International MUON Collider Collaboration

CERN

Muon Collider: Where are we?

D. Schulte for the International Muon Collider Collaboration

IPAC
June 2022

Introduction

Most of the muon collider R&D has been done by MAP in the US (some early in Europe)

- Experimental programme at MICE in the UK, alternative LEMMA concept considered mainly at INFN
- MAP is starting point for our effort and design

Now on European Accelerator R&D Roadmap and hopefully also soon in other regions, because

- **Change of goals**: Started looking for very high energy high-luminosity lepton collider
    - beyond highest energy of CLIC
- **Technology and design advances** since MAP
    - e.g. superconducting magnet technology (HTS), rectilinear cooling channel, …

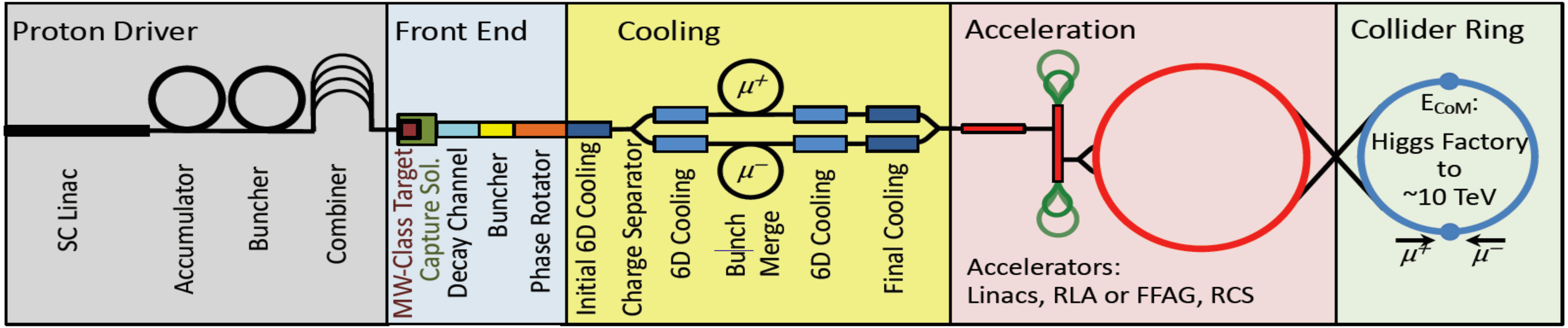
An International Muon Collider Collaboration, currently hosted by CERN, is starting to address the work

- Focus on **10 TeV**
- also consider initial lower energy stages, e.g. 3 TeV
- will also consider higher energies

Goal is to develop concept enough that next strategy processes can make informed decisions

Collider Overview

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



Short, intense proton bunch

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Physics Goals

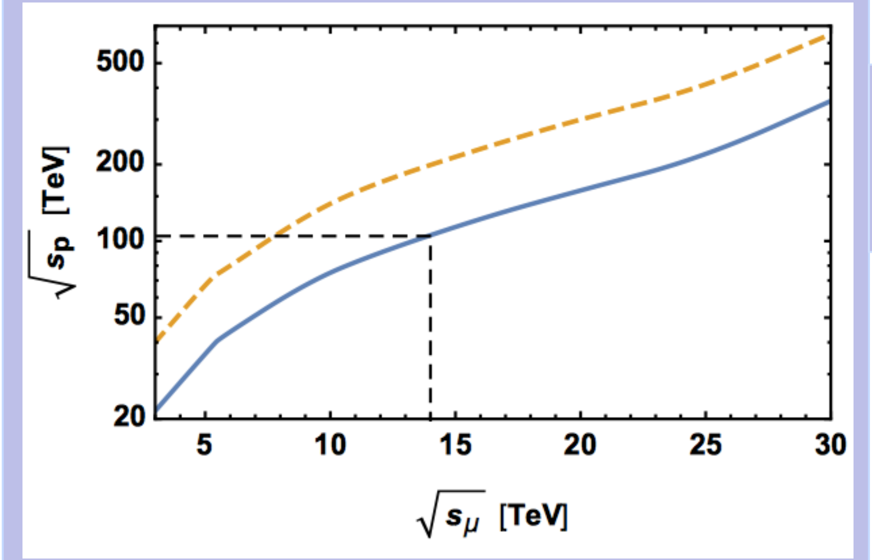
High energy lepton colliders are precision and discovery machines

