# Muon Collider

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On behalf of the International Muon Collider Collaboration

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This project has received funding from the European Union's Research and Innovation programme under GA No 101094300.

# Motivation and Goal

Previous studies in US (now very strong interest again), experimental programme in UK and alternatives studies by INFN

New strong interest in **high-energy, high-luminosity lepton collider**

- Combines **precision physics** and **discovery reach**
- Application of hadron collider technology to a lepton collider

Muon collider promises **sustainable** approach to the **energy frontier**

- limited power consumption, cost and land use

**Technology** and **design advances** in past years

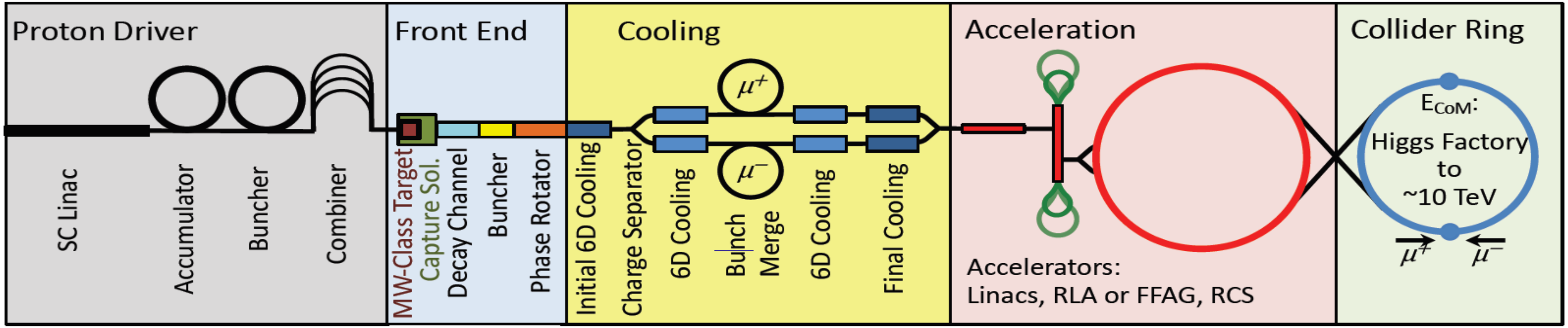
- review did not find any showstoppers

Goal is

- 10+ TeV collider
- potential initial energy stage (e.g. 3 TeV)
- higher energies to be explored later

# Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$




Short, intense proton bunch

Ionisation cooling of muon in matter

Acceleration to collision energy

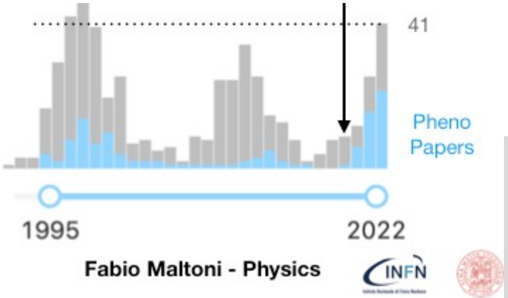
Collision

Protons produce pions which decay into muons
muons are captured

# A new Interest in Muon Colliders

## From, e.g., Snowmass21 EF report draft:

*"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. […] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. […] Multi-TeV muon colliders will have the benefit of excellent signal to background […] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential."*




from F. Maltoni at IMCC Annual Meeting

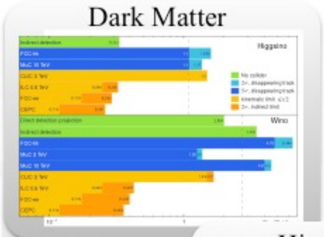
A. Wulzer, F. Maltoni, P. Meade et al.

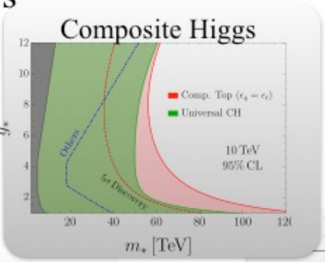
O(150) authors, 15 editors, 100 papers

DELPHES card available

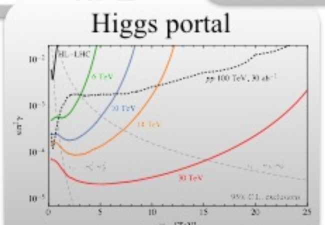
## Selected summary plots, from Snowmass21 reports:

2 IMCC reports, plus Muon Collider Forum report. Total of 15 editors, ~150 authors, based on ~100 papers from 3 past years



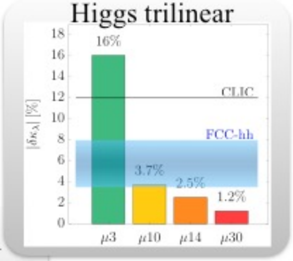





Higgs couplings

| | HL-LHC | HL-LHC +10 TeV | HL-LHC +10 TeV + ee |
|---|---|---|---|
| $\kappa_W$ | 1.7 | 0.1 | 0.1 |
| $\kappa_Z$ | 1.5 | 0.4 | 0.1 |
| $\kappa_g$ | 2.3 | 0.7 | 0.6 |
| $\kappa_\gamma$ | 1.9 | 0.8 | 0.8 |
| $\kappa_{Z\gamma}$ | 10 | 7.2 | 7.1 |
| $\kappa_c$ | - | 2.3 | 1.1 |
| $\kappa_b$ | 3.6 | 0.4 | 0.4 |
| $\kappa_\mu$ | 4.6 | 3.4 | 3.2 |
| $\kappa_\tau$ | 1.9 | 0.6 | 0.4 |
| $\kappa_t^*$ | 3.3 | 3.1 | 3.1 |

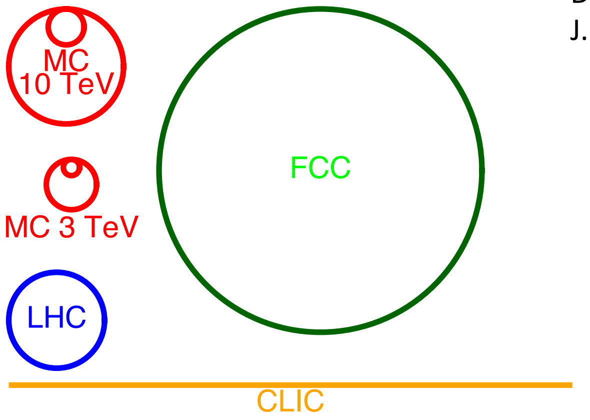
* No input used for $\mu$ collider

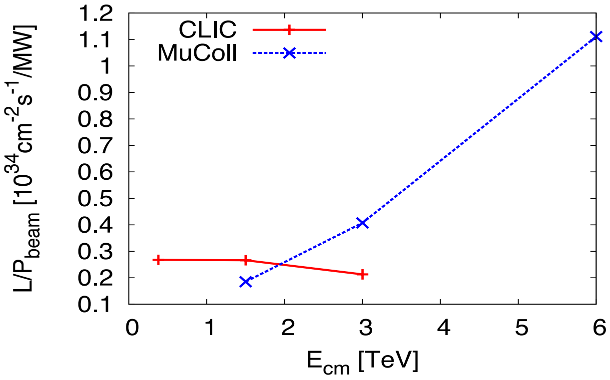



Strong US involvement starting with **Muon Smasher's Guide** and in **Muon Collider Forum**

# Muon Collider Promises

**US Snowmass Implementation Task Force**: Th. Roser, R. Brinkmann, S. Cousineau, D. Denisov, S. Gessner, S. Gourlay, Ph. Lebrun, M. Narain, K. Oide, T. Raubenheimer, J. Seeman, V. Shiltsev, J. Straight, M. Turner, L. Wang et al.




| | CME [TeV] | Lumi per IP [$10^{34}cm^{-2}s^{-1}$] | Years to physics | Cost range [B$] | Power [MW] |
|---|---|---|---|---|---|
| FCC-ee | 0.24 | 8.5 | 13-18 | 12-18 | 290 |
| ILC | 0.25 | 2.7 | <12 | 7-12 | 140 |
| CLIC | 0.38 | 2.3 | 13-18 | 7-12 | 110 |
| ILC | 3 | 6.1 | 19-24 | 18-30 | 400 |
| CLIC | 3 | 5.9 | 19-24 | 18-30 | 550 |
| MC | 3 | 1.8 | 19-24 | 7-12 | 230 |
| MC | 10 | 20 | >25 | 12-18 | 300 |
| FCC-hh | 100 | 30 | >25 | 30-50 | 560 |

Judgement by ITF, take it *cum grano salis*

# Goal and Accelerator R&D Roadmap

MuCol

International
MUON Collider
Collaboration

Muon collider is on European **Accelerator R&D Roadmap**

- Reviews in Europe and US found **no insurmountable obstacle**

Implementing workplan

- Goal: **Project Evaluation Report** and **R&D Plan** to next ESPPU/other processes
- 10+ TeV collider, potential 3 TeV initial stage
- CERN has budget in MTP, hosting a collaboration
- Design Study supported by EC, Switzerland, UK and partners contribute
- Strong interest in US community to join and contribute at same level as Europe

We still need more resources

- But **doubled last year** with EU Design Study
- **Might double** with US joining
- Preparing other requests
- Exploitation of synergies

| Label | Begin | End | Description | Aspirational | | Minimal | |
|---|---|---|---|---|---|---|---|
| | | | | [FTEy] | [kCHF] | [FTEy] | [kCHF] |
| MC.SITE | 2021 | 2025 | Site and layout | 15.5 | 300 | 13.5 | 300 |
| MC.NF | 2022 | 2026 | Neutrino flux mitigation system | 22.5 | 250 | 0 | 0 |
| MC.MDI | 2021 | 2025 | Machine-detector interface | 15 | 0 | 15 | 0 |
| MC.ACC.CR | 2022 | 2025 | Collider ring | 10 | 0 | 10 | 0 |
| MC.ACC.HE | 2022 | 2025 | High-energy complex | 11 | 0 | 7.5 | 0 |
| MC.ACC.MC | 2021 | 2025 | Muon cooling systems | 47 | 0 | 22 | 0 |
| MC.ACC.P | 2022 | 2026 | Proton complex | 26 | 0 | 3.5 | 0 |
| MC.ACC.COLL | 2022 | 2025 | Collective effects across complex | 18.2 | 0 | 18.2 | 0 |
| MC.ACC.ALT | 2022 | 2025 | High-energy alternatives | 11.7 | 0 | 0 | 0 |
| MC.HFM.HE | 2022 | 2025 | High-field magnets | 6.5 | 0 | 6.5 | 0 |
| MC.HFM.SOL | 2022 | 2026 | High-field solenoids | 76 | 2700 | 29 | 0 |
| MC.FR | 2021 | 2026 | Fast-ramping magnet system | 27.5 | 1020 | 22.5 | 520 |
| MC.RF.HE | 2021 | 2026 | High Energy complex RF | 10.6 | 0 | 7.6 | 0 |
| MC.RF.MC | 2022 | 2026 | Muon cooling RF | 13.6 | 0 | 7 | 0 |
| MC.RF.TS | 2024 | 2026 | RF test stand + test cavities | 10 | 3300 | 0 | 0 |
| MC.MOD | 2022 | 2026 | Muon cooling test module | 17.7 | 400 | 4.9 | 100 |
| MC.DEM | 2022 | 2026 | Cooling demonstrator design | 34.1 | 1250 | 3.8 | 250 |
| MC.TAR | 2022 | 2026 | Target system | 60 | 1405 | 9 | 25 |
| MC.INT | 2022 | 2026 | Coordination and integration | 13 | 1250 | 13 | 1250 |
| | | | Sum | 445.9 | 11875 | 193 | 2445 |

**Table 5.5:** The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment and similar costs. Colours are included for comparison with the resource profile Fig. 5.7.

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

http://arxiv.org/abs/2201.07895

# Muon Collider Timeline

Technically limited timeline

To be reviewed considering progress, funding and decisions

Muon collider important in the long term

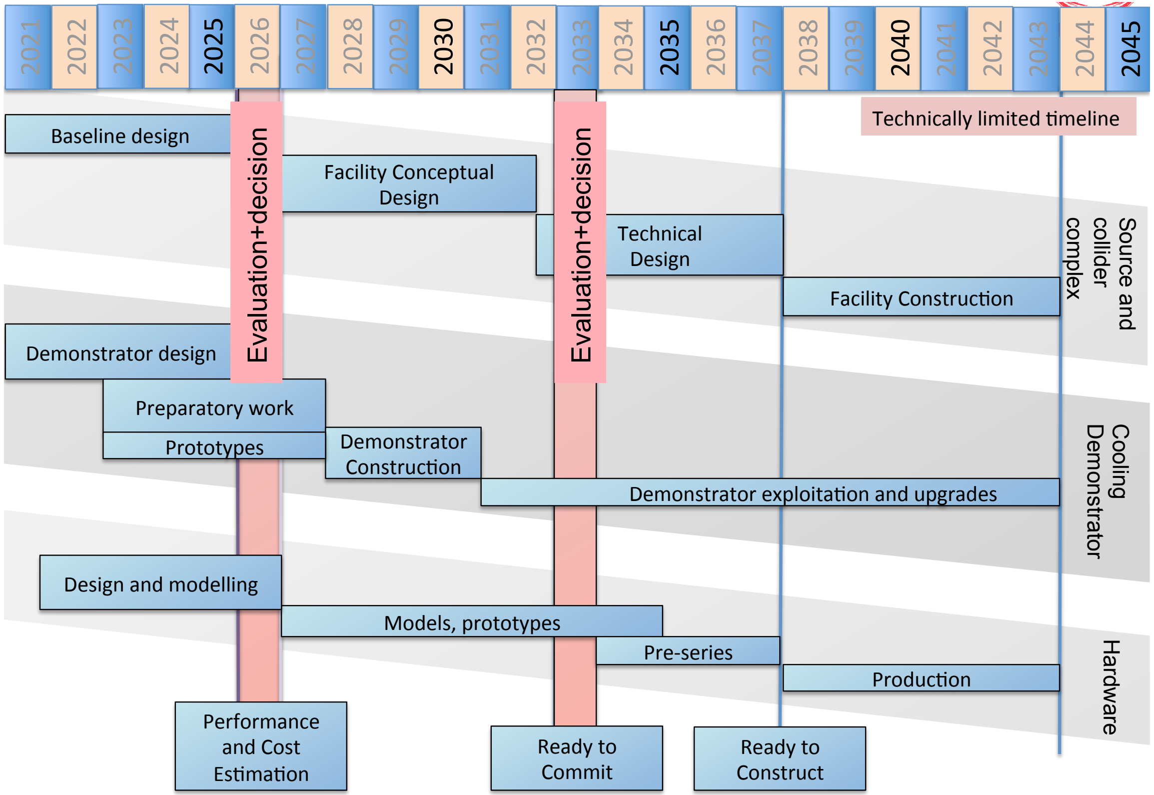
- Even after potential FCC-hh

But also **plan B as next project in Europe** and maybe **plan A in US** and elsewhere

