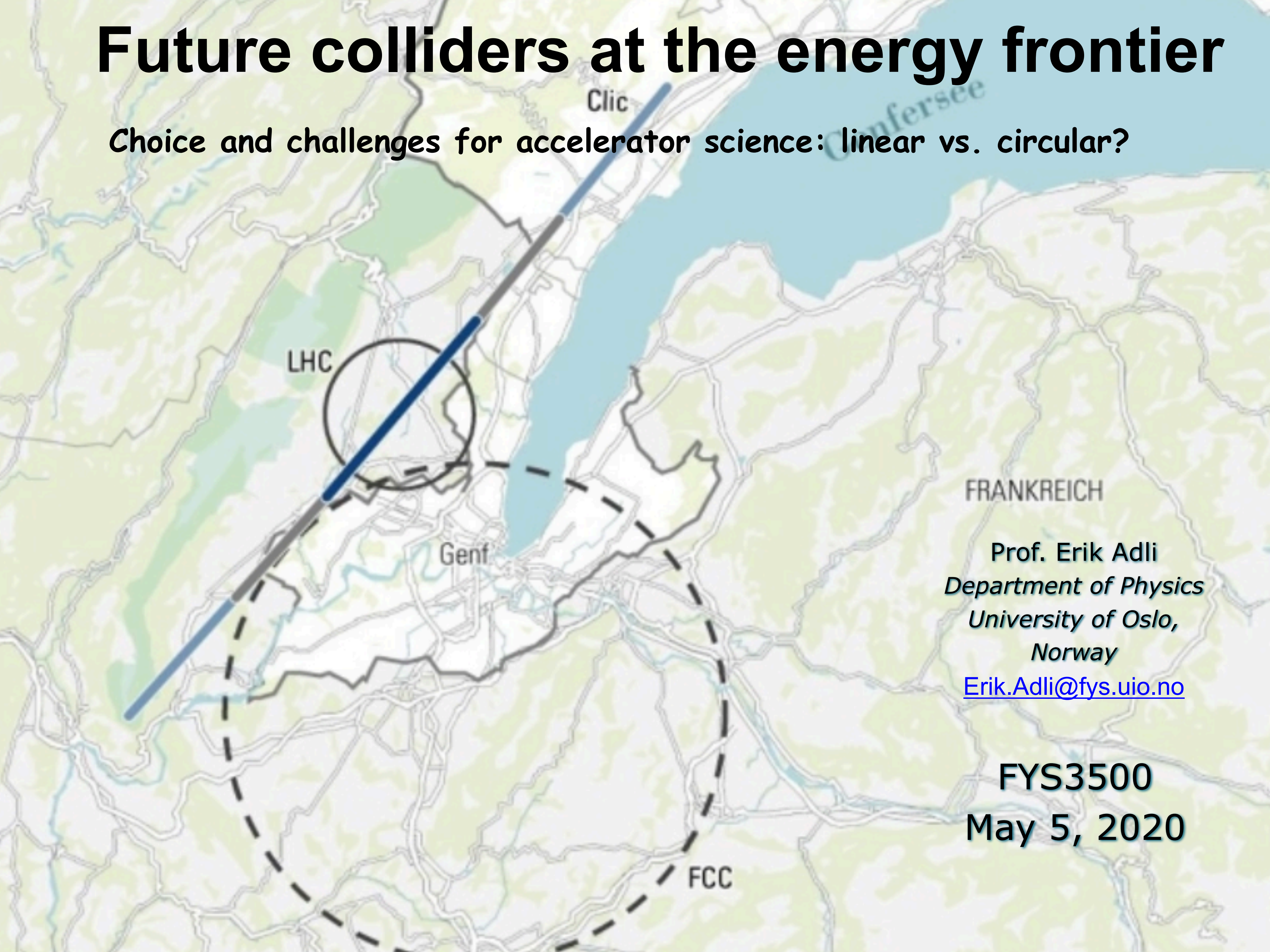
Future colliders at the energy frontier

Choice and challenges for accelerator science: linear vs. circular?



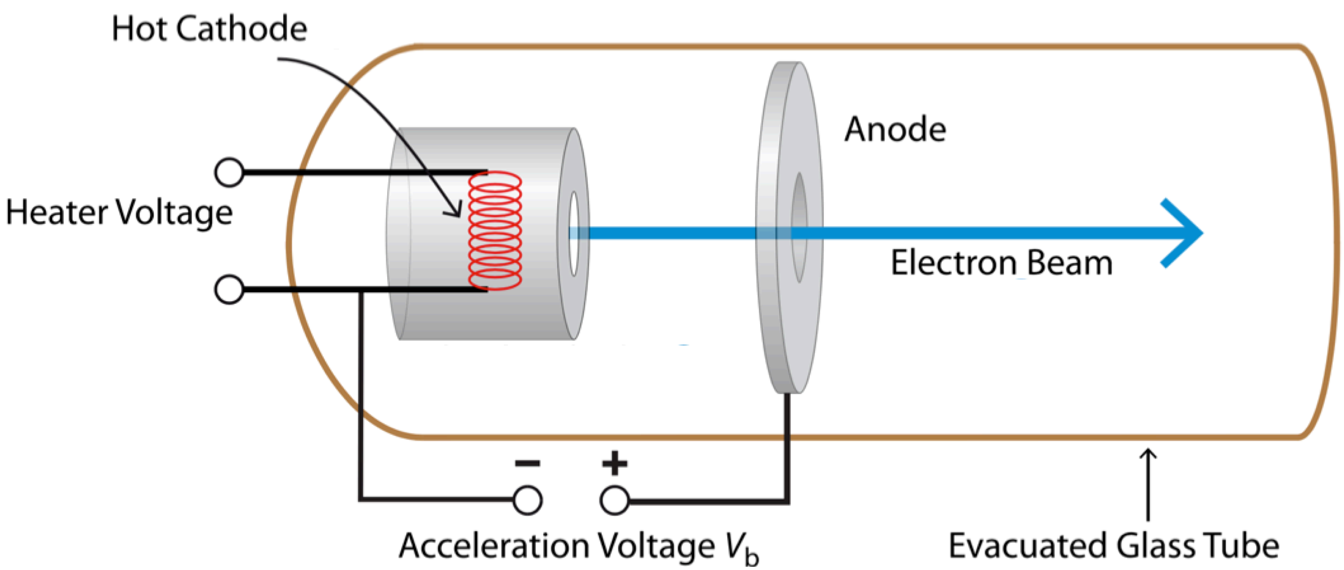
Prof. Erik Adli
Department of Physics
University of Oslo,
Norway
Erik.Adli@fys.uio.no

FYS3500
May 5, 2020

Particle acceleration: how many volt 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)



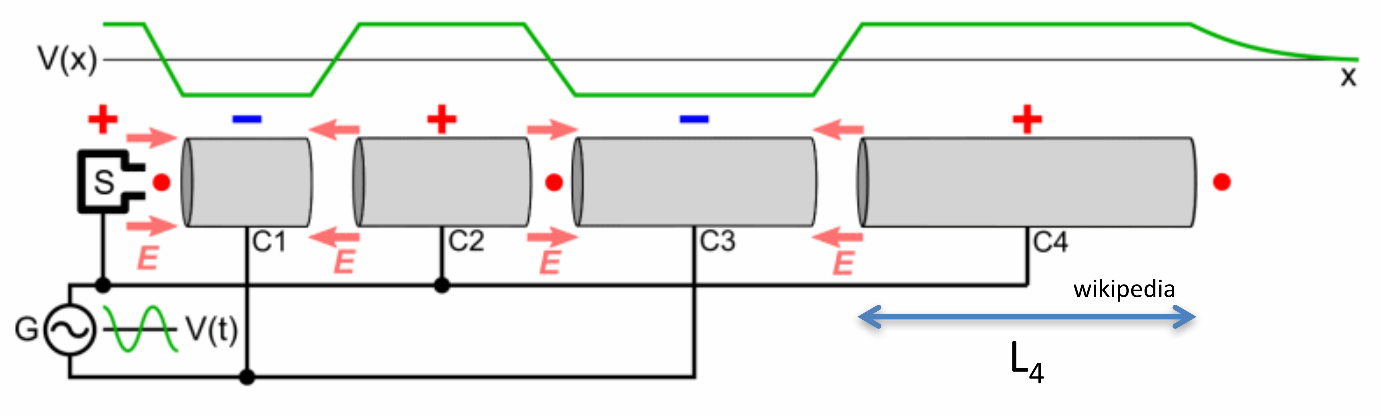
A simple way to make an electron accelerator: electrostatic acceleration with a cathode emitting electrons and an anode, at a higher potential, pulling the electrons towards it.

Voltage for **cathode ray televisions**: few 10 keV

Radio-frequency linear accelerators

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

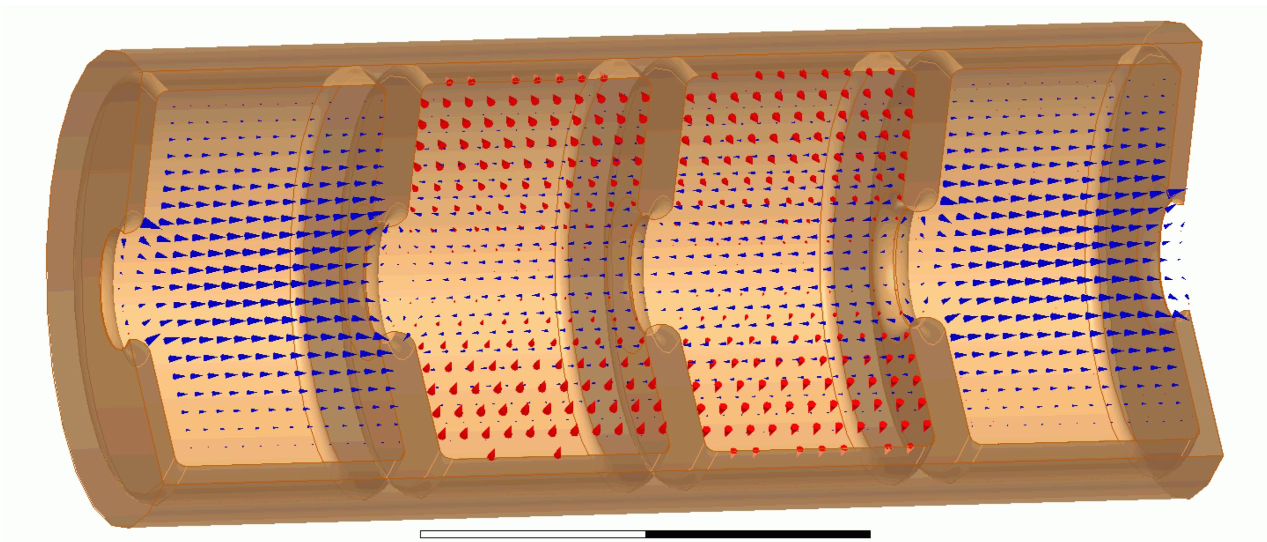
$\frac{1}{2}\ T_{RF}\ v = L$



Widerøe-type RF-linac.

RF-cavities is used in all high-energy particle accelerators today.

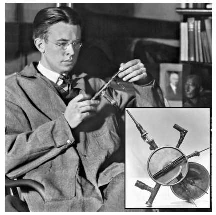
Typical voltage: ~ 10 MV/m

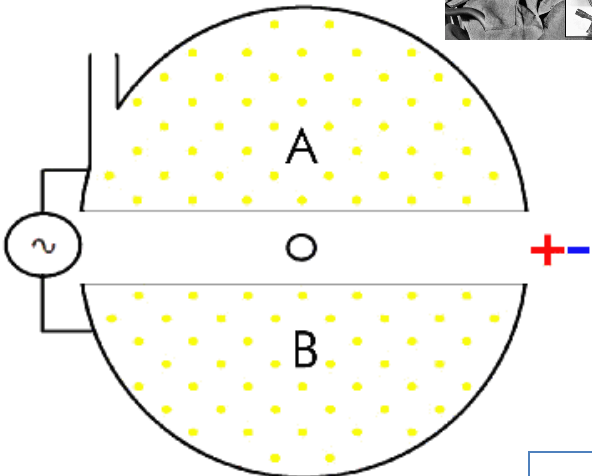


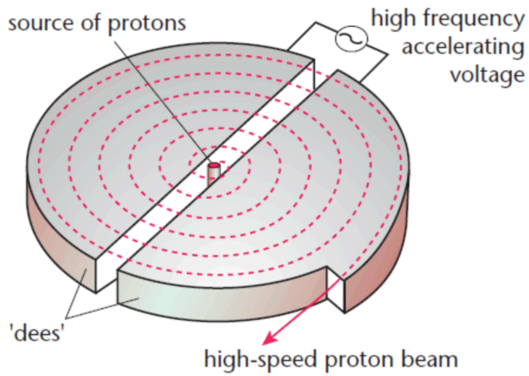
Later development: enclose RF-fields in metal cavities (RF cavities)

Circular accelerators

Cyclotrons :

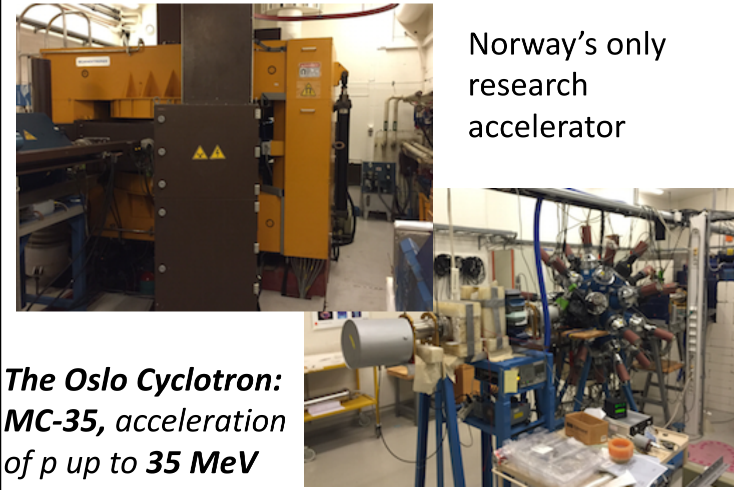






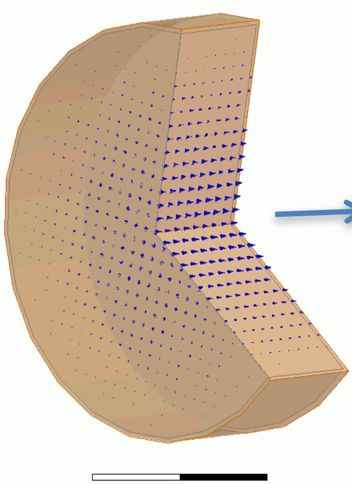
$$F_B = m\frac{v^2}{\rho} \Rightarrow \frac{1}{\rho} = \frac{qB}{p}$$

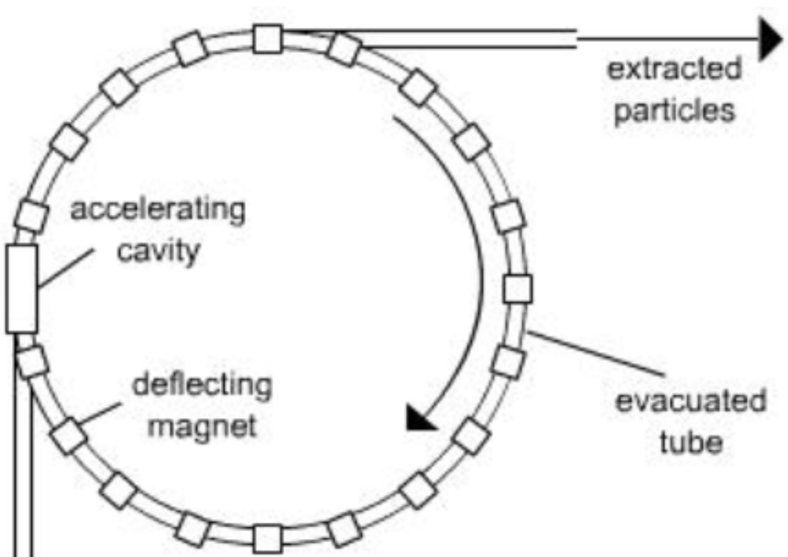
Norway's only research accelerator



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

Synchrotrons :