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

Precision potential

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

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



Discovery reach

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

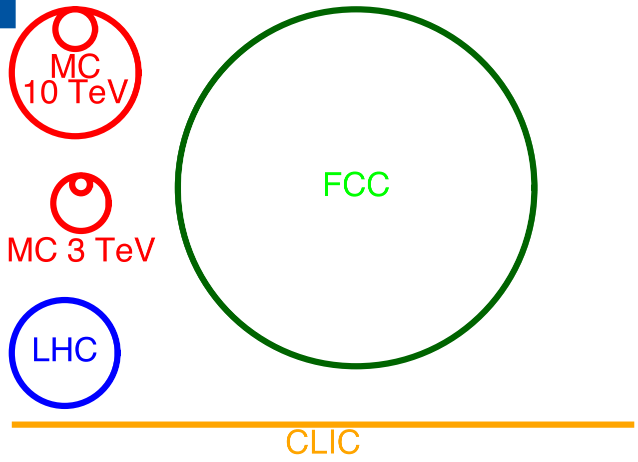
Luminosity goal

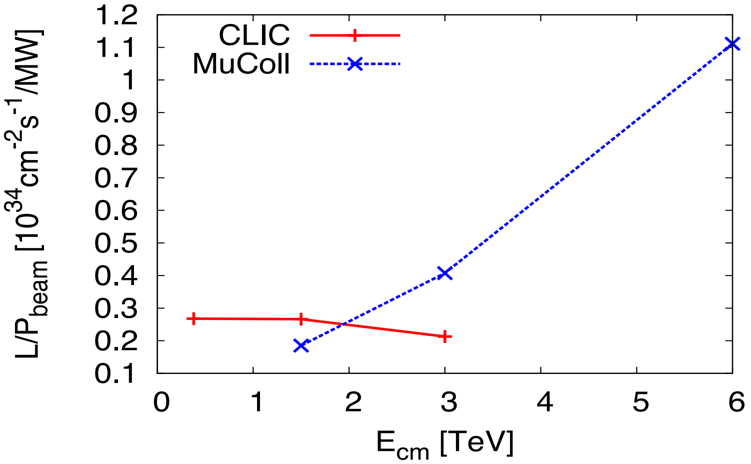
(Factor O(3) less than CLIC at 3 TeV)

$4x10^{35}$ $cm^{-2}s^{-1}$ at 14 TeV

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

Sustainability





CLIC is highest energy proposal with CDR

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

Cost 18 GCHF, power 590 MW

Muon Collider:

Acceleration and collision in multiple turns in rings promises

- **Power efficiency**
- **Compact tunnels,** 10 TeV similar to 3 TeV CLIC
- **Cost effectiveness**
- **Natural staging** is natural

Synergies exist (neutrino/higgs)

Unique opportunity for a **high-energy, high-luminosity lepton collider**

Initial Target Parameters

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 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

Feasiblity addressed, will evaluate luminosity performance, cost and power consumption

CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Accelerator R&D Roadmap

On request by **CERN Council** and led by Laboratory Directors Group (LDG):

Muon beam panel, including many experterts with neutral or even critical view (e.g. Mike Seidel, Philippe Lebrun, Tor Raubenheimer, Akira Yamamoto)

Panel organised community meetings and working groups with conveners from global community

Assessed **challenges** and defined **prioritised work packages** with resource estimates

- **Very promising** approach to high energy
- **Not as mature** as other proposals (linear collider)
- But **no insurmountable obstacle identified**

Goal is to provide input for next strategy processes (by end of 2025) and to deliver:

- a **Project Evaluation Report** that assesses the muon collider potential;
- an **R&D Plan** that describes a path towards the collider;
- an **Interim Report** by the end of 2023 that documents progress.

Thanks

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), Roberto Losito (CERN), Donatella Lucchesi (INFN)

Community conveners: *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), Sergo 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).

And the participants to the community meetings and the study

Workplan

Roadmap identifies muon collider challenges and two R&D scenarios to address them

- An **full scenario**
  - full achievement of objectives, about 5 years
- A **reduced scenario**
  - only a subset of objectives can be achieved, 4 years

Personnel: roughly ¼ staff, ½ fellow, ¼ PhD

Scenario	FTEy	M MCHF
Full scenario	445.9	11.9
Reduced scenario	193	2.45

http://arxiv.org/abs/2201.07895

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [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.

