Particle accelerators

Part I: principles and design, particle physics colliders

Norwegian Teachers at CERN
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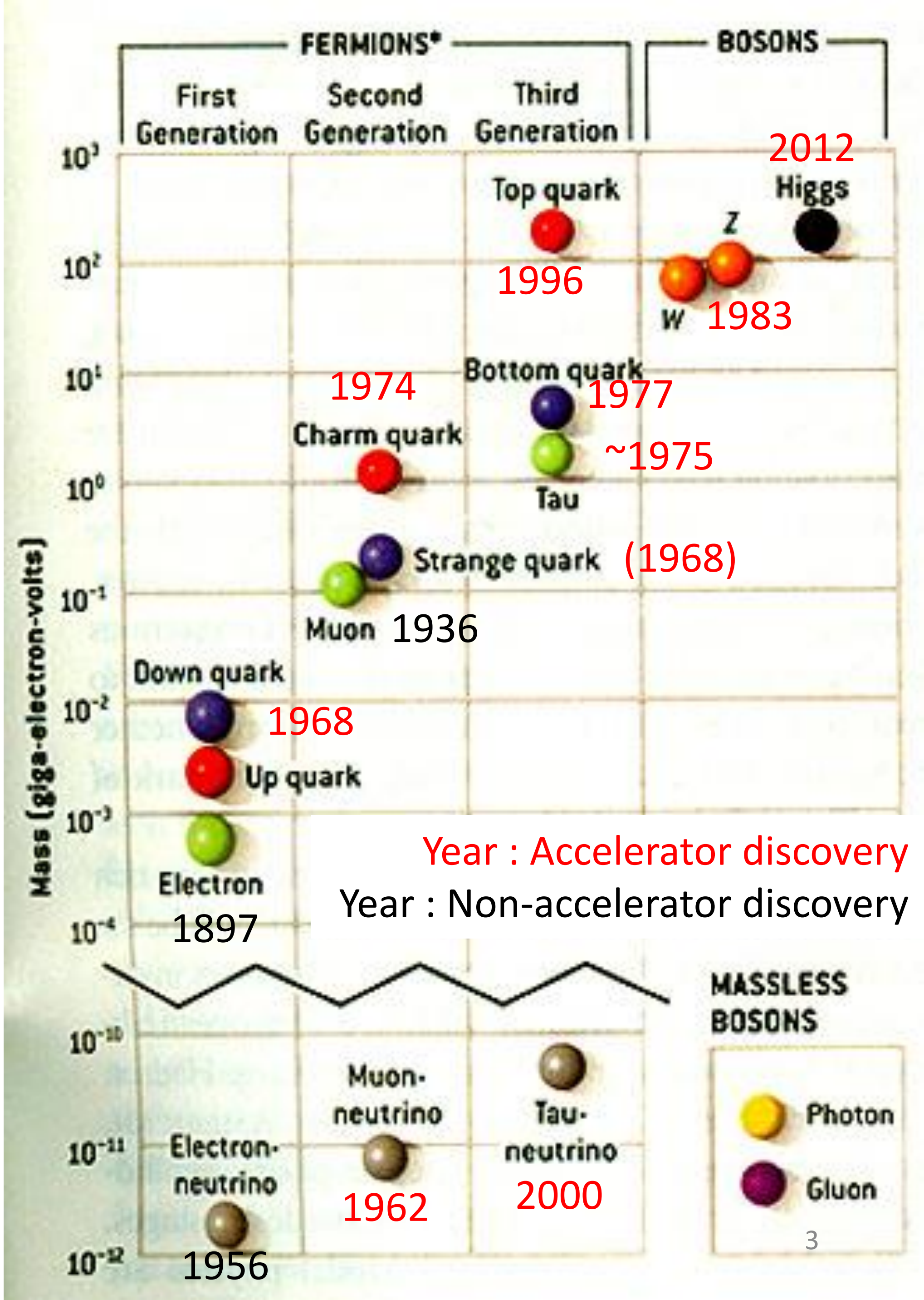
The 27 km LHC at CERN

Particle accelerators and CERN

Most fundamental particles have been discovered using beams from a particle accelerator.

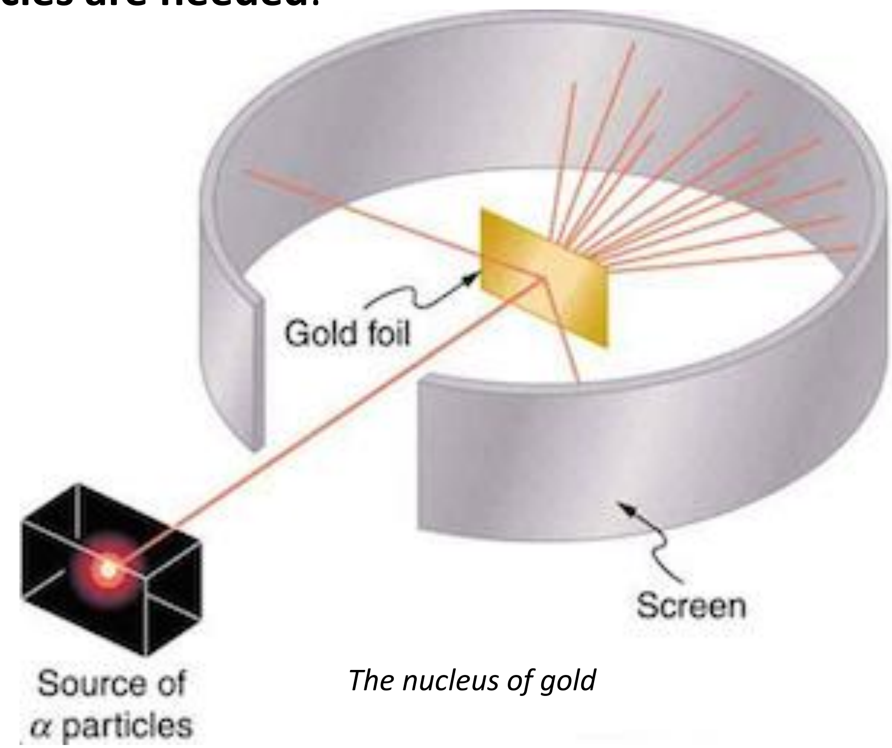
Discovery range increased as accelerators have become more powerful.

CERN: a particle accelerator laboratory - delivers unique particle beams to experiments (high energy, intense, good quality).



The dawn of particle accelerators

In 1909 E. Rutherford's team, in Manchester, shot alpha-particles from a radioactive source towards a gold foil. The scatter results were surprising**. To explore the tiny, very energetic particles are needed**.



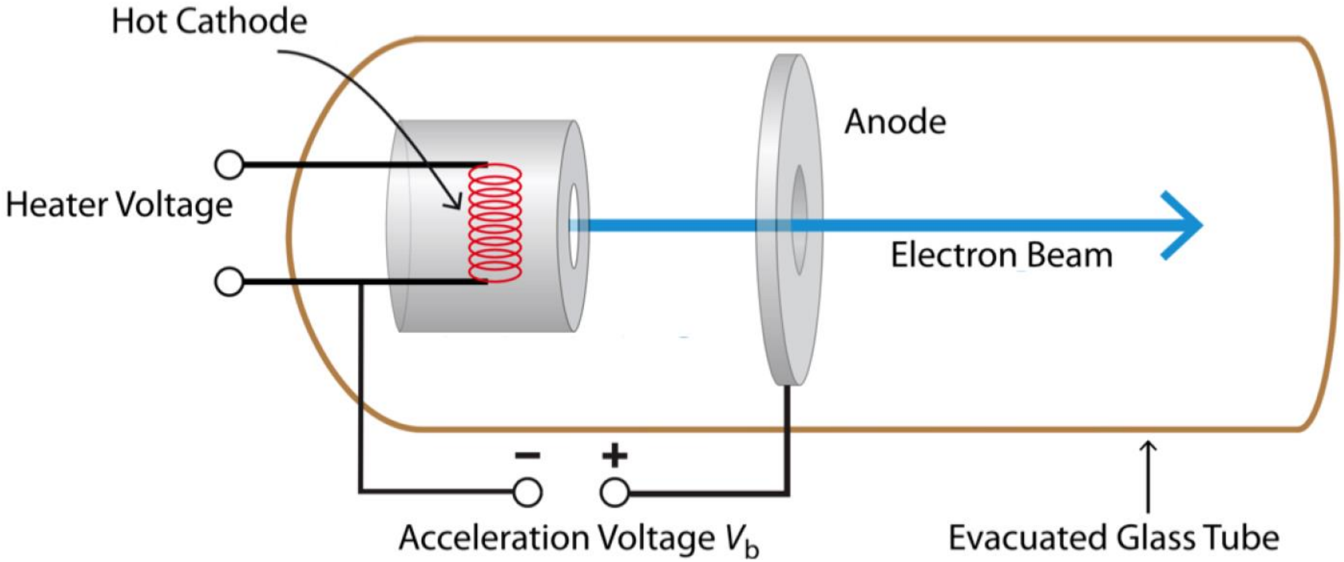
The nucleus of gold

..." 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". Rutherford (1927)

Particle acceleration: how many eV does your particle gain?

A particle accelerated by one volt has a kinetic energy of one electron volt (**eV**).

1000 eV = 1 **keV** (kiloelectronvolt)
1'000'000 eV = 1 **MeV** (Megaelectronvolt)
1'000'000'000 eV = 1 **GeV** (Gigaelectronvolt)
1'000'000'000'000 eV = 1 **TeV** (Teraelectronvolt)



A simple way to make an electrostatic acceleration, a cathode emitting electrons and an anode, at a higher potential, pulling the electrons towards it.
Energies ffrom **cathode rays**: few 10 keV

Electric breakdown limits electrostatic accelerators to a **few MeV** of total energy gain (same order as alpha radiation).

Modern accelerators: oscillating electromagnetic field

R. Wideröe, Archiv für Elektrotechnik, July 1928, **21**, 4, pp 387–406 :

3. Die experimentelle Untersuchung.

Die experimentellen Untersuchungen sollten vor allem die Richtigkeit des Prinzips beweisen und die Schwierigkeiten des Verfahrens näher klarlegen. Aus

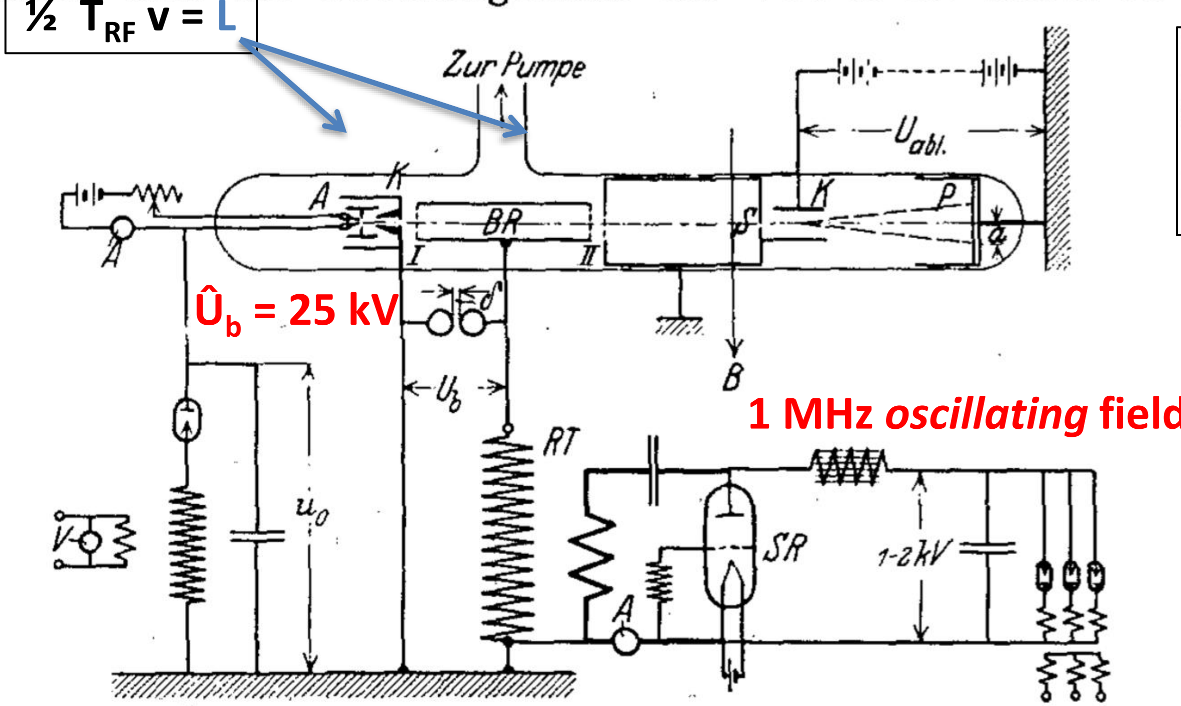


Bild 5. Die verwendete Schaltung.

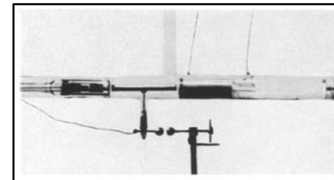
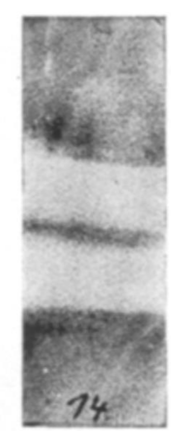


Bild 6. Die Versuchsröhre.



d) $\lambda = 235$ m, $\Sigma U = 56{,}0$ kV.

Based on an idea by **G. Ising**, Arkiv för matematik, astronomi och fysik. **18**, 4 (1924))

