Muon Colliders

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European Strategy for Particle Physics

Recently a process has updated the European Strategy for Particle Physcis

- Many studies prepared proposals (end of 2018)

A working group had been set up to evaluate muon collider for the strategy process

- chaired by Nadia Pastrone
- We provided input for the European Strategy
- In the past muon collider had been studied in the US (also UK contributions and others): the MAP study
  - But US strategy had no ambition for the energy frontier
- Also some activities existed, mainly in Italy, on an alternative scheme
- But no concerted study effort

The working group recommended to further explore the muon collider option since it has a unique potential for high energies

Friday June 19, 2020 Council approved the European Strategy Update

- it recommends that an international collaboration be formed to study the muon collider

Recommendations

High-priority future initiatives
a) [..]
b) Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*
[..]
In addition to the high field magnets the accelerator R&D roadmap could contain:

- [..]
- an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e+e–colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;

High-energy Frontier Proposals

European Strategy Process just finished

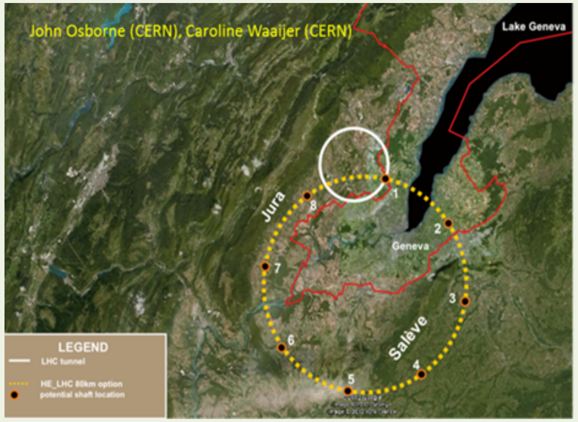
Four main high-energy facilities proposed
- two at CERN
- two in Asia

FCC (Future Circular Collider):

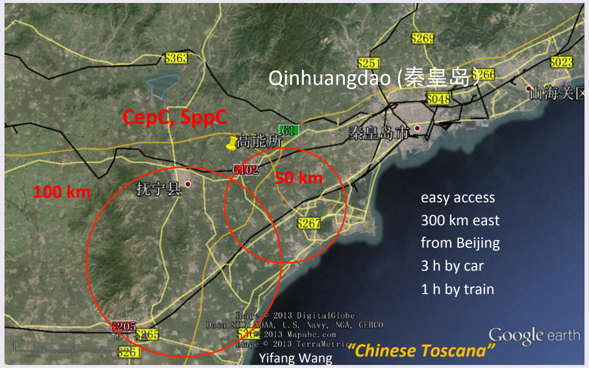
FCC-hh
- pp collider with 100 TeV cms
- ion option

FCC-ee
- Potential e^+e^- first stage

FCC-eh
- additional option



ILC
- 250 GeV electron-positron linear collider
- Japan might host
- limited in energy reach

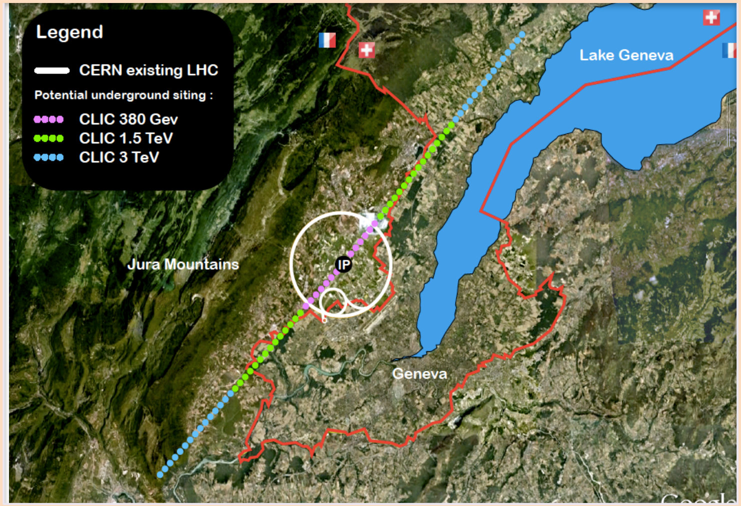


CEPC / SppC

CEPC
- e^+e^- collider 90-240 GeV

SppC
- 75-150 TeV hadron collider later in the same tunnel

CLIC
- 380 GeV, 1.5 TeV and 3 TeV electron positron collider

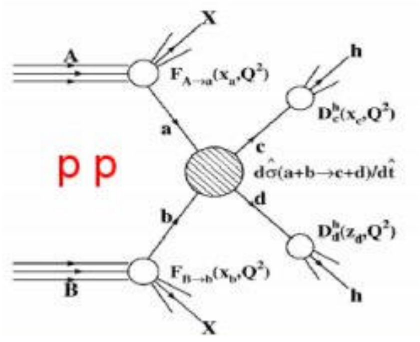


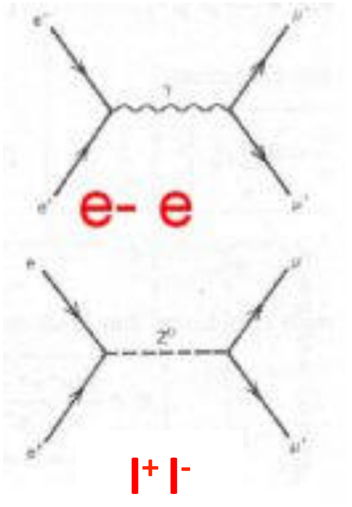
Proposed Projects

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

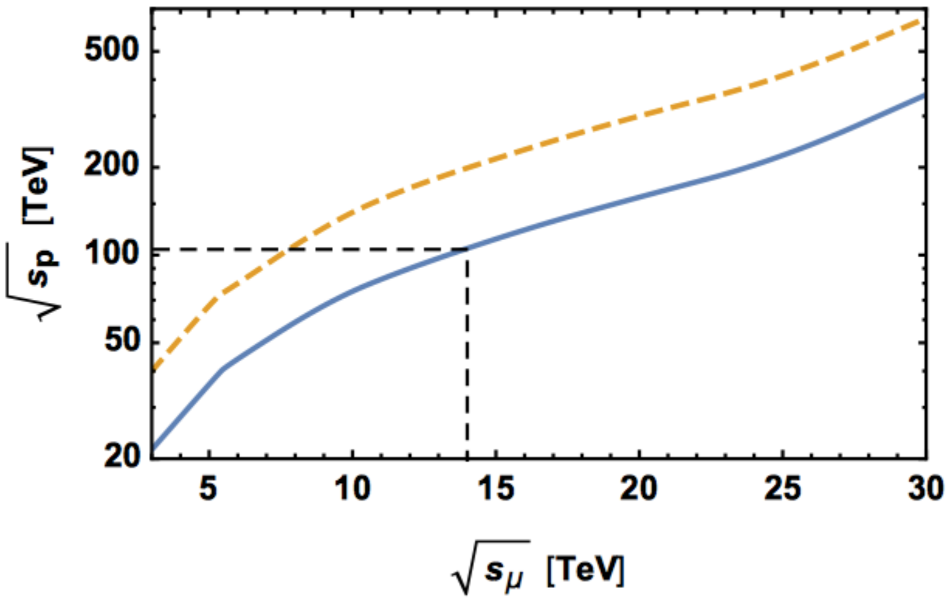
Motivation for High Energy Lepton Physics

High energy lepton colliders are **precision** and **discovery** machines





A. Wulzer



Luminosity goal (for s-channel physics)

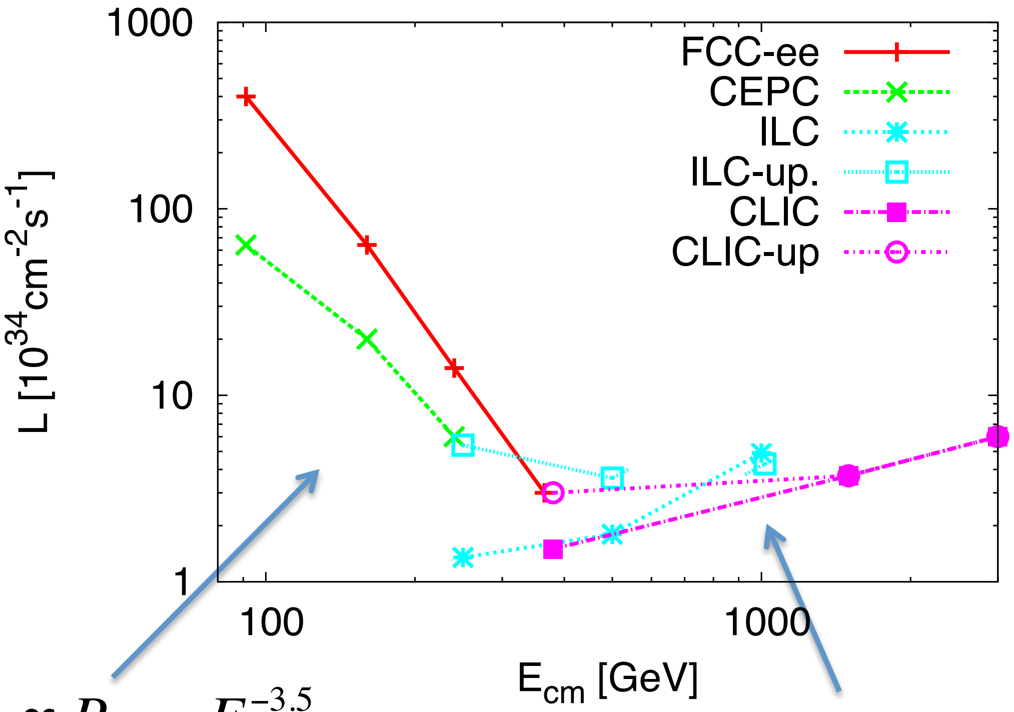
$$L \gtrsim \frac{5\,\mathrm{years}}{\mathrm{time}}\left(\frac{\sqrt{s_\mu}}{10\,\mathrm{TeV}}\right)^2 2\cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

FCC-hh reaches 100 TeV

So there should be interest in a 14 TeV lepton collider with L = 4 x 10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Proposed Lepton Colliders (Granada)

Luminosity per facility



$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF}$

Maximum proposed energy CLIC 3 TeV

- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy

But cost and power

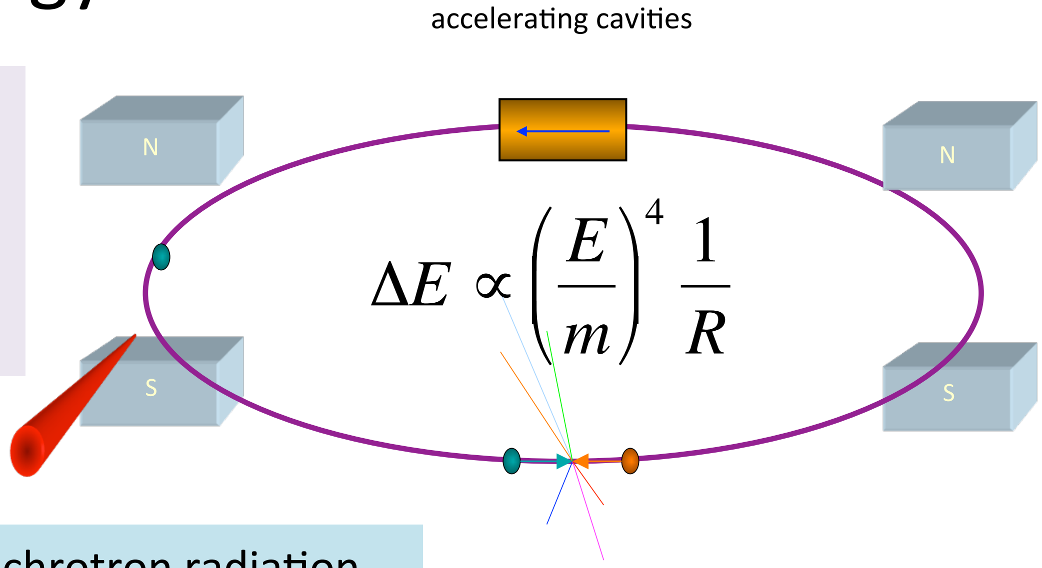
Extrapolated CLIC cost 59 GCHF
upgrade from 1.5 to 3 TeV is 8 GCHF
(14 TeV - 3 TeV) / 1.5 TeV * 8 GCHF = 59 GCHF

Extrapolated CLIC power consumption 1700 - 2800 MW
300 MW + 300 MW x 14 TeV / 3 TeV or even 600 MW x 14 TeV / 3 TeV
Another factor 1.5 to reach luminosity target

Energy Limit

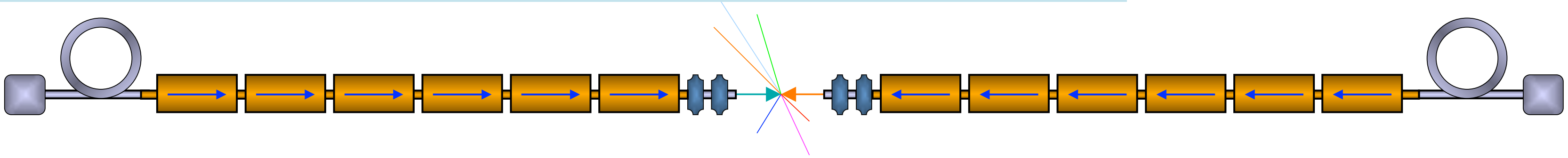
Electron-positron rings are **multi-pass** colliders limited by synchrotron radiation

That is why **proton rings** are energy frontier



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

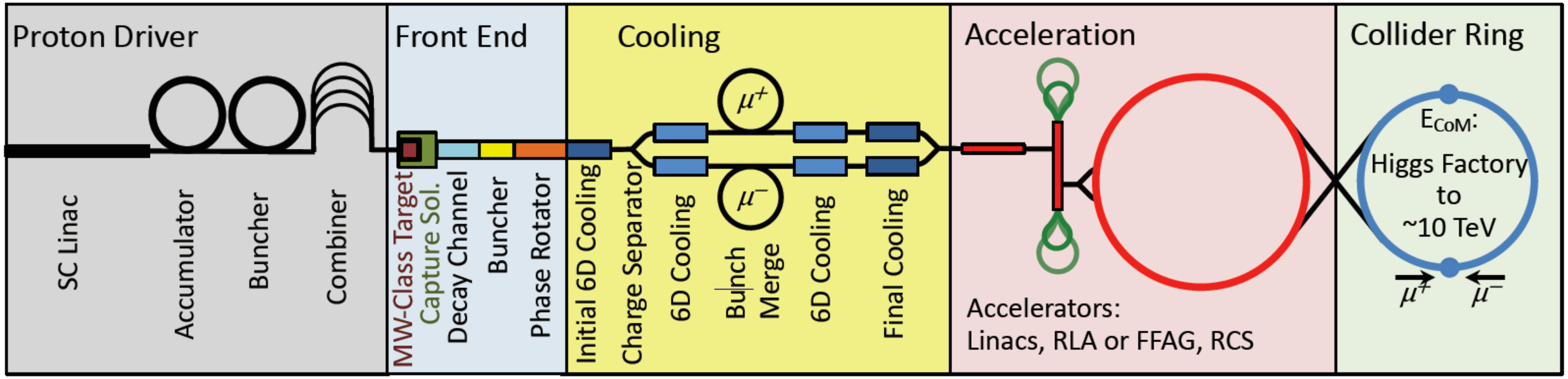
Electron-positron linear colliders avoid synchrotron radiation
But are **single pass** is acceleration and collision
This limits energy and luminosity



Novel approach: **muon collider**
Large mass suppresses synchrotron radiation => **multi-pass**
Fundamental particle requires less energy than protons
But lifetime at rest only 2.2 μs

Proton-driven Muon Collider Concept (MAP)

From the MAP collaboration:
Proton source (M. Palmer et al.)



