International
MUON Collider
Collaboration

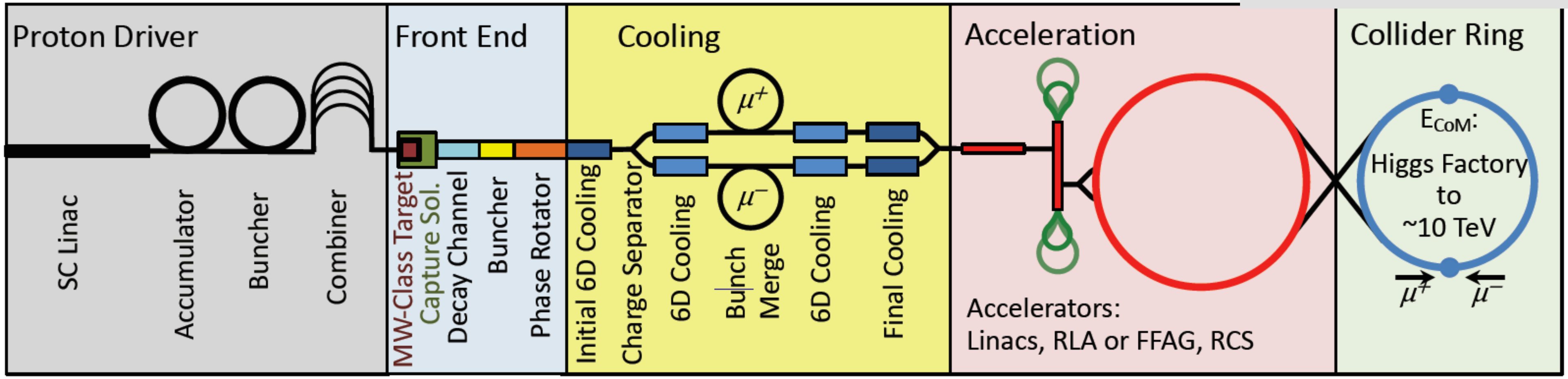
Muon Collider

Daniel Schulte for the Muon Collider Collaboration

Proton-driven Muon Collider Concept

The muon collider has been developed by the MAP collaboration mainly in the US
Muon cooling demonstration by MICE in the UK, some effort on alternative mainly at INFN

MAP collaboration



Short, intense proton bunches to produce hadronic showers

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

Collision

Protons produce pions
Pions decay to muons

Acceleration to collision energy

Muon collider is unique for very high lepton collision

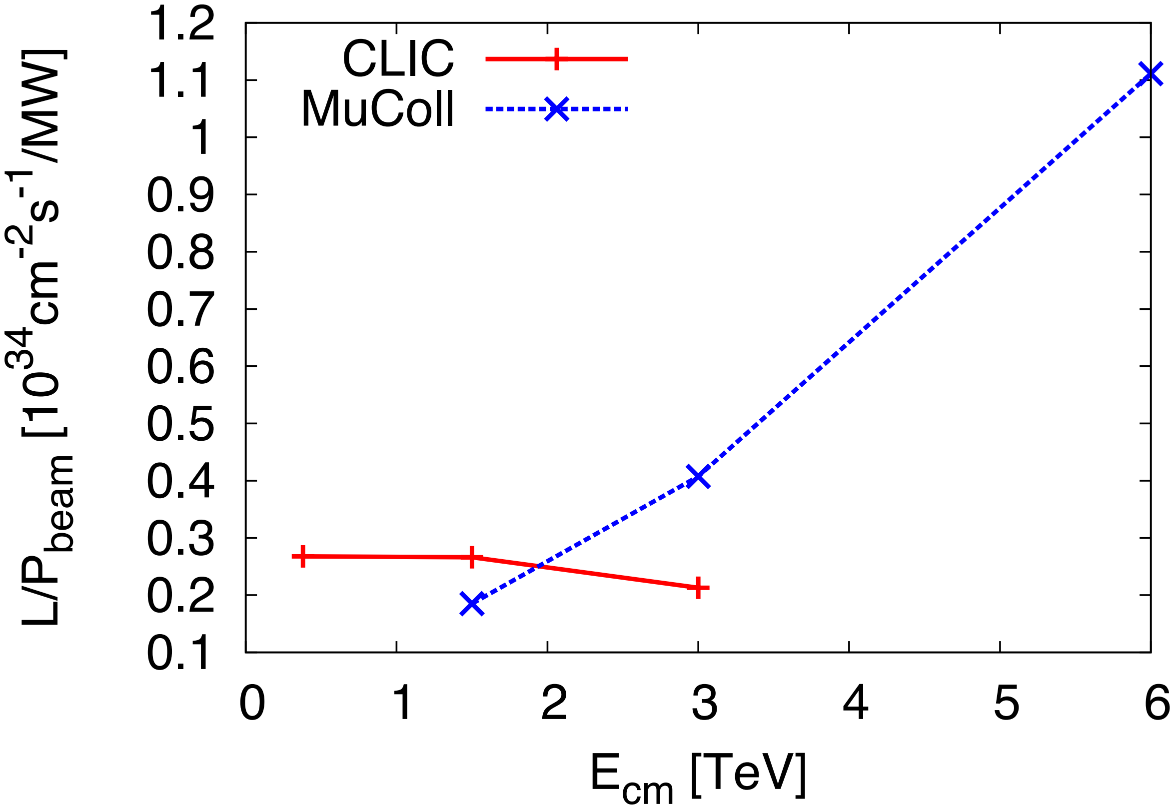
Comparing Luminosity in MAP vs. CLIC

In 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

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



Luminosity per beam power increases with energy in muon collider

Muon colliders have the 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:

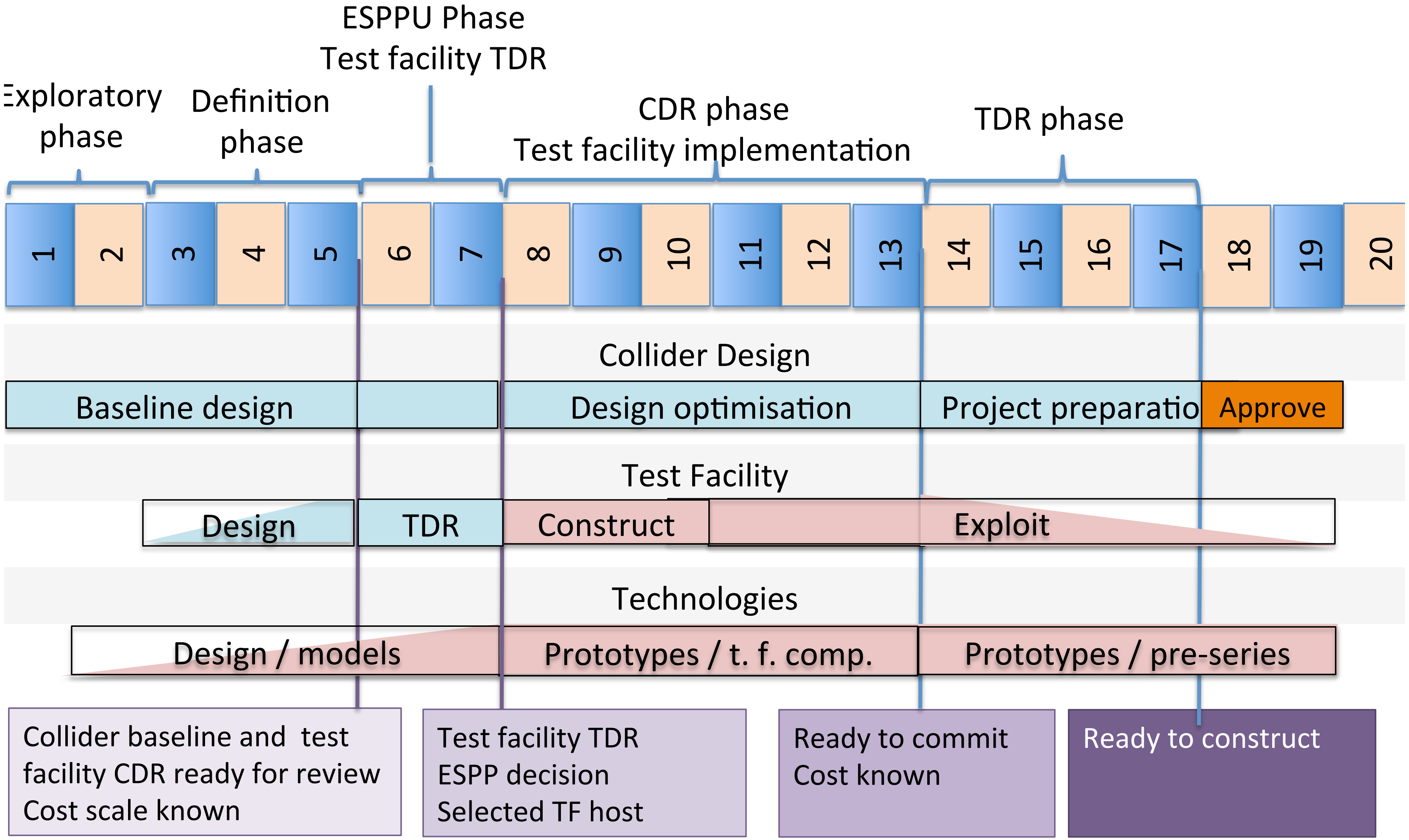
In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

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 15-20 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



xploratory phase

Definition phase

ESPPU Phase
Test facility TDR

CDR phase
Test facility implementation

TDR phase

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Collider Design

Baseline design | Design optimisation | Project preparatio | Approve

Test Facility

Design | TDR | Construct | Exploit

Technologies

Design / models | Prototypes / t. f. comp. | Prototypes / pre-series

Collider baseline and test facility CDR ready for review
Cost scale known

Test facility TDR
ESPP decision
Selected TF host

Ready to commit
Cost known

Ready to construct

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} $\text{cm}^{-2}\text{s}^{-1}$	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

