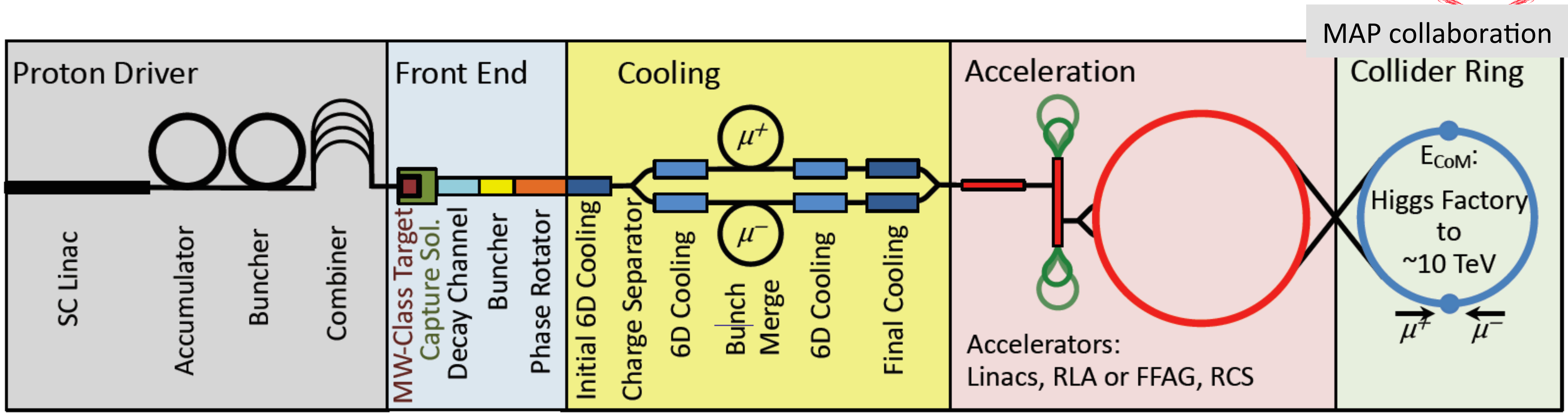
International
MUON Collider
Collaboration

Muon Collider Status

Daniel Schulte

Proton-driven Muon Collider Concept



Short, intense proton bunches to produce hadronic showers

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

Acceleration to collision energy

Collision

Pions decay into muons that can be captured

Work has been mainly performed in US (MAP Collaboration), test of muon cooling in UK
Some effort mainly in INFN on alternative

No CDR exists, no coherent baseline of machine, no cost estimate
US activity very much reduced after last P5
But many parts and no showstoppers

Comparing Luminosity in MAP vs. CLIC

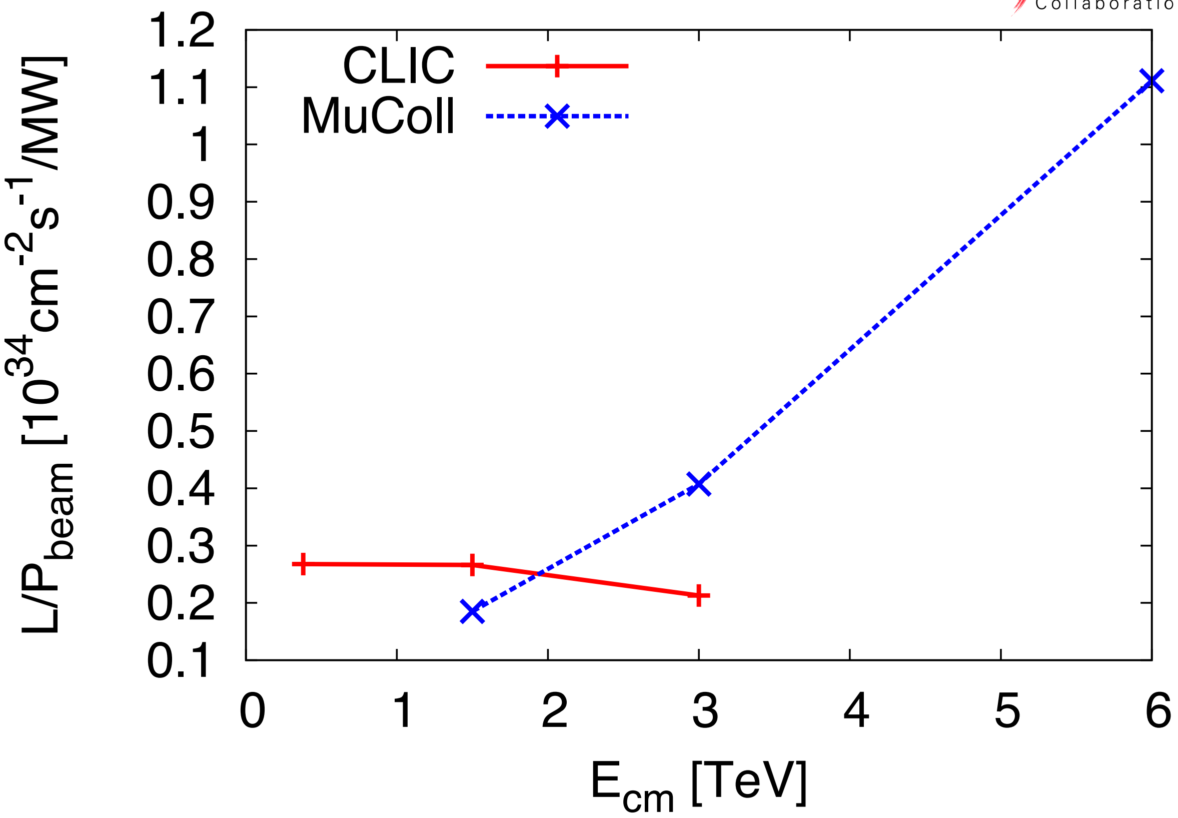
Linear colliders: Luminosity per beam power is independent of collision energy for same technology

CLIC is at the limit of what one can do (decades of R&D)

No obvious way to improve

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

Note: normalised emittances used, they do not decrease with energy



Muon collider: Luminosity per beam power can increase with energy

Potential for high energies

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

International Muon Collider Collaboration

Objective:

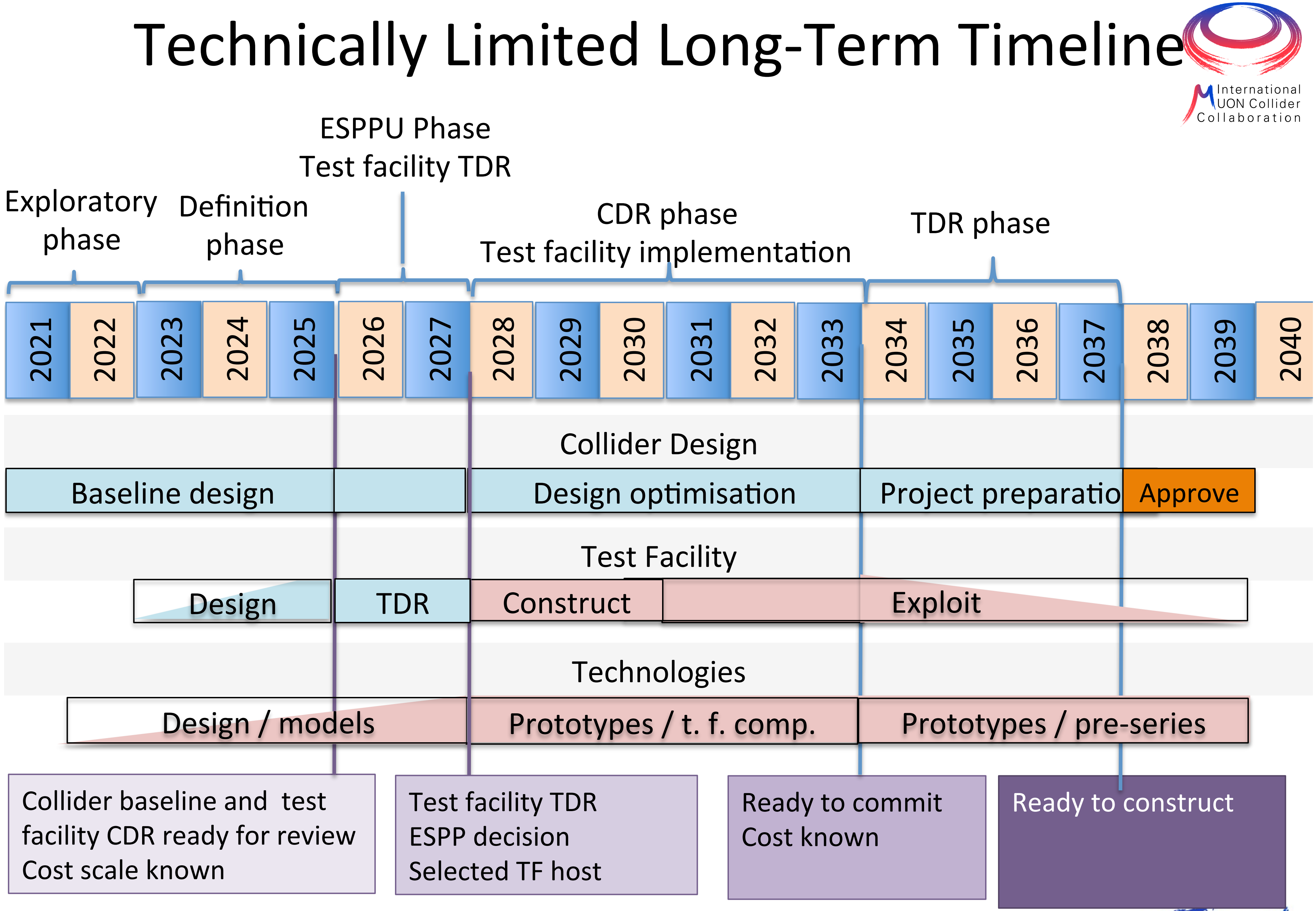
In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.

Scope:

- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, with more advanced technology, **the reason to do muon colliders**
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

Technically Limited Long-Term Timeline



Luminosity Goals

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 no staging
Would only do 10 or 14 TeV

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

Now study if these parameters lead to realistic design with acceptable cost and power

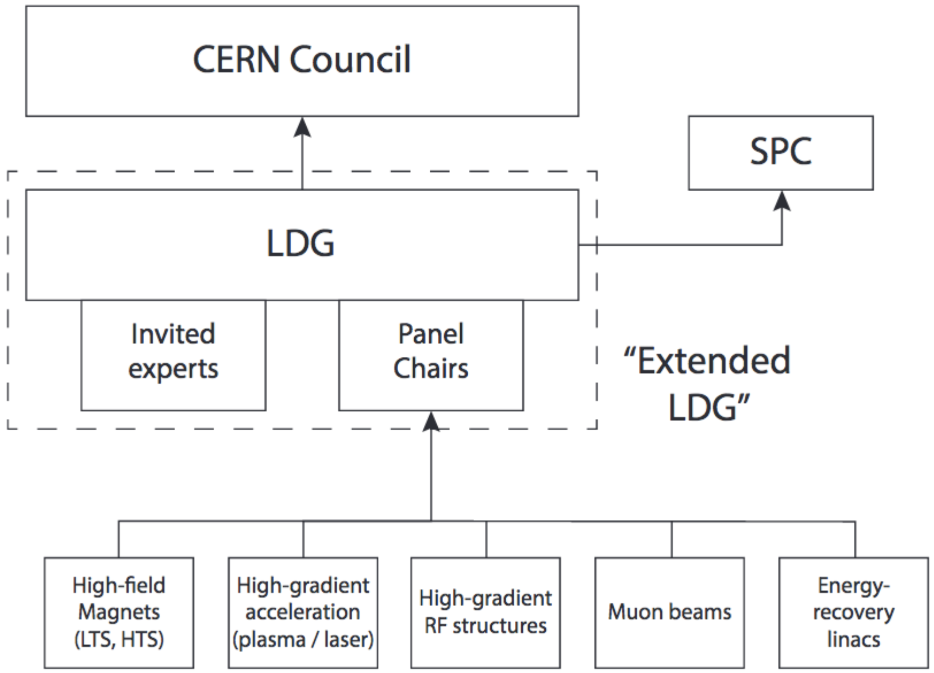
Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

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

European Accelerator R&D Roadmap

Council charged LDG to deliver European **Accelerator R&D Roadmap**



Panels

- Magnets: P. Vedrine
- Plasma: R. Assmann
- RF: S. Bousson
- Muons: D. Schulte
- ERL: M. Klein

Muon Beam Panel members: 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), Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI), Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN)

Roadmap Process

Report to **council** will include

- Potential deliverables and **demonstrators** for the next decade
- A **prioritised work plan**, taking into account the capabilities and interests of stakeholders
- A **range of scenarios** for engagement, ranging from '**minimal investment**' to '**maximum possible rate of progress**', with a first estimate of resources and timeline.