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

Did find that design is not complete
but did not find that does not work

No CDR exists, no coherent baseline of machine
No reliable cost estimate

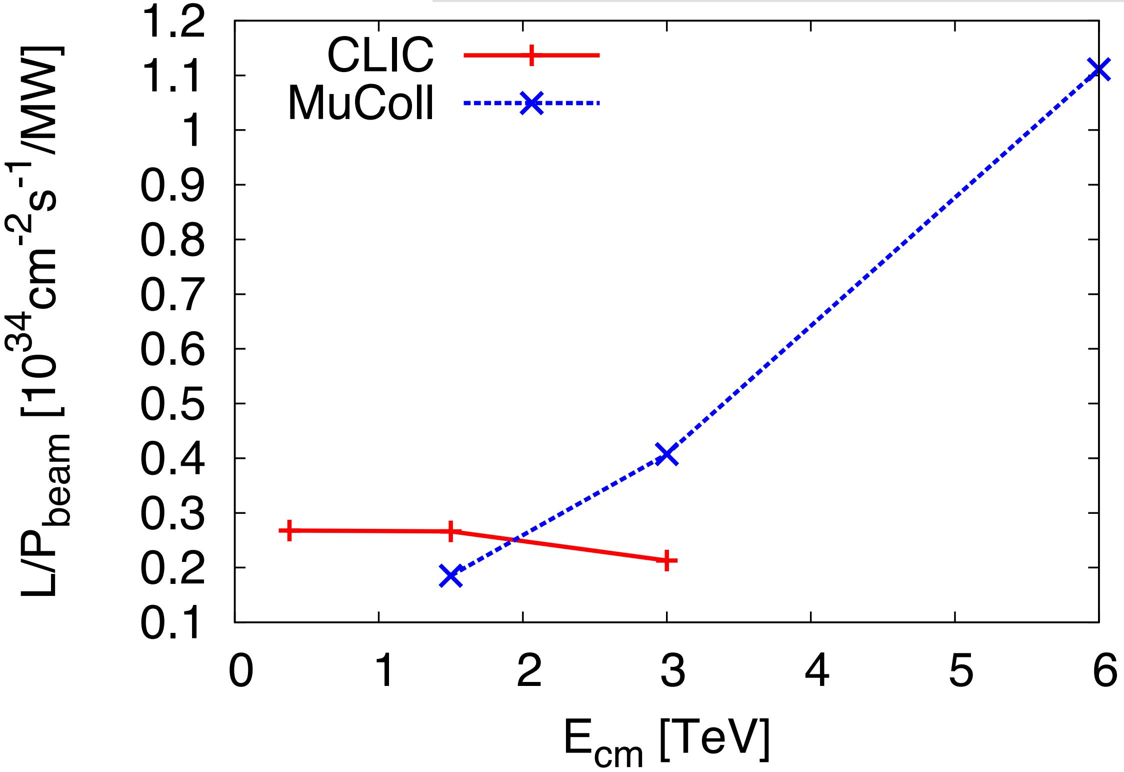
Luminosity Comparison

The luminosity per beam power is about constant in linear colliders

- Except if we can also change beam quality at production and focusing
- However, already worked on this for decades
- Using CLIC parameters

Novel technologies such as plasma acceleration make this even harder

MuColl parameters from MAP collaboration



A muon collider could potentially increase luminosity per beam power with energy

Tentative Target Parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2	2	2
f_r	Hz	6	4	4
P_{beam}	MW	5.8	12.8	17.9
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

Scaled from MAP parameters

Emittance is constant

$$\sigma_E \sigma_z = \text{const}$$

Collider ring acceptance is constant

$$\frac{\sigma_E}{E} = \text{const}$$

Bunch length decreases

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

Betafunction decreases

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

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$\langle B \rangle$	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

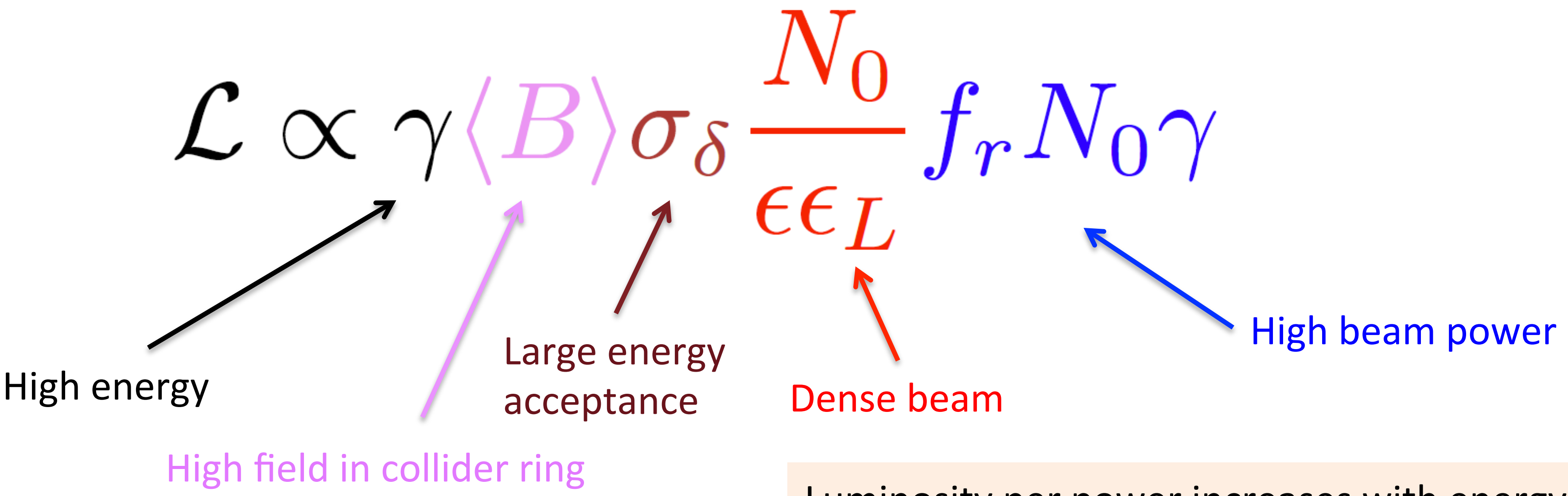
Scaled from MAP parameters

Beam power of CLIC is
28 MW @ 3 TeV
130 MW @ 14 TeV

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

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

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

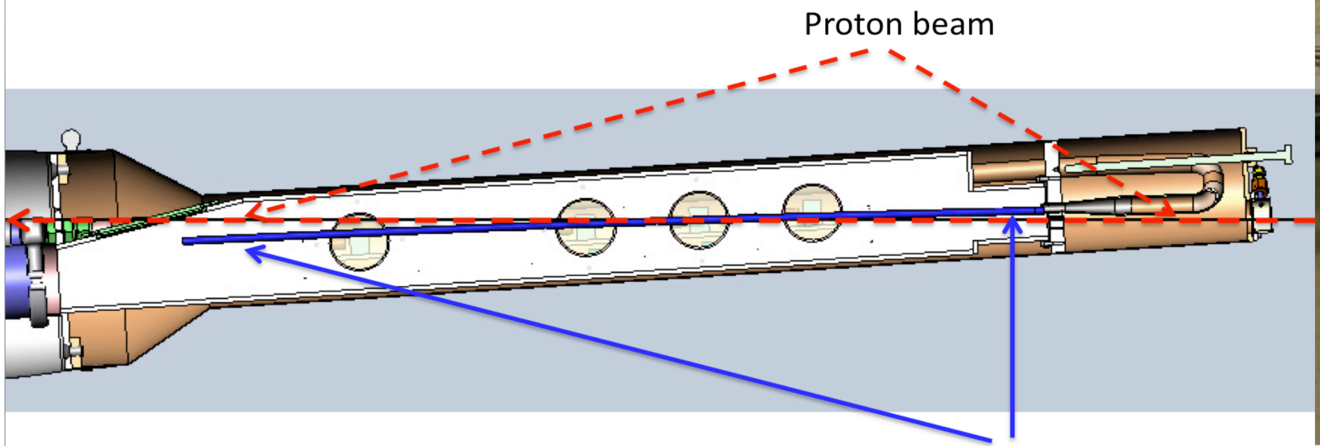
Luminosity per power increases with energy
Provided all technical limits can be solved

Constant current for required luminosity

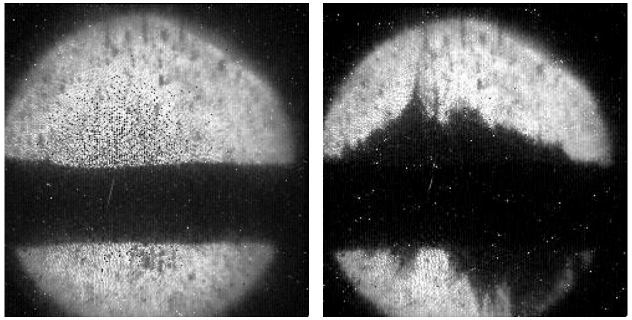
Better scaling than linear colliders

Source

Protons → Target → Pions → Muons



MERIT experiment at CERN



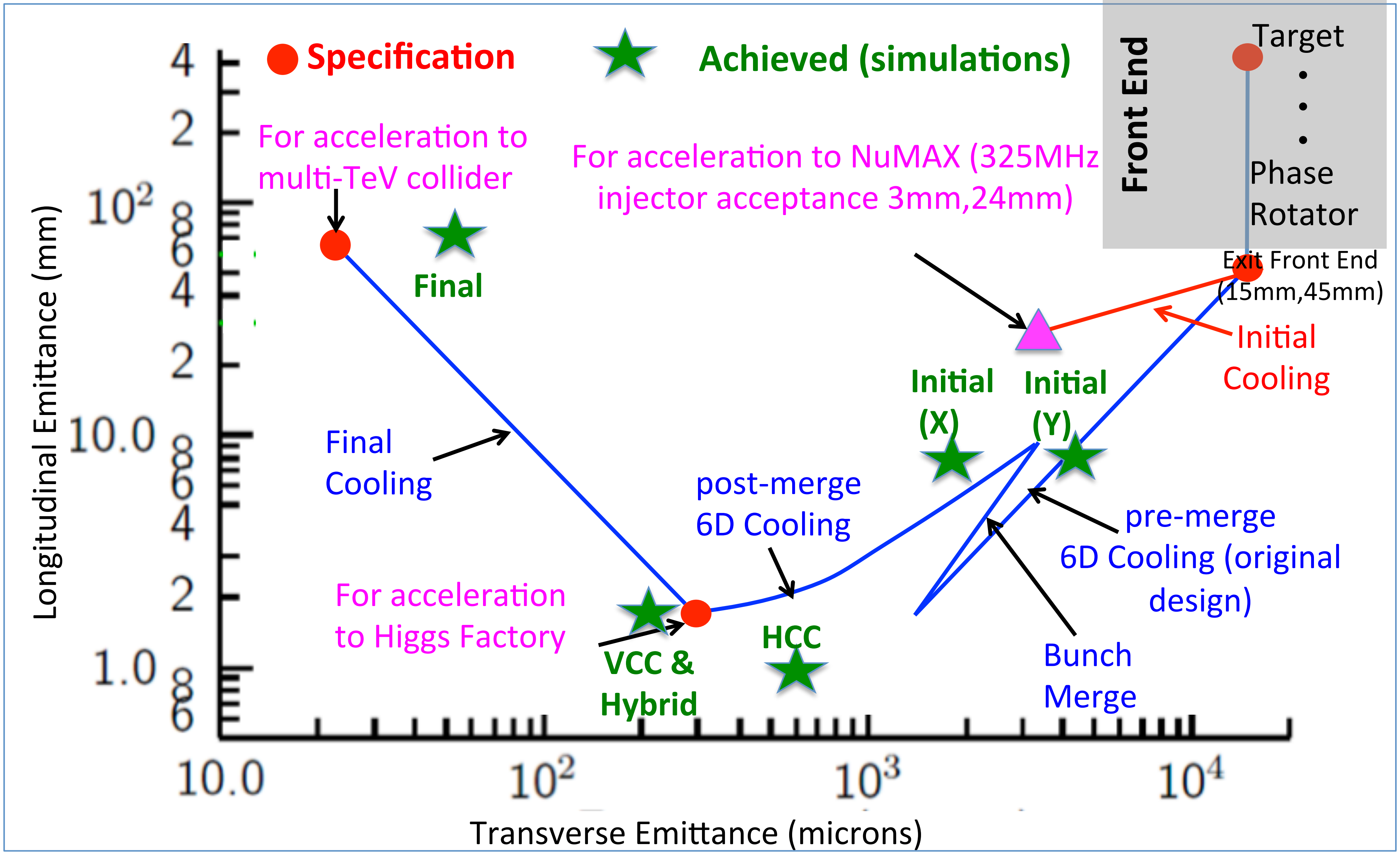
High power target (8 MW vs. 1.6-4 MW or even less required) has been demonstrated

Maximum of 30×10^{12} protons with 24 GeV yielded 9×10^{13} muons (would like to double)

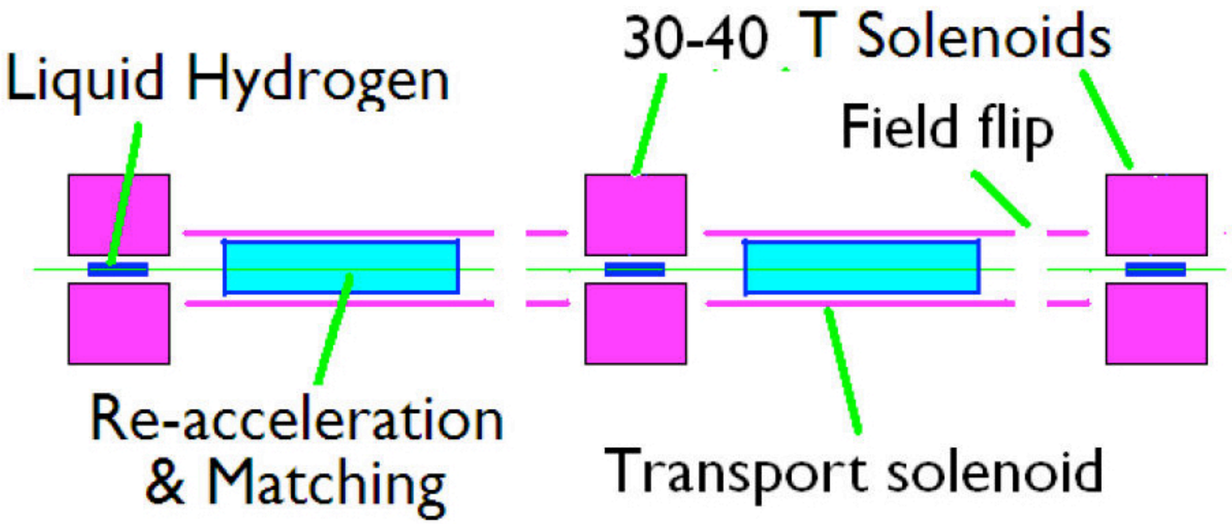
But radiation issues?
Maybe can use solid target

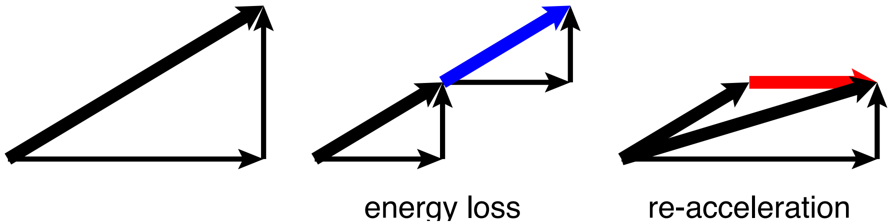
Example for capture solenoid
- Aperture 1.2 m and 15-20 T
- GJ stored energy

