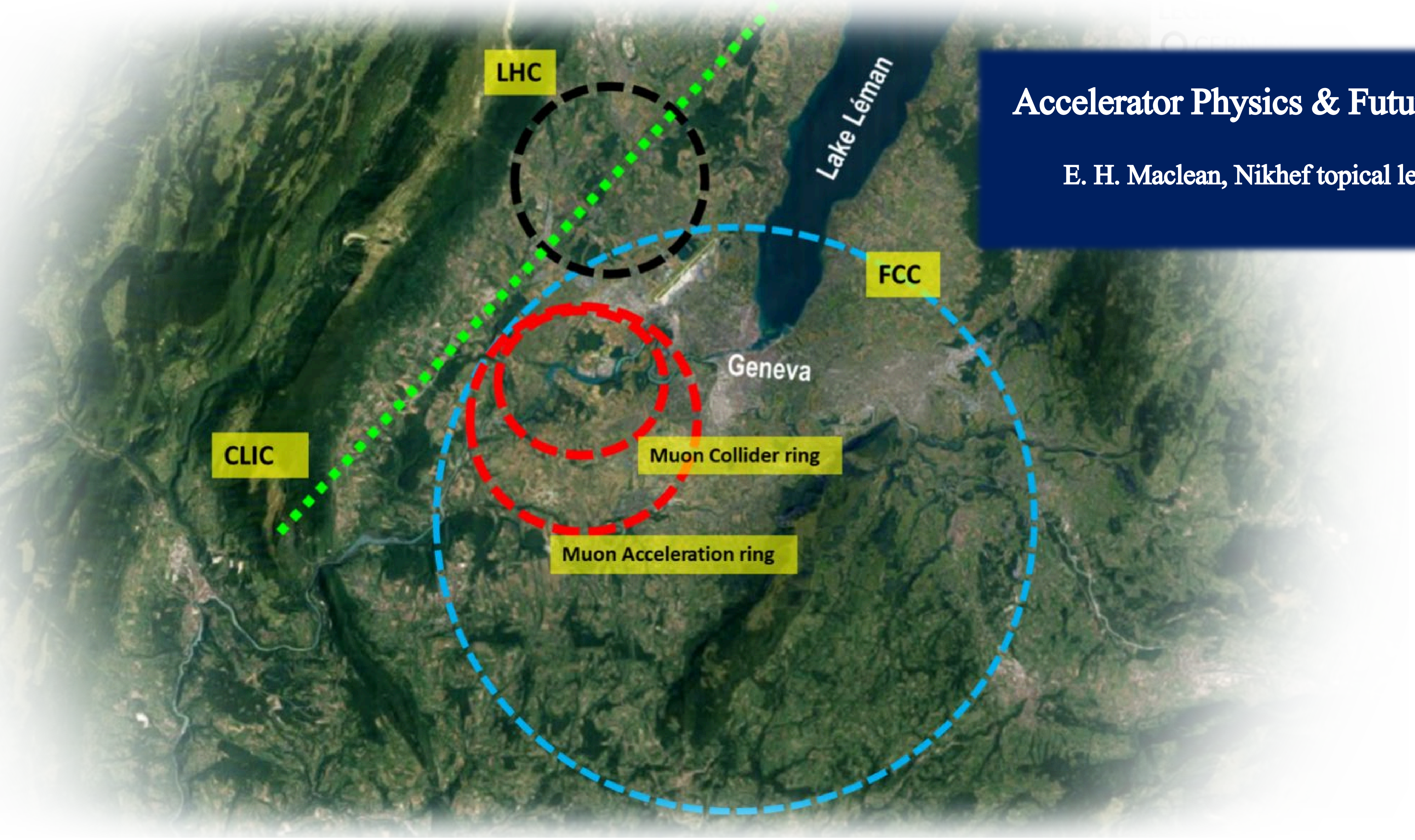
Accelerator Physics & Future colliders

E. H. Maclean, Nikhef topical lectures 2024



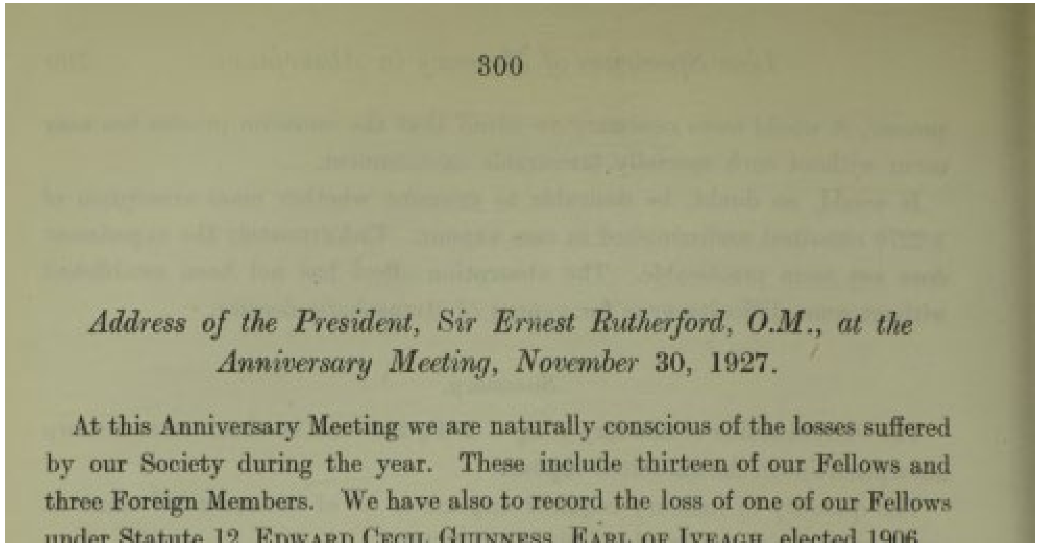
Overview

- **What do particle physicist care about?**
  - **Energy?**
  - **Luminosity?**
  - **Viability, cost, power, sustainability?**

- **Types of future particle collider? Design, challenges, technology…**
  - **Linear e^+e^- colliders (ILC and CLIC)**
  - **Circular e^+e^- colliders (CEPC and FCC-ee)**
  - **Circular pp colliders (SppS and FCC-ee)**
  - **Muon collider**

- **Future concepts in energy frontier accelerators**
  - **Lemma,γ-factory, γγ collider, C3, plasma-wakefield**

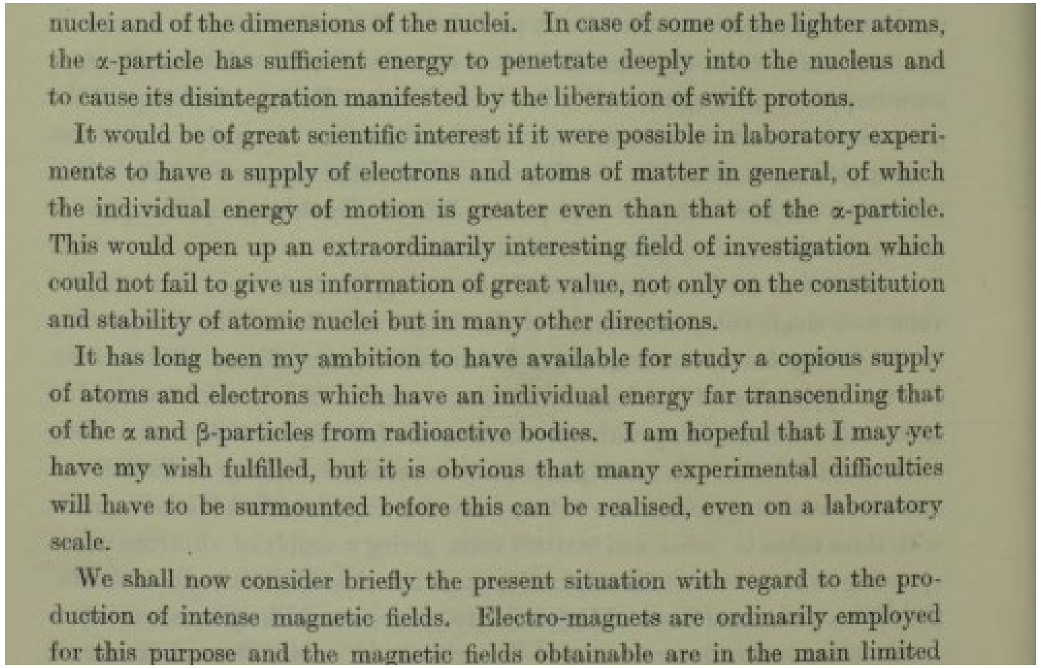
What are the key parameters of merit for HEP accelerators?



Address of the President, Sir Ernest Rutherford, O.M., at the Anniversary Meeting, November 30, 1927.

At this Anniversary Meeting we are naturally conscious of the losses suffered by our Society during the year. These include thirteen of our Fellows and three Foreign Members. We have also to record the loss of one of our Fellows under Statute 12, Edward Cecil Guinness, Earl of Iveagh, elected 1906.

…



nuclei and of the dimensions of the nuclei. In case of some of the lighter atoms, the α-particle has sufficient energy to penetrate deeply into the nucleus and to cause its disintegration manifested by the liberation of swift protons.

It would be of great scientific interest if it were possible in laboratory experiments to have a supply of electrons and atoms of matter in general, of which the individual energy of motion is greater even than that of the α-particle. This would open up an extraordinarily interesting field of investigation which could not fail to give us information of great value, not only on the constitution and stability of atomic nuclei but in many other directions.

It has long been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of the α and β-particles from radioactive bodies. I am hopeful that I may yet have my wish fulfilled, but it is obvious that many experimental difficulties will have to be surmounted before this can be realised, even on a laboratory scale.

We shall now consider briefly the present situation with regard to the production of intense magnetic fields. Electro-magnets are ordinarily employed for this purpose and the magnetic fields obtainable are in the main limited

https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.1928.0001

"It has long been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of the α and β particles" **E.Rutherford 1927**

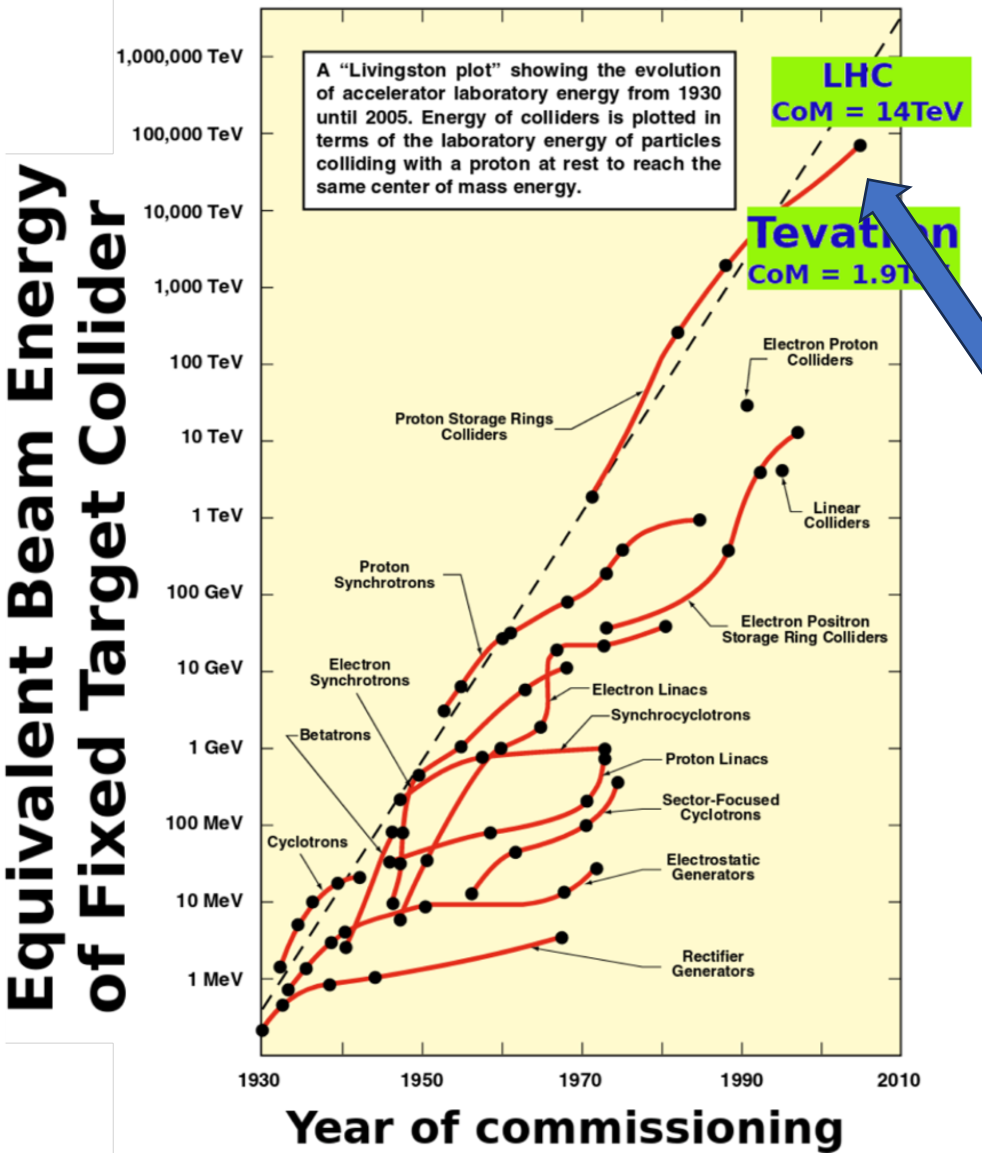
Not much has changed in 100 years:

- **We care about the energy achieved in collisions**
- **We care about the number of collisions generated ("*luminosity*")**

Design of the next generation of particle colliders is a trade off between these parameters, and the cost and viability

Energy

From 2001 Snowmass AQccelerator R&D report,
Part I : Executive Summaries, eConf C010630, SLAC-R-599
http://www.slac.stanford.edu/econf/C010630/papers/MT1001.PDF


A “Livingston plot” showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

Beam-beam collider is essential for operation at energy frontier

Fixed target CoM energy:

$$E_{CM} \approx \sqrt{2 m_t E_b}$$

Collider CoM energy:
(head-on, equal mass)

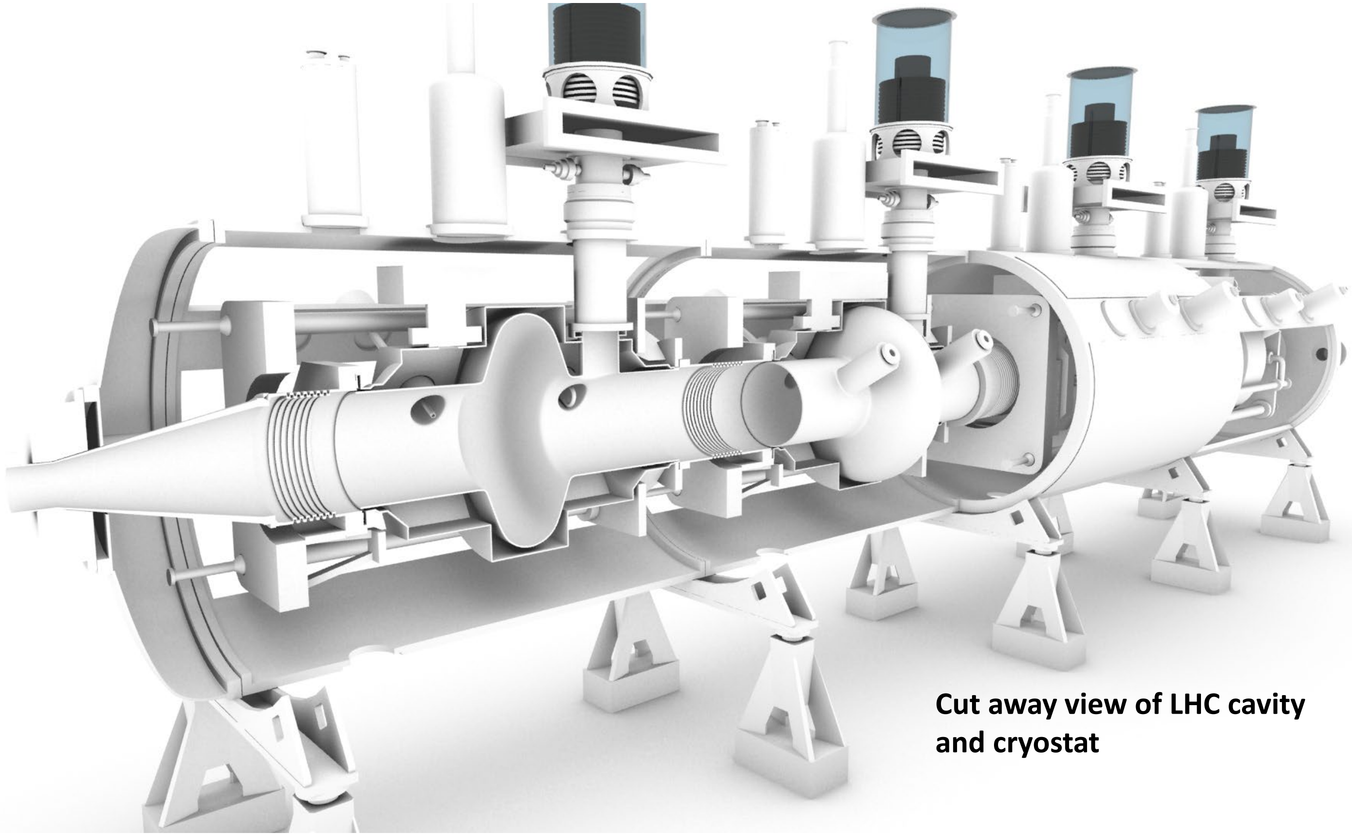
$$E_{CM} = 2E_b$$

To reach LHC c.o.m. collision energy with a fixed target experiment would require beam energy of 100,000 TeV

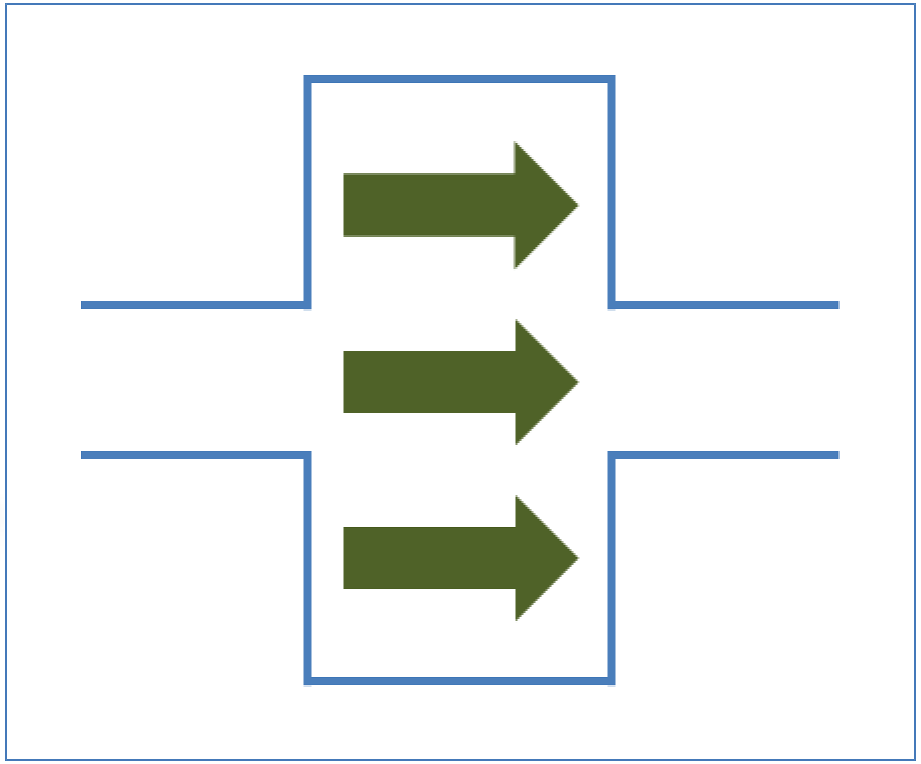
Still, even in a collider, we need to accelerate particles to very high energies.

Conventionally accelerate high-energy particle beams using ***RF cavities***

- **Some sort of conducting waveguide or cavity containing an oscillating EM field**
- **Boundary conditions on the electric field, which force it to periodically point in the correct direction to accelerate**
- **Only certain phases of the RF wave give acceleration: we collide bunches of high-energy particles**



Cut away view of LHC cavity and cryostat



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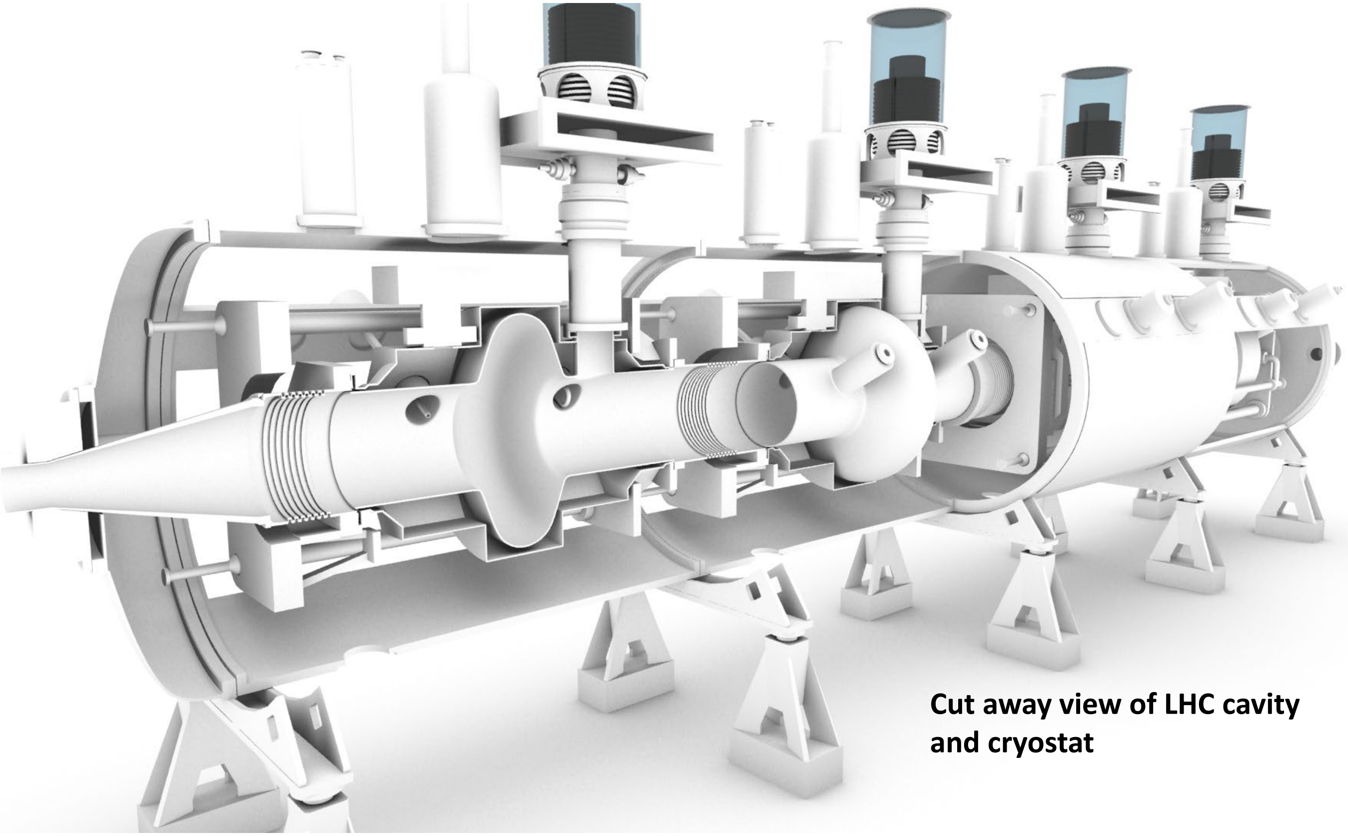

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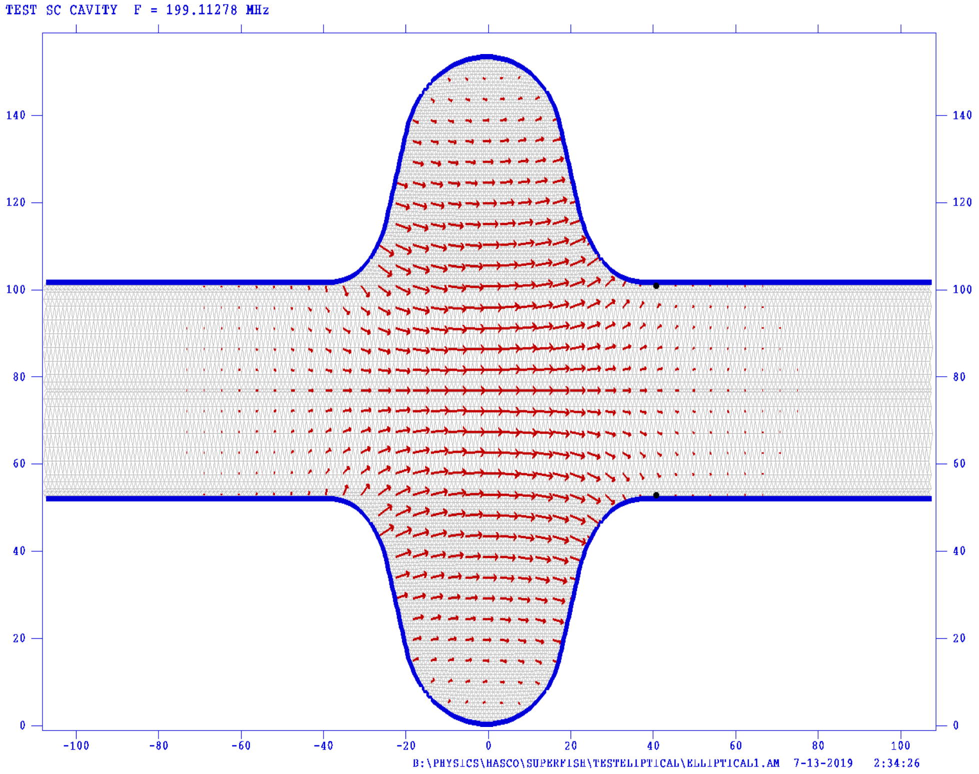
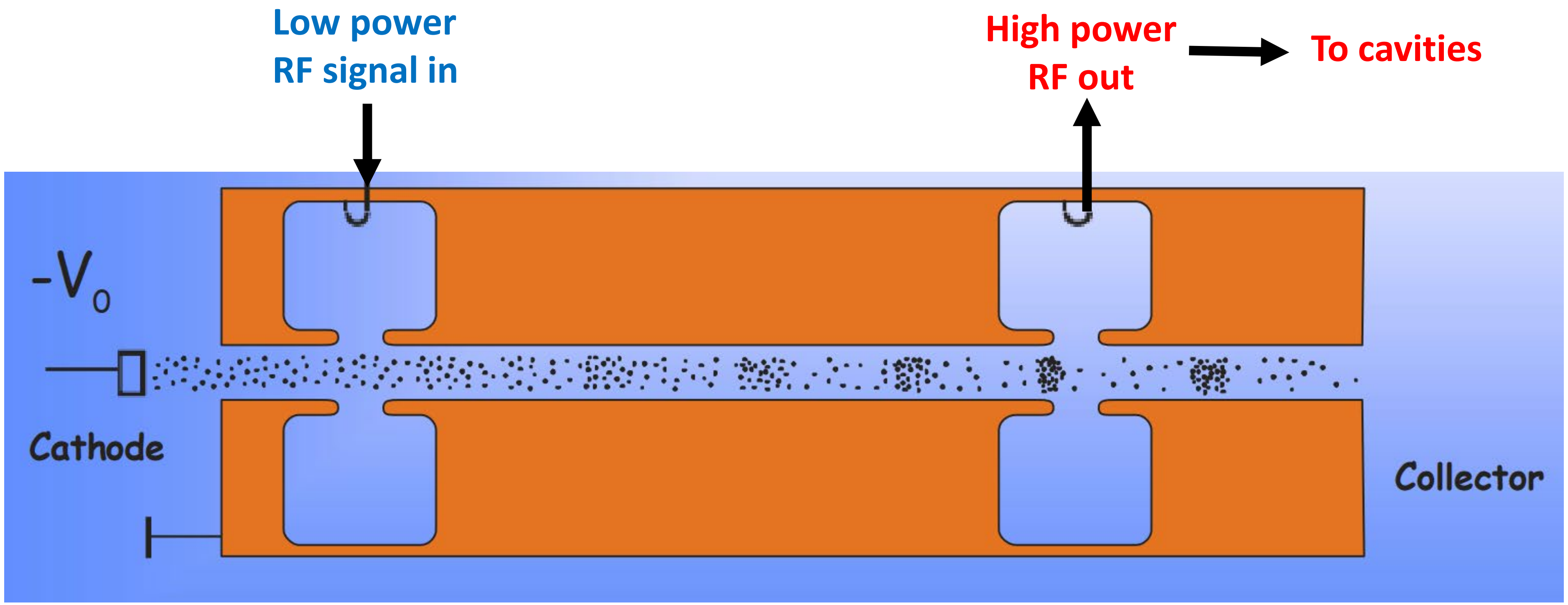


You can't just plug a cavity into the wall → need to generate the high RF power

- RF power at high energy typically generated using ***Klystrons***
- DC stream of electrons modulated by application of low amplitude RF signal
- Causes electrons to bunch up, amplified RF power extracted downstream



Steffen Döbert, CERN Accelerator School RF Power Systems, CLIC Drive Beam
https://cas.web.cern.ch/sites/default/files/lectures/zurich-2018/doebert2.pdf

That’s how we accelerate…

… but what limits the energy reach?

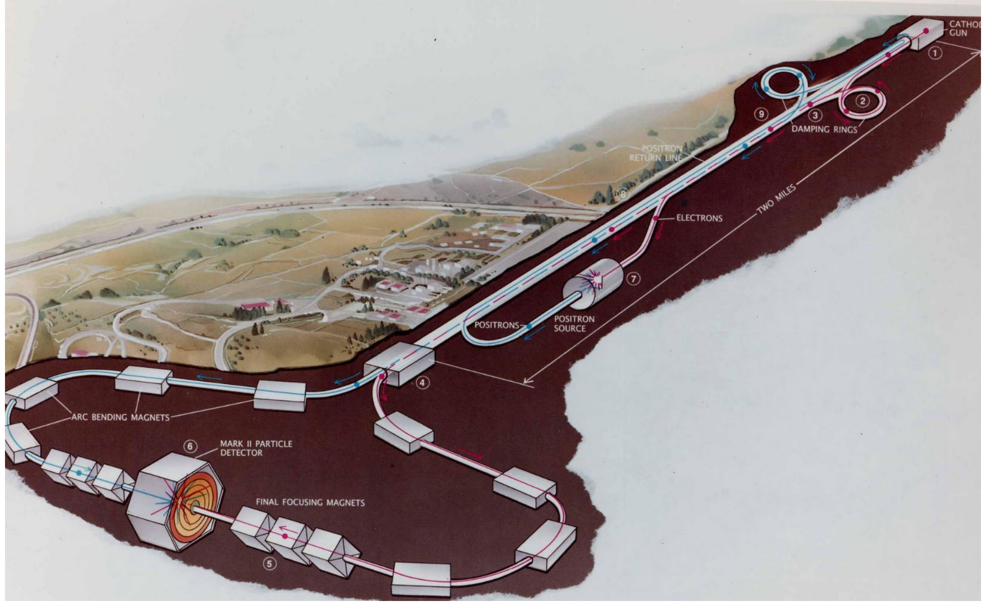
Acceleration generated by the RF cavities need to be sufficient

- **Defined by accelerating gradient of cavities ($\mathrm{MV/m}$) and total length of cavities**
  → Superconducting cavities limited by quench threshold of accelerating field on cavity walls.
  → Normal conducting limited by RF breakdown, can potentially deliver higher gradients

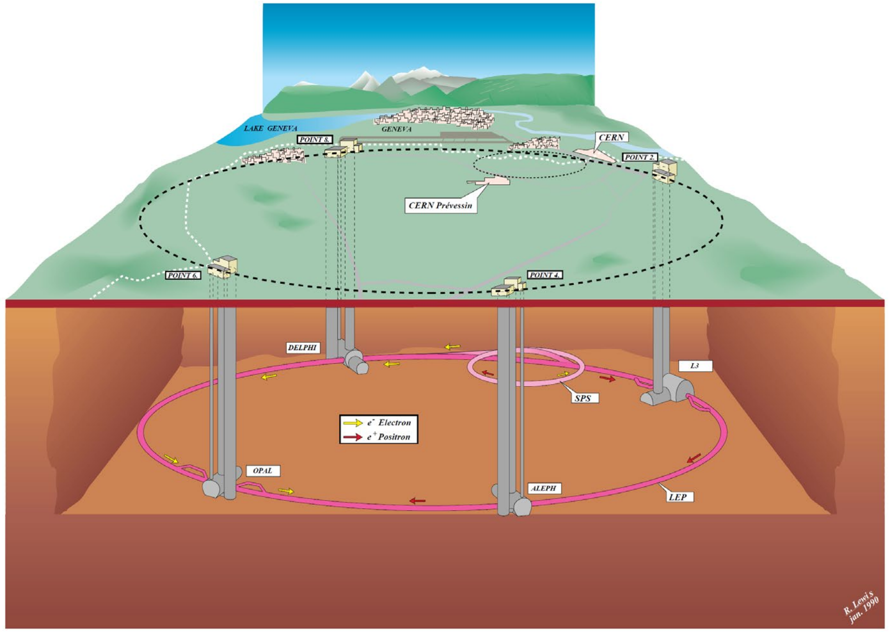
- **Can the klystrons (or other RF source) generate enough power to run the cavities**
  → superconducting cavities less losses
  → potentially more power efficient

Linear accelerator/collider e.g. SLC @ $\approx 90\mathrm{GeV}$
→ A chain of RF cavities + some magnets
→ Needs to accelerate beam in single pass
→ SLC @ $\approx 90\mathrm{GeV}$: about **2.8km** of $\approx \mathbf{21\ MV/m}$ cavities

Synchrotron collider e.g. LEP1 @ $\approx 91\mathrm{GeV}$
→ A ring of magnets + some RF cavities
→ Accelerates gradually over many turns, then maintain beam energy
→ LEP1 @ $\approx 91\mathrm{GeV}$: approximately **270m** of $\approx \mathbf{1.47\ MV/m}$ cavities

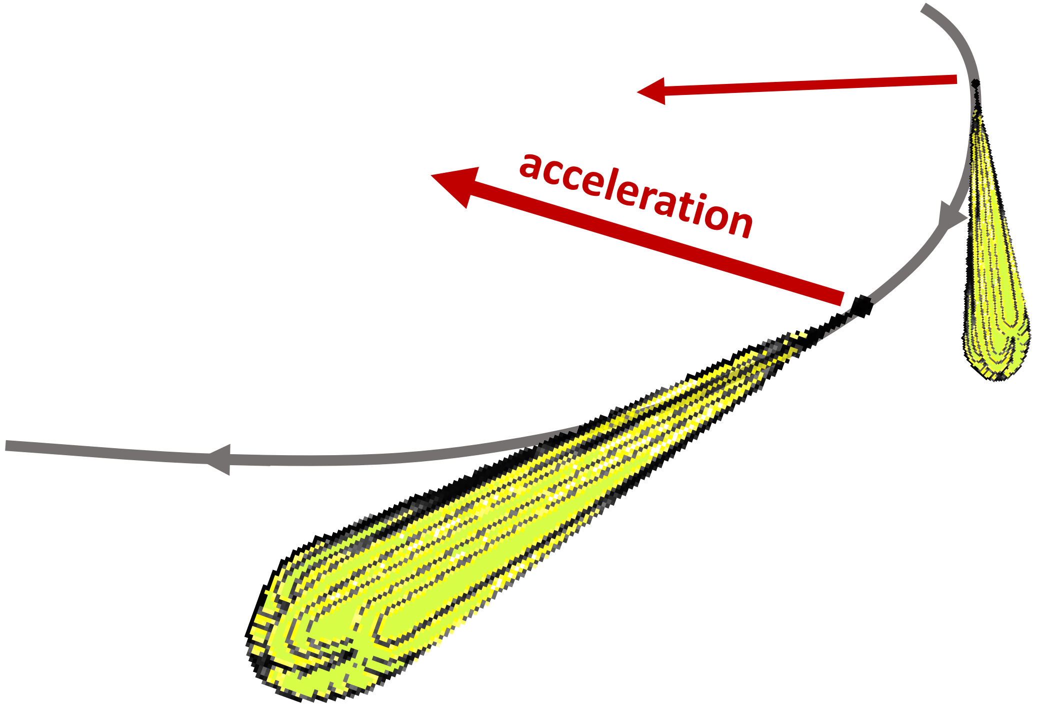


RF phase distribution systems at the SLC
https://www.slac.stanford.edu/pubs/slacpubs/4750/slac-pub-4893.pdf

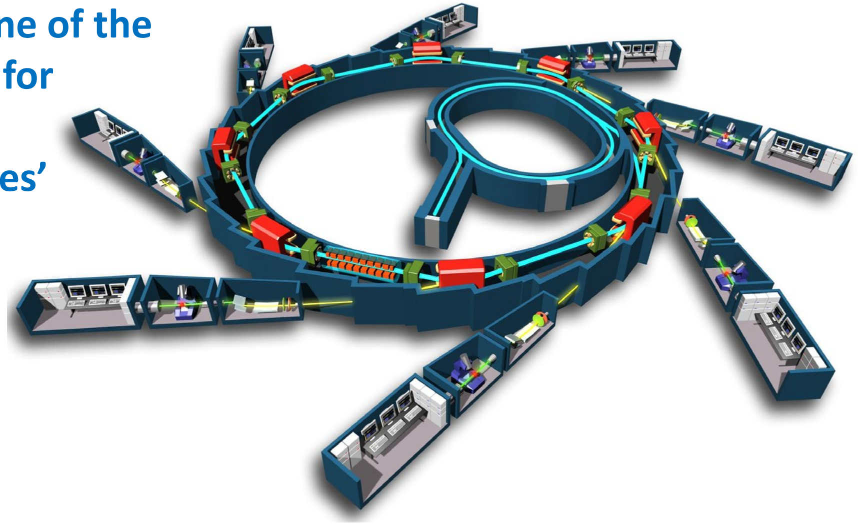


LEP Technical design report:
https://cds.cern.ch/record/102083/files/cm-p00047694.pdf

When particles are deflected around an accelerator ring, they emit synchrotron radiation



Synchrotron light is one of the most important tools for scientific discovery at dedicated `light sources'



For HEP synchrotron radiation is problematic as it carries away a portion of the particles energy

- **This must be restored every turn by the RF cavities**
  → increases the electrical power consumption of the accelerator

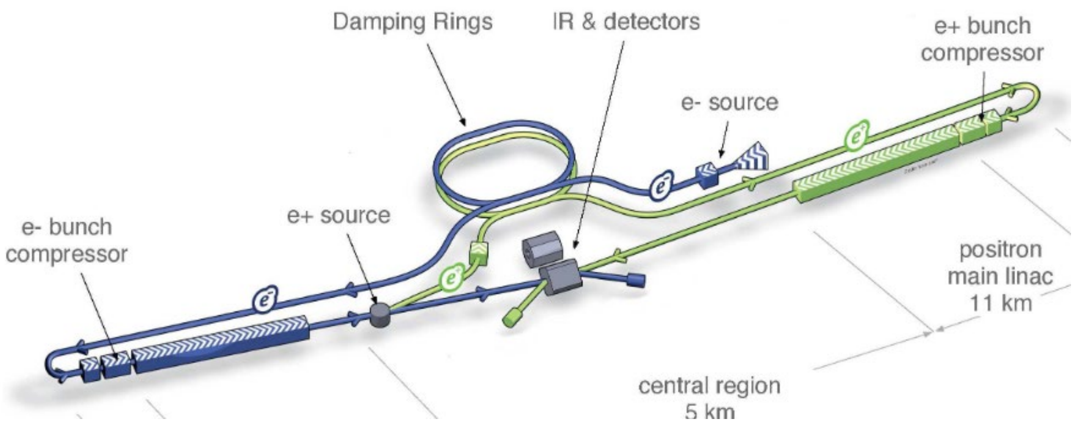
$$\boxed{\Delta E/\mathrm{turn} \propto \frac{(\beta_{rel}\gamma_{rel})^4}{\rho}}$$

$$\Delta E/\text{turn} \propto \frac{(\beta_{rel}\gamma_{rel})^4}{\rho}$$

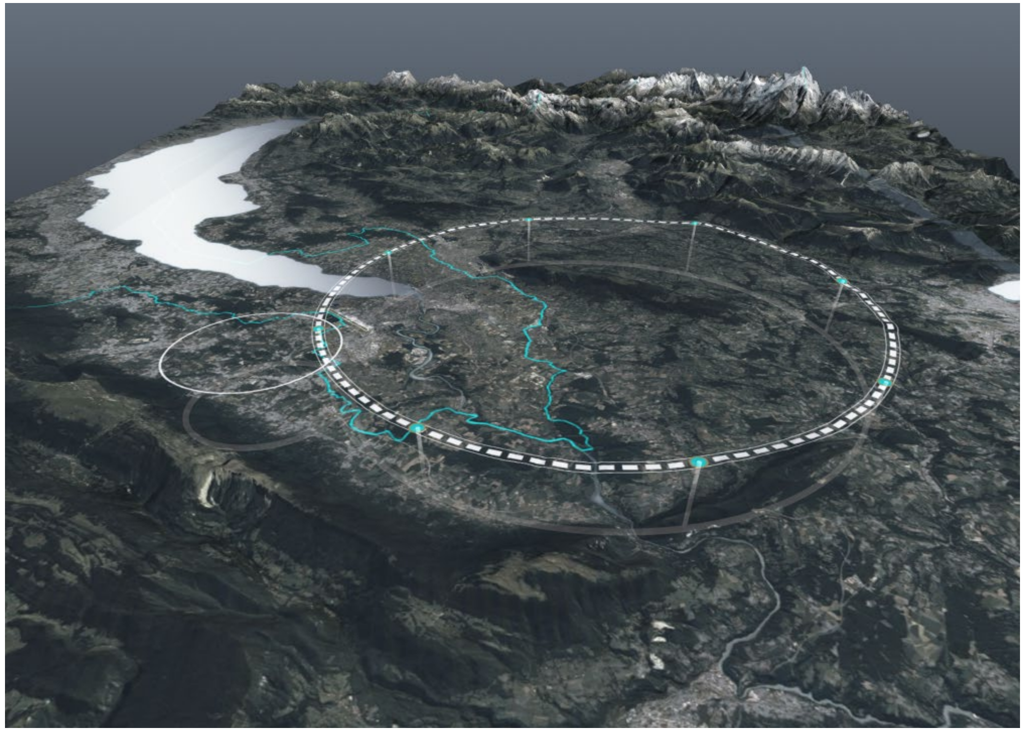
Collide more massive particles

- **LEP** (e) **energy loss:** $\sim 3\,\mathrm{GeV/turn}$ (@ $101\,\mathrm{GeV}$)
- **LHC** (p) **energy loss:** $\sim 5\,\mathrm{keV/turn}$ (@ $6.5\,\mathrm{TeV}$)

linear collider

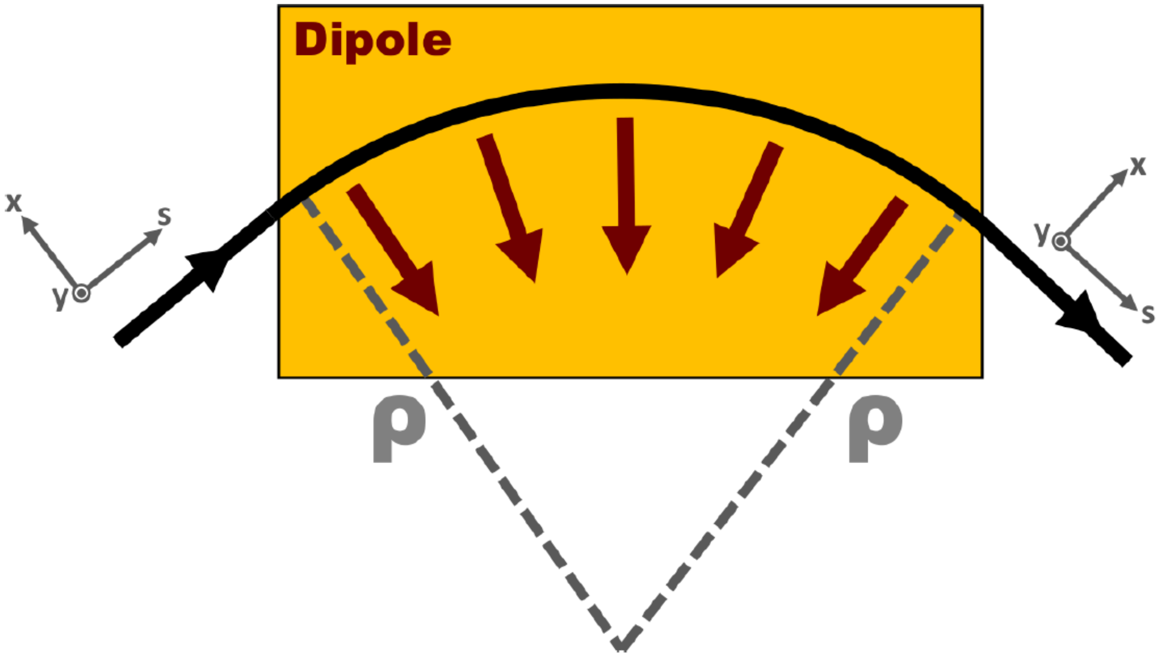


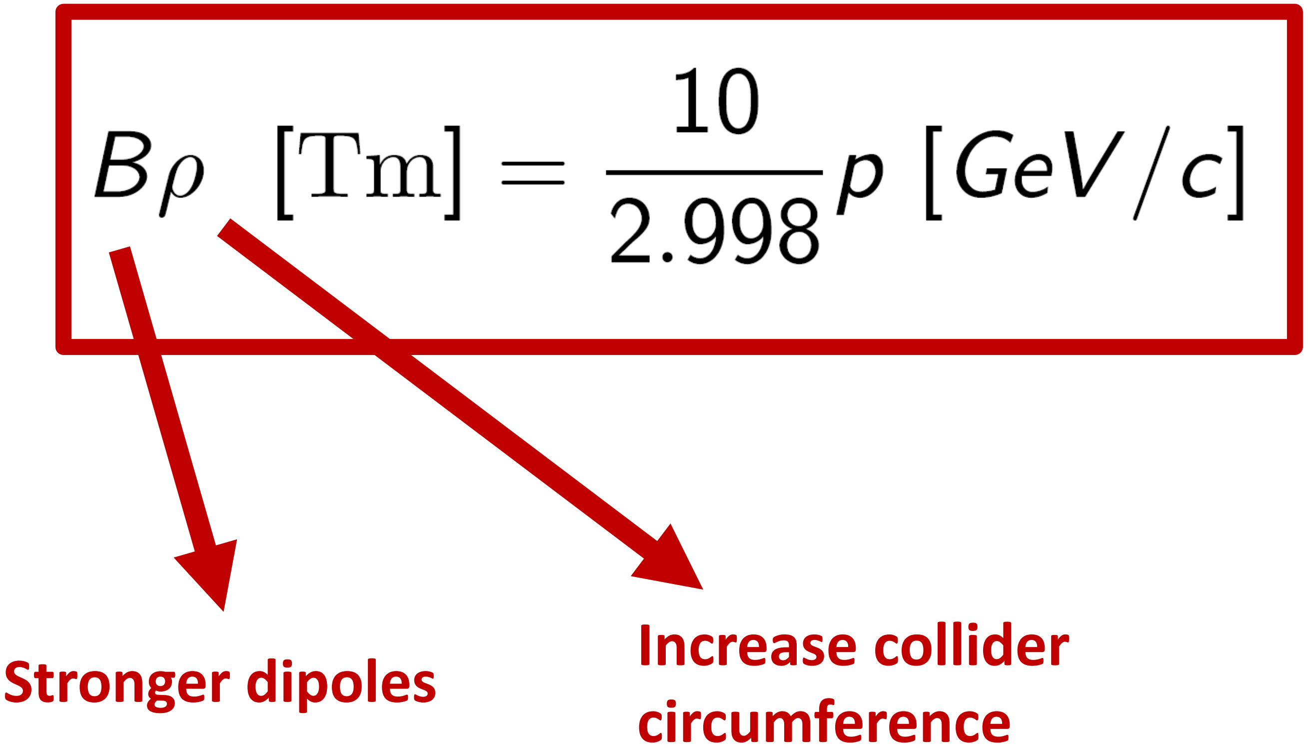
Increase collider circumference



Need strong enough magnetic fields to guide high energy beams around the ring

- **Magnetic Rigiditiy** (Bρ) defined the highest energy that can be reached in a synchrotron for a given tunnel geometry and dipole strength





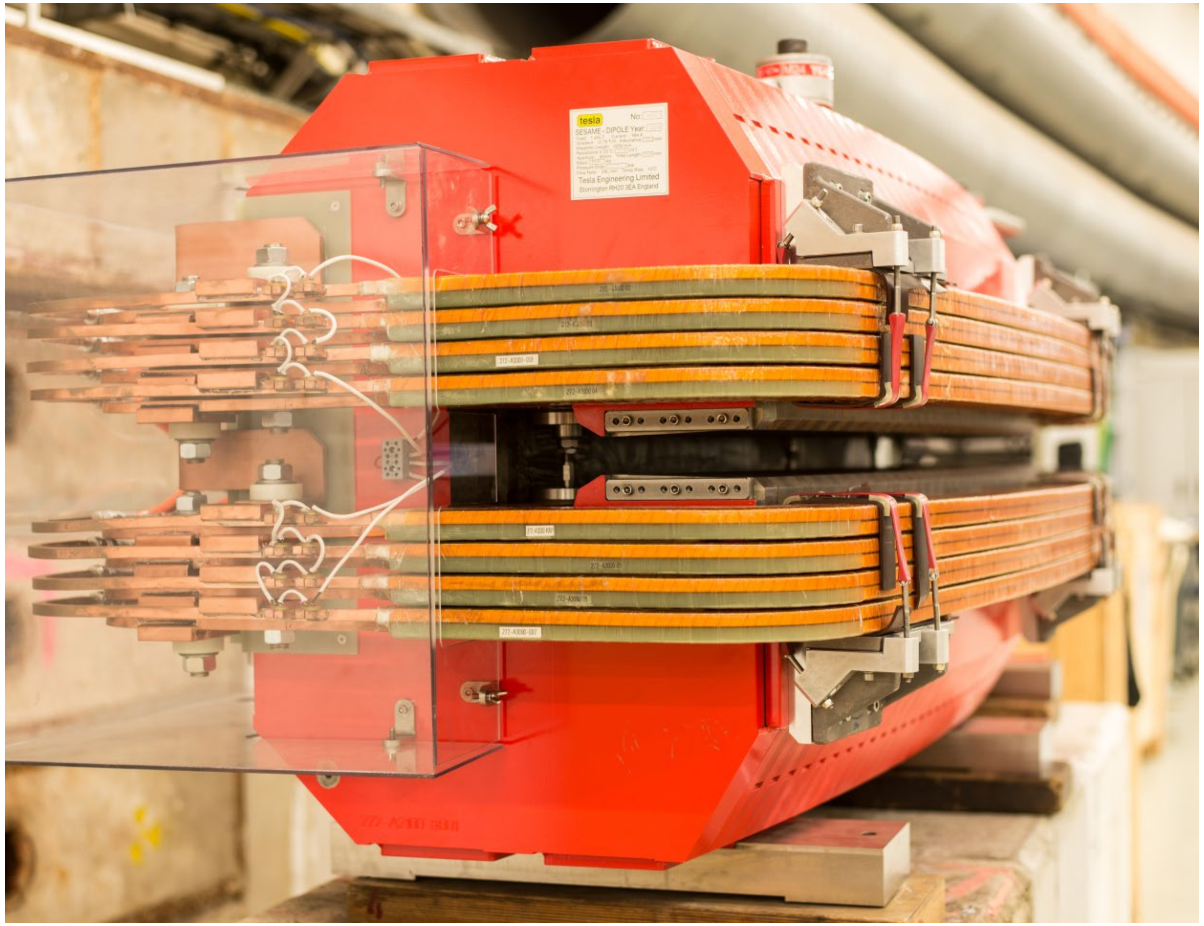
$$B\rho \ \ [\mathrm{Tm}] = \frac{10}{2.998} p \ [GeV/c]$$

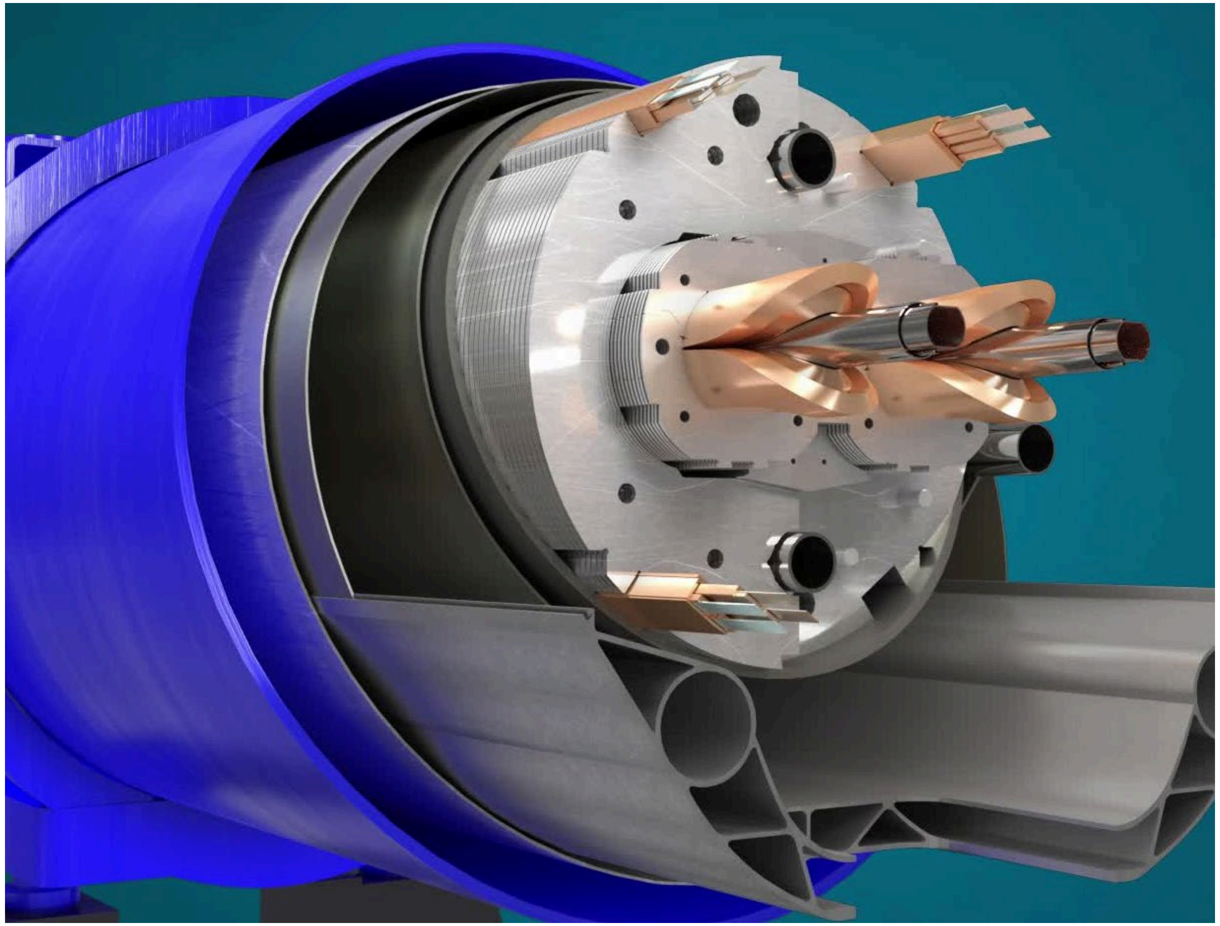
Stronger dipoles

Increase collider circumference

Conventional dipoles limited to ≈2T by saturation of iron core

For higher fields/energy (e.g. LHC = 8T) use cryogenic superconducting magnets





Significant challenges associated with running a high energy, high-field, cryogenic accelerator

- electrical power consumption from cryogenics
  → LEP RF system 16 MW → LHC cryogenic system 100 MW
- Machine Protection. Accelerator needs to be protected from beam- and system- induced quenches

Top Right: LHC 2008 quench incident. Magnet anchors ripped out of concrete floor

Bottom Right: LHC 2008 quench incident. Dipole bus bar evaporated

Bottom Left: Damage to copper target from impact of LHC bunch train at 450GeV during dedicated tests in SPS.

What about energy stability?

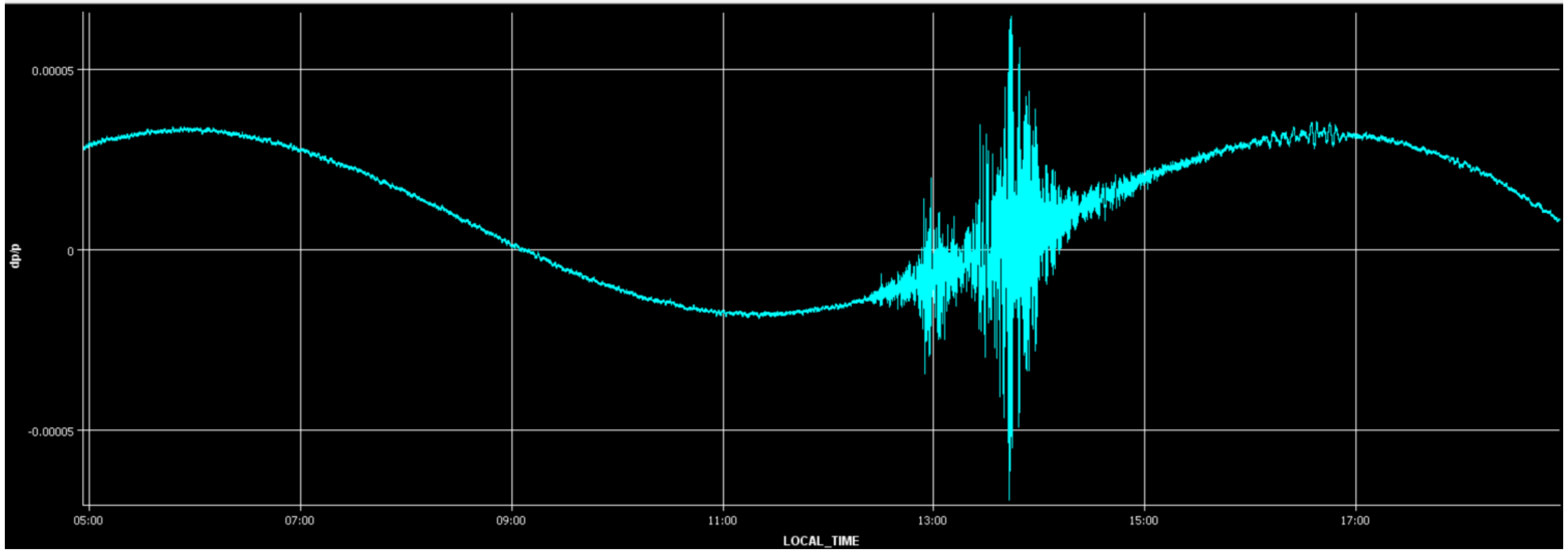
- Hadron accelerators collide composite particles → large spread in energy of individual events
  → not too worried about precise knowledge of <u>absolute</u> beam energy (and in any case very challenging to determine)

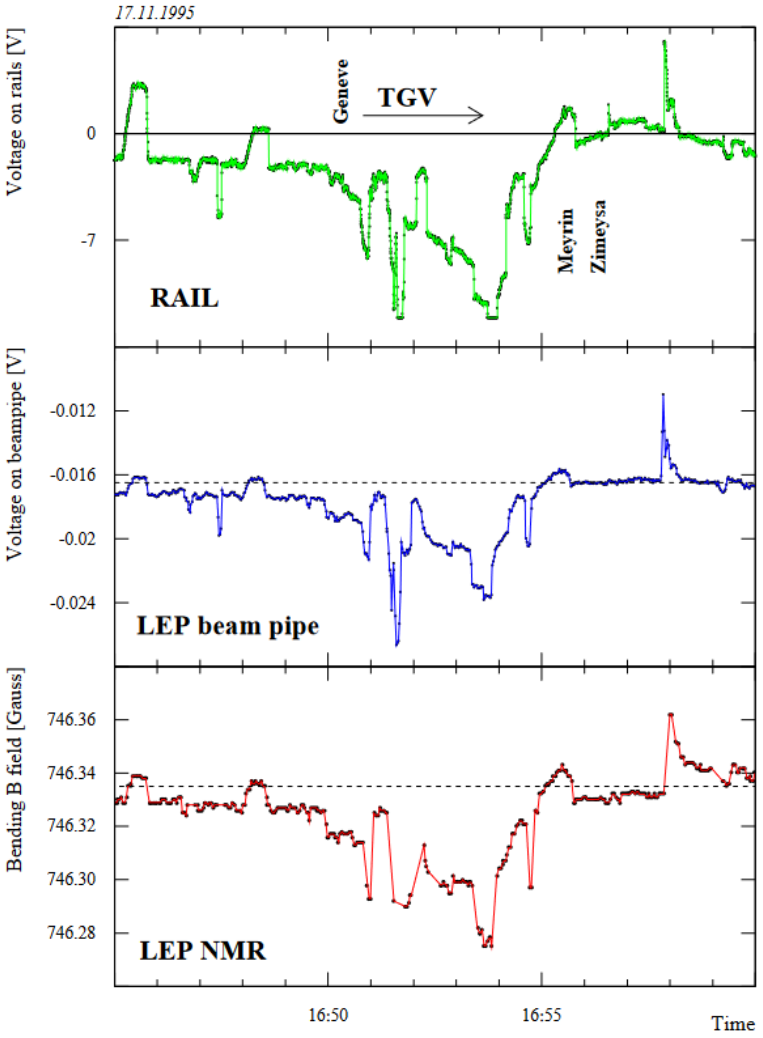
- Lepton accelerators collide fundamental particles → possibility to scan colliding beam energy around particular resonance
  → care about knowledge and control of absolute beam energy in lepton machines

- At LEP beam energy was famously influenced by the moon and passing trains going to Geneva station!