Key Topics

10+ TeV is uncharted territory

- **Physics potential** evaluation

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

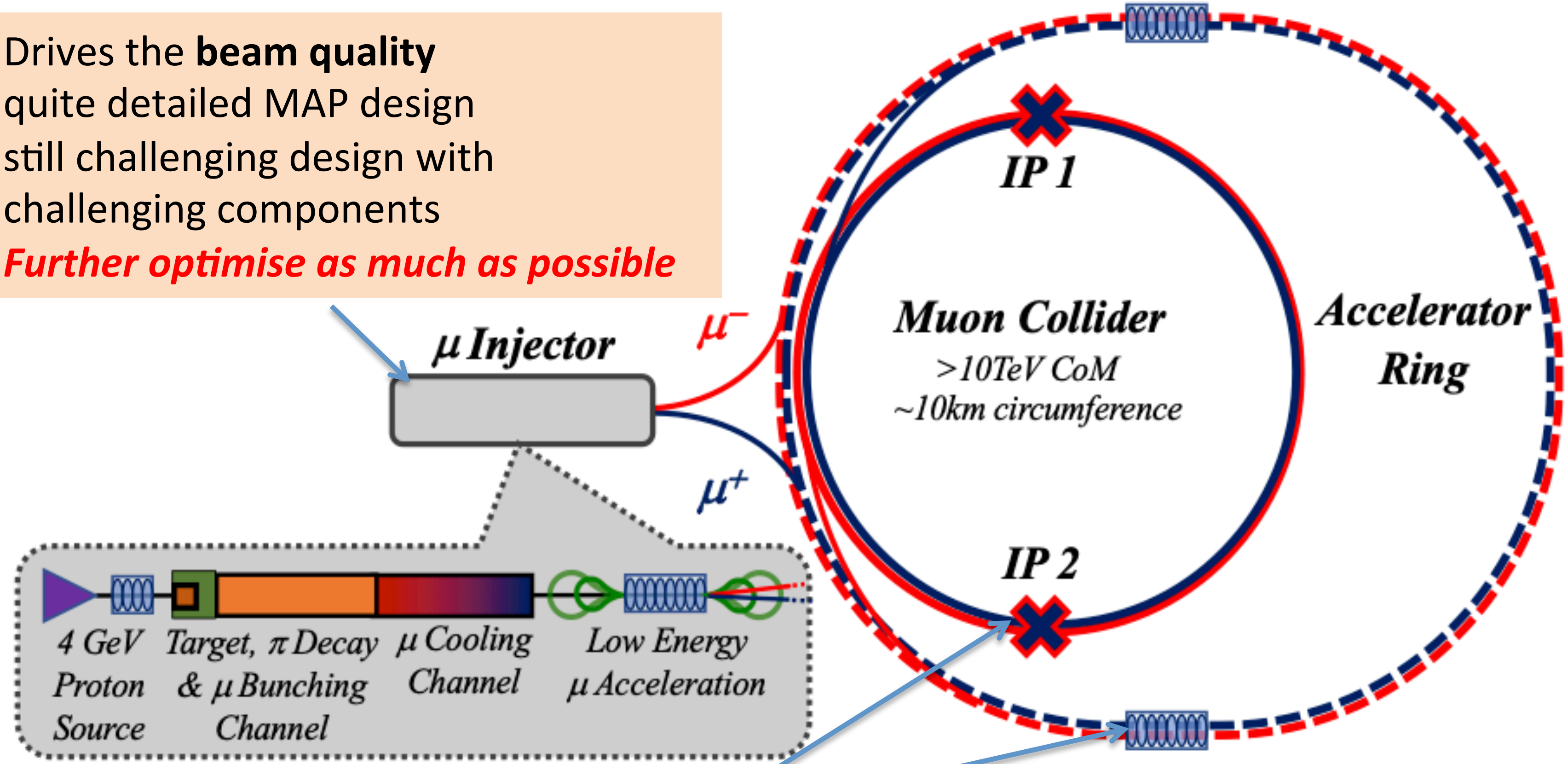
- The impact of **machine induced background** on the detector, as it might limit the physics reach.

- **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

Overall Considerations

Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
Further optimise as much as possible

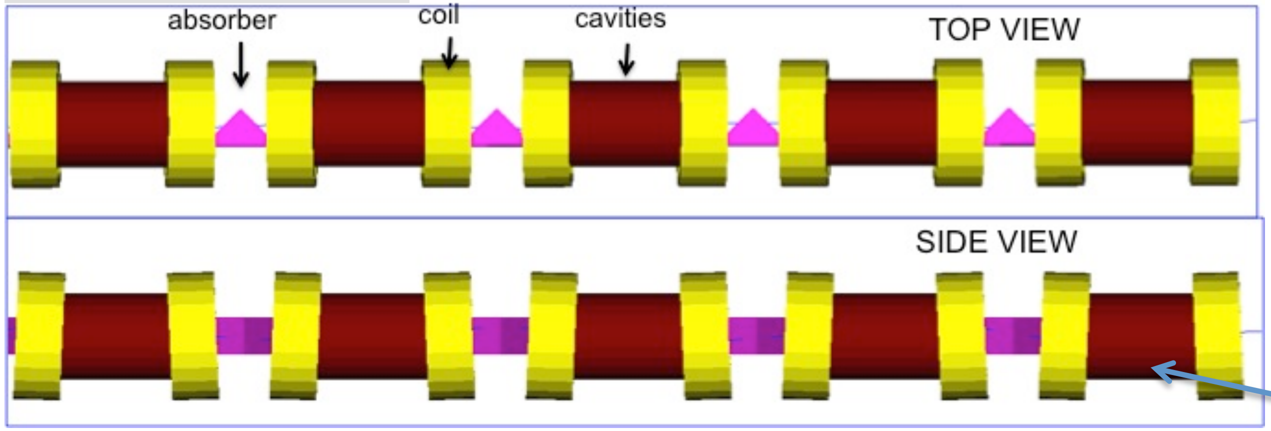


Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**
Drives **neutrino radiation** and **beam induced background**
Improve compared to MAP design and design for high-energy

