International
MUON Collider
Collaboration

# Roadmap Goal for the Muon Collider

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# 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.

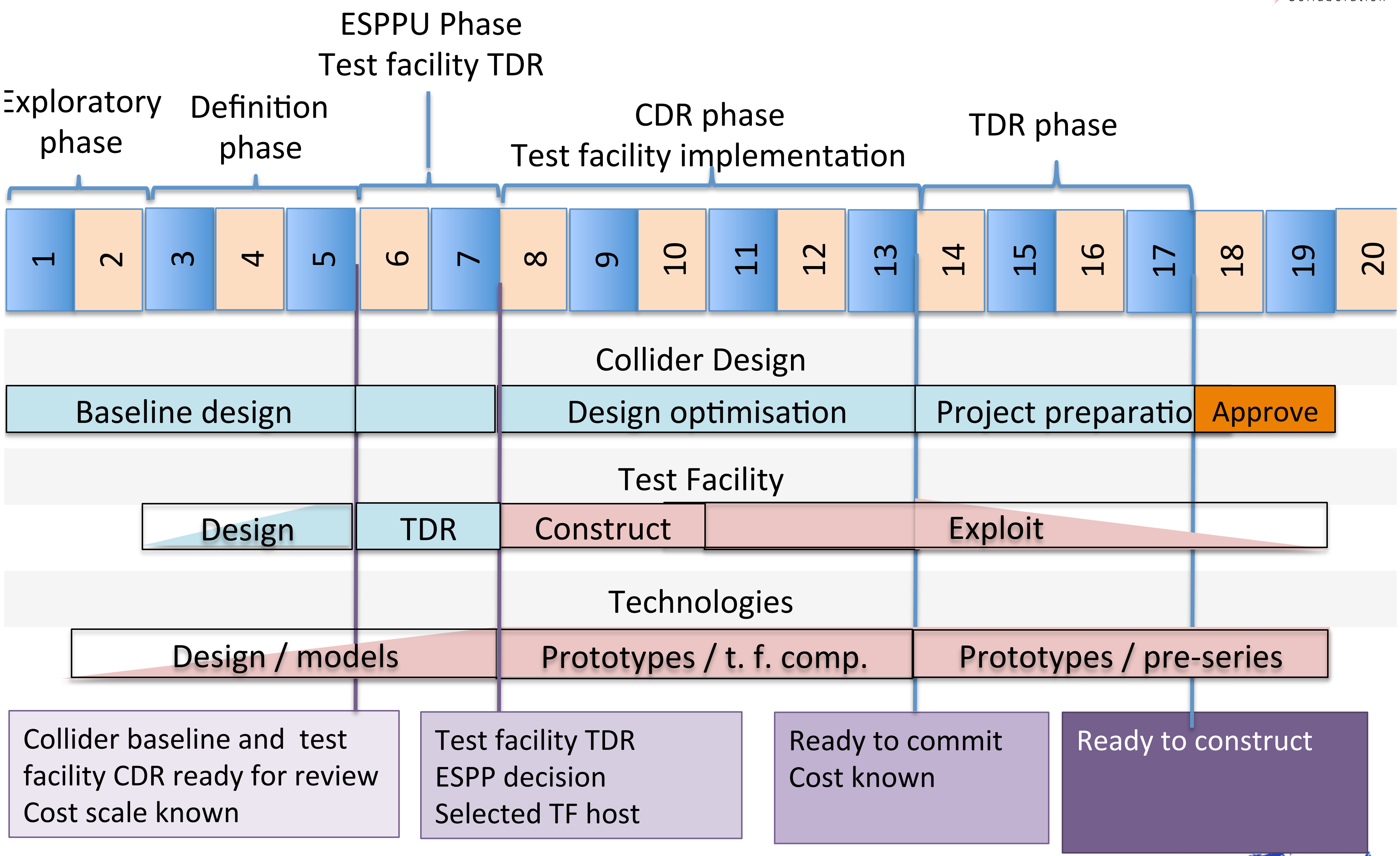
Scope:

- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 10-20 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



# 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 |
| $\varepsilon_L$ | MeV m | 7.5 | 7.5 | 7.5 |
| $\sigma_E$ / E | % | 0.1 | 0.1 | 0.1 |
| $\sigma_z$ | 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 |