Effects of terrestrial tides on the LEP beam energy
https://www.sciencedirect.com/science/article/pii/0168900294015260

A newly observed effect affects the LEP beam energy
https://cds.cern.ch/record/309231/files/sl-96-036.pdf





Measurement of absolute energy

→ **Relative changes in beam-energy relatively simple to monitor**

→ **Measurement of absolute beam-energy more challenging, but key for precision lepton machines**

→ **Various techniques** *Measurements of beam energy,* A.S. Müller, CERN Accelerator School https://cds.cern.ch/record/1213285/files/p427.pdf

Estimate momentum from magnetic model (need to include **all** fields and magnetic sources: not just the bending dipoles)

$$P = \frac{Ze}{2\pi}\oint B(s)ds$$

$\approx 1\%$

Used for e.g. LHC

Large Hadron Collider momentum calibration and accuracy, E.Todesco and J.Wenninger https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.20.081003

Compare revolution frequencies (via RF frequency) for different mass particles in same ring

$$p \approx m_p c \sqrt{\frac{f_{\mathrm{RF},p}}{2\Delta f_{\mathrm{RF}}}\left[\left(\frac{m_i}{Z m_p}\right)^2 - 1\right]}$$

Used at SPS, LEP1, LHC

$\approx 10^{-4}$

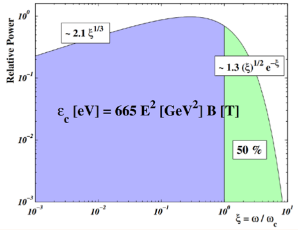
Magnetic spectrometer → measure deflection of beam though precisely known dipole field

$$\theta \propto \frac{1}{p_0}\int B ds$$

Used at SLC, LEP2

$\approx 10^{-4}$

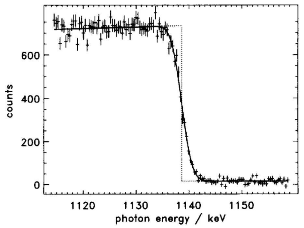
Synchrotron radiation spectrum depends on energy



Used at e.g. BESSY

$\approx 10^{-3}$

Compton backscattering: scattered photons show strong cuttoff depending on beam energy



$$\epsilon_2^{\max} \approx \epsilon_1\, 4\gamma^2$$

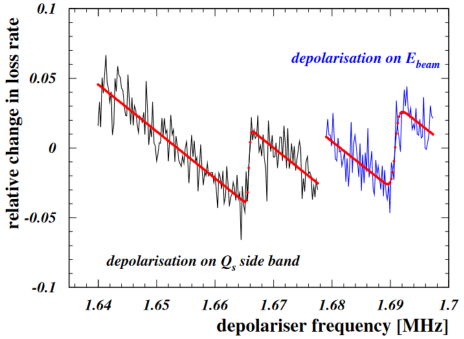
Used at e.g. BESSY

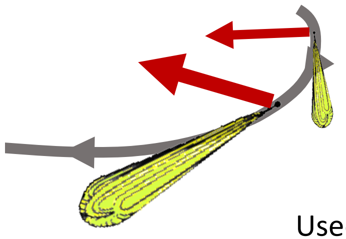
$\approx 10^{-4}$

Resonant depolarization

→ **historically this is highest precision measurement of absolute beam energy**

- SR emission has chance to flip particle spin → Probability favours orientation with dipole field
- Beams with high SR (circular e^+e^-) become transversely polarized over time
- Spin oscillation per revolution in accelerator Qspin depends on beam energy $Q_{spin} = (g_e - 2)/2 \times \gamma_{rel}$
- By exciting beam at the spin tune destroy the polarization.
- Measure properties dependent on beam polarization – e.g. Touschek lifetime while varying excitation frequency





So far, best precision of absolute beam energy possible in e^+e^- synchrotrons

Used at LEP, ANKA, KARA ...

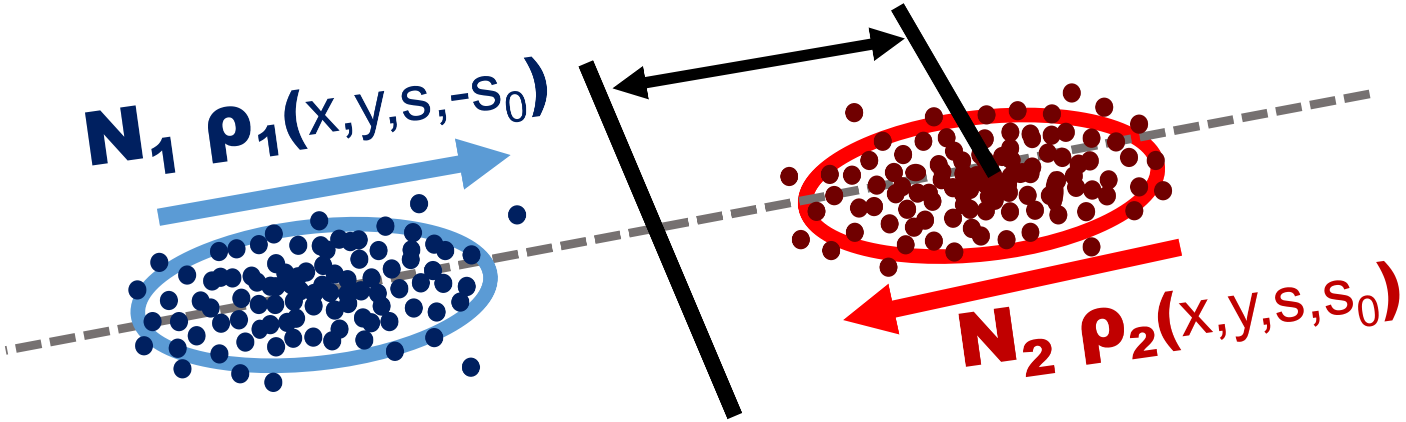
$\approx 10^{-5} - 10^{-6}$

Significant R&D underway to improve energy measurement techniques for next generation of colliders

Luminosity

$$\mathbf{R} = \mathbf{L} \times \boldsymbol{\sigma}$$

- **R:** *Event Rate* $[\mathbf{s}^{-1}]$
- $\boldsymbol{\sigma}$**:** *Cross Section* $[\mathbf{barn} = \mathbf{10^{-24}cm^2}]$
  property of the HEP interaction
- **L:** *Luminosity* **[inverse barn / s]**
  property of the collider



$$\mathbf{L} = f\sqrt{(\bar{v}_1-\bar{v}_2)^2-(\bar{v}_1\times\bar{v}_2)^2\ /\ c^2}\ N_1 N_2 \iiiint_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\rho_2(x,y,s,s_0)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}s\,\mathrm{d}s_0$$

Can approximate luminosity as (head-on collissions of uncorrelated Gaussian profiles, same profile in each bunch)

Number of colliding bunches

Number of particles in the colliding bunches

Repitition frequency
(e.g. revolution freq in circular collider)

$$L = \frac{f\, n_b\, N_1 N_2}{4\pi\, \sigma_x\, \sigma_y}$$

Bunch size

W.Herr, Concept of luminosity
https://cds.cern.ch/record/941318/

T.Suzuki, GENERAL FORMULAE OF LUMINOSITY FOR VARIOUS TYPES OF COLLIDING BEAM MACHINES
https://inspirehep.net/files/56200f5110f34e07afe6e25af9f95528

M.A.Furman,The Møller Luminosity Factor
https://escholarship.org/uc/item/3897k3zp

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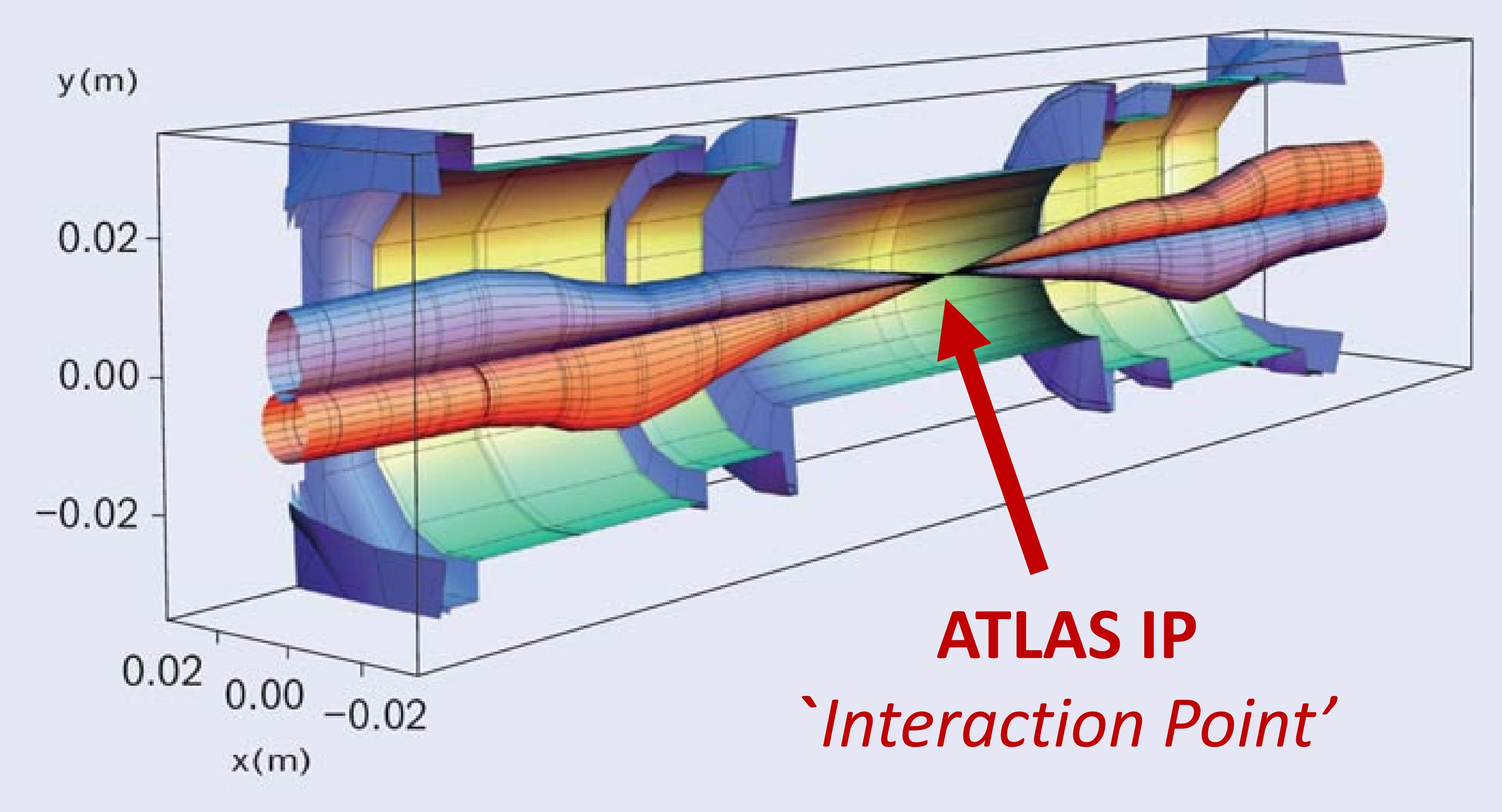
$$L = \frac{f\, n_b N_1 N_2}{4\pi \boxed{\sigma_x \sigma_y}}$$

To produce high luminosity squeeze beams at the interaction points down to a small size with quadrupole magnets

LHC beam sizes at collision:

$$\sigma = \mathbf{10\mu m - 20\mu m}$$



ATLAS IP

`Interaction Point'

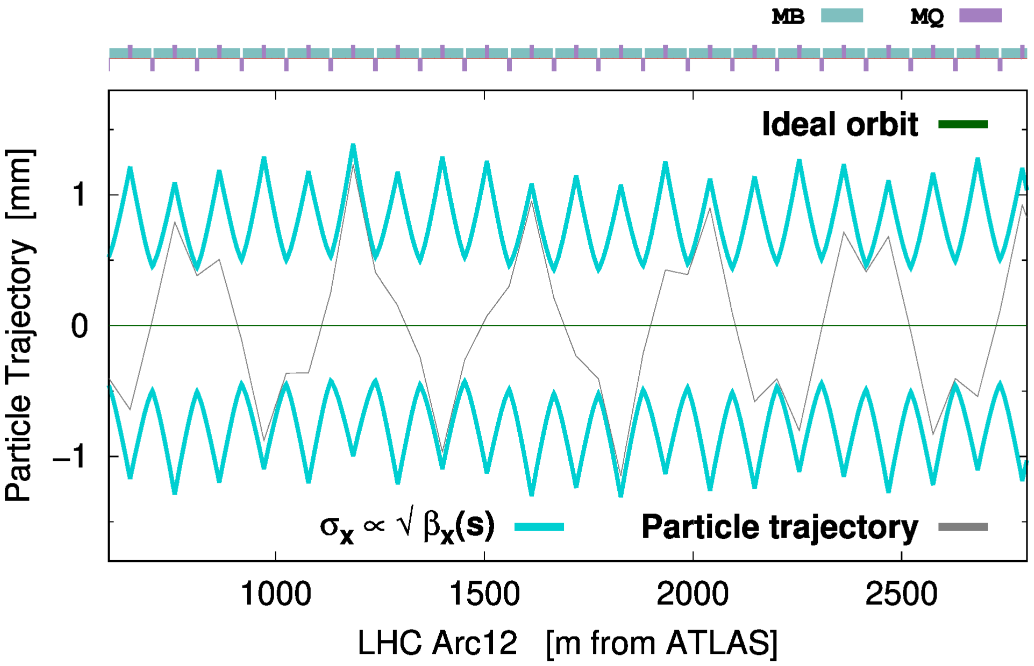
$$\sigma_{x,y} = \sqrt{\beta_{x,y}(s)\ \epsilon_{x,y}}$$

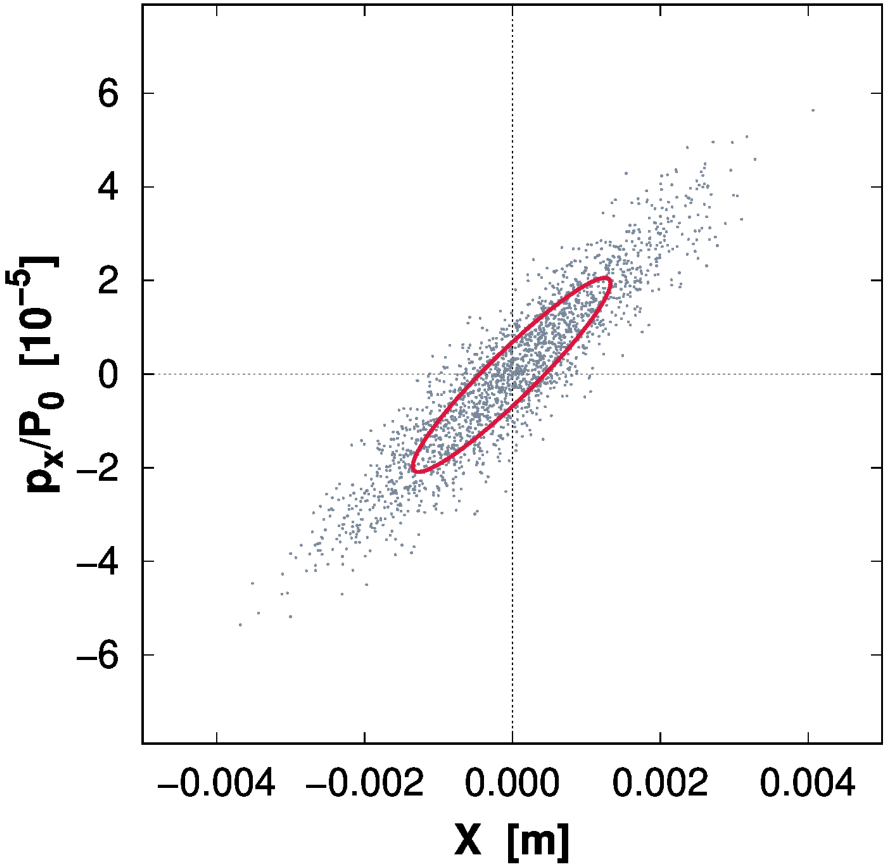
“emittance” : *measure of beam quality*

- emittance defines the volume of beam in phase space
- essentially the spread in transverse or longitudinal position and momentum of particles
- Invariant around the accelerator ring (at constant energy)

“*β-function*” : property of the accelerator

- Particles in the beam follow slightly different trajectories
- β(s) defines transverse envelope within which particles oscillate
- Defined by focusing quadrupole magnets in the accelerator

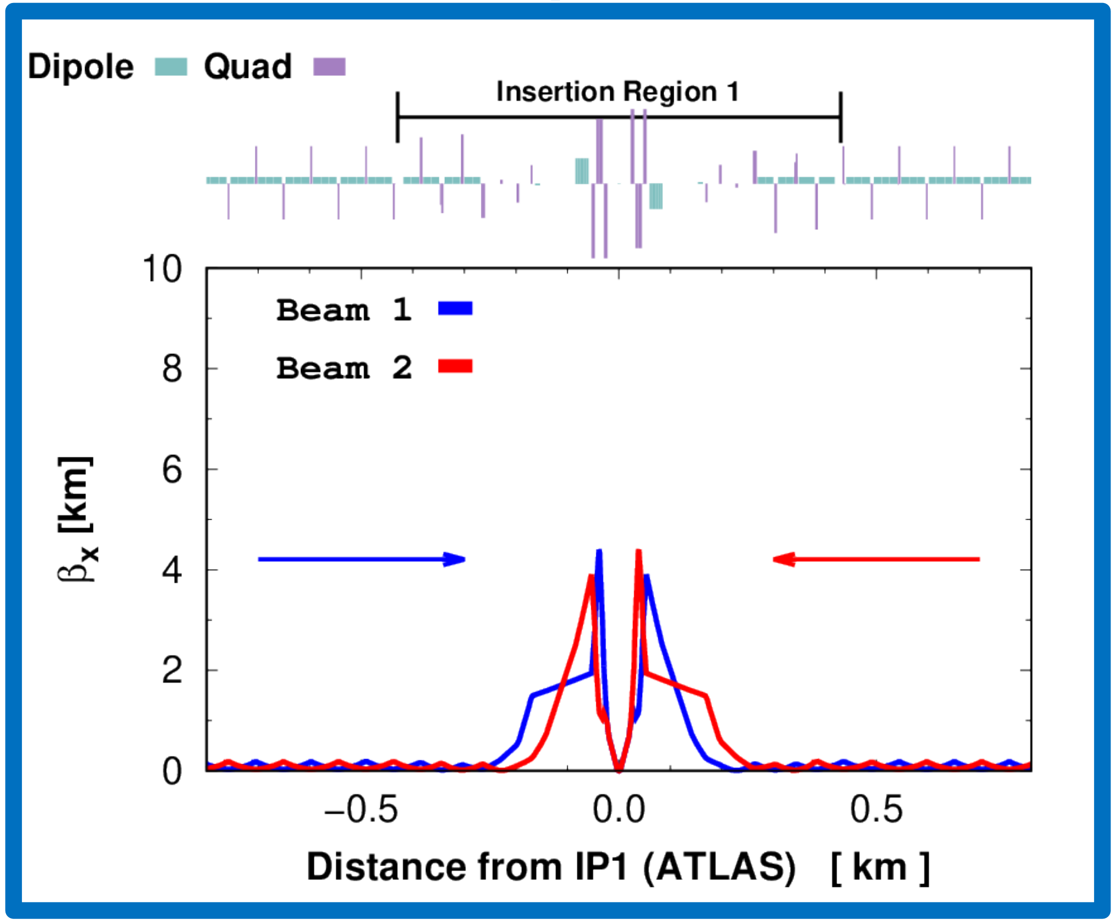




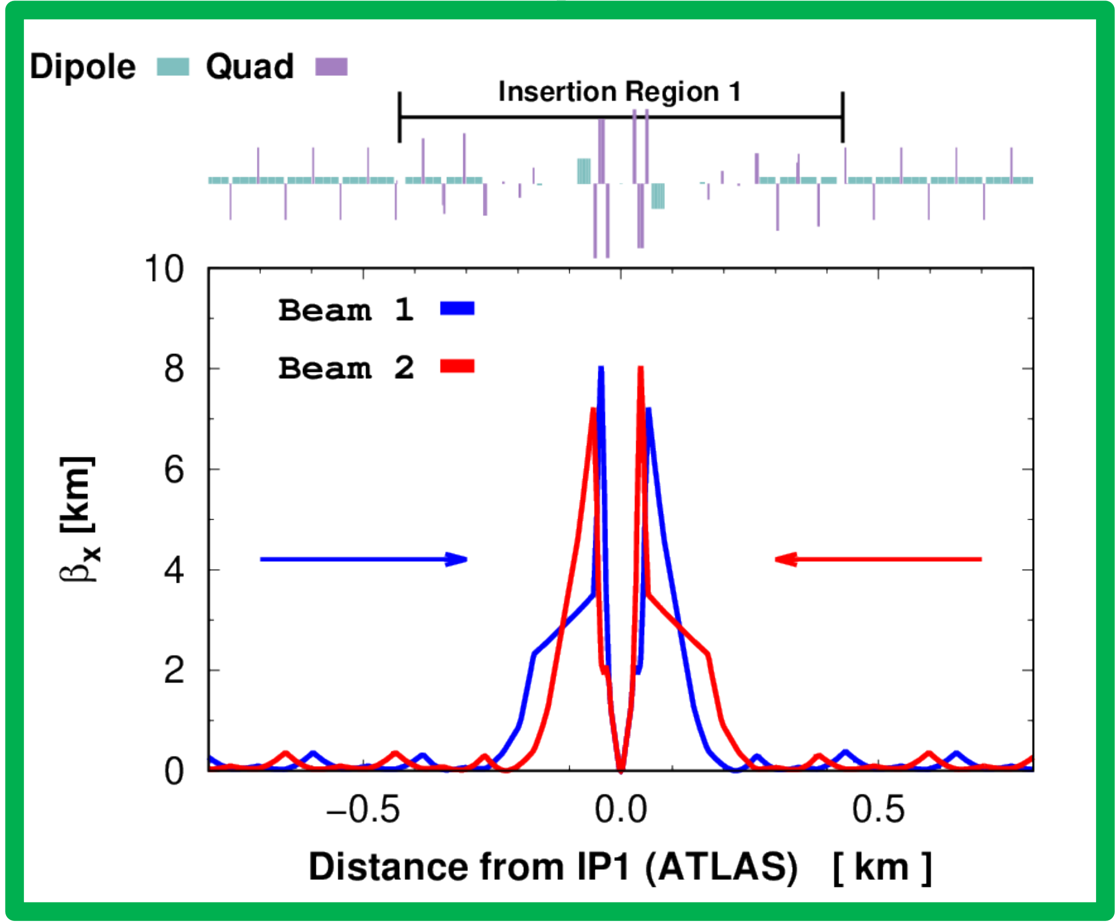
More precisely: strong quadrupole magnets focus the β-function down to a small value at IP

- **Increase luminosity by reducing β-function at experiments – requires large aperture either side of the IP**

LHC design $\beta^* = 55\text{cm}$

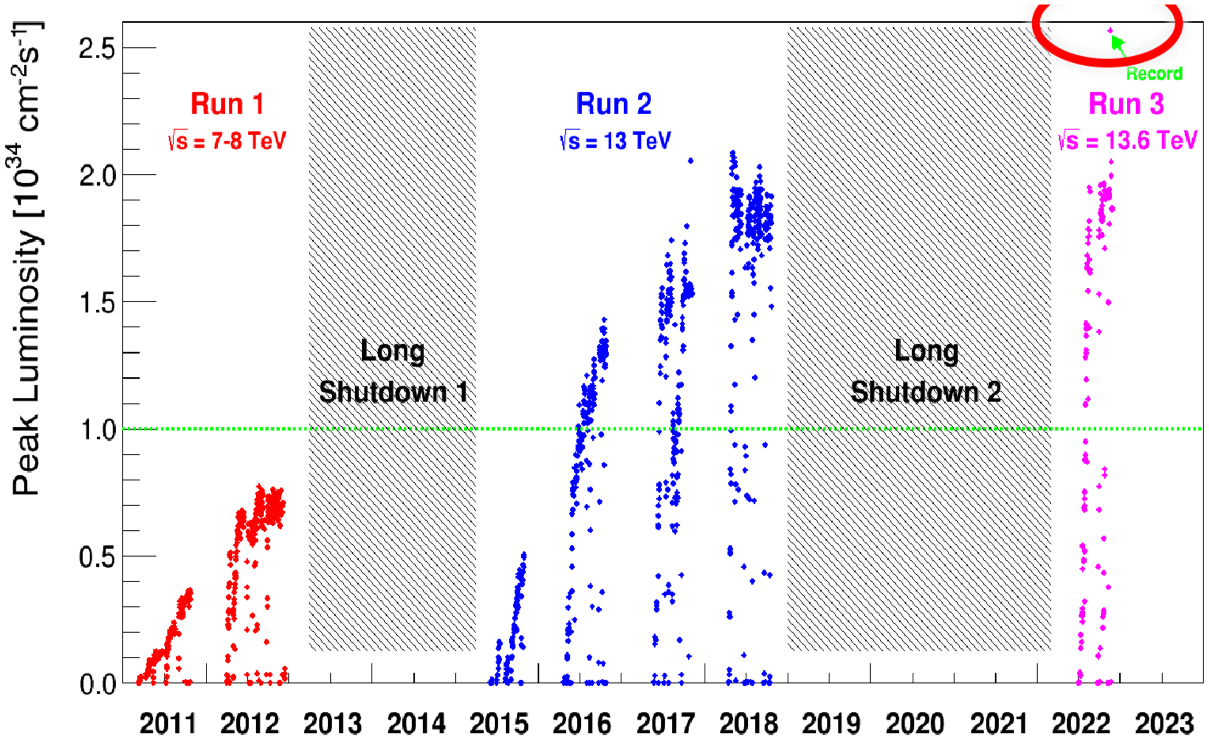


LHC in 2023 $\beta^* \geq 30\text{cm}$



More precisely: strong quadrupole magnets focus the β-function down to a small value at IP

- **Reduction in β at the experiments has been one of the main contributions to increase in LHC luminosity over time**
- **Further reduction is a key component of High-Luminoisity upgrade of the LHC**



Matteo Solfaroli Camillocci, Chaominx workshop 2023

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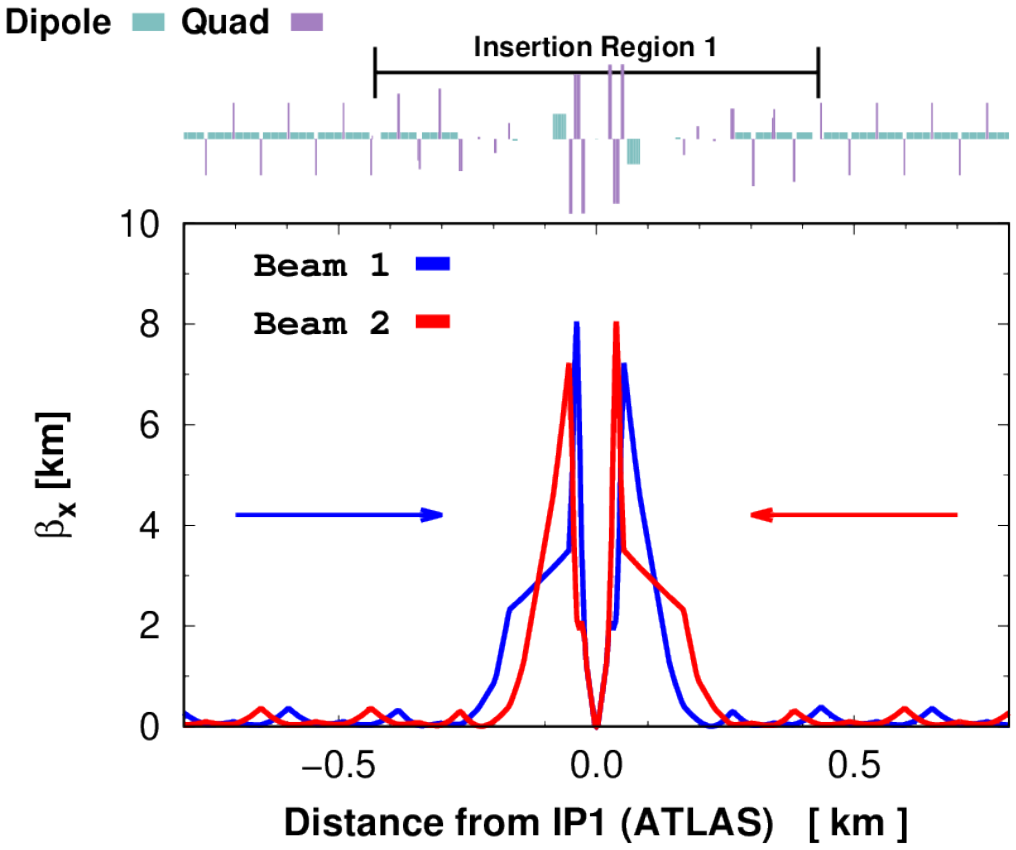
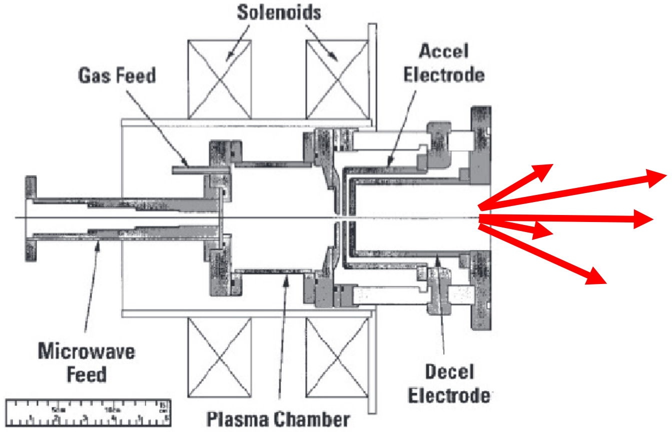
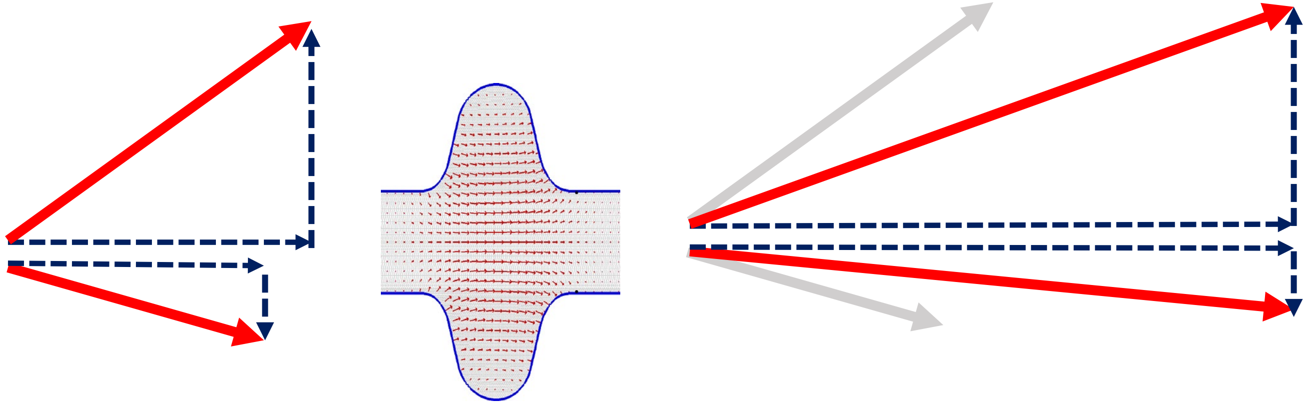


Emittance considerations very different between e^+e^- and heavy particles

- Particles created from source with spread in trajectories and momenta



- Since RF cavities increase momentum only longitudinally, angular divergence of particle trajectories decreases as beams are accelerated



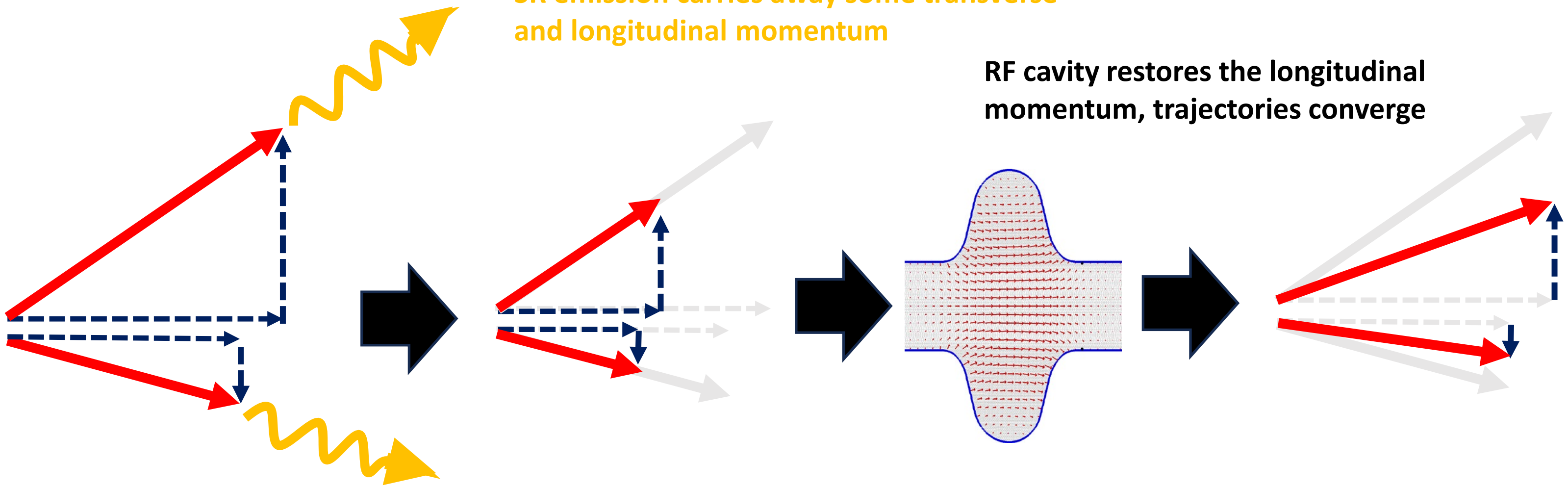
Beam emittance decreases with acceleration `adiabatic damping'

- May refer to `normalized emittance'
- Normalized emittance is constant with energy

$$\varepsilon^* = \varepsilon\, \beta_{rel}\gamma_{rel}$$

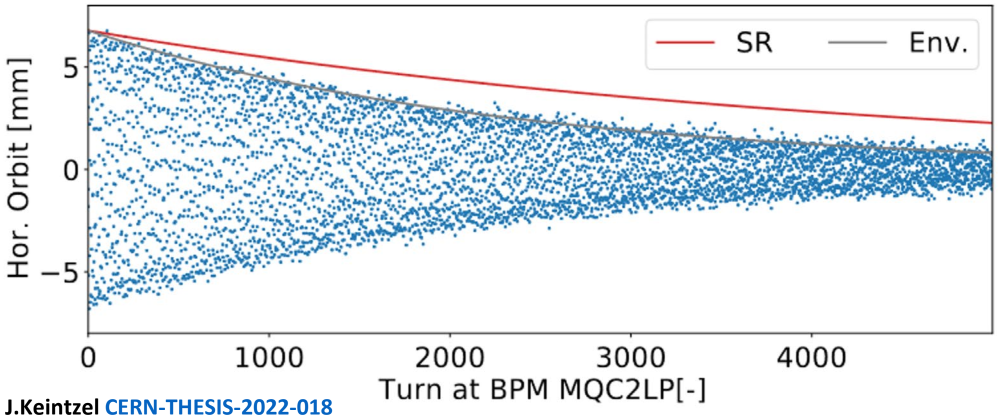
Emittance considerations very different between e^+e^- and heavy particles

- For heavy particles like protons, emittance is defined by source quality + degradation through the accelerator chain
- For electrons + positrons synchrotron radiation helps damp the emittance



SR emission carries away some transverse and longitudinal momentum

RF cavity restores the longitudinal momentum, trajectories converge

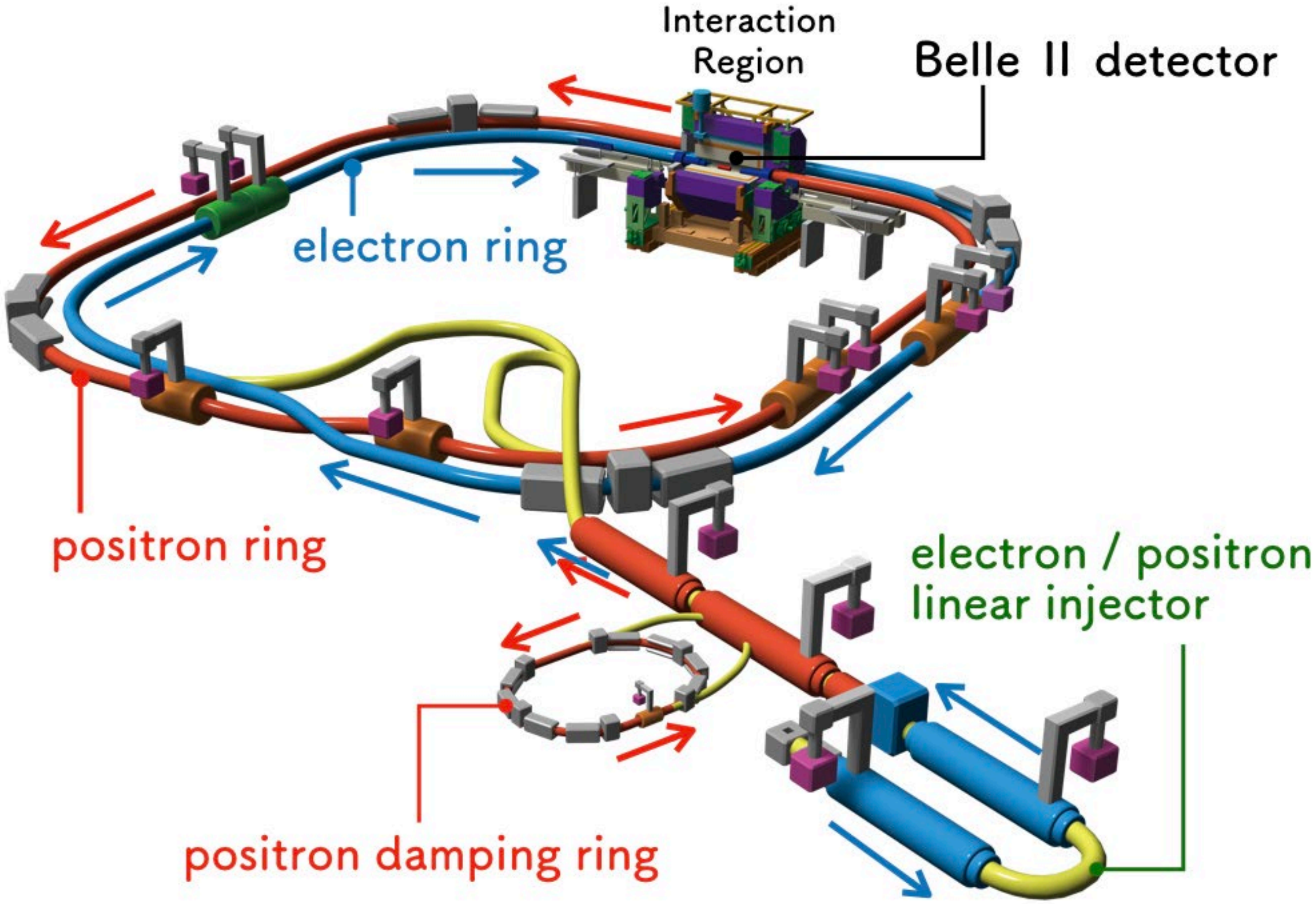


J.Keintzel CERN-THESIS-2022-018

- In high energy e^+e^- machines get synchrotron radiation damping towards (typically very small) equilibrium value, determined by balance between radiation damping rate and particle oscillations excited by quantum emission of the SR-photons

Highest luminosities ever achieved are with e^+e^- colliders!

e.g. Super-KEKB



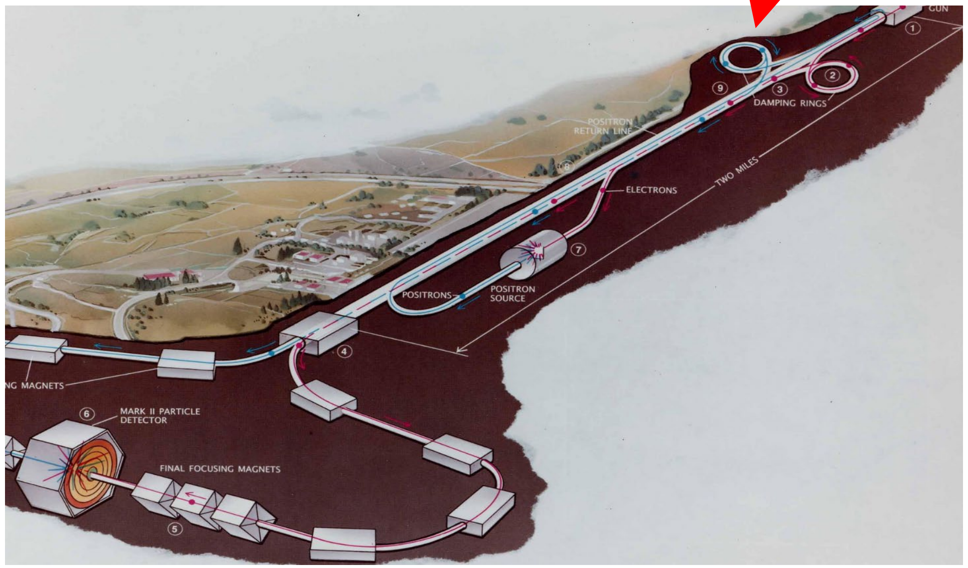
LHC record luminosity: $2.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

→ $\sigma_{x,y} \approx 10\mu\mathrm{m}, 10\mu\mathrm{m}$

SuperKEKB record luminosity: $4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

→ $\sigma_{x,y} \approx 10\mu\mathrm{m}, 0.8\mu\mathrm{m}$ (both ε and β contribute to smaller beam size)

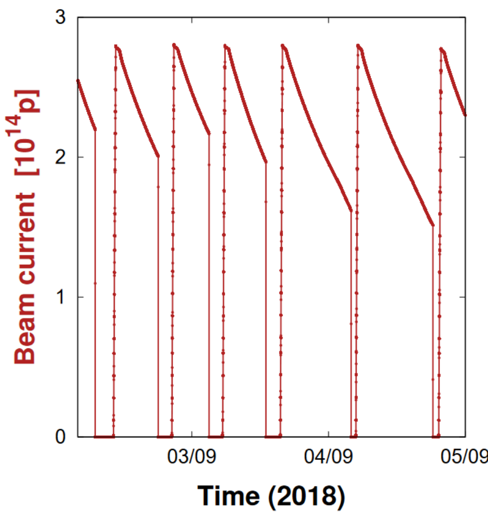
Even linear collider like SLC include damping rings to make use of SR



$$L = \frac{f\, n_b\, N_1 N_2}{4\pi\, \sigma_x\, \sigma_y}$$

Burn-off

- → Synchrotron lumi decays as particles lost via collisions
- → useful losses!
- → Can be compensated in synchrotron by lumi-levelling
- → In linear collider get fresh bunch every time

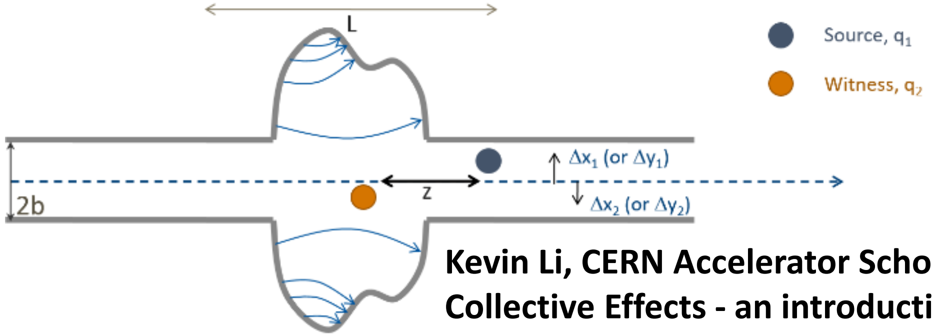


Particles need to survive acceleration & storage

→ Lots of effects in beam-dynamics can limit bunch intensity & survival

Collective effects

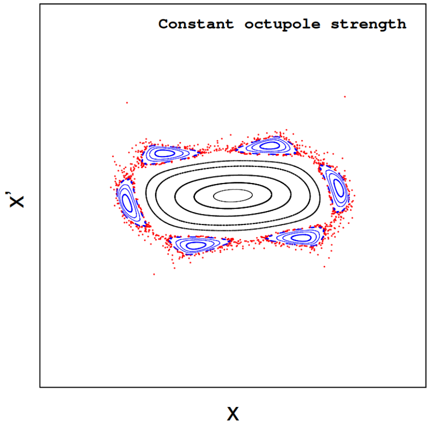
- → Perturbations driven by the beams themselves, scale with beam intensity
- → EM interaction of intense beams at the collision points can perturb each other
- → EM interaction of beam with surroundings, *wakefield effects*
- → EM interaction within bunches: *space charge effects*

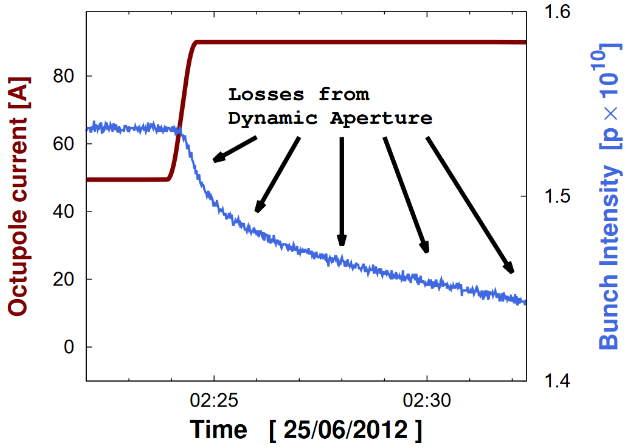


Kevin Li, CERN Accelerator School
Collective Effects - an introduction
https://arxiv.org/pdf/2107.06109.pdf

Dynamic aperture

- → Nonlinear perturbations can make particle motion unstable
- → Leads to beam loss and reduction in luminosity.





$$L = \frac{\boxed{f\, n_b} N_1 N_2}{4\pi\, \sigma_x\, \sigma_y}$$

Want to maximize frequency of bunch collisions

- **Linear collider: need to create + accelerate bunches each time collide**
- **Synchrotron: create+store bunches → collide at revolution frequency**
- **Larger ring = more space for bunches, but longer revolution period.**
  → maximize filling factor of ring with bunches

e.g. SLC: 1 bunch @ 120Hz

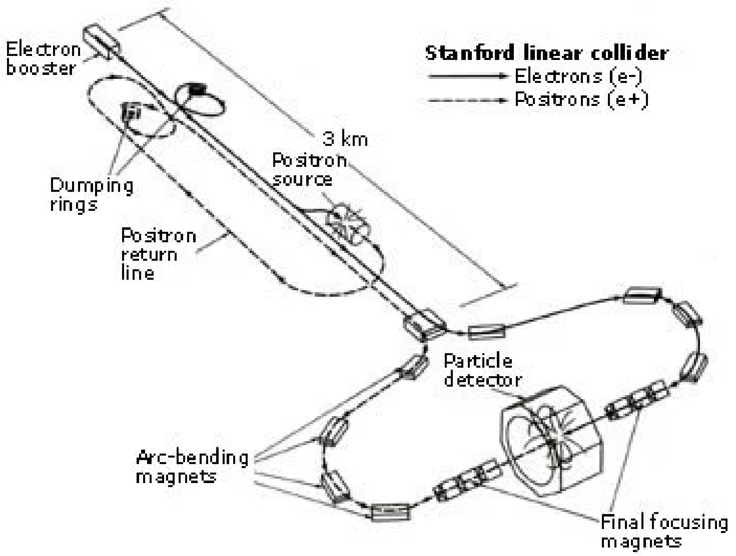
$L = 3 \times 10^{30}\ \mathrm{cm^{-2}s^{-1}}$ (300 Z^0/hour)

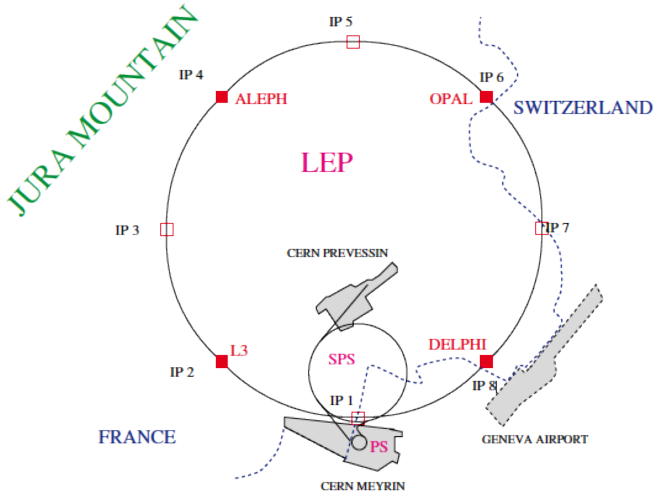
e.g. LEP1: 4 bunch @ 11,245Hz

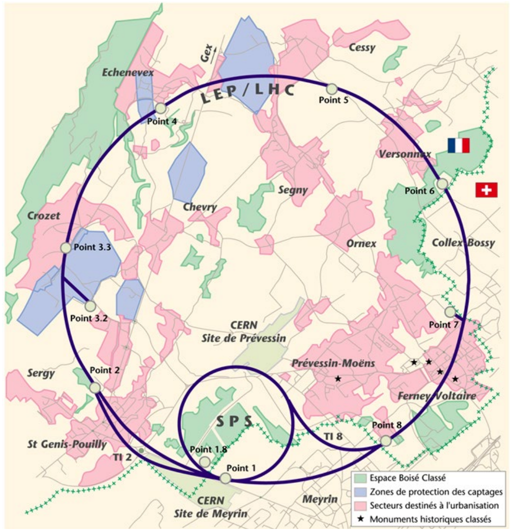
$L = 3 \times 10^{31}\ \mathrm{cm^{-2}s^{-1}}$

e.g. LHC: 2800 bunch @ 11,245Hz

$L = 2.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$





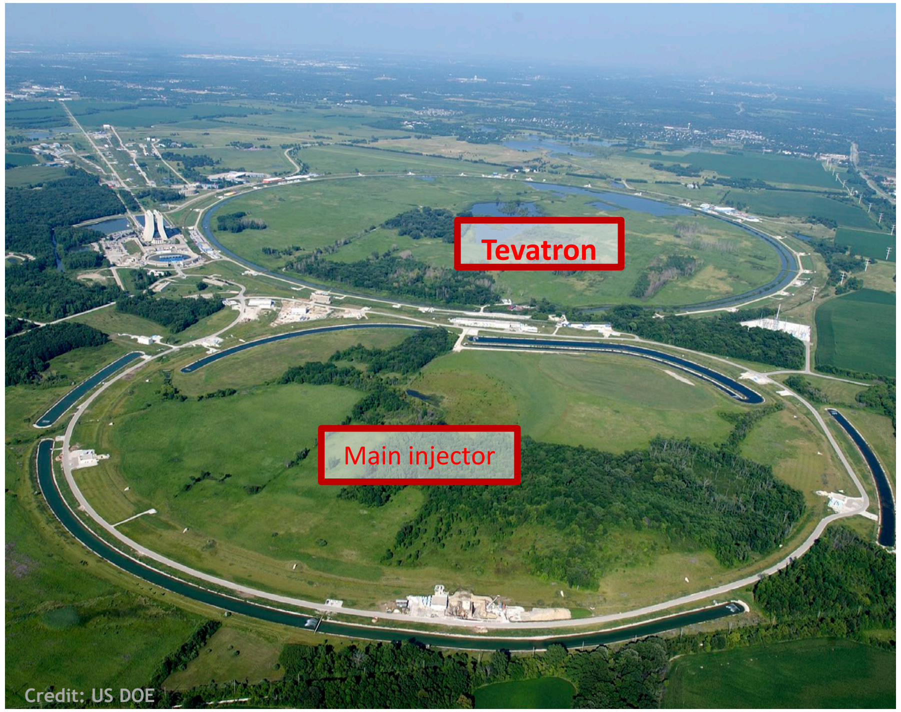


How fast can you create the particles for collision?

$$L = \frac{f\, \boxed{n_b\, N_1}\, N_2}{4\pi\, \sigma_x\, \sigma_y}$$

Relatively easy to create high-quality bunches of protons, electrons, much more challenging to create high-quality beams of secondary particles

- **Create beams of secondary particles by colliding electrons/protons with target and collecting desired particle type**
- **Secondary particles from target generally have large spread in momentum, trajectories**
  → large emittance! Need to `*cool*' secondary particle beam to reduce
  → easy for positrons – just use synchrotron radiation damping
  → for heavy particles this can be challenging or time consuming process



Credit: US DOE

$\overline{\mathrm{p}}$ production rate was primary limitation to Tevatron luminosity

- **Could only produce enough anti-protons for 103 bunches $\left(N_{\overline{p}} = 1 \times 10^{11}\right)$ per cycle**
- $\mathrm{L} \approx 5 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

This is one of the main reasons why LHC is a proton-proton collider is to benefit Luminosity from easier beam production:

$\sim$2500 bunches at $N_p = 1.6 \times 10^{11} \rightarrow \mathrm{L} = 2.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$$L = \frac{f\, n_b N_1 N_2}{4\pi\, \sigma_x \sigma_y}$$

RF power requirements scale with beam intensity

More intense beam requires more RF power to accelerate

→ Particular issue for linear accelerator where fully accelerate over & over

RF power can also impose intensity limit on heavy particle synchrotrons

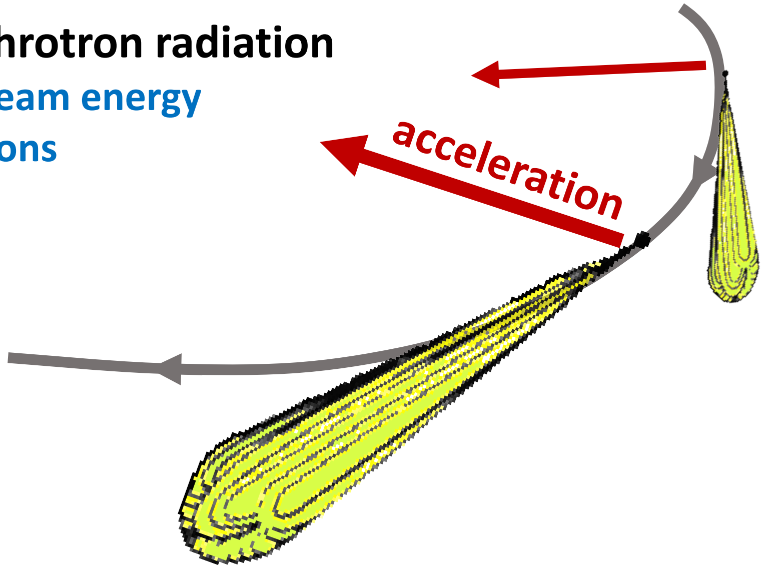
→ More intense beams perturb cavity fields

→ E.g. HL-LHC will require upgraded klystrons for its RF to cope with more intense beams

more intense beam emits more synchrotron radiation

→ More RF power needed to maintain beam energy

→ Particular issue for electron synchrotrons

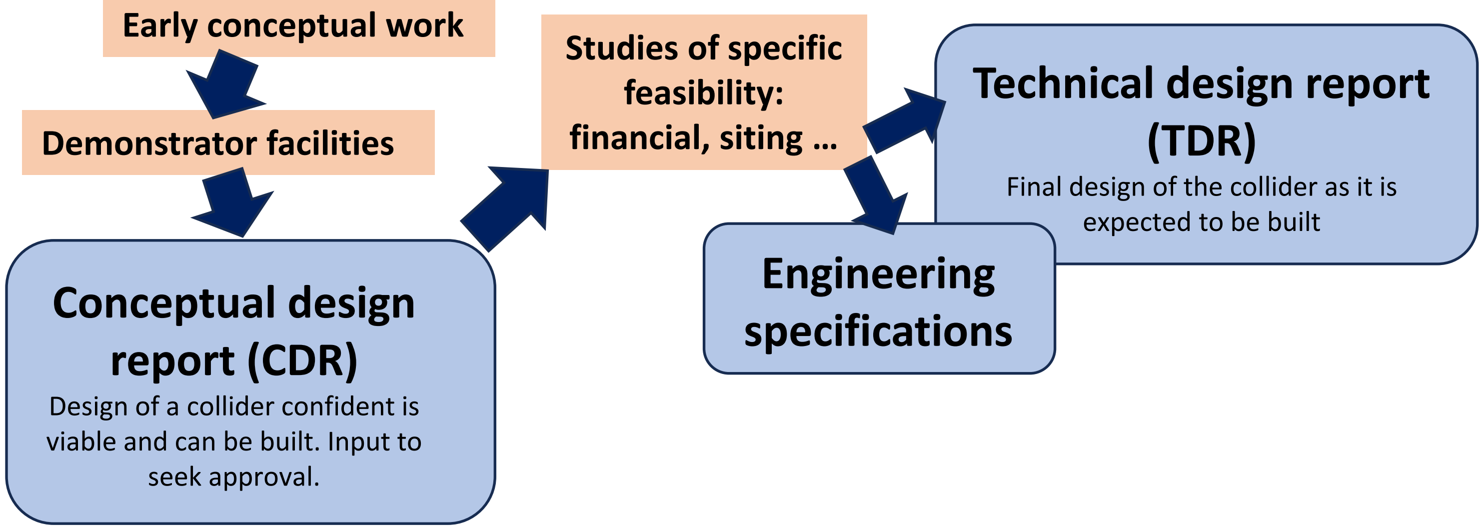


Often need to make a trade off between high-energy, high-luminosity, cost

Viability, cost, power, sustainability?

