Muon Collider

D. Schulte for the International Muon Collider Collaboration

ICHEP
July 2022

International
MUON Collider
Collaboration

CERN

Introduction

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

New strong interest:

- Focus on high energy
  - 10+ TeV
  - potential initial energy stage
- Technology and design advanced

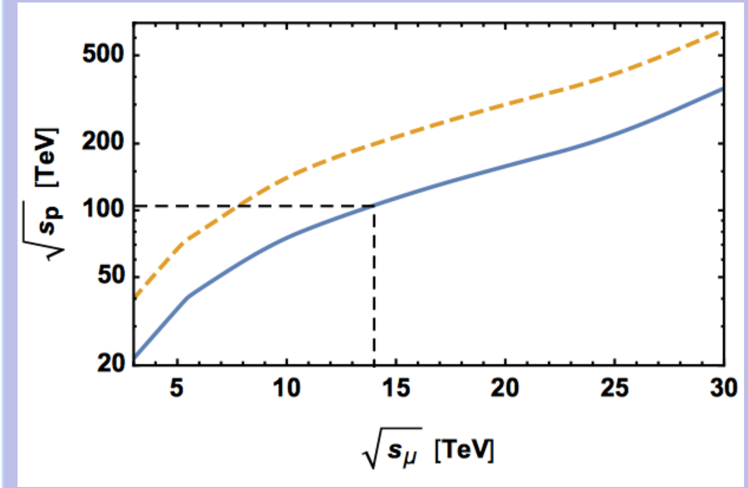
New collaboration started

Initial integrated luminosity targets

- could be reached in 5 years
- to be refined with physics studies

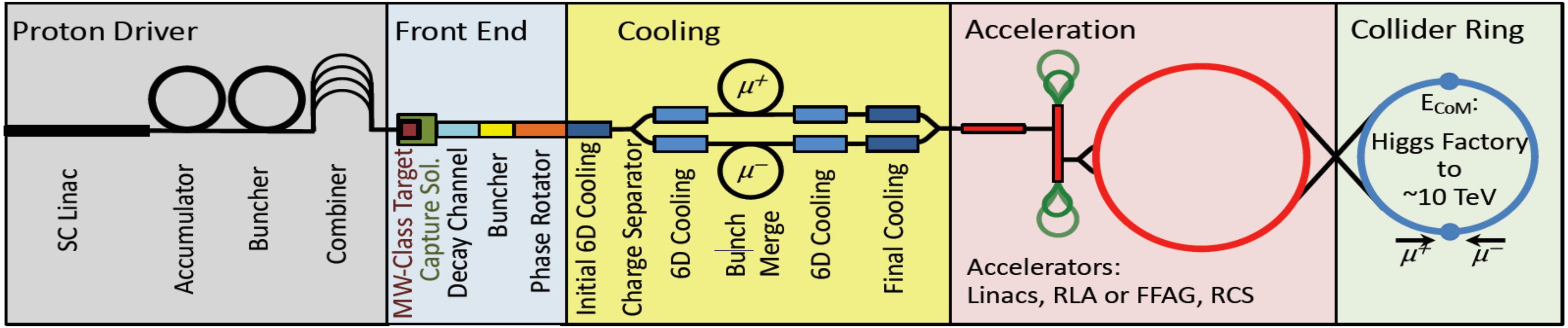
$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

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



Collider Overview

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



Short, intense proton bunch

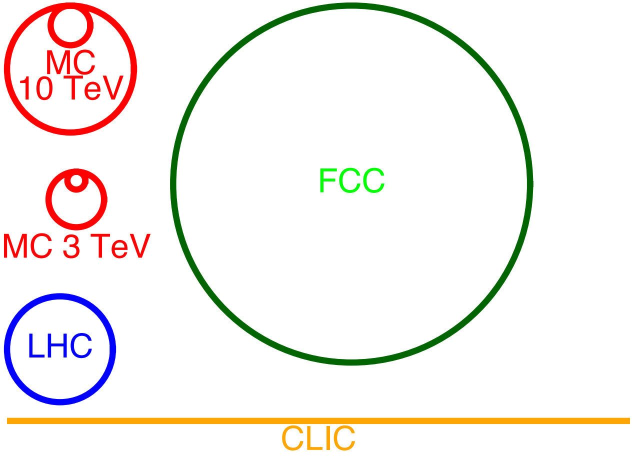
Protons produce pions which decay into muons
muons are captured

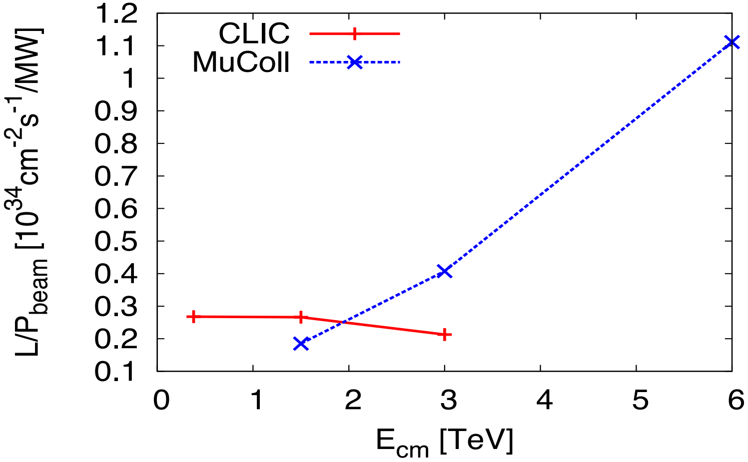
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Sustainability





CLIC is highest energy proposal with CDR
- No obvious way to further improve linear colliders (decades of R&D)
- Cost 18 GCHF, power 590 MW

Rough rule of thumb:
- cost proportional to energy
- power proportional to luminosity

Muon Collider challenging but reasonable **goals (10 TeV):**
- Much **more luminosity ($L=20\times10^{34}$, CLIC: $L=2\times10^{34}/6\times10^{34}$)**
- **Lower power consumption** than CLIC at 3 TeV ($P_{beam,MC}=0.5P_{beam,CLIC}$)
- **Lower cost**

Staging is possible
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	$1\ \mathrm{ab}^{-1}$
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 MW
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 Council LDG develop R&D Roadmap

- global community participated
- a global roadmap
- with estimates of required resources

No obstacle found for the muon collider

- but important need for R&D

Council asked for implementation plan

- We are trying to secure resources

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		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.

