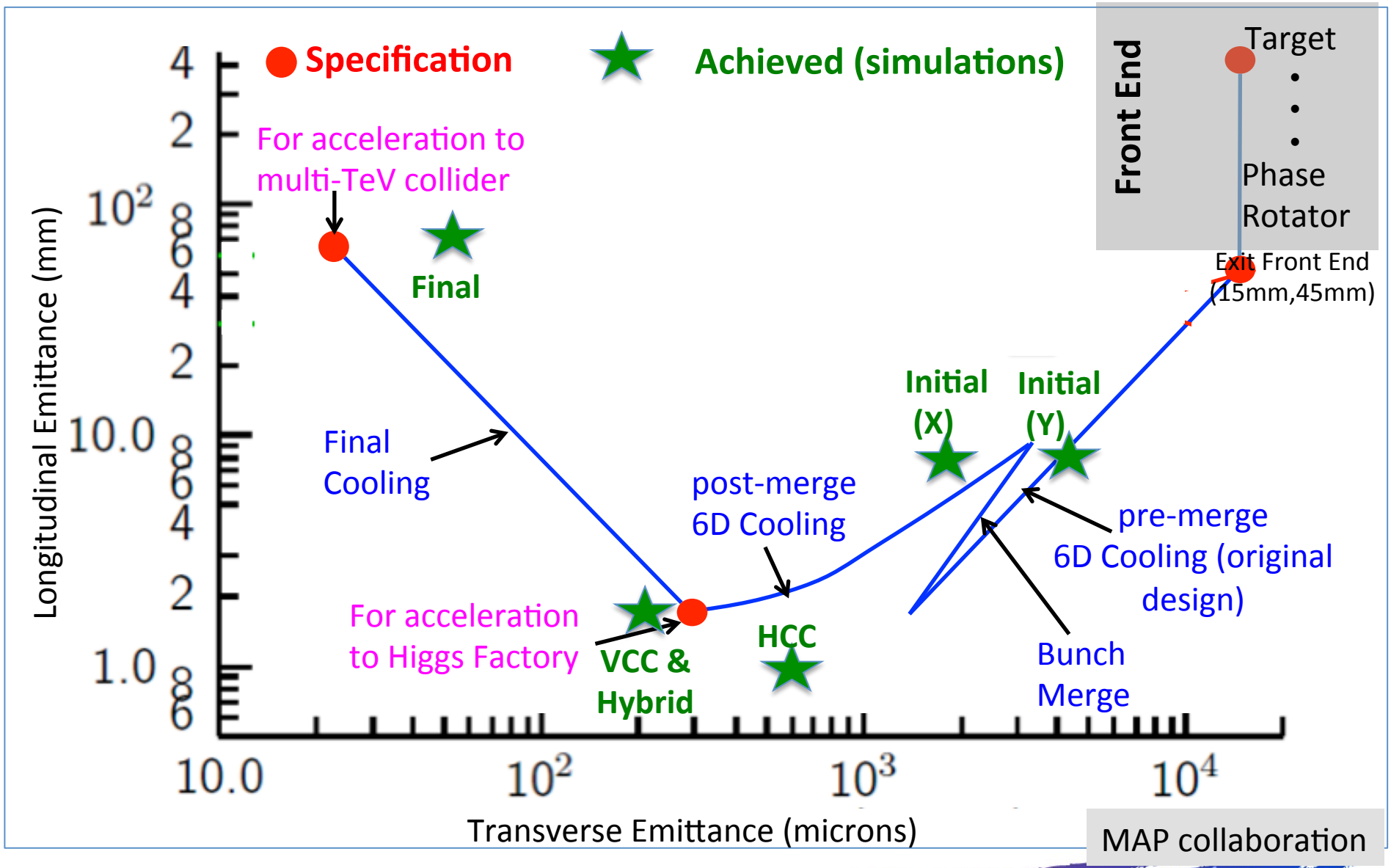
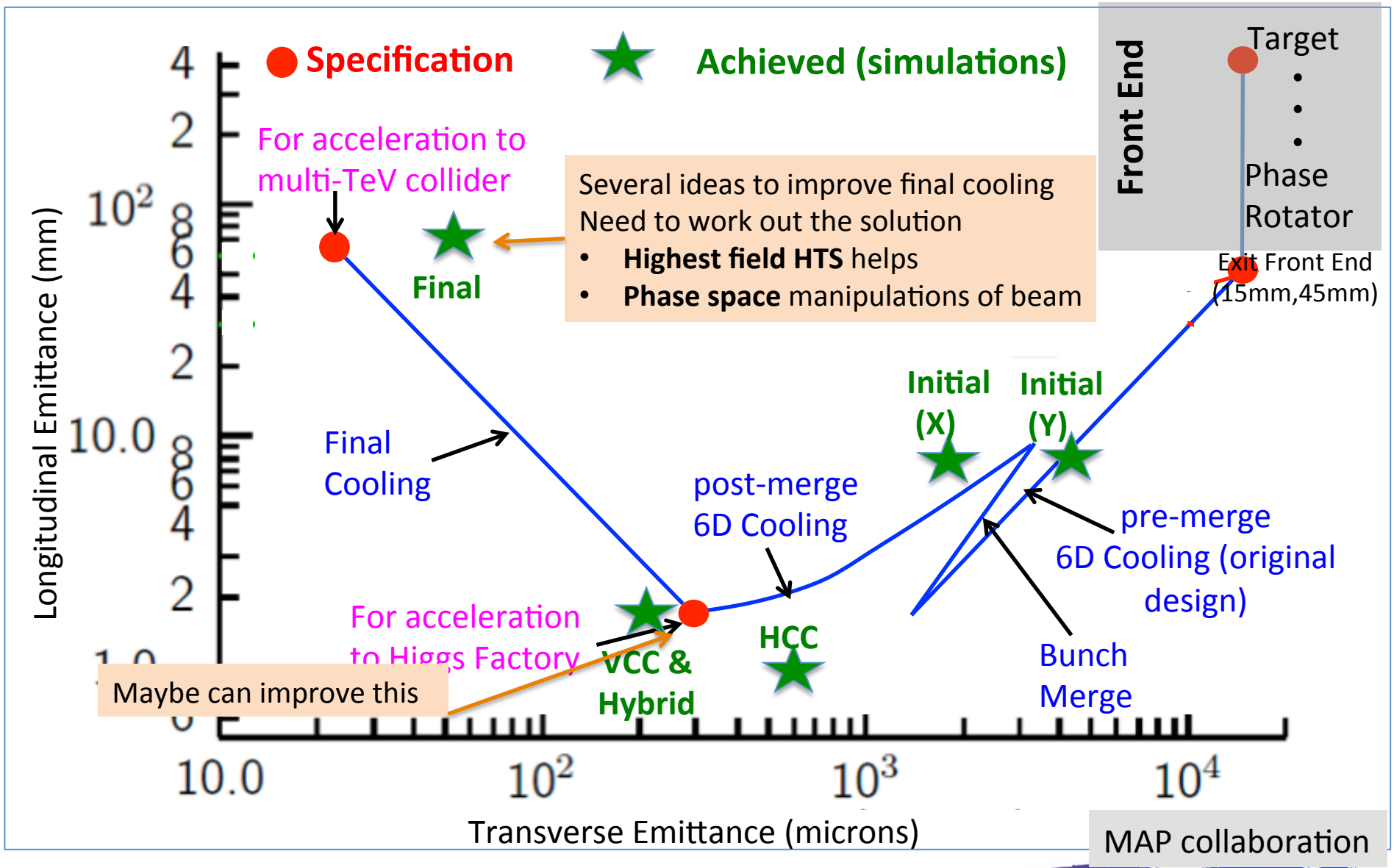


Cooling: The Emittance Path



Cooling Challenges and Status

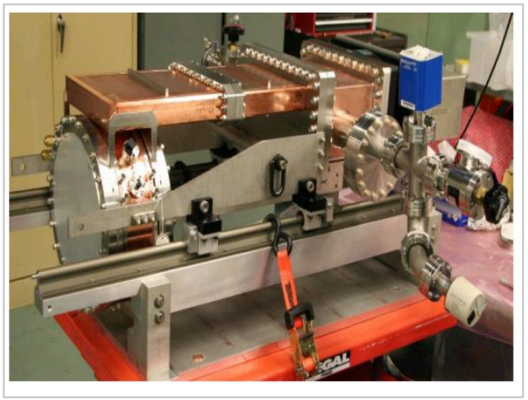
Cavities with very **high accelerating gradient in strong magnetic** field

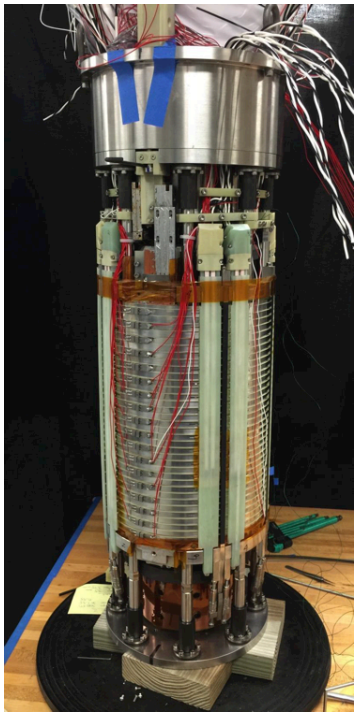
Very strong solenoids (> 30 T) for the final cooling
- simplified: Luminosity is proportional to the field

Integrated system test

MuCool: >50 MV/m in 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps



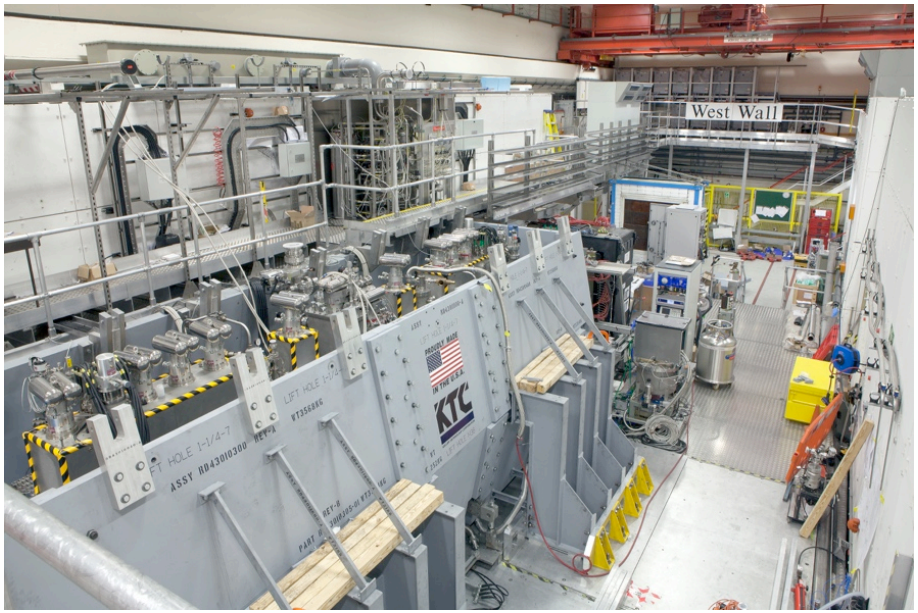


NHFML
32 T solenoid with low-temperature HTS

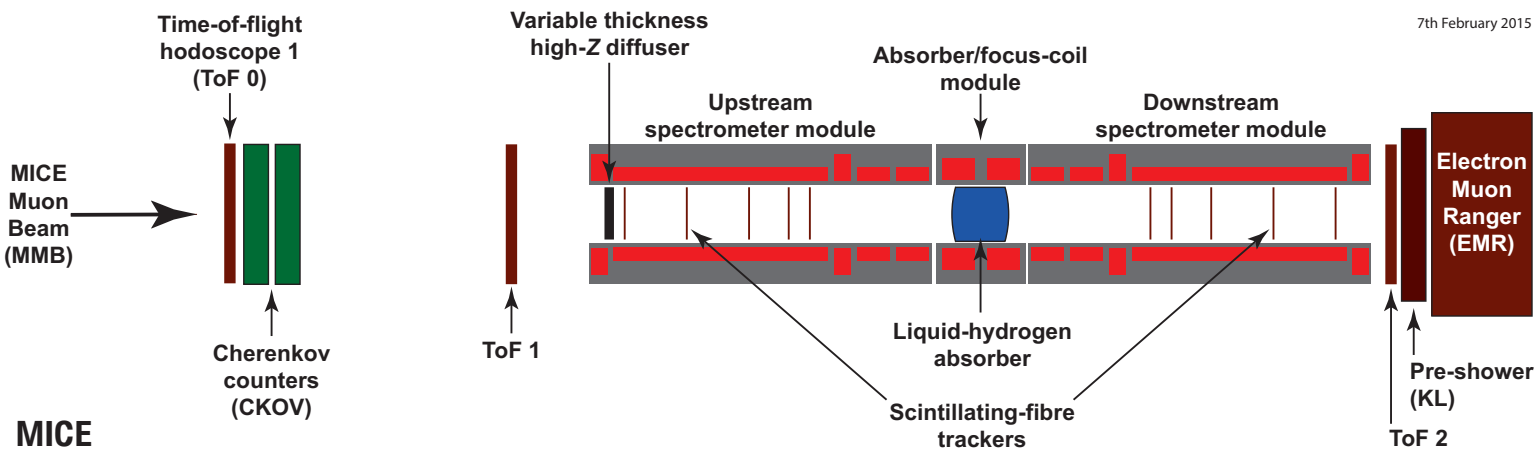
We would like to push even further

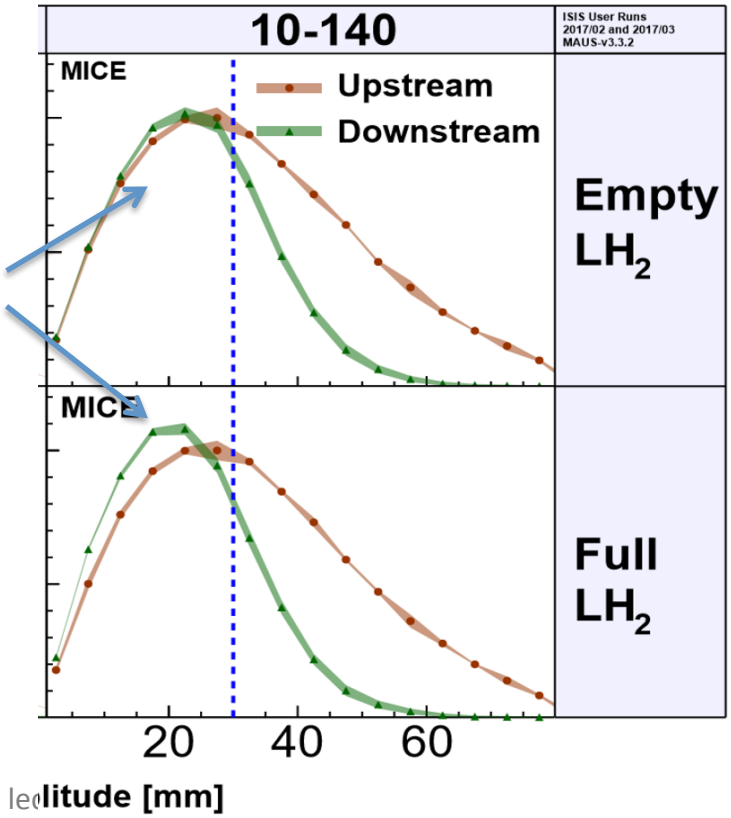
Plans for 40+ T exist

MICE (UK)