Viability: *if we're going to build a new accelerator need to be confident it will work when we turn it on*

→ Various usual milestones in an accelerators development



(not strict or to be taken completely literally)

Early conceptual work

Demonstrator facilities

Conceptual design report (CDR)

Design of a collider confident is viable and can be built. Input to seek approval.

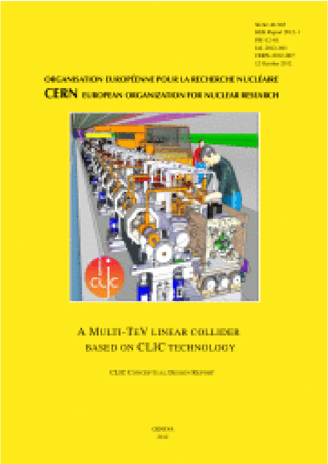
Studies of specific feasibility: financial, siting …

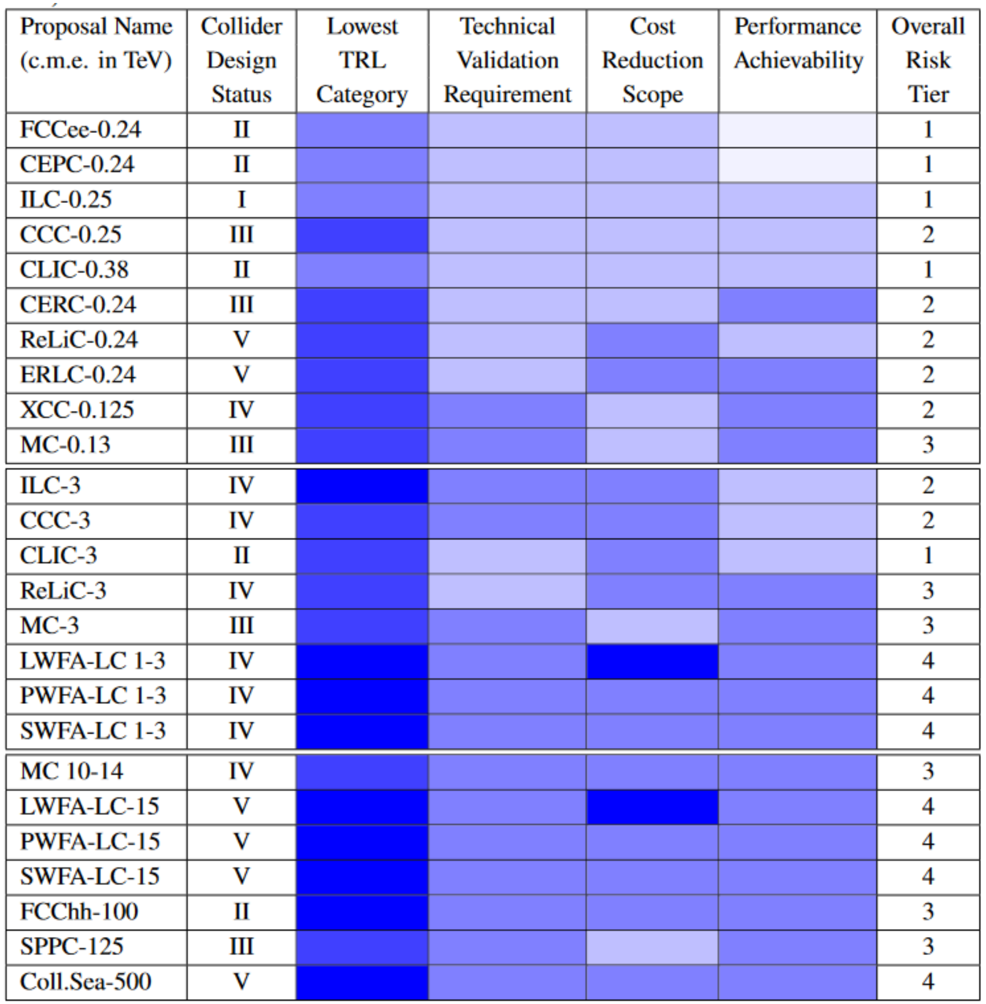
Technical design report (TDR)

Final design of the collider as it is expected to be built

Engineering specifications

e.g. CLIC CDR:
3 volumes ≈1000 pages





Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II	▒	░	░	□	1
CEPC-0.24	II	▒	░	░	□	1
ILC-0.25	I	▒	░	░	░	1
CCC-0.25	III	▓	░	░	░	2
CLIC-0.38	II	▒	░	░	░	1
CERC-0.24	III	▓	░	░	▒	2
ReLiC-0.24	V	▓	░	▒	░	2
ERLC-0.24	V	▓	░	▒	▒	2
XCC-0.125	IV	▓	▒	░	▒	2
MC-0.13	III	▓	▒	░	▒	3
ILC-3	IV	█	▒	▒	░	2
CCC-3	IV	▓	▒	▒	░	2
CLIC-3	II	▓	░	▒	░	1
ReLiC-3	IV	▓	░	▒	▒	3
MC-3	III	▓	▒	░	▒	3
LWFA-LC 1-3	IV	█	▒	█	▒	4
PWFA-LC 1-3	IV	█	▒	▒	▒	4
SWFA-LC 1-3	IV	█	▒	▒	▒	4
MC 10-14	IV	▓	▒	▒	▒	3
LWFA-LC-15	V	█	▒	█	▒	4
PWFA-LC-15	V	█	▒	▒	▒	4
SWFA-LC-15	V	█	▒	▒	▒	4
FCChh-100	II	█	▒	▒	▒	3
SPPC-125	III	▓	▒	░	▒	3
Coll.Sea-500	V	█	▒	▒	▒	4

Not always easy to compare project viability…

→ **Recent snowmass exercise made nice review of status/risk of various projects…**

2023, JINST 18 P0501 *On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force*
https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

Cost/Power

Any future accelerator will represent a considerable financial investment

Exercise extreme caution comparing construction/power/running-cost estimates

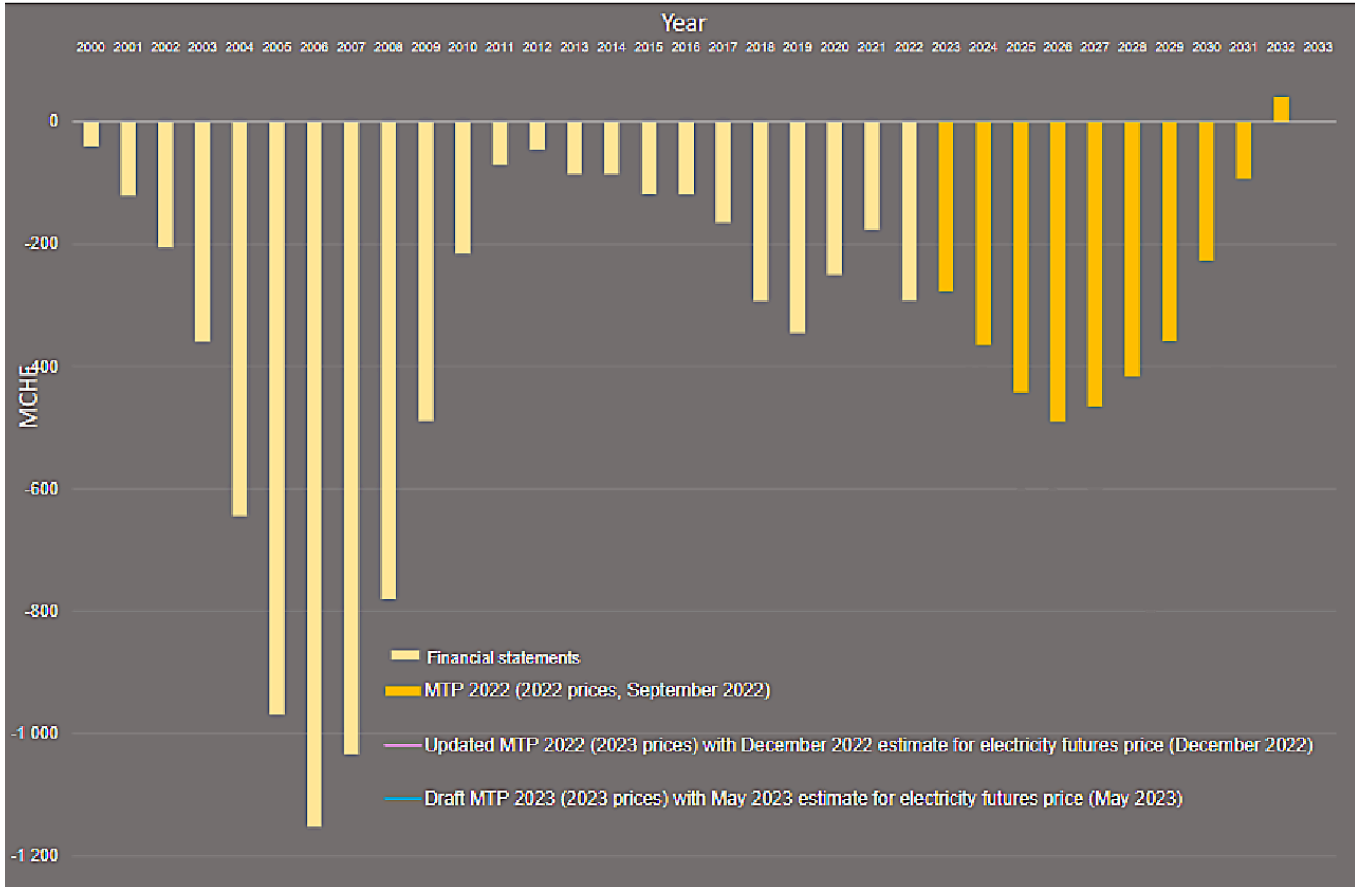
→ Uncertainty heavily influenced by project maturity

→ Many estimates are out-of-date: inflation/labour cost, technological/industrial improvements

At CERN industrial return of member states vs contributions monitored & procurement rules favour poorly balanced members

CERN relatively unique NGO/Lab in that it can take loans to fund development of future: helps limit up-front cost to member states. Subject to council.

Some financial support for future projects could come from non-member states (for example specific in-kind contributions e.g. some LHC magnets constructed by US**)**



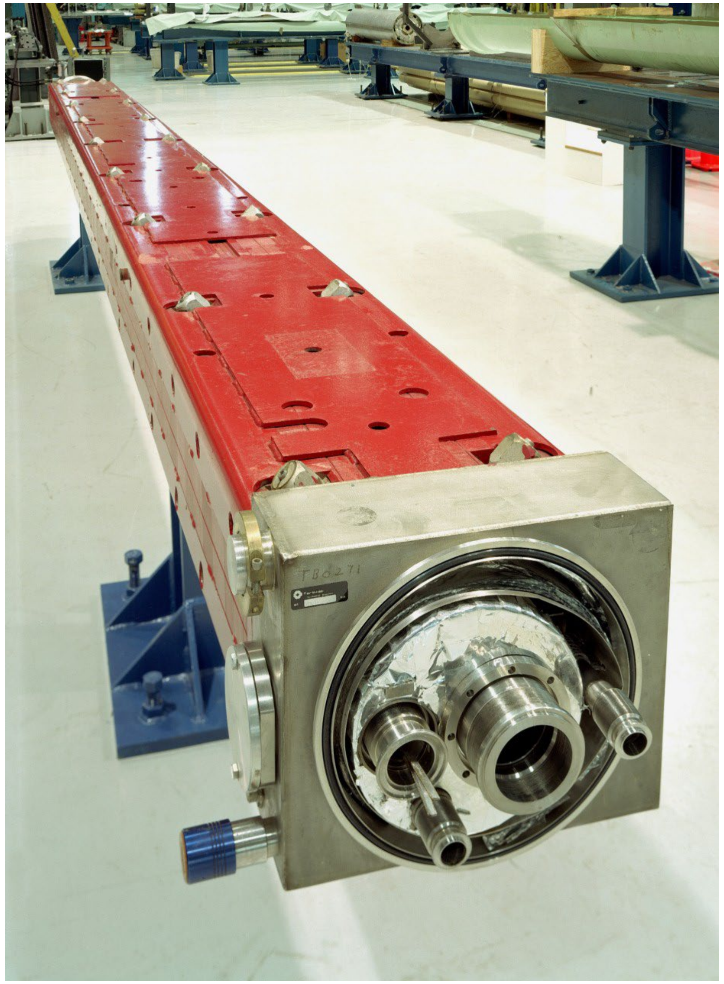
F.Sonnemann, FCC week 2023 *Funding options and integration of the FCC ee construction and operation in CERN's financial plan* https://indico.cern.ch/event/1202105/contributions/5431438/

Various financial figures of merit that can be considered

- **Capital construction cost , power requirements, but also:**

$$\frac{\text{Luminosity}}{\$} \quad \& \quad \frac{\text{Luminosity}}{\text{TWh}}$$

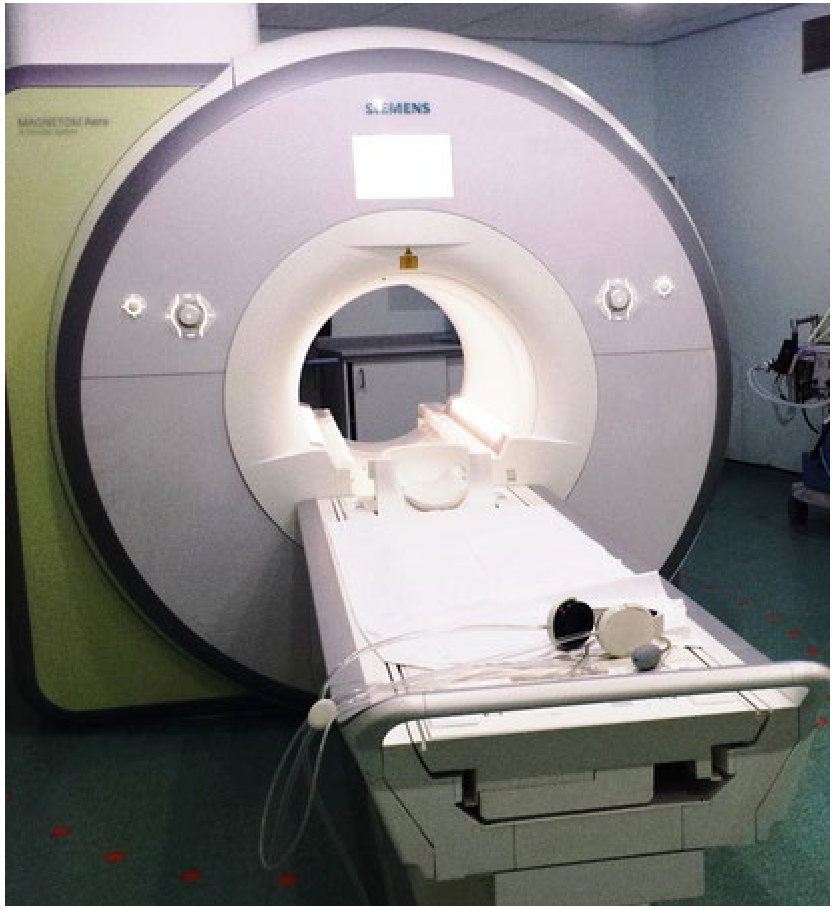
Large scale procurement in accelerator projects can act as a stimulus to relevant high-tech industries



When Tevatron was being built it accounted for around 90% of world procurement of NbTi superconducting cable

Generally credited with stimulating industrial capacity for superconducting magnets, contributing to wide spread availability of e.g. MRI machines

- **Accelerator R&D for major HEP projects often benefits society as a whole**



Sustainability

≈90% of CERN power comes from France non-fossil fuel sources, majority nuclear

- Helps partially decouple power requirements of future project from CO2
- Still important to seek energy savings and sustainability improvements wherever possible, and ensure future power supplies are sustainable!

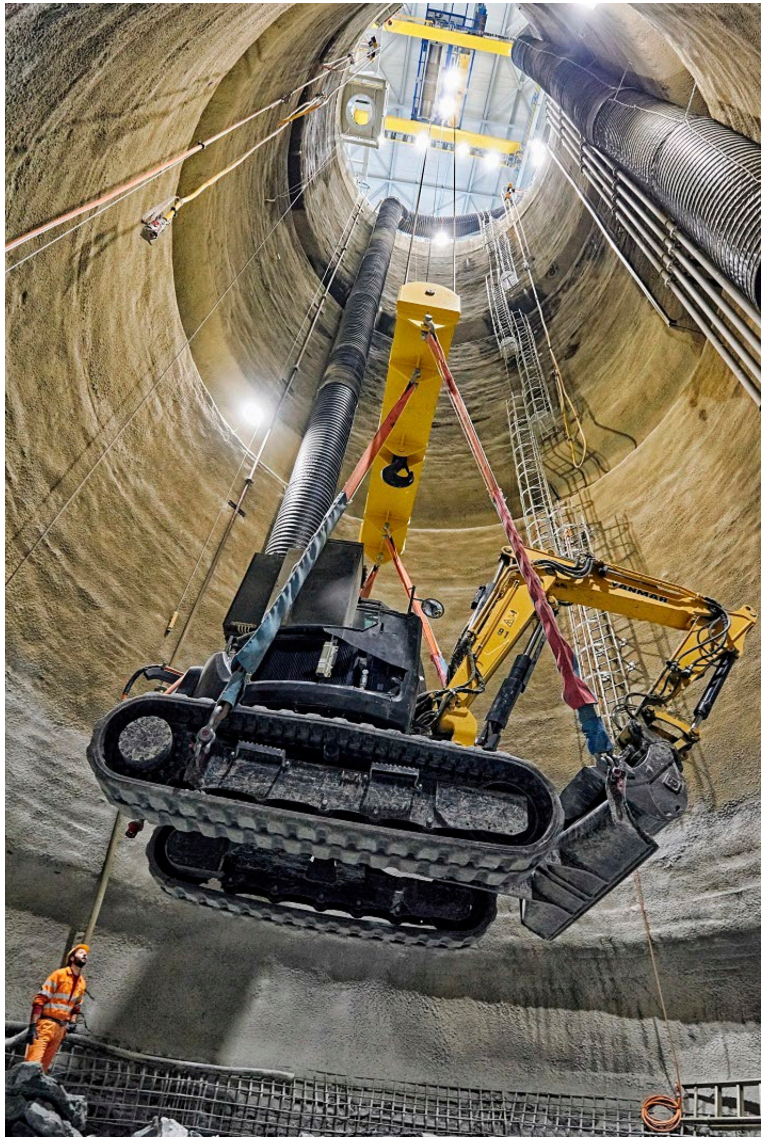
Concrete used in civil engineering is expected to dominate CO2 footprint of future project proposals (production inherently produces CO2 via calcination of limestone)

$CaCO_3 \rightarrow CaO + CO_2$

Various EU projects underway to help support low carbon footprint concrete

Reusability of civil engineering and upgrade paths is also important

Civil engineering work underway for the HL-LHC



Civil engineering work underway for the HL-LHC

Future colliders?

Linear e^+e^- collider

- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

e^+e^- synchrotron

- FCCee
- CEPC

hadron synchrotron

- FCChh
- SPPS

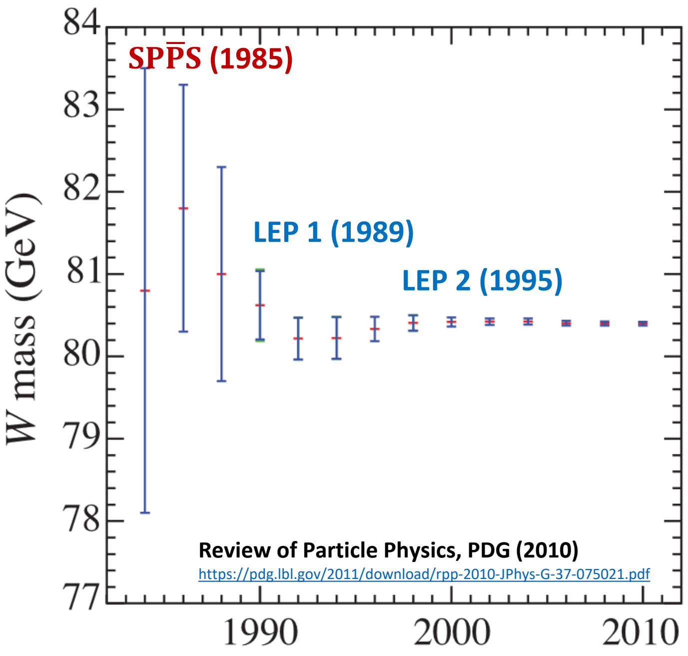
Muon Collider

Linear colliders: a pathway to highest energy e^+e^- collisions

Why an e^+e^- linear collider?

Hadron machines like LHC collide composite particles

- Don’t precisely know energy of constituents involved
- Probe large energy spread → great for discovery, harder for precision



Review of Particle Physics, PDG (2010)
https://pdg.lbl.gov/2011/download/rpp-2010-JPhys-G-37-075021.pdf

By colliding fundamental particles like e^+e^- know well the collision energy

- Can be beneficial for precision studies
- E.g. can precisely scan energy of collider over a resonance

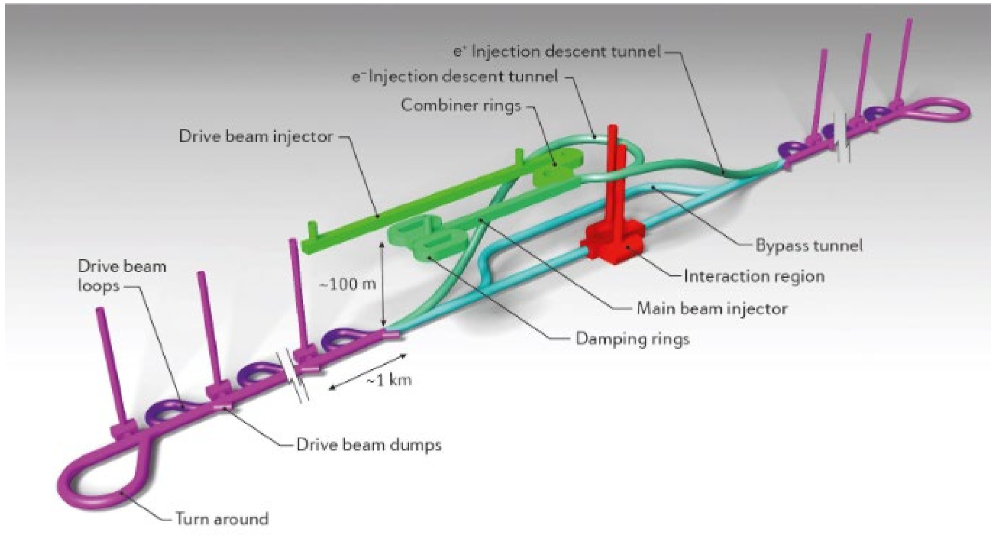
Energy reach of circular e^+e^- machines limited by synchrotron radiation

- Linear collider energy not subject to this restriction
- Linear collider offers potential for highest possible energy $\mathbf{e^+e^-}$ collisions

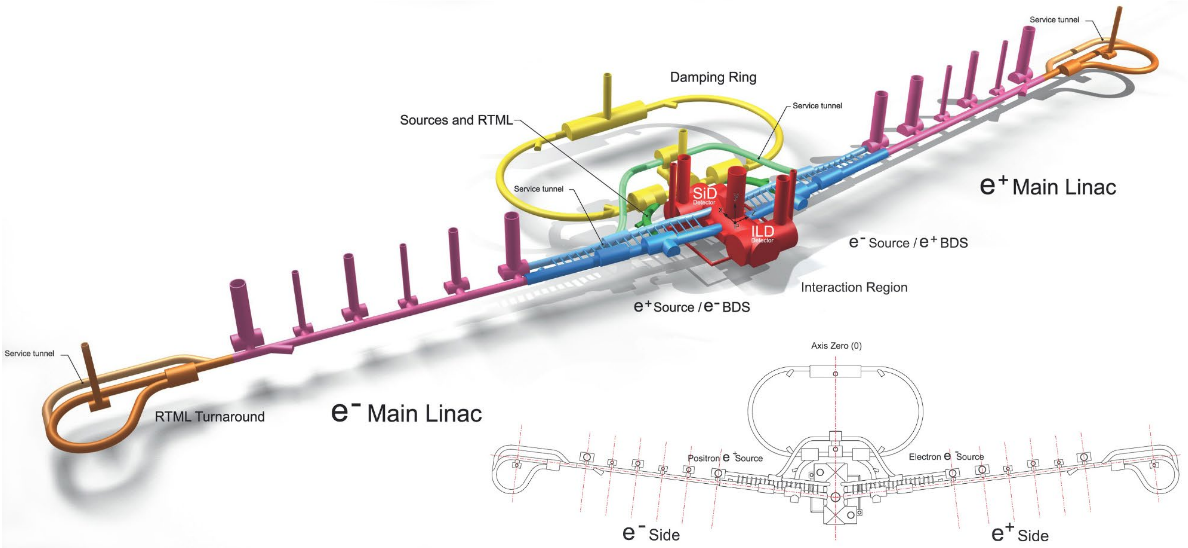
Linear colliders: a pathway to highest energy e^+e^- collisions

Two main proposals

Compact Linear Collider (CLIC) @ CERN

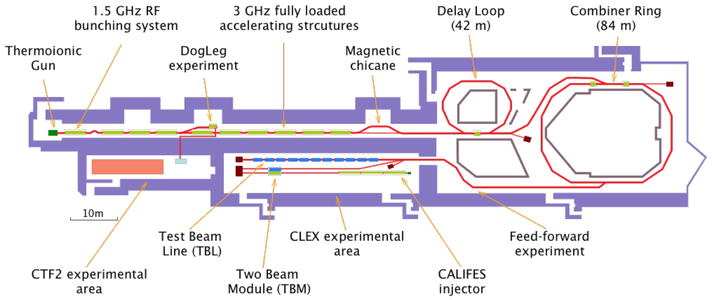


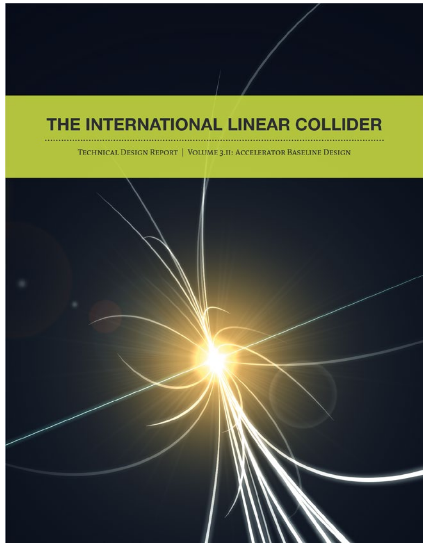
International Linear Collider (ILC) @ Japan

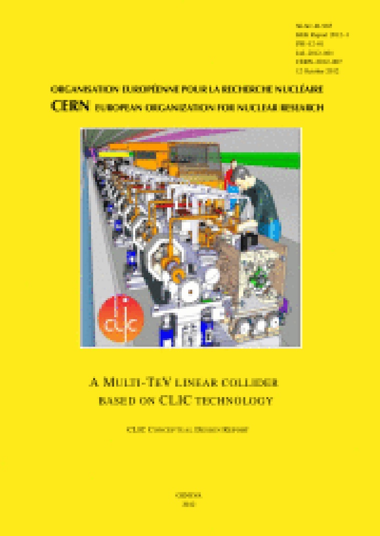


Both CLIC and ILC are extremely mature projects (lowest possible risk classification in 2021 Snowmass)

- **R&D for the CLIC / ILC projects began in 1985 / early 1990s!**
- **Multiple dedicated test facilities built & operated to demonstrate key technologies: CTF1** (1994)**, CTF2** (1996)**, CTF3** (2001-2016)**, ATF** (1995)**, ATF2** (2009)
- **ILC produced Technical Design report in 2013** https://cds.cern.ch/record/1601969/files/ILCTDR-VOLUME_3-PART_II.pdf
- **CLIC Conceptual Design Report published 2012 (focused on 3TeV collider viability)** http://project-clic-cdr.web.cern.ch/CDR_Volume1.pdf
- **Following discovery of Higgs CLIC published strategy update in 2018 (focused on initial staging from 380GeV) plus an implementation plan**
  https://arxiv.org/pdf/1812.06018.pdf , https://arxiv.org/pdf/1903.08655.pdf
- **Most recent CLIC update in 2022 for submission to US Snowmass** https://arxiv.org/pdf/2203.09186.pdf

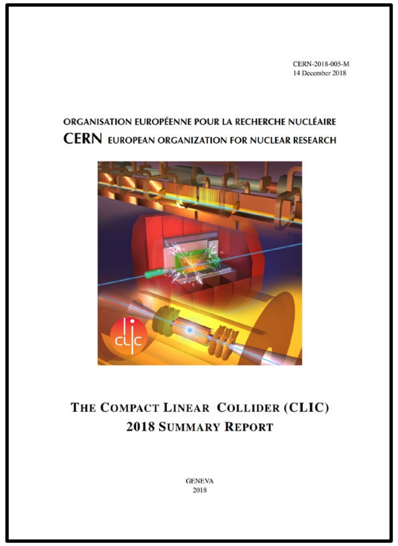



THE INTERNATIONAL LINEAR COLLIDER
Technical Design Report | Volume 3.II: Accelerator Baseline Design


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

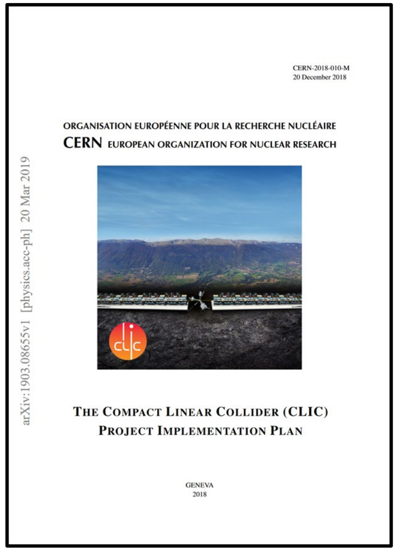
CLIC Conceptual Design Report


CERN-2018-005-M
14 December 2018

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE COMPACT LINEAR COLLIDER (CLIC)
2018 SUMMARY REPORT

GENEVA
2018

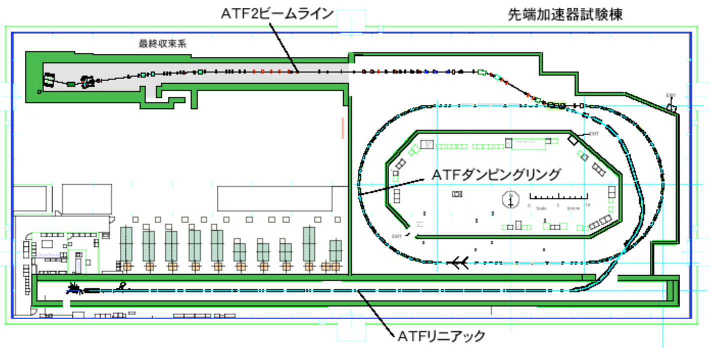

CERN-2018-010-M
20 December 2018

arXiv:1903.08655v1 [physics.acc-ph] 20 Mar 2019

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE COMPACT LINEAR COLLIDER (CLIC)
PROJECT IMPLEMENTATION PLAN

GENEVA
2018



Both linear colliders with staged increase in C.O.M energy achieved by increasing length of tunnel → more RF cavities

CLIC

$\leq 380\text{GeV}$ **(11.4km)**

$\leq 1.5\text{TeV}$ **(29.0km)**

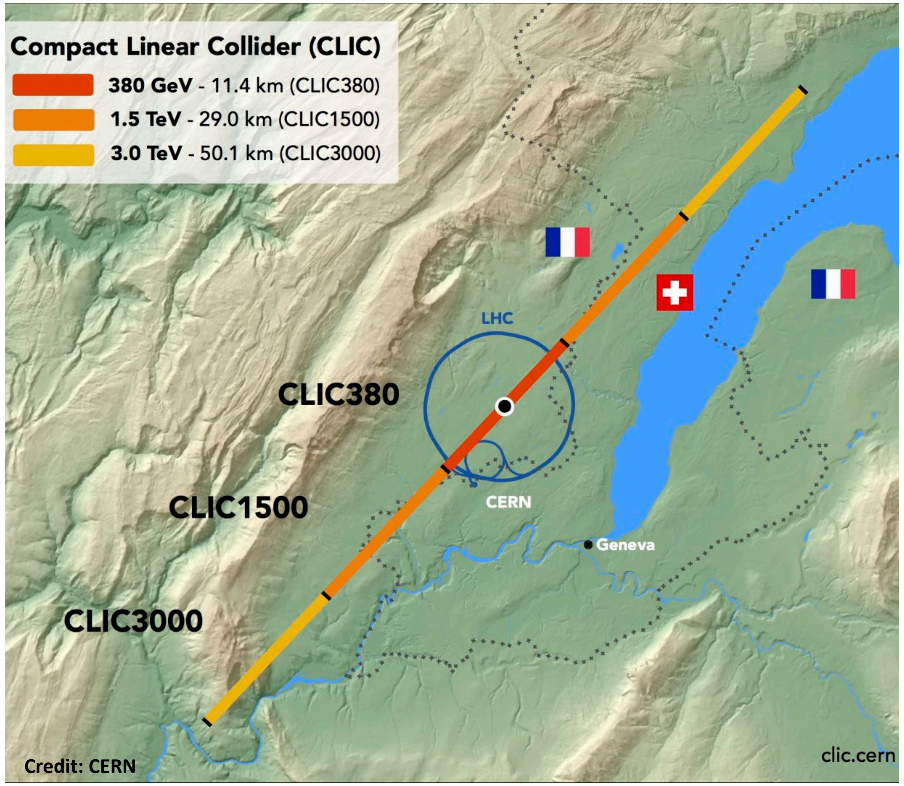
$\leq 3.0\text{TeV}$ **(50.1km)**

ILC

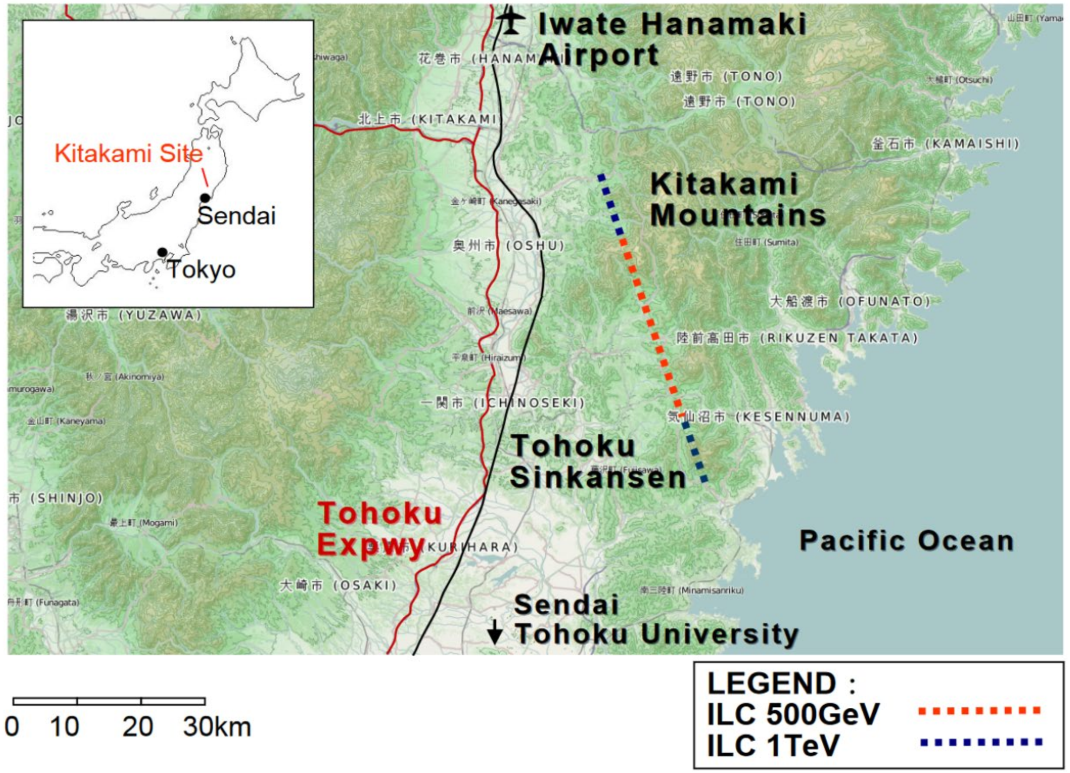
$\leq 250\text{GeV}$ **(20.5km)**

$\leq 500\text{GeV}$ **(31km)**

$\leq 1.0\text{TeV}$ **(40km)**



Credit: CERN



≈30km

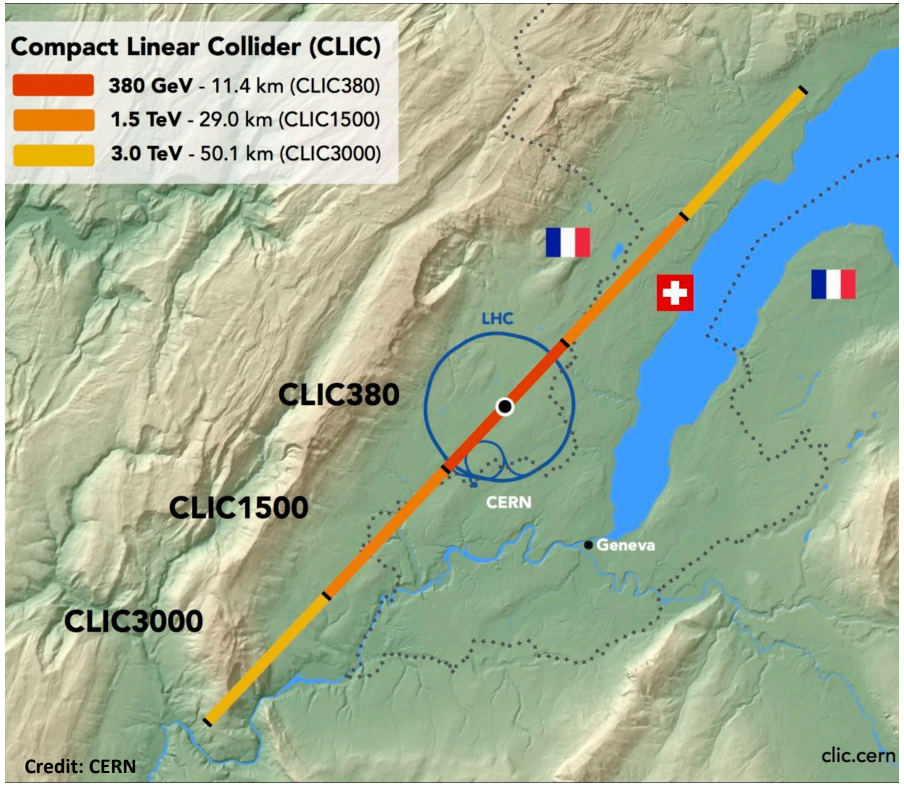
≈50km

Similar proposals at high level, but various differences e.g.

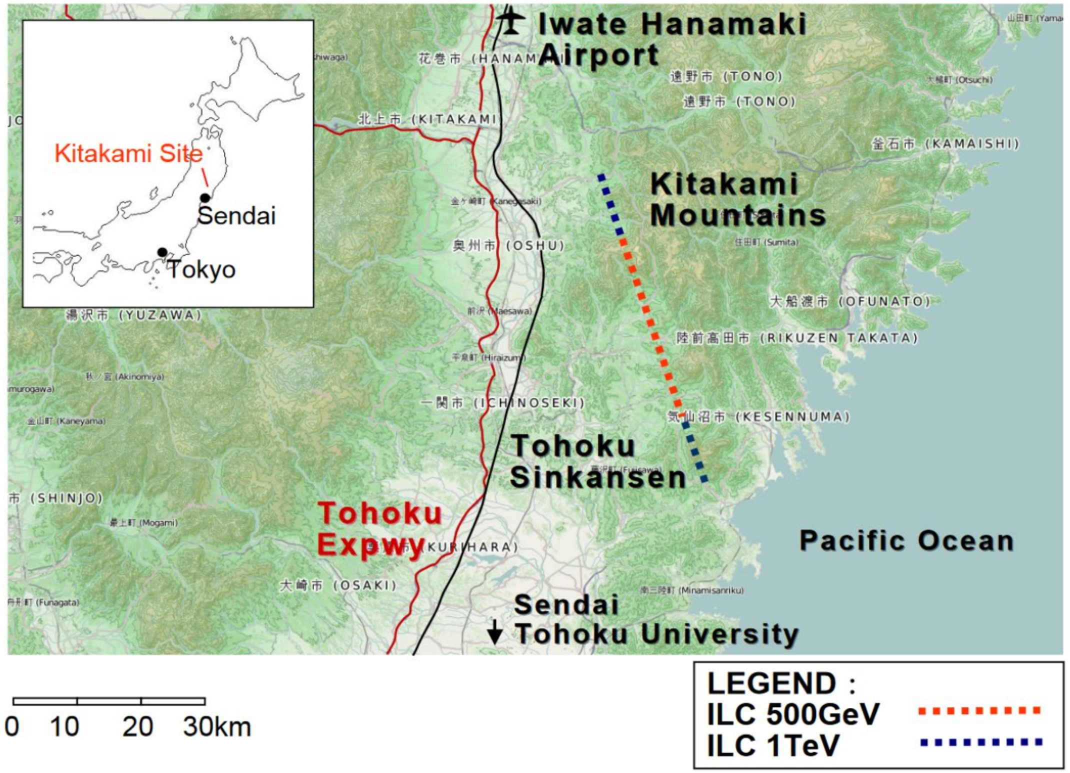
- CLIC baseline = single detector → ILC proposed 2 detectors sharing time via push/pull
- CLIC baseline = 80% polarized e^- colliding with unpolarized e^+ → ILC baseline 80% polarized e^- with ≈30% polarized e^+ (easier upgrade to high polarization)

Major differences arise from higher energy reach of CLIC in same length tunnel

- **ILC requires lower accelerating gradient ($\approx 31.5\,\mathrm{MV/m}$). Uses conventional superconducting RF cavities powered by Klystrons**
- **To reach 3TeV in 50km CLIC requires extremely high ($\approx 100\,\mathrm{MV/m}$) accelerating gradient.**
  → only possible with normal conducting cavities at very high-frequency (12GHz) + needs a novel method to power the cavities (Klystron option at 380GeV)

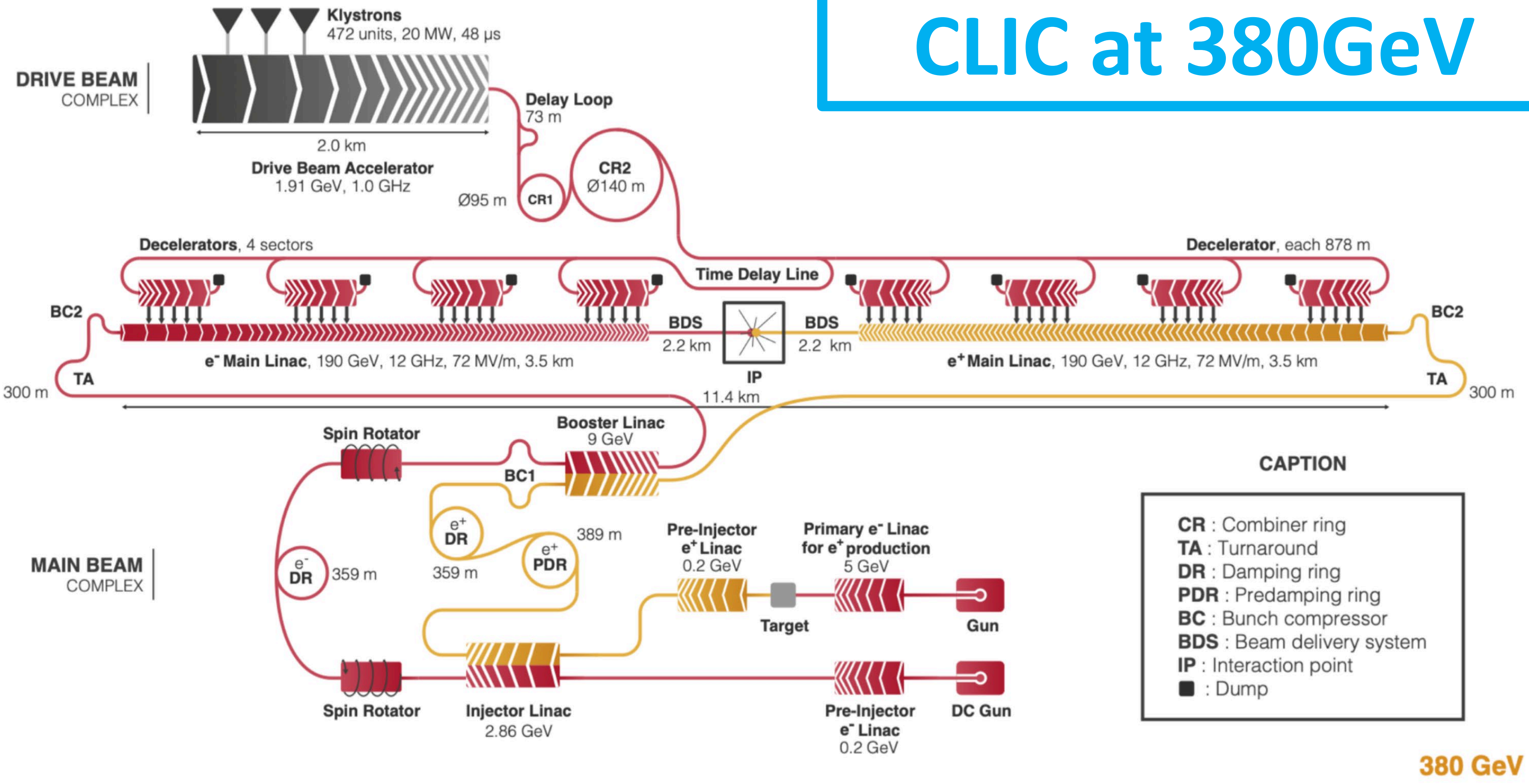


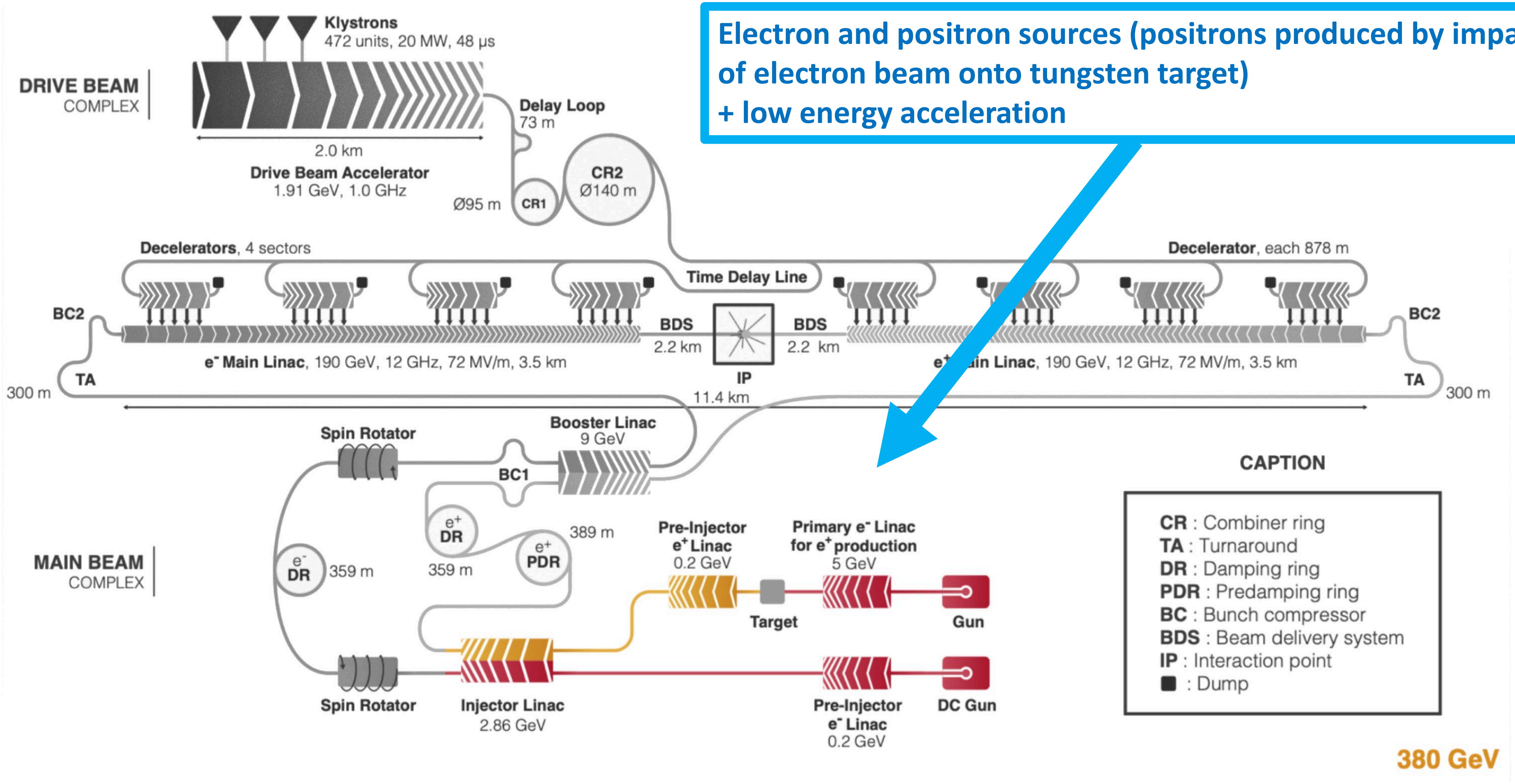
Credit: CERN



≈30km
≈50km

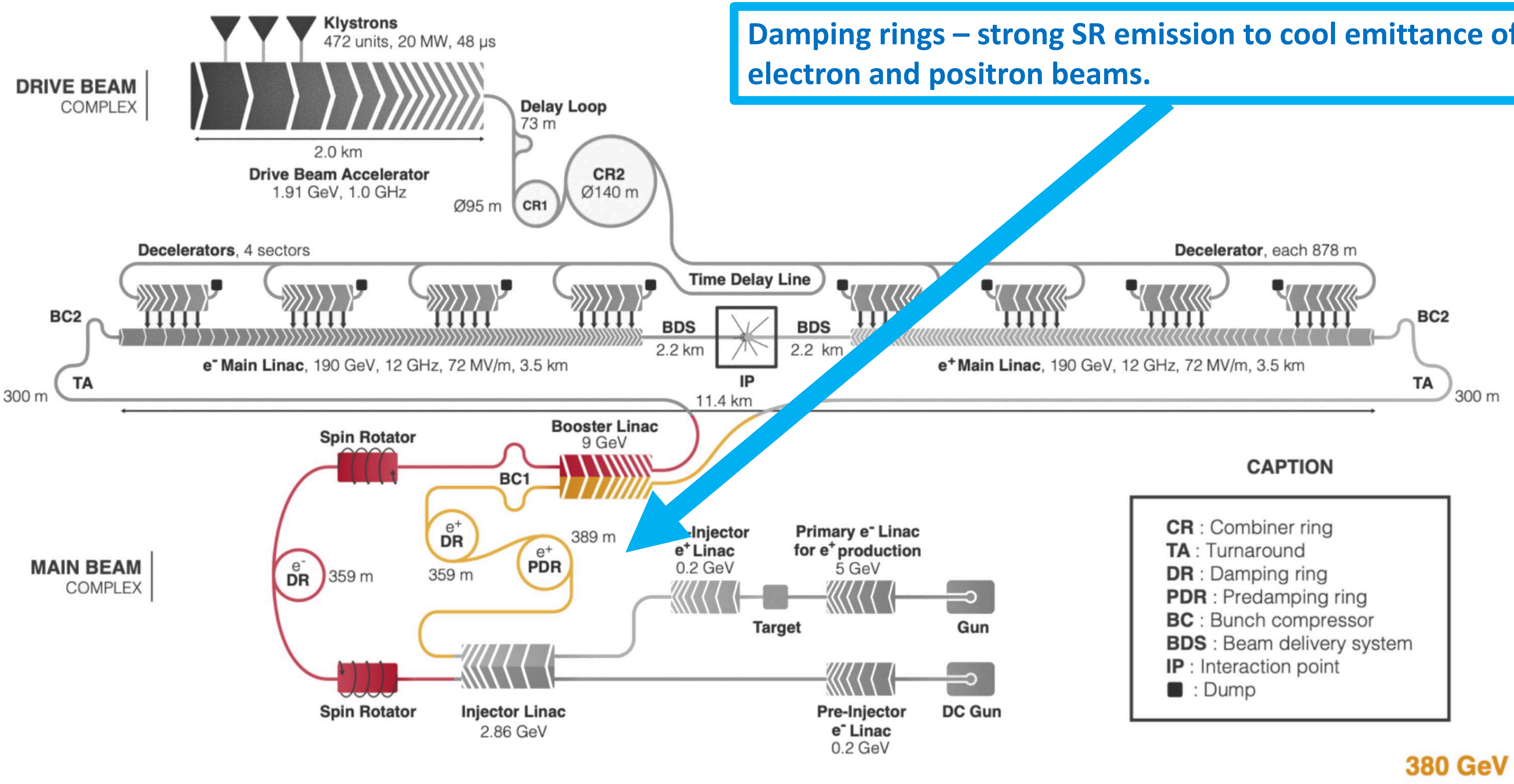
CLIC at 380GeV

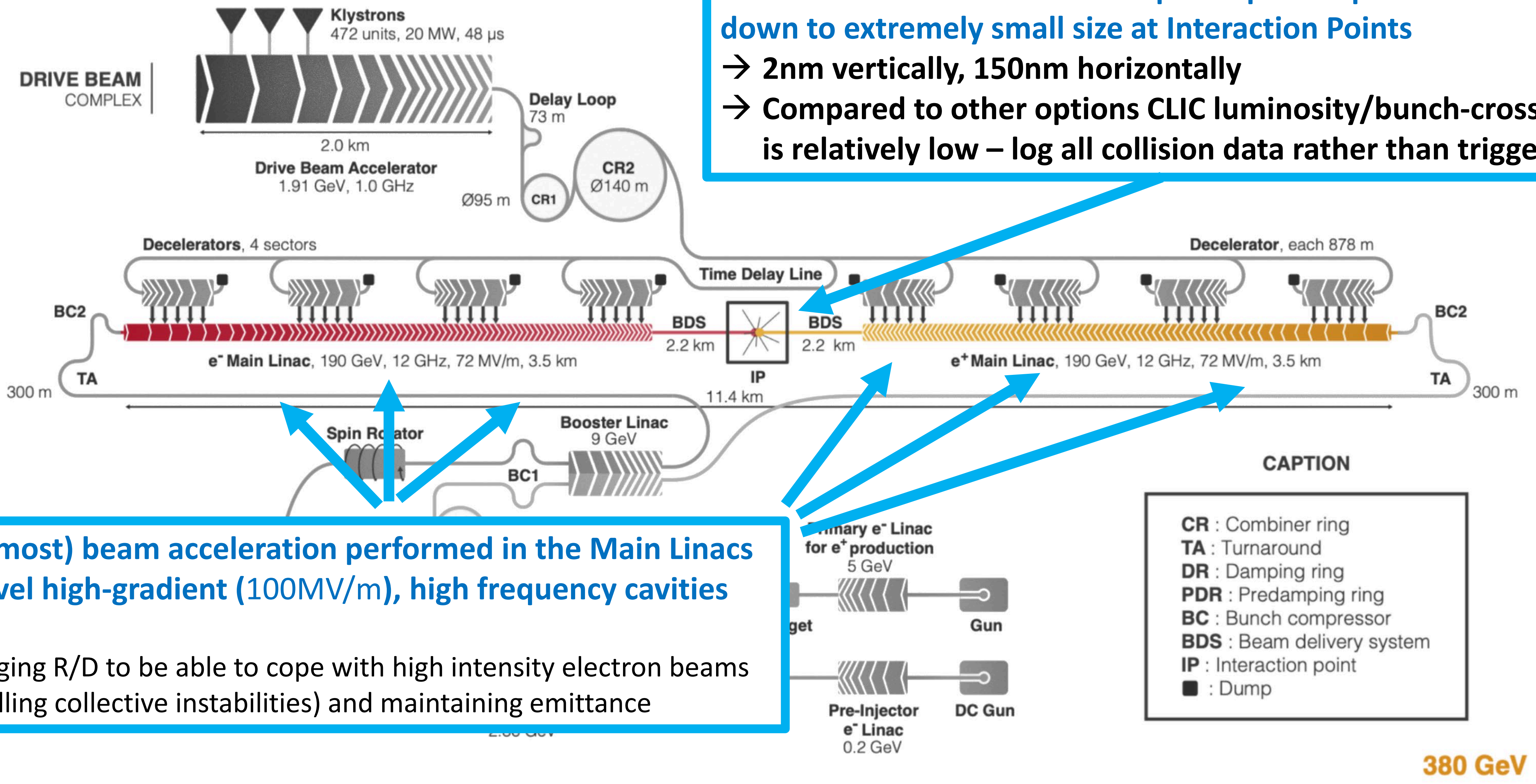




Electron and positron sources (positrons produced by impact of electron beam onto tungsten target)
+ low energy acceleration

Damping rings – strong SR emission to cool emittance of electron and positron beams.