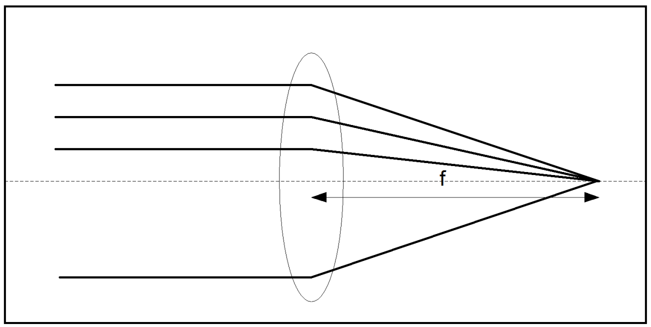


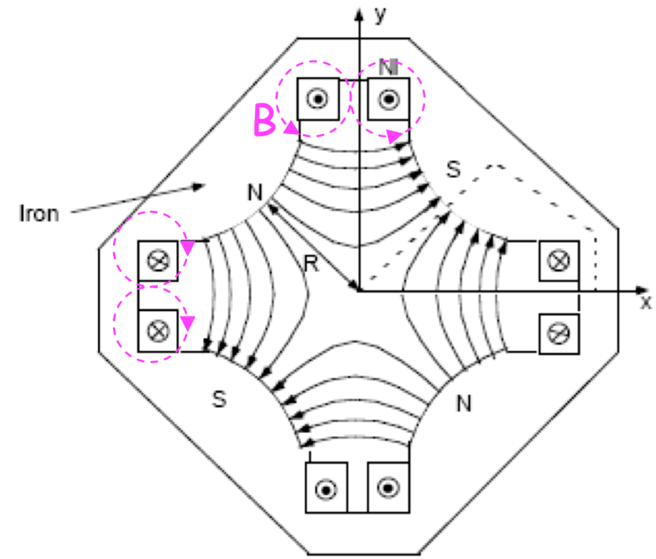


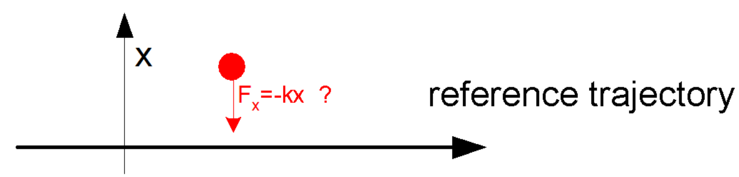
The CERN Proton-Synchrotron (1959, 628 m)
28 GeV (28 billion volts)

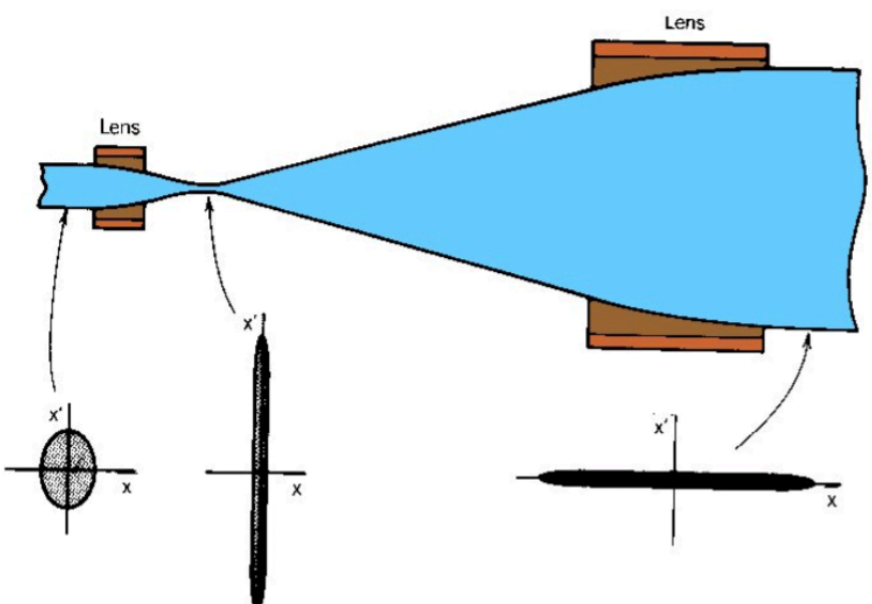
Focusing of particle beams

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









$$\sigma(s) = \sqrt{\varepsilon_{rms}\beta(s)}$$

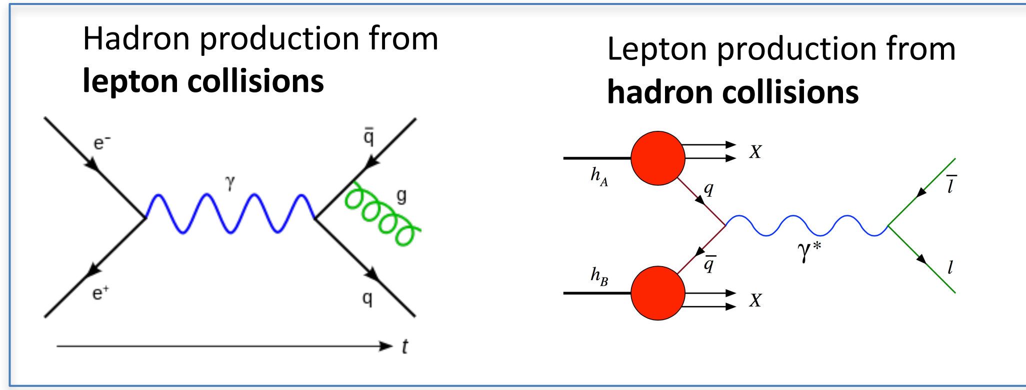
Lattice

Beam quality: emittance

What characterizes a particle collider?

I) Particle type

p, p_{bar}, Pb, Au…
e^-, e^+, μ, γ…



II) Centre of mass energy

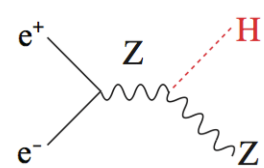
Centre-of-mass energy sufficient for particle production:

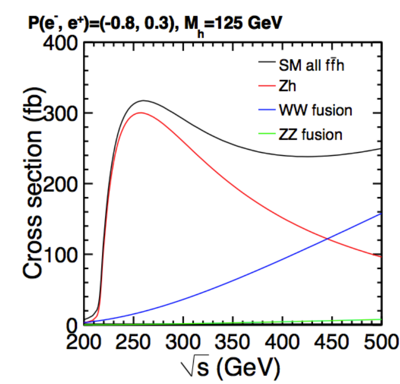
$$E_{CM} >= mc^2$$

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

III) Luminosity

Small cross sections -> production rate as important as energy





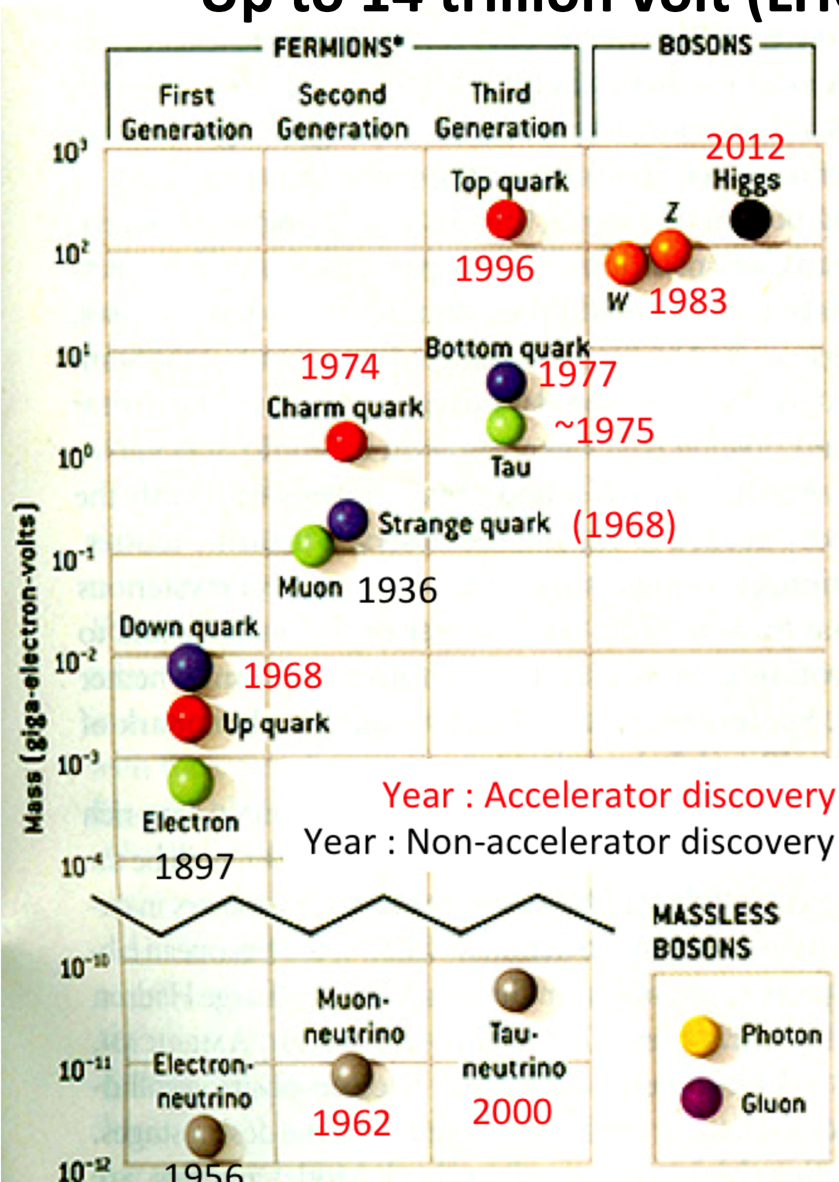
$$R = \mathcal{L}\sigma$$

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

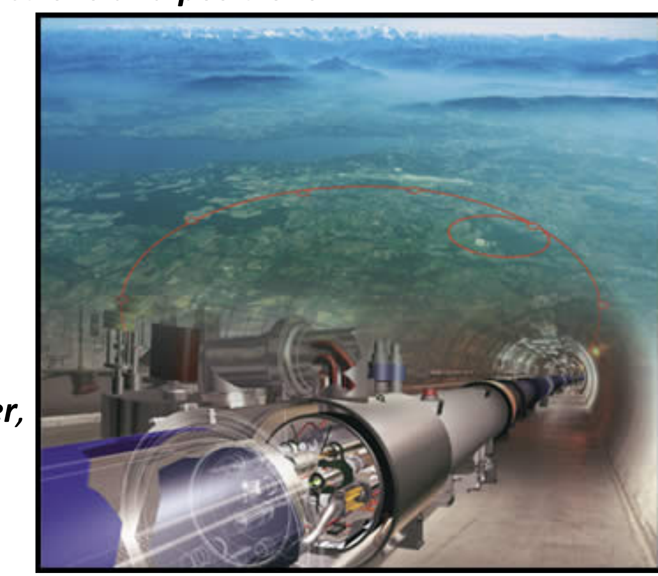
* n_1, n_2 :particles per bunch
* σ_x, σ_y : bunch transverse size at the interaction point
* bunch collision rate (f)

The **development of particle accelerators** has been driven by the quest for the understanding of the **fundamental origins of matter**.

Up to 14 trillion volt (LHC)



The Stanford Linear Accelerator (1966, 3 km) ***50 GeV electrons and positrons***
L ~ 10^{30}/cm^2/s

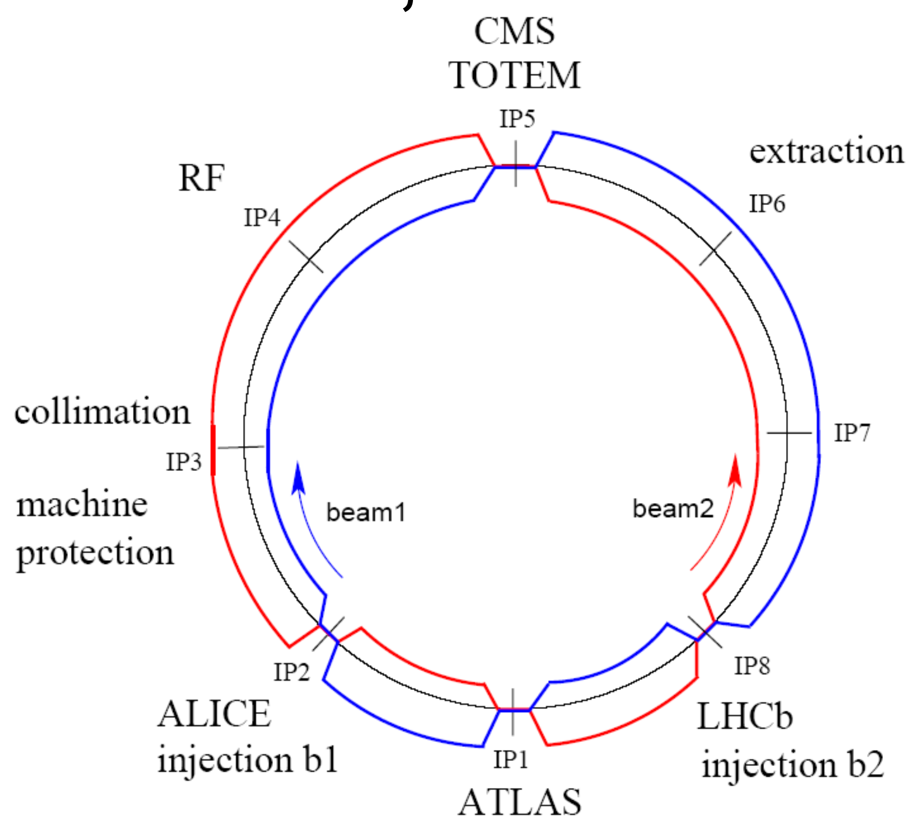


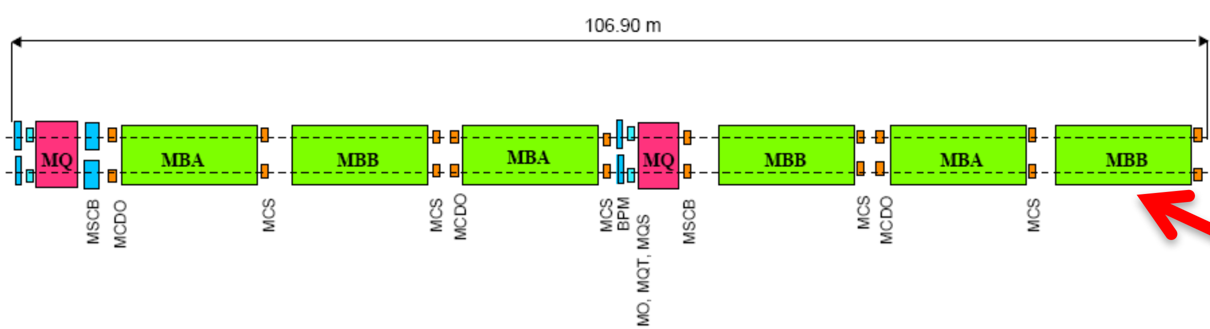
The ***Large Hadron Collider****, CERN (2008, 27 km)*
6.5 TeV protons
L ~ 10^{34}/cm^2/s

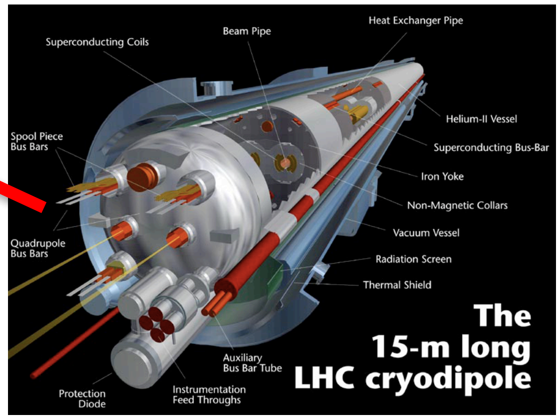
The Large Hadron Collider

The Large Hadron Collider, LHC

- Circumference = 26.7 km
- 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
- The arcs uses **1200 superconducting dipole magnets** to bend the paths of the protons