Milestones

- March 24+25: Community meeting on Testing Opportunities
- May 20+21: Community meeting to identify R&D issues
- tbd: First Stakeholder Meeting
- Particle Physics Meeting: tbd by LDG
- July 12+13: Community meeting to identify scope of R&D programme for next ESPPU
- End of July: Submission of Interim Report to LDG
- August/September: final R&D list, internal priorities, resources estimates, scenarios, may still answer questions of LDG
- September: LDG submits Interim Report to Council
- December: Final Report submitted to Council

Community Meeting Working Groups

Working groups and conveners (contact Panel members in blue)

- **RF**: Alexej Grudiev, Derun Li, Jean-Pierre Delahaye, Akira Yamamoto
- **Magnets**: Lionel Quettier, Soren Prestemon, Sasha Zlobin
- **High-energy complex**: Antoine Chance, Scott Berg, Alex Bogacz, Shinji, Machida, Christian Carli, Eliane Gianfelice-Wendt, Angeles Faus-Golfe
- **Muon production and cooling**: Chris Rogers, Diktys Stratakis, Marco Calviani, Chris Densham, Katsuya Yonehara
- **Proton complex**: Simone Gilardoni, Frank Gerigk
- **Beam Dynamics**: Elias Metral, Rob Ryne, Tor Raubenheimer
- **Radiation protection and other technologies**: Roberto Losito, Claudia Ahdida, Vladimir Shiltsev, Philippe Lebrun, Mike Seidel
- **MDI**: Donatella Lucchesi, Nicolai Mokhov, Christian Carli, Nadia Pastrone
- **Synergy**: Kenneth Long

- **Test facility**: Roberto Losito
- **Parameters etc.**: Mark Palmer, Daniel Schulte

Key Challenge Areas

10+ TeV is uncharted territory

- **Physics potential** evaluation

- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site

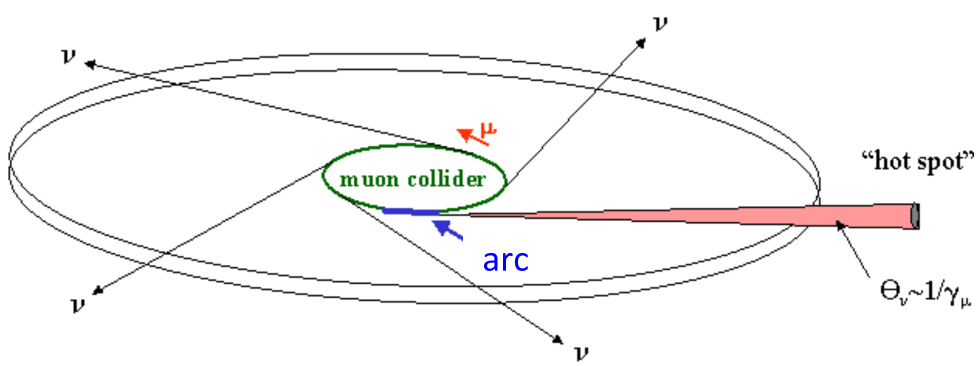
- The impact of **machine induced background** on the detector, as it might limit the physics reach.

- **High-energy systems** after the cooling (acceleration, collision, …)
  - This can limit the energy reach via cost, power and beam quality

- **High-quality beam production** of cooled muon beam
  - MAP did study this in detail
  - Need to optimise and prepare test facility

- **Integrated Collider Design** with choices, parameters, trade-offs
  - need to cover all accelerator areas

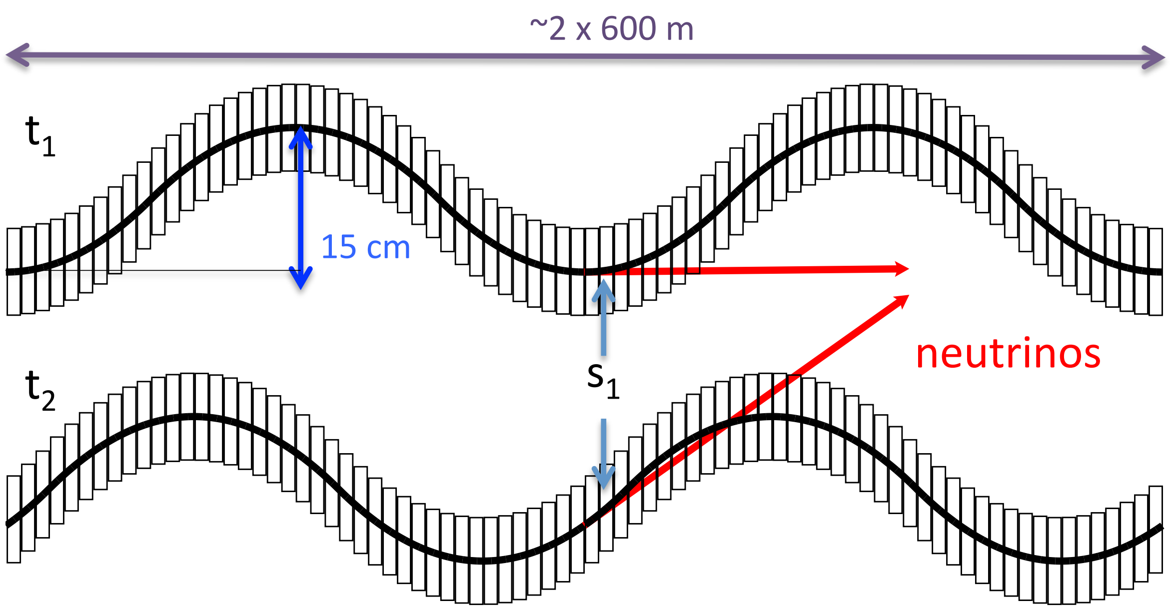
Neutrino Flux Mitigation



Legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
Our goal: arcs below threshold for legal procedure < 10 μSv/year
LHC achieved < 5 μSv/year

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV: idea of Mokhov, Ginneken to move beam in aperture
our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

14 TeV, in 200 m deep tunnel comparable to LHC case

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

Working on different approaches for experimental insertion

Physics, Detector and MDI

Still Important to establish physics potential

- Also need to show that we can indeed expect to extract the physics

Define a forward-looking detector design anticipating techology developments

- Need to refine detector performance specifications for 10+ TeV
  - Starting from initial DELPHES description
  - Iterative process between physics potential, detector and machine