At end of the linacs final focus quadrupoles squeeze beams down to extremely small size at Interaction Points

→ 2nm vertically, 150nm horizontally

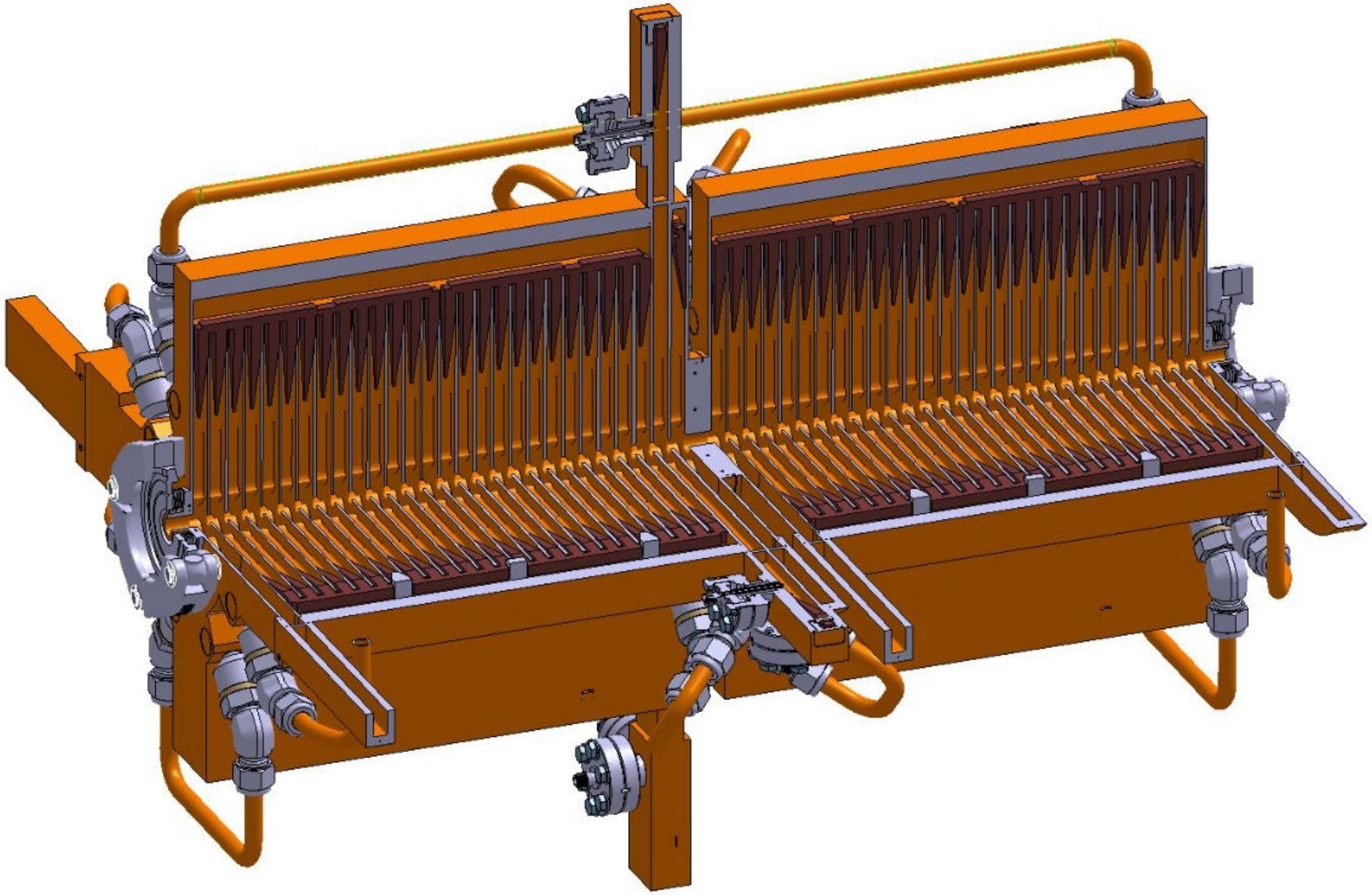
→ Compared to other options CLIC luminosity/bunch-crossing is relatively low – log all collision data rather than triggering

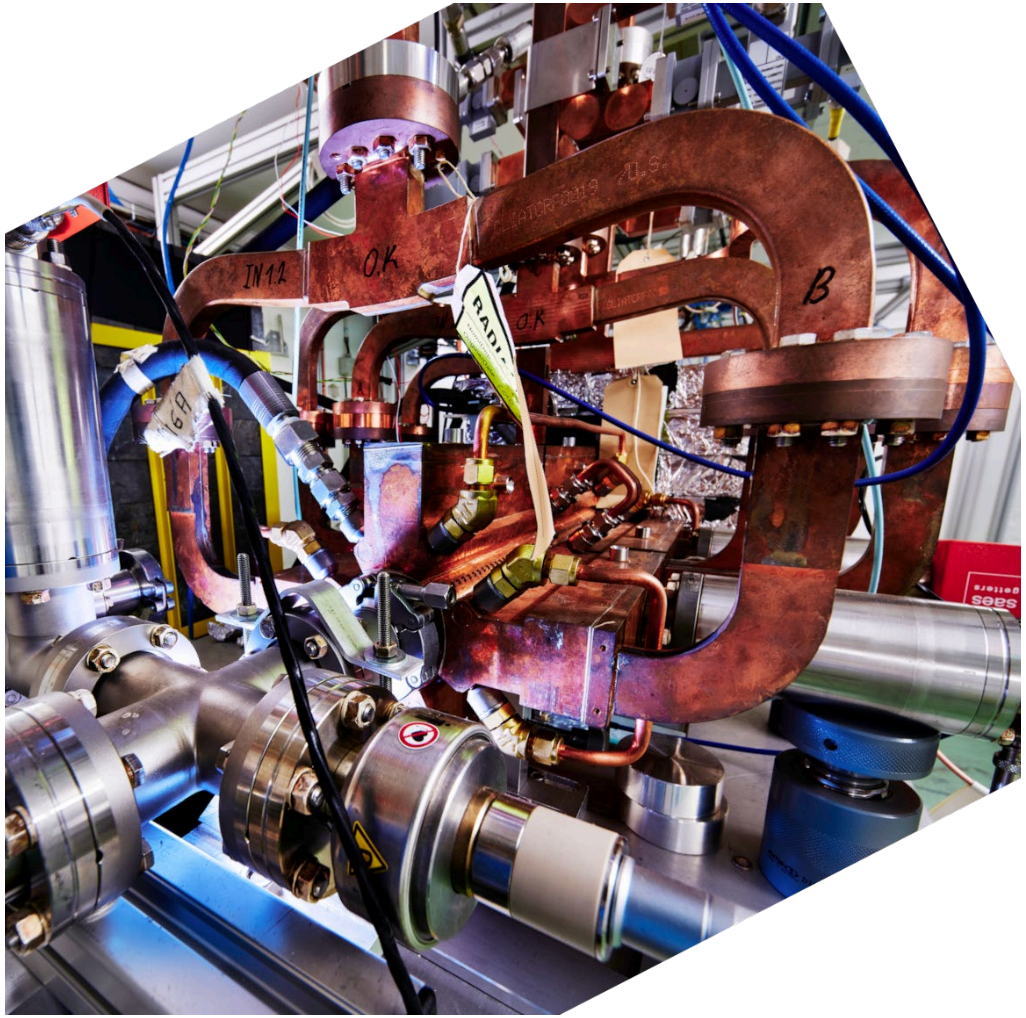
Final (most) beam acceleration performed in the Main Linacs via novel high-gradient (100MV/m), high frequency cavities

challenging R/D to be able to cope with high intensity electron beams (controlling collective instabilities) and maintaining emittance

To reach multi-TeV scale energy in acceptable tunnel CLIC project developed novel high-gradient cavities (100MV/m) capable of accelerating high-current high-quality electron beams

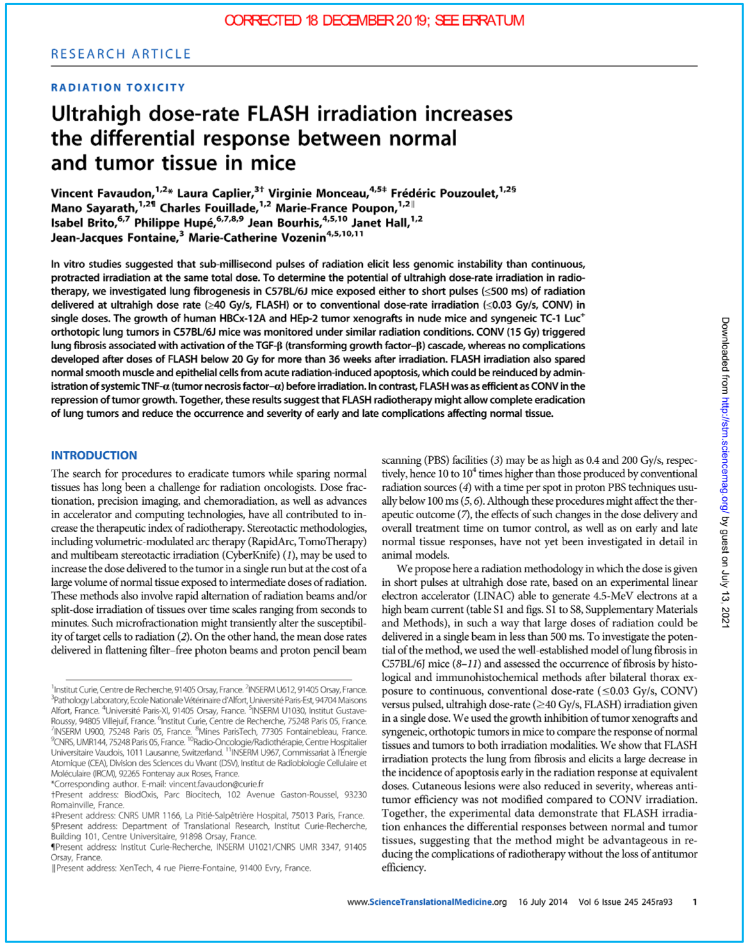
→ **Already delivering societal impact**





To reach multi-TeV scale energy in acceptable tunnel CLIC project developed novel high-gradient cavities (100MV/m) capable of accelerating high-current high-quality electron beams

→ Already delivering societal impact



CORRECTED 18 DECEMBER 2019; SEE ERRATUM

RESEARCH ARTICLE

RADIATION TOXICITY

Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice

Vincent Favaudon,[1,2*] Laura Caplier,[3†] Virginie Monceau,[4,5‡] Frédéric Pouzoulet,[1,2§]
Mano Sayarath,[1,2¶] Charles Fouillade,[1,2] Marie-France Poupon,[1,2‖]
Isabel Brito,[6,7] Philippe Hupé,[6,7,8,9] Jean Bourhis,[4,5,10] Janet Hall,[1,2]
Jean-Jacques Fontaine,[3] Marie-Catherine Vozenin[4,5,10,11]

In vitro studies suggested that sub-millisecond pulses of radiation elicit less genomic instability than continuous, protracted irradiation at the same total dose. To determine the potential of ultrahigh dose-rate irradiation in radiotherapy, we investigated lung fibrogenesis in C57BL/6J mice exposed either to short pulses (≤500 ms) of radiation delivered at ultrahigh dose rate (≥40 Gy/s, FLASH) or to conventional dose-rate irradiation (≤0.03 Gy/s, CONV) in single doses. The growth of human HBCx-12A and HEp-2 tumor xenografts in nude mice and syngeneic TC-1 Luc$^+$ orthotopic lung tumors in C57BL/6J mice was monitored under similar radiation conditions. CONV (15 Gy) triggered lung fibrosis associated with activation of the TGF-β (transforming growth factor–β) cascade, whereas no complications developed after doses of FLASH below 20 Gy for more than 36 weeks after irradiation. FLASH irradiation also spared normal smooth muscle and epithelial cells from acute radiation-induced apoptosis, which could be reinduced by administration of systemic TNF-α (tumor necrosis factor–α) before irradiation. In contrast, FLASH was as efficient as CONV in the repression of tumor growth. Together, these results suggest that FLASH radiotherapy might allow complete eradication of lung tumors and reduce the occurrence and severity of early and late complications affecting normal tissue.

INTRODUCTION

The search for procedures to eradicate tumors while sparing normal tissues has long been a challenge for radiation oncologists. Dose fractionation, precision imaging, and chemoradiation, as well as advances in accelerator and computing technologies, have all contributed to increase the therapeutic index of radiotherapy. Stereotactic methodologies, including volumetric-modulated arc therapy (RapidArc, TomoTherapy) and multibeam stereotactic irradiation (CyberKnife) (*1*), may be used to increase the dose delivered to the tumor in a single run but at the cost of a large volume of normal tissue exposed to intermediate doses of radiation. These methods also involve rapid alternation of radiation beams and/or split-dose irradiation of tissues over time scales ranging from seconds to minutes. Such microfractionation might transiently alter the susceptibility of target cells to radiation (*2*). On the other hand, the mean dose rates delivered in flattening filter–free photon beams and proton pencil beam scanning (PBS) facilities (*3*) may be as high as 0.4 and 200 Gy/s, respectively, hence 10 to 10^4 times higher than those produced by conventional radiation sources (*4*) with a time per spot in proton PBS techniques usually below 100 ms (*5, 6*). Although these procedures might affect the therapeutic outcome (*7*), the effects of such changes in the dose delivery and overall treatment time on tumor control, as well as on early and late normal tissue responses, have not yet been investigated in detail in animal models.

We propose here a radiation methodology in which the dose is given in short pulses at ultrahigh dose rate, based on an experimental linear electron accelerator (LINAC) able to generate 4.5-MeV electrons at a high beam current (table S1 and figs. S1 to S8, Supplementary Materials and Methods), in such a way that large doses of radiation could be delivered in a single beam in less than 500 ms. To investigate the potential of the method, we used the well-established model of lung fibrosis in C57BL/6J mice (*8–11*) and assessed the occurrence of fibrosis by histological and immunohistochemical methods after bilateral thorax exposure to continuous, conventional dose-rate (≤0.03 Gy/s, CONV) versus pulsed, ultrahigh dose-rate (≥40 Gy/s, FLASH) irradiation given in a single dose. We used the growth inhibition of tumor xenografts and syngeneic, orthotopic tumors in mice to compare the response of normal tissues and tumors to both irradiation modalities. We show that FLASH irradiation protects the lung from fibrosis and elicits a large decrease in the incidence of apoptosis early in the radiation response at equivalent doses. Cutaneous lesions were also reduced in severity, whereas antitumor efficiency was not modified compared to CONV irradiation. Together, the experimental data demonstrate that FLASH irradiation enhances the differential responses between normal and tumor tissues, suggesting that the method might be advantageous in reducing the complications of radiotherapy without the loss of antitumor efficiency.

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[1]Institut Curie, Centre de Recherche, 91405 Orsay, France. [2]INSERM U612, 91405 Orsay, France. [3]Pathology Laboratory, Ecole Nationale Vétérinaire d'Alfort, Université Paris-Est, 94704 Maisons Alfort, France. [4]Université Paris-XI, 91405 Orsay, France. [5]INSERM U1030, Institut Gustave-Roussy, 94805 Villejuif, France. [6]Institut Curie, Centre de Recherche, 75248 Paris 05, France. [7]INSERM U900, 75248 Paris 05, France. [8]Mines ParisTech, 77305 Fontainebleau, France. [9]CNRS, UMR144, 75248 Paris 05, France. [10]Radio-Oncologie/Radiothérapie, Centre Hospitalier Universitaire Vaudois, 1011 Lausanne, Switzerland. [11]INSERM U967, Commissariat à l'Énergie Atomique (CEA), Division des Sciences du Vivant (DSV), Institut de Radiobiologie Cellulaire et Moléculaire (IRCM), 92265 Fontenay aux Roses, France.
*Corresponding author. E-mail: vincent.favaudon@curie.fr
†Present address: BiodOxis, Parc Biocitech, 102 Avenue Gaston-Roussel, 93230 Romainville, France.
‡Present address: CNRS UMR 1166, La Pitié-Salpêtrière Hospital, 75013 Paris, France.
§Present address: Department of Translational Research, Institut Curie-Recherche, Building 101, Centre Universitaire, 91898 Orsay, France.
¶Present address: Institut Curie-Recherche, INSERM U1021/CNRS UMR 3347, 91405 Orsay, France.
‖Present address: XenTech, 4 rue Pierre-Fontaine, 91400 Evry, France.

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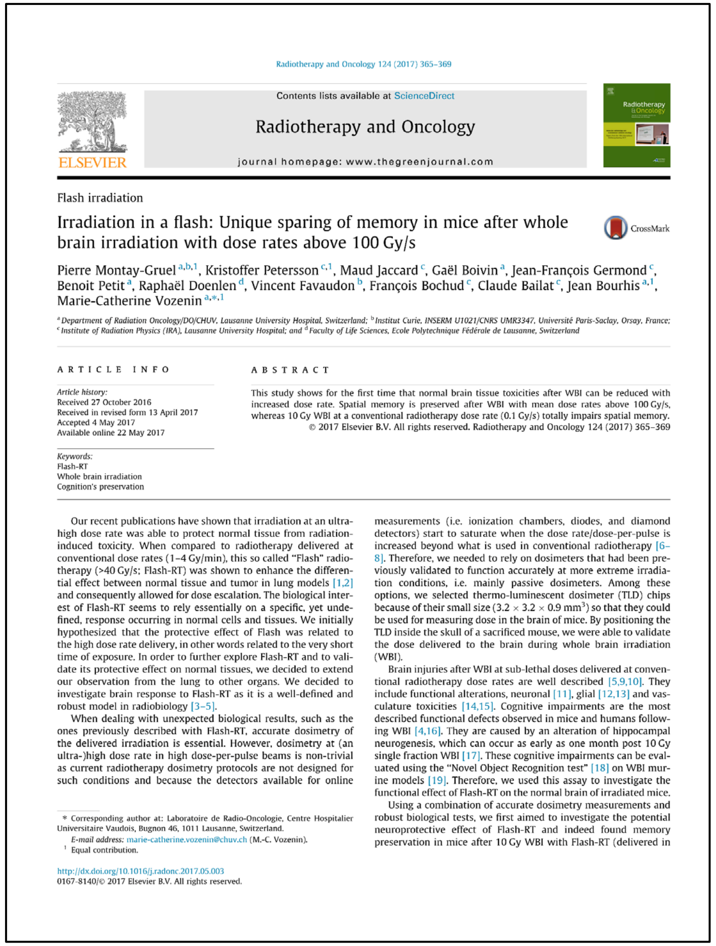

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Flash irradiation

Irradiation in a flash: Unique sparing of memory in mice after whole brain irradiation with dose rates above 100 Gy/s

Pierre Montay-Gruel[a,b,1], Kristoffer Petersson[c,1], Maud Jaccard[c], Gaël Boivin[a], Jean-François Germond[c], Benoit Petit[a], Raphaël Doenlen[d], Vincent Favaudon[b], François Bochud[c], Claude Bailat[c], Jean Bourhis[a,1], Marie-Catherine Vozenin[a,*,1]

[a] *Department of Radiation Oncology/DO/CHUV, Lausanne University Hospital, Switzerland;* [b] *Institut Curie, INSERM U1021/CNRS UMR3347, Université Paris-Saclay, Orsay, France;* [c] *Institute of Radiation Physics (IRA), Lausanne University Hospital; and* [d] *Faculty of Life Sciences, Ecole Polytechnique Fédérale de Lausanne, Switzerland*

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Cognition's preservation

ABSTRACT

This study shows for the first time that normal brain tissue toxicities after WBI can be reduced with increased dose rate. Spatial memory is preserved after WBI with mean dose rates above 100 Gy/s, whereas 10 Gy WBI at a conventional radiotherapy dose rate (0.1 Gy/s) totally impairs spatial memory.

Our recent publications have shown that irradiation at an ultra-high dose rate was able to protect normal tissue from radiation-induced toxicity. When compared to radiotherapy delivered at conventional dose rates (1–4 Gy/min), this so called "Flash" radiotherapy (>40 Gy/s; Flash-RT) was shown to enhance the differential effect between normal tissue and tumor in lung models [1,2] and consequently allowed for dose escalation. The biological interest of Flash-RT seems to rely essentially on a specific, yet undefined, response occurring in normal cells and tissues. We initially hypothesized that the protective effect of Flash was related to the high dose rate delivery, in other words related to the very short time of exposure. In order to further explore Flash-RT and to validate its protective effect on normal tissues, we decided to extend our observation from the lung to other organs. We decided to investigate brain response to Flash-RT as it is a well-defined and robust model in radiobiology [3–5].

When dealing with unexpected biological results, such as the ones previously described with Flash-RT, accurate dosimetry of the delivered irradiation is essential. However, dosimetry at (an ultra-)high dose rate in high dose-per-pulse beams is non-trivial as current radiotherapy dosimetry protocols are not designed for such conditions and because the detectors available for online measurements (i.e. ionization chambers, diodes, and diamond detectors) start to saturate when the dose rate/dose-per-pulse is increased beyond what is used in conventional radiotherapy [6–8]. Therefore, we needed to rely on dosimeters that had been previously validated to function accurately at more extreme irradiation conditions, i.e. mainly passive dosimeters. Among these options, we selected thermo-luminescent dosimeter (TLD) chips because of their small size (3.2 × 3.2 × 0.9 mm^3) so that they could be used for measuring dose in the brain of mice. By positioning the TLD inside the skull of a sacrificed mouse, we were able to validate the dose delivered to the brain during whole brain irradiation (WBI).

Brain injuries after WBI at sub-lethal doses delivered at conventional radiotherapy dose rates are well described [5,9,10]. They include functional alterations, neuronal [11], glial [12,13] and vasculature toxicities [14,15]. Cognitive impairments are the most described functional defects observed in mice and humans following WBI [4,16]. They are caused by an alteration of hippocampal neurogenesis, which can occur as early as one month post 10 Gy single fraction WBI [17]. These cognitive impairments can be evaluated using the "Novel Object Recognition test" [18] on WBI murine models [19]. Therefore, we used this assay to investigate the functional effect of Flash-RT on the normal brain of irradiated mice.

Using a combination of accurate dosimetry measurements and robust biological tests, we first aimed to investigate the potential neuroprotective effect of Flash-RT and indeed found memory preservation in mice after 10 Gy WBI with Flash-RT (delivered in

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[*] Corresponding author at: Laboratoire de Radio-Oncologie, Centre Hospitalier Universitaire Vaudois, Bugnon 46, 1011 Lausanne, Switzerland.
E-mail address: marie-catherine.vozenin@chuv.ch (M.-C. Vozenin).
[1] Equal contribution.

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Application of particle accelerators to cancer therapy are well known → x-ray sources, proton therapy, ion therapy

Late 2010s it was discovered that very high dose rates over a shorter period (much higher than conventional radiotherapy) preferentially treated cancer while sparing healthy tissue
→ `FLASH effect'

Not possible yet to combine hadron therapy with FLASH, but promising results achieved with high-energy electron beams

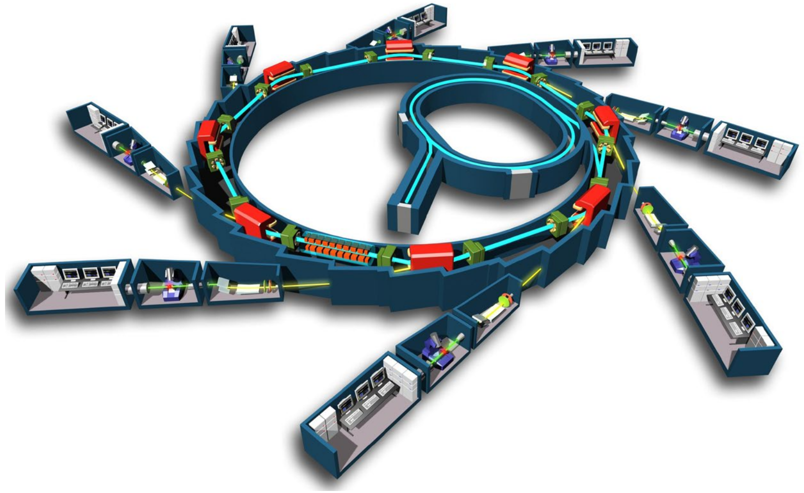
To be practical to install in existing hospital need to be able to produce high-quality high-energy electron beams in a compact form factor → similar criteria to the CLIC accelerating structures

Since 2020 CERN + Lausanne university hospital collaborating on development of treatment facility based on CLIC accelerating technology. Aims for clinical trials in 2025.

https://kt.cern/flash-radiotherapy

To reach multi-TeV scale energy in acceptable tunnel CLIC project developed novel high-gradient cavities (100MV/m) capable of accelerating high-current high-quality electron beams

→ Already delivering societal impact



Synchrotron light sources offer immense value to broad range of scientific research

→ **generally require relatively large facility**

Alternative is to produce high energy photons via inverse Compton scattering of laser light on high-energy electron beam

Smart light project aims to produce compact lab scale ICS light source using high-frequency high-gradient cavities modified/further developed on from CLIC R&D

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Smart*Light progress

CLIC workshop, 1 Oct 2020

Peter Mutsaers, Tom Lucas, Xavier Stragier, Linda Stoel, Wiebe Toonen, Ali Rajabi, Marco van der Sluis, Eddy Rietman, Harry van Doorn, Frans van Setten, Jom Luiten

Department of Applied Physics

Smart*Light: a LINAC-based ICS source

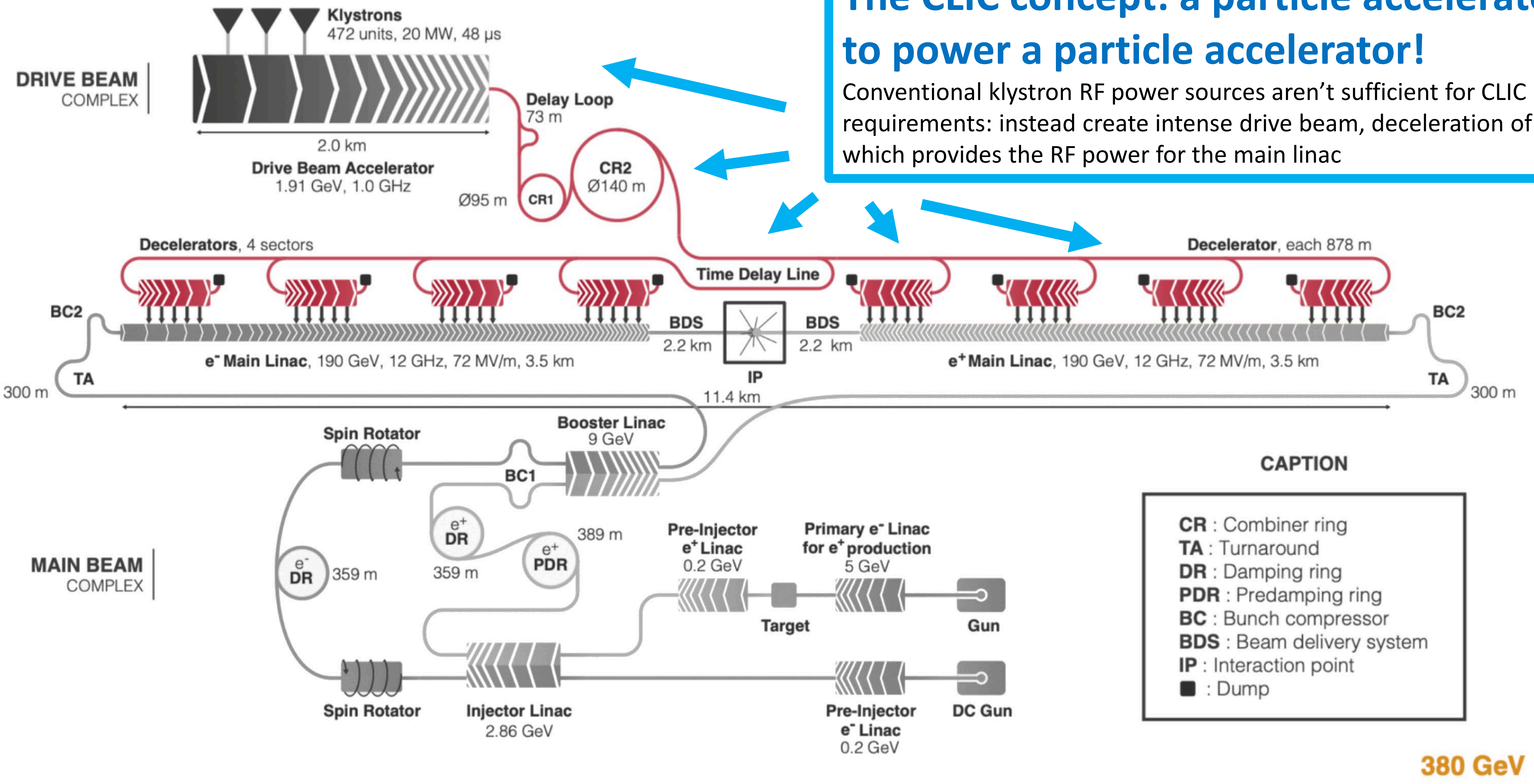
- Compact X-band technology
- Fast change of X-ray energy
- Scalable to higher energies by adding sections
- Modular: swap electron injector

13 CLIC workshop, 1 Oct 2020 TU/e

https://indico.cern.ch/event/952778/contributions/4013809/

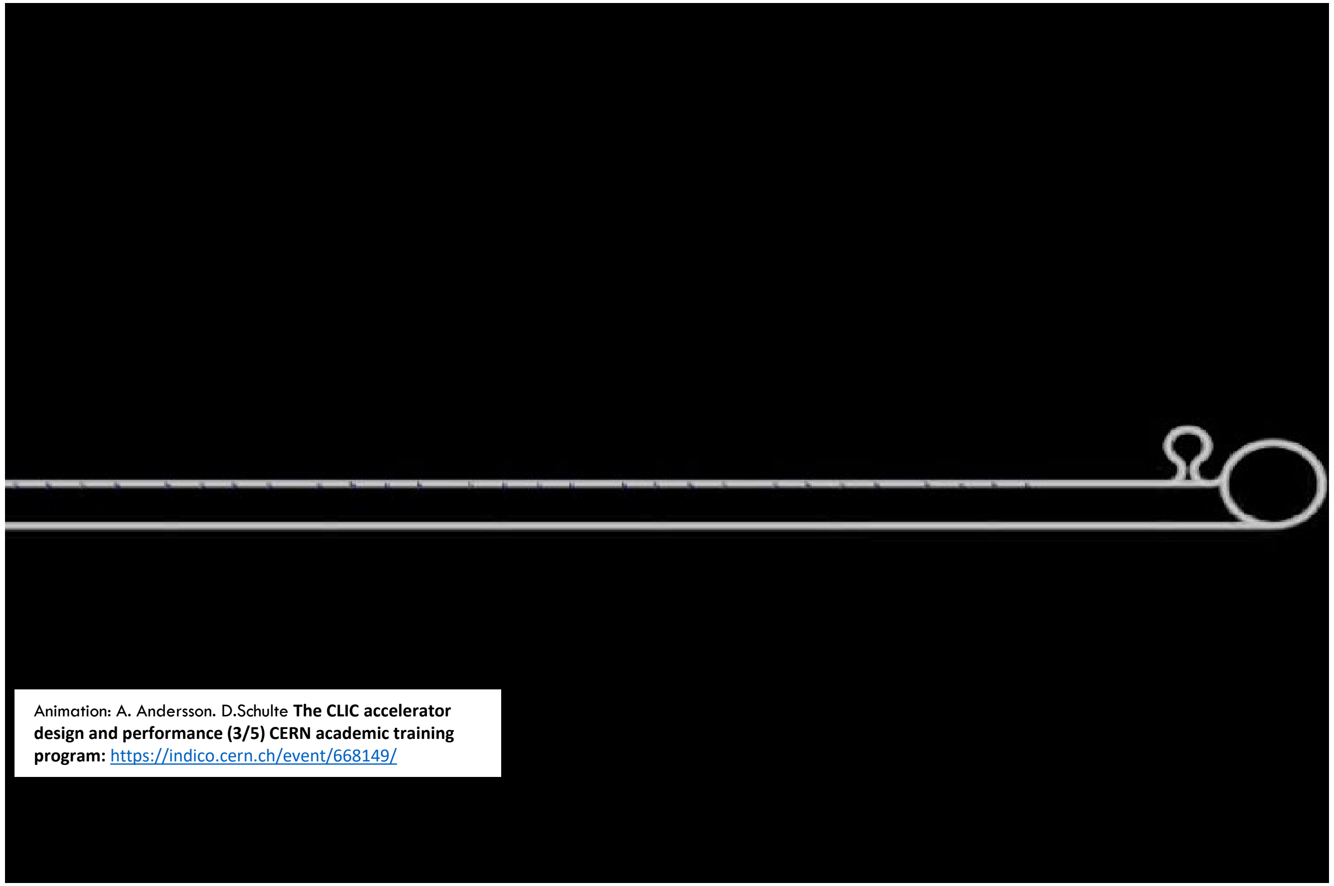
The CLIC concept: a particle accelerator to power a particle accelerator!

Conventional klystron RF power sources aren’t sufficient for CLIC requirements: instead create intense drive beam, deceleration of which provides the RF power for the main linac

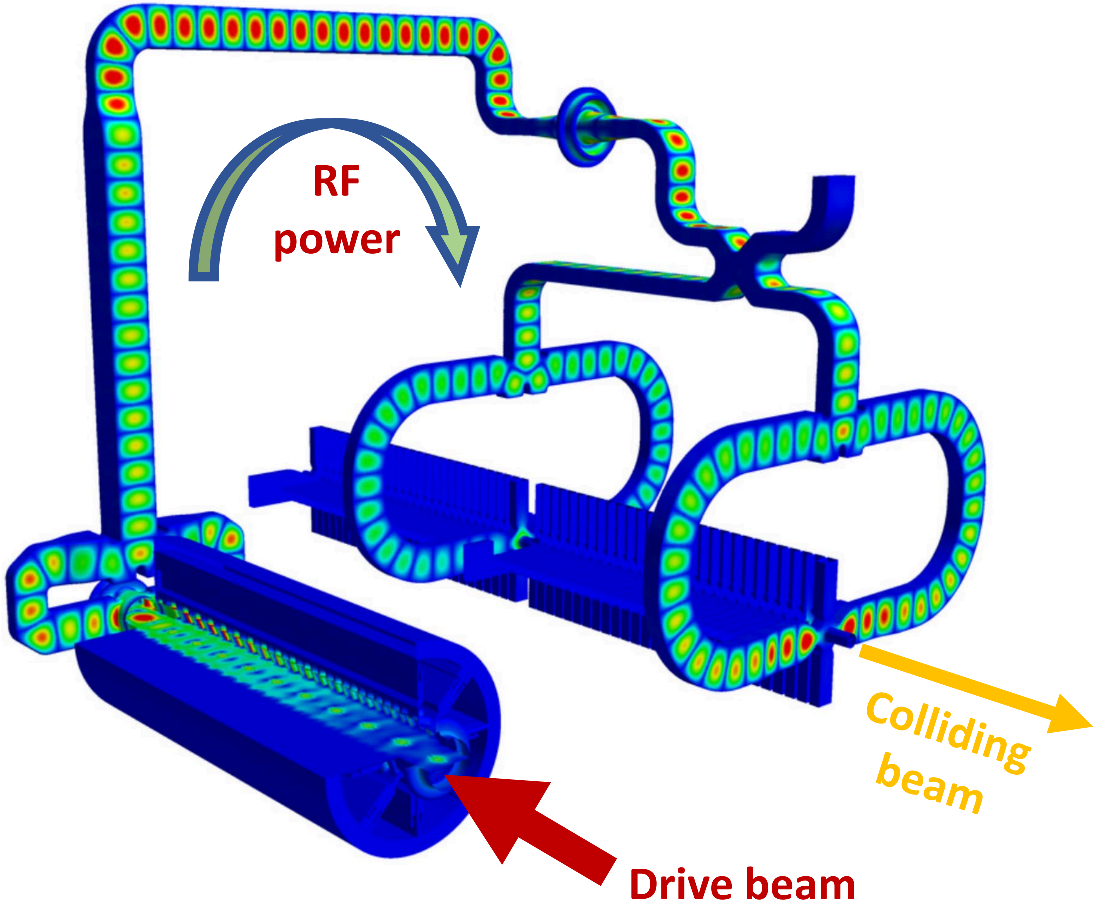


Conventional klystron sources can't produce the short-pulse high-RF power needed to drive the 100MV/m CLIC cavities*

- CLIC concept uses Klystrons to produce a low-energy high-current drive beam, then decelerated to produce RF power for the main linac
- Bunches in the drive beam concentrated by passing through multiple delay loops
- Pass through series of decelerating cavities which extract RF power from the drive beam, transfer it over to the main accelerating cavities



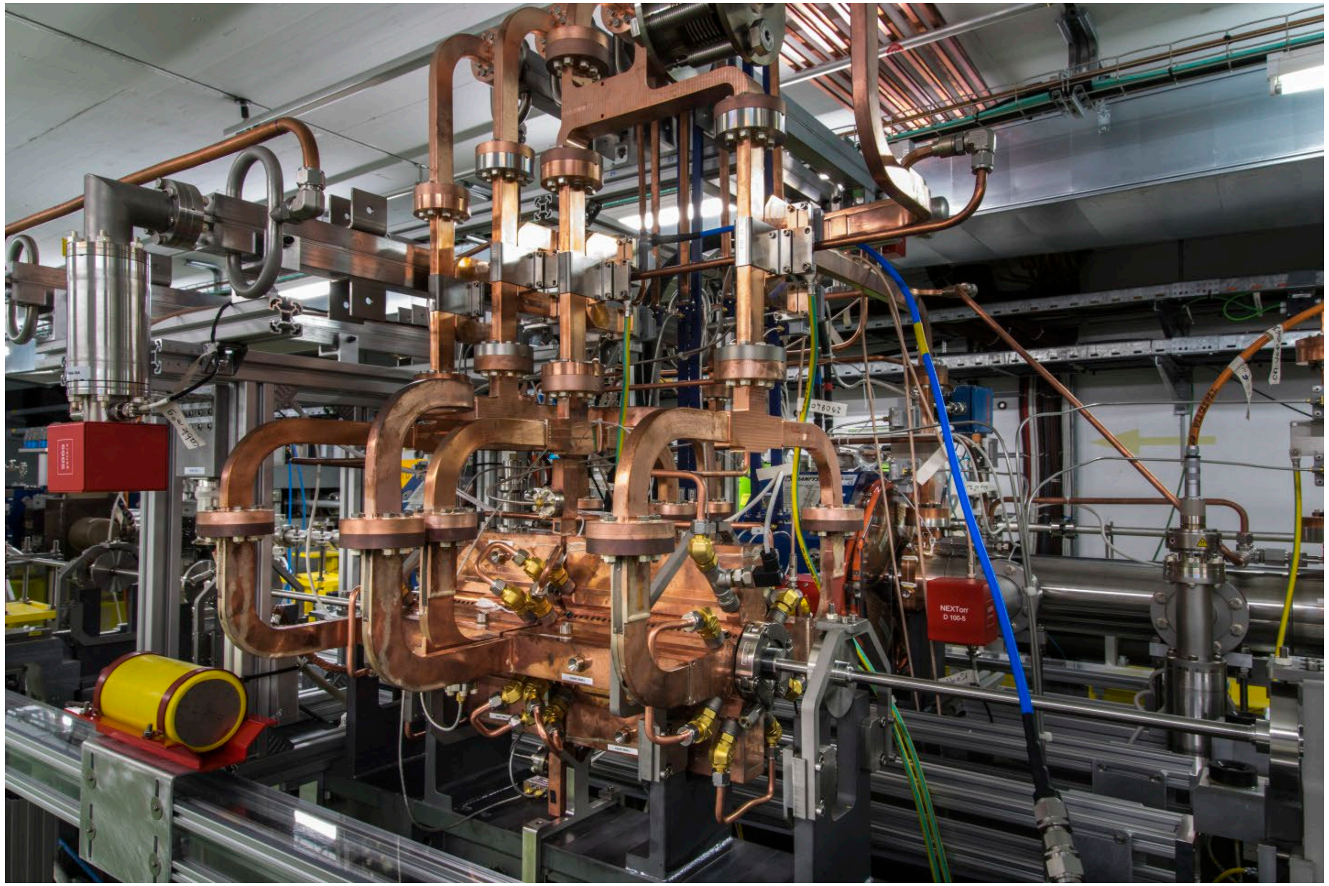
Animation: A. Andersson. D.Schulte **The CLIC accelerator design and performance (3/5) CERN academic training program:** https://indico.cern.ch/event/668149/



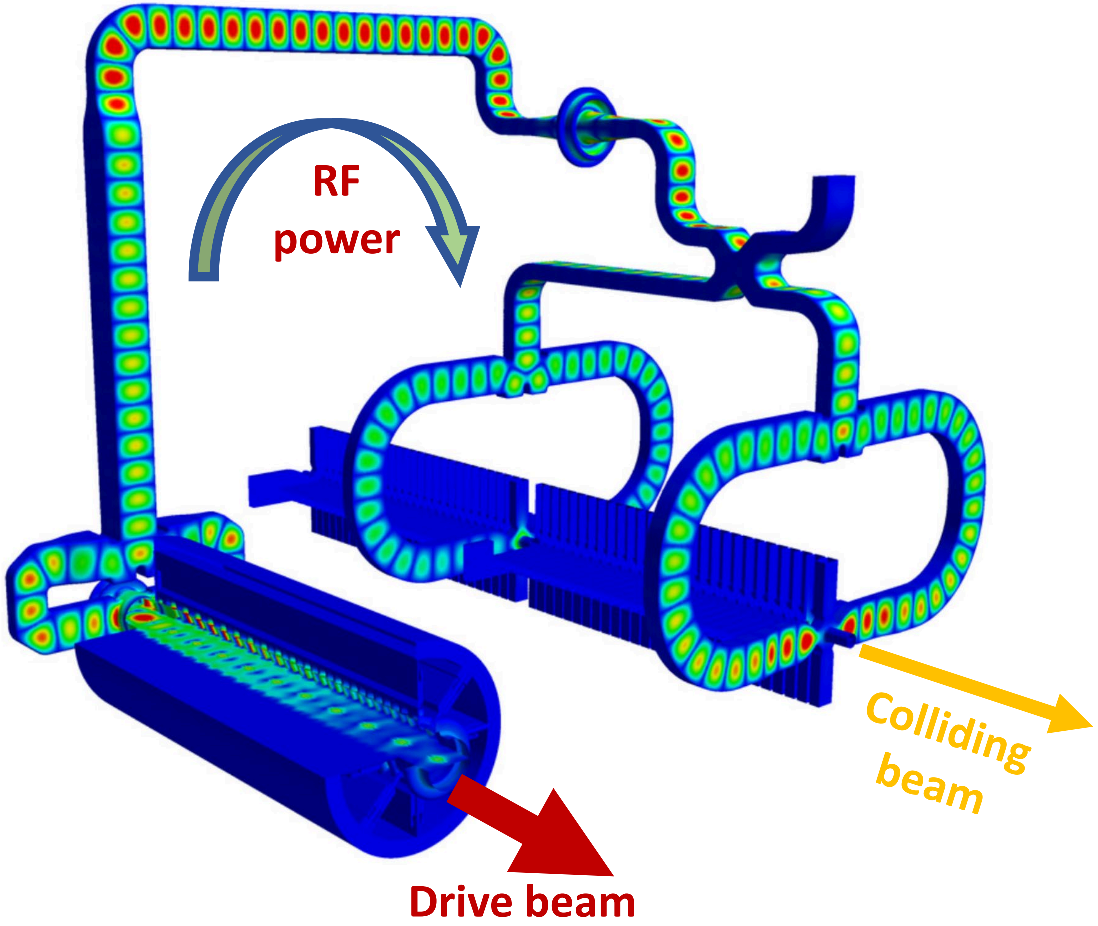
*(A potential klystron option could be considered for 380GeV at expense of larger tunnel and increased upgrade cost)

Conventional klystron sources can't produce the short-pulse high-RF power needed to drive the 100MV/m CLIC cavities*

- CLIC concept uses Klystrons to produce a low-energy high-current drive beam, then decelerated to produce RF power for the main linac
- Two beam acceleration concept was successfully demonstrated at CLIC Test Facility 3 (CTF3) !



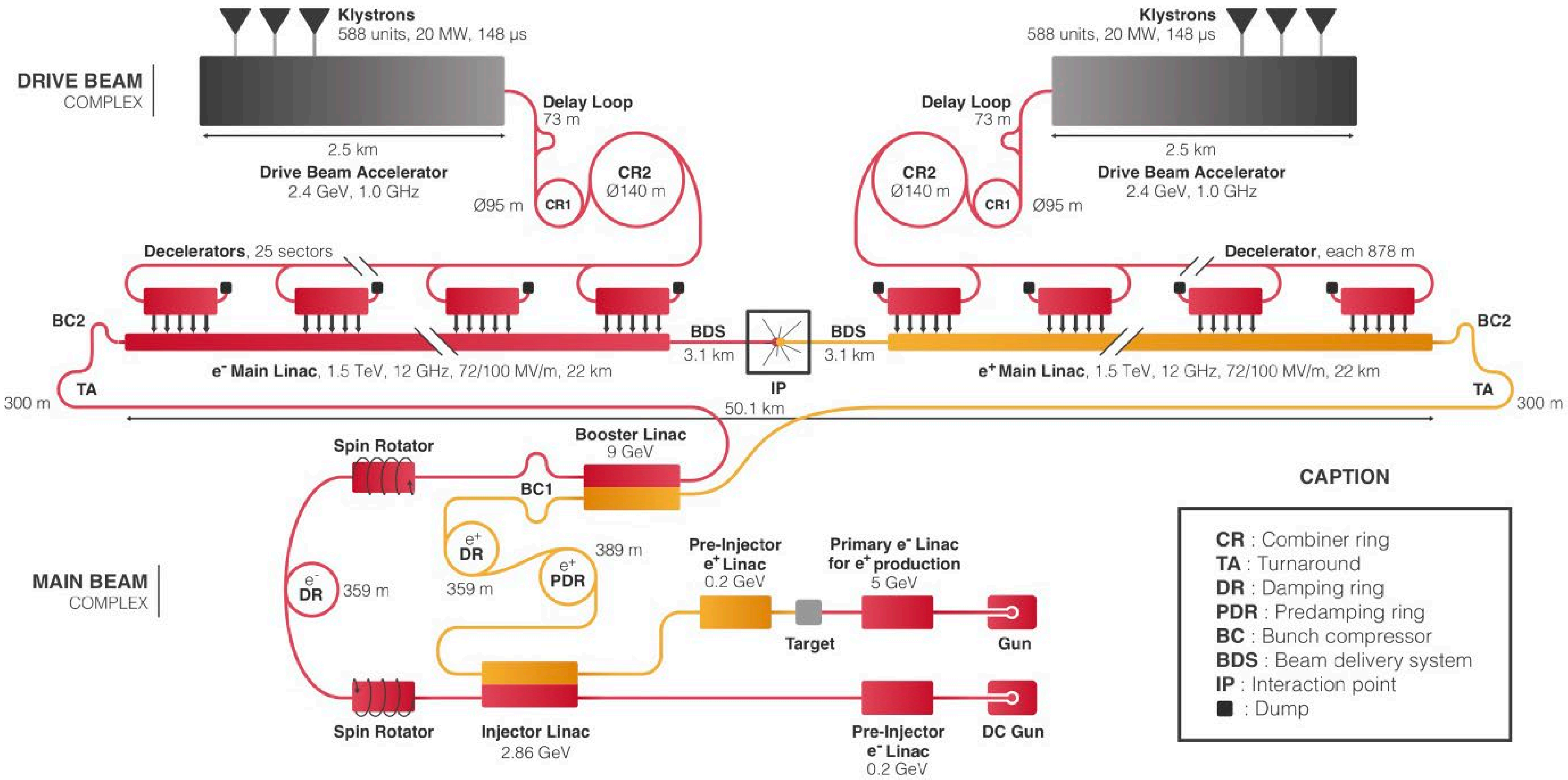
CTF3: CLIC PETS and accelerating structure



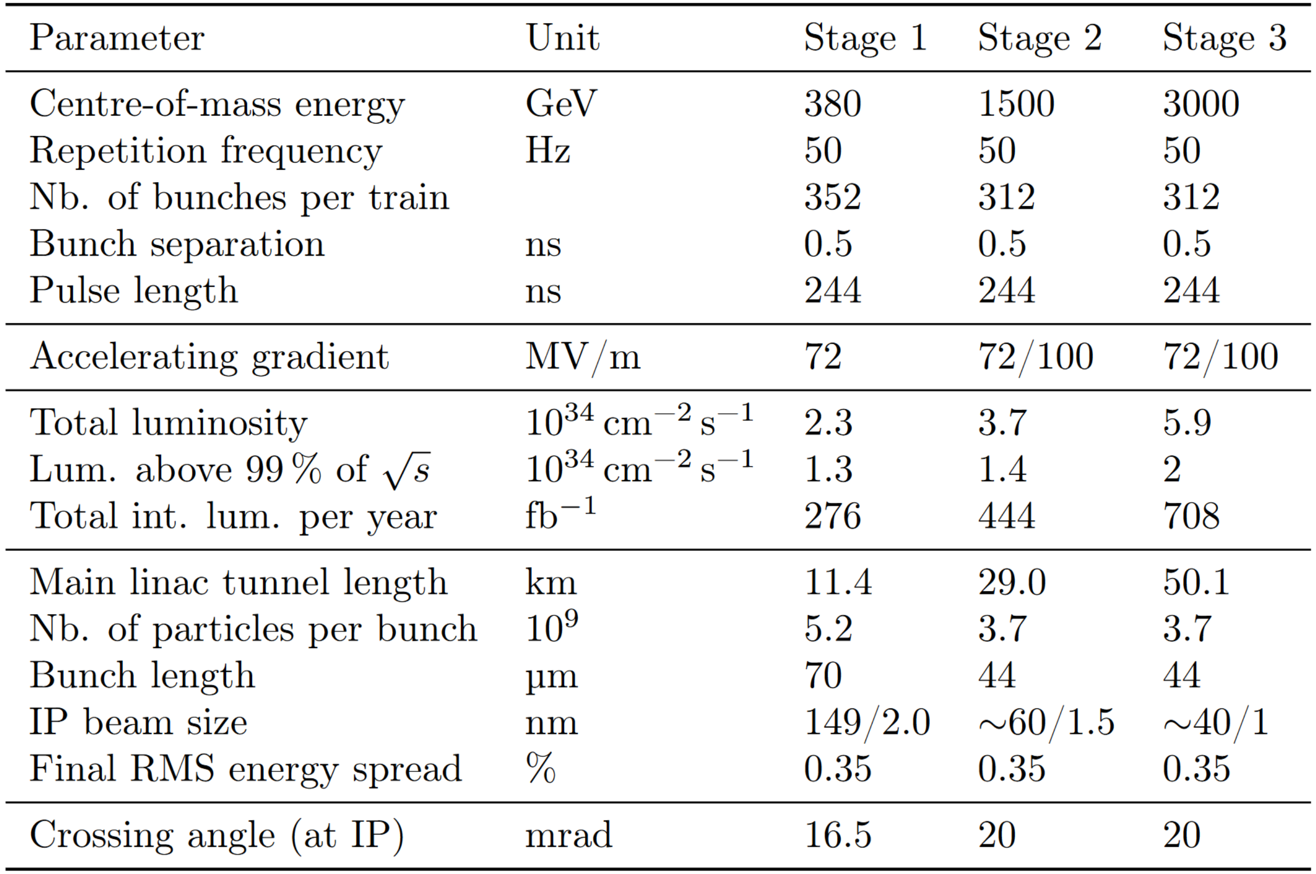
*(A potential klystron option could be considered for 380GeV at expense of larger tunnel and increased upgrade cost)

CLIC at 3TeV

Second drive beam required for full energy reach



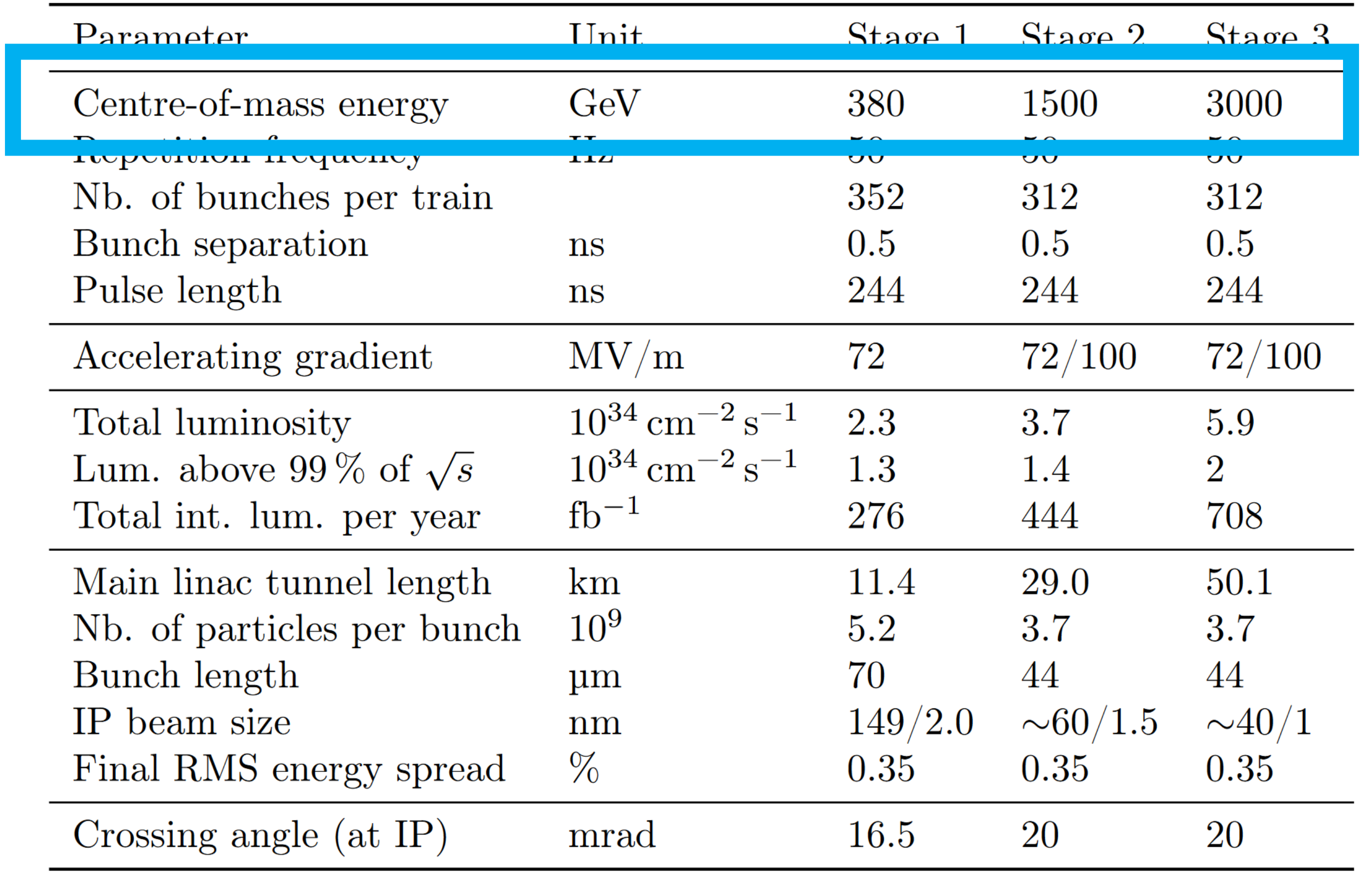
What does CLIC plan to achieve?



Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	10^9	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

What does CLIC plan to achieve?

→ Staged increase in energy up to 3TeV



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Why stop at 3TeV?

- Cost… Practicality of tunnel length…
- **\`Beamstrahlung' (SR at the IP produced in the field of the opposing beam)**
- Even in linear collider SR results in diminishing return w.r.t luminosity at top energy above 1TeV

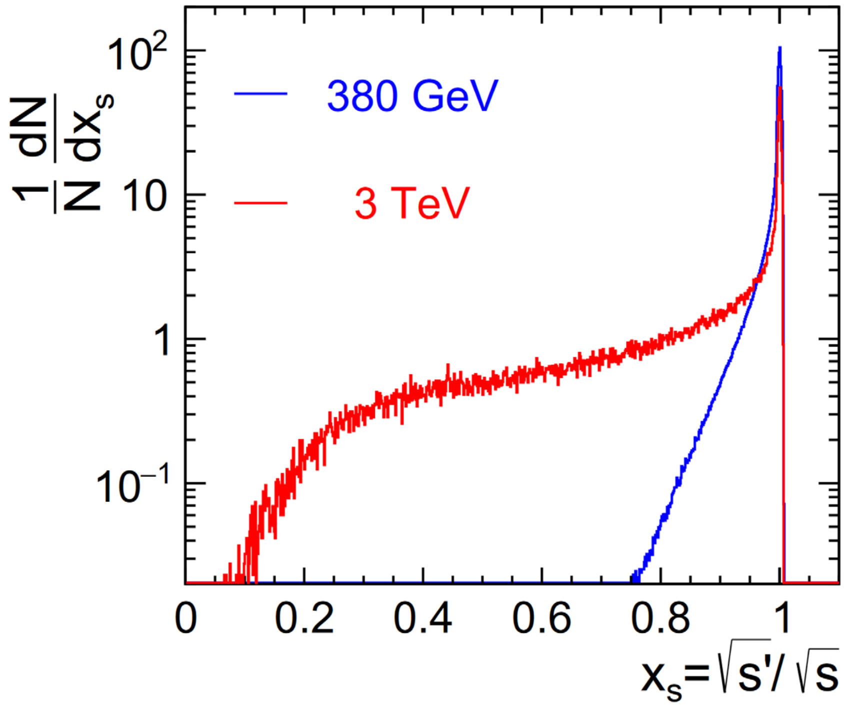

Figure 1: The luminosity spectra for CLIC operating at $\sqrt{s} = 380\,\mathrm{GeV}$ and 3 TeV, where x_s denotes the ratio of the effective centre-of-mass energy after beamstrahlung, $\sqrt{s'}$, to the nominal centre-of-mass energy $\sqrt{s}$ [4].

Top-Quark Physics at the CLIC Electron-Positron Linear Collider
https://arxiv.org/pdf/1807.02441.pdf

What does CLIC plan to achieve?

Linear colliders likely target lowest target luminosity of future proposals

→ Relatively low e/bunch to keep RF power down

→ But collide polarized e-bunch

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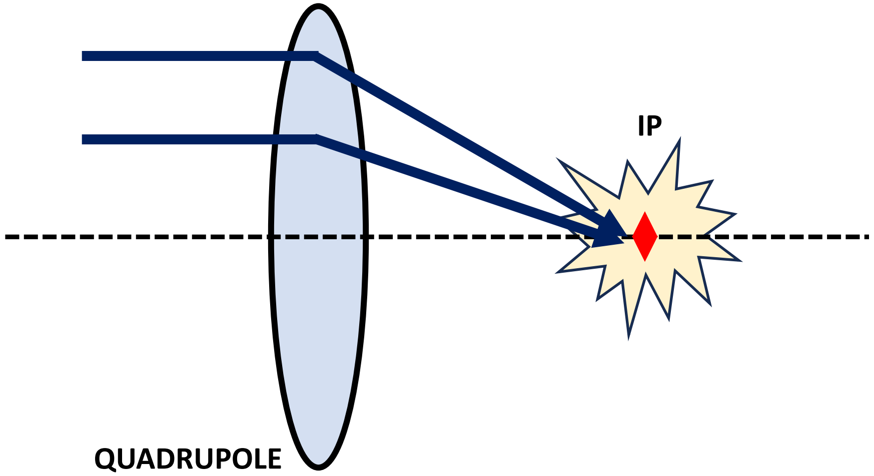
Why not just squeeze beams more?

→ **"Oide effect"**

K. Oide, Phys. Rev. Lett. 61, 1713 (1988)

→ Emission of SR from particle deflection in the final focus quadrupoles limits beamsize at IP



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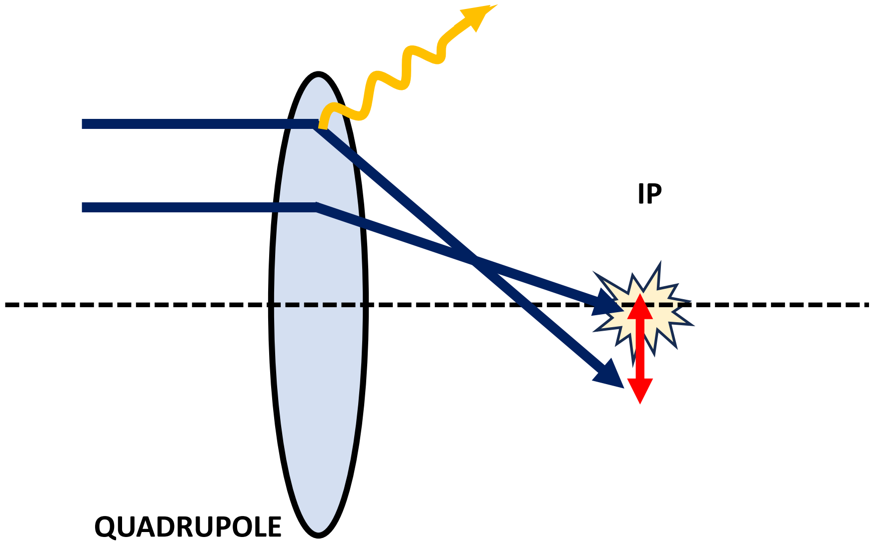

What does CLIC plan to achieve?

Most recent cost estimates for 380GeV option in from 2018

→ **NOT ADJUSTED FOR INFLATION OR LABOUR COST CHANGED**

→ **Approximately 6000-7000 MCHF for stage 1**

Parameter	Unit	Stage 1	Stage 2	Stage 3
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Repetition frequency	Hz	50	50	50
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Crossing angle (at IP)	mrad	16.5	20	20

Upgrades to stage 1→2 & 2→3 estimated at approximately 5000 MCHF & 7000 MCHF

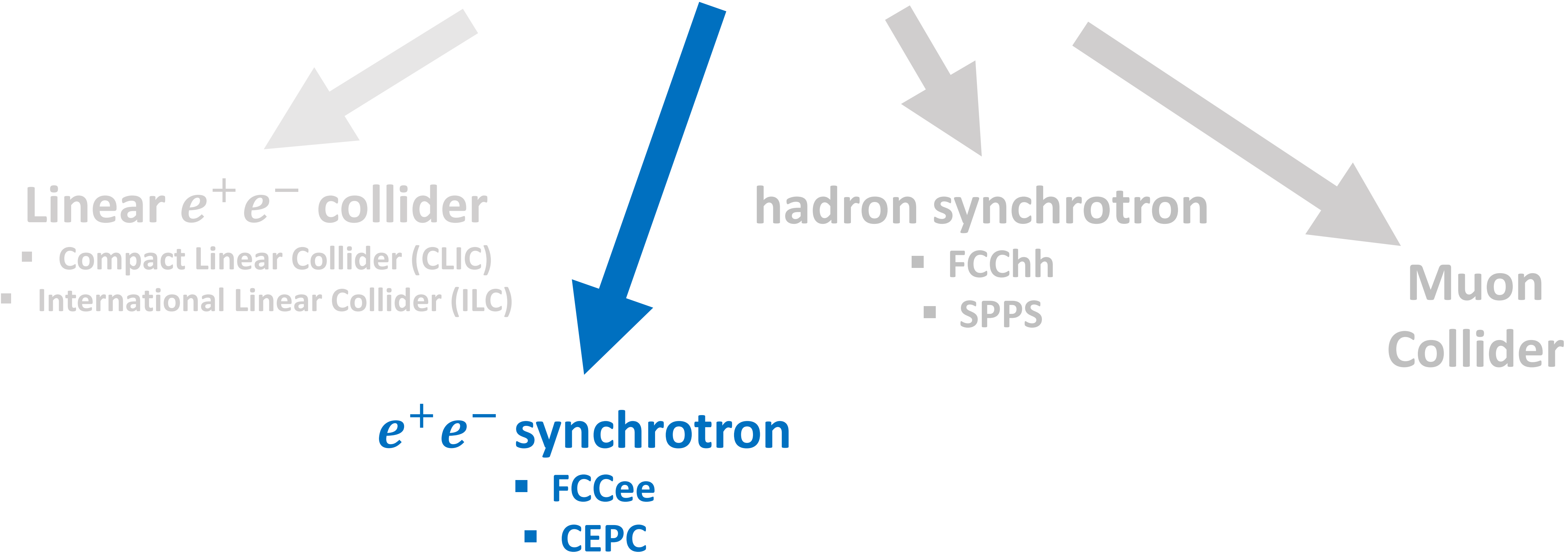
→ **NOT ADJUSTED FOR INFLATION OR LABOUR COST**

Power estimates from most recent (2022) snowmass summary report

Collision energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	110	25	9
1500	364	38	13
3000	589	46	17

Collision energy [GeV]	Annual Energy Consumption [TWh]
380	0.6
1500	1.8
3000	2.8

Future colliders?



