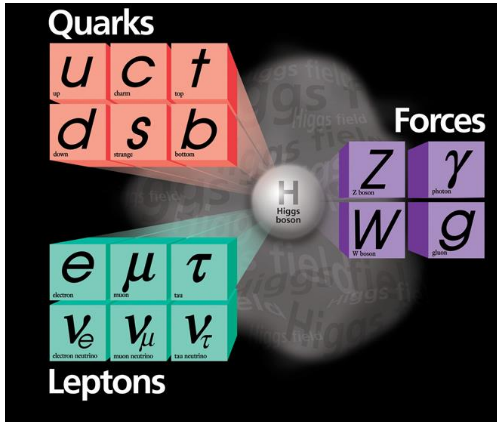
High Energy Muon and Hadron Collider Projects - within the overall future accelerator panorama

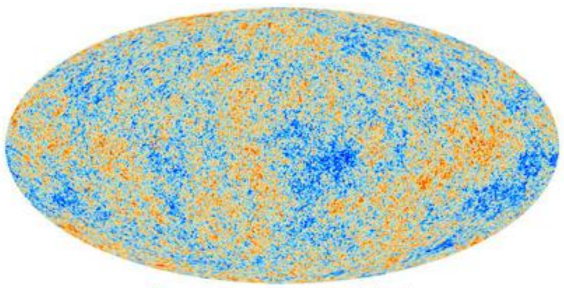
Steinar Stapnes, CERN

Sao Paulo 31.08.2023

Outline
- Introduction
- Scope 1: e+e- Higgs factories
- Scope 2: Beyond Higgs factories
- Some accelerator concepts
- Proton and muon colliders
- General challenges and main points

Higgs and Beyond the Standard Model





The universe as seen by Planck

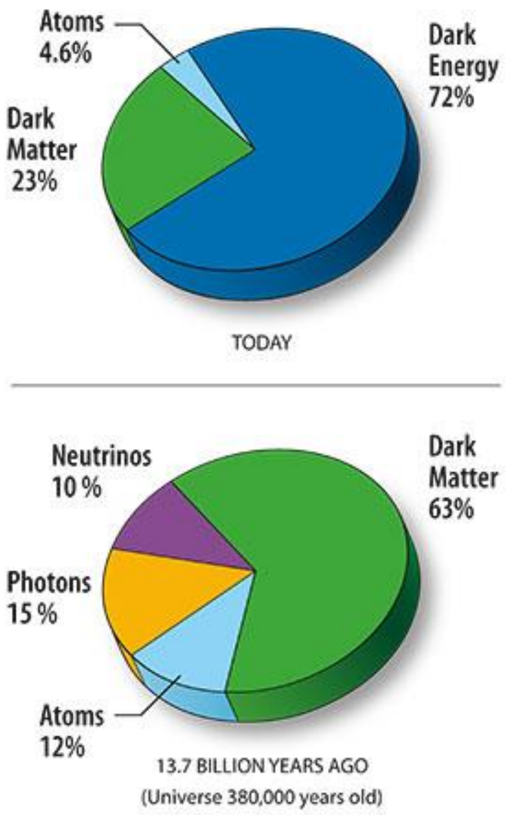
The Higgs is new, it is special, we believe studying it in detail can be a portal to new physics

Many unknowns:

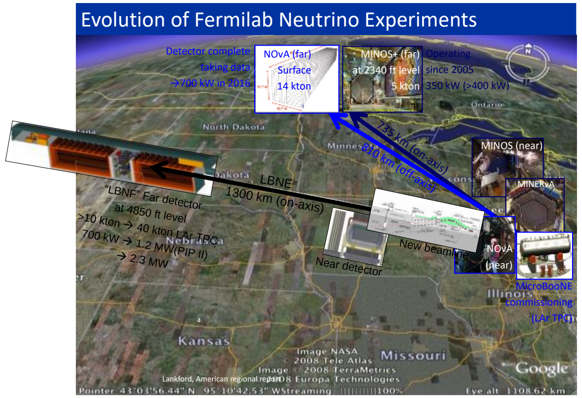
- Flavour structure
- Matter-antimatter
- Why is the Higgs so light ?
- etc

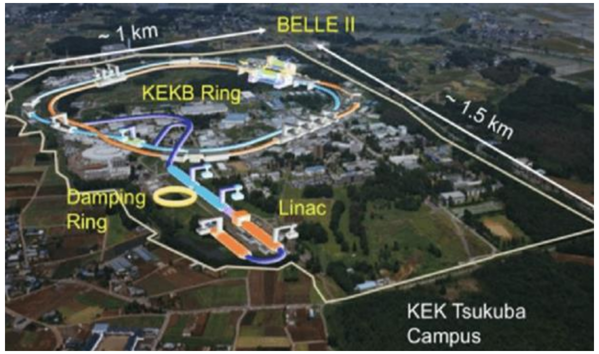
- General Relativity versus Quantum Field Theories

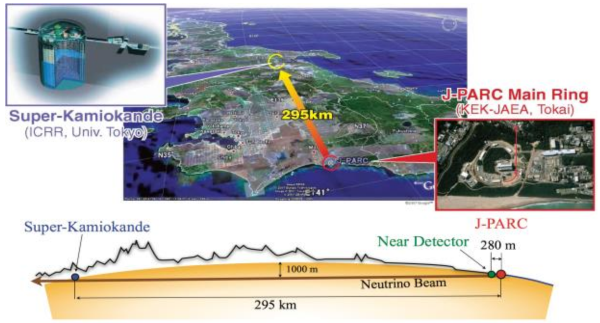
- Dark Matter and Energy



Some of our existing tools







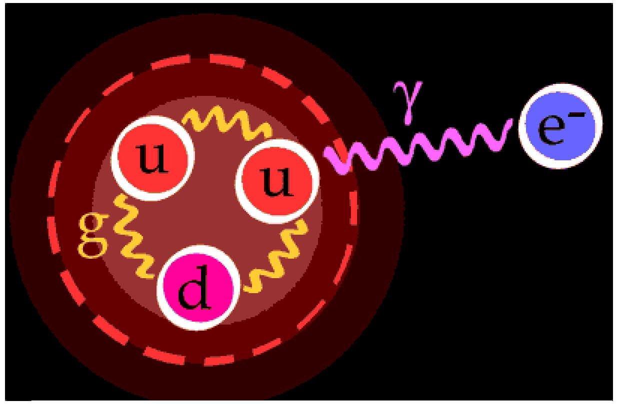
"The T2K Experiment", K. Abe, et al., Nucl. Instr. and Meth. A **659**, 106 (2011)

Colliders and proton drivers

Particle types to accelerate

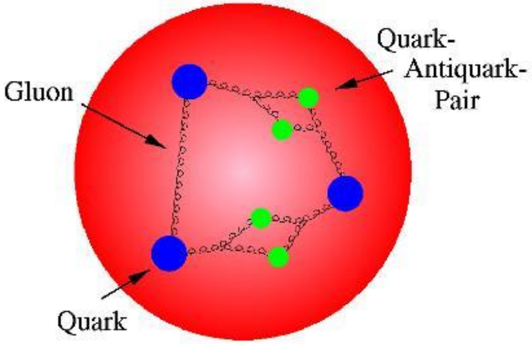
Not so many choices:

- Need stable charges particles: protons, electrons, (muons), ions – most used: electrons (and positrons) and protons
- Secondary beams: photons, pions, kaons, neutrons, neutrinos, …..



Proton collisions: compound particles

- Mix of quarks, anti-quarks and gluons: variety of processes
- Parton energy spread
- QCD processes large background sources



Electron/positron collisions: elementary particles

- Collision process known
- Well defined energy
- Background from other physics limited

Muons: elementary particle, but lifetime only 2.2 μs

$$\frac{\text{proton mass}}{\text{electron mass}} \approx 2000$$

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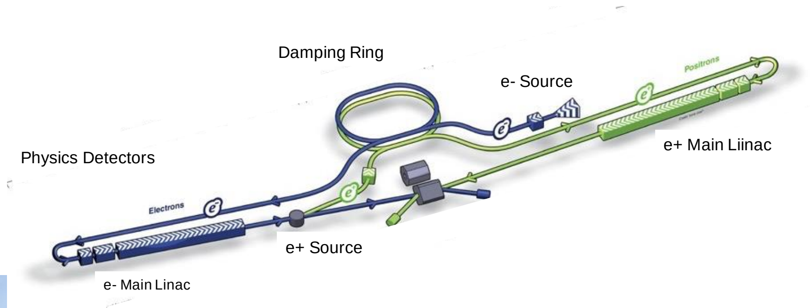
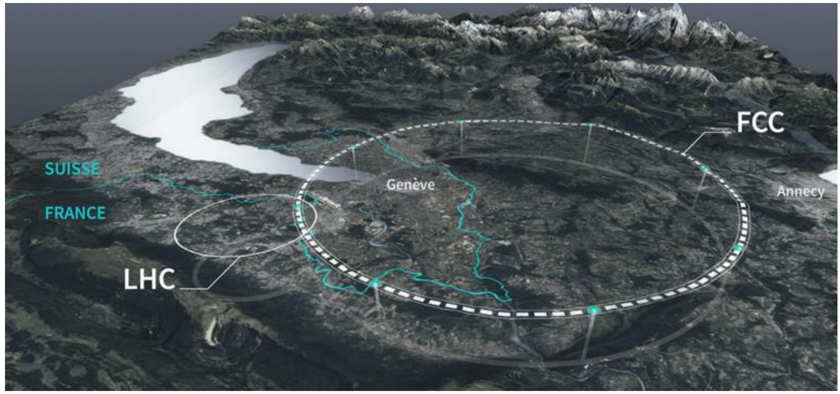
Scope 1: A Higgs factory



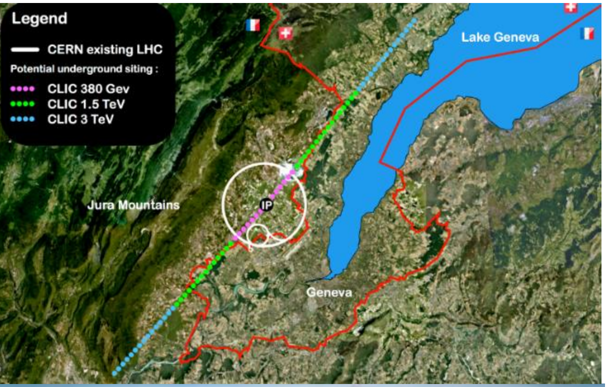


Need e+e- collisions at least at 250 GeV, four alternatives:

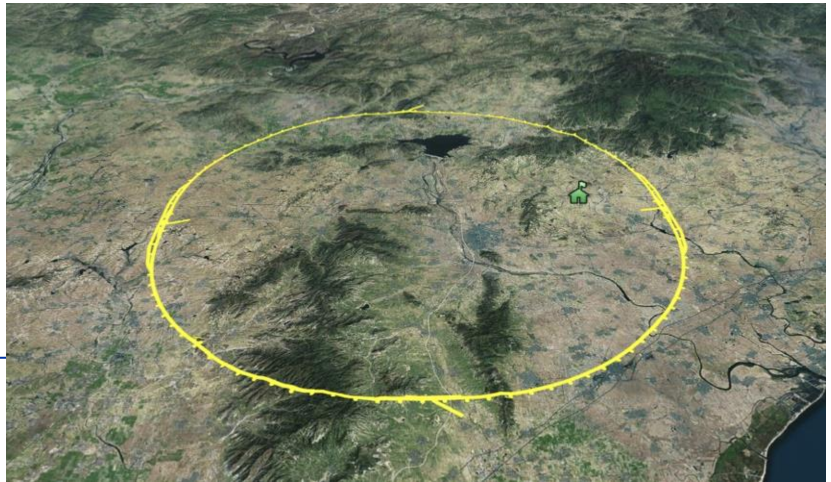
ILC in Japan (linear) FCC at CERN (ring)

CLIC at CERN (linear) CEPC in China (ring)

Linear colliders: 13 (Higgs) -> 50 (max) km for higher energies later



Rings ~100km, can be used for protons after

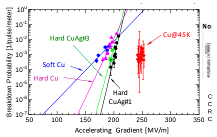


New ideas being developed

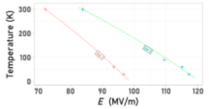
C3 Accelerator Complex

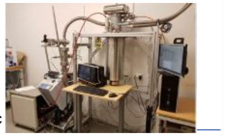
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m
- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site

Large portions of accelerator complex are compatible between LC technologies
- Beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline
- Reliant on work done by CLIC and ILC to make progress

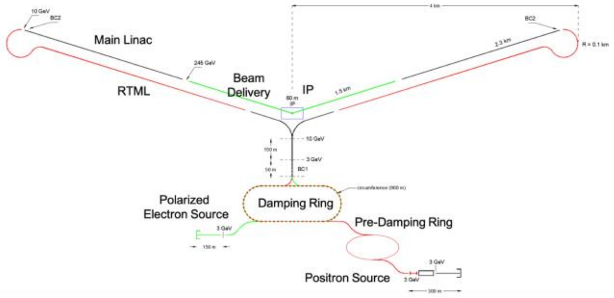


Cryo-cooled copper cavity, SLAC





Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN



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Various energy recovery based ideas

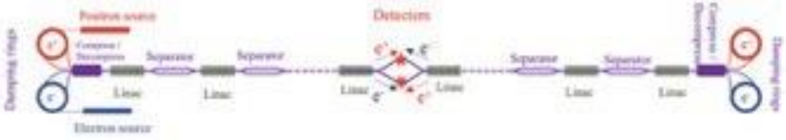


Figure 3-8. Conceptual layout of ReLiC.

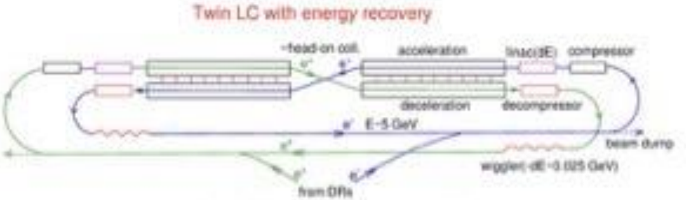
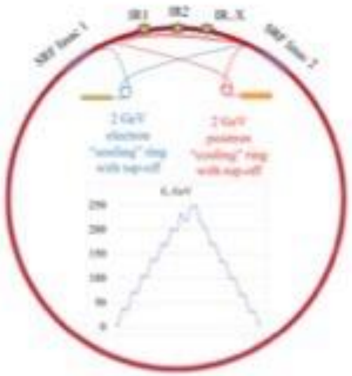


Figure 3-10. Conceptual layout of the ERLC.



A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration

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[1] John Adams Institute for Accelerator Science at University of Oxford, Oxford, UK
[2] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[3] Department of Physics, University of Oslo, Oslo, Norway
(Dated: March 17, 2023)

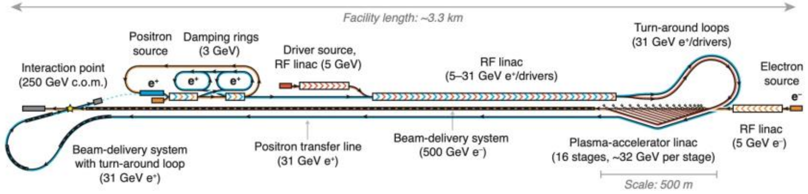
The construction of an electron–positron collider "Higgs factory" has been stalled for a decade, not because of feasibility but because of the cost of conventional radio-frequency (RF) acceleration. Plasma-wakefield acceleration promises to alleviate this problem via significant cost reduction based on its orders-of-magnitude higher accelerating gradients. However, plasma-based acceleration of positrons is much more difficult than for electrons. We propose a collider scheme that avoids positron acceleration in plasma, using a mixture of beam-driven plasma-wakefield acceleration to high energy for the electrons and conventional RF acceleration to low energy for the positrons. We emphasise the benefits of asymmetric energies, asymmetric bunch charges and asymmetric transverse emittances. The implications for luminosity and experimentation at such an asymmetric facility are explored and found to be comparable to conventional facilities; the cost is found to be much lower.

HALHF

https://arxiv.org/abs/2303.10150

Certainly very compact so embedded CO_2, likely very reduced costs compared to other Higgs-factories, not clear of power is different to any other LC.

Technically still uncertain.