Cooling: The Emittance Path



Transverse Cooling Concept



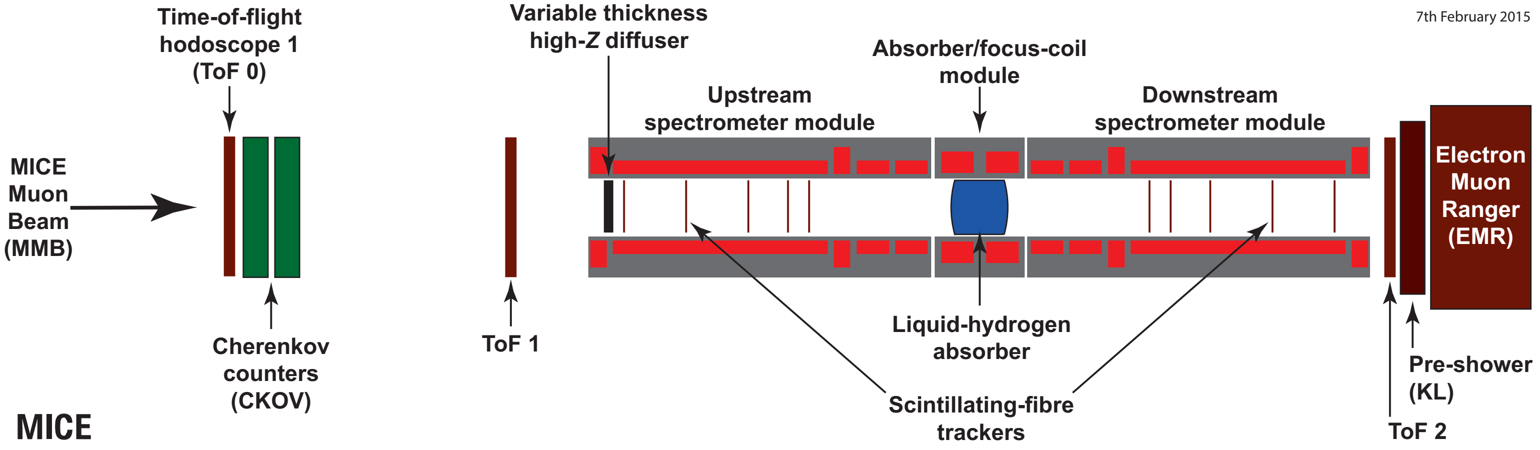


Strong solenoids to minimise betafunction

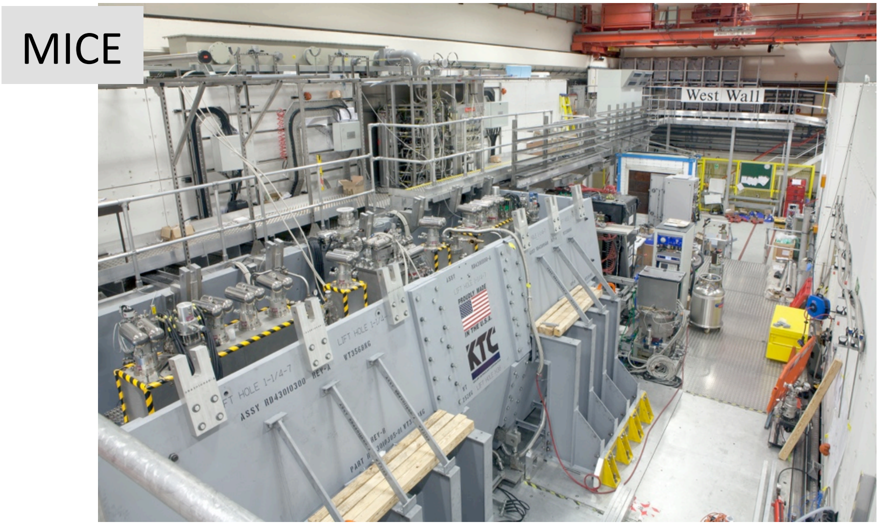
$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Example: final cooling solenoids >30 T aperture 25 mm
Higher field means better emittance and more luminosity

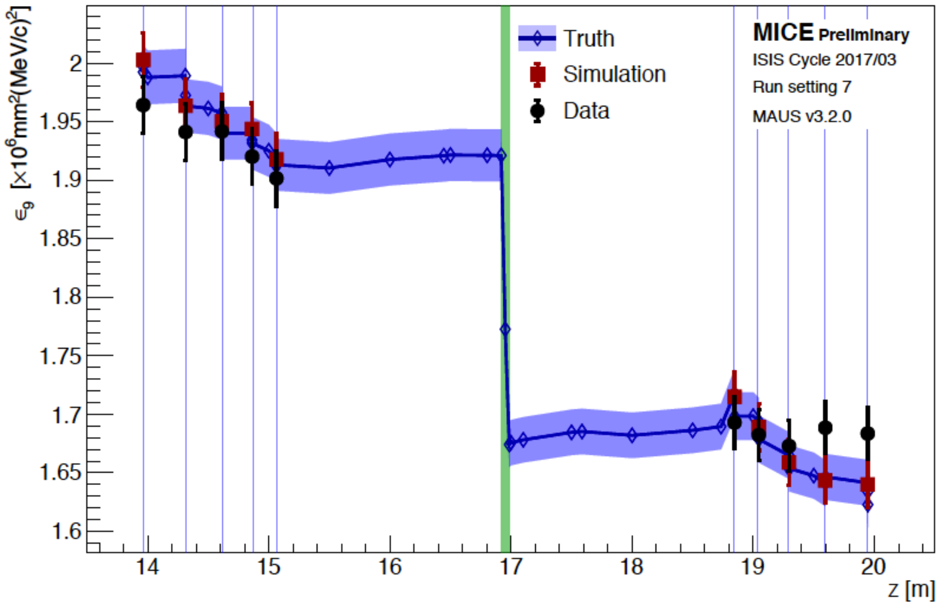
MICE (in the UK)



Principle of ionisation cooling has been demonstrated



Noticeable reduction of 9% emittance



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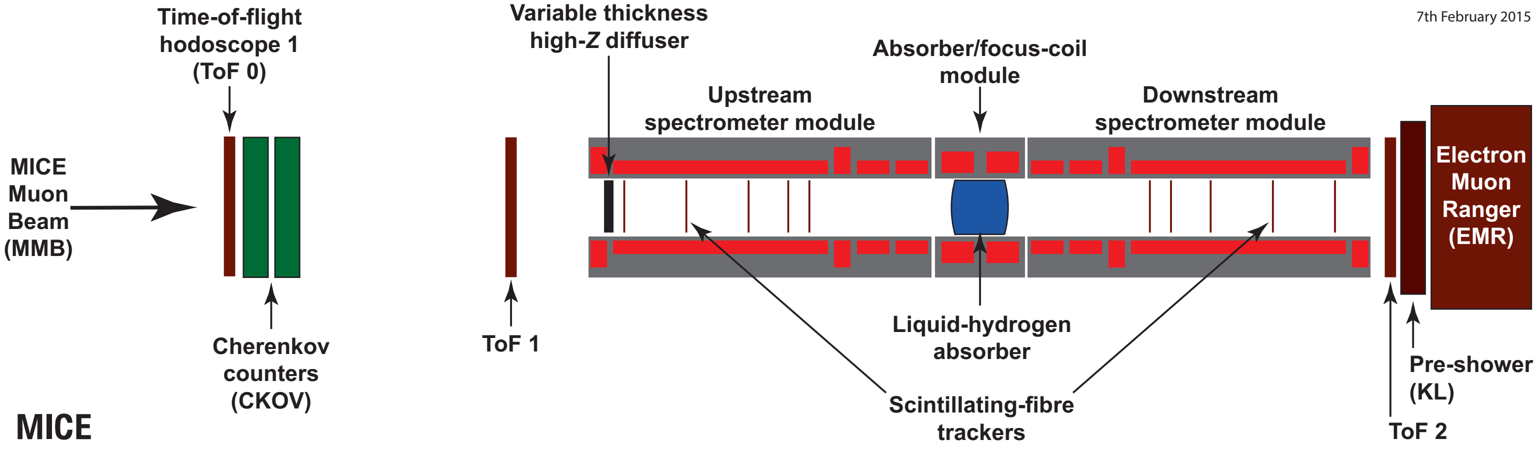

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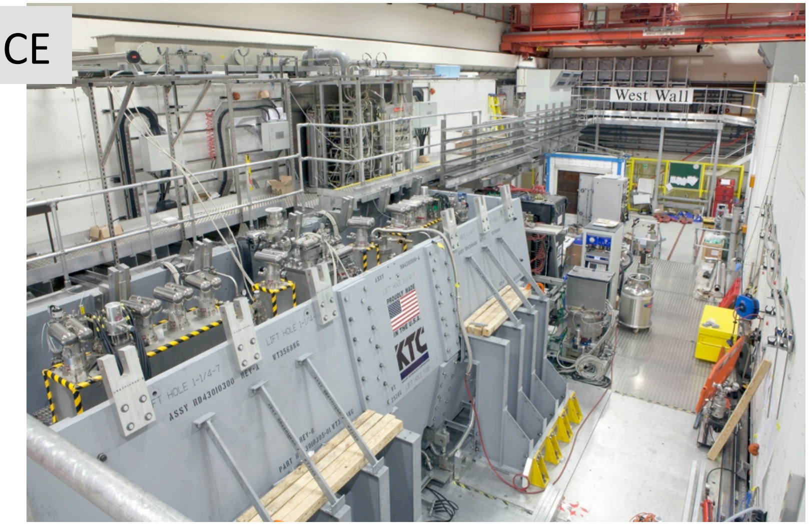

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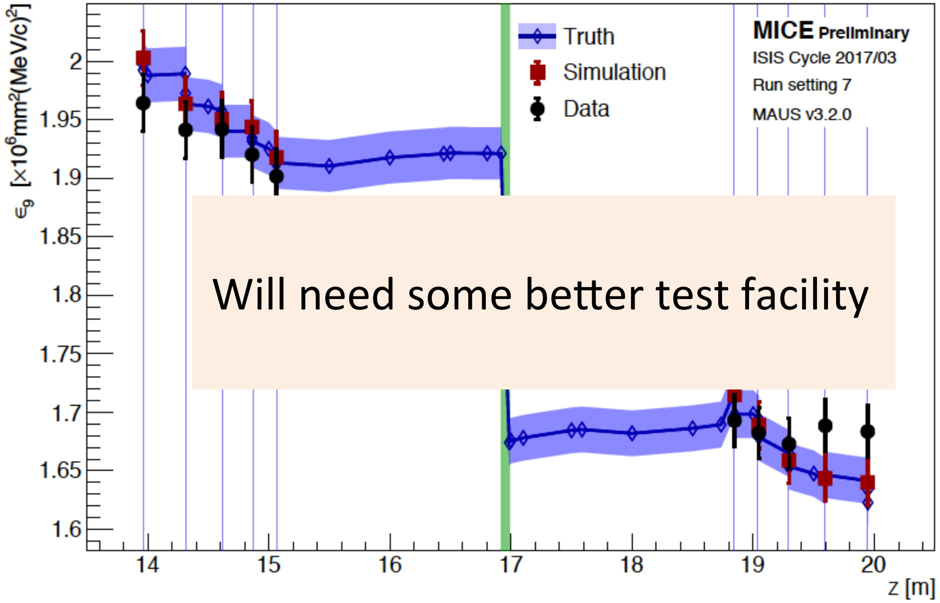
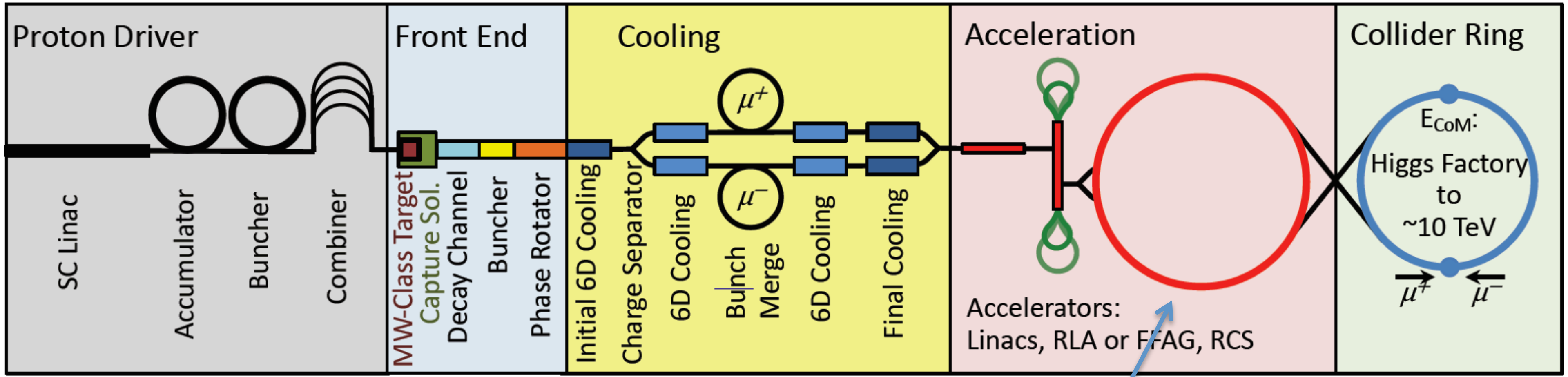


Will need some better test facility

Beam Acceleration



Much larger than collider ring

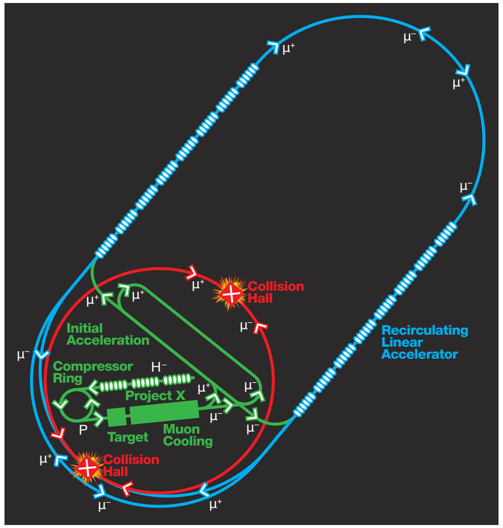
An important cost driver

Important for power consumption

A trade-off between cost and muon survival

Not detailed design, several approaches considered

- Linacs
- Recirculating linacs
- FFAGs
- Rapid cycling synchrotrons



Challenge is large bunch charge but single bunch

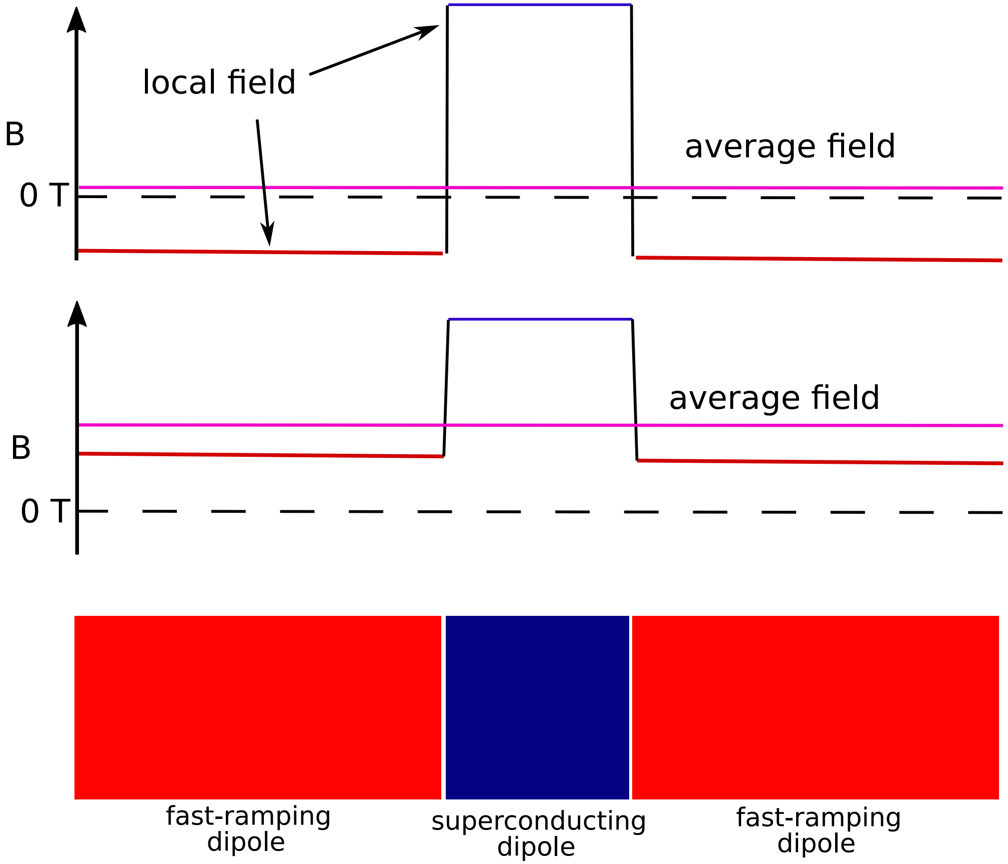
Example Acceleration

Rapid cycling synchrotron (RCS)