Linear e^+e^- collider

- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

e^+e^- synchrotron

- FCCee
- CEPC

hadron synchrotron

- FCChh
- SPPS

Muon Collider

Synchrotron colliders: a pathway to luminosity frontier
e^+e^- collisions at high energy

Why an e^+e^- circular collider?

LHC discovered Higgs at relatively low mass, but no major hints of new physics at the TeV scale

Circular e^+e^- provides potential for high-precision studies at high-luminosity in energy range of known interest

- **One of highest priorities from European Strategy Review was precision study of Higgs**

Offers natural upgrade path to hadron-hadron collider which would facilitate high-luminosity exploration over largest energy spread of future options

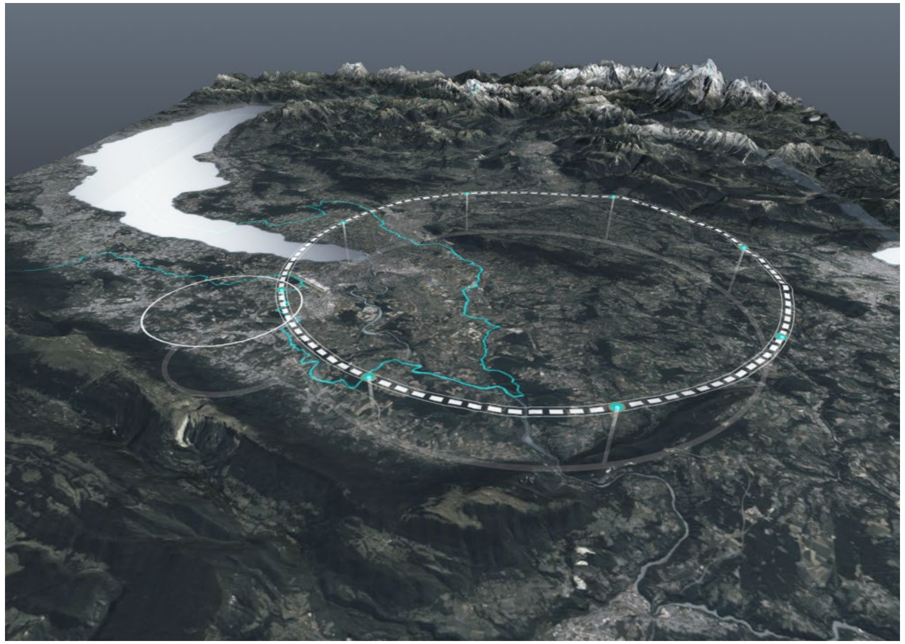
Circular e^+e^- machines can support most HEP experiments of any future collider option

- **Up to 4 experimental insertions on the same collider ring**

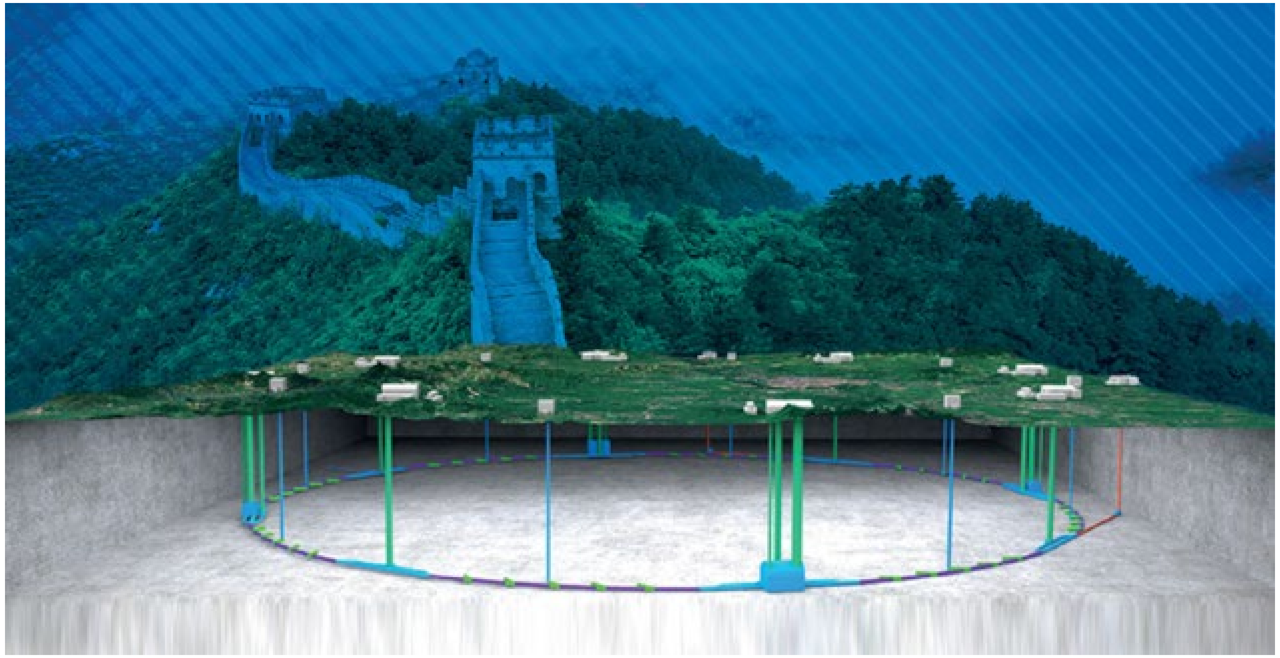
Synchrotron colliders: a pathway to luminosity frontier
e^+e^- collisions at high energy

Two main proposals

Future Circular Collider (FCCee) @ CERN



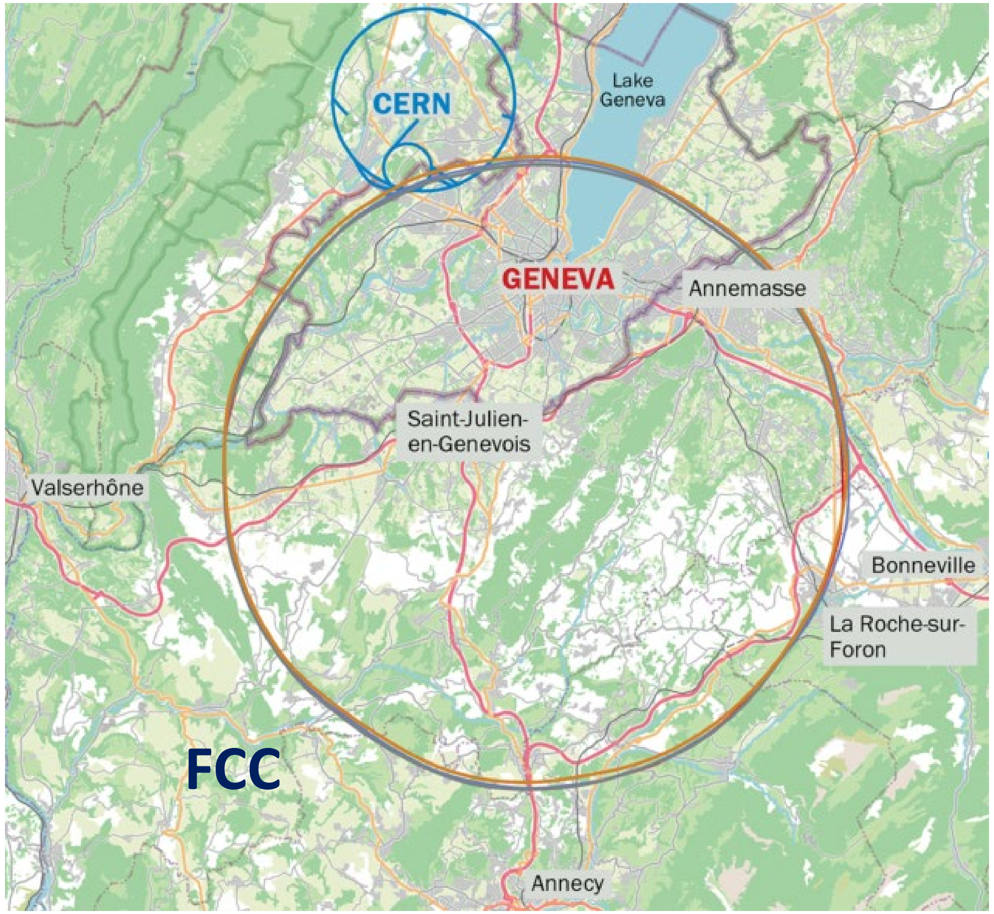
Circular Electron Positron Collider (CEPC) @ China

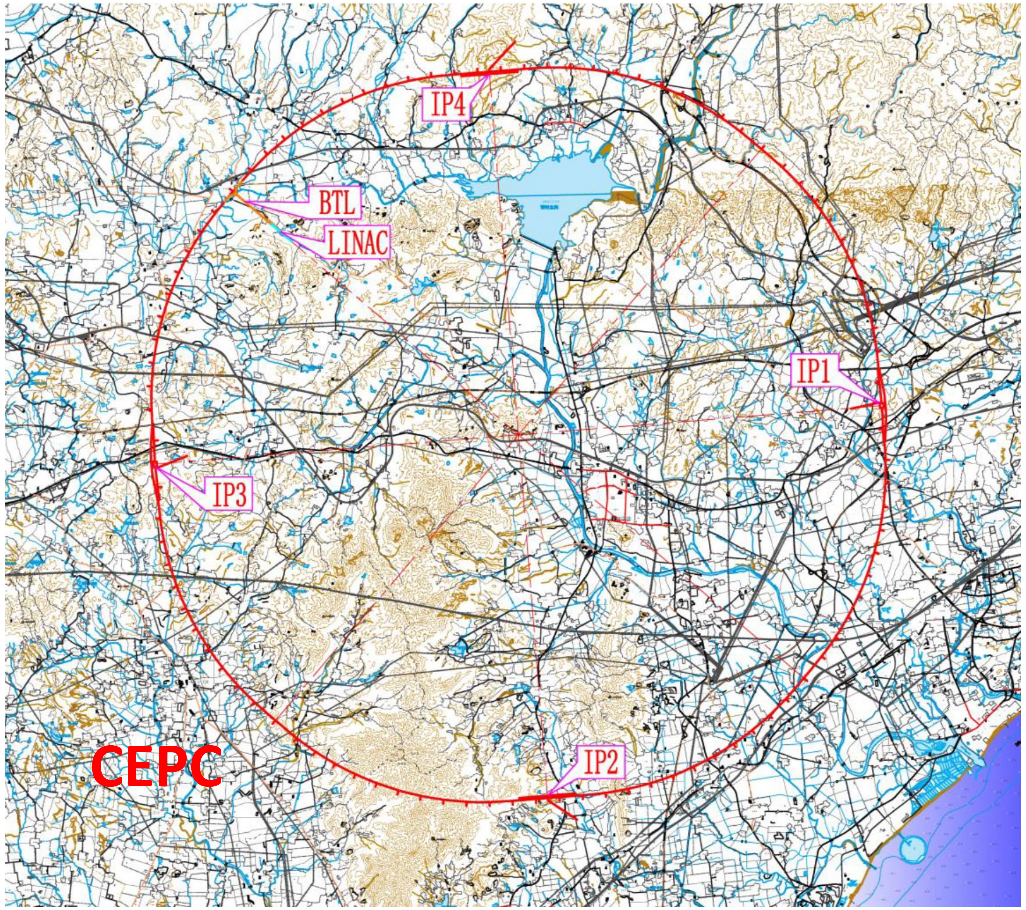


FCC: 90.6km ring building on existing CERN infrastructure
Similar C.O.M. energy range 90 - 365
Similar Luminosities / IP
FCC hosts 4 experimental insertions

CEPC: 100km greenfield site with larger tunnel aperture
Similar C.O.M. energy range 90 - 365
Similar Luminosities / IP
CEPC hosts 2 experimental insertions

Baseline is to collide unpolarized beams: equivalent info via high-lumi & achieving high longitudinal polarization would reduce lumi

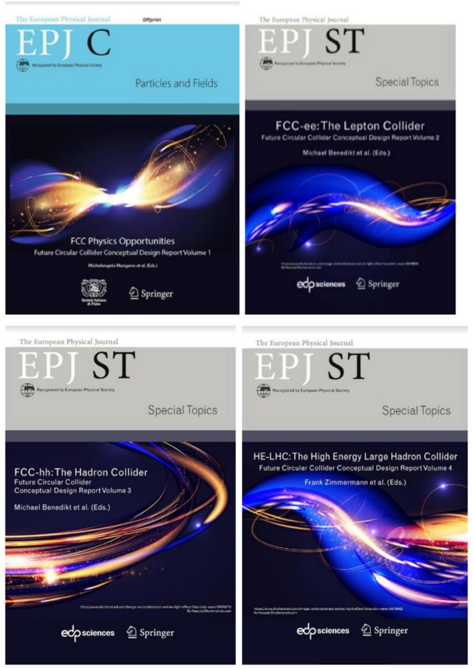




Both FCCee and CEPC are very mature projects

(FCCee = lowest risk classification in 2021 Snowmass, CEPC not reviewed)

- **FCC CDR published in 2018** https://fcc-cdr.web.cern.ch/
- **Detailed feasibility and implementation study ongoing**
  → mid term report released in Feb
  → final results of Feasibility Study expected in 2025
- **Viability as a design constraint**
  → design building on significant body of global experience from previous colliders and light source community to achieve ambitious but low risk baseline
- **No purpose build demonstrators for FCCee/CEPC but significant cross-over work with e.g. superKEK, LightSources**



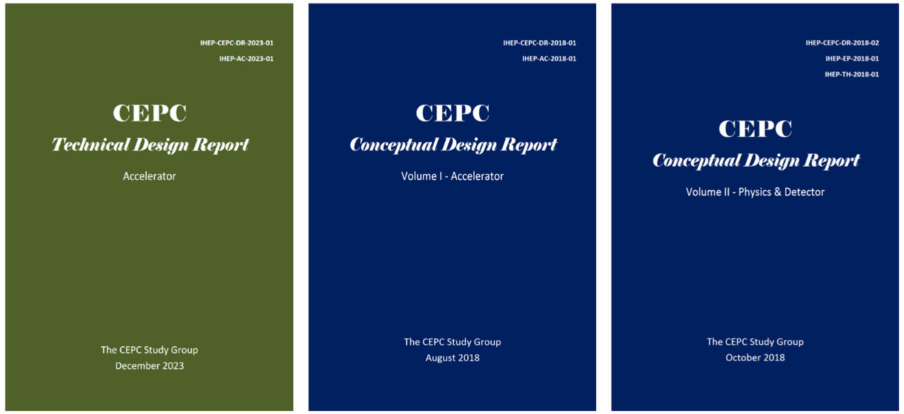
The European Physical Journal
EPJ C
Particles and Fields
FCC Physics Opportunities
Future Circular Collider Conceptual Design Report Volume 1
Springer

The European Physical Journal
EPJ ST
Special Topics
FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2
Michael Benedikt et al. (Eds.)
edp sciences Springer

The European Physical Journal
EPJ ST
Special Topics
FCC-hh: The Hadron Collider
Future Circular Collider Conceptual Design Report Volume 3
Michael Benedikt et al. (Eds.)
edp sciences Springer

The European Physical Journal
EPJ ST
Special Topics
HE-LHC: The High Energy Large Hadron Collider
Future Circular Collider Conceptual Design Report Volume 4
Frank Zimmermann et al. (Eds.)
edp sciences Springer

- **CEPC published CDR in 2018** http://cepc.ihep.ac.cn/CEPC_CDR_Vol1_Accelerator.pdf
- **CEPC published TDR in Dec 2023** http://cepc.ihep.ac.cn/CEPC_tdr.pdf



IHEP-CEPC-DR-2023-01
IHEP-AC-2023-01
CEPC
Technical Design Report
Accelerator
The CEPC Study Group
December 2023

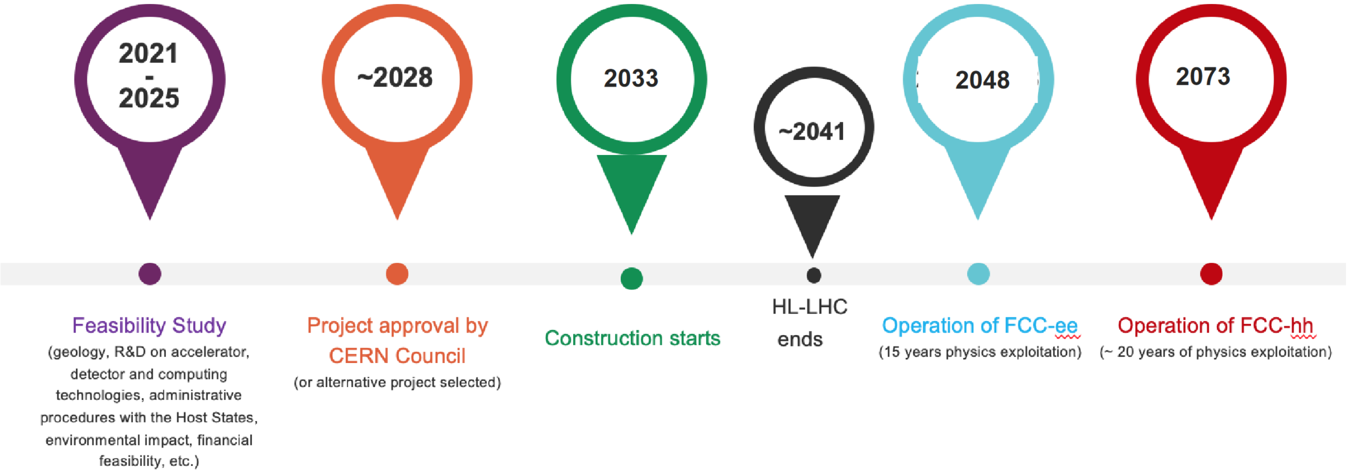
IHEP-CEPC-DR-2018-01
IHEP-AC-2018-01
CEPC
Conceptual Design Report
Volume I - Accelerator
The CEPC Study Group
August 2018

IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01
CEPC
Conceptual Design Report
Volume II - Physics & Detector
The CEPC Study Group
October 2018

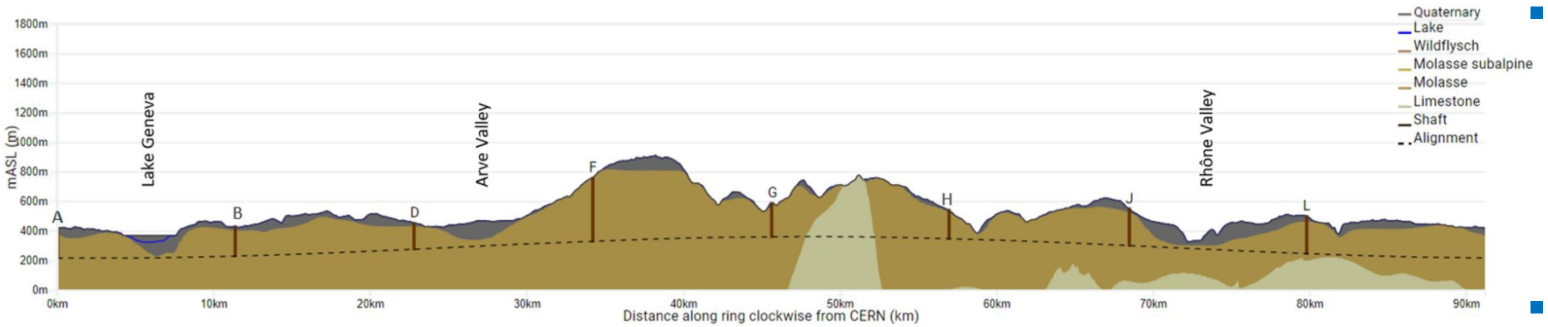
Project status/timeline for CEPC and FCCee

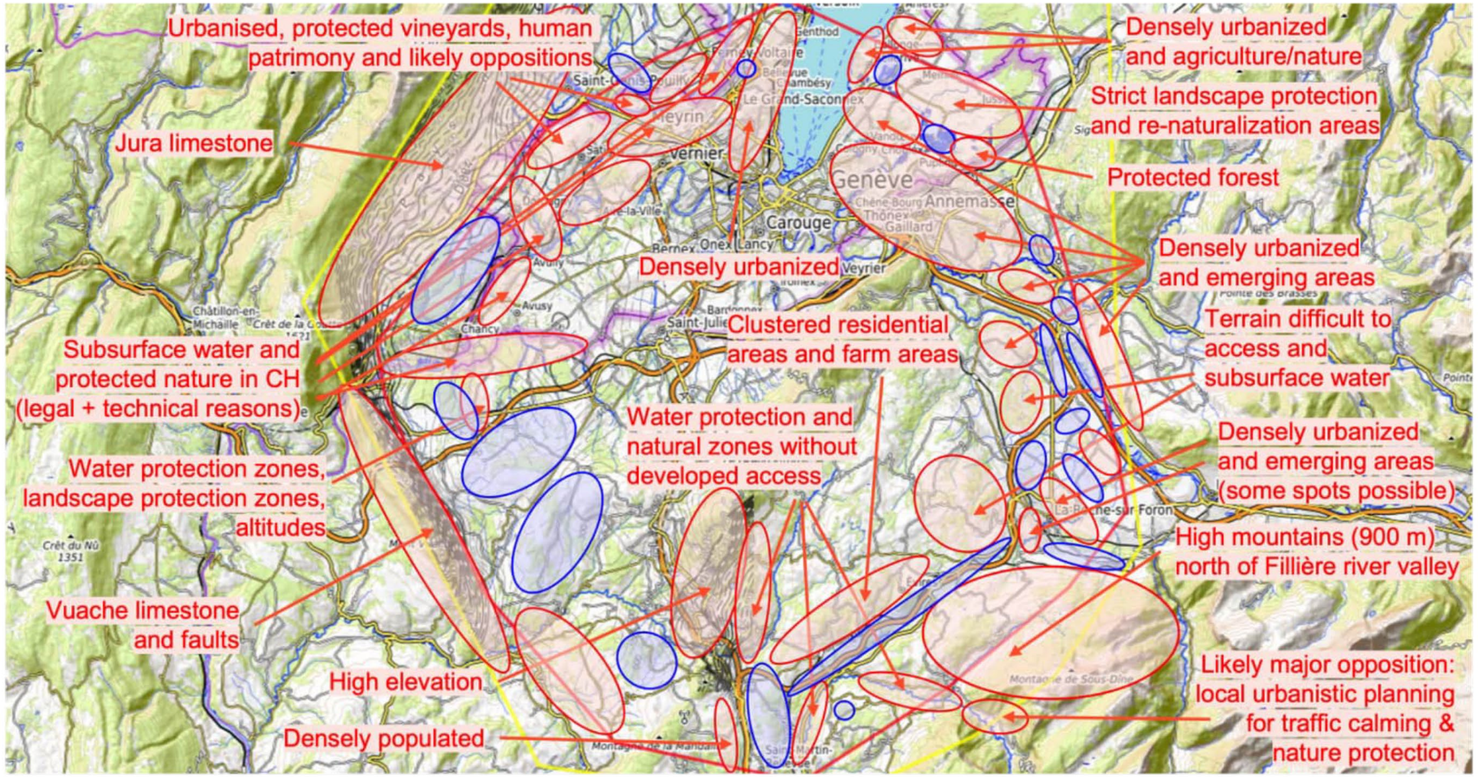
- **Following publication of accelerator TDR at end of 2023, CEPC collaboration aims to seek project approval at next 5-year plan (2025)**
- **CEPC TDR estimate construction could begin 2027.**

- **FCCee timeline more conservative. Aim to begin operation several years after end of HL-LHC. Collaboration proposed a *realistic FCC timeline* based on previous experience of CERN approval and construction**
- **Significant interest in advancing timeline to seek approval and begin construction earlier**



Why 91km for the FCC? → challenging to find suitable site without compromising performance





J.Gutleber Reference implementation scenario & work with the host states, FCC week 2023, https://indico.cern.ch/event/1202105/contributions/5423506/

- **Developing from existing CERN site allows FCCee and FCChh to utilize existing infrastructure: accelerator, electrical, cryogenic…**
  → substantial cost savings vs greenfield
  → one of the key issues with SSC project in US

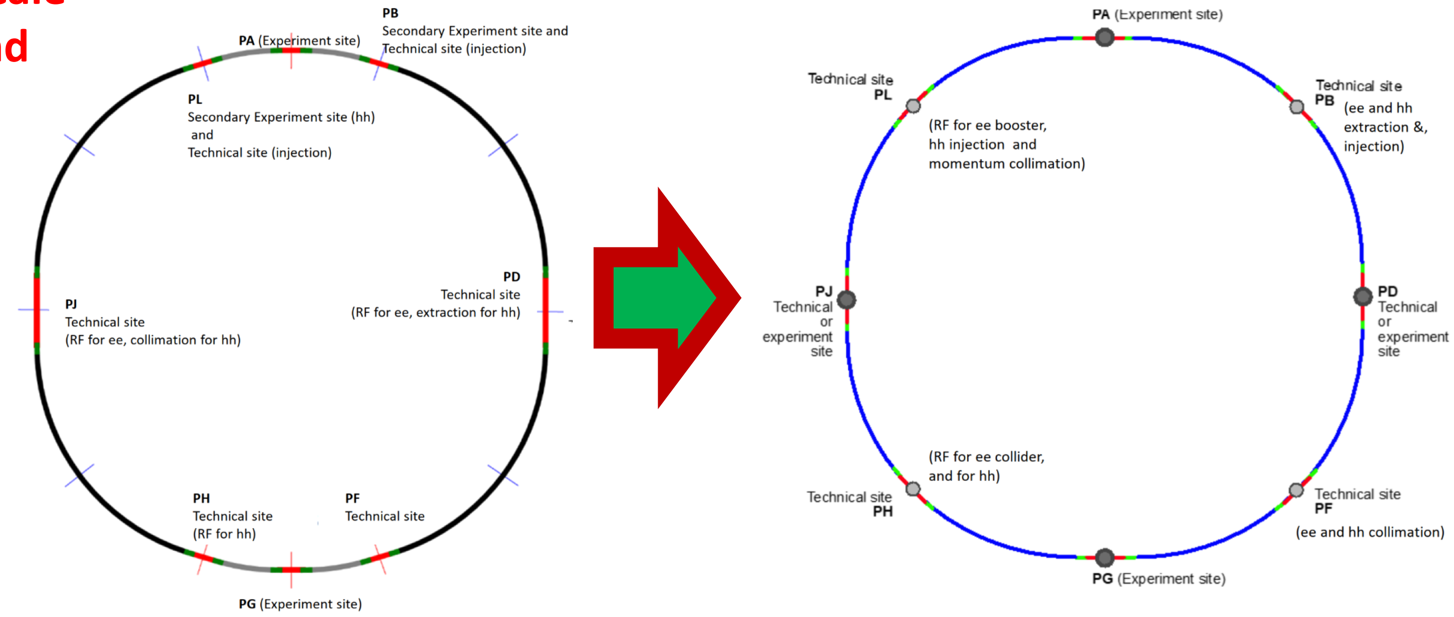
- **Geology:**
  → geometry limited by nearby mountain ranges
  → avoid tunnelling too deep for access shafts
  → avoid extensive regions of e.g. limestone
  → remain in shallow region of lake Geneva

- **Social / legal / practical**
  → many protected areas where civil construction not permitted
  → highly urbanized areas
  → viability of access + new infrastructure
  → minimize new infrastructure requirements e.g. new road construction…

Why 91km for the FCC?

Original CDR design for FCCee: 97km, 12 insertions, 2 experiments, 2-fold superperiodicity

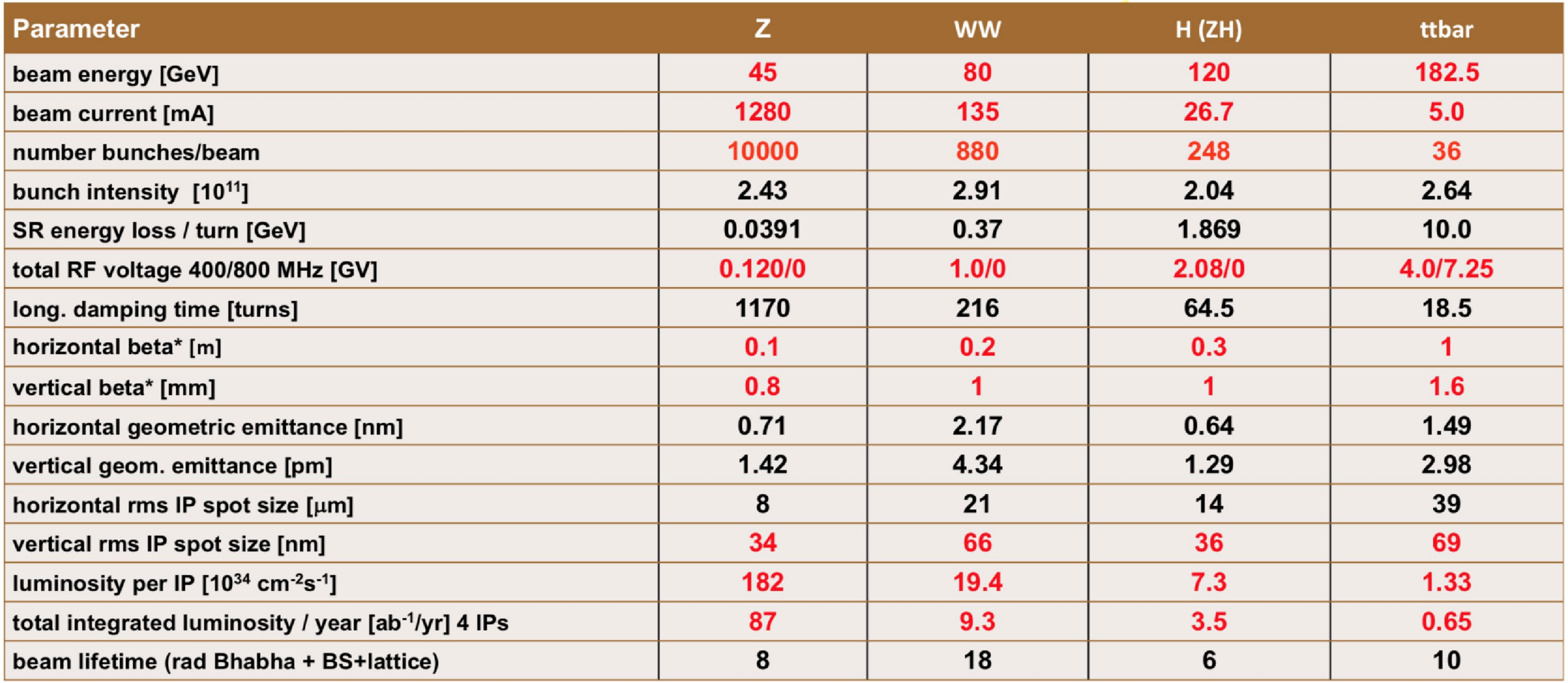
- **After studying 100s of possible machine layouts no viable $\geq 97\text{km}$ options were found**
- **Located 1 particularly scientifically promising + low-risk site with : 91km, 8 insertions, 4 experiments, 4-fold superperiodicity, various additional benefits/flexibility for e.g. FCChh beam dynamics**
- **Land use in Geneva basin evolves rapidly: even since start of study lost option for any 12-IP layouts in 90-100km range**
- **If we want to build an accelerator on >90km scale at CERN site it will be important to reserve land for surface site use relatively rapidly**



What does FCCee expect to achieve? (subject to ongoing optimization, precise numbers will vary)

Latest cost estimates put construction of the accelerator around 12.5 billion CHF (≈1/2 of that civil engineering)

+ 1.5 billion CHF for tt energy upgrade

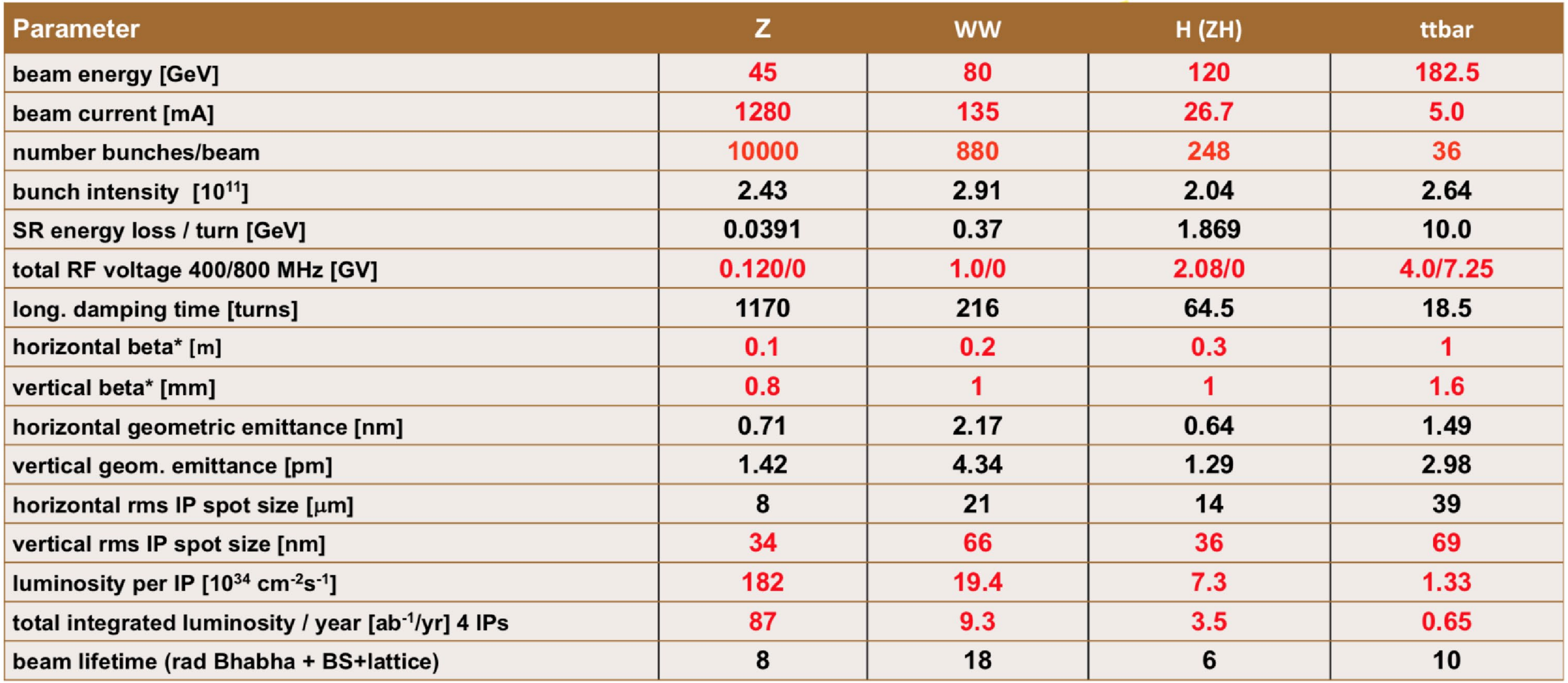


Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10

M.Benadikt, FCC week 2023 https://indico.cern.ch/event/1202105/contributions/5423504/attachments/2659109/4606291/230605_FCC-FS-Status_ap.pdf

What does FCCee expect to achieve? (subject to ongoing optimization, precise numbers will vary)

Staged multi-year operation over energy regimes around COM ≈ 88 - 365GeV (with RF upgrade for tt)



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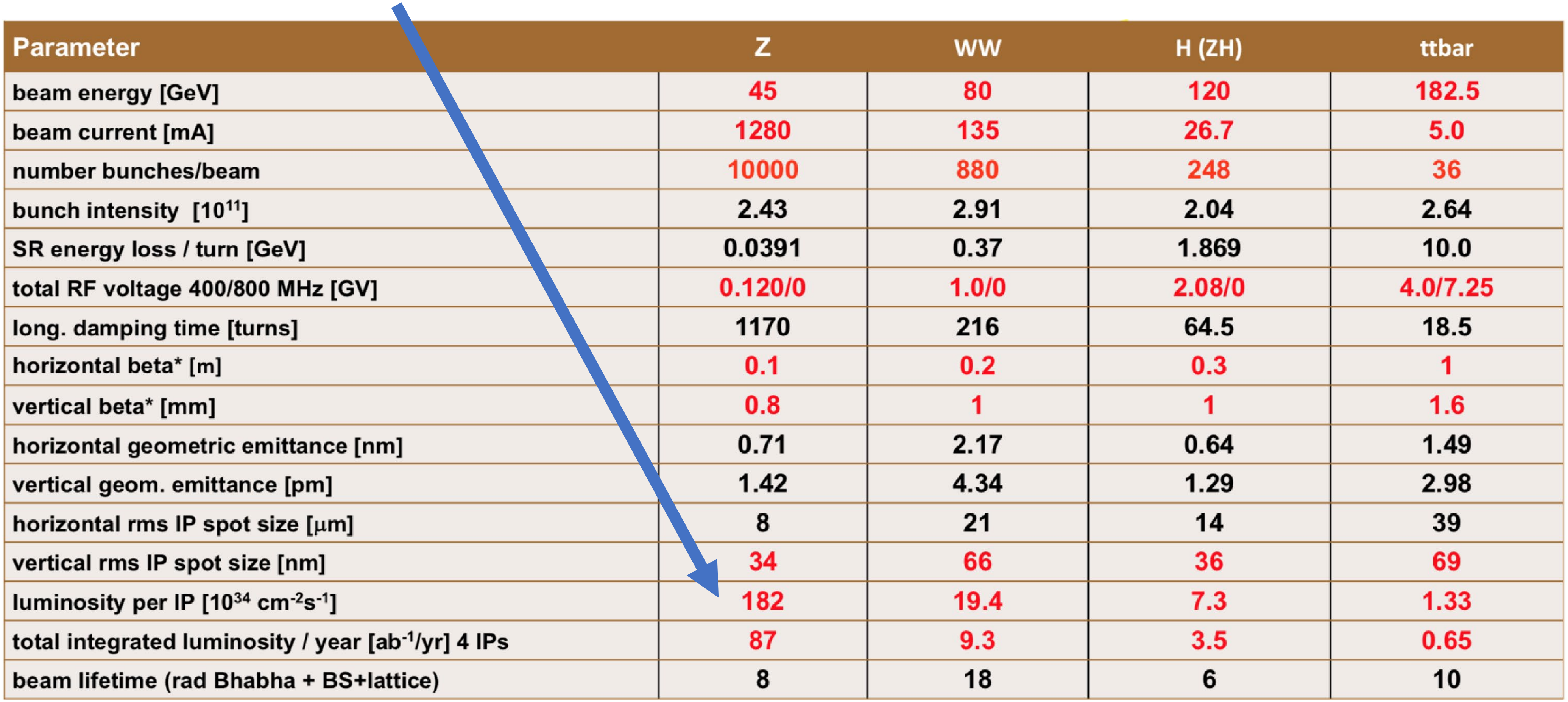
What does FCCee expect to achieve? (subject to ongoing optimization, precise numbers will vary)

Huge luminosity, particularly at lower energy e.g. : **`TeraZ program' → produce 5e12 Z in 4year run – LEP every few minutes!**

2 orders of magnitude more luminosity than LHC or any previous collider!



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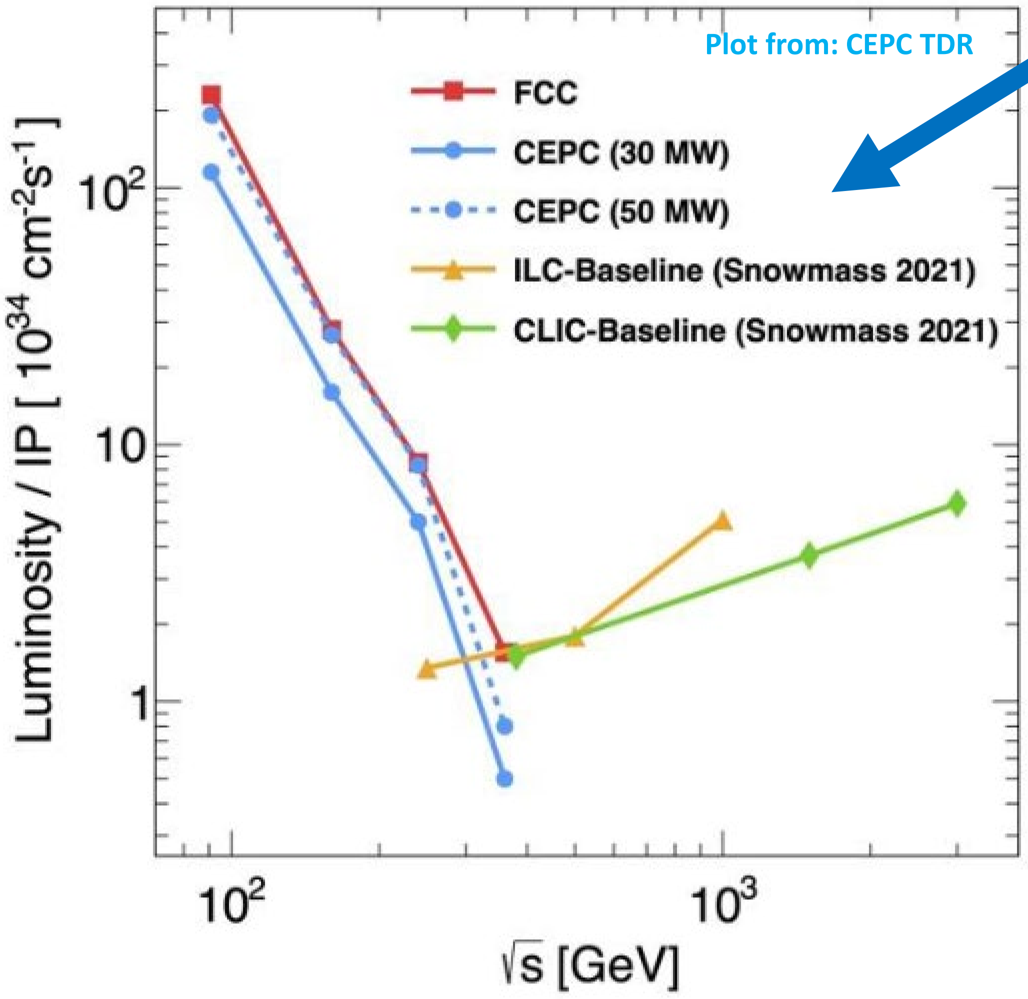
What does FCCee expect to achieve?



FCC luminosity decreases with collision energy:

→ Trade off between energy / luminosity / cost to replenish energy loss from synchrotron radiation

→ Operation plan is to reduce number of bunches in ring at higher energy to run at approximately constant total SR power

Luminosity per IP of FCCee breaks even with CLIC around the tt.

→ FCC has 4 IPs vs CLIC single IP

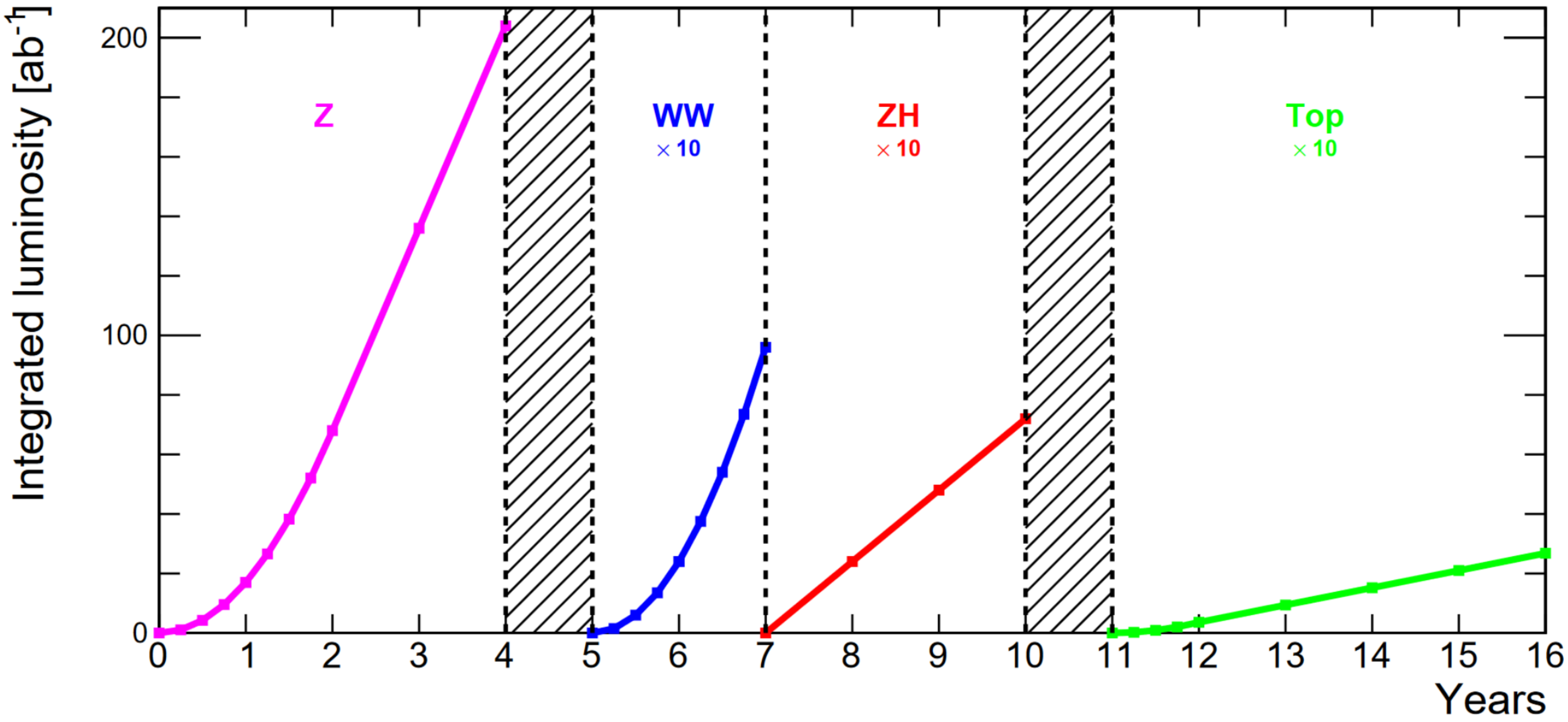
Even per-IP get significantly higher FCCee luminosity at ZH!

FCCee may cost more to construct than CLIC (latest CLIC estimates are from 2018)

→ **but Luminosity-per-CHF expected to be better for FCCee**

CLIC can be upgraded to higher lepton collision energy than FCCee

What is likely operational scenario for FCC



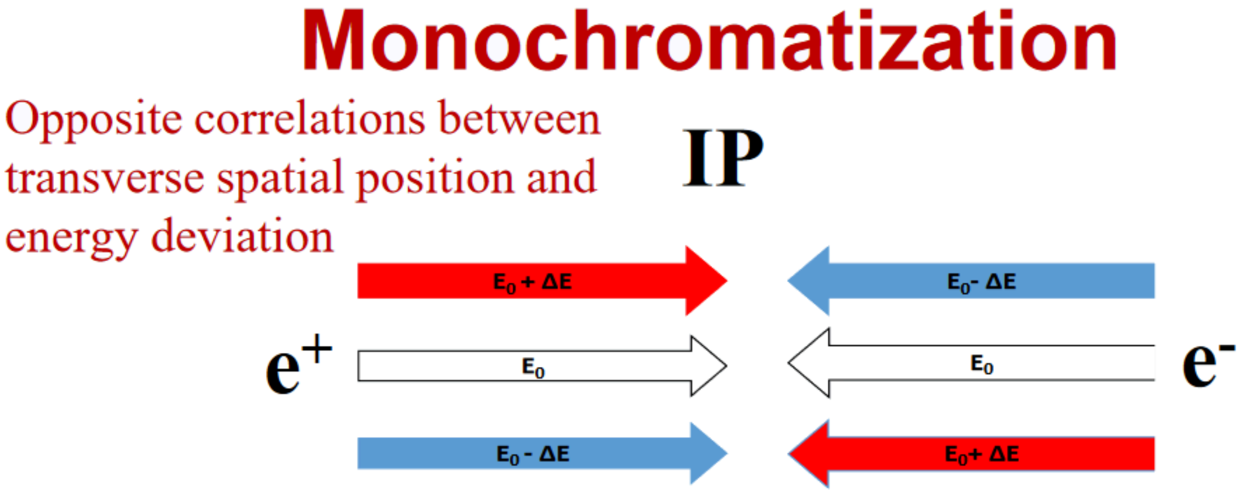
Monochromatization

Various other operational runs are under active study: **one of the most exciting is $\sqrt{s} = 125.09\mathrm{GeV}$ for direct Higgs production**

- **Measurement of electron Yukawa coupling highlighted as possible no-loose scenario for FCCee**

- **Extremely challenging as require very large statistics (**high-luminosity**) but extremely small energy spread in particle collision energy at the IP (**limited by beamstrahlung**)**

- **Solution could be to purposefully distort the beam-optics in the insertion region to create anti-correlated dispersion (relation between transverse particle position and momentum) in the two beams**



Monochromatization

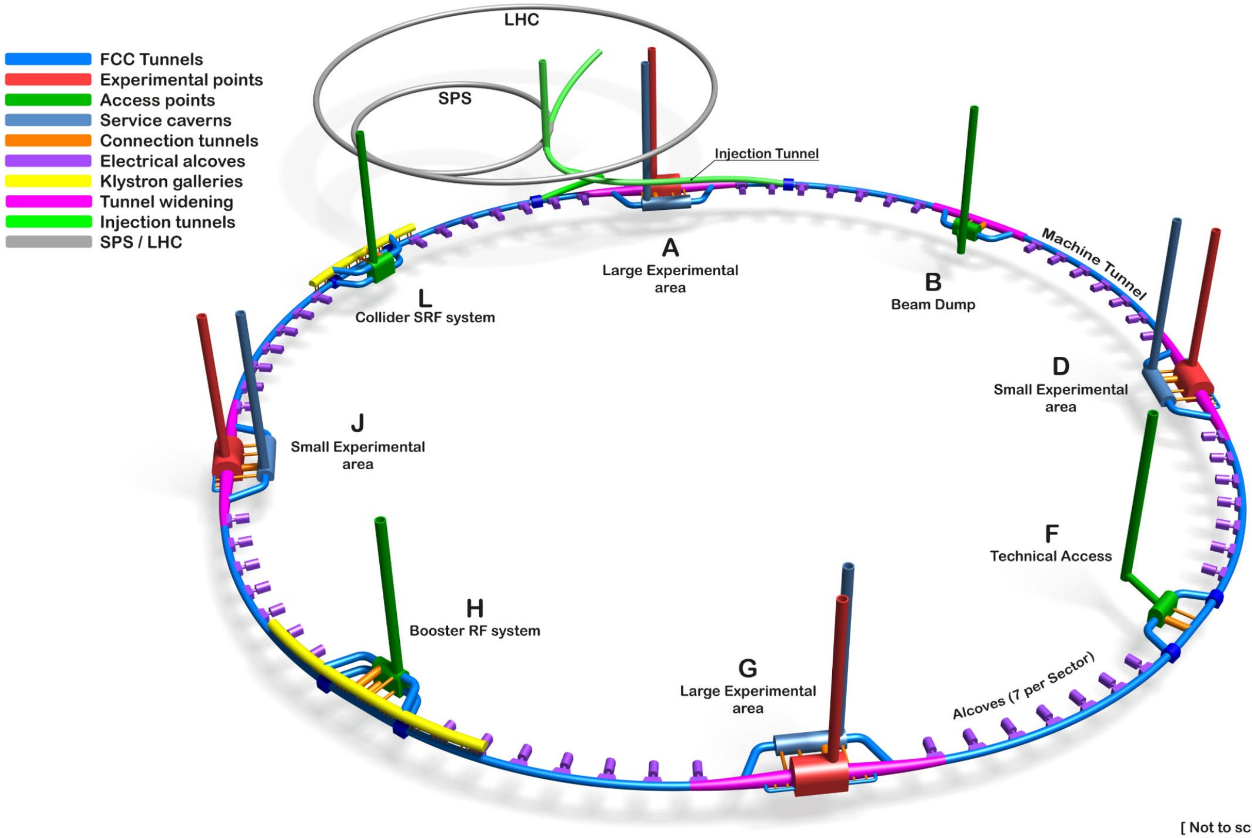
Opposite correlations between transverse spatial position and energy deviation

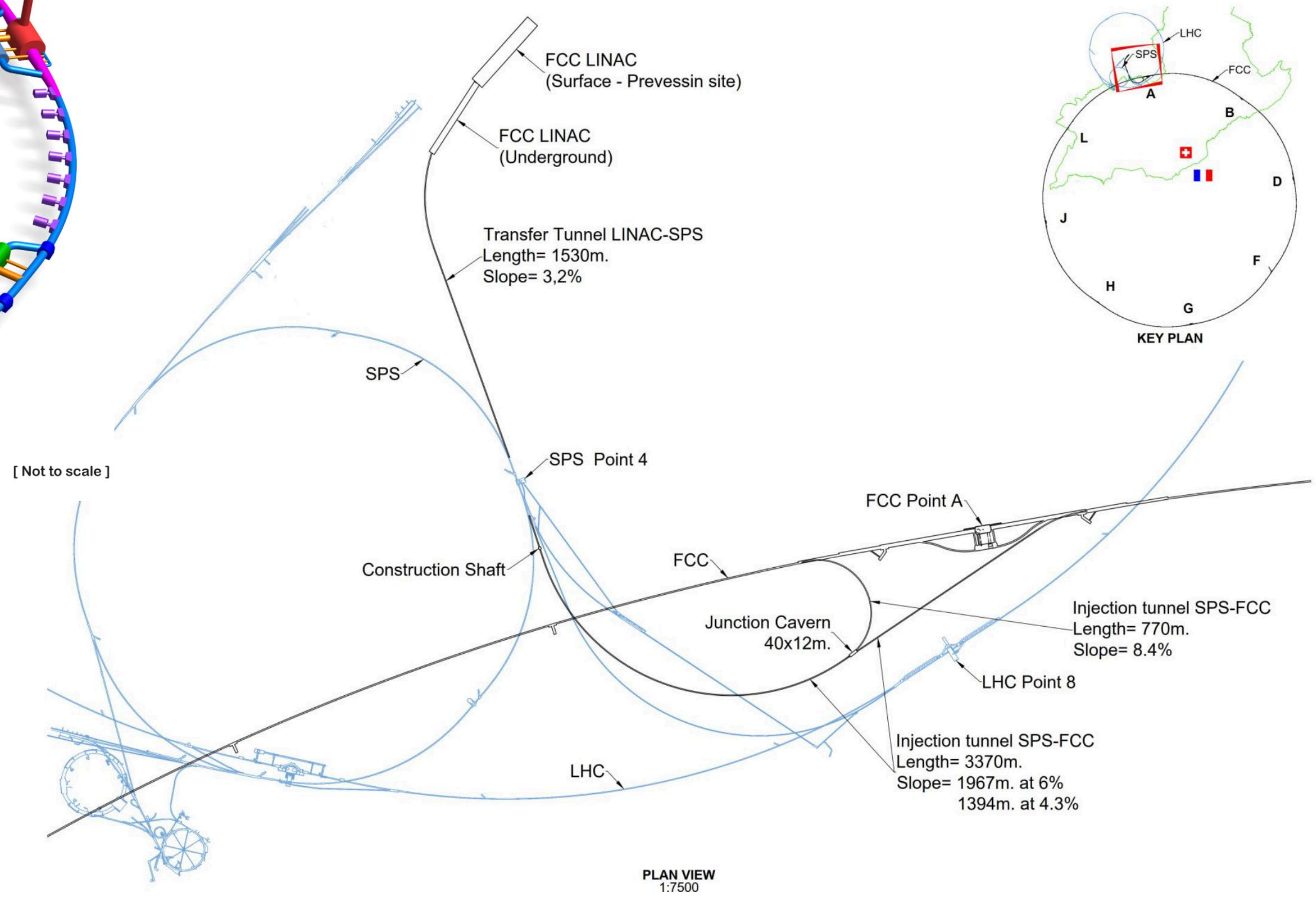
- **Lots of R&D ongoing!**

Z.Zhang (Paris-Saclay), Monochromatisation optics for FCC-ee lattices, FCC week 2023
https://indico.cern.ch/event/1202105/contributions/5396871/

How will FCCee operate?

