Muon Collider Collaboration

D. Schulte for the forming International Muon Collider Collaboration

Introduction

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

Other activities mainly in UK (MICE: demonstration of ionisation cooling, EMMA: FFA) 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 very 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
- Core team: Lenny Rivkin, Nadia Pastrone, Daniel Schulte (ad interim study leader)

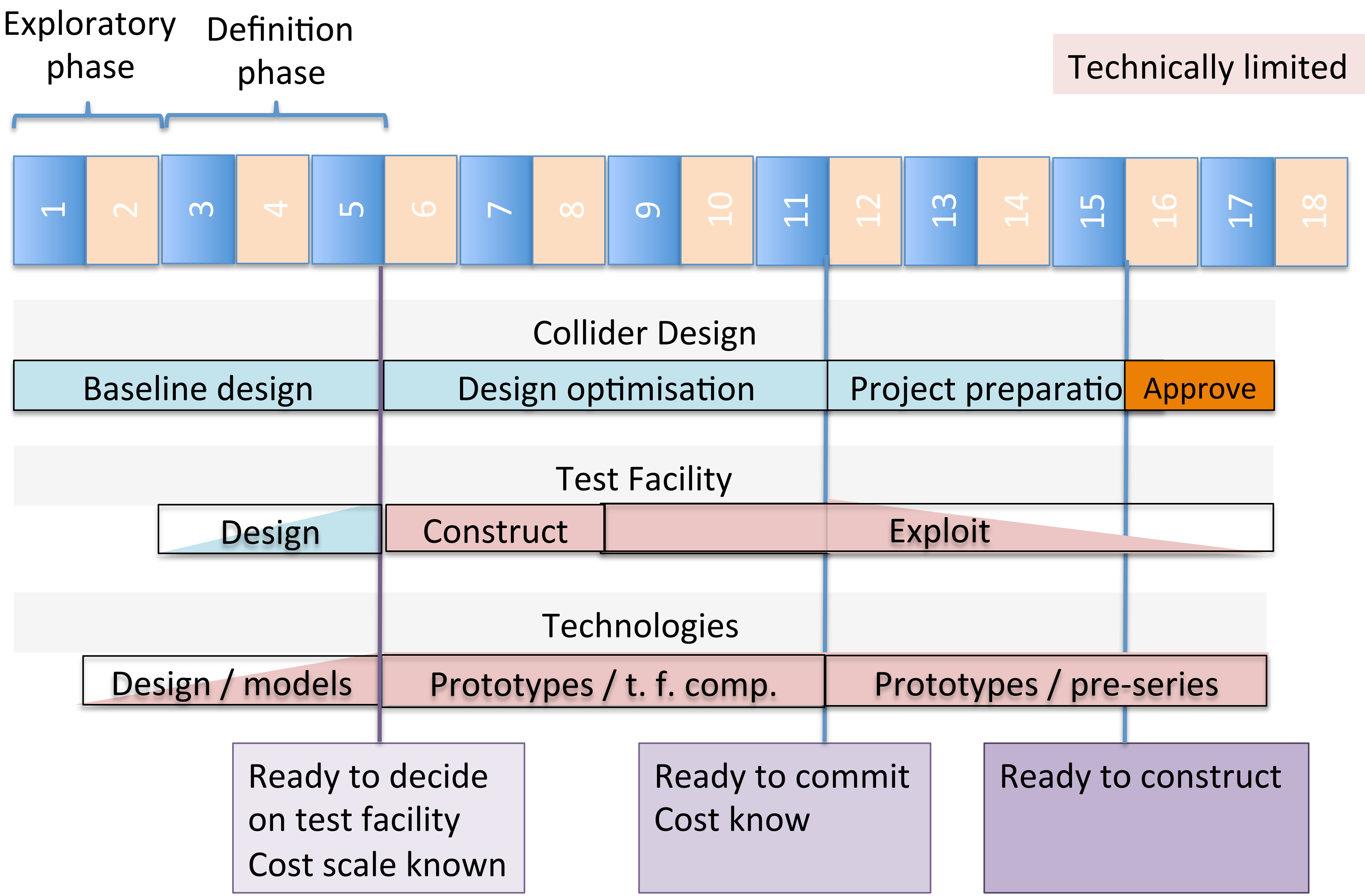
So the new collaboration is starting in a region that did not work on it much …

Current Constraints

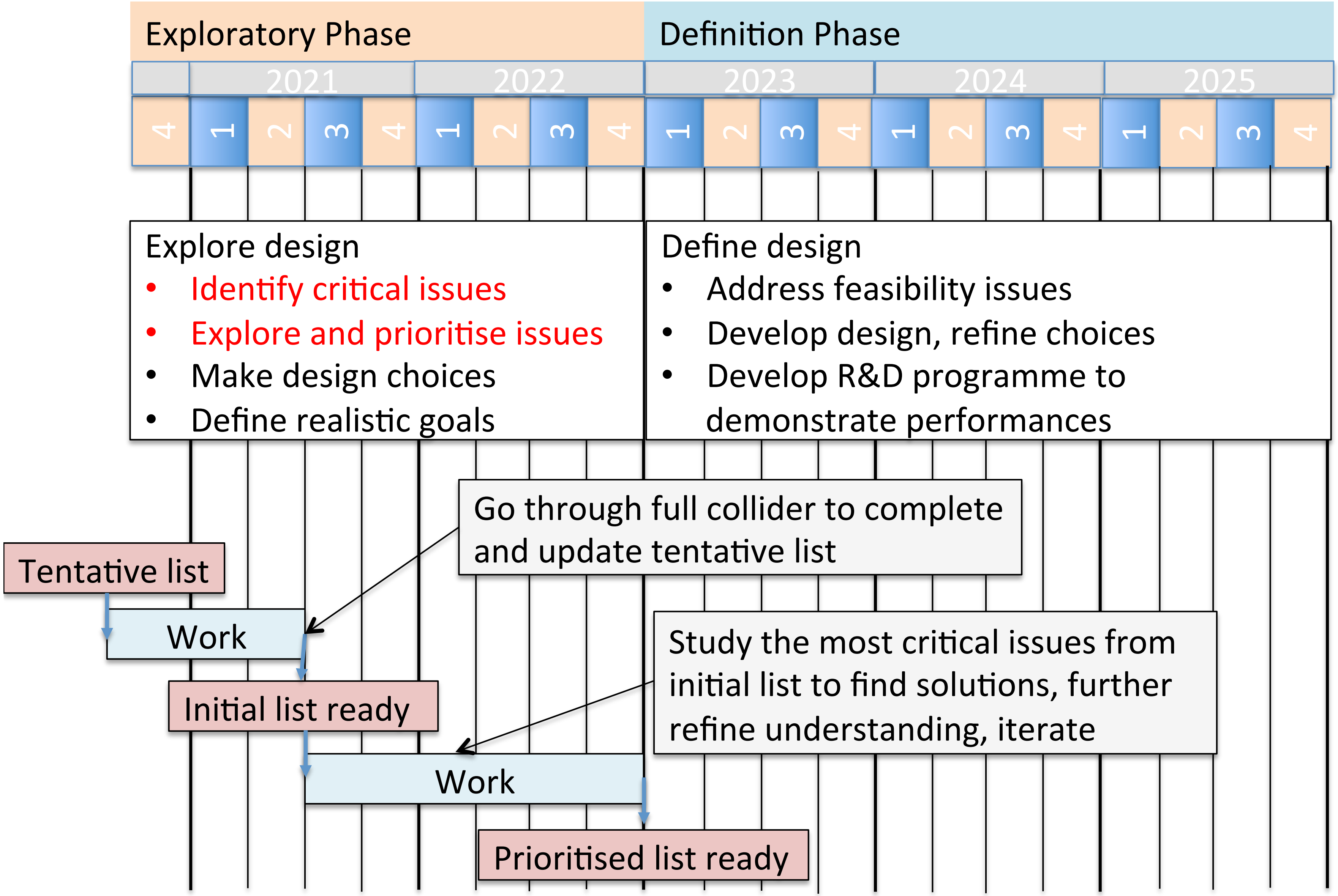
- Definition of European **Accelerator R&D Roadmap** by LDG
  - Define scope of muon collider study until September 2021
  - Organisation not yet known
  - Some overlap with our planed organisation (**IRAP**, Interim R&D Advisory Panel) delays the latter

- **Snowmass/P5** process in the US
  - Input until June 2021, decisions in 2022
    - will have to prepare white papers
  - Submitted several Letters Of Interest from the collaboration
    - In addition, others refer to the muon collider, e.g. technologies, physics, …
  - High priority for us
  - Might change situation dramatically after P5 concluded in 2022

(Updated) Timeline



Tentative Roadmap



Muon Collider Collaboration: Objective and Scope

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.