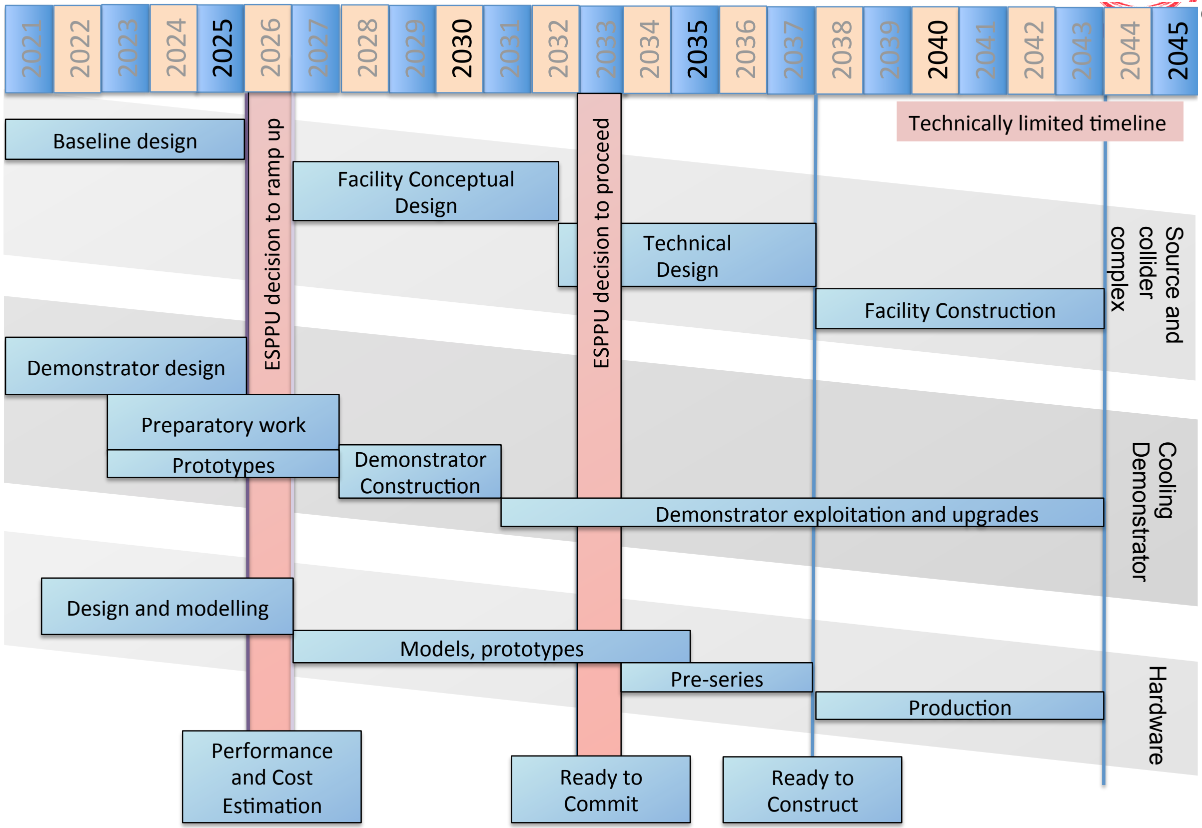
Timeline

Goals for next strategy

- Assessment report
- R&D plan ready for implementation

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

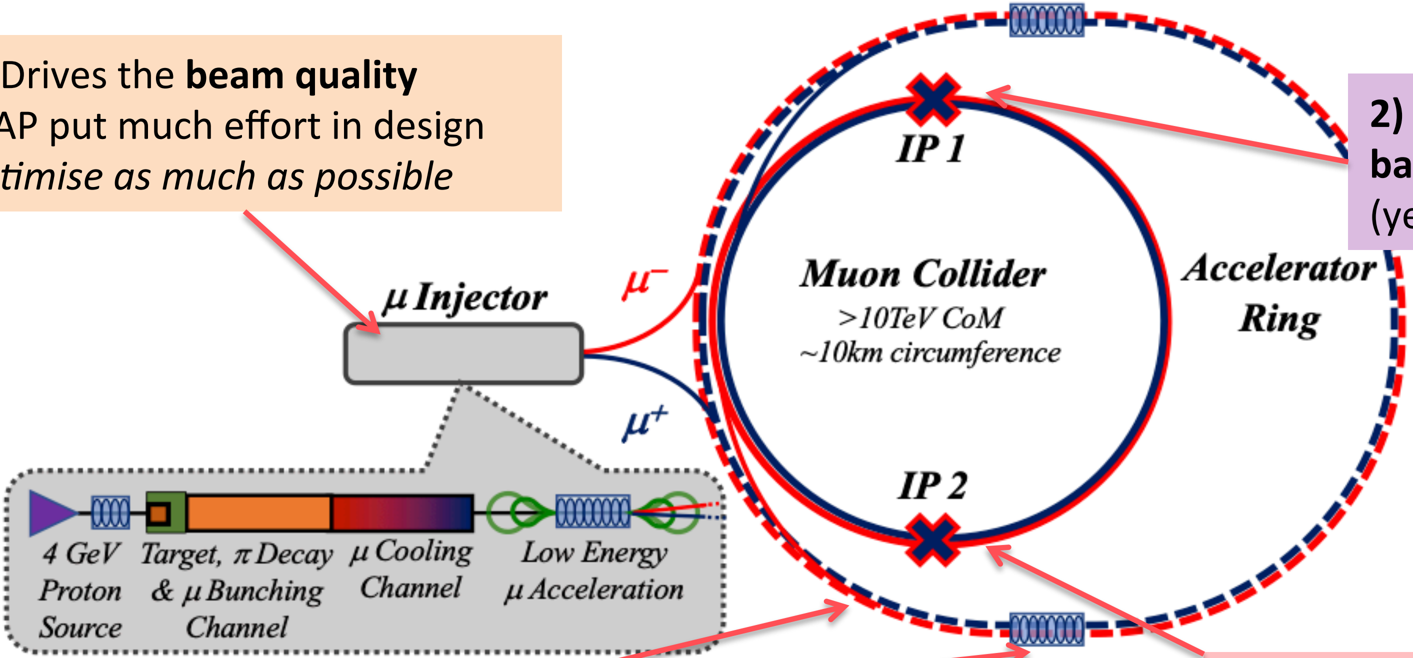
- e.g. in Europe if higgs factory built elsewhere
- very strong ramp-up required after 2026
- some compromises on initial performance



International MUON Collider Collaboration

Key Challenges

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



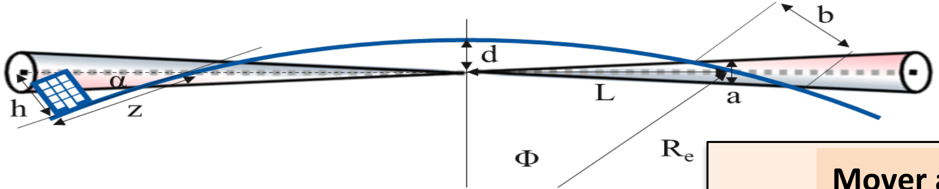
2) Beam-induced background
(yesterday)

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

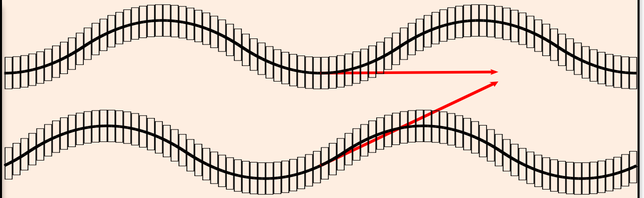
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Neutrino Flux

Goal: **similar to LHC**: i.e**. negligible**, "fully optimised" (10% of MAP goal) **likely OK for 14 TeV**

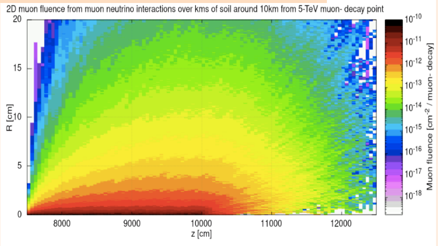


Mover and support system



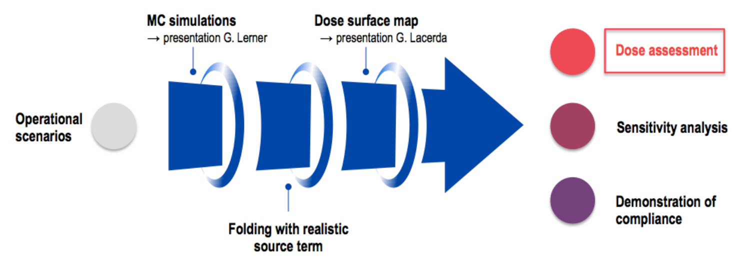
F. Bertinelli et al. (CERN, Riga)

FLUKA dose studies



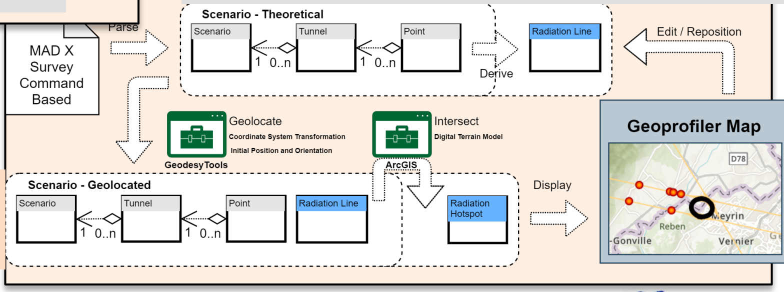
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme

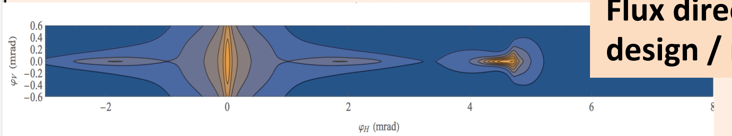


C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

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



Flux direction map / lattice design / mover impact on beam

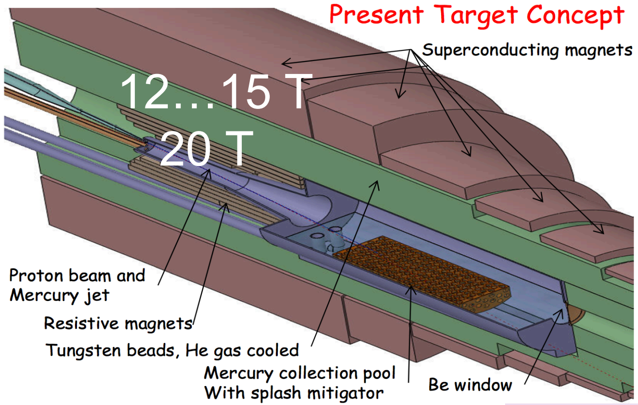


C. Carli, K. Skoufaris (CERN)

Mitigation: Site choice tool

Target

MAP target design, K. McDonald, et al.

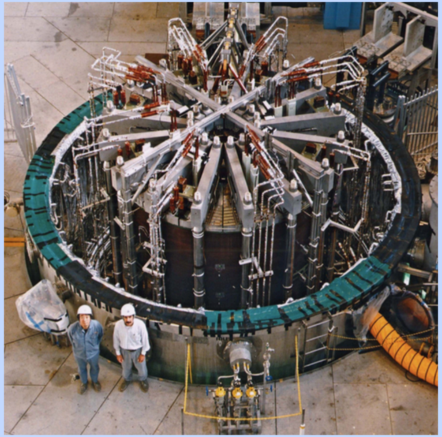


Two approaches:

- 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.



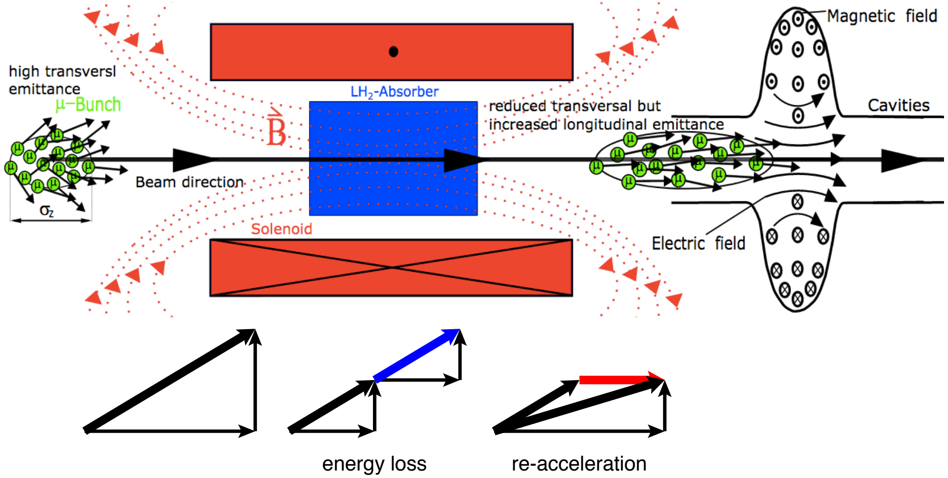
ITER Central Solenoid Model Coil
13 T in 1.7 m (LTS)

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

STFC will also study alternatives

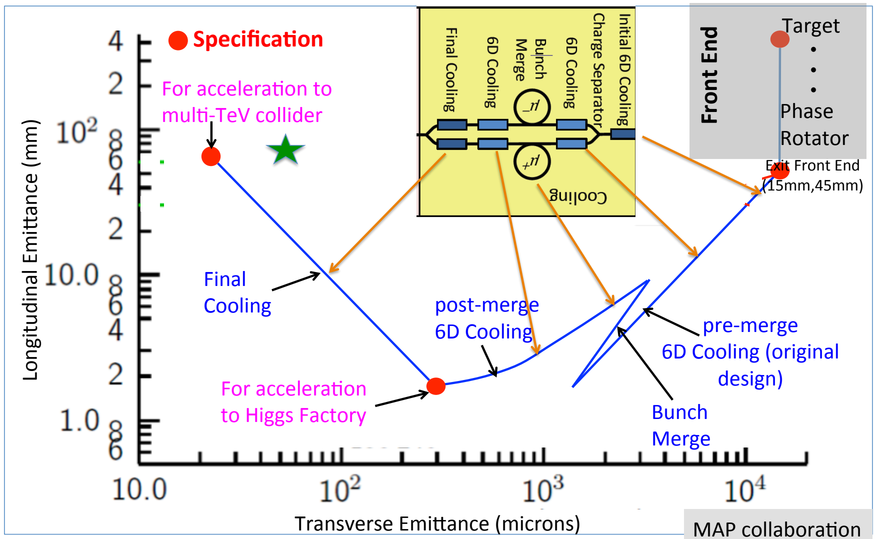
Operation at 2000 °C to maximise stress resistance