- Inject beam at low energy and ramp magnets to follow beam energy
- Potentially important acceleration range at affordable cost

- Could use combination of static superconducting and ramping normal-conducting magnets
- First the normal magnets have opposite field
- Then they are ramped to add to static field

- Important energy in fast pulsing magnets
  - O(40 MJ) @ 3 TeV
  - O(200 MJ) @ 14 TeV



- Efficient energy recovery and storage is required
  - Concepts exist and have been used at much smaller scale

Collider Ring

High field dipoles to minimise collider ring size and maximise luminosity

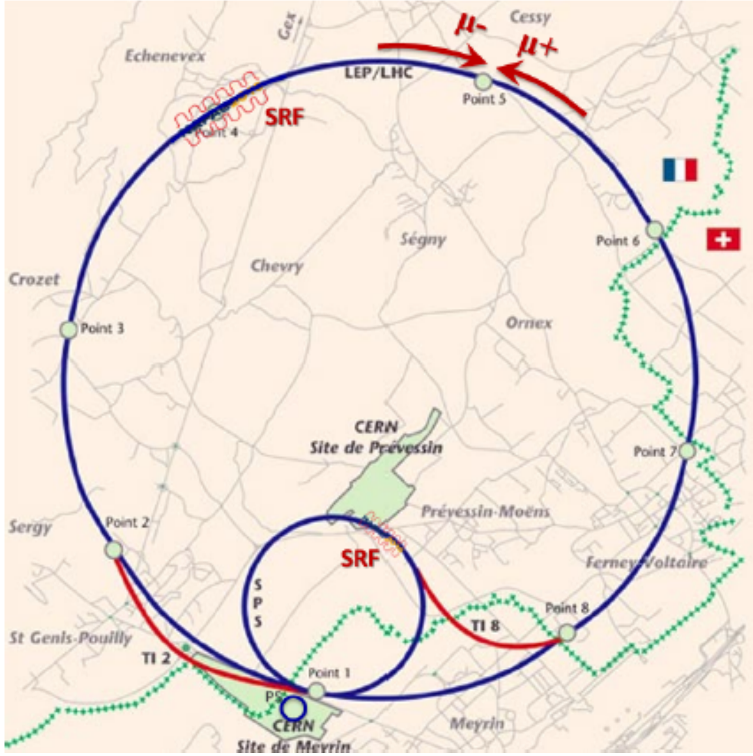
Decaying muons impact accelerator components, detector and public

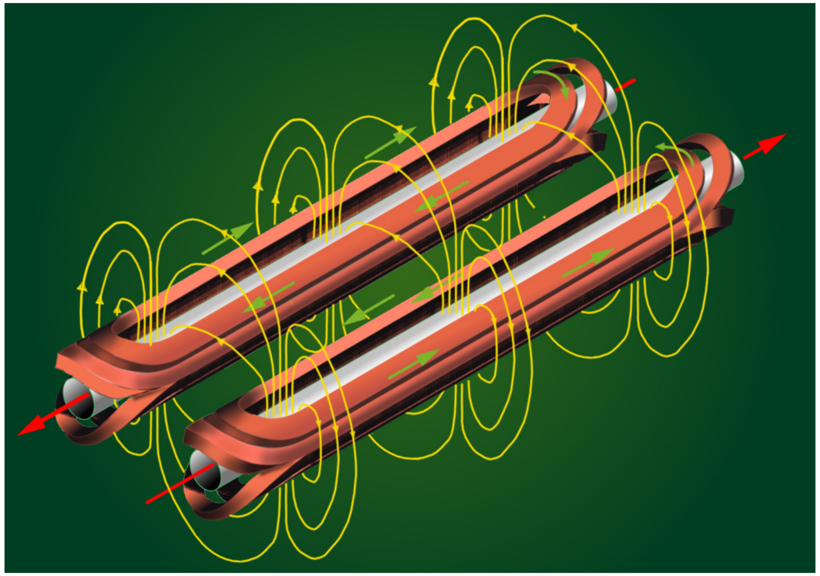
- The latter becomes much worse with energy
- Minimise distances with no bending

Protect dipole magnets and experiments
from electrons / positrons from muon decay

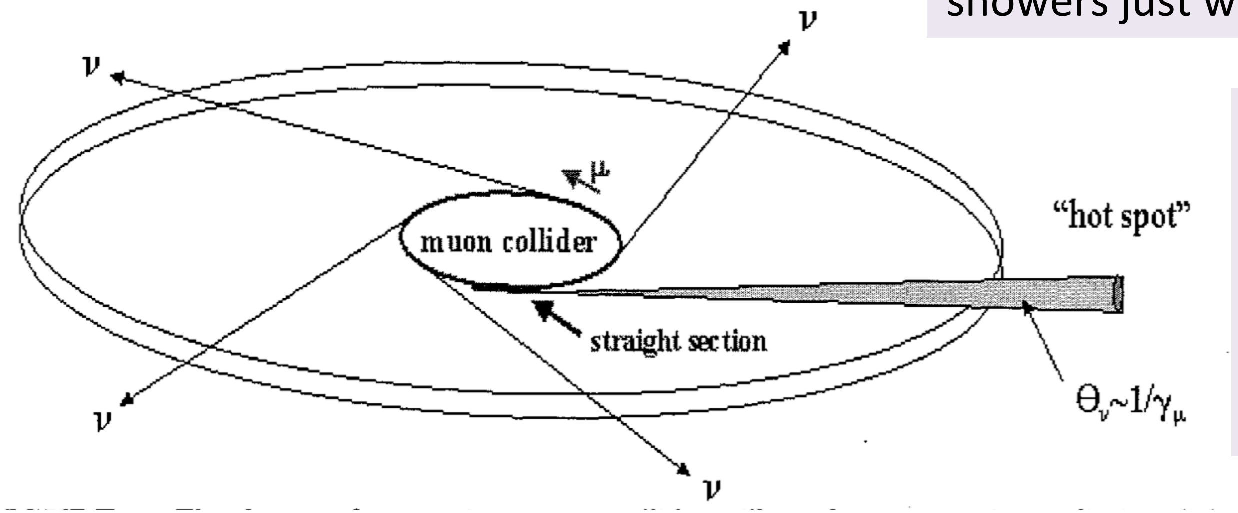
E.g. remove part of coil in midplane

- But reduces field





Neutrino Radiation Hazard



Neutrinos from decaying muons can produce showers just when they exit the earth

Particularly bad in direction of straights
Mitigated by owning the land at exit

But also an issue in the arcs

Becomes more important at higher energies (scaling E^3)

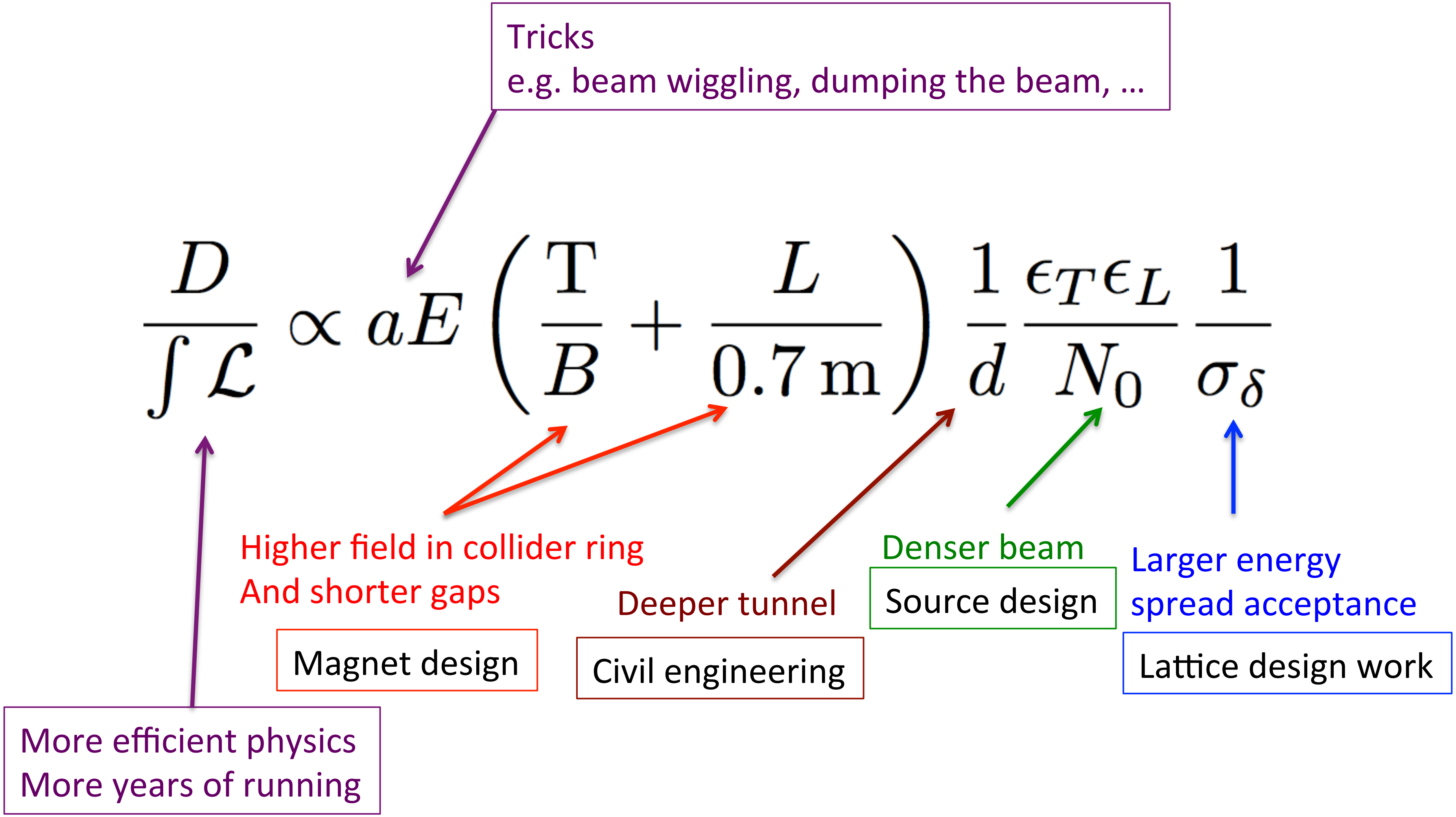
US study concluded that 6 TeV parameters are OK

Reasonable goal is 0.1 mSv/ year, but to be verified

For 1.5 + 1.5 TeV 40 m depth is required
LHC effective depth is 23 m in worst direction

For 7 + 7 TeV 500 m depth requires factor 8 improvement

Mitigation Approaches



Tricks
e.g. beam wiggling, dumping the beam, …

$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\,\frac{\epsilon_T\epsilon_L}{N_0}\,\frac{1}{\sigma_\delta}$$

Higher field in collider ring
And shorter gaps

Magnet design

Deeper tunnel

Civil engineering

Denser beam

Source design

Larger energy
spread acceptance

Lattice design work

More efficient physics
More years of running

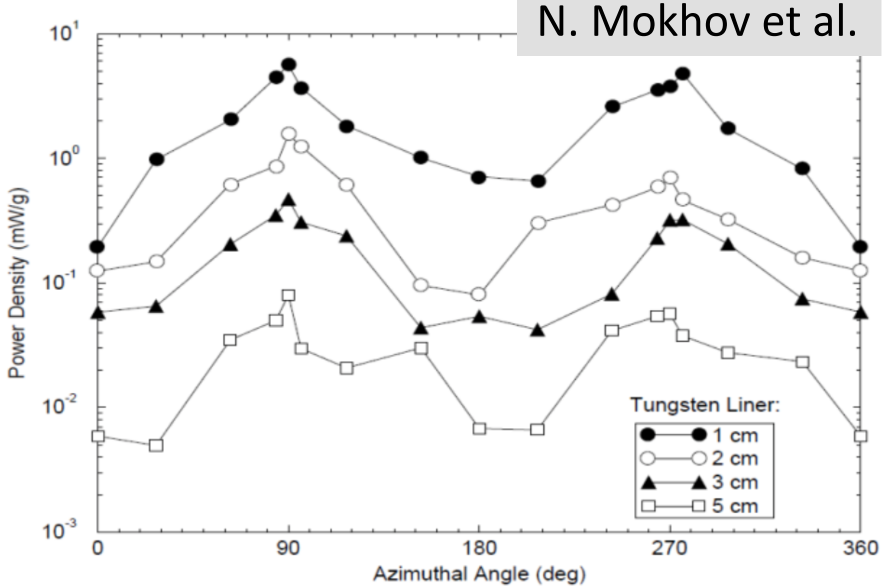
Collider Ring (MAP Example)

O(400 W/m) beam loss (1/3 of beam energy)

Tungsten shielding 50 mm and 30 mm
1.5 mW/g but 10 W/m

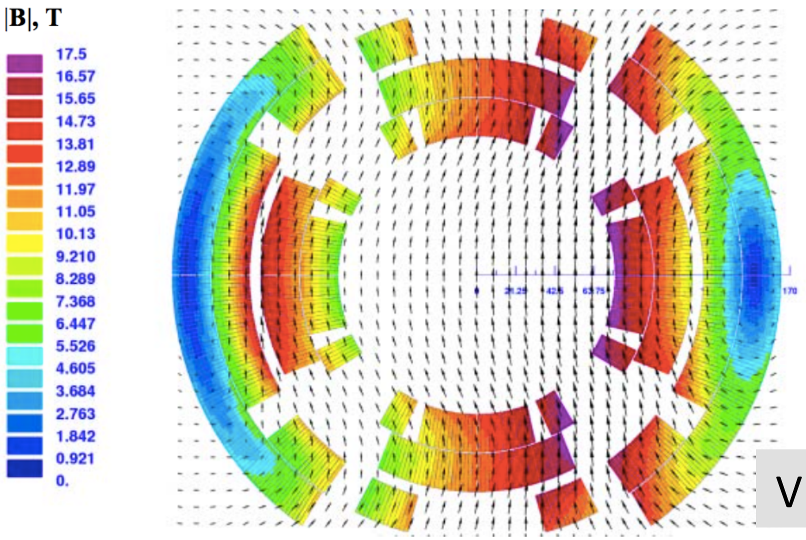
Efficient cooling of magnet and shield needed

Study at high energy essential

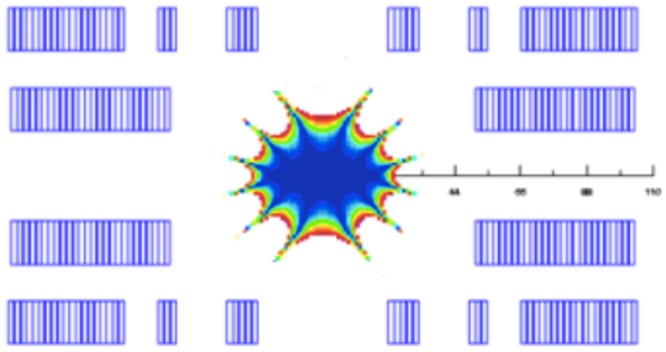


N. Mokhov et al.

Combined function magnet design



Or open midplane dipole design



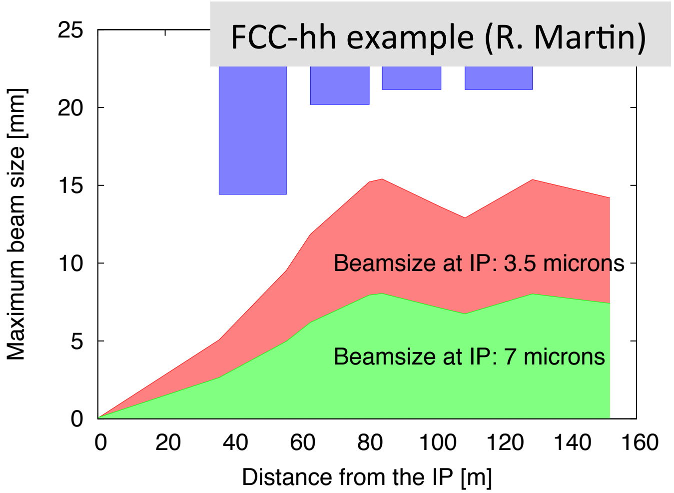
V.V. Kashikhin et al.

