International
MUON Collider
Collaboration

MuCol

Muon Collider

D. Schulte
On behalf of the International Muon Collider Collaboration

HFM Annual Meeting , CERN, October 2023

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

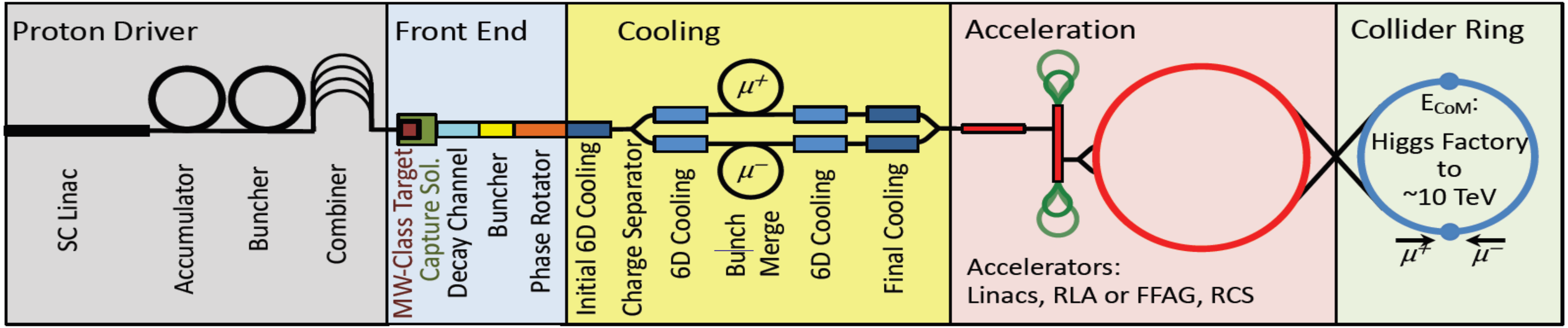
Muon collider promises **sustainable** approach to the **energy frontier**
- limited power consumption, cost and land use

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

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

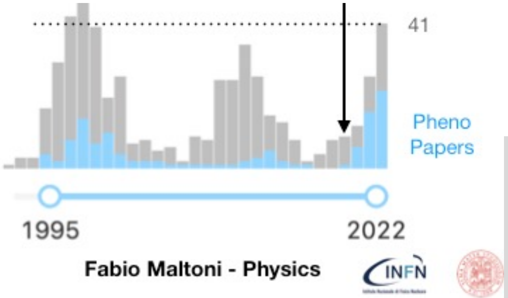
Acceleration to collision energy

Collision

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

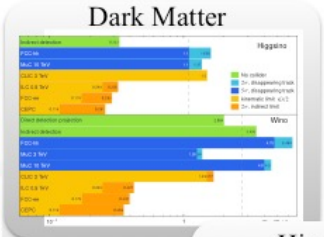
A. Wulzer, F. Maltoni, P. Meade et al.

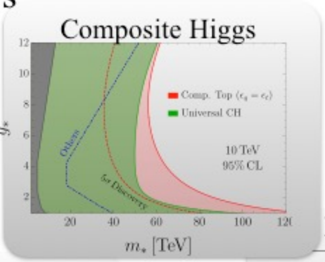
O(150) authors, 15 editors, 100 papers

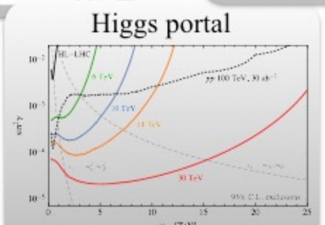
DELPHES card available

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



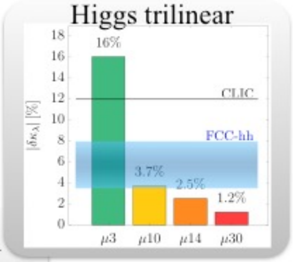




Higgs couplings

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

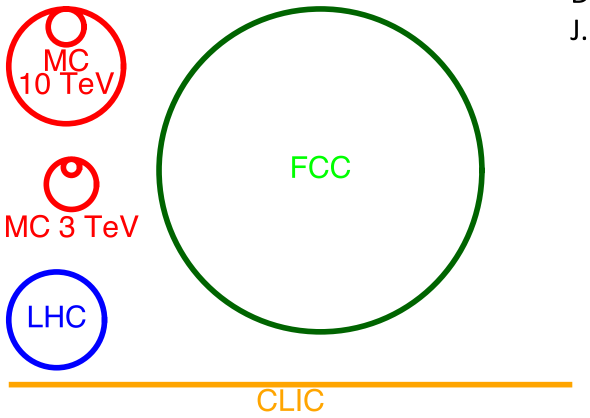
* No input used for μ collider

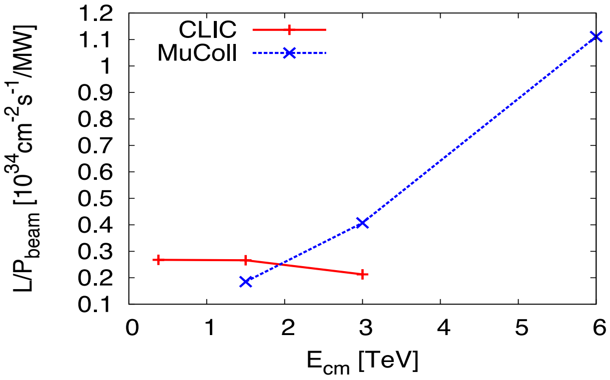


Strong US involvement starting with **Muon Smasher's Guide** and in **Muon Collider Forum**

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

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	$1\ \mathrm{ab}^{-1}$
10 TeV	$10\ \mathrm{ab}^{-1}$
14 TeV	$20\ \mathrm{ab}^{-1}$

http://arxiv.org/abs/2201.07895

Muon Collider Timeline

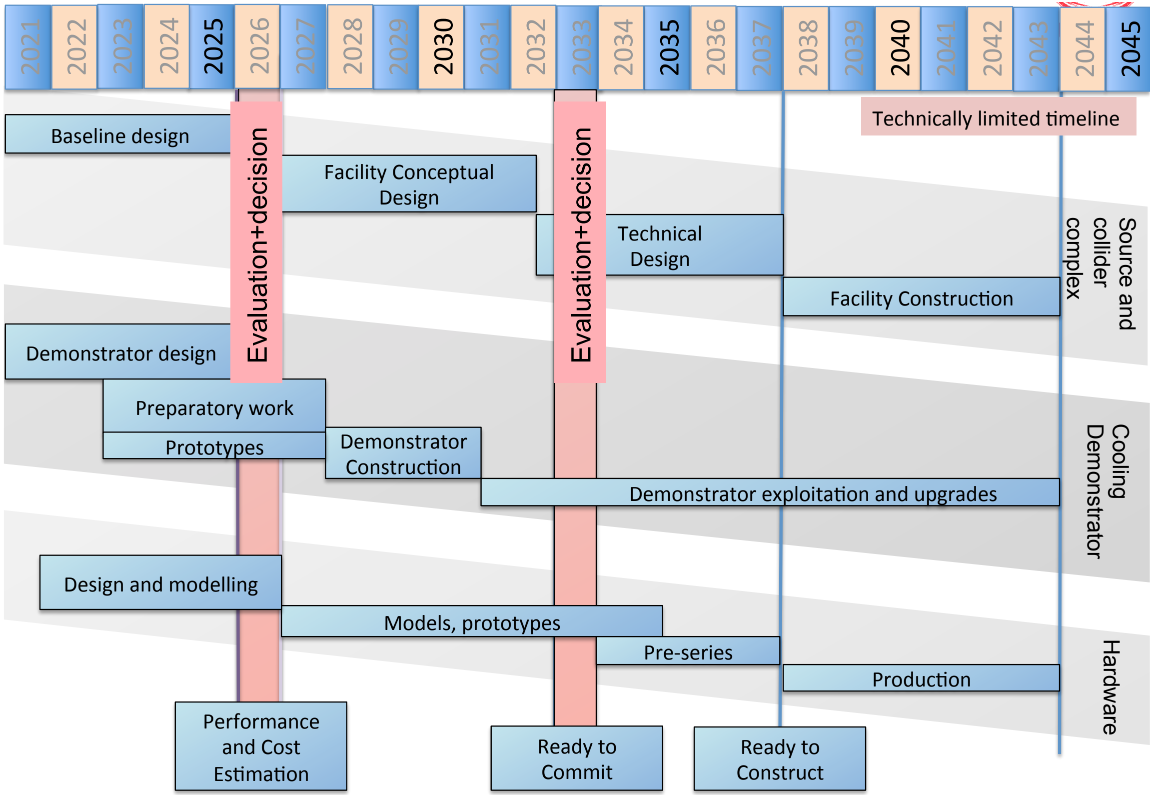
Muon collider important in the long term
- Even after potential FCC-hh

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

Technically limited timeline
To be reviewed considering progress, funding and decisions



Initial Target Parameters

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Target integrated luminosities

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

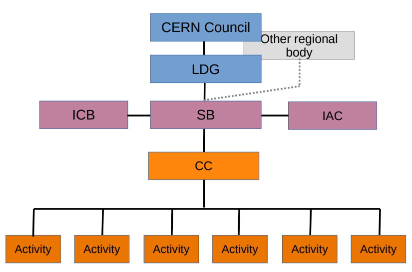
Note: currently focus on 10 TeV, also explore 3 TeV

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
  - 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	
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	

Muon Collider Community

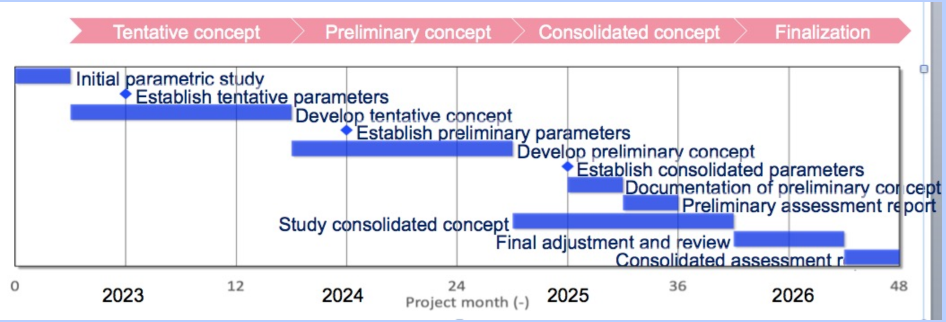
Formed **collaboration** hosted by CERN to implement R&D Roadmap for CERN Council



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, …**

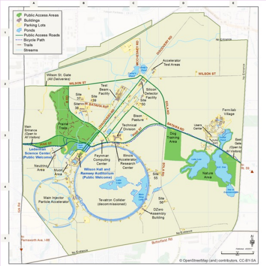
TIARA wants magnet proposal

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



US P5 Ask

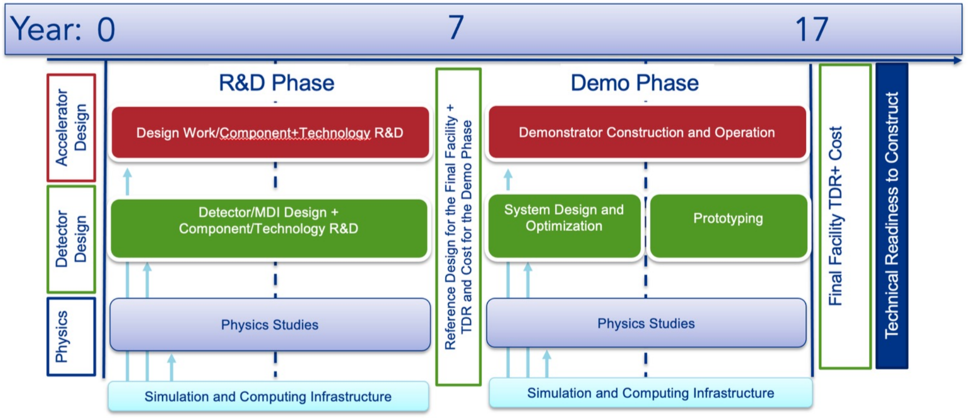
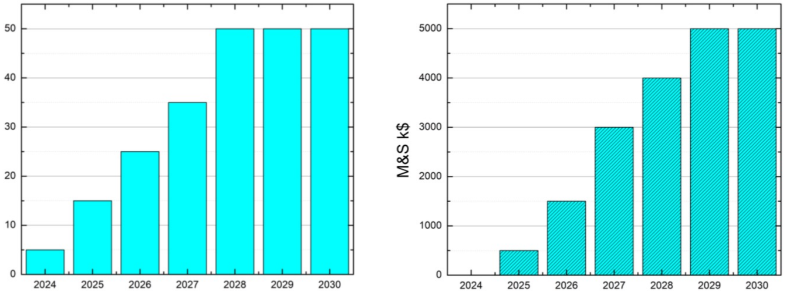


Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.