- **Well understood electron/positron sources. Positron beams produced by e-beam on target. Performance validated in many other machines.**
- **Some early designs utilized SPS as FCCee pre-injector: most recent designs based on electron linac → allows concurrent operation of FCCee and proton fixed target programs + LHC end-of-life scenarios + FCChh R&D**



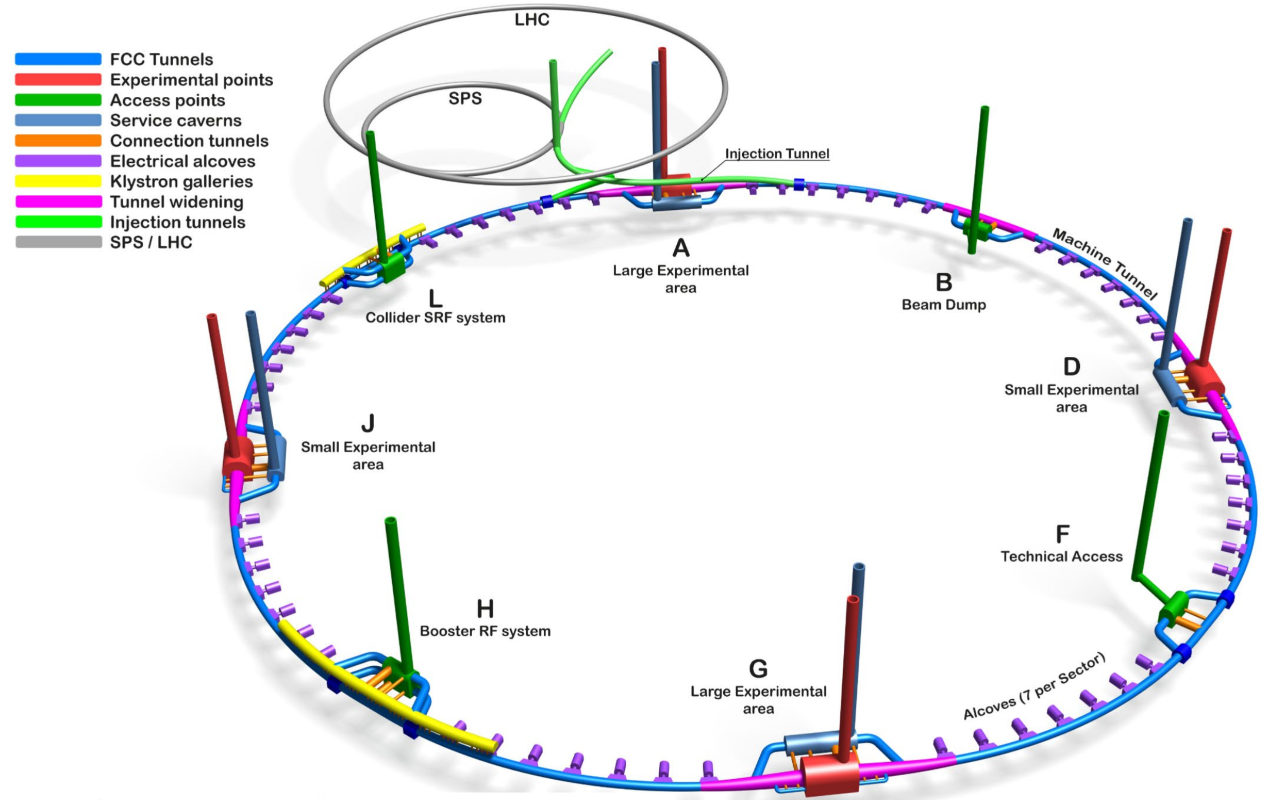


FCCee is actually 2 accelerators:

→ **Booster:** accelerates bunches from injectors to top energy

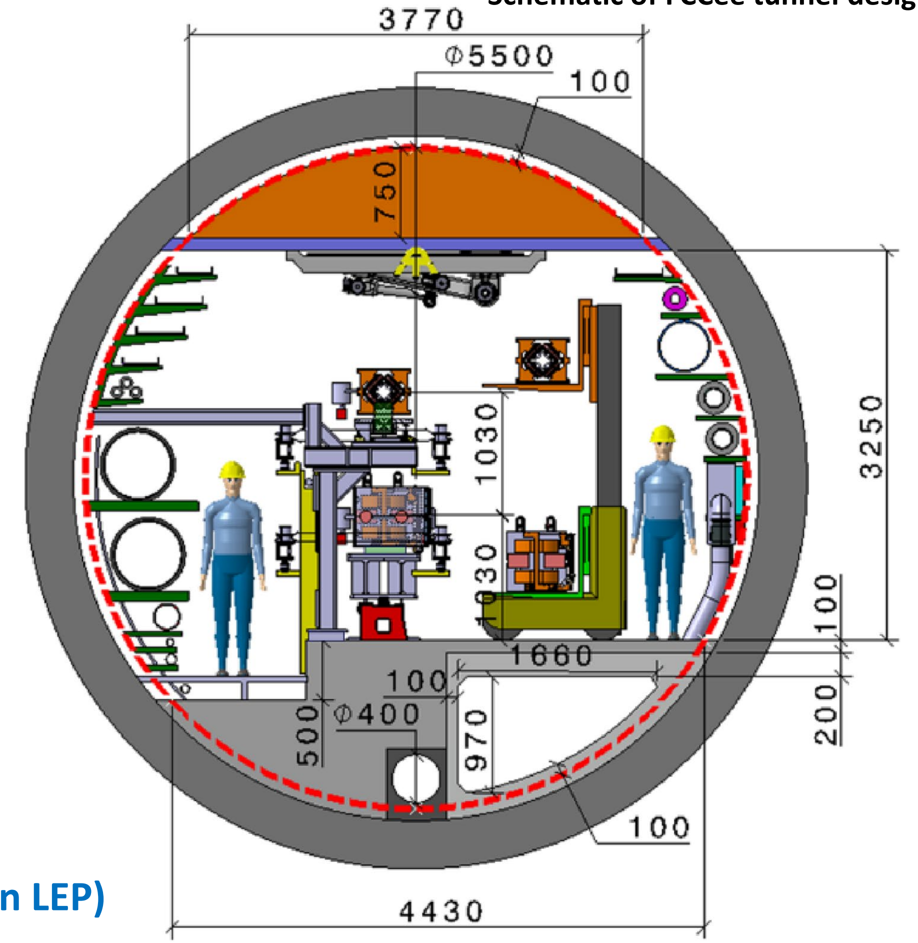
→ **Storage ring:** where beams circulate and collide

$\geq 10,000$ colliding bunches in the storage ring!

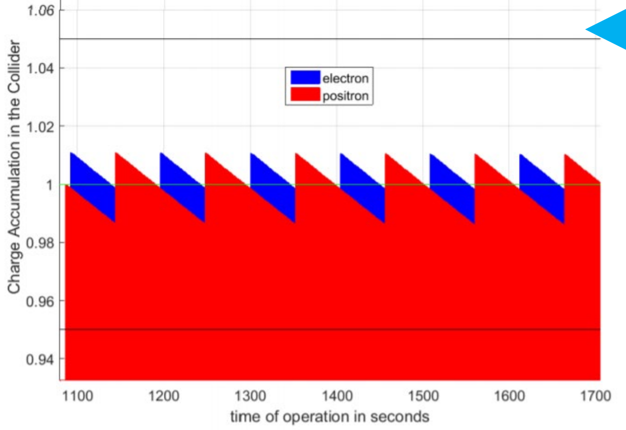


[Not to scale]

Schematic of FCCee tunnel design



F.Zimmerman, Shaping Future of High-Energy Physics. CERN academic training
https://cds.cern.ch/record/2790073

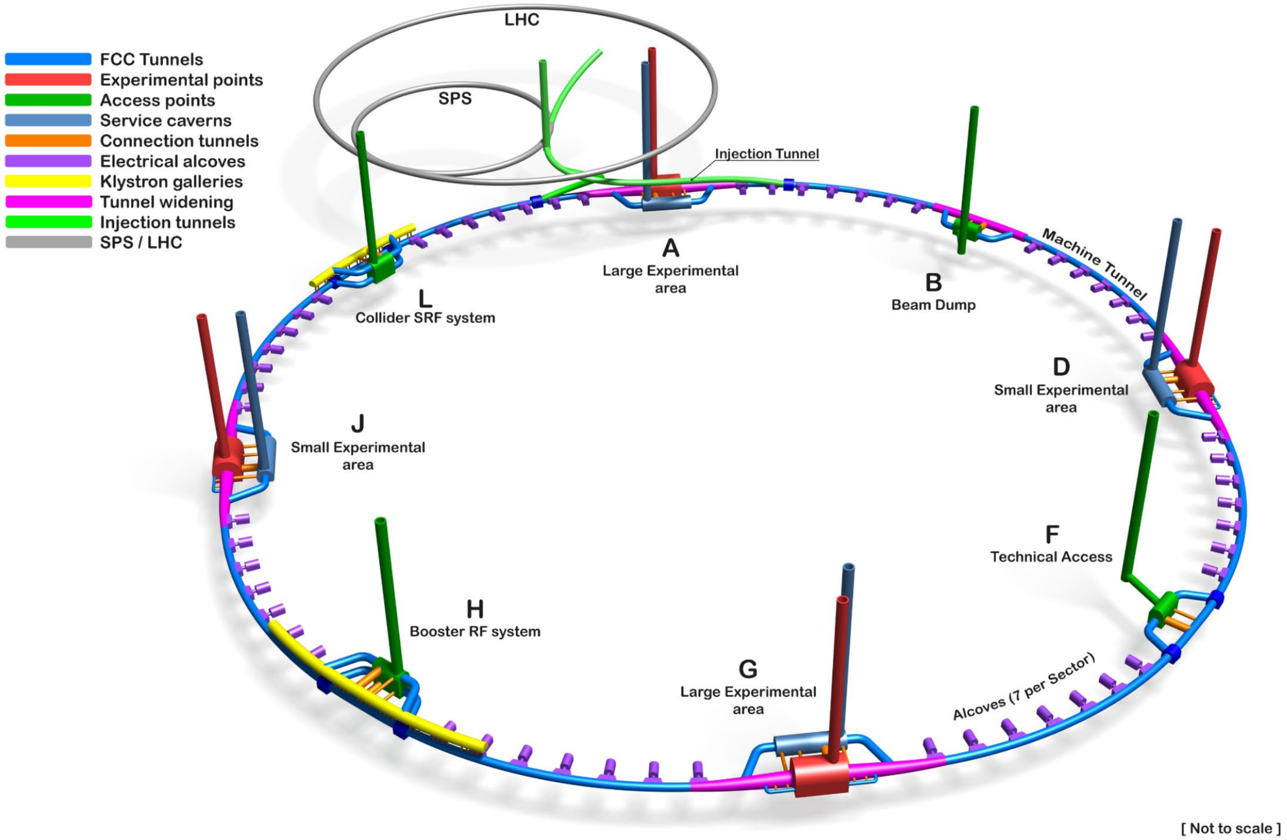


FCCee can run with top-up injection:

→ New bunches continually being fed in from the booster to replace old bunches which have burned-away

→ Keeping beam currents and luminosity stable within few % during regular production

Around 250 non-colliding bunches included for energy calibration multiple times per hour via resonant depolarization (compared to weekly in LEP)

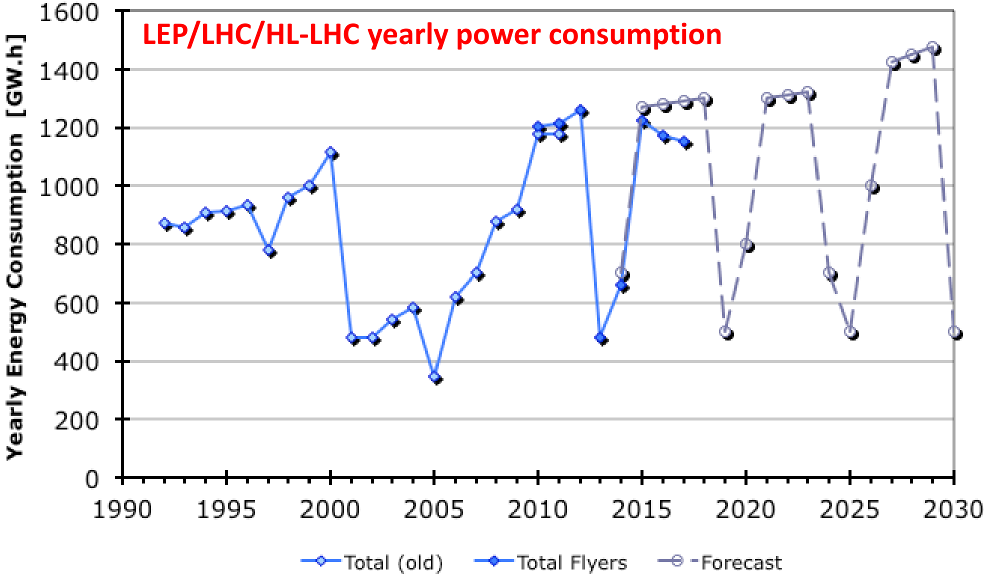


M.Benadikt, FCC week 2023 https://indico.cern.ch/event/1202105/contributions/5423504

Updated FCC-ee energy consumption	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Max. power during beam operation (MW)	**222**	**247**	**273**	**357**
Average power / year (MW)	122	138	152	202
Total yearly consumption (TWh)	**1.07**	**1.21**	**1.33**	**1.77**

One of big challenges for FCCee is handling the synchrotron radiation emitted while beams are circulating in the collider!

- **Taken as a design criteria that FCCee should operate at ≈constant total SR power of 100MW**
  → energy loss / m viable with today technology
  → reduce number of bunches with energy
- **Significant increase in total RF power compared to LEP, but FCC power requirements comparable to LHC operation**



F.Zimmerman, Shaping Future of High-Energy Physics. CERN academic training
https://cds.cern.ch/record/2790073

FCCee luminosity / TWh very competitive compared to other projects

FCCee aims to bring together lots of exciting innovations in lepton accelerator design together with many novel improvement to achieve high-energy high-luminosity

$[10^1\mathrm{nm}]$ beam sizes in collision

$\beta_y^* < 1\mathrm{mm}$ demonstrated at super-KEK

Monochromatization

High-energy leptons

Top up injection

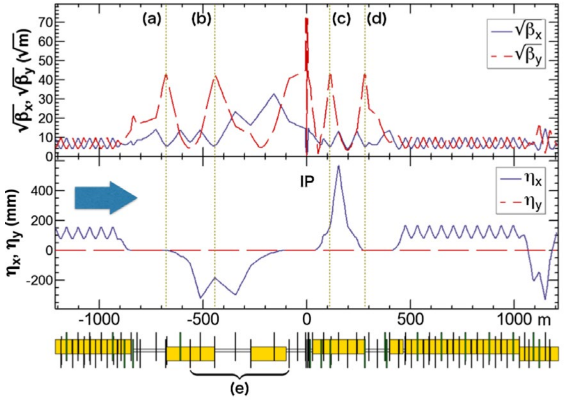
Crab waist for collisions

Optimization of chromatic optics in the insertion region

FCC-ee

Assymetric optics in experimental IRs

Reduces SR into the detectors

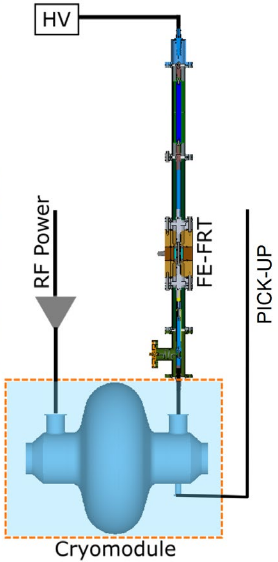


Dual ring lepton collider

High-precision energy calibraion

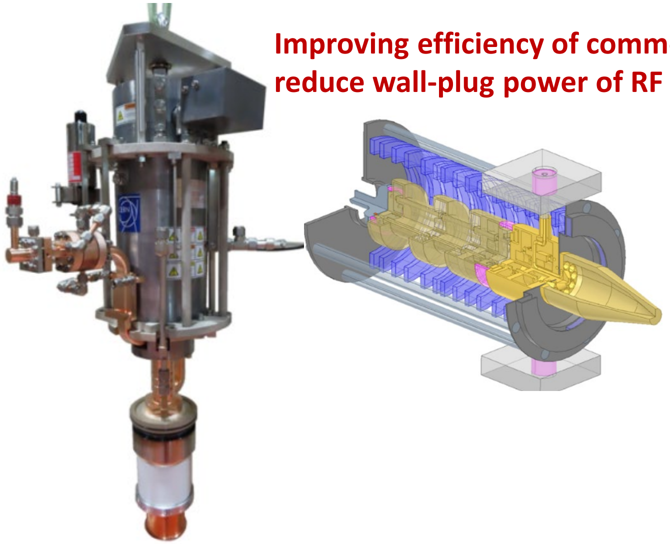
High current positron source

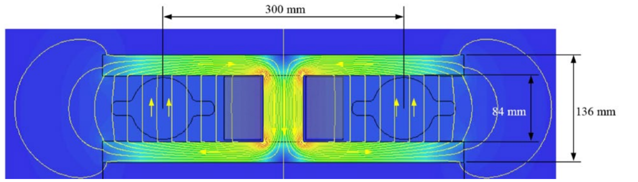
Intensive R&D for FCC-ee technology ongoing: focused on reducing cost and power



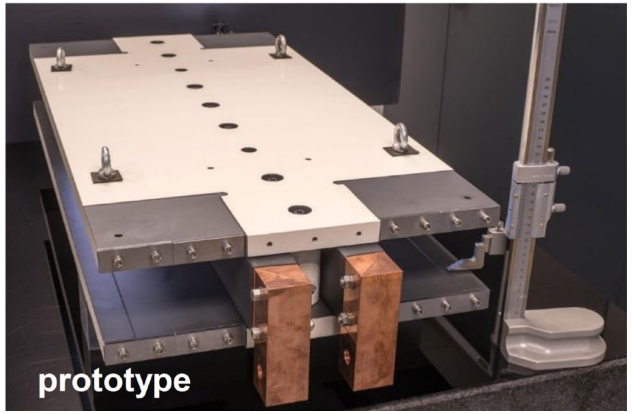
Novel Ferro-electric Fast Cavity Tuners to reduce RF power requirements with intense beams

Improving efficiency of commercial klystrons to reduce wall-plug power of RF systems





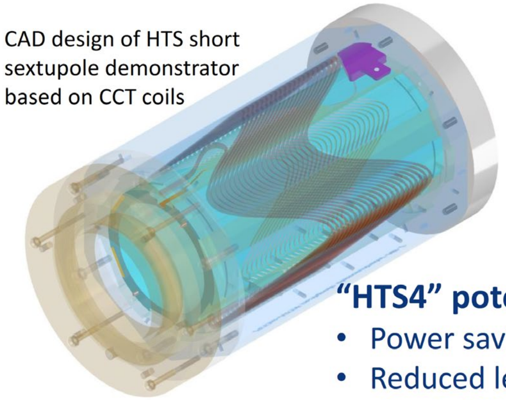
Design and prototyping of novel high-efficiency dual beam main dipole magnets

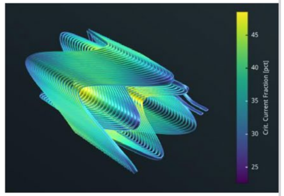


FCC-ee

Design and prototyping of low-field high-temperature superconducting magnets for sextupoles and correctors

CAD design of HTS short sextupole demonstrator based on CCT coils



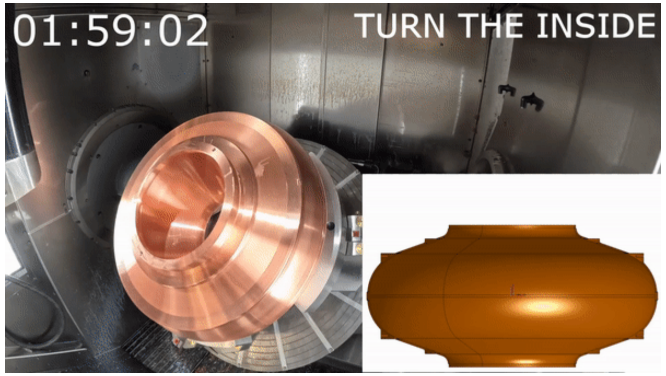


"HTS4" potential

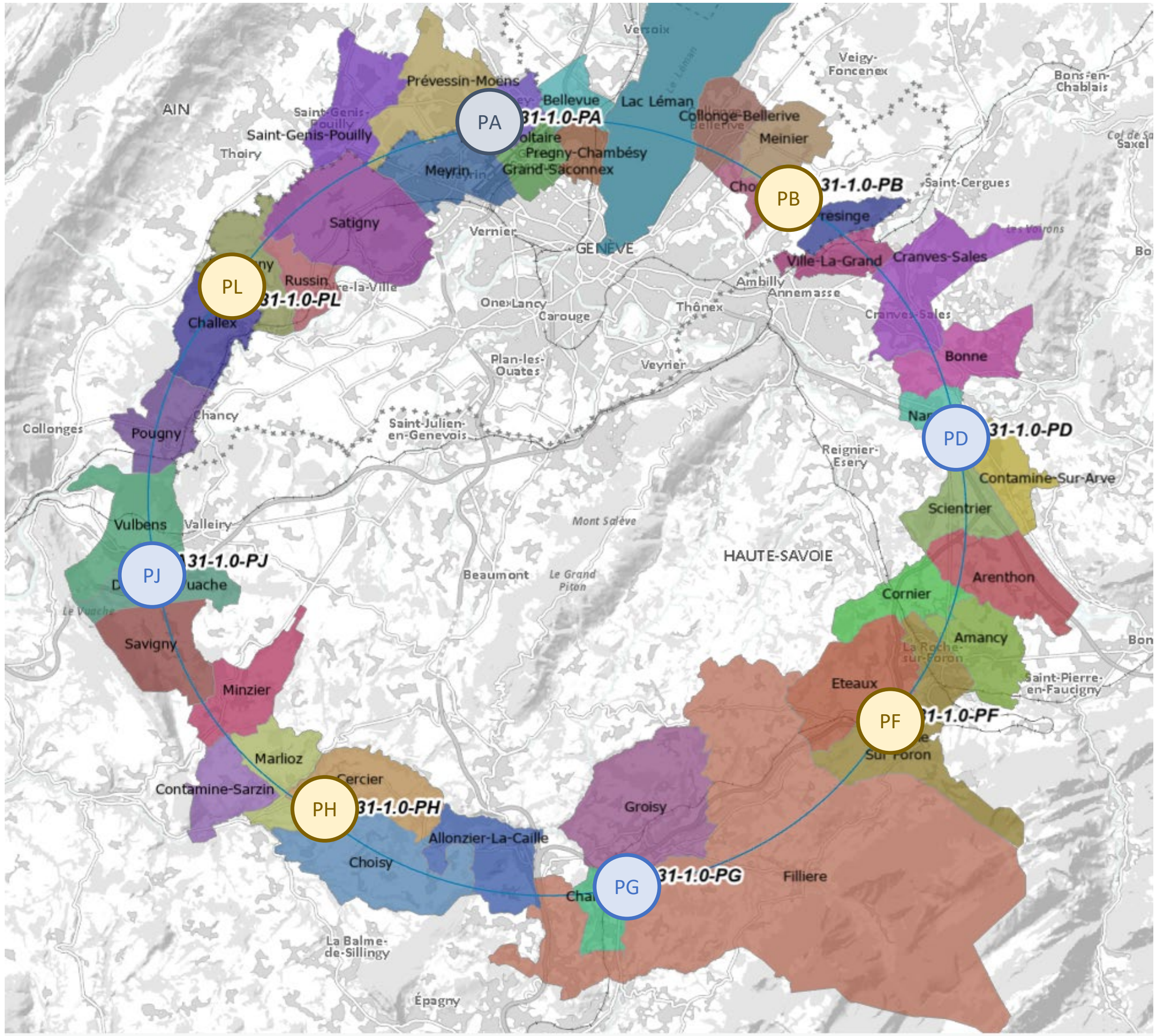
- Power saving
- Reduced length and increased dipole filling factor
- Optics flexibility

M. Koratzinos, B. Auchmann

Design, construction, surface treatments to produce higher-Q cavities with less RF power losses



Lots of work on how to integrate FCC project with local communities



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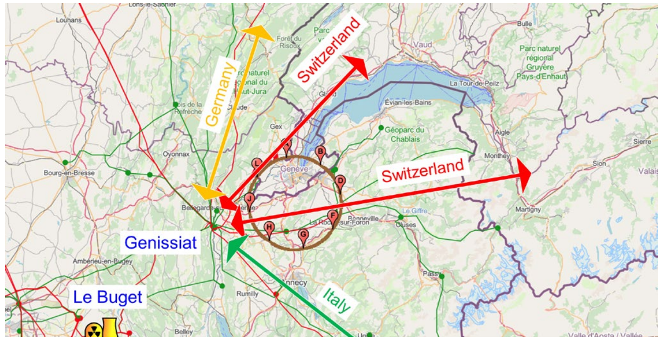
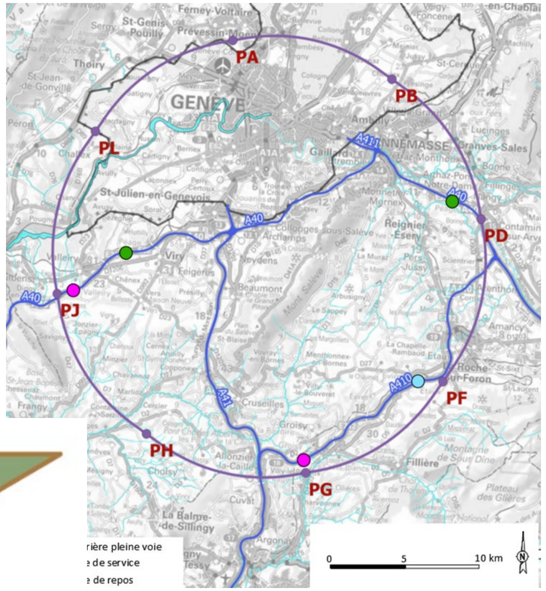
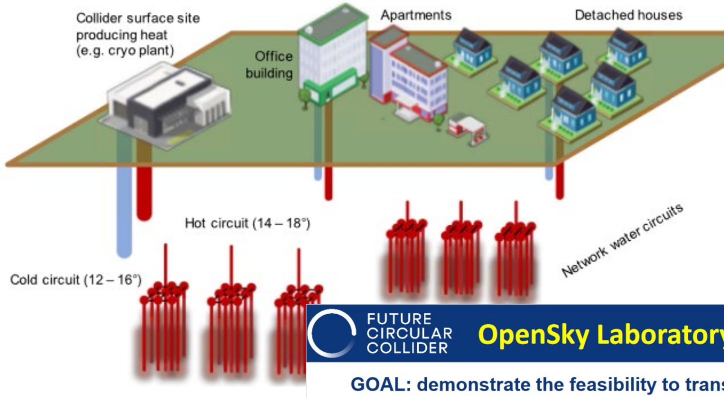






FUTURE CIRCULAR COLLIDER

OpenSky Laboratory: demonstrate molasse reuse cases

GOAL: demonstrate the feasibility to transform Molasse (excavated material) into fertile soil.

- **5500 m² near LHC P5 in Cessy, France.**
- Trial with 5 000 t of excavated local molasse

Layout :

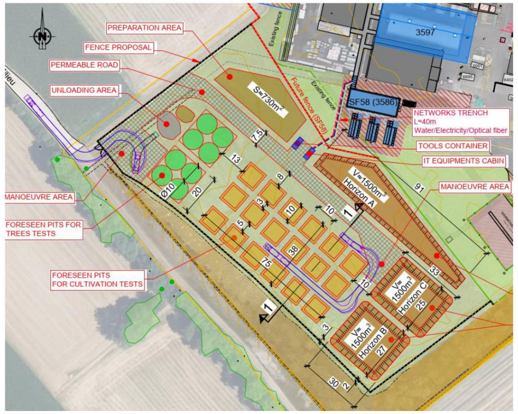
- cells for agriculture trials (10*10 m)
- cells for forestry trials (20*20 m)

Different types of plants selected in function of regional specificities and possible soil reuse cases

Project phases:

1) Initial laboratory analysis to **identify** the **most suitable mix** of molasse and amendments.

2) **Field tests** in a **controlled environment** (**monitoring** of the field conditions)



Future colliders?

Linear e^+e^- collider
- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

e^+e^- synchrotron
- FCCee
- CEPC

hadron synchrotron
- FCChh
- SPPS

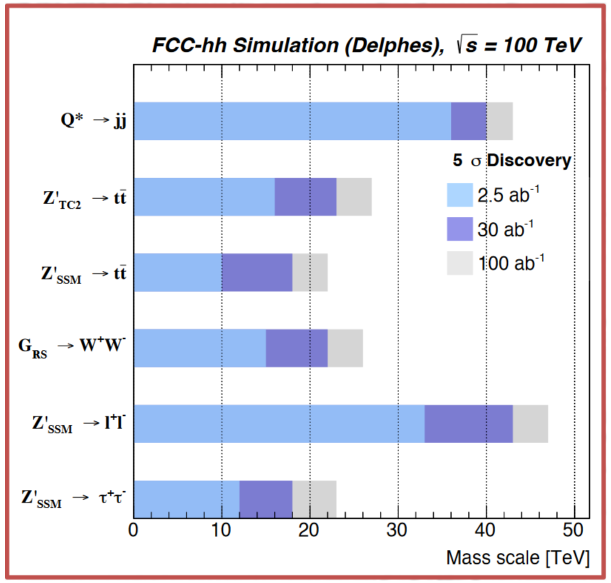
Muon Collider

Synchrotron colliders: a pathway to hadron-hadron collisions at the highest energies

Why a pp **circular collider?**

LHC has so far found no major hints of new physics. Don't know at what energy this might appear

Circular pp collider is natural upgrade path to FCCee: allows highest possible beam energy of all future proposals at high-luminosity



M.Mccullough, FCC Physics landscape, Chamonix'24

Circular pp collider gives broadest possible discovery potential with full integrated lumi

→ Up to 40TeV **scale reach**

FCC CDR,
https://cds.cern.ch/record/2651300/files/CERN-ACC-2018-0058.pdf

Circular pp **machines can support most experiments of any high-energy option**

- **Up to 4 experiments**

Re-uses FCCee tunnel and infrastructure. Potential upgrade paths in same facility

→ 150TeV with higher magnets

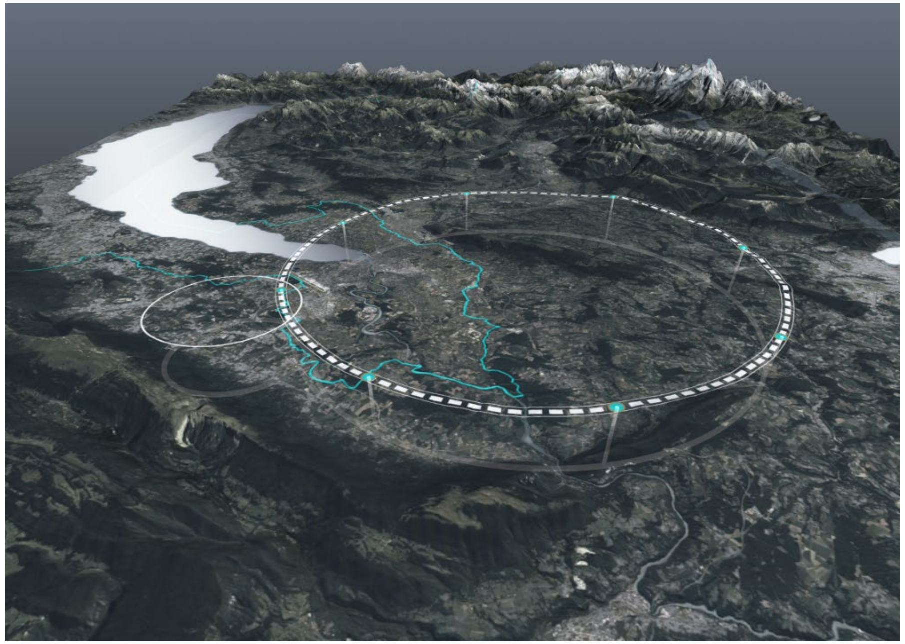
→ Lepton hadron upgrade option

Diverse collider program option → not only proton, also heavy ions at high-energy

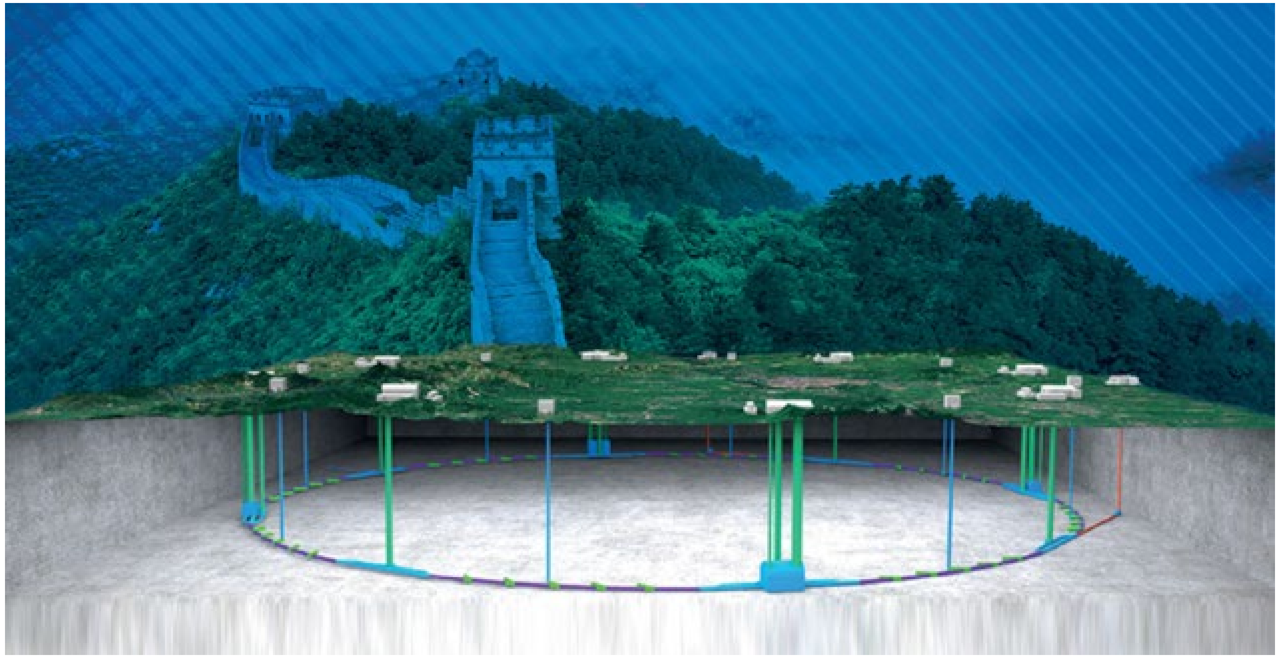
Synchrotron colliders: a pathway to hadron-hadron collisions at the highest energies

Two main proposals

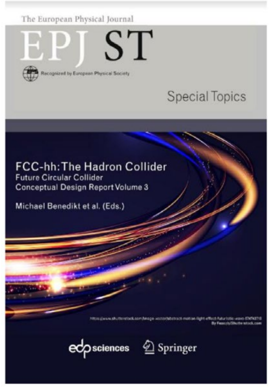
Future Circular Collider (FCChh) @ CERN
→ FCCee upgrade

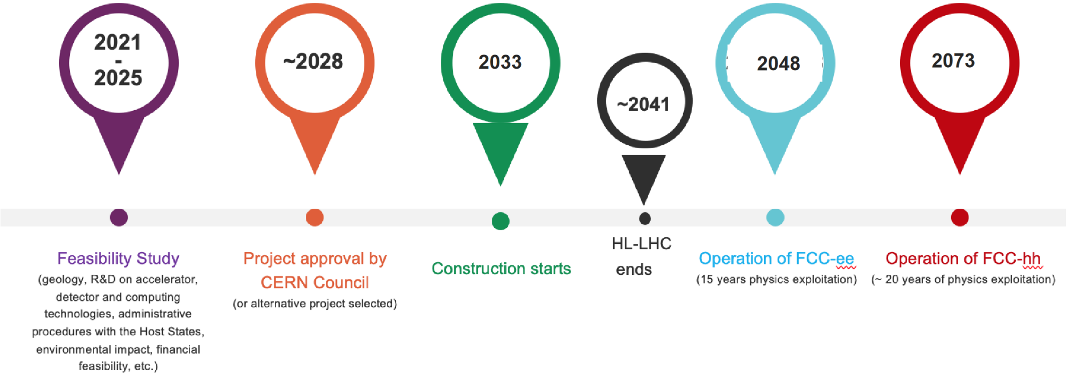


Super Protron Proton Collider (SppC) @ China
→ CEPC upgrade



FCChh and SppC are less mature projects than electron/positron equivalents


The European Physical Journal
EPJ ST
Special Topics
FCC-hh: The Hadron Collider
Future Circular Collider
Conceptual Design Report Volume 3
Michael Benedikt et al. (Eds.)
edp sciences Springer



Feasibility Study (geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

Project approval by CERN Council (or alternative project selected)

Construction starts

HL-LHC ends

Operation of FCC-ee (15 years physics exploitation)

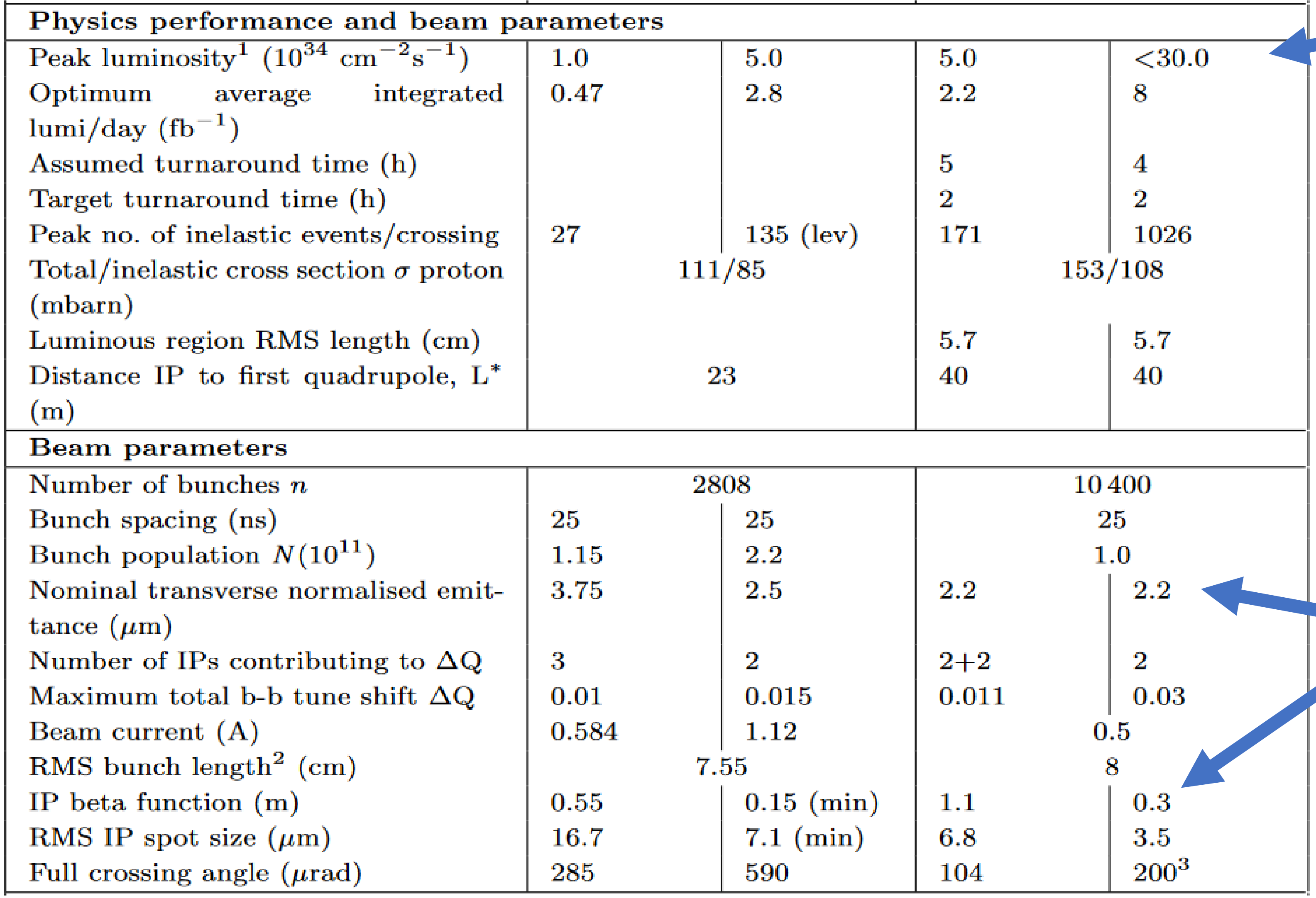
Operation of FCC-hh (~ 20 years of physics exploitation)

But also expected to begin operation on much longer timeline

→ plenty of time for R&D!

- **Project design and integration with lepton colliders are well documented**
  → e.g. FCC-hh CDR published in 2018 https://fcc-cdr.web.cern.ch/
- **No dedicated demonstrator facility required** → LHC as FCChh/SppC demonstrator
- **Collider and lattice designs well advanced and compatible with FCCee and FCChh performance goals**
- **Snowmass'21 exercise listed FCC-hh risk as ¾, probably two main considerations:**
  → FCChh project reliance on prior construction of FCCee
  → reflects that FCChh targets R&D for high-field superconducting magnets, beyond what is already achieved today

What does FCChh expect to achieve? (subject to ongoing optimization, precise numbers will vary)



	LHC	HL-LHC	FCC-hh initial	FCC-hh target
Physics performance and beam parameters				
Peak luminosity[1] (10^{34} cm^{-2}s^{-1})	1.0	5.0	5.0	$<$30.0
Optimum average integrated lumi/day (fb^{-1})	0.47	2.8	2.2	8
Assumed turnaround time (h)			5	4
Target turnaround time (h)			2	2
Peak no. of inelastic events/crossing	27	135 (lev)	171	1026
Total/inelastic cross section σ proton (mbarn)	111/85		153/108	
Luminous region RMS length (cm)			5.7	5.7
Distance IP to first quadrupole, L* (m)	23		40	40
Beam parameters				
Number of bunches n	2808		10 400	
Bunch spacing (ns)	25	25	25	
Bunch population $N(10^{11})$	1.15	2.2	1.0	
Nominal transverse normalised emittance (μm)	3.75	2.5	2.2	2.2
Number of IPs contributing to ΔQ	3	2	2+2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.011	0.03
Beam current (A)	0.584	1.12	0.5	
RMS bunch length[2] (cm)	7.55		8	
IP beta function (m)	0.55	0.15 (min)	1.1	0.3
RMS IP spot size (μm)	16.7	7.1 (min)	6.8	3.5
Full crossing angle (μrad)	285	590	104	200[3]

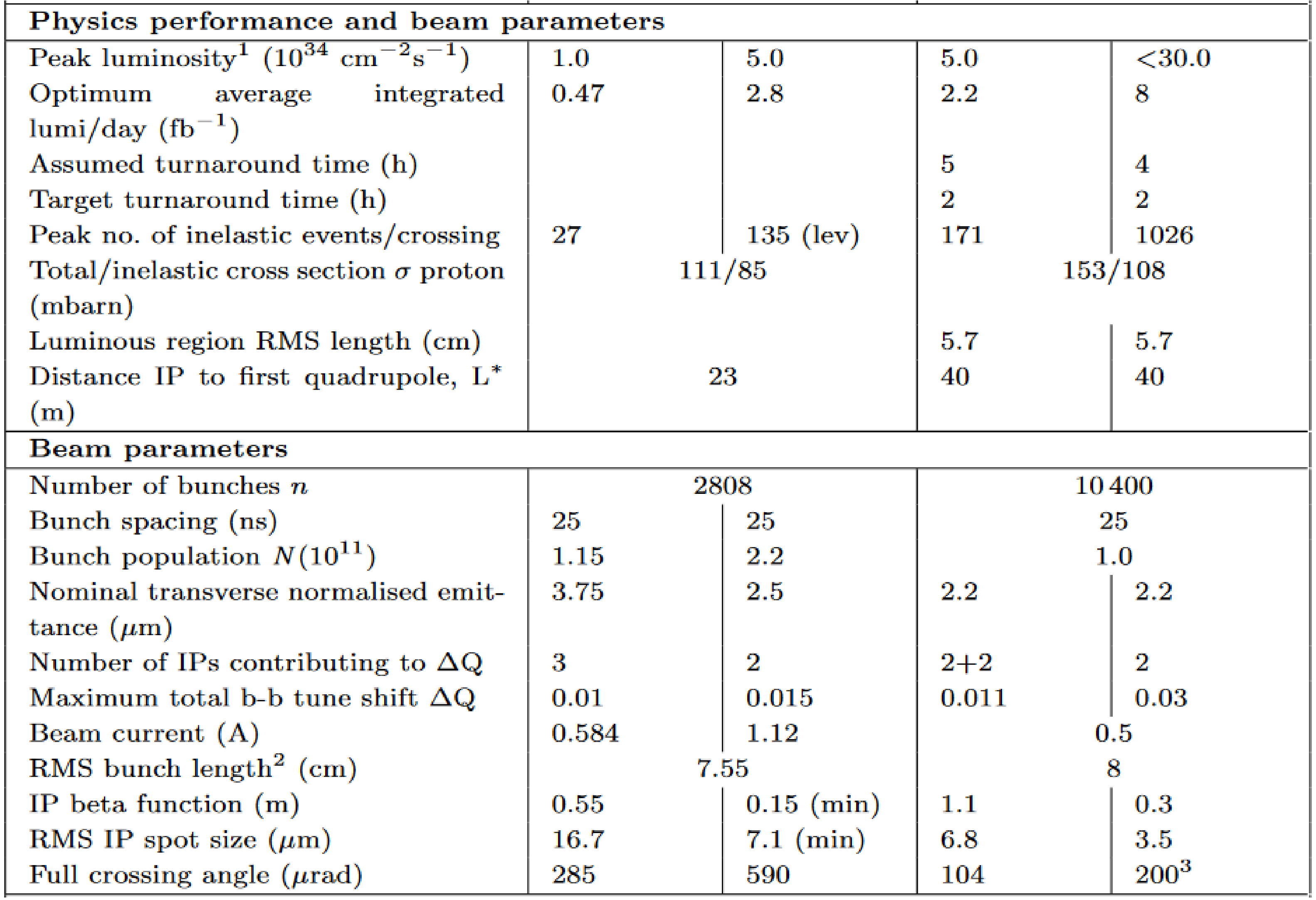
Ultimately target order of magnitude higher peak-luminosity vs LHC-era

Lifetime target of $30\mathrm{ab}^{-1}$!

Can be achieved with very realistic beta-functions at the IP (comparable to LHC today) and realistic emittance

Option for High-luminosity upgrade if experiments can handle it??

What does FCChh expect to achieve? (subject to ongoing optimization, precise numbers will vary)



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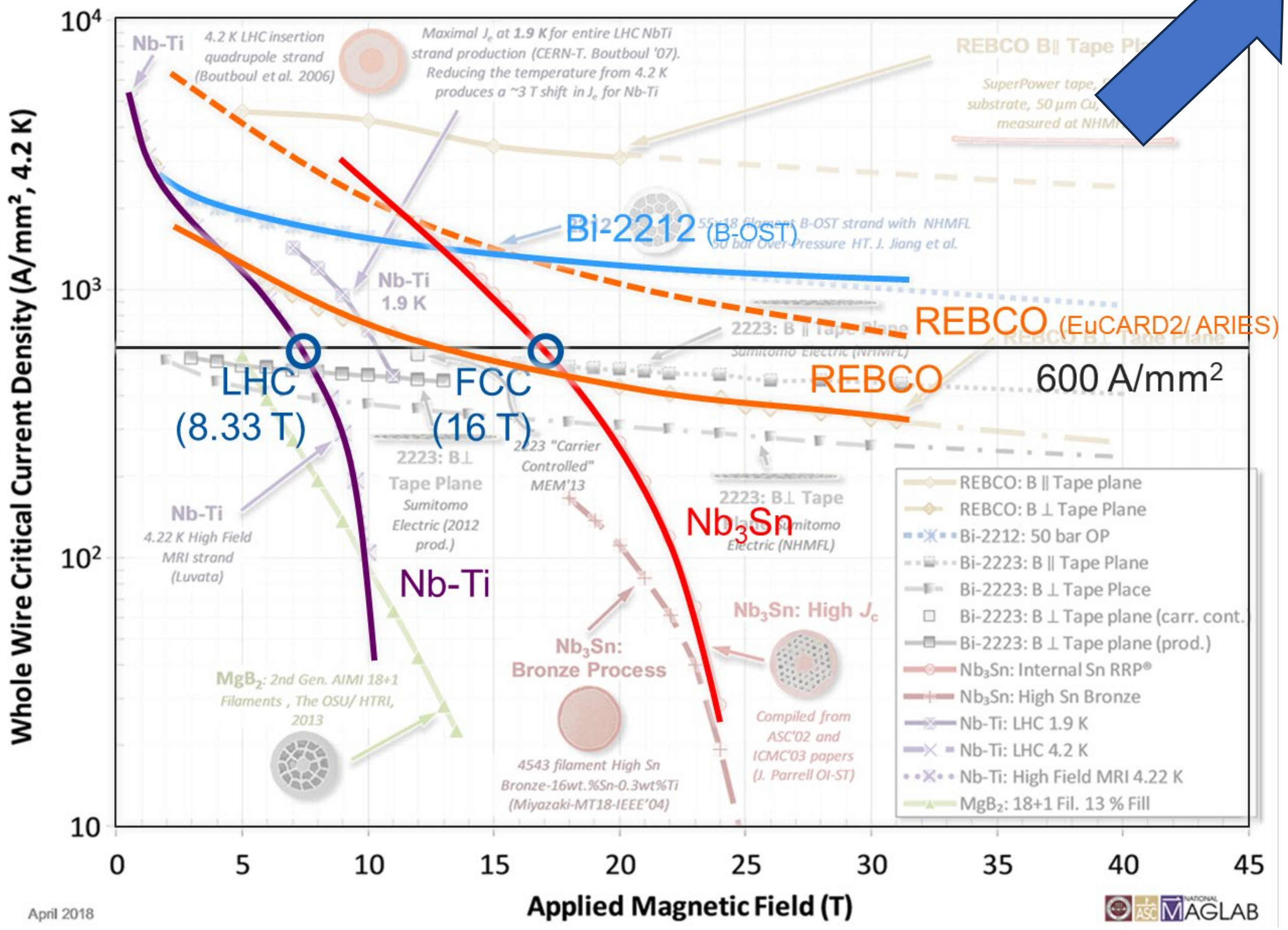
Full crossing angle (μrad)	285	590	104	200[3]

Hard to precisely estimate cost of a project so far from start date, while key R&D is ongoing…

FCChh CDR (2018) estimated cost of upgrade from FCCee to FCChh as ~17bCHF

What R&D is needed for FCChh?

→ high-field superconducting magnets!



To reach high-energy beam energy with reasonable magnet design want SC cables that can tolerate high-magnetic field and high current density

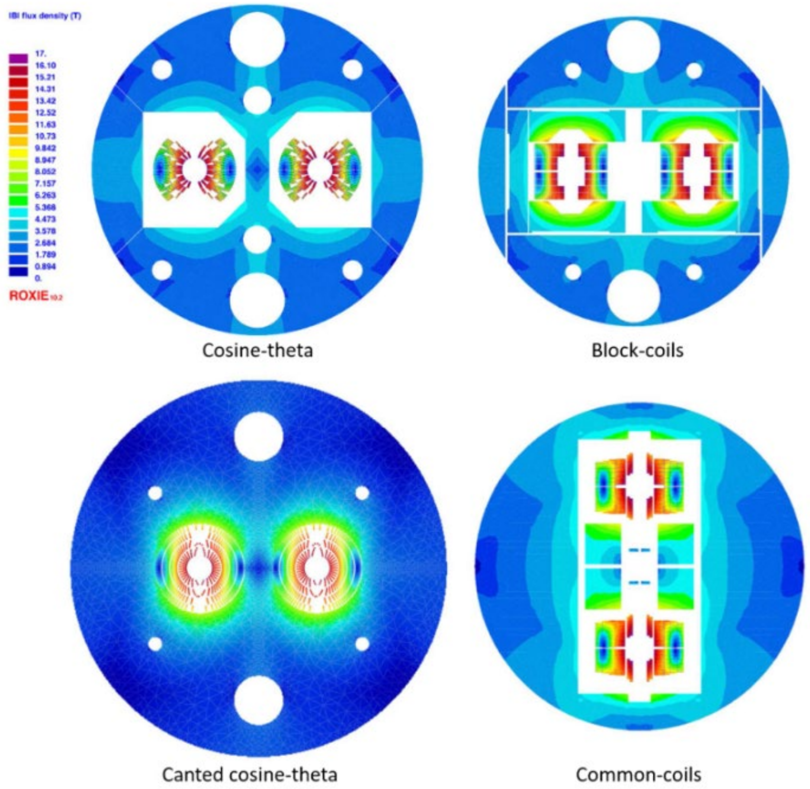
LHC magnets were 8.3T NbTi
→ Not strong enough field to reach 100TeV in FCC ring

2 main R&D streams for FCC magnets

- **Baseline Nb_3Sn at 16T**
  → already used for HL-LHC IR quads
  → more challenging material to construct magnets than NbTi
- **High Temperature SC e.g. ReBCO,…**
  → **Run at low temperature higher-field**
  → **Same field higher-temp**

Both Nb3Sn and HTS options face practical challenges for magnet construction

- Nb3Sn more brittle than NbTi – coils need to handle stress and forces generated in construction / operation
- HTS cable geometries can differ from historical SC cables used in accelerators. Needs novel designs!
- **R&D on coil material goes hand-in-hand with R&D on magnet design and incorporation**
- **Operation in 2070s gives plenty of time for technologies to mature and industrialize**
- **FCC would be large scale procurement of such technologies – clear potential for societal cross-over**



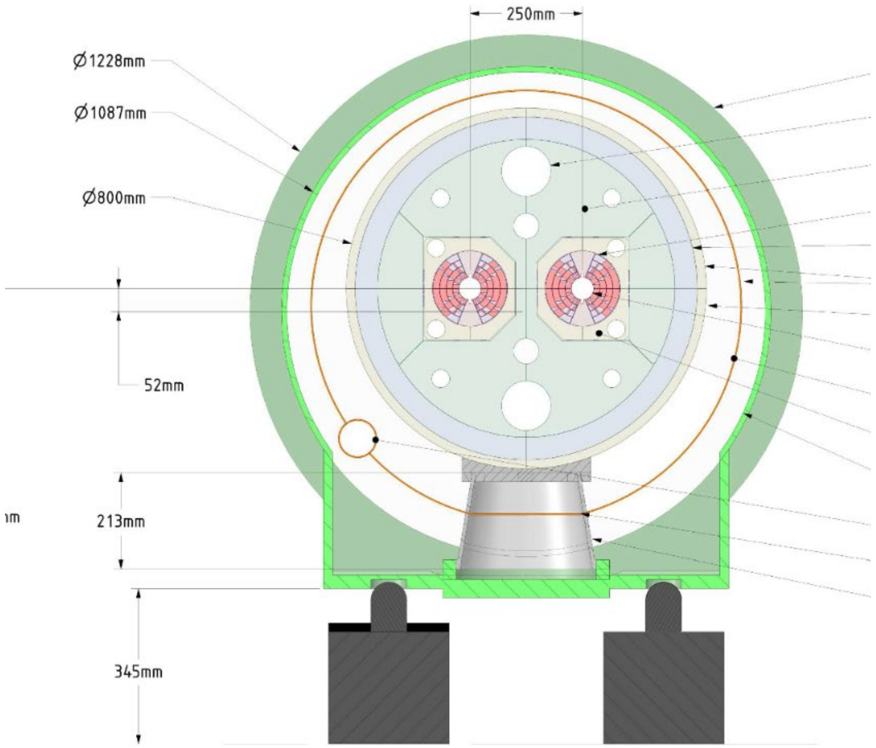
Cosine-theta

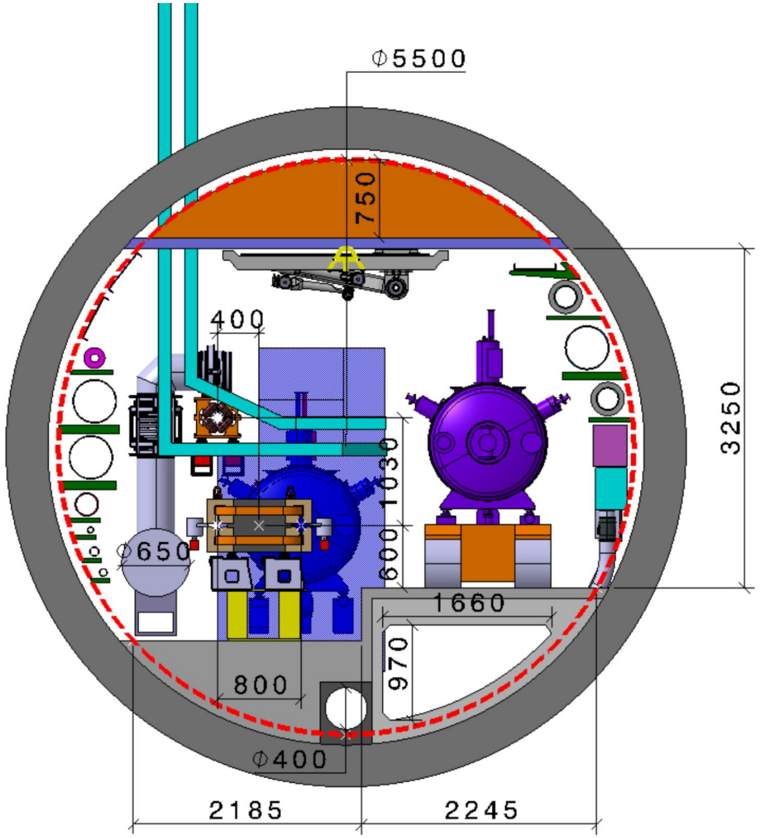
Block-coils

Canted cosine-theta

Common-coils

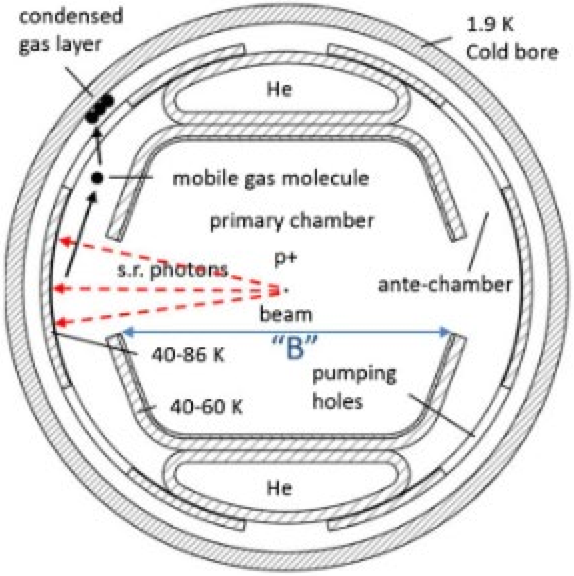
Fig. 3.7. Electromagnetic cross sections of the 16 T dipole design variants.