Circular versus linear

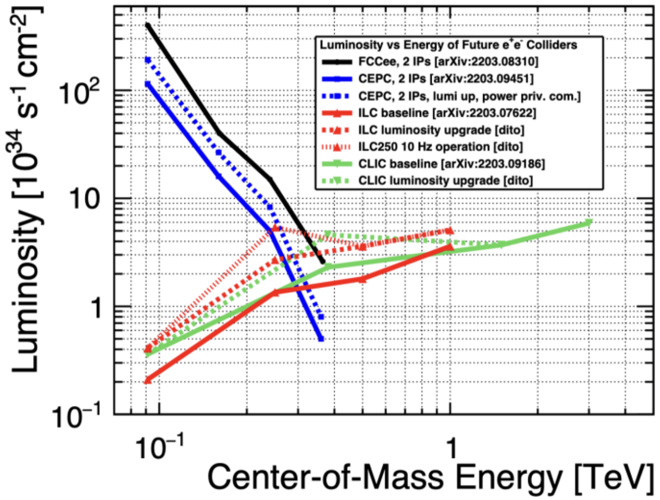
High energy limited by how strong electric fields you can have inside metallic structures:

- Make accelerators circular, then we become limited by magnetic fields for bending – as in LHC, accelerating protons
- It also allows us to re-collide “bunches” for hours (moderns machines are ”topped” up)

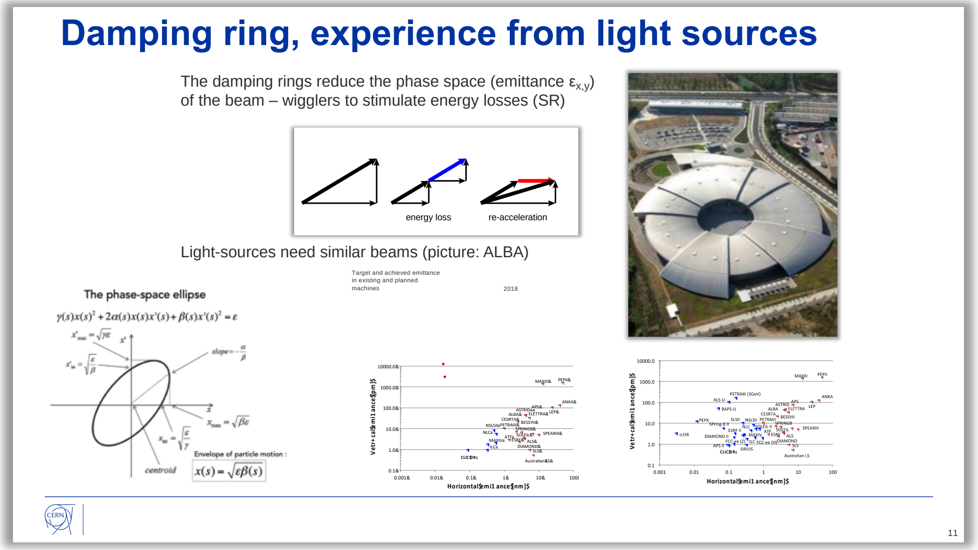
For electrons we are limited by synchrotron radiation when bending a particle, at some point cannot provide enough energy in a circle to compensate for these losses, go back to linear accelerators (CLIC/ILC designed for 3/1 TeV at ~50km)

CLIC is ~11km (380 GeV), ILC ~20km (250 GeV), FCC/CEPC ~100km (~350 GeV)

$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

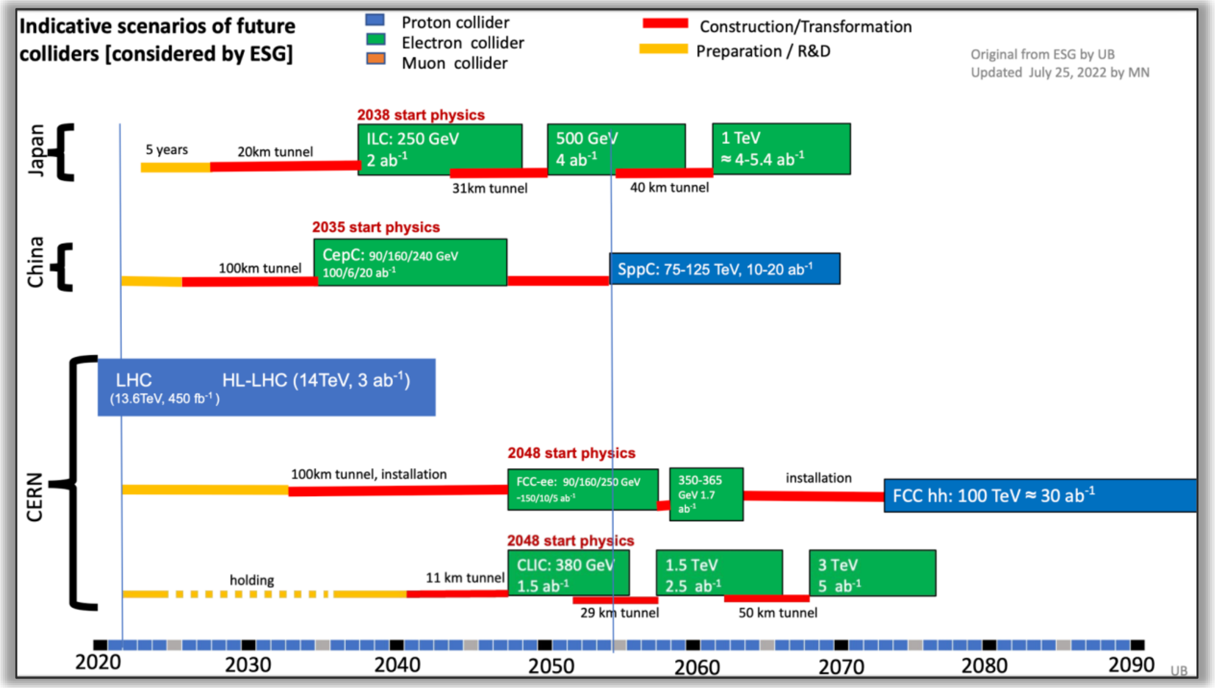


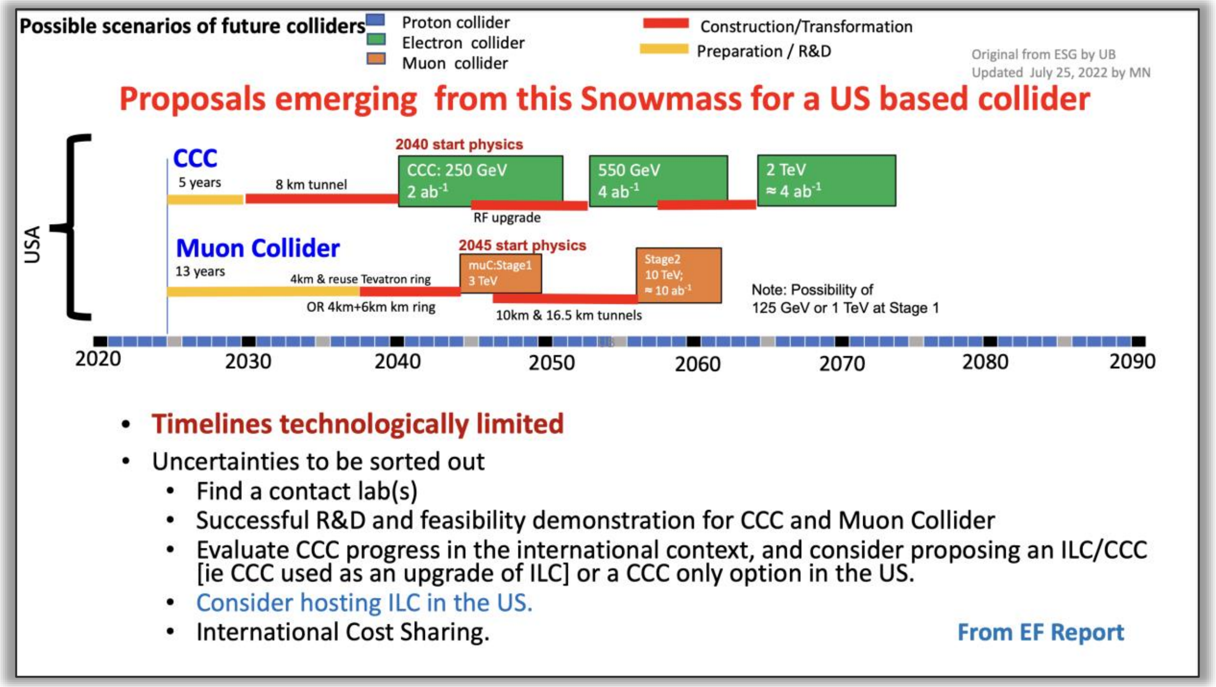
Several large electron linac and ring projects outside particle physics



Electron accelerators providing a lot of technical expertise, industry support – but not colliders

Timelines in Snowmass Energy Frontier summary





Comments:

- Timelines are technologically limited – except for the CERN projects that are linked to completion of the HL-LHC
- CEPC and ILC schedules are mature, but the projects need to pass approval processes in the near future to maintain these schedules
- CCC and MC are less well defined but R&D and project development on the shown timescales is reasonable, CCC can also upgrade ILC

- From Meenakshi Narain "EF summary" Snowmass

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Scope 2: Beyond Higgs Factories (BHF)

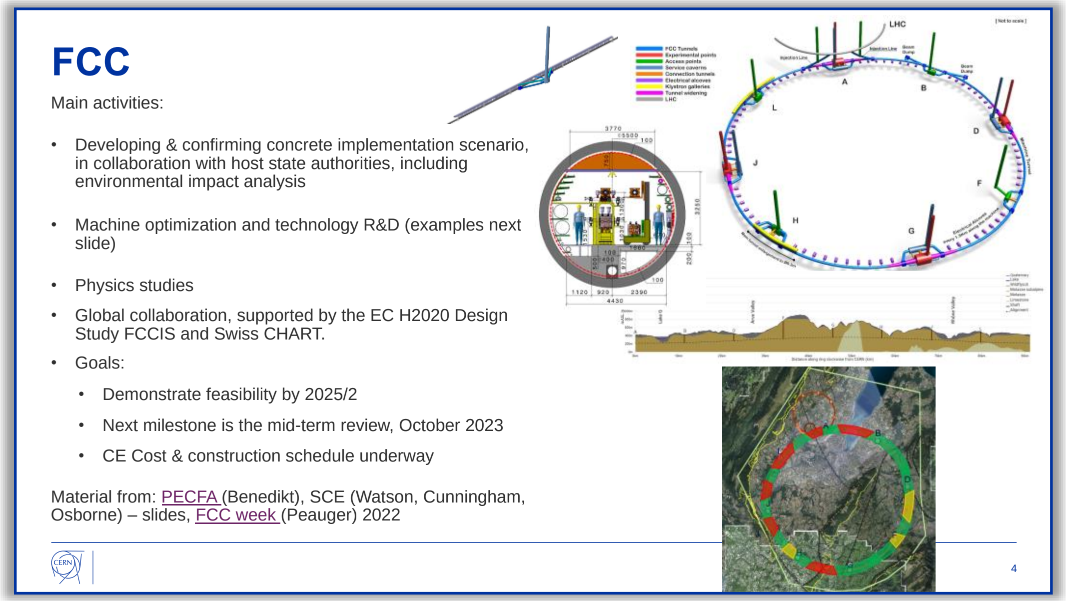
- ref presentation Tuesday by Carlos Wagner about physics -

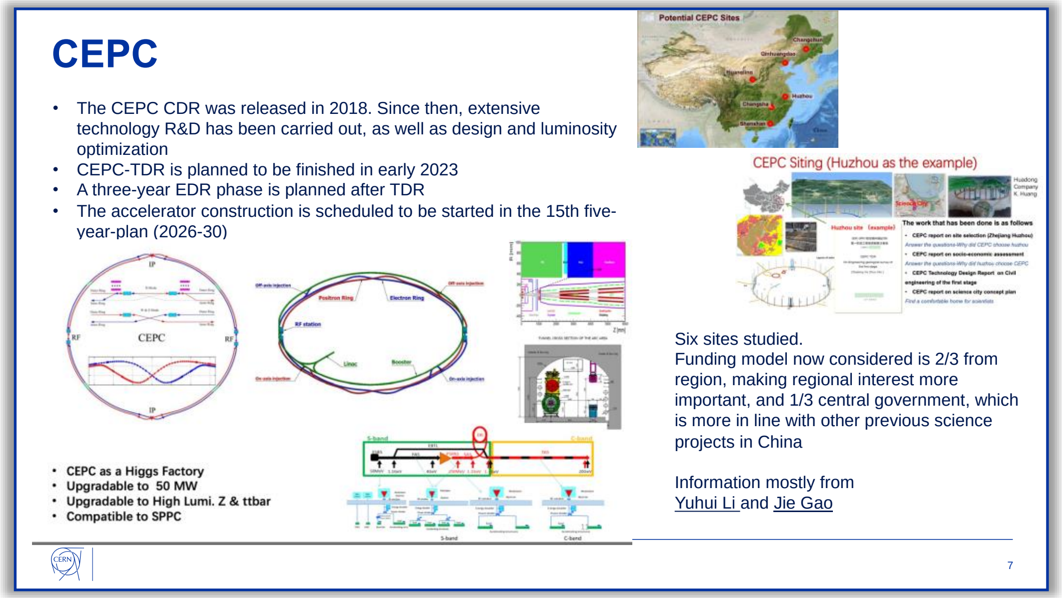
Beyond Higgs-factories we want a proton collider at least at 100 TeV (the more the better), and lepton colliders towards 10 TeV (also here more is better)
In all cases luminosities at least around ~10^{35} cm^{-2} s^{-1} are needed

Note: the experimental conditions are different, the clean nature of e+e- collisions would give advantages but reaching ~10 TeV difficult, the muon collider background looks manageable and hadron collisions are notoriously difficult with large pileup, but with a lot of LHC and HL LHC experience giving confidence

How close – or rather how far away – are we from these goals ?

Circular machines, e+e- and later hadrons



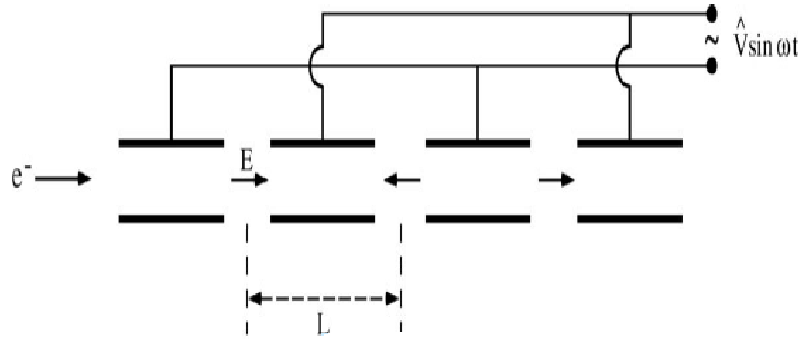


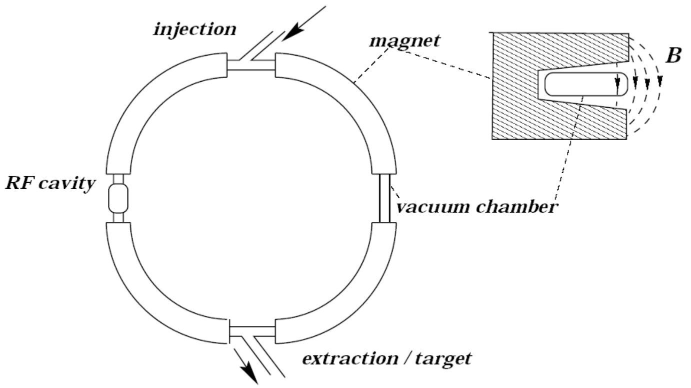
In both cases the initial civil engineering, and to the extend possible tunnels and caverns are prepared for replacing the initial Higgs factories (e+e-) with proton-proton colliders

FCC-hh and SppC

(see presentation in a moment about CEPC - > SppC by Prof. Tang)

Energy reach of circular accelerators





The technological limit on the electrical field in an RF cavity (breakdown)

Gives a limited ΔE per distance

⇒ Circular accelerators, in order to re-use the same RF cavity

This requires a bending field F_B in order to follow a circular trajectory

In circular arc sections the magnetic field must provide the desired radius,

$$\frac{1}{r} = \frac{eB}{p}$$

and the energy achievable is limited by radius (i.e. cost) and bending field

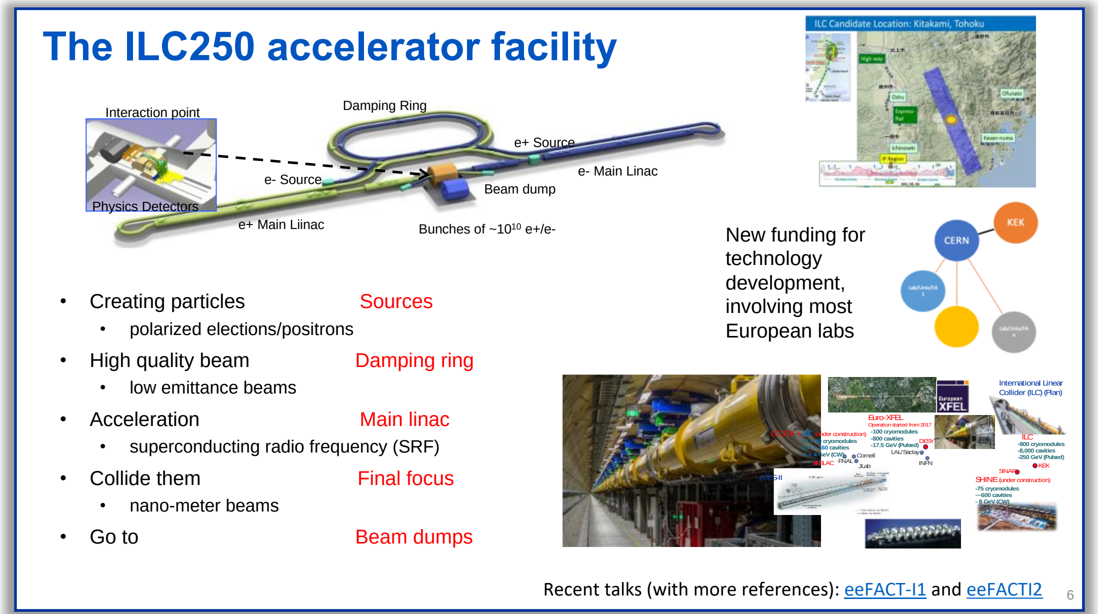
(other effects as radiation losses in super conducting magnets and overall beam power represent additional challenges for future circular hadron machines)

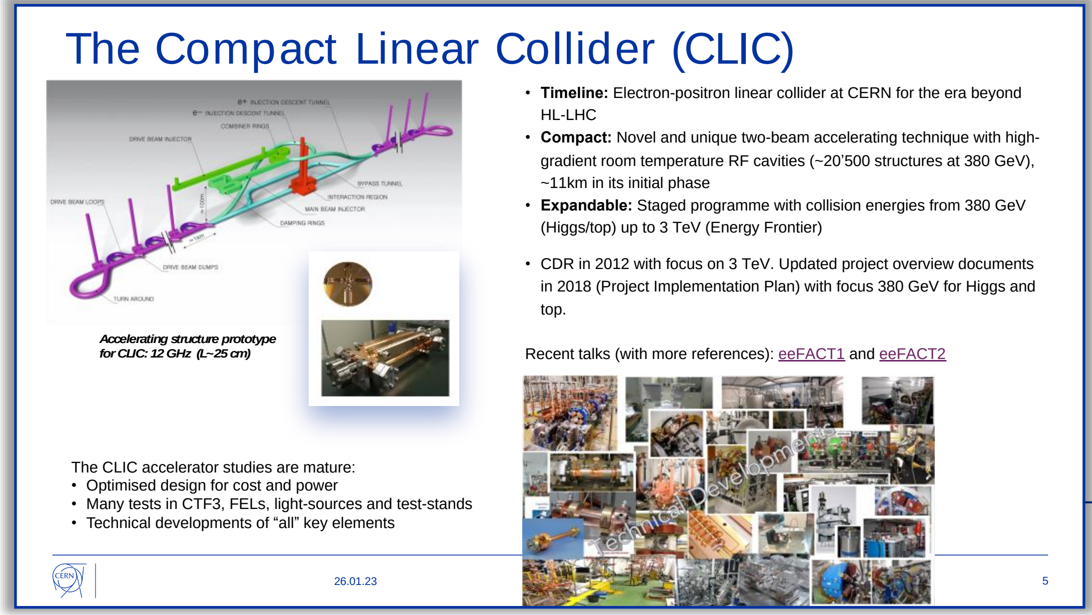
Hence the importance of high field magnet development as presented yesterday by P.Vedrine

These considerations are applicable for other particles as electrons and muons as well. For electrons the synchrotron radiation is much more limiting such that the magnet strength achievable are not an issues

(the FCC-ee and CEPC machines are limited to ~350 GeV as e+e- colliders, while aiming for ~100 TeV with protons)

Linear Colliders, for Higgs, top and later 1-3 TeV





Both CLIC and ILC can be extended in energy, by lengthening, higher gradients (in fact CLIC is primarily designed for 3 TeV with a very extendable drivebeam).