: 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.

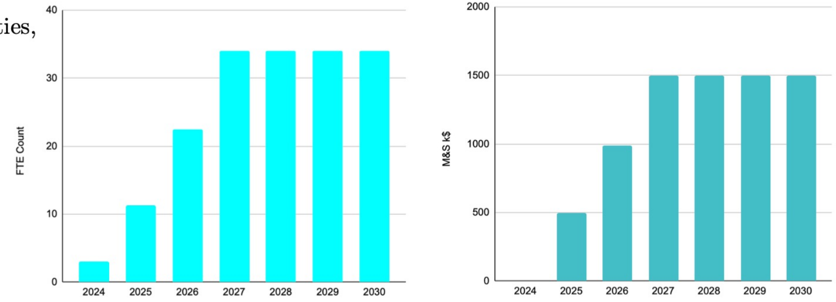


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

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

MoC and Design Study Partners

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International MUON Collider Collaboration

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**

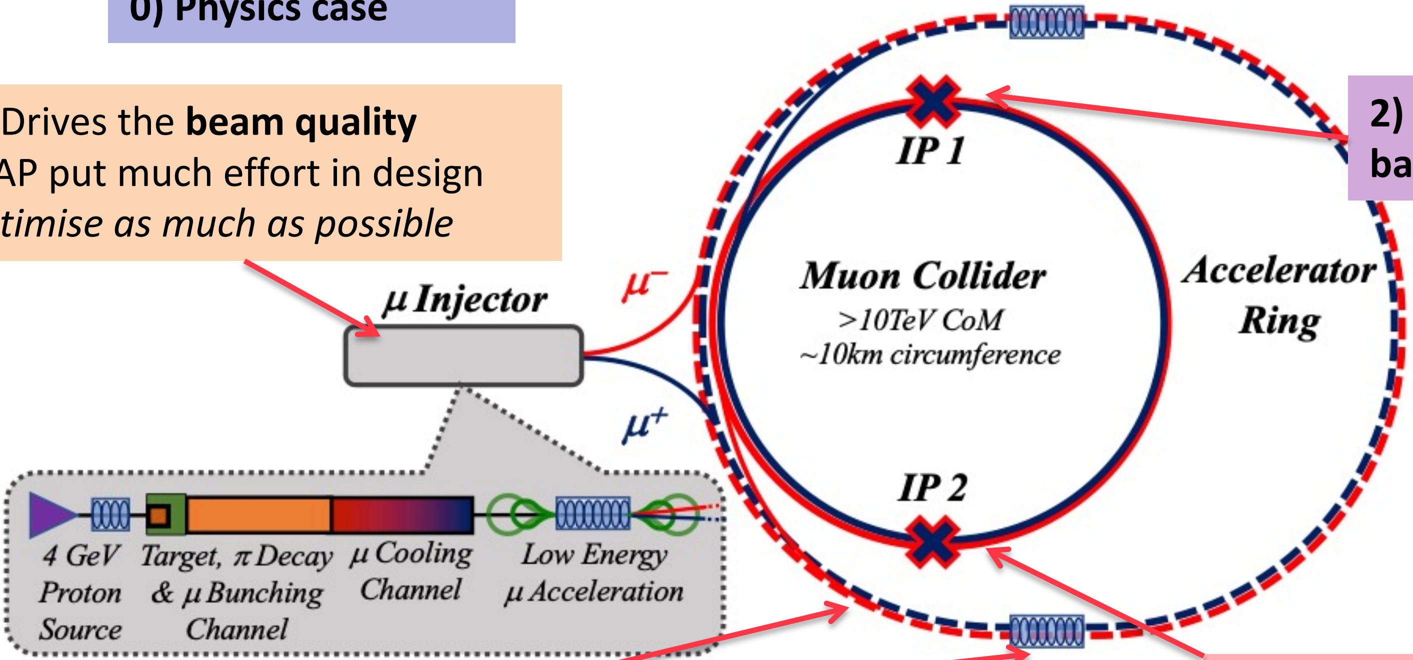
China	***Sun Yat-sen University***
	IHEP
	Peking University
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
KO	**KEU**
	Yonsei University
India	***CHEP***

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

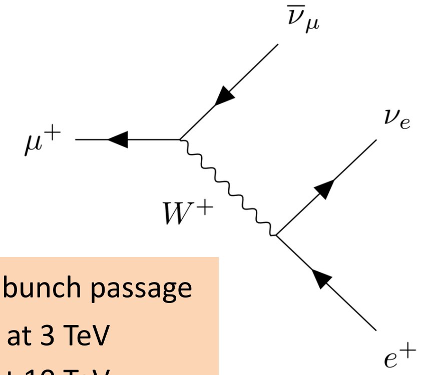


2) Beam-induced background

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

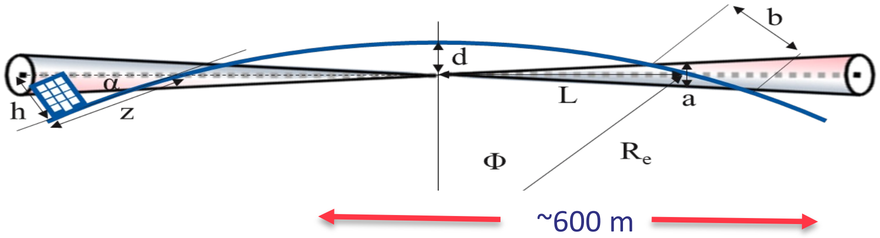
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

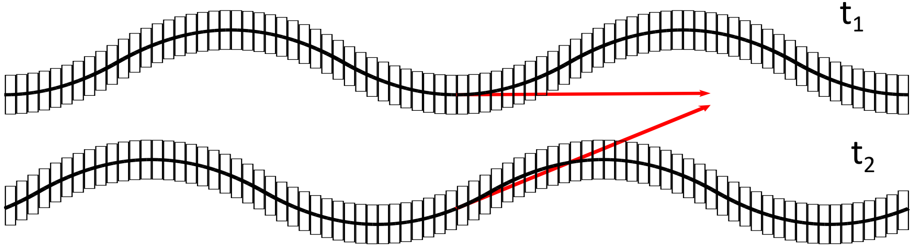
Muon Decay and Neutrino Flux



Muon decays per bunch passage

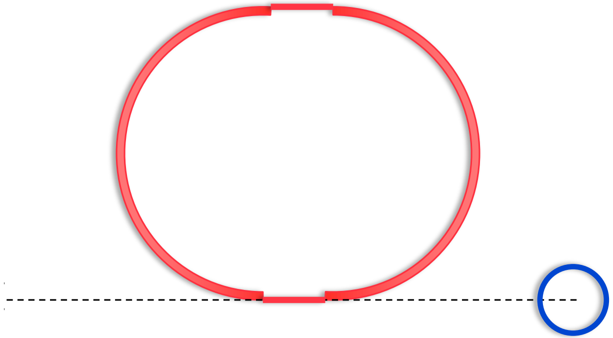
- 235,000 m^{-1} at 3 TeV
- 58,000 m^{-1} at 10 TeV





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

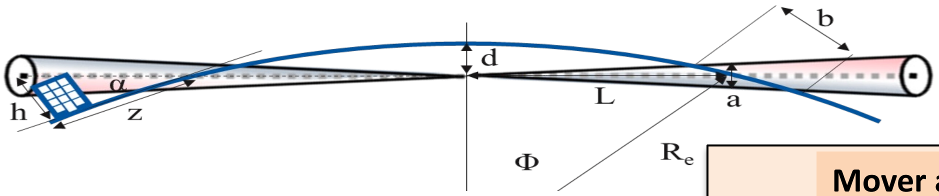


Impact of experimental insertions

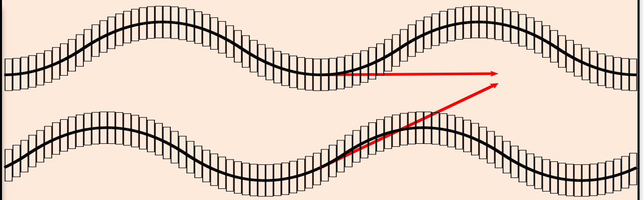
- 3 TeV design acceptable with no further work
- Maybe acquire land in direction of experiment, also for 10 TeV

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

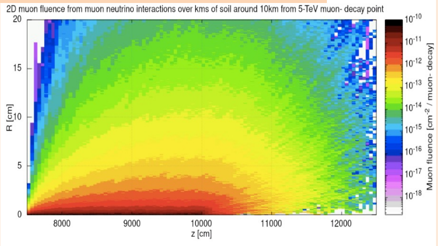


Mover and support system



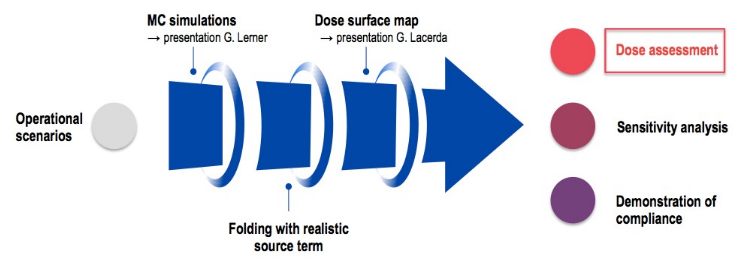
F. Bertinelli et al. (CERN, Riga)

FLUKA dose studies



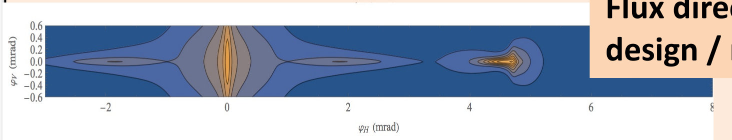
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme



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

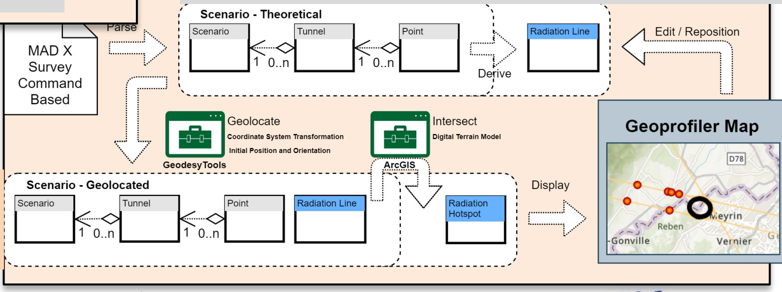
Flux direction map / lattice design / mover impact on beam