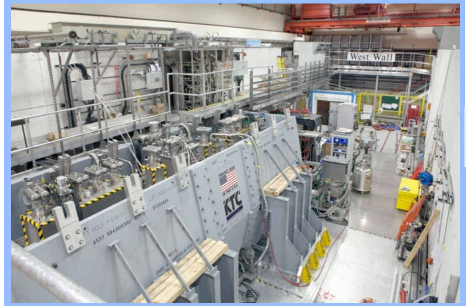
Muon Cooling



MAP designs almost achieve 10 TeV goal

- miss factor two for final cooling





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

Integration/optimisation of overall cooling design

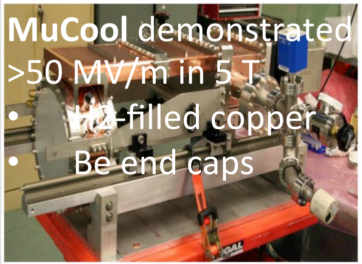
Integrating **improved technology**

C. Rogers et al.

Cooling Cell Technology

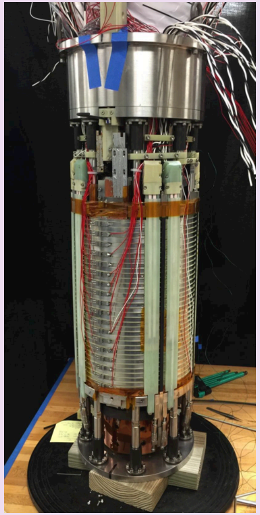
C. Marchand, Alexej Grudiev et al. (CEA, Milano, CERN, Tartu)

RF cavities
MAP demonstrated higher than goal gradient
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



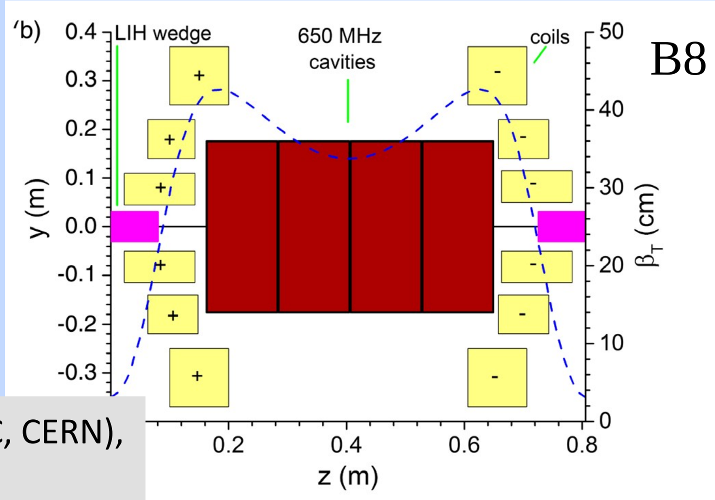
MuCool demonstrated
>50 MV/m in 5 T
- H_2-filled copper
- Be end caps

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



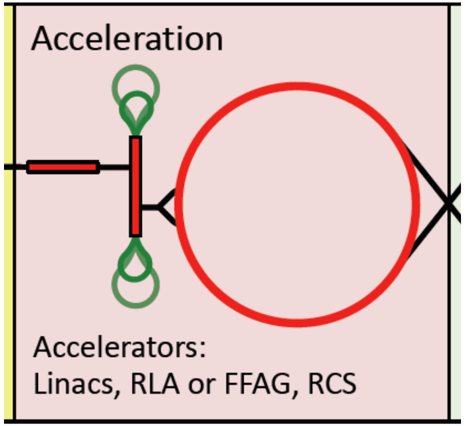
L. Bottura et al. INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP

Will develop **cooling cell 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.

Acceleration Complex

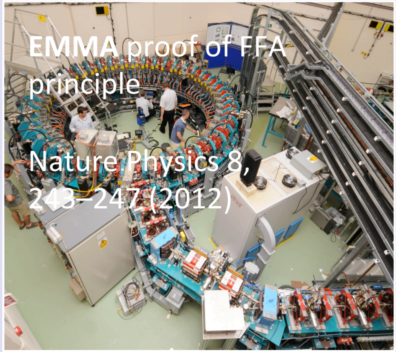


Baseline is sequence of pulsed synchrotron (0.4-11 ms)
Important cost and power consumption
started to develop integrated design

- Lattice design for larger energy bandwidth — A. Chance et al. (CEA)
- Fast-ramping normal magnets — L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
  - HTS starts to look interesting
  - profit from MAP study and US
- Power converter with energy recovery — F. Boattini et al.
- RF with high transient beam loading — H. Damerell, F. Batsch, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)

FNAL 290 T/s HTS magnet

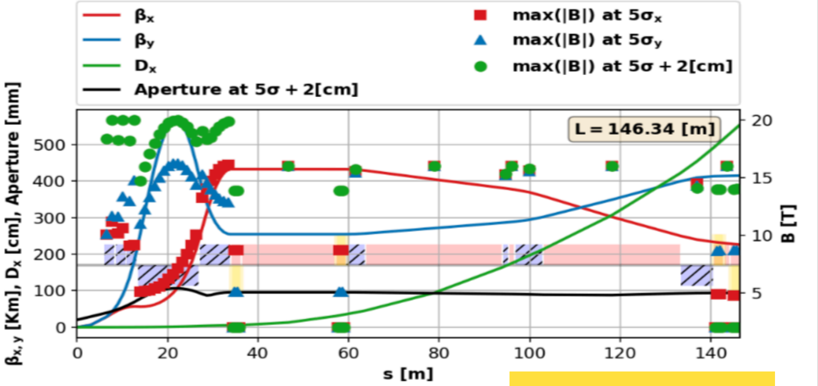
Alternative FFA



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

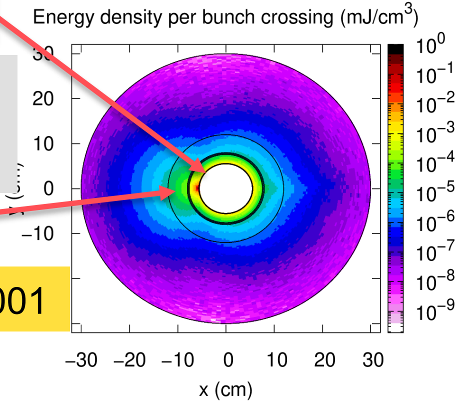
INFN, Milano, Kyoto, CERN, profit from US

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

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
    - first results for aperture requirements
- potential instability of interaction of muon beam with matter

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

Power and **cost optimisation**

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

Vacuum and **absorber, instrumentation, cryogenics**, …

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 exists** on CERN land and can use **PS proton beam**

- could combine with **NuStorm** or other option

Other sites should be explored (FNAL?)

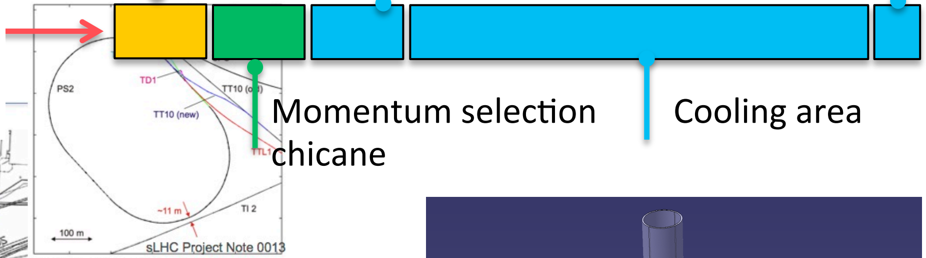
Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

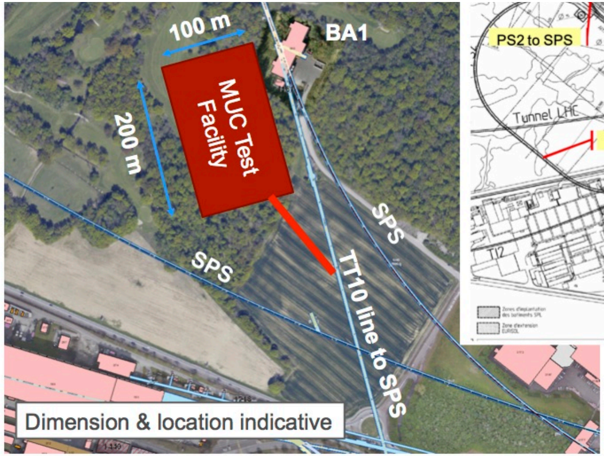
Collimation and upstream diagnostics area