**Fast track option** if require next as project after HL-LHC:

- Lower energy initial option, e.g. 3 TeV
- Upgrade to 10 TeV later
  - Little extra cost

Subject to funding



# Initial Target Parameters

**Target integrated luminosities**

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

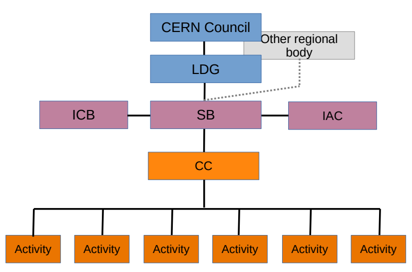
**Note: currently focus on 10 TeV, also explore 3 TeV**

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
  - Probably have more time
  - FCC-hh to operate for 25 years
- Aim to have two detectors

| Parameter | Unit | 3 TeV | 10 TeV | 14 TeV | CLIC at 3 TeV |
|---|---|---|---|---|---|
| **L** | **$10^{34}$ cm$^{-2}$s$^{-1}$** | **1.8** | **20** | **40** | **2 (6)** |
| N | $10^{12}$ | 2.2 | 1.8 | 1.8 | |
| $f_r$ | Hz | 5 | 5 | 5 | |
| **$P_{beam}$** | **MW** | **5.3** | **14.4** | **20** | **28** |
| 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 | |
| $\beta$ | mm | 5 | 1.5 | 1.07 | |
| $\varepsilon$ | µm | 25 | 25 | 25 | |
| $\sigma_{x,y}$ | µm | 3.0 | 0.9 | 0.63 | |

# Muon Collider Community

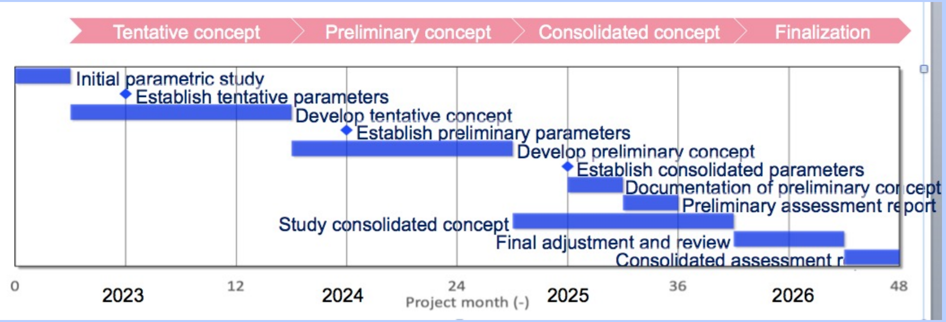
Formed **collaboration** hosted by CERN to implement R&D Roadmap for CERN Council




60+ partners, 40+ already signed MoC

**EU Design Study approved**

(EU+Switzerland+UK and partners)




Plan to participate to **HORIZON-INFRA-2024-TECH**

Goal: prepare experimental programme, e.g. **demonstrator, prototypes, …**

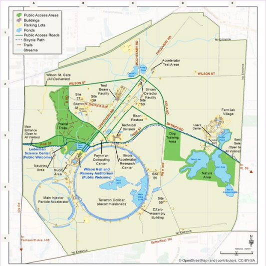
**TIARA wants magnet proposal**

**US Snowmass** has **strong support**

- to contribute to R&D
- as a collider in the US

Lia Merminga appointed team that prepared P5 ask, aim for **50 FTE** for accelerators

Some first contacts with others



# MoC and Design Study Partners

| | |
|---|---|
| IEIO | **CERN** |
| FR | **CEA-IRFU** |
| | CNRS-LNCMI |
| DE | DESY |
| | **Technical University of Darmstadt** |
| | **University of Rostock** |
| | KIT |
| SE | **ESS** |
| | **University of Uppsala** |
| PT | **LIP** |
| NL | **University of Twente** |
| FI | **Tampere University** |
| LAT | **Riga Technical Univers.** |
| CH | **PSI** |
| | **University of Geneva** |
| | EPFL |
| EST | ***Tartu University*** |
| BE | **Univ. Louvain** |

| | |
|---|---|
| UK | **RAL** |
| | UK Research and Innovation |
| | ***University of Lancaster*** |
| | **University of Southampton** |
| | **University of Strathclyde** |
| | **University of Sussex** |
| | **Imperial College London** |
| | **Royal Holloway** |
| | **University of Huddersfield** |
| | **University of Oxford** |
| | **University of Warwick** |
| | **University of Durham** |
| US | **Iowa State University** |
| | **Wisconsin-Madison** |
| | ***Pittsburg University*** |
| | **Old Dominion** |
| | BNL |
| | **Florida State University** |
| | **RICE University** |
| | ***Tennessee University*** |

| | |
|---|---|
| IT | **INFN** |
| | **INFN, Univ., Polit. Torino** |
| | **INFN, Univ. Milano** |
| | **INFN, Univ. Padova** |
| | **INFN, Univ. Pavia** |
| | **INFN, Univ. Bologna** |
| | **INFN Trieste** |
| | **INFN, Univ. Bari** |
| | **INFN, Univ. Roma 1** |
| | ENEA |
| | **INFN Frascati** |
| | **INFN, Univ. Ferrara** |
| | **INFN, Univ. Roma 3** |
| | INFN Legnaro |
| | **INFN, Univ. Milano Bicocca** |
| | **INFN Genova** |
| | **INFN Laboratori del Sud** |
| | INFN Napoli |
| Mal | **Univ. of Malta** |

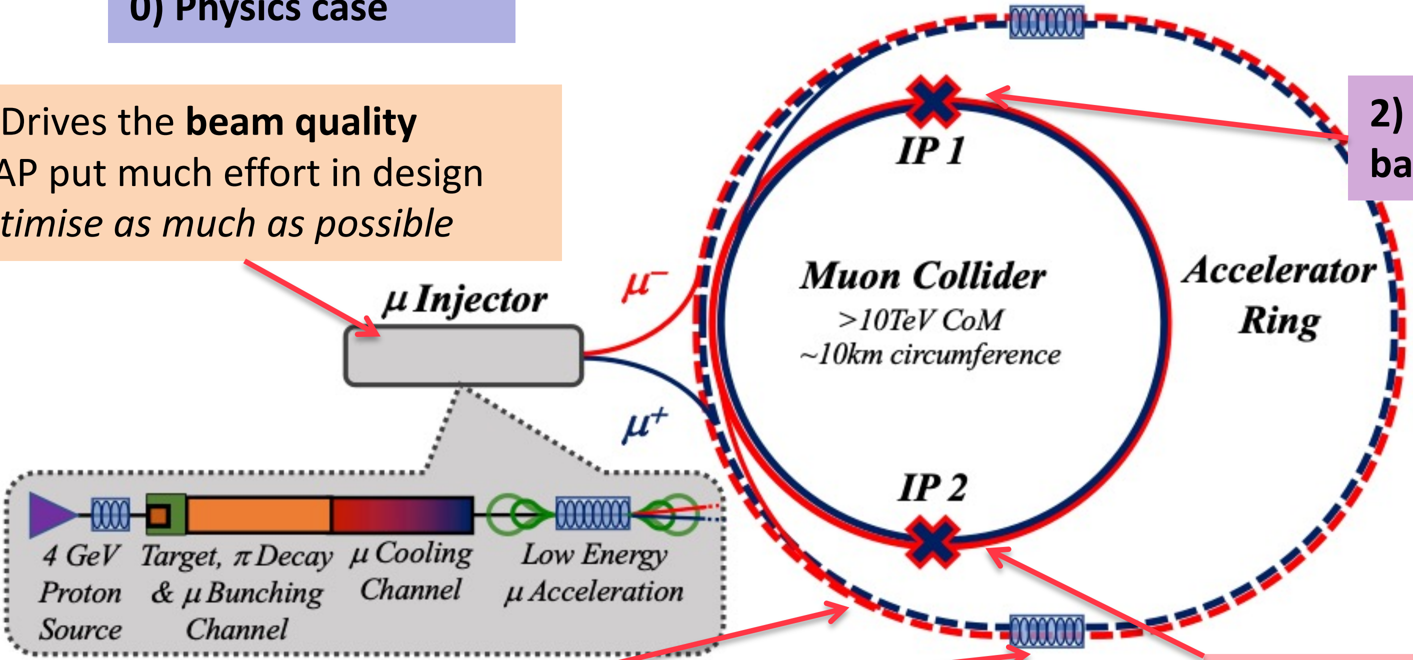
| | |
|---|---|
| China | ***Sun Yat-sen University*** |
| | **IHEP** |
| | **Peking University** |
| AU | **HEPHY** |
| | ***TU Wien*** |
| ES | **I3M** |
| | ***CIEMAT*** |
| | **ICMAB** |
| KO | **KEU** |
| | **Yonsei University** |
| India | ***CHEP*** |

| | |
|---|---|
| US | FNAL |
| | LBL |
| | JLAB |
| | Chicago |

# Key Challenges

0) **Physics case**

4) Drives the **beam quality**
MAP put much effort in design
*optimise as much as possible*

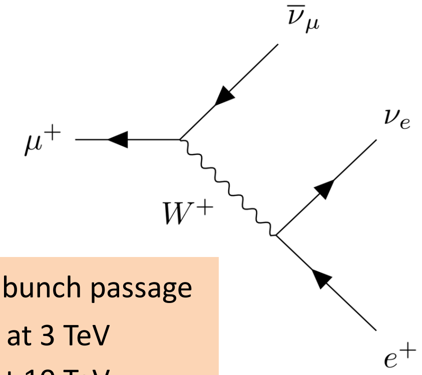


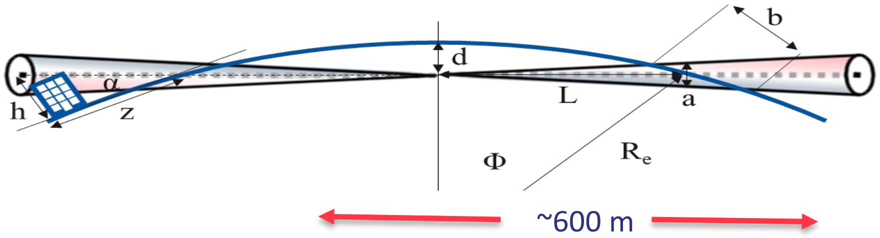

2) **Beam-induced background**

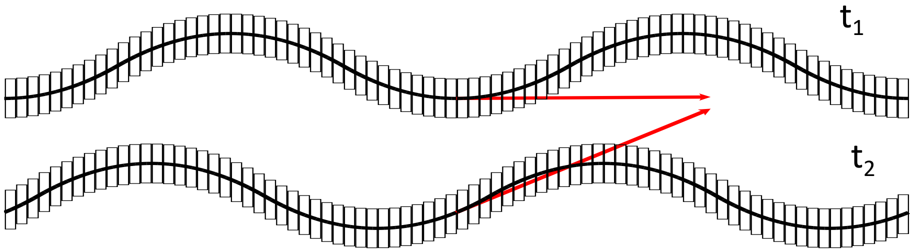
**1) Dense neutrino flux**
mitigated by mover system
and site selection

**3) Cost** and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

# Muon Decay and Neutrino Flux



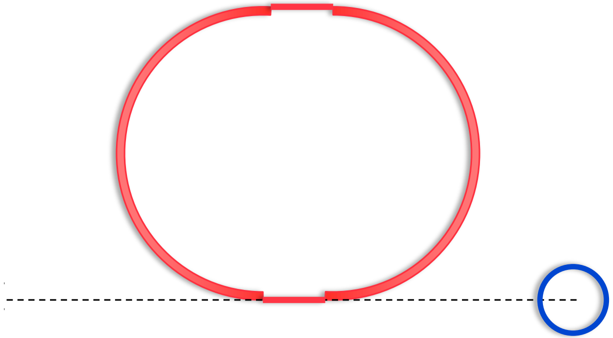




Muon decays per bunch passage

- 235,000 $m^{-1}$ at 3 TeV
- 58,000 $m^{-1}$ at 10 TeV

But want to have **negligible impact from arcs**

- Similar impact as LHC
- At 3 TeV this is the case for 200 m depth
- At 10 TeV use angle change of +/- 1 mradian to go from acceptable to negligible level
  - Mockup of mover system planned
  - Impact on beam to be checked



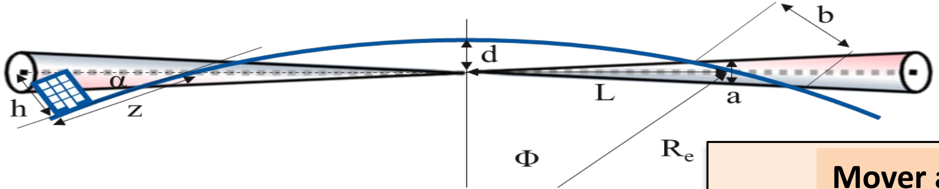
**Impact of experimental insertions**

- 3 TeV design acceptable with no further work
- Maybe acquire land in direction of experiment, also for 10 TeV

