Roadmap Process of the Muon Beam Panel

Daniel Schulte, Mark Palmer for the Muon Beam Panel
Muon Beam Panel

Muon Beam Panel works with collaboration and community meetings:

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

New Muon Collider Collaboration

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

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 synergies (neutrino facility/higgs factory)
- Define R&D path

Community meetings
- 24-25 March: Muon Collider Testing Opportunities
- May 20+21: Identify R&D challenges, first scope
- July 12-14: Identify the R&D for next five years,
- September: Final R&D list, scenarios, may still answer questions of LDG
Community Meeting Convener

Conveners list (to be updated)

**Radio-Frequency (RF):** Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK).

**Magnets:** Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL).

**High-Energy Complex (HEC):** Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL).

**Muon Production and Cooling (MPC):** Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL).

**Proton Complex (PC):** Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS).

**Beam Dynamics (BD):** Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL).

**Radiation Protection (RP):** Claudia Ahdida (CERN).

**Parameters, Power and Cost (PPC):** Daniel Schulte (CERN), Mark Palmer (BNL), Jean-Pierre Delahaye (CERN retiree), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP), Akira Yamamoto (KEK).

**Machine Detector Interface (MDI):** Donatella Lucchesi (University of Padova), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergio R Jindariani (FNAL).

**Synergy:** Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK).

**Test Facility (TF):** Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (ESS, Uppsala University).
The muon collider has been developed by the MAP collaboration mainly in the US. Muon cooling demonstration by MICE in the UK, some effort on alternative mainly at INFN.

Short, intense proton bunches to produce hadronic showers.

Protons produce pions.
Pions decay to muons.

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

Acceleration to collision energy.

Muon collider is unique for very high lepton collision.
Comparing Luminosity in MAP vs. CLIC

CLIC is at the limit of what one can do (decades of R&D)
- No obvious way to improve

Luminosity per beam power increases with energy in muon collider
- **power efficient**

Site is **compact**
- 10 TeV comparable to 3 TeV CLIC

**Staging** is natural
- acceleration by a factor of a few is done in rings

Appears to promise **cost effectiveness**
- but need detailed study

Other **synergies** exist (neutrino/higgs)

Muon collider promises unique opportunity for a **high-energy, high-luminosity lepton collider**
Luminosity Goals

Target integrated luminosities

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<tr>
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<td>1 ab$^{-1}$</td>
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<tr>
<td>10 TeV</td>
<td>10 ab$^{-1}$</td>
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<tr>
<td>14 TeV</td>
<td>20 ab$^{-1}$</td>
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Tentative target parameters Scaled from MAP parameters

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<th>Unit</th>
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<th>10 TeV</th>
<th>14 TeV</th>
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<tr>
<td>L</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>1.8</td>
<td>20</td>
<td>40</td>
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<tr>
<td>N</td>
<td>$10^{12}$</td>
<td>2.2</td>
<td>1.8</td>
<td>1.8</td>
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<td>$f_r$</td>
<td>Hz</td>
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<td>5</td>
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<td>$P_{\text{beam}}$</td>
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<td>14.4</td>
<td>20</td>
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<td>C</td>
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<td>$\varepsilon$</td>
<td>$\mu$m</td>
<td>25</td>
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<td>25</td>
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<td>$\sigma_{x,y}$</td>
<td>$\mu$m</td>
<td>3.0</td>
<td>0.9</td>
<td>0.63</td>
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</table>

Comparison: CLIC at 3 TeV: 28 MW

Note: currently consider 3 TeV and either 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
Key Challenge Areas

10+ TeV is uncharted territory

- **Physics potential** evaluation, including detector concept and technologies

- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site (first concept exists)

- 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, technical risk and beam quality

- **High-quality muon beam production**
  - MAP did study this in detail
  - First experimental verification in MICE
  - Need to optimise and prepare cooling string demonstration

- **Integrated Collider Design** with choices, parameters, trade-offs, cost, power, site, ...
  - need to cover all accelerator areas
Physics Potential, Detector and MDI

**Physics potential** studies including detector and background
- Theory and phenomenology
- Detector technologies, simulation studies
- Collider and mask design
- Important effort is required *your help is important*

Main background sources
- Muon decay products (40,000 muons/m/crossing at 14 TeV)
- Beam-beam background
- Note: background reduces while beam burns off

Mitigation methods
- masks
- detector granularity
- detector timing
- solenoid field
- event reconstruction strategies
- ...