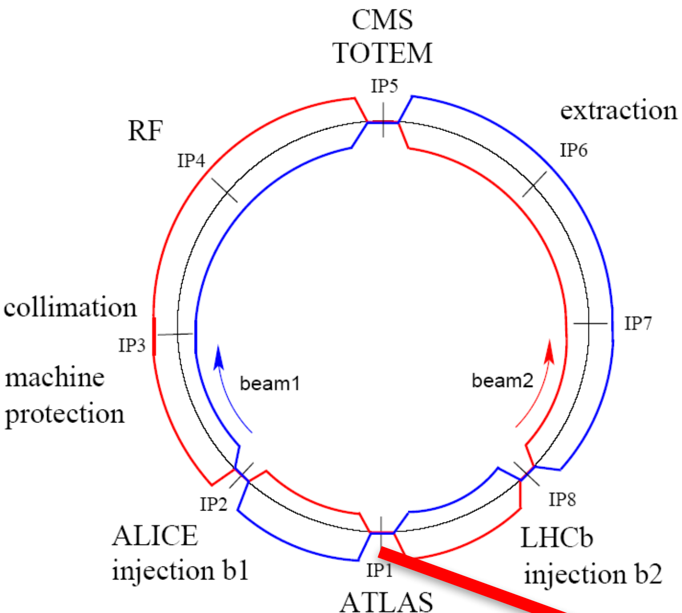


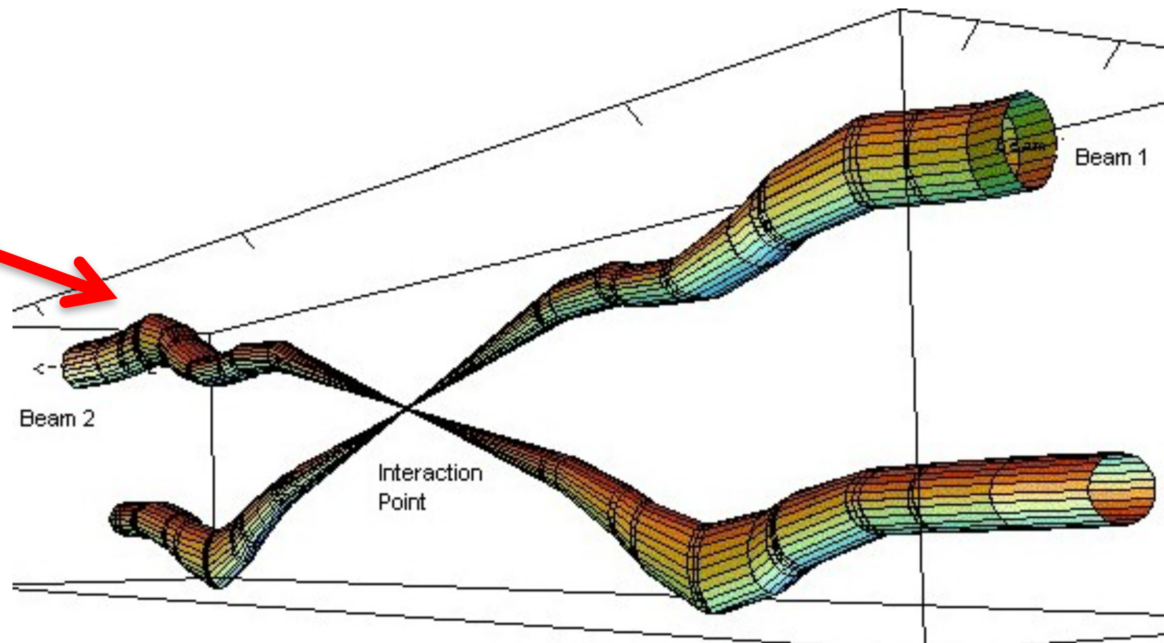
B=8.3 T maximum field, limits proton beam energy to **7 TeV**. Generated by a current **of 12 kA** in the superconducting Rutherford coils.

LHC beam focusing

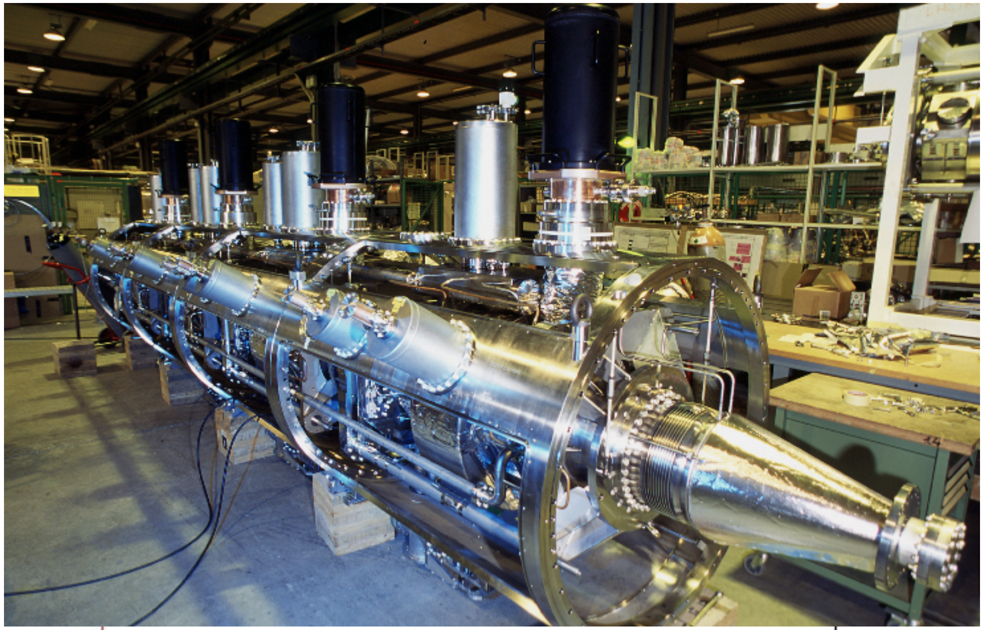
Bunches with n=**1e11 protons**, at f=**40 MHz**, are focused to 1 mm σ in arcs, squeezed down **to σ=20 um** at the IP.

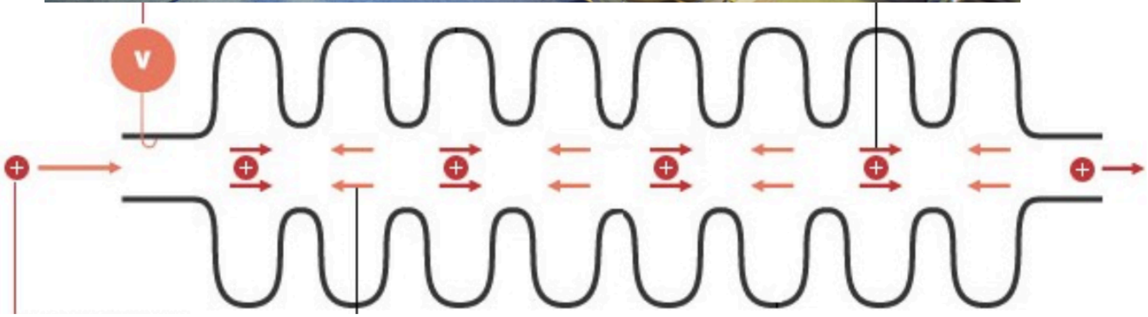
$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$





LHC cavities



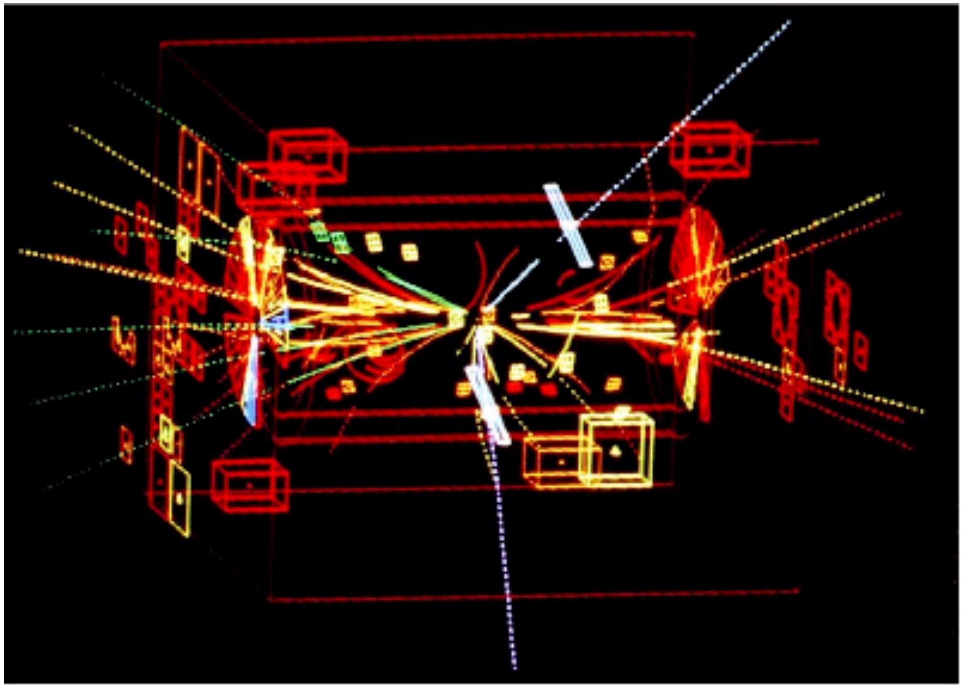


- Superconducting RF cavities. Standing wave, f = 400 MHz
- Each beam: one cryostat at 4.5 K, 4+4 cavities in each cryostat
- **5 MV/m accelerating gradient**, 16 MeV energy gain per turn

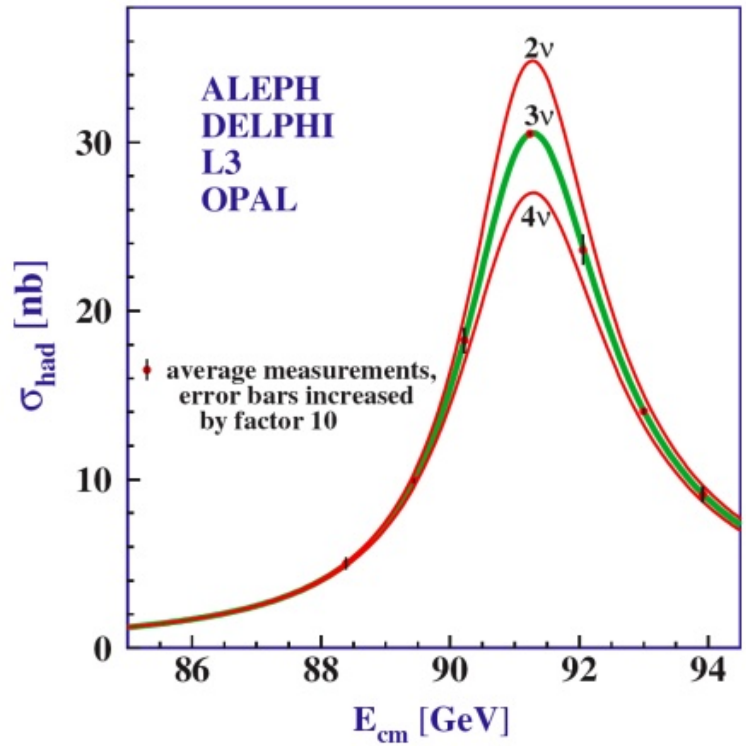
Future Colliders

Example of physics
at **Lepton Colliders vs Hadron colliders**

1983

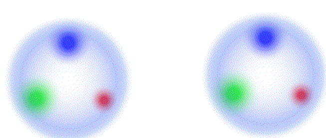


1990s

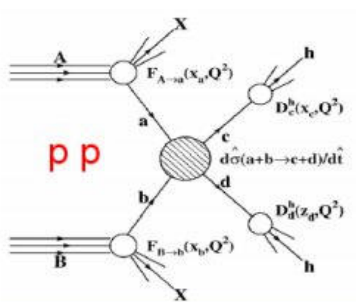


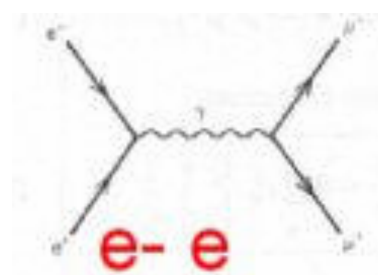
Hadron collider Sp$\bar{p}$S, $\sqrt{s}$=540 GeV, $W^{+/-}$ and Z^0 discovery

Lepton collider LEP, $\sqrt{s}_{max}$=209 GeV, precision measurements of Z^0 decay width



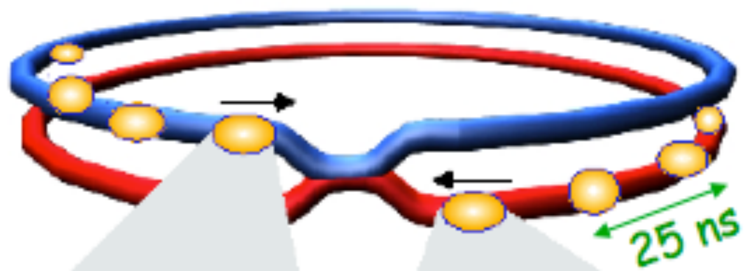
p p





Hadron versus lepton,
Linear versus circular colliders

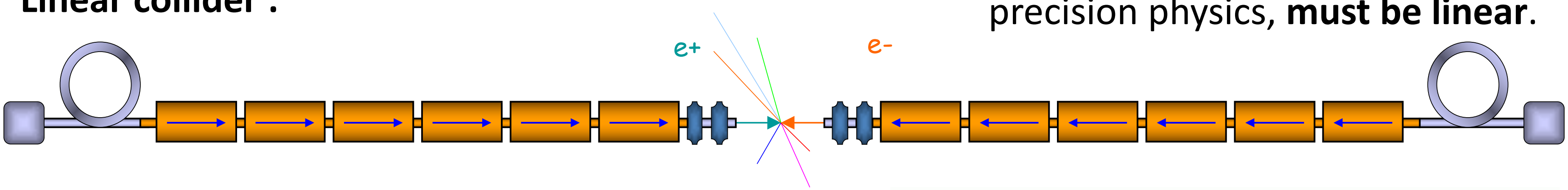
Circular collider :



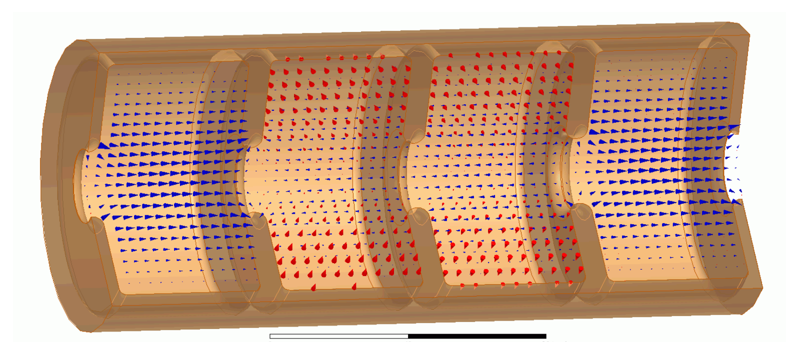
$$P_e = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

Due **to synchrotron radiation**, a TeV-scale electron-positron collider, for precision physics, **must be linear**.