C3 also foresees extending in energy to above 500 GeV and can in principle go further

HALVH is somewhat extendable

There is no real design beyond 3 TeV for e+e- colliders

Plasma acceleration promising for electrons, positrons less so currently

Issues like RF efficiency increasingly important – for any acceleration technology

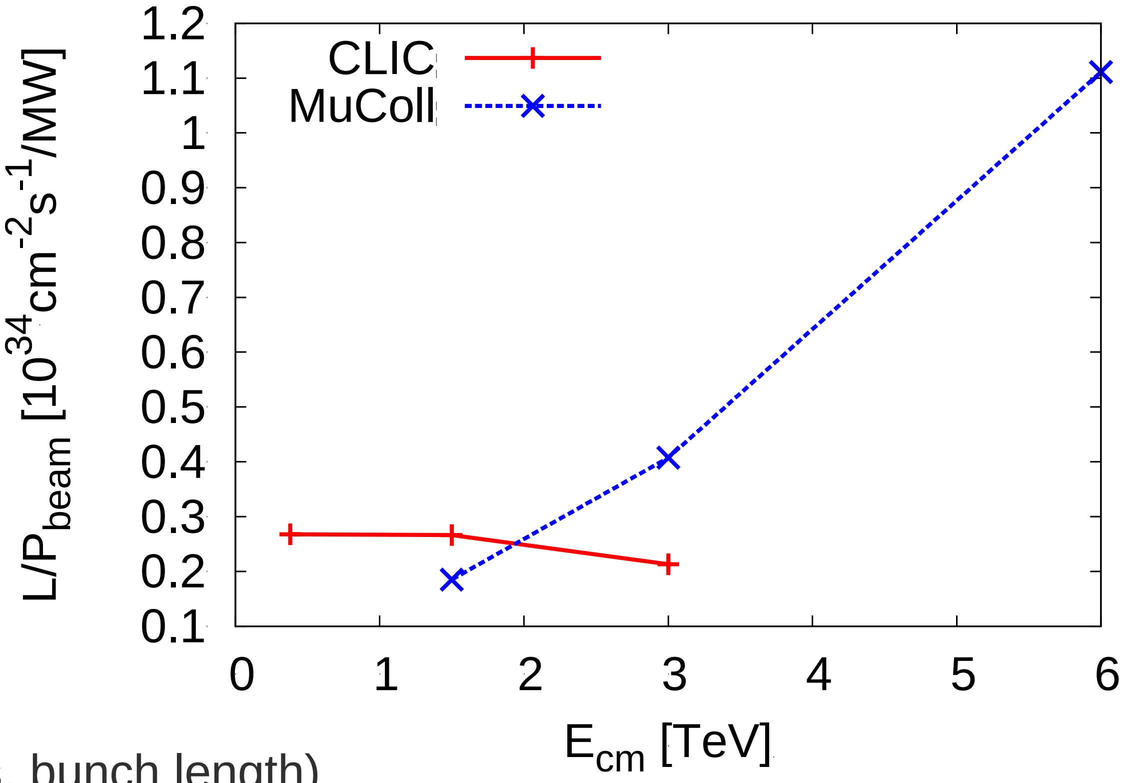
CLIC at 3 TeV is around 500 MW (~2.5 TWh annually).

.. but there are also other limitations (see next slide)

Muon collider

The luminosity per beam power is about constant in linear colliders

It can increase in muon colliders



Strategy CLIC:
Keep all parameters at IP constant
(charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)

Slide from talk by D. Schulte in the SPC, June 2019

This bring us to proton and muon colliders (in the title of the talk) as primary candidates for very high energy colliders

“High Energy Muon and Hadron Collider Projects - within the overall future accelerator panorama”

Not excluding linear colliders can make transformative improvements, plasma acceleration is radically more compact than “conventional” RF while most other technology changes in our field are gradual

Some reminders and concepts are useful first

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Lorentz equation

The two main tasks of an accelerator

- Increase the particle energy
- Change the particle direction (follow a given trajectory, focusing “bunches” of particles)

Lorentz equation:

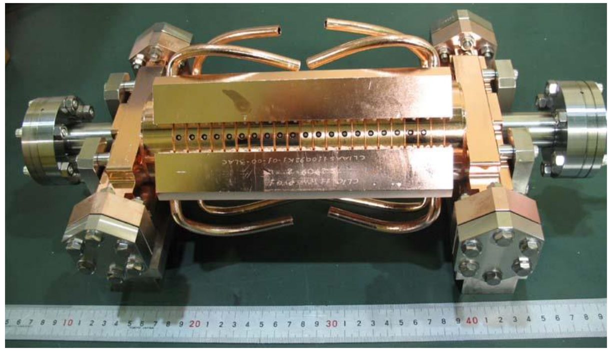
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) = q\vec{E} + q\vec{v} \times \vec{B} = \vec{F}_E + \vec{F}_B$$

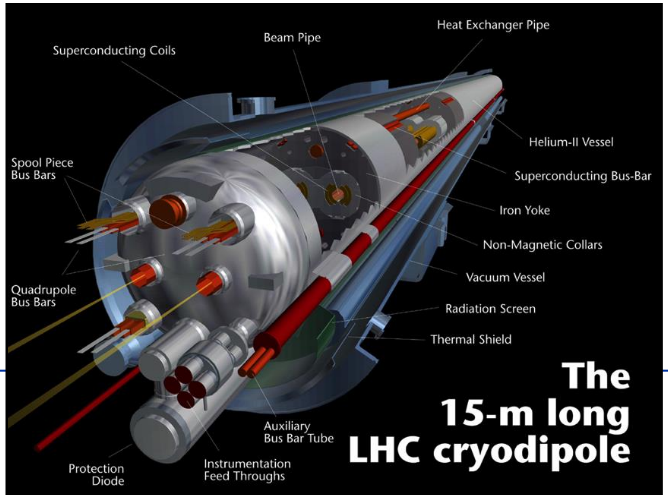
$F_B \perp v \Rightarrow F_B$ does no work on the particle

- Only F_E can increase the particle energy

F_E or F_B for deflection? $v \approx c \Rightarrow$ Magnetic field of 1 T (feasible) same bending power as en electric field of $3{\cdot}10^8$ V/m (NOT feasible)

- F_B is by far the most effective in order to change the particle direction (steering, focusing)

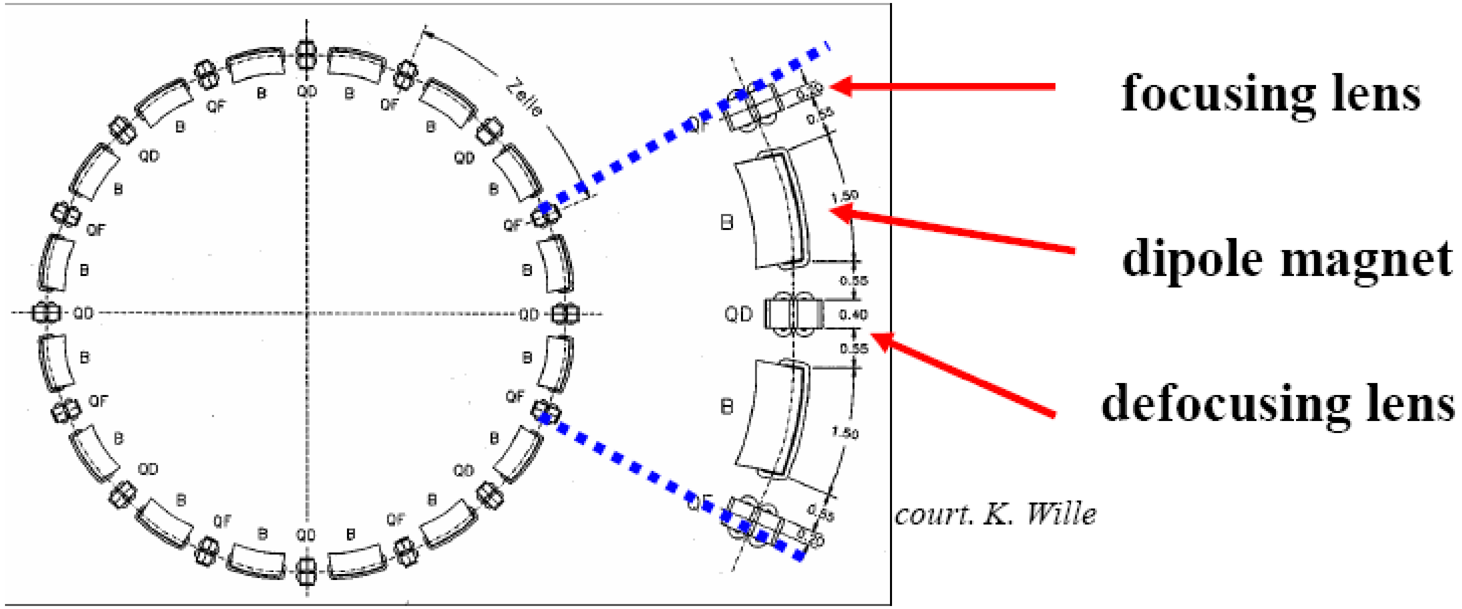




The Lattice of an accelerator

An accelerator is composed of bending magnets, focusing magnets and usually also sextupole magnets, bending (dipole magnets) the performance driver for energy reach

The ense
lattice"



The elements

M: drift space

- The element with the simplest transfer matrix **M**: drift space between magnets (no field), with length **l** :

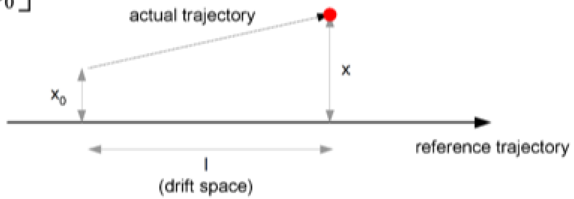
$$\boldsymbol{M} = \begin{bmatrix} 1 & l \\ 0 & 1 \end{bmatrix}$$

- Written out this gives:

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix} = \begin{bmatrix} 1 & l \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}$$

$$\Downarrow$$

$$x = x_0 + l x'_0$$
$$x' = x'_0$$

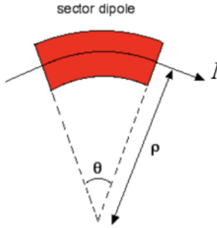


- This simply says that in a drift space x' is unchanged, and x drifts

Dipole transfer matrix

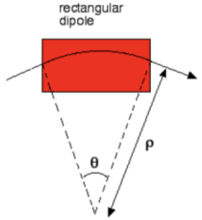
Bending magnets introduce focusing terms as well.

The solution of Hill's equation provid the focusing terms for a idealized sector dipole :



$$\boldsymbol{M}_{sec} = \begin{bmatrix} \cos\frac{l}{\rho} & \rho\sin\frac{l}{\rho} \\ -\frac{1}{\rho}\sin\frac{l}{\rho} & \cos\frac{l}{\rho} \end{bmatrix}$$

The more common type of dipole found in accelerators is a rectangular dipole, which does not provide the focusing term.

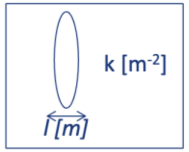


$$\boldsymbol{M}_{rect} = \begin{bmatrix} 1 & \rho\sin\frac{l}{\rho} \\ 0 & 1 \end{bmatrix}$$

Quadrupole transfer matrix

- Full solution :

$$\boldsymbol{M} = \begin{bmatrix} \cos(l\sqrt{k}) & \frac{1}{\sqrt{k}}\sin(l\sqrt{k}) \\ -\sqrt{k}\sin(l\sqrt{k}) & \cos(l\sqrt{k}) \end{bmatrix}$$

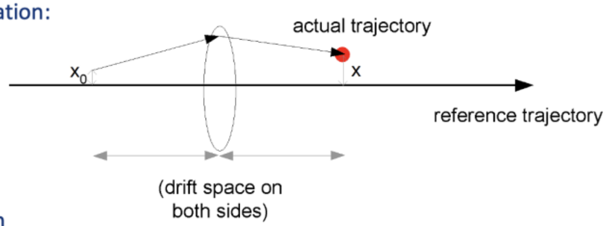


- **Thin lens approximation** :
  - Real quadrupole may be modeled as a infinitely thin lens that focuses or defocuses, plus the drift space to represent the length of the quadrupole
  - valid if focal length **f=1/kl >> l**

$$\boldsymbol{M}_{thin} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix}$$

- Written out multiplication:

$$x = x_0$$
$$x' = x'_0 - \frac{1}{f} x_0$$



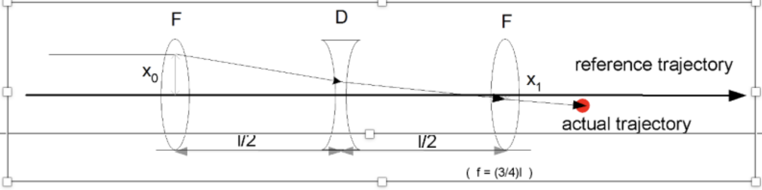
- -1/f is a ***focusing*** term
- A defocusing quadrupole in x (rotated 90°): **-f → f**

Quadrupole FODO doublet

- A FODO quadrupole doublet consist of a focusing quadrupole followed by a drift, a defocusing quadrupole and a drift
- Using the thin lens approximation we can calculate the total matrix :

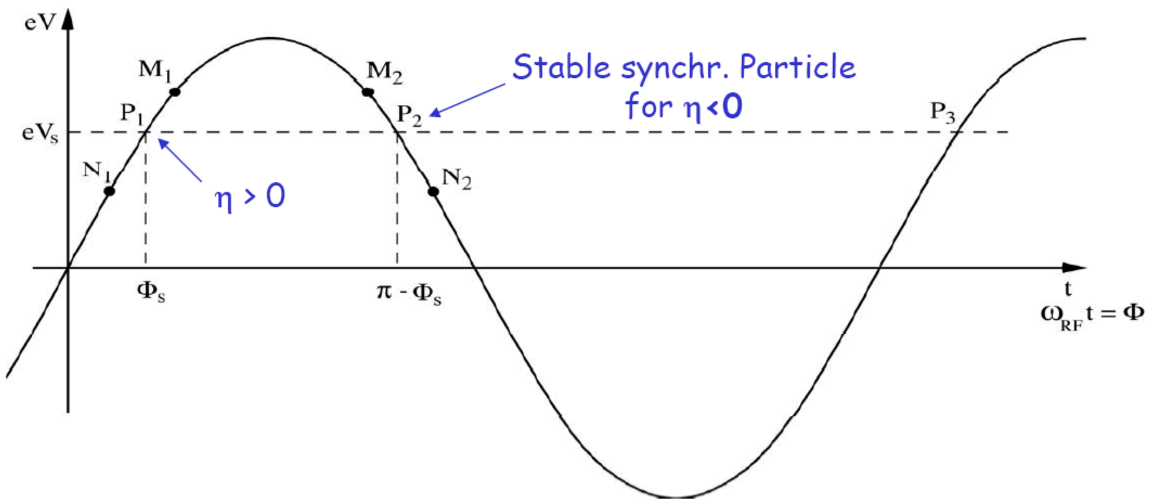
$$\boldsymbol{M}_{doublet} = \begin{bmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & l/2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & l/2 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1+\frac{l}{2f} & l+\frac{l^2}{4f} \\ -\frac{l}{2f^2} & 1-\frac{l}{2f}-\frac{l^2}{4f^2} \end{bmatrix}$$

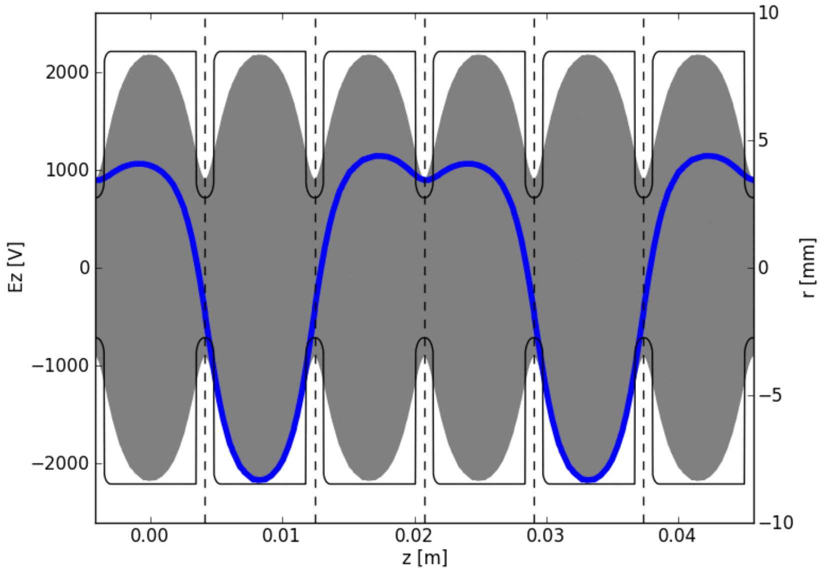
- FODO is focusing in **both** the horizontal and the vertical planes (since changing plane equals f = -f)



Phase stability in a synchrotron

h>0: velocity increase dominates, f_r increases





Animation from Kyrre Sjøbæk, showing optimal phasing of a beam (red) in a periodic loaded structure.