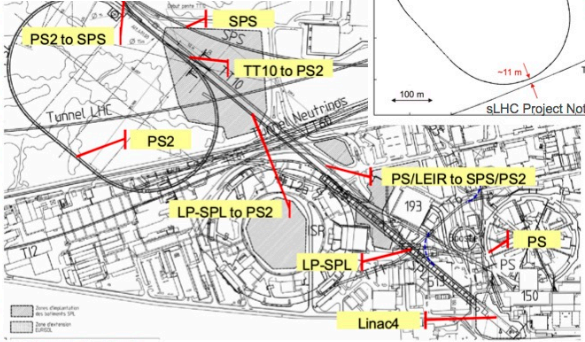
Downstream diagnostics area

Momentum selection chicane

Cooling area

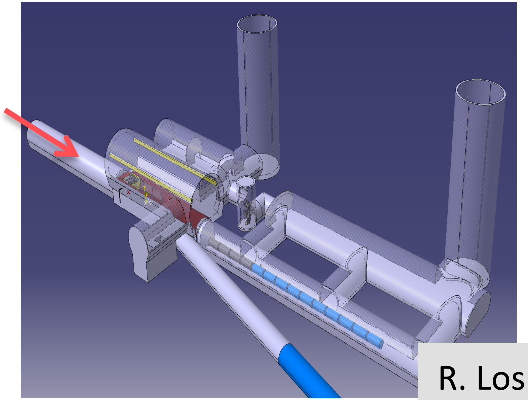






M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061



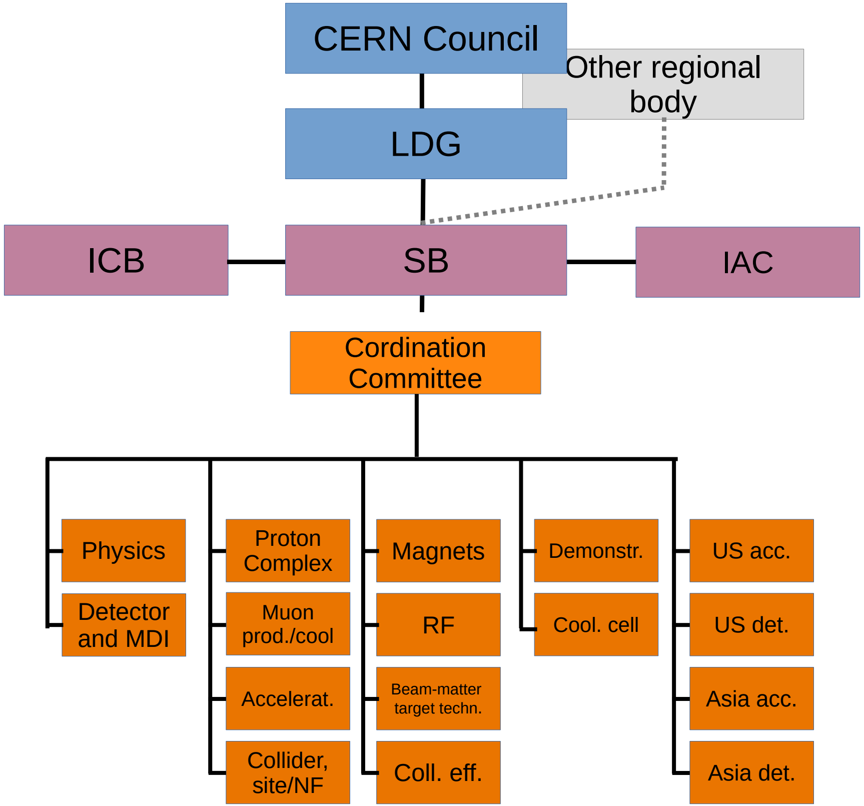
R. Losito et al.

Key Next Steps

Turn the Roadmap into an evolving workplan
- adjusting to priorities and resources

Securing resources
- In different institutes
- Request to national funding
- EU Design Study proposal submitted
- EU technology study planned for next call
- US Snowmass/P5 process
- …

But are already working



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 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 of 10+ TeV
  - potential 3 TeV intermediate stage explored
  - will consider other options later

- Need to turn Roadmap into a workplan to change this
- Important activities have started
- First important results are already obtained

http://muoncollider.web.cern.ch

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

Reserve

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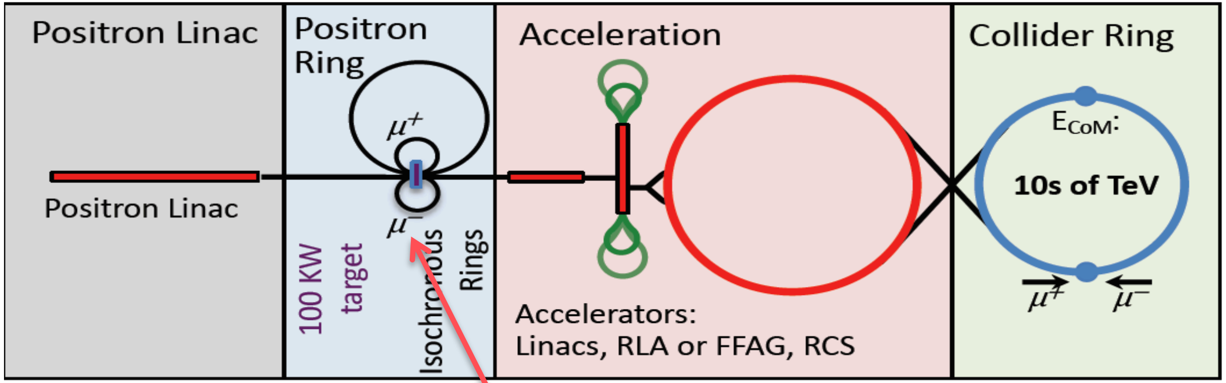
Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



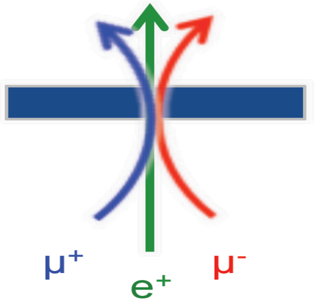
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

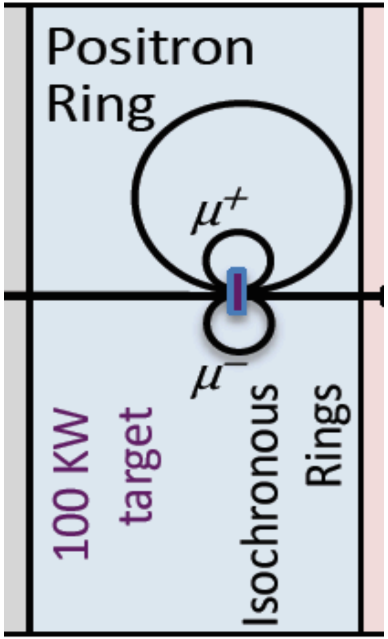
- Uses Bethe-Heitler production with electrons

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**

MICE: Cooling Demonstration

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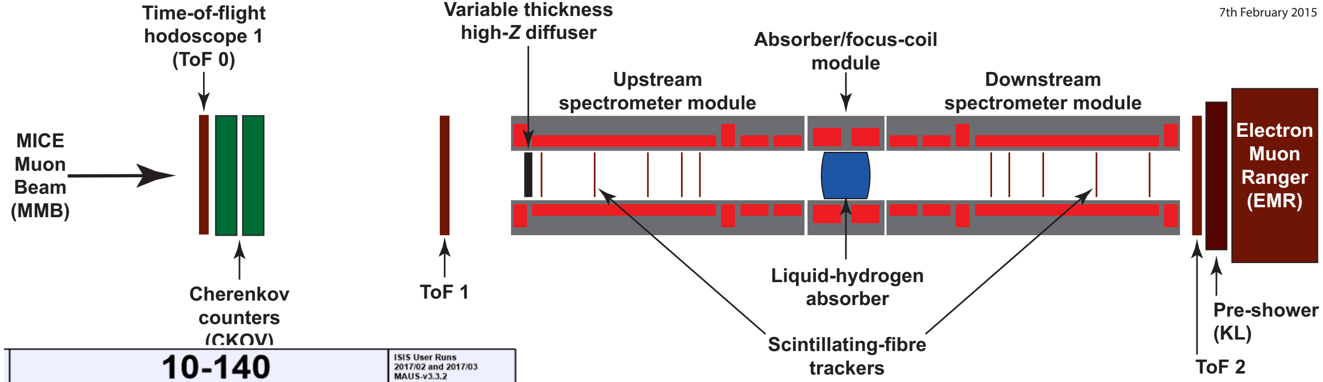

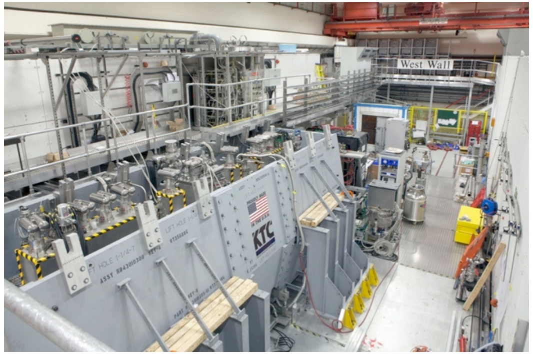

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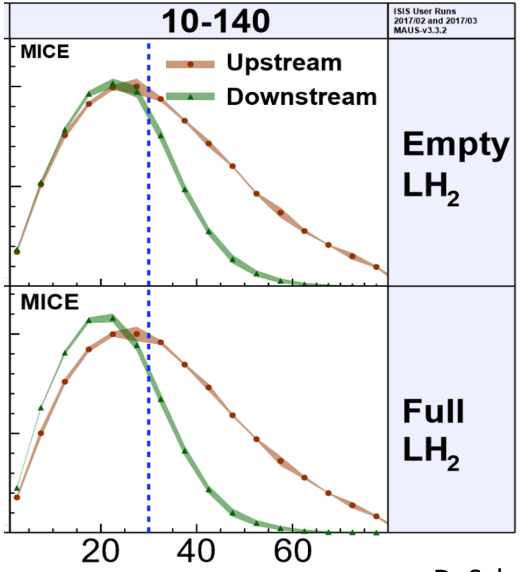

More particles at smaller amplitude after absorber is put in place

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

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

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

WEPOPT053

Neutrino Flux

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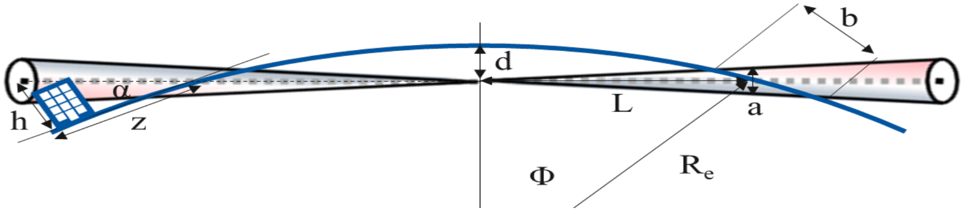
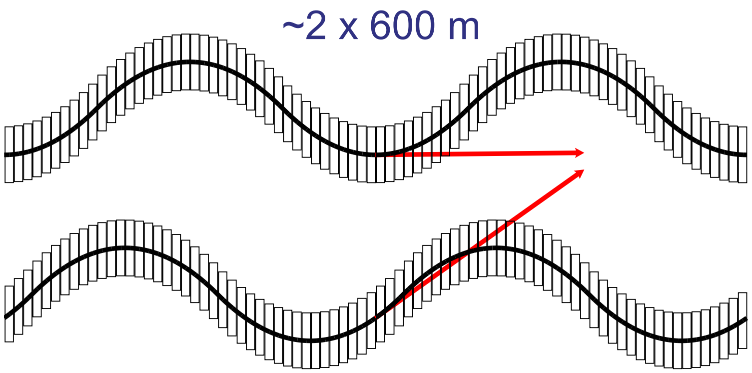
Dense neutrino flux cone can impact environment
Challenge scales with **E x L**