$$\eta_U = \frac{\Sigma U - u_0}{2\,U_b}$$

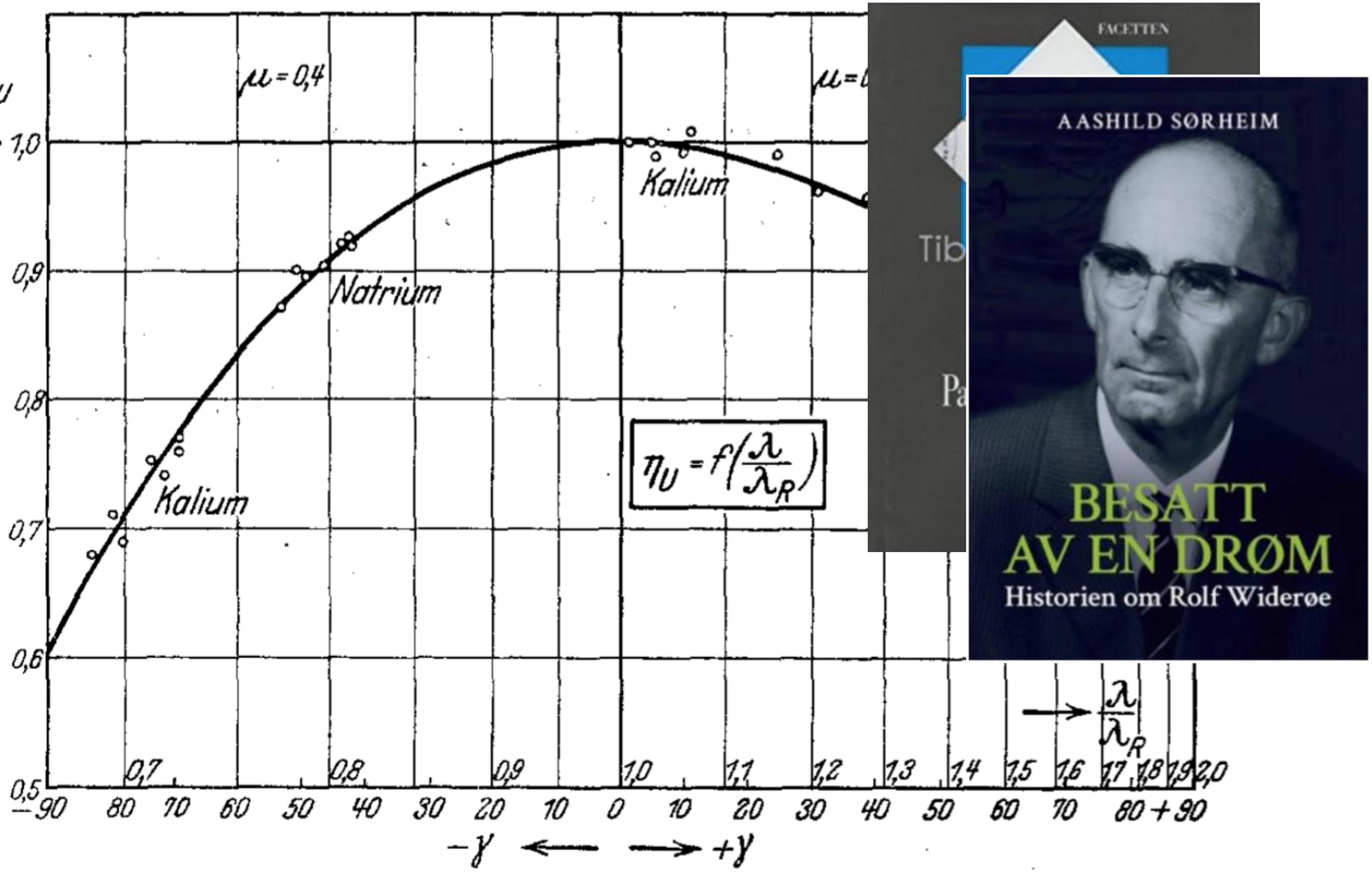


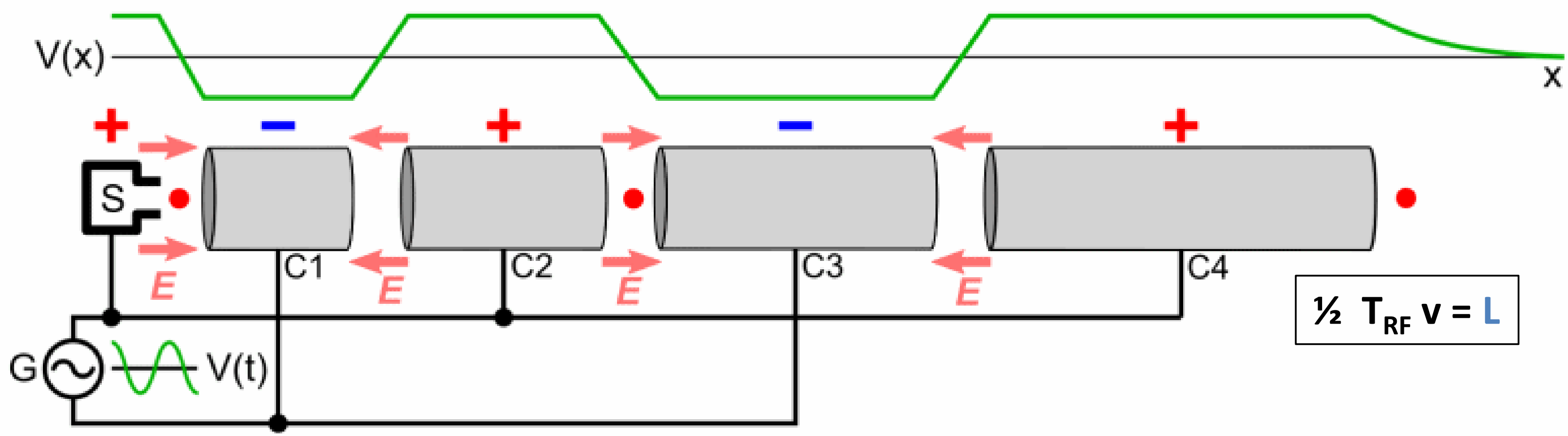
Bild 10. Vergleich der gemessenen mit den berechneten Werten für den Spannungswirkungsgrad bei verschiedenen Wellenlängen.

Widerøe accelerated Kalium beams to 50 keV kinetic energy, equal to twice the applied voltage.

This is not possible using electrostatic voltages.

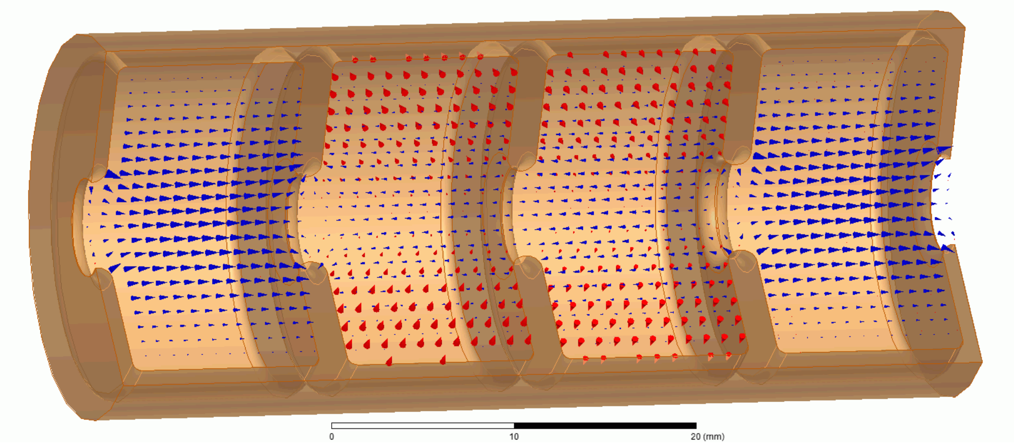
The importance of Widerøe's demonstration:

By using time-varying fields, oscillating at radiofrequency **(RF)**, particles can **in principle be accelerated to any energy**, using a limited peak voltage.

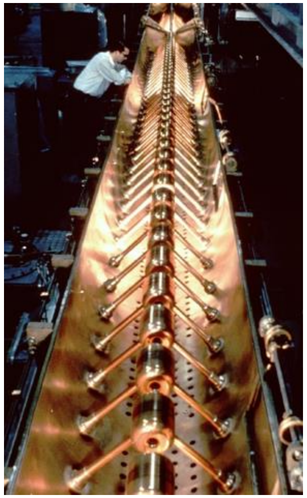


Widerøe-type RF-LINAC ("LINear ACcelerator)

Today: RF-fields enclosed in metal **RF-cavities**, is used in high-energy particle accelerators.

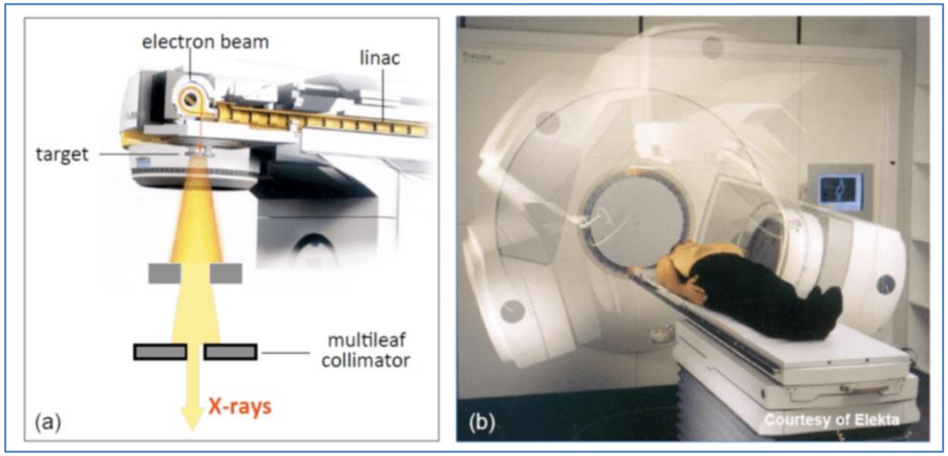


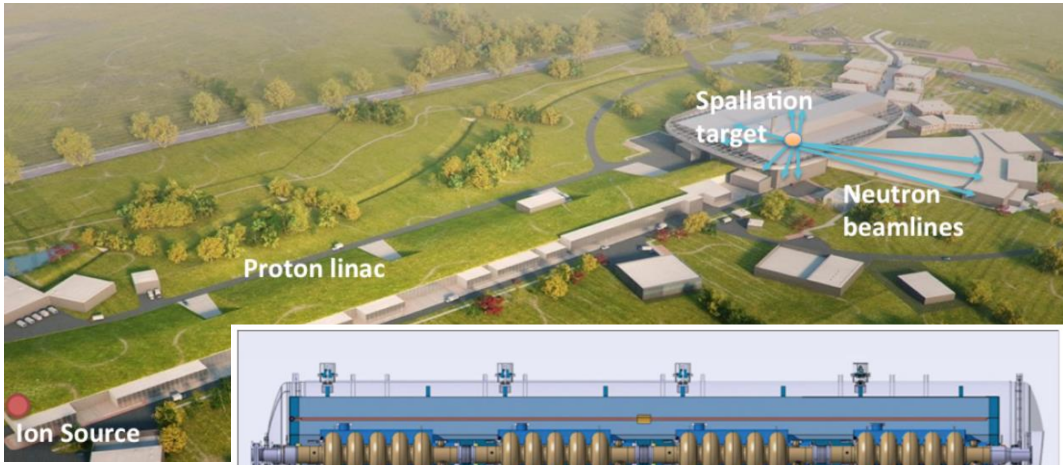
Example of linear accelerators



Injectors to the LHC.

Radiotherapy





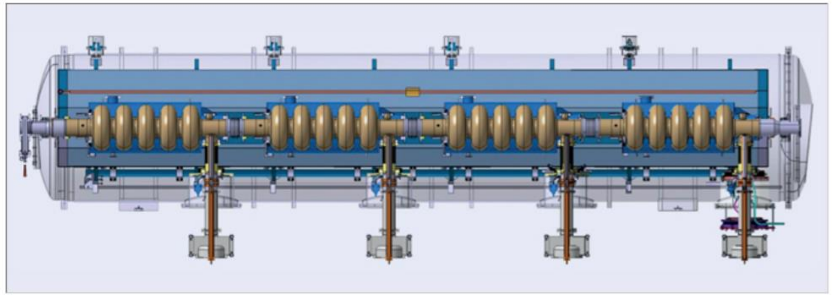


Fig. 3. Preliminary design of a high-beta cryomodule from IPN Orsay and CEA Saclay.

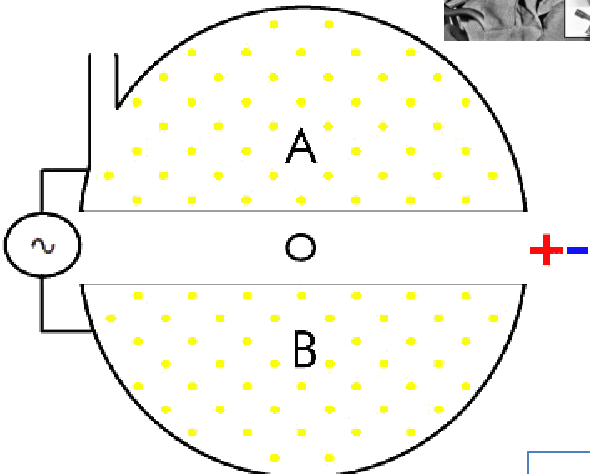
The 3 km **Stanford Linear Accelerator**; 2.8 GHz normal conducting cavities

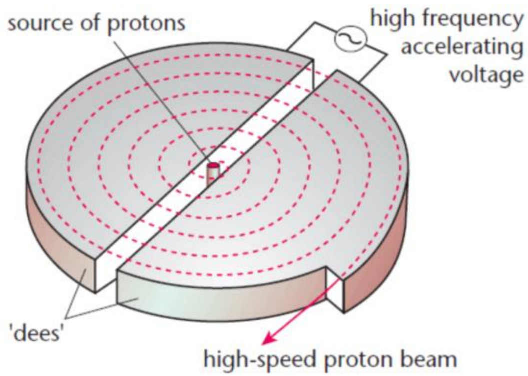
The 1 km **European Spallation Source**; 752 MHz superconducting cavities

RF-acceleration is equally important for **circular accelerators**:

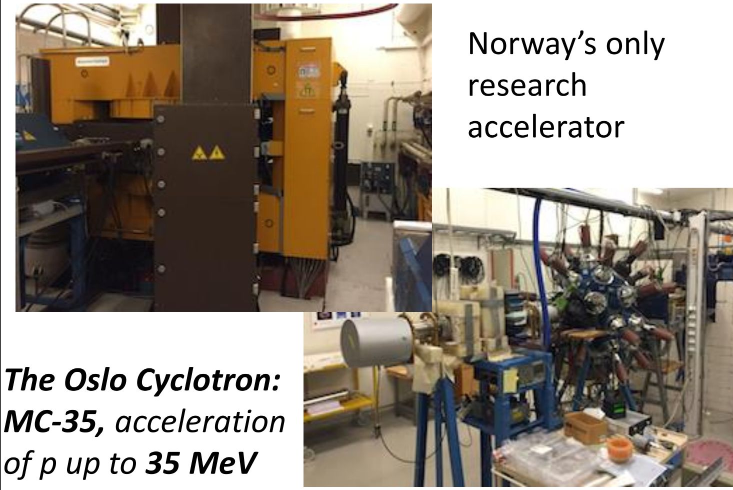
E. Lawrence

Cyclotrons :





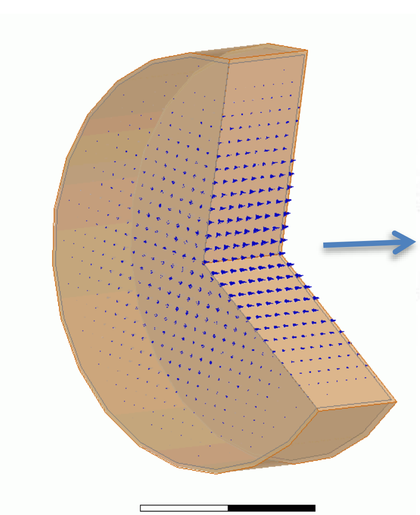
$$F_B = m\frac{v^2}{\rho} \Rightarrow \frac{1}{\rho} = \frac{qB}{p}$$

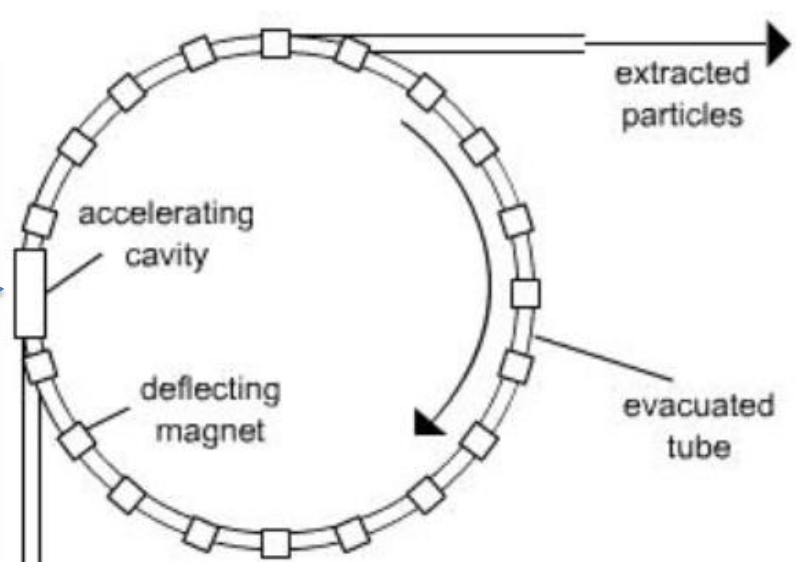


Norway's only research accelerator

The Oslo Cyclotron: MC-35, *acceleration of p up to* ***35 MeV***

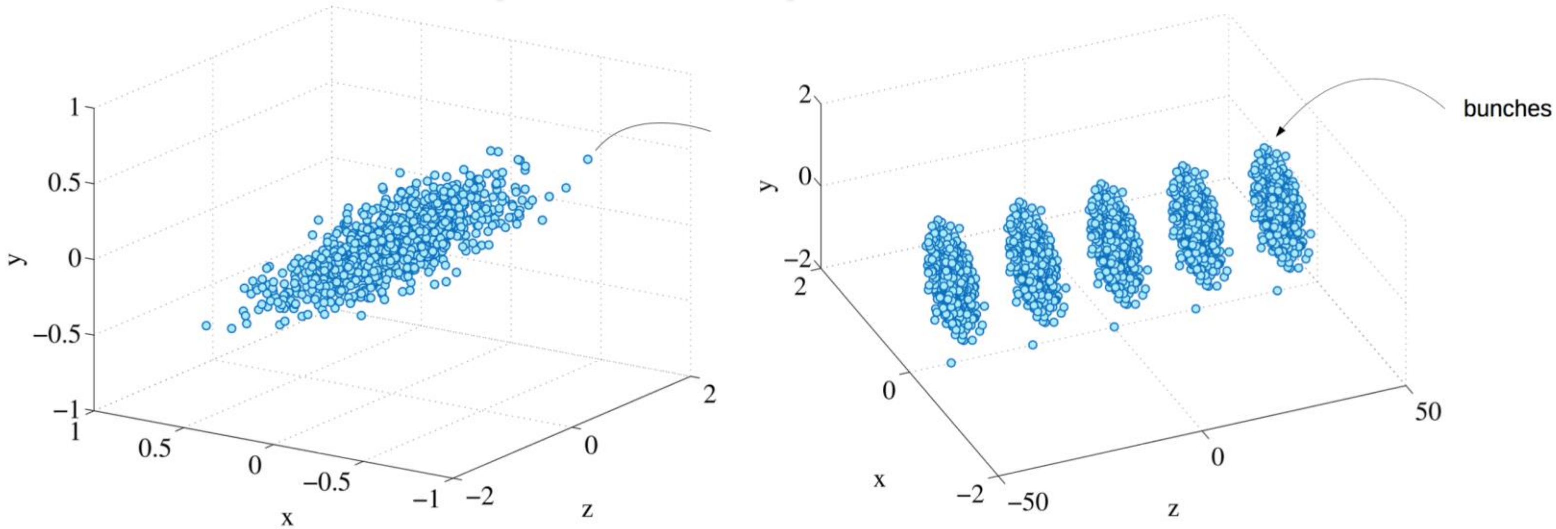
Synchrotrons :





The CERN Proton-Synchrotron (1959, 628 m)
28 GeV (28 billion volts)

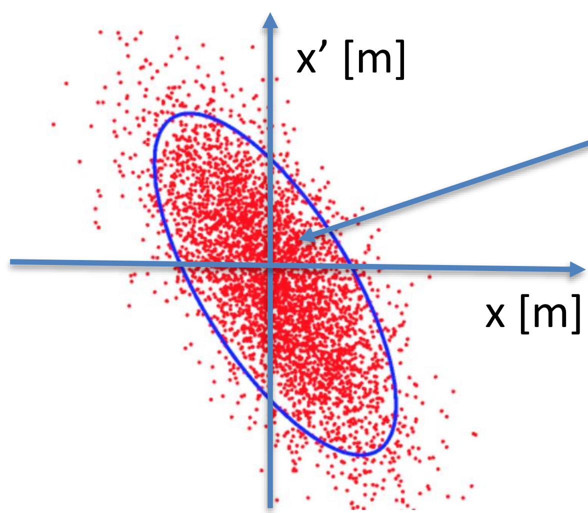
Description of particle beams



$$\psi = \psi(x, x', y, y', z, E)$$

$x' = p_x/p$

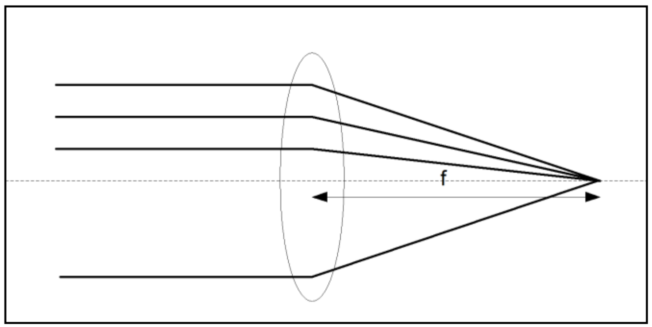
Particle beam: 6D distribution, two transverse planes + one longitudinal plane.