MICE (in the UK)





Nature volume 578, pages 53-59 (2020)

More particles at smaller amplitude after absorber is put in place

Principle of ionisation cooling has been demonstrated

More complete experiment with higher statistics, more than one stage required

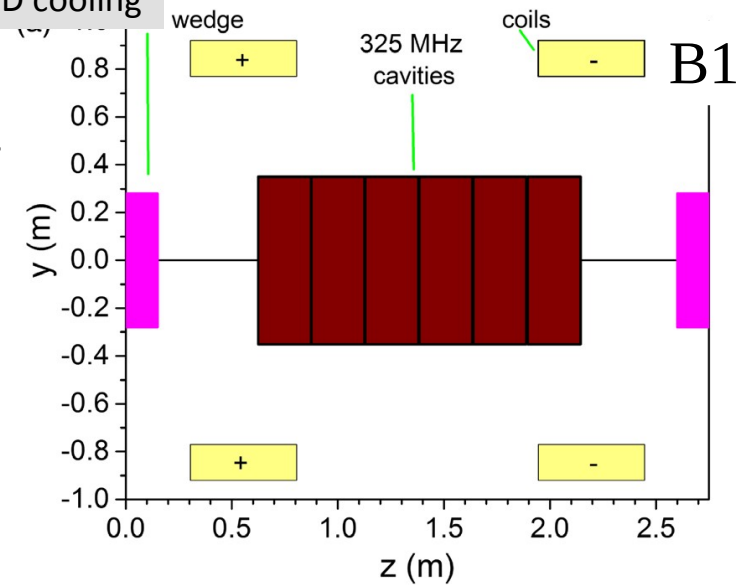
Integration of magnets, RF, absorbers, vacuum is engineering challenge

Example Cell Designs

Main 6D-cooling has many magnets and needs **tight integration** with RF and absorbers

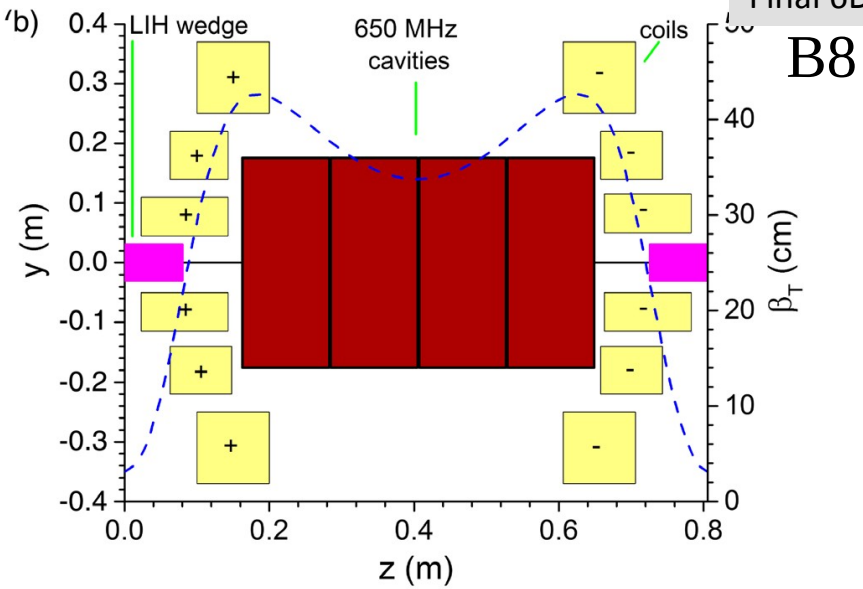
Initial 6D cooling

2.2 T



Final 6D cooling

13.6 T



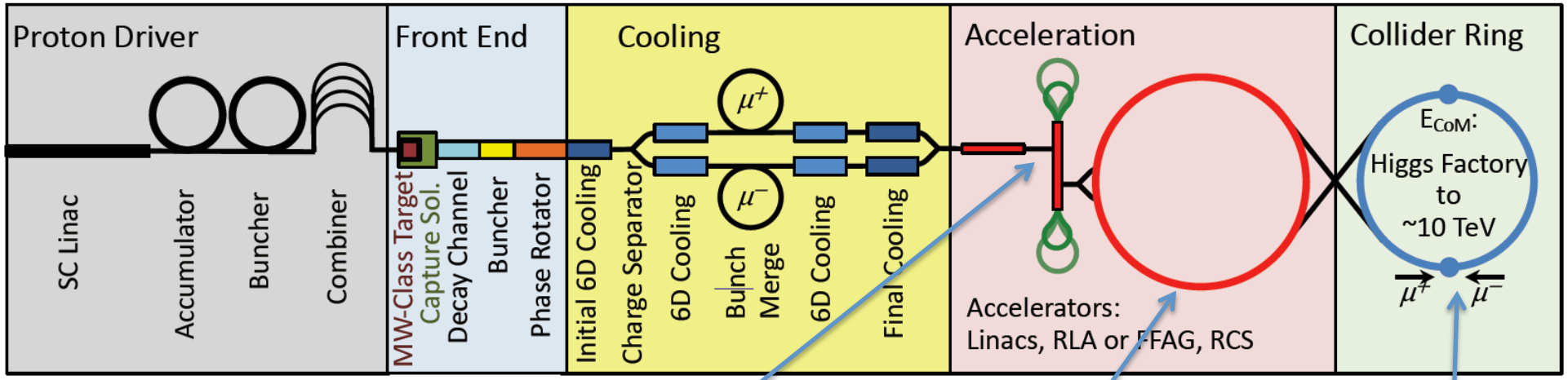
Are already aware of slightly violated space constraints

- maybe cool copper can help both gradient, space and peak power

Alignment has to be integrated (e.g. additional bellows)

Beam operation is important, e.g. beam position on absorber wedge, diagnostics integration, …

High-energy Complex



Initial acceleration
Linacs/recirculating linacs
Detailed designs from MAP
Alex Bogacz

Final acceleration
- FFAG (static superconducting magnets)
- or RCS (rapid cycling synchrotron)

High-energy designs required

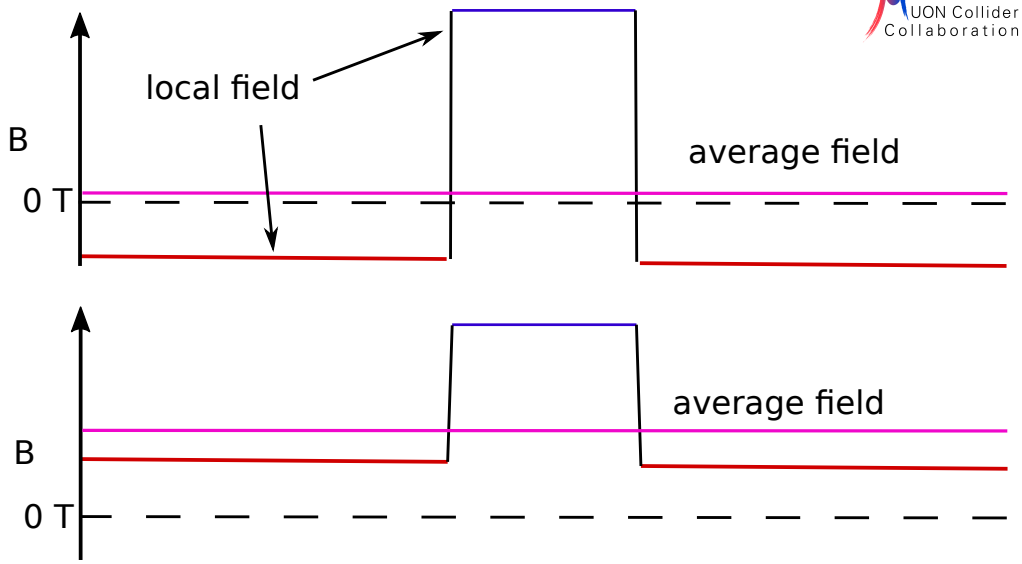
Start-to-end simulations
To be started

Collider ring
High-energy designs required

High-energy Acceleration

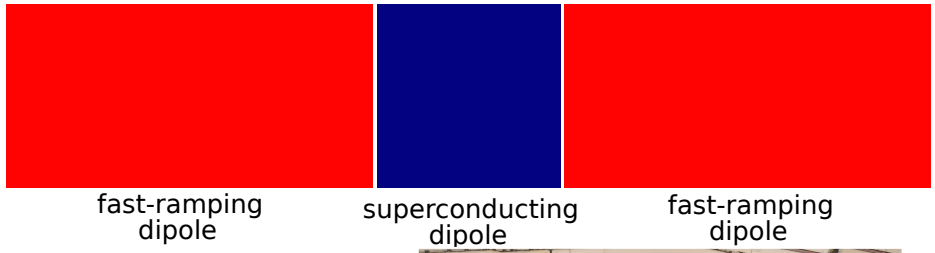
Rapid cycling synchrotron (RCS)

- Ramp magnets to follow beam energy
- Combine static and ramping magnets
- Possible circumference
  - 14-26.7 km at 3 TeV
  - O(30 km) for 10 and 14 TeV
- Power consumption of fast-ramping systems is important



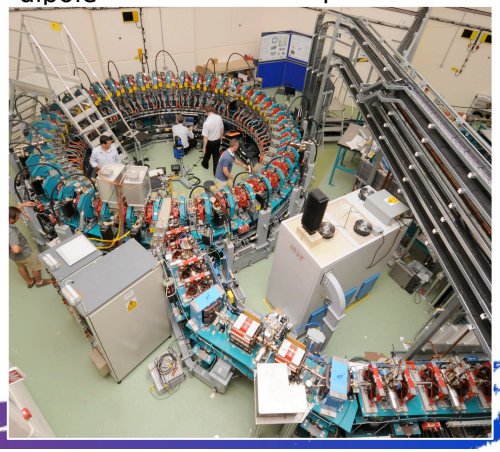
FFAG

- Fixed (high-field) magnets but large energy acceptance
- Challenging lattice design for large bandwidth and limited cost
- Complex high-field magnets
- Challenging beam dynamics



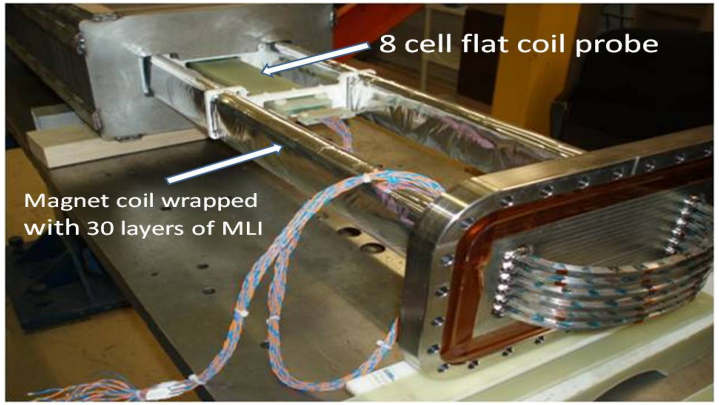
EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



Key RCS Components

Fast-ramping, normal-conducting magnets
(5 km of 2 T of per TeV beam energy in hybrid design)
Design optimisation needed



⇒ S. Prestemon, D.14.00003

Test of **fast-ramping normal-conducting magnet** design

Fast, high-field HTS ramping magnets could benefit 10+ TeV design
Need O(100) improvement in speed and O(few) in amplitude

Acceleration 0.3 to 1.5 TeV				
Length	km	13.8	26.7	26.7
8 T dipole	km	2.36	2.36	-
L_{ramp}	km	6.3	15.8	18.2
B_{ramp}	T	-2 / 2	-1 / 1	0.34 / 1.7

FNAL
12 T/s HTS
0.6 T max

Need to push in field and speed

Power converters (recovery of energy in ramping magnets, O(200 MJ) at 14 TeV) *Design started*

RF (also for FFA):
Single-bunch beam, high charge (10 x HL-LHC), maintain small longitudinal emittance, high efficiency
Design started

Final Focus

Pushing beta-functions down at higher energy is key to luminosity

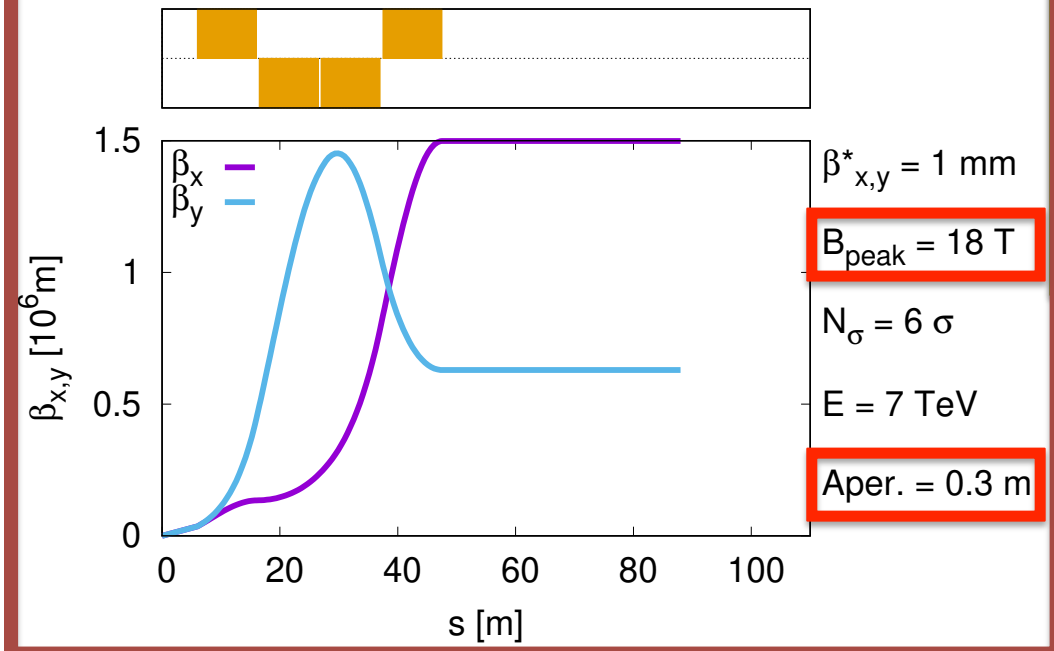
$$\beta^* \propto \frac{1}{E}$$

Focusing of higher energy beam is more difficult

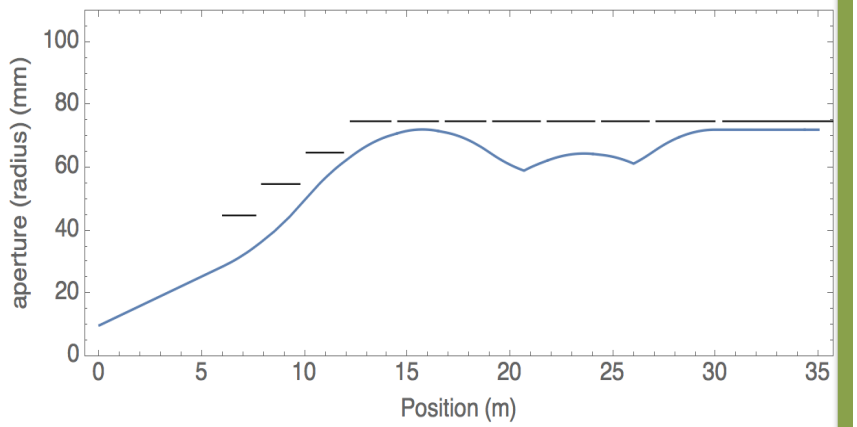
Want to keep triplet short

- rule of thumb: shorter triplet is better for the beam

First considerations on 14 TeV Design (R: Tomas)



3 TeV Design (MAP)



Parameter	Q1	Q1	Q3	Q4
Aperture (mm)	90	110	130	150
Gradients (T/m)	267	218	-154	-133.5
Peak field (T)	12	12	10+	10+
Dipole field (T)	0	0	2.00	2.00

High gradient important at high energy

- HL-LHC level at 3 TeV
- HTS at 14 TeV

What can we hope for from Nb_3Sn and HTS in 30 years?