C. Carli, K. Skoufaris (CERN)

Mitigation: Site choice tool

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



Muon Decay and Detector Background

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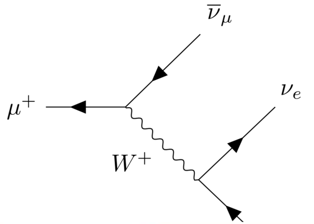
Muon decays produce electrons and positrons
- Loss per unit length almost independent of energy
- First results indicate that background does not increase much with energy

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**

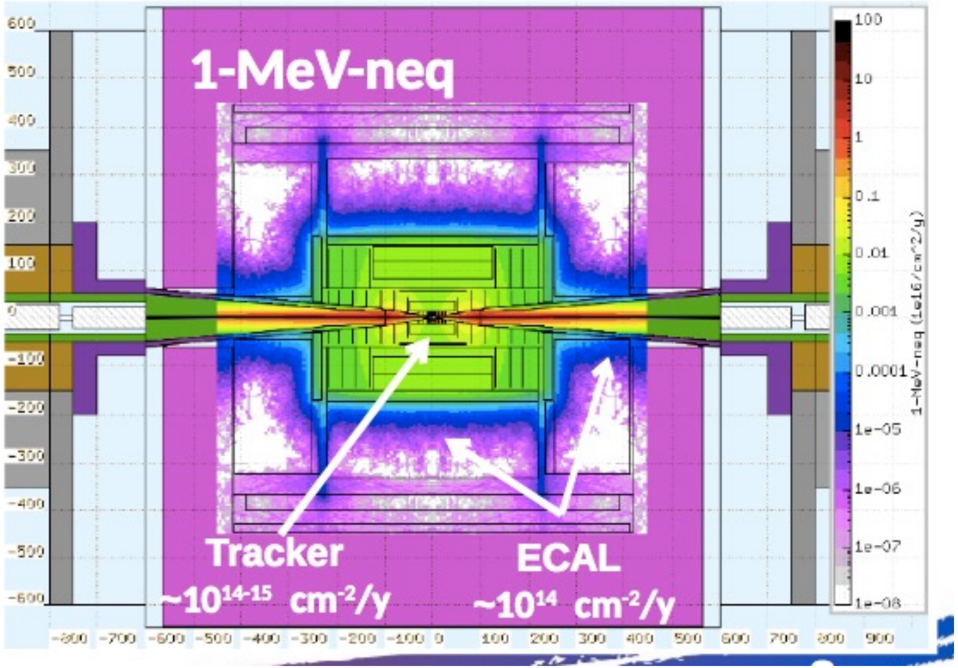
Studies with **beam-induced background** in progress
- some channels are not affected by background
- some improvement required for other channels

Concept for **10 TeV** in progress

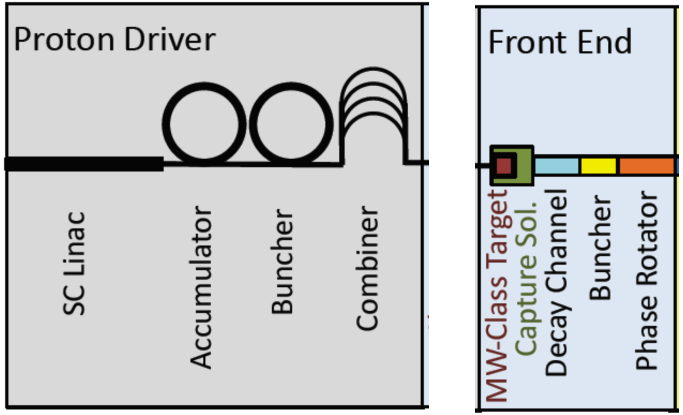


Detector team
O(69) authors, O(150 signatories)

D. Lucchesi, F. Meloni et al.

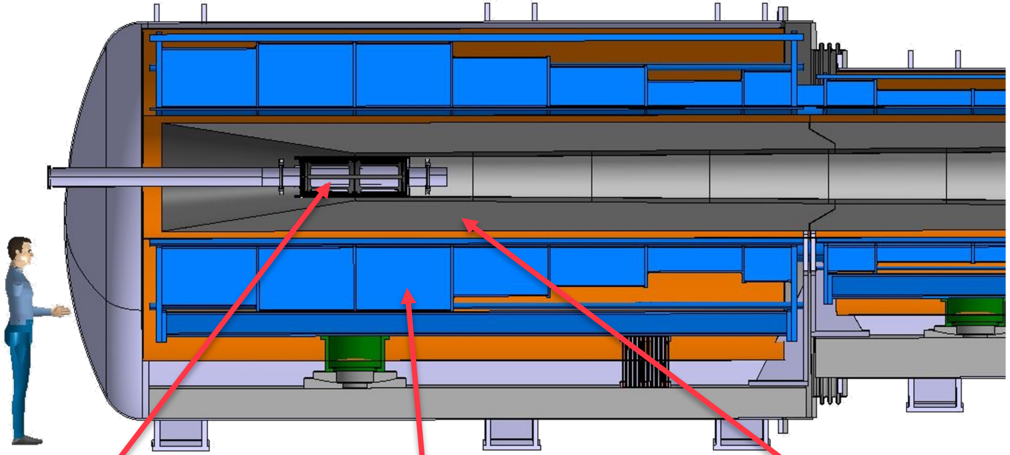


Proton Complex and Target



protons → (in target) → pions → (decay) → muons

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



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

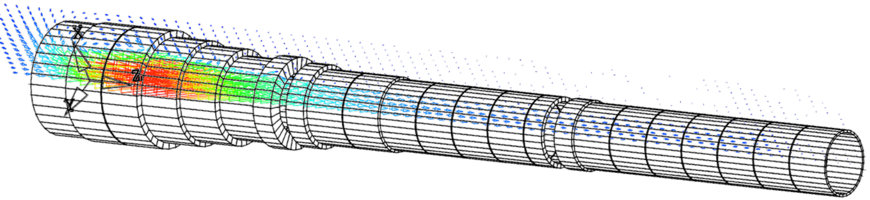
Graphite **Target**

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

Tungsten shielding
To protect magnet

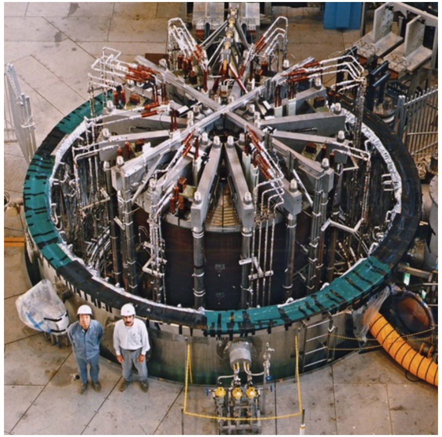
Target Studies

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

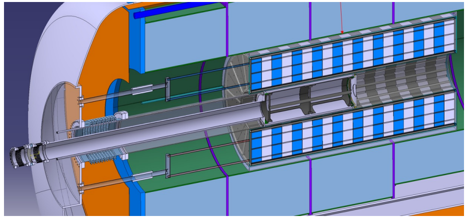


ITER model coil: 13 T
Nb_3Sn 1.7 m diameter

Our work is relevant for fusion

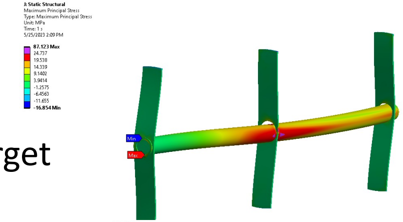
FLUKA studies:
2 MW target: stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

Integration

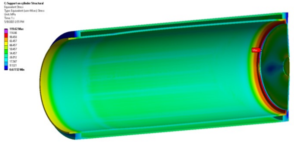


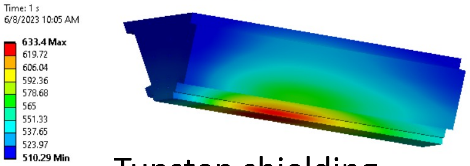
Cooling, vacuum, mechanics, …

Target



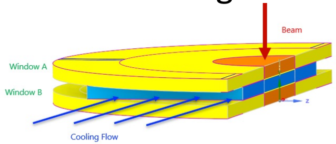
Vessel





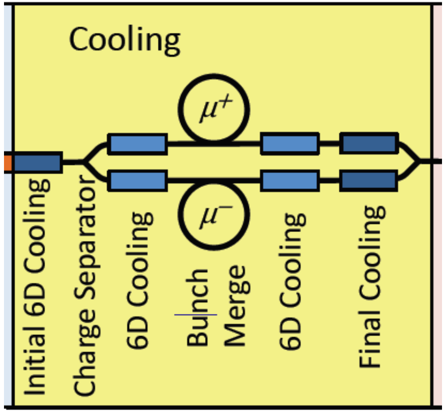
Tunsten shielding

Window

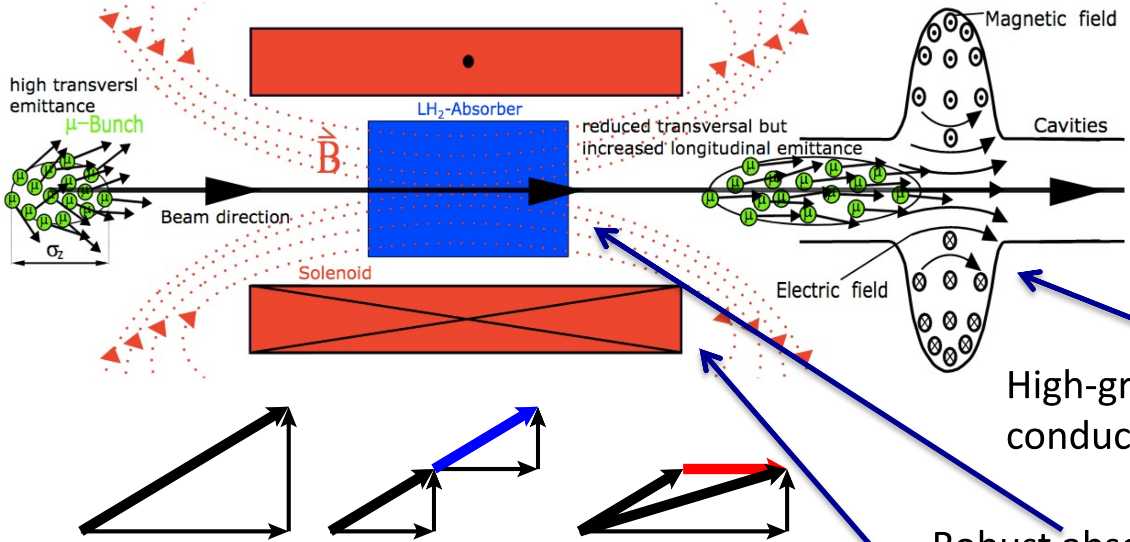


A. Lechner, D. et al.

Muon Cooling Principle



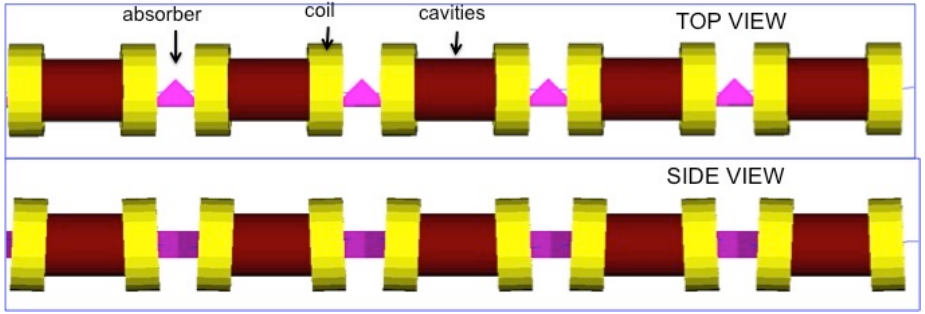
C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid



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

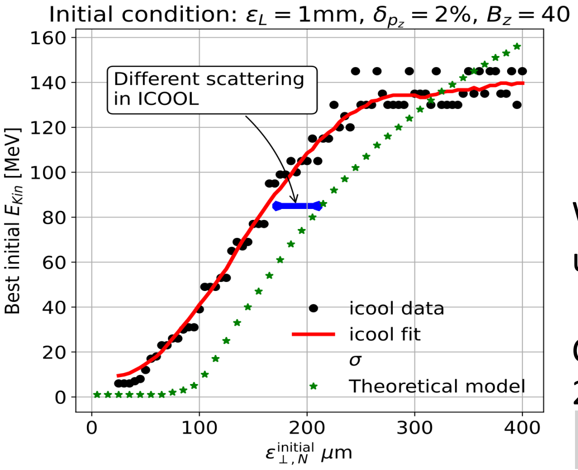
Muon Cooling Performance

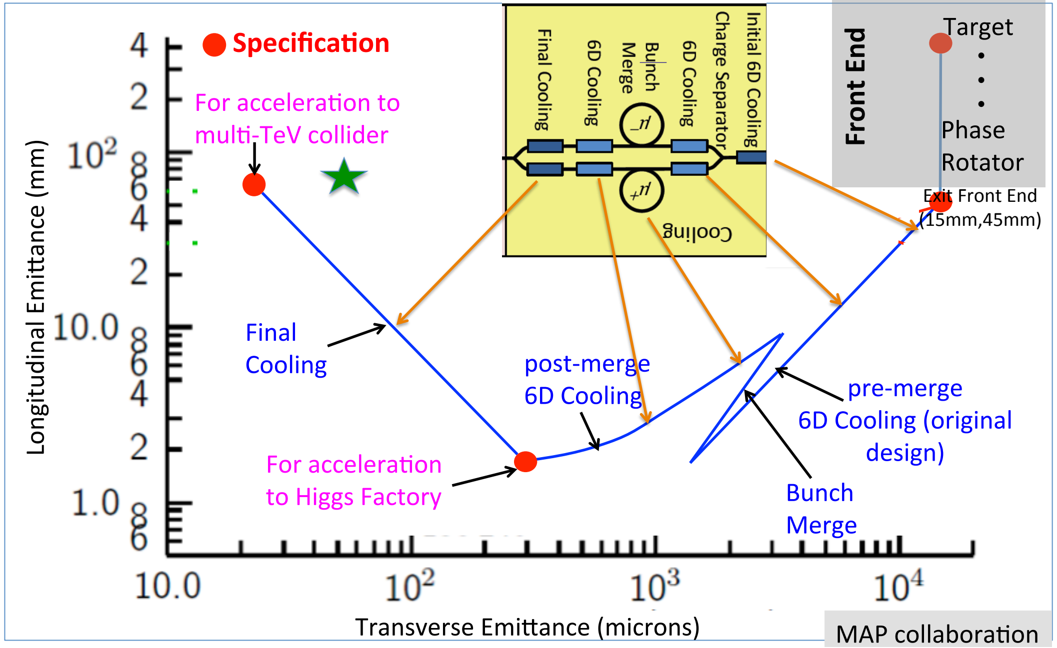
MAP design achieved 55 um based on achieved fields

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.

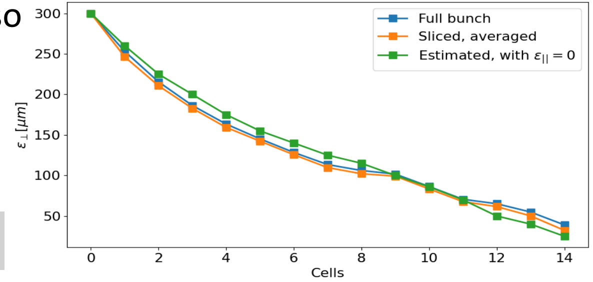




Working on **improved, systematic design**, also using better magnets and RF

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

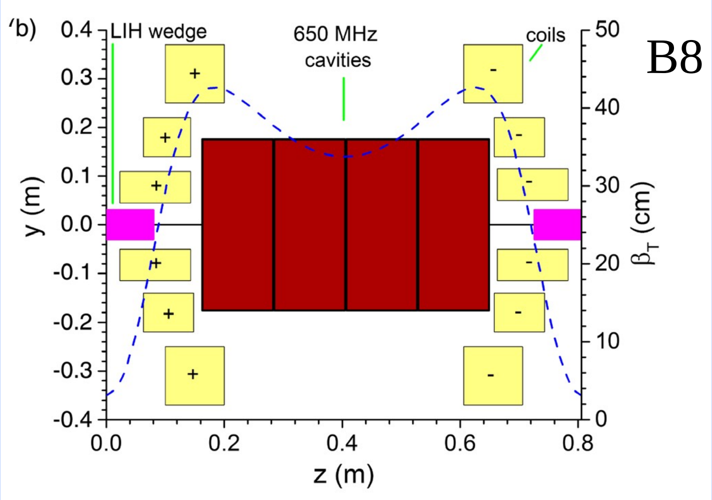
Ch. Rogers, Zhu Ruihu, B. Stechauner, E. Vol et al.



Cooling Cell Technology

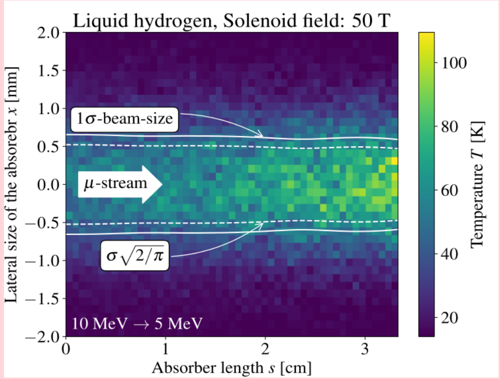
Will develop example **cooling cell with integration**
- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**

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

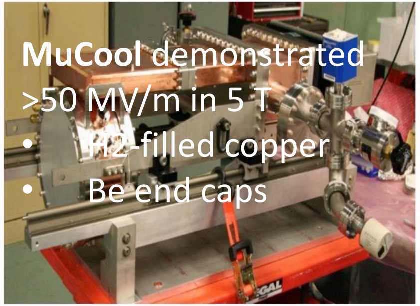


RF cavities in magnetic field

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



MuCool demonstrated >50 MV/m in 5 T
- H_2-filled copper
- Be end caps

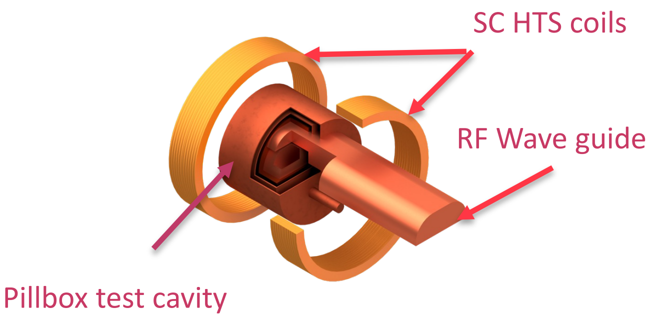
C. Marchand, Alexej Grudiev et al. (CEA, Milano, CERN, Tartu)

RF Test Stand

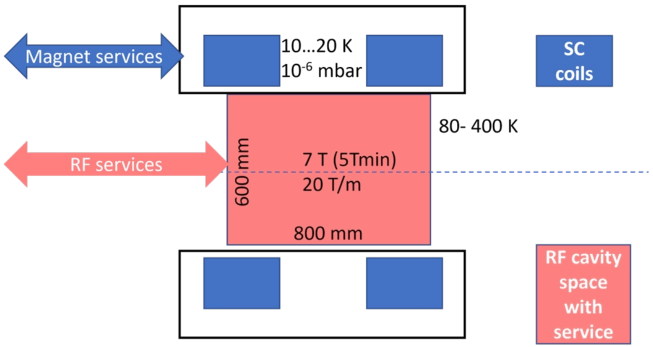
Module work focuses on RF test stand at this moment

- 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

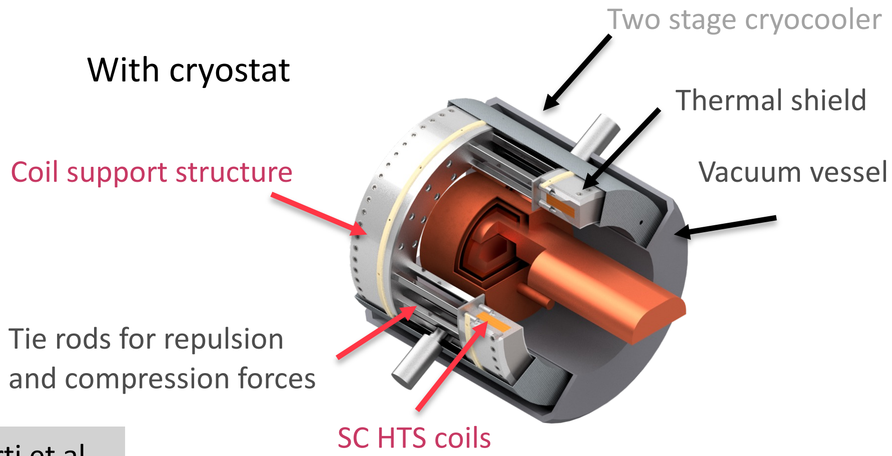
Bare coils and RF cavity



Schematic of the RFMF test facility single cryostat



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, …

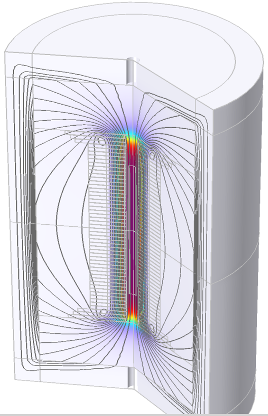
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