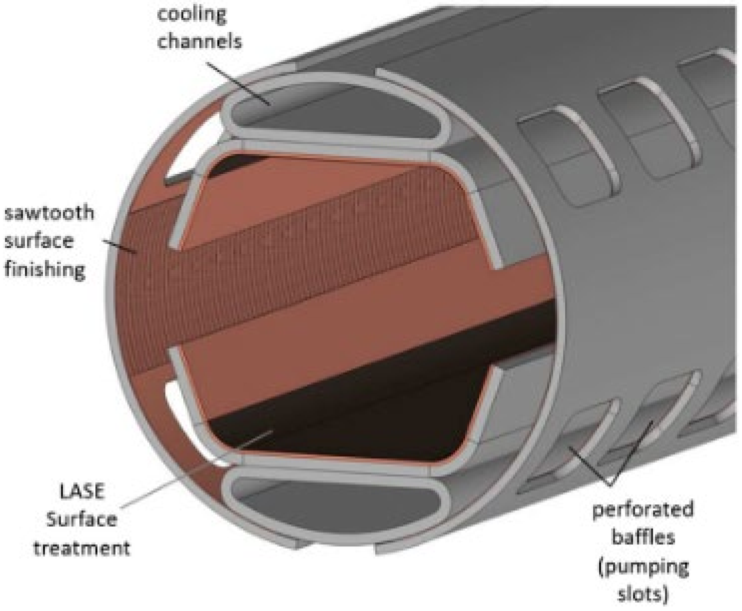




FCChh will be first pp collider where synchrotron radiation plays a significant role

- Have some non-neglible radiation damping which can help with emittance preservation
- SR expected to deposit about 5MW of heat into FCC magnets → requires 100MW of wall-plug-power to remove!
- Requires stainless steel beam-screen to intercept heat load from synchrotron radiation at 40-60K, rather than letting it be absorbed by magnet coil at ≈5K



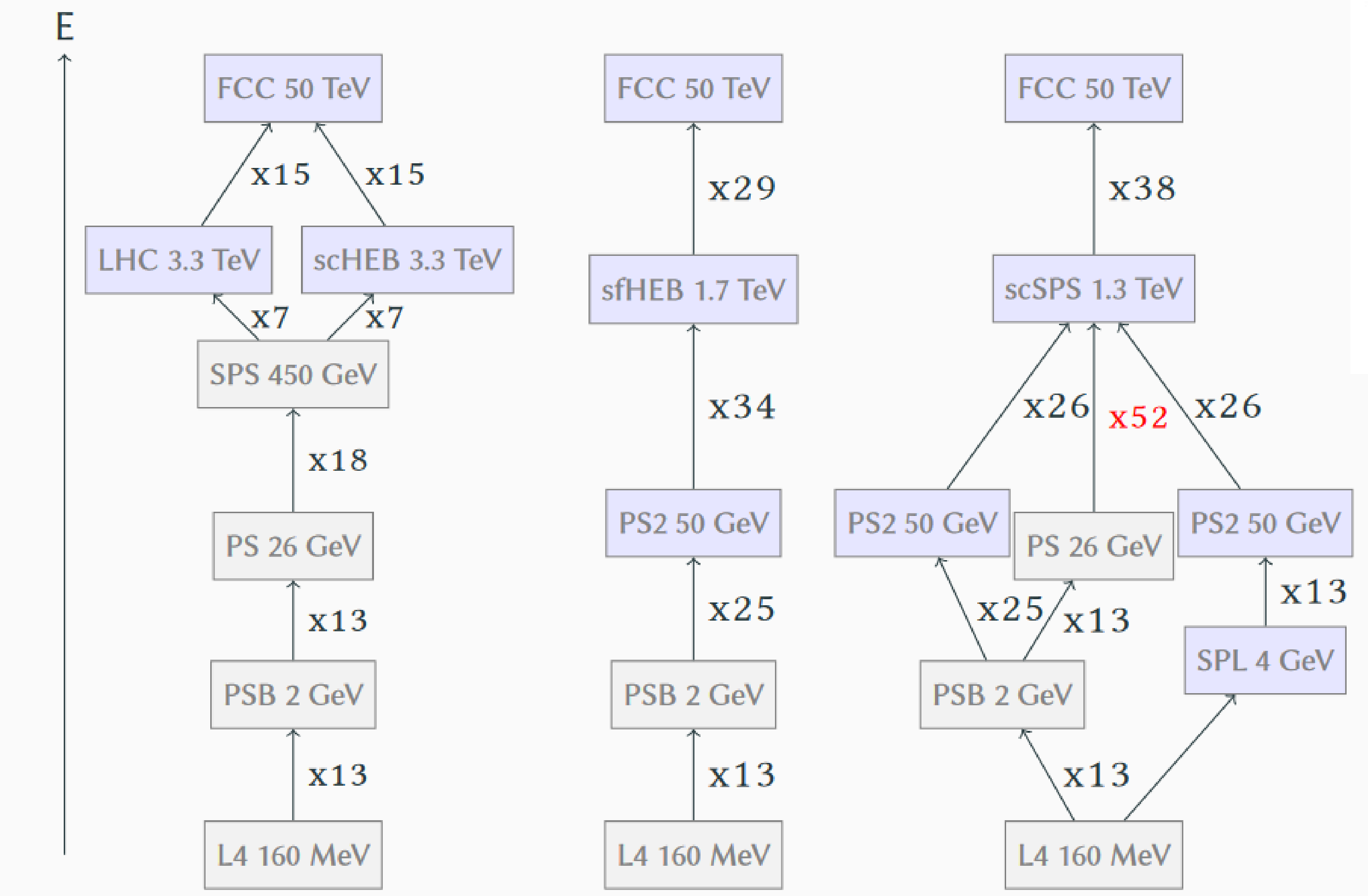


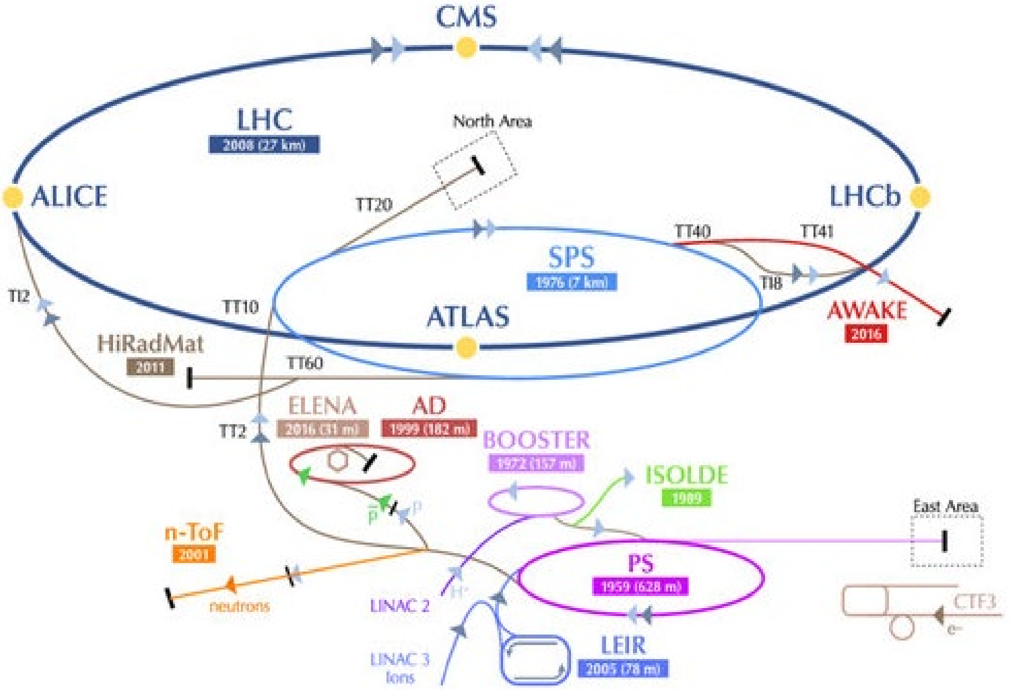
Estimated total wall plug power of FCChh during top energy collisions

≈ 550-580 MW (based on CDR)
≈ 4 TWh annual consumption

About 2.6x **expected HL-LHC power consumption, comparable peak power draw to CLIC at 3TeV**

FCChh will use the existing LHC injector chain as an FCC injector → various configuration being studied





Can potentially achieve better cost / performance by injecting directly from SPS

R&D needed to understand if larger energy swing / machine can be tolerated

Studies proposed to try LHC operation with lower injection energy to test concept!

Future colliders?

Linear e^+e^- collider

- Compact Linear Collider (CLIC)
- International Linear Collider (ILC)

e^+e^- synchrotron

- FCCee
- CEPC

hadron synchrotron

- FCChh
- SPPS

Muon Collider

Muon colliders: a new approach to HEP accelerators, and a pathway to lepton-lepton collisions at the highest energies

Why a μμ collider?

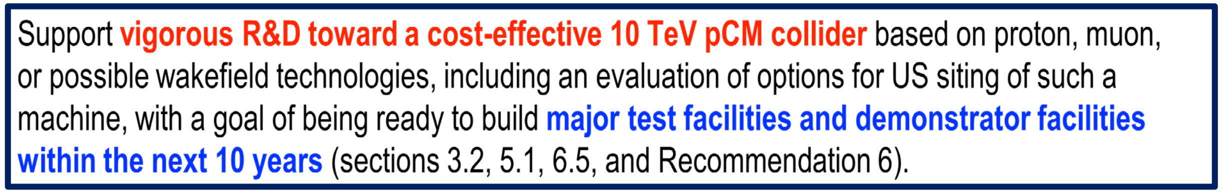
electron/positron colliders are limited at high-energy by SR power and beamstrahlung

SR emission scales strongly with particle mass: a muon collider at the 10TeV scale would not be limited by SR, allowing precision lepton-lepton measurements at high-energy

Beamstrahlung emission scales strongly with particle mass. Even at high-energy muon-muon collisions would not suffer from beamstrahlung induced energy spread. Potential for fine resolution measurements of particle width if low momentum spread beams can be created

muons collide at the beam energy, unlike parton collisions in HH machines. Could reach comparable energy scale at lower beam-energy / smaller machine

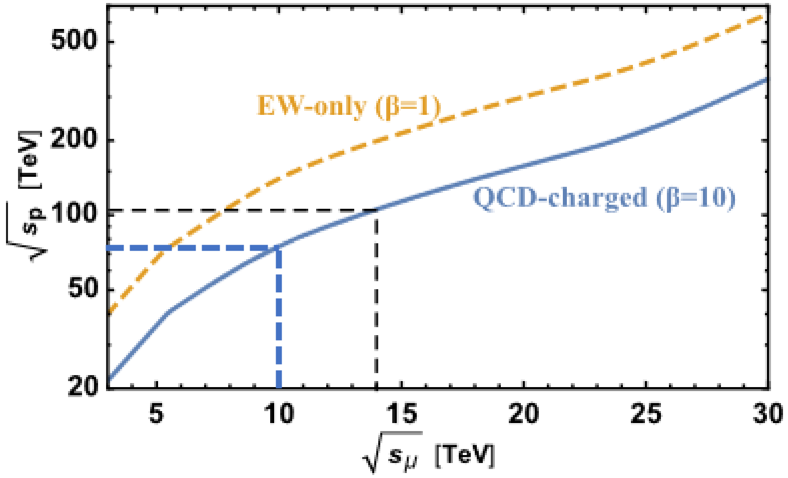
Muon colliders gained significant attention in recent months following US **Particle Physics Project Prioritization Panel** (P5)


Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).


As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design

Why 10TeV?

- **Fits inside the existing Fermilab site!**
- **10TeV muon collisions could approach comparable energy scale as 100TeV pp machine (assuming equivalent collider performance)**



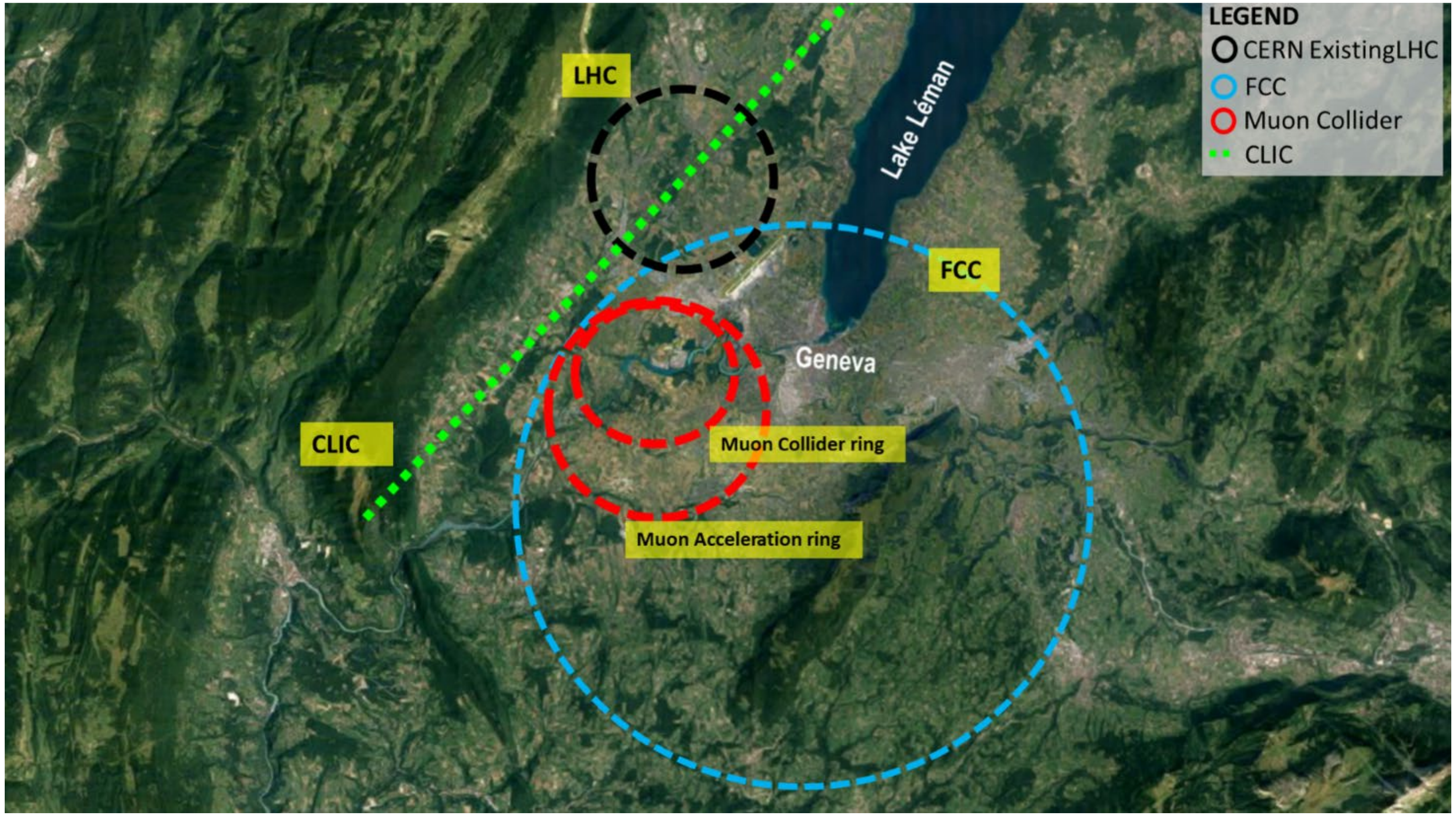
Towards a muon collider
https://link.springer.com/article/10.1140/epjc/s10052-023-11889-x

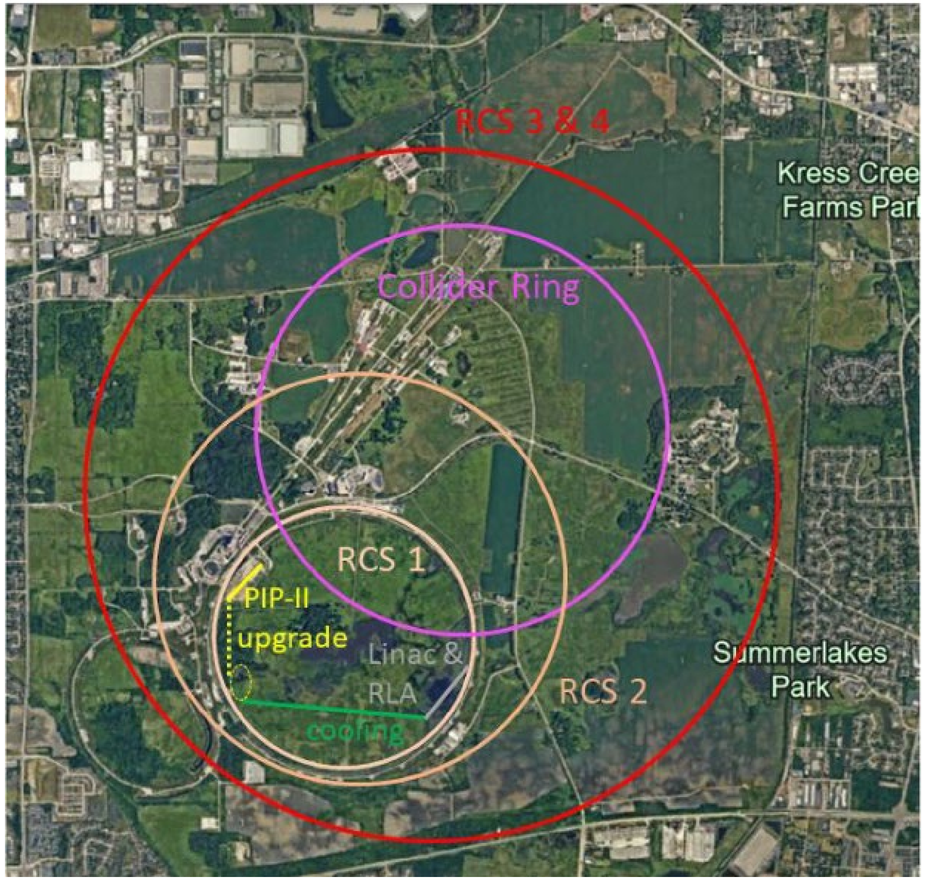
No definitive muon collider proposals yet, but large collaborations

International
MUON Collider
Collaboration

https://muoncollider.web.cern.ch/

In general designs expected to support 1 or 2 HEP experiments at ≈10TeV





Muon collider offers some very exciting opportunities!
→ But is also the least mature of the main future project proposals

- **No Conceptual design report published: however there is a nice review article prepared by IMC which does good job of outlining baseline options** **Towards a muon collider** https://link.springer.com/article/10.1140/epjc/s10052-023-11889-x

- **No muon collider demonstrator facility already exists, likely some will be needed and R&D towards this was one of P5 key recommendations, aiming to determine the feasibility of a muon collider**

- **Snowmass 2021 exercise ranked Muon collider on any energy scale as 3 / 4 risk. Comparable to FCChh.**
  → likely reflecting that multiple core technologies will require some significant R&D to be ready

- **Lost of active research, and lots of synergy with other projects**

IMCC and MuCol Annual Meeting 2024

12-15 March 2024, CERN

Scientific Program Committee - Chairs: L. Bottura & C. Carli (CERN). Members: M. Casarsa (INFN), A. Chance (CEA), R.Franqueira Ximenes (CERN), S. Gilardoni (CERN), D. Giove (INFN), A. Grudiev (CERN), S. Jindariani (FNAL), A.Lechner (CERN), R. Losito (CERN), D. Lucchesi (INFN), E. Metral (CERN), N. Milas (ESS), M. Palmer (BNL), N. Pastrone (INFN), L. Quettier (CEA), C. Rogers (STFC), D. Schulte (CERN), A. Wulzer (IFAE/ICREA), A. Yamamoto (CERN).

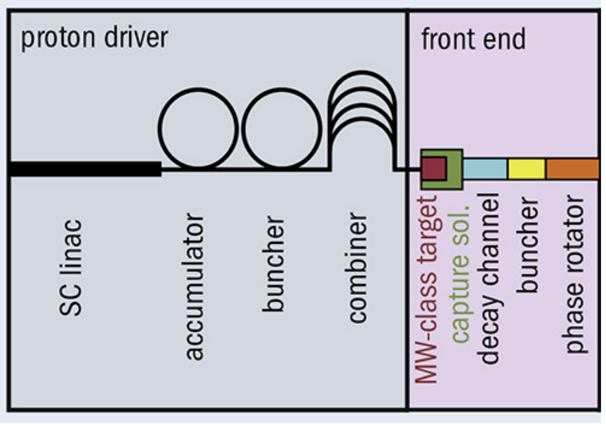
CERN Organising Committee : D. Schulte (Project Leader), A. Augier, M. Lancellotti.

Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

indico.cern.ch/event/1325963/

https://indico.cern.ch/event/1325963/overview

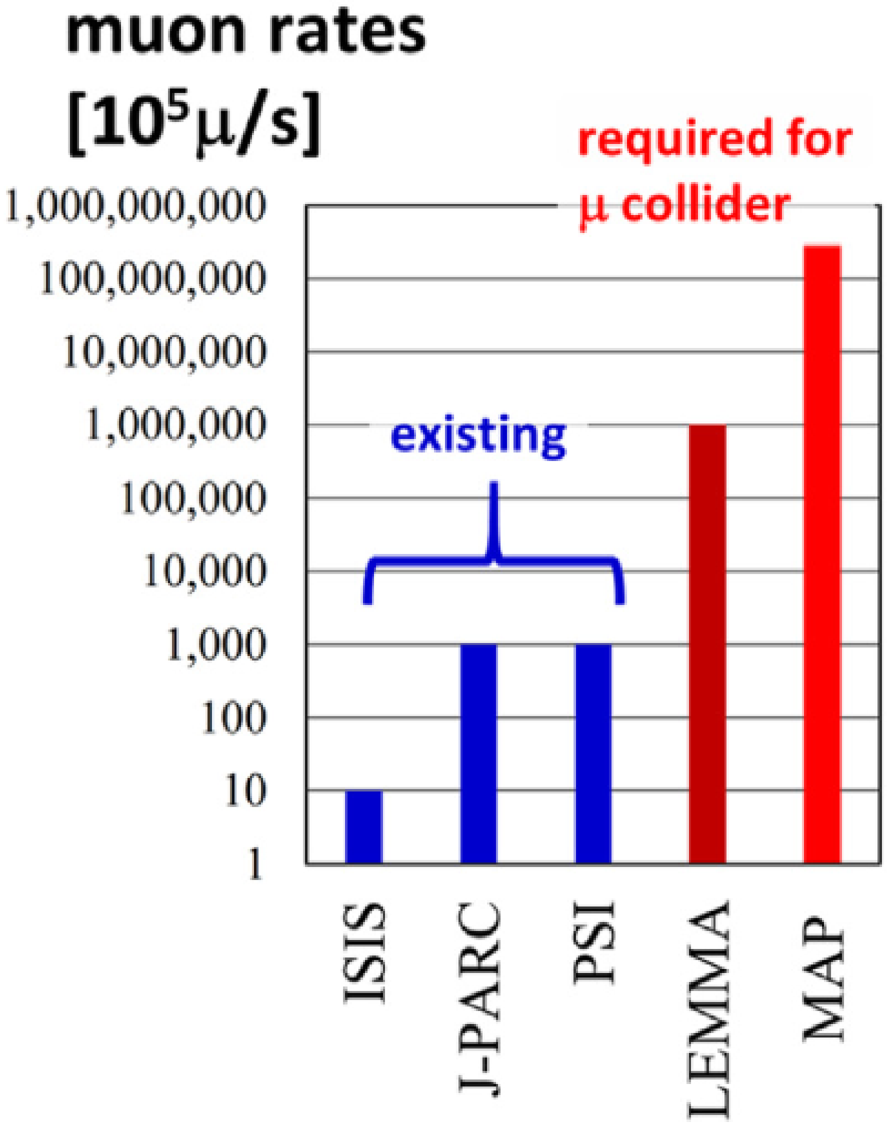
What are some of the challenges facing muon colliders?



Muon beams are created indirectly from decay of pions generated by high intensity proton bunch collisions with target

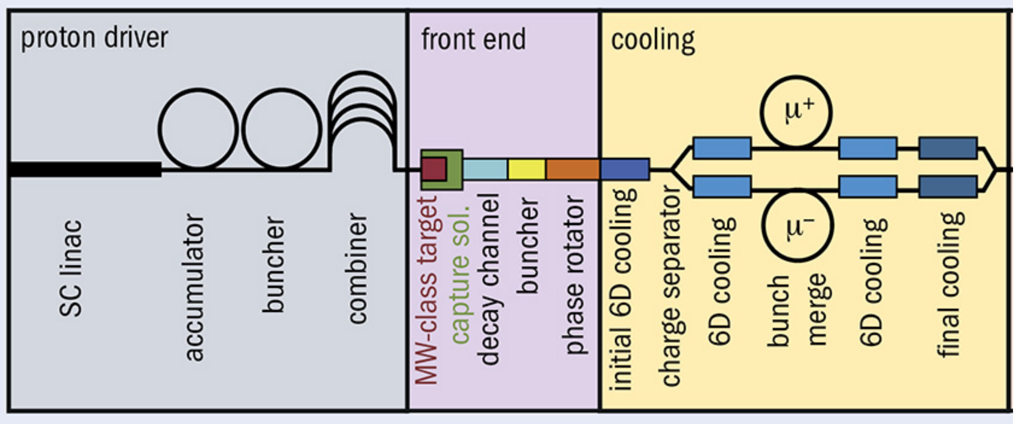
Source needs to create sufficient muon flux to provide competitive luminosity

Lots of R&D ongoing into design and development of necessary proton drive beam and target



F.Zimmerman, Accelerator Technology and Beam Physics of Future Colliders
https://www.frontiersin.org/articles/10.3389/fphy.2022.888395/full

What are some of the challenges facing muon colliders?



Muon beams are created indirectly from decay of pions

→ **Obtain a very low quality beam naturally from the pion decay: large emittance, large momentum spread**

Muon beams need to be cooled to small emittance in order to generate decent luminosity

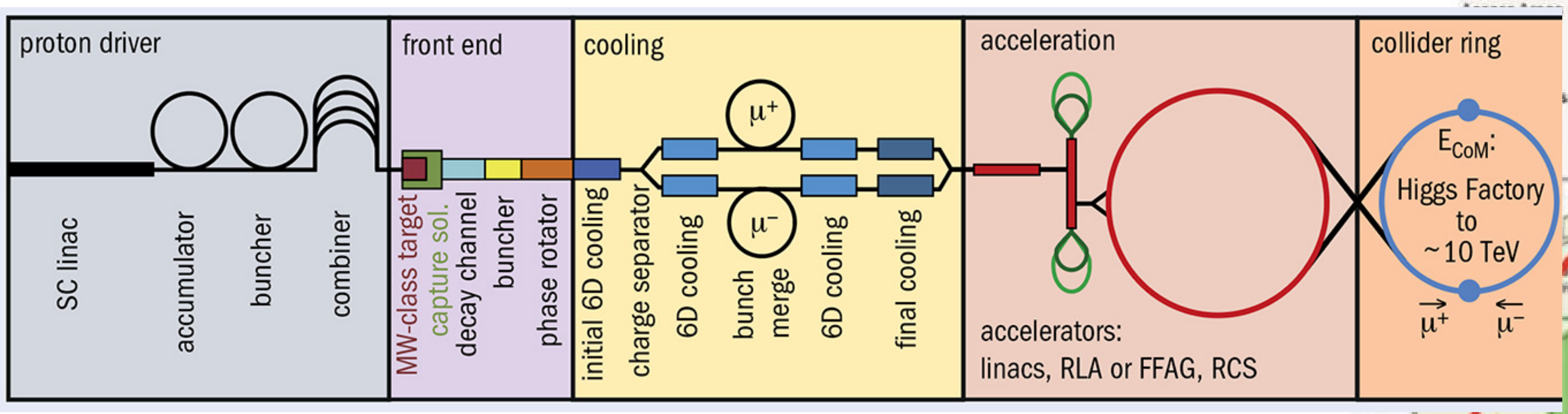
→ **Muons created by pion decay have very short lifetime in the LAB. All conventional cooling techniques would be too slow**

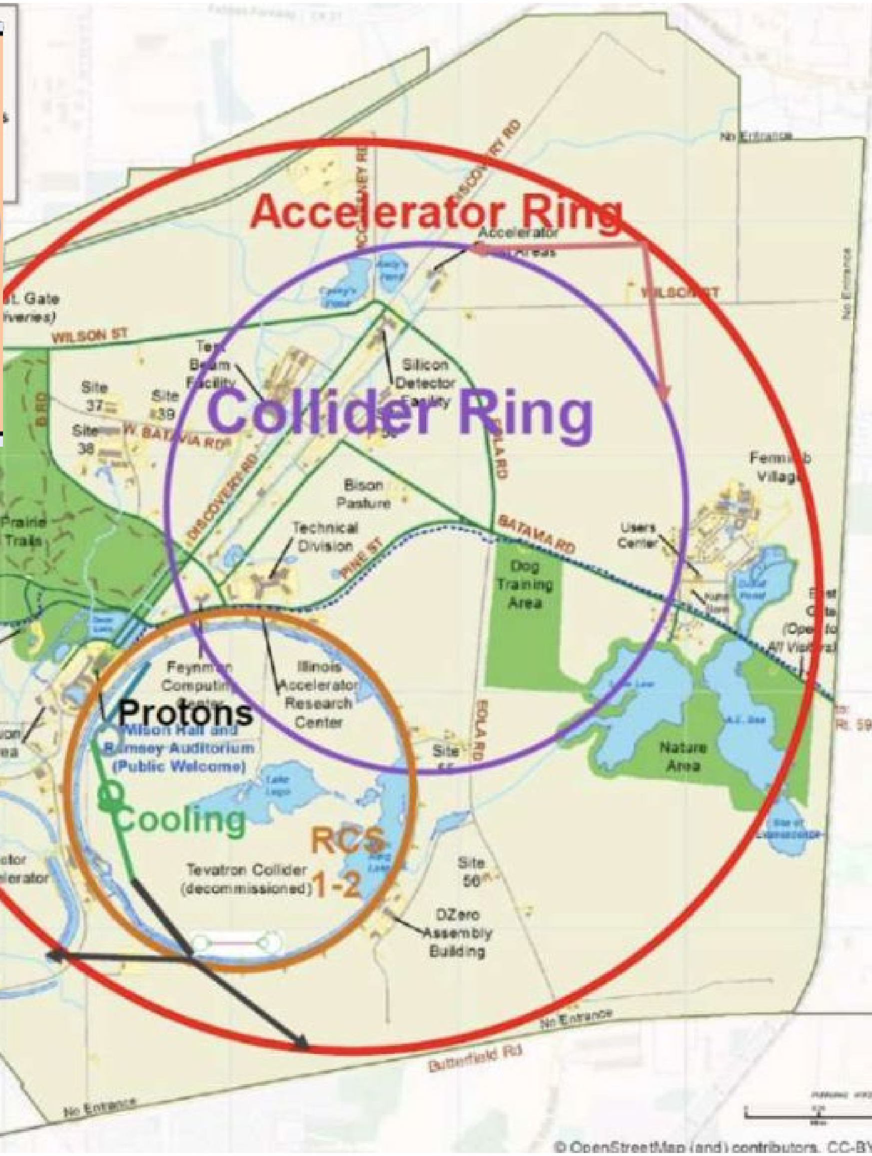
Use ionization cooling to rapidly cool muon beams: demonstrated by MICE collaboration

→ **Demonstrated for single pass in transverse plane. MuColl will require demonstration of multiple pass 6D cooling**

Demonstration of cooling by the Muon Ionization Cooling Experiment https://www.nature.com/articles/s41586-020-1958-9

What are some of the challenges facing muon colliders?





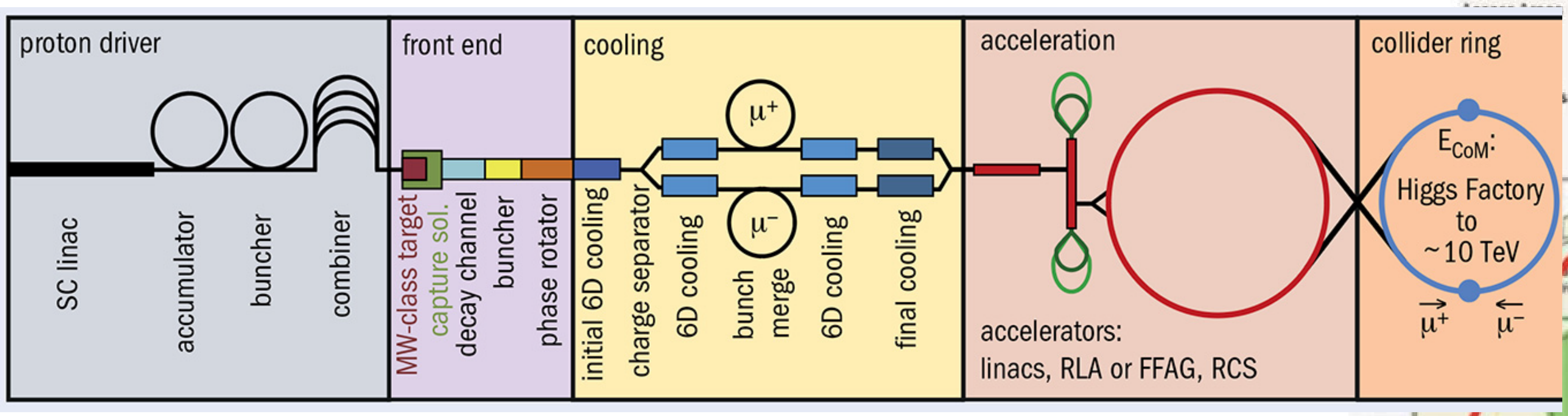
Muons have a short lifetime even at 10TeV (≈0.1s)

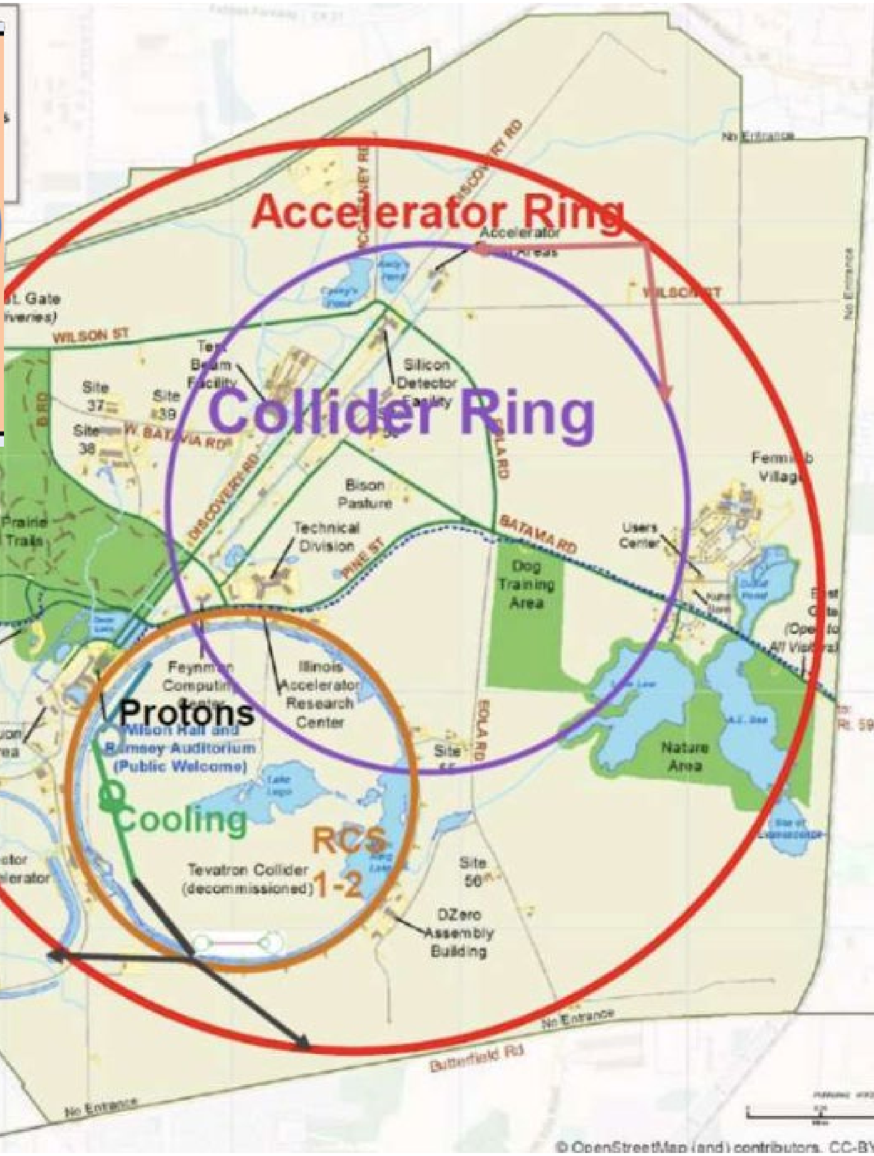
→ **Need to be collided in as small a ring as possible so that they make many turns before they decay**

→ **Cryogenic high-field magnets: for 10TeV collider requirements are equivalent to FCChh (16T Nb3Sn). FCChh expects large scale industrialization ready for 2070's operation**

→ **Some plans suggest 3TeV collider based on 10T Nb3Sn could be ready on FCCee timescale. Not universally accepted timeline. 11T Nb3Sn LHC dipole recently de-baselined from HL-LHC run4 as after 100MCHF still couldn't produce working prototype on required timeline**

What are some of the challenges facing muon colliders?





Muons have a short lifetime even at 10TeV (≈0.1s)

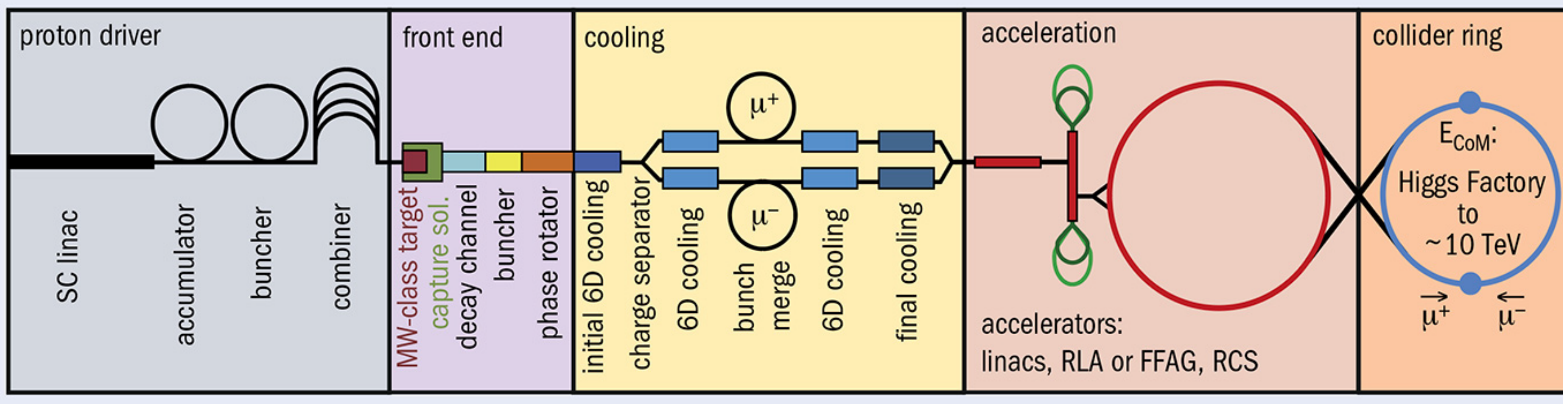
→ Need to be accelerated to top energy in as short a time as possible

→ Multiple rapid cycling synchrotrons (RCS) are used to quickly increase the beam energy. Final acceleration to 5GeV done in large 35km ring with a mix of high field SC magnets and normal conducting fast ramped magnets

→ RCS magnets need to ramp between +/- 1.5T on timescales of [ms]. Ramp rates several orders higher than existing magnets

→ Need to demonstrate ramp rate, but also power efficiency!

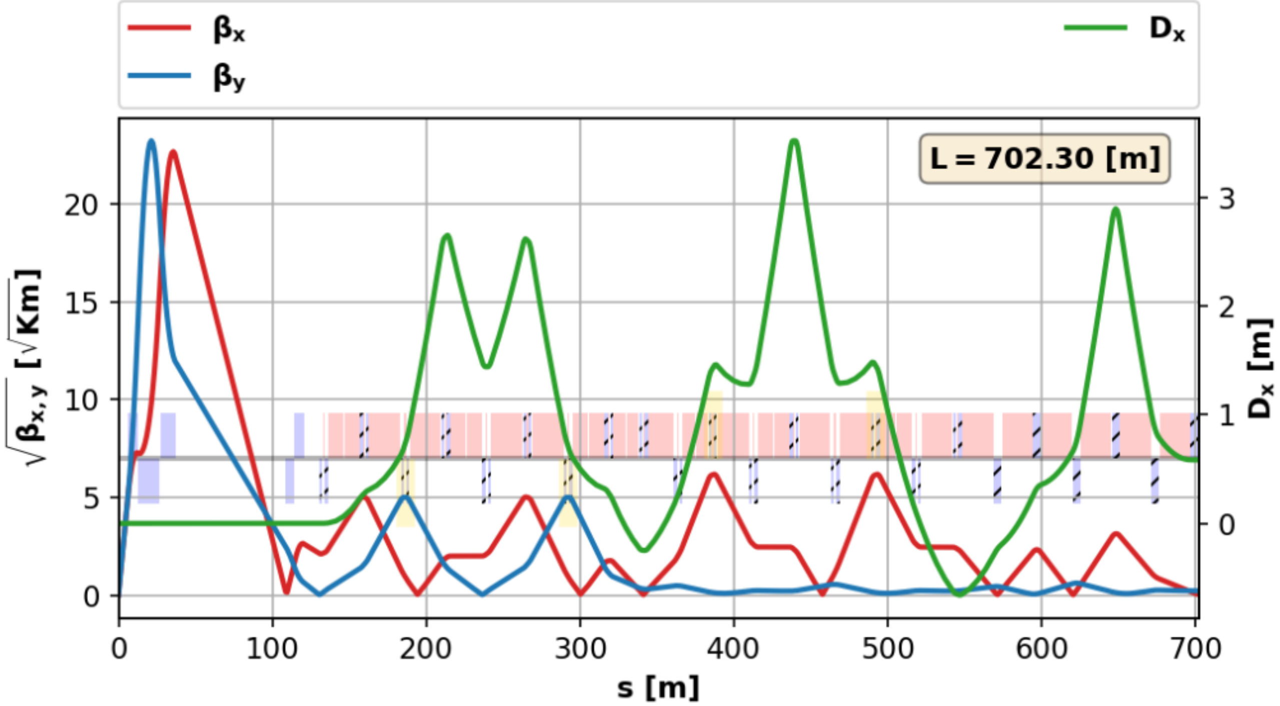
What are some of the challenges facing muon colliders?



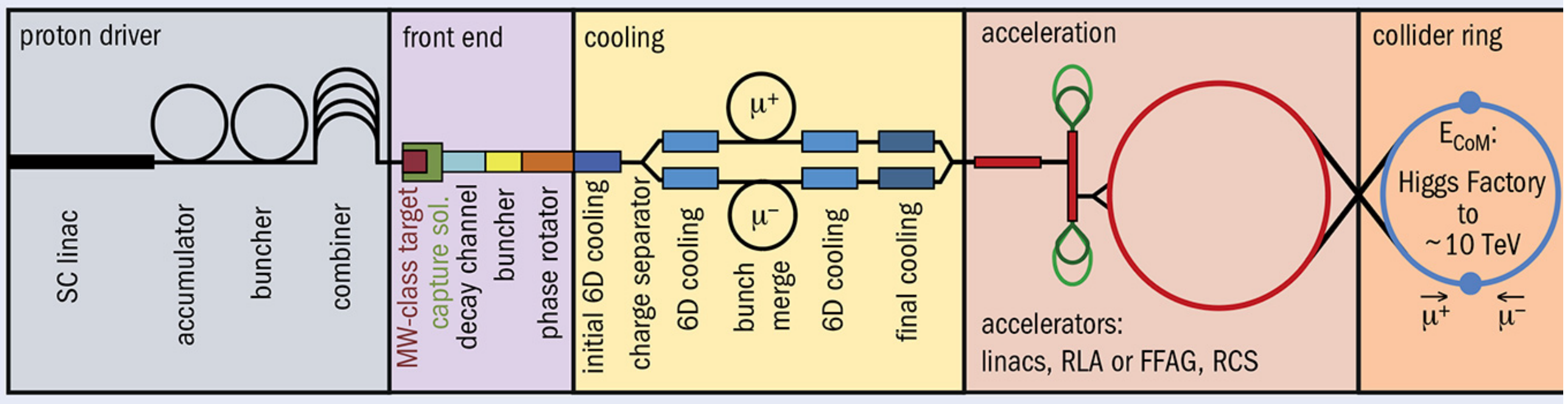
Even with cooling muons bunches expected to have poor emittance and low repetition frequency compared to typical hh options

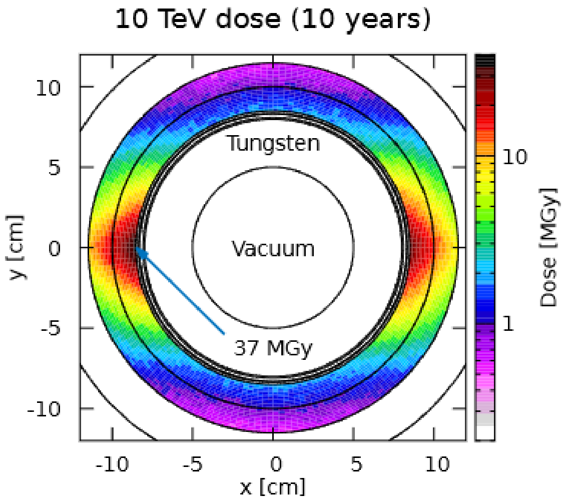
→ **To reach high-luminosity need to squeeze beams to extremely small beta-functions at IP → 1mm**

→ **Challenging from design and operation: extreme sensitivity to optics errors in final focus**



What are some of the challenges facing muon colliders?





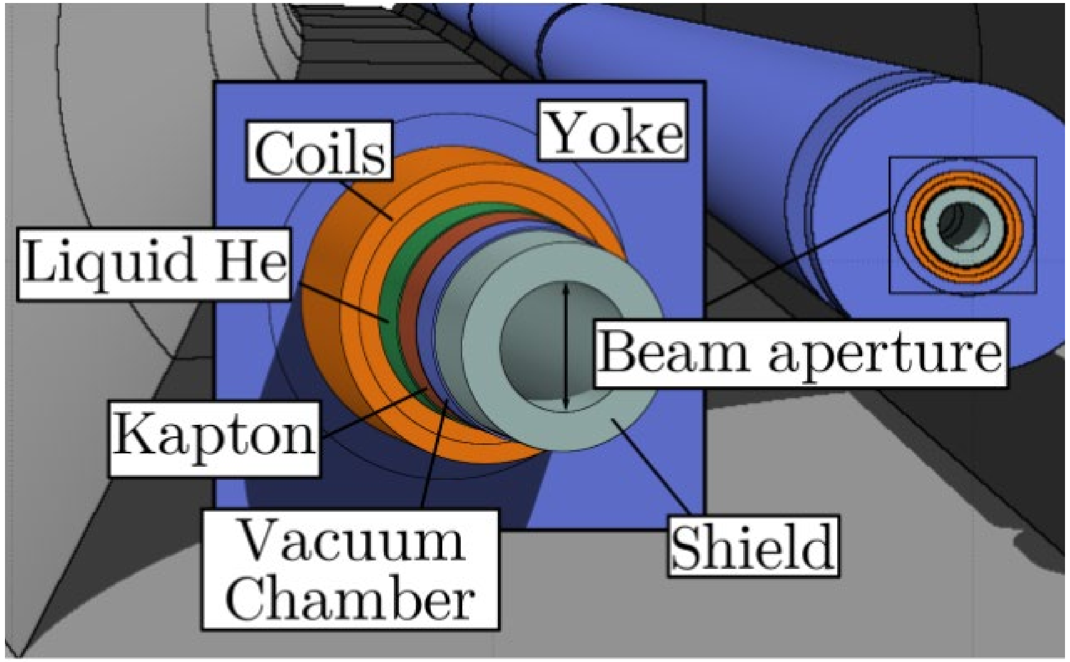
RADIATION LOAD STUDIES FOR SUPERCONDUCTING MAGNETS IN A 10 TeV MUON COLLIDER https://cds.cern.ch/record/2845834/files/document.pdf

Muons have a short lifetime even at 10TeV (≈0.1s)

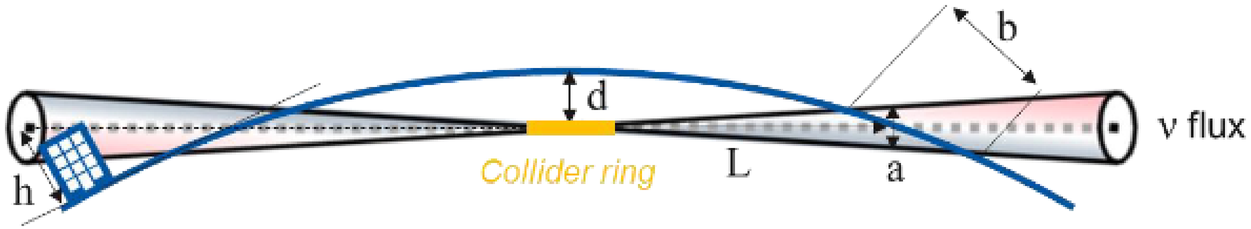
→ **Decay while stored in accelerator**

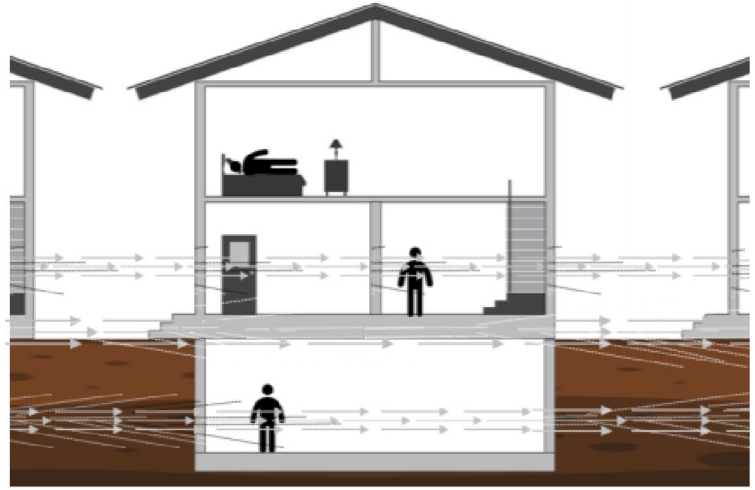
→ **Decay products induce a heat load on the magnet cryo** (500W/m/beam)

→ **Need to include significant shielding to magnet design to limit heat load and radiation damage to magnets**



What are some of the challenges facing muon colliders?

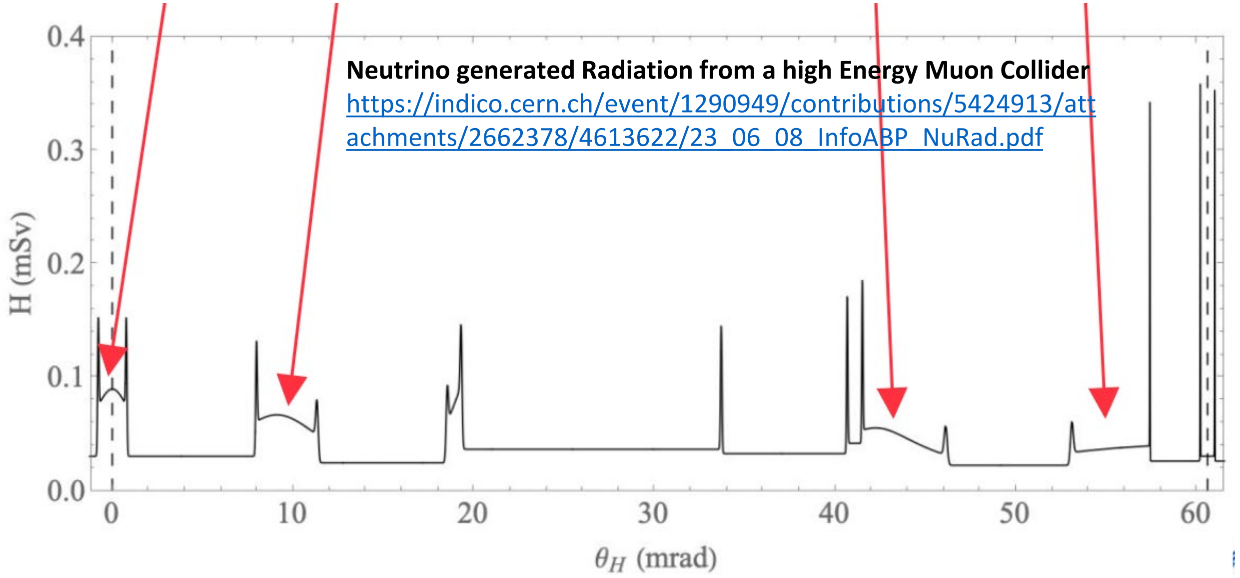




Overview of Neutrino Radiation Model
https://indico.cern.ch/event/1325963/contributions/5837736/attachments/2819626/4923686/RP_IMCCAnnualMeeting_0324_Final.pdf

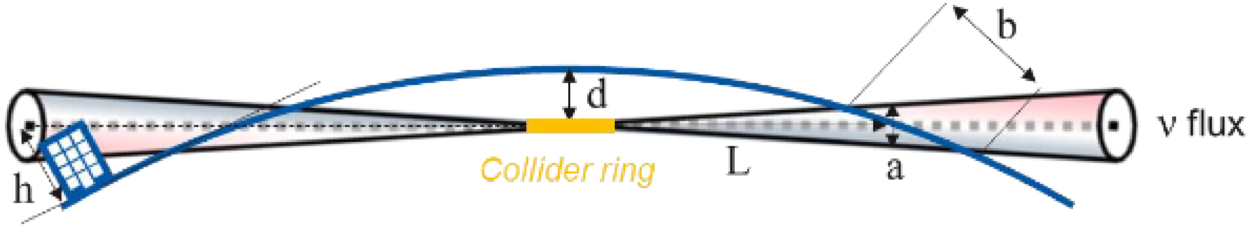
Muons have a short lifetime even at 10TeV (≈0.1s)

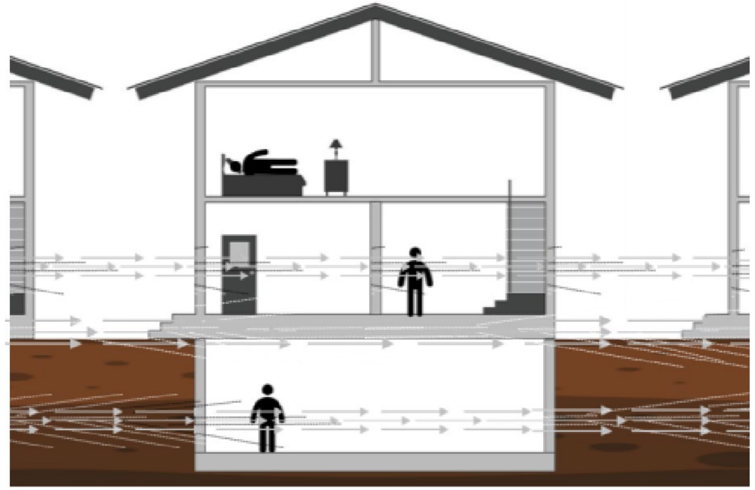
- → Decay while stored in accelerator
- → Neutrino's produced in the decay escape the collide tunnel and generate radiation does at surface
- → Require negligible impact on public (10 µSv/year)



Neutrino generated Radiation from a high Energy Muon Collider
https://indico.cern.ch/event/1290949/contributions/5424913/attachments/2662378/4613622/23_06_08_InfoABP_NuRad.pdf

What are some of the challenges facing muon colliders?





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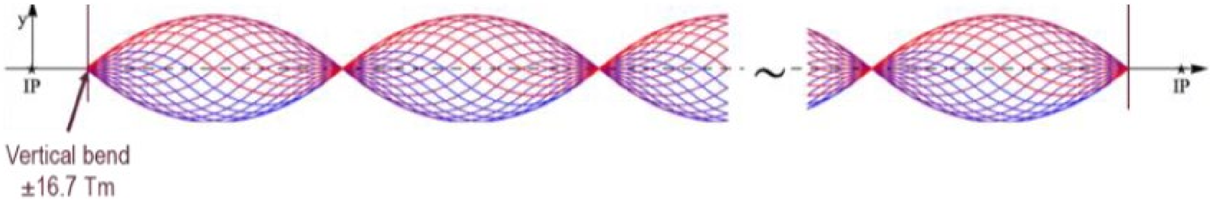
Muons have a short lifetime even at 10TeV (≈0.1s)
→ Decay while stored in accelerator

→ **Mechanically move accelerator orientation over time to spread dose over larger area (at lower energy can be done non-mechanically)**

→ **Buy and secure regions emergence points in non-populated areas to cope with HEP IRs where moving not viable**

→ **May be challenging from operational control perspective but `not a show stopper'**



C. Carli, "Neutrino Radiation for a realistic Collider", IMCC Annual Meeting 2022

muon colliders exciting proposal with lots of potential advantages, but also significant R&D challenges which need to be overcome.

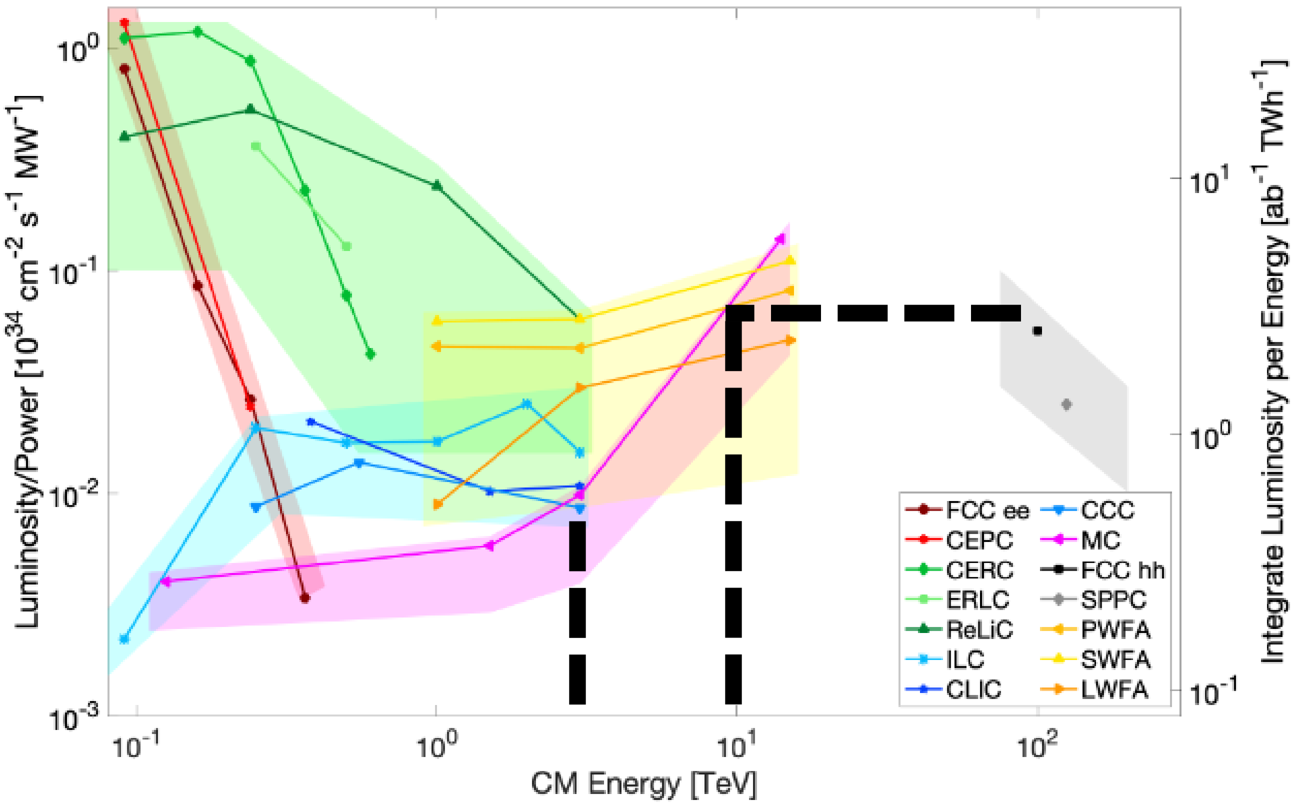
Many of these challenges are synergistic with other projects or very valuable in their own right! High-field magnets, rapid cycling magnets, intense muon sources…

Hard to estimate cost and power consumption for project at such and early stage. Snowmass included some estimates

At 10TeV Luminosity per power consumption looks similar for FCChh and MuColl

At 3TeV Luminsoity / power consumption similar between MuColl and CLIC

At lower energy muons decay too fast to achieve good Lumi/power



2023, JINST 18 P0501 *On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force*
https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

muon colliders exciting proposal with lots of potential advantages, but also significant R&D challenges which need to be overcome.

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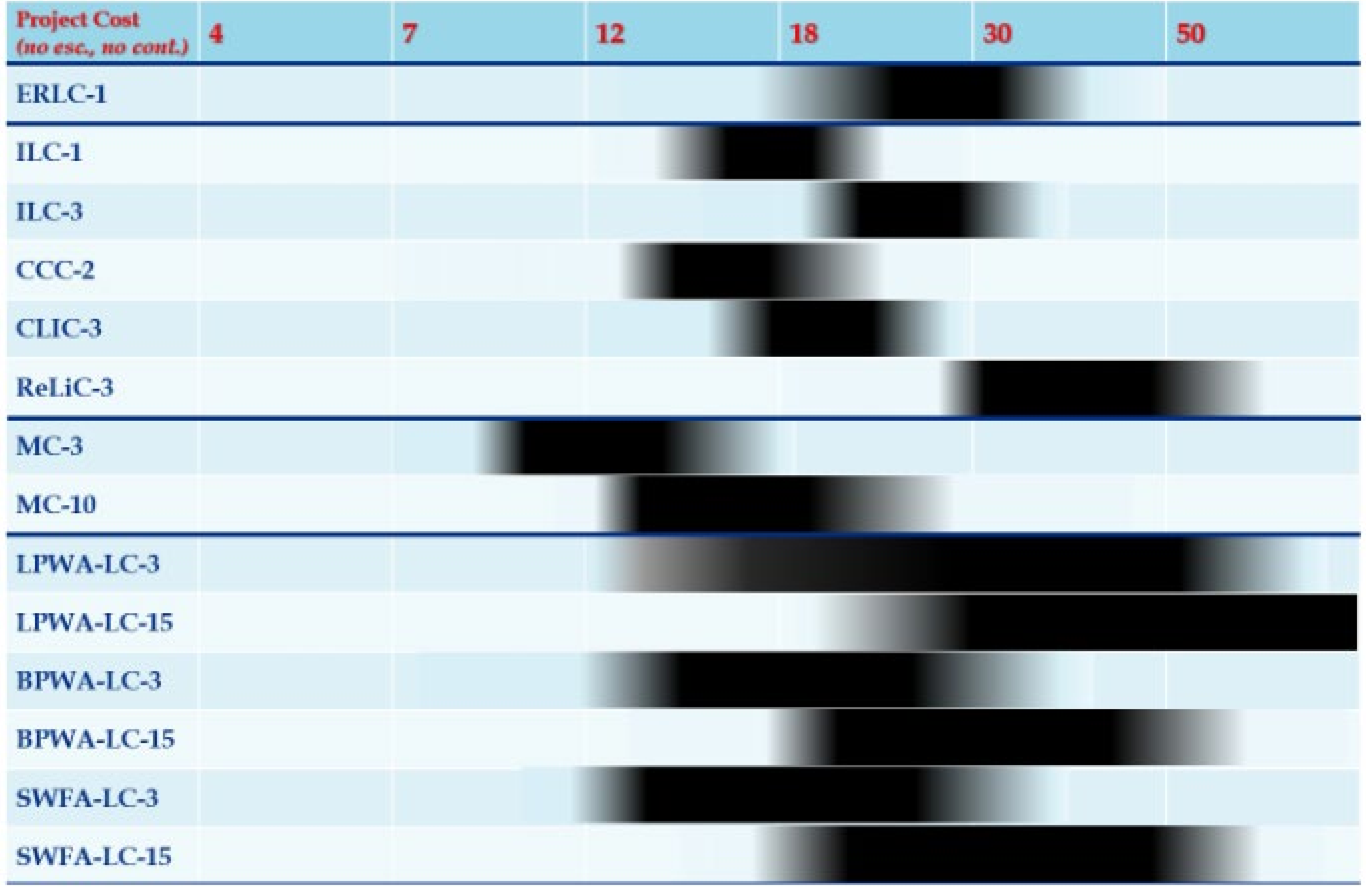
On greenfield site 10TeV muon collider would require

35km accelerator + 10km collider + ~km low energy rings

One possibility could be to re-use LHC tunnel, but viability not yet studied in detail by Muon collaboration



Future technologies for HEP accelerators?