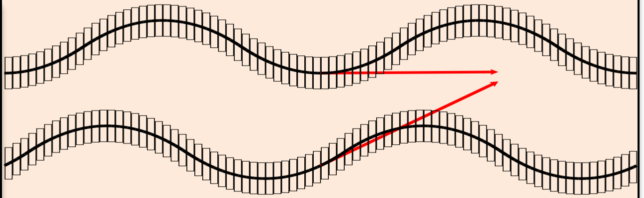
# Neutrino Flux

Goal: **similar to LHC**: limit neutrino flux to have **negligible impact**, "fully optimised" (10% of MAP goal)

**Verify performance of concept to be good for 14 TeV**

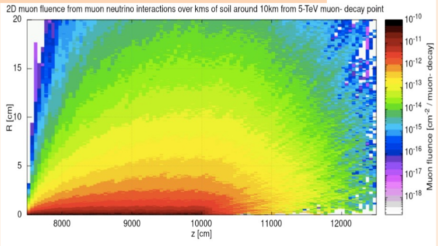



## Mover and support system



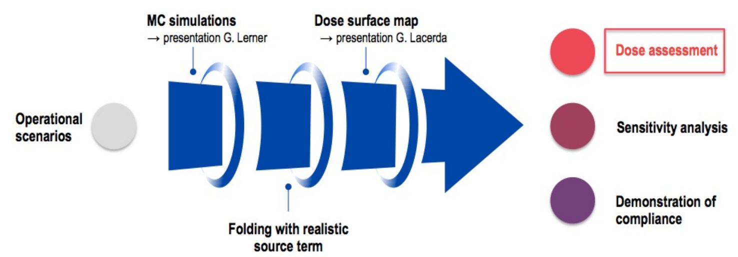
F. Bertinelli et al. (CERN, Riga)

## FLUKA dose studies



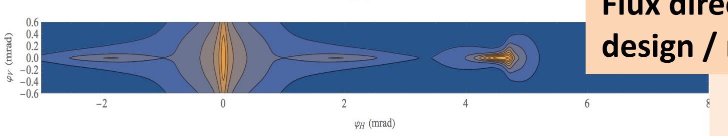

G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

## Conformity Verification Scheme




C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

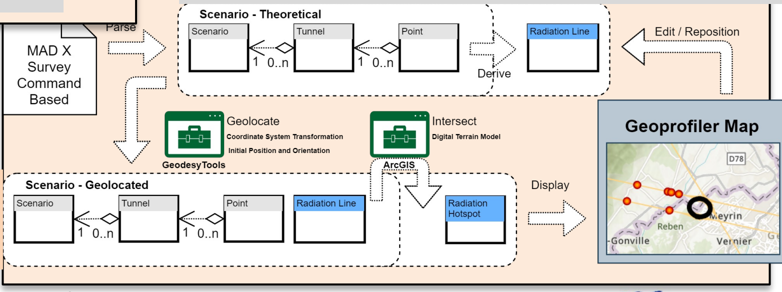
## Flux direction map / lattice design / mover impact on beam




C. Carli, K. Skoufaris (CERN)

## Mitigation: Site choice tool

G. Lacerda, Y. Robert, N. Guilhaudin (CERN)



# Muon Decay and Detector Background

Muon decays produce electrons and positrons

- Loss per unit length almost independent of energy
- First results indicate that background does not increase much with energy

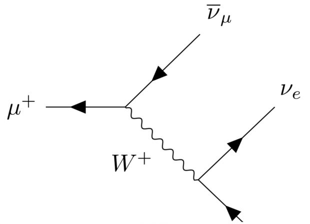
1.5 and 3 TeV studies, concept based on CLIC detector

- **Masks** to mitigate background
- Detailed **FLUKA studies** of masks/beamline
- **Tracking detector radiation level similar to HL-LHC**

Studies with **beam-induced background** in progress

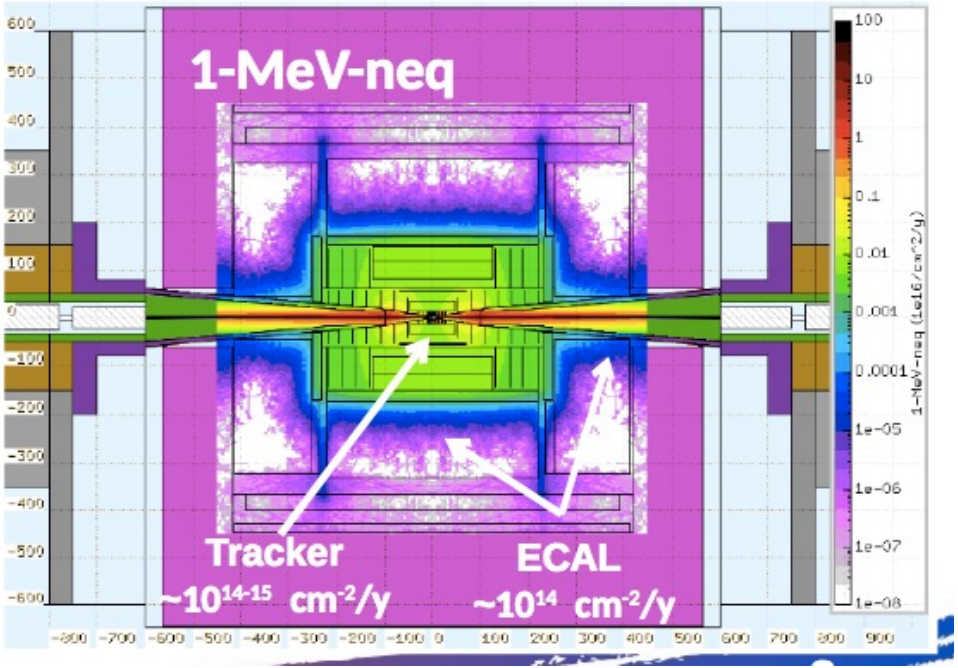
- some channels are not affected by background
- some improvement required for other channels

Concept for **10 TeV** in progress

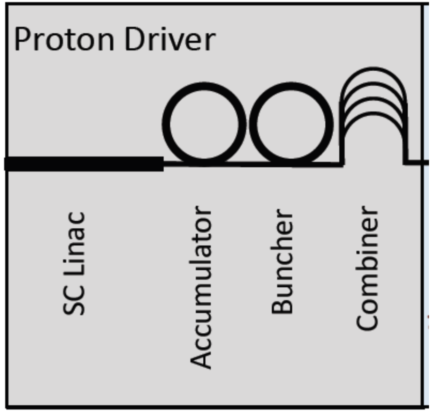



Detector team
O(69) authors, O(150 signatories)

D. Lucchesi, F. Meloni et al.



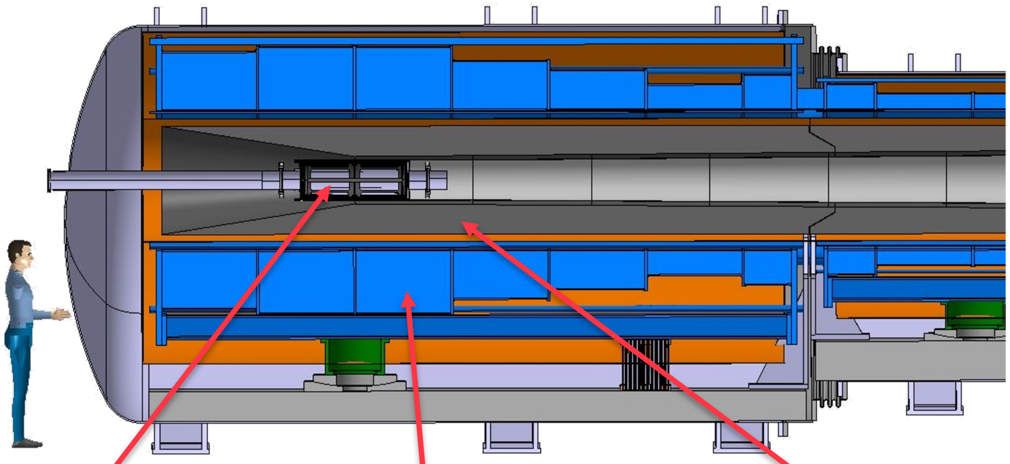
# Proton Complex and Target





protons $\xrightarrow{\text{in target}}$ pions $\xrightarrow{\text{decay}}$ muons

400 kJ protons to produce 5 x $10^{13}$ captured muon pairs



Graphite **Target**

20 T **solenoid**
to guide pions and muons

**Tungsten shielding**
To protect magnet

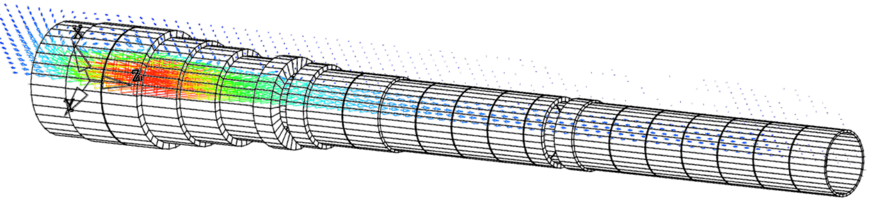
5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand

ESS and Uppsala will focus on merging beam into high-charge pulses

Optimisation of parameters planned

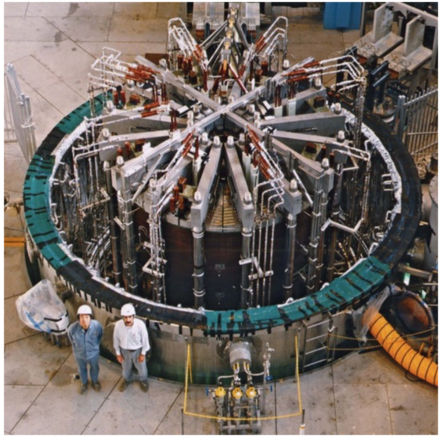
# Target Studies

**Target solenoid design** ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert



**HTS target solenoid:** 20 T, 20 K

A Portone, P. Testoni, J. Lorenzo Gomez, F4E

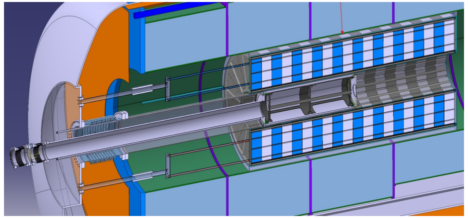


ITER model coil: 13 T
$Nb_3Sn$ 1.7 m diameter

**Our work is relevant for fusion**

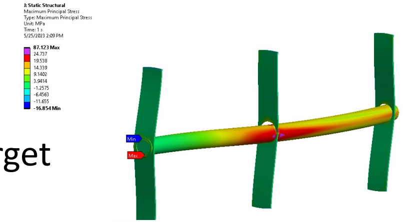
**FLUKA studies**:
**2 MW target:** stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

**Integration**

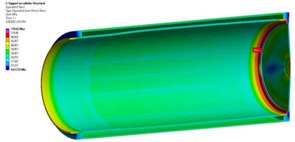


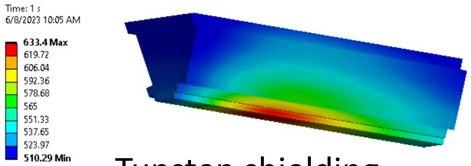
Cooling, vacuum, mechanics, …

Target



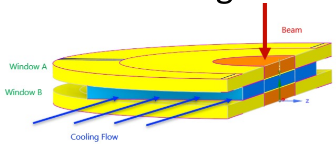
Vessel





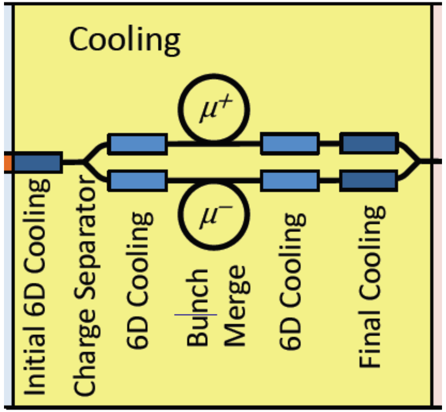

Tunsten shielding

Window

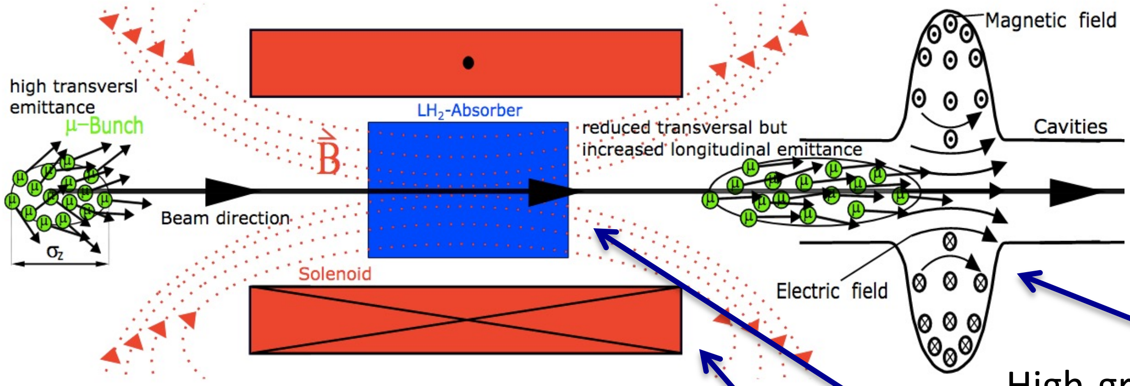


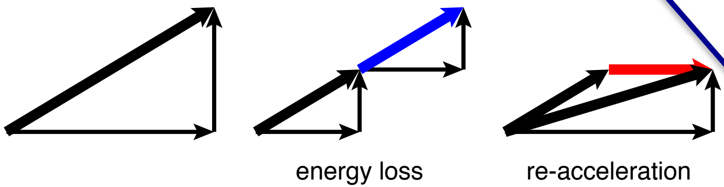

A. Lechner, D. et al.

# Muon Cooling Principle




C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)