Deliverable:

Report assessing muon collider potential and describing R&D path to CDR

Scope:

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

Memorandum of Understanding

Basically ready, final refinement by CERN DG

- mainly role of host laboratory
- Anticipating that the study might become large once the demonstrator is under construction and that the host wants to have some control

CERN is initially hosting the study

- but can transfer to other host later

- International collaboration board (ICB) representing all partners
  - elect chair and appoint 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

Comment on Resources

Interest expressed in many institutes

- CEA, CNRS (IJClab), INFN, University of Chicago, IFIC, Jefferson Lab, Spanish Network, KIT, Darmstadt University, University of Rostock, Helmholz-Zentrum Dresden-Rossendorf, Sofia University, Lund University, Uppsala University, Oslo University, LBL, EPSL, PSI, ESS, University of Mississippi, NIKHEF, HEPHY, FNAL, SLAC, …

Actual work already ongoing (mainly volunteers)

Formal resources are starting to be defined

- EU-cofunded **IFAST** WP 5.1, N. Pastrone, **300 kEUR** from EU
- EU- cofunded **aMUSE** WP "Muon beams" and "Tools", D. Lucchesi, **integrated 117 pm** includes BNL
- **Proposal to German BMBF** for funding of magnet and RF work, T. Arnd, U. van Rienen, KTI, Darmstadt University, Rostock University, **9 FTE-years total**
- **More request in preparation**
- **JAI students** worked on rapid cycling synchrotron as project (E. Tsesmelis)

CERN Medium Term Plan has dedicated budget line for muon collider (approved by Council) from January 1rst, 2021

- Per year 5 FTE staff, 6 fellows, 4 students, 1 associate, 5 x 2 MCHF

Note: Snowmass Submissions

Submitted by the collaboration:
Muon Collider Physics Potential (c.a.: A. Wulzer)
Muon Collider: Study of Higgs couplings and self-couplings precision (C. Aimè et al.)
International Muon Collider Collaboration (corresponding author: D. Schulte)
Muon Collider Facility (c.a.: D. Schulte)
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)

Others may be relevant, e.g.
EW effects in very high-energy phenomena (C. Arina et al.)
Beyond the standard model with high-energy lepton colliders (H. Al Ali et al.)
Muon Collider: A Window to New Physics (D. Berry et al.)
Electroweak Multiplets at the muon collider (R. Capdevilla et al.)
Higgs and Electroweak Physics at the Muon Collider (A. Apyan et al.)

Exploratory Phase – Key Topics

- Physics potential evaluation
  - requires to define energy, luminosity and detector performance goals
- Impact on the environment
  - The neutrino radiation and its impact on the site. This is known to require mitigation strategies for the highest energies.
  - Power consumption (accelerating RF, magnet systems, cooling)
- The impact of machine induced background on the detector, as it might limit the physics reach.
- High-energy systems that might limit energy reach or performance
  - Acceleration systems, beam quality preservation, final focus, cost, power consumption
- High-quality beam production, preservation and use

Luminosity Goals

Target integrated luminosities

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

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters, scaled from MAP parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	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

Snowmass process to give feedback on this

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
- Based on FCC-hh and CLIC performances
- including masks against beam against beam-induced background (BIB)
- assumes the BIB can be mitigated

- Took somewhat more effort than expected to agree
- Would like to thank M. Selvaggi for convening task force, Werner Riegler, Ulrike Schnoor and A. Sailer for providing input from FCC-hh and CLIC, D. Lucchesi, Andrea Wulzer et al. for contributing to discussion

- Please find the card here: https://muoncollider.web.cern.ch/node/14

- For use by physics potential studies
  - Are the performances sufficient or too good?

see Andrea Wulzer, Michele Selvaggi, et al.

- For detector studies to work towards

see Donatella Lucchesi, Sergo Jindariani

Detector Studies

Verify/ensure that detector **target performance can be reached**

- main challenge is BIB

Simulation infrastructure mostly in place (D. Lucchesi et al., S. Jindariani et al.)

Background data for 125 GeV and 1.5 TeV available, hope to have 3 TeV in time for Snowmass

- Working on accelerator design higher energies, but will need time

Try to develop **BIB mitigation strategy**, characterise background

- Total effort to develop detector and reconstruction more than we can hope for Snowmass

Use full simulation of CLIC-like detector and reconstruction to see how far we have to go to reach tentative performance goal

- Guide the work after Snowmass

Have to also check technologies, use what should become available, make specific requests to community, pick-up good ideas

Ongoing Accelerator Work

Muon collider is new in Europe

- Have to get up to speed

Together with US colleges are starting to take (shared) ownership of design

- Detailed presentations and discussions in Design Meetings
  - dedicated cooling meetings
- Transfer of lattice decks
- People get engage and form their own opinions
- Identifying issues that have been neglected (sorry)
- Already part of generating the critical issues list
- Understanding the challenges and the resource needs

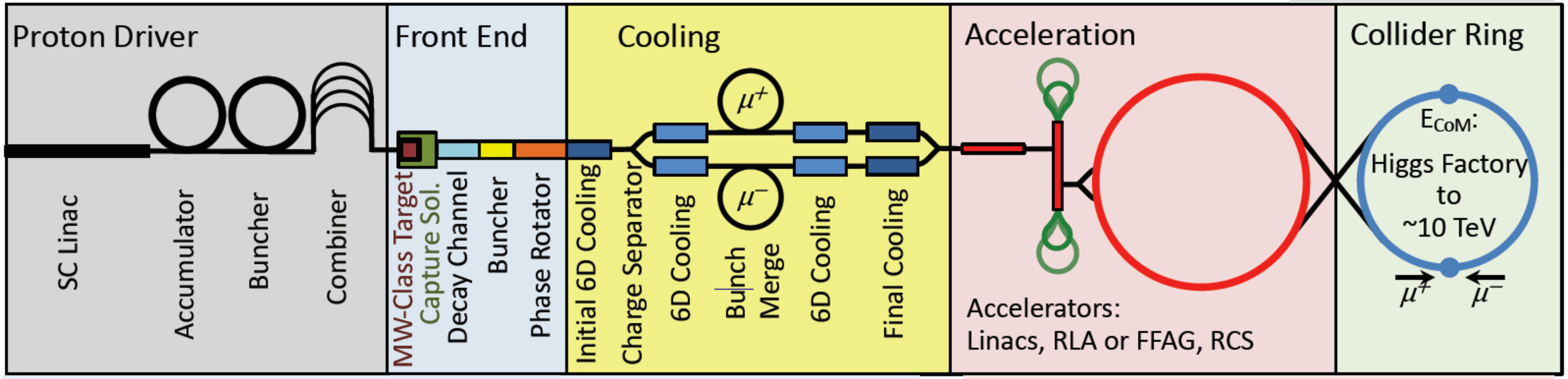
An important phase, excellent time to identified overlooked issues due to fresh view

Also find consensus on sometimes diverging opinions or define way to do so

A bit community-based, like the Snowmass process

Muon Collider Baseline Concept

MAP collaboration



Proton Driver, Front End, Cooling and Initial Acceleration have **same challenge level** as MAP designs

Final cooling needs to be improved by factor 2
Overall consolidation and optimisation

Still a **challenging design** with **challenging components**

Started to review and complete R&D item list and prepare priority

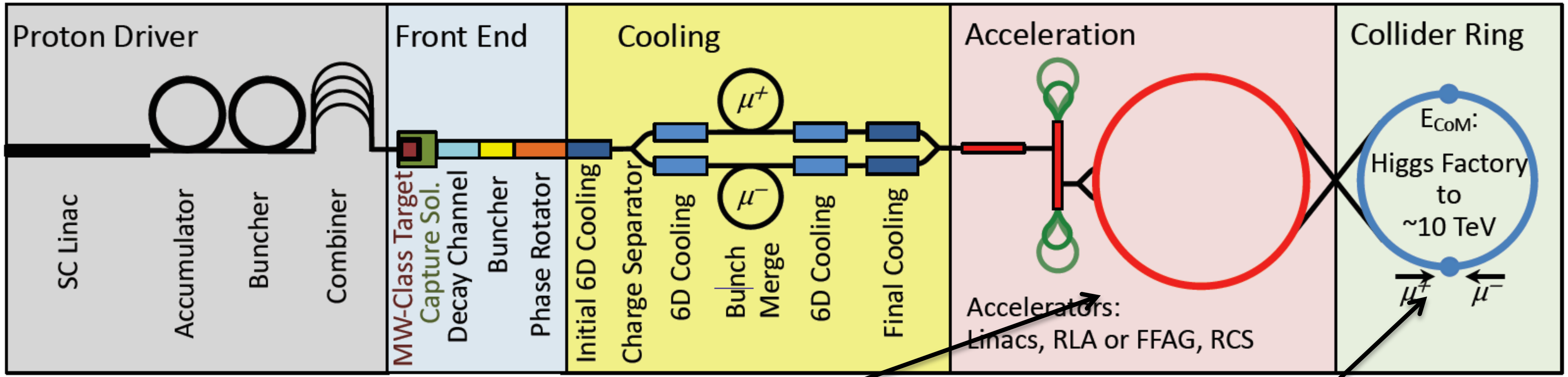
Accelerator Ring, Collider Ring, Interaction Region, MDI, neutrino radiation become **technically more challenging with energy**
Also drive cost and power

They will **limit energy reach**

Challenging design with **challenging components**

Full integration remains to be done, e.g. beam evolution through systems,…

Example Issues

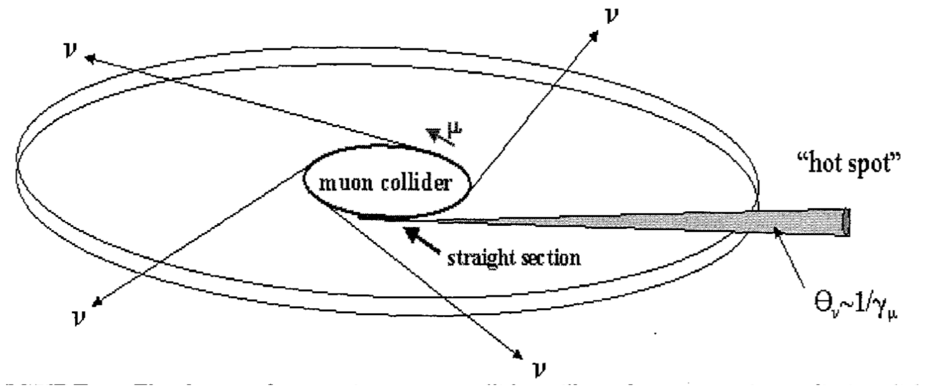


- Very efficient recovery of energy from fast-ramping magnets
- RF system for high-charge, short bunch with large gaps
- Protection of magnets (O(30 W/m loss))
- FFA design
- …

- Very small beta-functions at high energy
- Larger aperture final quadrupoles
- Shielding against losses (O(400 W/m))
- Large aperture dipoles (stress and cost)
- Maintaining bunch short with limited RF
- BIB
- Neutrino radiation
- …