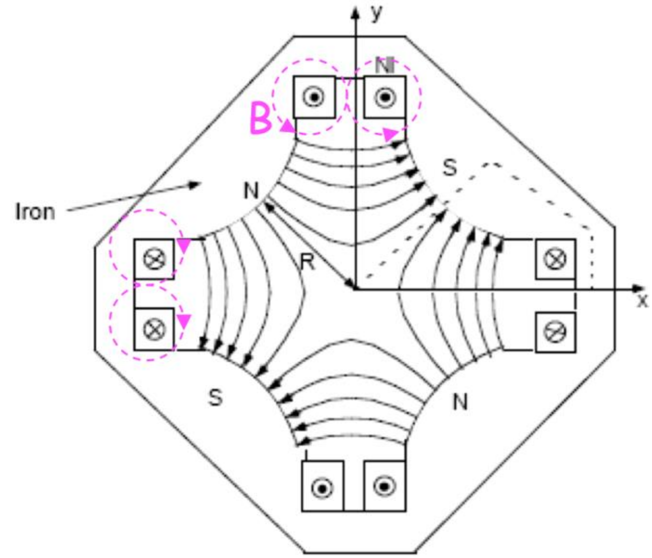


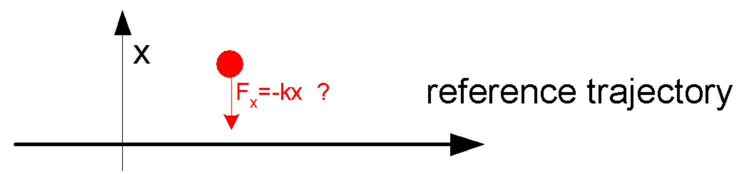
- Phase-space area is conserved under beam transport
- Metric of how well the beam can be focused, named **emittance**

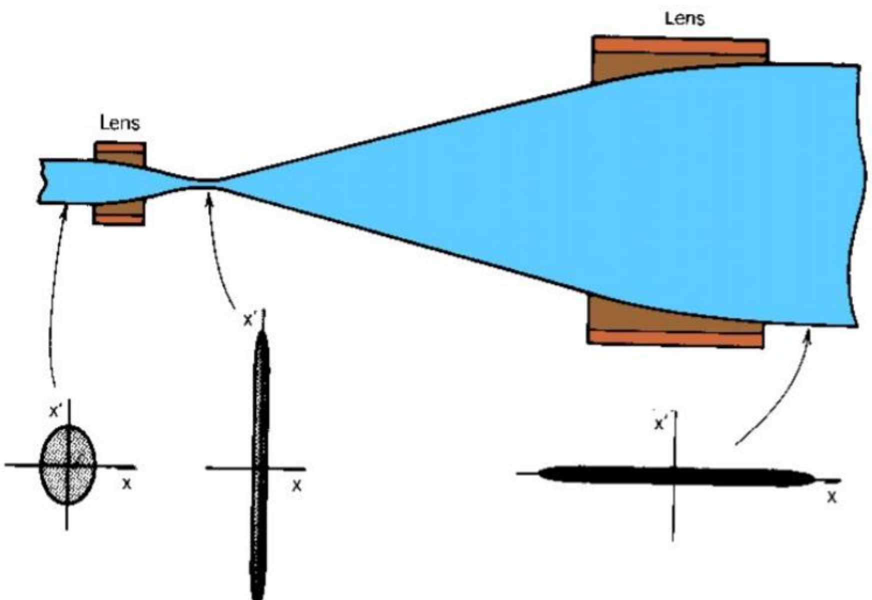
Focusing of particle beams

Magnetic lenses, often **quadrupole magnets**, are used to focus the charged beams. Analogous to optical lenses.









$$s(s)=\sqrt{e_{rms}b(s)}$$

Lattice

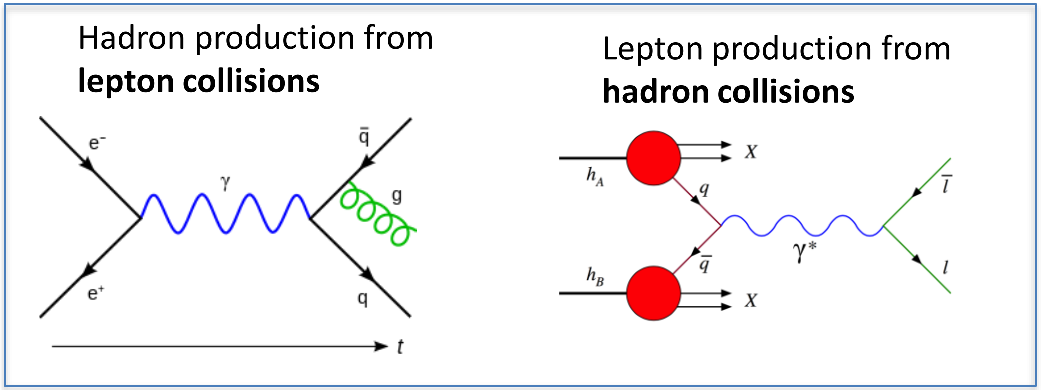
Beam quality: emittance

What *beam parameters* characterizes a particle collider?

I) Particle type

p, $\bar{p}$, Pb, Au…

e^-, e^+, μ, γ…



II) Centre of mass energy

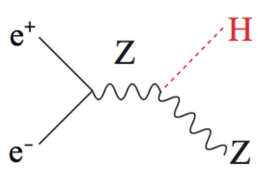
Centre-of-mass energy sufficient for particle production:

$$E_{CM} >= mc^2$$

Wavelength of probe should be smaller than the object you want to study. De Broglie wavelength: $\lambda = h / p$ (~ 1 Å for 100 MeV e-)

III) Luminosity

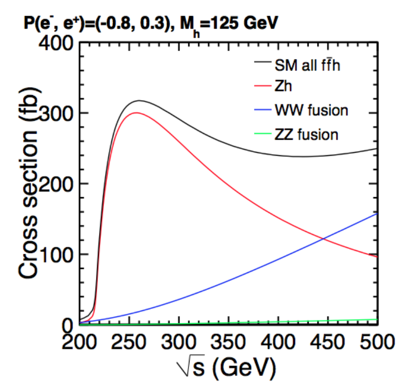
Small cross sections -> production rate as important as energy



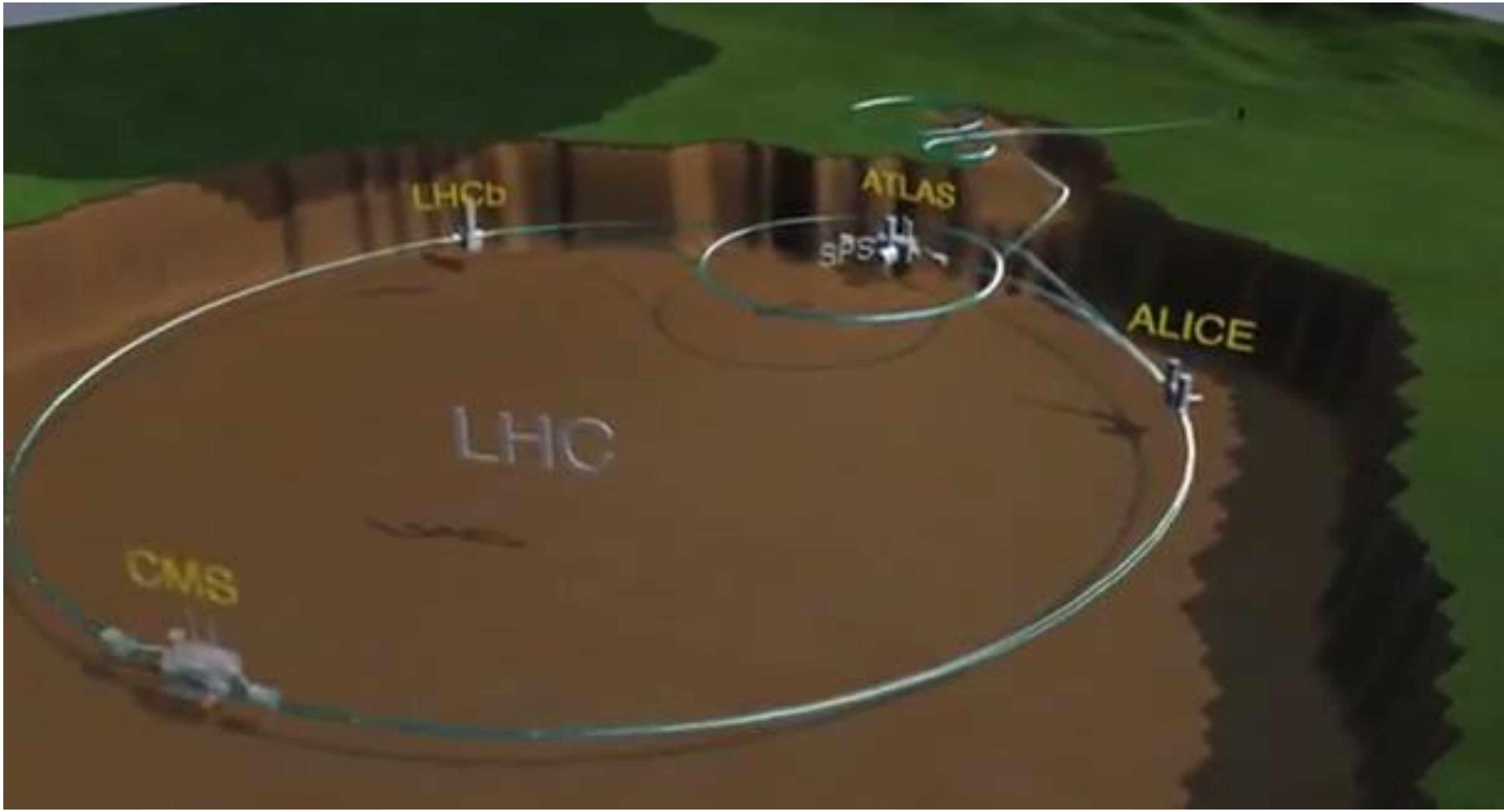
$$R = \mathcal{L}\sigma$$

$$\mathcal{L} = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

* n_1, n_2 :particles per bunch
* σ_x, σ_y : bunch transverse size at the interaction point
* bunch collision rate (f)



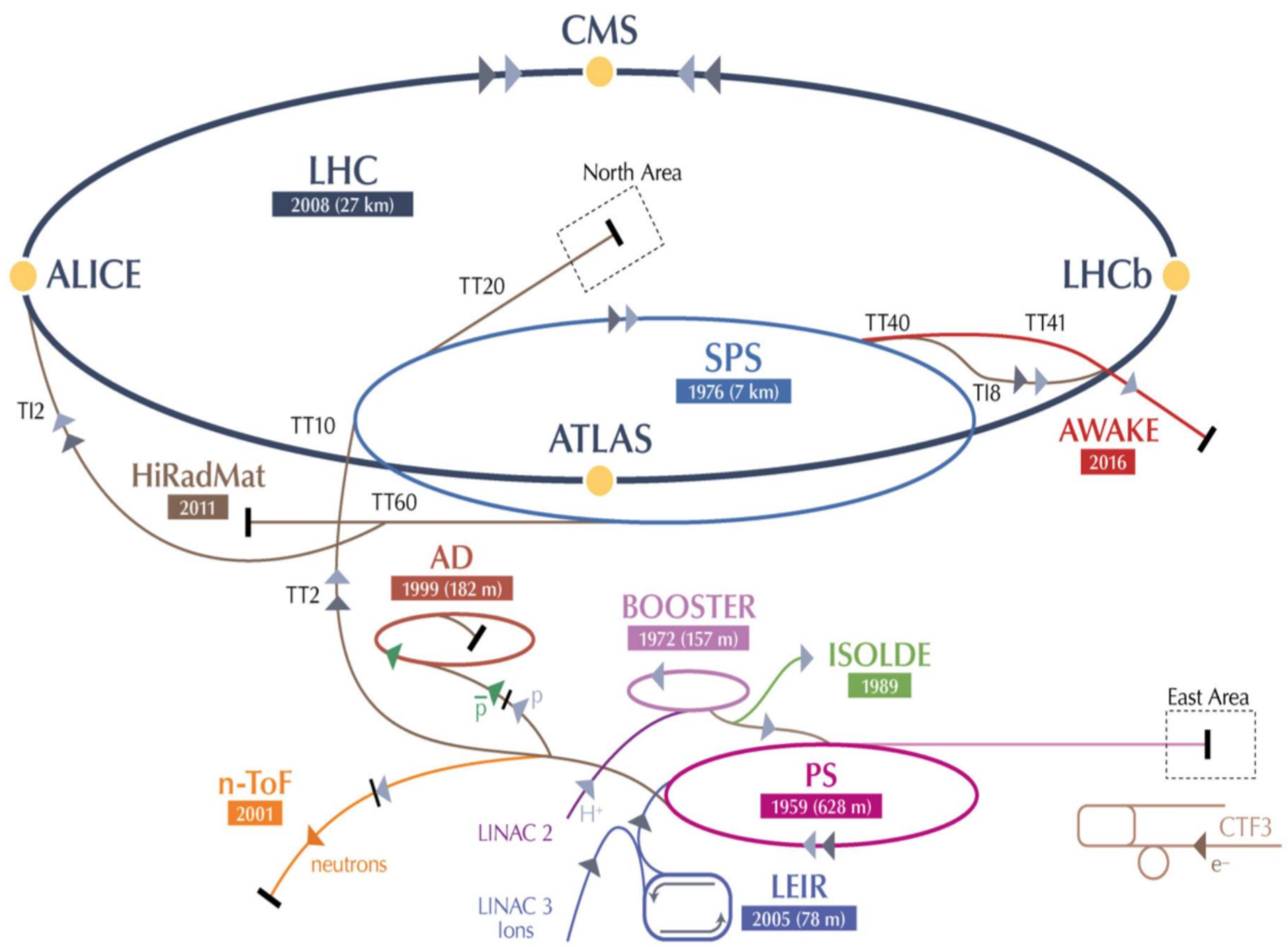
The Large Hadron Collider



[youtube: the LHC Accelerator]