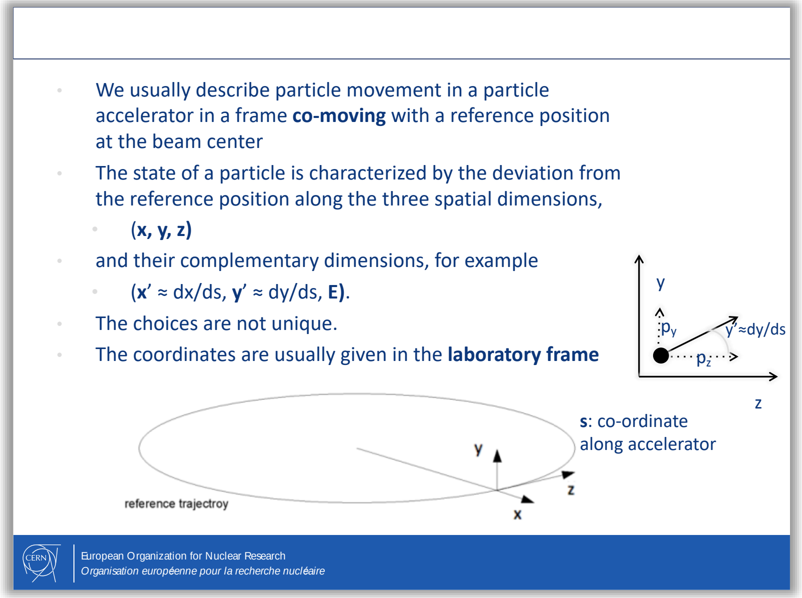
Synchronous particle stable for 0º<f_s<90º

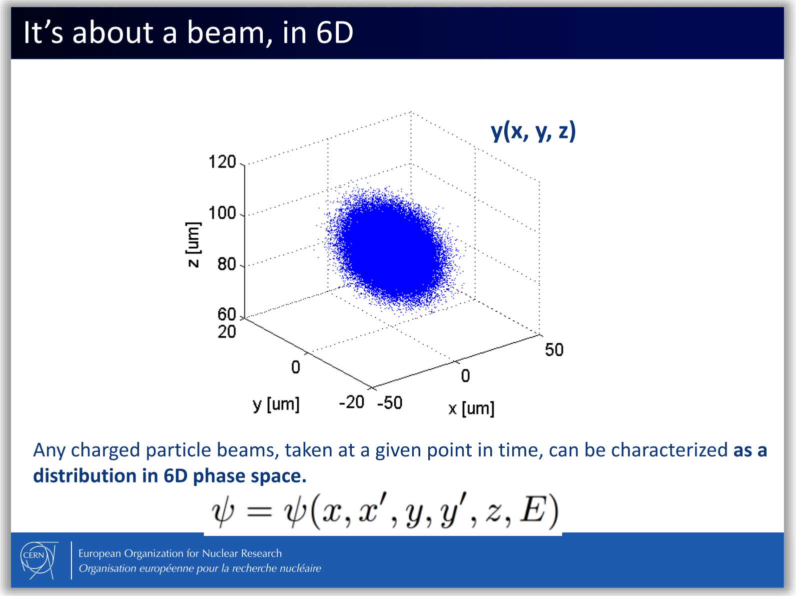
- A particle N_1 arriving early with f= f_s-Df will get a lower energy kick, and arrive relatively later next pass
- A particle M_1 arriving late with f= f_s+Df will get a higher energy kick, and arrive relatively earlier next pass

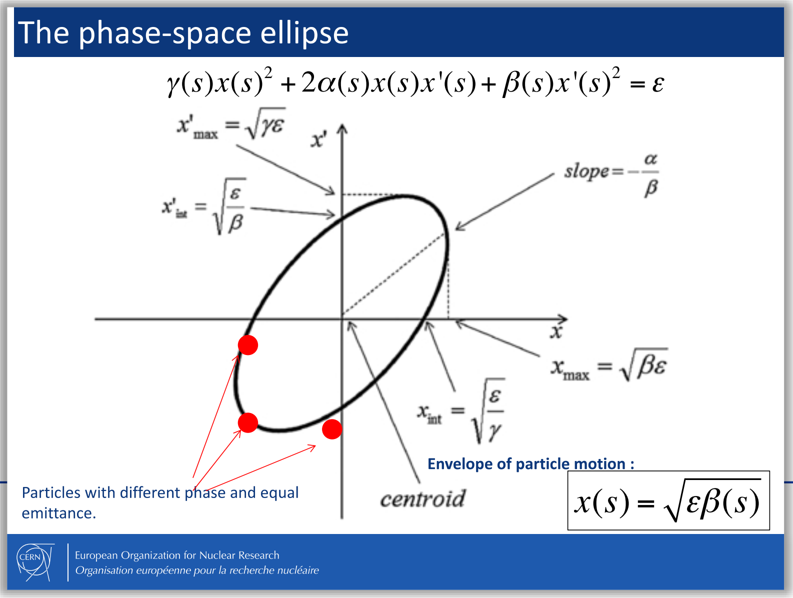
h<0: stability for 90º<f_s<180º

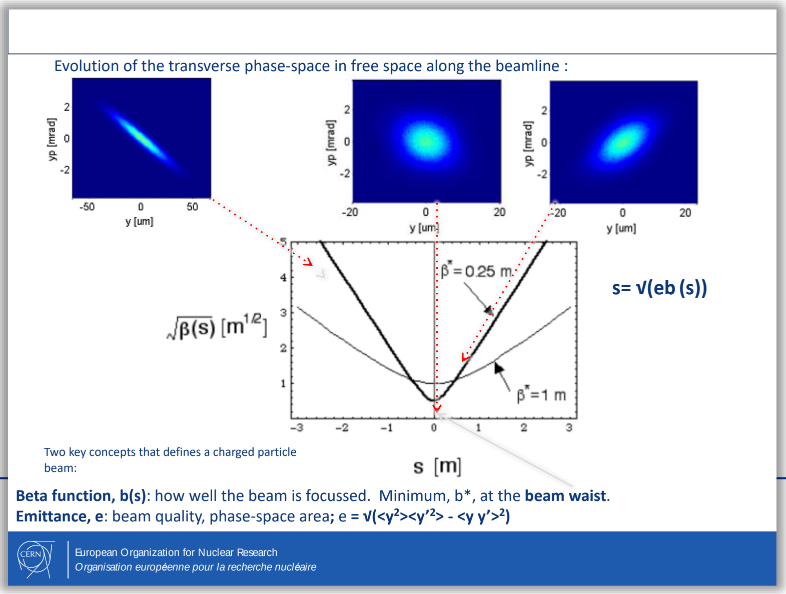
h=0 at the transition energy. When the synchrotron reaches this energy, the RF phase needs to be switched rapidly from f_s to 180-f_s

Bunches in collision









Outline

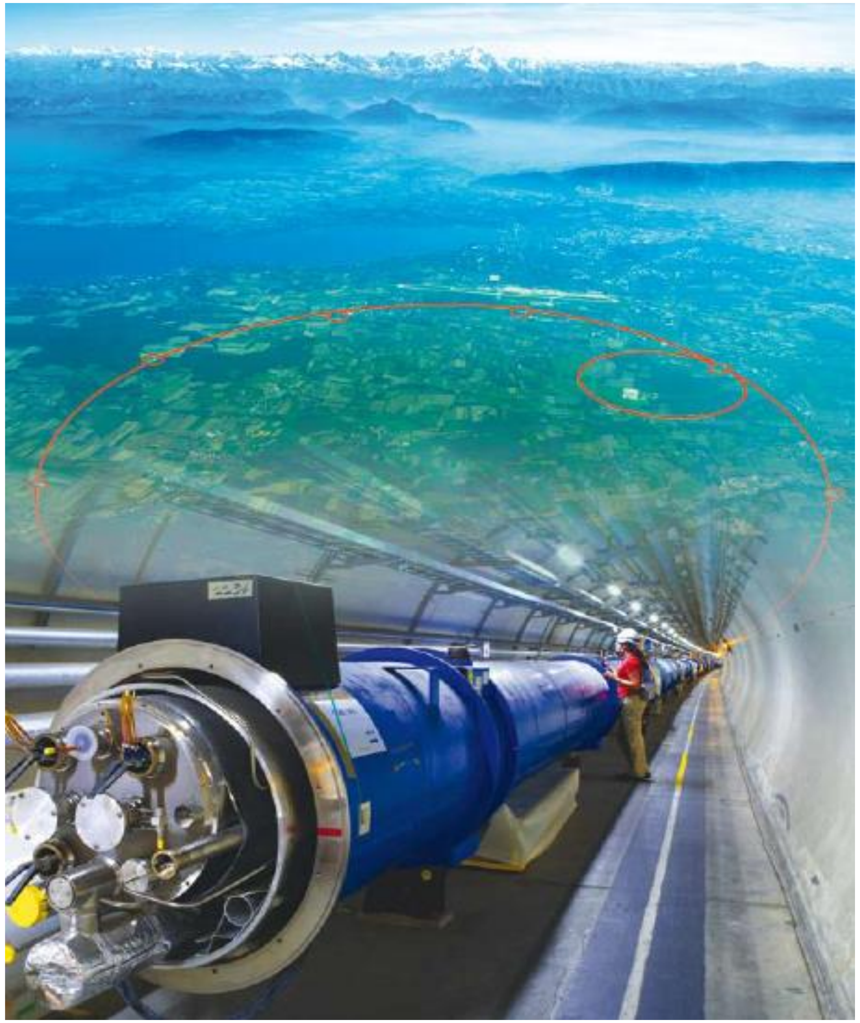
- Introduction
- Scope 1: e+e- Higgs factories
- Scope 2: Beyond Higgs factories
- Some accelerator concepts
- **Proton** and muon **colliders**
- General challenges and main points

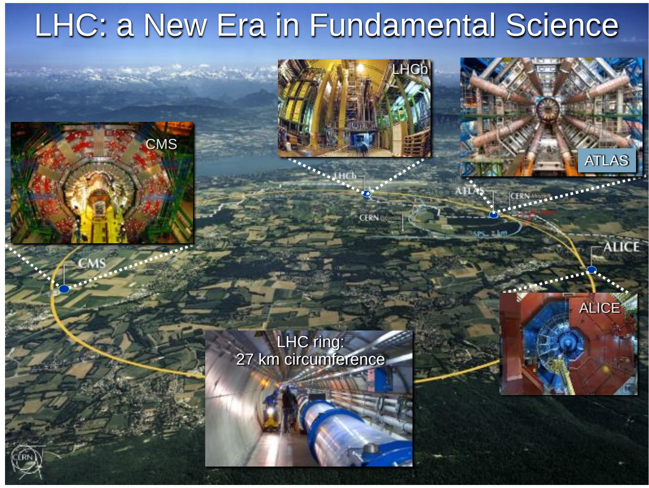
Hadron colliders – LHC: the ultimate proof of concept

14 TeV proton-proton collider built in the LEP tunnel

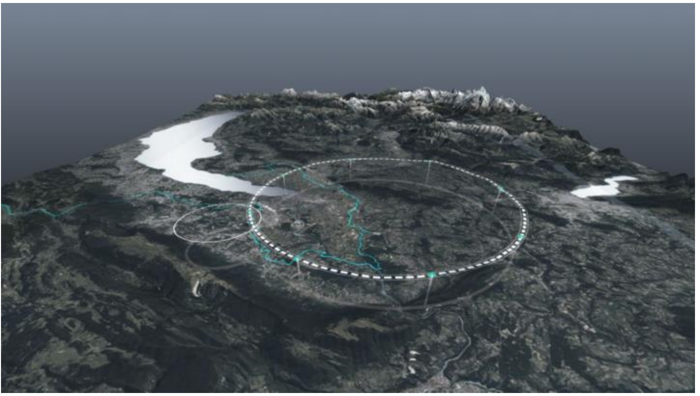
Lead-Lead (Lead-proton) collisions

1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1989-1994 : Approval process
1996-1999 : Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000 : Placement of the main production contracts
2004 : Start of the LHC installation
2005-2007 : Magnets Installation in the tunnel
2006-2008 : Hardware commissioning
2008-2009 : Beam commissioning and repair
2009-2040 : Physics exploitation and HL upgrade



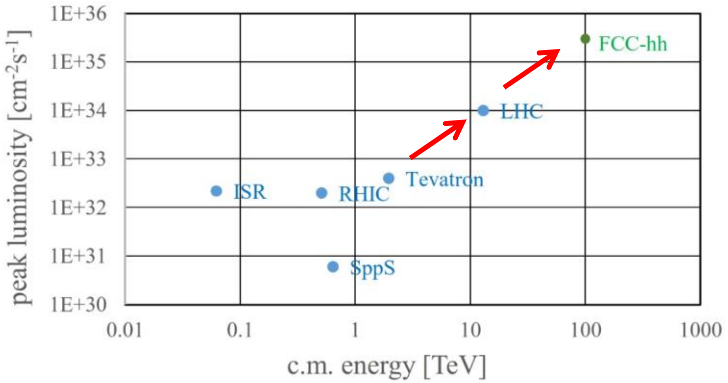


FCC-hh – conceptual design reports in 2018



The basic design was pursued strongly towards towards the European Strategy process update in 2018-19, and the main design and technical issues identified

- Will show some slides on the CDR studies – magnets recognised as critical
- The High Field Magnet studies (was covered yesterday by P.Vedrine)



During the last 3-4 years a much more detailed design of the FCC-ee has been made, and the FCC-hh design is being updated to match/adapt to these changes

- Change of circumference and hence lattice
- More work of the injector and technical studies
- Will show some examples

Link to the CDR

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [mm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

2018: Circular hadron colliders - FCC-hh and SppC

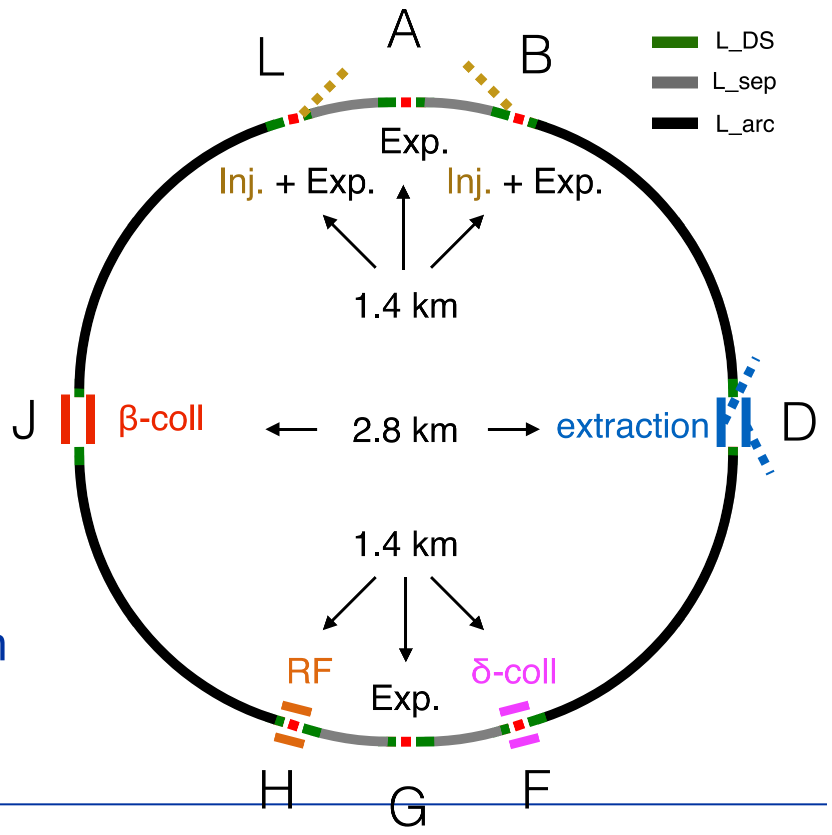
Circumference ~100 km, two high-luminosity experiments up to 3 (1) x 10^{35} $cm^{-2}s^{-1}$, two additional experiments possibly combined with injection section, collimation insertions (betatron and momentum cleaning), extraction/dump insertion, RF insertion

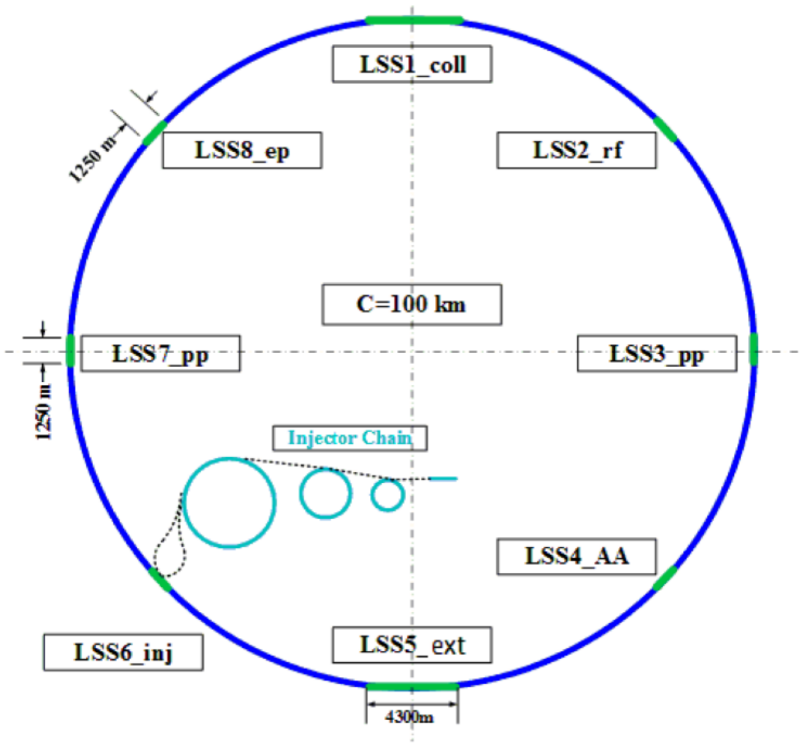
values in brackets refer to CEPC

FCC-hh

based on existing CERN injector chain,

Luminosity goal ~20 ab-1 per main IP within 25 years





SppC

new injector chain,

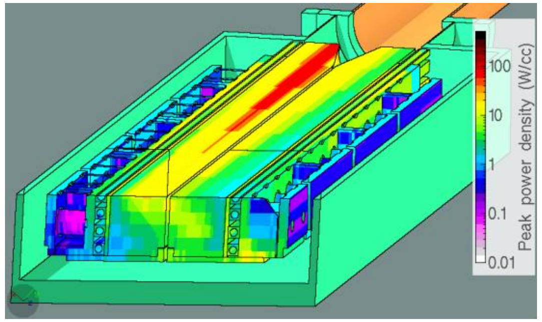
simultaneous operation with e+e- collider

For more recent studies of the SppC see next talk by J.Tang

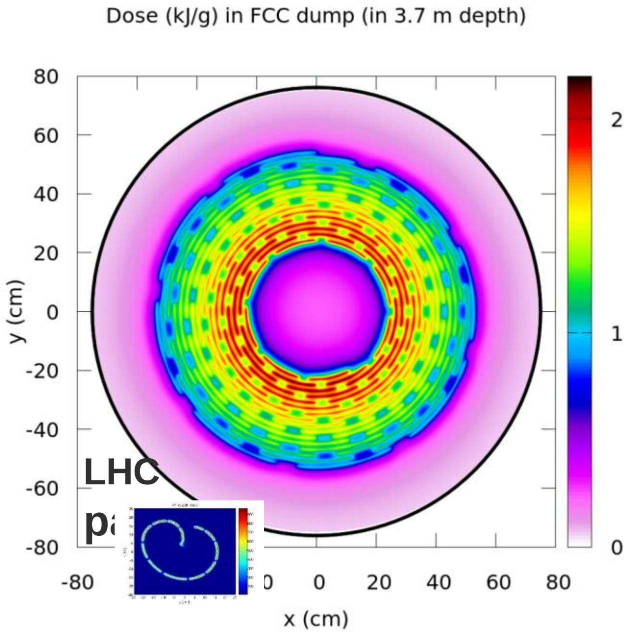
2018: Challenges for hadron colliders

- **High stored energy in the beam ~8-9 GJ**
  - Beam handling and dumping
  - Collimation cleaning system optimization
  - Kinetic energy of Airbus A380 (empty) at 880 km/h