Cost scale of components
Power consumption

Neutrino Radiation and Site Considerations



Tentative considerations on reuse of LHC tunnel:

- Too long for 3 TeV collider (need 4.5-6 km)
- 14 TeV collider ring suffers from neutrino radiation, not clear this can be solved
- Use for 3 TeV accelerator ring appears possible

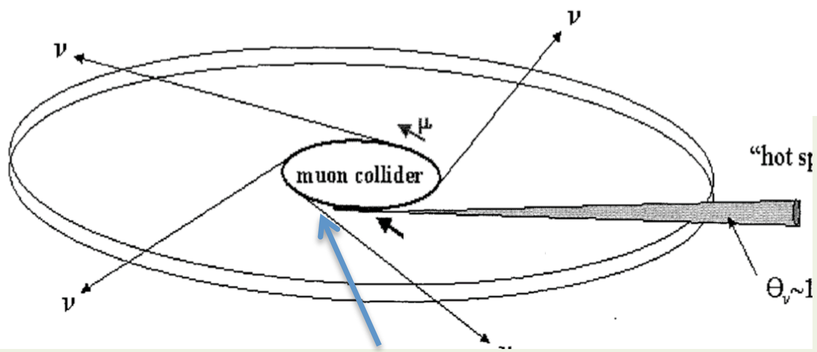
Neutrino radiation from collider ring is key for site and layout

- At 3 TeV 40 m with deep tunnel arcs: stay below 10% of legal limit, have to own land in direction of straights
- At 14 TeV with 500 m deep tunnel: arc stays just below legal limit

Want to minimise radiation as much as possible
CERN civil engineering will develop tool to optimise orientation of collider ring (J. Osborn)
Discussion started with neutrino experts on potential use of neutrinos in direction of long straight (A. De Roeck et al.)
Development of lattice is starting
Discussion with HSE-RS (radiation safety) started
Consider mitigation techniques, even challenging ones

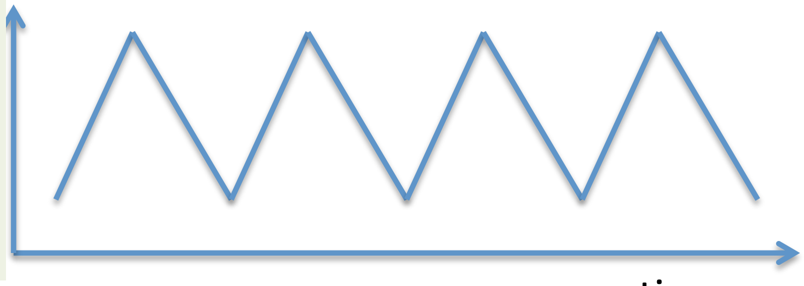
Example Neutrino Radiation Mitigation

Mitigation by varying beam orbit in collider is limited and costly (more space in magnets needed)

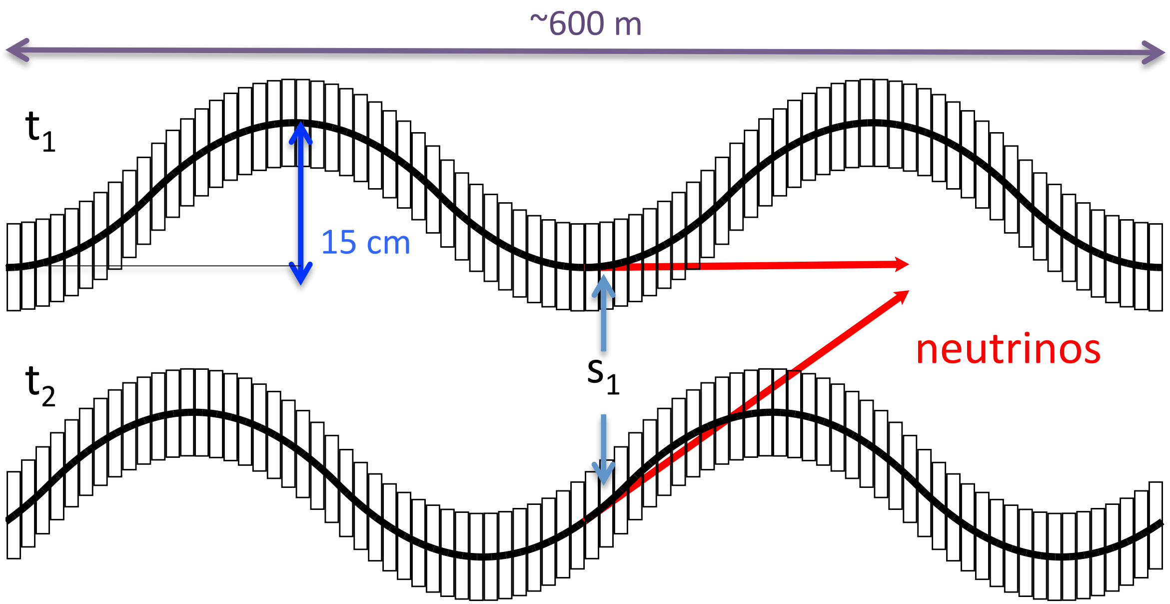


Relevant length of arc at s_1 is O(10 cm)

Vary vertical beam angle at s_1 in time



Move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

O(100) larger than decay cone
⇒ gain O(100) in radiation

In straights, additional improvement in horizontal

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

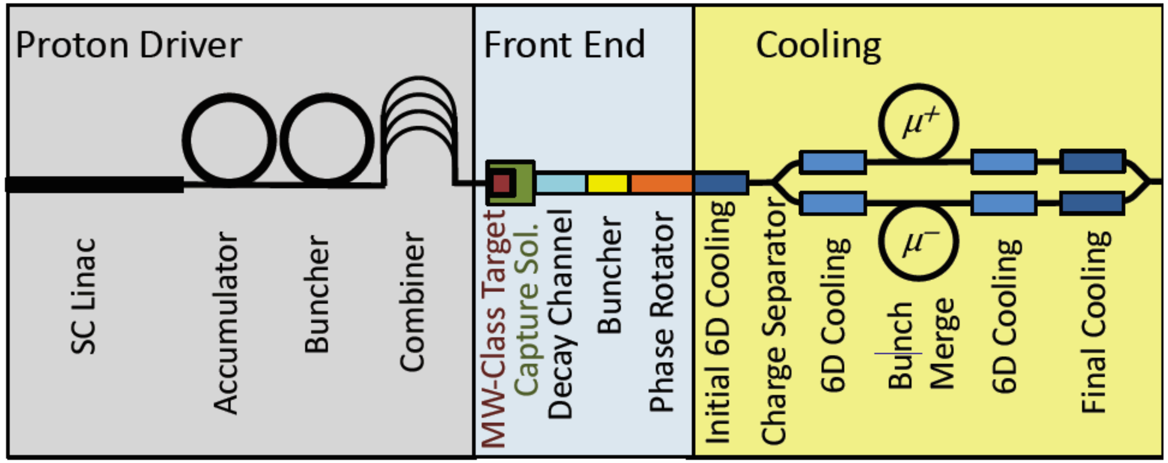
Demonstrator and Neutrinos

Need to develop R&D programme for implementation after next ESU and Snowmass/P5

Key will be demonstrator facility to produce useful muon beam

Risks not being that cheap

Can this be combined with a neutrino facility such as NuSTORM?



Will explore synergies

Also explore if the neutrinos from the straights of the collider could be used for physics

First suggestion (A. De Roeck, E. Tsesmelis):
Deep-sea installations in Mediterranean (KM3NeT-Fr, KM3NeT-It, KM3NeT-Gr)
But could be too deep, maybe interesting for test facility/NuSTORM

Ideas are very welcome

Way Forward

Are in gradual transition from community effort to organised effort

Foresee **IRAP (Interim R&D Advisory Panel)**

- should provide **prioritised R&D list** by middle of next year
- to be coordinated with the European Roadmap, hence a bit slow …

Prepare one comprehensive but compact **report** to describe muon collider

- Identify critical R&D challenges
- Identify R&D priorities
- Input to Snowmass and European Roadmap, can extract executive summaries

Then need to define in addition

- what Europe (and others) should do, in particular in the next two years
- what the US should do after P5
- need to coordinate this

Will start in January

Conclusion

Started to address the R&D on muon collider as requested by European Strategy

Formal collaboration at any moment

Actual work started with meetings on design

- Accelerator design (-> daniel.schulte@cern.ch)
- Physics and detectors (-> nadia.pastrone@cern.ch)
- Physics potential (-> andrea.wulzer@cern.ch),
- Detector simulations (-> donatella.lucchesi@pd.infn.it),
- Muon cooling (-> chris.rogers@stfc.ac.uk, klaus.hanke@cern.ch)

Will have project meeting with accelerator and physics

- Every few months, half day long

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

- Find link to meetings in menu "Organisation"

Mailing lists: MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch, MUONCOLLIDER_FACILITY@cern.ch

Many thanks to all
MAP collaboration, M. Palmer
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
…

Reserve

Critical Issues Include:

- **Advanced detector concepts and technologies**, requiring excellent timing, granularity and resolution, able to reject the background induced by the muon beams.
- **Advanced accelerator design** and beam dynamics for high luminosity and power efficiency.
- **Robust targets and shielding** for muon production and cooling as well as collider and detector component shielding and possibly beam collimation.
- **High field, robust and cost-effective superconducting magnets** for the muon production, cooling, acceleration and collision. High-temperature super-conductors would be an ideal option.
- **High-gradient and robust normal-conducting RF** to minimise muon losses during cooling.
- High rate **positron production** source and high current positron ring (LEMMA).
- **Fast ramping normal-conducting, superferric or superconducting magnets** that can be used in a rapid cycling synchrotron to accelerate the muons and efficient power converters.
- **Efficient, high-gradient superconducting RF** to minimise power consumption and muon losses during acceleration.
- **Efficient cryogenics systems** to minimise the power consumption of the superconducting components and minimise the impact of beam losses.
- Other accelerator technologies including high-performance, compact **vacuum systems** to minimise magnet aperture and cost as well as fast, robust, **high-resolution instrumentation**.