Collider Ring Arcs

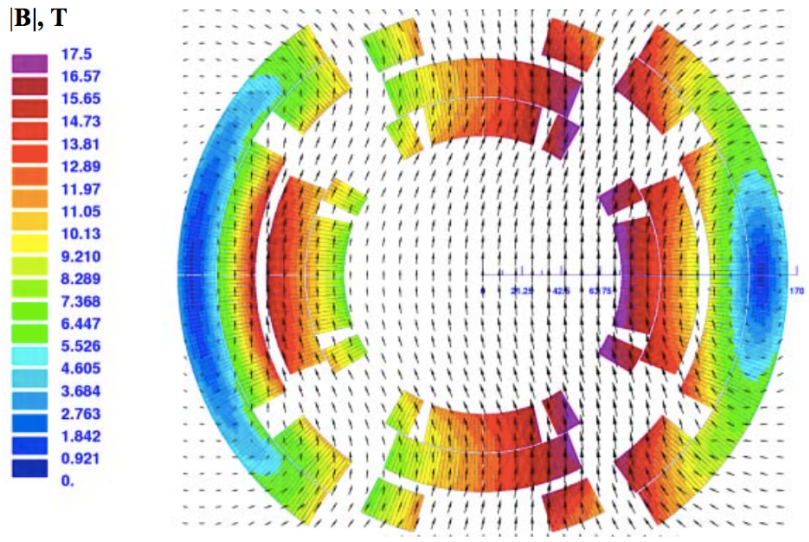
MAP 3 TeV example:

- **10.4 T** 6 m-long dipoles, 150 mm aperture
- 5 m-long combined function magnets with **8 T and 85 T/m** and **9 T and -35 T/m**
- **50/30 mm shielding**
- 500 W/m losses
- In cold mass 1.5 mW/g but 10 W/m

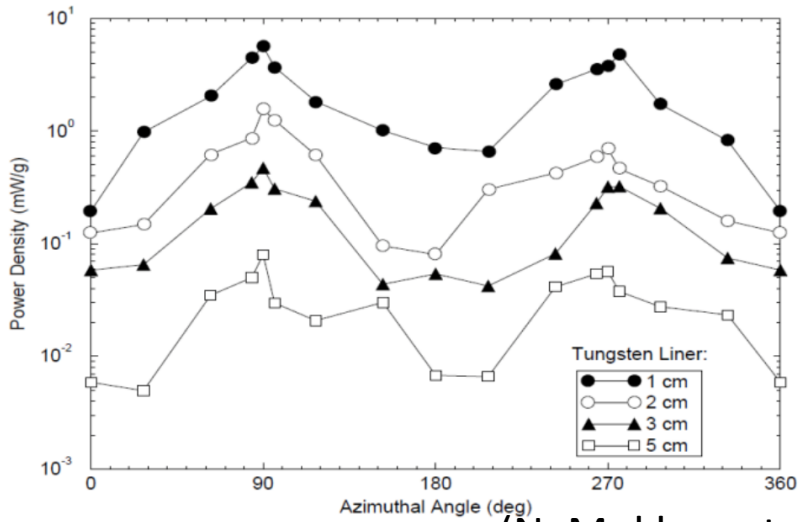
- Expect shielding/aperture not to increase dramatically with beam energy
- Currently no 10 TeV design
- One US 6 TeV design requires 20 T dipoles, but seems very high
- Open midplane seems difficult

At 3 TeV: Is NbTi worth considering for cost effectiveness?

What can we expect for each technology?



(V.V. Kashikhin et al.)



(N. Mokhov et al.)

Technology Progress

Important progress on high-field magnets for many projects, HL-LHC, FCC, …

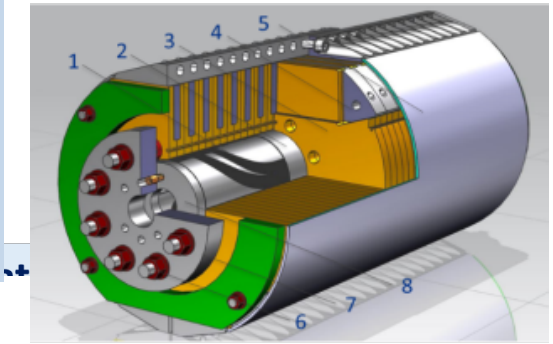
General development of magnets (Nb_3Sn and HTS) in all regions

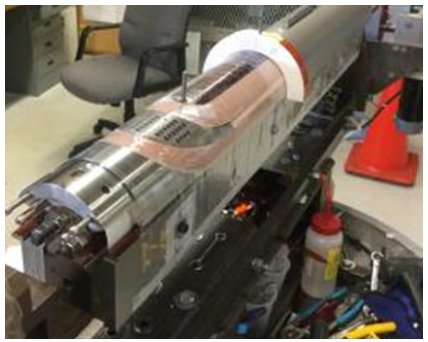
Consider more conventional for first stage, more advanced technology for second stage

U.S. MAGNET DEVELOPMENT PROGRAM

Fermilab 50 Years of Discovery

15 T dipole demonstrator, 60-mm aperture, 4-layer graded coil





Development of conductors (FCC)

Switzerland: CERN

Japan: KEK, Furukawa Electric, Jastec Superconductor

Russia: Bochvar Institute of Inorganic Materials JSC VNIINM, Fuel Company of Rosatom TVEL

Korea: Kiswire

China: Western Superconducting Technologies Co., Ltd.

Austria: TU Wien

Germany: Technische Universität Bergakademie Freiberg

Italy: Columbus Superconductors

Finland/USA: Luvata Special Products

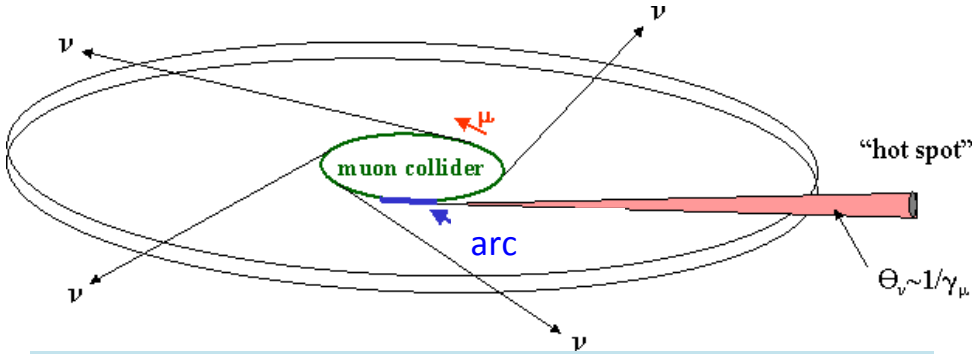
Italy: SPIN

Switzerland: Université de Genève

7 companies, two universities and two national research institutes

Magnet progress is important
Need to share magnet work for muon collider

Neutrino Radiation



Important luminosity limitation
Particularly high in direction of the straights
⇒ buy land in direction of straights

Have to still cover arcs

Typical legal limit 1 mSv/year

MAP goal < 0.1 mSv/year

No legal procedure < 10 μSv/year

LHC achieved < 5 μSv/year

No mitigation, 500 m deep tunnel:

3 TeV: close to LHC

14 TeV: around legal limit

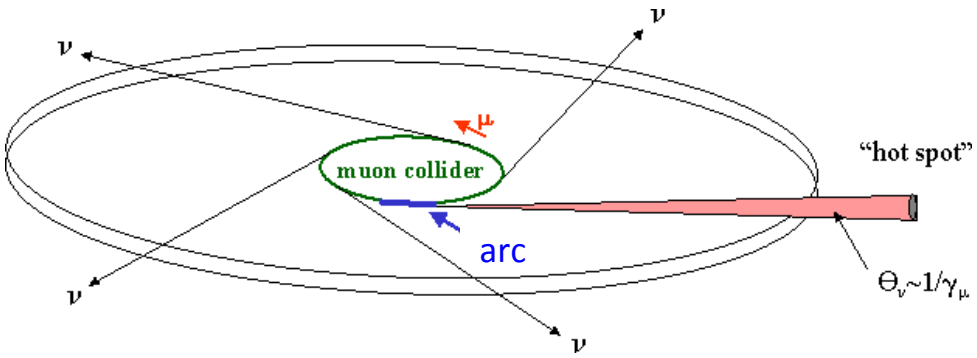
Needed to find a solution

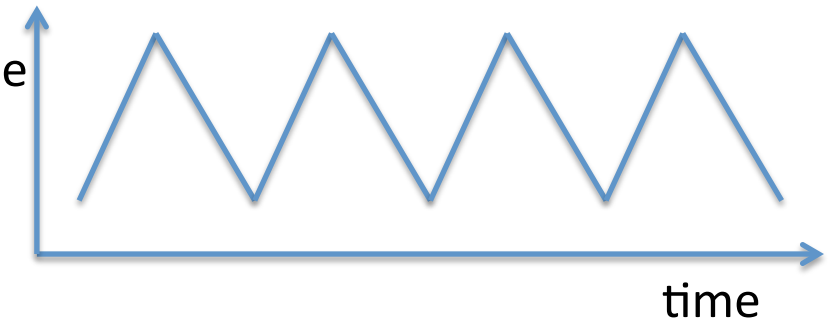
Work with **Radiation Protection, Civil Engineering, Geometers** and **Lattice Design** started to find solutions

Mitigate radiation to a level as low as reasonably achievable

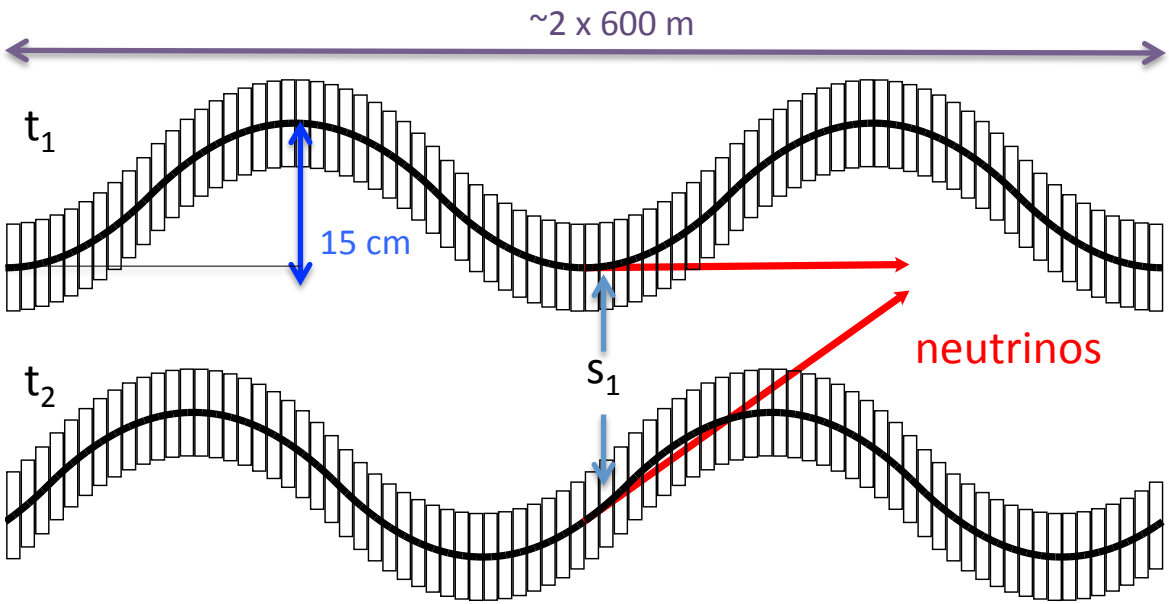
Similar to LHC

Neutrino Radiation Mitigation Proposal





Mokhov, Ginneken: move beam in collider aperture
Investigating: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

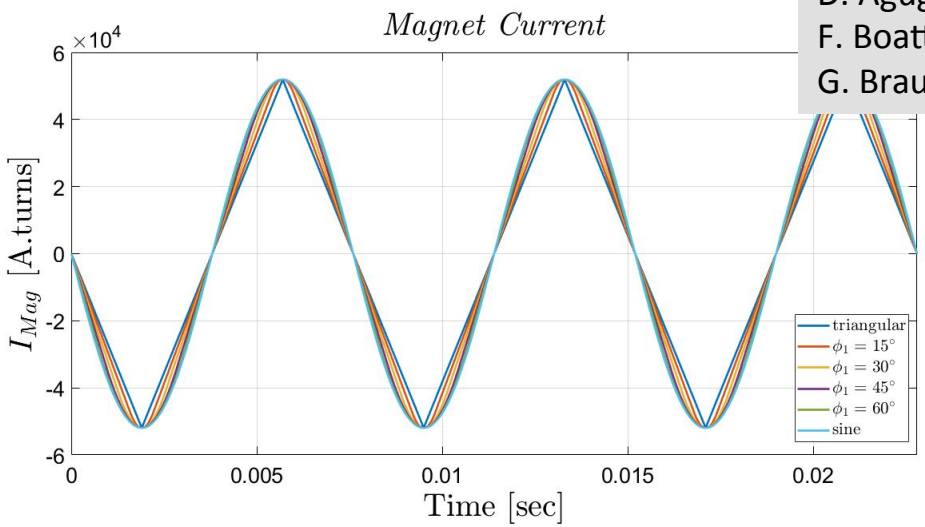
Even at 14 TeV
200 m deep tunnel would be comparable to LHC case

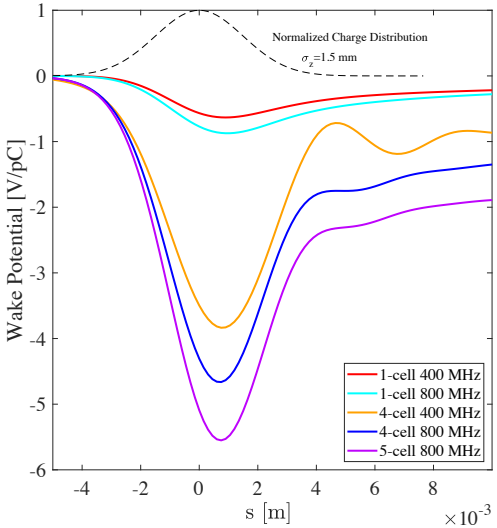
Need to study impact on beam operation, e.g. dispersion control, and components

Selected Recent Progress

D. Aguglia
F. Boattini
G. Brauchli

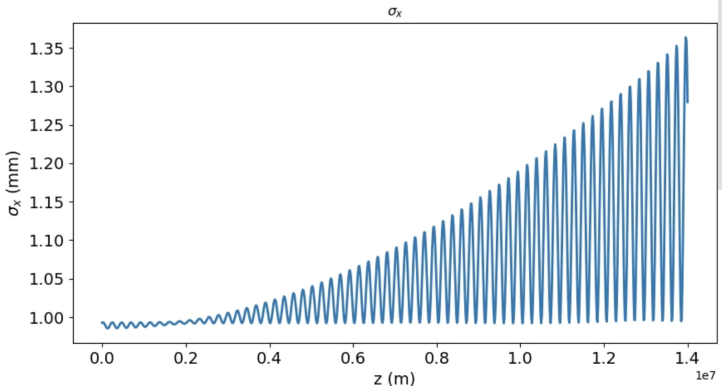
Ramping **magnet challenge**
At 14 TeV, energy in field is O(200 MJ)
Need to recover it pulse to pulse
Started to develop **powering scheme** with energy recovery