Could use FCC tunnel for accelerator
would allow to go up to O(30 TeV) with normal magnets

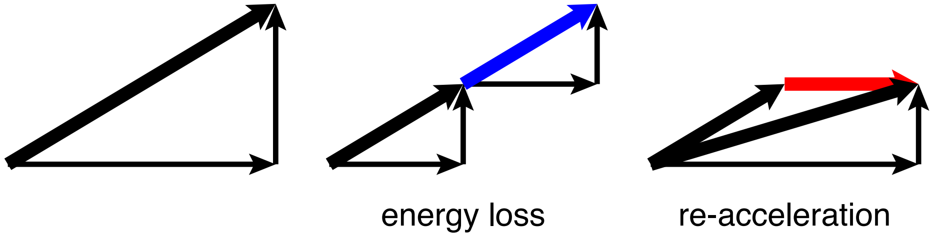
Muon Cooling Concept

MAP collaboration



Superconducting solenoids
High-field normal conducting RF
Liquid hydrogen targets
Compact design

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



Minimise betafunction with **strong solenoids**

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

Component Status

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

Very strong solenoids (> 30 T) for the final cooling

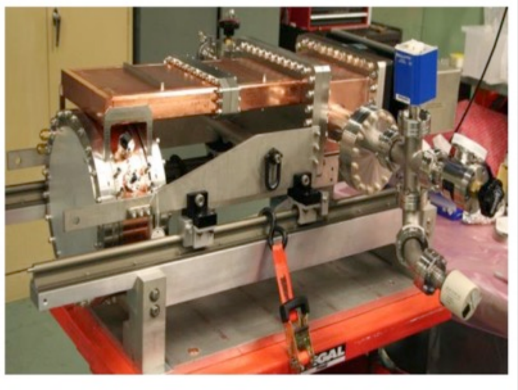
- simplified: Luminosity is proportional to the field

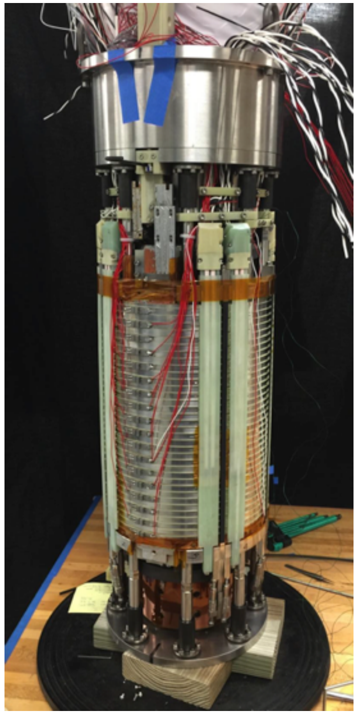
Promising performance, try to push further

MuCool: >50 MV/m in 5 T field

Two solutions

- Copper cavities filled with hydrogen
- Be end caps



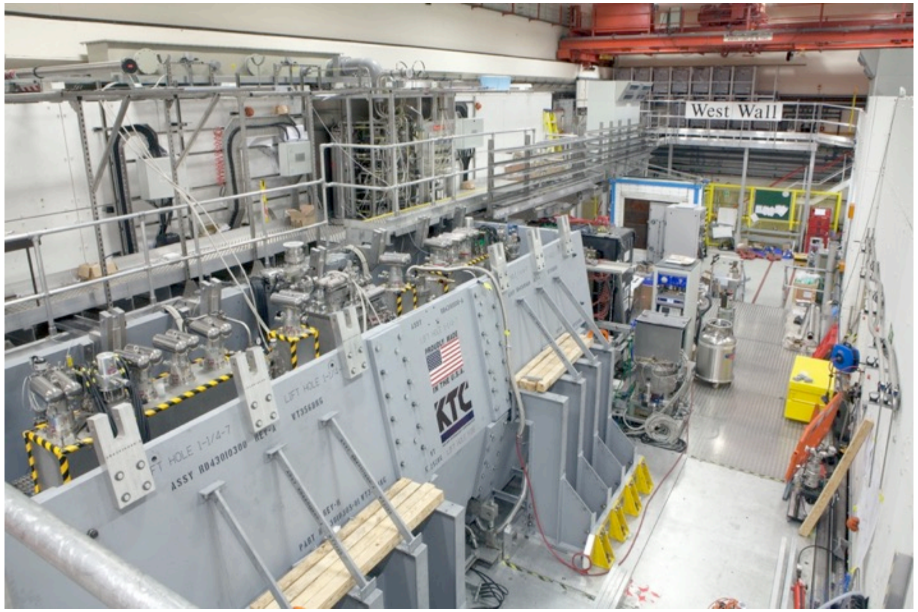


NHFML

32 T solenoid with low-temperature HTS

We would like to push even further

MICE (UK)