Comparison MAP vs. CLIC

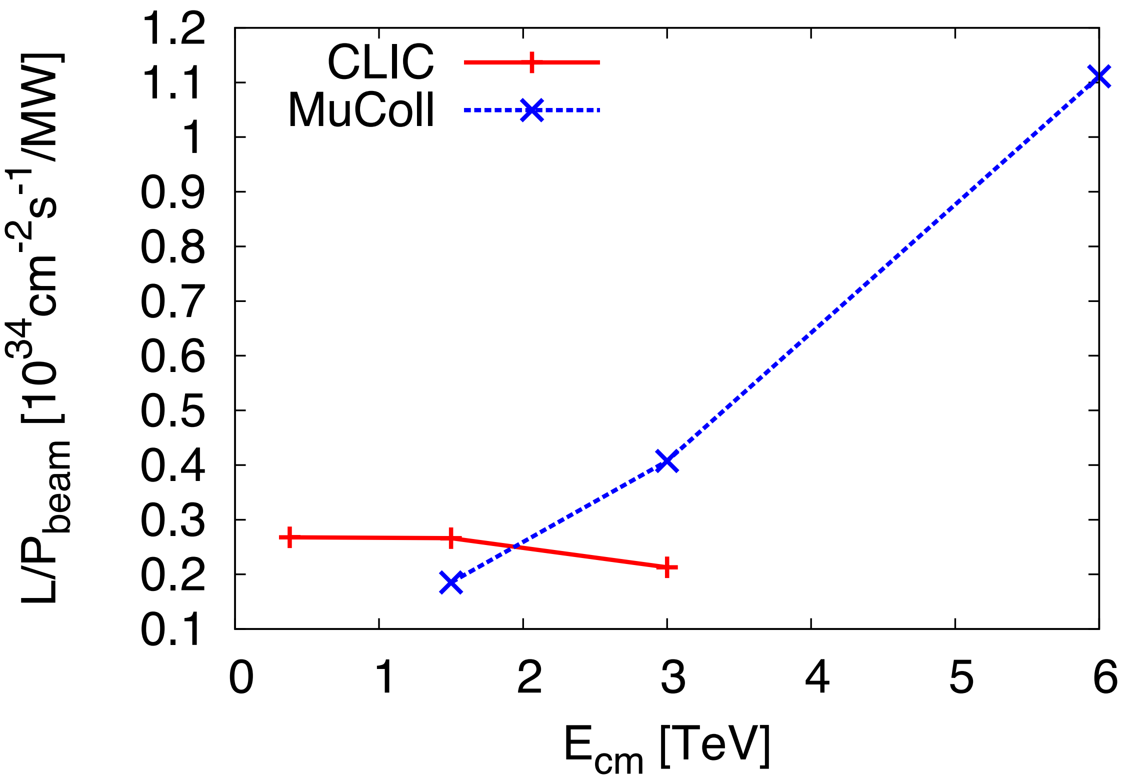
In linear collider, the luminosity per beam power is about constant

In muon collider, luminosity can increase linearly with energy

A linear collider is single-pass so need full voltage in main linac

Muon collider is multi-pass so have lower voltage

But have to carefully verify this



Overall muon colliders have the potential for high energies

May overcome the energy limitations of linear colliders

The working group concluded that an International collaboration should be formed to study the muon collider

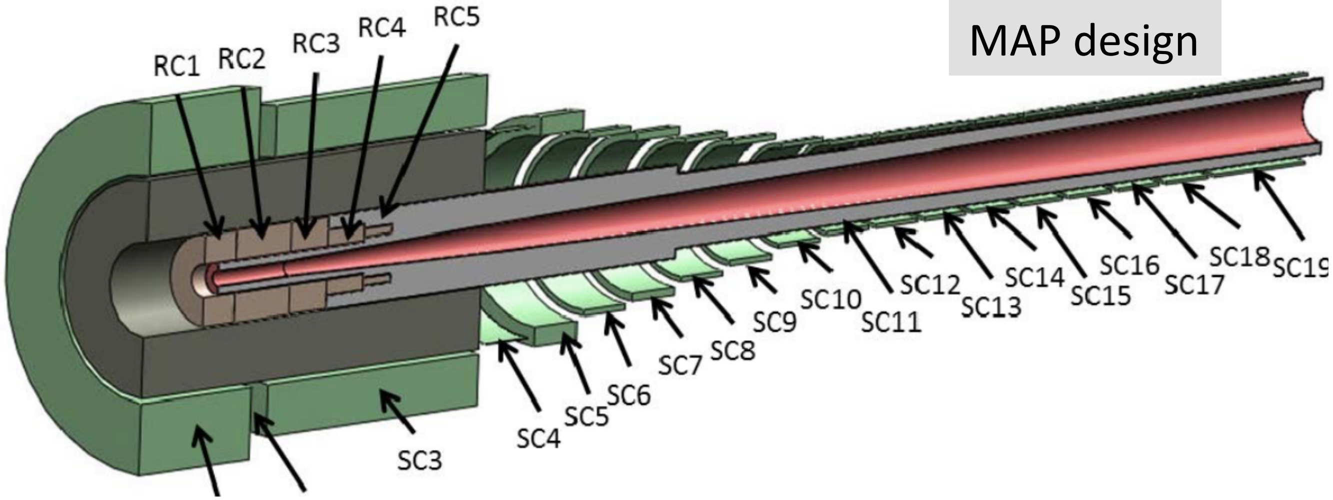
Source

Intense proton beam is challenging

Need to make choices for the **target**

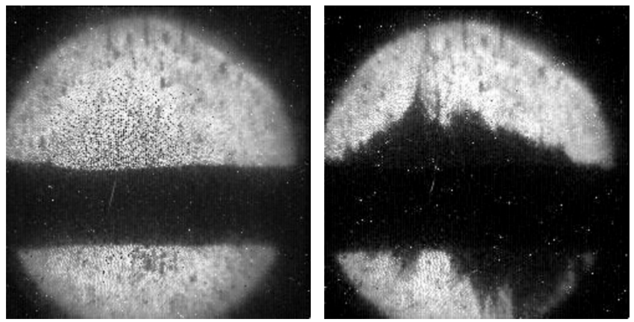
Ambitious high-field solenoid

MAP design



Target has to withstand **strong shock**

- liquid mercury target successfully tested at CERN (MERIT)
- but solid target better for safety
- or beads
- or …



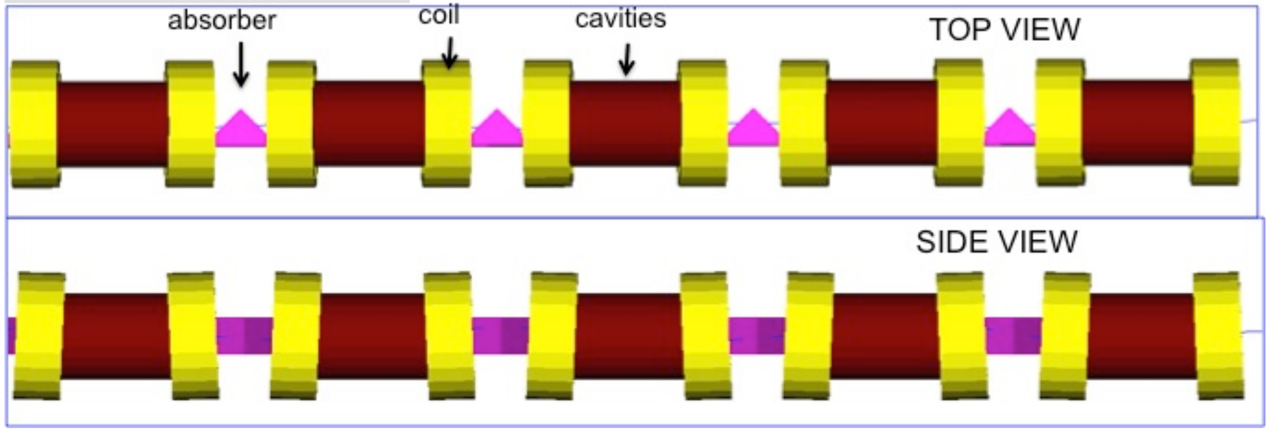
Important power of proton driver O(MW)
need to take care of debris for downstream systems
need to cool