Goal is to reduce to negligible level, similar to LHC
- **3 TeV, 200 m deep tunnel is about OK**



Expand idea of Mokhov, Ginneken to move beam in aperture: move collider ring components, e.g. vertical bending with 1% of main field
- **14 TeV, in 200 m deep tunnel comparable to LHC case with +/- 1 mradian**
- **scales with luminosity toward higher E**



Need to study mover system, magnet, connections and impact on beam

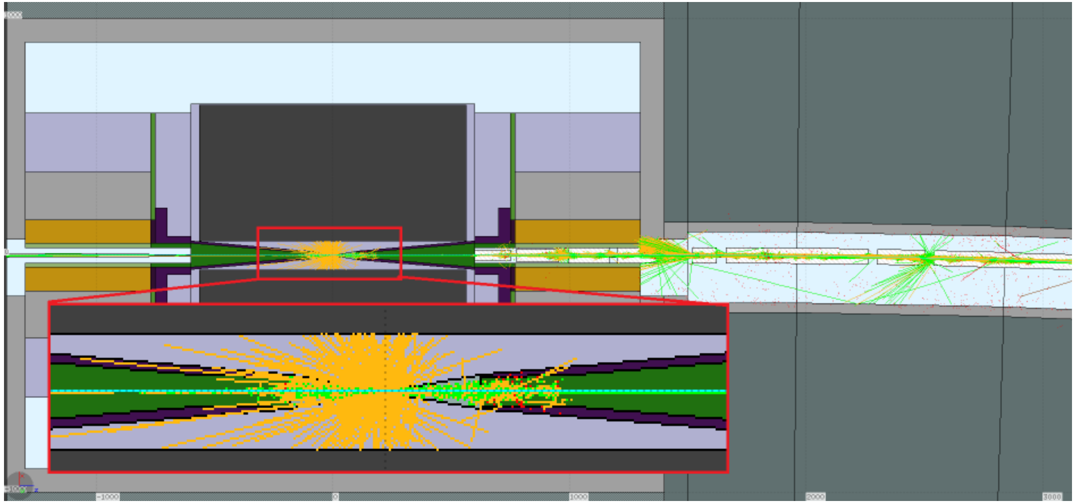
Working on different approaches for experimental insertion

Other optimisations are possible (magnetic field, emittance etc.)

Machine-Detector Interface

Main background sources

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



Mitigation methods

- masks
- detector granularity
- detector timing (background out of time)
- track direction (background from wrong vertices)
- event reconstruction strategies
- …

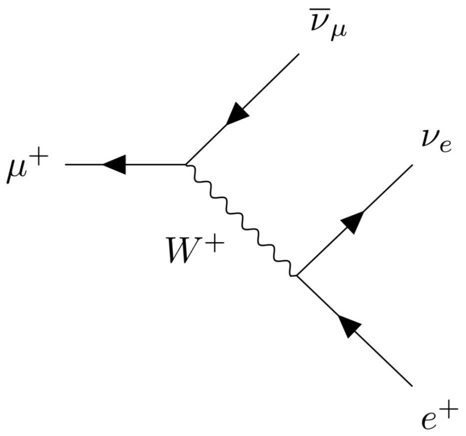
Active study of background is ongoing

- Encouraging results at 1.5 and 3 TeV
- 10 TeV studies started, lower rate of loss
- Beam-beam started
- started to study impact of lattice design

ICHEP

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

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
- first results look encouraging
- will be discussed at ICHEP

Collider ring magnets need to be shielded from losses

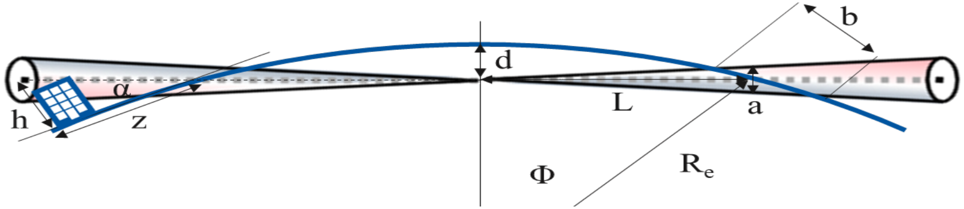
Losses elsewhere will also need to be considered but are less severe

ICHEP

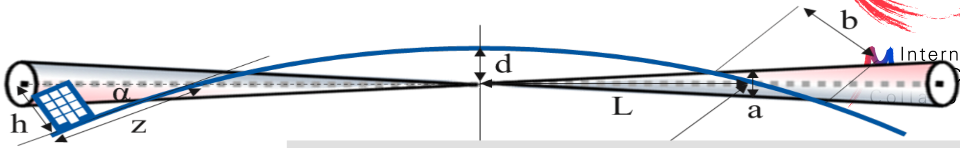
D. Lucchesi, A. Lechner, C Carli et al.

Neutrino flux to have negligible impact on environment

- want to be **negligible**
- opening cone decreases with energy
- cross section and shower energy increase with energy
- need to do something above around 3 TeV

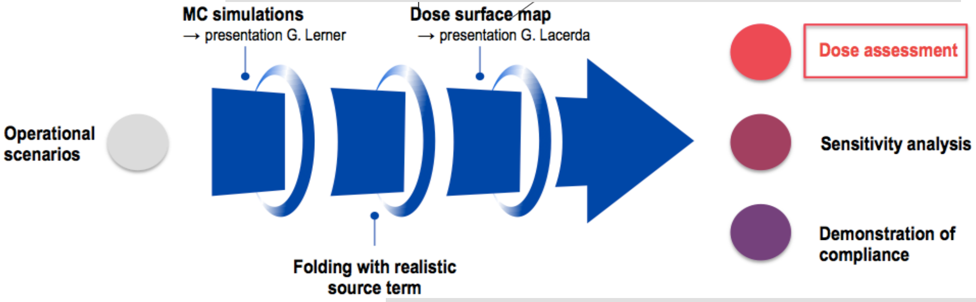


Neutrino Flux



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)

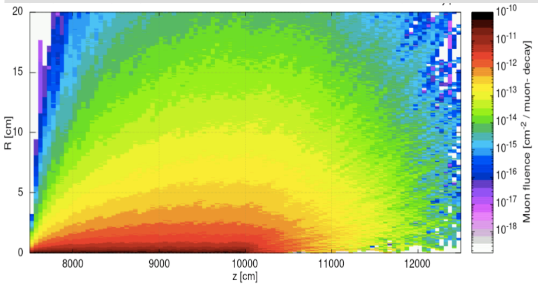
C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

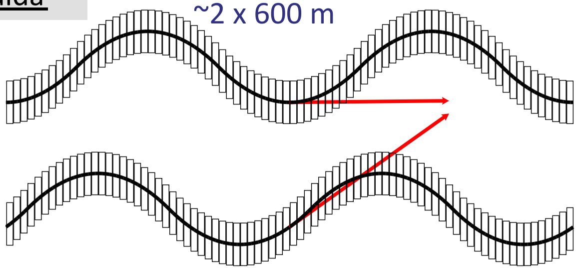


Site choice
Mechanical mover system in arcs (based on CLIC remote mover system but larger range)

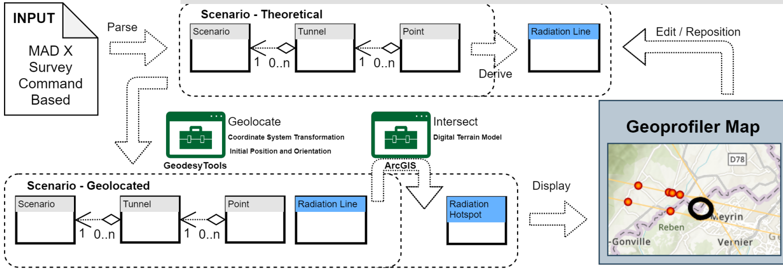
- allows 14 TeV in 200 m deep tunnel

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





G. Lacerda, Y. Robert, N. Guilhaudin



Mover system and impact on beam will be addressed in the coming years before end if 2025

Collider Ring

Three considerations:

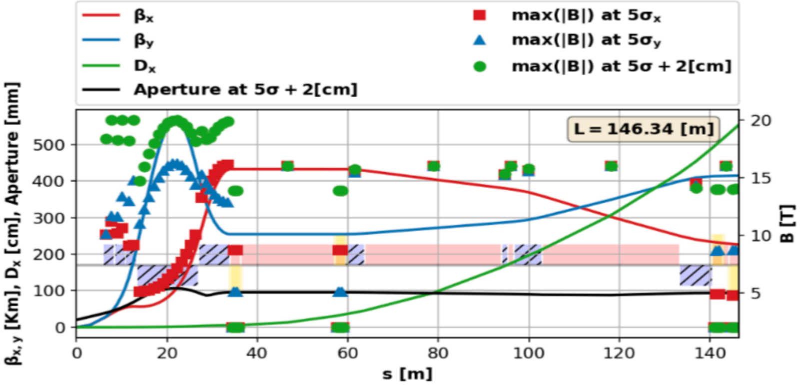
- luminosity is proportional to average magnetic field
- muon beam decay requires larger apertures (O(15cm)
- very small beta-function at IP required

MAP developed 3 TeV with Nb_3Sn magnets and 4.5 km circumference

- magnet specifications in the HL-LHC range

Work on 10 TeV collider ring with 10 km circumference and either Nb_3Sn or HTS magnets

- around 16 T dipole field aperture around 15 cm
- final focus based on HTS



C. Carli et al.

MOPOTK031

Option:

at 3 TeV, **NbTi** with 8 T in arcs could fit in 6 km ring, slight decrease of L = 1.35 x 10^{34} cm^{-2}s^{-1}, could be

at 10 TeV, use of HL-LHC performances would lead to 15 km ring and L=13 x 10^{34} cm^{-2}s^{-1}