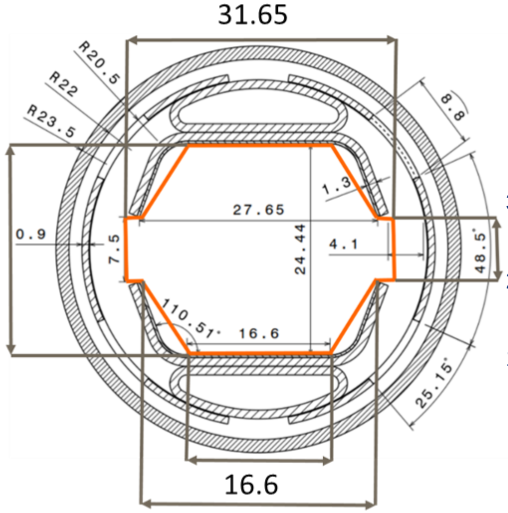
FCC Secondary Collimator
max power density
115 Wcm^{-3}

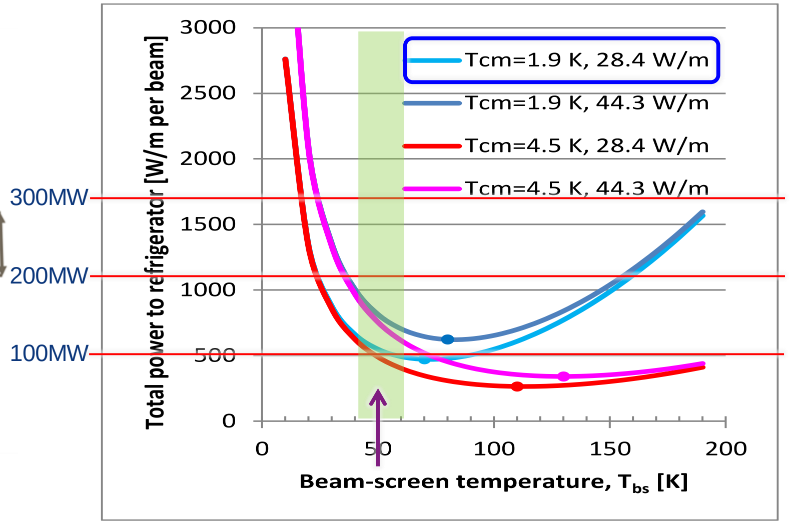


FCC dump pattern

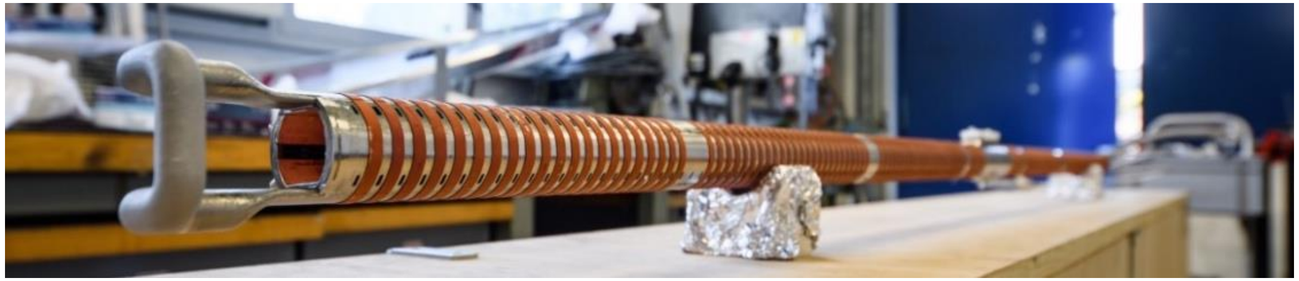


- **High synchrotron radiation inside magnets several MW**
  - **Beam screen design and cryogenic efficiency**





Beam screen prototype



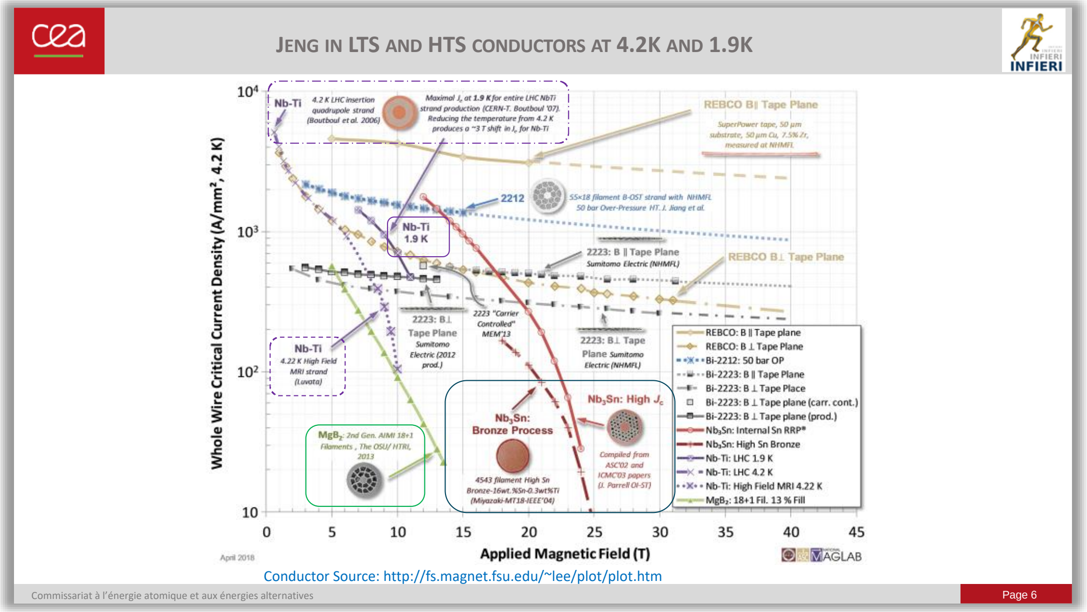
- **R&D on new materials, kickers & generators, vacuum systems, cryogenic system, electron lenses, ….**

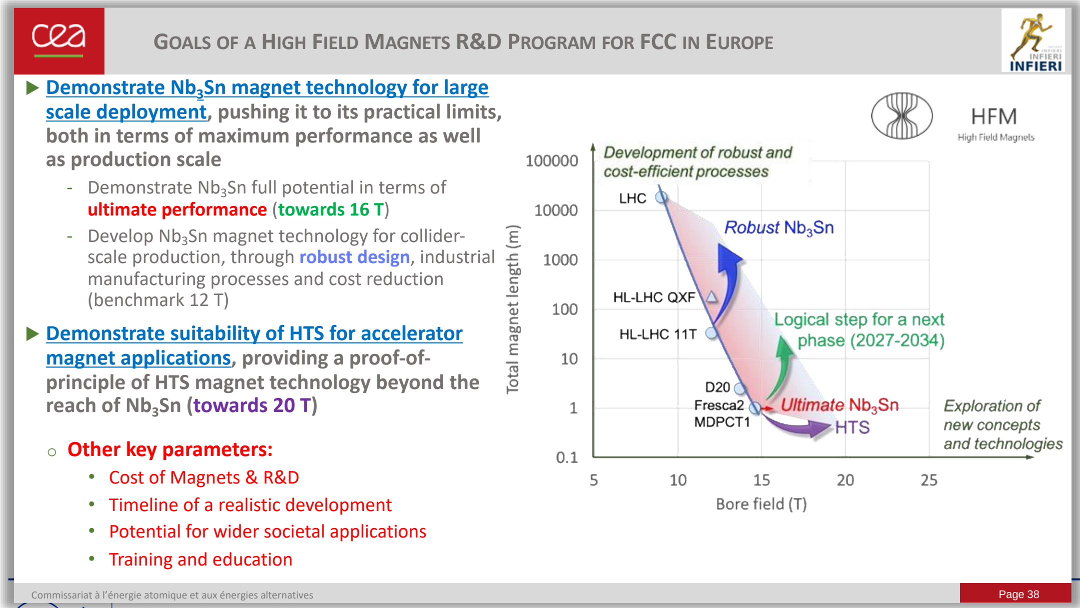
Slide from M.Benedikt: Link

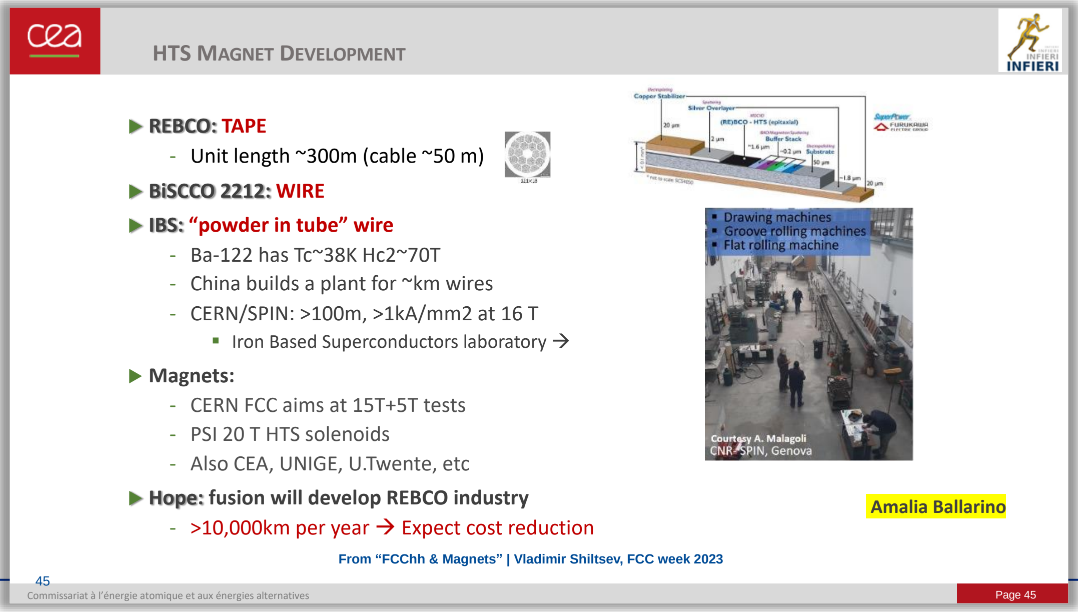
High Field Magnets

High field magnets, crucially important for the hadron colliders energy reach, costs and power consumption

See talk of P.Vedrine yesterday (LINK)



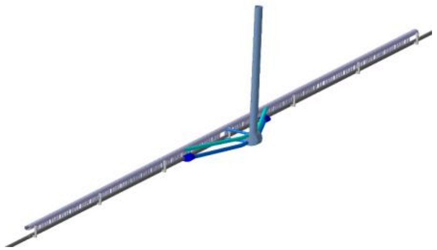


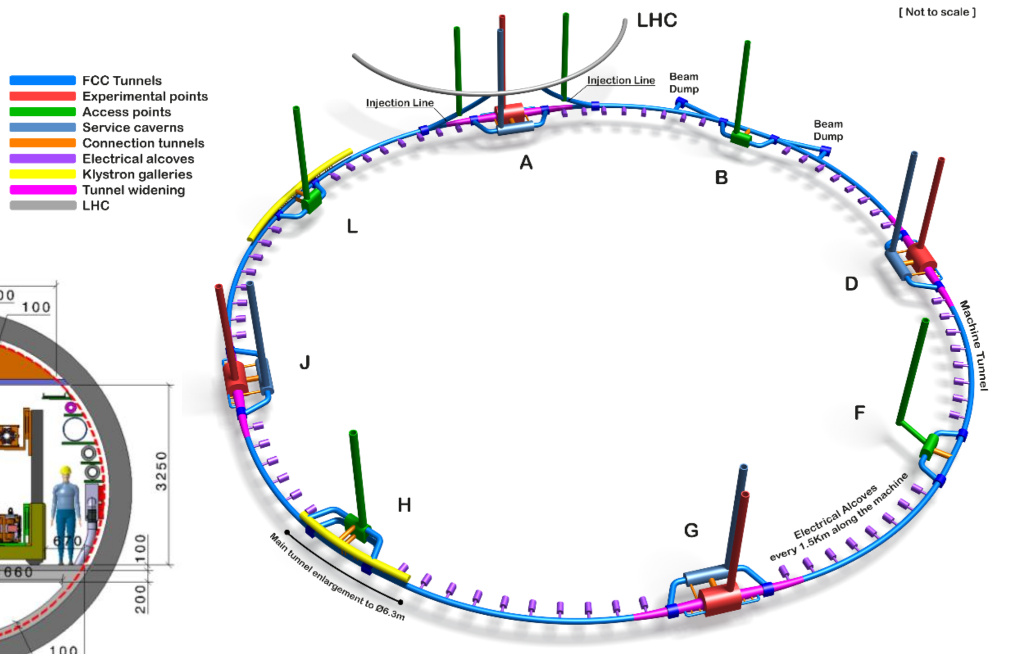


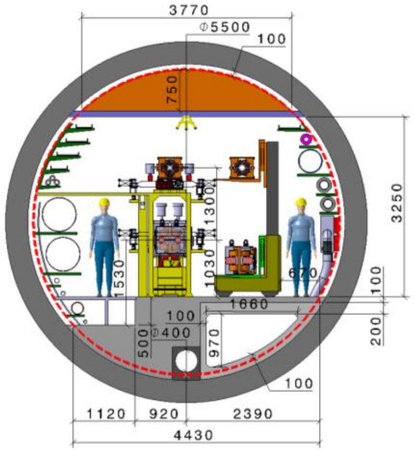
FCC feasibility study

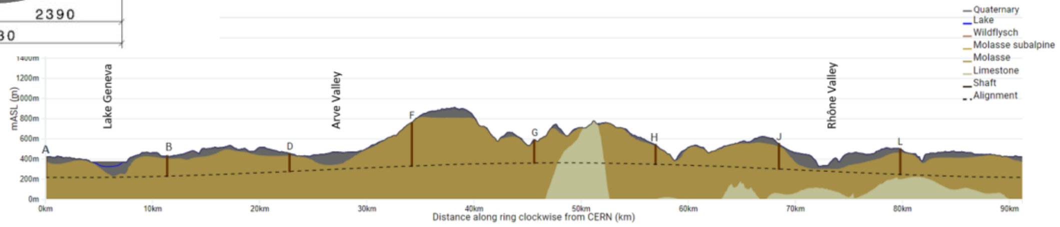
Main activities:

- Developing & confirming concrete implementation scenario, in collaboration with host state authorities, including environmental impact analysis
- Global collaboration, supported by the EC H2020 Design Study FCCIS and Swiss CHART.
- Goals:
  - Demonstrate feasibility by 2025/2
  - Next milestone is the mid-term review this year
  - CE Cost & construction schedule underway









Progress on underground design
- 90.6km alignment, PA31-3.0
- Integration studies (klystrons, alcoves, caverns, beam dump)
- 8 point baseline design frozen
- Excavated materials study

This leads to changes for FCC-hh

FCC-hh updates

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [mm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

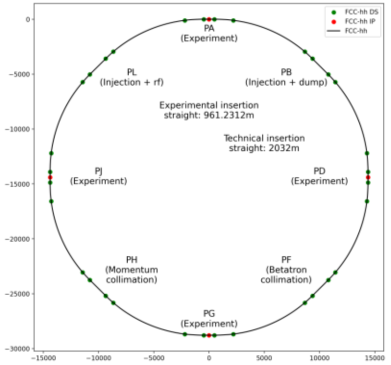
Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb_3Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

FUTURE CIRCULAR COLLIDER

Current layout of the FCC-hh ring

New beam energy (for 16 T dipoles): 48 TeV

- IPA, IPD, IPG, IPJ: experimental insertions
- Two collimation insertions
  - IPF: betatron cleaning
  - IPH: momentum cleaning
- IPB: extraction (both beams) + injection (external)
- IPL: RF (both beams) + injection (external)
- Last part of transfer lines in the ring tunnel
- Compatible with LHC or a superconducting SPS as injector



Circumference: 90.66 km

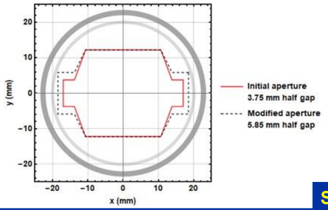
FCC-hh ring: overview of the new layout
Massimo Giovannozzi
FCC Week, 8 June 2023

FUTURE CIRCULAR COLLIDER

Design of regular arcs and dispersion suppressors

The new layout has been used to optimise as much as possible the ring design

- 12-dipole FODO cells have been replaced with 16-dipole FODO cells
  - Increase dipole filling factor
  - Larger beam sizes can be compensated by a minor review of the beam screen geometry



	CDR cell 12-dipole	New cell 16-dipole
# dipoles	4668	4464
Cell length (m)	213.030	275.792
# of regular cells/arc	42	26
# of cells in dispersion Suppressor (TECH/EXP)		4/7

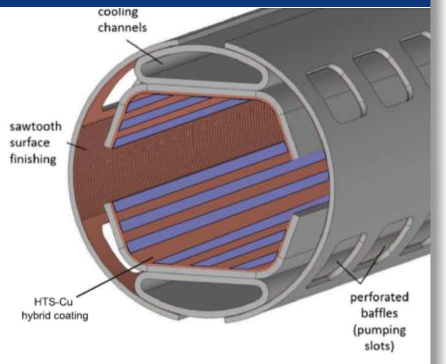
FCC-hh ring: overview of the new layout
Massimo Giovannozzi
FCC Week, 8 June 2023

See talks by
G. Perez Segurana for optics design
R. Bruce for performance of collimation system

FCC-hh technical update examples

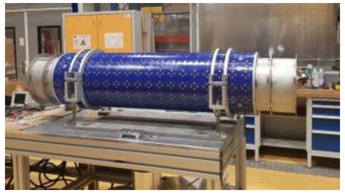
The Hybrid REBCO – Cu Coating

- **The FCC-hh beam screen (BS) has become a high-tech device and several activities are on going to study the novel configuration.**
- **The increased operating temperature imposes an HTS coating to reduce beam impedance.**
- **Full HTS coating generates a field distribution with poor properties.**
- **Alternated REBCO – Cu longitudinal segments achieve**
  - low overall surface impedance
  - decreased trapped field in the HTS, resulting in a better field quality than pure HTS

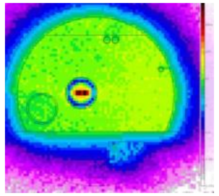


Permanent Magnet Concepts

- **Permanent Magnets (PMs) are highly suitable for transfer line specifications:**
  - Single-pass beam requires less stringent field quality requirements
- **PMs are already used in accelerators, although on a smaller scale.**
- **Temperature dependence of PMs is sufficiently small.**
- **The lifetime radiation dose is expected to be compatible with NdFeB or SmCo PMs.**
  - The provisional designs use a high coercivity NdFeB grade (N42UH)
- **Developing industrial-scale assembly processes will be a significant focus of future research.**