Linear collider :

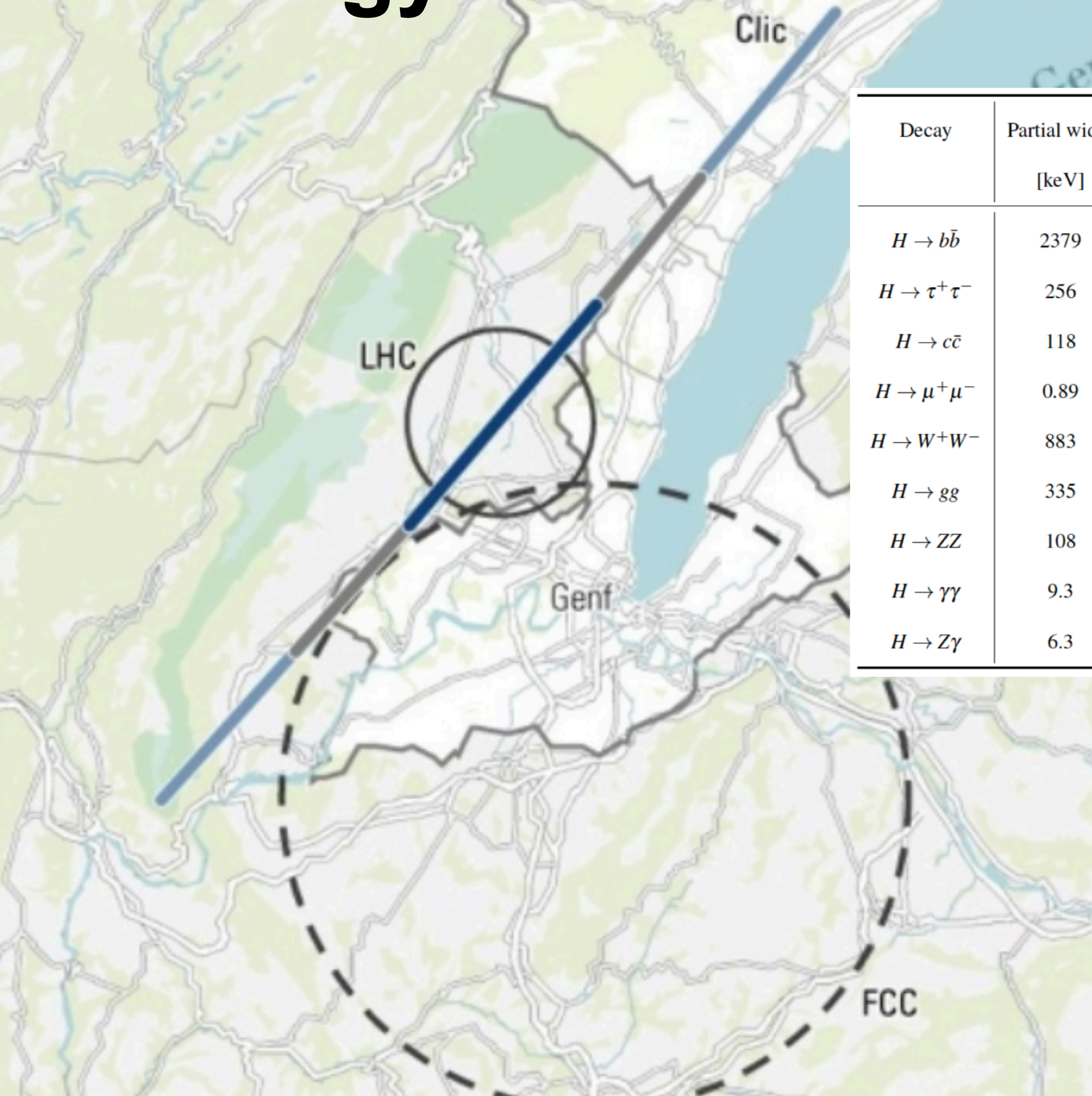


Length of a linear collider: Each cavity accelerates each bunch only once. Collider length is driven by how large electric field can be sustained in a metallic cavity.

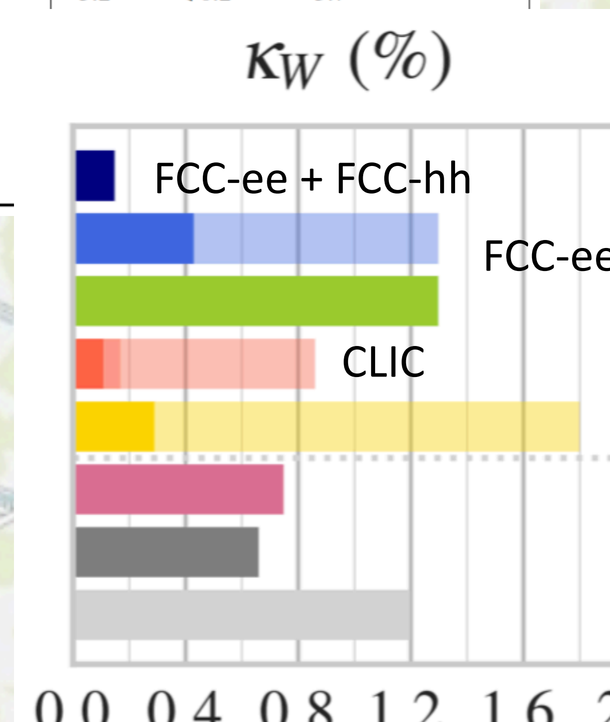


Electromagnetic field break down :
Limits acceleration to **10 - 100 MV/m**

The energy frontier: what to build nex



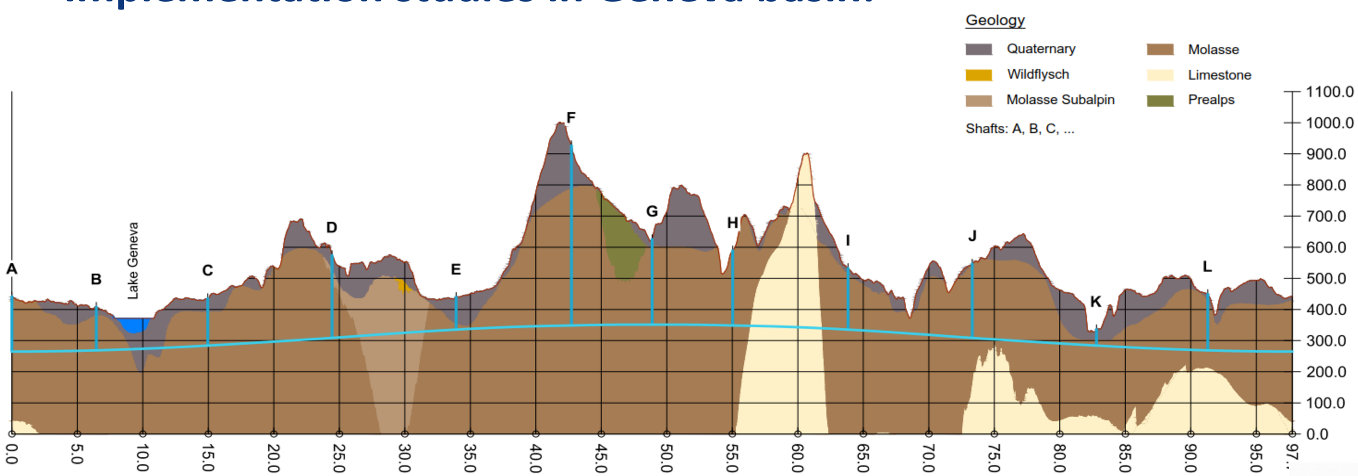
Decay	Partial width [keV]	current unc. $\Delta\Gamma/\Gamma$ [%] $\mathrm{Th_{Intr}}$	$\mathrm{Th_{Par}}(m_q)$	$\mathrm{Th_{Par}}(\alpha_s)$	$\mathrm{Th_{Par}}(m_H)$
$H \to b\bar{b}$	2379	< 0.4	1.4	0.4	–
$H \to \tau^+\tau^-$	256	< 0.3	–	–	–
$H \to c\bar{c}$	118	< 0.4	4.0	0.4	–
$H \to \mu^+\mu^-$	0.89	< 0.3	–	–	–
$H \to W^+W^-$	883	0.5	–	–	2.6
$H \to gg$	335	3.2	< 0.2	3.7	–
$H \to ZZ$	108				
$H \to \gamma\gamma$	9.3				
$H \to Z\gamma$	6.3				

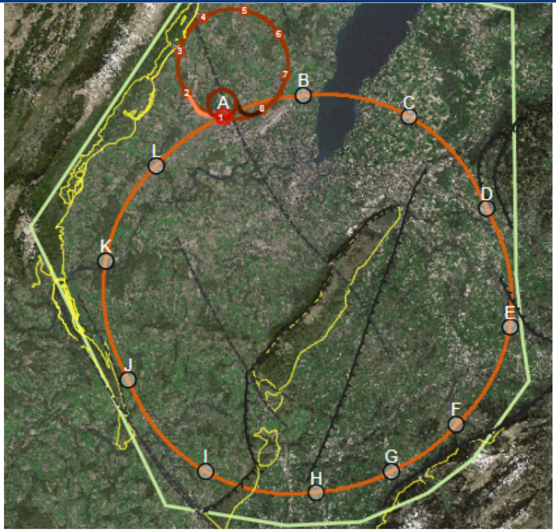


The Future Circular Collider

FCC integrated program
inspired by succesful LEP – LHC programs at CERN

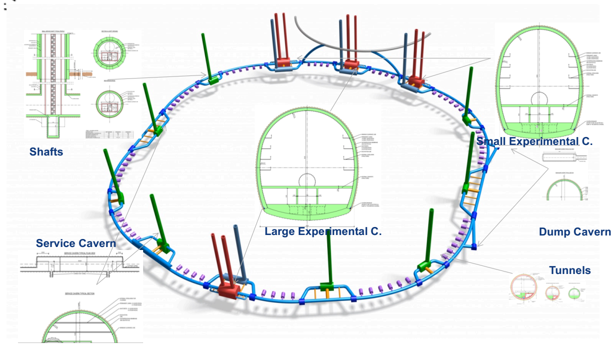
Implementation studies in Geneva basin:





baseline position was established considering:

- minimum risk for construction, fastest and cheapest construction
- efficient connection to CERN accelerator complex

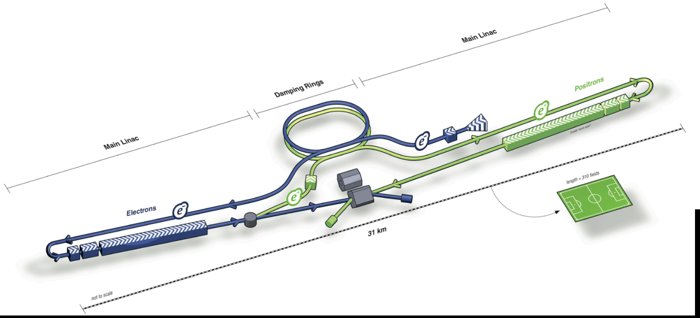


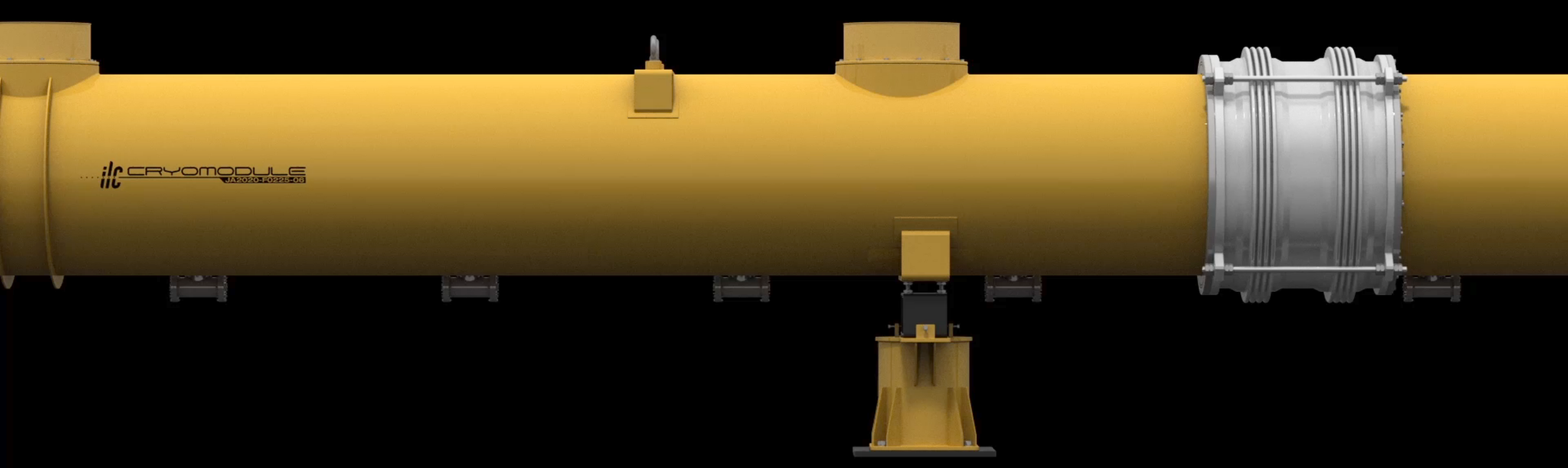
- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

Up 100 TeV protons, with 16 T Nb3Sn magnets (time scale ~ 40 years)

Up to 365 GeV electrons-positron collisions (time scale ~ 15 years)

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



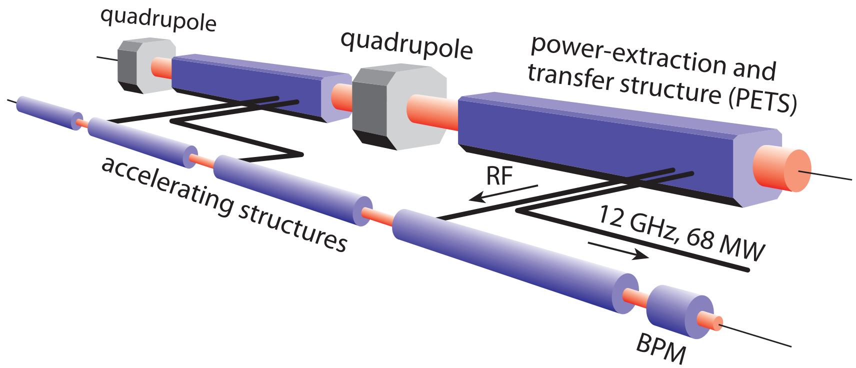


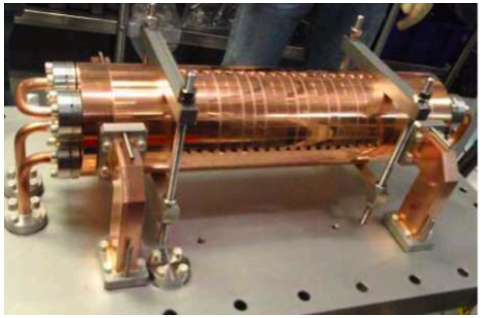
At some point cost and practical considerations will limit the size of future colliders.