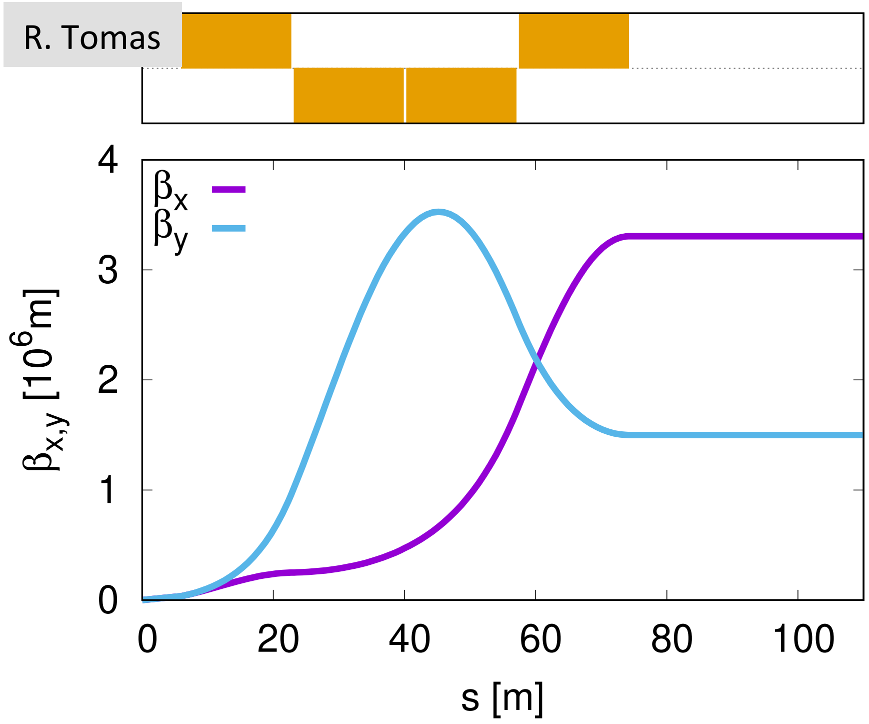
Final Focus

Need smaller betafunctions at higher energy
Or smaller longitudinal emittance / larger energy acceptance

$$\beta^* \propto \frac{1}{E}$$

And focusing of higher energy beam is more difficult


FCC-hh example (R. Martin)


R. Tomas

$\beta^*_{x,y}$ = 1 mm
B_{peak} = 18 T
N_σ = 10 σ
E = 7 TeV
Aper. = 0.7 m

0.7 m for 10 σ
0.3 m for 6 σ

First look from Rogelio Tomas on final triplet at 14 TeV (L* = 6 m):

Challenging system
Need to add shielding

RF and Optics Challenge

Longitudinal motion in collider ring

- average lifetime is O(3000) turns
- want short bunches O(1mm) @ 14 TeV
- significant energy spread O(10^{-3})
- large ring (14 km @ 14 TeV)
- Need very small momentum compaction

Almost completely suppress motion for

- i.e. 2.5×10^{-8} @ 14 TeV
- 5×10^{-6} @ 3 TeV

$$\alpha \ll \frac{\epsilon_L m_\mu c}{\sigma_\delta^2 E^2 \tau c}$$

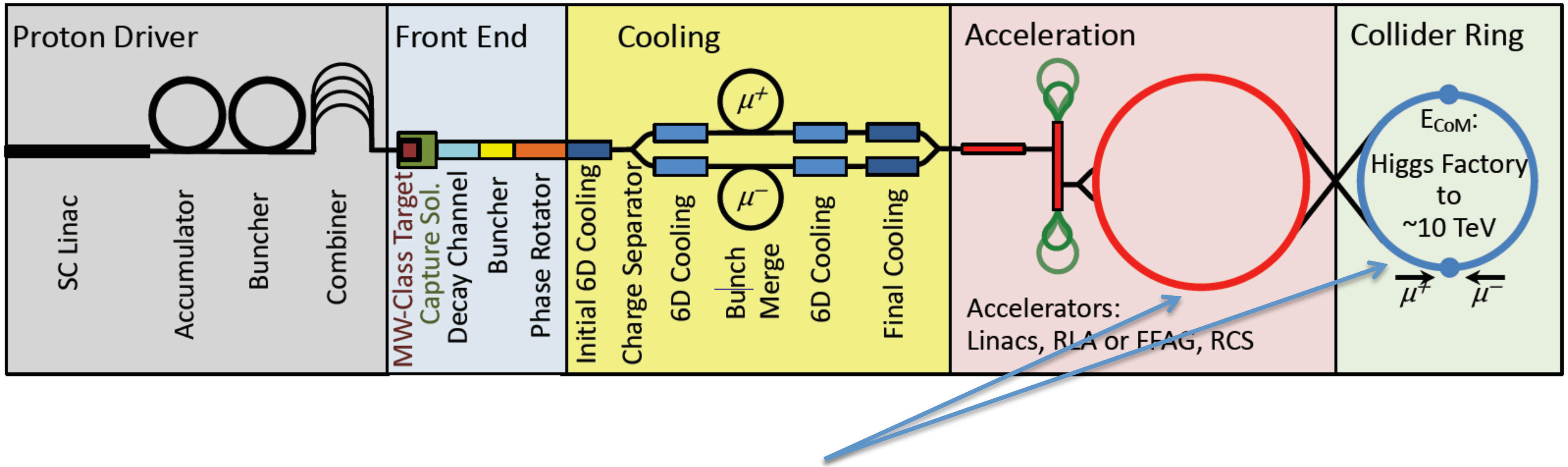
Or need enough RF voltage

- e.g. 4 GV @ 14 TeV, $\alpha = 10^{-6}$, $f_{RF} = 1$ GHz
- e.g. 86 MV @ 3 TeV, $\alpha = 10^{-5}$, $f_{RF} = 1$ GHz

$$U = \frac{\sigma_\delta^4}{\epsilon_L^2} \frac{E^4 \alpha_c \lambda_{RF} (\mathrm{Tm/GeV})}{0.3\langle B \rangle}$$

Need to minimise momentum compaction

Combined Option



Proposal to combine last accelerator ring and collider ring (D. Neuffer / V.Shiltsev)

- Might reduce cost
- But creates many specific challenges
  - Would have to ramp final focus system
  - or find a bypass
  - …

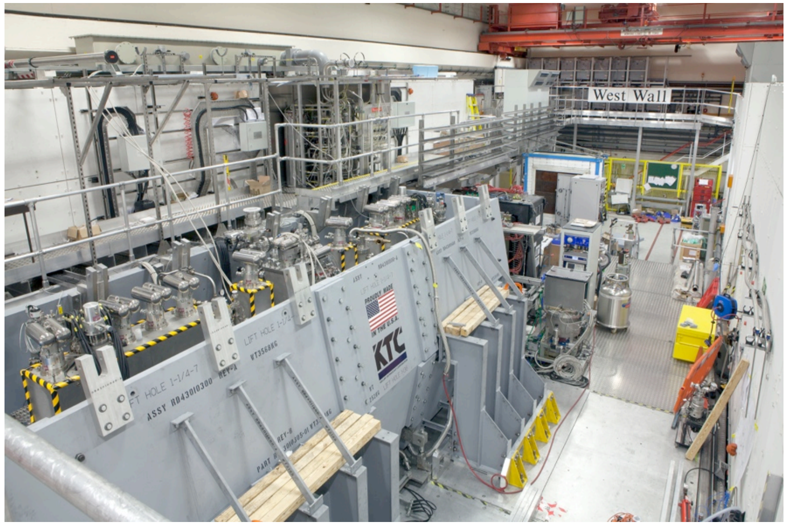
- This would be largest tunnel

Design Status

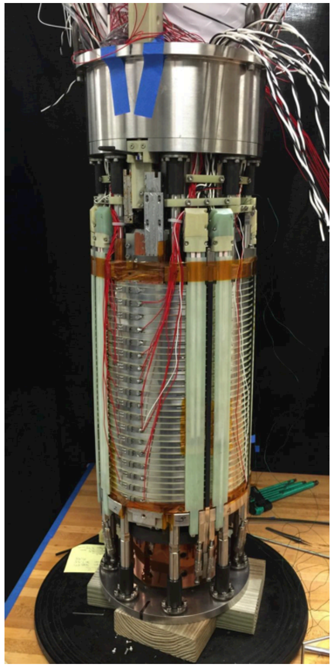
Key systems designed for 3 TeV in US
A number of key components has been developed
Cooling test performed according to theory

But no CDR, no integrated design, no reliable cost estimate
More work to be done, e.g. substantial, 6D cooling

MICE (UK)