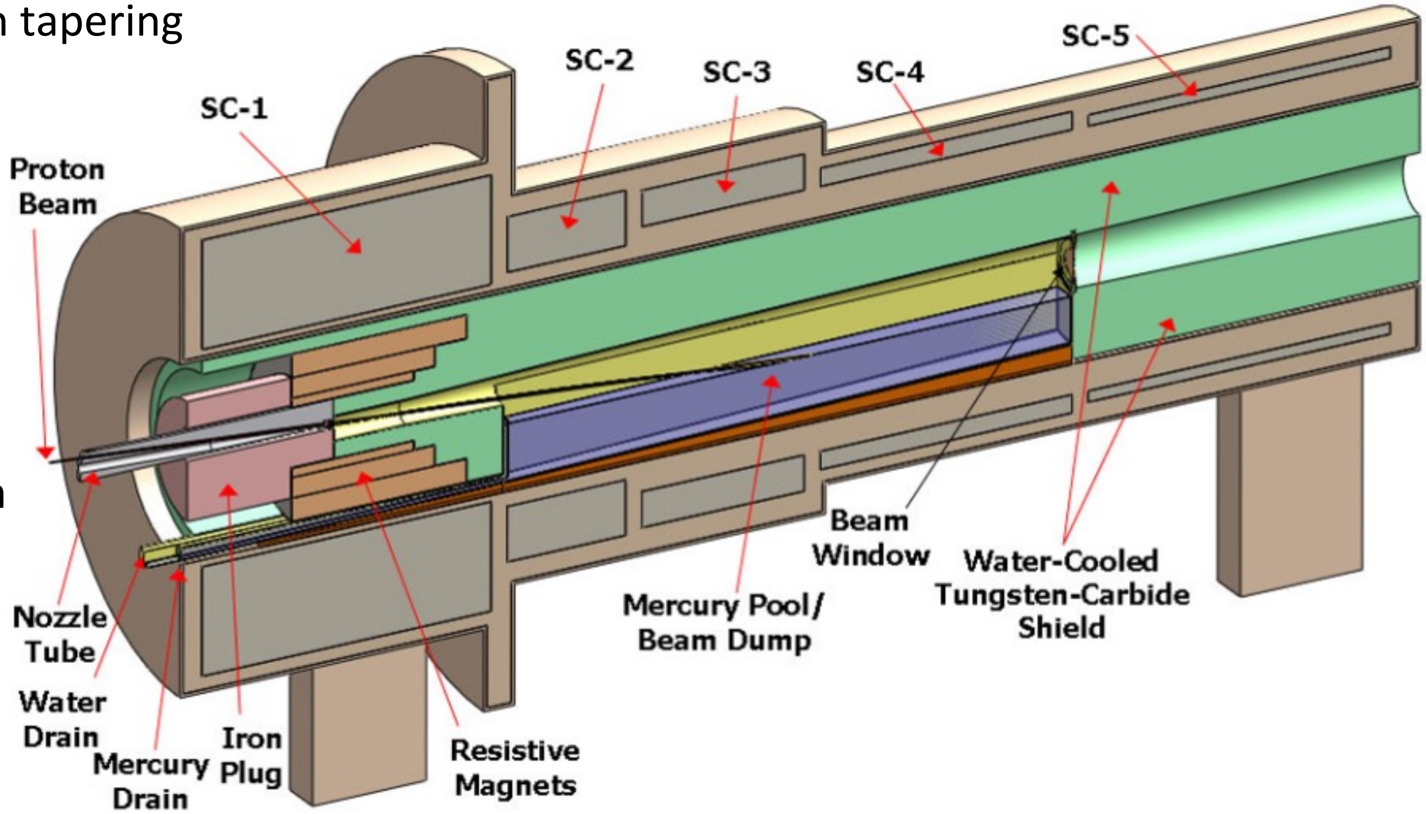
Fully cover the main background sources and mitigation methods

- Physics, muon decay products (40,000 muons/m/crossing at 14 TeV), beam-beam background, ...
- Masks, detector granularity, detector timing, solenoid field, event reconstruction strategies, …

Aim of this workshop

Target Solenoid

High field to efficiently collect pions/muons:
20 T then tapering



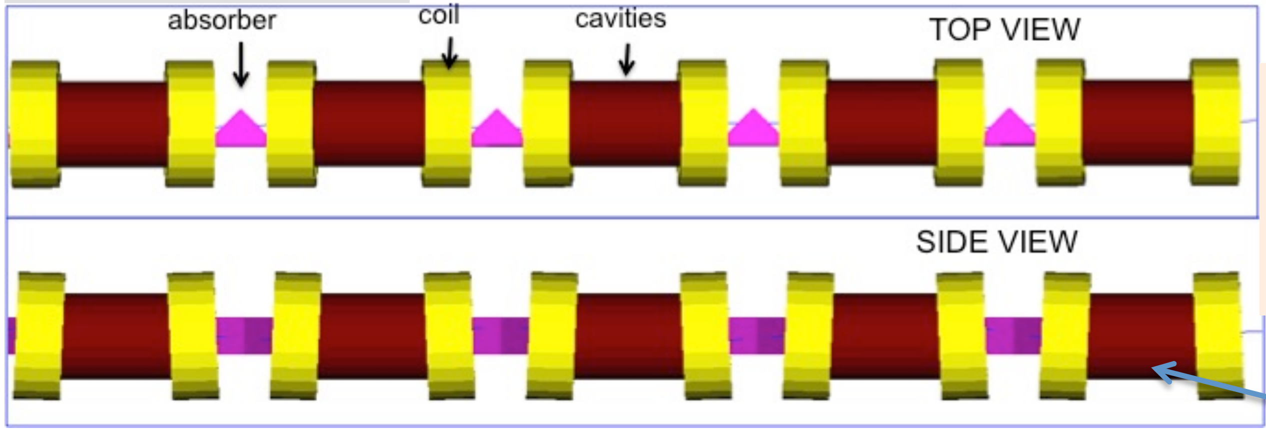
2-4 MW proton beam requires **radiation protection**

Large aperture O(1m) to allow shielding

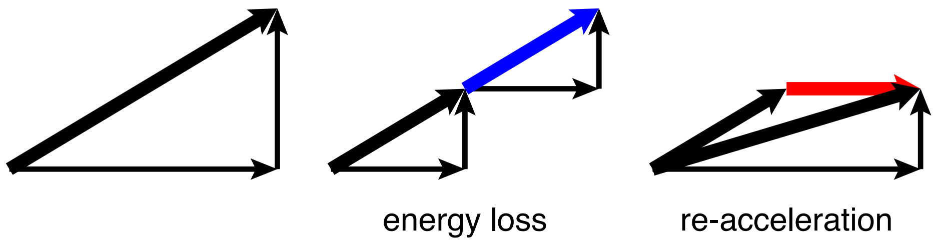
Copper insert reduced requirement for cold solenoid and provides some shielding

Muon Cooling Concept

MAP collaboration



Tight integration of
Superconducting solenoids
High-field normal conducting RF
Liquid hydrogen targets



Limit muon decay, cavities with **very high gradient in a strong magnetic field**

Minimise beta-function in final cooling with **strongest solenoids (goal: 40-50 T)**

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

Component Status

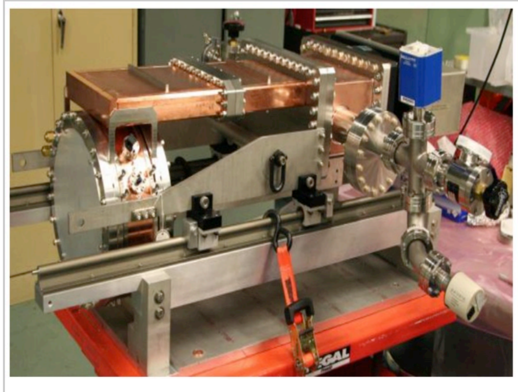
Cavities with very **high accelerating gradient in strong magnetic** field