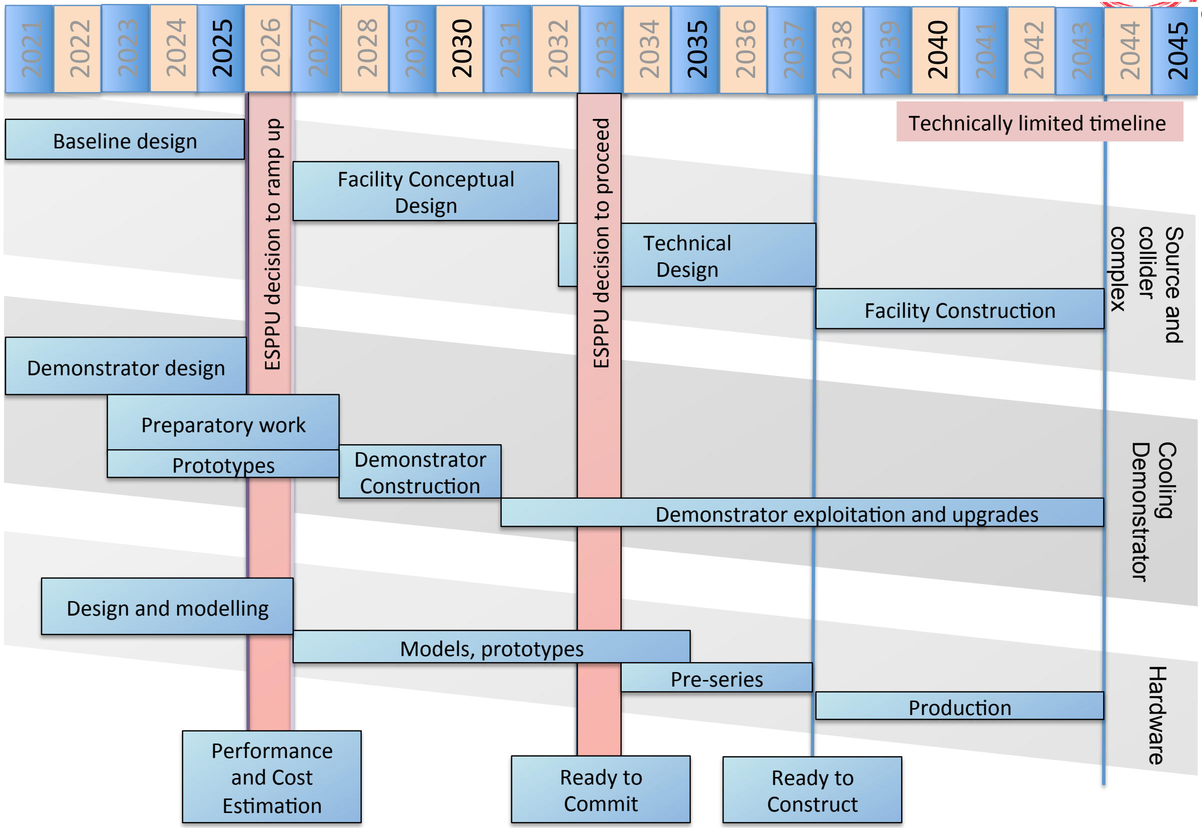
Timeline

Goal is to know by next ESPPU and other strategy processes if muon collider is credible option

Timeline depends on strategies and technical progress

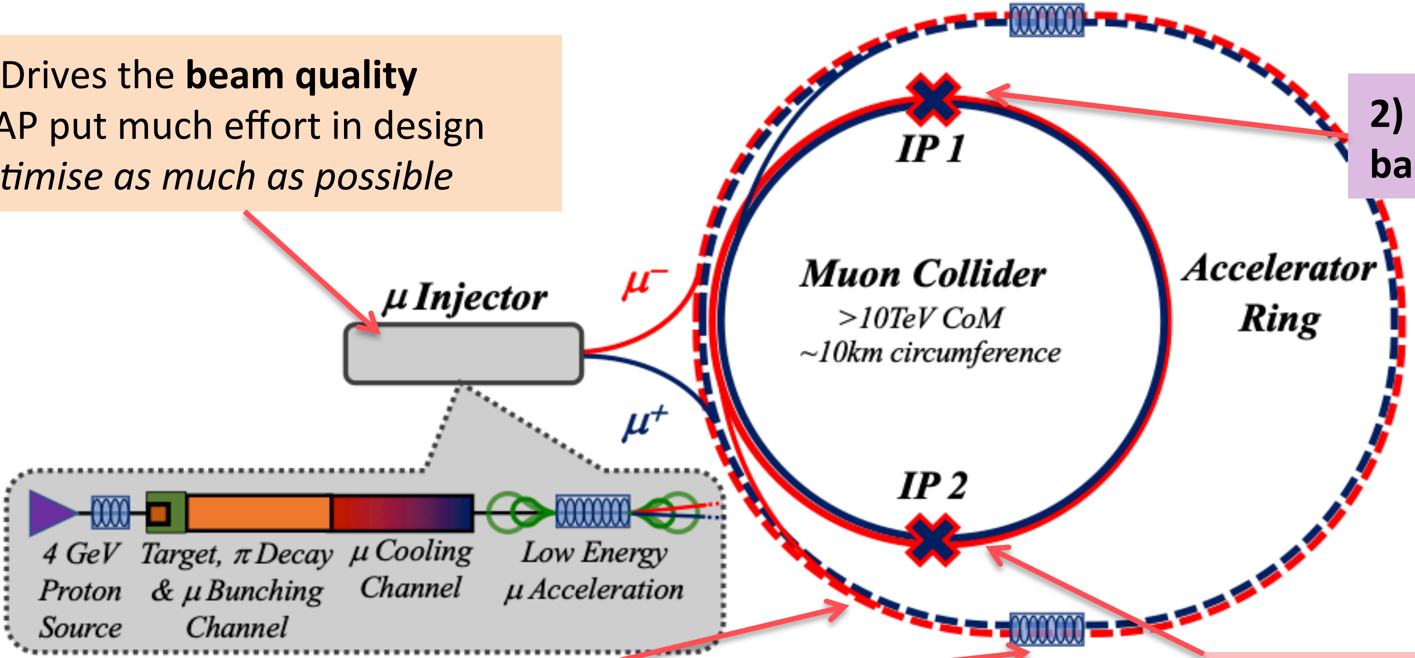
Prudently explore if MuC can be option as next project (i.e. operation mid 2040s)

- e.g. in Europe if higgs factory built elsewhere
- strong ramp-up required after 2026
- some compromises on initial performance



Key Challenges

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

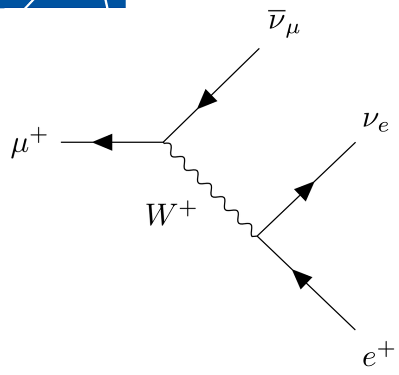


2) Beam-induced background

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



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

ICHEP

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

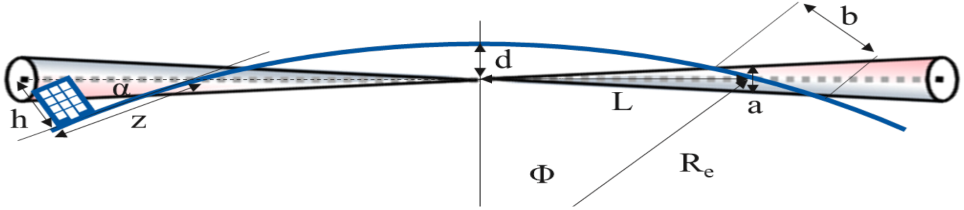
Neutrino flux to have negligible impact on environment