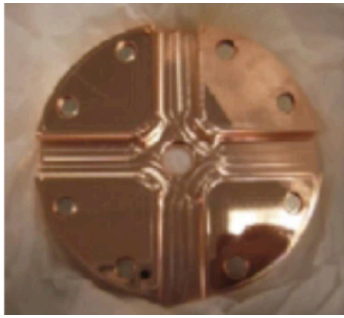
Linear Collider Projects

The Compact Linear Collider, CLIC

Main linac technology: two-beam scheme**. Normal conducting Cu RF 12 Ghz TW cavities**, **100 MV/m**. Nominal design for $\mathbf{E_{CM}}$ **= 3 TeV, 50 km** (375 GeV to 3 TeV)

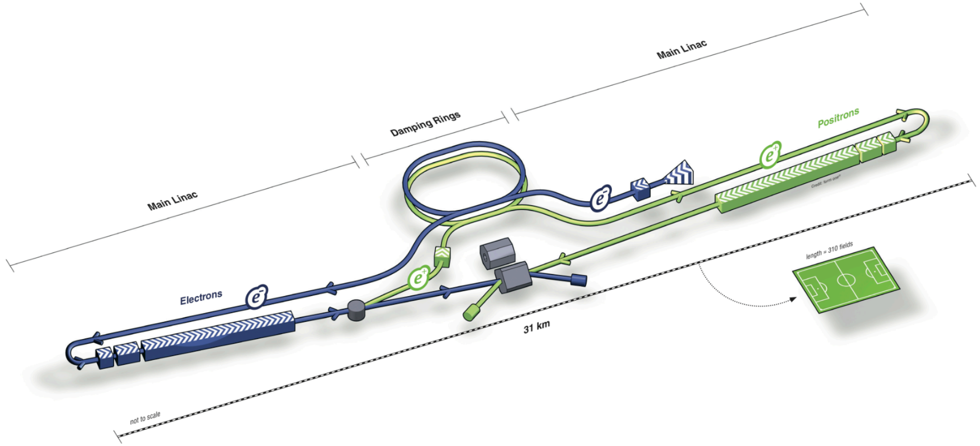


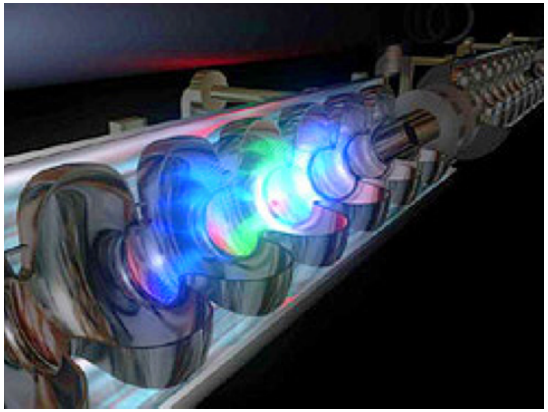




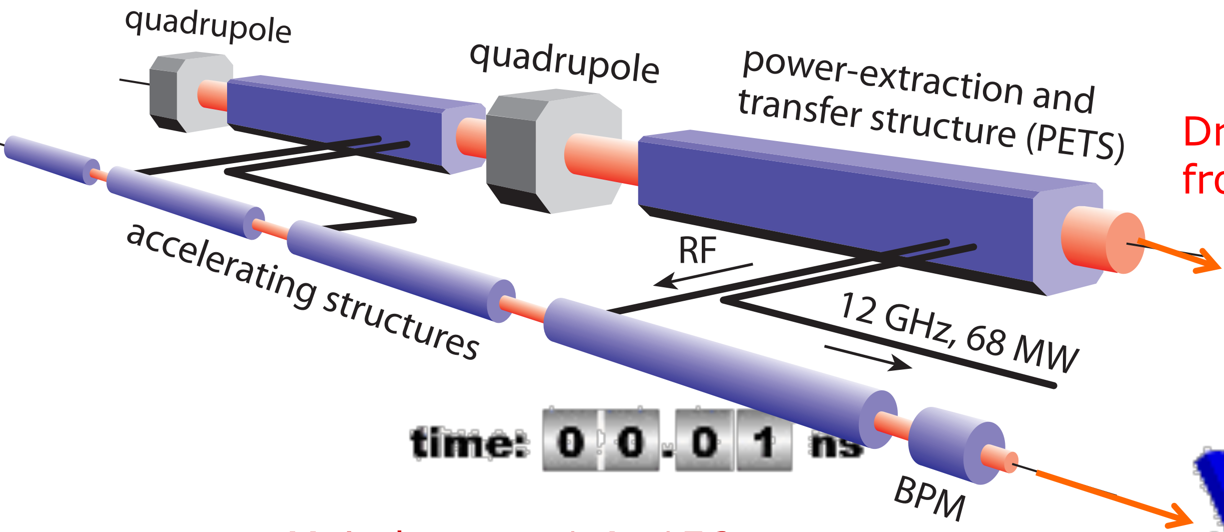
The International Linear Collider, ILC

Main linac technology: **super conducting RF 1.3 GHz SW cavities**, **31.5 MV/m**
Nominal design for $\mathbf{E_{CM}}$ **= 0.5 TeV, 31 km** (250 GeV to 1 TeV)



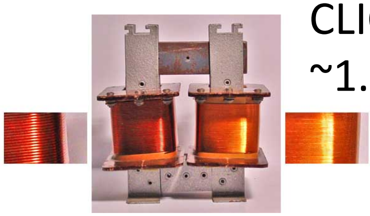


The CLIC Two-Beam scheme

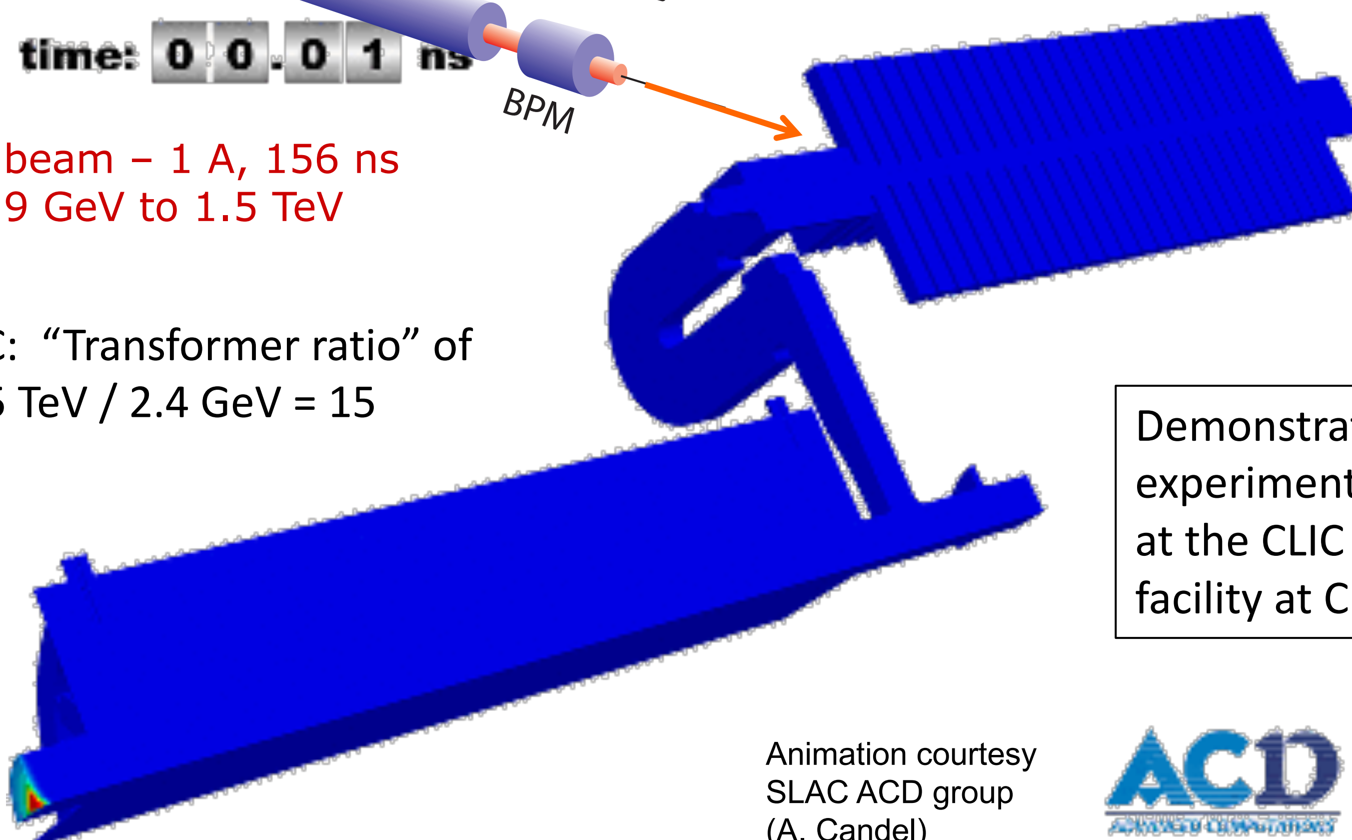


Drive beam - 101 A, 240 ns
from 2.4 GeV to 240 MeV

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



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



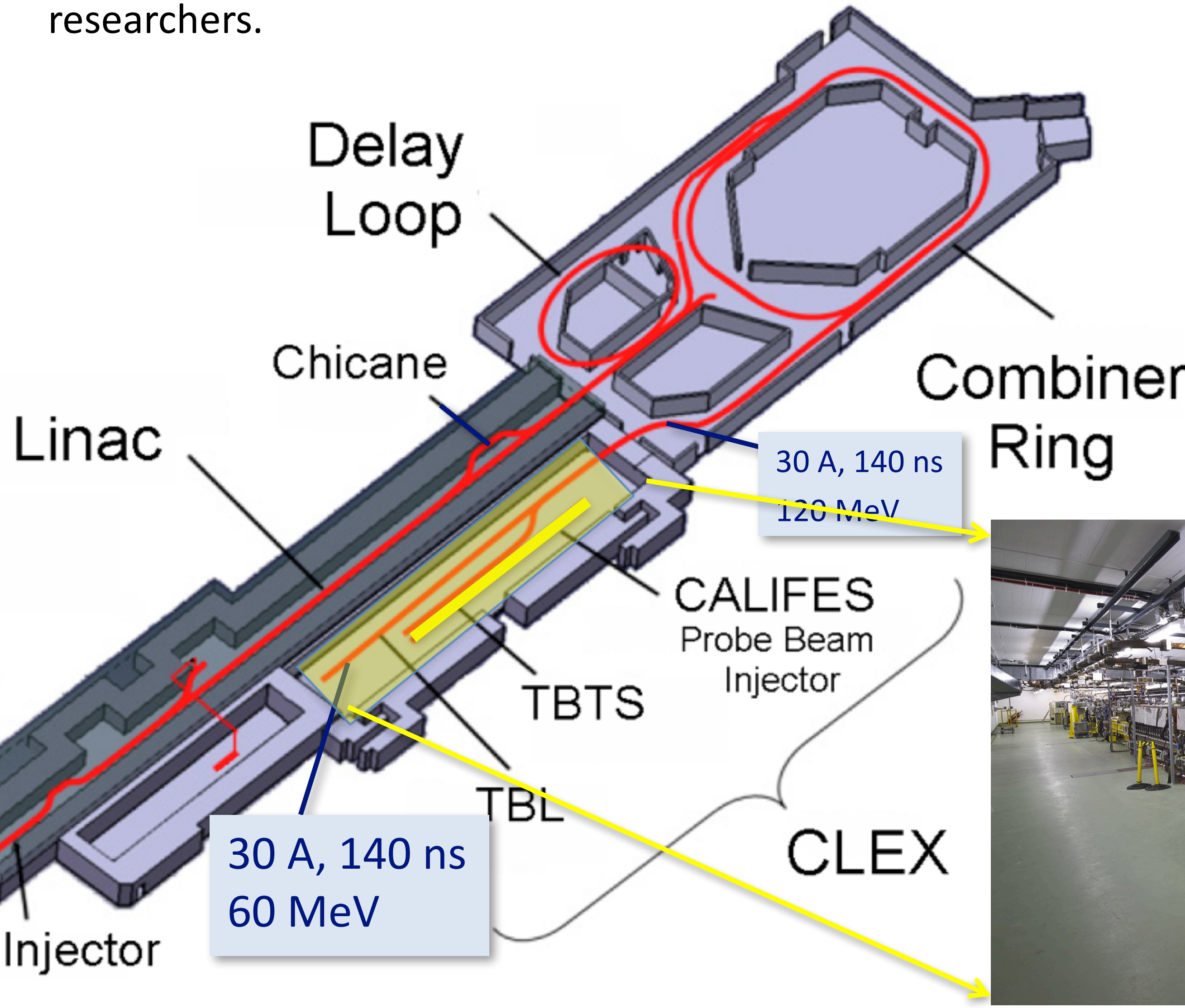
Demonstrated experimentally at the CLIC Test facility at CERN.

Animation courtesy
SLAC ACD group
(A. Candel)

CLIC Test Facility and CLEAR

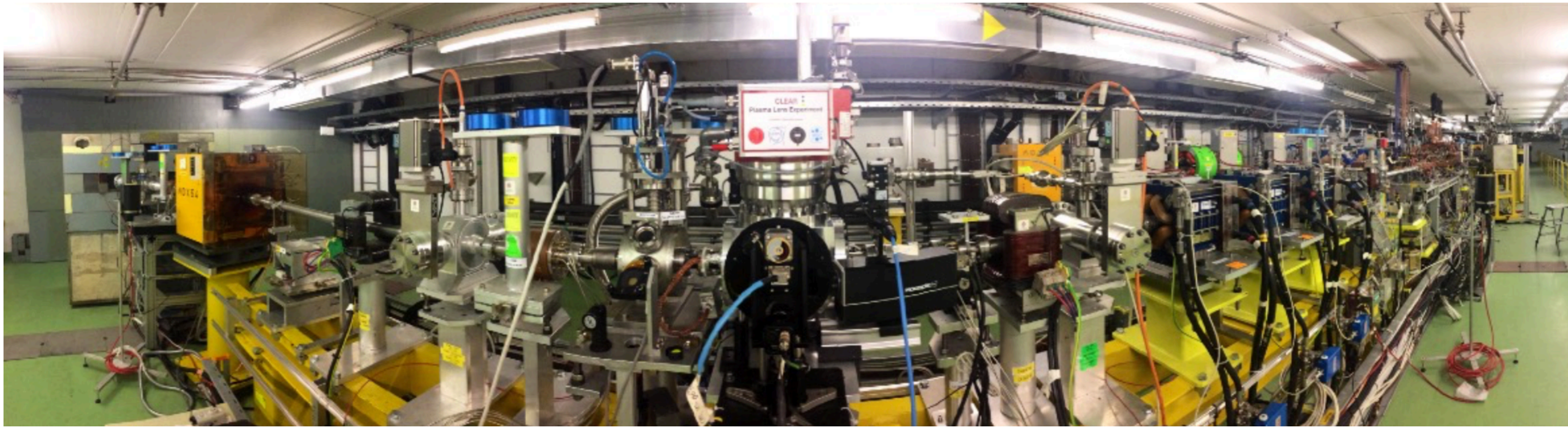
Test beam facility at CERN.
Research peformed by Oslo students and Oslo researchers.

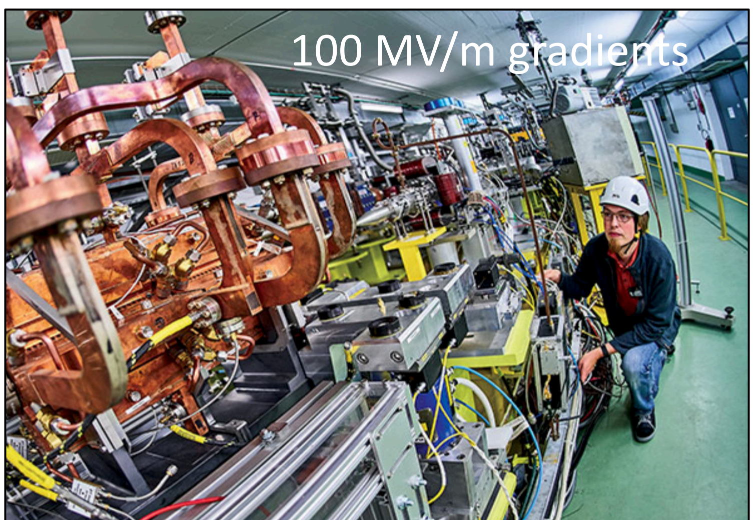
CLEAR consists of the experimental hall, CLEX, housing the 200 MeV S-band electron CALIFES linac.