Collider Ring

WEPOST001

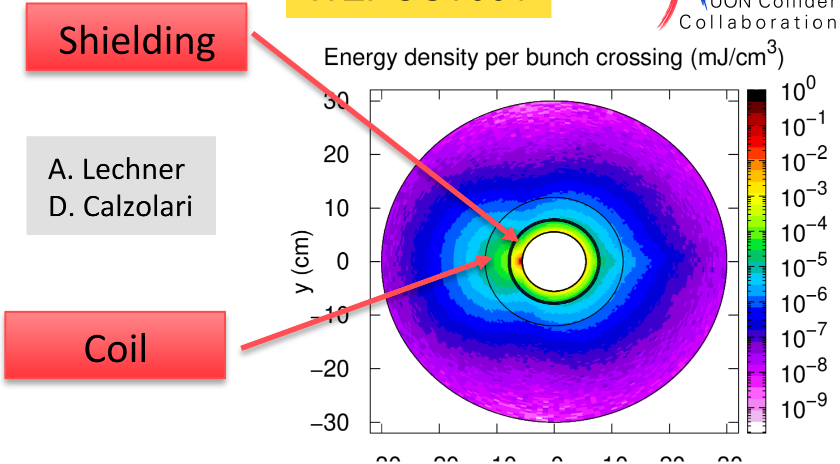
Muon beam decay produces high-energy electrons and positrons (1/3 of beam power, 500 W/m)

⇒ need to shield magnets

⇒ Mokhov et al. showed shielding to 1% at 3 TeV with 30-50mm shielding

⇒ new study at 10 TeV shows that radiation dose is OK with 30 mm shielding, similar to 3 TeV

A. Lechner
D. Calzolari



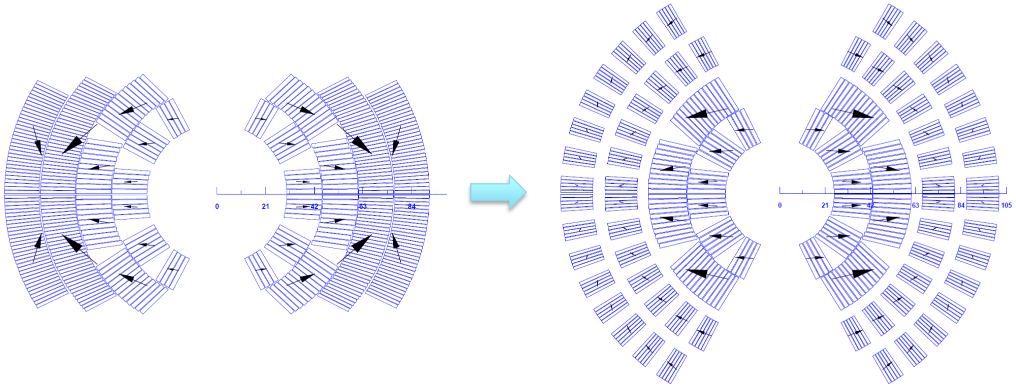
Cooling power required at 10 TeV

for 2 K 700 x 0.01 x 1/3 x 14 MW = 33 MW

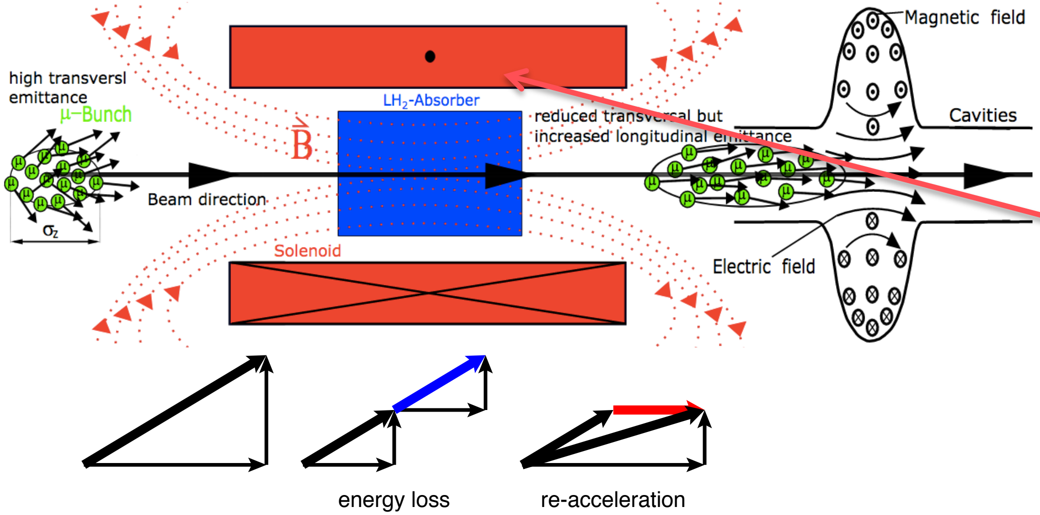
for 20 K 70 x 0.01 x 1/3 x 14 MW = 3.3 MW

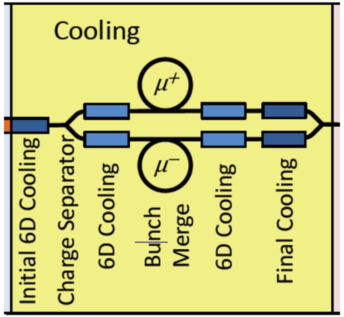
Magnets require stress management

L. Bottura et al.



Cooling Principle





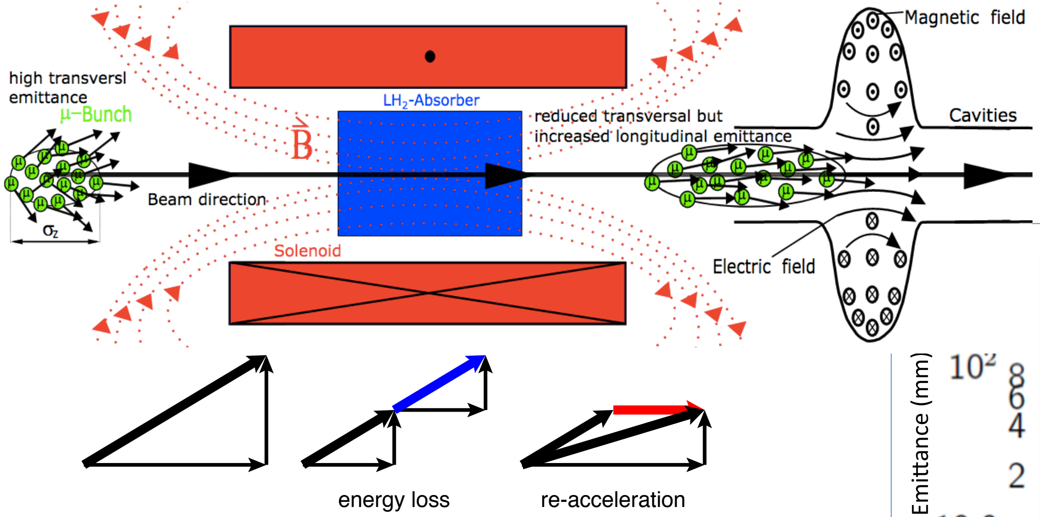
High field solenoids minimise beta-function and impact of multiple scattering

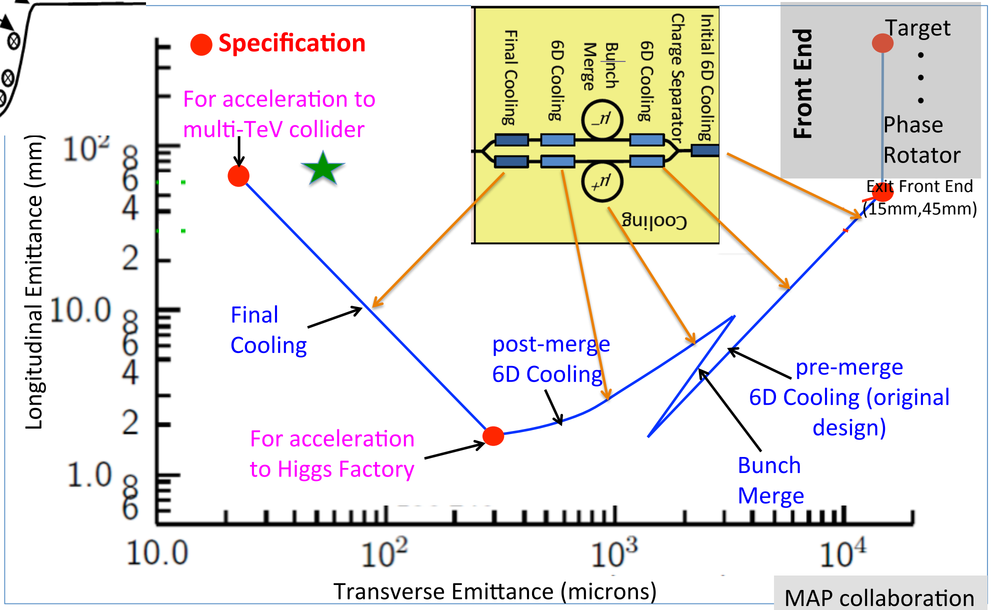
Energy loss = cooling

Multiple scattering = heating

$$\frac{d\epsilon_\perp}{ds} = \boxed{-\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E}} + \boxed{\frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}}$$