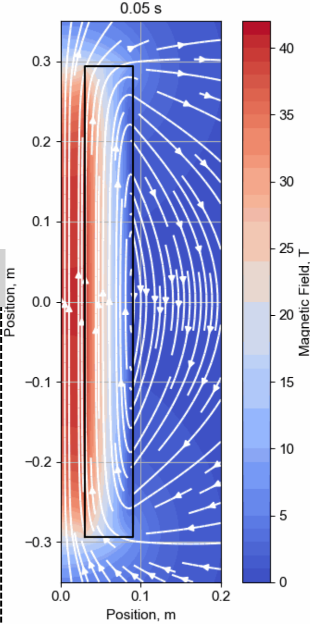
Final Cooling solenoid

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

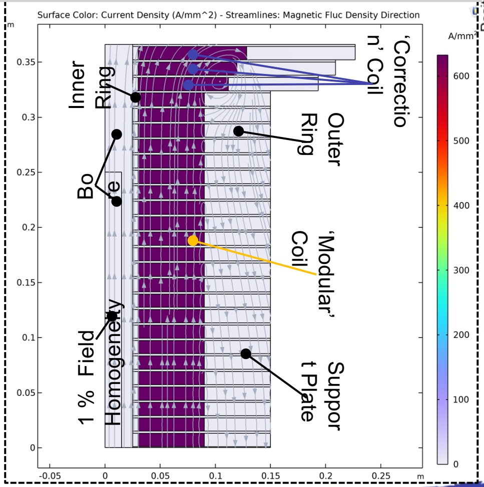
σ_{max} = 600 MPa

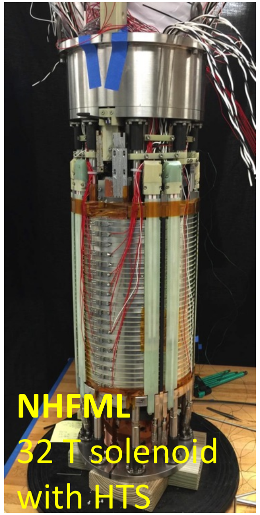
$B_{max} \approx$ **55 T**



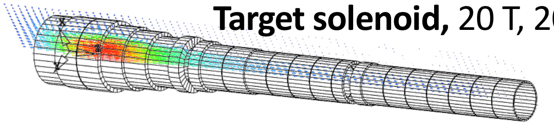


A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



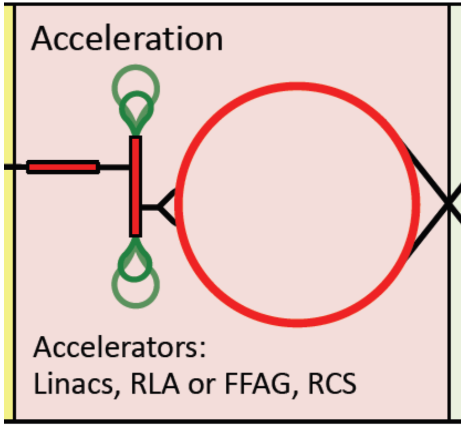


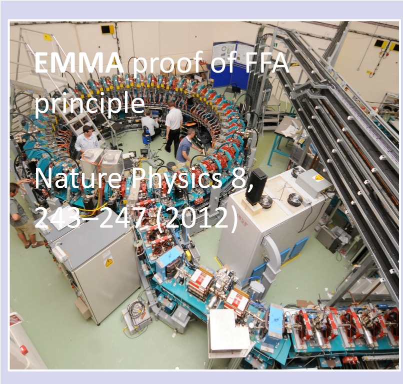
32 T LTS/HTS solenoid demonstrated



Target solenoid, 20 T, 20 K

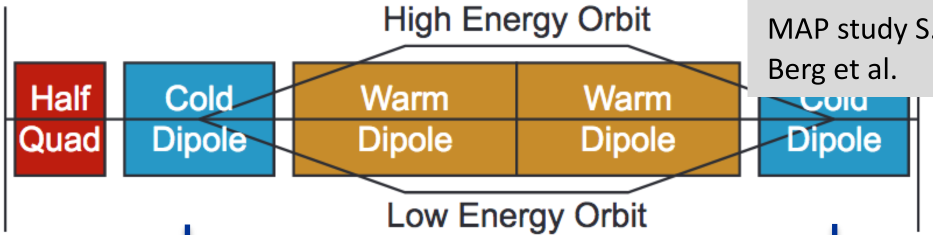
Acceleration Complex





Core is sequence of hybrid pulsed synchrotron (0.4-11

- Alternative FFA



MAP study S. Berg et al.

initial

final

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

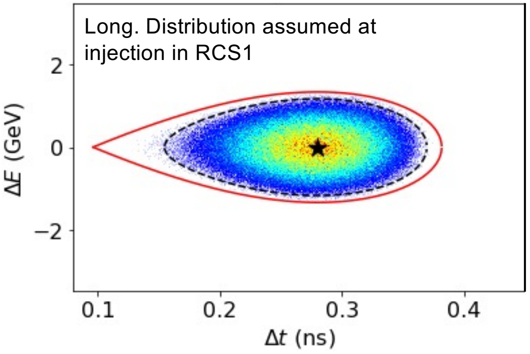
Lattice and integration: A. Chance et al. (CEA)
Long. dynamics and RF systems: H. Damerell, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)
Power converter: F. Boattini et al.
Magnets: L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
FFA: S. Machida et al. (RAL)

Collective Effects and RF Design

Longitudinal dynamics and RF important due to high bunch charge

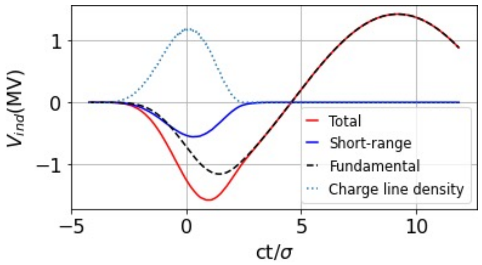
- > 30 RF stations needed
- Orbit length changes require frequency tuning required
- Single-bunch HOM power loss up to 10 kW during pulse
- CW average is lower, development of high-capacity couplers needed

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

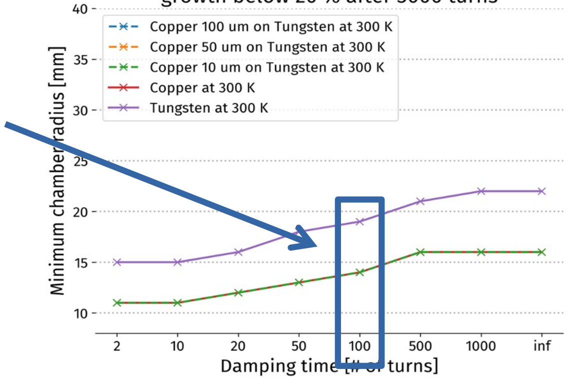


Collider ring single beam instability limits

Conservative feedback

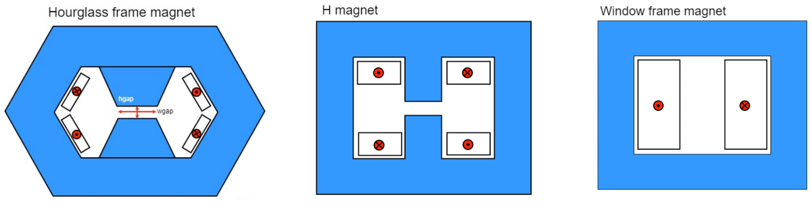
Copper coating beneficial (few microns)

Beam-beam studies started



Fast-ramping Magnet System

F. Boattini et al.



5.07 kJ/m | 5.65…7.14 kJ/m | 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

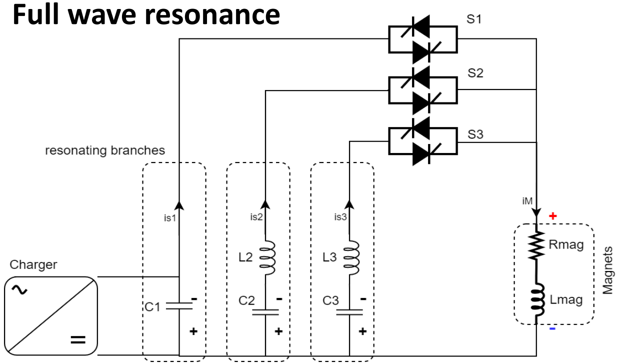
FNAL 300 T/s HTS magnet

Could also use HTS driven dipoles

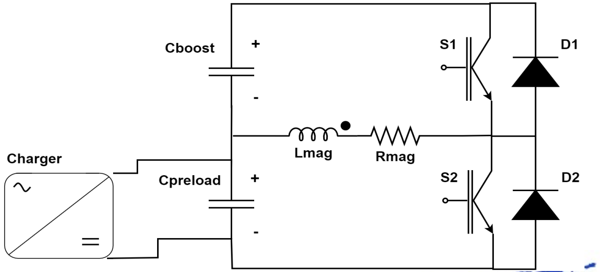
Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

Full wave resonance



Commutated resonance (new)

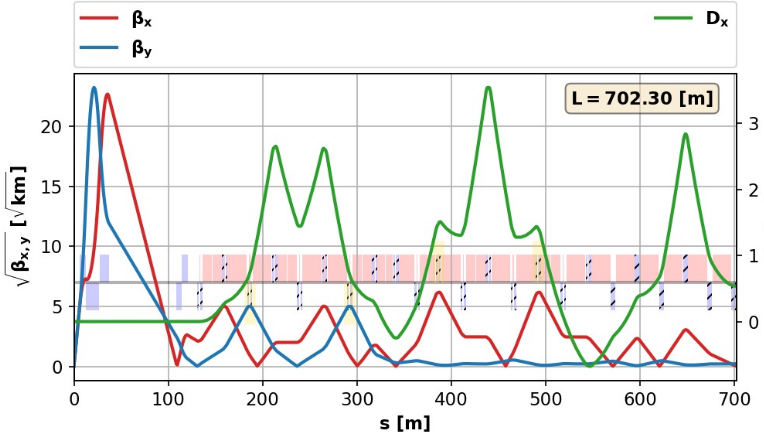


Collider Ring

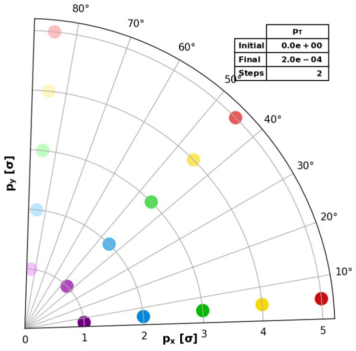
Challenges:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

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

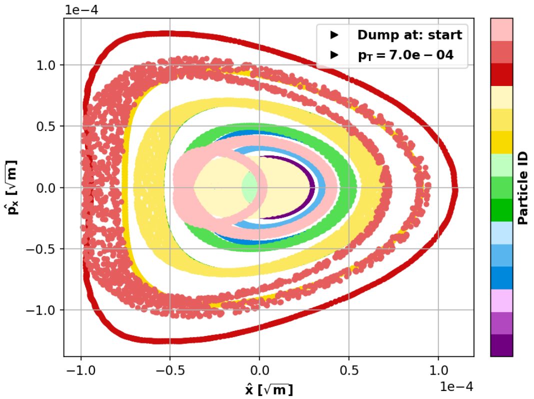
Work progressing on **10 TeV collider ring**
- around 16 T HTS dipoles or lower Nb_3Sn
- final focus based on HTS



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

MuCol

International MUON Collider Collaboration

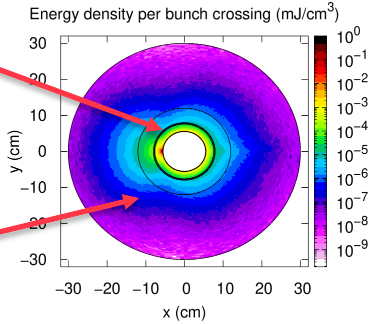
Power loss due to muon decay 500 W/m
FLUKA simulation of **shielding:**
Require 30-40 mm tungsten

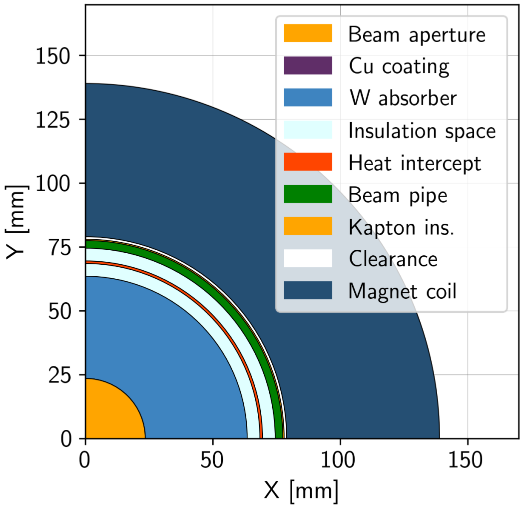
- Few W/m in magnets
- No problem with radiation dose