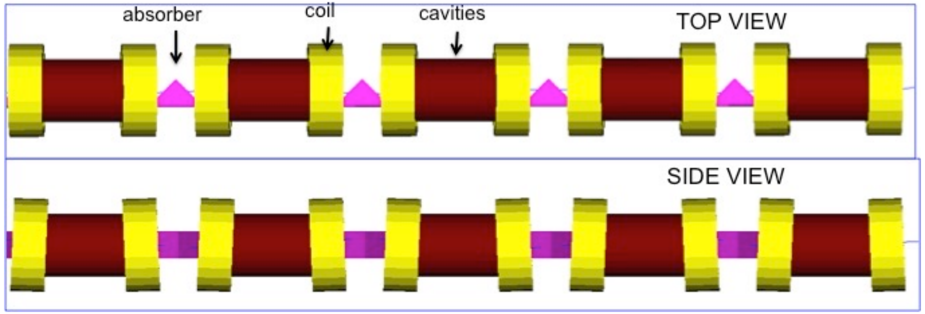



High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid




Principle has been demonstrated in MICE Nature vol. 578, p. 53-59 (2020)

# Muon Cooling Performance

MuCol

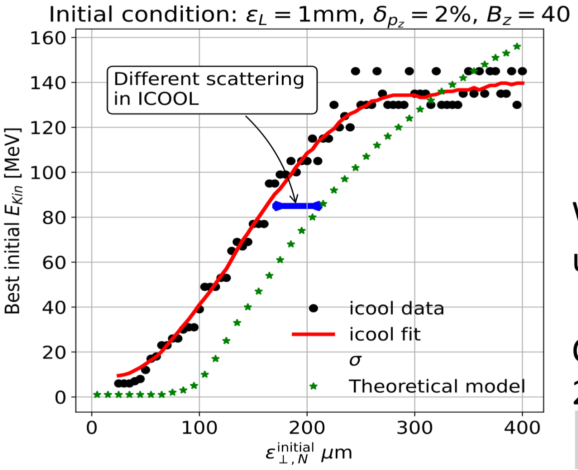
International MUON Collider Collaboration

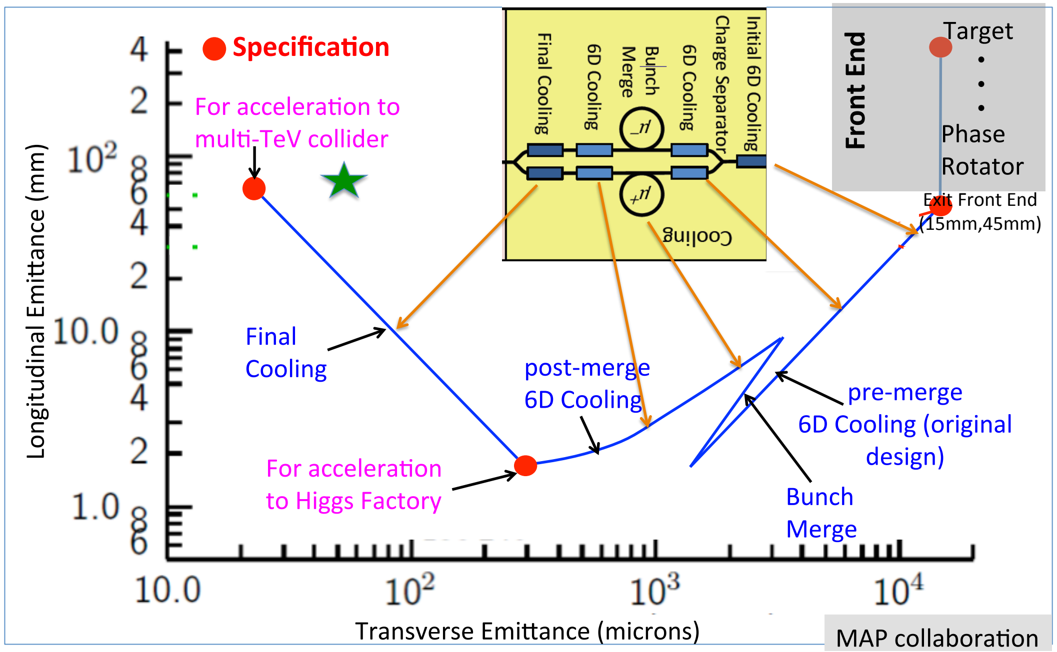
MAP design achieved 55 um based on achieved fields

Can expect better hardware

Integrating physics into **RFTRACK**, a CERN simulation code with single-particle tracking, collective effects, …

A. Latina, E. Fol, B. Stechauner at al.



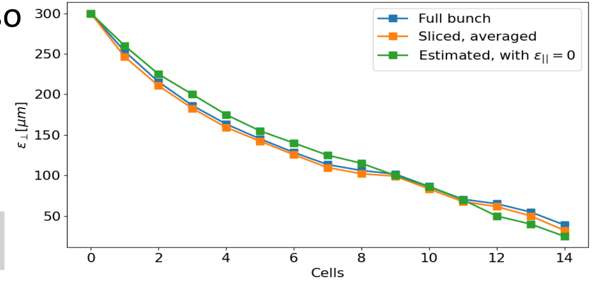




MAP collaboration

Working on **improved, systematic design**, also using better magnets and RF

Currently improved from 55 um to 33 um, 25 um is the goal

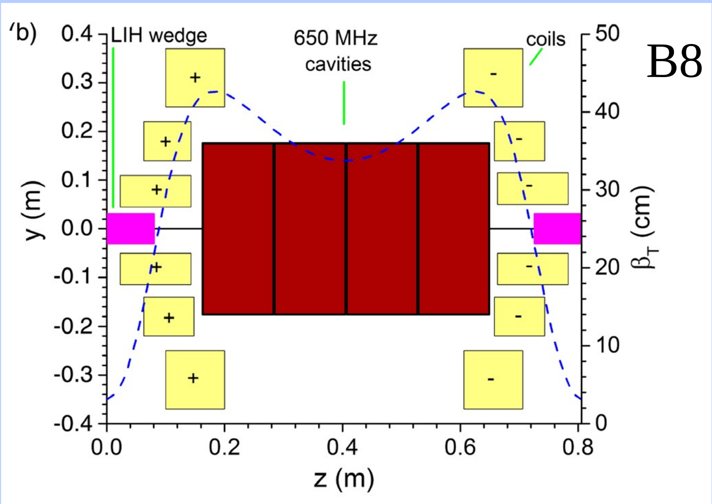
Ch. Rogers, Zhu Ruihu, B. Stechauner, E. Vol et al.



# Cooling Cell Technology

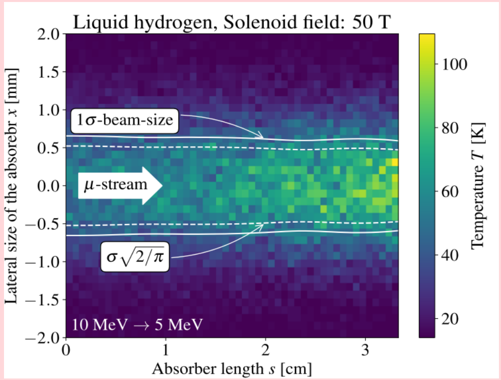
Will develop example **cooling cell with integration**
- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**

L. Rossi et al. (INFN, Milano, STFC, CERN),
J. Ferreira Somoza et al.




Most complex example 12 T

Windows and absorbers for high-density muon beam
- Pressure rise mitigated by vacuum density
- Plan window test in HiRadMat

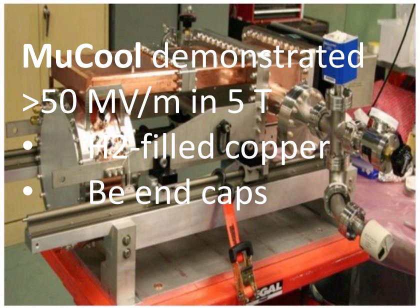



**RF cavities in magnetic field**

MAP demonstrated higher than goal gradient

Improve design based on theoretical understanding

Preparation of **new test stand**, but needs funding
- Test stand at CEA (700 MHz, need funding)
- Test at other frequencies in the UK considered
- Use of CLIC breakdown experiment considered



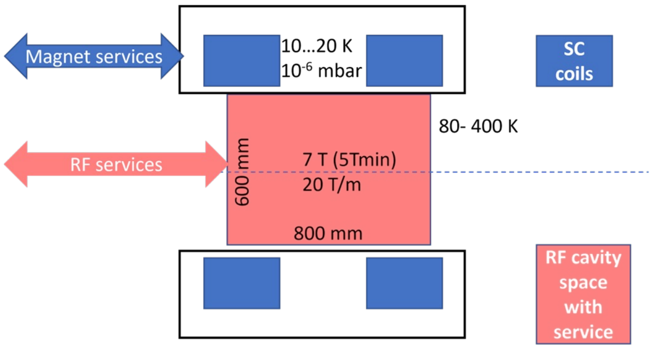

C. Marchand, Alexej Grudiev et al. (CEA, Milano, CERN, Tartu)

# RF Test Stand

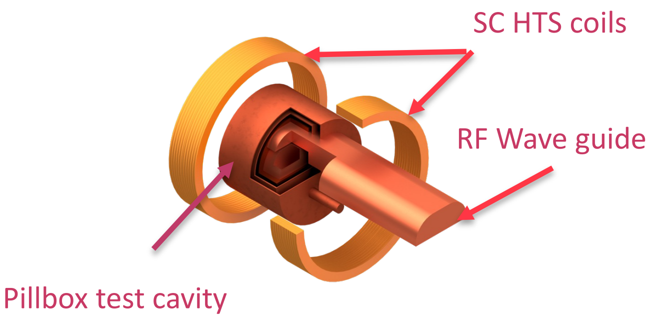
Module work focuses on RF test stand at this moment

- Important ensure timely R&D plan
- Try to identify infrastructure for this
  - CEA, INFN, Cockroft, CERN, …
  - Will not be cheap so need to find resources

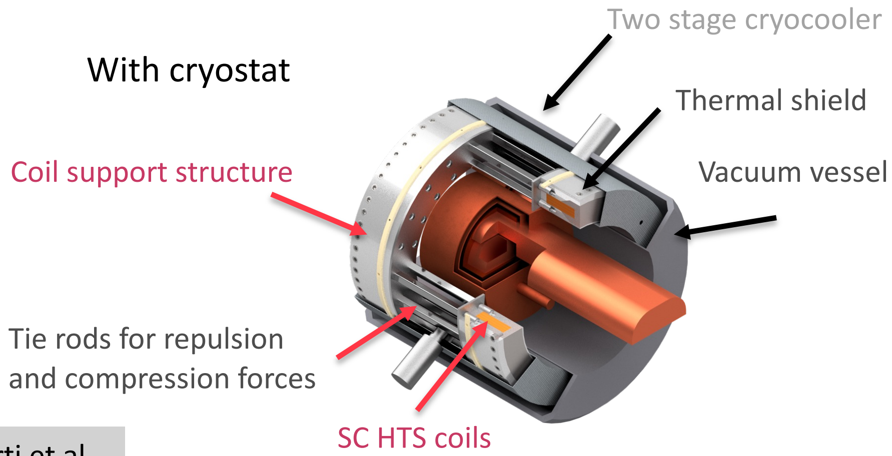
Schematic of the RFMF test facility single cryostat




Bare coils and RF cavity




With cryostat




L. Rossi, C. Marchand, D. Giove, A. Gurdiev, G. Ferrand, M. Castoldi, S. Sorti et al.

# Solenoid R&D

Started **HTS solenoid** development for high fields
Synergies with fusion reactors, NRI, power generators for windmills, …

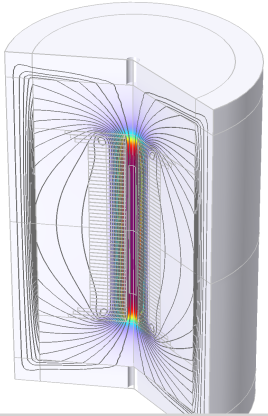
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

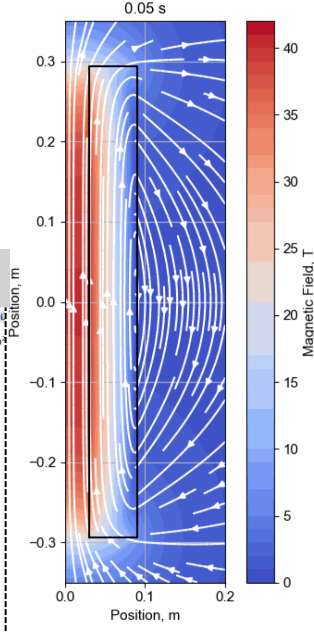
**Final Cooling solenoid**

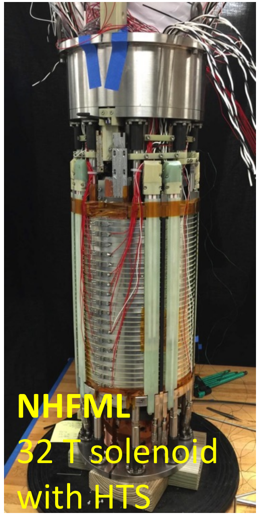
$$\mathbf{B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}}$$