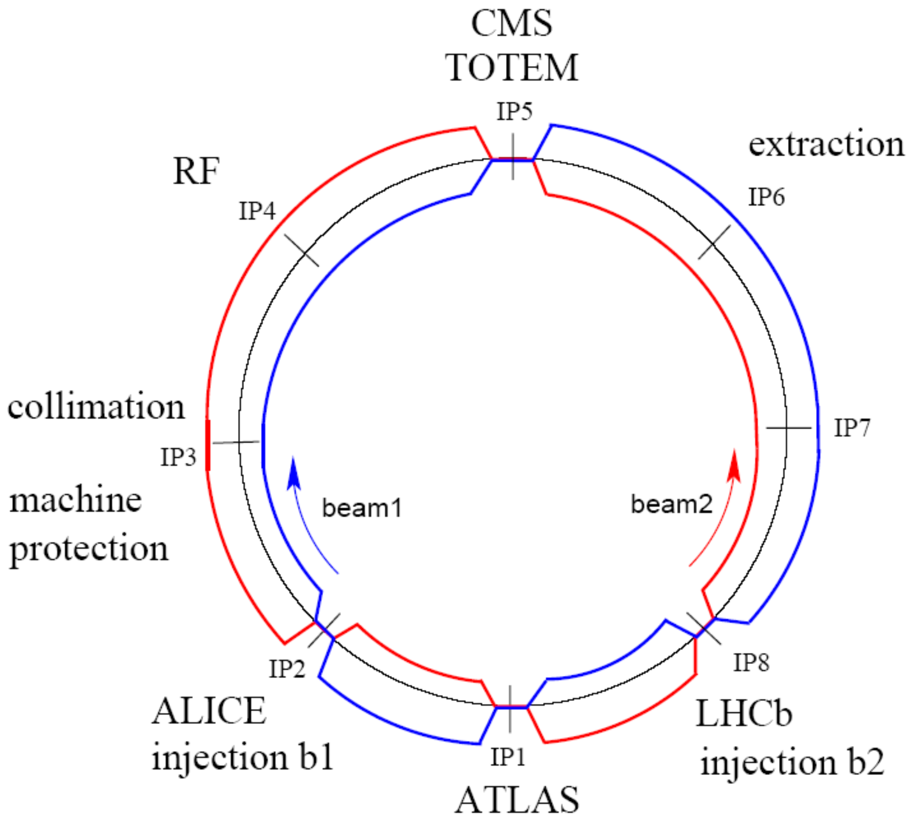
LHC and the CERN accelerator complex

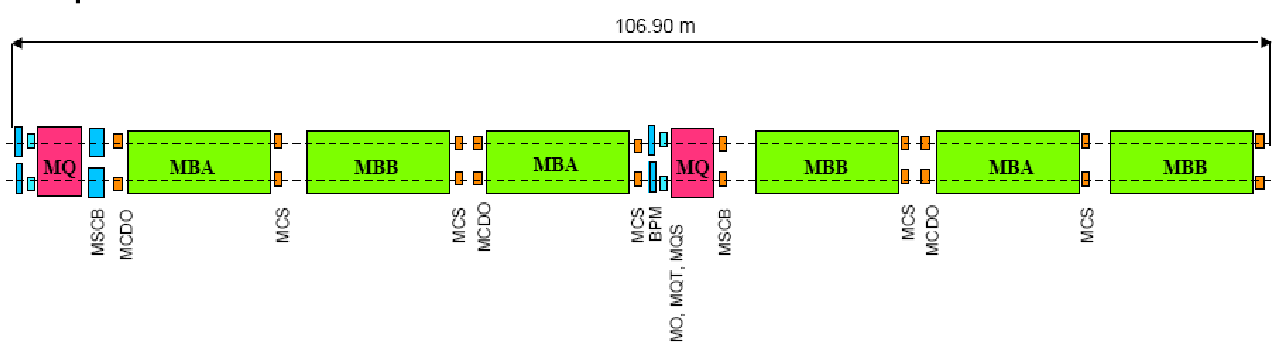
- LHC is responsible for accelerating protons from 450 GeV up to 7000 GeV
- 450 GeV protons injected into LHC from the SPS
- PS injects into the SPS
- LINACs injects into the PS
- The protons are generated by a proton source where a H_2 gas is heated up to provide protons
- The limitations in the earlier part of the acceleration chain originates from space charge -> collective effects lecture



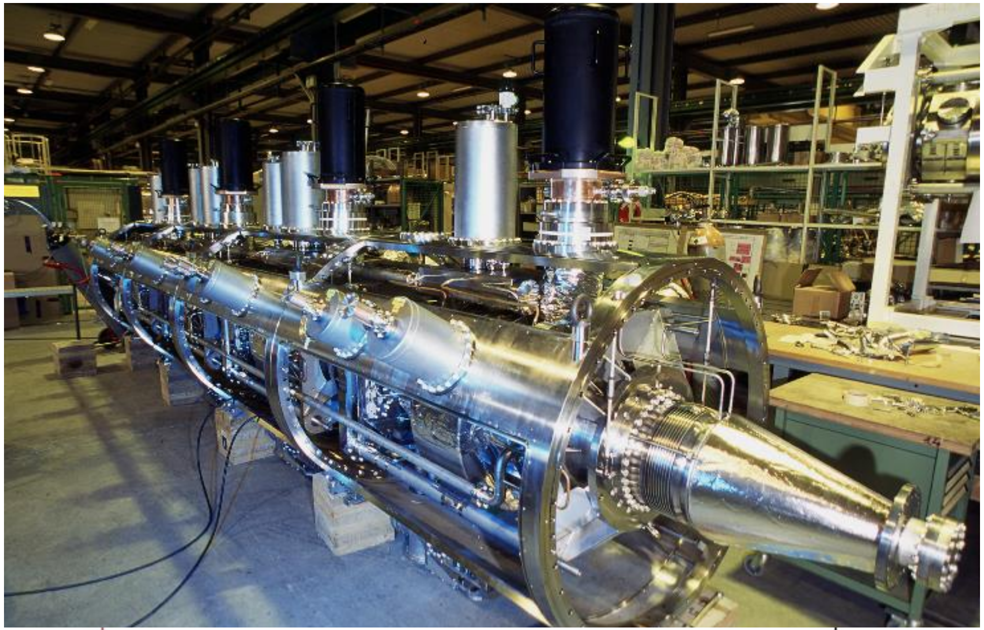
LHC layout

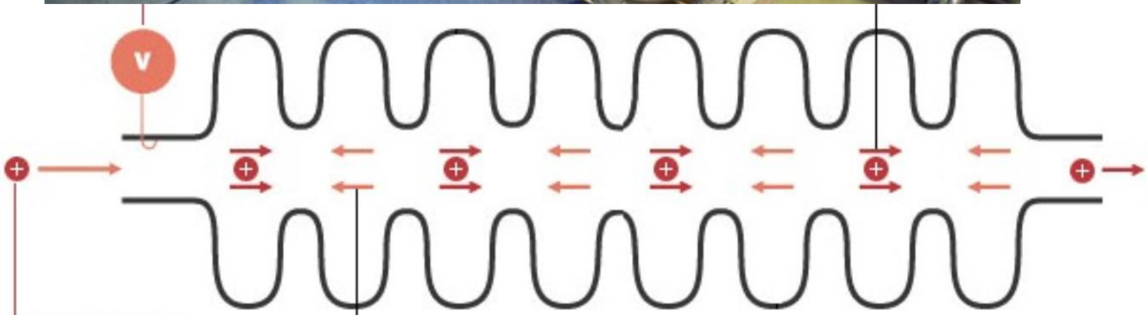
- Circumference = 26658.9 m
- Four interactions points, where the beams collide, and massive particle physics experiments record the results of the collisions (ATLAS, CMS, ALICE, LHCb)
- Eight straight sections, containing the IPs, around 530 m long
- Eight arcs with a regular lattice structure, containing 23 arc cells
- Each arc cell has a periodic FODO-lattice, 106.9 m long





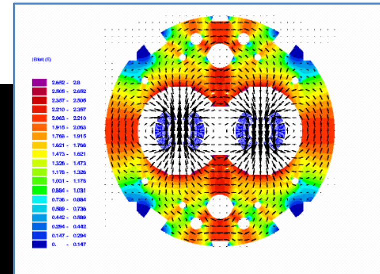
LHC cavities

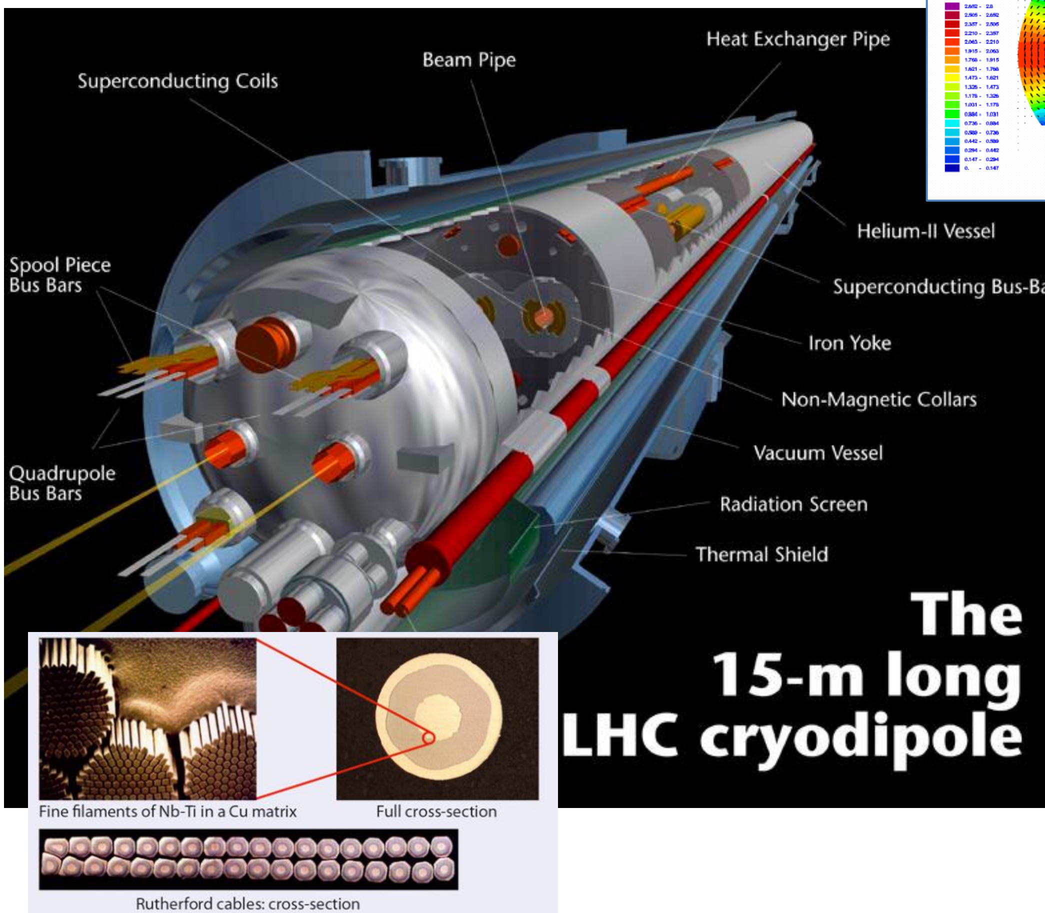


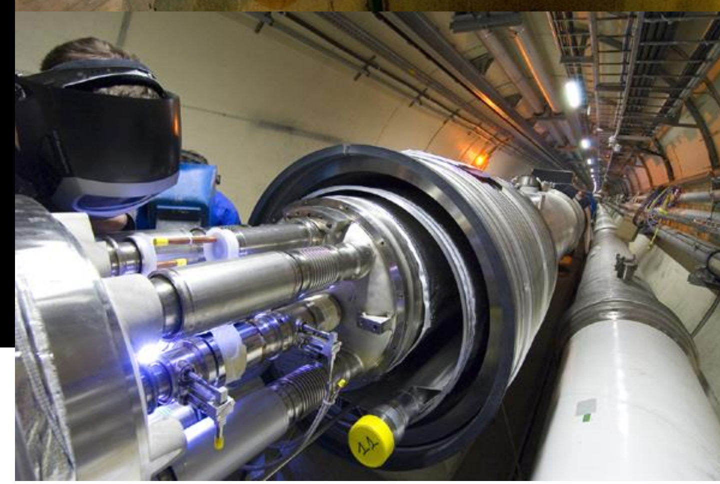


- Superconducting RF cavities. Standing wave, f = 400 MHz
- Each beam: one cryostat at 4.5 K, 4+4 cavities in each cryostat
- 5 MV/m accelerating gradient, 16 MeV energy gain per turn

LHC bending magnets



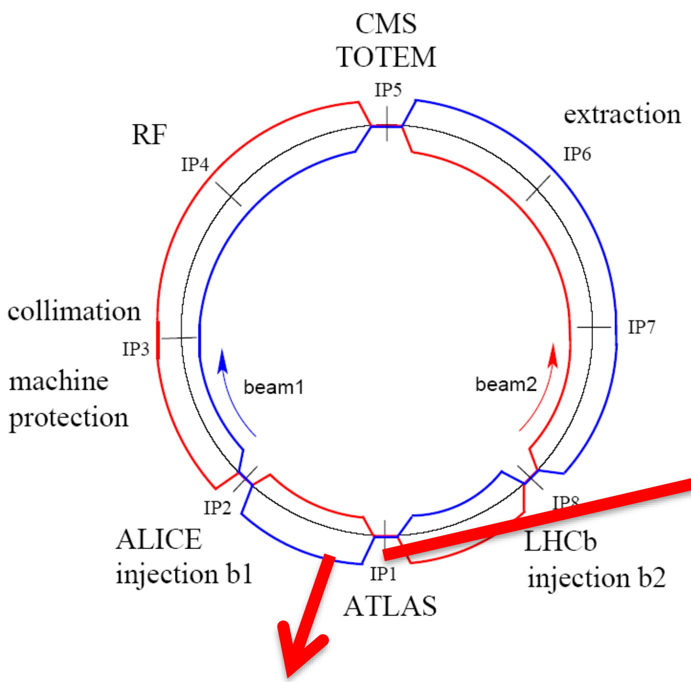




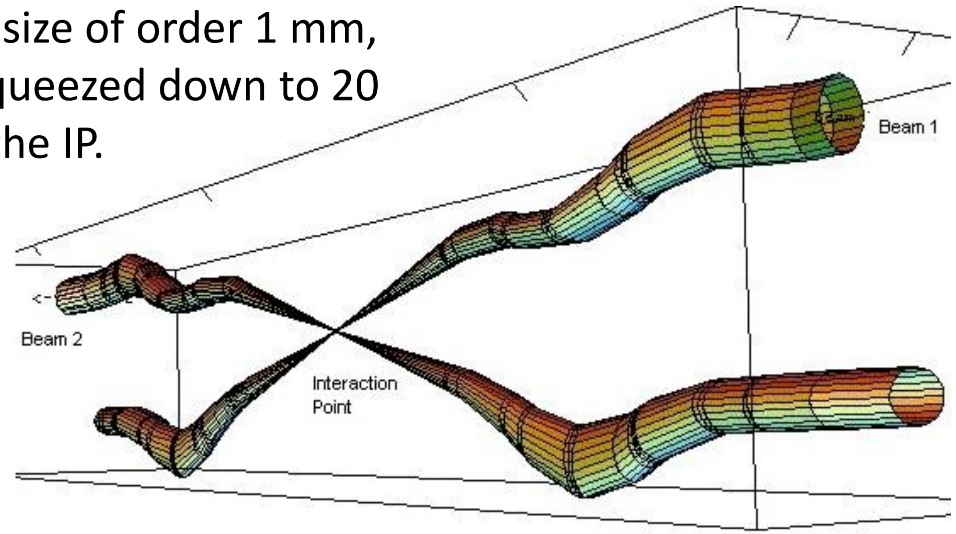
8.3 T maximum field (allows for 7 TeV per proton beam). Generated by a current of 12 kA in the superconducting Rutherford coils.