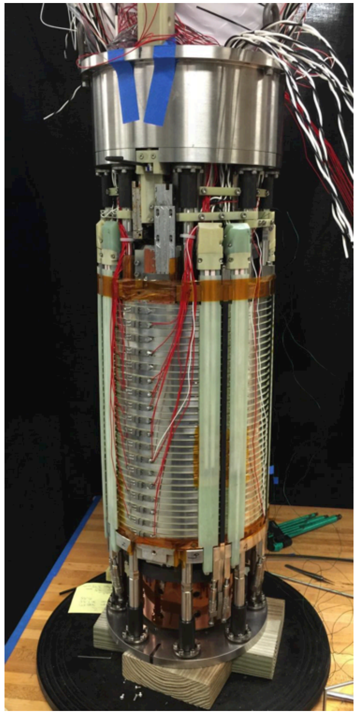
Very strong solenoids (> 30 T) for the final cooling
- simplified: Luminosity is proportional to the field

Promising performance, try to push further

MuCool: >50 MV/m in 5 T field

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

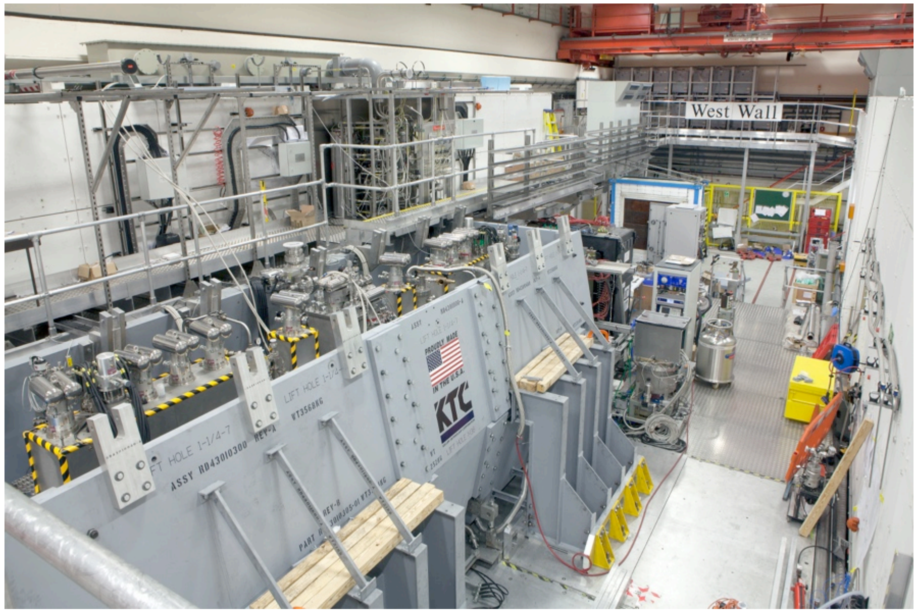




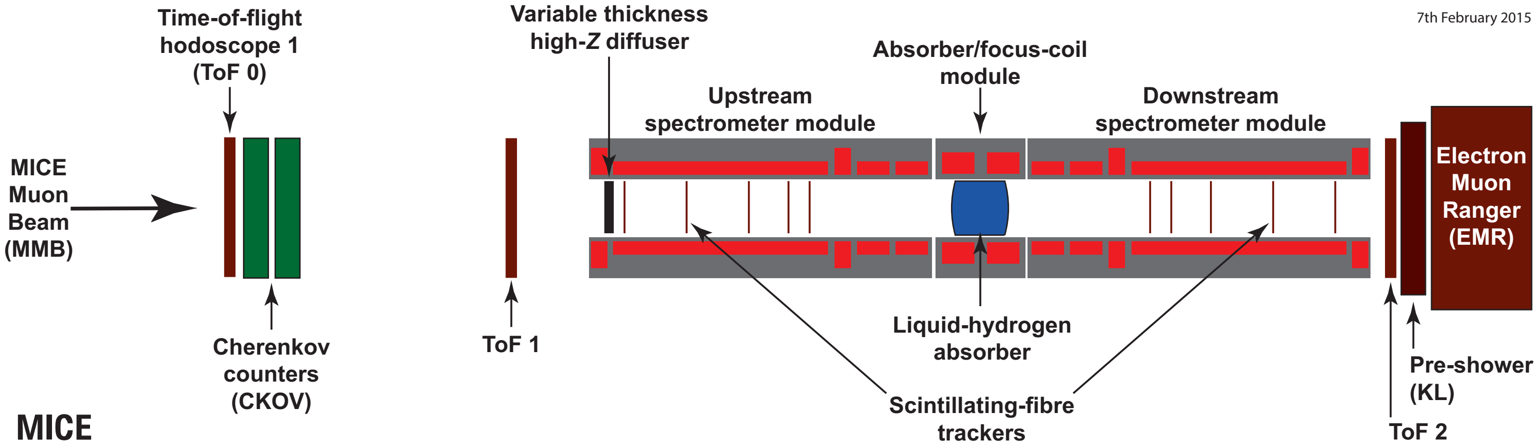
NHFML
32 T solenoid with low-temperature HTS

Different developments towards higher fields, e.g in the US and in France

MICE (UK)



Demonstration Status

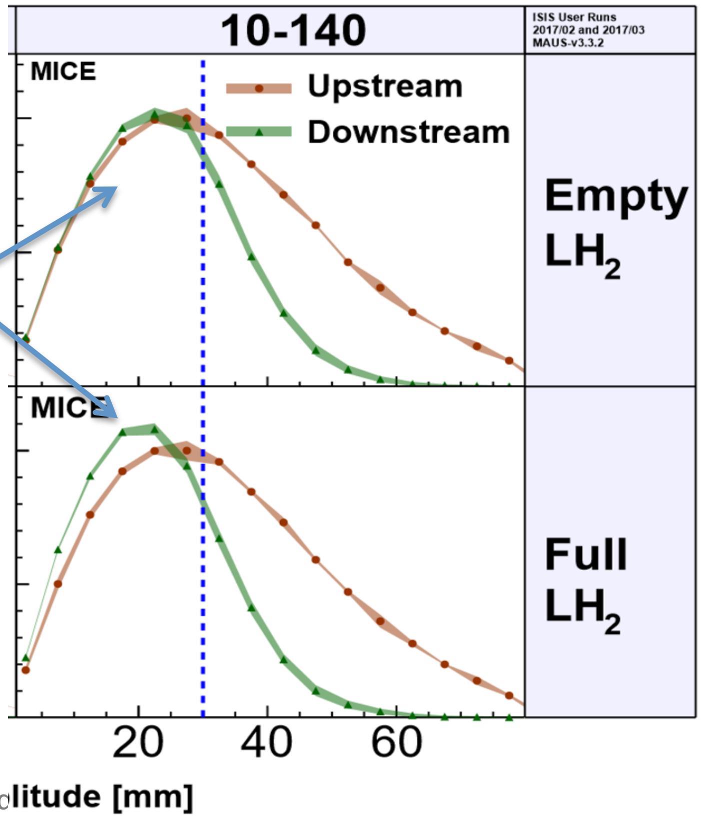


MICE collaboration

Nature volume 578, pages 53-59 (2020)