Shielding

A. Lechner
D. Calzolari
(CERN)

Coil

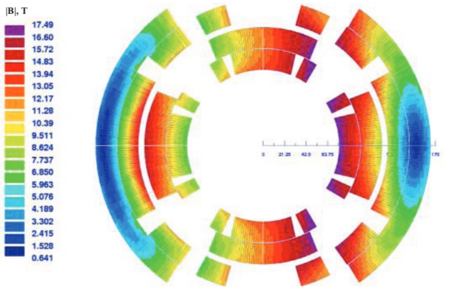


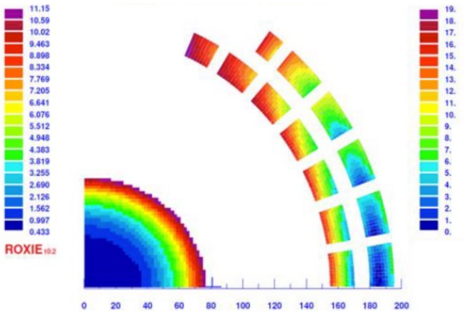


K. Skoufaris, Ch. Carli, D. Amorim, A. Lechner, R. Van Weelderen, P. De Sousa, L. Bottura et al.

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

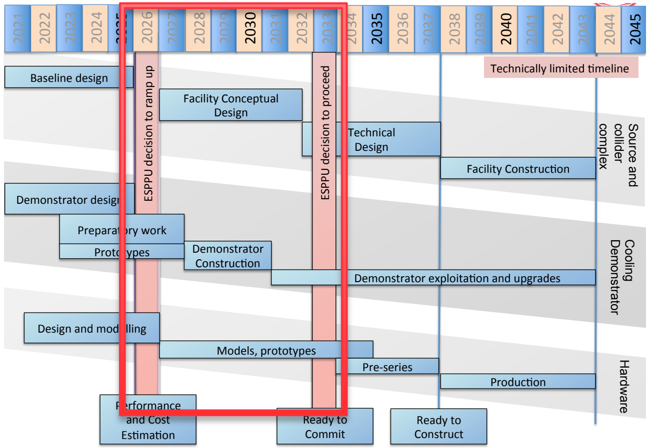
CDR Phase, R&D and Demonstrator Facility

MuCol

International UON Collider Collaboration

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

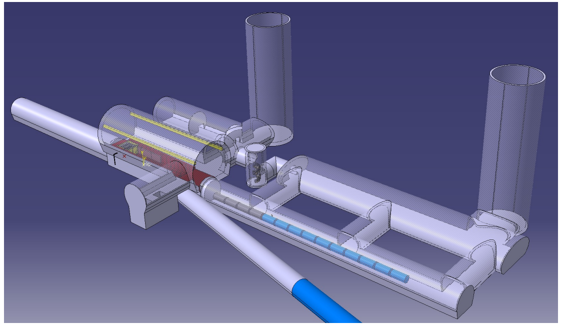
- look for an existing proton beam with significant power

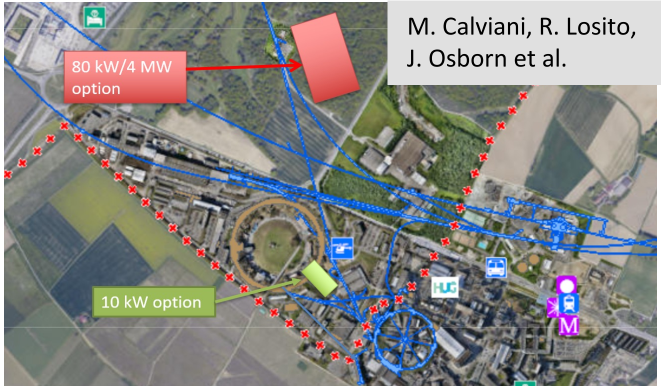
Different sites are being considered

- 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.

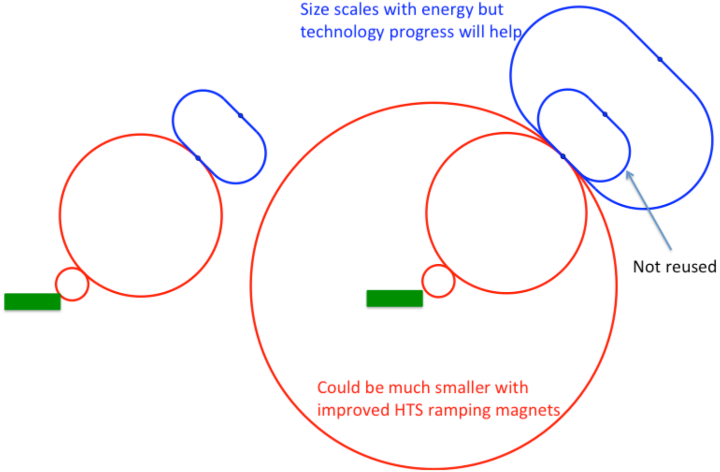
Schedule

Will develop new timeline by 2026

Tentative rational:

- First stage with technology that is available in 15 years
  - Around 3 TeV
  - Normal-conducting fast ramping magnets
  - HTS solenoids in production and cooling
  - Nb_3Sn dipoles in accelerator and collider ring
    - E.g. O(11 T, 150mm, 4K) dipoles

- Second stage full performance 10 TeV
  - Probably 25-30 years to reach maturity
  - Also HTS/hybrid dipoles in rings
  - Improved performance of key solenoids
  - Maybe HTS for fast-ramping dipoles
  - Reuse first stage almost completely



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)

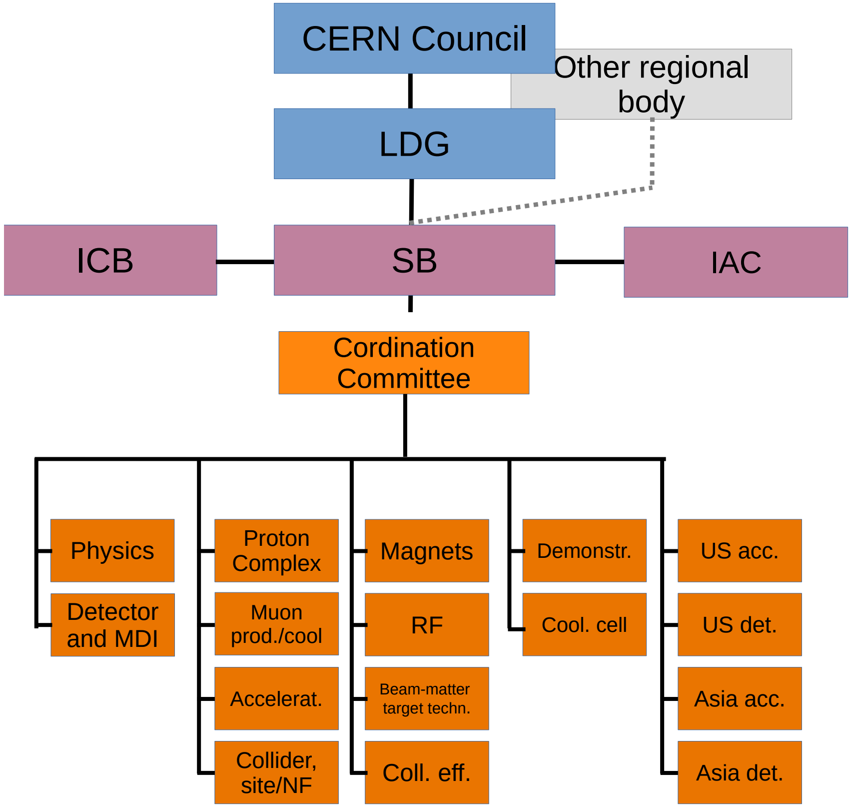
- Chair **Steinar Stapnes**
- CERN members: Mike Lamont, Gianluigi Arduini
- ICB members: Dave Newbold (STFC), Mats Lindroos (ESS), Pierre Vedrine (CEA), N. Pastrone (INFN)
- Study members: SL and deputies
- Will add US but wait for US decision on members

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

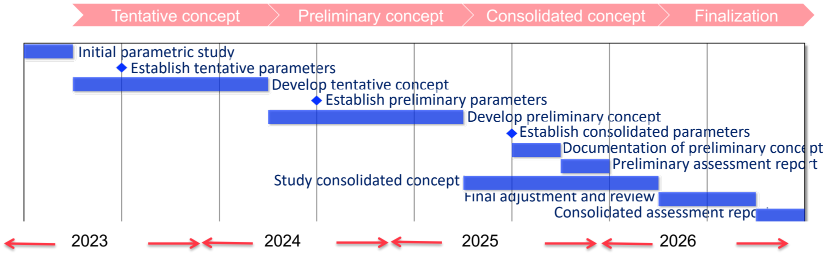
Has been approved summer 2022

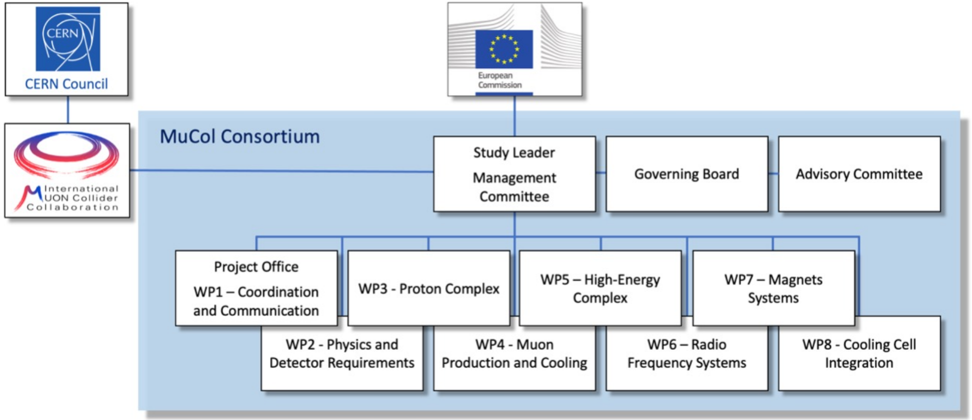
- Very helpful to kick-start collaboration

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

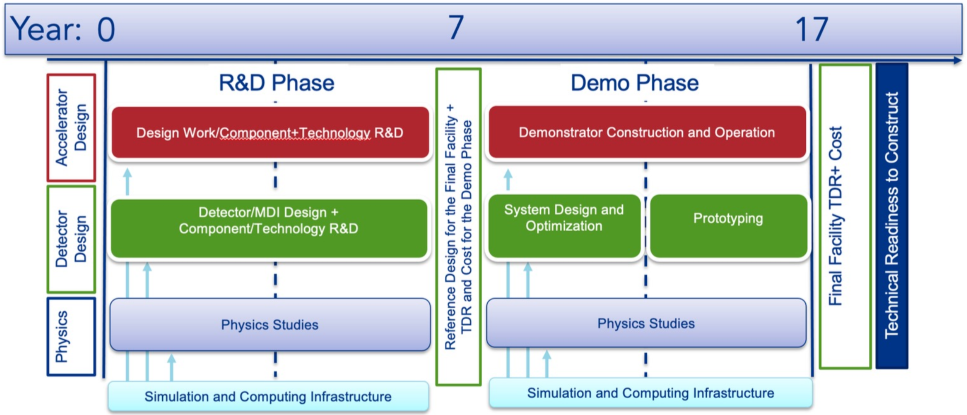
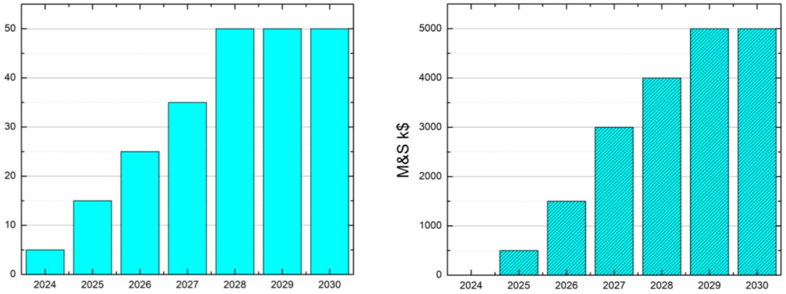


Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.