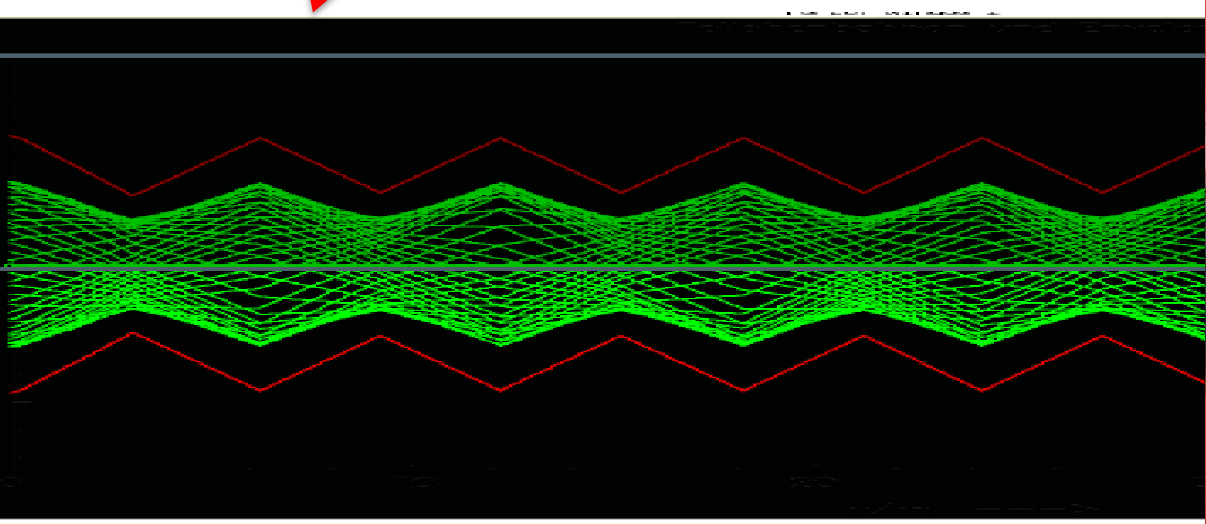
Developments for higher energy hadron colliders (HE-LHC, FCC) : Nb_3Sn, HTS

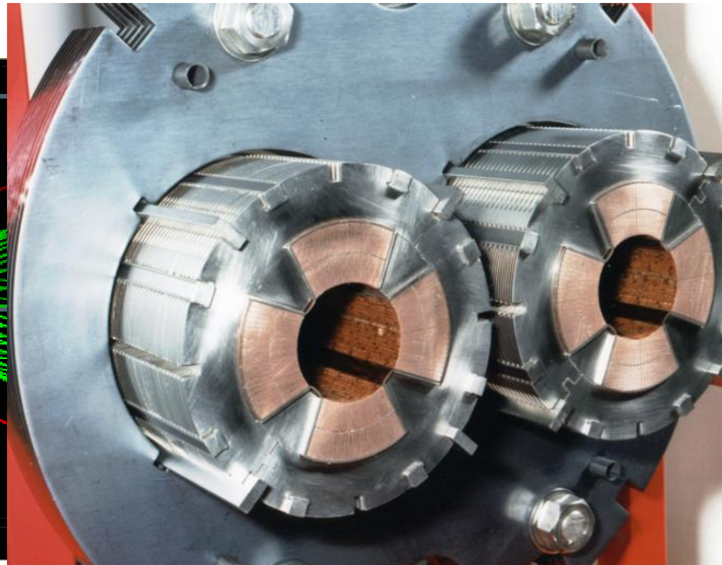
LHC beam focusing



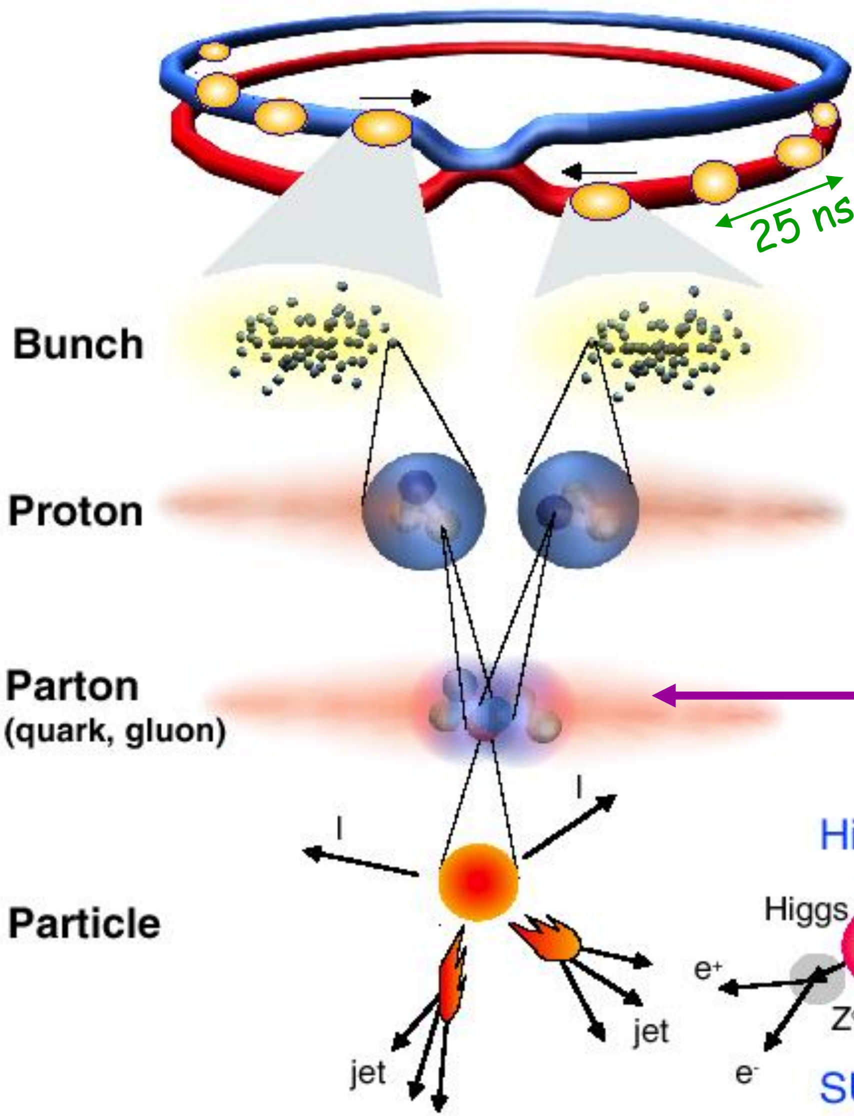
The beam is kept focused in arcs to size of order 1 mm, then squeezed down to 20 um at the IP.







Collisions at LHC



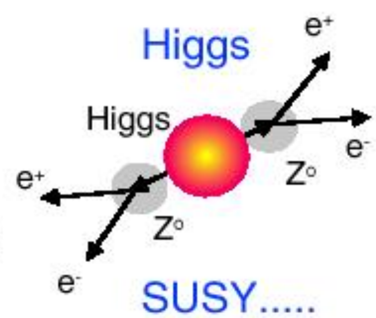
Proton-Proton	
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate in ATLAS :

$N = L \times \sigma\,(pp) \approx$ 10^9 interactions/s

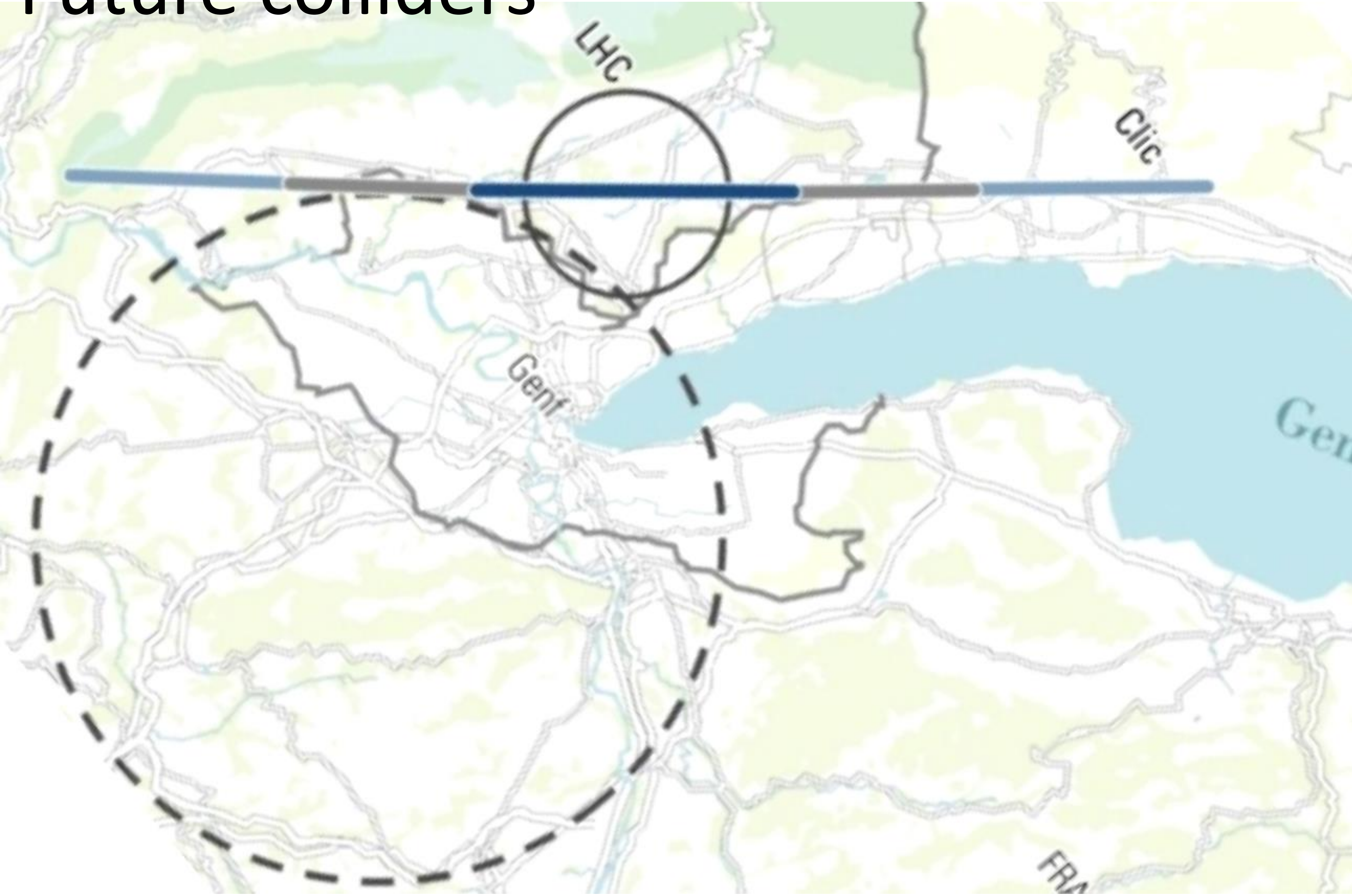
Mostly soft (low p_T) events

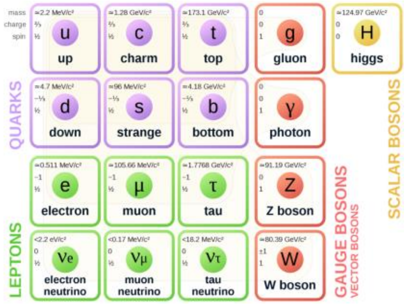
Interesting hard (high-p_T) events are rare



Selection of 1 in 10,000,000,000,000

Future colliders



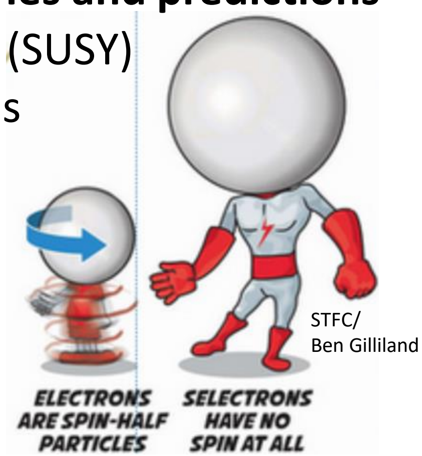


Unanswered questions

- Three families? 19+7 free parameters?
- Nature of the Higgs field?
- Difference matter-antimatter?
- 95% of universe non-baryonic matter? Dark matter?
- ..

Theories and predictions

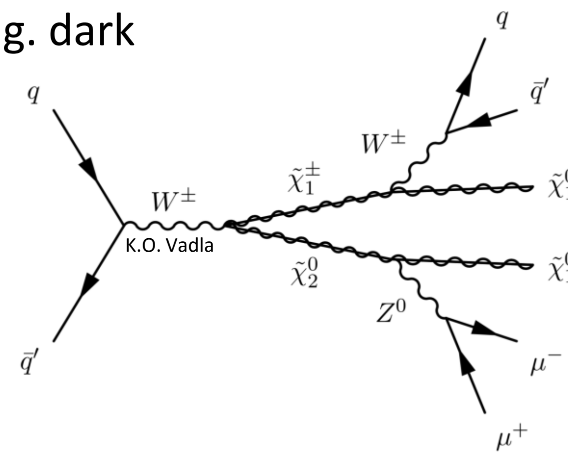
- Supersymmetry (SUSY)
- Extra dimensions
- String Theory
- ..



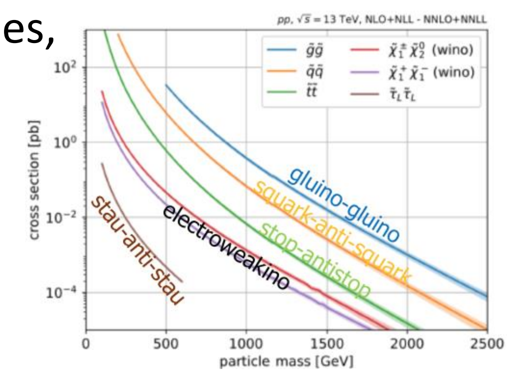
Experimental results required to guide us!

Searches and analyses

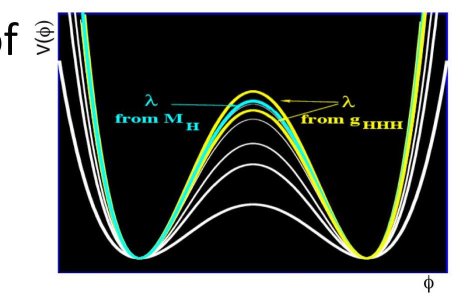
- Direct discovery of new physics. e.g. dark matter particle



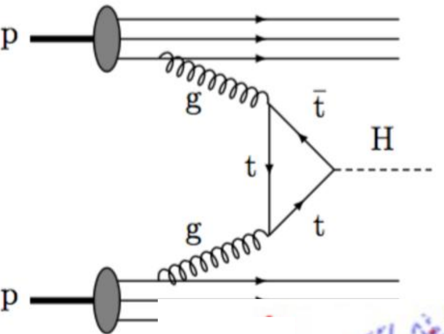
- Constraining theories, e.g. exclude SUSY parameter space



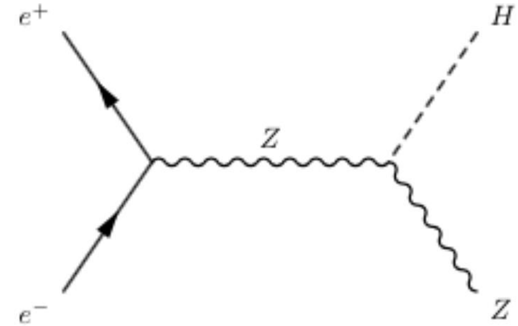
- Precision measurement as proof for new physics, e.g. deviation from coupling parameters

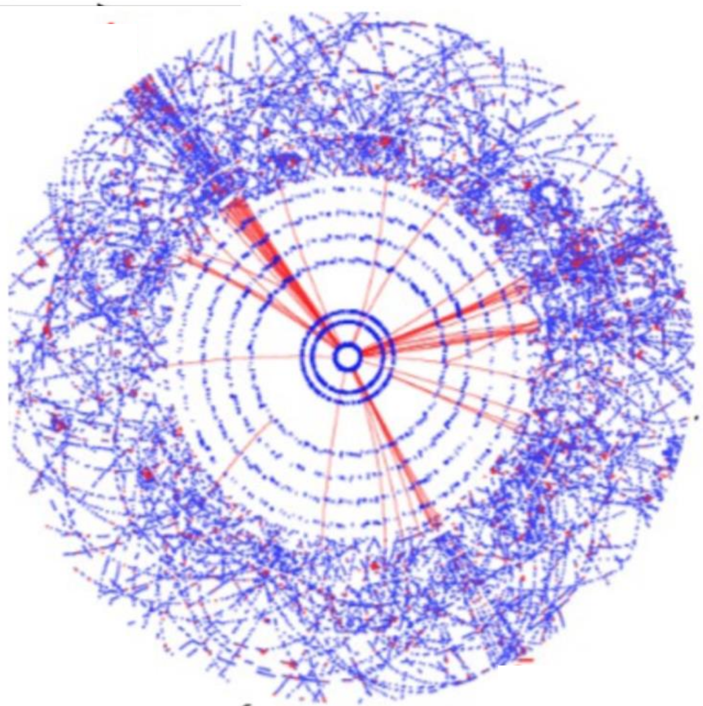


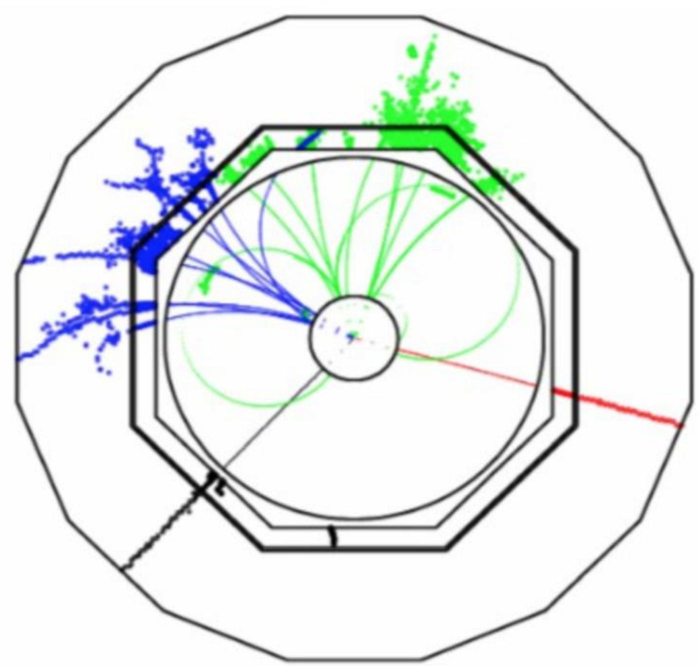
Particle type: proton-proton versus $e^+ e^-$ colliders