More particles at smaller amplitude after absorber is put in place

Principle of ionisation cooling has been demonstrated



New test facility
- **With better statistics**
- **Integration of magnets, RF, absorbers, vacuum is engineering challenge**
- **For implementation after ESU**

High-energy Acceleration

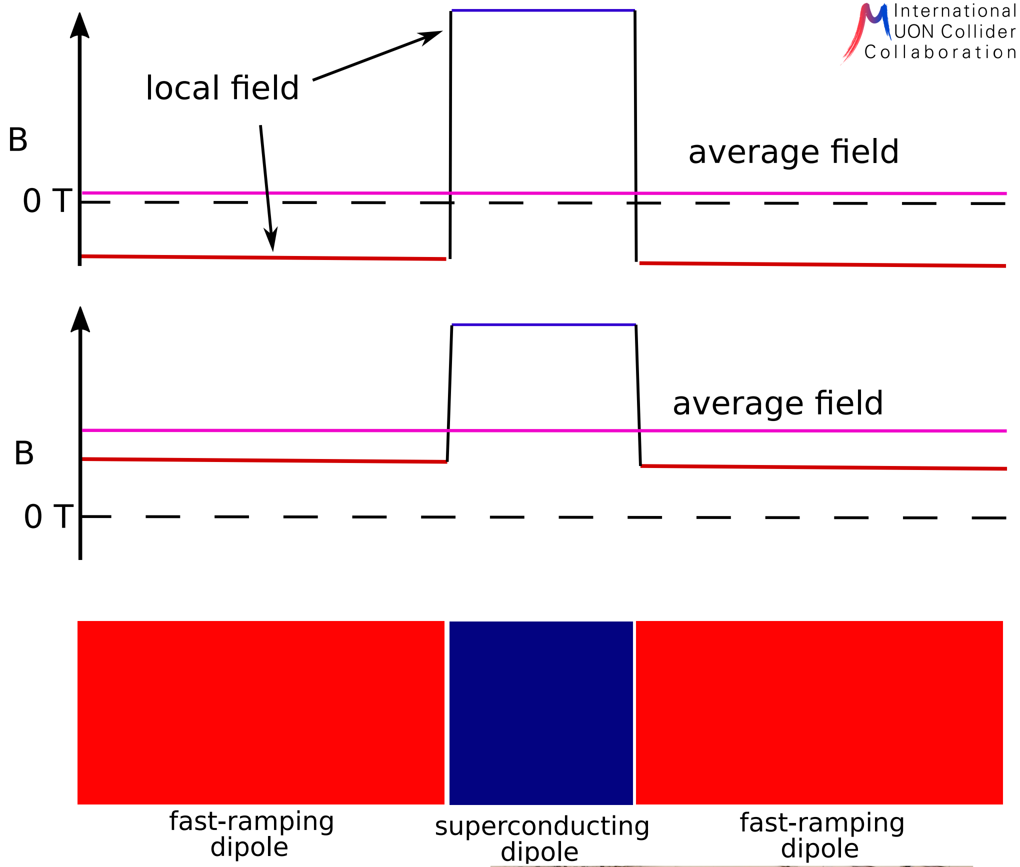
Rapid cycling synchrotron (RCS)
- Ramp magnets to follow beam energy
- Combine static and ramping magnets

- need **5 km of 2 T magnets per TeV**
- or **develop fast HTS dipoles**
- **Power converters and energy efficiency**
- **Protection from muon decays**

RF (RCS and FFA):
High single-bunch charge (10 x HL-LHC), maintain small longitudinal emittance, high efficiency

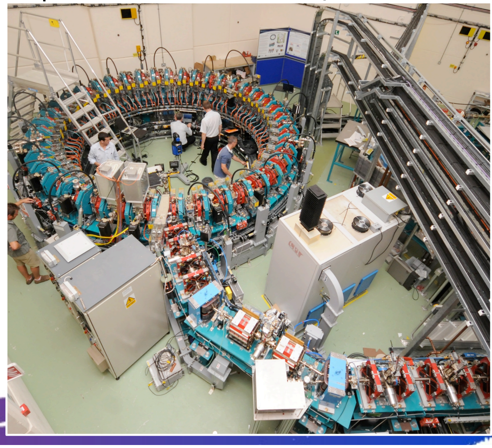
FFAG (alternative)
- Fixed (high-field) magnets but large energy acceptance

- **Complex high-field magnets**
- **Challenging beam dynamics**



EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



Collider Ring

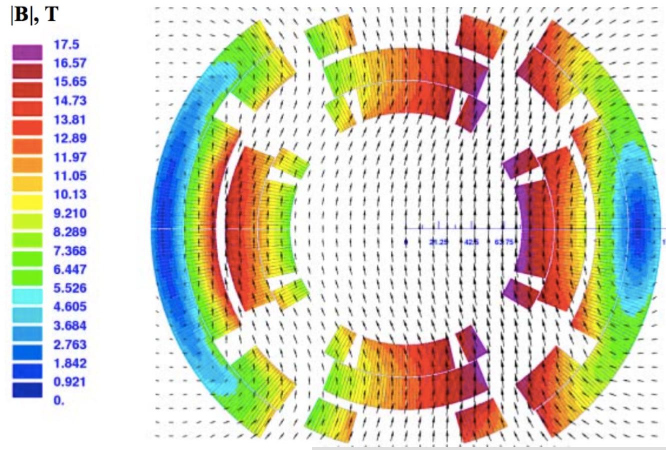
High field dipoles to minimise collider ring size and maximise luminosity
4.5 km at 3 TeV, 10/14 at 10/14 TeV

Beam loss protection O(500 W/m)
- MAP shielding solution for 3 TeV: 150 mm aperture and 30-50 mm shielding

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy
Lattice and magnet design challenge