: 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.

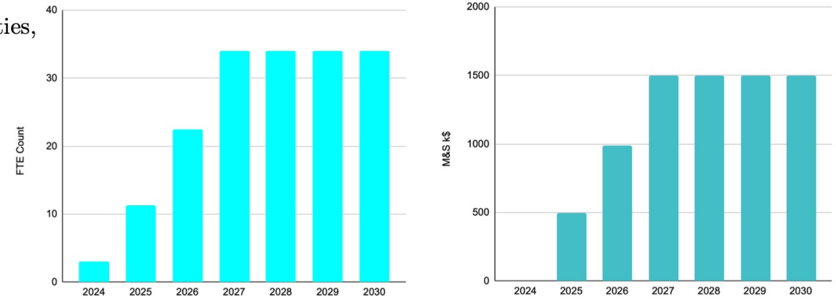


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

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

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

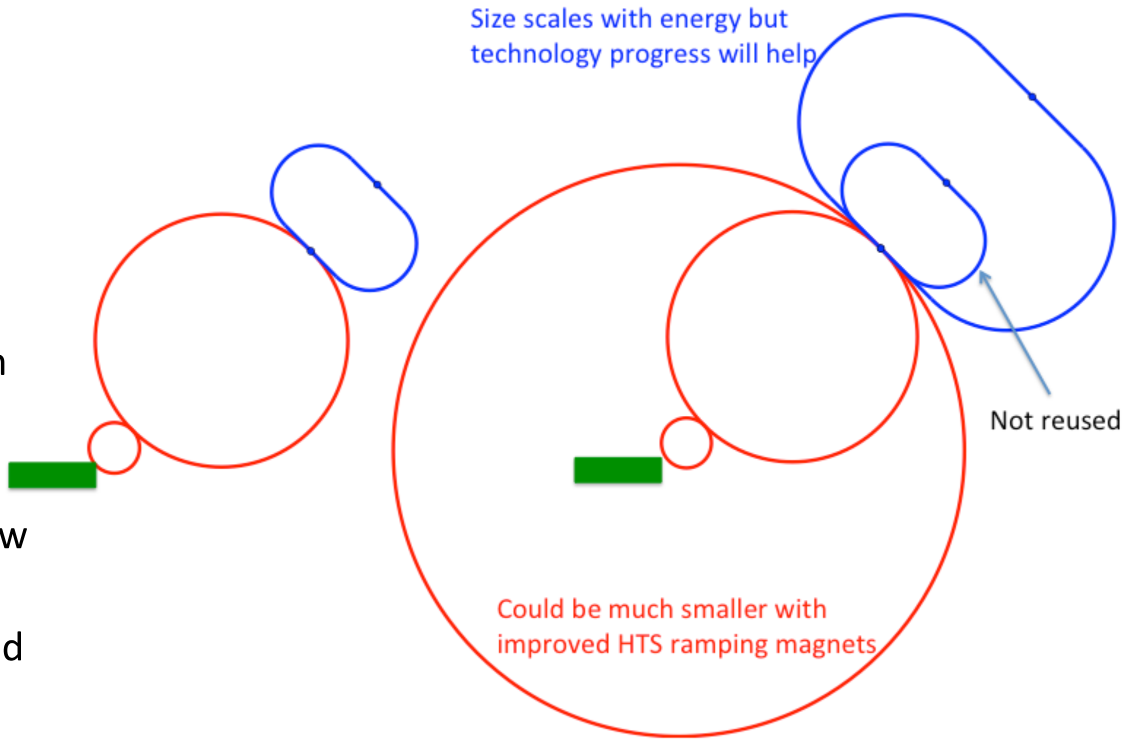
MuCol

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

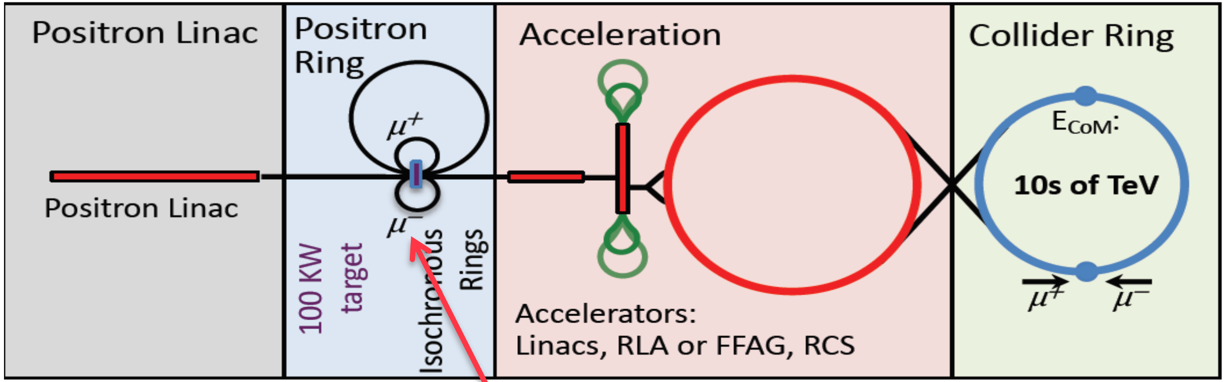
Upgrade adds one more accelerator and new collider ring

- only first collider ring is not being reused



Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



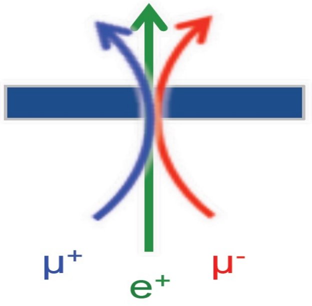
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

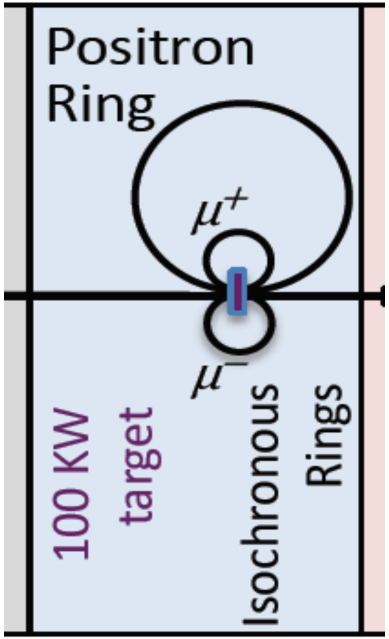
- Uses Bethe-Heitler production with electrons

45 GeV positrons to produce muon pairs

Accumulate muons from several passages

$$e^+e^- \rightarrow \mu^+\mu^-$$



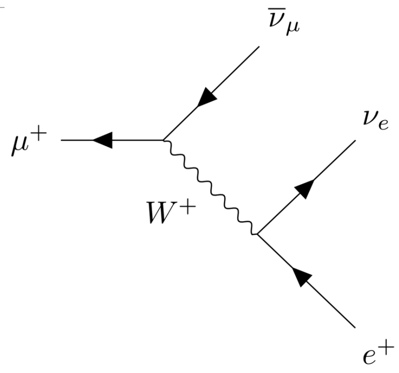


Excellent idea, but nature is cruel

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.

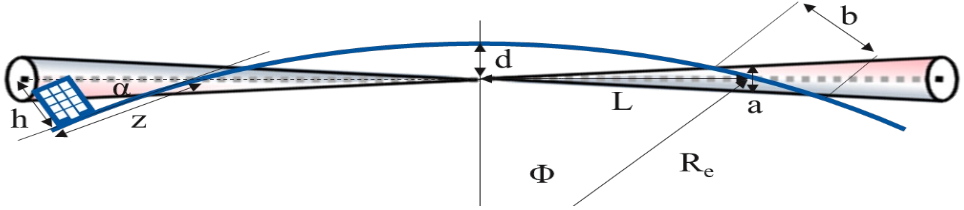
Neutrino flux to have negligible impact on environment

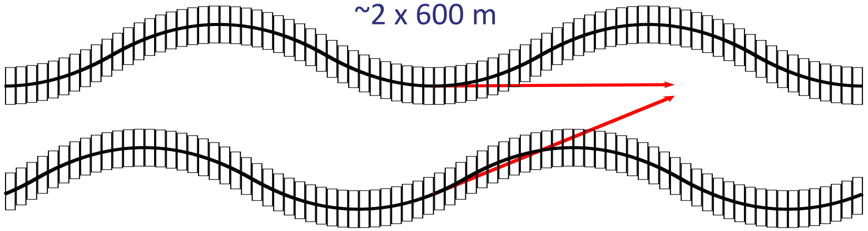
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

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

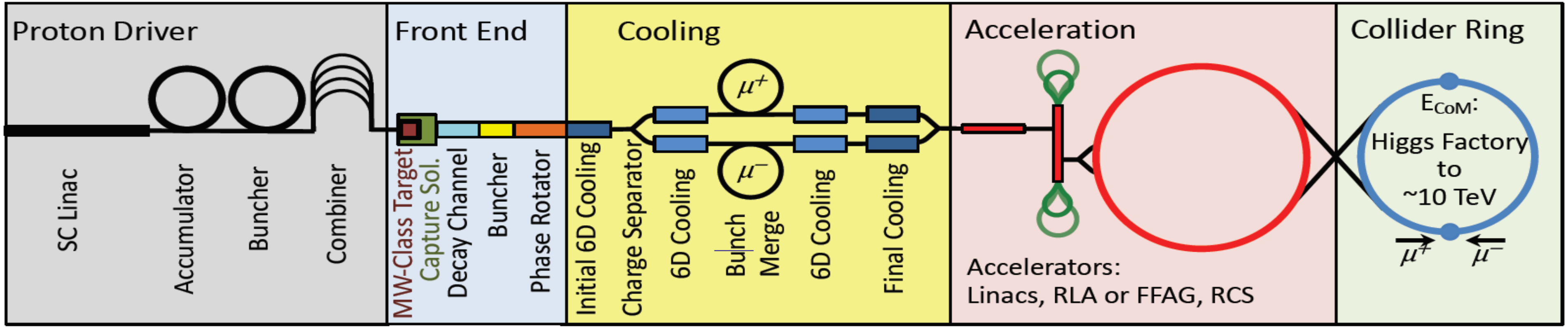
Mechanical system with 15cm stroke, 1% vertical bending

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

MuCol

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

International
MUON Collider
Collaboration

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

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.