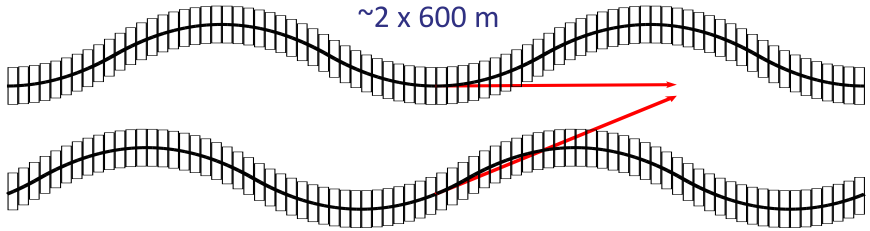
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

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

Mechanical system with 15cm stroke, 1% vertical bending

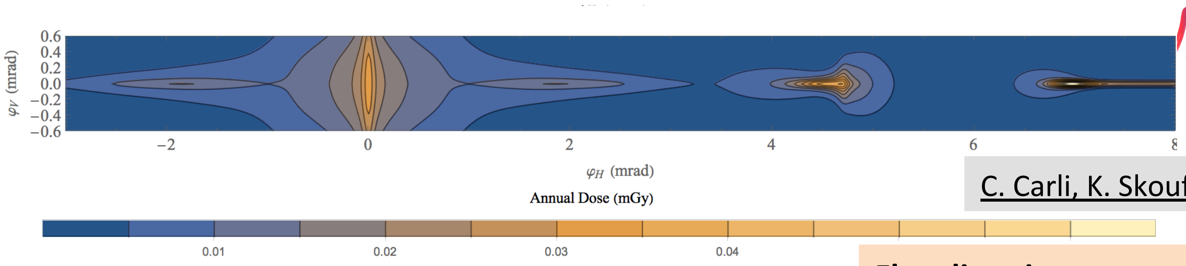
Length of pattern to be optimised for minimal impact on beam





Neutrino Flux

Team of RP experts, civil engineers, beam physicists and FLUKA experts
Goal: **similar to LHC**: i.e**. negligible**, <10 µSv “fully optimised” (10% of MAP goal, 1% of legal limit)

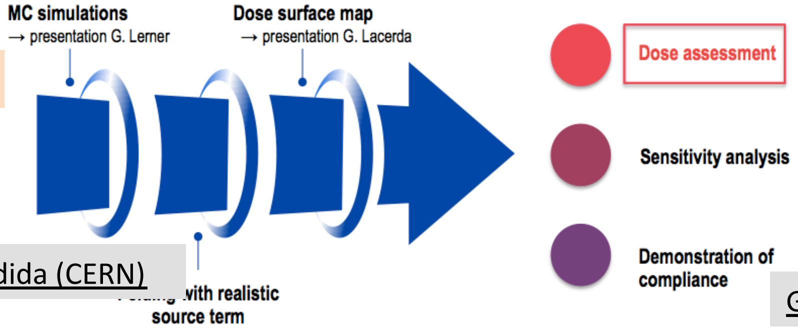


C. Carli, K. Skoufaris (CERN)

Flux direction map
Lattice design
Impact of mover on operation

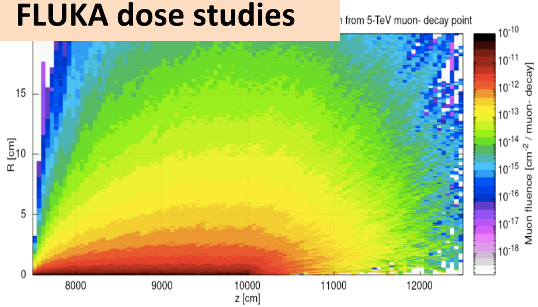
Conformity Verification Scheme

C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke (CERN)



G. Lerner, D. Calzolari, A. Lechner, C. Ahdida (CERN)

FLUKA dose studies

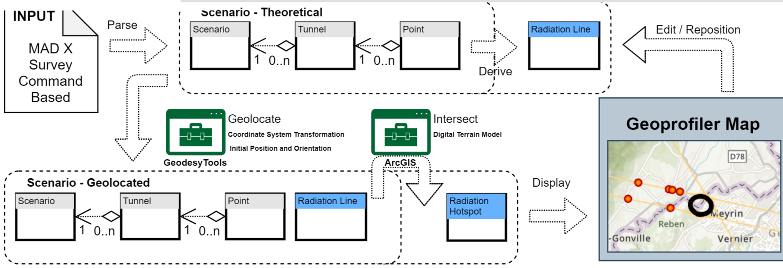


G. Lacerda, Y. Robert, N. Guilhaudin (CERN)

Mitigation:
Mover and support system

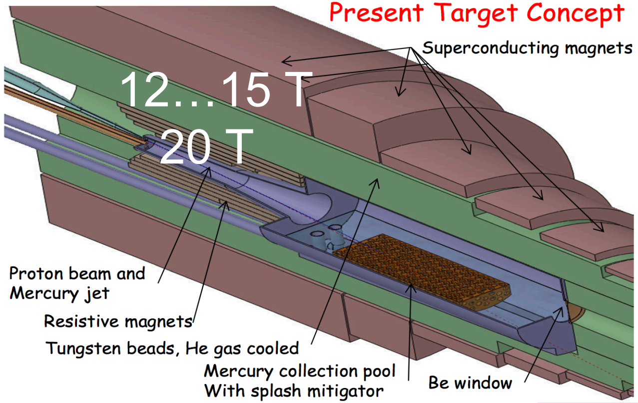
F. Bertinelli et al. (CERN, Riga)

Mitigation:
Site choice tool



Target

MAP target design, K. McDonald, et al.