S. Zadeh
U. van Rienen

RF challenge (also for FFA):
High efficiency for power consumption
High-charge (10 x HL-LHC), short, single-bunch beam
Maintain small longitudinal emittance
Studies on cavity wakefields and longitudinal dynamics started

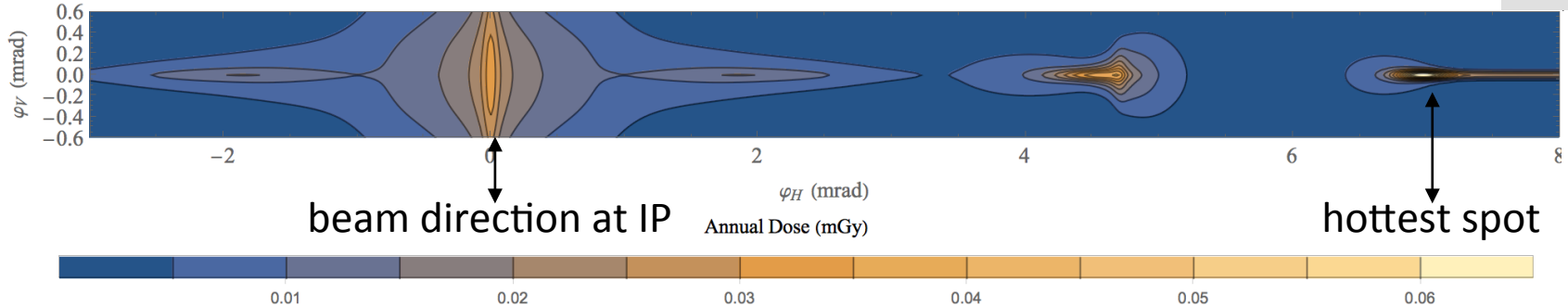


M. Magliorati
E. Metral,
T. Raubenheimer
D.S.

Collective effects might be a bottleneck
Revisiting for higher energies
Need to develop tools for collective effects in matter

Selected Recent Progress, cont.

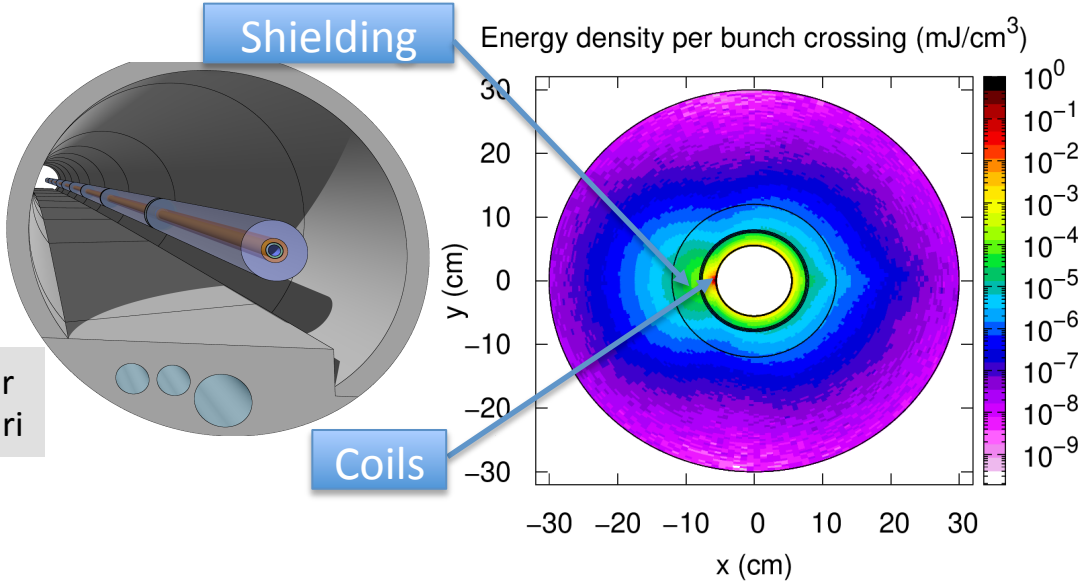
C. Carli



Collider Ring Lattice Design:
Based on MAP design, lattice design for high energy is starting
Started production of **radiation maps** and identified hot spots around IP and in arcs
Need to include radiation considerations in lattice design

Loss challenge in collider ring:
Loss per unit length is constant
fewer, but higher energy particles
Simulations of shielding started

A. Lechner
D. Calzolari



Tentative Detector Performance Specification

10+ TeV collider enters uncharted territory

Need to establish physics case and detector feasibility

Established tentative detector performance specifications in form of DELPHES card (thanks to M. Selvaggi, Werner Riegler, Ulrike Schnoor, A. Sailer, D. Lucchesi, N. Pastrone M. Pierini, F. Maltoni, A. Wulzer et al.), based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)

- For use by physics potential studies
  - Are the performances sufficient or too good?
- For detector studies to work towards
  - make sure technologies are reasonable
  - ensure background is OK
- Please find the card here: https://muoncollider.web.cern.ch/node/14

Detector simulation studies/design will now have to verify/ensure that this is realistic considering background and technologies

Detector

D. Lucchesi et al.

Detector is based on CLIC detector

Nozzles added to protect from beam-induced background (BIB)

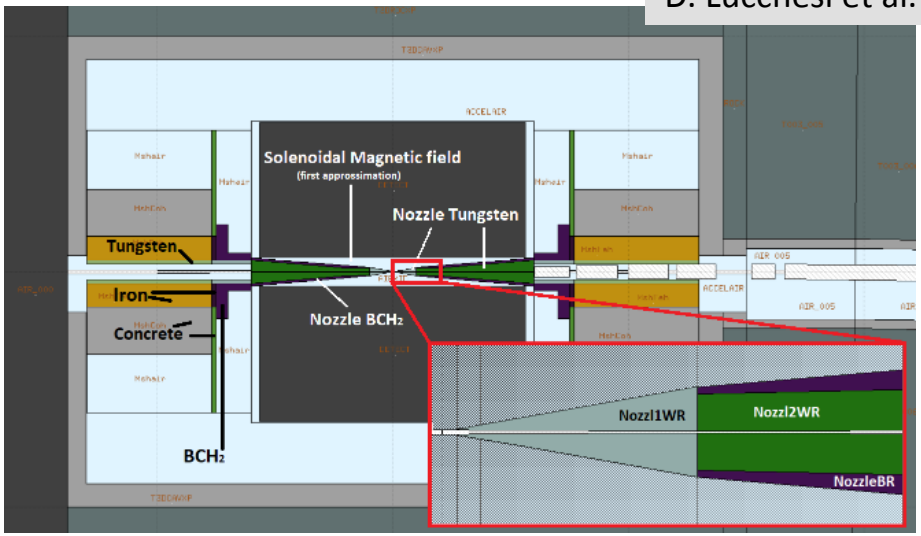
Each beam contains one bunch crossing every 15 µs (3 TeV) or 47 µs (14 TeV)

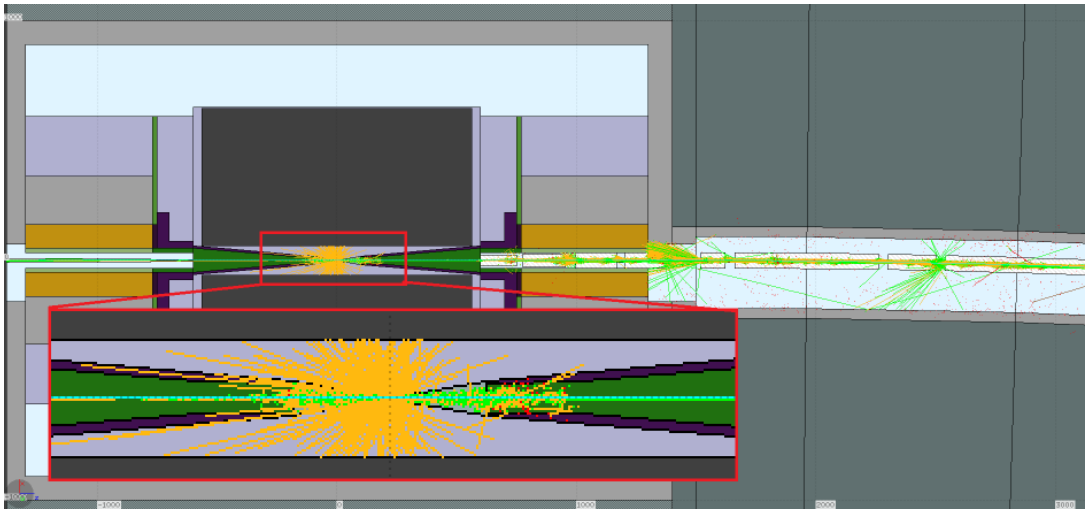
Muon decay rate at 3 TeV: 200,000 bx^{-1} m^{-1}

Rate decreases with energy but energy in each decays increases

Simulations for 1.5 TeV with LineBuilder and FLUKA comparing to previous MAP results (MARS)

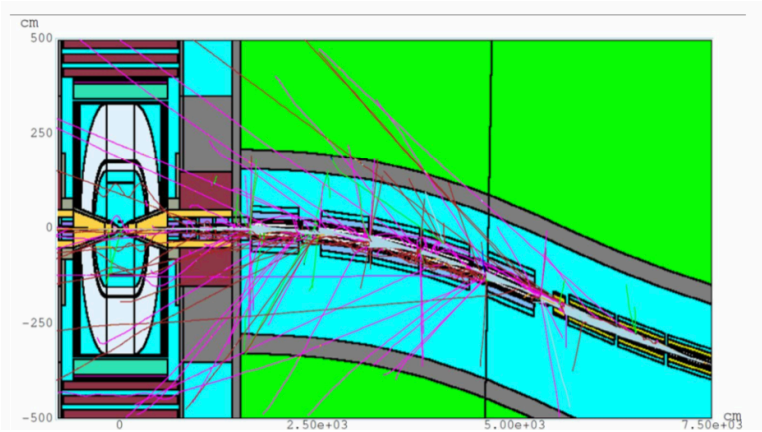
Will study higher energies as machine designs become available