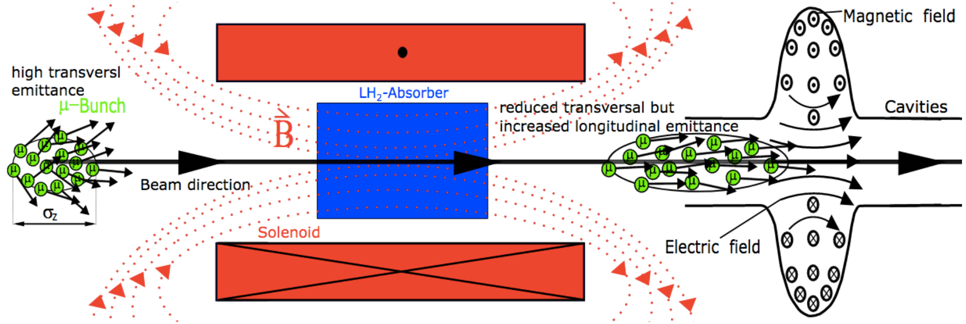
Cooling Principle

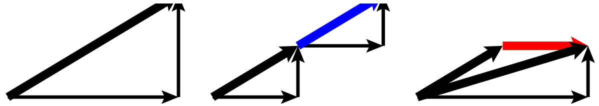


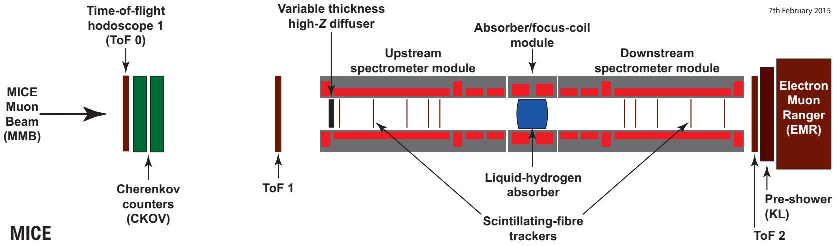


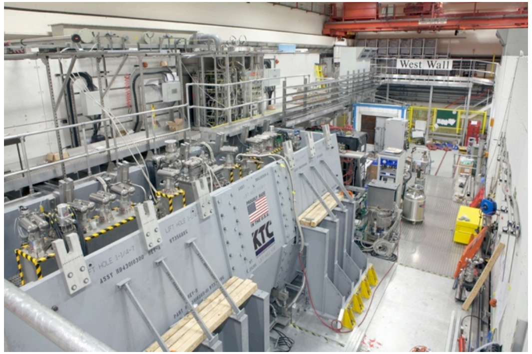
Cooling Principle and Demonstration

International MUON Collider Collaboration

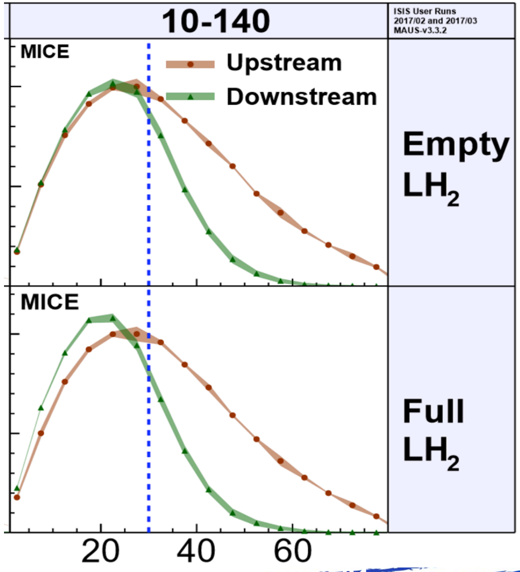








More particles at smaller amplitude after absorber is put in place



Principle of ionisation cooling has been demonstrated in **MICE at RAL**
Use of data for benchmarking is still ongoing

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

WEPOPT053

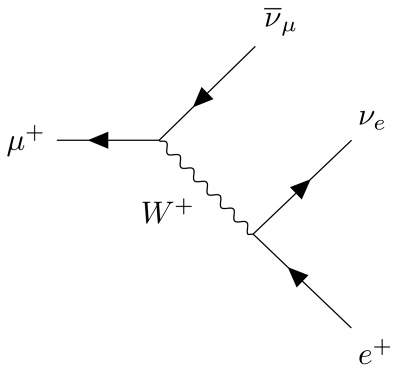
Thanks

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

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

Donatella, ICHEP

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

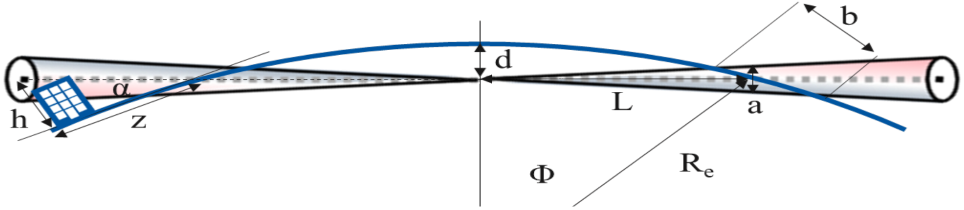
Neutrino flux to have negligible impact on environment

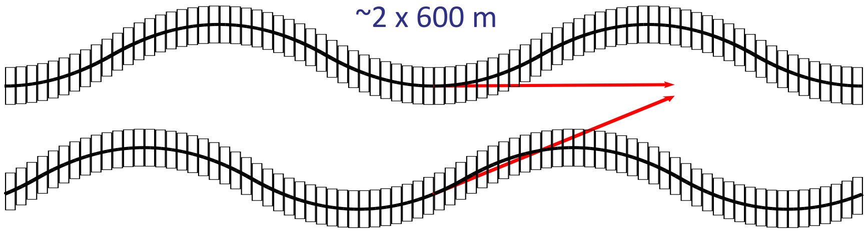
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

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

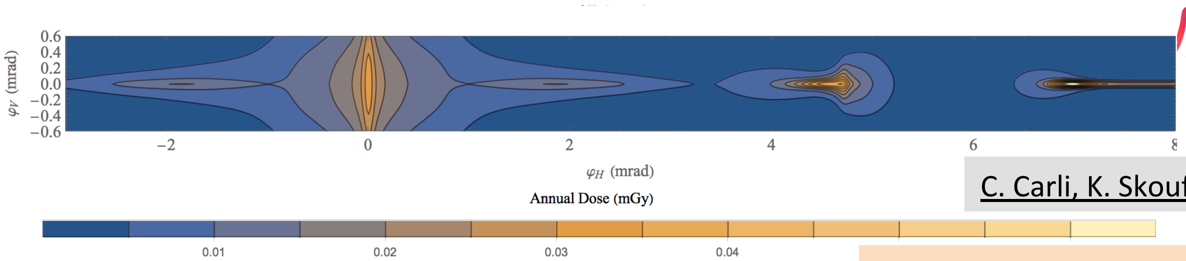




Neutrino Flux

International MUON Collider Collaboration

Team of RP experts, civil engineers, beam physicists and FLUKA experts
Goal: **similar to LHC**: i.e**. negligible**, "fully optimised" (10% of MAP goal)

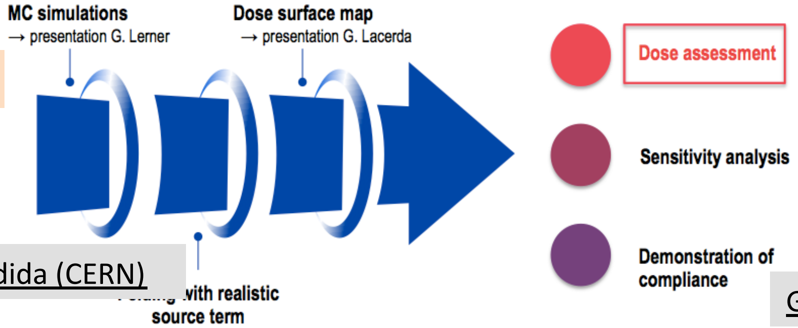


C. Carli, K. Skoufaris (CERN)

Flux direction map
Lattice design
Impact of mover on operation

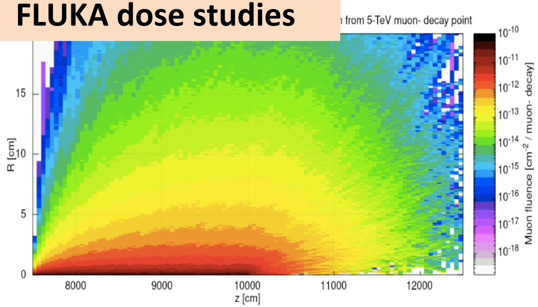
Conformity Verification Scheme

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



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

FLUKA dose studies

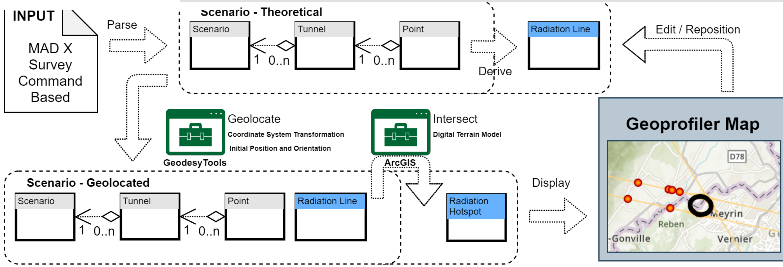


Mitigation:
Mover and support system

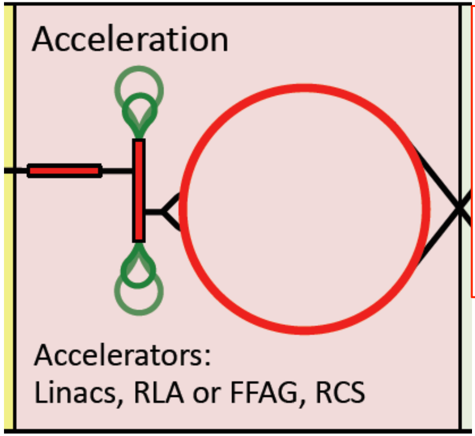
F. Bertinelli et al. (CERN, Riga)

Mitigation:
Site choice tool

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

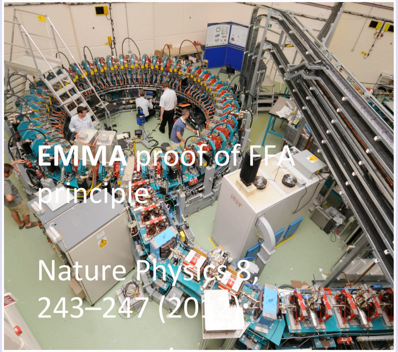


Acceleration Complex

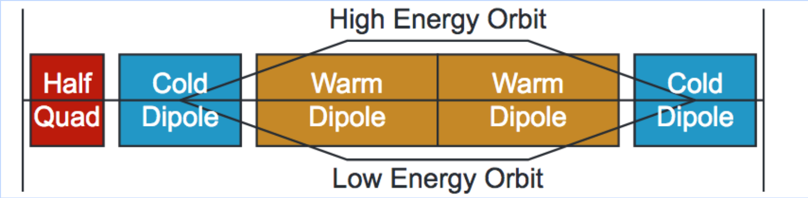


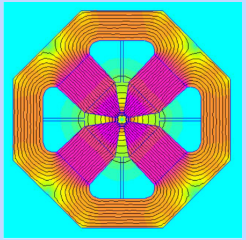
Linac
Recirculating linacs
Sequence of rings
- baseline: pulsed synchrotron (RCS)
- alternative: FFA

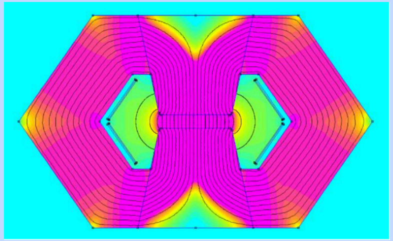
Alternative *FFA*
- Fixed (high-field) magnets but large energy acceptance
- Challenging **lattice design** for large bandwidth and limited cost
- **Complex high-field magnets**
- Challenging beam dynamics

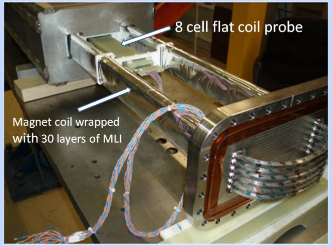


Hybrid RCS combines static superconducting magnets and fast-ramping normal-conducting magnets









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

MAP study S. Berg et al.