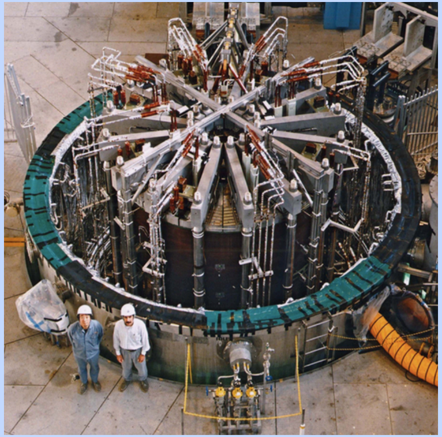


Two approaches:

- 15 T outer superconducting
  + 5 T inner resistive solenoid
- O(20 T) HTS solenoid

Shield superconducting solenoid
⇒ larger aperture
Synergy with ITER

A. Lechner et al.
L. Bottura et al.



ITER Central Solenoid Model Coil
13 T in 1.7 m (LTS)

Shock in target: Simulations of graphite target indicate 2 MW could be acceptable

STFC will also study alternatives

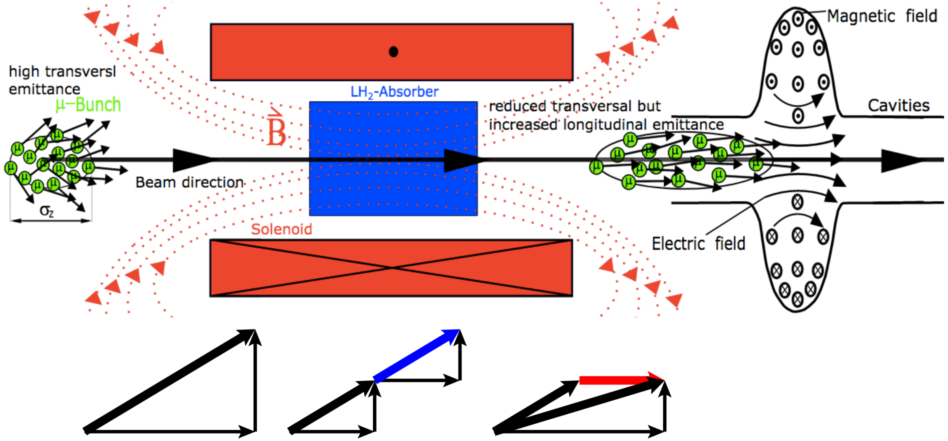
Rui Franqueira Ximenes et al.

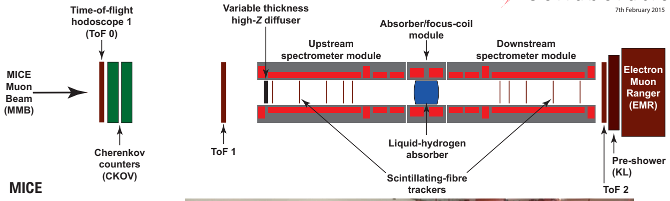
Proton beam

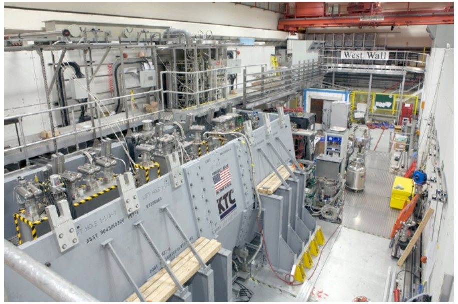
Operation at 2000 °C to maximise stress resistance

THPOTK052

Cooling Principle







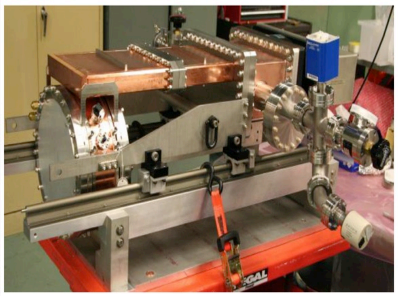
WEPOPT053 Nature vol. 578, p. 53-59 (2020)

Principle of ionisation cooling with no RF has been demonstrated in **MICE at RAL**
Use of data for benchmarking is still ongoing