$\sigma_{max}$ = 600 MPa

$\mathbf{B_{max} \approx 55\ T}$

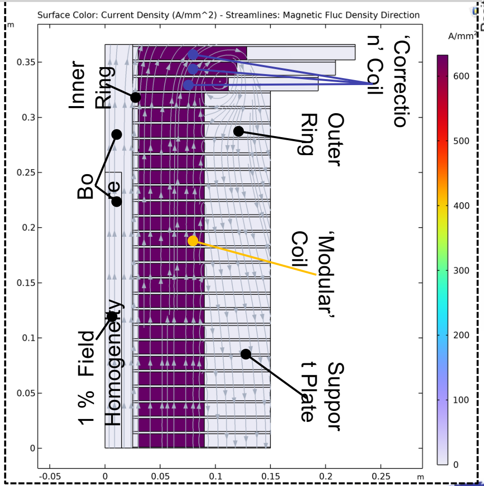


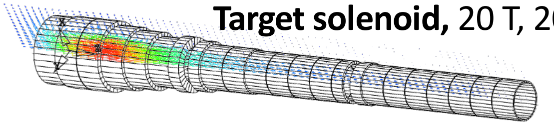



32 T LTS/HTS solenoid demonstrated

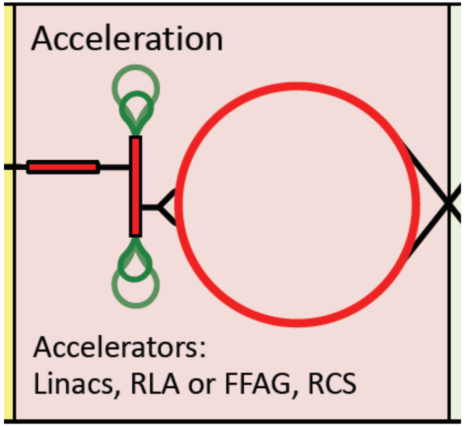

A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



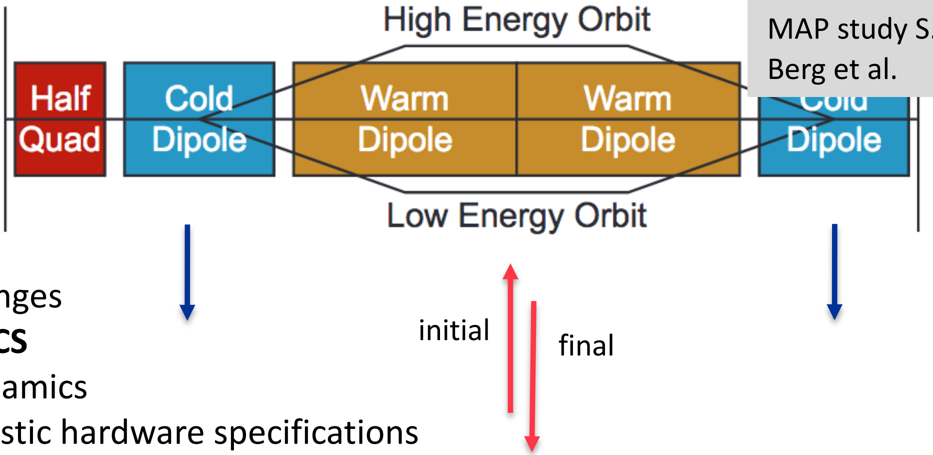
**Target solenoid,** 20 T, 20 K

# Acceleration Complex




Core is sequence of hybrid pulsed synchrotron (0.4-11

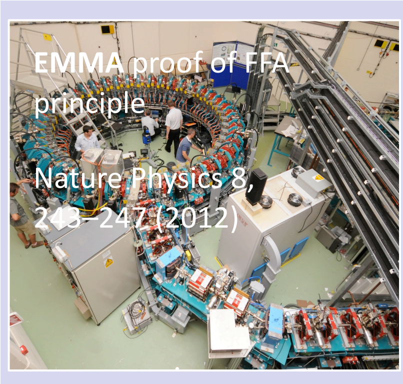
- Alternative FFA




MAP study S. Berg et al.

Started work on key challenges

- **Integrated design of RCS**
  - Longitudinal dynamics
  - Lattice with realistic hardware specifications
  - Collective effects
- **Concept of key components**
  - Fast-ramping normal magnets
  - HTS alternative
  - Efficient power converters
  - RF with transient beam loading




Lattice and integration: A. Chance et al. (CEA)
Long. dynamics and RF systems: H. Damerell, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)
Power converter: F. Boattini et al.
Magnets: L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
FFA: S. Machida et al. (RAL)

# Collective Effects and RF Design

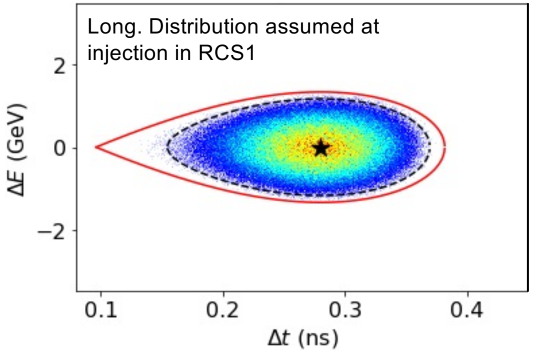
MuCol

Longitudinal dynamics and RF important due to high bunch charge

International MUON Collider Collaboration

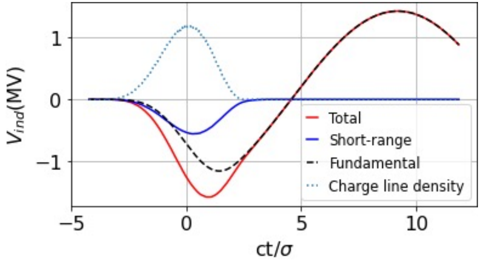
- > 30 RF stations needed
- Orbit length changes require frequency tuning required
- Single-bunch HOM power loss up to 10 kW during pulse
- CW average is lower, development of high-capacity couplers needed

A. Chance, H. Damerell, F. Batsch, U. van Rienen, A. Grudiev et al. (CEA, Rostock, Milano, CERN)
E. Metral, D Amorim et al. (CERN)




**1.3 GHz appears possible for longitudinal effects and stability**

Induced voltages in RCS1 for a single bunch →

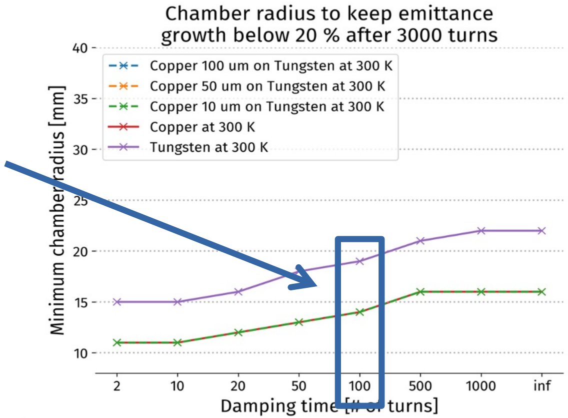



**Collider ring** single beam instability limits

Conservative feedback

Copper coating beneficial (few microns)

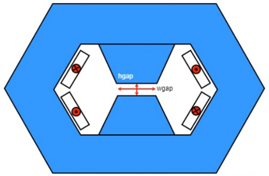
Beam-beam studies started



# Fast-ramping Magnet System

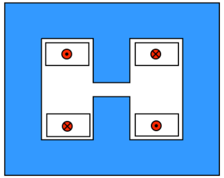
F. Boattini et al.

Hourglass frame magnet



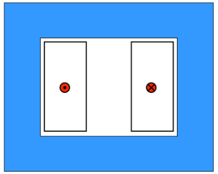

5.07 kJ/m

H magnet



5.65…7.14 kJ/m

Window frame magnet



5.89 kJ/m

Management of the **power in the resistive dipoles** (several tens of GW):

- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

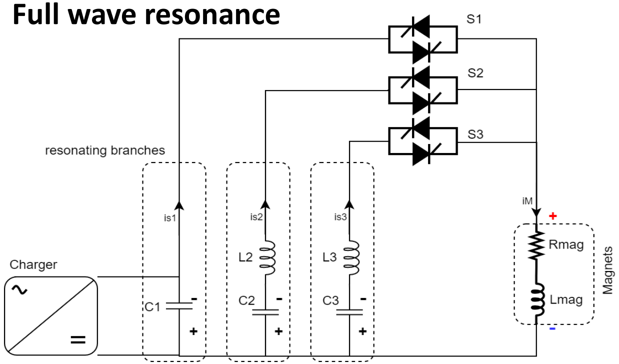
**FNAL** 300 T/s HTS magnet

Could also use HTS driven dipoles

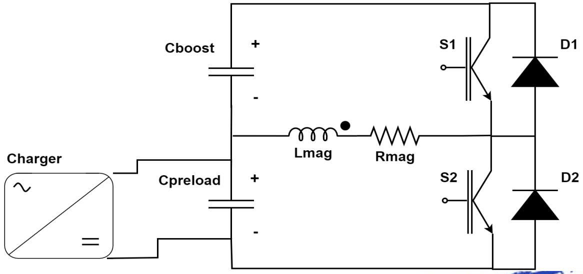
*Simple* HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

**Full wave resonance**




**Commutated resonance (new)**

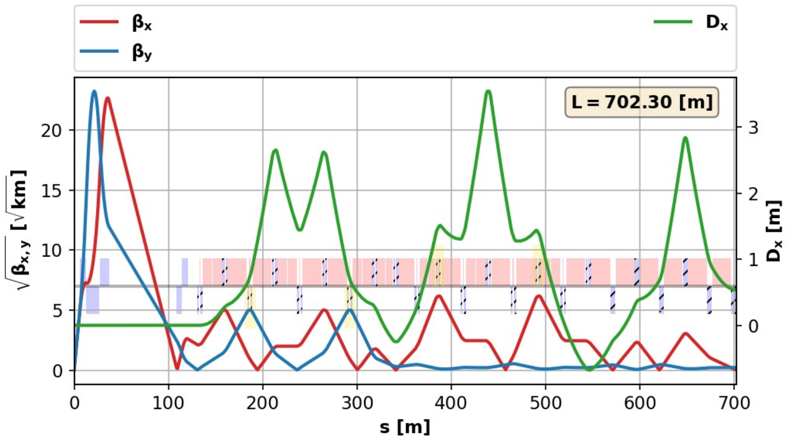


# Collider Ring

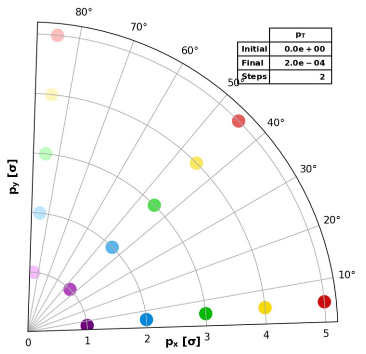
Challenges:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

MAP developed 4.5 km ring for 3 TeV with $Nb_3Sn$
- magnet specifications in the HL-LHC range

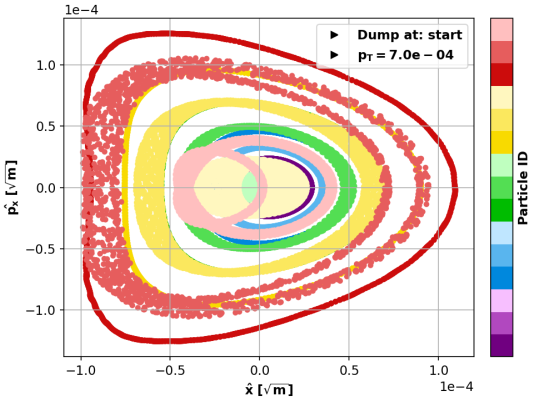
Work progressing on **10 TeV collider ring**
- around 16 T HTS dipoles or lower $Nb_3Sn$
- final focus based on HTS




K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas




| pT [%] | DAmin [σ] |
|---|---|
| 0.07 | 5 |
| 0.08 | 4 |
| 0.09 | 3 |
| 0.1 | <1 |




Important progress: V0.6 good dynamic aperture at almost 0.1% off-energy, approaching the target

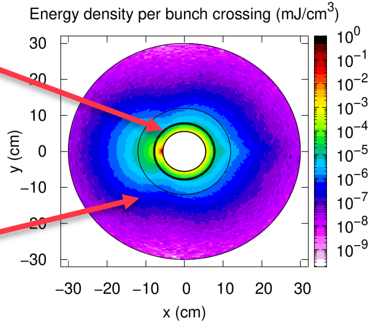
# Collider Ring Technology

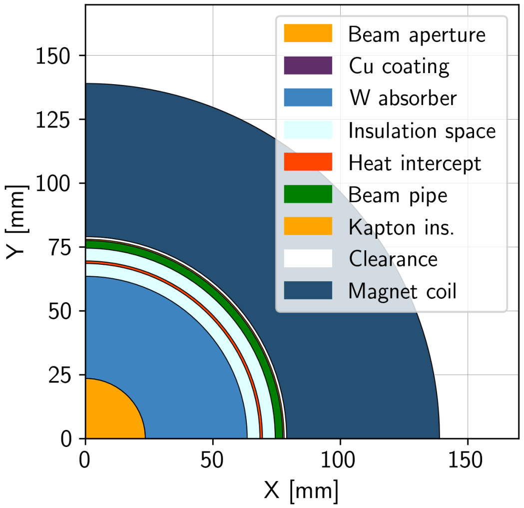
Power loss due to muon decay 500 W/m
FLUKA simulation of **shielding:**
Require 30-40 mm tungsten
- Few W/m in magnets
- No problem with radiation dose

Shielding

A. Lechner
D. Calzolari
(CERN)

Coil

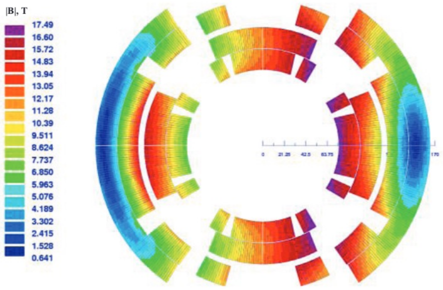


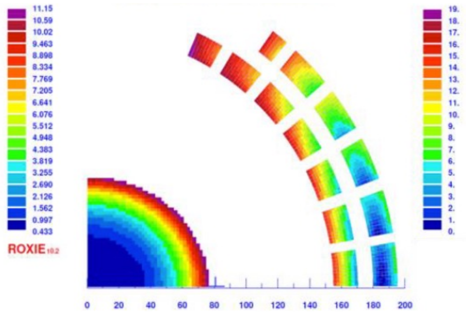




K. Skoufaris, Ch. Carli, D. Amorim, A. Lechner, R. Van Weelderen, P. De Sousa, L. Bottura et al.

L. Bottura et al.

Initial **estimate of magnet field limits**:
9 T for NbTi, 14 T for $Nb_3Sn$
Need **stress management**