MAP study

RCS Challenge

International
UON Collider
Collaboration

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

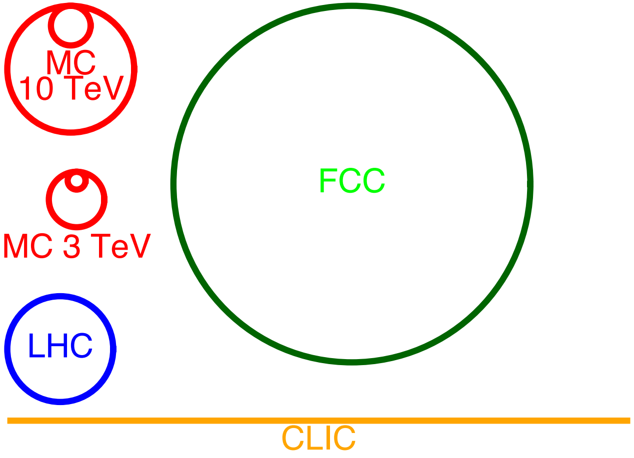
Need to match ramping speed of magnets with accelerating RF

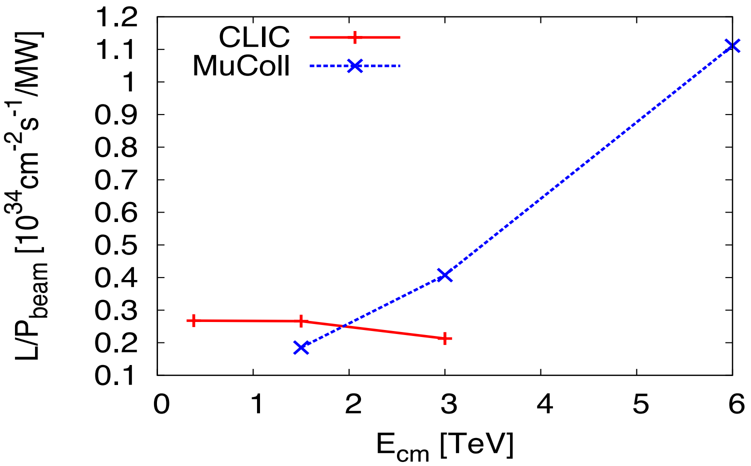
- Integrated design optimisation is needed
- Energy recovery from pulse to pulse is critical

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, F. Batsch, 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)

Sustainability





CLIC is highest energy proposal with CDR

- at the limit of what one can do (decades of R&D)
- No obvious way to further improve linear colldiers
- Cost 18 GCHF, power 590 MW

Muon Collider:

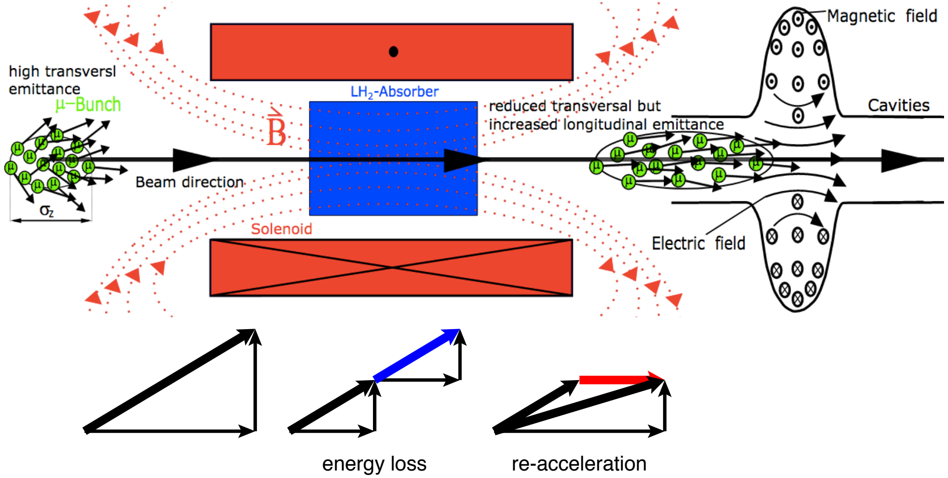
Acceleration and collision in multiple turns in rings promises

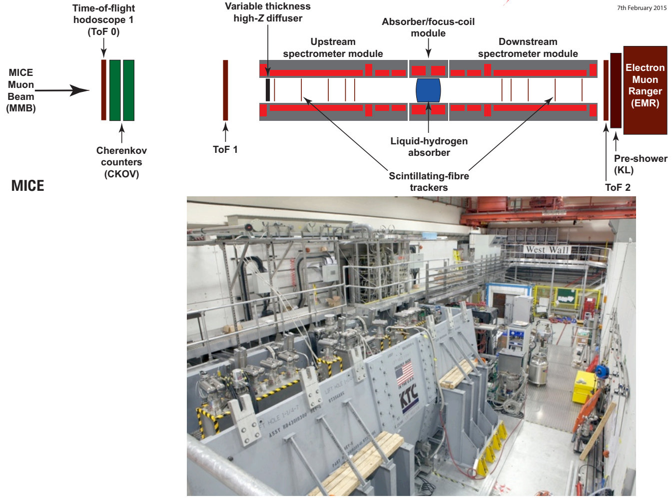
- **Power efficiency**
- **Compact tunnels,** 10 TeV similar to 3 TeV CLIC
- **Cost effectiveness**
- **Natural staging** is natural

Synergies exist (neutrino/higgs)

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

Cooling Principle

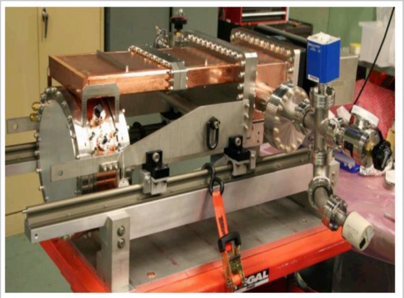




Nature vol. 578, p. 53-59 (2020)

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

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



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

Emittance Development

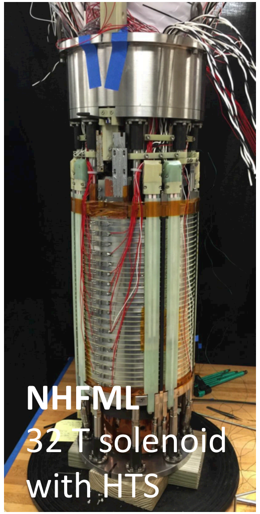
MAP designs almost achieve 10 TeV goal

- 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

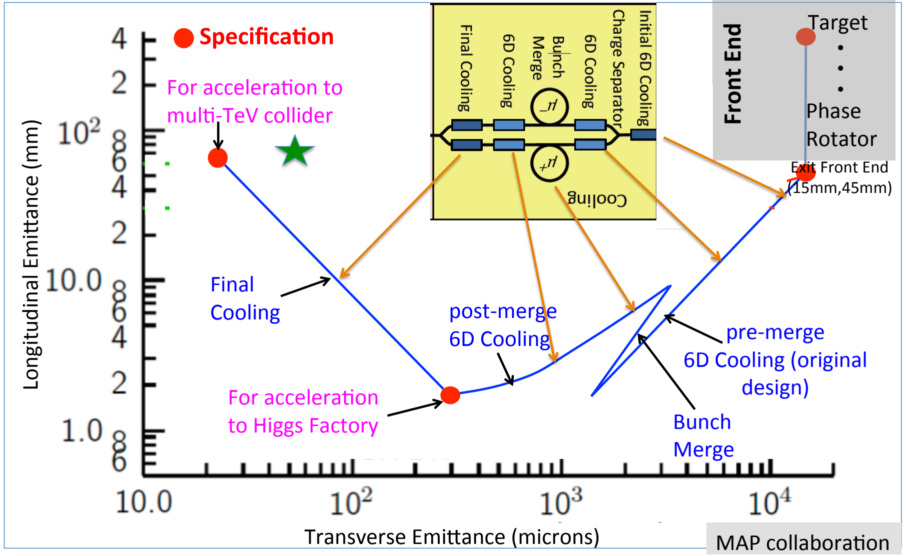
WEPOMS046
WEPOMS047



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.

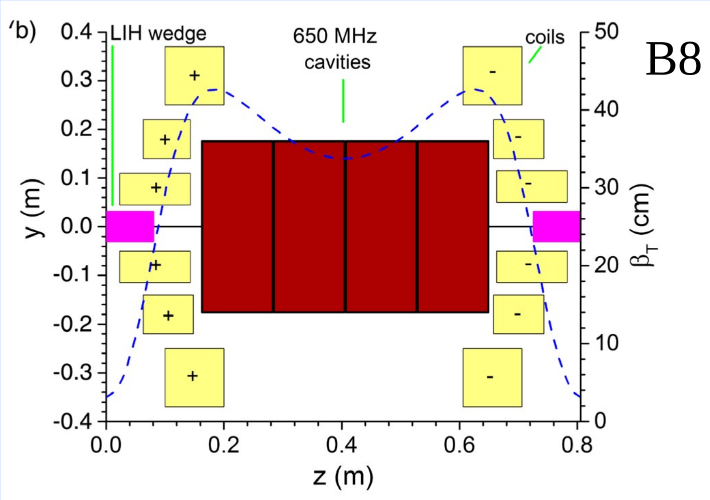
Cooling Cell Technology

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)
J. Ferreira Somoza et al.