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

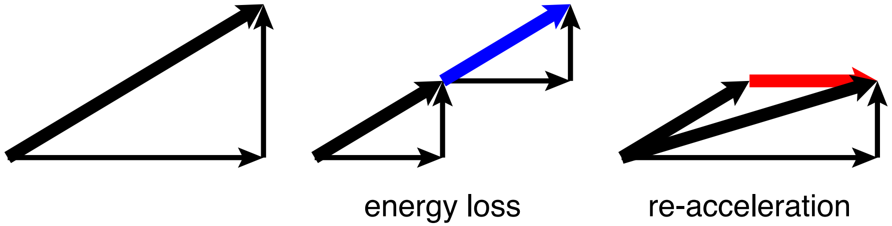
Cooling Concept

See previous presentation by J. Pasternak

MAP collaboration

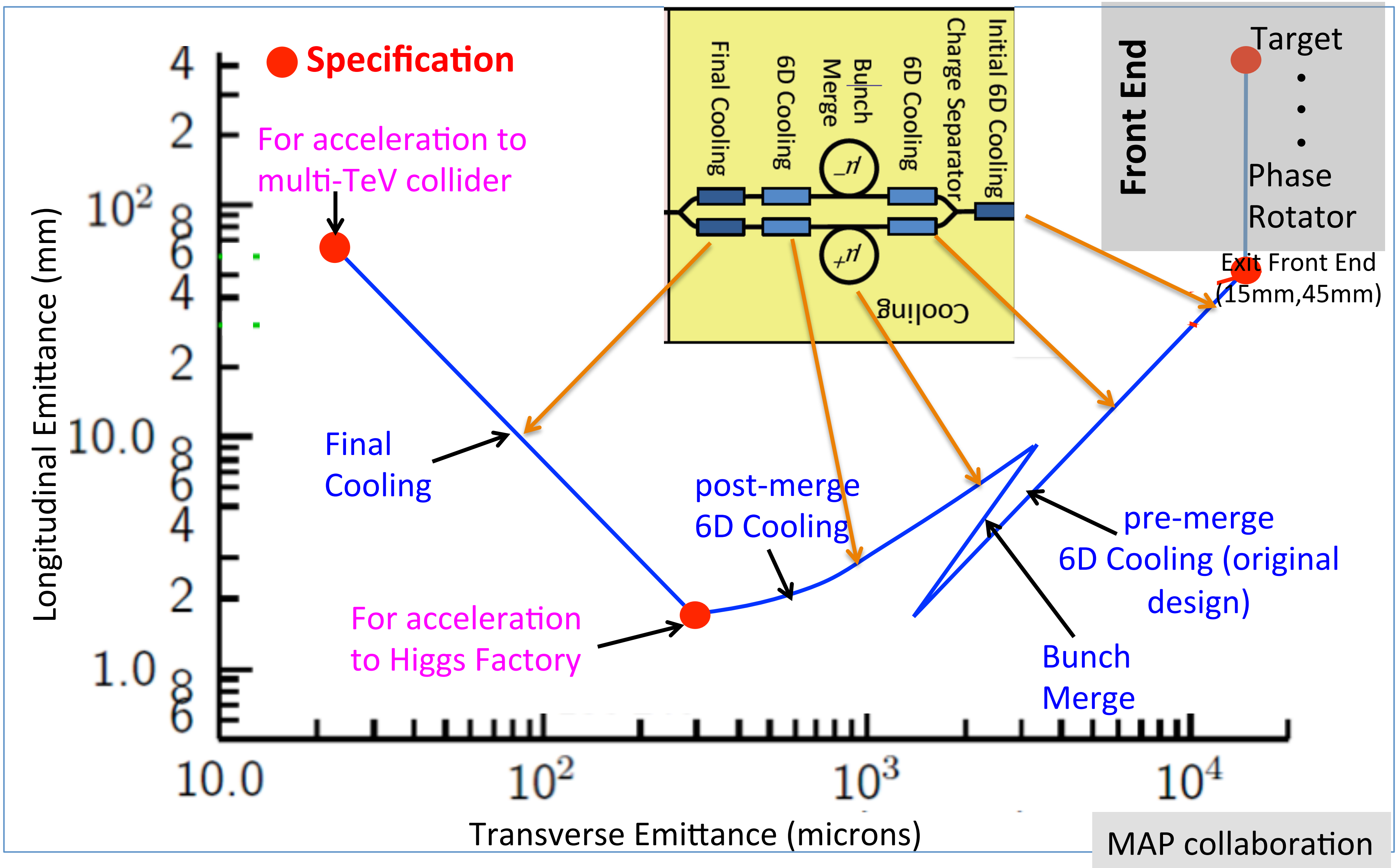


- Superconducting solenoids
- High-field normal conducting RF
- Liquid hydrogen targets
- Compact design



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

Cooling: The Emittance Path



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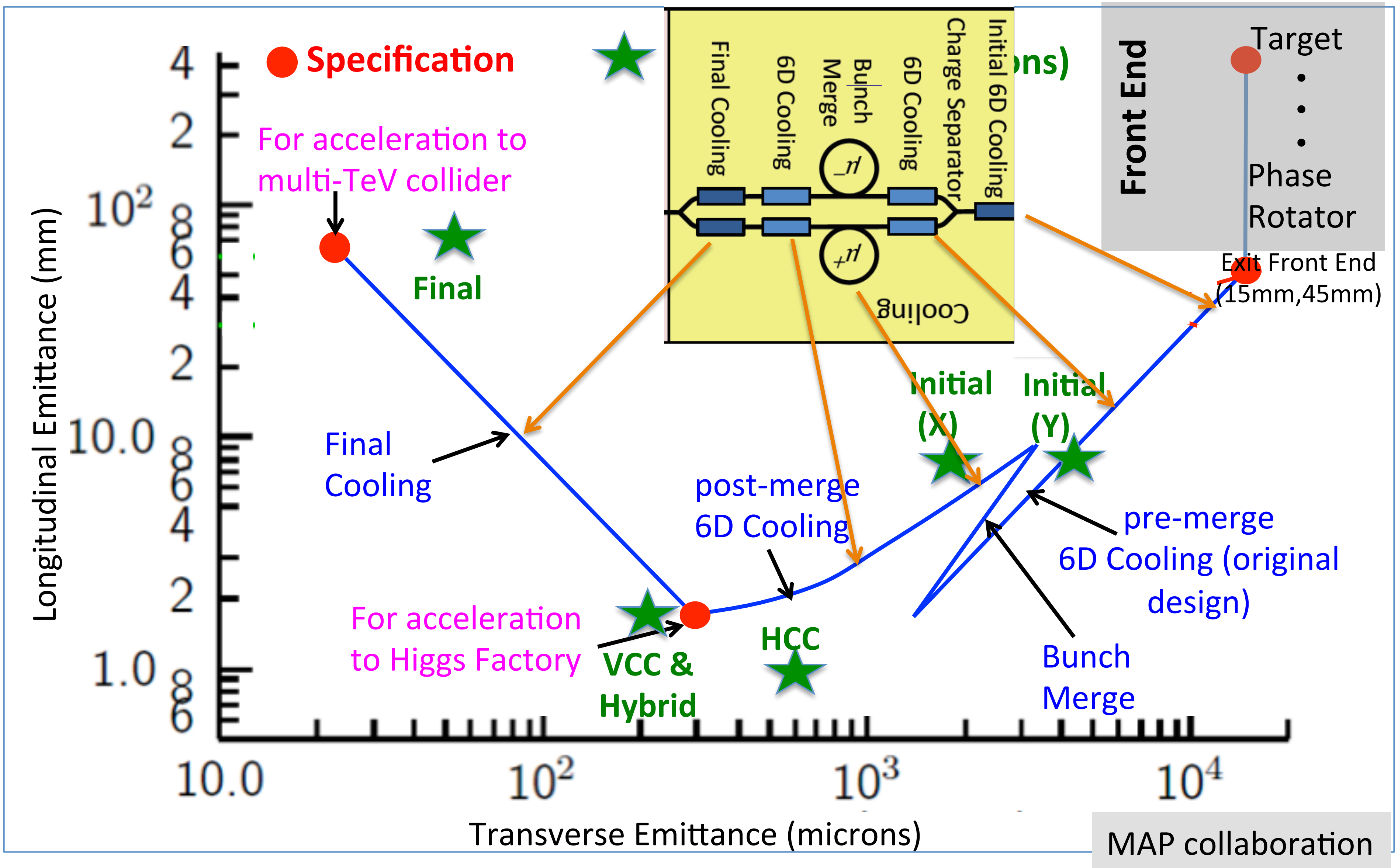

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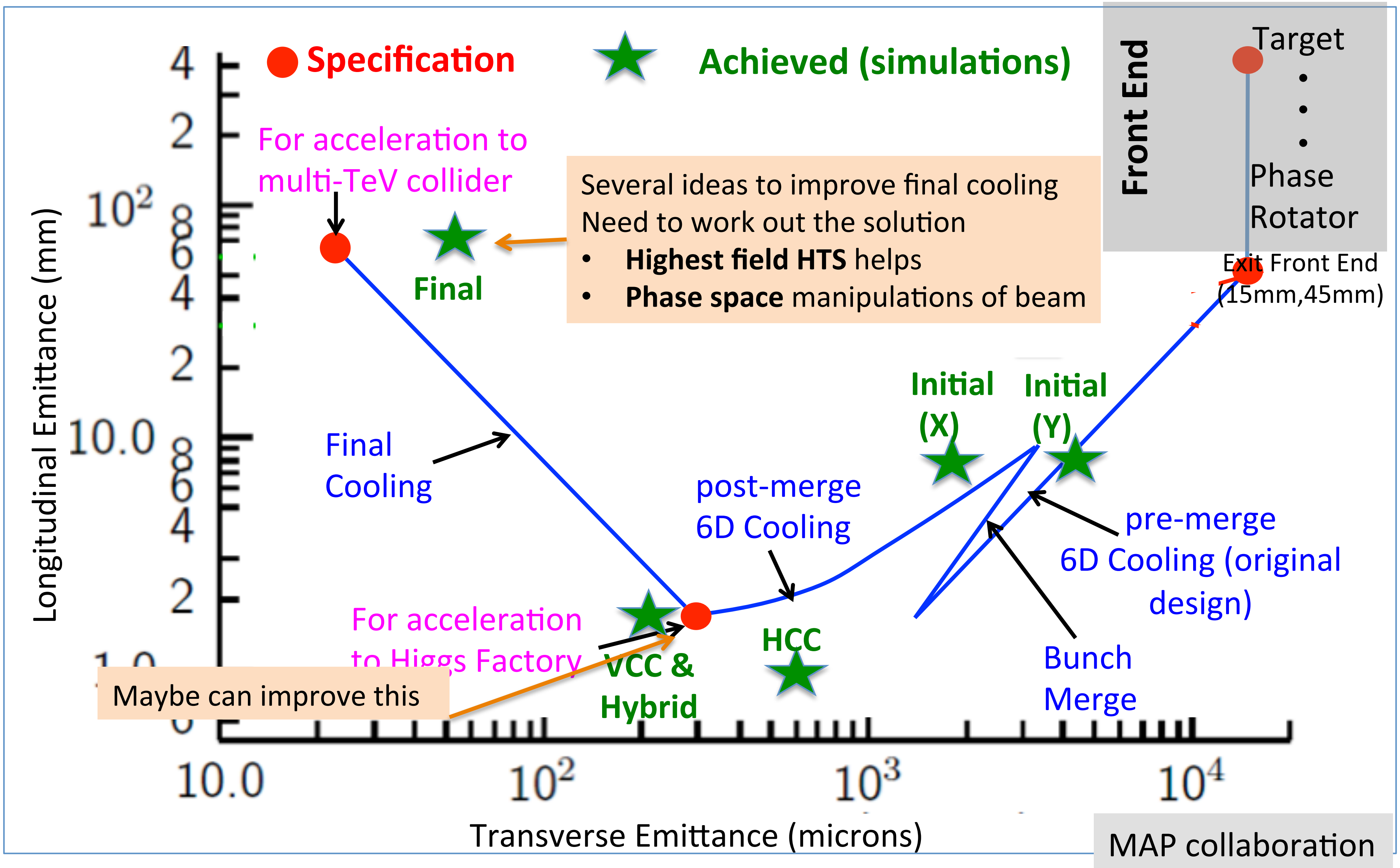