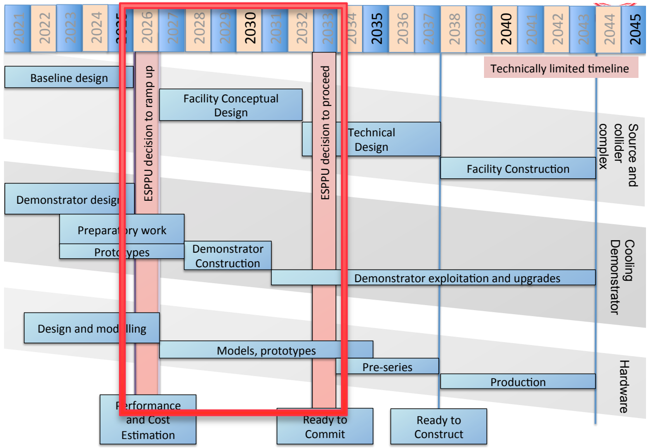




Different **cooling scenarios** studied
< 25 MW power for cooling possible
Shield with $CO_2$ at 250 K (preferred) or water
Support of shield is important for heat transfer
Discussion on options for magnet cooling

R. Van Weelderen, P. De Sousa

# CDR Phase, R&D and Demonstrator Facility

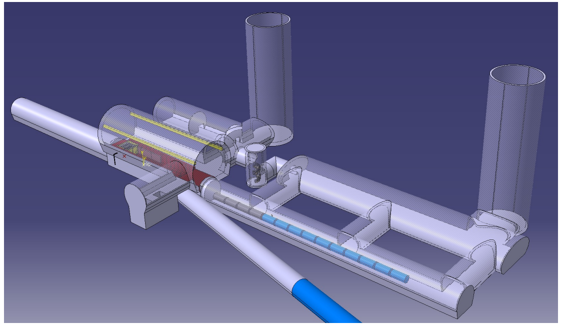
**Broad R&D programme** can be distributed world-wide
- **Models** and **prototypes**
  - Magnets, Target, RF systems, Absorbers, …
- **CDR** development
- **Integrated tests**, also with beam

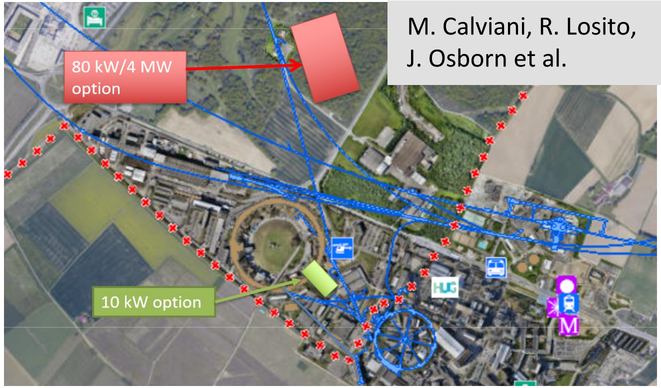



**Cooling demonstrator** is a key facility
- look for an existing proton beam with significant power

Different sites are being considered
- CERN, FNAL, ESS …
- **Discussed at ACE at FNAL**
- **Site at CERN possible**
- J-PARC also interesting as option

Could be used to house physics facility
- **Synergies workshop** to explore good options






M. Calviani, R. Losito, J. Osborn et al.

# Conclusion

- Muon collider unique opportunity for high-energy, high-luminosity lepton collider

- Currently working toward 10+ TeV, potential 3 TeV intermediate stage explored
  - Design
  - Technology
  - R&D programme preparation including demonstrator

- Collaboration exists, promises to increase
  - More request to EC and other funding agencies
  - and in the US P5 process
  - Feel that there is important synergy with other facilities and technologies

http://muoncollider.web.cern.ch        To join contact muon.collider.secretariat@cern.ch

# Reserve

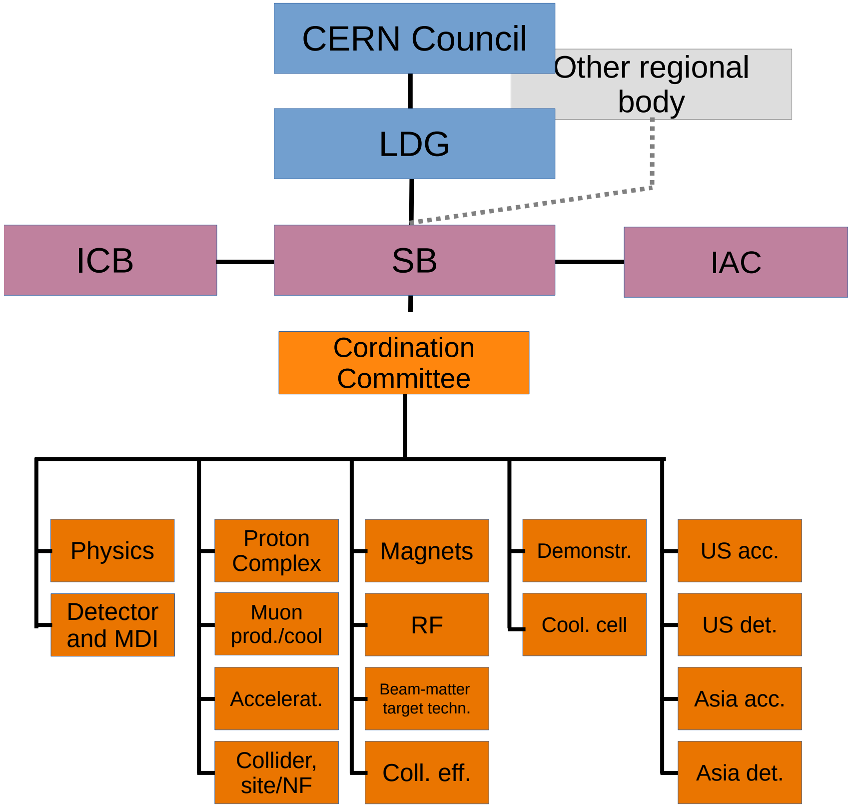
# Organisation

**Collaboration Board (ICB)**
- Elected chair: **Nadia Pastrone**

**Steering Board (ISB)**
- Chair **Steinar Stapnes**
- CERN members: Mike Lamont, Gianluigi Arduini
- ICB members: Dave Newbold (STFC), Mats Lindroos (ESS), Pierre Vedrine (CEA), N. Pastrone (INFN)
- Study members: SL and deputies
- Will add US but wait for US decision on members

**Advisory Committee**
- To be defined, discussion in SB

**Coordination committee (CC)**
- Study Leader: **Daniel Schulte**
- Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**



# EU Design Study

MuCol

International MUON Collider Collaboration

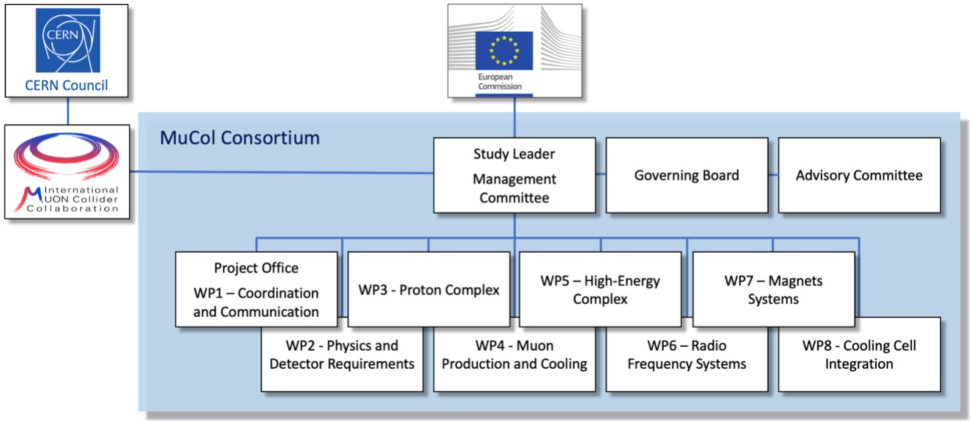
Has been approved summer 2022

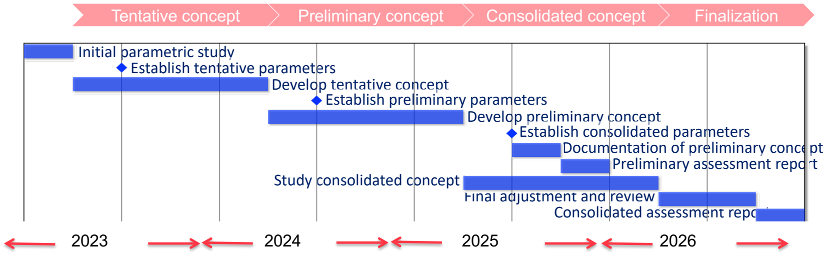
- Very helpful to kick-start collaboration

Reapproved early 2023

- It appears that there has been some issue with the refereeing of several projects, probably not directly with the muon collider

Brings 3 MEUR from the European Commission, the UK and Switzerland and about 4 MEUR from the partners
Basically nothing for CERN




Kick-off meeting in March 2023:
https://indico.cern.ch/event/1219912

Many thanks to all that contributed

https://mucol.web.cern.ch

Sat celeriter fieri quidquid fiat satis bene

# US P5 Ask

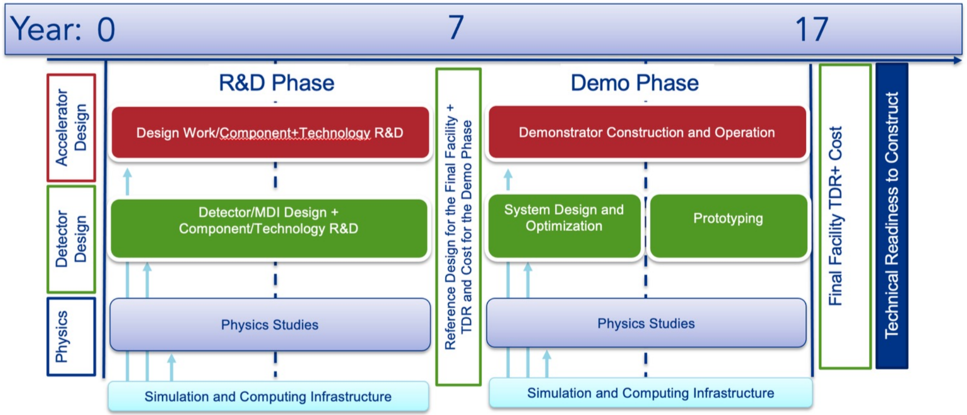



Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.

S. Jindariani, D. Stratakis, Sridhara Dasu et al.

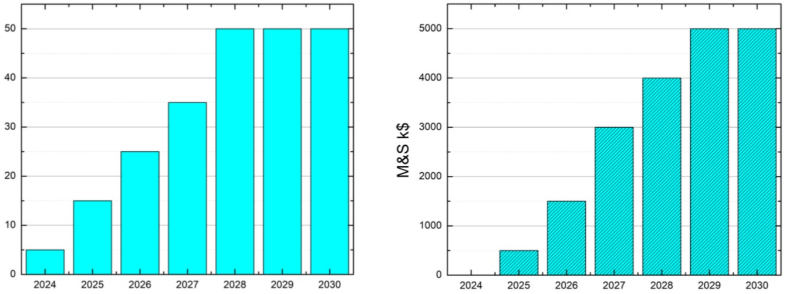
Goal is to contribute as much as Europe

Start of construction a bit later than in Roadmap

Will try to harmonise/define scenarios once US joins

Total resources would approach Roadmap

- Some increase in Europe and Asia assumed
- 1-2 years delay
- But profile is different




: FTE and M&S profiles for accelerator R&D corresponding to the first phase of the
. We assume here that funding can start in 2024. The M&S is in FY23 dollars and
n is not included in these estimates.

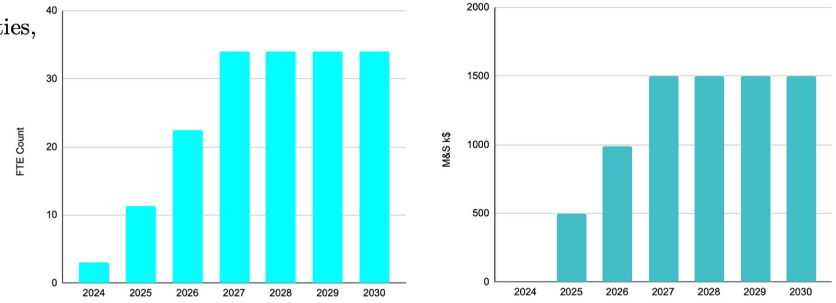



Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

# Muon Collider Luminosity Scaling

Fundamental limitation

Requires emittance preservation and advanced lattice design

Applies to MAP scheme

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

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

Luminosity per power increases with energy
Provided technologies can be made available

Constant current for required luminosity scaling

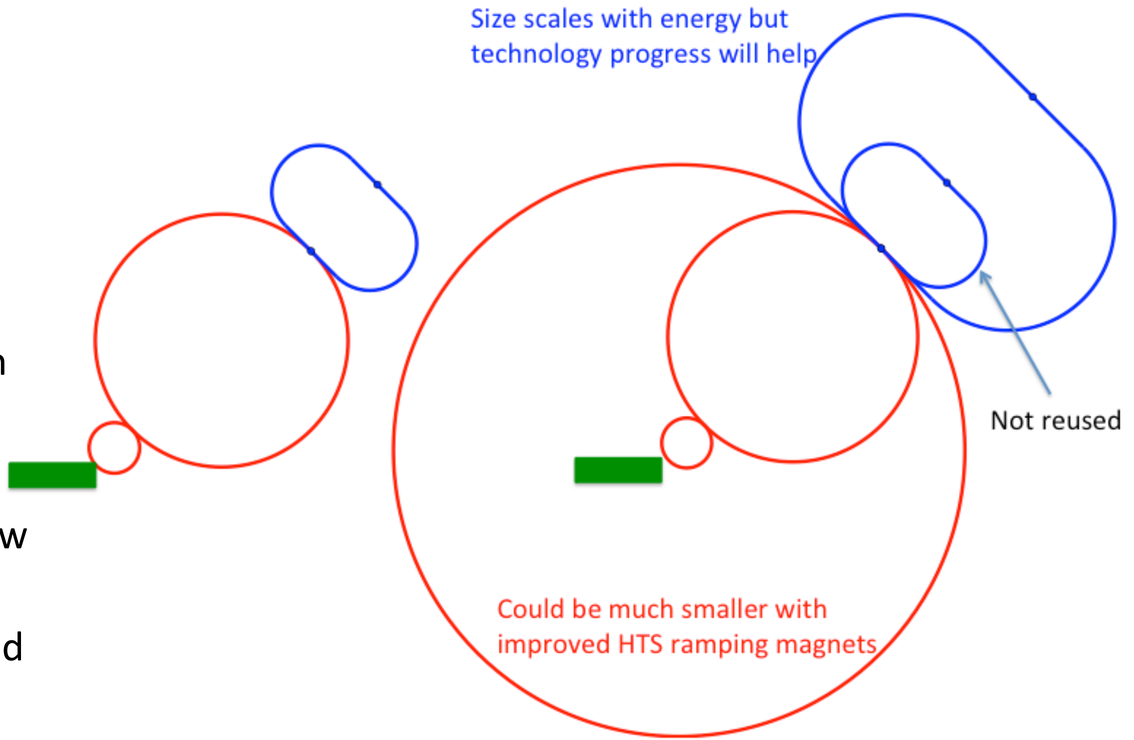
# Staging

Ideally would like full energy right away, but staging could lead to faster implementation