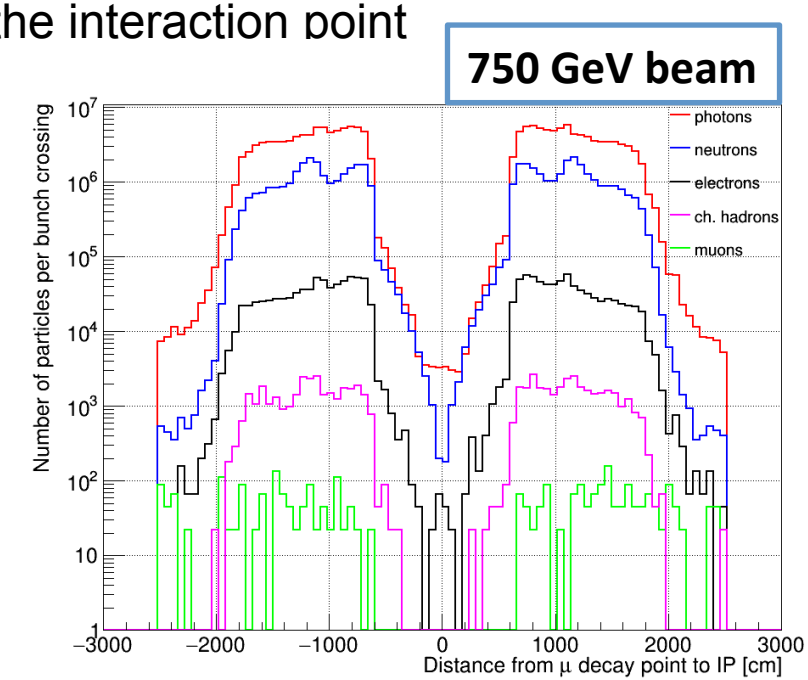


Beam induced background studies on detector at $\sqrt{s}$ =1.5 TeV

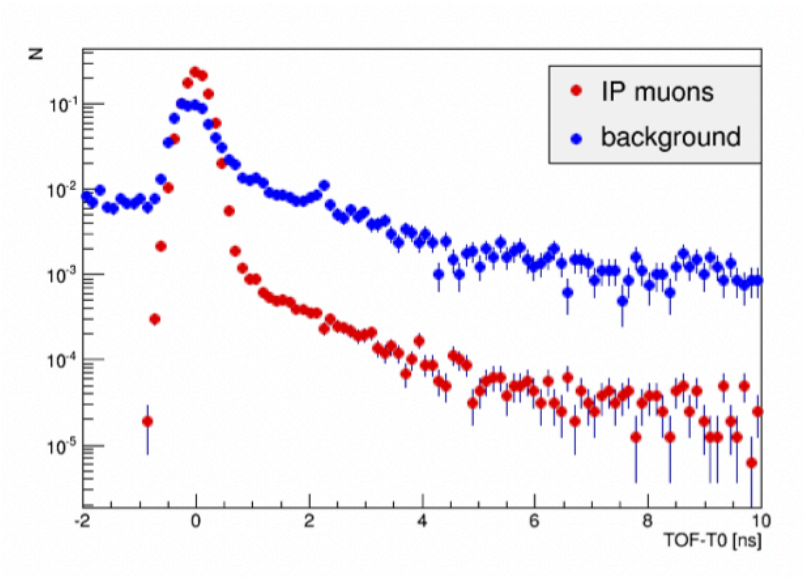
arXiv:1905.03725



MARS15 simulation in a range of ±100 m around the interaction point

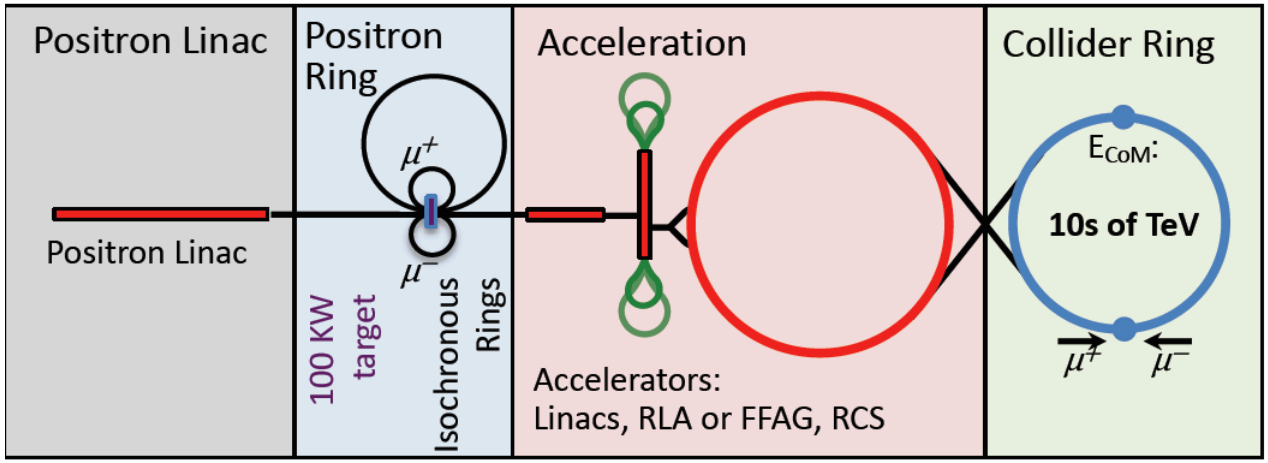


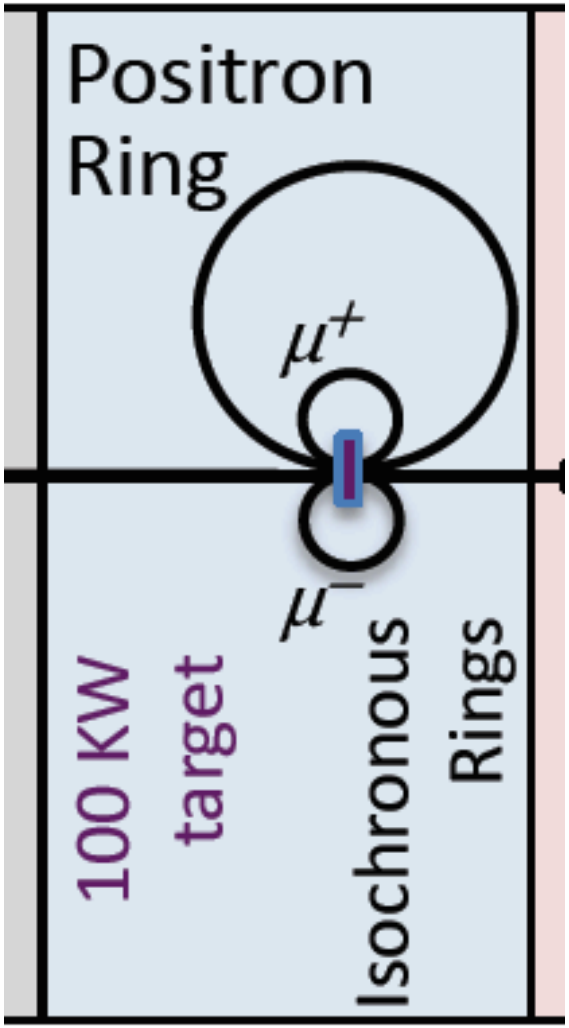
Particle composition of the beam-induced background as a function of the muon decay distance from the interaction point



Simulated time of arrival (TOF) of the beam background particles to the tracker modules with respect to the expected time (T0) of a photon emitted from IP

Alternative: The LEMMA Scheme



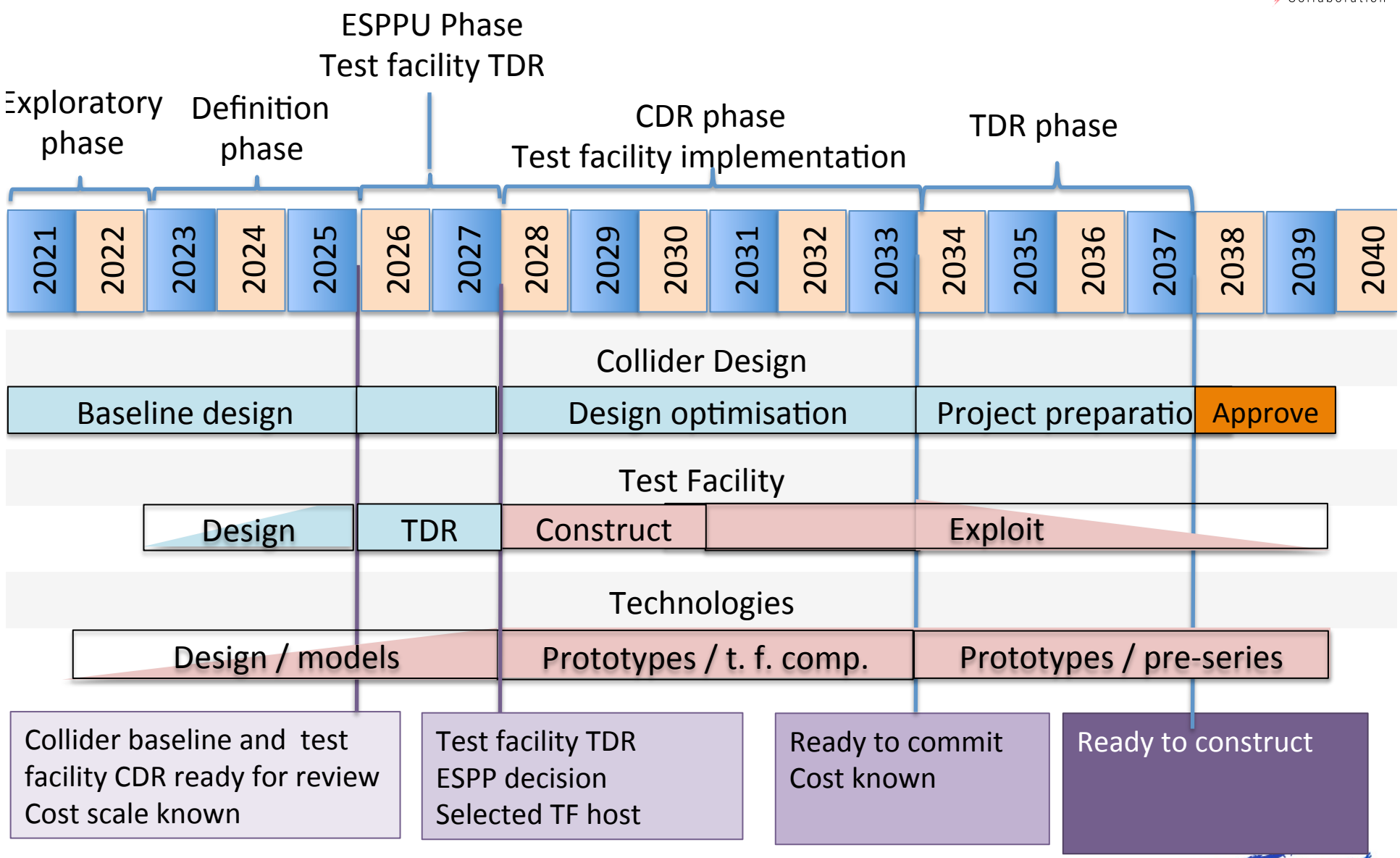


45 GeV positrons to produce muon pairs
Accumulate muons from several passages

Low-emittance muon beam can reduce radiation

Less mature than proton-driven scheme
Large positron current required
Target is challenging
Large positron production rate [O(10^{17}/s)]
Currently do not reach luminosity goal

Technically Limited Long-Term Timeline



Test Programme

High-energy complex mostly consists of known components with pushed performances

- Can be tested as individual prototypes
- Synergies with other developments exist
- Some beam experiments might be useful but could be considered at other accelerators, e.g. control of longitudinal phase space

Production and cooling complex is novel and unique to the muon collider

- Many components are unconventional
  - e.g. high-gradient cavities in magnetic field with Be windows or filled with gas
  - massive use of absorbers in the beam path
- Novel technologies beyond MAP design can be considered
  - e.g. very short RF pulse to reduce breakdown probability
  - e.g. use of cooled copper
- Also compact integration is required to maximise muon survival
  - strong superconducting solenoids next to RF at room temperature
  - complex lattice design optimisation
- Almost no experience with beam in these components
  - MICE has been a limited model (no RF, single muons, …)

⇒ Need to have a test facility

Site Considerations

- Are open to any site proposed for the muon collider test facility

- However, design depends on available proton infrastructure
  - proton energy, pulse structure, …

- Resources will be limited
  - Appears hard to support several studies of proton infrastructure with the design study

- Need to develop for one example site
  - Consider covering proton infrastructure and specific civil engineering by CERN
    - i.e. workpackage with no EU resources
  - Allows others to include similar studies for other sites
    - at their own cost

CERN Infrastructure

Main proton injectors considered

- PS booster provides 1.4/2 GeV protons
- PS provides 20 and 26 GeV protons with fast extraction
- SPS provides up to 460 GeV protons

Currently focus on PS and still consider SPS

- PSB energy is quite low
- PS energy is closer to real collider (5 - 8 GeV)
- Interferes less with other users than SPS
- SPS at 100 GeV has been considered for nuSTORM and provides highest pulse energy

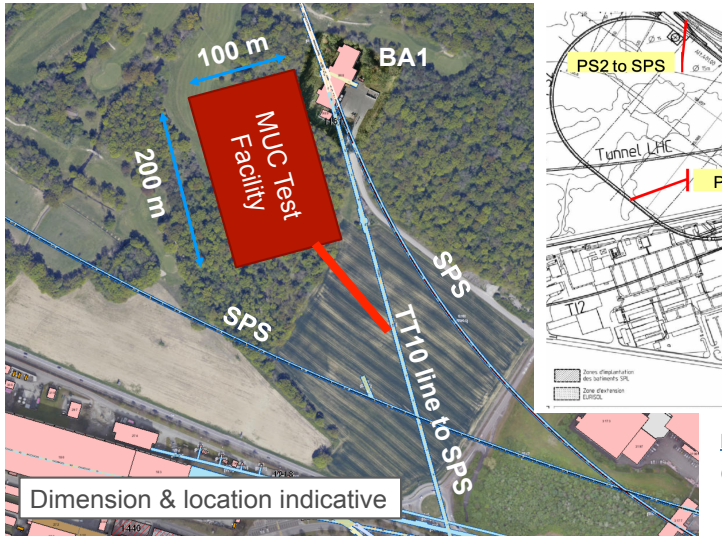
PS total proton pulse energy

- Full beam 4 x 10^{13} protons with 20 GeV O(10^{13}): 130 kJ
- One 20 ns bunch 1 x 10^{13} protons with 20 GeV O(10^{13}): 30 kJ
- Collider design 400 kJ
- Need to update with LIU (improved) numbers

Need to establish list of beam modes for different measurements

Demonstration Programme

Core test facility to demonstrate muon cooling
- on CERN land
- can allow for 4 MW of proton power (but would need SPL)
- Consider O(10 kW) target and beam from PS



Willingness of TIARA to support as EU Design Study
Need to define scope and involvement for EU and prepare commitments

Models and prototypes of key components
- magnets
- RF systems
- target
- …

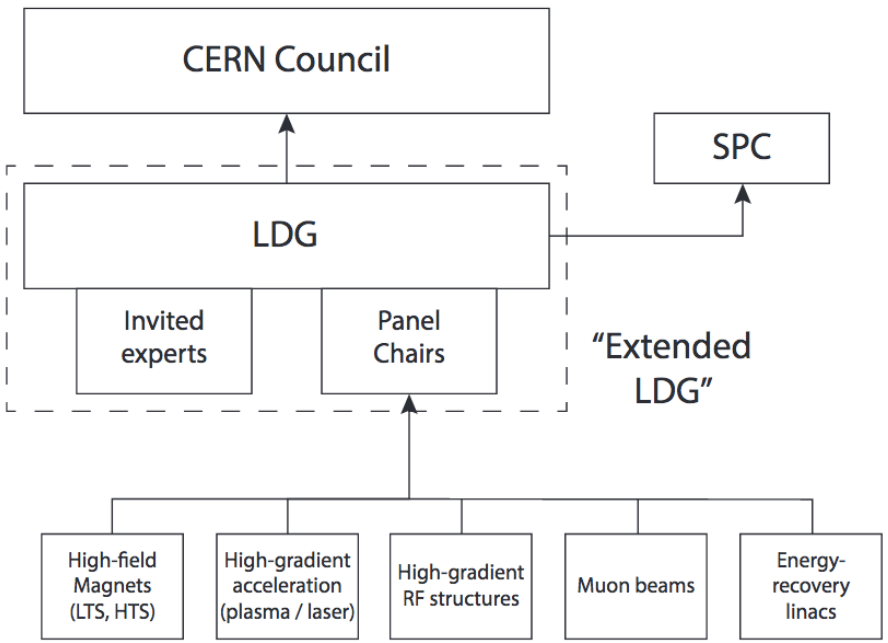
Programme needs to be modular
Tentative rough cost scale 500 CHF
Initial test facility material cost about 150 MCHF?

But not to forget:
- The collider justifies the demonstration programme

European Accelerator R&D Roadmap

Council charged Laboratory Directors Group (LDG) to deliver European **Accelerator R&D Roadmap**

Panels
- Magnets: P. Vedrine
- Plasma: R. Assmann
- RF: S. Bousson
- Muons: D. Schulte
- ERL: M. Klein



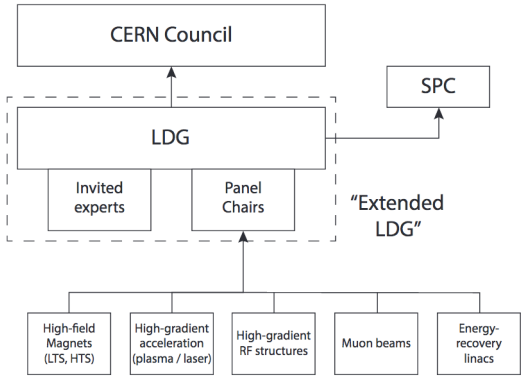
The extended LDG will deliver a report to **council**:
- The scientific drivers for R&D, and the progress needed to enable future facilities
- The current state-of-the-art, and the further steps to be taken over the next decade
- Potential deliverables and **demonstrators** for the next decade
- A **prioritised work plan**, taking into account the capabilities and interests of stakeholders
- A range of scenarios for engagement, ranging from 'minimal investment' to 'maximum possible rate of progress', with a first estimate of resources and timeline.