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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

MuCol

International MUON Collider Collaboration

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 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

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	
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	

US Snowmass

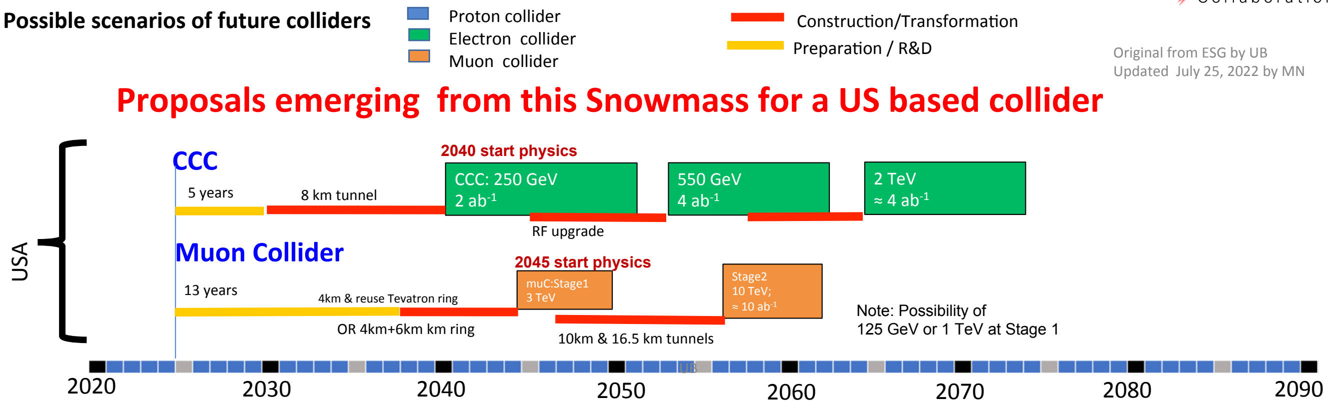
Strong interest in the US community in muon collider

- 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

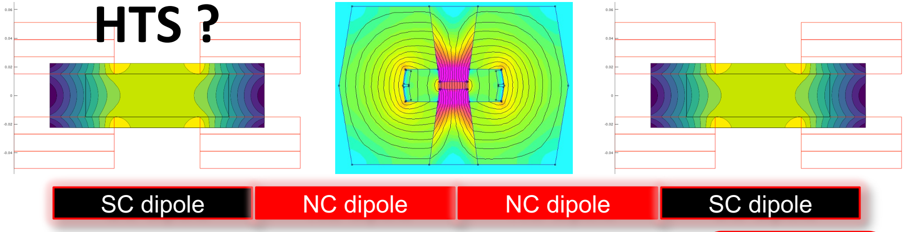
Muon Collider magnets

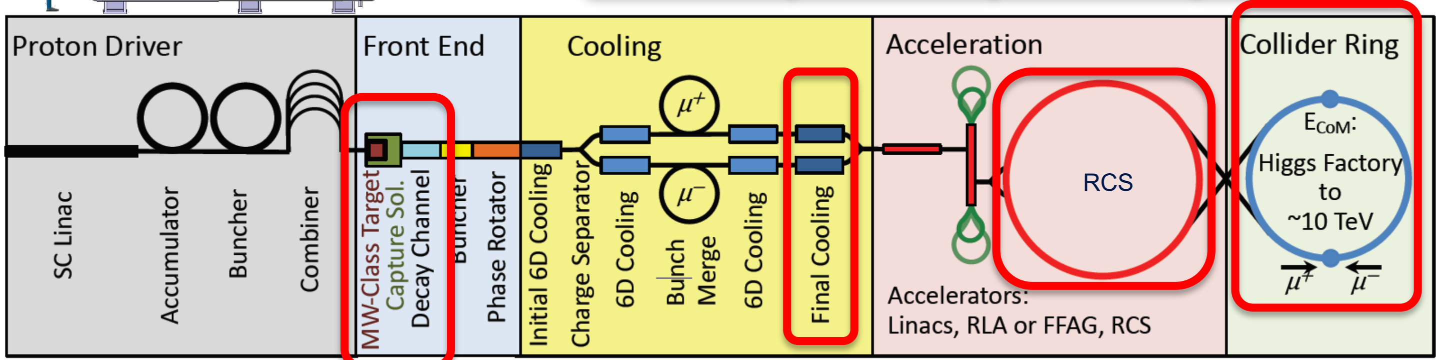
20 T, 200 mm **HTS !**
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy

HTS ?

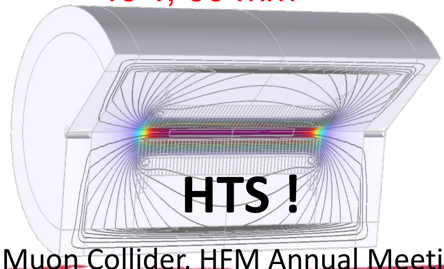
NC ±1.8 T, 400 Hz
100 mm x 30 mm

SC < 10T
100 mm x 30 mm

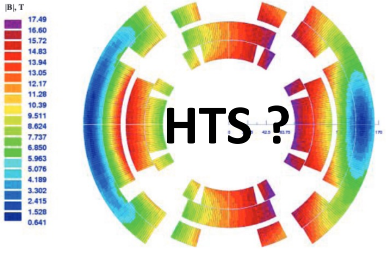




> 40 T, 60 mm



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



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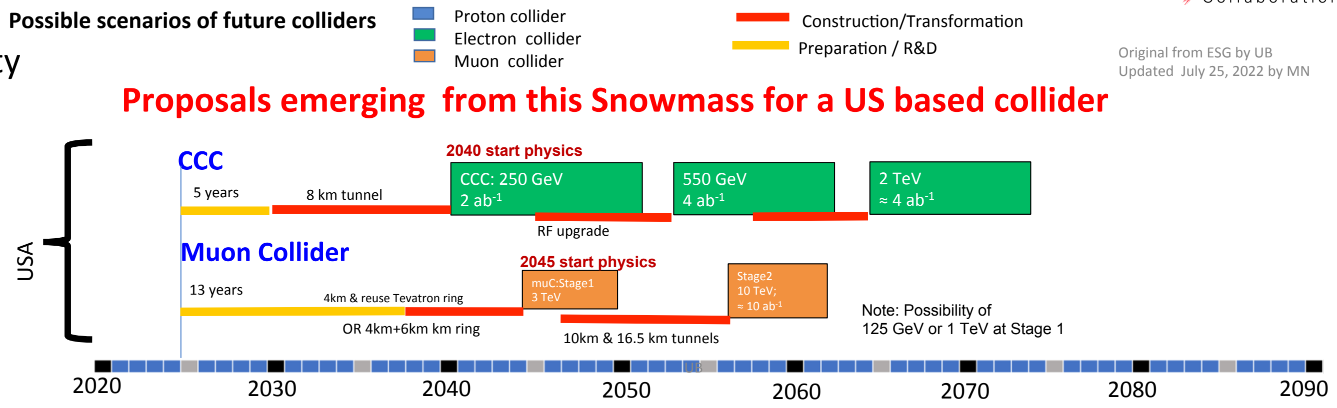

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Meenakshi Narain: Energy Frontier / Large Experiments, Snowmass Community Summer Study July 17-26, 2022

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

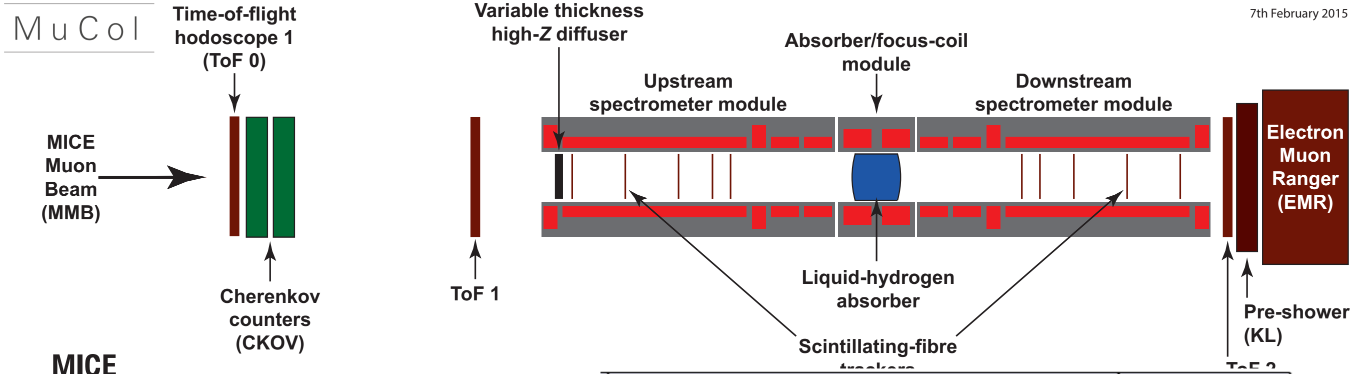
Magnets	Luca Bottura
RF	Alexej Grudiev, Dario Glove
Beam-matter int. target systems	Anton Lechner
Collective effects	Elias Metral

Cooling cell design	Lucio Rossi
Demonstrator	Roberto Losito

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

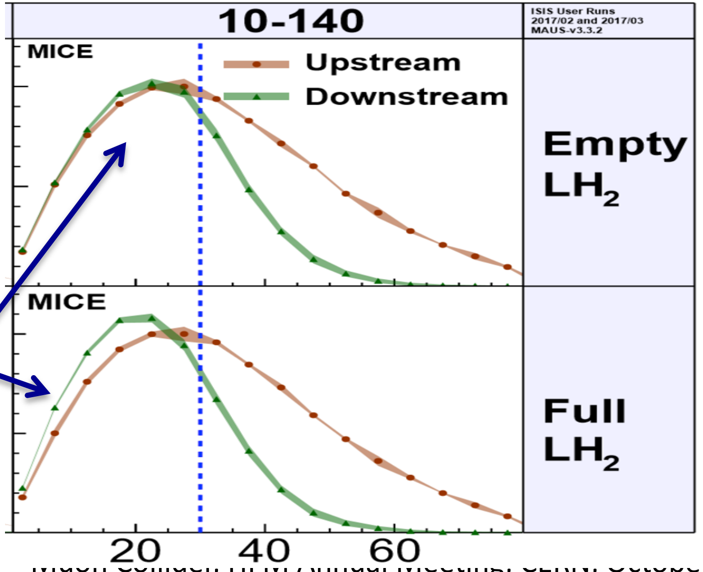
A strengthening on the physics and detector side is planned

MICE: Cooling Demonstration

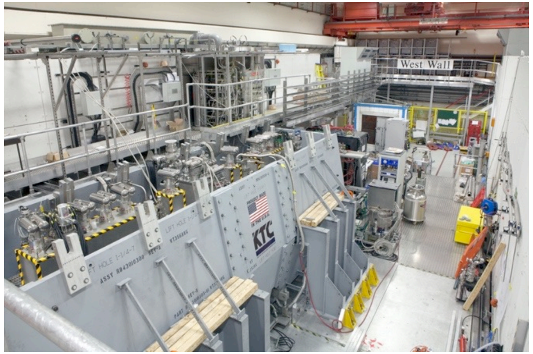


Principle of ionisation cooling has been demonstrated

Use of data for benchmarking is still ongoing



More particles at smaller amplitude after absorber is put in place



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

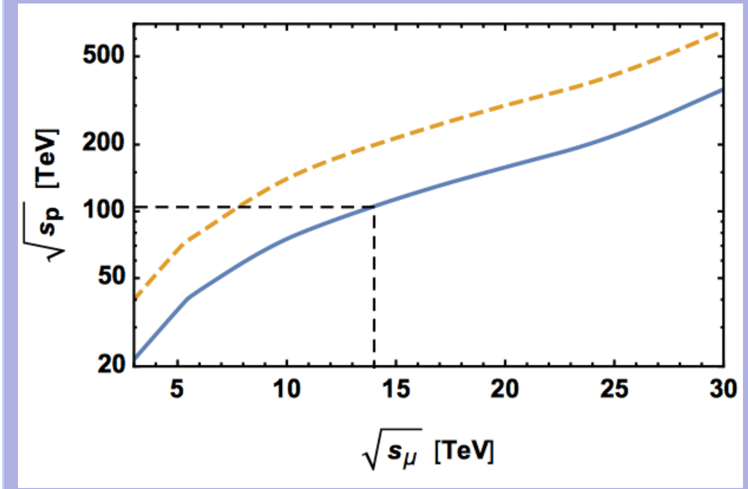
More complete experiment with higher statistics, more than one stage required

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)
$4 \times 10^{35}\ cm^{-2}s^{-1}$ at 14 TeV

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

Yields constant number of events in the s-channel

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

Physics Studies

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