- Substantially less cost for a first stage
- Can make technical compromises
  - e.g. 8 T NbTi magnets would increase collider ring from 4.5 to 6 km and reduce luminosity by 25%
- Timeline might be more consistent with human lifespan

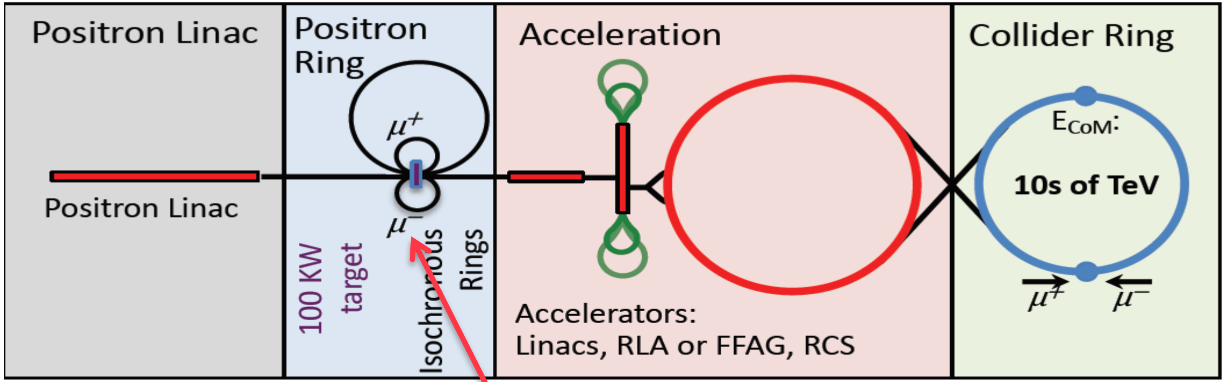
Upgrade adds one more accelerator and new collider ring

- only first collider ring is not being reused



# Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



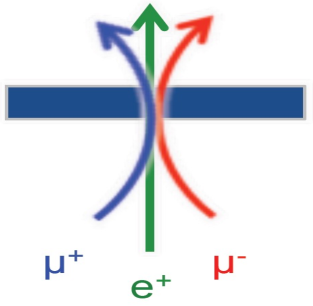

Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

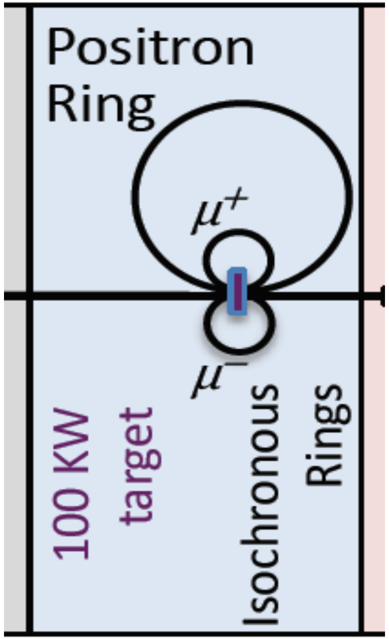
- Uses Bethe-Heitler production with electrons

45 GeV positrons to produce muon pairs

Accumulate muons from several passages

$$e^+e^- \to \mu^+\mu^-$$



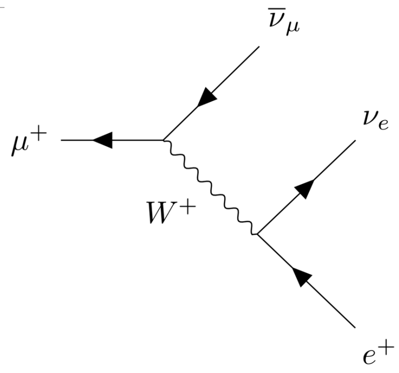




**Excellent idea, but nature is cruel**

Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

$\Rightarrow$ **Need same game changing invention**

# Muon Decay




About 1/3 of energy in electrons and positrons:

**Experiments** needs to be protected from **background** by masks

- simulations of 1.5, 3 and 10 TeV
- optimisation of masks and lattice design started
- first results look encouraging
- will be discussed at ICHEP

**Collider ring magnets** need to be shielded from losses

Losses elsewhere will also need to be considered but are less severe

D. Lucchesi, A. Lechner, C Carli et al.

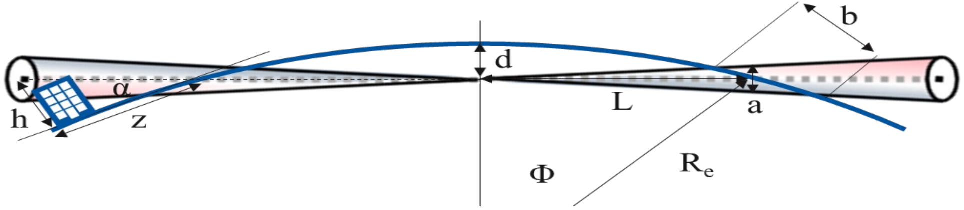
**Neutrino flux** to have negligible impact on environment

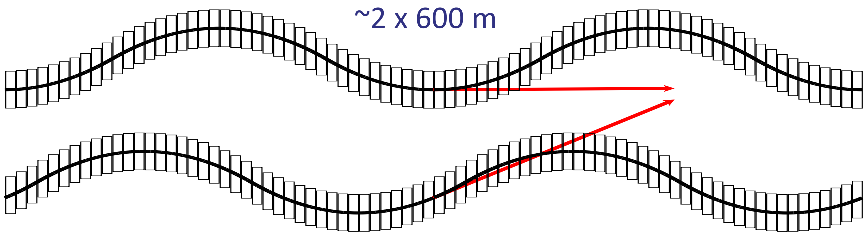
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

Above about 3 TeV need to make beam point in different vertical directions

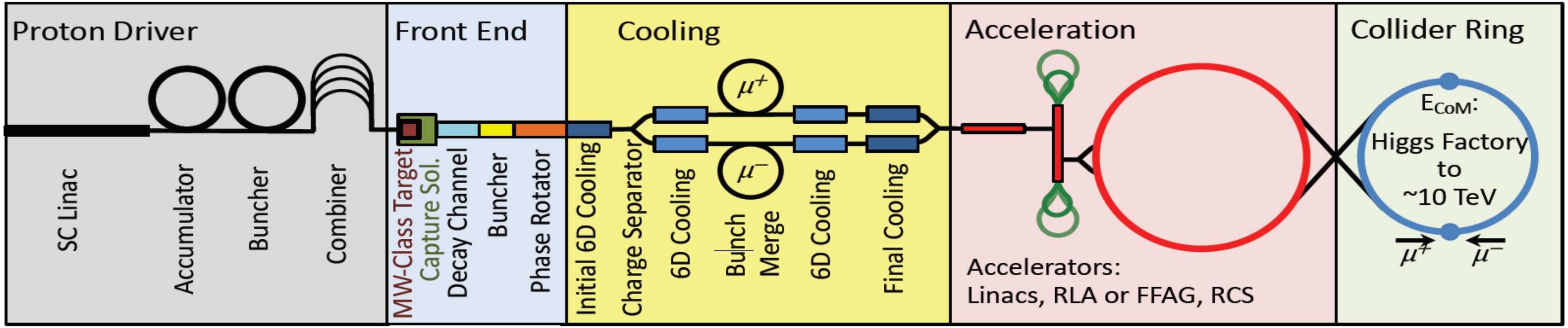
Mechanical system with 15cm stroke, 1% vertical bending

Length of pattern to be optimised for minimal impact on beam



# Key Challenges




**Proton complex**
- Compressing protons to few bunches

**Target**
- Target
- Solenoid

**Cooling channel**
- Channel design
- Solenoids
- RF in magnetic field
- Absorbers
- Integration

**RCS**
- Beam dynamics
- Ramping magnets
- Power converter
- RF system

**Collider ring**
- Optics
- Magnets
- Neutrino flux
- Detector background

# Roadmap

In **aspirational scenario** can make **informed decisions**:

Three main deliverables are foreseen:

- a **Project Evaluation Report** for the next ESPPU will contain an assessment of whether the 10 TeV muon collider is a promising option and identify the required compromises to realise a 3 TeV option by 2045. In particular the questions below would be addressed.
    - What is a realistic luminosity target?
    - What are the background conditions in the detector?
    - Can one consider implementing such a collider at CERN or other sites, and can it have one or two detectors?
    - What are the key performance specifications of the components and what is the maturity of the technologies?
    - What are the cost drivers and what is the cost scale of such a collider?
    - What are the power drivers and what is the power consumption scale of the collider?
    - What are the key risks of the project?
- an **R&D Plan** that describes an R&D path towards the collider;
- an **Interim Report** by the end of 2023 that documents progress and allows the wider community to update their view of the concept and to give feedback to the collaboration.

# R&D Plan

The R&D plan will describe the R&D path toward the collider, in particular during the CDR phase, and will comprise the elements below.

- An integrated concept of a muon cooling cell that will allow construction and testing of this key novel component.
- A concept of the facility to provide the muon beam to test the cells.
- An evaluation of whether this facility can be installed at CERN or another site.
- A description of other R&D efforts required during the CDR phase including other demonstrators.

This R&D plan will allow the community to understand the technically limited timeline for the muoncollider development after the next ESPPU.

# Minimal Scenario

Will allow **partially informed decisions**

- No conceptual design of neutrino flux and alignment system
- No alternative superconducting fast-ramping magnet system
- Several collider systems would (almost) not be covered, in particular
  - the linacs
  - the target complex
  - the proton complex
  - engineering considerations of the muon cooling cells
  - alternative designs for the final cooling system, acceleration, collider ring
- No RF test stand would be constructed for the muon cooling accelerating cavities
- No conceptual design of a muon cooling cell for the test programme
- No conceptual design of a muon cooling demonstrator facility
- No concept of RF power sources
- No tests/models to develop solenoid technology.

# Key Technologies

MuCol

Magnets

- Superconducting solenoids for target and cooling profit from developments for society
  - target solenoid comparable to ITER central solenoid fusion
  - 6D cooling solenoids similar and wind power generators, motors
  - final cooling solenoids synergetic with high-field research, NMR
- Collider ring magnets
  - profit from developments for other colliders  FCC-hh, stress-managed magnets
- Fast-ramping normal-conducting magnet system
  - HTS alternative, power converter

RF systems

- superconducting RF, normal-conducting RF, efficient klystrons

Target, cooling absorbers, windows, shielding

Neutrino mitigation mover system, cooling cell integration, …

Detector

# Key Technologies, cont.

MuCol

International
MUON Collider
Collaboration

RF systems

- Normal-conducting cooling cavities in magnetic field
  - profit from CLIC work
- Superconducting accelerator RF
  - profit from ILC, …
- Efficient power sources
  - profit from CLIC work

Beam-matter interaction

- Proton target
- Cooling absorbers
- Shielding (accelerator and detector)

Mechanical system

- Neutrino flux mitigation system
- Muon cooling cell integration

# Collaboration Vision

IMCC is an **international** collaboration and aims to

- Enlarge the collaboration
  - Physics interest in all regions, strong US contribution to the muon collider physics and detector, interest in Japan
  - First US university have joined collaboration, try to see how to move forward, also with labs
- Combine the R&D efforts for the design and its technologies
  - Critical contributions in all relevant fields in the US
- Consider several sites for the collider
  - CERN would be one, FNAL and others should also be considered
  - A proposal with alternative sites is stronger for a single site
- Consider several sites for the demonstrators
  - E.g. Muon production and cooling demonstrator at CERN, FNAL, ESS, JPARC
  - e.g. RCS at ESRF or elsewhere
  - Target tests
  - …

# Initial Target Parameters

**Target integrated luminosities**

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

**Note: currently focus on 10 TeV, also explore 3 TeV**

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

| Parameter | Unit | 3 TeV | 10 TeV | 14 TeV | CLIC at 3 TeV |
|---|---|---|---|---|---|
| L | $10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | 1.8 | 20 | 40 | 2 (6) |
| N | $10^{12}$ | 2.2 | 1.8 | 1.8 | |
| $f_r$ | Hz | 5 | 5 | 5 | |
| $P_{beam}$ | MW | 5.3 | 14.4 | 20 | 28 |
| 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 | |

# US Snowmass

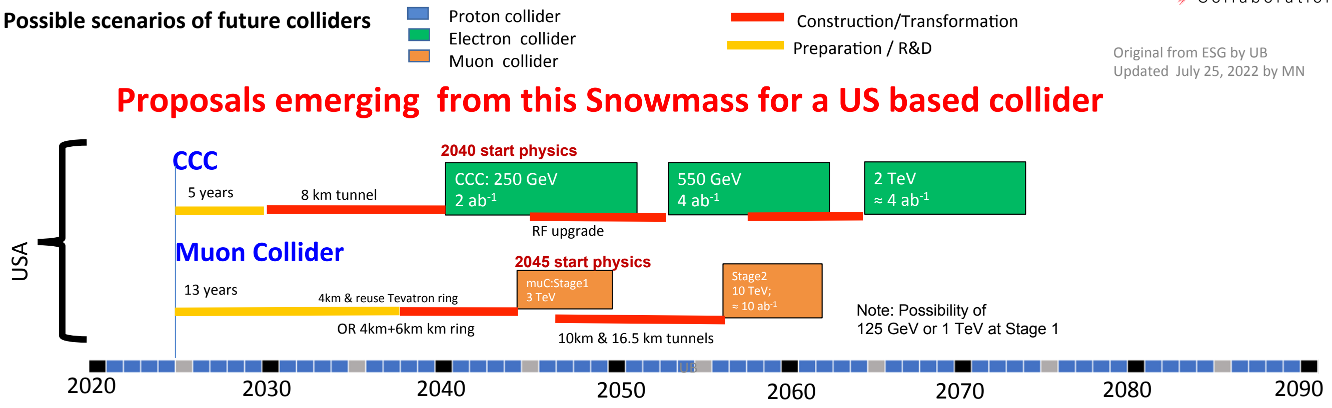
**Strong interest** in the US community in muon collider

- seen as an energy frontier machine
- decoupled from LC

US community wants funding for **R&D**

- **Goal: match European effort**

Community interested in the US to **host a muon collider**



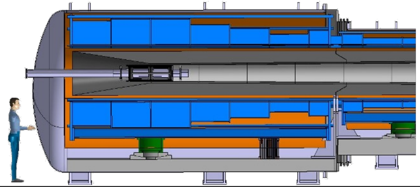

- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

Consider proposing hosting ILC in the US.