hadron vs leptons



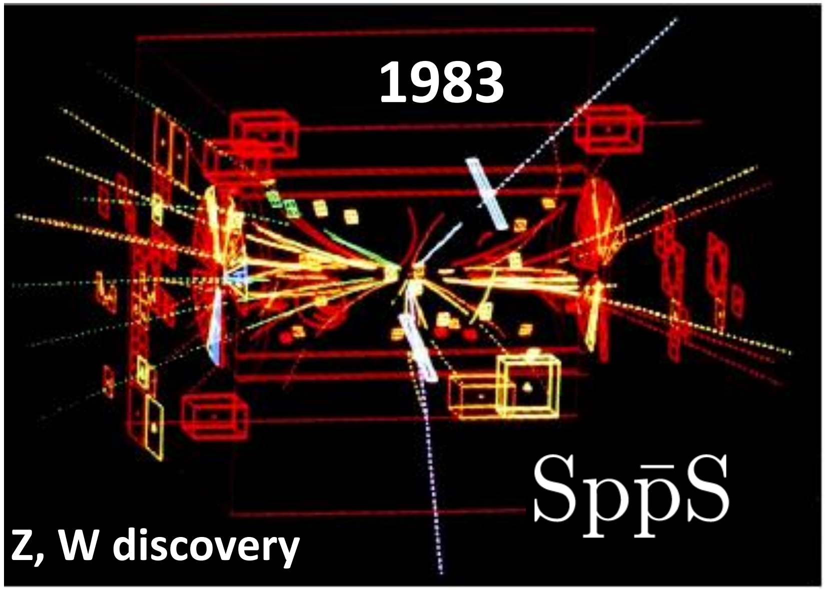


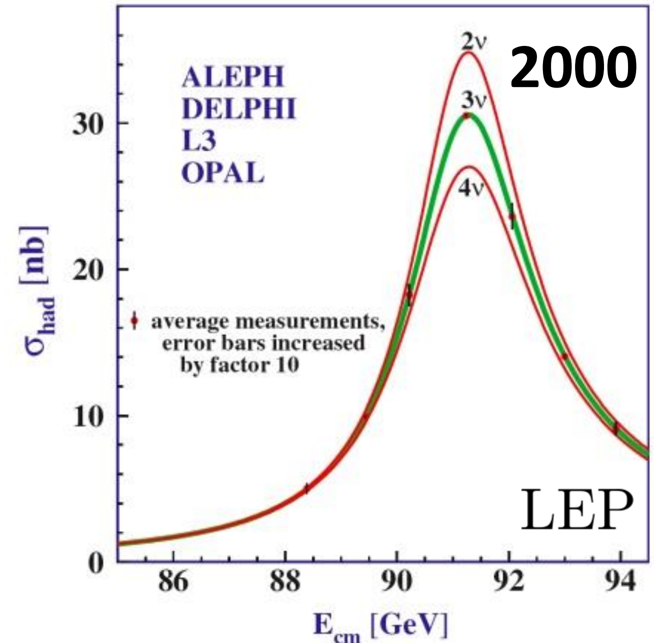


- Initial state not available
- Strong background, busy events, filtering, triggers

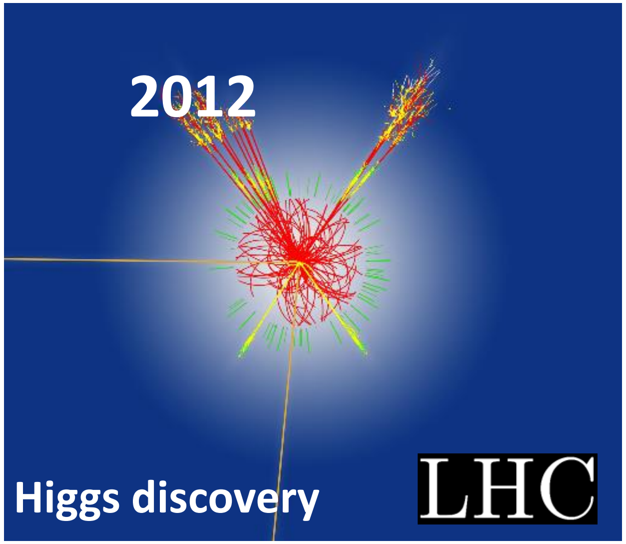
- High signal-to-noise; cleaner events
- Well defined initial stage
  - Higgs decay width can be established, model independent coupling measurements,

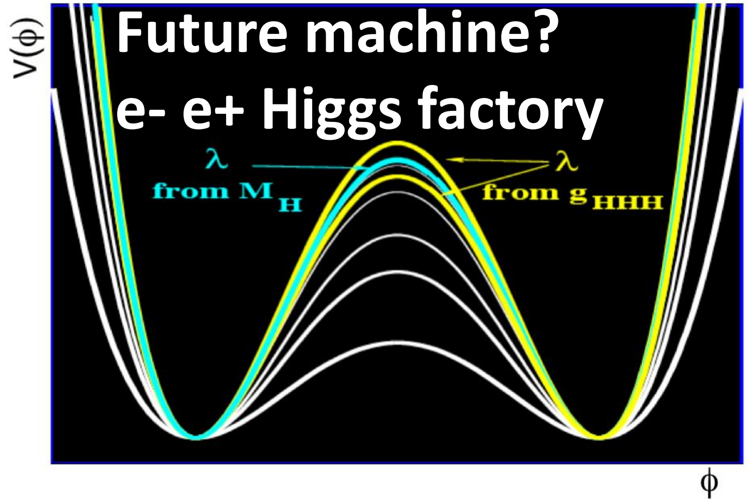
Recent colliders at CERN





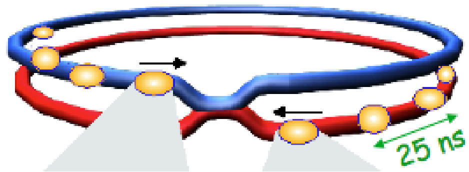
"LEP changed high-energy physics from a 10% to a 1% science."
H. Schopper





Future machine: **per mille precision**, model independence

Energy and luminosity limitations, for rings and linacs



Energy challenges

Luminosity challenges (examples)

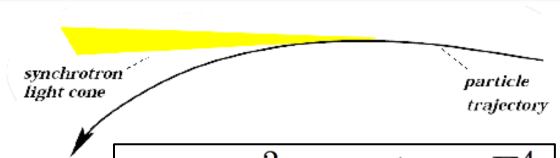
Circular proton-proton colliders

LHC: 14 TeV collision energy, **limited by 8T** SC magnet field

$$p = eB\rho$$

Collective electromagnetic effects constrain charge

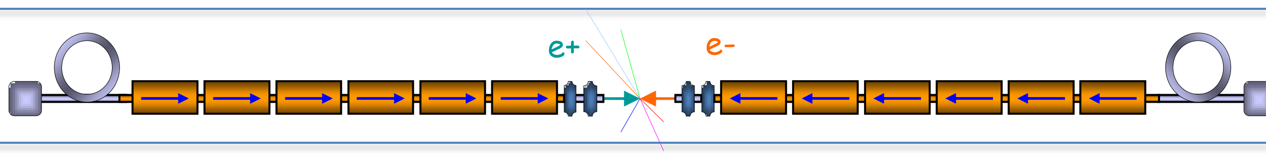
Circular e- e+ colliders



Synchrotron radiation loss limited LEP collision energy to 209 GeV.

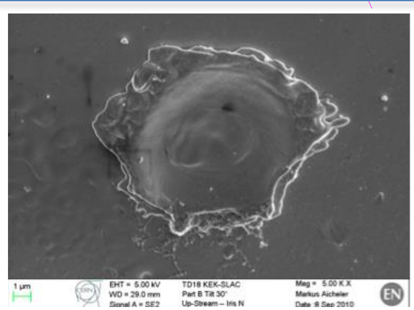
$$P_e = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

Synchrotron radiation loss constrains charge



Linear e- e+ colliders

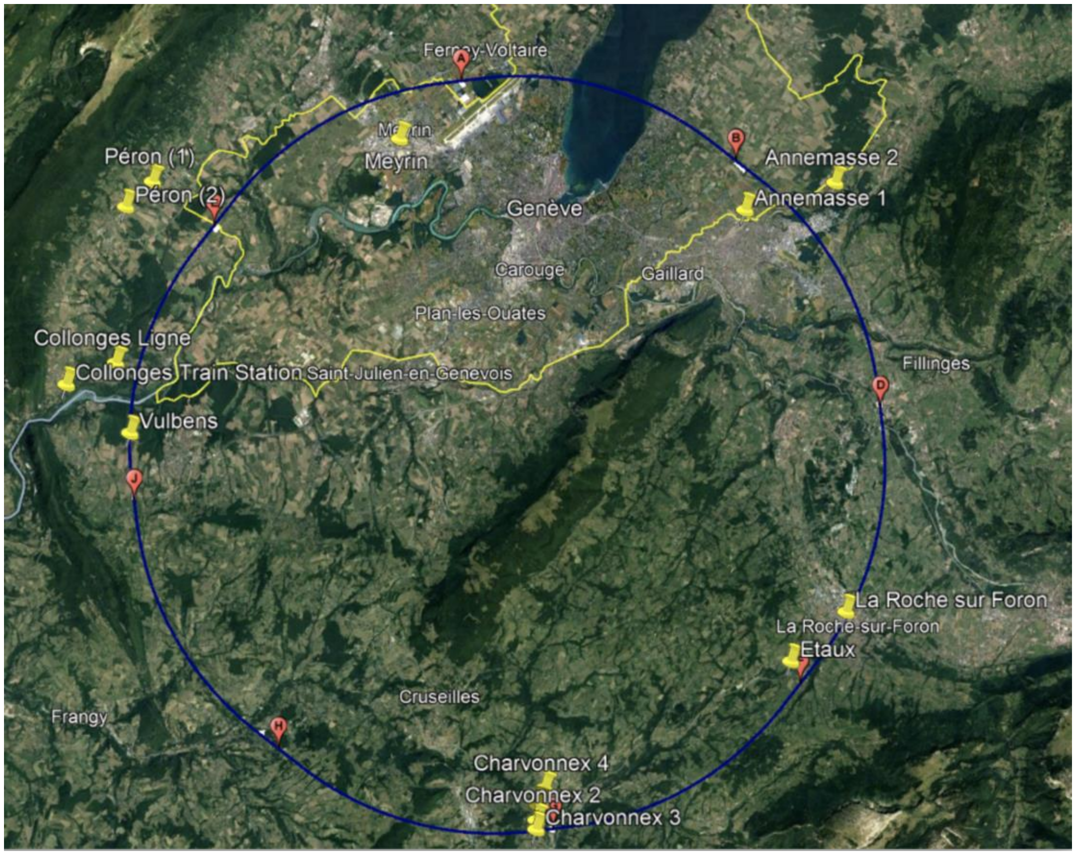
Reaching high accelerating RF fields. **100 MV/m** is the state of the art. 10 km <= 1 TeV.



Colliding beams with nm width**,** as opposed to µm width for LHC, required for the same luminosity.

The Future Circular Collider as e- e+ Higgs Factory

Use the FCC tunnel first for **e- e+ collisions**, up to 365 GeV (1.7 x LEP energy). Current adjusted to keep **synchrotron radiation loss at 100 MW** for all energies.
No technological show stoppers. Est. cost: **ca 12 BCHF.** FCC-hh magnet development in parallel.



91 km tunnel

Also Chinese ”FCC” studies

- Chinese has proposed a ”FCC-ee“ (CEPC) and a “FCC-hh” (SppS), to be built in China (2012)
- Would be very similar to the FCCs
- CEPC CDR finalized (2018)
- Funding not ensured
- Requires international cooperation

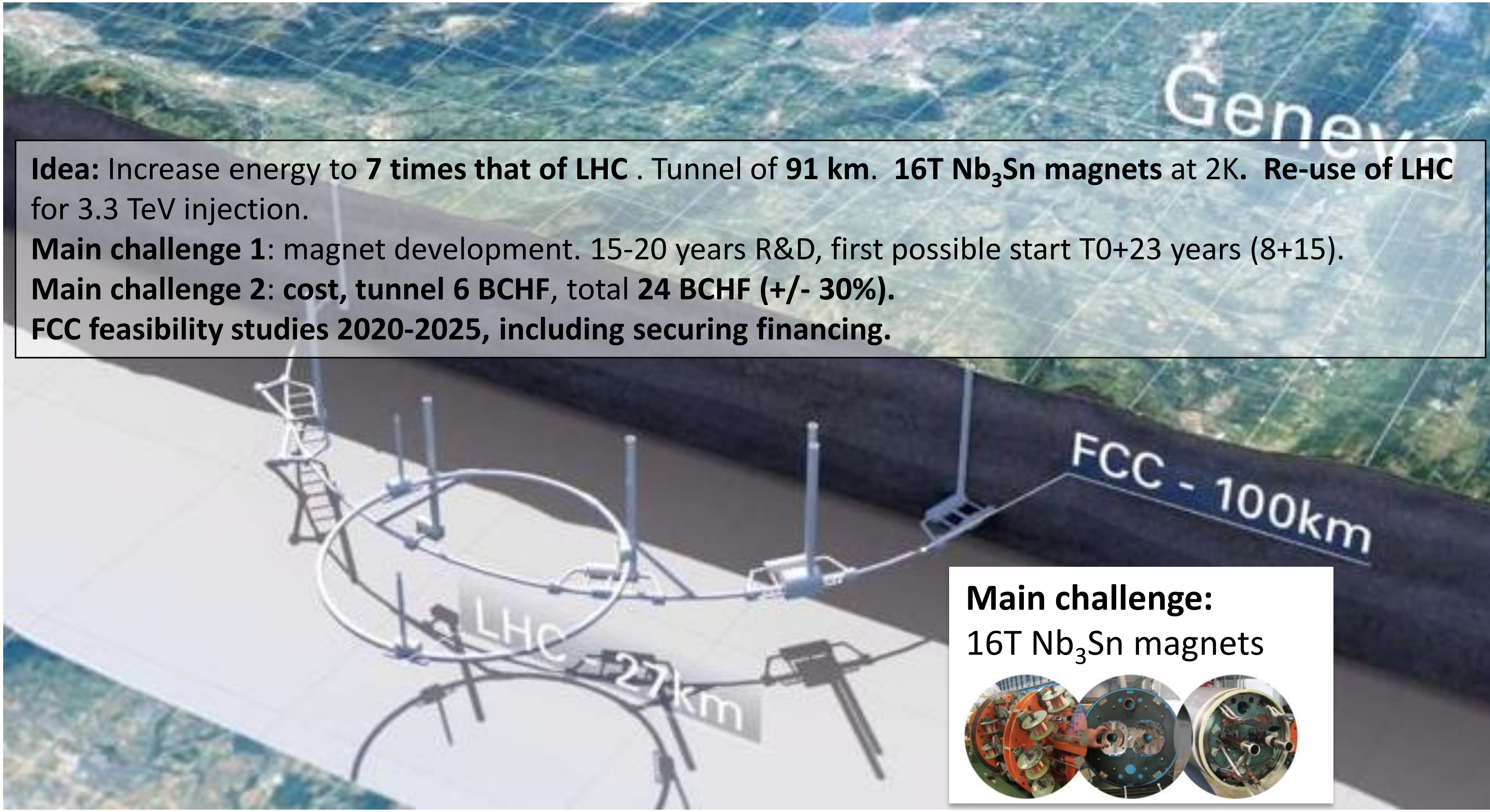
The Future Circular Collider - **FCC-hh**

Idea: Increase energy to **7 times that of LHC** . Tunnel of **91 km**. **16T Nb_3Sn magnets** at 2K. **Re-use of LHC** for 3.3 TeV injection.

Main challenge 1: magnet development. 15-20 years R&D, first possible start T0+23 years (8+15).

Main challenge 2: **cost, tunnel 6 BCHF**, total **24 BCHF (+/- 30%).**

FCC feasibility studies 2020-2025, including securing financing.

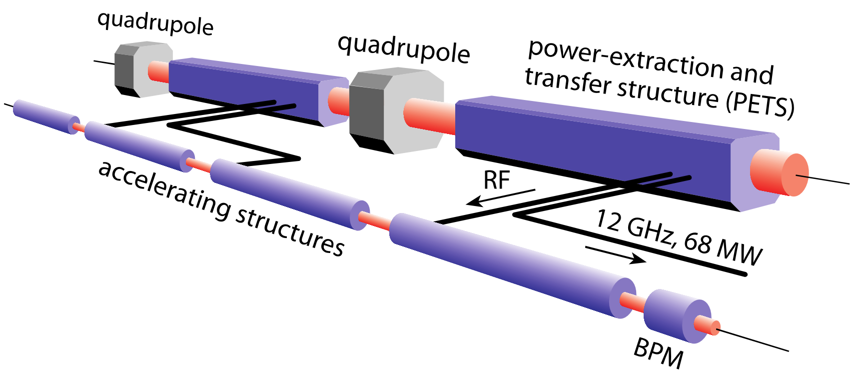


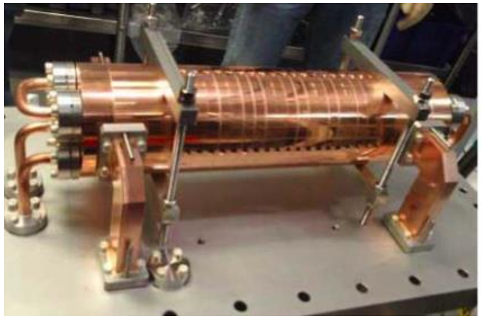
Main challenge:
16T Nb_3Sn magnets

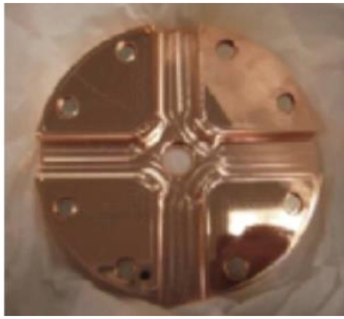
Linear e^+e^- Collider Projects

The Compact Linear Collider, CLIC

Main linac technology: two-beam scheme**. 100 MV/m**. Normal conducting Cu 12 GHz cavities, First stage **380 GeV, 11 km.** Upgradable to 3 TeV, 50 km.