High-energy Acceleration

Rapid cycling synchrotron (RCS)

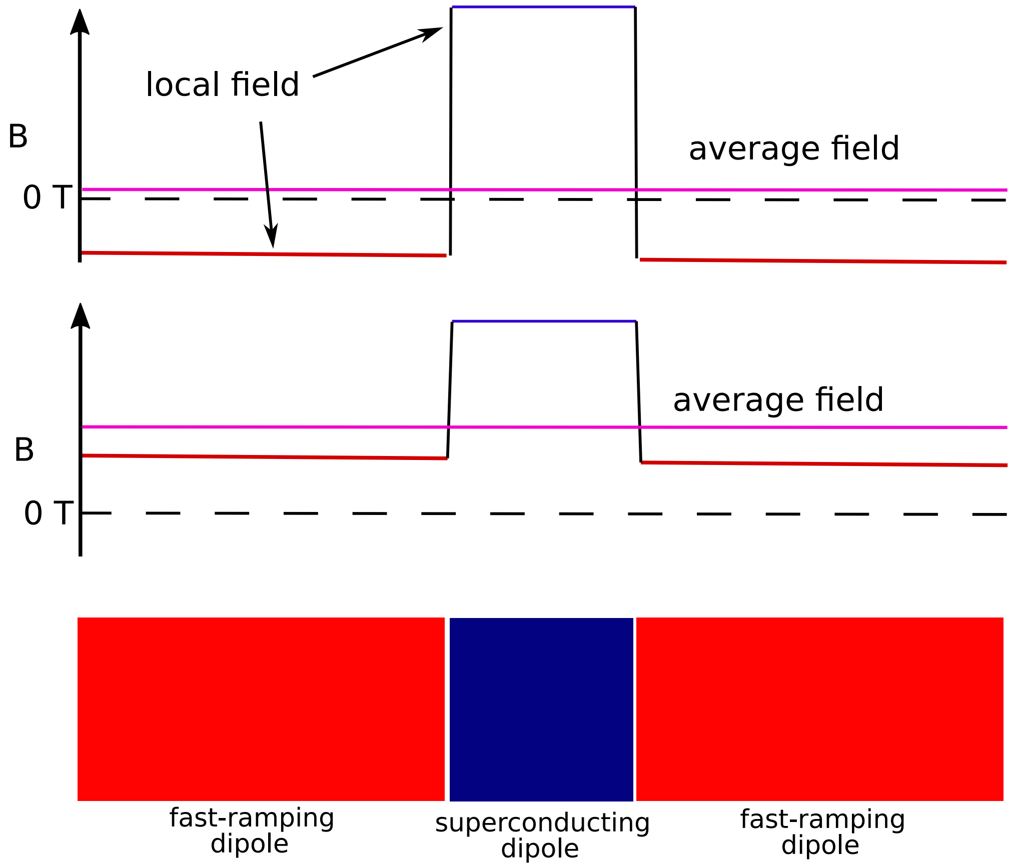
- Inject beam at low energy and ramp magnets to follow beam energy
- Could use combination of static superconducting and ramping normal-conducting magnets

Fast-pulsing magnets (O(ms) ramps))
Field defines size of accelerator ring

- normal-conducting
- HTS is interesting

Important energy in fast pulsing magnets

- O(200 MJ) @ 14 TeV
- need **very efficient energy recovery**



FFAG
Challenging lattice design for large bandwidth and limited cost
High field magnets

RF challenge:
High efficiency for power consumption
High-charge, single-bunch beam (10 x HL-LHC)
Maintain small longitudinal emittance

RF Challenge

Acceleration and collider ring RF

14 TeV: 1 mm long bunch with 0.1 % energy spread in collider ring

Almost same longitudinal emittance as after muon cooling

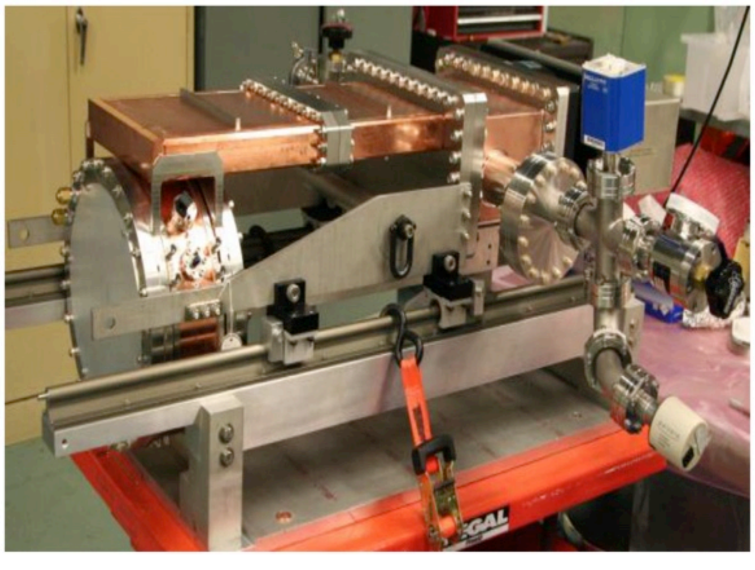
High bunch charge of 2×10^{12} muons

Start with long bunch that is subsequently compressed

Need concept of longitudinal dynamics all along the accelerator

Challenging to maintain emittance

MuCool: >50 MV/m in 5 T field



Muon cooling RF

Proof of principle in US (gas-filled copper and vacuum beryllium cavities)

Other RF

e.g. proton complex RF

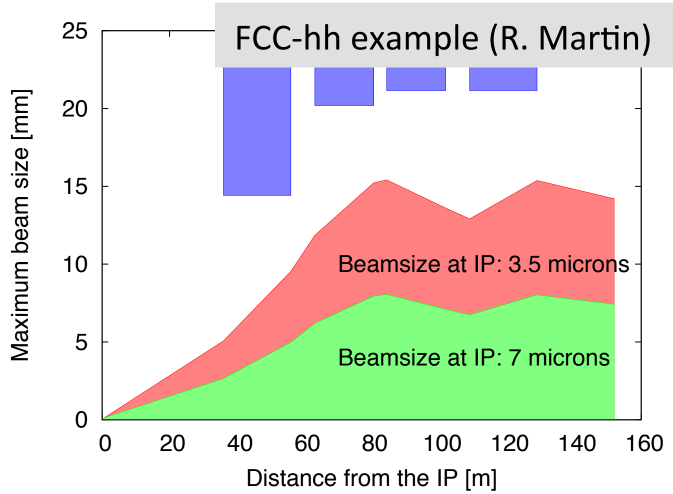
making contact, may need more effort later

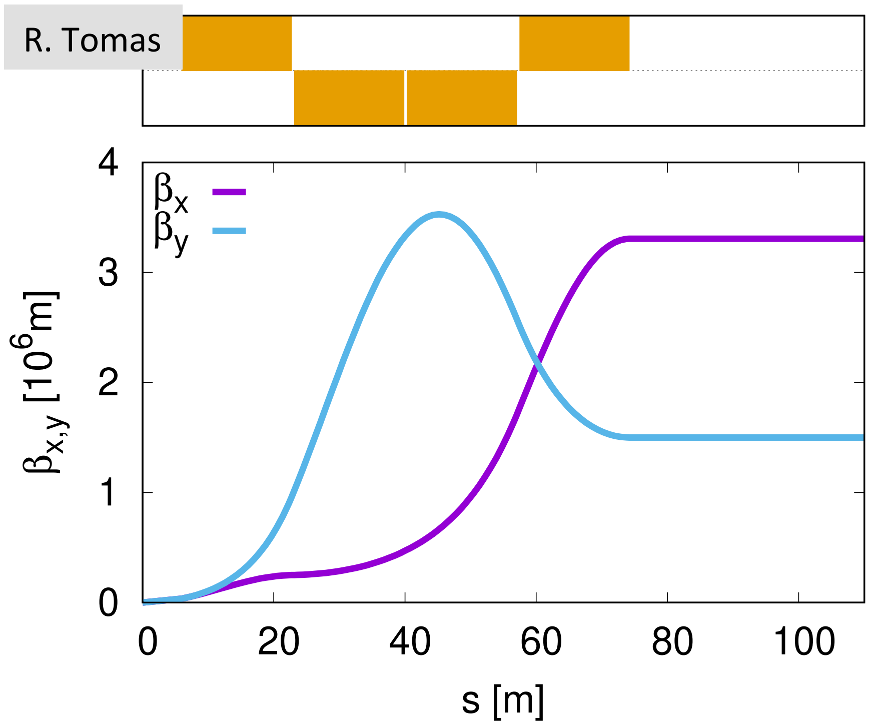
Final Focus

Need smaller betafunctions at higher energy
Or smaller longitudinal emittance / larger energy acceptance