Need to develop full cooling demonstrator

MuCool: demonstrated cavity with >50 MV/m in 5 T solenoid

- H2-filled copper cavities
- Cavities with Be end caps

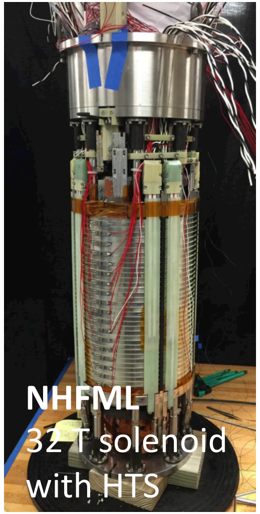


Emittance Development

MAP designs almost achieve 10 TeV goal
- miss factor two for final cooling

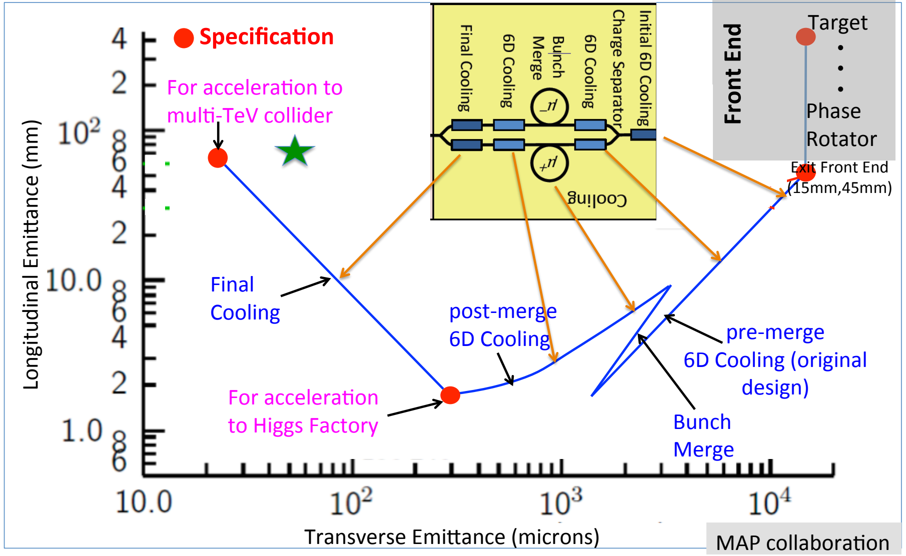
Work on improvement of **final cooling** by design and improved solenoid
- **lower beam** energy helps
- **higher solenoid field** helps

WEPOMS046
WEPOMS047



MAP design with demonstrated 30 T solenoid
- now magnets aim for 40+ T
- even more can be possible
- synergy with high-field research

L. Bottura et al.
INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP



Integration/optimisation of overall cooling design, also considering integrating improved technology
- HTS has synergies with power applications

C. Rogers et al.

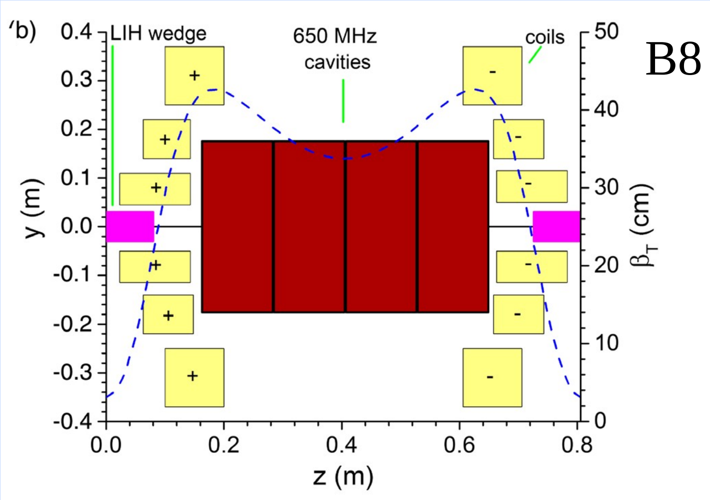
Cooling Cell Technology

RF cavities
Improve design based on theoretical understanding

Preparation of new experiments
- 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)

Consider **HTS solenoids** for 6D cooling

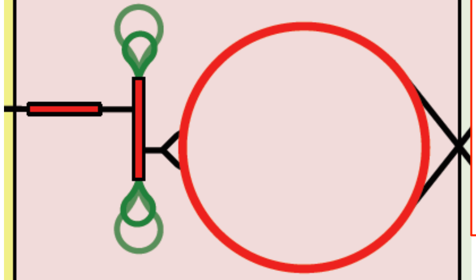


Will develop **cooling cell integration**
- tight constraints
- additional technologies (absorbers, instrumentation,…)
- early preparation of **demonstrator facility**

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

Acceleration Complex

Acceleration



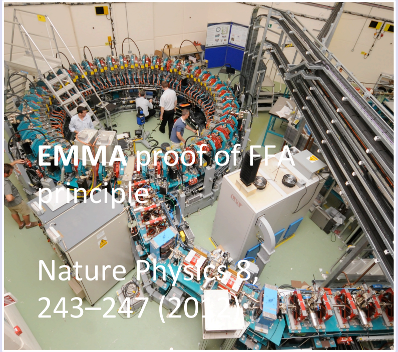
Accelerators:
Linacs, RLA or FFAG, RCS

Linac
Recirculating linacs
Sequence of rings

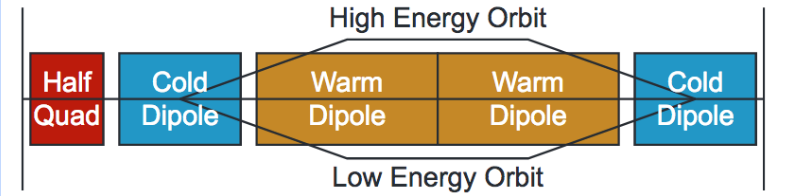
- baseline: pulsed synchrotron (RCS)
- alternative: FFA