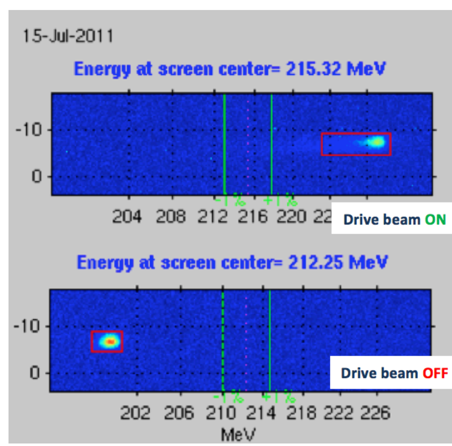


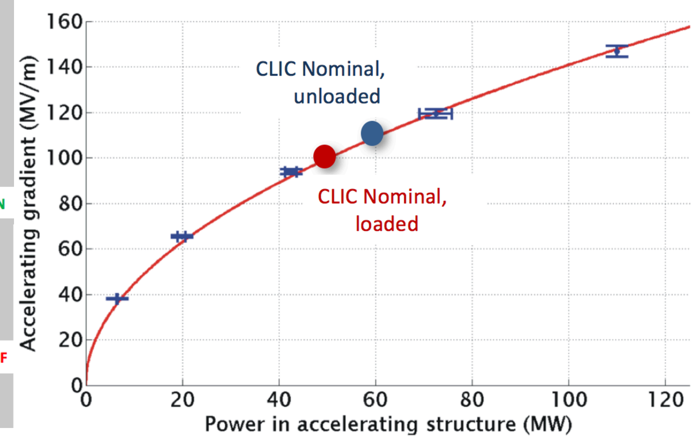
FI@UiO research

Experiments at the CLIC test-facility





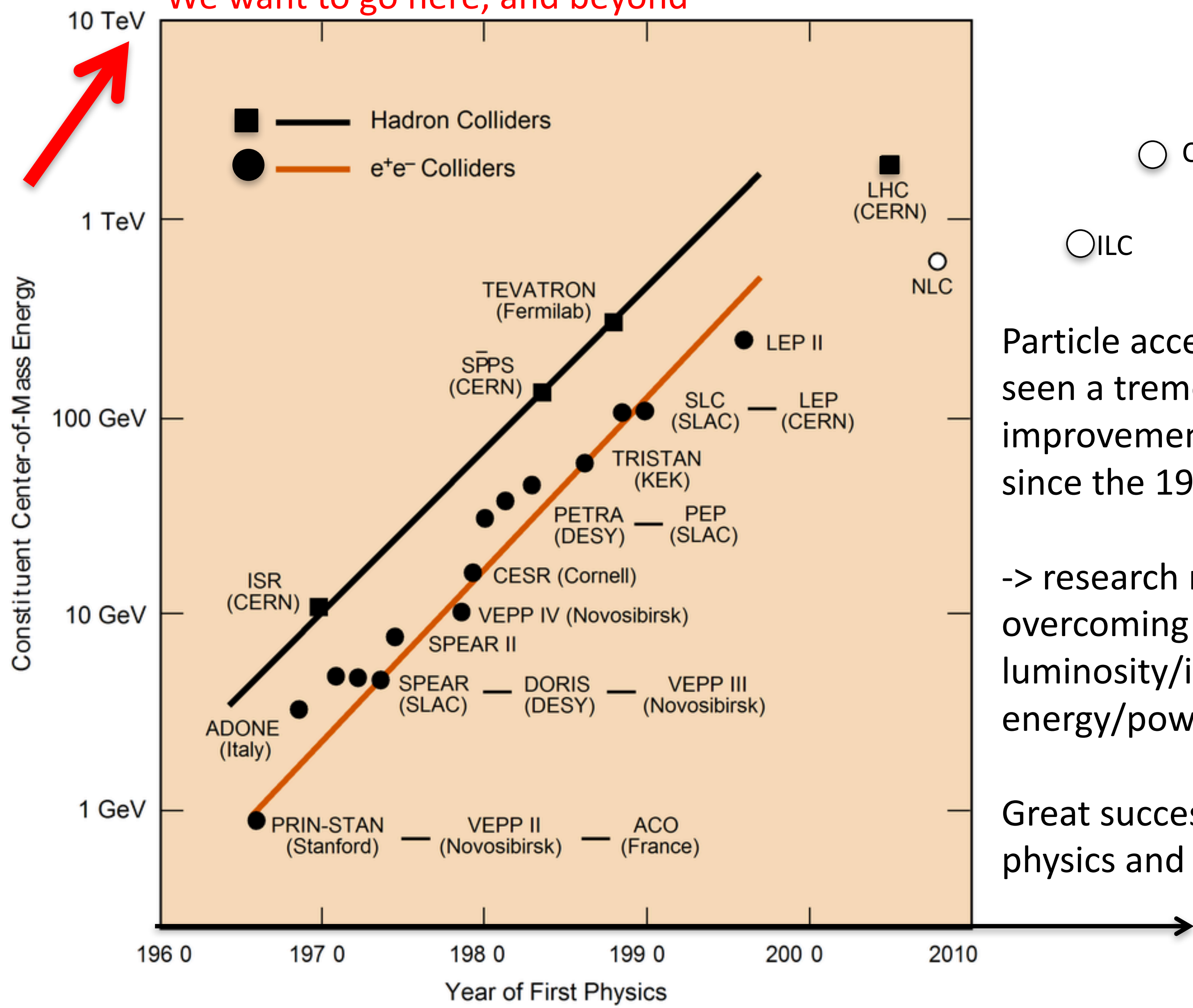




Novel Accelerator Concept:
- plasmas acceleration
- **muon** colliders

Particle collider Livingstone plot

We want to go here, and beyond



Particle accelerators have seen a tremendous improvement in performance since the 1960s.

-> research required to overcoming limits in luminosity/intensity and energy/power.

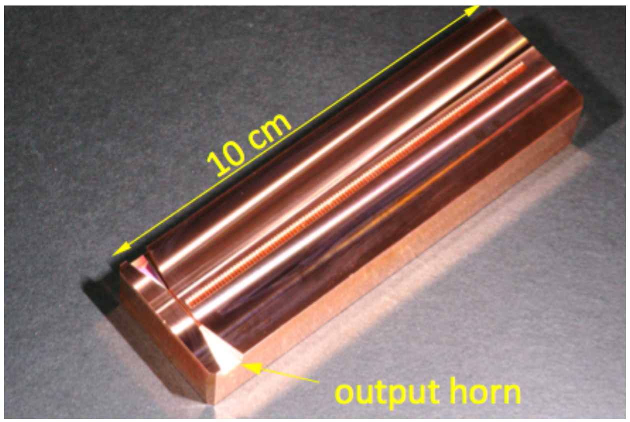
Great success of accelerator physics and technology.

Novel accelerator research

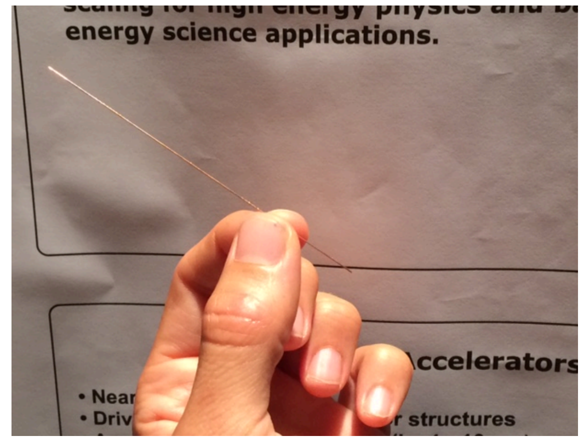
Cutting edge accelerator physics research, with the objective of **overcoming limitations** of conventional accelerator technology.

Very high frequency normal conducting rf structures (~100 GHz to ~THz)

116 GHz structure (SLAC)



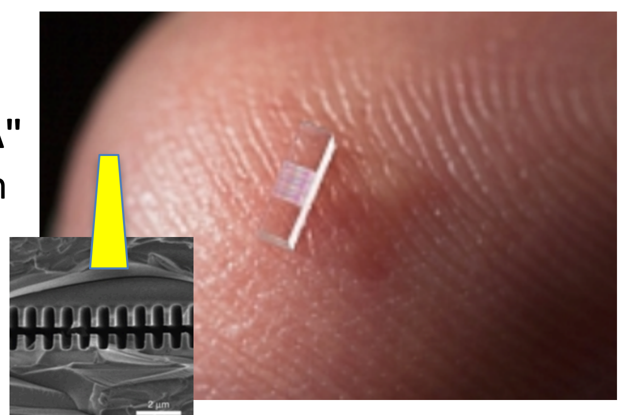
Dielectric structures



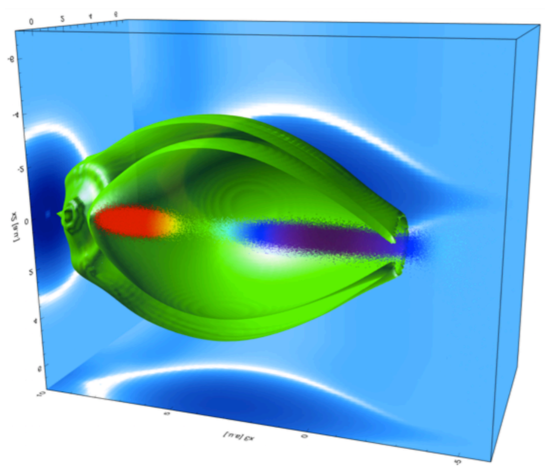
SiO_2

~1.0 THz, 1-10GV/m

Laser based acceleration "DLA"
Several 100 MV/m demonstrated (SLAC)



Feed of laser beam into Si structure



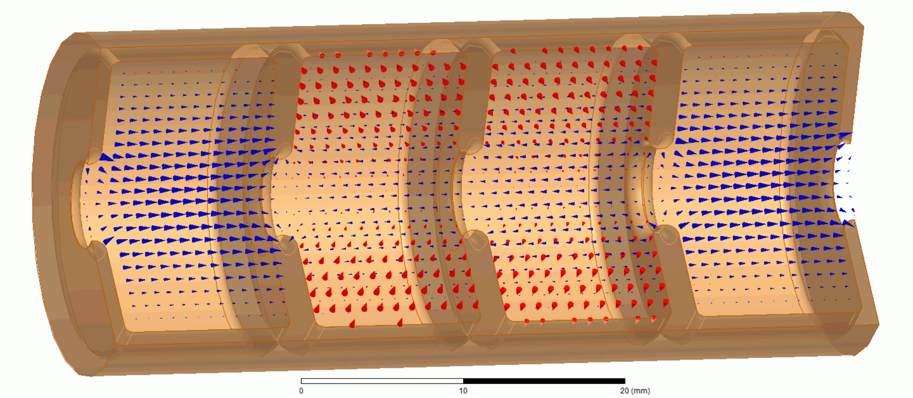
Plasma wakefield acceleration

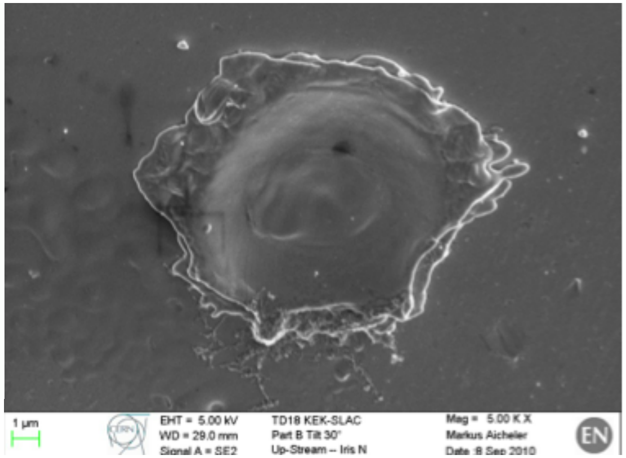
The topic here.

Breakdown limits and plasma

In **metallic structures** : break down of the surfaces, creating electric discharge. Field cannot be sustained. **Current practical limit (CLIC): order of 100 MV/m gradients**..

Break down of field *limits the gradient.*

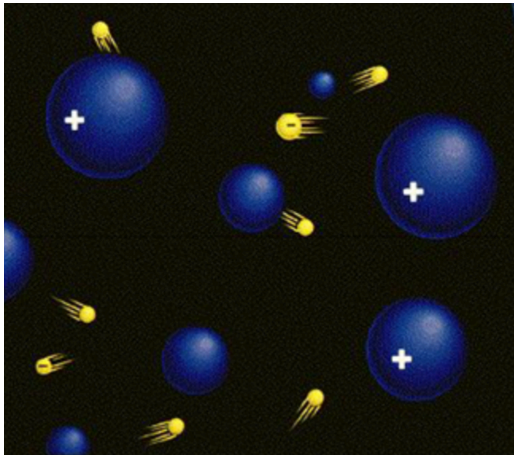




Alternative to high fields in vacuum: high fields in plasmas:

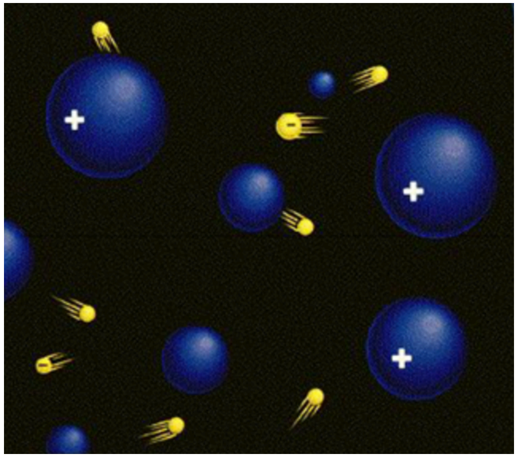
collection of free ions and electrons.

- Plasmas of a large range of densities can be produced. Fields scales with density. **Very high fields can be generated**.
- Material is already broken down. The plasma can **sustain the very high fields.**



Gauss law : estimate fields in a plasma wave

Assume that the **plasma electrons are pushed out** of a small volume of neutral plasma, with plasma density $n_0 = n_e = n_{ion}$:



Scale of electrical fields (1D) :

Gauss' law:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \sim \frac{e n_{\text{ions}}}{\varepsilon_0} \sim \frac{e n_0}{\varepsilon_0}$$

Assume wave solutions:

$$\mathbf{E} \sim \mathbf{E_0} \exp(-i\omega_p/cz)$$

Apply Gauss' law:

$$\frac{e n_0}{\varepsilon_0} = E_0 \frac{\omega_p}{c} \Rightarrow \boxed{E_{WB} = \frac{e c n_0}{\varepsilon \omega_{0p}}} \sim \sqrt{n_0}$$

Field scale, E_{WB}
"wave breaking field"

Plasma electron frequency :

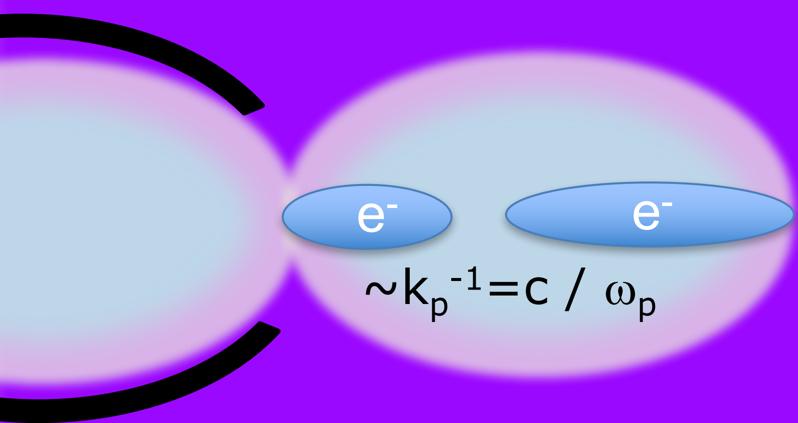
$$\omega_p = \sqrt{\frac{n_0 e^2}{m_e \varepsilon_0}}$$

Typical plasma density, available by many types of plasma source :

$\mathbf{n_0}$ = 1e17/cm3 : $\mathbf{E_{WB}}$ = **30 GV/m**

Plasma Wakefield acceleration

Typical scales :



$\mathbf{n_0}$ ~ 10^{14}-10^{18}/cm3

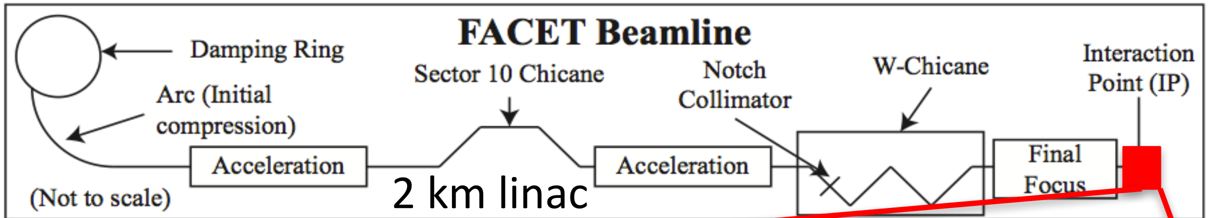
Fields: E_{WB} ~ **1-100 GV/m** ~ $\sqrt{n_0}$