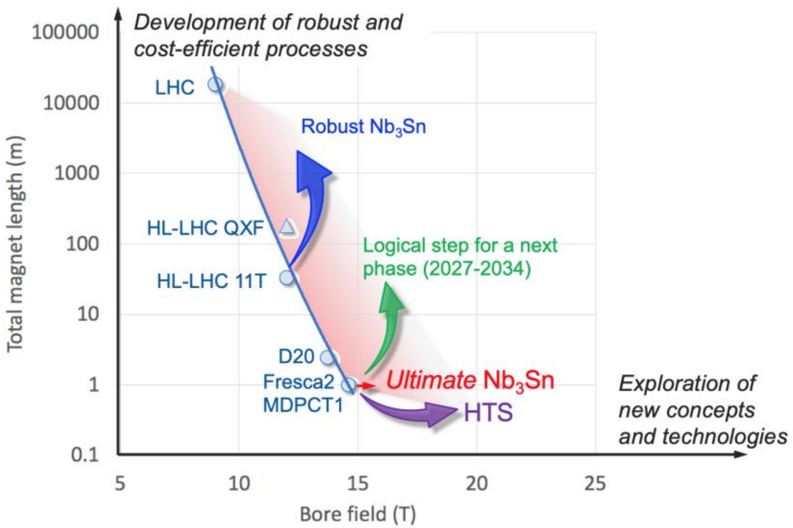


Halbach dipole magnet for FASER experiment



Transverse radiation dose plots for FCC-hh collider

FCC-hh ring: overview of the new layout
Massimo Giovannozzi
FCC Week, 8 June 2023

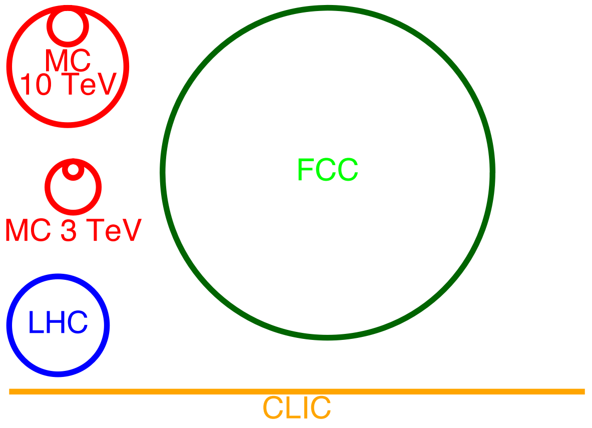


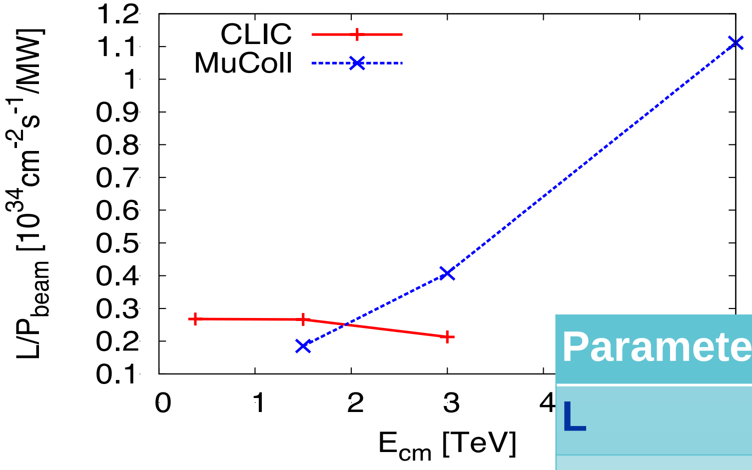
HFM remain the main performance, costs and power consumption drivers

Outline

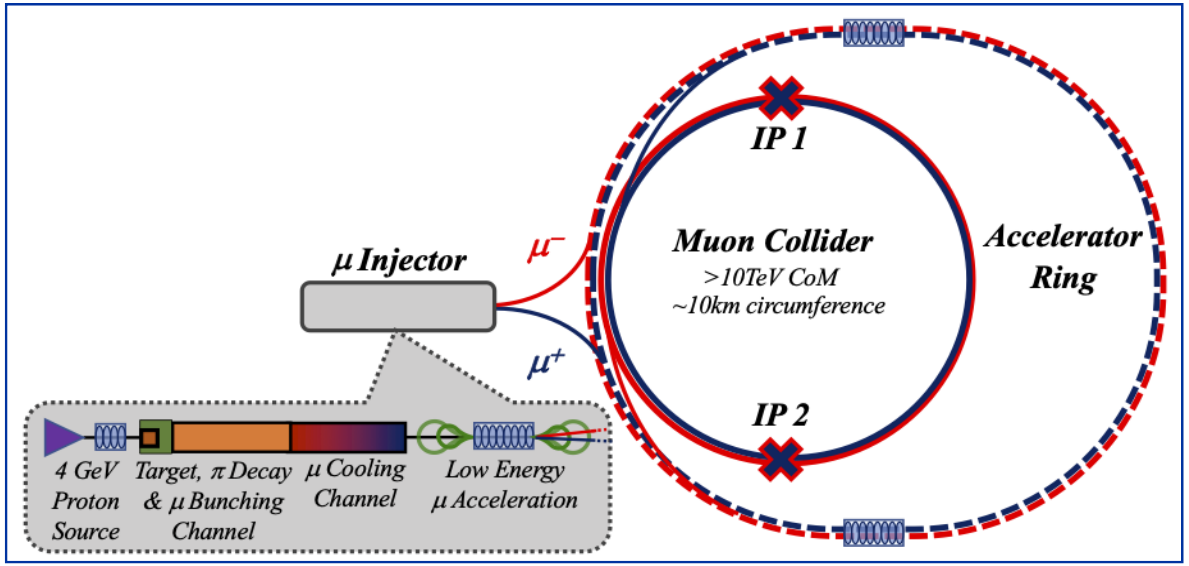
- Introduction
- Scope 1: e+e- Higgs factories
- Scope 2: Beyond Higgs factories
- Some accelerator concepts
- Proton and **muon colliders**
- General challenges and main points

A muon collider addressing size, luminosity, power



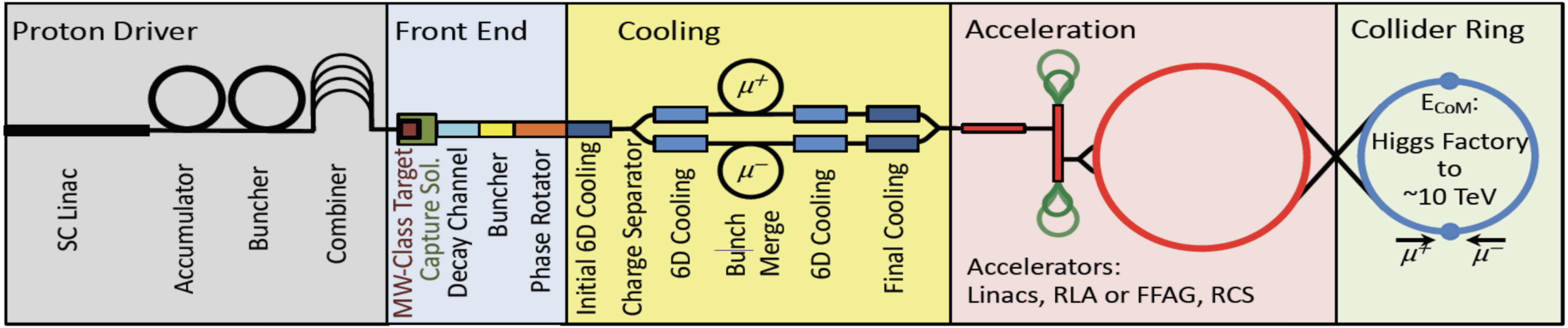


Comparing to FCC ~100km and CLIC 3 TeV ~50km



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
σ_δ	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε_L	MeV m	7.5	7.5	7.5
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

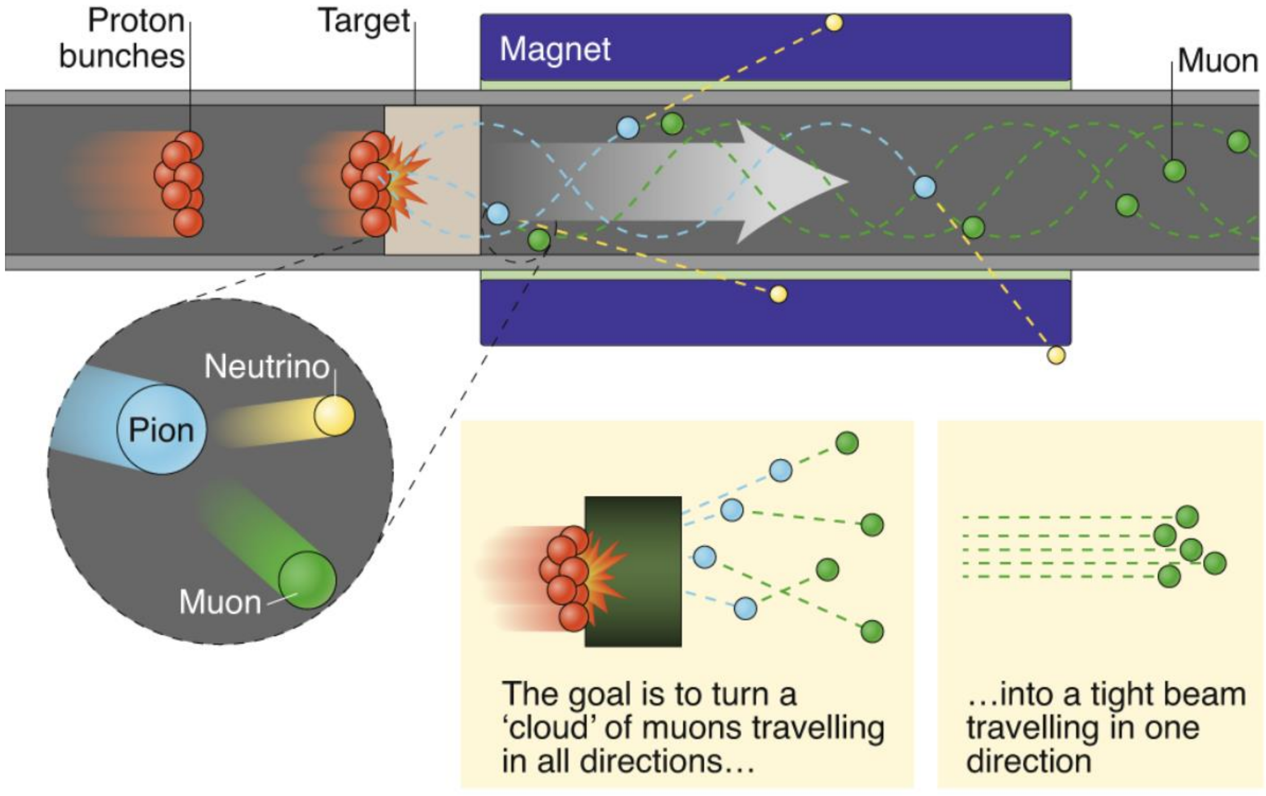
Overview of the muon collider systems

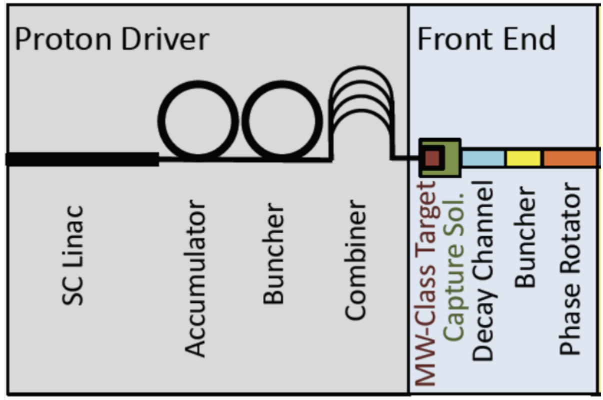


- High power proton beam (short intense bunches) and low repetition rate on target.
- Target and capture channel, protons produce pions which decay into muons.
- Large energy spread μ beam split to sequence of bunches.
- Stages of muon ionisation cooling in matter.
- Merging of μ bunches into one bunch.
- Low energy acceleration with recirculating linacs.
- Acceleration to collision energy in a sequence of pulsed synchrotrons.
- Collider packed with high field magnets to minimise circumference and maximise luminosity.

Short muon life-time —> Ionization cooling, fast acceleration, high RF gradients and high field magnets!

Muon Production and Capture



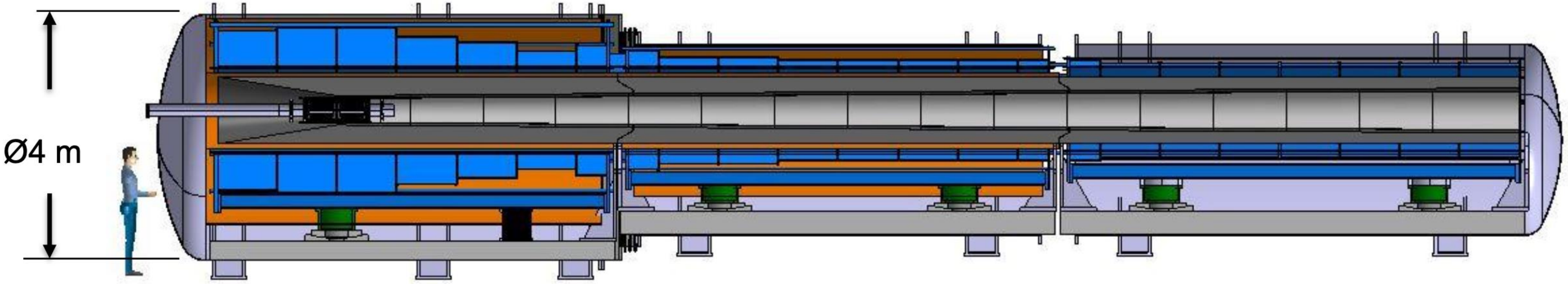


Proton complex:

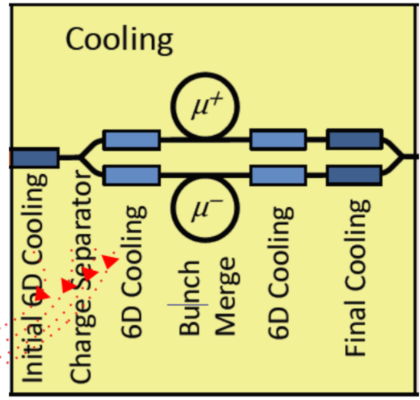
- Baseline lattice for accumulator-compressor based on neutrino factory lattice.
- Work ongoing on limitations to accommodate the 2MW beam at 5Hz.

Studying 2 MW target:

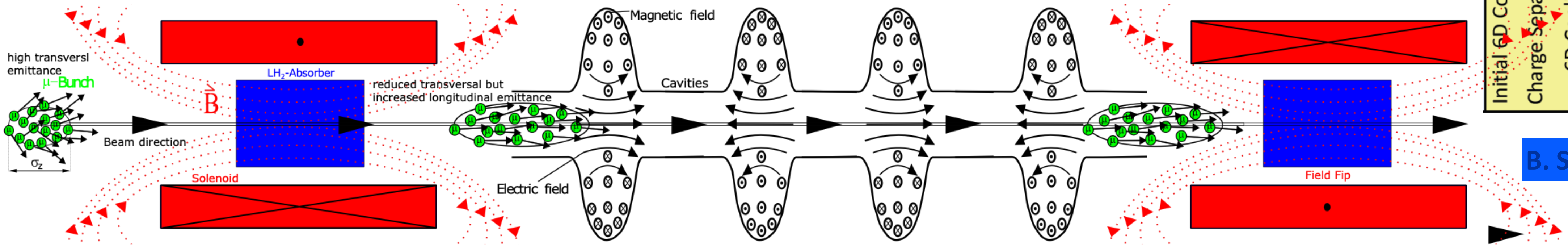
- Stress in target, shielding, vessel and window being studied.
- Studies of HTS solenoids ongoing.



Muon Cooling

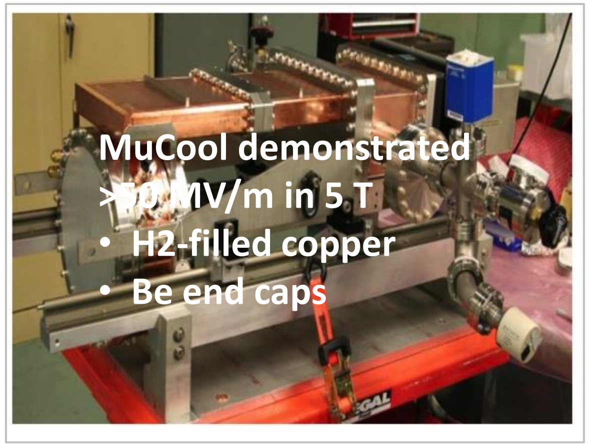


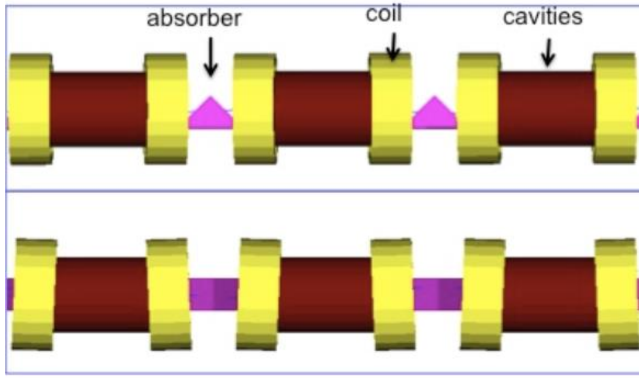
Short muon lifetime —> **Ionisation cooling only option**

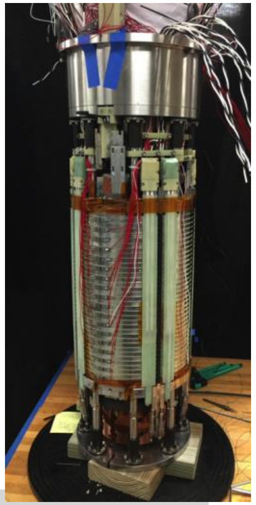


B. Stechauner

6D cooling

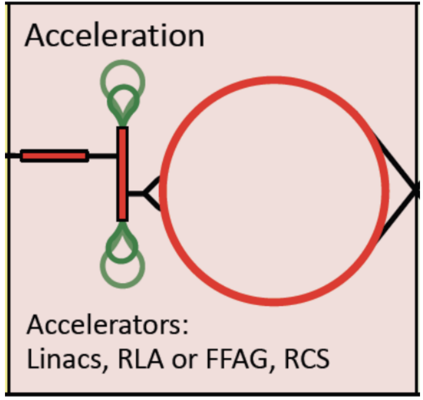




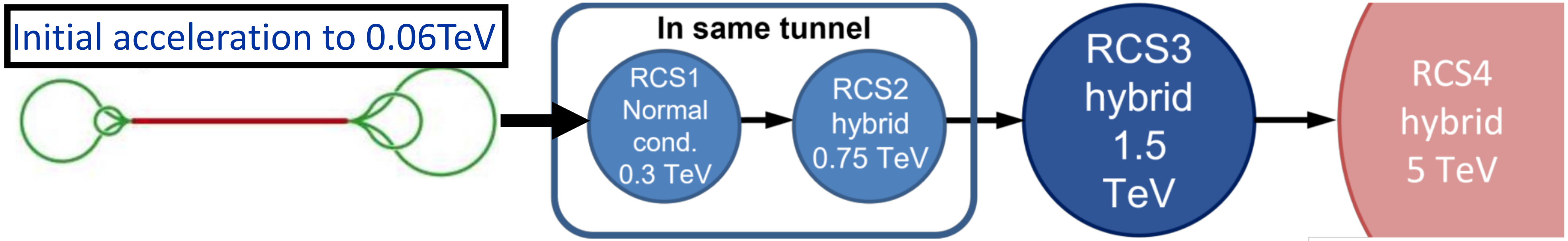


Absorber: reduction of longitudinal and transverse momentum
High Field solenoids: 30-40 or above T
Scattering: beam blow-up —> need for strong solenoids and low Z absorbers.
Cavities: acceleration, RF in magnetic field, i.e., increase of only longitudinal momentum.
Net effect: reduction of transverse momentum and thus beam cooling.