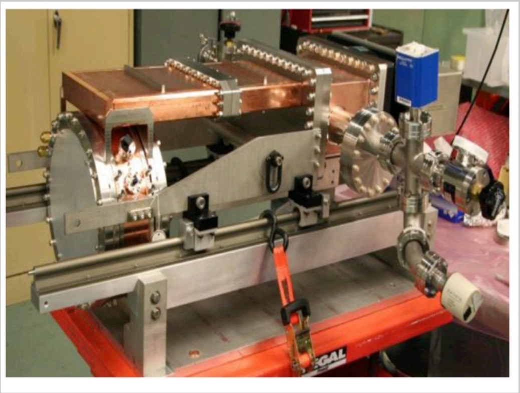


FNAL
Breakthrough in HTS cables



NHFML
32 T solenoid with low-temperature HTS

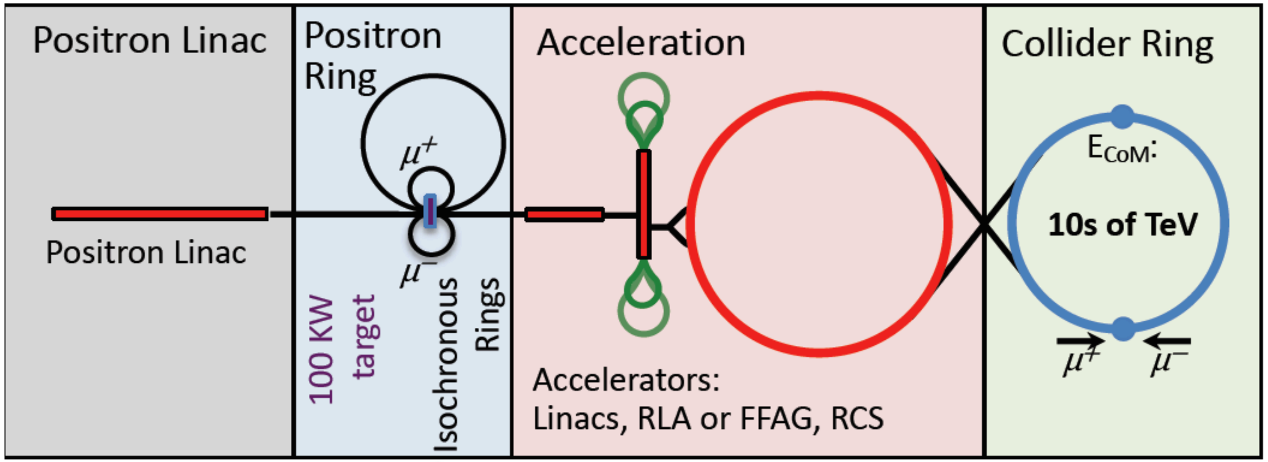
MuCool: >50 MV/m in 5 T field

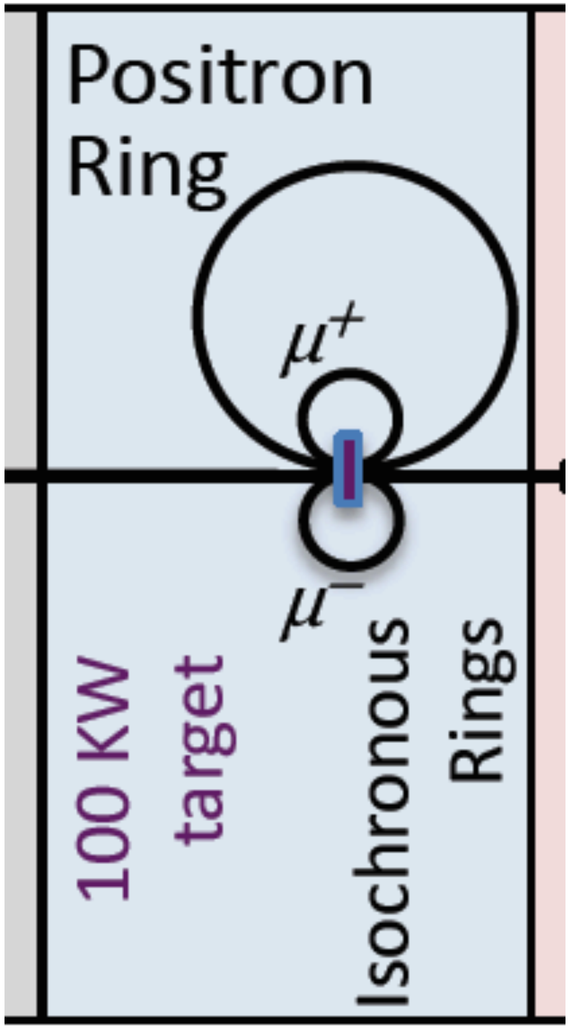


FNAL
12 T/s HTS
0.6 T max

Mark Palmer

The LEMMA Scheme

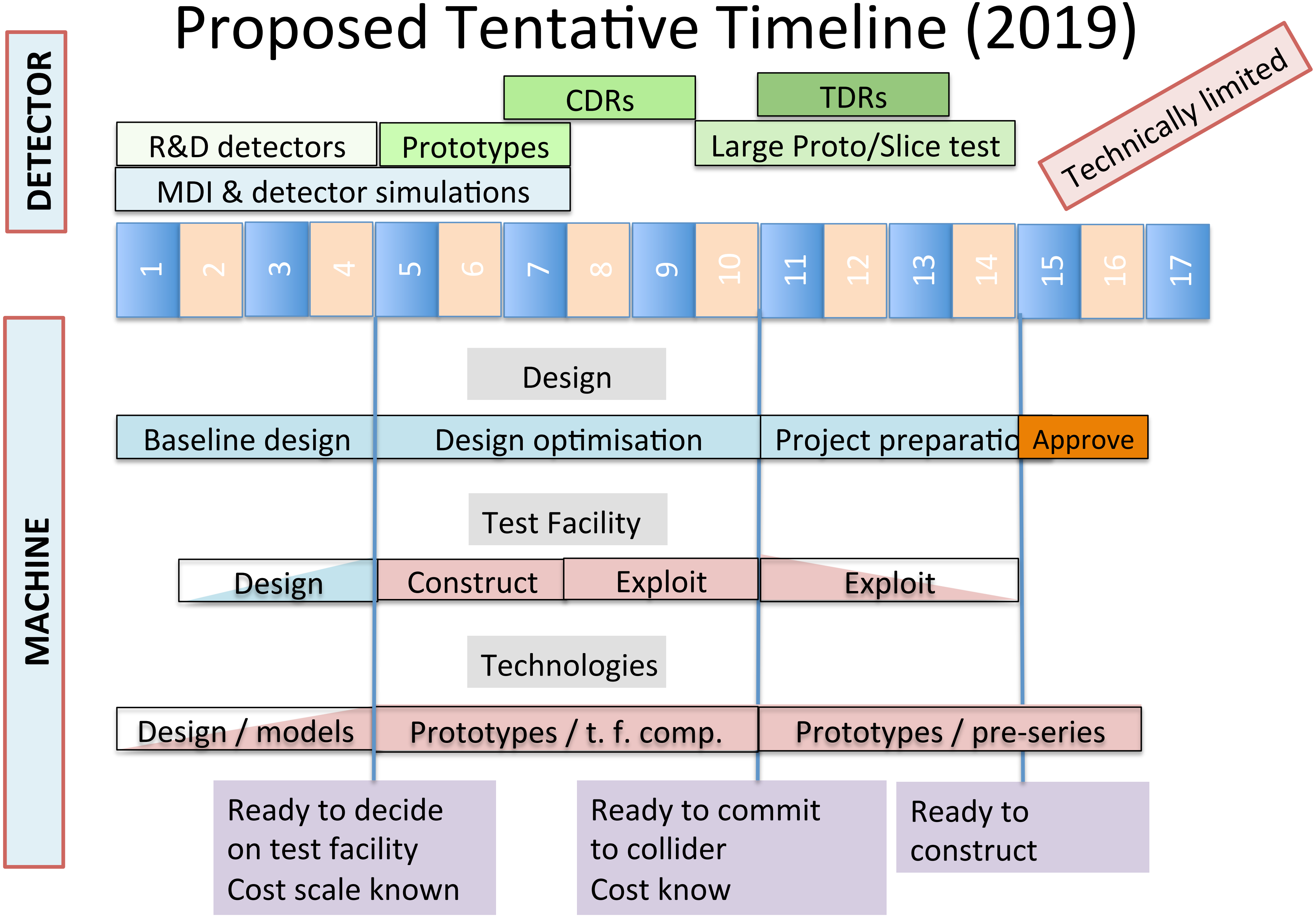




45 GeV positrons to produce muon pairs
Accumulate muons from several passages

Low emittance muon beam
But very large positron current required
Target is challenging
Need large positron production rate [O(10^{17}/s)]
Currently do not reach luminosity goal

Proposed Tentative Timeline (2019)



DETECTOR

CDRs

TDRs

Technically limited

R&D detectors

Prototypes

Large Proto/Slice test

MDI & detector simulations

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

MACHINE

Design

Baseline design

Design optimisation

Project preparatio

Approve

Test Facility

Design

Construct

Exploit

Exploit

Technologies

Design / models

Prototypes / t. f. comp.

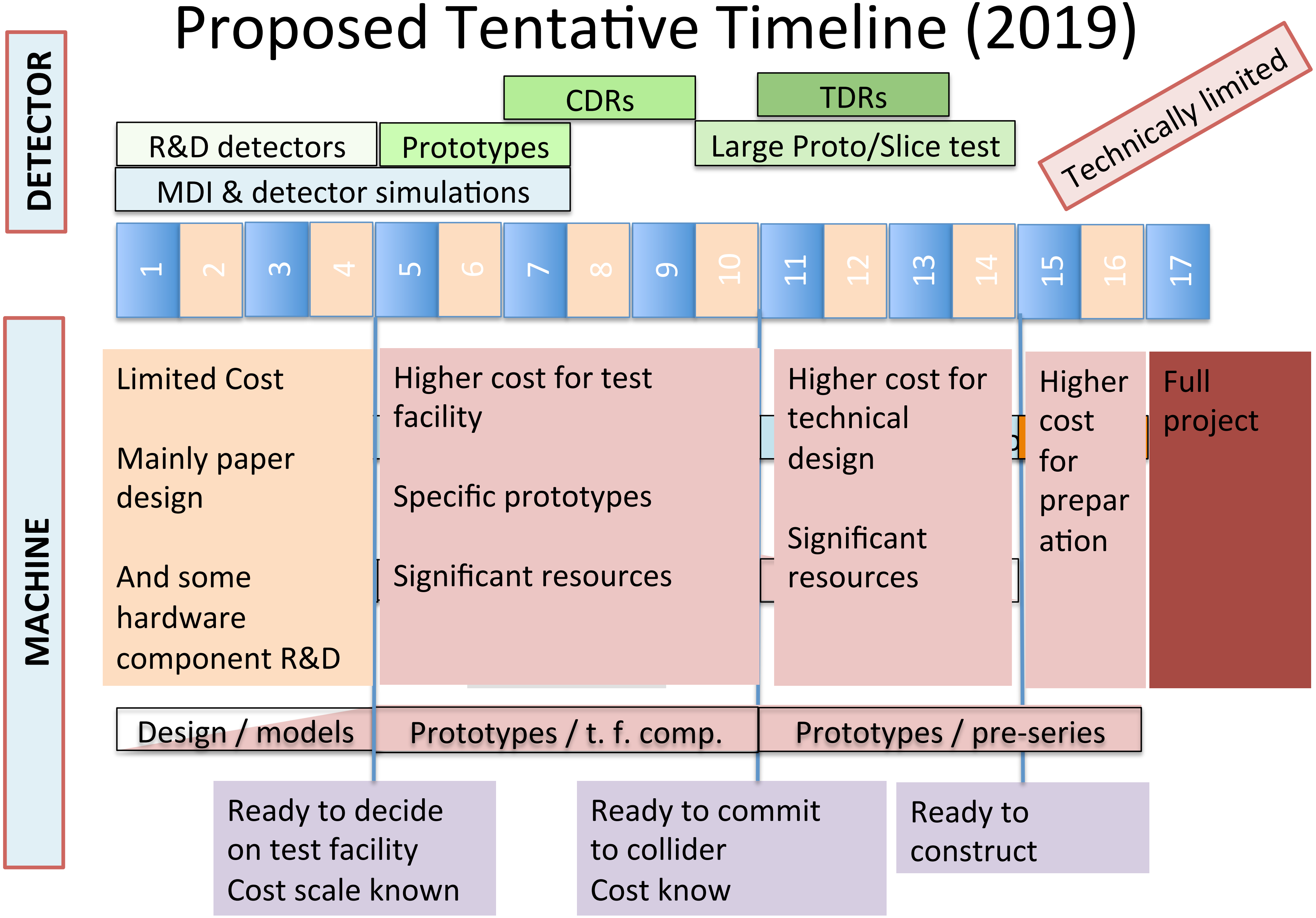
Prototypes / pre-series

Ready to decide
on test facility
Cost scale known

Ready to commit
to collider
Cost know

Ready to
construct

Proposed Tentative Timeline (2019)



DETECTOR

CDRs

TDRs

Technically limited

R&D detectors

Prototypes

Large Proto/Slice test

MDI & detector simulations

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

MACHINE

Limited Cost

Mainly paper design

And some hardware component R&D

Higher cost for test facility

Specific prototypes

Significant resources

Higher cost for technical design

Significant resources

Higher cost for preparation

Full project

Design / models

Prototypes / t. f. comp.

Prototypes / pre-series

Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

Tentative Considerations on Baseline

- Stage with energy of O(1.5 + 1.5 = 3 TeV)
  - To come after higgs factory and matching highest CLIC energy
  - Using the high-energy strength of muon colliders
  - Realistic design for implementation at CERN, with cost power and risk scale
  - If successful, feasibility demonstration for CDR

- Explore 14 TeV as further step
  - To match FCC-hh discovery potential
  - Mainly exploration of parameters to guide choices
  - Provide evidence for feasibility, maybe cost frame

- Exploration of synergies
  - Higgs factory
  - Neutrino factory

Objective for First Period

- Important resources for R&D are required to make the muon collider mature enough that we can commit to it

- Goal is to establish until the next European Strategy Update that this effort is worthwhile, i.e.
  - A muon collider addresses the needs of the physics community
  - It appears feasible
    - Risks, performances, cost, power consumption are expected to be acceptable
  - Provide R&D plan to bring the technology to sufficient maturity for commitment
    - with estimated cost

Conclusion

Muon colliders are a promising option for the high-energy frontier

Important work to demonstrate feasibility and performance

Combination of challenges from proton colliders and electron machines

Strong support by European Strategy for Particle Physics

Hopefully strong support in Germany

Collaboration is forming

Meeting (remote) on July 3 14:00-18:00
- web page (agenda being prepared) https://indico.cern.ch/event/930508/
- purpose is to start collecting statements of intent to collaborate
  - collaboration will be on best-effort basis
  - indication of fields of interest
  - obviously, no moral commitment possible now since every one needs to find resources

Reserve

Linear Collider Scaling with Energy

Normalised emittances always used

$$\mathcal{L} \propto H_D \frac{n_\gamma^{\frac{3}{2}}}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\epsilon_y \beta_y}} \frac{R+1}{R} \frac{\eta P_{wall}}{mc^2}$$

Beamstrahlung
limited by physics
requirements

Beam quality and
focusing design

RF-to-beam efficiency
Power consumption

At high energy

$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

For unchanged technologies:
Luminosity per power remains constant with energy
Provided we can focus the beam accordingly

$R=\sigma_x/\sigma_y$

Other Options

Variations of the muon sources were suggested

- E.g. use of channeling in crystals
- Use of gamma factory to produce muons
- Use of gamma factory to produce positrons for LEMMA

But all at a very tentative level for now

e.g. W. Krasny, X. Buffat, …

Also suggested were use of LHC and FCC tunnel for the collider ring

- Obviously something that needs to be explored
- Come back to this later

e.g. V. Shiltsev, D. Neuffer, F. Zimmermann, …

Combination of final accelerator stage and collider ring

- Could maybe save some cost
- But likely will compromise performance
- And generate its own challenges
- So trade-off has to be understood

e.g. V. Shiltsev, D. Neuffer

Also some other ideas

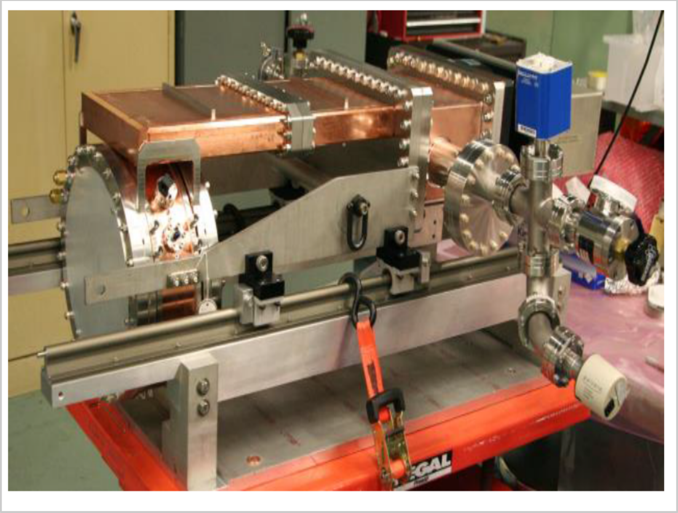
- But too early to

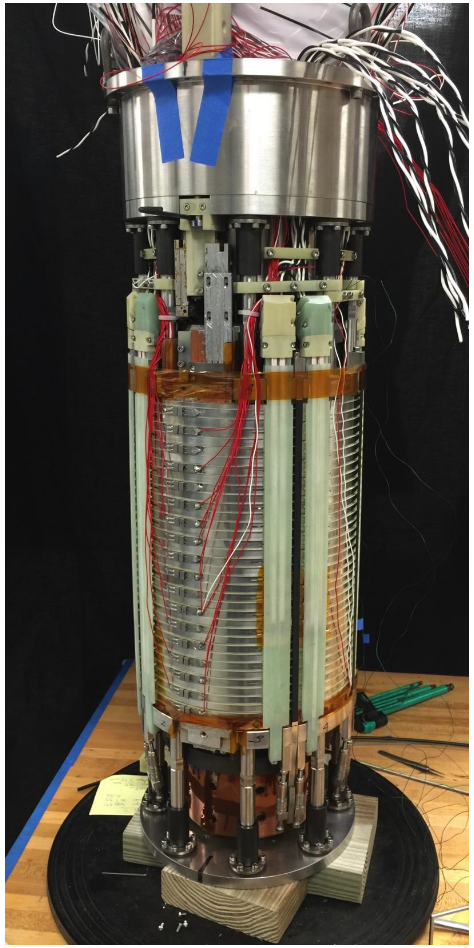
Other Tests

FNAL
Breakthrough in
HTS cables

A number of key components
has been developed

MuCool: >50 MV/m in 5 T field





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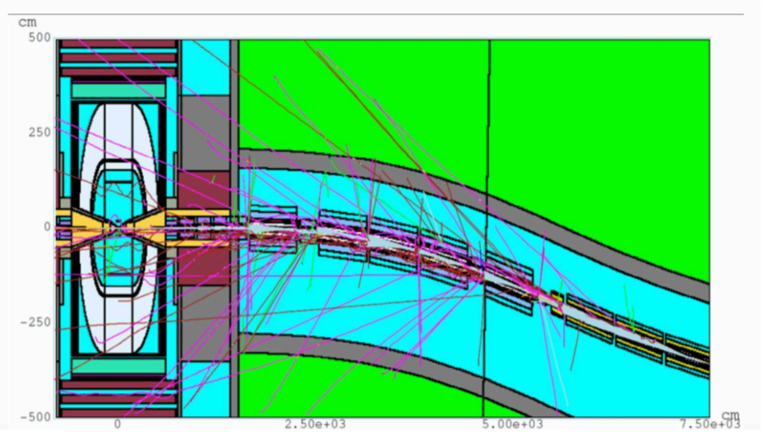
12 T/s HTS
0.6 T max