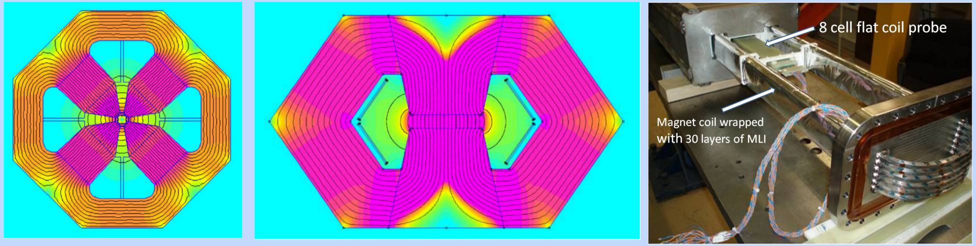
Alternative *FFA*

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



Hybrid RCS combines static superconducting magnets and fast-ramping normal-conducting magnets





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

MAP study S. Berg et al.

MAP study

RCS Challenge

RCS is probably the main cost driver and could be substantial power user

Numbers for illustration, are subject to optimisation

Studies started on the key challenges:

- Longitudinal dynamics along whole complex and RF system
  - distribution around ring, frequency choice
- Lattice design
  - energy swing, path length control, distribution of RF, …
- Fast-ramping magnets and power converter system
  - cost of stored energy seems OK, cost of ramp shaping to be developed with RF experts

Need to match ramping speed of magnets with accelerating RF

- Integrated design optimisation is needed
- Energy recovery from pulse to pulse is critical

Param.	unit	RCS 1	RCS 2	RCS 3
E	GeV	60-300	300-1500	1500-5000
C	km	2.8	13.8	35
<G>	MV/m	2	2	1
turns		44	44	95
T_{ramp}	ms	0.4	2	11.67
dB/dt	kT/s	10	2	0.34
E_{ramp}	MJ	6.4	32	93.3

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)

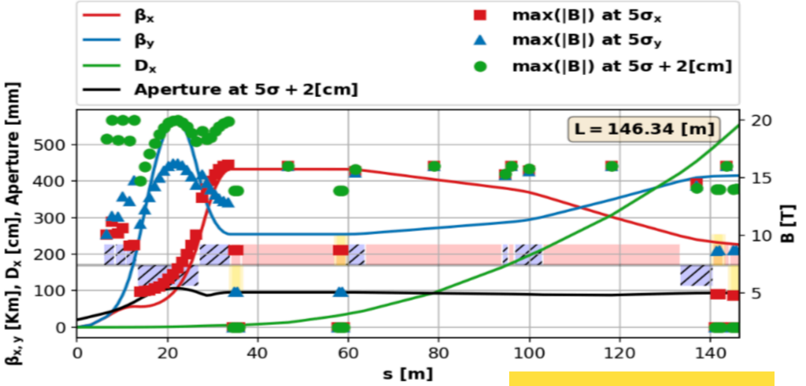
Collider Ring

MAP developed 4.5 km ring for 3 TeV with Nb_3Sn

- magnet specifications in the HL-LHC range
- 5 mm beta-function at IP

Work on 10 km ring for 10 TeV collider ring

- around 16 T Nb_3Sn or HTS dipole field around 15 cm
- final focus based on HTS
- 1.5 mm beta-function at IP



C. Carli, K. Skoufaris (CERN)

MOPOTK031

15 cm aperture for shielding to ensure magnet lifetime

Need stress managed magnet designs

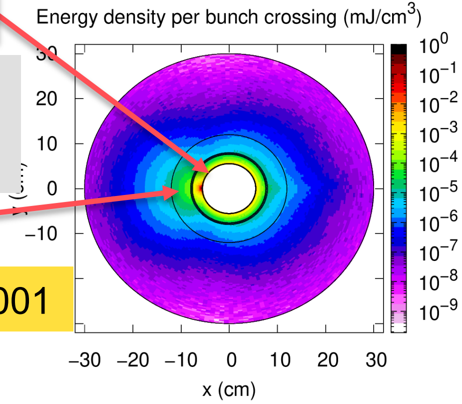
INFN, Milano, Kyoto, CERN, profit from US

Shielding

A. Lechner
D. Calzolari
(CERN)

Coil

WEPOST001



Field choice will be reviewed for cost

Example alternatives:

- a 6 km 3 TeV ring with **NbTi** at 8 T in arcs
- a 15 km 10 TeV ring with HL-LHC performances
- slight reduction in luminosity

Other Key Studies

ESS experts will lead work package to review proton complex

- average power of 2 MW is no problem
- but merging into 5 pulses of 400 kJ per second needs to be verified

N. Milas et al. (ESS, Uppsala)

Collective effects across the whole complex to identify bottlenecks

- review apertures, feedback and other specifications
- potential instability of interaction of muon beam with matter