Acceleration



Fast acceleration to avoid significant muon losses due to decay



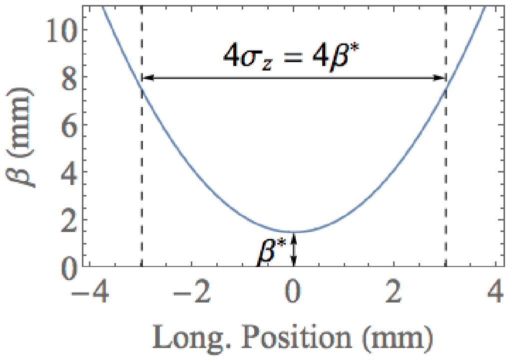
Re-Circulating Linacs

Rapid Cycling Sychrotron

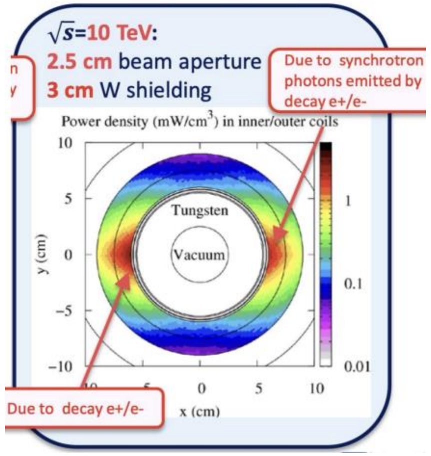
- Use of high (average) RF gradients to accelerate single μ^+/μ^- bunch.
- Start with re-circulating linacs (RCL).
- Followed by rapid cycling synchrotrons (RCS)
  - acceleration within few tens of turns, studies based on Tesla cavities
  - hybrid RCSs have fast ramping normal conducting and constant superconducting dipoles
  - the fast-ramping magnet system and energy management are expected to be important cost and power drivers
  - FFAs a possible alternative.

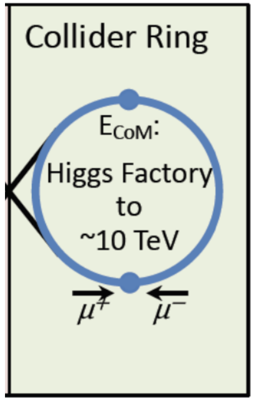
Muon Collider Ring - radiation due to muon decay

Beam-parameters and lattice design challenging



A. Lechner et al.



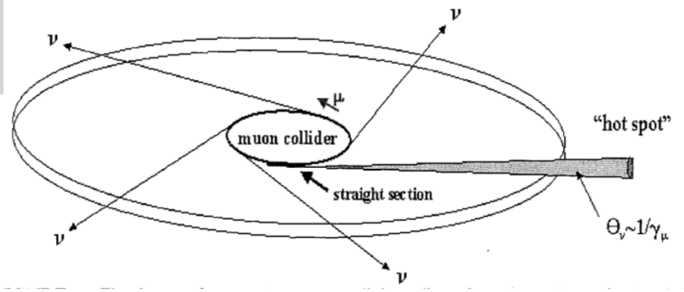


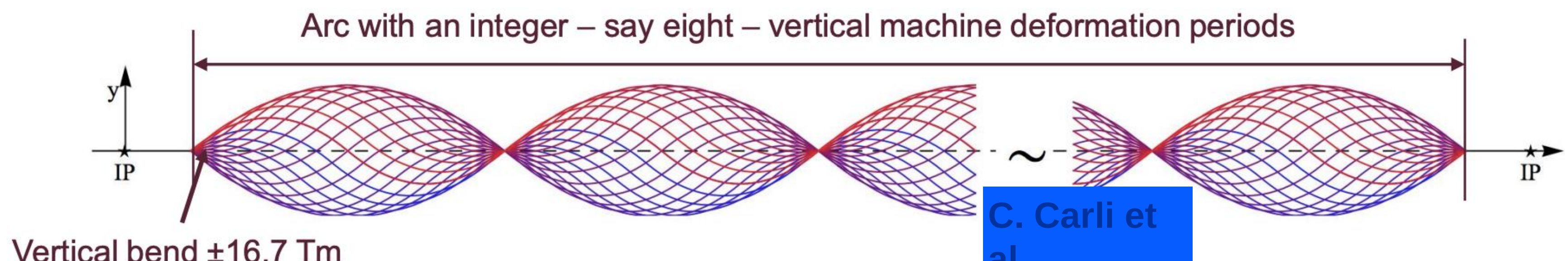
Radiation due to photons and e^-/e^+:

- Residual power "leaking" into cold mass.
- Cryo load, radiation damage etc. "under control" with 30-40mm absorber.
- W absorber to intercept most of shower (~500 W/m for 10km).

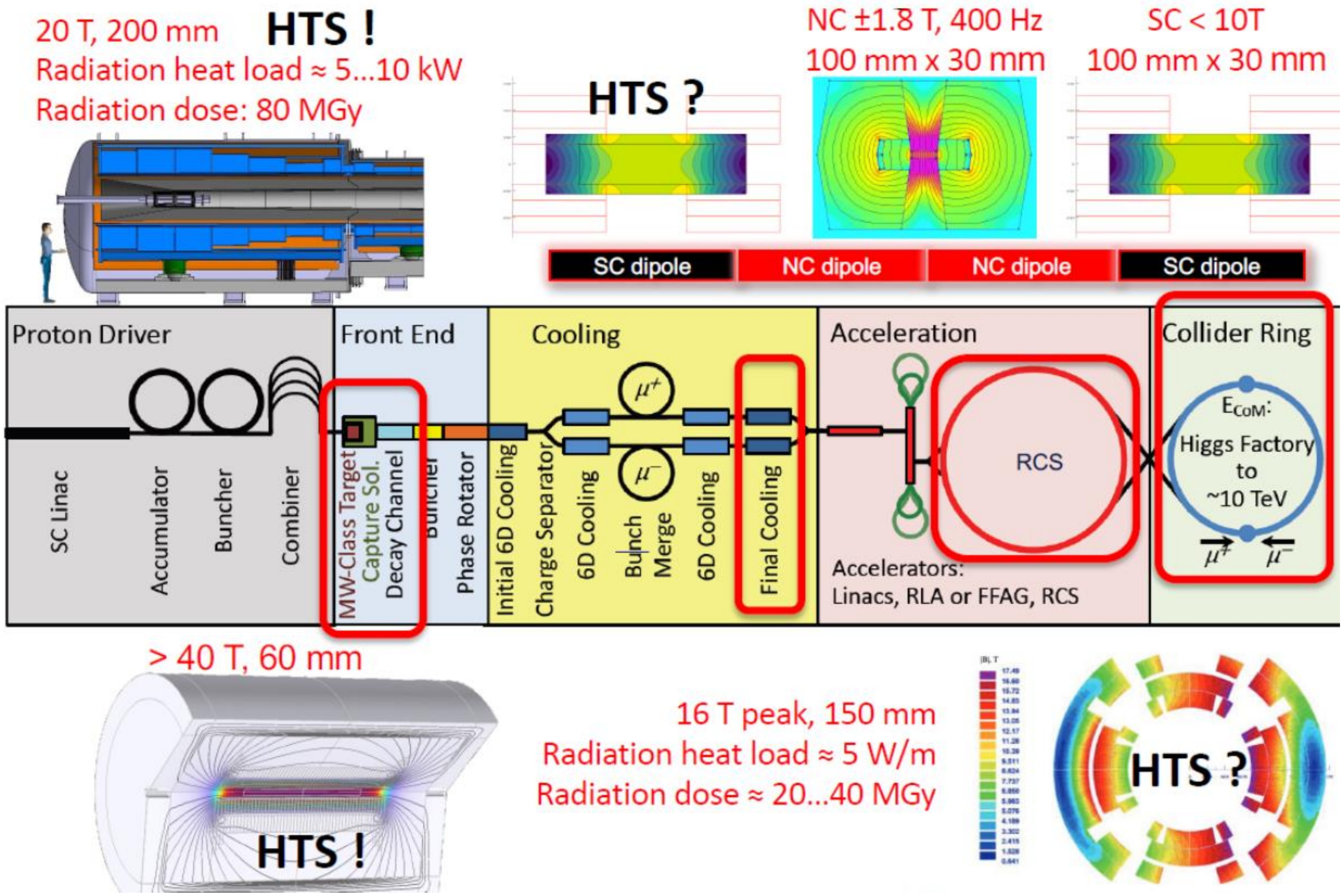
Due to neutrinos:

- Showers generated by neutrinos close the earth surface
  - extensive use of dipoles and combined function magnets for evenly distribute the neutrino radiation
  - wobbling of machine in vertical direction (modulation within ±1 mrad reduce peak dose by factor ~100)
  - positioning such that neutrinos from IR reach earth surface in uncritical areas.
- Strong increase of maximum dose with muon energy.

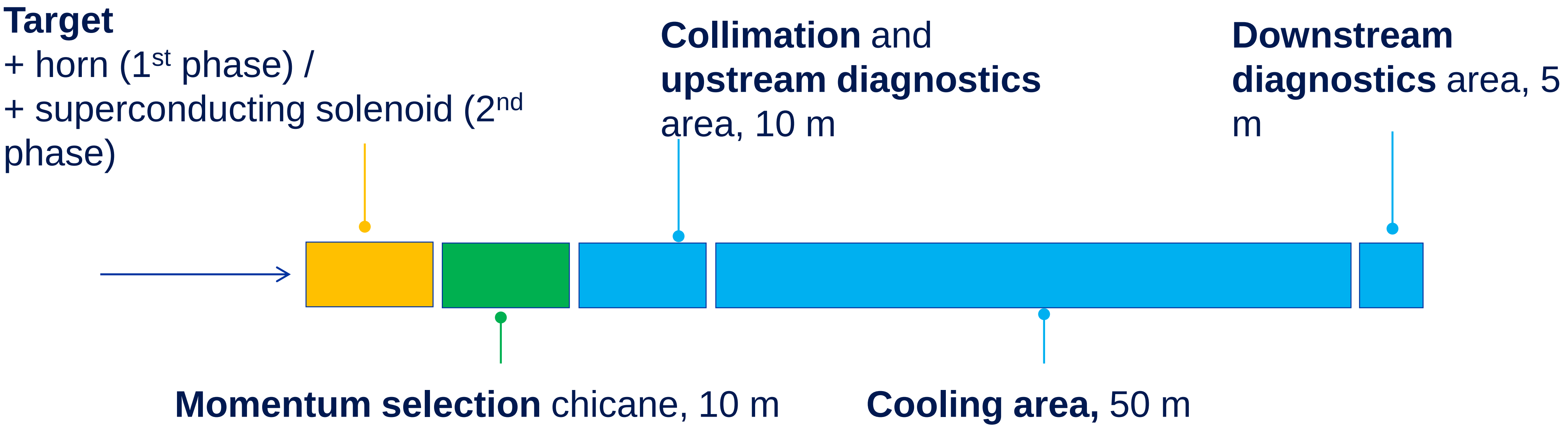




C. Carli et al.

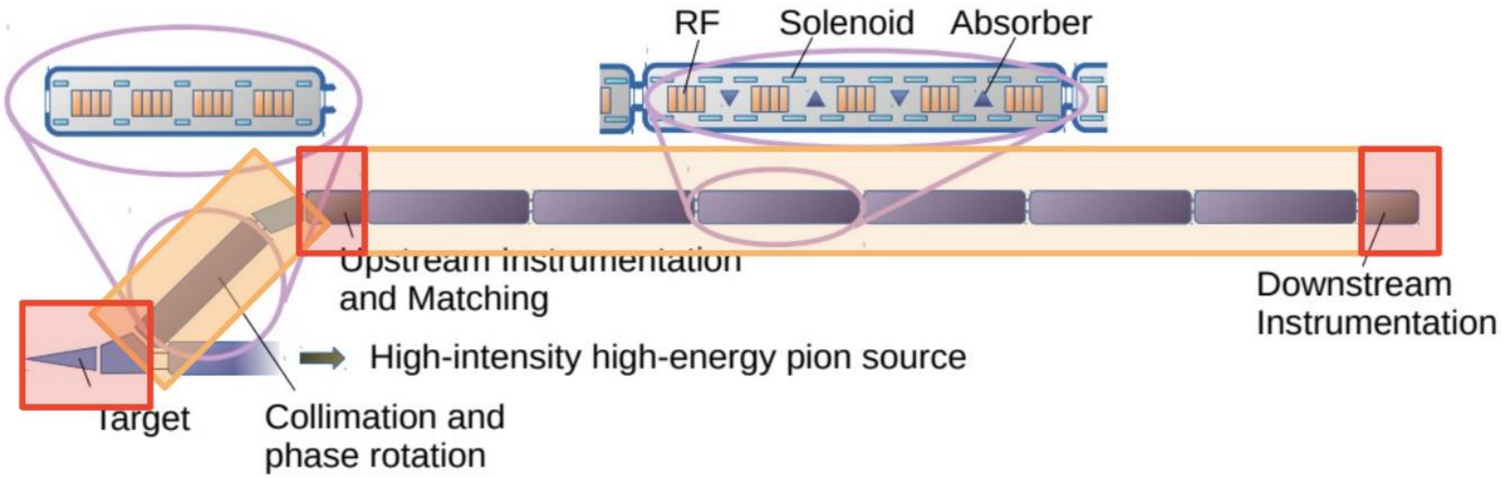

20 T, 200 mm
HTS !
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy
HTS ?
NC ±1.8 T, 400 Hz
100 mm x 30 mm
SC < 10T
100 mm x 30 mm
SC dipole
NC dipole
NC dipole
SC dipole
Proton Driver
SC Linac
Accumulator
Buncher
Combiner
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cooling
Initial 6D Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
Acceleration
RCS
Accelerators:
Linacs, RLA or FFAG, RCS
Collider Ring
E_{CoM}:
Higgs Factory
to
~10 TeV
> 40 T, 60 mm
HTS !
16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 MGy
HTS ?

Cooling Test Facility



Look for an existing proton beam with significant power.

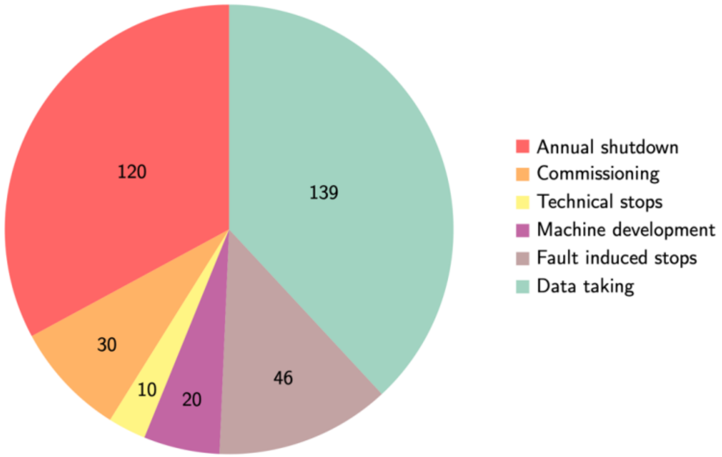
Different sites are being considered
- CERN, FNAL, ESS are being discussed
- J-PARC also interesting as option



Outline

- Introduction
- Scope 1: e+e- Higgs factories
- Scope 2: Beyond Higgs factories
- Some accelerator concepts
- Proton and muon colliders
- **General challenges and main points**

Power and energy



Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I
ILC (3 TeV)	∼400	59 km	II	II
CLIC (3 TeV)	∼550	50.2 km	III	II
CCC (3 TeV)	∼700	26.8 km	II	II
MC (3 TeV)	∼230	10-20 km	II	III
MC (14 TeV)	∼300	27 km	III	III
FCC-hh (100 TeV)	∼560	91 km	II	III
SPPC (125 TeV)	∼400	100 km	II	III

100 MW corresponds to ~0.6 TWh with the running scenario on the left

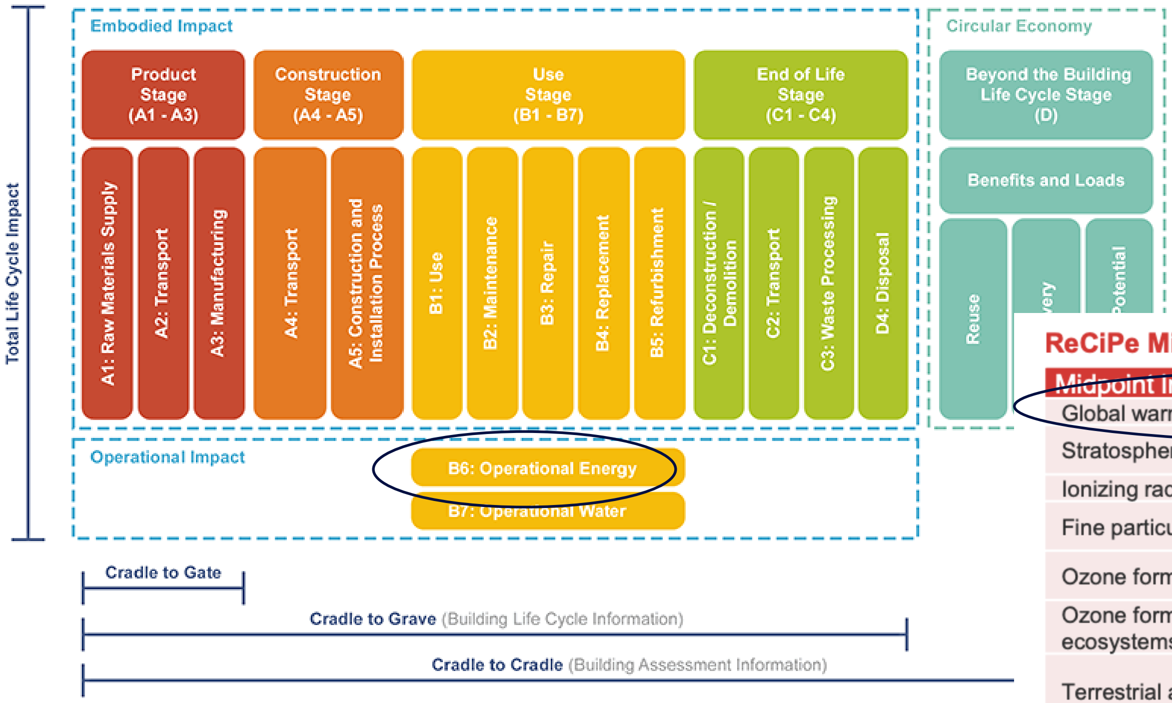
1 TWh very roughly 100 MCHF

Power/energy is generally associated with carbon footprint but we can probably access and adapt to use of green energy by ~2050 (nuclear, sun, wind, hydro, thermal …)