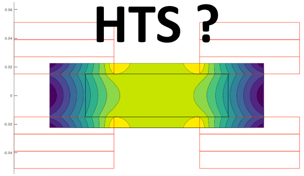
Meenakshi Narain: Energy Frontier / Large Experiments, Snowmass Community Summer Study July 17-26, 2022

# Muon Collider magnets

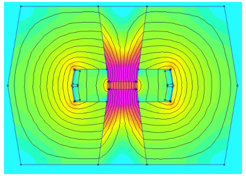
20 T, 200 mm **HTS !**
Radiation heat load ≈ 5...10 kW
Radiation dose: 80 MGy



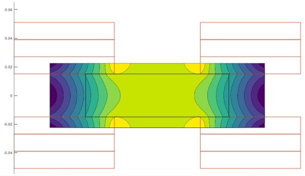
**HTS ?**

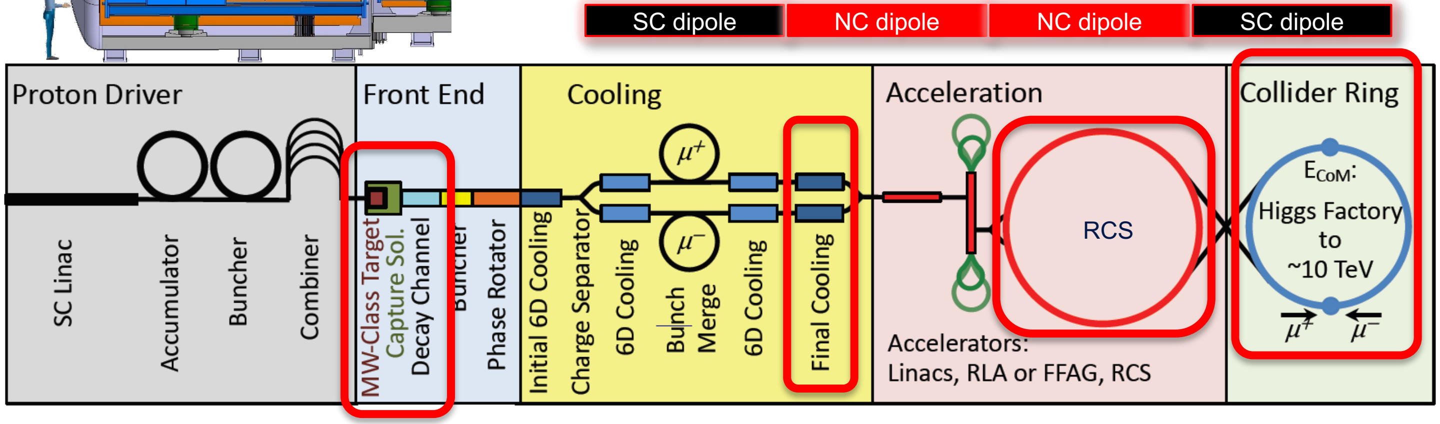


NC ±1.8 T, 400 Hz
100 mm x 30 mm

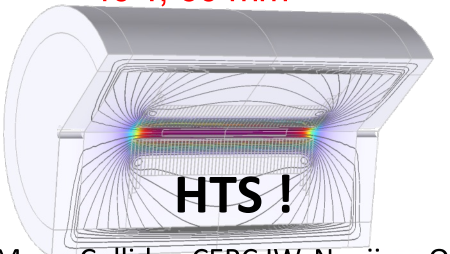


SC < 10T
100 mm x 30 mm



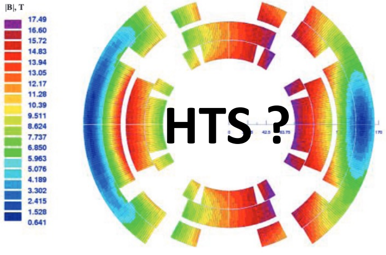



\> 40 T, 60 mm



**HTS !**

16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20...40 MGy



**HTS ?**

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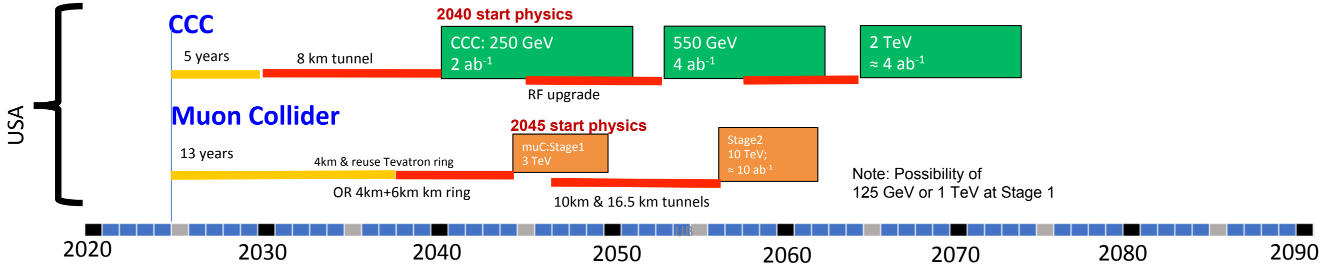
**Possible scenarios of future colliders**

Proton collider
Electron collider
Muon collider

Construction/Transformation
Preparation / R&D

Original from ESG by UB
Updated July 25, 2022 by MN

**Proposals emerging from this Snowmass for a US based collider**

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Consider proposing hosting ILC in the US.

Meenakshi Narain: Energy Frontier / Large Experiments, Snowmass Community Summer Study July 17-26, 2022

# Coordination Committee Members

| | |
|---|---|
| Physics | Andrea Wulzer |
| Detector and MDI | Donatella Lucchesi |

| | |
|---|---|
| Protons | Natalia Milas |
| Muon production and cooling | Chris Rogers |
| Muon acceleration | Antoine Chance |
| Collider | Christian Carli |

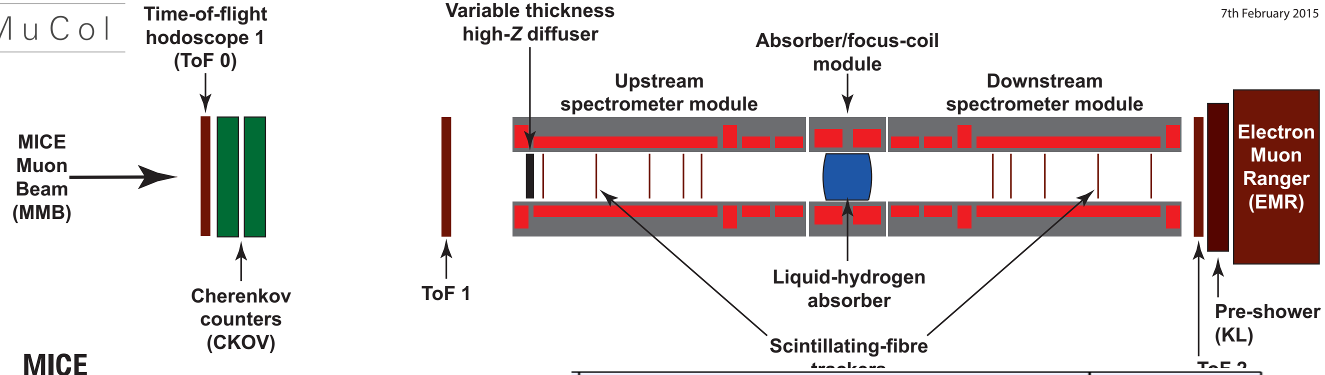
| | |
|---|---|
| Magnets | Luca Bottura |
| RF | Alexej Grudiev, Dario Glove |
| Beam-matter int. target systems | Anton Lechner |
| Collective effects | Elias Metral |

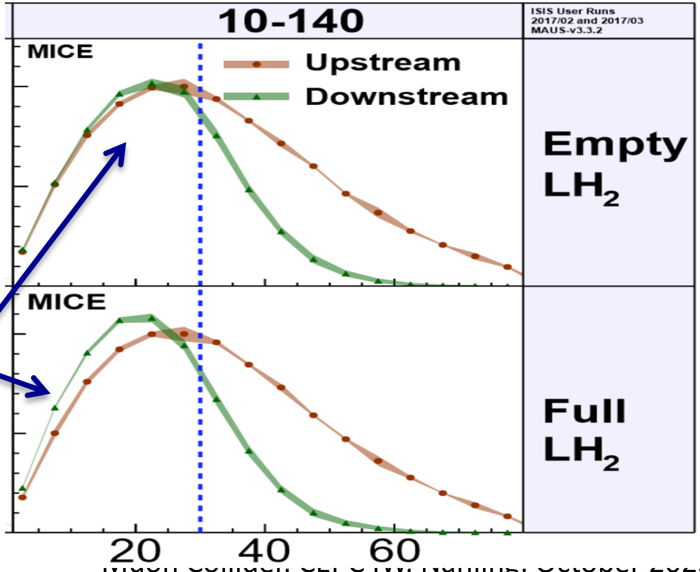
| | |
|---|---|
| Cooling cell design | Lucio Rossi |
| Demonstrator | Roberto Losito |

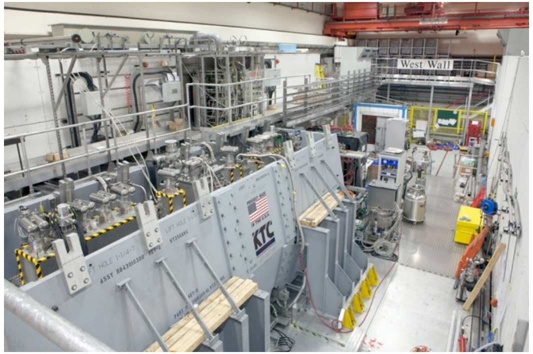
| | |
|---|---|
| US (detector) | Sergo Jindariani |
| US (accelerator) | Mark Palmer |
| Asia (China) | Jingyu Tang |
| Asia (Japan) | tbd |

A strengthening on the physics and detector side is planned

# MICE: Cooling Demonstration



Nature vol. 578, p. 53-59 (2020)

Principle of ionisation cooling has been demonstrated
Use of data for benchmarking is still ongoing

More particles at smaller amplitude after absorber is put in place

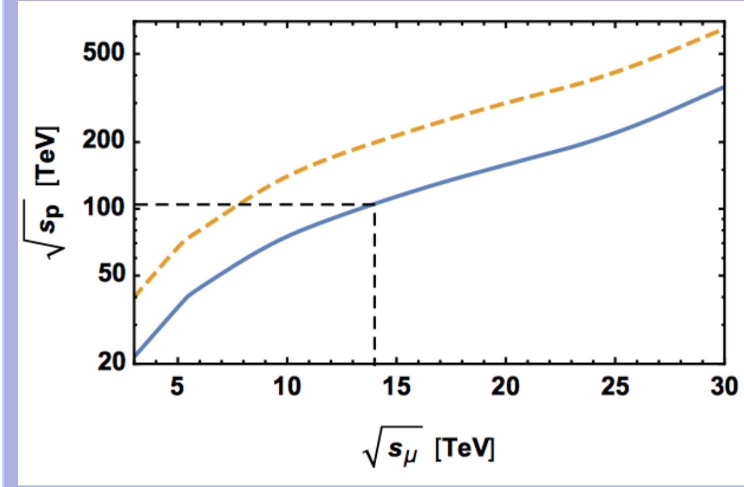
More complete experiment with higher statistics, more than one stage required

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

# Physics Goals

Full lepton energy available for production of new particles, in protons only a fraction

**Discovery reach**
10-14 TeV lepton collisions are comparable to 100-200 TeV proton collisions for production of heavy particle pairs




Need more luminosity at higher energies as production cross section decreases

**Luminosity goal**
(Similar to $L(E_{CM} > 0.99\, E_{CM,0})$ CLIC at 3 TeV)
$4\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 14 TeV

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

Yields constant number of events in the s-channel

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

# Physics Studies

MuCol

International MUON Collider Collaboration

Details on physics case, detector and accelerator can be found in

- Snowmass white papers https://indico.cern.ch/event/1130036/
- EPJC report in preparation

**Used tentative detector performance specifications** in form of DELPHES card

- based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)
- Please find the card here: https://muoncollider.web.cern.ch/node/14

M. Selvaggi, W. Riegler, U. Schnoor, A. Sailer, D. Lucchesi, N. Pastrone, M. Pierini, F. Maltoni, A. Wulzer et al.

Initial detector simulation studies at 1.5 and 3 TeV indicate that this is a **good model**

Now moving to 10 TeV

D. Lucchesi, F. Meloni et al.

If you are interested to contribute please contact me or the responsible deputies:

**Andrea Wulzer (Physics)** and **Donatella Lucchesi (Detector and MDI)**

# Possible CERN Locations

Consider nTOF-like beam from PS for cooling experiment:

- 1 pulse of $10^{13}$ p at 20 GeV per 1.2 s, i.e. 27 kW
- maybe O(100kW) possible

If SPL were, installed could use its beam, e.g. 5 GeV, 4 MW