# Deliverables for the Roadmap

International MUON Collider Collaboration

- Should focus on concrete programme that we want to propose
- What is needed as input for next for Strategy update to make informed decisions?
  - What will be reasonable concerns regarding the muon collider?
  - What do we need before to address the concern?
  - What do we need to prepare for the test facility?
  - And the other R&D programme?
- Probably should think in terms of scope from the beginning
  - For each R&D item define required level
- In parallel define risks
  - Challenging to define a ranking and not spending too much time on it
- CERN DG would like to have cost scale for test facility and collider as soon as possible (within a year if possible)

# Proposal for Report Structure

- Introduction
- Executive summary
- Muon collider motivation
- Muon collider design overview
- Status of design (and history)
- Muon collider challenges
  - Parameters and layout
  - Proton complex
  - Target
  - Muon cooling
  - Muon acceleration
  - Muon collider
  - MDI
  - Project challenges
    - Power, cost and risk drivers
    - Radiation protection and site considerations
    - Other challenges
- Work programme (deliverables)
  - Accelerator design
    - Proton complex
    - Muon production and cooling
    - High-energy acceleration
    - Collider ring
    - Beam dynamics
  - MDI
  - Magnets
  - RF
  - Target and shielding
  - Neutrino flux mitigation
  - Other technologies
  - Test facility preparation
- Synergies
- Scenarios

# Required Information on R&D Item

R&D item title

- Why is it important?
- What are the key issues?

Muon collider challenges

- What do we need as input to the next ESPPU/other strategy process?
  - What is done somewhere else?
  - What do we have to do for this?

Work programme

- Which resources are required?
- Who is willing to do it?

To define work programme and scenarios

- Initial proposal for deliverable level
  - no work needed
  - concept, basic parameters, parametric model
  - lattice, reasonable basic performance specifications
  - lattice with tolerances, advanced performance specifications
  - conceptual design
  - engineering design
  - model, test of specific parameters
  - prototype
- Please help to define better levels, in particular for hardware

# A Not Very Perfect Example

Final triplet

- Why is it important?
  - This is the key component to squeeze the beam and drives luminosity
- What are the key issues?
  - At high energies large aperture and high gradient are required
    - e.g. 30 cm radius, 18 T poletip field in indicative design by Rogelio
    - the high stress will impact the magnet feasibility and limit performance
    - *what else you think should be said*

- What do we need before next ESPPU?
  - What others will do:
    - *develop technology and radiation hardness*
  - What we need to do:
    - A parametric model for the lattice optimisation (early for the optimisation)
    - *A conceptual design (for the ESPPU)?*
      - *magnet experts to judge if needed because of large aperture*
    - *An assessment of the radiation effects*

- Which resources are required?
  - *up to the magnet experts to judge*

# Roadmap Milestones

- LGD requires interim reports in late July
- Community meetings
  - **May 20+21: Identify R&D issues, first scope, if possible**
  - **June 7: First Stakeholder Meeting**
  - **July 12+13: Identify scope of R&D for next ESPPU, priorities, resource estimates, scenarios**
  - August/September: **final R&D list, internal priorities, resources estimates, scenarios**

# Goals of First Community Meeting

The goal is to identify the R&D that has to be carried out before the next ESPPU to scientifically justify the investment into a full CDR for the muon collider and the corresponding demonstration programme. This includes R&D to develop a baseline collider concept, well-supported performance expectations and to assess the associated key risks, cost and power drivers. Further, the main components of the demonstration programme should be identified together with the corresponding preparatory work.

The working groups should propose realistic but ambitious targets for the performance goals of the different collider systems. In particular they should consider what could be assumed for the demonstration programme, i.e. in one or more test facilities starting in 2026, as well what one can anticipate to be available in 2035-2040 for a first collider stage and in 2050 for an energy upgrade.

# 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

# Key Topics

10+ TeV is uncharted territory

- **Physics potential** evaluation

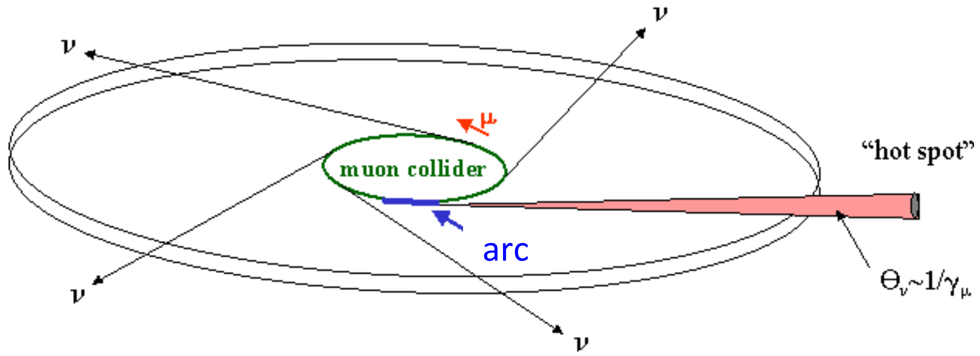
- Impact on the environment
  - The **neutrino radiation** and its impact on the site