Length : $k_p^{-1} = \lambda_p/2\pi$ ~ **5-500 μm** ~ $\sqrt{n_0}$

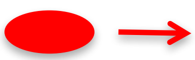
Focusing : $F_r = \frac{1}{2} e n_0 r/\varepsilon_0 c$ ~ **0.03-30 MT/m**

Ideas of **100s GV/m** electric fields in plasma, using 10^{18} W/cm^2 lasers: 1979 **T.Tajima and J.M.Dawson** (UCLA), Laser Electron Accelerator, Phys. Rev. Lett. 43, 267–270 (1979).
Using partice beams as drivers: P. **Chen et al**. Phys. Rev. Lett. 54, 693–696 (1985)

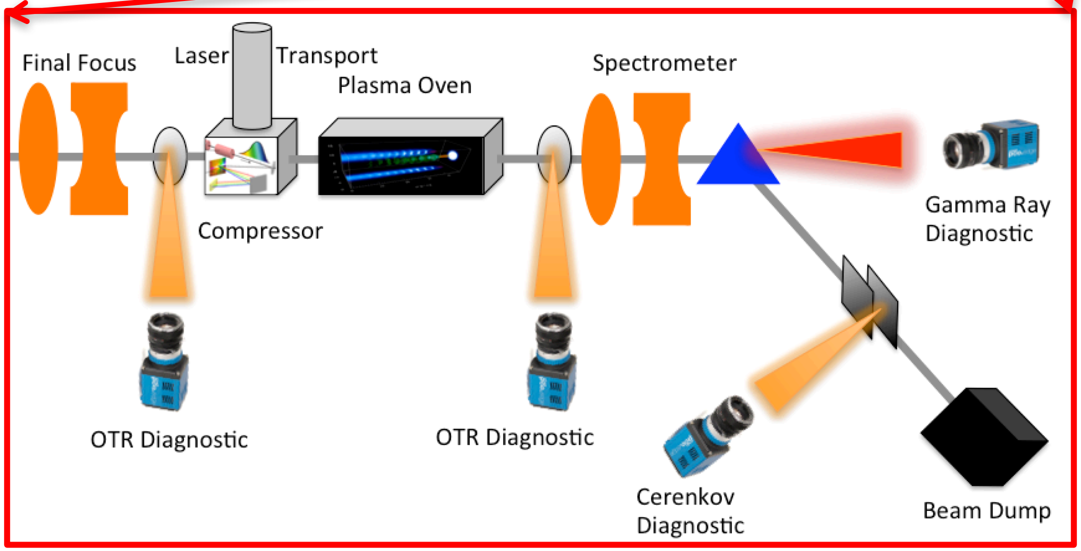
Development of novel accelerators



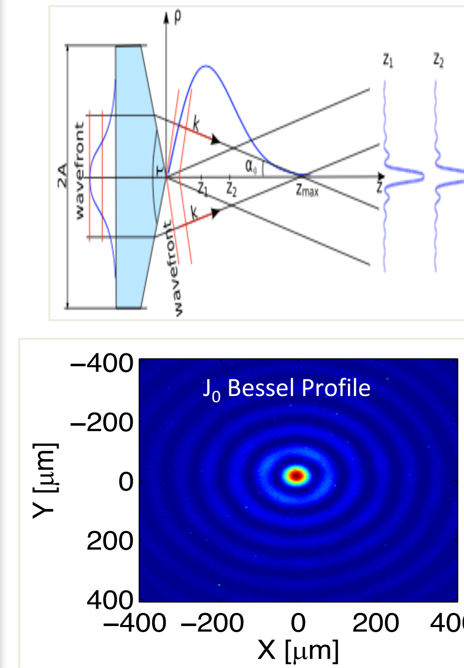
Electron, or Positron bunch



E = 20 GeV
Q = 3 nC
$\sigma_{z,min}$ = 20 um
$\sigma_{r,min}$ = 20 um
ε_n ~ 100 um

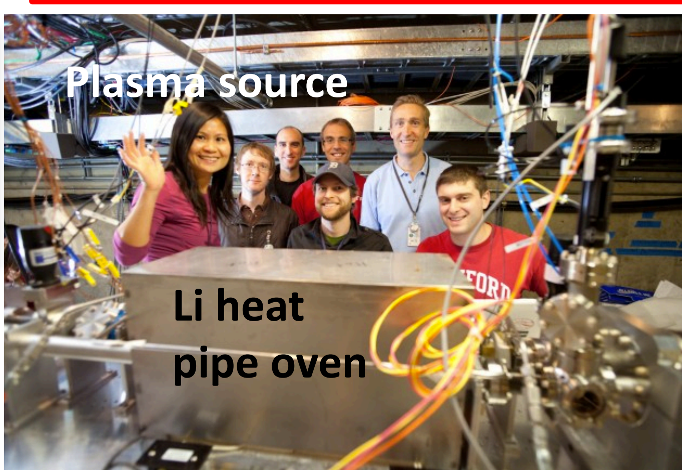


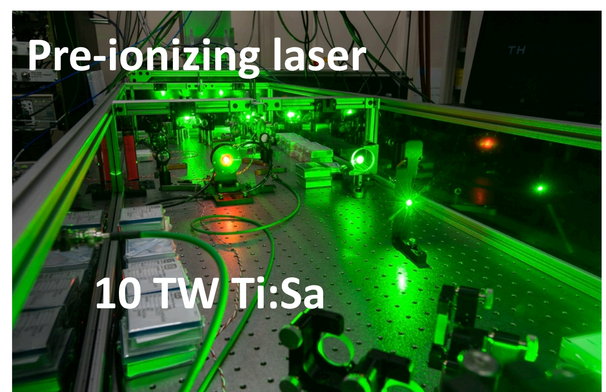
Laser axicon focusing



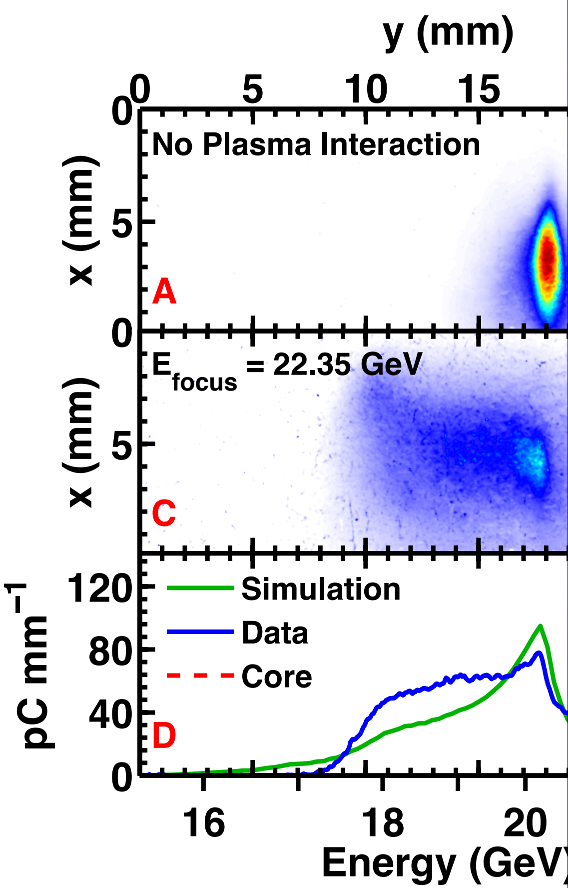
Plasma densities, n_0, 10^{16}-10^{17}cm^{-3}

~ 1 m length





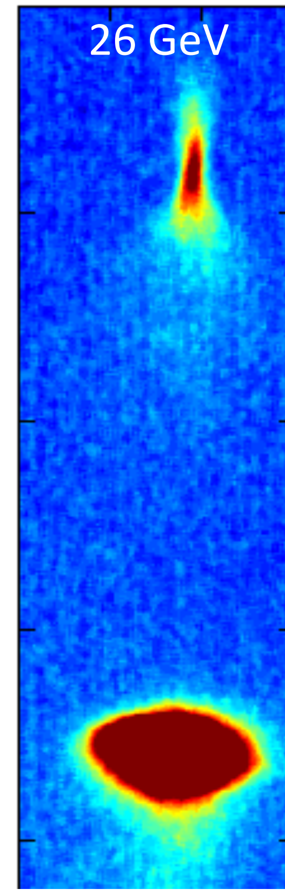
FACET two-bunch results



2013

n in
d Li
sfer
3%).
in

1.3 m plasma



2014

M. Litos *et al.*, Nature **515**, 92 (2014)

Active plasma lenses

- Active plasma lenses consist of three main parts:
  - A **hollow capillary**, typically made from sapphire for durability
  - **Gas inlets** to fill the capillary with a low density gas (~mbar)
  - **Electrodes** on either side (upstream/downstream) to break down the gas and provide current.
- Works equally well for electrons and positrons

$$g = \frac{\partial B_\phi}{\partial r} = \frac{\mu_0 I_z}{2\pi R^2}$$

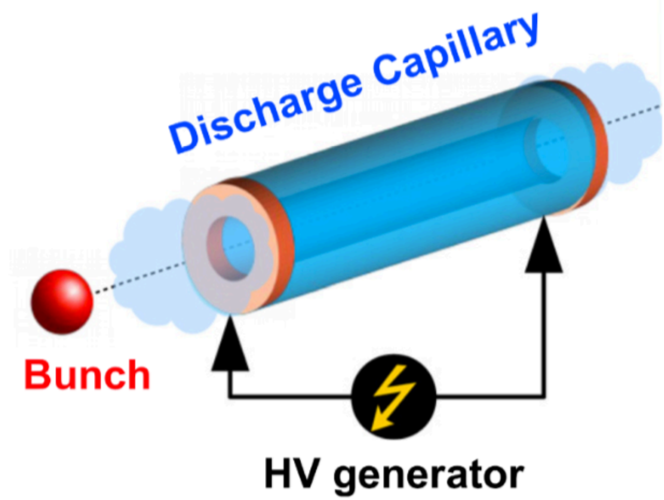


Image source: ***R. Pompili, Appl. Phys. Lett. 100 104101 (2017)***

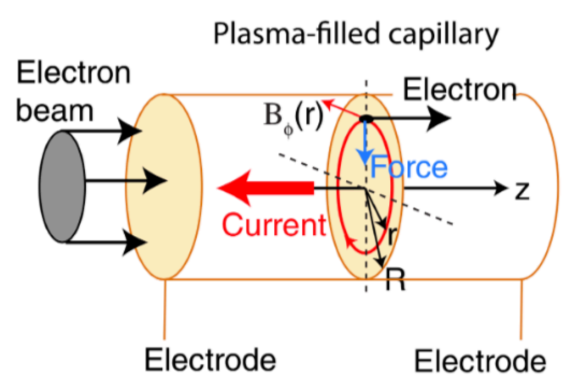


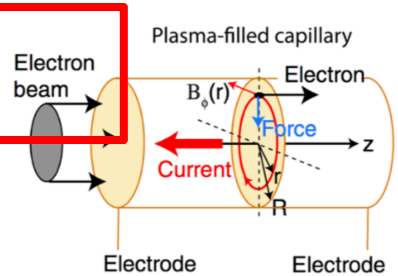
Image source: ***J. van Tilborg, Phys. Rev. Lett 115, 184802 (2015)***

The Oslo plasma lens experiment at CLEAR, CERN

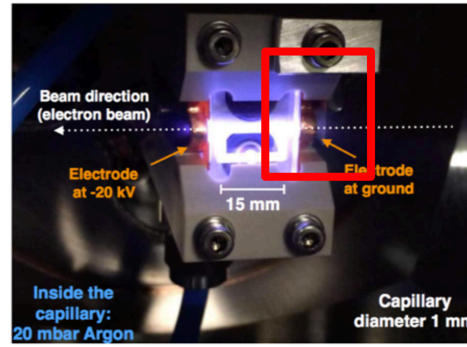
a) Normal conducting magnetic focusing quadrupole at the FACET high energy test facility

100 cm

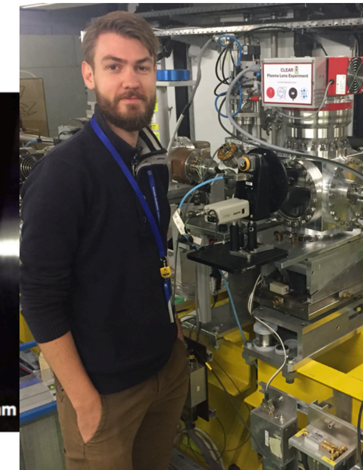
c) Principle of an active plasma lens

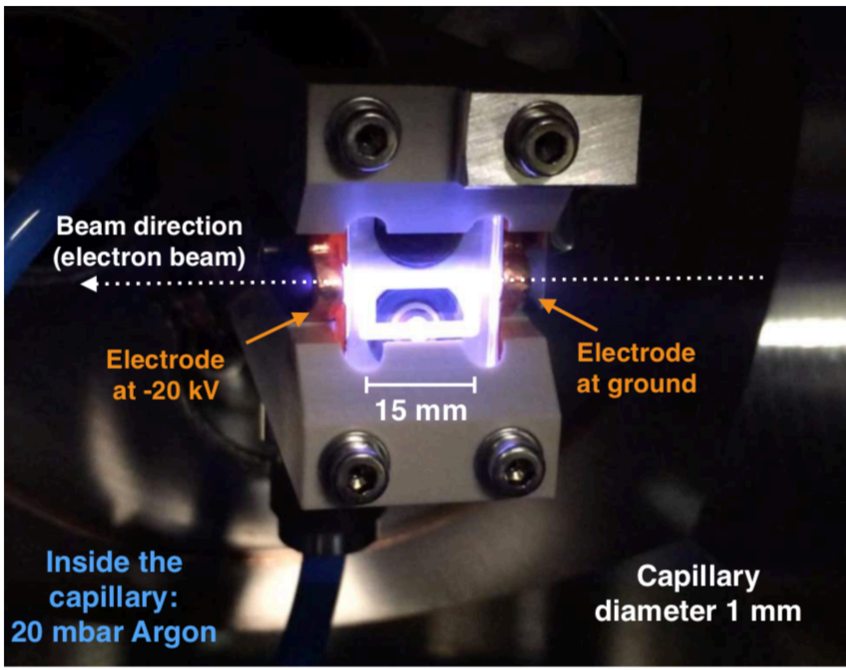


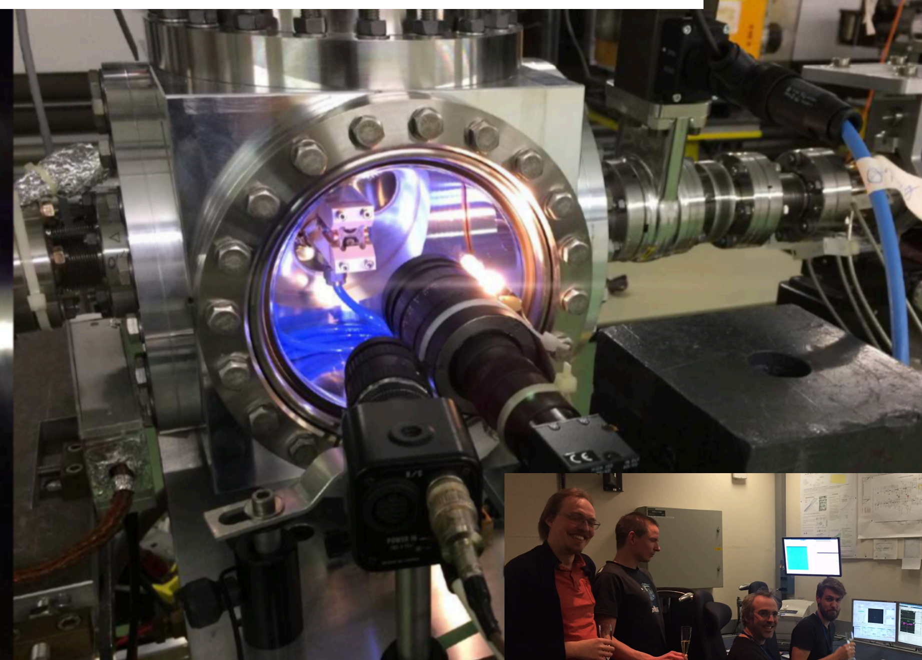
b) The Oslo active plasma lens focusing device