Mark Palmer

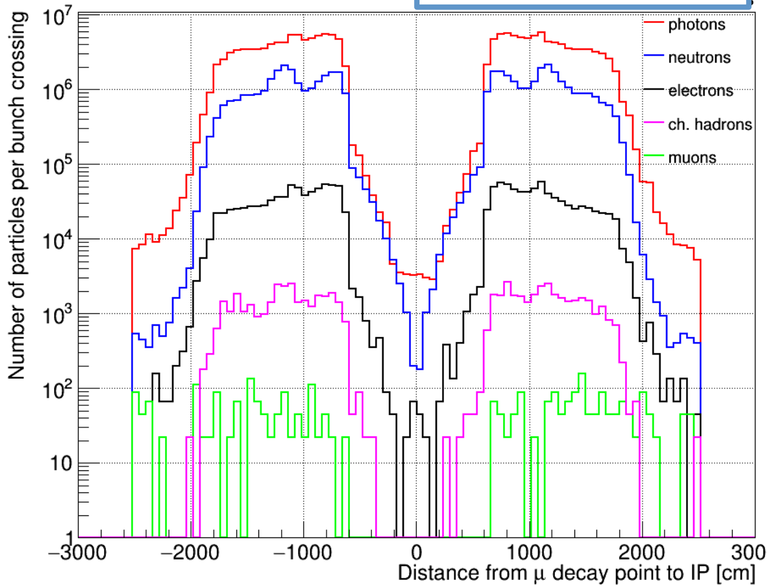
Beam induced background studies on detector at $\sqrt{s}$ =1.5 TeV

arXiv:1905.03725

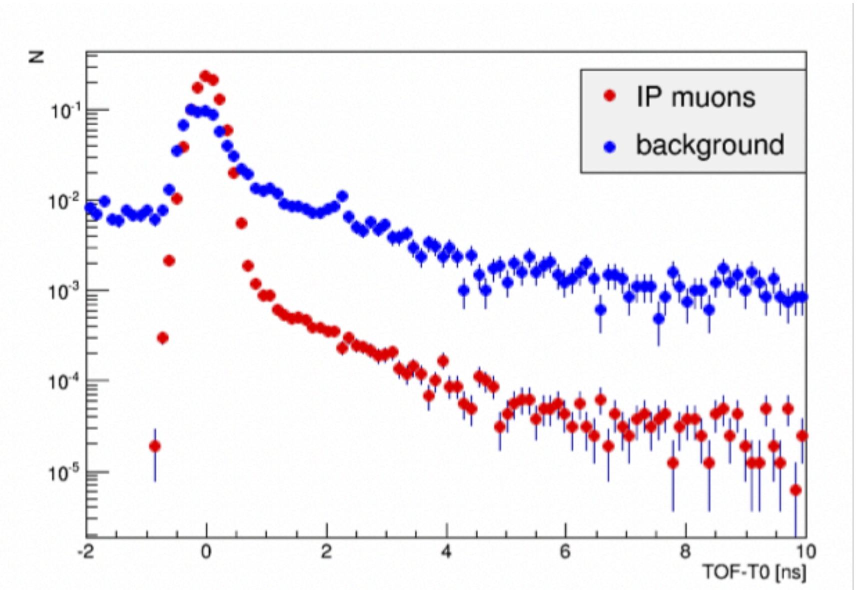


MARS15 simulation in a range of ±100 m around the interaction point

750 GeV beam



Particle composition of the beam-induced background as a function of the muon decay distance from the interaction point



Simulated time of arrival (TOF) of the beam background particles to the tracker modules with respect to the expected time (T0) of a photon emitted from IP

Note: Total Power Consumption

Power consumption estimates are based on a table calculated by R. Palmer
- Leaves out a number of components, e.g. magnets
- Quote: “These numbers are preliminary, with large uncertainties”

J.-P. Delahaye added a constant value

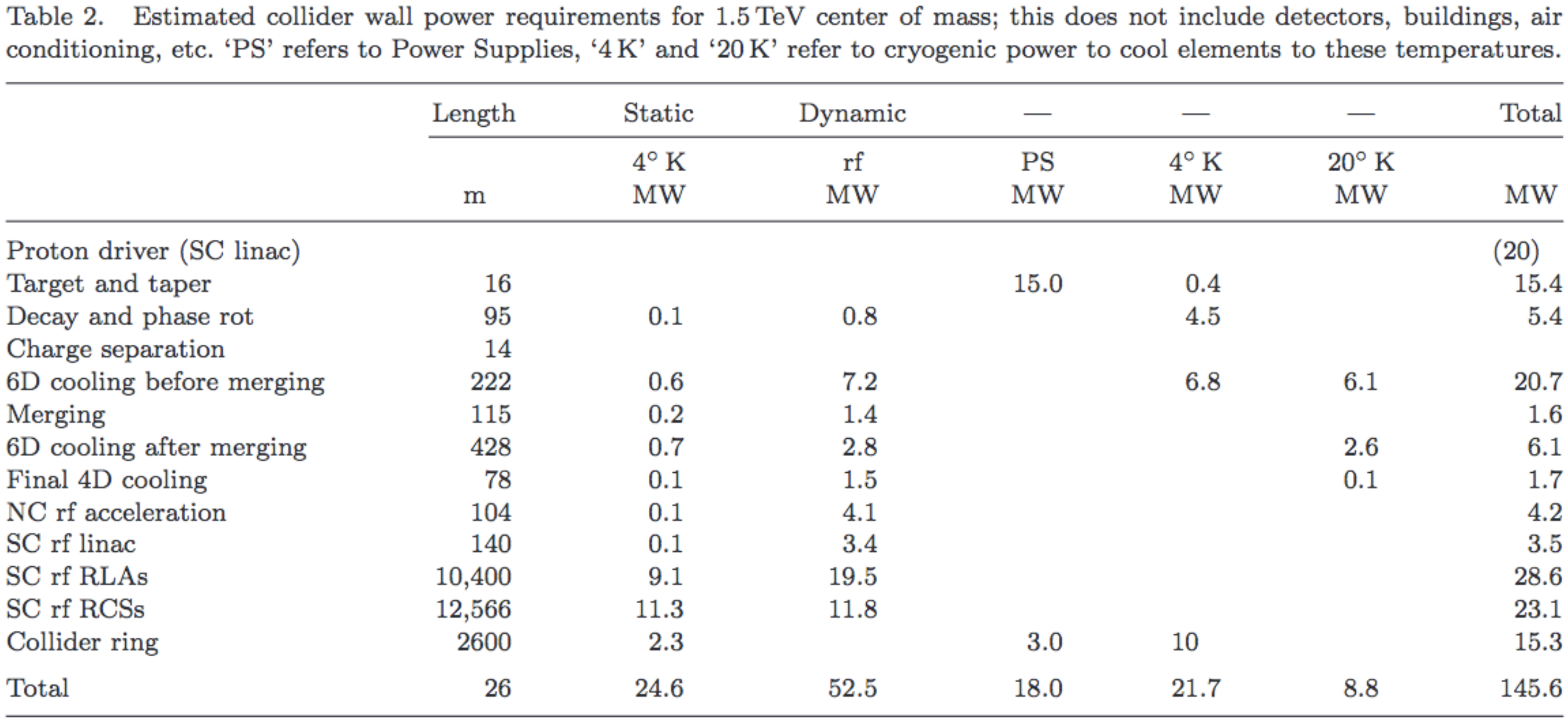


Table 2. Estimated collider wall power requirements for 1.5 TeV center of mass; this does not include detectors, buildings, air conditioning, etc. ‘PS’ refers to Power Supplies, ‘4 K’ and ‘20 K’ refer to cryogenic power to cool elements to these temperatures.

	Length	Static	Dynamic	—	—	—	Total
	m	4° K MW	rf MW	PS MW	4° K MW	20° K MW	MW
Proton driver (SC linac)							(20)
Target and taper	16			15.0	0.4		15.4
Decay and phase rot	95	0.1	0.8		4.5		5.4
Charge separation	14						
6D cooling before merging	222	0.6	7.2		6.8	6.1	20.7
Merging	115	0.2	1.4				1.6
6D cooling after merging	428	0.7	2.8			2.6	6.1
Final 4D cooling	78	0.1	1.5			0.1	1.7
NC rf acceleration	104	0.1	4.1				4.2
SC rf linac	140	0.1	3.4				3.5
SC rf RLAs	10,400	9.1	19.5				28.6
SC rf RCSs	12,566	11.3	11.8				23.1
Collider ring	2600	2.3		3.0	10		15.3
Total	26	24.6	52.5	18.0	21.7	8.8	145.6

Loss of stored energy in magnets is not considered

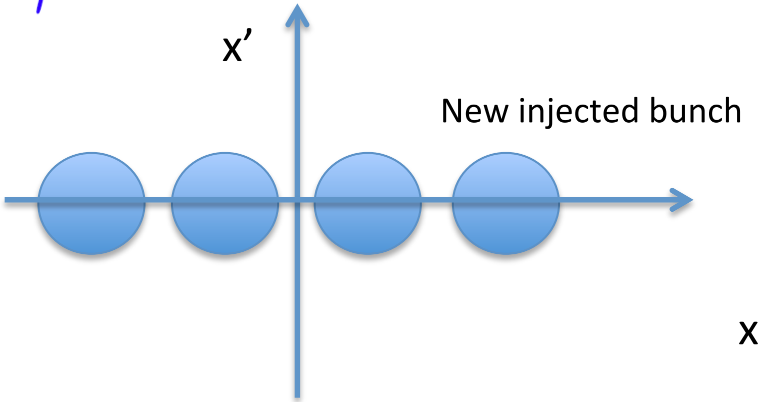
⇒ Should review design more

Note: Stacking

Can increase relevant beam density by stacking n bunches side by side in phase space

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

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



Shift common orbit for next turn

Could combine bunches in transverse phase space
Theoretically, $\varepsilon_x \varepsilon_y$ scales with number of bunches
Charge also scales with number of bunches
Hence

$$\frac{N}{\epsilon} \approx \sqrt{n} \frac{N_0}{\epsilon_0}$$

But difficult to do…

Particularly interesting for LEMMA with high rate of bunches
But only with square root of combination factor

Rough Estimate for CLIC

CLIC additional cost at 14 TeV: 40-50 GHCF ?

- upgrade 1.5 to 3 TeV about 8 GCHF
- some cost reduction due to large-scale production
- (14 TeV - 3 TeV) / 1.5 TeV * 8 GCHF = 59 GCHF

Power consumption: 1700 to 2800 MW ?

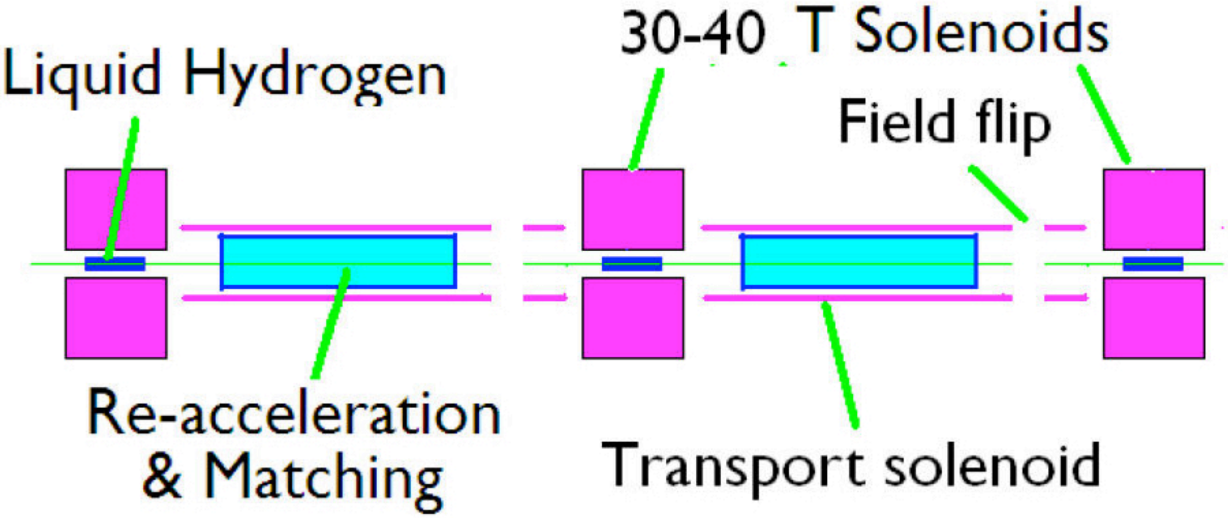
- Same beam current leads to 130 MW beam power
- 300 MW + 300 MW x 14 TeV / 3 TeV = 1700 MW
- 600 MW * 14 TeV / 3 TeV = 2800 MW

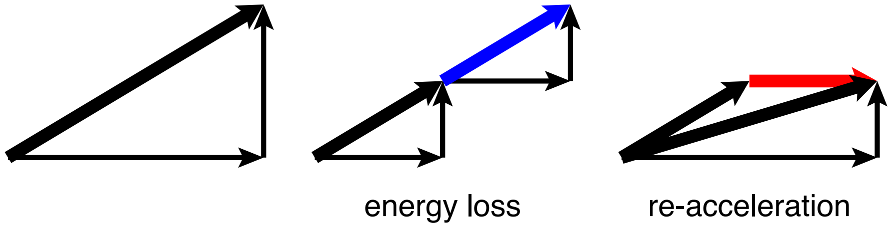
Luminosity 2.8 x 10^{35} $cm^{-2}s^{-1}$?

- same repetition rate, same quality of focusing (hard)
- luminosity scales linearly with energy for constant beam current
- 6 x 10^{34} $cm^{-2}s^{-1}$ x 14 TeV / 3 TeV = 28 x 10^{34} $cm^{-2}s^{-1}$

Luminosity is a bit marginal (could be fixed by higher rate)
Cost and power consumption are very high

Transverse Cooling Concept



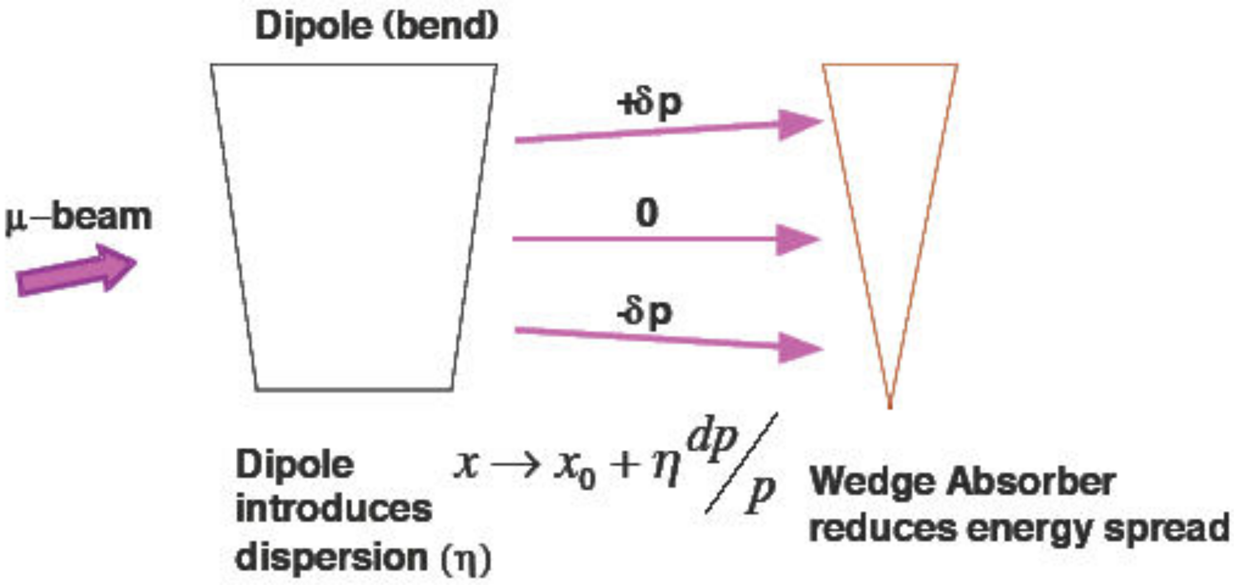


$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Longitudinal Cooling/Emittance Exchange