E. Metral et al. (CERN, EPFL/CHART)

Power and cost optimisation

Vacuum and absorber, instrumentation, cryogenics, …

J. Ferreira Somoza, M. Wendt, et al.

Reuse of existing infrastructure, e.g. LHC tunnel to house accelerator

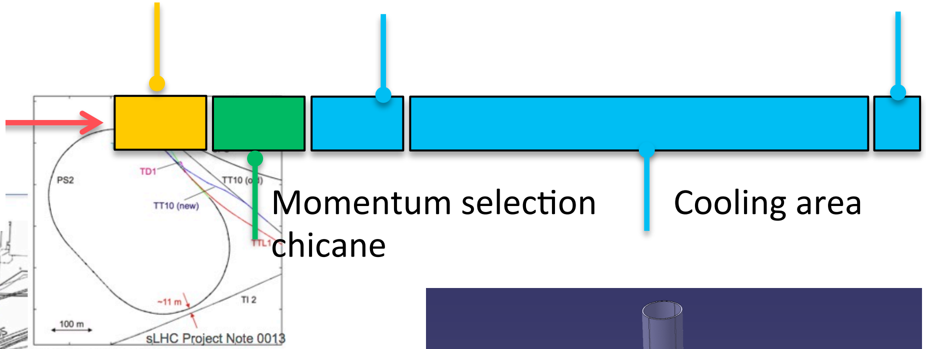
Demonstrator Facility Consideration

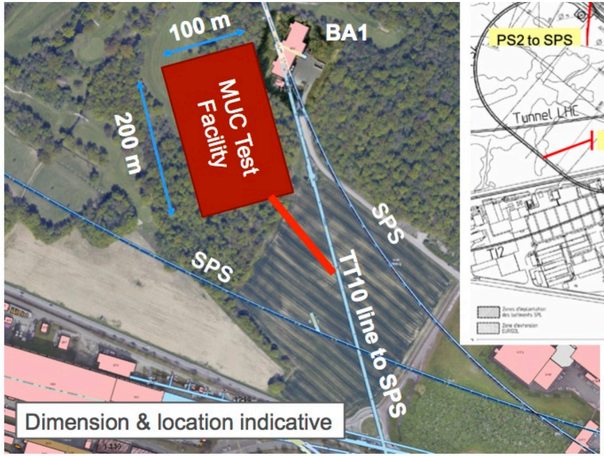
Planning demonstrator facility with muon production target and cooling stations

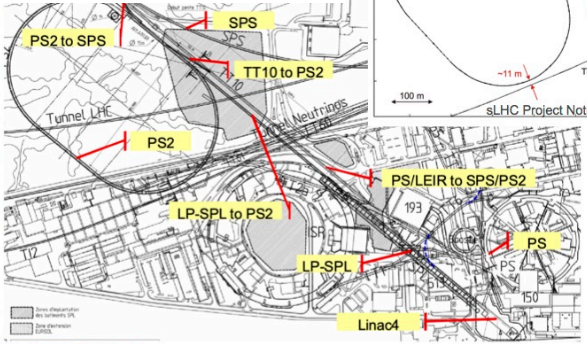
Suitable site on CERN land exists that can use PS proton beam

- could combine with NuStorm or other option

Other sites should be explored (FNAL?)

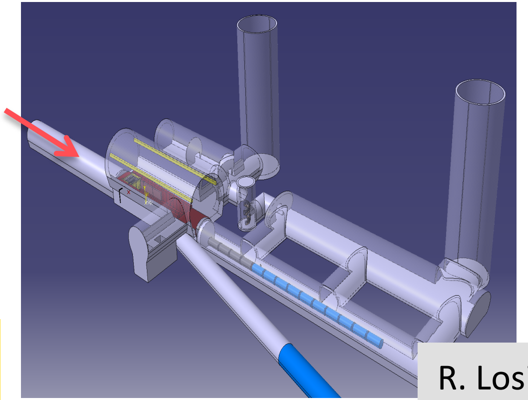






M. Benedikt, LHC Performance Workshop, Chamonix 2010
CERN-AB-2007-061

WEPOPT027
THPOTK052



R. Losito et al.

The Way Forward

Resources are being made available in several institutes

- in all regions

But at this moment not yet at the level of the reduced programme

Increase funding by

- Submitted proposal of a EU Design Study
    - 8 workpackages, 3 MEUR from EU, 4 MEUR from partners, 3 MEUR from CERN
    - decision September 2022
- Will submit a technology development proposal in 2024
- Submitted white papers and hope that Snowmass and P5 will lead to strong US involvement
- …

MoC and Design Study Partners

IEIO	**CERN**
FR	**CEA**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
	University of Milano
	University of Padova
	University of Pavia
	University of Bologna
	ENEA
CH	PSI
	University of Geneva

UK	**STFC-RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College
	Royal Holloway
	University of Huddersfield
	University of London
	JAI
	University of Oxford
	University of Warwick
SE	***ESS***
	University of Uppsala

PT	LIP
NL	University of Twente
FI	**Tampere University**
US	**Iowa State University**
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
LAT	***Riga Technical Univers.***
AU	***HEPHY***
ES	***I3M***

CHART is contributing (and EPFL)
Informal contributions (US, Japan)

Note: *some MoC still being prcessed*

Conclusion

- Muon collider is unique opportunity for high-energy, high-luminosity lepton collider
- Currently two different options considered
  - goal is 10+ TeV
  - potential 3 TeV intermediate stage explored
- Not as mature as ILC or CLIC
  - have to address **important R&D** items
  - but **no showstopper** identified, feasibility is addressed
  - see the (sometimes stony) path forward
  - No inventions needed
- Aim to establish solid basis for performance claim and cost and power estimates
- Aim at **maturity level** to make **informed choices by the next ESPPU** and other strategy processes
- An important opportunity that we should not miss
  - http://muoncollider.web.cern.ch

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