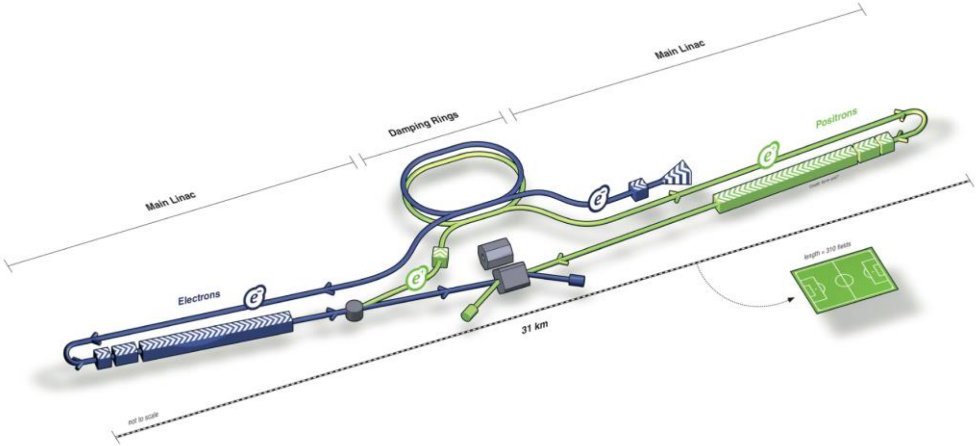


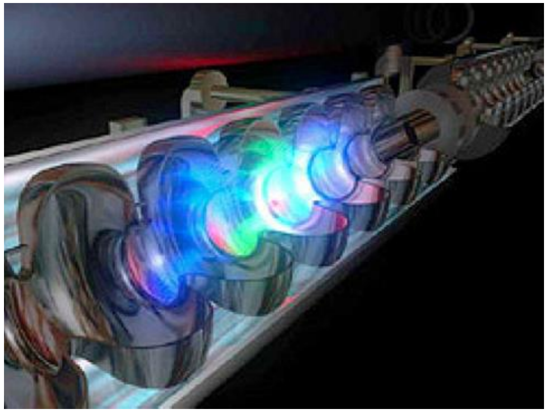




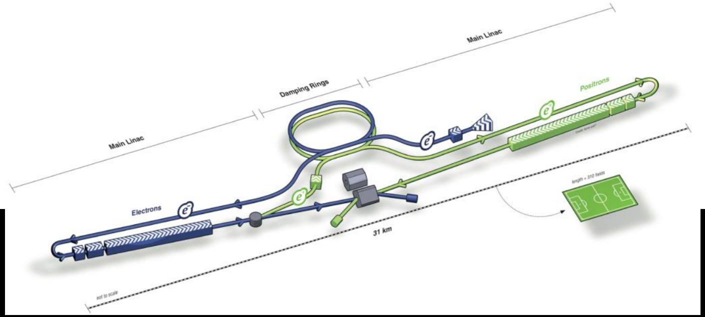
The International Linear Collider, ILC

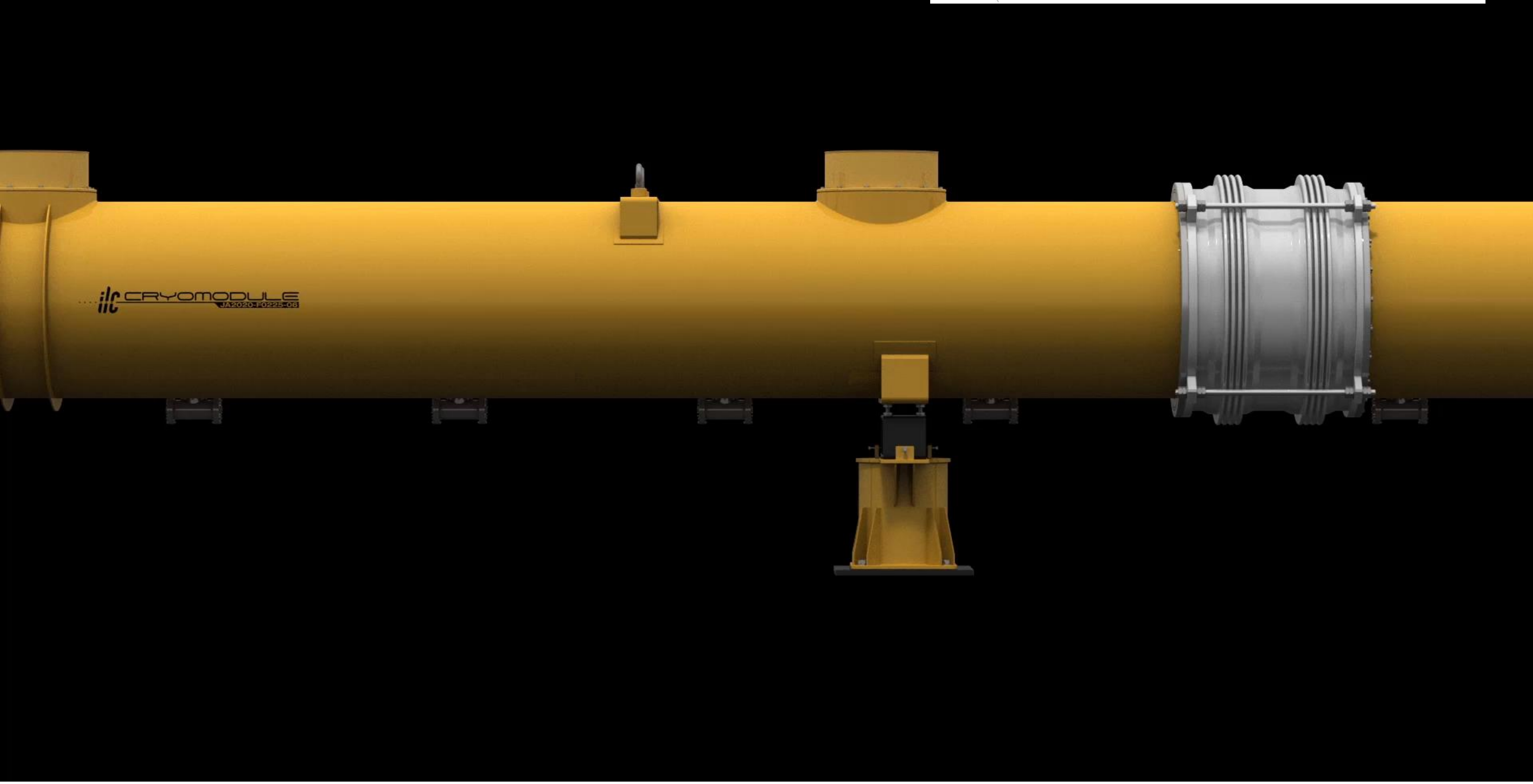
Main linac technology: **super conducting RF 1.3 GHz SW cavities, 31.5 MV/m**
First stage **250 GeV, ~20 km**. Upgradable to 1 TeV, ~50 km.



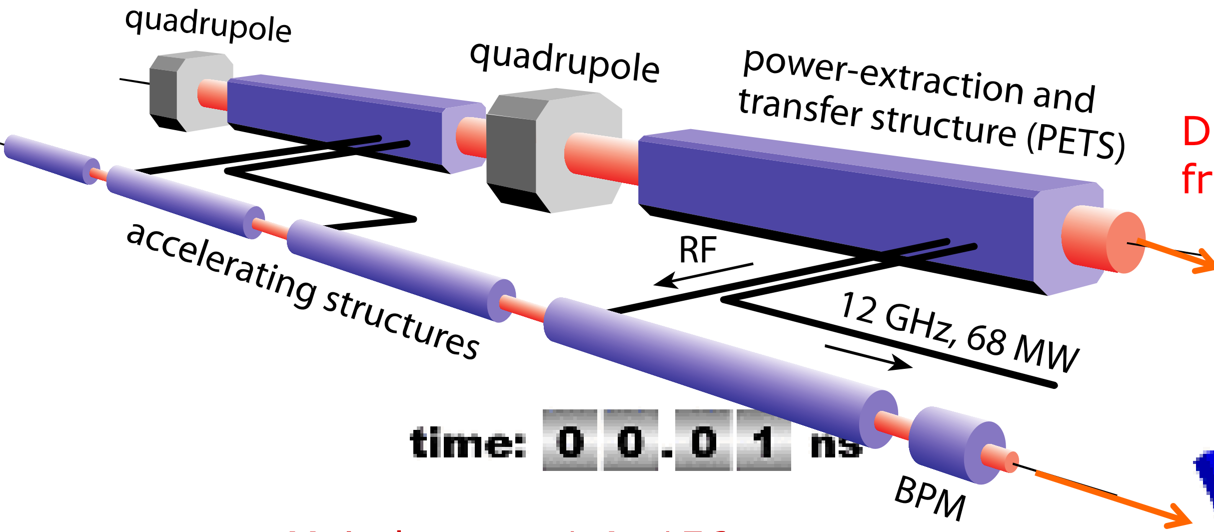


Linear Colliders:
Fly-through of how to make 500 GeV collisions with superconducting RF technology





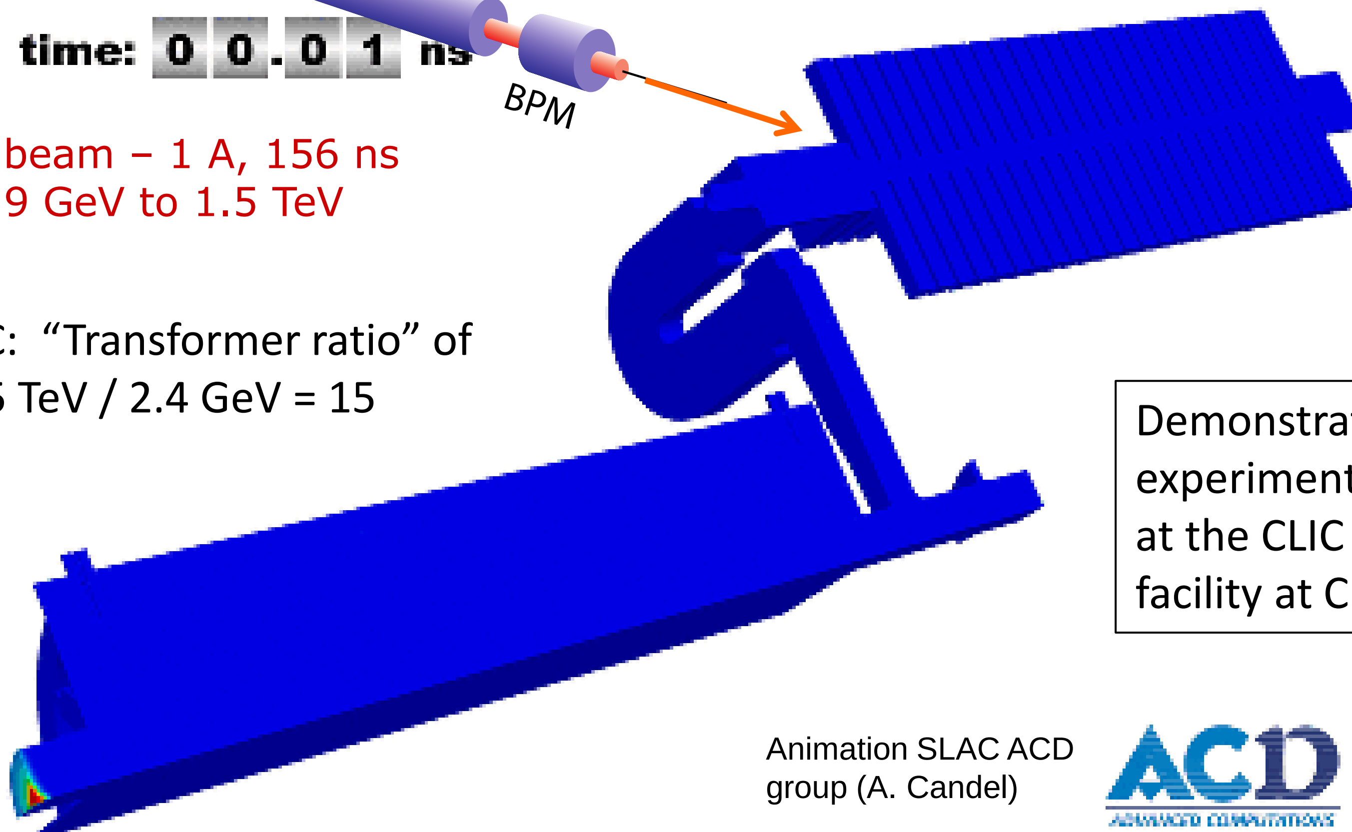
The CLIC Two-Beam scheme



Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV

Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV

CLIC: "Transformer ratio" of
~1.5 TeV / 2.4 GeV = 15

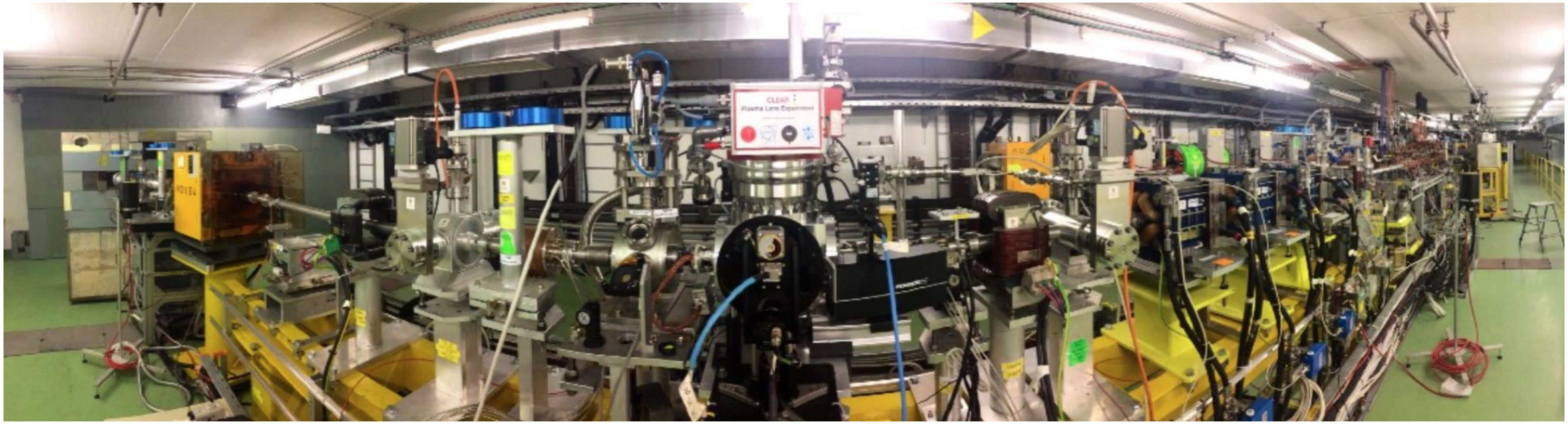


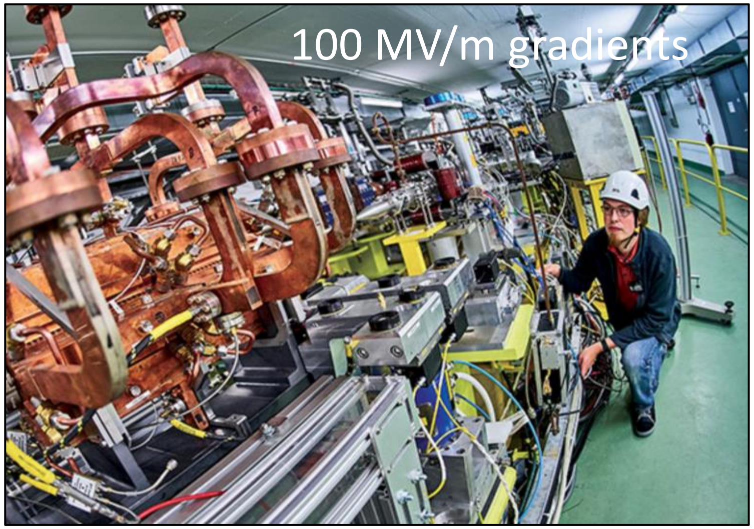
Demonstrated experimentally at the CLIC Test facility at CERN.