Simulation tools exist
First studies at lower energies (125 GeV and 1.5 TeV are encouraging (D. Lucchesi et al.)
Will develop systems for higher energies

D. Schulte  Muon Collider, EPS-HEP, July 2021
Facility Design

**Design of the key accelerator systems**
- e.g. muon cooling, collider ring, ...
- Lattice design with functional specifications
- Beam dynamics
- Neutrino flux mitigation (impact on beam, components and site)
  - Promising concept needs to be further developed
- Beam loss mitigation
  - Shielding and collimation, optics, component robustness
- Some basis from MAP studies but
  - Some challenges in proton complex
  - Need improvement for muon production and cooling complex
  - Novel design for 10 TeV and improvement of 3 TeV

**Develop R&D programme** to demonstrate functional specifications where they exceed state of the art and to develop maturity
- For implementation after next ESPPU
- Design of important systems
- Some experimental efforts already before next ESPPU

**Considerations on cost, power and site**
- Identification of cost, power and site drivers (tentative list exists)
- Determination of cost scale
- and integration into overall optimisation
Magnet Development

- Will depend on high-field programme (Roadmap), in particular for HTS
- **Fast-ramping magnets** and **powering** is muon collider specific
  - needs to be further developed, longest part of the accelerator

- For 3 TeV
  - **Final cooling solenoid**: small aperture, highest field
    - HTS solenoids are quite advanced but will know more in 5 years
    - goal 45 T (beam studies may relax), 32 T demonstrated, 40 T planned
    - risk is factor two in luminosity
  - **Target solenoid** is engineering challenge
    - Ni$_3$Sn with resistive insert or HTS
    - engineering challenge, mitigation options can be explored
  - Other cooling solenoids within reach
  - Interaction region and collider arc magnets are very close

- In addition, at 10 TeV
  - Timescale depends on the HTS progress, will know more in 5 years
  - Have been warned to remain open for important progress

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**NHFML**
32 T solenoid with HTS
Planned efforts to push even further
Other Technology Development

RF:
• Proof of principle of cooling RF in high magnetic field exists for two options and reach more than the target gradient
  – Move from single demonstrations into practical cavities
• Superconducting RF needs to be further developed

Target:
• Studies of the shock by beam impact and of radiation
• Some material test to improve shock resistance

Neutrino radiation mitigation:
• Design the system
  – Impact on magnet, cryogenics etc.
  – Impact on operation

Cooling cell design:
• Very involved engineering design required

Sofar, no showstopper identified
no inconsistency with 10-20 years timescale identified

Will know at next ESPPU
Test Facility Considerations

Test **cooling cell string**, ultimately with beam

Option:
- CERN land, extract PS beam from TT10 ($10^{13}$ 26 GeV protons in 5 ns, O(10%) of collider, with O(Hz))
- In molasse (no ground water)

**Indicative dimensions by C. Rogers**

- Target + horn (1st phase) / + superconducting solenoid (2nd phase)
- Momentum selection chicane
- Collimation and upstream diagnostics area
- Cooling area
- Downstream diagnostics area
- Services (Cryogenics, cooling & ventilation, power, transport, etc)

Other options to be explored

Accumulator test at ESS?
My Impression of Discussions

Muon collider has a high potential
• The muon collider presents enormous potential for fundamental physics research at the energy frontier.
• Not as mature as some other lepton collider options such as ILC and CLIC; but promises attractive cost, power consumption and time scale for the energy frontier, reaching beyond linear colliders.

Challenges but no showstoppers
• The panel identified the key R&D challenges.
• At this stage the panel did not identify any showstopper in the concept.
• Strong support of feasibility from previous studies.
• The panel considers baseline parameter set viable starting point.