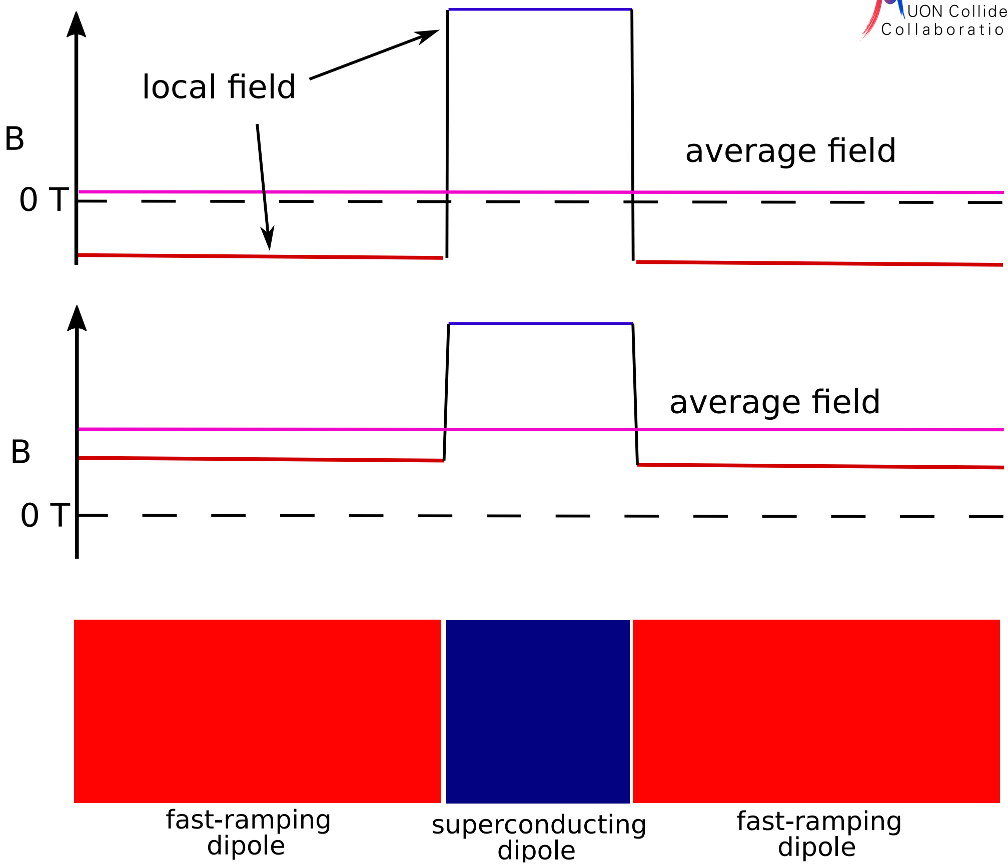


High-energy Acceleration

Rapid cycling synchrotron (RCS)
- Combine static and ramping magnets
- **Ramp magnets** to follow beam energy
  - normal conducting
  - or novel HTS
- **Power consumption** of fast-ramping systems is important
- 38 km ring for 10 TeV collider

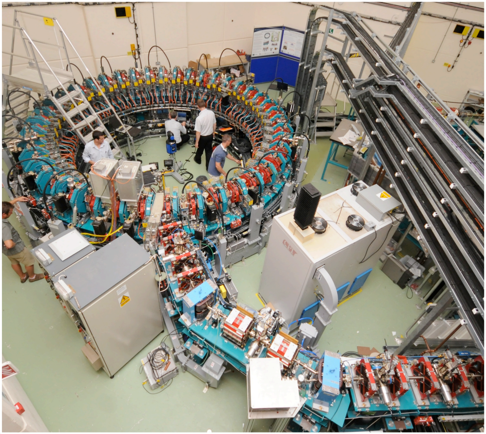
RF system
- **Important single-bunch beam loading**