- 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

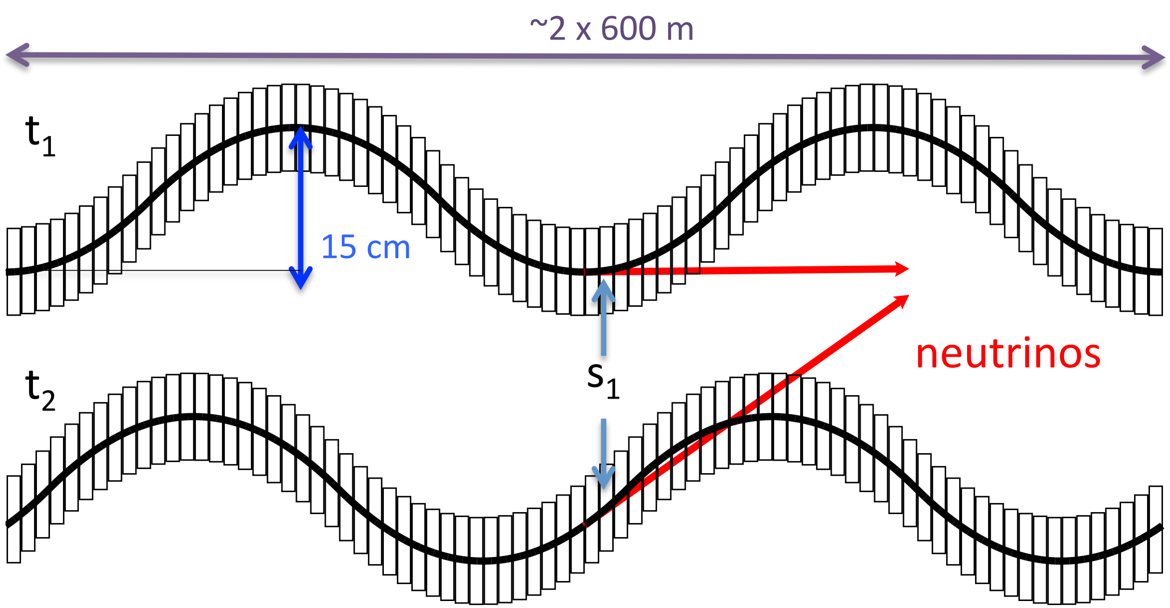
# Neutrino Flux Mitigation




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
- Detector 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

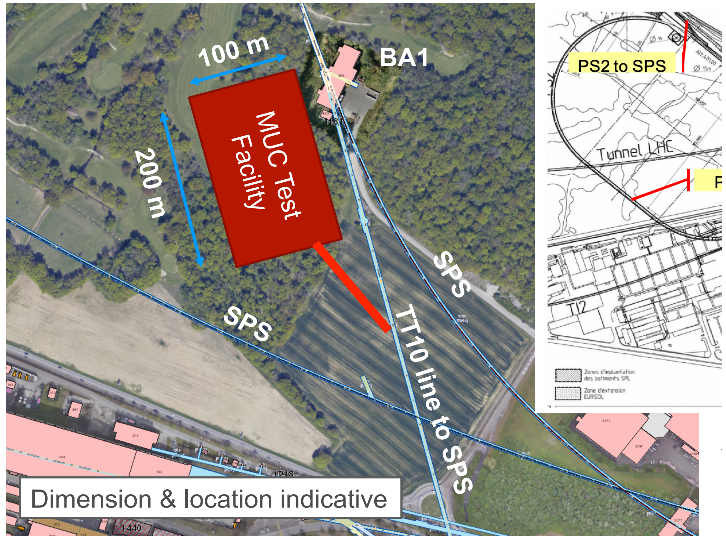
- Target
  - Energy per pulse (also power, but muons per bunch is critical and cannot be mitigated by multiple targets)
  - Challenge depends on muon survival, scaling of MAP parameter tables 1.3 MW, other estimates up to 4 MW
  - ⇒ Best to plan for some reserve

- 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

# 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
- Advisory committee reporting to ICB

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 |
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| $N_{in}$ | $10^{12}$ | 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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| 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