Lemma source for a muon collider

2 of the major obstacles to successful muon collider are requirement for rapid cooling + neutrino radiation

→ LEMMA concept seeks to overcome both of these!

***Nucl.Instrum.Meth.A* 807 (2016)**
https://inspirehep.net/literature/1393535

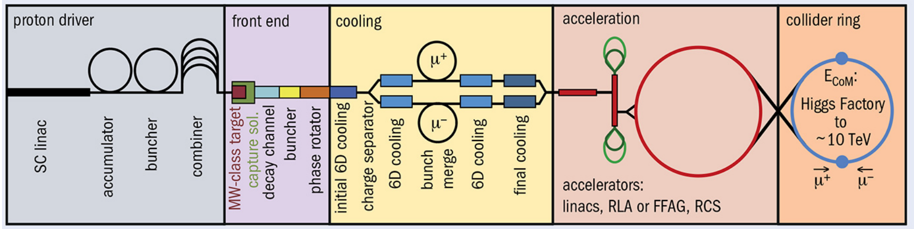
PHYSICAL REVIEW ACCELERATORS AND BEAMS 21, 061005 (2018)
https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.21.061005

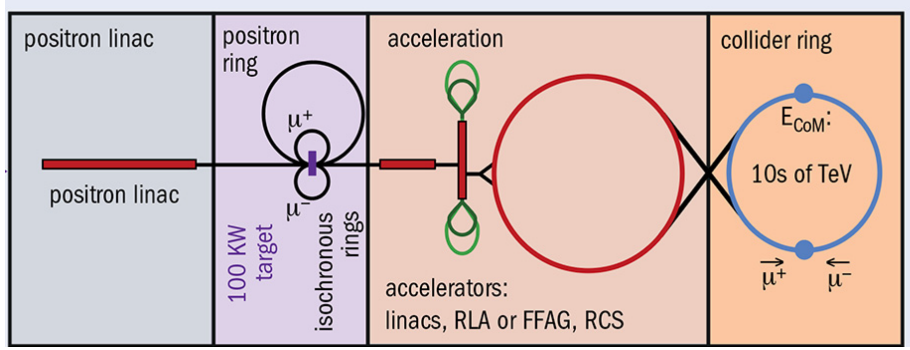
$$e^+e^- \rightarrow \mu^+\mu^-$$

Rather than creating tertiary muon bunches from decay of pions created by proton beam hitting target, create secondary muon bunches via impact of 45GeV positron beam on target

- **Muons created at higher γ than conventional source**
  → higher initial lifetime in lab frame = less demanding for initial acceleration

- **Muons have much lower initial emittance**
  → less demanding cooling requirements
  → achieve same luminosity with lower beam current
    → lower heat load on magnets
    → lower background to detectors
    → lower neutrino radiation levels





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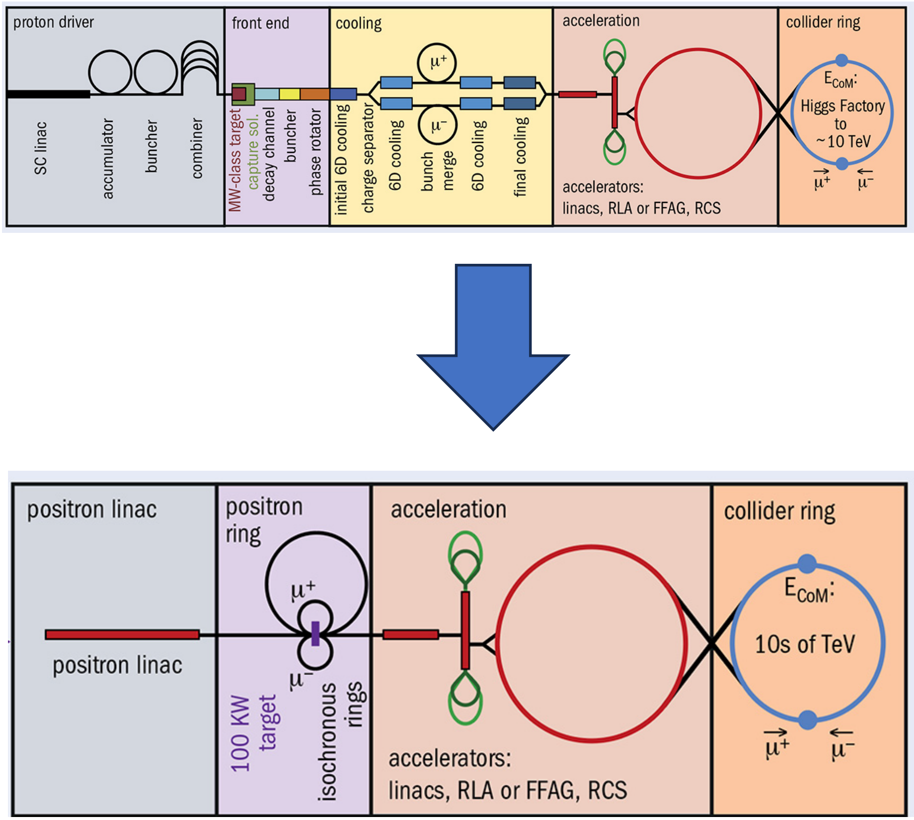
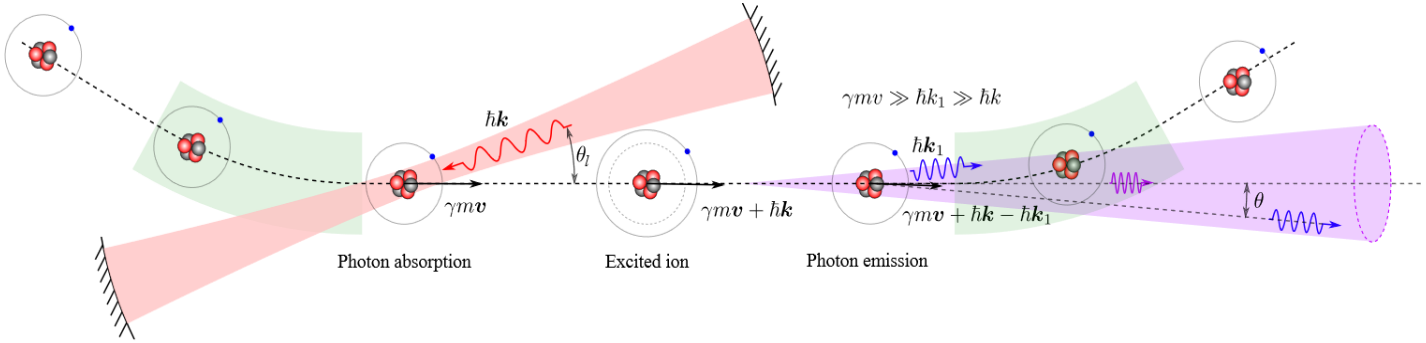


- **Face many challenges to be realized in real life**
  → Need high-current 45GeV positron beam
    – no conventional positron source yet meets requirements
    - FCC and linear collider sources several orders of magnitude low
  → positron target needs to be able to withstand high collision rates
  → positron beam degradation during production
- **Elegant proposal that could dramatically change muon collider prospects, but very substantial R&D needed on the source**

Gamma factory

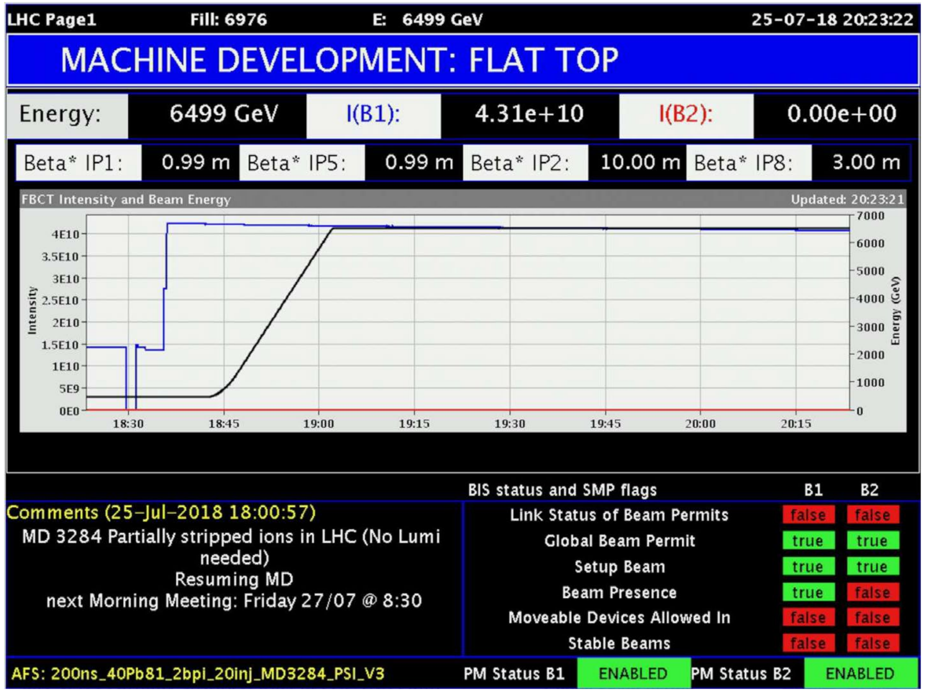
https://doi.org/10.1142/9789811280184_0021

Create intense beam of polarized high-energy photos using partially stripped ions in LHC or FCChh



- **Partially stripped ions – e.g. Pb^{81+} circulate in ring**
- **Incident laser excites electron in PSI to higher state**
- **Decay of electron to ground emits photon**
- **Emitted photon gains huge energy boost:** (1e8 for LHC)

$$\boxed{4\gamma_{beam}^2}$$



LHC Page1 Fill: 6976 E: 6499 GeV 25-07-18 20:23:22

MACHINE DEVELOPMENT: FLAT TOP

Energy:	6499 GeV	I(B1):	4.31e+10	I(B2):	0.00e+00

Beta* IP1:	0.99 m	Beta* IP5:	0.99 m	Beta* IP2:	10.00 m	Beta* IP8:	3.00 m

Comments (25-Jul-2018 18:00:57)
MD 3284 Partially stripped ions in LHC (No Lumi needed)
Resuming MD
next Morning Meeting: Friday 27/07 @ 8:30

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: 200ns_40Pb81_2bpi_20inj_MD3284_PSI_V3 PM Status B1 ENABLED PM Status B2 ENABLED

Storage of partially stripped Pb ions already demonstrated in LHC

Plans to try and demonstrate principle of photon excitation/emission in SPS

Proposed end-of-life scenario for LHC:

→ **Applications to nuclear physics**

→ **Applications to muon colliders:** photon beam can generate LEMMA level positron source, or even create highly polarized muons directly

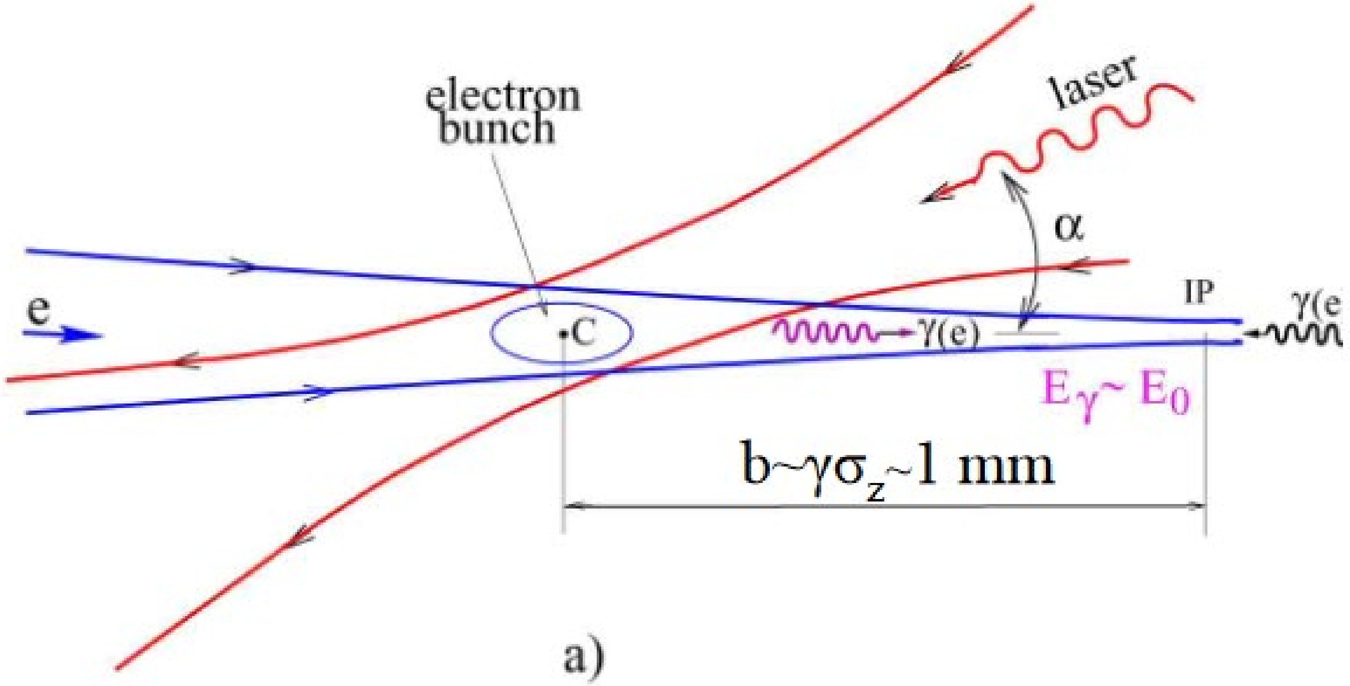
→ **Even suggested this could act as pathway to 100TeV FCC-μμ** (not yet a serious R&D topic however)

Gamma-gamma collider

Can generate high-energy photon beams via inverse compton scattering on high-energy beams in a linear collider

→ potential upgrade option for linear e^+e^- to collide photons instead of electrons/positrons

→ long-running idea in the linear collider community: potentially rather cheap compared to typical e^+e^- upgrade path



Noted as a possible upgrade path in the ILC TDR

Cooled Copper Collider (C^3)

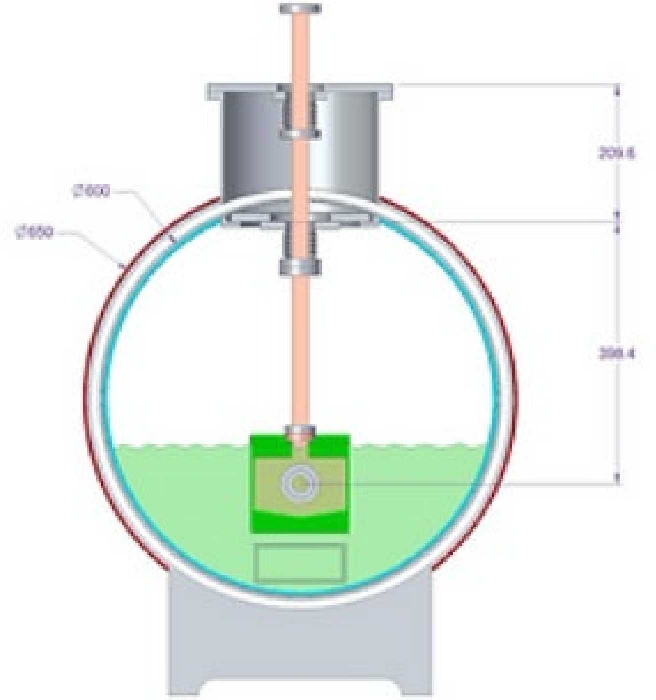
Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature
https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.24.093201

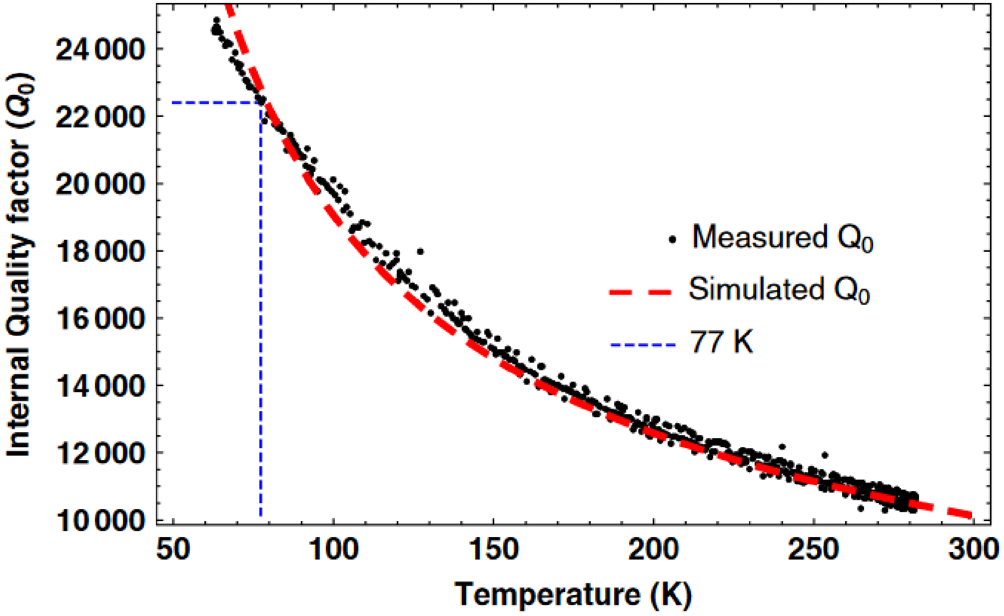
A "Cool" route to the Higgs boson and beyond. The Cool Copper Collider
https://iopscience.iop.org/article/10.1088/1748-0221/18/07/P07053

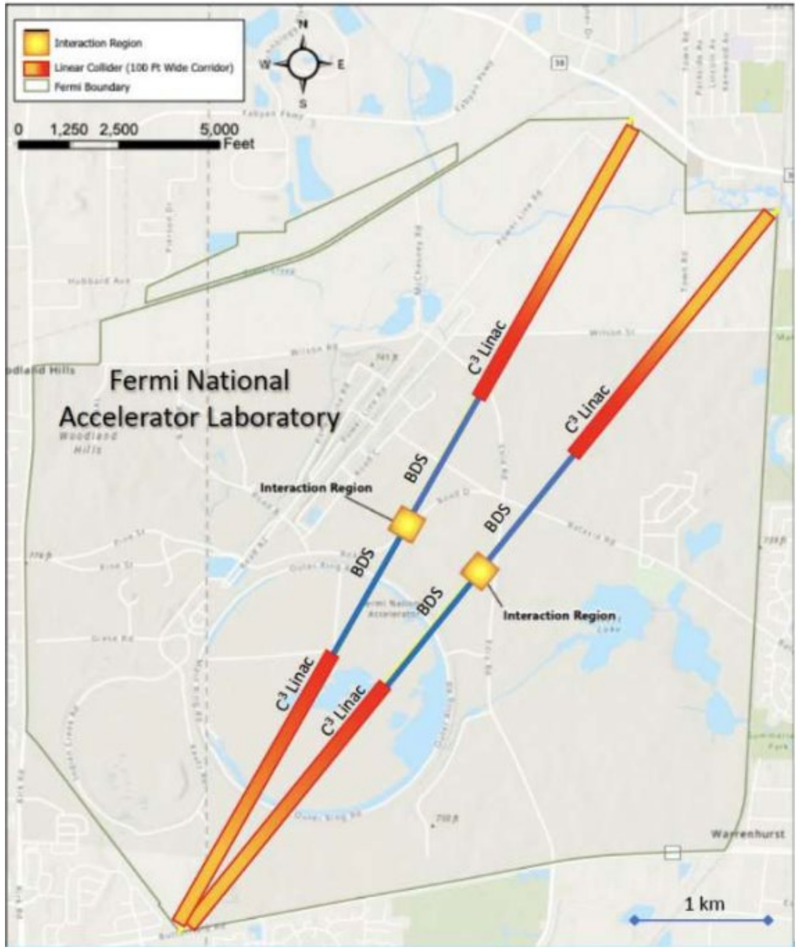
Can improve the performance of high-frequency normal conducting cavities (like CLIC) by chilling the copper

→ **Allows to reach higher accelerating gradients: e.g. C3 at 120MV/m vs CLIC at 100MV/m.**

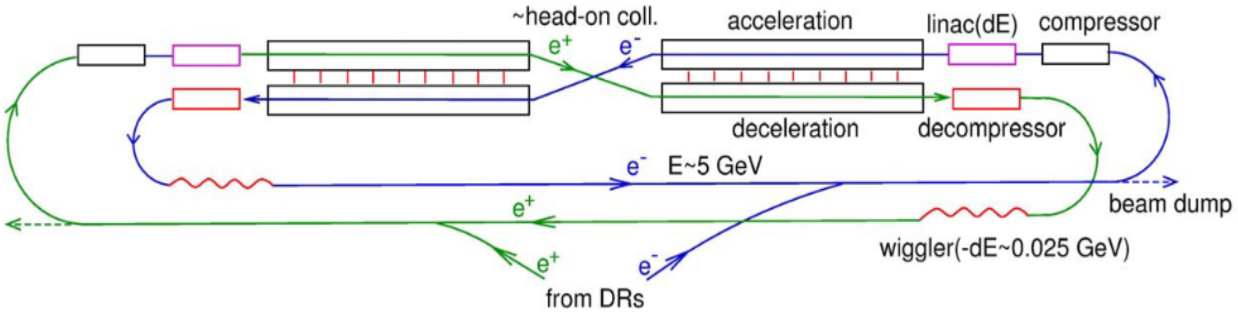
→ **Can make Higgs factory in more compact tunnel able to fit on FermiLab site!**





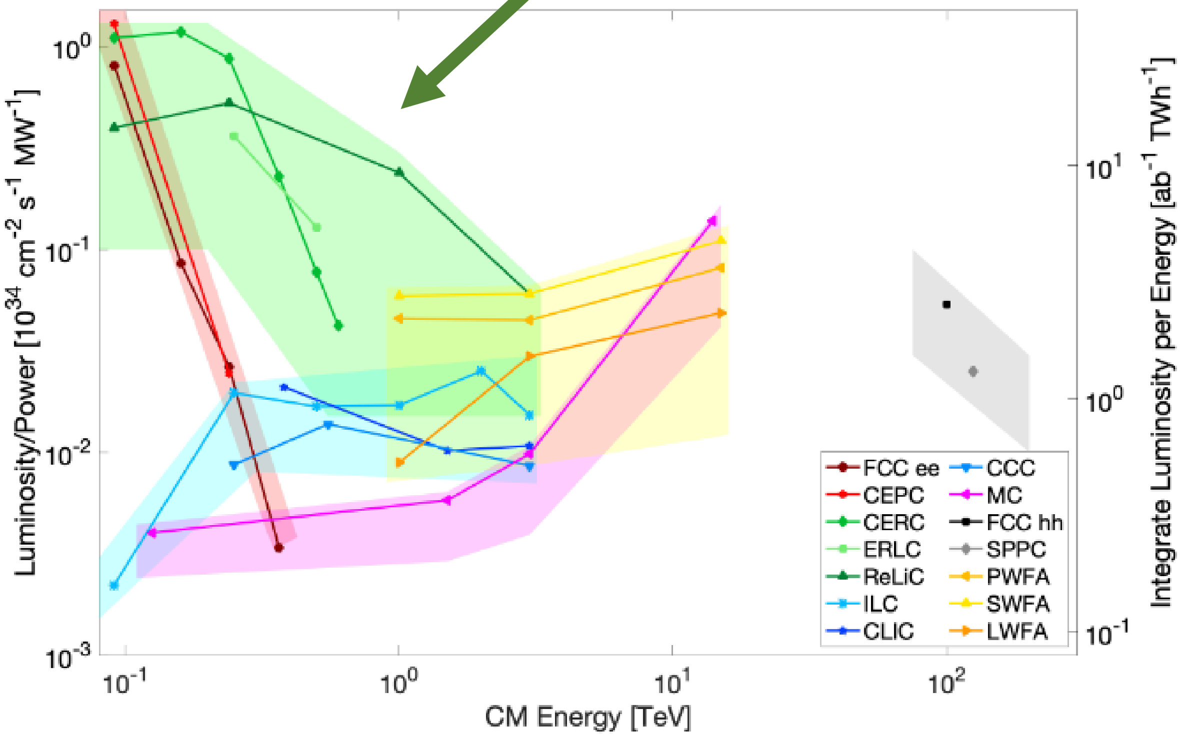


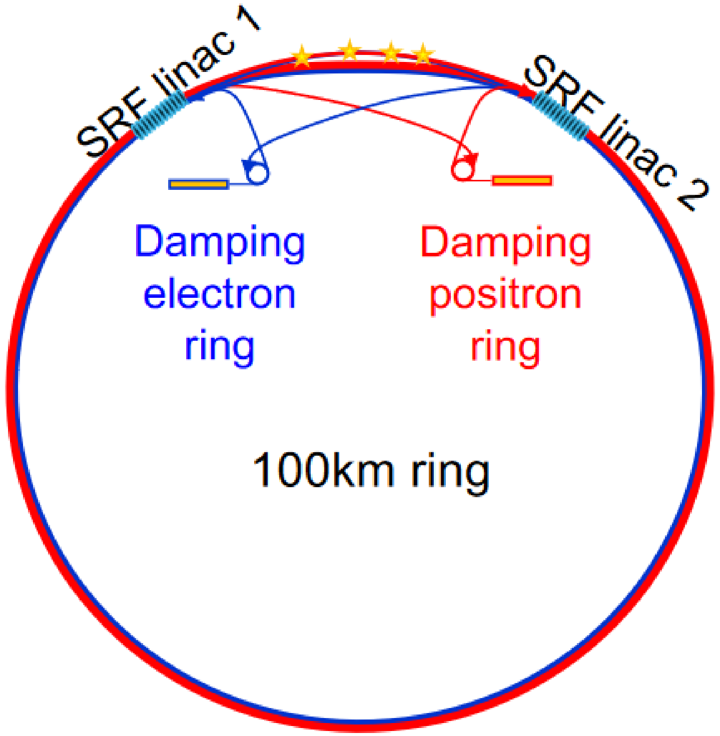
Energy-Recovering Linac collider (ERL)



Power to accelerate ingoing bunch provided by deceleration of outgoing bunch from the IP

Could hypothetically significantly improve luminosity/power of FCC and CLIC/ILC designs





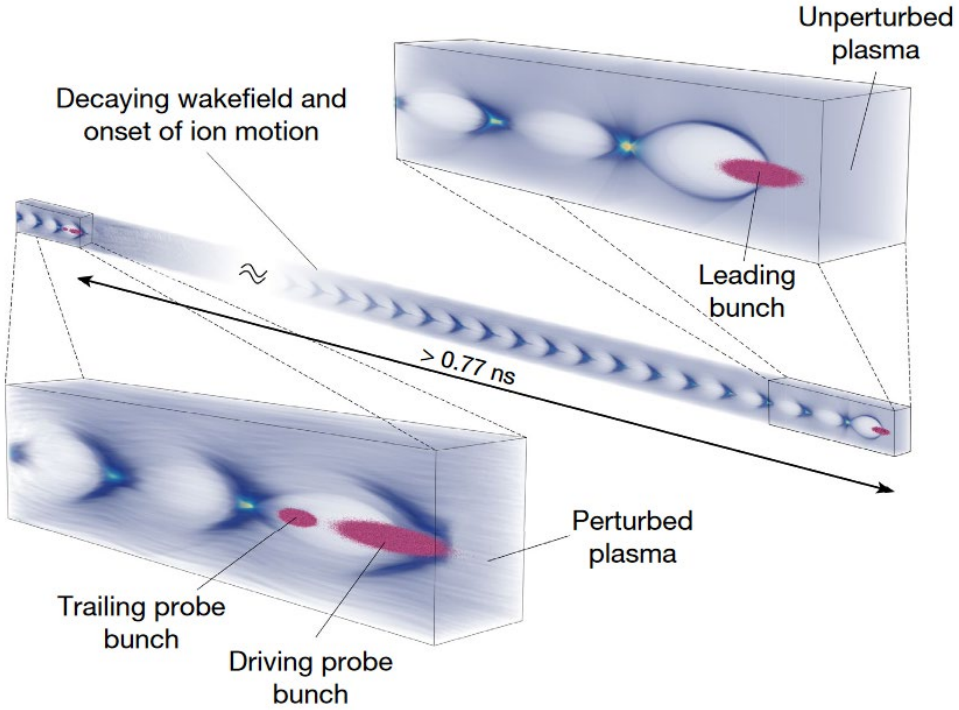
Plasma Wakefield acceleration (PWA)

CLIC cavities achieve 100MV/m, C3 around 120MV/m

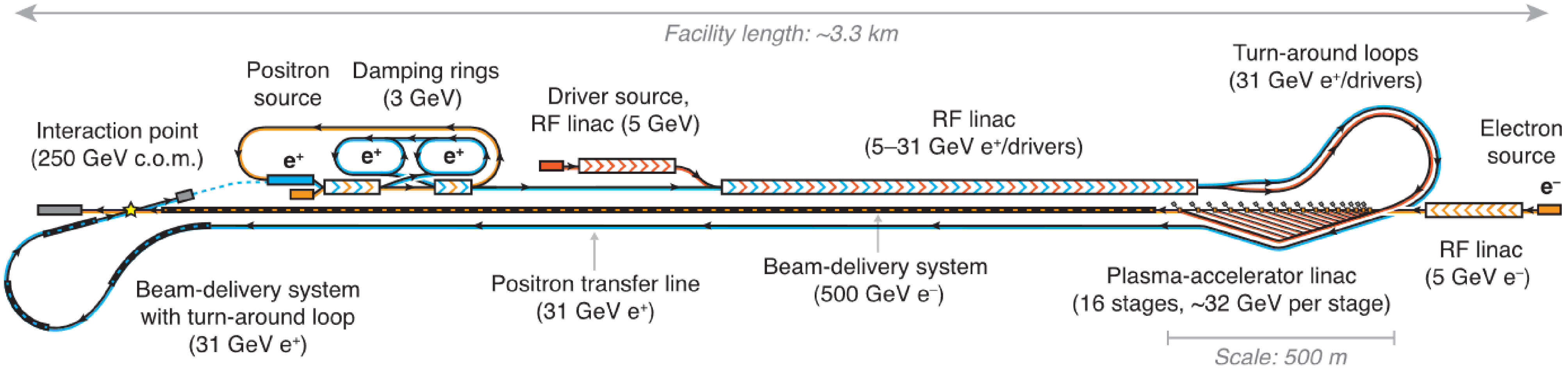
Plasma wakefield acceleration can provide gradients in the GeV/m range. Could potentially allow more compact linear colliders.

Acceleration of electrons clearly demonstrated, but acceleration of positrons is challenging: one proposal is HALHF – adaption of ILC to use PWA on the e- line.

Lots of R&D required to demonstrate viability of acceleration through many plasma cells + reptation rates necessary for high lumi



Recovery time of a plasma-wakefield accelerator
https://www.nature.com/articles/s41586-021-04348-8



A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency Acceleration
https://iopscience.iop.org/article/10.1088/1367-2630/acf395/pdf

Conclusions

Lots of truly exciting options on the table for future collider programs in Europe and globally!

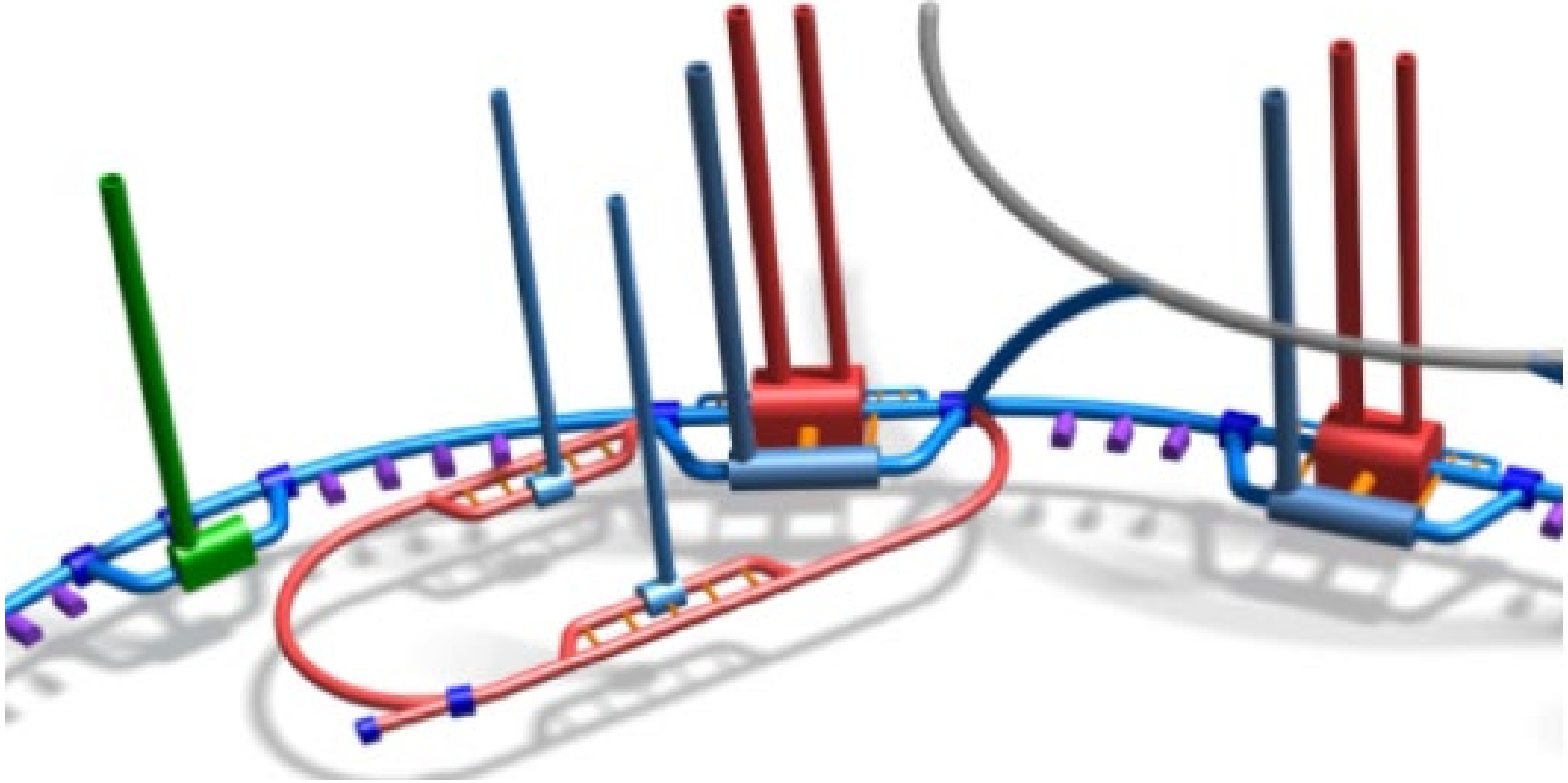
Several leading candidates for the next big European project, all involve lots of exciting R&D with clear societal benefit. Lots of promising future technologies to be explored!

Any choice will be a trade off between luminosity, energy, upgradeability, running cost, construction cost, and risk.

A choice is needed soon!

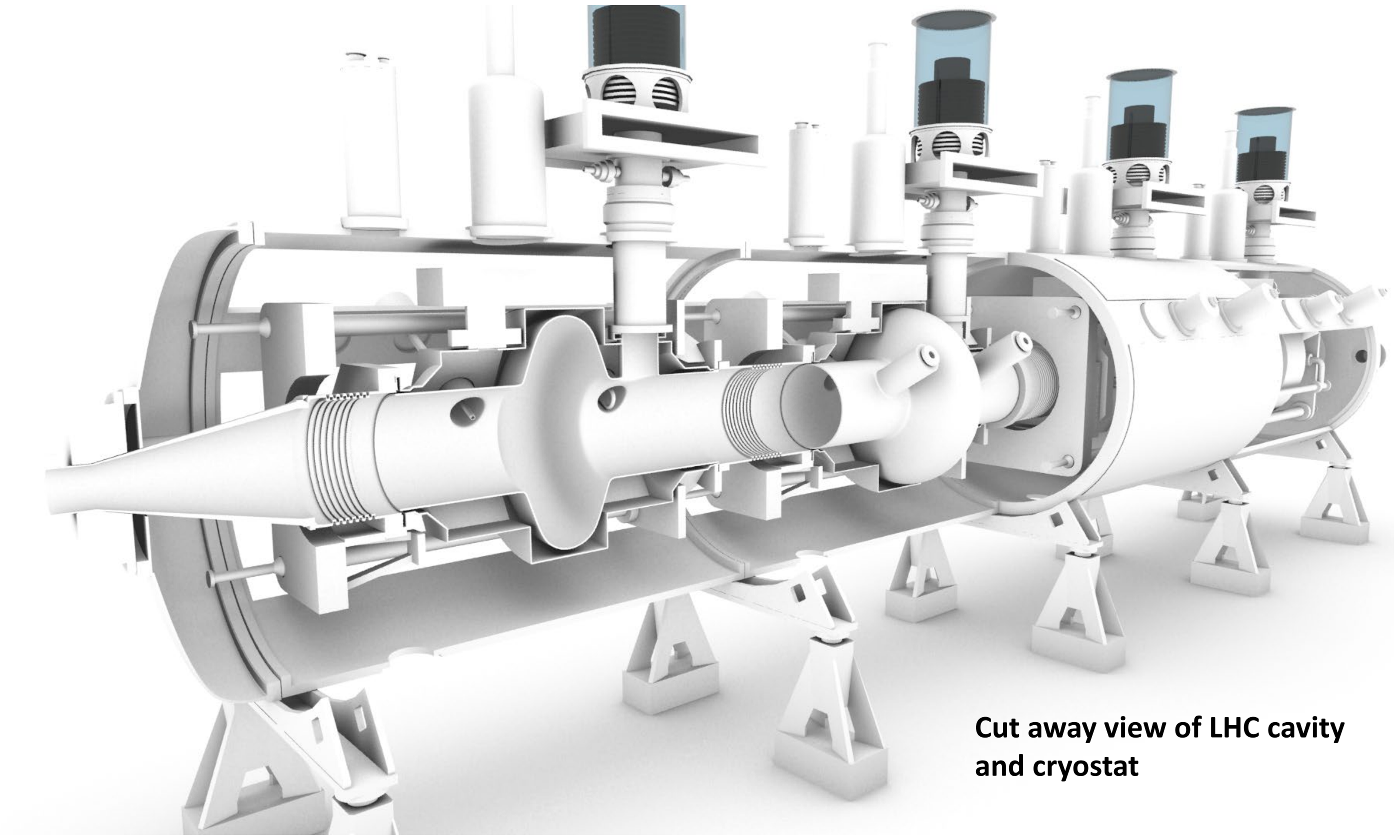
Reserve

Possible implementation of FCCeh

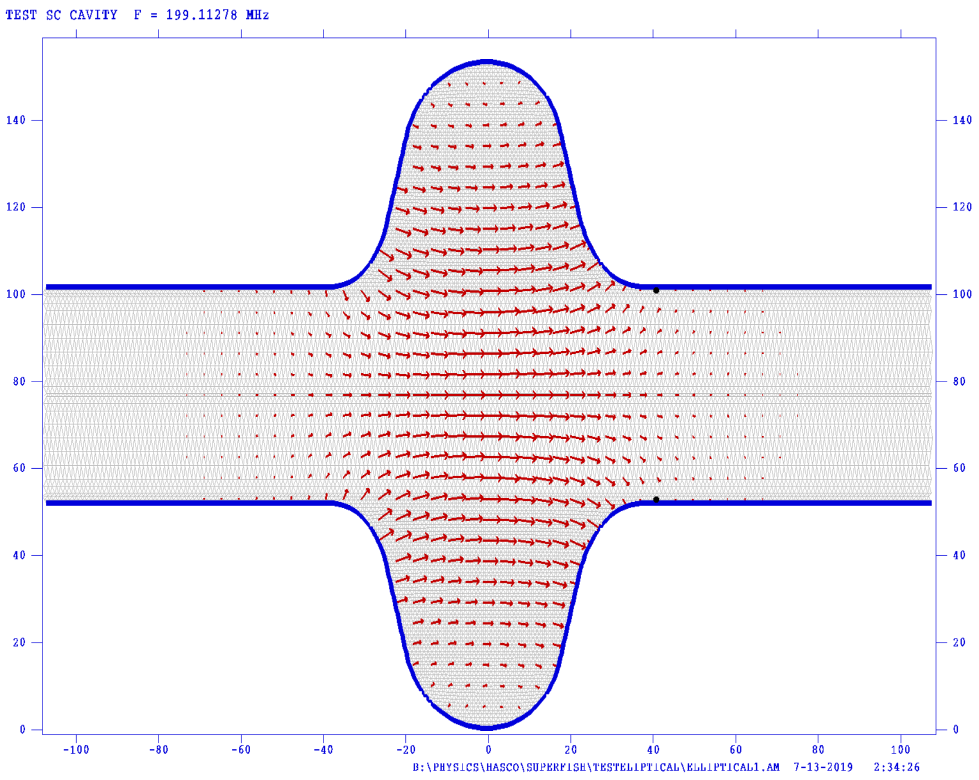


Conventionally accelerate high-energy particle beams using ***RF cavities***

- **Cavity can be normal conducting or superconducting.**
  → superconducting has potential to be more energy efficient
  → higher fields and accelerating gradients can be achieved with normal conducting cavities

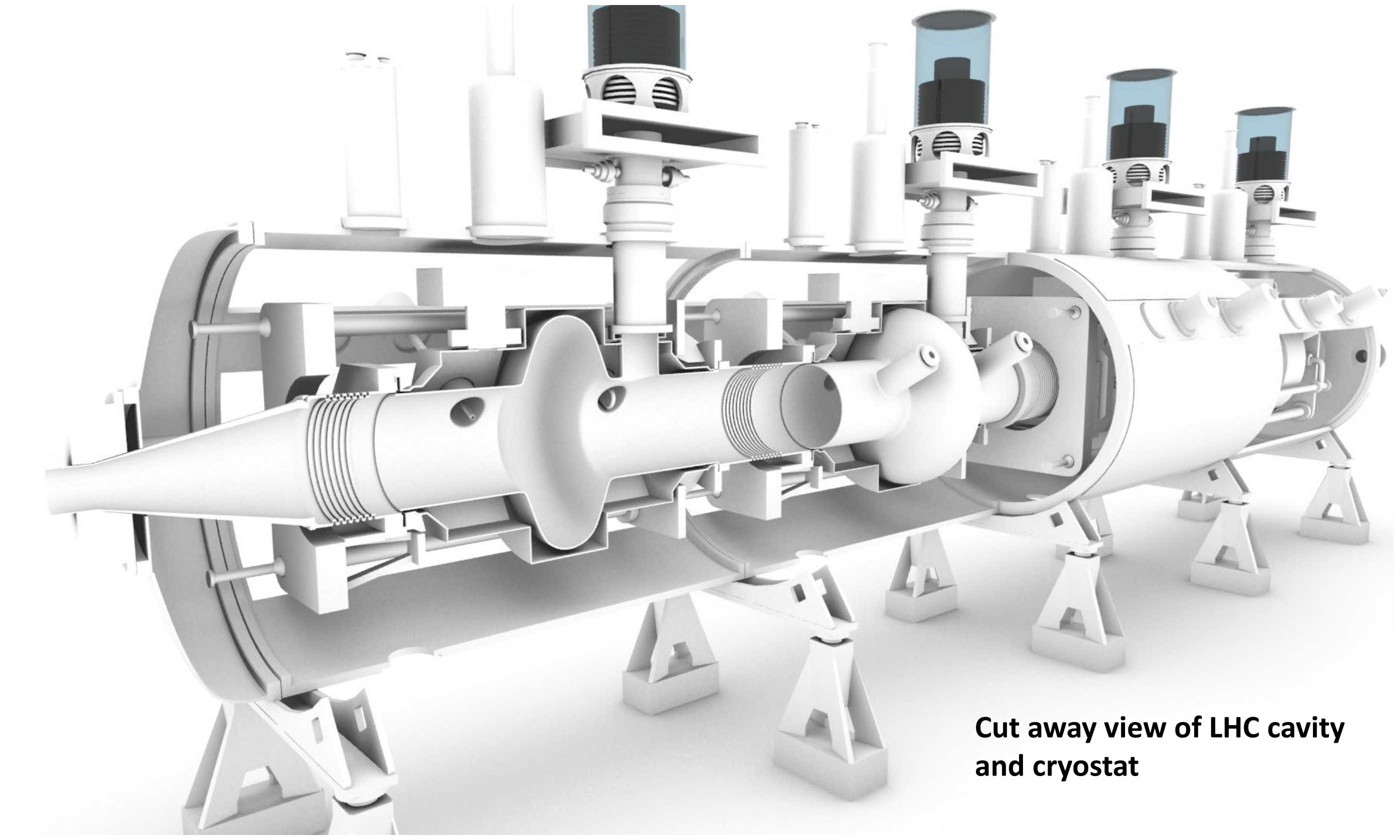


Cut away view of LHC cavity and cryostat



Conventionally accelerate high-energy particle beams using ***RF cavities***

- **RF cavities come in many different designs**
  → Standing wave, e.g. LHC



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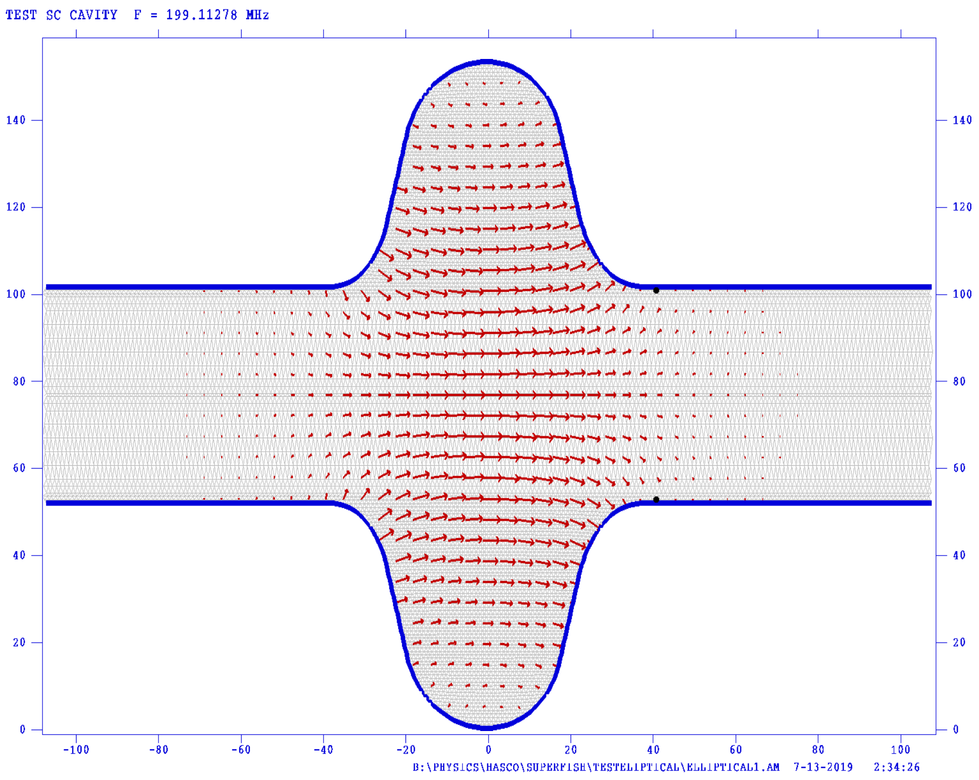
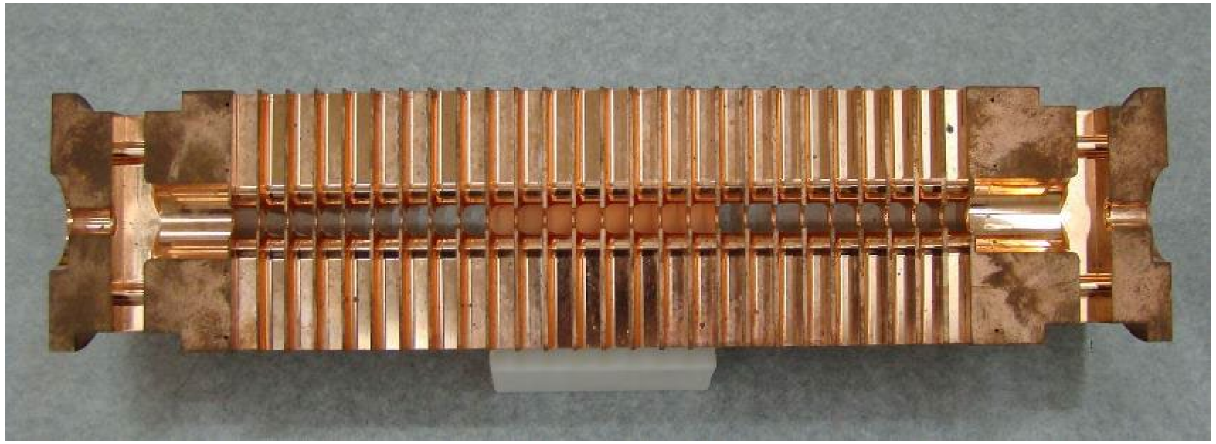


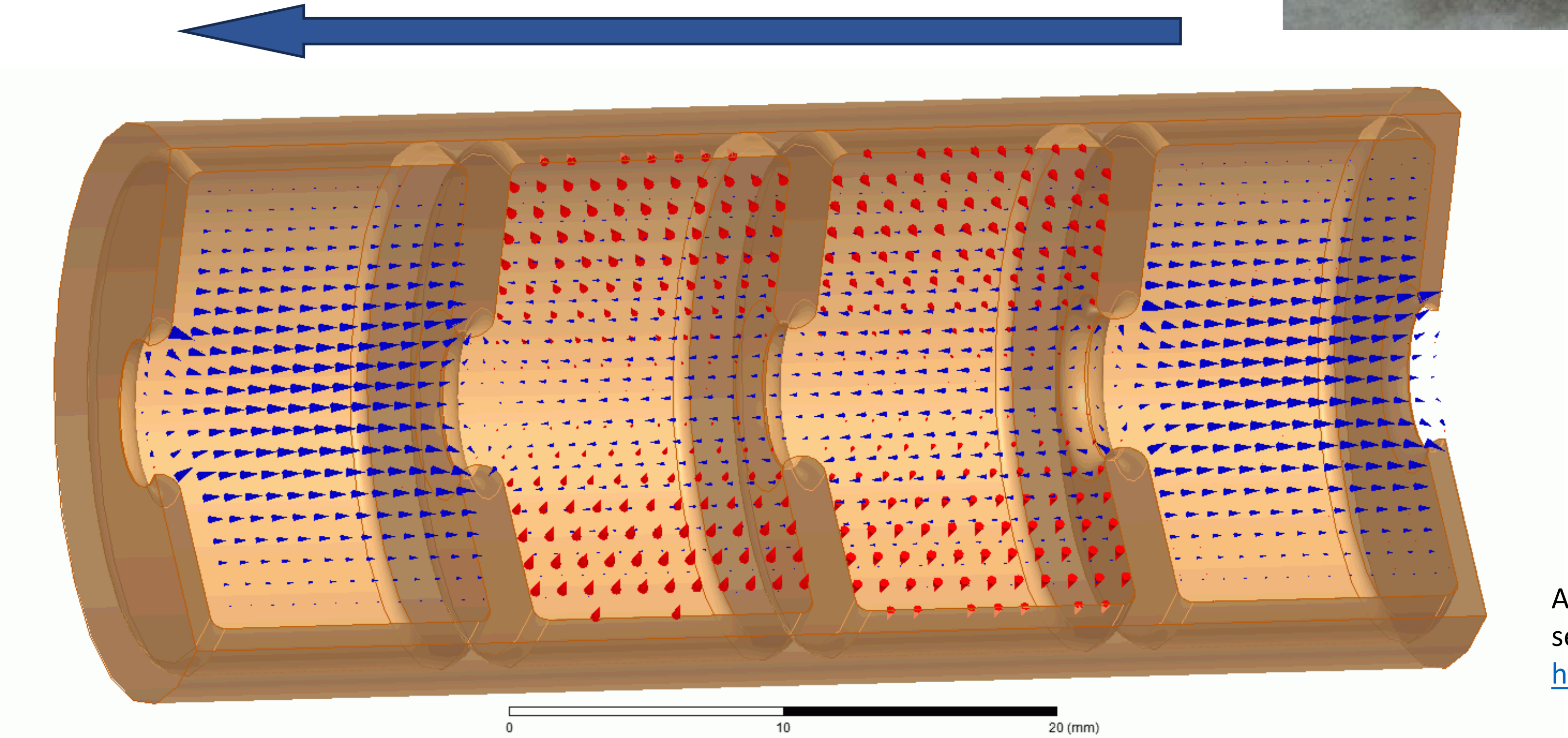
Conventionally accelerate high-energy particle beams using *RF cavities*

- **RF cavities come in many different designs**
  → Travelling wave e.g. CLIC



Cut away view of CLIC travelling wave RF cavity

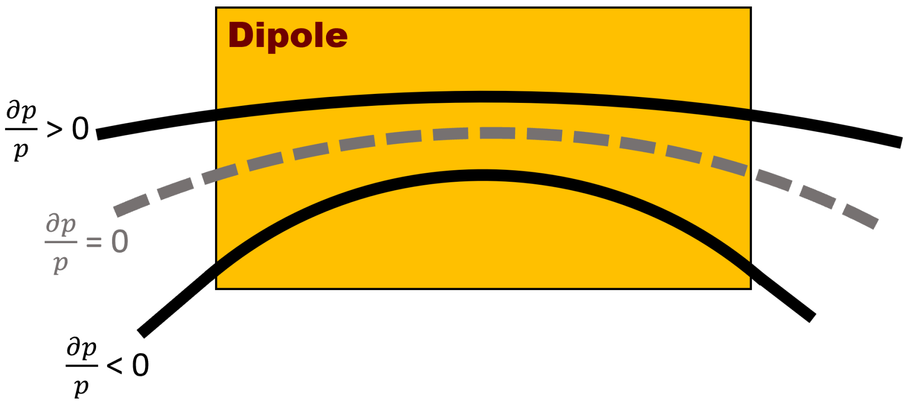
Beam accelerated from right to left



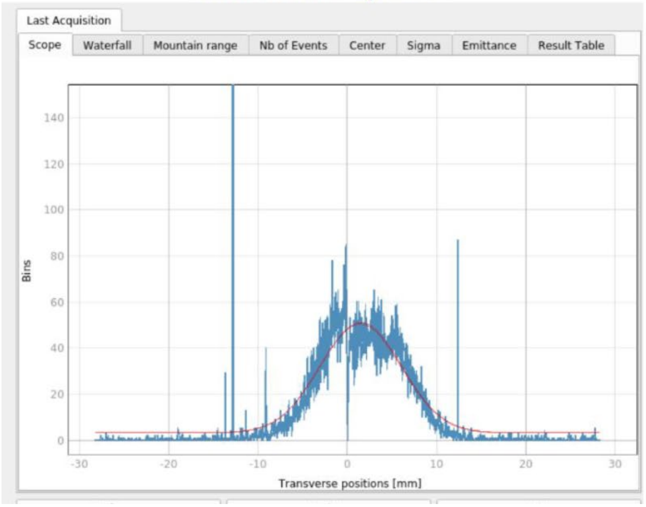
An accelerator system for the FLASH treatment of large deep-seated tumors. Walter Wuensch, CERN Accademic Training Program https://indico.cern.ch/event/1131207/

$$\sigma_x = \sqrt{\beta_x(s)\ \epsilon_x + D_x(s)\sigma_\delta}$$

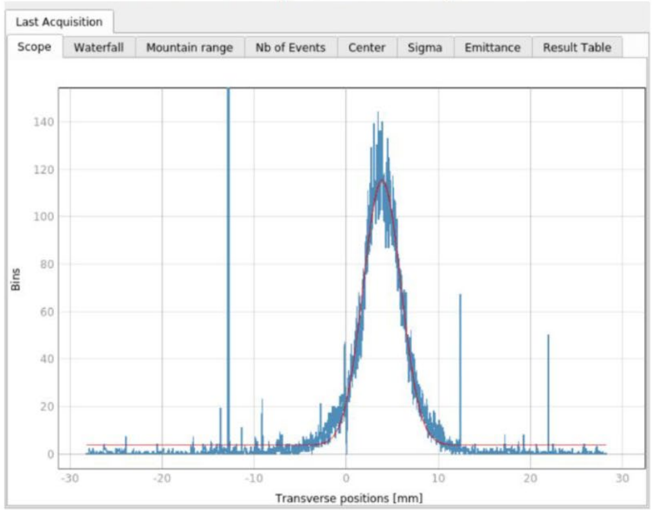
Dispersion: dependence of particles displacement from the ideal orbit due to its momentum error

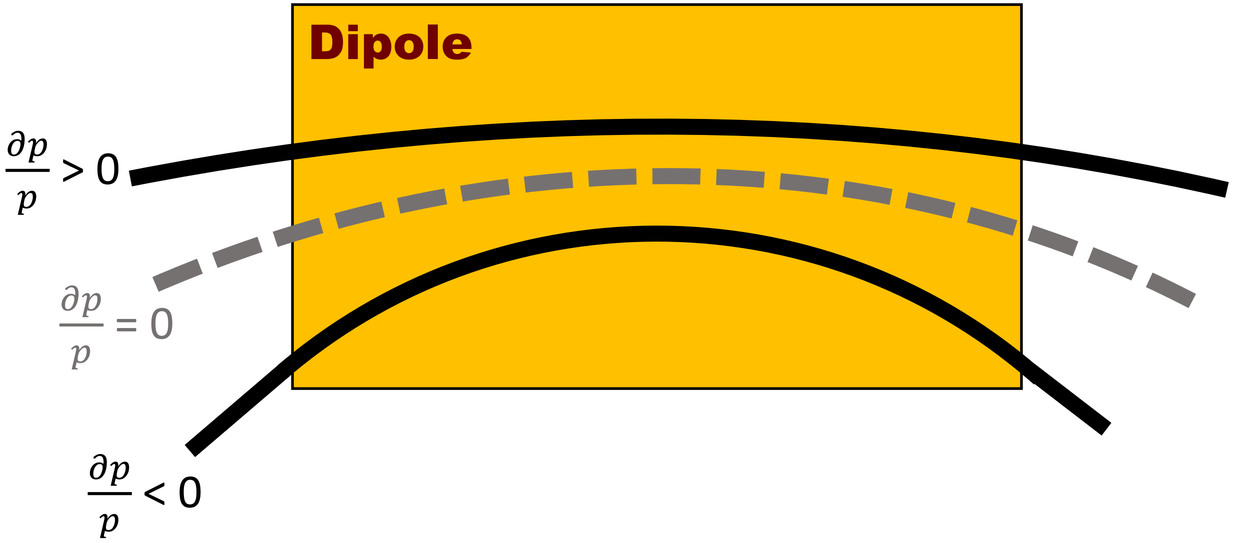


Normal Optics



Zero Dispersion Optics




Dipole
$\frac{\partial p}{p} > 0$
$\frac{\partial p}{p} = 0$
$\frac{\partial p}{p} < 0$