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

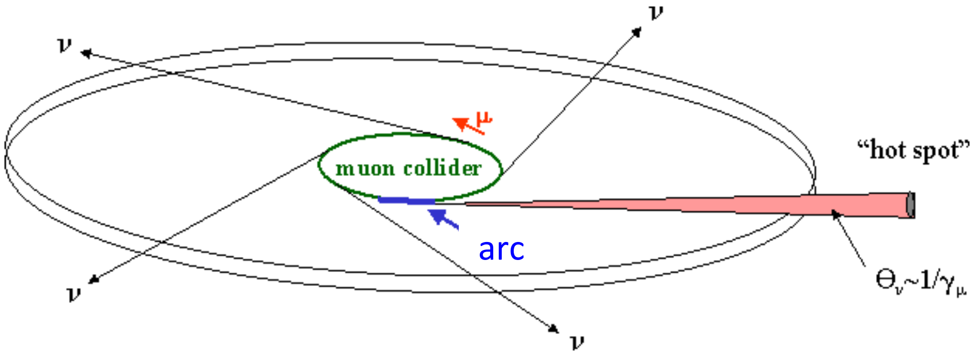


EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



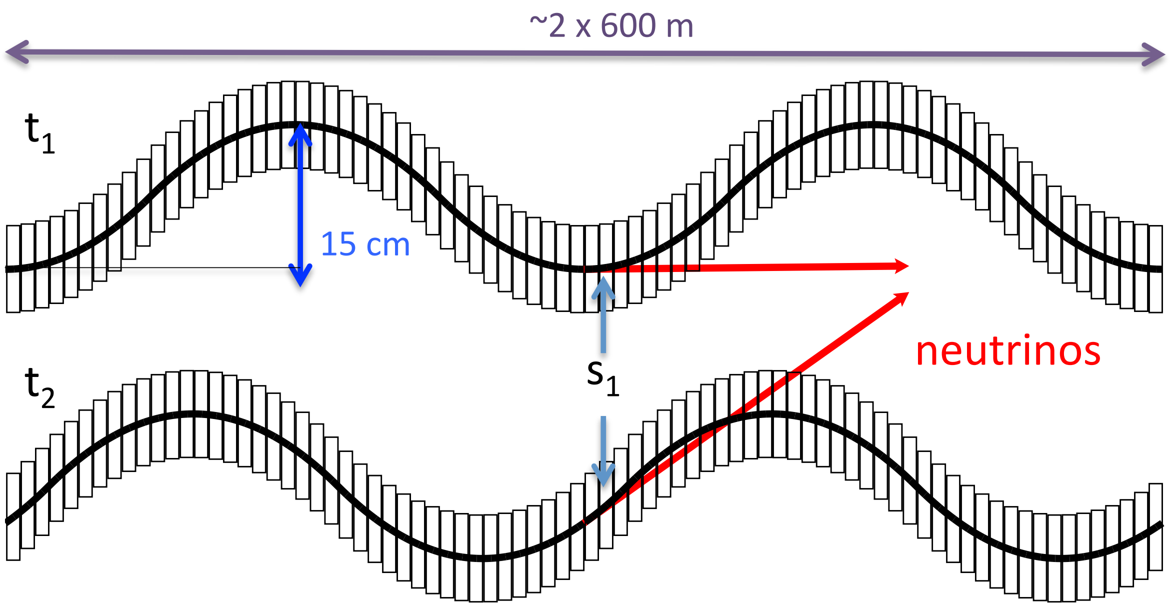
Neutrino Flux Mitigation



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 OK

Need mitigation of arcs at 10+ TeV: idea of Mokhov, Ginneken to move beam in aperture
our goal: 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

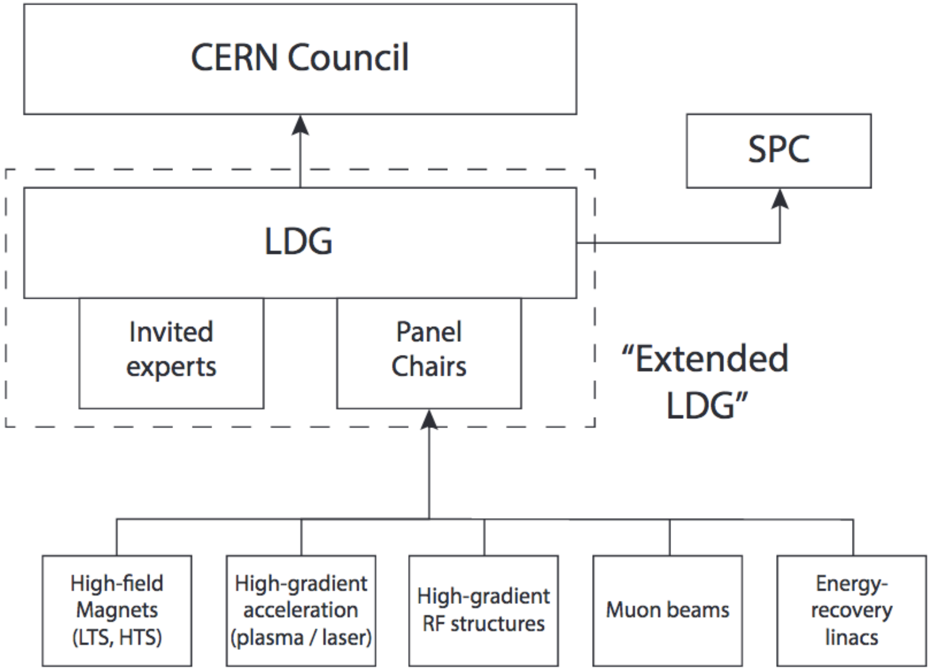
Need to study mover system (also cryogenics and vacuum) and impact on beam

Working on different approaches for experimental insertion

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


CERN Council
SPC
LDG
Invited experts
Panel Chairs
"Extended LDG"
High-field Magnets (LTS, HTS)
High-gradient acceleration (plasma / laser)
High-gradient RF structures
Muon beams
Energy-recovery linacs

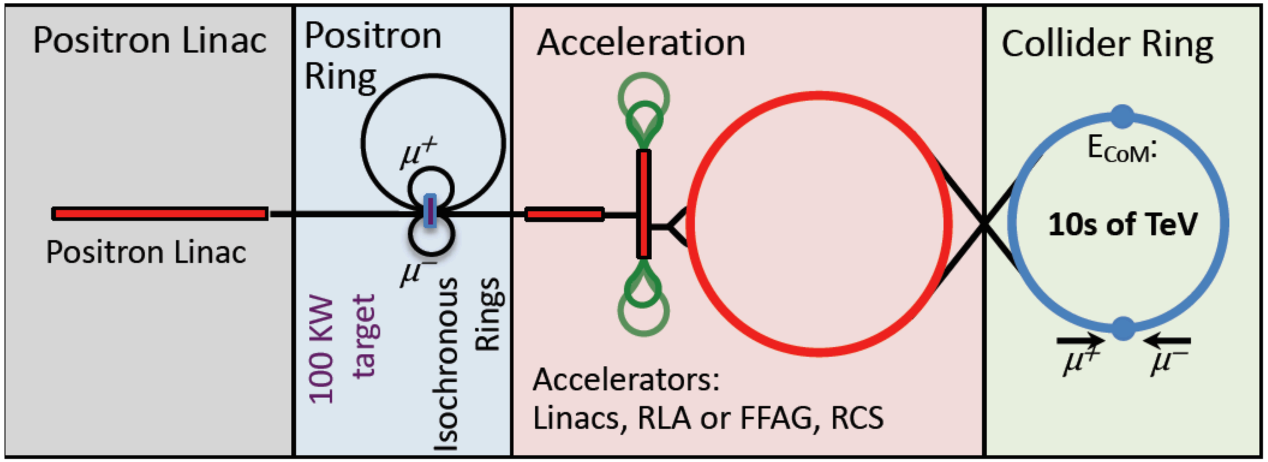
Report to **council** (by the end of this year) will include
- Potential deliverables and **demonstrators** for the next decade
- A **prioritised work plan**, taking into account the capabilities and interests of stakeholders
- A **range of scenarios** for engagement, ranging from '**minimal investment**'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