Muon Beam Panel

Daniel Schulte (CERN, chair)
Mark Palmer (BNL, co-chair)
Tabea Arndt (KIT)
Antoine Chance (CEA/IRFU)
Jean-Pierre Delahaye (retired)
Angeles Faus-Golfe (IN2P3/IJClab)
Simone Gilardoni (CERN)
Philippe Lebrun (European Scientific Institute)
Ken Long (Imperial College London)
Elias Metral (CERN)
Nadia Pastrone (INFN-Torino)
Lionel Quettier (CEA/IRFU), Magnet Panel link
Tor Raubenheimer (SLAC)
Chris Rogers (STFC-RAL)
Mike Seidel (EPFL and PSI)
Diktys Stratakis (FNAL)
Akira Yamamoto (KEK and CERN)

Contributors:
Alexej Grudiev (CERN), RF panel link
Roberto Losito (CERN), Test Facility link
Donatella Lucchesi (INFN) MDI link

https://muoncollider.web.cern.ch/organisation



Work with collaboration, panel and community meetings:

- May 20+21: Identify R&D challenges, first scope
- July 12-14: Identify the R&D for next five years, internal priorities, resource estimates
- July 16: Submission of Interim Report to LDG
- September: Final R&D list, scenarios, may still answer questions of LDG
- September LDG submits Interim Report to Council
- December Final Report submitted to Council

Community Meeting Conveners

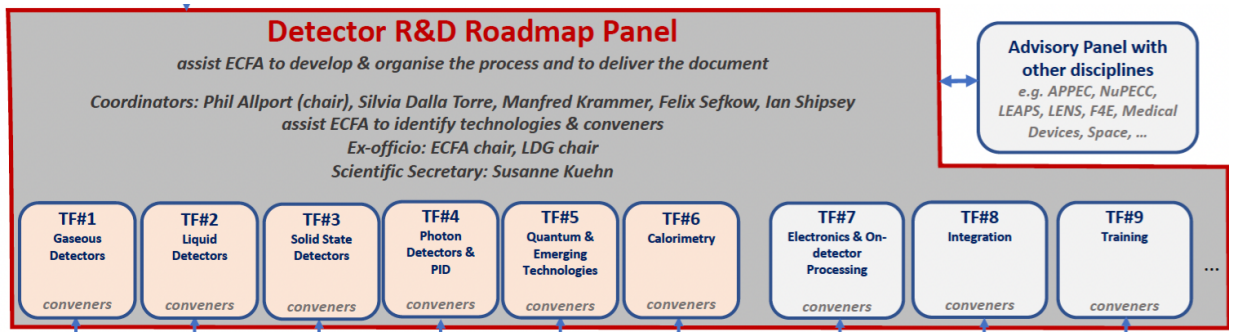
Some replies still missing

- **Radio-Frequency (RF):** Alexej Grudiev, Jean-Pierre Delahaye, Derun Li, Akira Yamamoto, (suggestion from Alexej).
- **Magnets:** Lionel Quettier, Toru Ogitsu, Soren Prestemon, Sasha Zlobin, (Riccardo Musenich, Stefania Farinon).
- **High-Energy Complex (HEC):** Antoine Chance, J. Scott Berg, Alex Bogacz, Christian Carli, , Angeles Faus-Golfe, Eliana Gianfelice-Wendt, Shinji Machida.
- **Muon Production and Cooling (MPC):** Chris Rogers, Marco Calviani, Chris Densham, Diktys Stratakis, Akira Sato, Katsuya Yonehara.
- **Proton Complex (PC):** Simone Gilardoni, Hannes Bartosik, Frank Gerigk, Natalia Milas, (Sarah Couisineau for September).
- **Beam Dynamics (BD):** Elias Metral, Tor Raubenheimer, Rob Ryne.
- **Radiation Protection (RP):** Claudia Ahdida.
- **Parameters, Power and Cost (PPC):** Daniel Schulte, Mark Palmer, Philippe Lebrun, Mike Seidel, Vladimir Shiltsev, Jingyu Tang, Akira Yamamoto
- **Machine Detector Interface (MDI):** Donatella Lucchesi, Christian Carli, Anton Lechner, Nicolai Mokhov, Nadia Pastrone.
- **Synergy:** Kenneth Long, Roger Ruber, Koichiro Shimomura.
- **Test Facility (TF):** Roberto Losito, Alan Bross, Tord Ekelof.

Detector Technologies

Will rely largely on European Detector R&D Roadmap (ECFA)

- Will provide link persons to relevant working groups



Currently consider the following most important (N. Pastrone)

- solid state tracking
- calorimetry
- emerging technologies
- electronics and in detector processing

Will also include other regions

Physics potential studies and machine background studies will verify if performances similar to CLIC and FCC-hh are sufficient

US Snowmass/P5

Submitted a number of proposals for white papers

- physics potential
- detector
- accelerator

Growing interest in the community

Aiming to coordinate the regional efforts

International Muon Collider Collaboration (corresponding author: D. Schulte)
Muon Collider Facility (c.a.: D. Schulte)
Muon Collider Physics Potential (c.a.: A. Wulzer)
Machine Detector Interface Studies at a Muon Collider (c.a.: D. Lucchesi)
Muon Collider experiment: requirements for new detector R&D and reconstruction tools (c.a.: N. Pastrone)
A Proton-Based Muon Source for a Collider at CERN (c.a.: Chr. Rogers)
Issues and Mitigations for Advanced Muon Ionization Cooling (c.a.: Chr. Rogers)
LEMMA: a positron driven muon source for a muon collider (c.a.: M.E. Biagini)
Applications of Vertical Excursion FFAs(vFFA)and Novel Optics (c.a.: Sh. Machida)

Physics Potential

A. Wulzer et al.

The muon collider physics potential emerges from **a variety** of measurements and searches that offer **opportunities** for new physics **discoveries** that are **comparable** or **superior** to "standard" future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in **multiple directions**.

Our plans for Snowmass21:

https://indico.cern.ch/event/944012/contributions/3989516/attachments/2091456/3518021/Physics_SnowMass_LoI.pdf

Letter of Interest: Muon Collider Physics Potential

D. Buttazzo, R. Capedevilla, M. Chiesa, A. Costantini, D. Curtin, R. Franceschini, T. Han, B. Heinemann, C. Helsens, Y. Kahn, G. Krnjaic, I. Low, Z. Liu, F. Maltoni, B. Mele, F. Meloni, M. Moretti, G. Ortona, F. Piccinini, M. Pierini, R. Rattazzi, M. Selvaggi, M. Vos, L.T. Wang, **A. Wulzer**, M. Zanetti, J. Zurita

On behalf of the forming muon collider international collaboration [1]

We describe the plan for muon collider physics studies in order to provide inputs to the Snowmass process. The goal is a first assessment of the muon collider physics potential. The target accelerator design center of mass energies are 3 and 10 TeV or more [2]. Our study will consider energies $E_{\rm CM} = 3, 10, 14$, and the more speculative $E_{\rm CM} = 30$ TeV, with reference integrated luminosities $\mathcal{L} = (E_{\rm CM}/10\ \text{TeV})^2 \times 10\,\text{ab}^{-1}$ [3]. Variations around the reference values are encouraged, aiming at an assessment of the required luminosity of the project based on physics performances. Recently, the physics potentials of several future collider options have been studied systematically [4], which provide reference points for comparison for our studies.

Physics Potential

A. Wulzer et al.

The muon collider physics potential emerges from **a variety** of measurements and searches that offer **opportunities** for new physics **discoveries** that are **comparable** or **superior** to "standard" future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in **multiple directions**.

And we are not alone

MUON COLLIDER: A WINDOW TO NEW PHYSICS

Douglas Berry[1], Kevin Black[2], Anadi Canepa[1], Swapan Chattopadhyay[1,3], Matteo Cremonesi[1], Sridhara Dasu[2], Dmitri Denisov[4], Karri Di Petrillo[1], Melissa Franklin[5], Zoltan Gecse[1], Allison Hall[1], Ulrich Heintz[6], Christian Herwig[1], James Hirschauer[1], Tova Holmes[7], Andrew Ivanov[8], Bodhitha Jayatilaka[1], Sergo Jindariani[1], Young-Kee Kim[9], Jacobo Konigsberg[10], Lawrence Lee[5], Miaoyuan Liu[11], Zhen Liu[12], Chang-Seong Moon[13], Meenakshi Narain[6], Scarlet Norberg[14], Isobel Ojalvo[15], Katherine Pachal[16], Simone Pagan Griso[17], Kevin Pedro[1], Alexx Perloff[18], Elodie Resseguie[17], Stefan Spanier[7], Maximilian Swiatlowski[19], Ann Miao Wang[5], Lian-Tao Wang[9], Xing Wang[20], Hannsjörg Weber[1*], David Yu[6]

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Electroweak multiplets at the Muon Collider

R. Capdevilla, D.Curtin, Y. Kahn, G. Krnjaic, F. Meloni, J. Zurita

August 2020

Letter of Interest: EW effects in very high-energy phenomena

C. ARINA, G. CUOMO, T. HAN, Y.MA, F. MALTONI, A. MANOHAR, S. PRESTEL, R. RUIZ, L. VECCHI, R. VERHEYEN, B. WEBBER, W. WAALEWIJN, A. WULZER, K. XIE

to be submitted to the Theory Frontier (TF07) and Energy Frontier (EF04)

Beyond the Standard Model with High-Energy Lepton Colliders

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Tianji Cai[1], Junyi Cheng[1], Tim Cohen[3], Nathaniel Craig[1], JiJi Fan[4], Isabel Garcia Garcia[5], Seth Koren[6,1], Giacomo Koszegi[1], Zhen Liu[7], Kunfeng Lyu[8], Amara McCune[1], Patrick Meade[9], Isobel Ojalvo[10], Umut Oktem[1], Matthew Reece[11], Raman Sundrum[7], Dave Sutherland[12], Timothy Trott[1], Chris Tully[10], Ken Van Tilburg[5], Lian-Tao Wang[6], and Menghang Wang[1]

HIGGS AND ELECTROWEAK PHYSICS AT THE MUON COLLIDER: AIMING FOR PRECISION AT THE HIGHEST ENERGIES

Aram Apyan[1], Jeff Berryhill[1], Pushpa Bhat[1], Kevin Black[2], Elizabeth Brost[3], Anadi Canepa[1], Sridhara Dasu[2], Dmitri Denisov[3], Karri DiPetrillo[1], Zoltan Gesce[1], Tao Hann[4], Ulrich Heintz[5], Rachel Hyneman[6], Young-Kee Kim[7], Da Liu[8], Mia Liu[9], Zhen Liu[10], Ian Low[11,12], Sergo Jindariani[1], Chang-Seong Moon[13], Isobel Ojalvo[14], Meenakshi Narain[5], Maximilian Swiatlowski[15*], Marco Valente[15], Lian-Tao Wang[7], Xing Wang[16], Hannsjörg Weber[1], David Yu[5]

Muon Collider: Study of Higgs couplings and self-couplings precision

C. Aimè[a], F. Balli[b], N. Bartosik[c], L. Buonincontri[d], M. Casarsa[e], M. Chiesa[f], F. Collamati[g], C. Curatolo[d], D.Lucchesi[d], B. Mele[g], F. Maltoni[h], B. Mansoulié[b], A. Nisati[g], N. Pastrone[c], F. Piccinini[i], C. Riccardi[a], P. Sala[l], P. Salvini[i], L. Sestini[m], I. Vai[a], D. Zuliani[d]

Global Collaboration

We do see this as a global effort

- are ready to improve
- profit from US expertise on the collider
- profit from Japanese expertise on muons
- new enthusiasm in Europe, revived enthusiasm in the US, hopefully enthusiasm in Japan

Submitted a number of proposals for white papers to Snowmass

- physics potential
- detector
- accelerator

Will be ready to support any other decision making processes

Ideally, we will form a common collaboration with different proposed sites

Conclusion

The muon is a unique promising option at highest lepton energies

We need to fully explore the physics case, which goes well beyond 3 TeV (studied for CLIC)

Have to address the feasibility

A great challenge but also a great opportunity

Community meeting July 12-14:
https://indico.cern.ch/event/1043242/

Web page: http://muoncollider.web.cern.ch

Mailing lists:
MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch,
MUONCOLLIDER_FACILITY@cern.ch
go to https://e-groups.cern.ch and search for groups with “muoncollider” to subscribe

Many thanks to all that contributed
MAP collaboration
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
Muon collider collaboration
…

Reserve

Memorandum of Cooperation

Basically ready, waiting for final polishing

CERN is initially hosting the study

- International collaboration board (ICB) representing all partners
  - elect chair and study leader
  - can invite other partners to discuss but not vote (to include institutes that cannot sign yet)
- Study leader
- Advisory committee reporting to ICB

Addenda to describe actual contribution of partners

Linear Collider Luminosity

For constant technology

- keep bunch charge and length constant

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

- emittances and betafunctions are constant
  - same beam quality and same focusing
  - these are not directly linked to the acceleration technology
    - emittance is determined by damping rings
    - and degradation during acceleration
    - betafunction is quality of the focusing system
  - actually becomes harder at higher energies
    - more emittance degradation
    - harder to focus beam because of synchrotron radiation in focusing system
    - actually already visible at CLIC at 3 TeV

$\Rightarrow$ **Luminosity per beam power independent of energy**

Linear Collider Luminosity

CLIC requires about 300 MW of wall plug power for the RF to produce 28 MW of beam power and 300 about MW for other systems (e.g. magnets)

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

For CLIC about **190 MW beam power** to reach 40 x 10^{34}cm^{-2}s$^{\wedge -1}$ at 14 TeV

If we consider only luminosity above 99% of nominal centre-of-mass energy, we need about **570 MW beam power**

Efficiency from wall plug power into RF systems to beam power is O(10%)

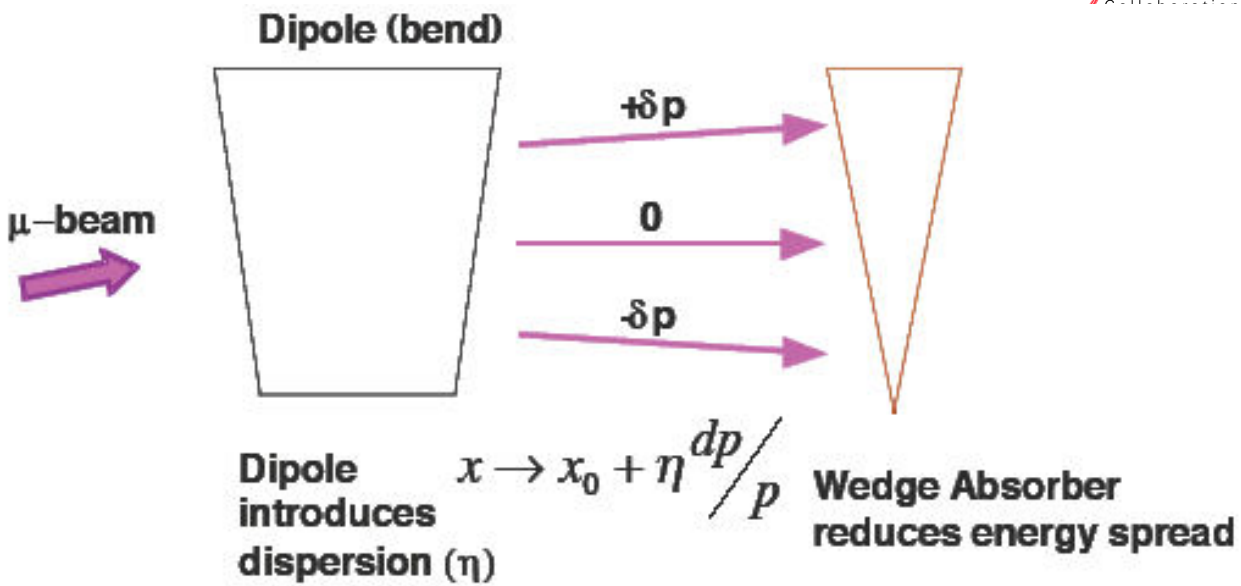
- so **O(2-6 GW)** of **total power** consumption

Need to add the other systems (which also will increase compared to 300 MW)

Longitudinal Cooling/Emittance Exchange

Combined with transverse cooling at beginning

Several options considered



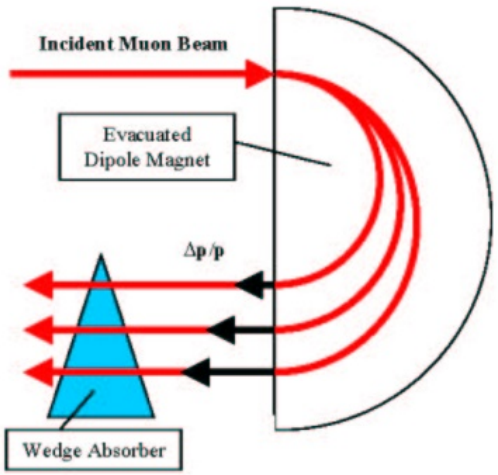


Figure 1. Use of a Wedge Absorber for Emittance Exchange

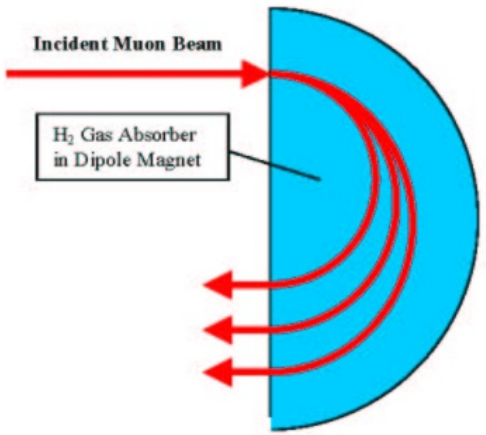


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Allows 6-D cooling

Physics Potential

A. Wulzer et al.

The muon collider physics potential emerges from **a variety** of measurements and searches that offer **opportunities** for new physics **discoveries** that are **comparable** or **superior** to "standard" future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in **multiple directions**.