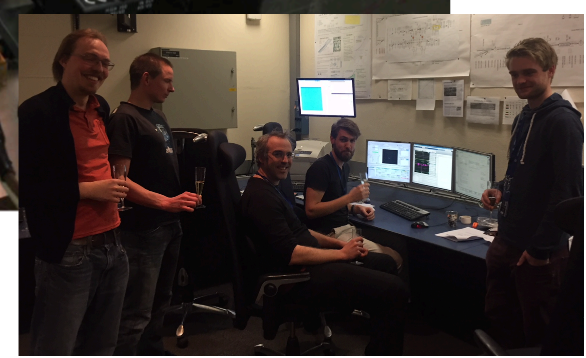


15 mm







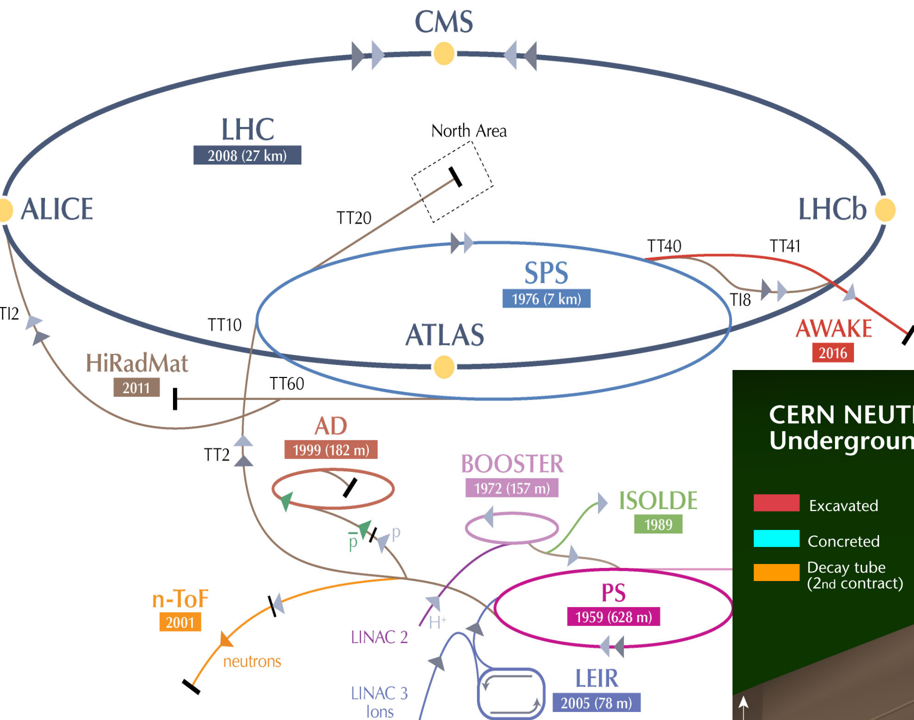


- An experiment to test the operation and characteristics of an active plasma lens.

FI@UiO research

AWAKE: proton driven plasma wakefield at CERN

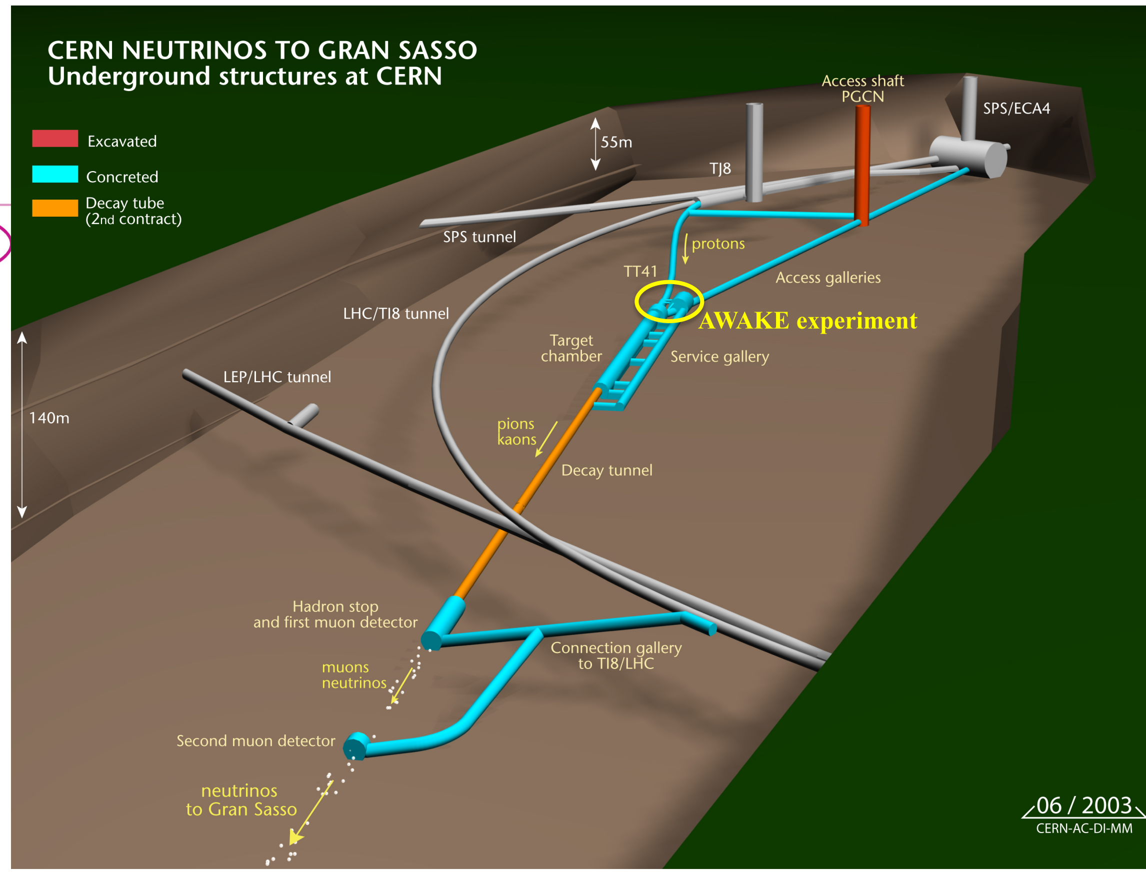
Department of Physics, UiO is member of AWAKE



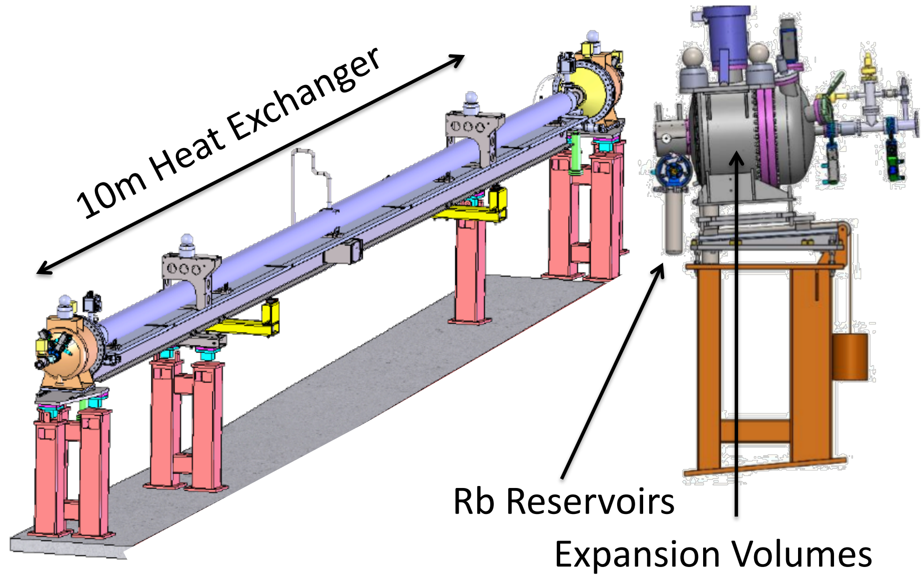
AWAKE is installed in

CNGS Facility (CERN Neutrinos to Gran Sasso)

→ CNGS physics program finished in 2012

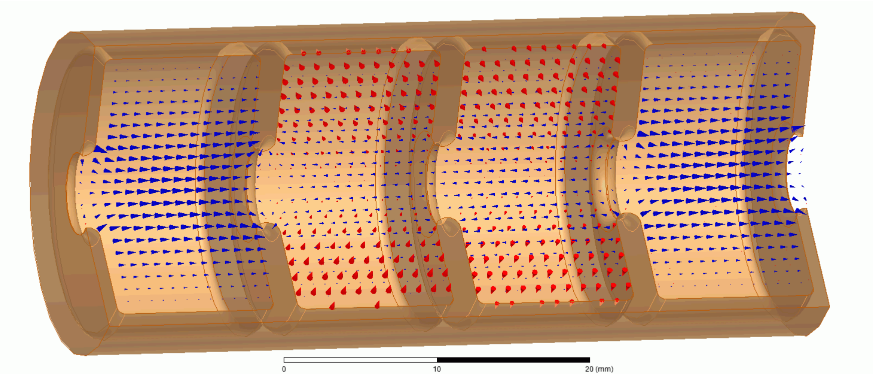


The AWAKE experiment



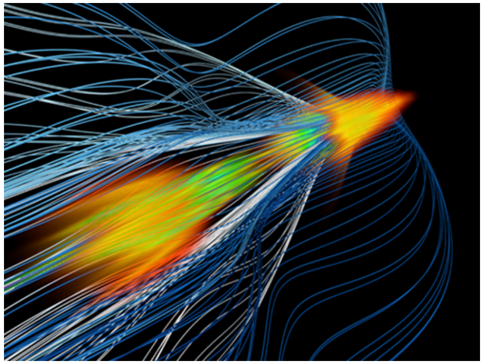
Summary

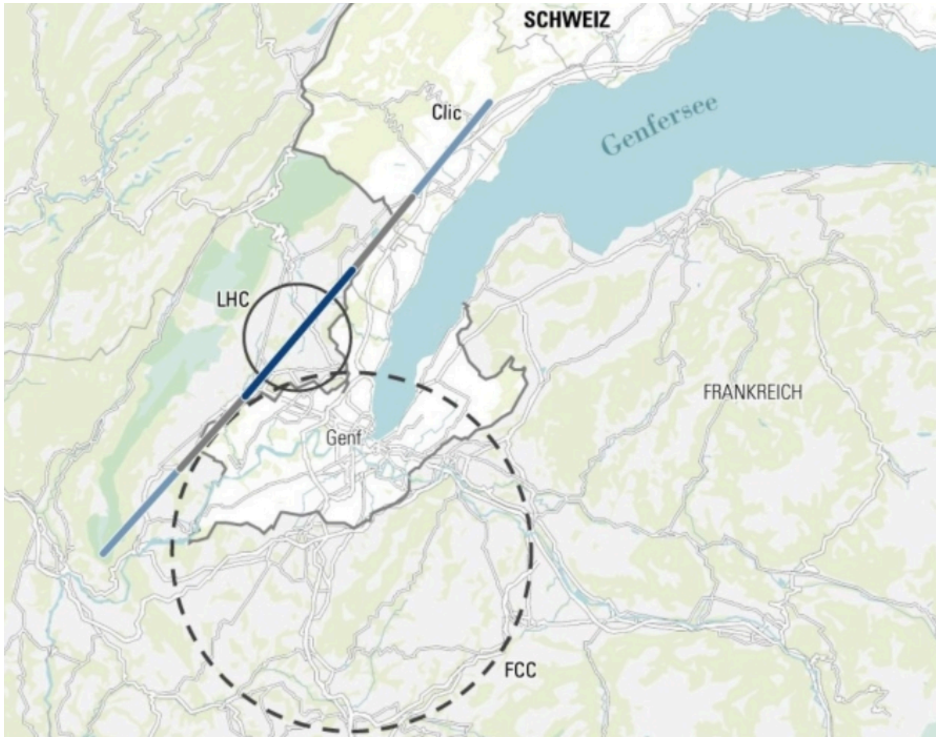
The compact linear collider, CLIC



CLIC 100 MV/m accelerating structure

Plasma wave with accelerating fields





Size of possible future particle colliders, compared to the LHC

Extra

Advanced accelerator movies

Two-bunch:
https://www.youtube.com/watch?v=N2lmtSk-rYE

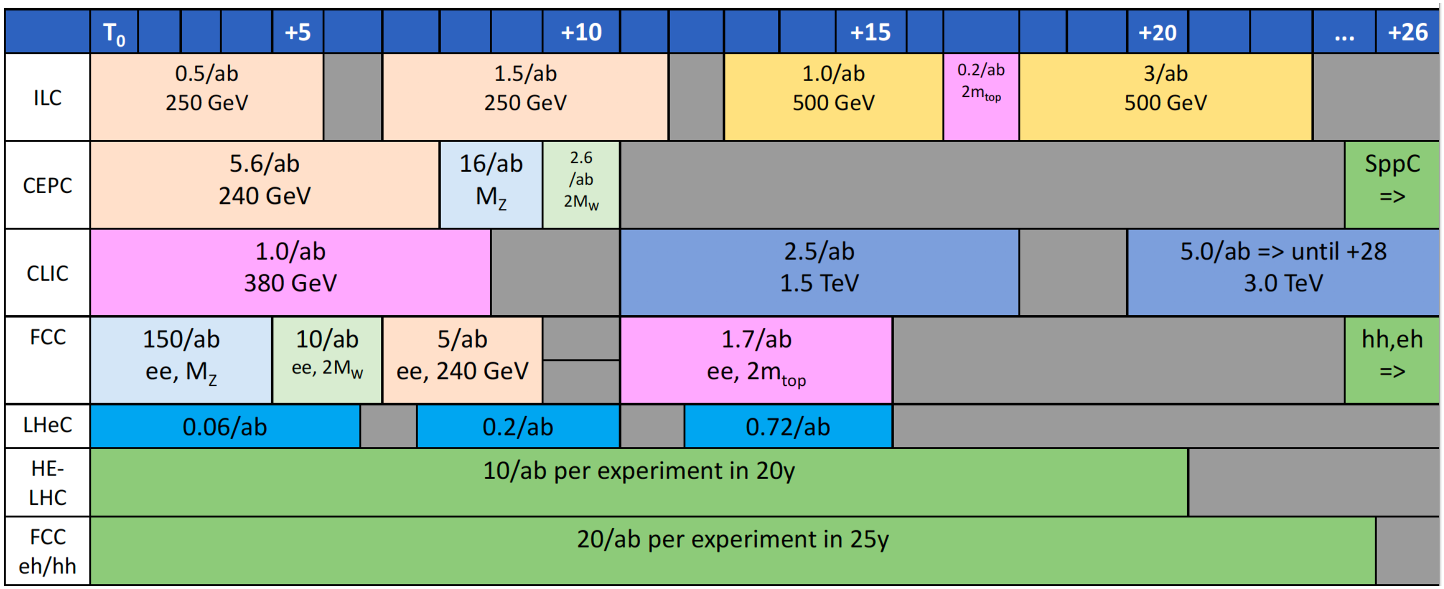
Positrons:
https://www.youtube.com/watch?v=LVXj5hRyP8s

Accelerator on a chip:
https://www.youtube.com/watch?v=V89qvy8whxY

AWAKE TEDX:
https://www.youtube.com/watch?v=5Ryp6UTCeUo

From "European Strategy Update" meetings (2019)

The energy frontier: what machine to build next



Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.