Sustainable facilities

Optimize with respect to:

- Energy reach, luminosities, experimental conditions
- Facility size and schedule
- Costs and Power
- Environmental Impact and Sustainability (we are learning what this means)



ReCiPe Midpoint (H) 2016 Impact Categories

Midpoint Impact Categories	Abbr.	Unit
Global warming	GWP	kg CO_2 eq
Stratospheric ozone depletion	ODP	kg CFC-11 eq
Ionizing radiation	IRP	kBq Co-60 eq
Fine particulate matter formation	PMFP	kg PM2.5 eq
Ozone formation, Human health	HOFP	kg NOx eq
Ozone formation, Terrestrial ecosystems	EOFP	kg NOx eq
Terrestrial acidification	TAP	kg SO_2 eq
Freshwater eutrophication	FEP	kg P eq
Marine eutrophication	MEP	kg N eq
Terrestrial ecotoxicity	TETP	kg 1,4-DCB
Freshwater ecotoxicity	FETP	kg 1,4-DCB
Marine ecotoxicity	METP	kg 1,4-DCB
Human carcinogenic toxicity	HTPc	kg 1,4-DCB
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB
Land use	LOP	m^2a crop eq
Mineral resource scarcity	SOP	kg Cu eq
Fossil resource scarcity	FFP	kg oil eq
Water consumption	WCP	m^3

Reference: ReCiPe Midpoint (H) 2016

"Not enough to look at operation power and guess the CO2 from this power in ~2050 in your favourite country"

Keep in mind: This is not only more constraints but also a new opportunity for R&D, new ideas, collaboration

Personnel estimate and cost – for Higgs factories

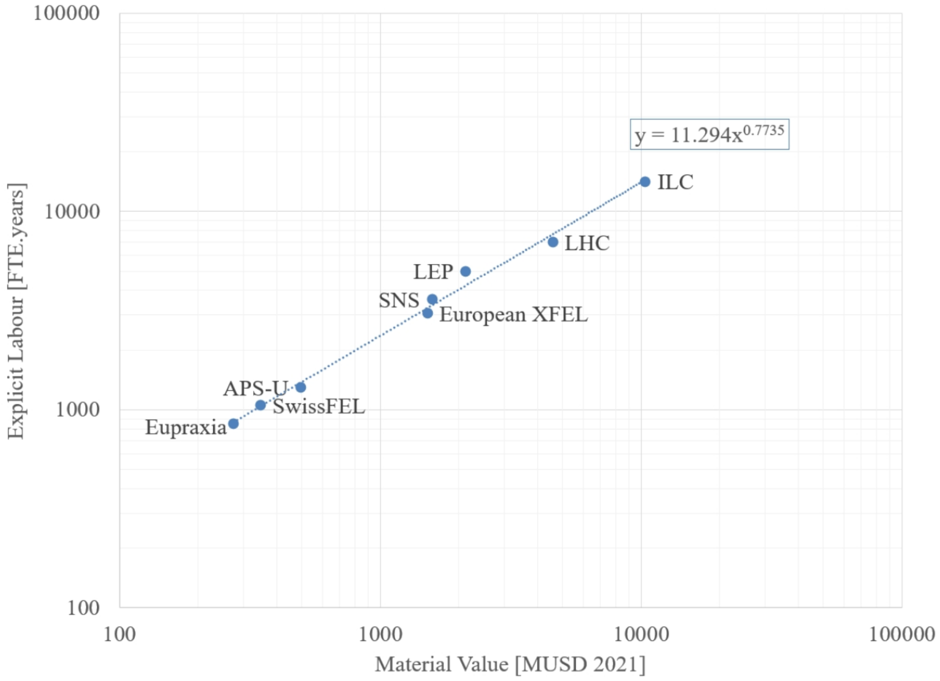


Figure 5: Explicit labor for several large accelerator projects vs. project value.

One FTEy estimated to 200kUS$

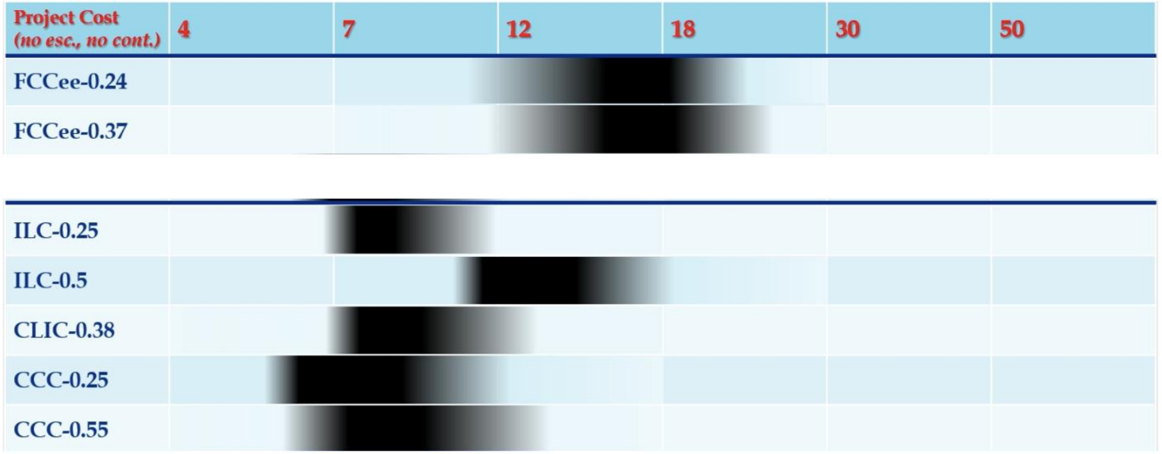
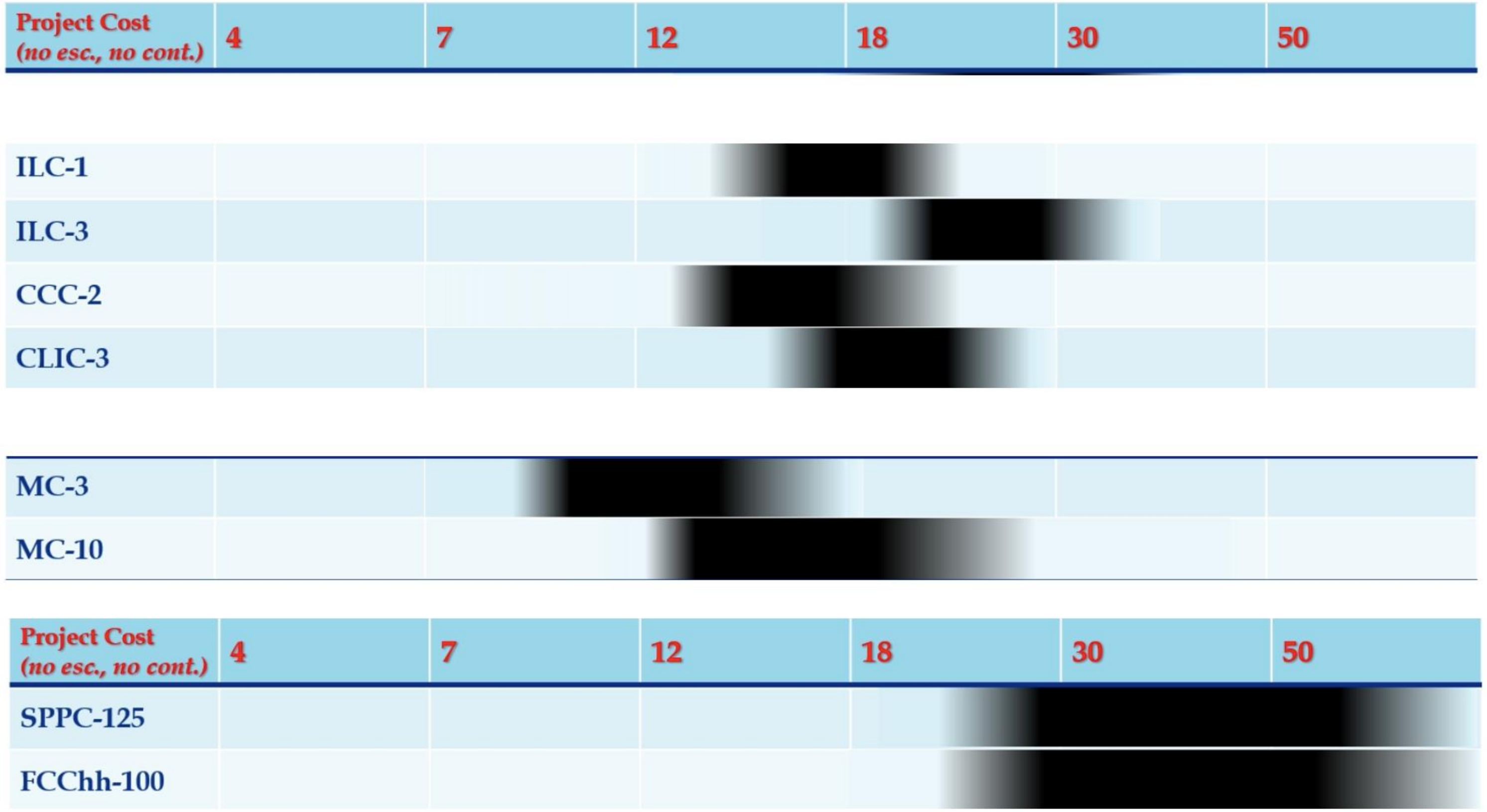


Figure 8: The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

Higher energy projects – and costs



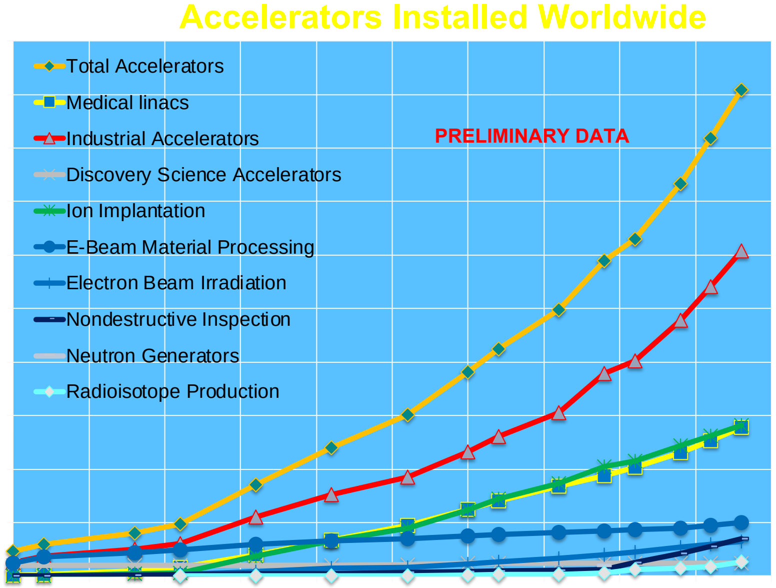
Impact on/from – and collaboration with – other fields

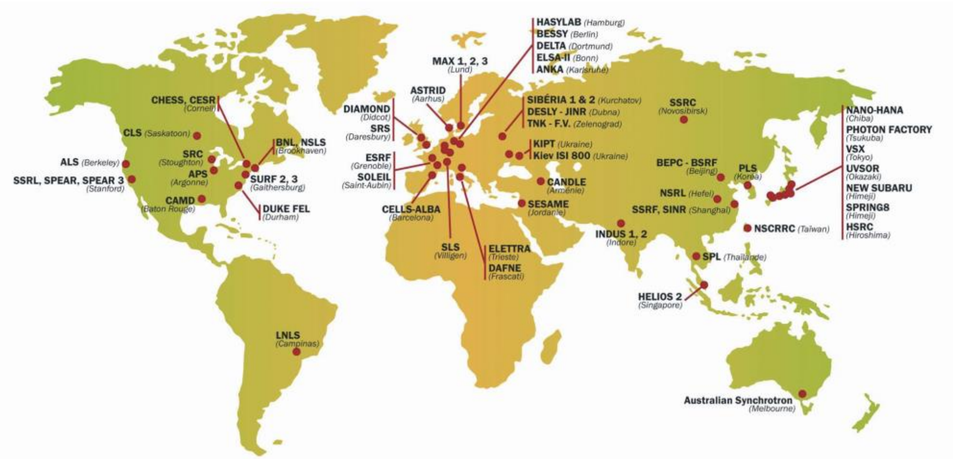
Landscape of accelerators

- The large markets are medical and industrial small accelerators (dominated by electron linacs and ion implantation)
- Material and life-sciences: Synchrotron-sources (new or upgrades) and FELs, ESS (0.5 - 2B projects)
- Research in particle and nuclear physics, LHC and HL, EiC, Neutrino “Factories”, Future colliders …

Whenever possible we benefit strongly from aligning to overall accelerator landscape – connected industry, connected laboratories

In some cases we can link to use of “our” key technologies in other fields, e.g. energy sector with HF magnets a very good example (fusion, power generators, etc)





Summary

Higgs-factories are well in reach technically – much needed

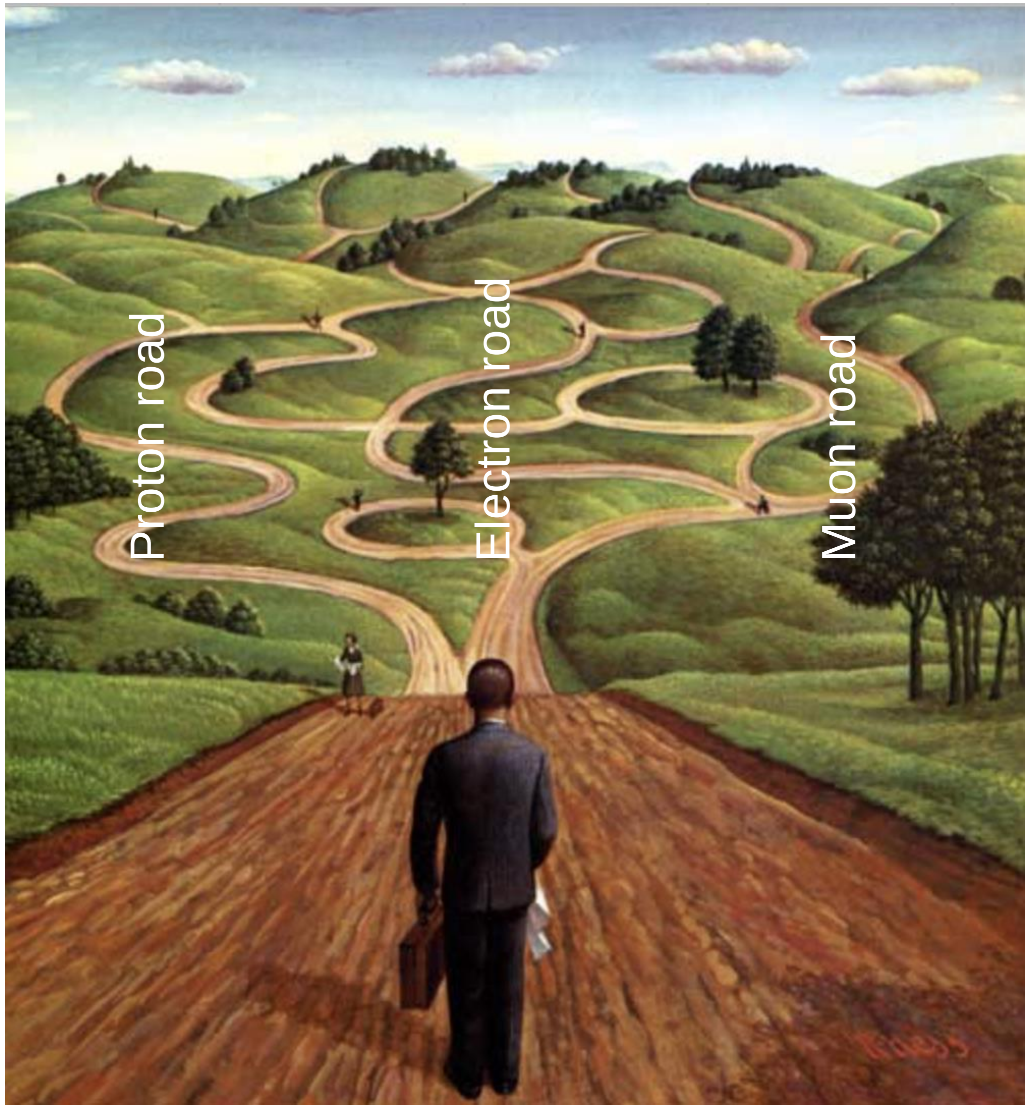
Beyond this a hadron collider and/or muon collider are ambitious and very interesting opportunities:

- for the hadron collider the magnets are crucial, drives energy reach, cost and power
- for the muon collider a wider range of challenges, cooling, RF and and also magnets

LC e+e- can be pushed to ~3 TeV.
Unclear (to me at least) if realistic 10 TeV e+e- collider concepts can be established, even though plasma acceleration can provide very high gradients

Resources needed are large, and sustainability issues will need to be part of the design throughout

Many opportunities for students and young scientists, these project studies are open collaborations



We are not in a position to ignore any of them

Most of the slides/information from:

The Snowmass Implementation Task Force (chair T.Roser)

M.Benedikt, T.Raubenheimer, M.Giovannozzi
D.Schulte, K.Skoufaris

B.List and ARUP team
E.Adli
M.Narain

Earlier talks in the school, in particular Carlos Wagner (physics) and Pierre Vedrine (high field magnets)

….

THANKS

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