Direct search of heavy particles	High energy measurements	High rate Higgs production
SUSY-inspired, WIMP, VBF production, 2->1	difermion, diboson, EFT, Higgs compositeness	Higgs single and self-couplings, rare Higgs decays, exotic decays

Few Preliminary Results

A. Wulzer et al.

International MUON Collider Collaboration

Higgs 3-linear coupling: **$\delta\kappa_\lambda$=(5%, 3.8%, 1.6%) for E = (10, 14, 30) TeV**

[2008.12204; 2005.10289; Buttazzo, Franceschini, Wulzer, to appear]

[FCC reach is from 3.5 to 8.1% depending on systematics assumptions]

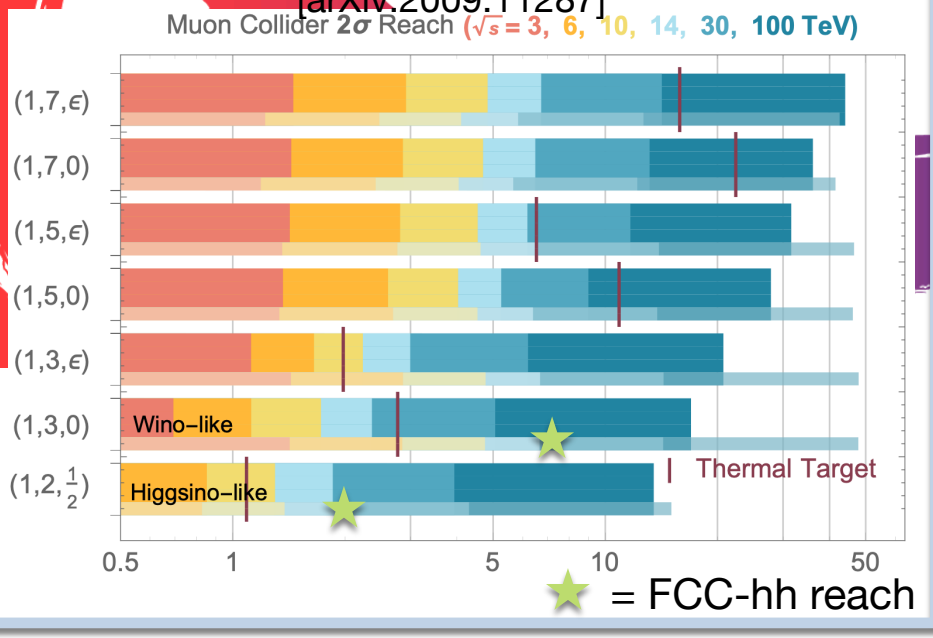
Higgs compositeness scale: **(38, 53, 115) TeV for E = (10, 14, 30) TeV**

[Buttazzo, Franceschini, Wulzer, to appear]

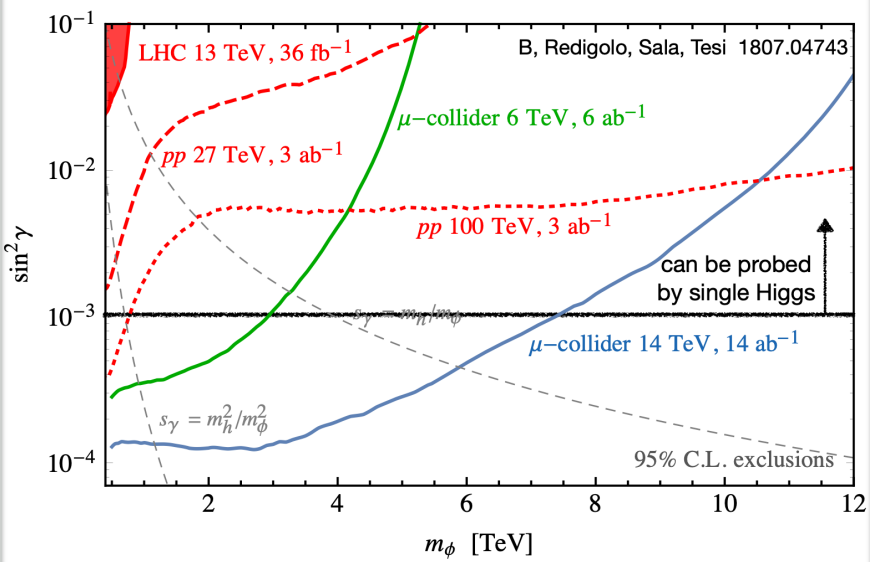
[other F.C.: from 20 to 40 TeV depending on model]

WIMP DM

[arXiv:2009.11287]



Scalar Singlet



Community Meeting Working Groups

Working groups and conveners (contact Panel members in blue)

- **RF**: Alexej Grudiev, Derun Li, Jean-Pierre Delahaye, Akira Yamamoto
- **Magnets**: Lionel Quettier, Soren Prestemon, Sasha Zlobin
- **High-energy complex**: Antoine Chance, Scott Berg, Alex Bogacz, Shinji, Machida, Christian Carli, Eliane Gianfelice-Wendt, Angeles Faus-Golfe
- **Muon production and cooling**: Chris Rogers, Diktys Stratakis, Marco Calviani, Chris Densham, Katsuya Yonehara
- **Proton complex**: Simone Gilardoni, Frank Gerigk
- **Beam Dynamics**: Elias Metral, Rob Ryne, Tor Raubenheimer
- **Radiation protection and other technologies**: Roberto Losito, Claudia Ahdida, Vladimir Shiltsev, Philippe Lebrun, Mike Seidel
- **MDI**: Donatella Lucchesi, Nicolai Mokhov, Christian Carli, Nadia Pastrone
- **Synergy**: Kenneth Long

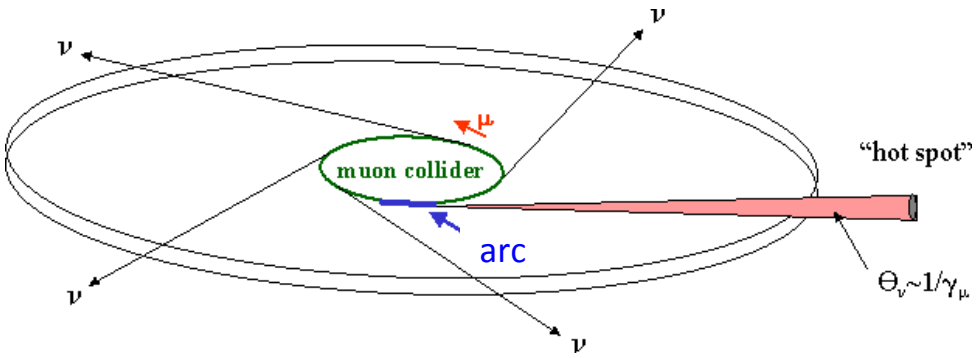
- **Test facility**: Roberto Losito
- **Parameters etc.**: Mark Palmer, Daniel Schulte

Key Challenge Areas

10+ TeV is uncharted territory

- **Physics potential** evaluation
- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site
- The impact of **machine induced background** on the detector, as it might limit the physics reach.
- **High-energy systems** after the cooling (acceleration, collision, …)
  - This can limit the energy reach via cost, power and beam quality
- **High-quality beam production** of cooled muon beam
  - MAP did study this in detail
  - Need to optimise and prepare test facility
- **Integrated Collider Design** with choices, parameters, trade-offs
  - need to cover all accelerator areas

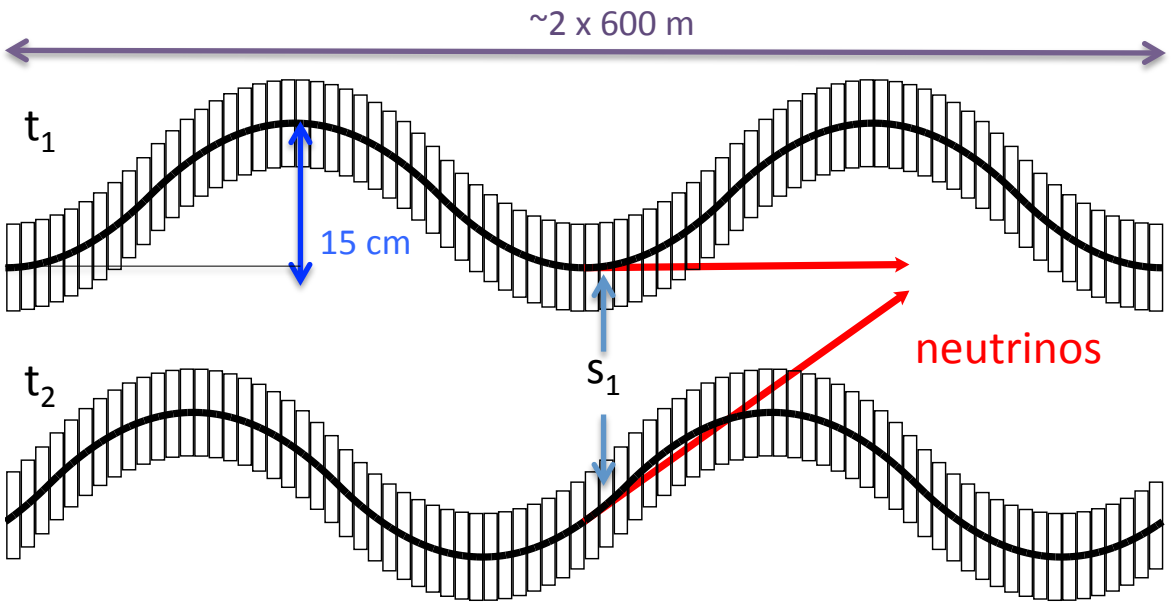
Neutrino Flux Mitigation



Legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
Our goal: arcs below threshold for legal procedure < 10 µSv/year
LHC achieved < 5 µSv/year

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV: idea of Mokhov, Ginneken to move beam in aperture
our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

MDI

Need to show that we can expect to extract the physics

Main background sources

- Muon decay products (40,000 muons/m/crossing at 14 TeV)
  - tertiary muons produced far from collision point
  - showers products produced in final triplets
- Beam-beam background

Mitigation methods

- masks
- detector granularity
- detector timing
- solenoid field
- event reconstruction strategies
- …

Need to ensure they do not compromise physics

Background changes while beam decays

- parts of the luminosity delivered with lower background

Key High-energy Systems

- Lattice designs
  - in particular IP and collider ring, accelerator rings, also linacs
- Longitudinal beam dynamics along complex
  - including single bunch beam loading
- Collective effects estimates
  - not sure that they were explored completely

- Final triplet magnets
  - drive the luminosity, require large aperture and high gradient
- Collider arc magnets
  - key cost driver, large aperture, radiation load, vertical bending field, impact of mover system?
- RCS fast-ramping magnets and power system
  - Cost driver
  - Efficient energy recovery from magnetic field, low losses
- FFA magnet and optics design

- Mitigation of beam loss
  - Interaction region and detector shielding
  - In collider ring at 10 TeV about 5 MW (500 W/m), leads to 35 MW of cryo power for 1% shielding inefficiency
  - O(200) kW in cold accelerator parts, goal 10% inefficiency or better

- RF
  - very high single-bunch beam loading
  - efficiency

- Mover system
  - also impact on components

Key Muon Production and Cooling

- Lattice design optimisation
  - Do not yet reach the target transverse emittance
  - Most muons are lost here
  - Room to optimise the cooling system for emittance and muon survival

- Highest-field solenoid for final cooling
  - Aim for 40+ T
- Target solenoid
  - High field, large aperture, high radiation
- Other cooling magnets
  - High field, large aperture, required for test facility

- High-gradient, RF in strong magnetic field
- Have to limit peak power

- Cooling cell design
  - Tight integration of components

- Target
  - Energy per pulse (also power, but muons per bunch is critical and cannot be mitigated by multiple targets)
  - Challenge depends on muon survival, scaling of MAP parameter tables 1.3 MW, other estimates up to 4 MW
  - ⇒ Best to plan for some reserve

- Radiation from target

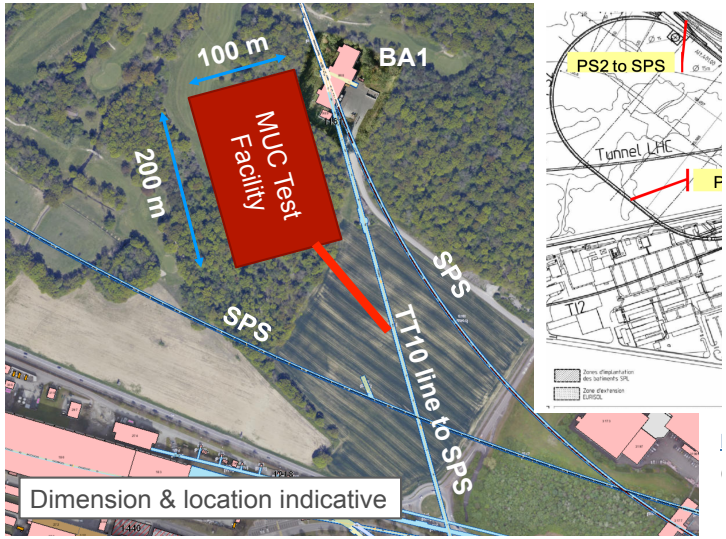
- Proton complex
  - Challenge is to compress proton pulse

Demonstration Programme

Core test facility to demonstrate muon cooling
- needs muon production with reasonable intensity but below real collider (e.g. 10 kW target)
- Identify potential sites
  - At least one good candidate at CERN
  - ESS, US labs?

Willingness of TIARA to supports as EU Design Study
Need to define scope and involvement for EU and prepare commitments

Models and prototypes of key components
- magnets
- RF systems
- target
- …



Programme needs to be modular
Tentative rough cost scale 500 CHF
Initial test facility material cost about 150 MCHF?