Panel sees way forward
• The panel will propose the R&D effort that it considers essential to address these challenges during the next five years to a level that allows estimation of the performance and cost with greater certainty.
• Ongoing developments in underlying technologies will be exploited as they arise in order to ensure the best possible performance.
• This R&D effort will allow the next ESPPU to make fully informed decisions. It will also benefit equivalent strategy processes in other regions.

and potential ramp-up
• Based on these decisions a significant ramp-up of resources could be envisaged, in particular if a fast implementation is deemed essential.
**Timeline**

**Initial design phase 2021-2025**

- Establish whether investment into full CDR and demonstrator is scientifically justified.
- Provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.
- Identify an R&D path toward the collider, considering High-field Magnet and RF Roadmap results.

**Design phase 2026-**

- Develop concept and technology to be ready to commit
- Verify performance of all key components. In particular, build cooling cell string and test with beam. Build and test magnet models and RF components.

**Technical design phase**

- Prepare approval and project implementation
- Prepare industrial production of components, e.g. build magnet prototypes and preseries with industry.
- Prepare site for construction. Refine cost, power and construction schedule.

**Strategy decision (2026)**

- Define performance goals and timeline for muon collider
- Potentially ramp up of muon collider effort

**Decision to move to technical design**

- Pre-commitment to project

**Project Approval**

D. Schulte  
Muon Collider, EPS-HEP, July 2021
Ongoing Timeline Discussions

Muon collider is a long-term direction toward high-energy, high-luminosity lepton collider

Collaboration prudently also explores if muon collider can be option as next project (i.e. operation mid2040s) in case Europe does not build higgs factory

Exploring shortest possible aggressive timeline with initial 3 TeV stage on the way to 10+ TeV
• Important ramp-up 2026

High-field magnet and RF programmes will allow to judge maturity what can be reached in a collider with this timeline

Preparation of R&D programme needs to be advanced enough for implementation after next ESPPU

Based on strategy decisions a significant ramp-up of resources could be made to accomplish construction by 2045 and exploit the enormous potential of the muon collider.

Tentative Target for Aggressive Timeline

to assess when 3 TeV could be realised, assuming massive ramp-up in 2026
Conclusion

• Muon colliders are a unique opportunity for a high-energy, high-luminosity lepton collider
  – high luminosity to beam power ratio
  – cost efficiency to be assessed

• Two different options considered
  – 3 TeV collider that can start construction in less than 20 years
  – 10 TeV collider that uses advanced technologies

• Not as mature as ILC or CLIC
  – have to address important R&D items
  – but no showstopper identified

• Aim to develop concept to a maturity level that allows to make informed choices by the next ESPPU and other strategy processes
  – Baseline design
  – R&D and demonstration programme

• An important opportunity that we should not miss

Many thanks to the Muon Beam Panel, the collaboration, the MAP study, the MICE collaboration, and many others
Memorandum of Cooperation

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
Neutrino Flux Mitigation

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

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

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 and Detector Design

Vertex detector properly designed to not overlap with the BIB hottest spots around the interaction region.

BIB particles not coming from primary vertex, double layer structure can be exploited correlate hit pairs on adjacent sensors to estimate incoming particle direction.

Tracking performance have been studied applying timing on clusters reconstruction compatible with IP time time spread.
Proton Complex and Target Area

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

2 MW proton beam requires radiation protection

High field to efficiently collect pions/muons: 20 T, then tapering Using copper solenoid in superconducting solenoid

Large aperture O(1.2m) to allow shielding
Cooling Concept

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

Need to optimise lattice design to gain factor 2 in emittance, integrating demonstrated better hardware performances

This is the unique and novel system of the muon collider
Will need a test facility
The principle has been demonstrated in MICE
MICE (in the UK)

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
High-energy Acceleration

System of linacs followed by sequence of RCS and/or FFA

**RF system**
- Important single-bunch beam loading

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

**Rapid cycling synchrotron (RCS)**
- Combine static and ramping magnets
- **Ramp magnets** to follow beam energy
  - normal conducting
  - or novel HTS
- **Power consumption** of fast-ramping systems is important

**FNAL**
12 T/s HTS now 290 T/s

Test of fast-ramping normal-conducting magnet design

**EMMA** proof of FFA principle

**Strong focusing** at IP to minimise betafunction and maximise luminosity

\[ \beta_x^* \propto \frac{1}{E} \]