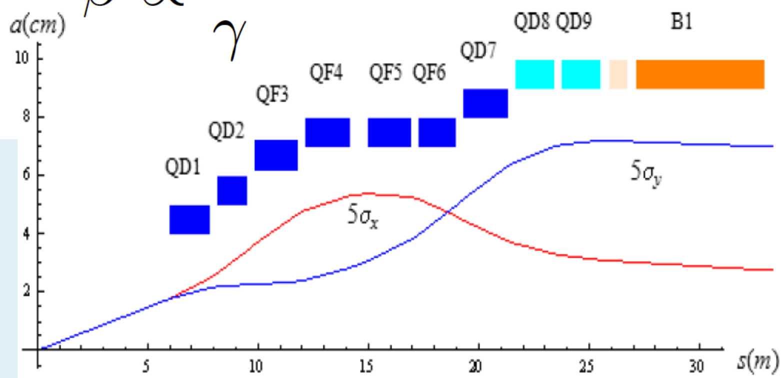
Lattice design/beam dynamics
e.g. Short bunch preservation (1 mm) in large ring
- Careful control of longitudinal motion
- Beam dynamics of frozen beam
- Synergy with light sources might exist

Combined function magnet design



V.V. Kashikhin et al.

$$\beta \propto \frac{1}{\gamma}$$



High-field Magnet Efforts

Important progress on high-field magnets for many projects, HL-LHC, FCC, …

General development of magnets (Nb_3Sn and HTS) in all regions

For 3 TeV, consider still using NbTi for mass production and HTS for single systems
For 10+ maybe HTS is better than Nb_3Sn

U.S. MAGNET DEVELOPMENT PROGRAM

Fermilab
50 Years of Discovery

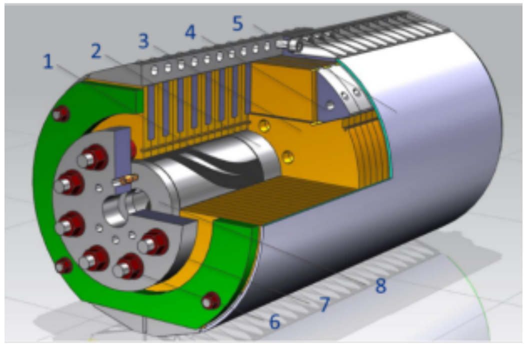
15 T dipole demonstrator
60-mm aperture
4-layer graded coil

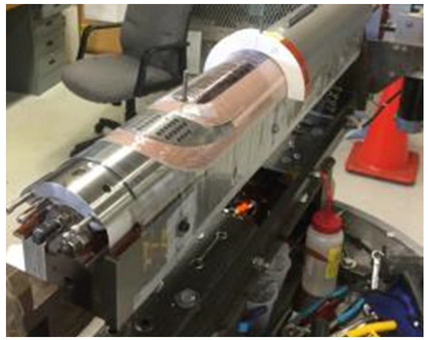
Development of conductors (FCC)

Participants

Switzerland: CERN
Japan: KEK, FURUKAWA ELECTRIC, JASTEC
Russia: BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM, TVEL
China: Western Superconducting Technologies Co., Ltd.
Austria: TU WIEN
Korea: Kiswire
Germany: Technische Universität Bergakademie Freiberg
Italy: Columbus Superconductors
Finland/USA: LUVATA Special Products
Italy: SPIN
Switzerland: Université de Genève

7 companies, two universities and two national research institutes

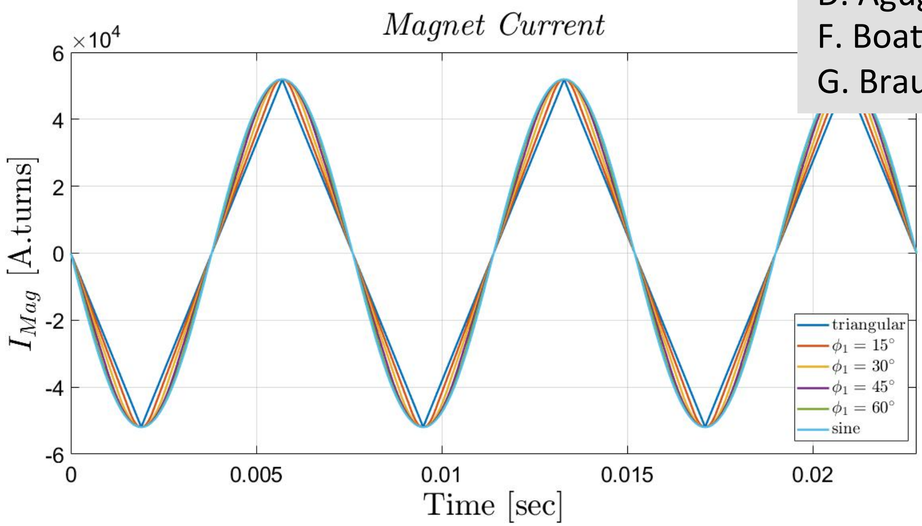




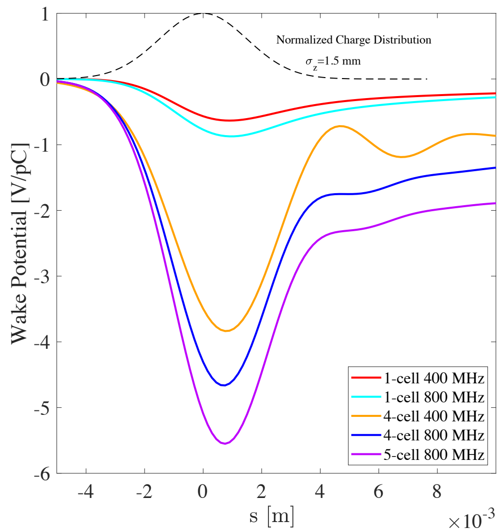
Magnet progress is important
Need to share magnet work for muon collider

Selected Recent Progress

Ramping **magnet challenge**
At 14 TeV, energy in field is O(200 MJ)
Need to recover it pulse to pulse
Started to develop **powering scheme** with energy recovery