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| 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 | 10 | 8.9 | 15.7 |

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**
  - **7 MW** of power for cryogenics for Q=2 x $10^{10}$
- RCS3 cryogenics
  - Beam losses in cold systems: 17 W/m x 10 km ~170 kW
  - assume mitigation down to 10% at 2 K
  - **12 MW** power for cryogenics
  - **7 MW** for static losses
  - need to also develop shielding for this
  - but maybe later?
- Total goal 94 MW + 50 MW 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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| dB/dt | kT/s | 10 | 2 | 0.34 |
| Beam loss | W/m | 10 | 8.9 | 15.7 |

# Muon Beam Panel Roadmap Milestones

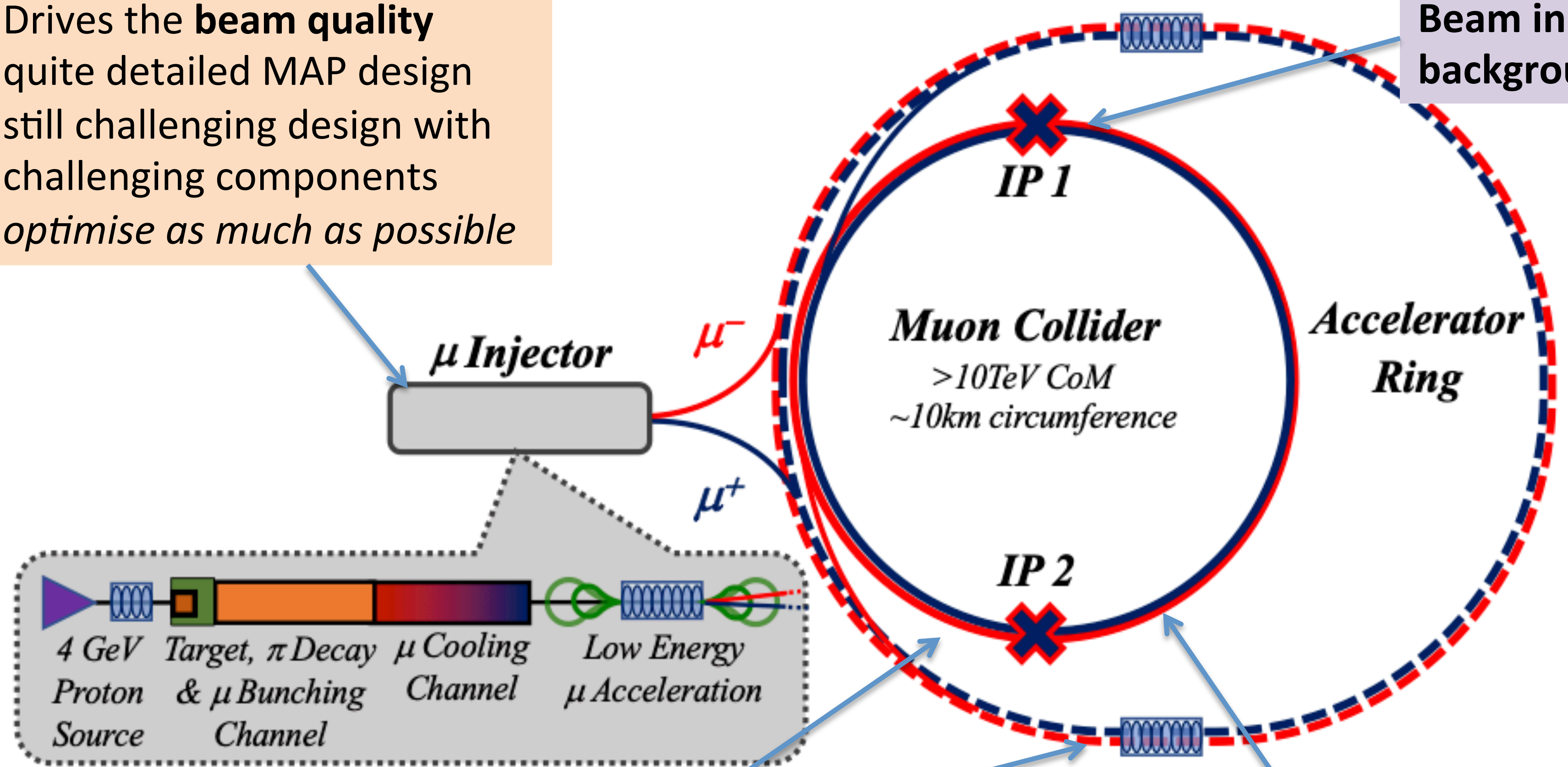
| Date | action |
| --- | --- |
| May 20+21 2021 | Community meeting to collect R&D items lists |
| First week of June 2021 | Panel provides R&D list to LDG |
| June Council 2021 | LDG presents R&D lists as background |
| June 2021 | LDG decision on structure, content and format of interim reports |
| 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**