But not to forget:
- The collider justifies the demonstration programme

Test Facility Goals

Muon capture and cooling are the key novel ingredients
⇒ Experimental validation of theoretical studies, mainly in longitudinal (energy straggling)

Horn vs. solenoid

MICE demonstrated the very principle
- but need to further the experiment

LiH vs option to test LH
Key R&D issues
- Inclusion of RF for 6D cooling
- Good statistics, real muon bunches

- Very thin windows for absorbers are needed
  - Be, mylar, …
- Very high RF gradients in a magnetic field
  - 50 MV/m at 800 MHz demonstrated but very specific spearhead technology
- High-field solenoids
- Instrumentation, vacuum, cryogenics, cooling, alignment, …

- Full integration of components
  - superconducting magnets and normal-conducting RF
  - RF and absorber windows, vacuum, sparks

Conclusion

- Muon colliders could be a unique opportunity for a high-energy lepton collider
- Face important challenges
- Need to develop concept to a maturity level that allows to make informed choices by the next ESPPU and other strategy processes
- Have the opportunity to define a workprogramme
- Let us do a good job
  - in spite of the short timescale
  - and the fact that half of us are still learning and the other half is only allowed a limited amount of work

Reserve

Memorandum of Cooperation

Basically ready, waiting for final polishing

CERN is initially hosting the study

- International collaboration board (ICB) representing all partners
  - elect chair and study leader
  - can invite other partners to discuss but not vote (to include institutes that cannot sign yet)
- Study leader
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Addenda to describe actual contribution of partners

Example Basic Parameters

Parameter common for all RCS	unit	
B_{static} (NiTi)	T	8
B_{ramp}	T	2
Ramping dipole gap size (seems much larger than in MAP)	cm	8x4
Effective dipole filling factor (could be with combined function magnets)	%	80
G	MV/m	20
f_{RF}	MHz	400
RF filling factor	%	65
Q	10^{10}	2
Mains power to RF efficiency	%	60
Beam loading compensation / bucket forming	ignored	
Fraction of beam loss in cold parts at 2 K after mitigation	%	10
Static heat load per m of cold system	W	1
Power consumption per W of 2 K heat load	W	700

Example of RCS Parameters

Parameter	unit	RCS 1	RCS 2	RCS 3
E_1	GeV	60	300	1500
E_2	GeV	300	1500	5000
<G>	MV/m	2	2	1
N_{in}	10^{12}	2.82	2.48	2.18
N_{out}	10^{12}	2.48	2.18	1.8

Defines muon survival

Approximate Example Parameters

Parameter	unit	RCS 1	RCS 2	RCS 3
E_1	GeV	60	300	1500
E_2	GeV	300	1500	5000
<G>	MV/m	2	2	1
N_{in}	10^{12}	2.82	2.48	2.18
N_{out}	10^{12}	2.48	2.18	1.8
L_{static}	km	0.47	2.35	8.5
L_{ramp}	km	1.26	6.28	18.3
L_{RF}	km	0.28	1.38	1.9
C	km	2.8	13.8	38
beam turns		44	44	92
T_{ramp}	ms	0.4	2	11.67

All lengths follow from magnet field, filling factor and energy choices

RF length follows from gradient, filling factor and average gradient target

Add a bit for injection/ extraction

Beam turns to achieve energy (slight adjustment required)

Ramp time from circumference and turns

Approximate Example Parameters

Parameter	unit	RCS 1	RCS 2	RCS 3
E_1	GeV	60	300	1500
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C	km	2.8	13.8	38
beam turns		44	44	92
T_{ramp}	ms	0.4	2	11.67
P_{RF}	MW	509	450	192
T_{RF}	ms	0.8	4.3	19.1
$\eta_{RF\text{-}to\text{-}beam}$	%	50	47	61

RF power from average beam current (variation is not taken into account nor bucket-forming voltage)

Approximate Example Parameters

Parameter	unit	RCS 1	RCS 2	RCS 3
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C	km	2.8	13.8	38
beam turns		44	44	92
T_{ramp}	ms	0.4	2	11.67
dB/dt	kT/s	10	2	0.34
E_{ramp}	MJ	6.4	32	93.3
P_{ramp}	GW	32	32	16
Beam loss	W/m	20	17.8	31.4

Magnet ramp rate from ramp time

energy in magnetic field from aperture, field and length

Power flow during linear ramp proportional to average RF gradient

Beam loss follows from number of turns and average current

Key Power in Collider Ring and RCS

- Electrons/positrons from muon decay in collider ring
  - at 10 TeV about 5 MW (500 W/m)
  - Shielding goal: 1% to reach magnets (at 2 K)
  - need **35 MW** of power for cryo-system
  - about 1W/m static heat load requires **7 MW** power for cryogenics

- RCS3 fast-ramping magnets
  - Goal: limit total loss to 10 MJ per cycle (tbc)
  - Need > 90% energy recovery, including losses in magnets, distribution etc.

- RCS3 RF
  - ignore beam loading / bucket forming
  - beam extracts 2.2x stored energy in cavities
  - RF to beam efficiency is 60%
  - Mains to RF assume 60%
  - total of **26 MW**

- RCS3 cryogenics
  - Beam losses in cold systems: 32 W/m x 13.5 km ~425 kW
  - assume mitigation down to 10% at 2 K
  - **30 MW** power for cryogenics due to beam loss
  - **7 MW** for static losses
  - **7 MW** of power for cryogenics to remove RF power loss with $Q=2 \times 10^{10}$
  - need to also develop shielding for this
  - but maybe later?

- Total goal 47 MW + 65 MW for beam loss cooling + 50 MW for ramping magnets

Key Power in RCS1 and RCS2

- Fast-ramping magnets
  - 38.4 MJ in magnetic field
  - Goal: limit total loss to 5 MJ per cycle (tbc)
  - Need > 90% energy recovery, including losses in magnets, distribution etc.

- RF
  - ignore beam loading / bucket forming
  - 5 x (0.8 ms x 509 MW + 4.3 ms x 450 MW) / 0.6 = **11.7 MW**
  - RF to beam efficiency is 50% and 47 %
  - Mains to RF assume 60%
  - total of **11.7 MW**

- Cryogenics
  - Beam losses in cold systems: 20 and 17.8 W/m
  - assume mitigation down to 10% at 2 K
  - **7.7 MW** power for cryogenics due to beam loss
  - **4.25 MW** for static losses
  - **1.1 MW** of power for cryogenics to remove RF power loss with $Q=2 \times 10^{10}$
  - need to also develop shielding for this
  - but maybe later?

- Total goal 17 MW + 7.7 MW for beam loss cooling + 25 MW for ramping magnets

Approximate Example Parameters

Parameter	unit	RCS 1	RCS 2	RCS 3
E_1	GeV	60	300	1500
E_2	GeV	300	1200	5000
<G>	MV/m	2	2	1
N_{in}	10^{12}	2.82	2.48	2.18
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beam turns		44	44	92
T_{ramp}	ms	0.4	2	11.67
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dB/dt	kT/s	10	2	0.34
Beam loss	W/m	20	17.8	31.4

Muon Beam Panel Roadmap Milestones

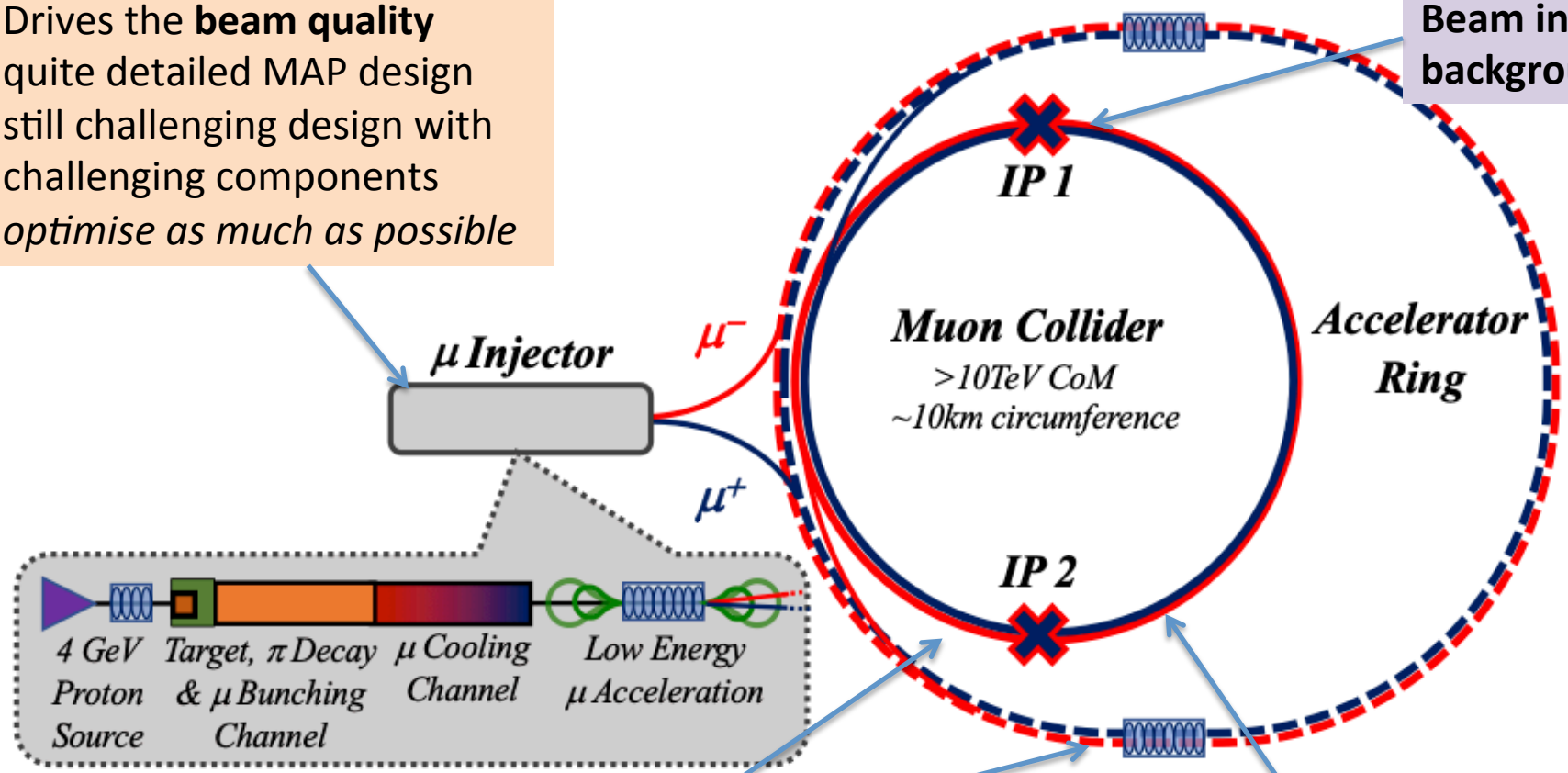
Date	action
May 20+21 2021	Community meeting to collect R&D items lists
First week of June 2021	Panel provides R&D list to LDG
June Council 2021	LDG presents R&D lists as background
June 2021	LDG decision on structure, content and format of interim reports
Mid July 2021	Community meeting to define required scope
Late July 2021	Panel interim report to LDG
September Council 2021	LDG provides interim report to Council
December Council 2021	LDG provides final report to Council

Very short timescale
Need to collect ideas on scope early

Key Challenges

Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
optimise as much as possible

Beam induced background

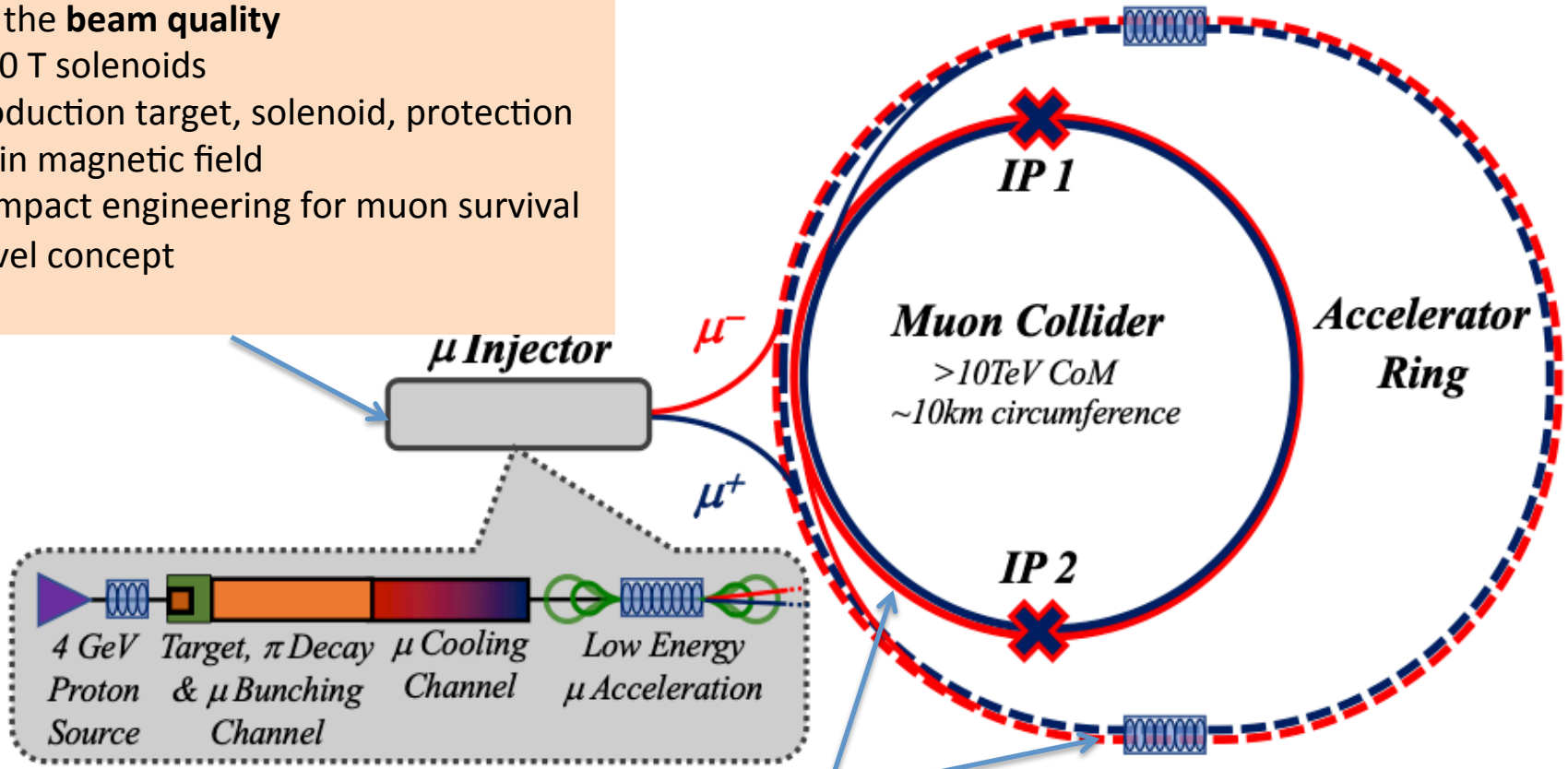


Dense neutrino flux
mitigated by mover system
and site selection

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**

R&D Challenges

Drives the **beam quality**
- > 30 T solenoids
- Production target, solenoid, protection
- RF in magnetic field
- Compact engineering for muon survival
- novel concept
- …



Cost and **power** consumption limit energy reach
- Superconducting collider ring magnets
- Protection of collider (and other) magnets from muon decays
- Fast ramping magnets with energy recovery
- Efficient RF for high bunch charge
- FFA

Neutrino flux on Earth surface limits energy and site choice
MDI might limits energy reach

Integrated coherent concept/parameters

A Not Very Perfect Example

- **The final focus magnets.** The final focus quadrupoles limit the beta-function in the collision point and hence the luminosity. They become more challenging at higher collider energies, since the target beta-functions decrease and the beam becomes more rigid. Therefore these magnets will be one of the key limitations toward high energy and an important design driver. Currently, apertures of up to 30-50 cm radius at 10 TeV and around 10 cm at 3 TeV are envisaged, but this has to be revised. *The magnet team should propose ambitious but reasonable goals for the quadrupolar field as a function of radius for the different technologies, assuming we invest into the R&D. Obviously, one then will have to confirm this goal by detailed work. I think we need a design by 2025.* Proposed goals: **Parametric target field model for design optimisation (2021); conceptual design (2025)**

I wrote the text, magnet experts have to write a proper version
Text in italics is comments on how to expand.