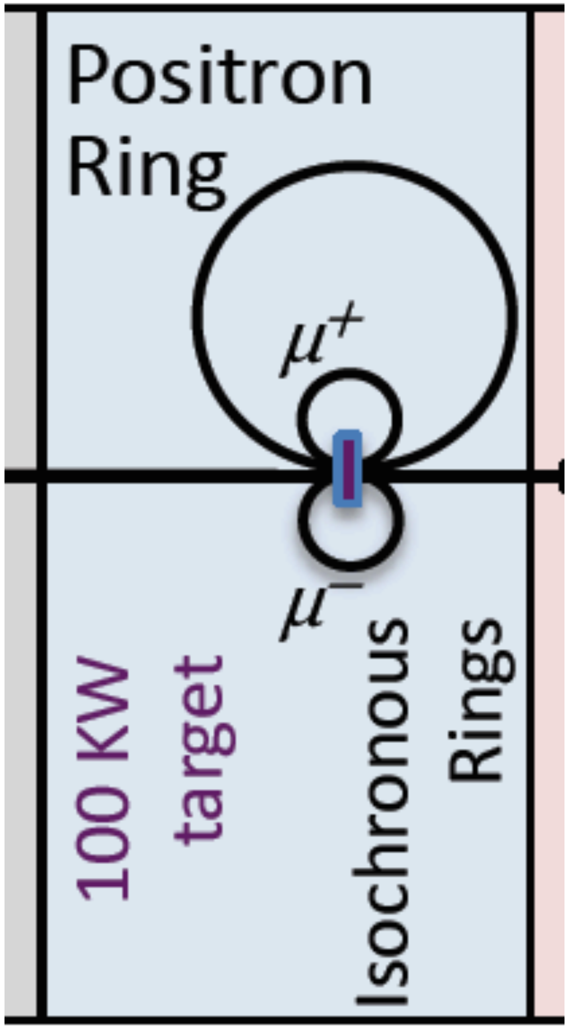
Muon Collider and FCC

- A similar magnet development is required for FCC-hh and MC collider ring
- The large tunnel could be used to accelerate the muons to 15 TeV with mixed RCS using normal-conducting ramping dipoles
- Higher energy is possible with ramping HTS or a second ring in the same tunnel
- A smaller collider ring should be used (O(30km) for 30 TeV centre-of-mass)

- No clear path to use FCC-ee to generate a muon beam that can provide enough luminosity
  - The LEMMA scheme requires new ideas to reach luminosity goal
  - Other alternatives need to be studied in detail
  - Calculations

Alternative: The LEMMA Scheme





45 GeV positrons to produce muon pairs
Accumulate muons from several passages

Low-emittance muon beam can reduce radiation

Could consider the FCC-ee as positron ring

Muon Collider Luminosity Scaling

Fundamental limitation
Assumes no emittance growth after source and no technical limitation
Applies to MAP and LEMMA scheme

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

Muon current for MAP scheme 10^{13} s^{-1}
LEMMA scheme O(1 mJ) positrons lost per muon pair
for 100 MW lost only 1.4 10^{11} s^{-1} muons
Beam density needs to be 70 times larger

Each passage through target gives emittance growth for muon beam
⇒ have to minimise passages
⇒ Need 3 x 10^{15} positrons in each bunch into the target to produce enough muons per passage
⇒ Only 500 passages per second
⇒ Need bursts of O(100 passages in 1 ms)
⇒ not practical

Some Comments

F. Zimmermann 2018 J. Phys.: Conf. Ser.1067 022017 claims

$$L \approx f_{\mathrm{rev}} \dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \frac{1}{3^6} \gamma \tau^2 \frac{1}{4\pi\beta^*}$$

$$= \frac{1}{3^6} \left\{ \left(\frac{eF_{\mathrm{dip}}}{2\pi m_\mu} \right)^3 \frac{\tau_0^2}{4\pi c^2} \right\} \left[B^3 C^2 \right] \left[\dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \right] \frac{1}{\beta^*}$$

The paper assumes that muons can be stacked but ignores the associated emittance growth
with these assumption LEMMA would be viable

the LEMMA scheme

scheme	p-γ	G.-F. μ	e^+	G.-F. e^+
base	LHC/FCC-hh		FCC-ee	FCC
rate $\dot{N}_\mu$ [GHz]	1	400	0.003	100
μ/pulse [10^4]	0.01	4	0.2	6,000
p. spacing [ns]	100	100	15	15
energy [GeV]	2.5	0.1	22	22
rms en. spread	3%	10%	10%	10%
n. emit. [μm]	7	2000	0.04	0.04
$\dot{N}_\mu/\varepsilon_N$ [10^{15} m^{-1}s^{-1}]	0.1	0.2	0.1	3,000

at 14 TeV:
9 GW beam power

30 times more beam power/particles

Note: Stacking

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

stacking in longitudinal plane does not increase luminosity
bunch length and beta-function increase with the charge