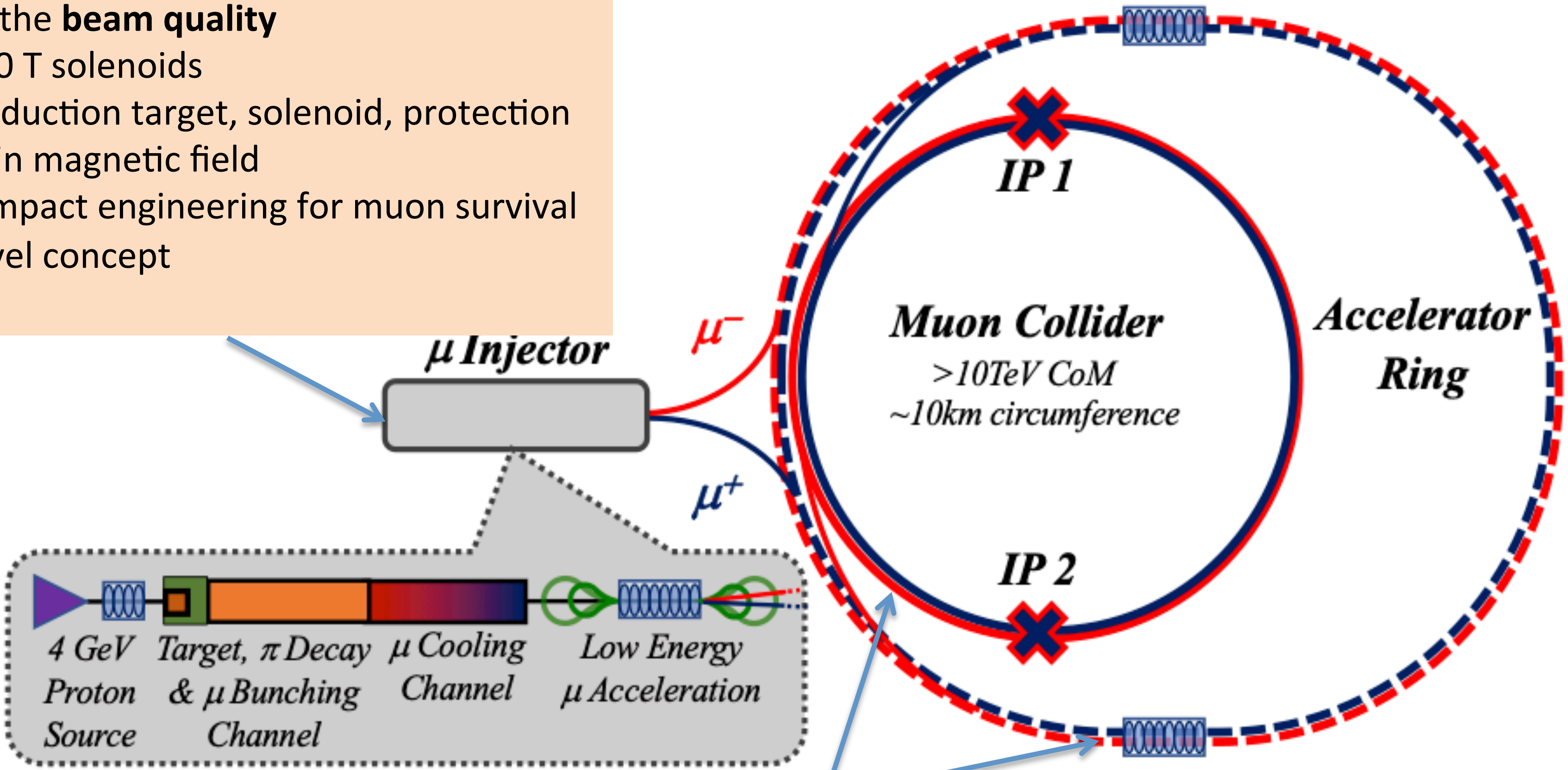



**Dense neutrino flux**
mitigated by mover system
and site selection

**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.