**At 3 TeV:** Field level close to HL-LHC (12 vs 11 T)

**At 10+ TeV:** Higher field is likely required

### 3 TeV Design (MAP)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Q1</th>
<th>Q1</th>
<th>Q3</th>
<th>Q4</th>
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<td>Aperture (mm)</td>
<td>90</td>
<td>110</td>
<td>130</td>
<td>150</td>
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<tr>
<td>Gradients (T/m)</td>
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<td>218</td>
<td>-154</td>
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<tr>
<td>Peak field (T)</td>
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<td>10+</td>
<td>10+</td>
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<td>Dipole field (T)</td>
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</table>

**First considerations on 14 TeV Design (R: Tomas)**

- \( \beta_{x,y} = 1 \text{ mm} \)
- \( B_{\text{peak}} = 18 \text{ T} \)
- \( N_\sigma = 6 \sigma \)
- \( E = 7 \text{ TeV} \)
- \( \text{Aper.} = 0.3 \text{ m} \)

**At 3 TeV:**

Close to state of the art

**At 10+ TeV:**

Higher field \( \text{Nb}_3\text{Sn} \) or better HTS is potentially required
Collider Ring Arcs

**High field dipoles** to minimise collider ring size and maximise luminosity

**Beam loss protection** $O(500 \, \text{W/m})$

**MAP 3 TeV example:**
- **10.4 T** in 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**
- Acceptable losses in cold mass: 1%, maximum of 1.5 mW/g

**At 10 TeV**
- Currently no real design
- Ring length assume shorter ring per TeV at 10+ TeV, 16 T might be sufficient
- But will adjust to magnet performance
- Expect shielding/aperture not to increase dramatically with beam energy

(V.V. Kashikhin et al.)

(N. Mokhov et al.)
Collaboration Timeline Goals

3 TeV collider option

• Goal: option ready to take data before 2045
• Important step up in energy after a higgs factory
• Maximum energy of CLIC
  – CLIC integrated cost is 18 GCHF and it uses 590 MW power
  – aim for significantly lower cost and power consumption
• One option with technologies expected to be available in 15-20 years
  – will adjust design accordingly

10+ TeV collider option

• Goal: Highest lepton energies, well above the reach even of CLIC
• To explore energy reach for a realistic collider and understand if muon collider is right direction for long-term future
  – aim for competitive cost and power
• Employing advanced technologies, not yet concerned about schedule
• Could be upgrade of a 3 TeV collider
  – splitting the cost into two stages, only 3 TeV collider ring cost is lost
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 that produces and cools muons
Cooling Challenges and Status

**FNAL**
- 12 T/s
- HTS
- 0.6 T max

Need to push in field and speed

**MuCool**: >50 MV/m in 5 T field

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

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

**NHFML**
- 32 T solenoid with HTS

Planned efforts to push even further

**MICE (UK)** Muon cooling principle
Key Challenges

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

**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**

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Dense neutrino flux mitigated by mover system and site selection

Beam induced background
Physics at Muon Collider

Muon Collider can be the game changer

D. Buttazzo

Muon Collider, EPS-HEP, July 2021

The Muon Smasher’s Guide

P. Maede

A Muon Collider is great!

P. Maede

CONCLUSIONS

There are BROAD EXCITING PHYSICS THEMES to pursue at future colliders:

Dark Matter, Baryogenesis, SUSY, Compositeness, Flavor origins, parallel gauge sectors, long-lived particles, precision Higgs structure.

Need a collider at highest energies, clean enough & with sensitive enough detectors, to pursue both high mass &/or weakly coupled BSM at high precision & to excite & challenge next generation of experimentalists.

If new physics (dimly) seen in DM, flavor, EDM, precision, gravitational wave, cosmological expts, we need collider with reach/precision to complement, corroborate, clarify...

Di-Higgs too!

P. Maede

D. Schulte
Challenges and Status

MuCool: >50 MV/m in 5 T field

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

FNAL
12 T/s HTS
0.6 T max

now 290 T/s

Test of fast-ramping normal-conducting magnet design

NHFML
32 T solenoid with HTS

Planned efforts to push even further

MICE (UK) Muon cooling principle
Example Cell Designs

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

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, ...