Combined with transverse cooling at beginning

Several options considered



Dipole introduces dispersion (η)

$$x \rightarrow x_0 + \eta \, {dp}/{p}$$

Wedge Absorber reduces energy spread

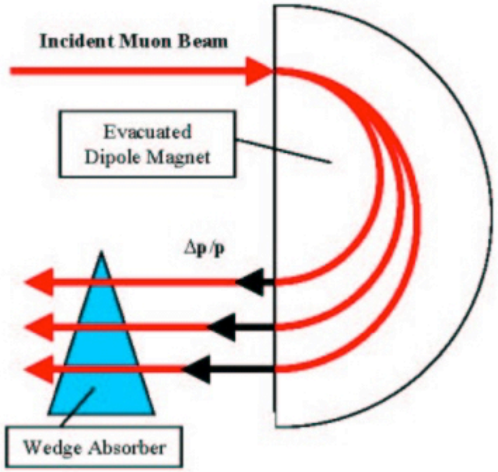


Figure 1. Use of a Wedge Absorber for Emittance Exchange

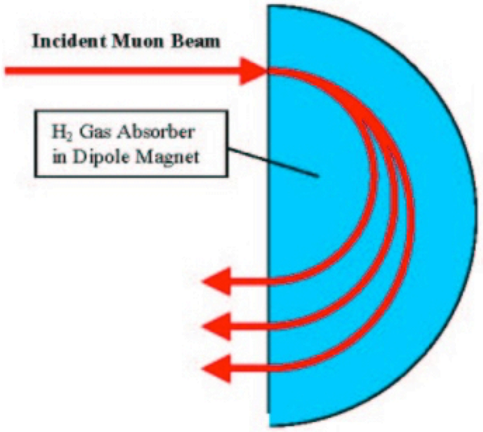
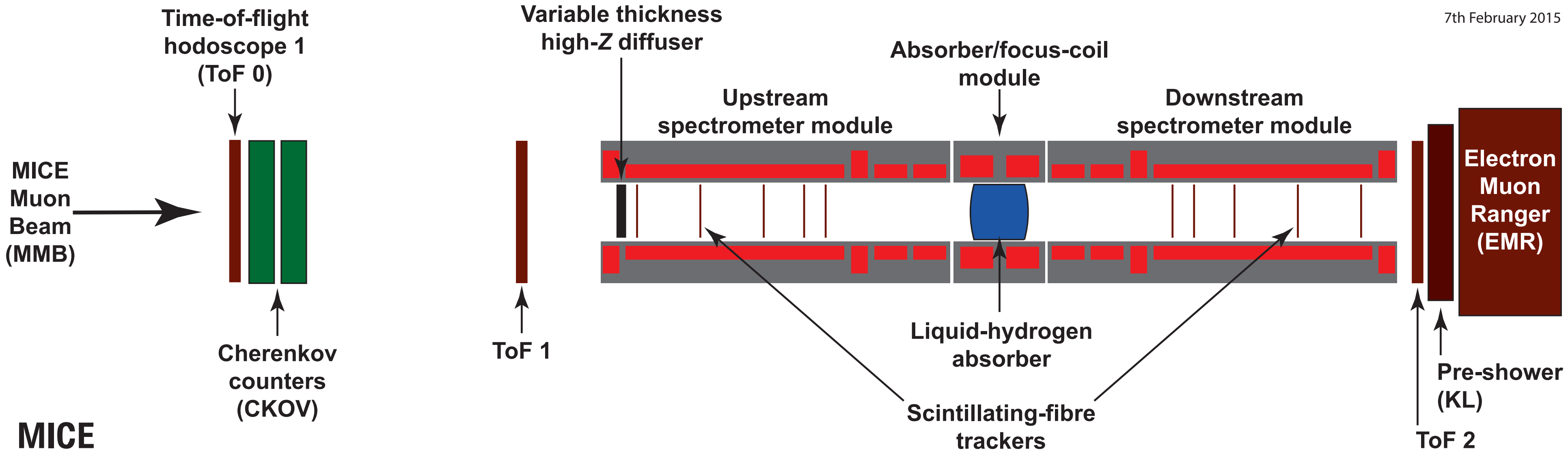


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Allows 6-D cooling

Cooling and MICE



Time-of-flight hodoscope 1 (ToF 0)

Variable thickness high-*Z* diffuser

7th February 2015

Absorber/focus-coil module

Upstream spectrometer module

Downstream spectrometer module

MICE Muon Beam (MMB)

Electron Muon Ranger (EMR)

Cherenkov counters (CKOV)

ToF 1

Liquid-hydrogen absorber

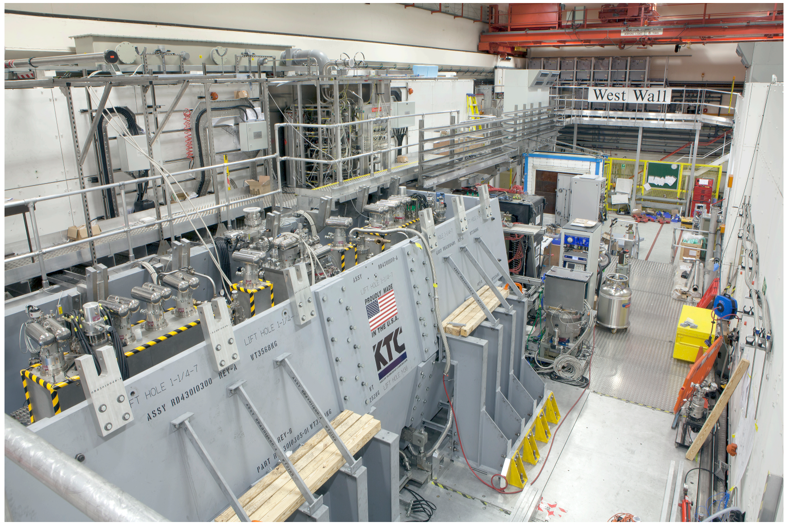
Pre-shower (KL)

Scintillating-fibre trackers

ToF 2

MICE

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

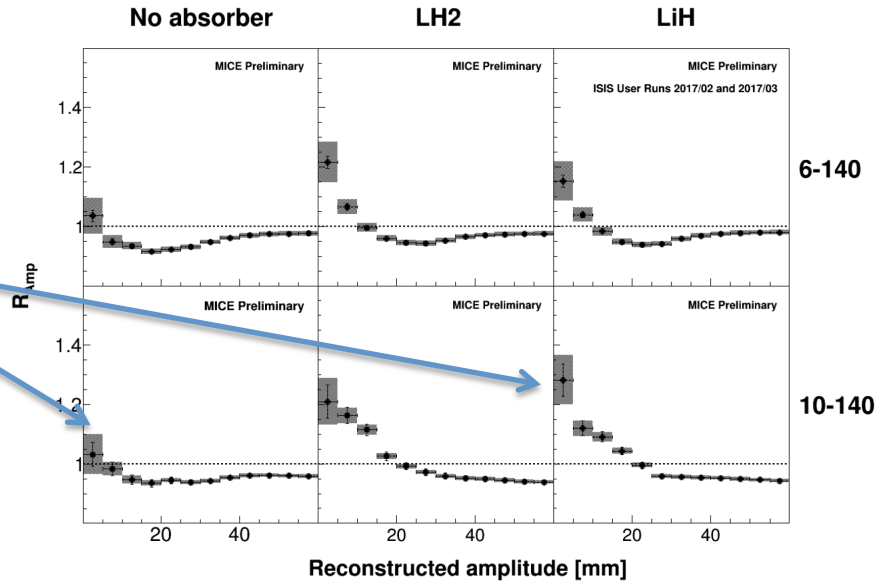


MICE allows to address 4D cooling with low muon flux rate

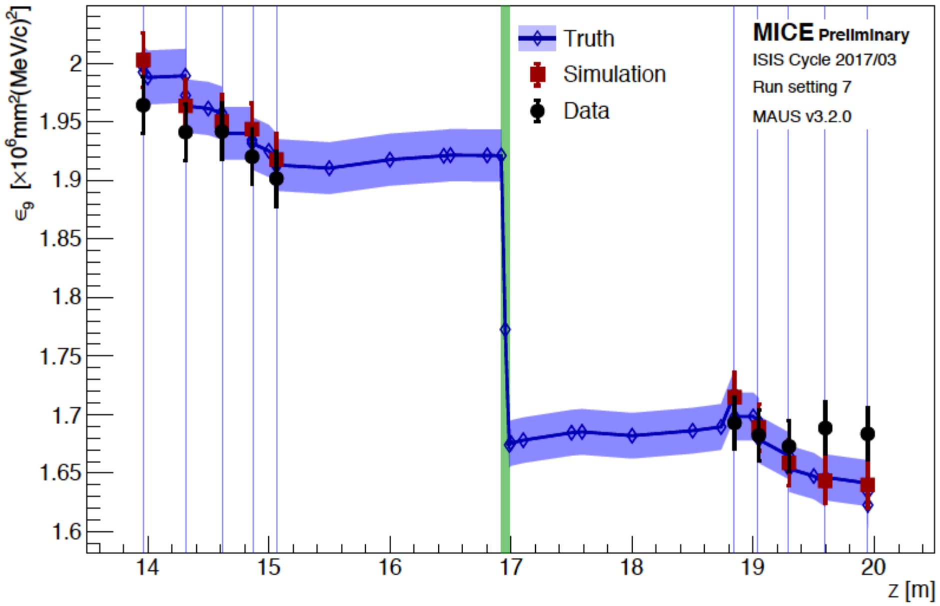
MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude



Noticeable reduction of 9% emittance



But still some way to go

- 6D cooling
- Stages
- Small emittances

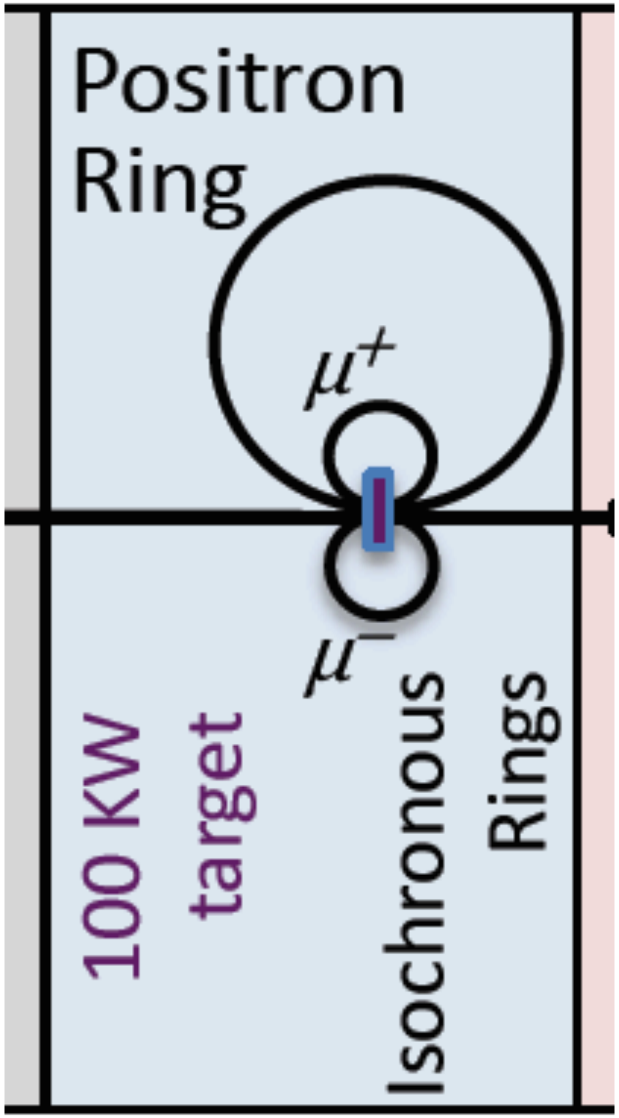
The LEMMA Scheme

Key concept (original numbers in brackets)

Produce muon beam with low emittance using a positron beam (40 nm vs. 25 µm in proton scheme)

- No cooling required, use lower muon current
- Positron beam (45 GeV, 3×10^{11} particles every 200 ns) passes through target and produces muon pairs
- Muon bunches are circulated through target O(2000) times accumulating more muons (4.5×10^{7})
- Every 0.5 ms, the muon bunches are extracted and accelerated
- They are combined in the collider ring, where they collide

Muon current 10^{11} s^{-1} is 300 times lower compared to 3×10^{13} s^{-1} for proton driver



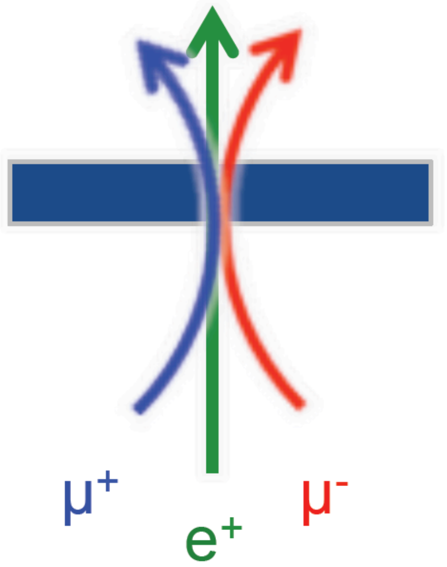
Key Issues

Need 10^{11} muons per s

Small cross section for muon production $O(10^{-7})$ per passage

$$e^+e^- \rightarrow \mu^+\mu^- \qquad O(1\mu b)$$

$\Rightarrow$ Need to pass 10^{18} positrons per s



Large fraction of positrons is lost

- Mainly due to bremsstrahlung

$$e^+e^- \rightarrow e^+e^-\gamma \qquad O(100mb),\ E_\gamma \geq 0.01\ E_p$$

$\Rightarrow$ Need to produce 10^{16} positrons per s ($O(10^7)$ per muon)

High current generates heat load and stress in target (also difficult)

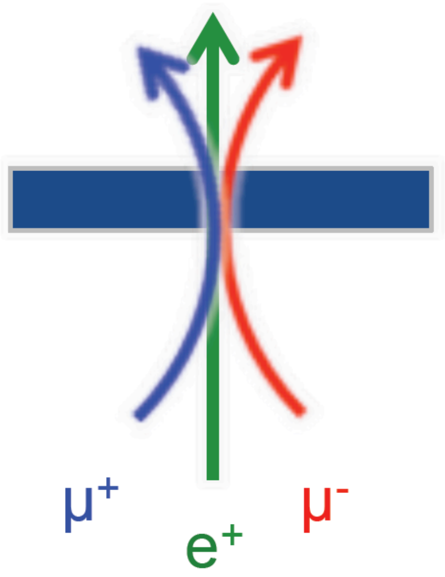
Circulating current produces O(100MW) synchrotron radiation

Key Issues, cont.

Two additional severe issues were identified in the review

- The multiple scattering of the muons in the target
  - Theoretical best emittance of 600 nm instead of assumed 40 nm
  - Reduction of luminosity by factor 15

- Small bunches were accelerated and later merged
  - But they were merged into the same phase space
    - No design exists for the merger
  - The combination factor is proportional to beam energy
    - Lifetime at high energy is larger
    - Extract muons at 22 GeV after one lifetime from accumulator
    - But they survive E/22 GeV times longer in collider
  - If the combination does not work, loose a large factor of luminosity



Working on a better design but have to wait and see the outcome

Ongoing LEMMA Effort

Ongoing effort to address identified challenges

- Positron production
  - Rotating target (like ILC)
  - Use of positron beam for production

- Positron ring challenge
  - larger ring, pulsed ring, lower energy accumulator ring

- Large emittance from target
  - use sequence of thin targets, H_2 targets, …
  - Increased muon bunch charge, e.g. better capturing, …
  - muon cooling (crystals, stochastic, …)

- Difficulty of combining muon bunches at high energy
  - Increasing charge at the source (producing bunches in pulsed fashion)
  - increase muons per positron bunch

More detailed studies needed to understand what does work and how well