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

And focusing of higher energy beam is more difficult





$\beta^*_{x,y}$ = 1 mm
B_{peak} = 18 T
N_σ = 10 σ
E = 7 TeV
Aper. = 0.7 m

0.7 m for 10 σ
0.3 m for 6 σ

First look from Rogelio Tomas on final triplet at 14 TeV (L* = 6 m):

Challenging system
Need to add shielding

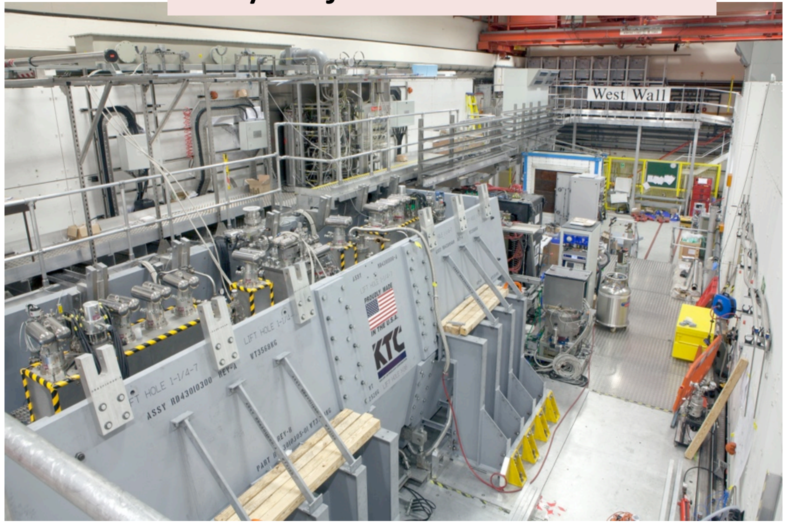
Design Status

Key systems designed for 3 TeV in US
A number of key components has been developed
Cooling test performed according to theory

But no CDR, no integrated design, no reliable cost estimate
More work to be done, e.g. substantial, 6D cooling

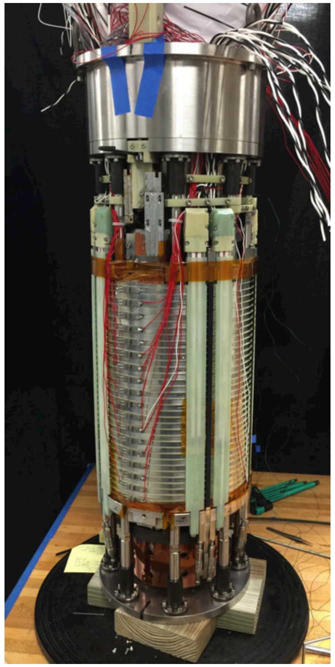
As you just heard in detail

MICE (UK)

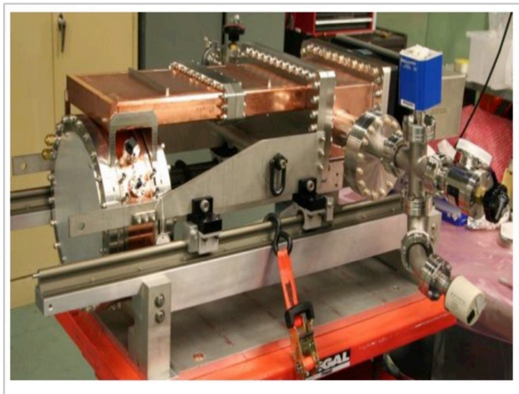


FNAL
Breakthrough in HTS cables

NHFML
32 T solenoid with low-temperature HTS



MuCool: >50 MV/m in 5 T field

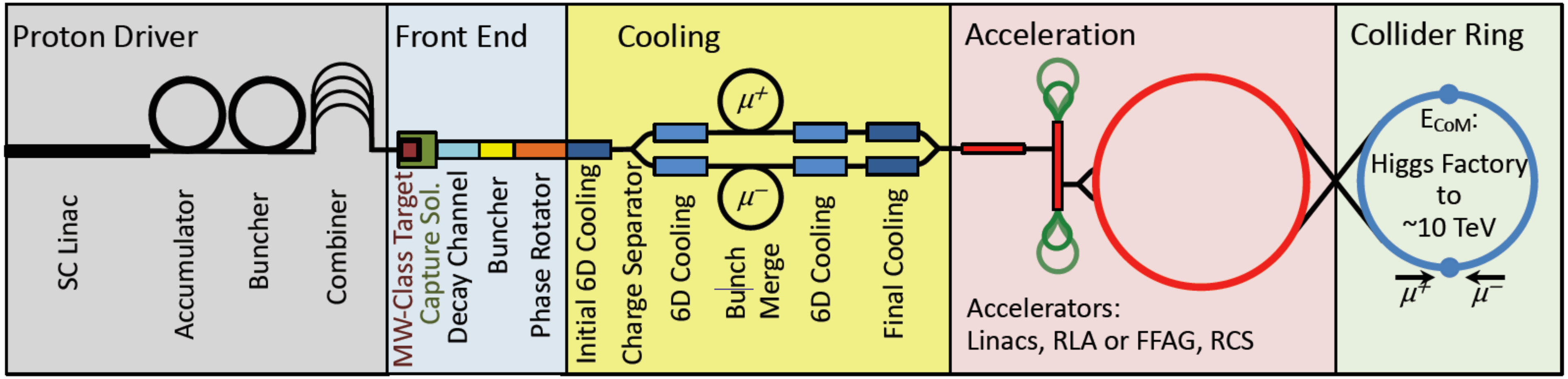


FNAL
12 T/s HTS
0.6 T max

Mark Palmer

Muon Collider Baseline Concept

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

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

Acceleration to collision energy

Collision

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

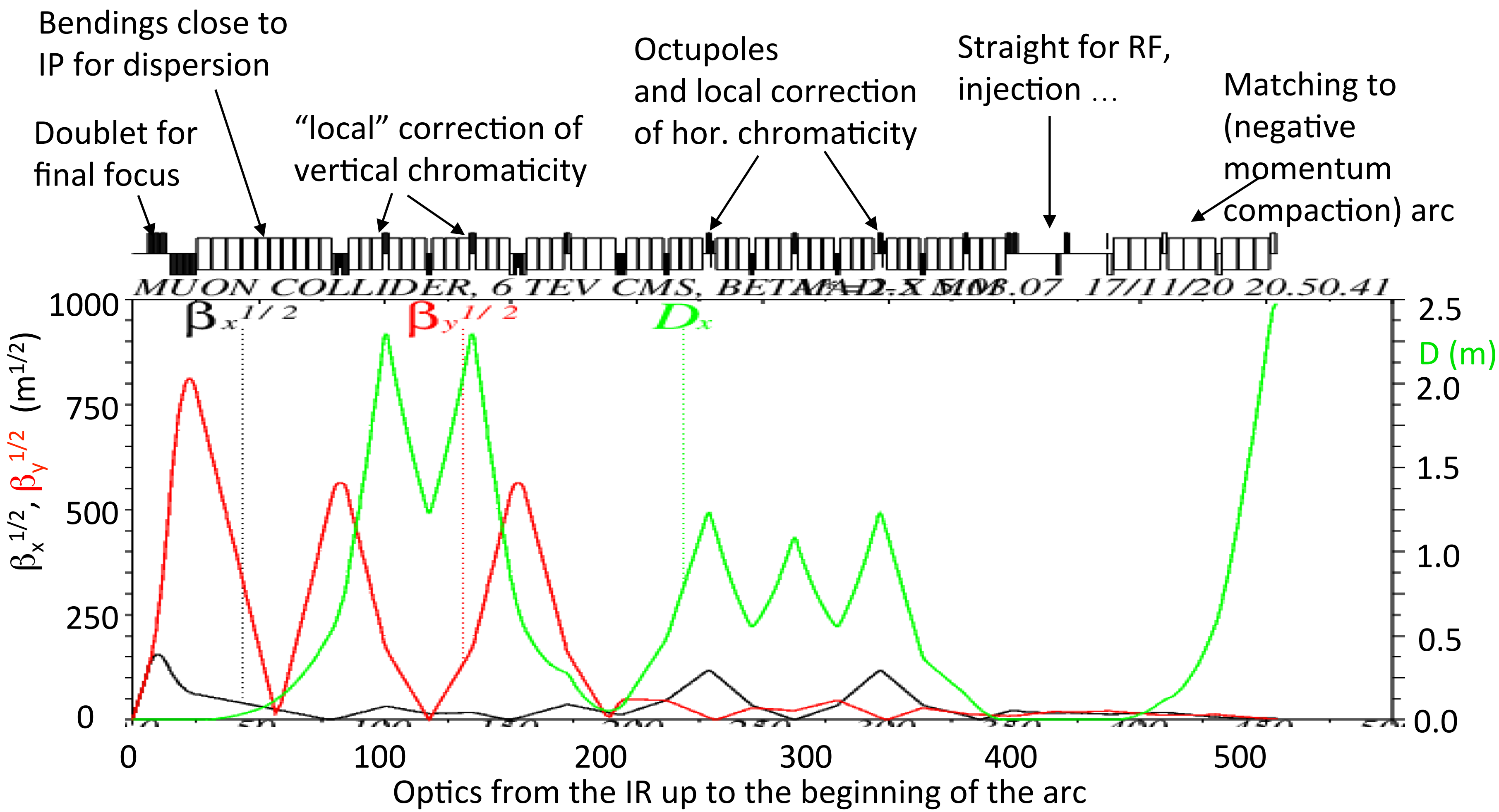
Interaction Region (IR)

Very challenging design

- Typical design example to be used as starting point for our design

Chr. Carli

6 TeV design by M-H. Wang, Y. Nosochkov, Y. Cai and M. Palmer



Collider Ring

Challenging optics (short bunch, long ring, minimal RF)
Important **collective effects** (beam-beam etc.)