Stacking in transverse plane can help because

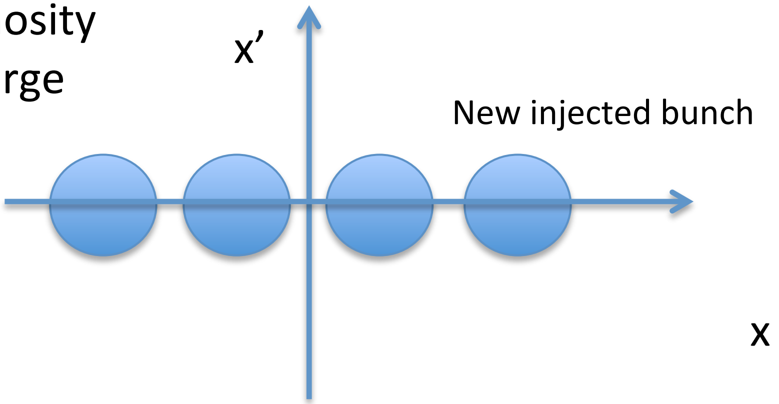
$$\epsilon = \sqrt{\epsilon_x \epsilon_y}$$

stacking m^2 bunches leads to

$$N = m^2 N_1 \qquad \epsilon = m \epsilon_1$$

and the luminosity scales as

$$\frac{N}{\epsilon} = m \frac{N_1}{\epsilon_1}$$



Shift common orbit for next turn

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

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta m \frac{N_0}{\epsilon_0 \epsilon_{L,0}} f_{r,0} N_0 \gamma$$

Conclusion

The muon is a unique promising option at highest lepton energies

We need to fully explore the physics case, which goes well beyond 3 TeV (studied for CLIC)

Have to address the feasibility

A great challenge but also a great opportunity

Many thanks to all that contributed
MAP collaboration
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
Muon collider collaboration
…

Web page: http://muoncollider.web.cern.ch

Mailing lists:
MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch,
MUONCOLLIDER_FACILITY@cern.ch
go to https://e-groups.cern.ch and search for groups with “muoncollider” to subscribe

Reserve

High-energy Acceleration

Rapid cycling synchrotron (RCS)

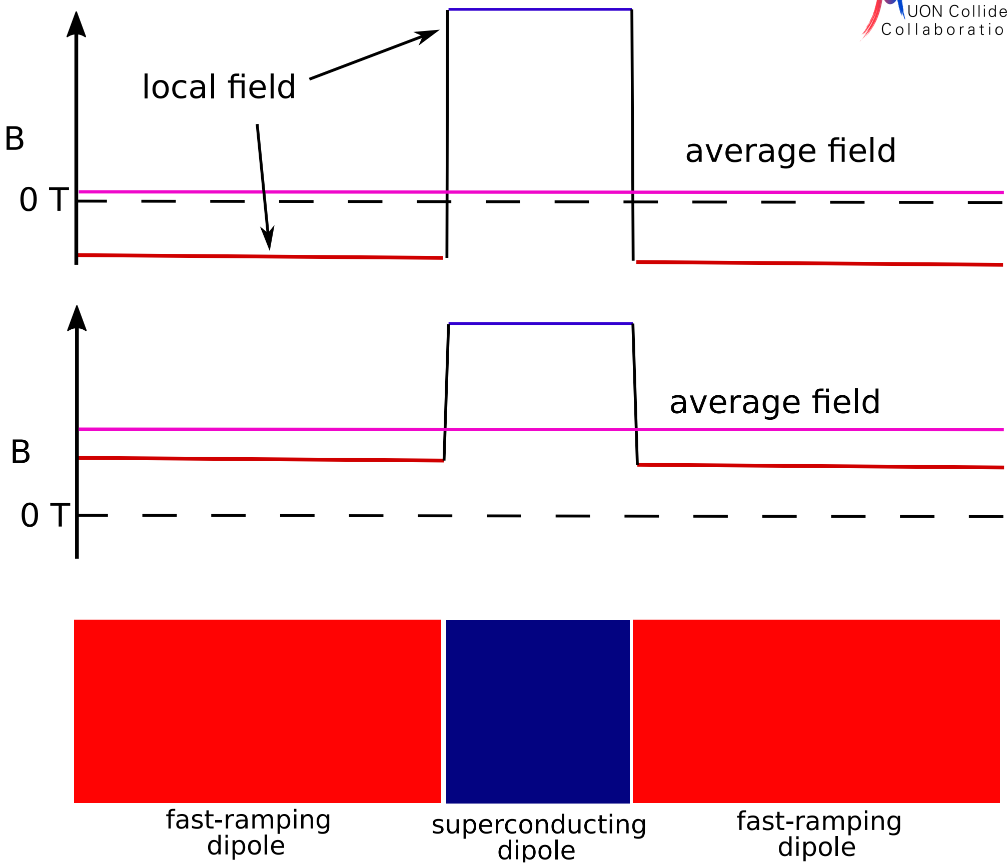
- Combine static and ramping magnets
- **Ramp magnets** to follow beam energy
  - normal conducting
  - or novel HTS
- **Power consumption** of fast-ramping systems is important

RF system

- **Important single-bunch beam loading**

FFAG

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



EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)