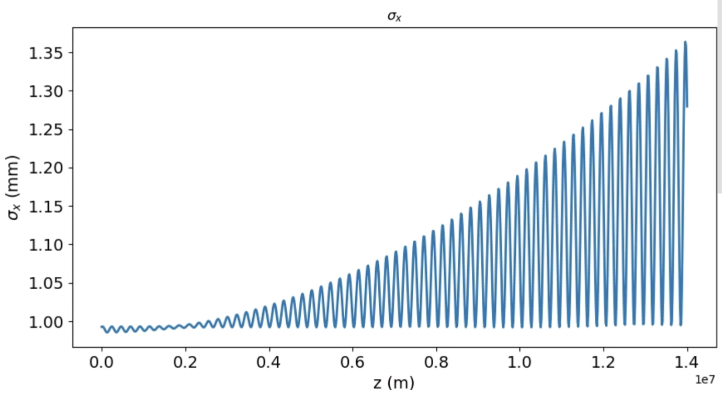


D. Aguglia
F. Boattini
G. Brauchli



S. Zadeh
U. van Rienen
H. Demarau
I Karpov
A. Grudiev

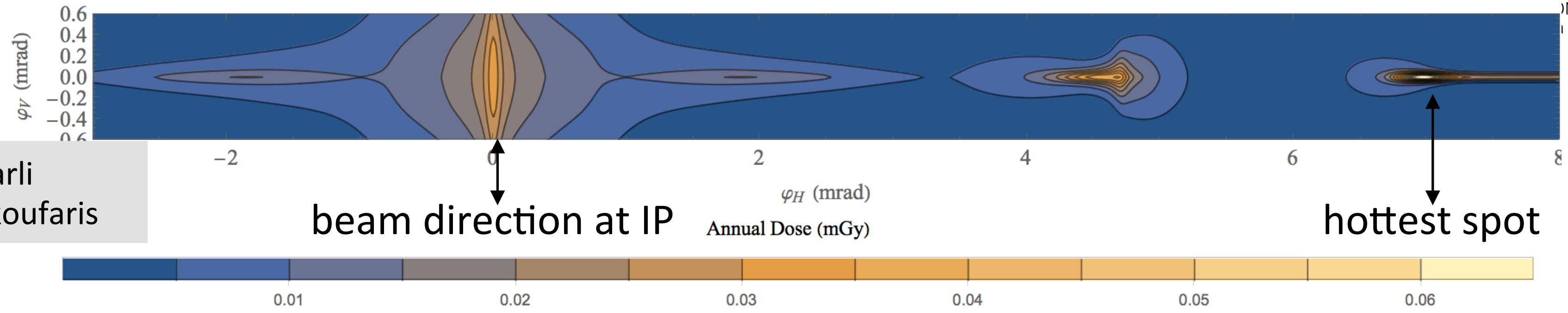
RF challenge (also for FFA):
High efficiency for power consumption
High-charge (10 x HL-LHC), short, single-bunch beam
Maintain small longitudinal emittance
Studies on cavity wakefields and longitudinal dynamics started



M. Magliorati
E. Metral,
T. Raubenheimer
D.S.

Collective effects might be a bottleneck
Revisiting for higher energies
Need to develop tools for collective effects in matter

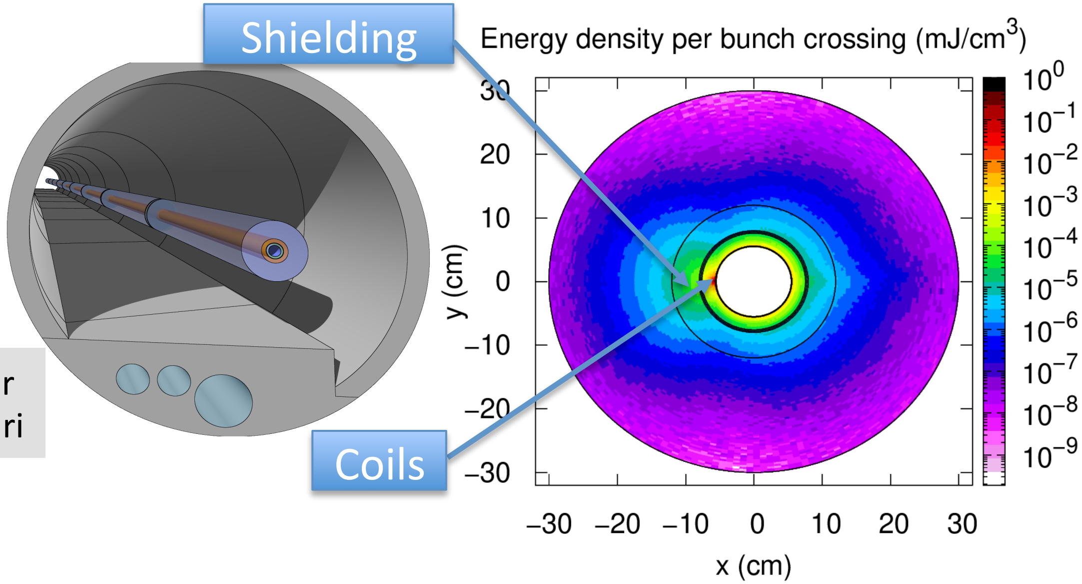
Selected Recent Progress, cont.



C. Carli
K. Skoufaris

Collider Ring Lattice Design:
Based on MAP design, lattice design for high energy is starting
Started production of **radiation maps** and identified hot spots around IP and in arcs
Need to include radiation considerations in lattice design

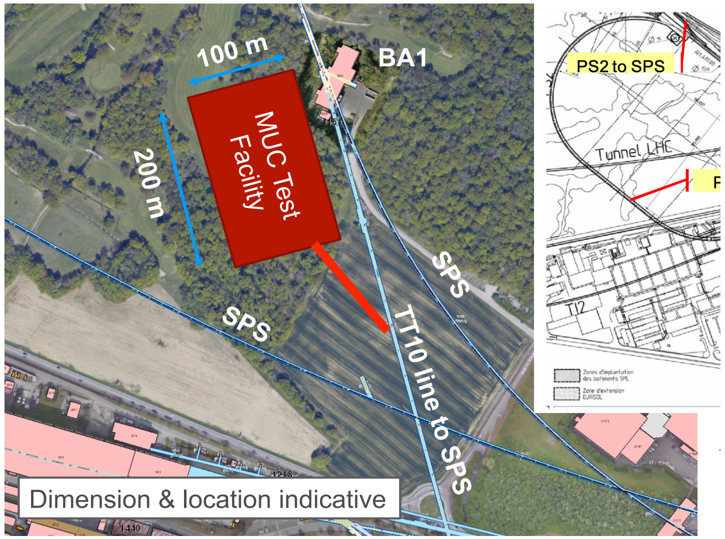
Loss challenge in collider ring:
Loss per unit length is constant
fewer, but higher energy particles
Simulations of shielding started



A. Lechner
D. Calzolari

Demonstration Programme

Core test facility to demonstrate muon cooling
- needs muon production with reasonable intensity but below real collider (e.g. 10 kW target)
- Identify potential sites
  - At least one good candidate at CERN
  - ESS, US labs, other regions?



Models and prototypes of key components
- magnets
- RF systems
- target
- …

Exploring development of RF test infrastructure to further develop cavities in high field for the cooling cells of test facility

Programme needs to be modular

But not to forget:
- The collider justifies the demonstration programme

Global Collaboration

We do see this as a global effort

- profit from US expertise
- and new enthusiasm in Europe and revived enthusiasm in the US
- prepare to include the US in the collaboration after P5
  - and before, where possible
- include Asia

Submitted a number of proposals for white papers to Snowmass

- physics potential
- detector
- accelerator

Ideally, we will form a common collaboration with different proposed sites

Conclusion

- Muon colliders could be a unique opportunity for a high-energy lepton collider
- Need to develop concept to a maturity level that allows to make informed choices by the next ESPPU and other strategy processes
- Collider faces important challenges and opportunities
- Important progress in development of workplan
- Actual studies started, but more is needed
- Let us do a good job