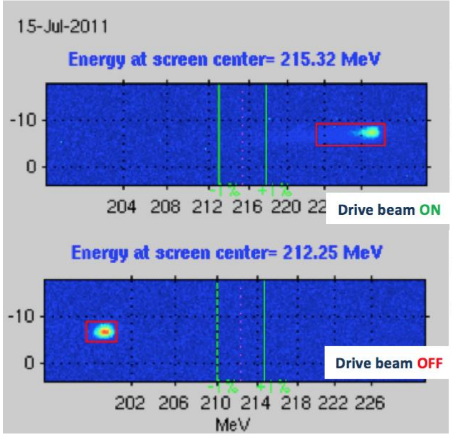
Animation SLAC ACD group (A. Candel)

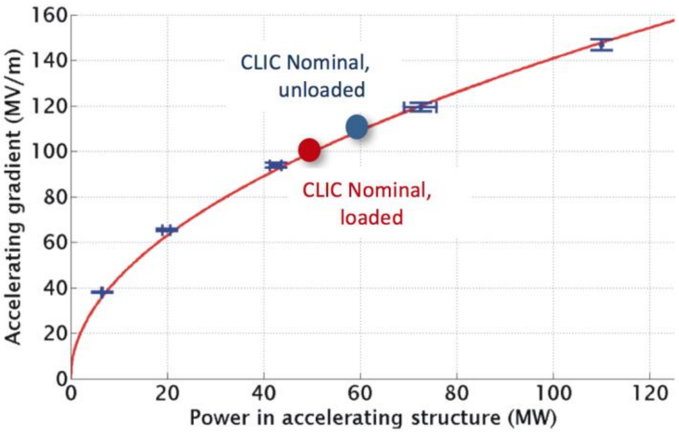
FI@UiO research

Experiments at the CLEAR test-facility

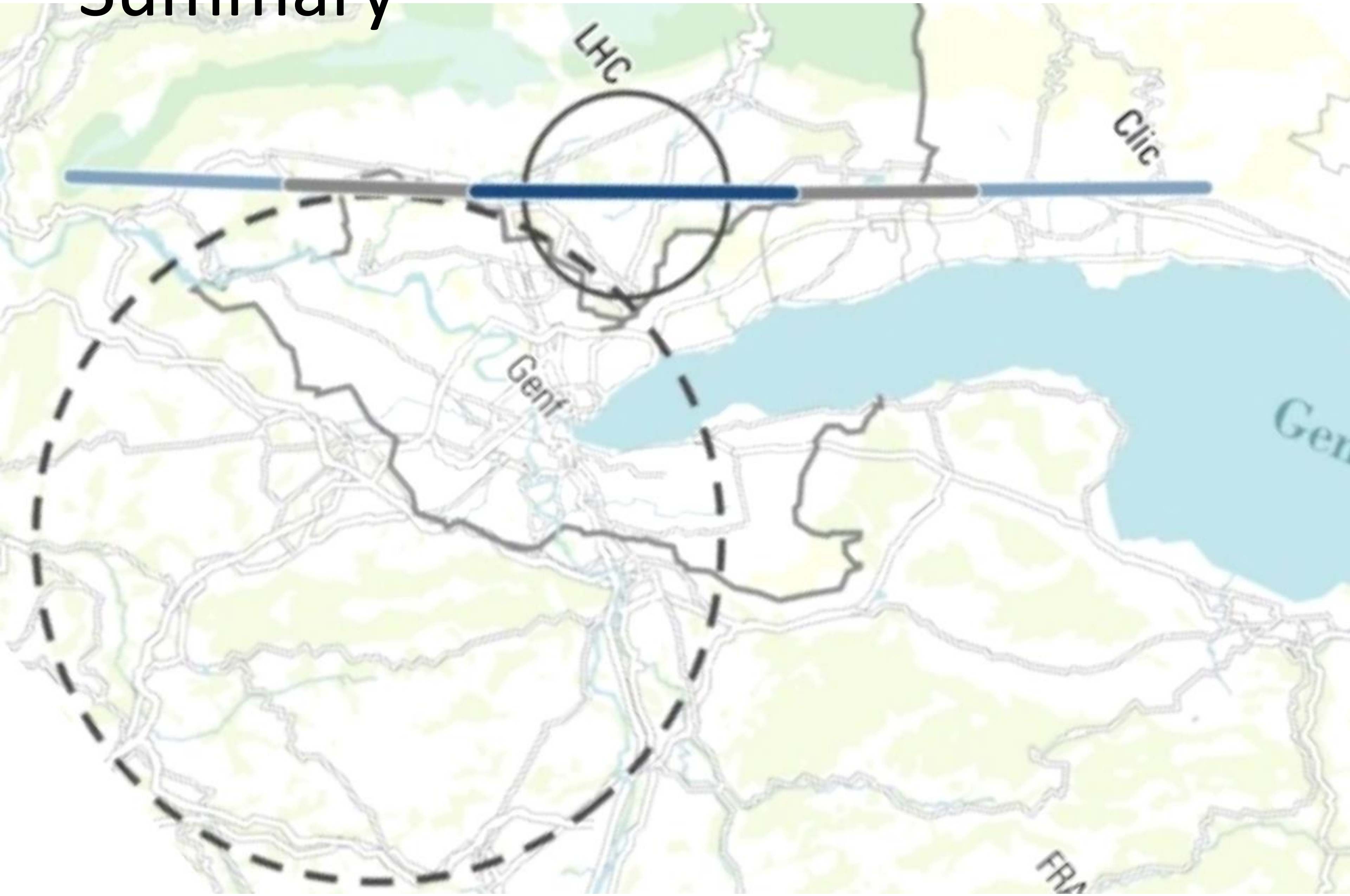








Summary

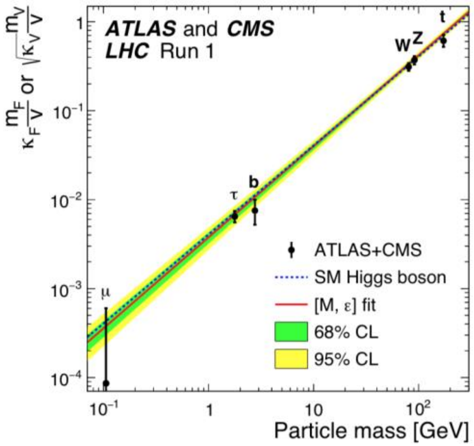


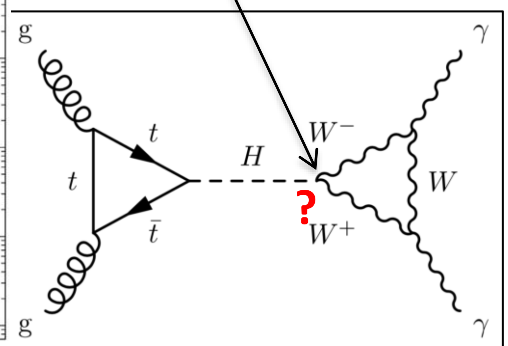
Extra

Comparison of machine physics potential: examples

Precision measurements of Higgs couplings

$$g_{hXX} = \kappa_X \, g_{hXX}^{\mathrm{SM}}$$





Improvement of precision compared to HL-LHC

	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

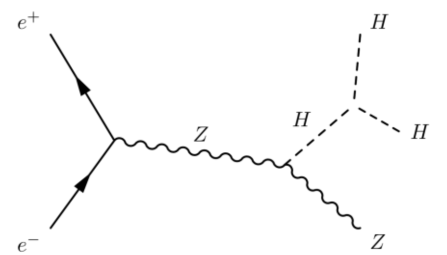
Color scale: 0 – 5

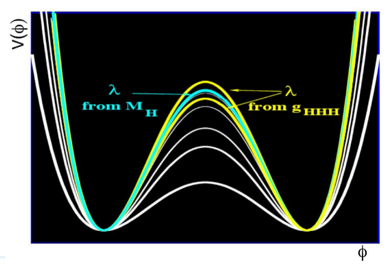
(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC

M. Cepeda, ESU meeting, Granada, 2019 arXiv:1905.03764 [hep-ph]

Probing the Higgs potential

$$V(\phi)$$





$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Measurements of the Higgs potential could be done at a FCC-hh, or at a Multi-TeV e- e+ collider

Current opinions seem to be: an e-e+ Higgs factory desired as first machine

"The guaranteed physics of new machines is centered on revealing **the deeper nature of the Higgs**."

Nima Arkani-Hamed

Novel accelerator concepts: **muon collider**

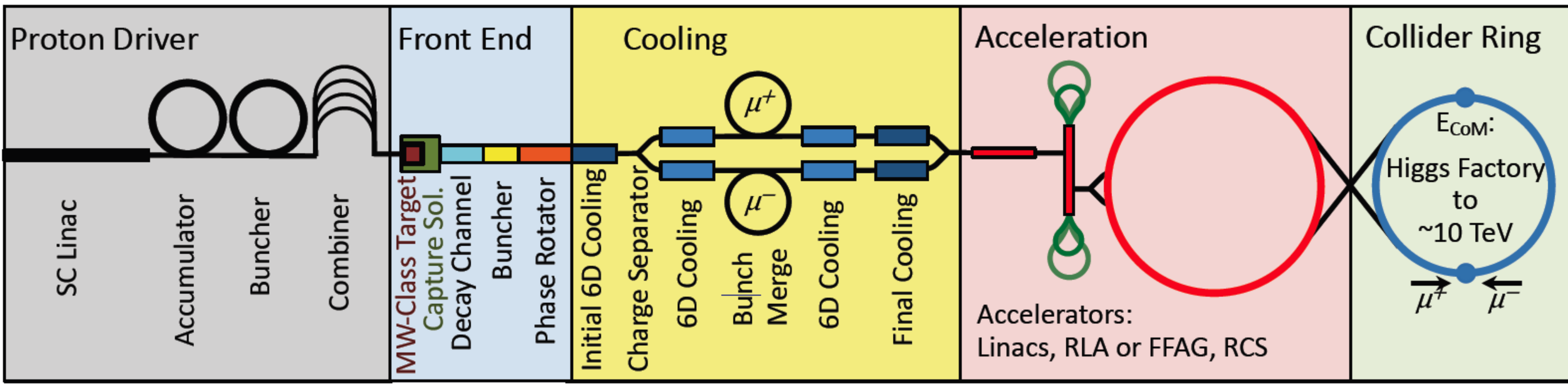
Novel concepts: boost accelerator performance with **radical change in technology**
Very promising and interesting research, many hurdles to overcome before use in a collider.

Muon collider pros and cons

Negligible synchrotron radiation

Main challenge: $\tau_\mu = 2.2\ \mu s$

- Produce sufficiently dense muon beams
- Rapid acceleration
- Mitigate radiation hazards



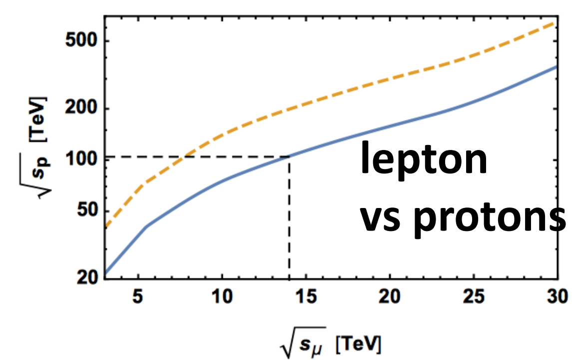
Protons on target
hadronic showers,
Pions decay into muons

Muon are captured,
bunched and then cooled.

Rapid acceleration
to collision energy

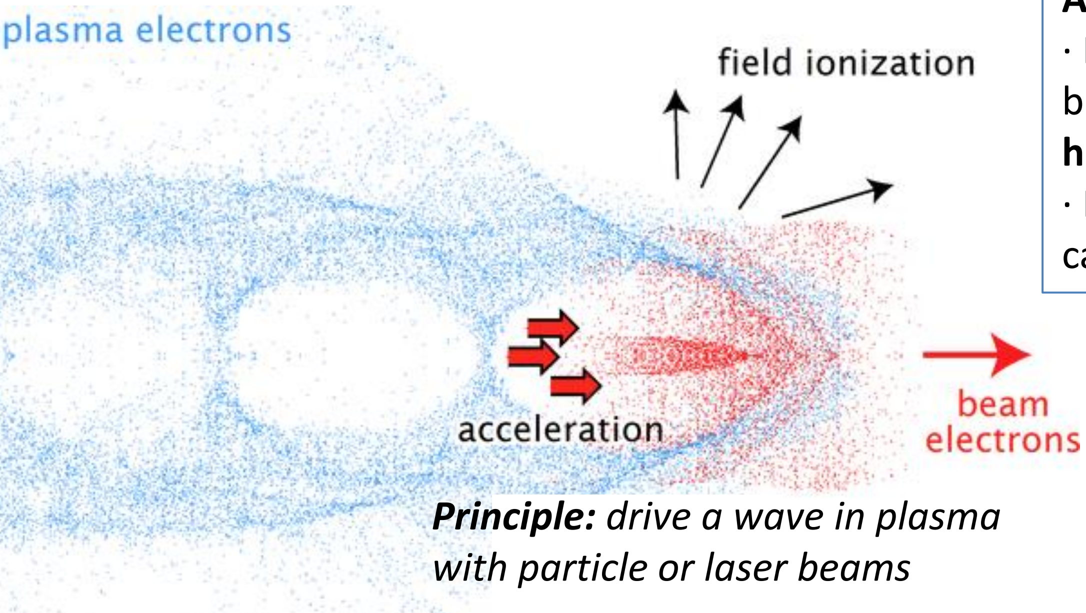
Collision

Precision, plus discovery potential!
3 TeV ~ LHC
14 TeV ~ FCC-hh;
30 TeV ~ "amazing"



Novel accelerator concepts: **plasma acceleration**

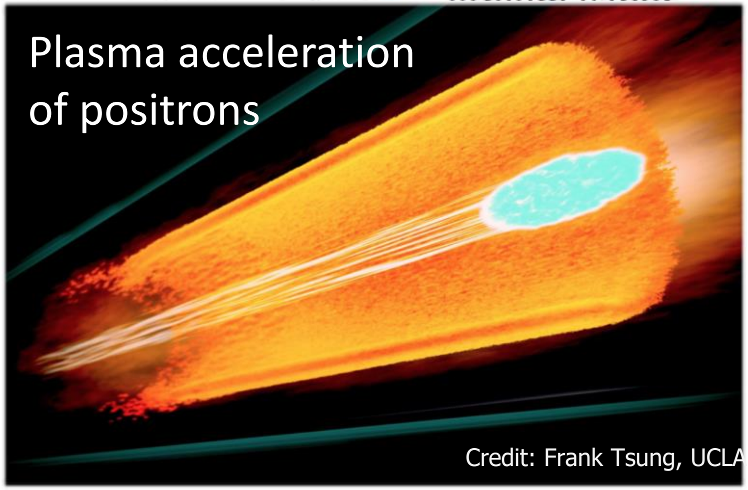
See parallel session talk by Ben Chen (UiO)



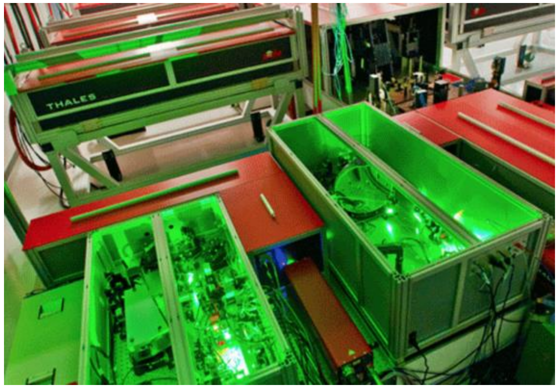
Principle: *drive a wave in plasma with particle or laser beams*

RF cavities: limited by metal surface break down
Alternative: high fields inside plasmas:
· Plasmas of a large range of densities can easily be produced. Fields scale with density. **Very high fields can be generated**.
· Plasmas are already broken down. The plasma can **sustain the very high fields.**

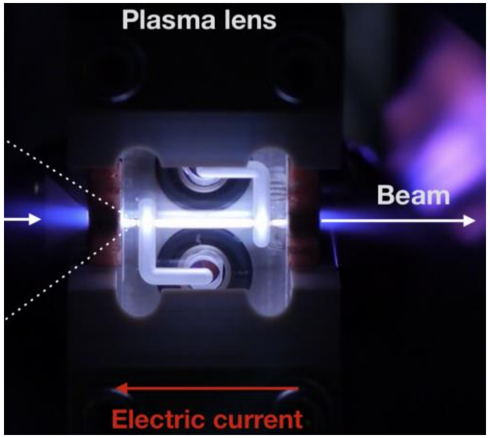
Typical numbers :
Plasma density ~ **10^{16-18}/cm^3**
Field scale: 10-100 GV/m
Length scale : $\lambda_p/2\pi$=**10-100** μ**m**



Great experimental progress recent years:
50 GV/m accelerating fields, positron acceleration, AWAKE... See UiO-thesis of Carl A. Lindstrøm



TW-PW laser technology



Plasma lenses for particle beams

See parallel session talk by Kyrre Sjøbæk (UiO)