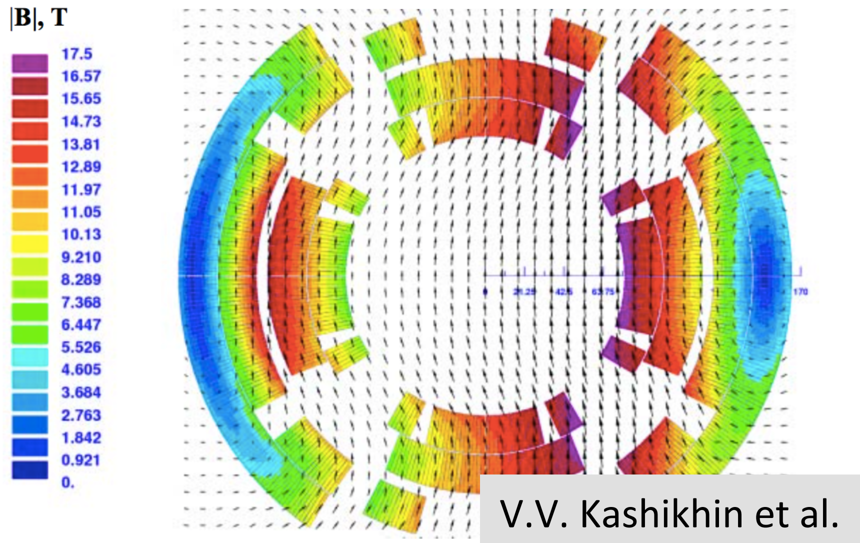
High-field, large aperture dipoles to minimise collider ring size and maximise luminosity

Combined function magnets replace quadrupoles to avoid straights

O(400 W/m) **beam loss**

- 5 MW total at 10 TeV
- Need to shield magnets
  - MAP at 3 TeV: 30-50 mm shielding
- Large apertures
  - MAP at 3 TeV: 150 mm

Combined function magnet design



Will consider different technology options at different energies (NbTi, Nb_3Sn, HTS)
Balance performance, cost and timescale

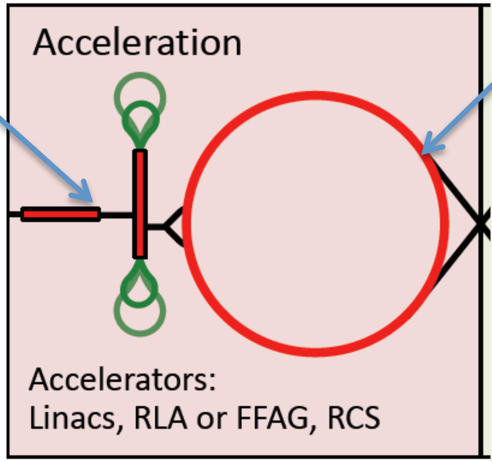
Muon Acceleration

Initial acceleration looks very solid (A. Bogacz, JLAB)

Does not change with collider energy

Main question is if we can further optimise

Alex will be able to work on this



Accelerator ring is cost driver

Changes with collider energy

- potential energy limit

Two options are considered (presented by S. Berg, S. Machida, D. Summers)

- RCS (Rapid Cycling Synchrotron) with fast-ramping magnets
- FFAG with static magnets and special optics

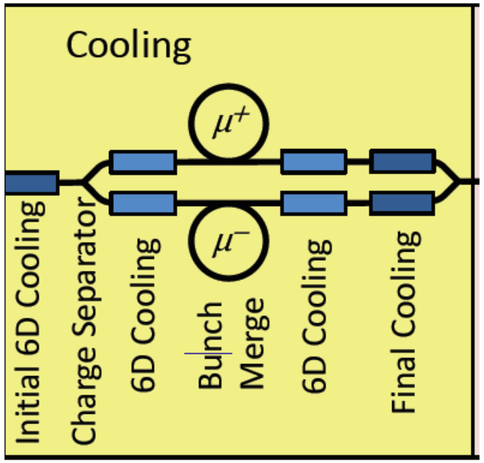
Optics design (Interest: RCS: A. Chance, CEA, FFAG: S. Machida, Rutherford Lab)

Fast-pulsing magnets (normal-conducting or HTS (Interest: L. Rossi, INFN))

Efficient energy recovery of fast pulsing magnets (Interest: CERN)

Efficient superconducting RF for short, intense bunches (Interest: U. van Rienen, Rostock, A. Grudiev, CERN)

Muon Cooling



Presentations: Chr. Rogers, D. Neuffer, D. Bowring, P. Jurj, D. Summers

6D cooling can probably be better than foreseen

- Review integration aspects (supercondcuting magnet coils next to normal-conducting RF)
- Optimise the design

Final cooling misses target transverse emittance by factor 2

- Higher field solenoids should help (>> 30 T), KTI proposal to BMFT (T. Arndt)
- Equilibrium emittance proportional to 1/B

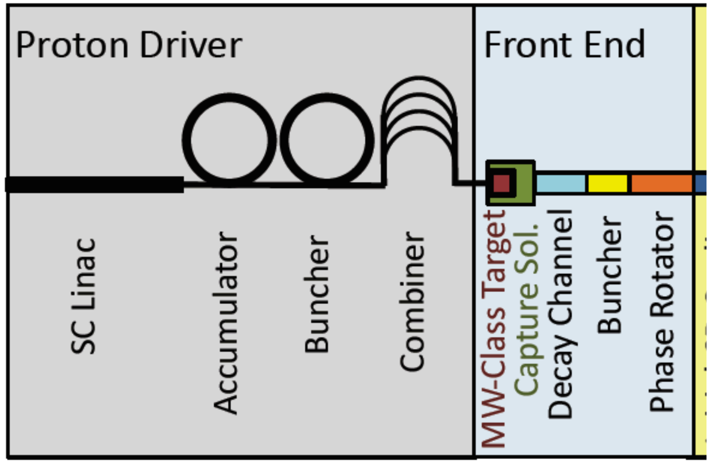
Chopping and recombining bunch as alternative to final cooling suggested (D. Summers)

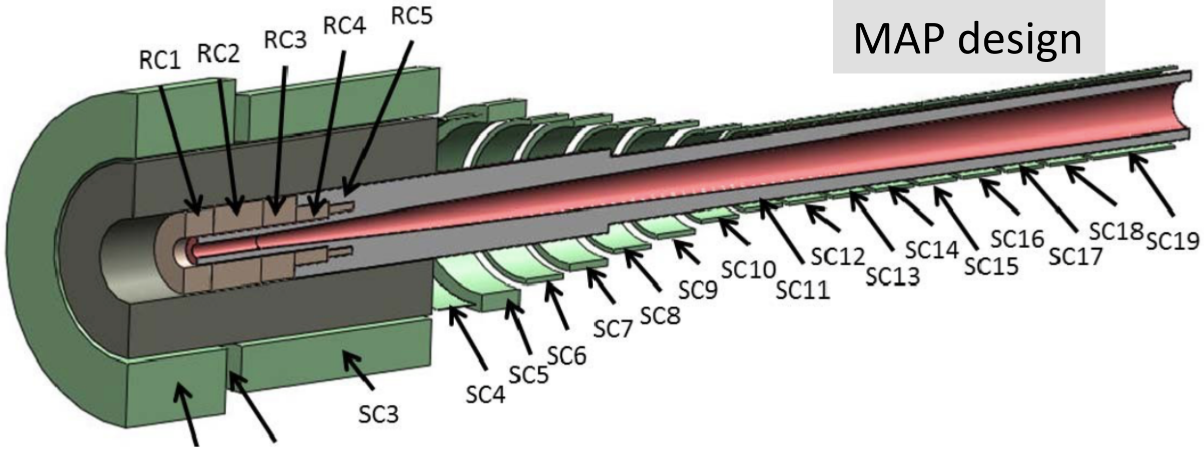
- To be reviewed

Experimentally proven RF gradients are higher than in design

- More muons will survive
- Can have more cooling
- Maybe can reuse some CLIC drive beam hardware for tests of RF

Proton Complex and Front-end





Intense proton beam is challenging

Need to make choices for the **target**

Ambitious **high-field solenoid**

Radiation in magnet

Downstream radiation from MW proton beam

Need to quantify challenges

Will launch activity soon

Medium Term Plan

“The muon collider study is aimed to evaluate the feasibility of a muon collider. Such a facility could allow reaching lepton collision energies beyond the range of linear colldiers and hence define the lepton energy frontier.”

24c. Muon colliders

Goal	The muon collider study is aimed to evaluate the feasibility of a muon collider. Such a facility could allow reaching lepton collision energies beyond the range achieved in linear colliders and hence define the lepton energy frontier. Workshops and meetings were organized since 2018; Raising interest was demonstrated by the physics community. The feasibility study shall build on this interest and aim at forming an international collaboration.
Approval	Presented to Council 2020.
Start date	To be defined.
Costs	The feasibility study foresees resources at the level of 6 fellows, 4 PhD students and one 1 associate. In addition, the CERN personnel needs to be secured. External contributions to the study are expected in the framework of the collaboration that has to be set up. Minor expenses for travel and consulting are foreseen.
Competitiveness	The muon collider study provides input on the feasibility of a muon collider, as requested for the next EPPSU. If its feasibility can be established, Muon colliders open another option to maintain CERN's world-leading role in particle physics and push the high-energy lepton frontier.
Risks	In the long term, the failure to support the study might put at risk CERN's potential leading role in Muon colliders, which is an option to be assessed by CERN, as world-leading high-energy frontier laboratory, in particular in view of potential developments in other regions.
2021 targets	The EPPSU results will be presented in 2020. It is anticipated that it identifies the muon collider as an important subject for the accelerator R&D. The main goal for 2021 is the definition of a programme of work and the initiation of an international collaboration.
Future prospects & longer term	The study will address fundamental feasibility issues and limitations for the energy reach. It will develop a baseline concept and prepare an R&D programme that can lead to a CDR. In the first half of the period toward the next EPPSU the specific high energy limitations will be explored. In the second half of this period a wider effort will address all critical technical systems.