Particle accelerators

for High-Energy Physics

Norwegian Teachers at CERN
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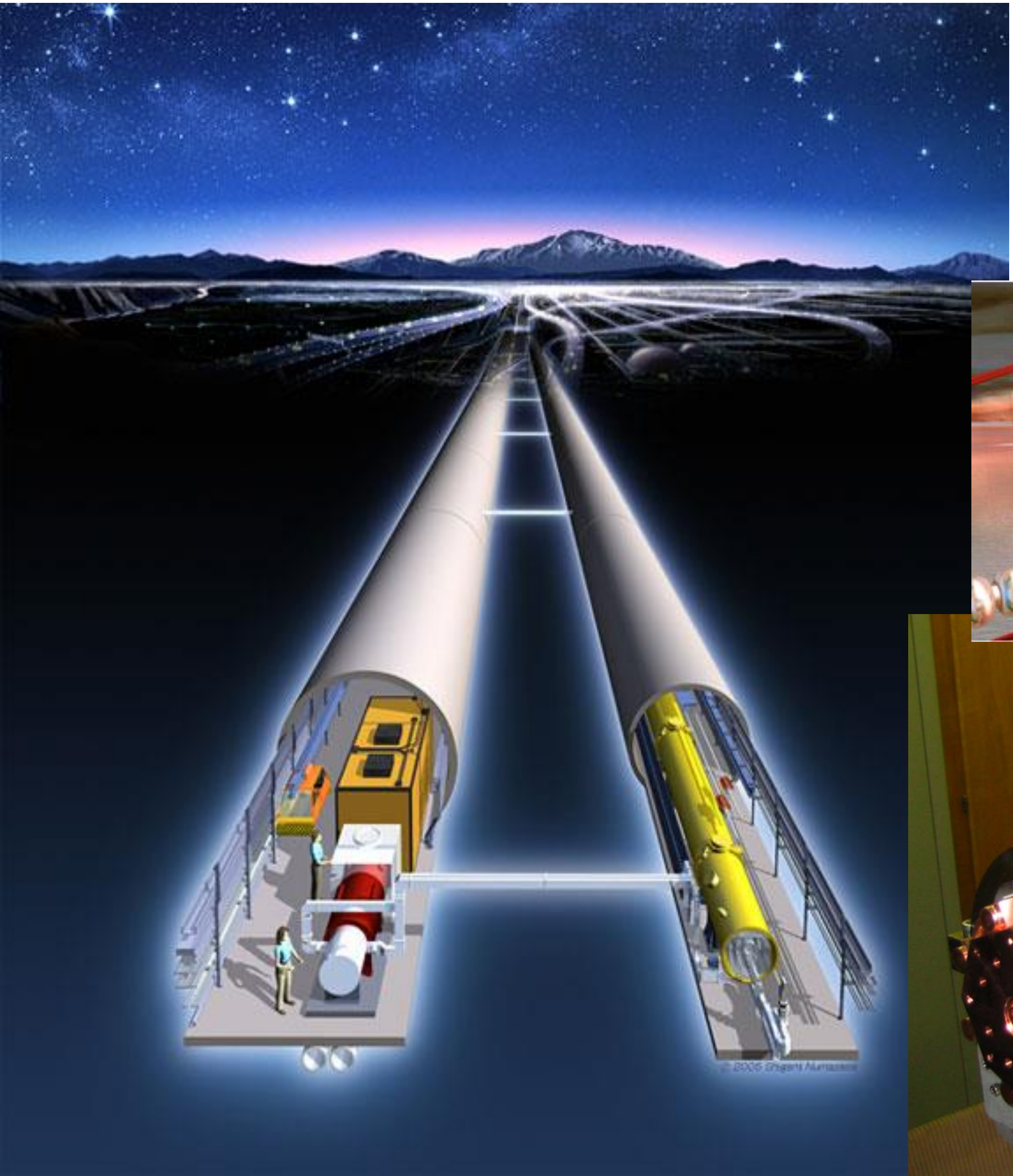
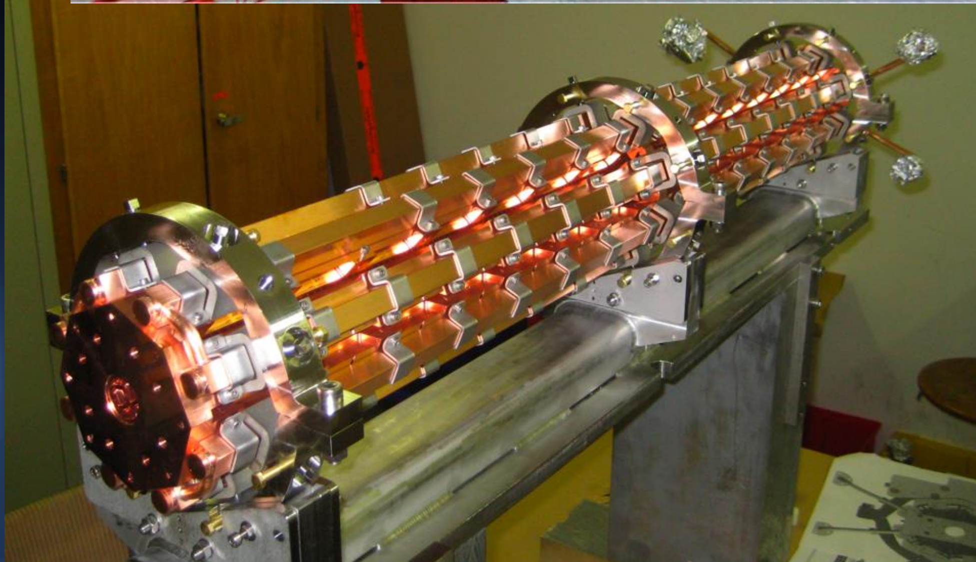
The 27 km LHC at CERN

Future colliders



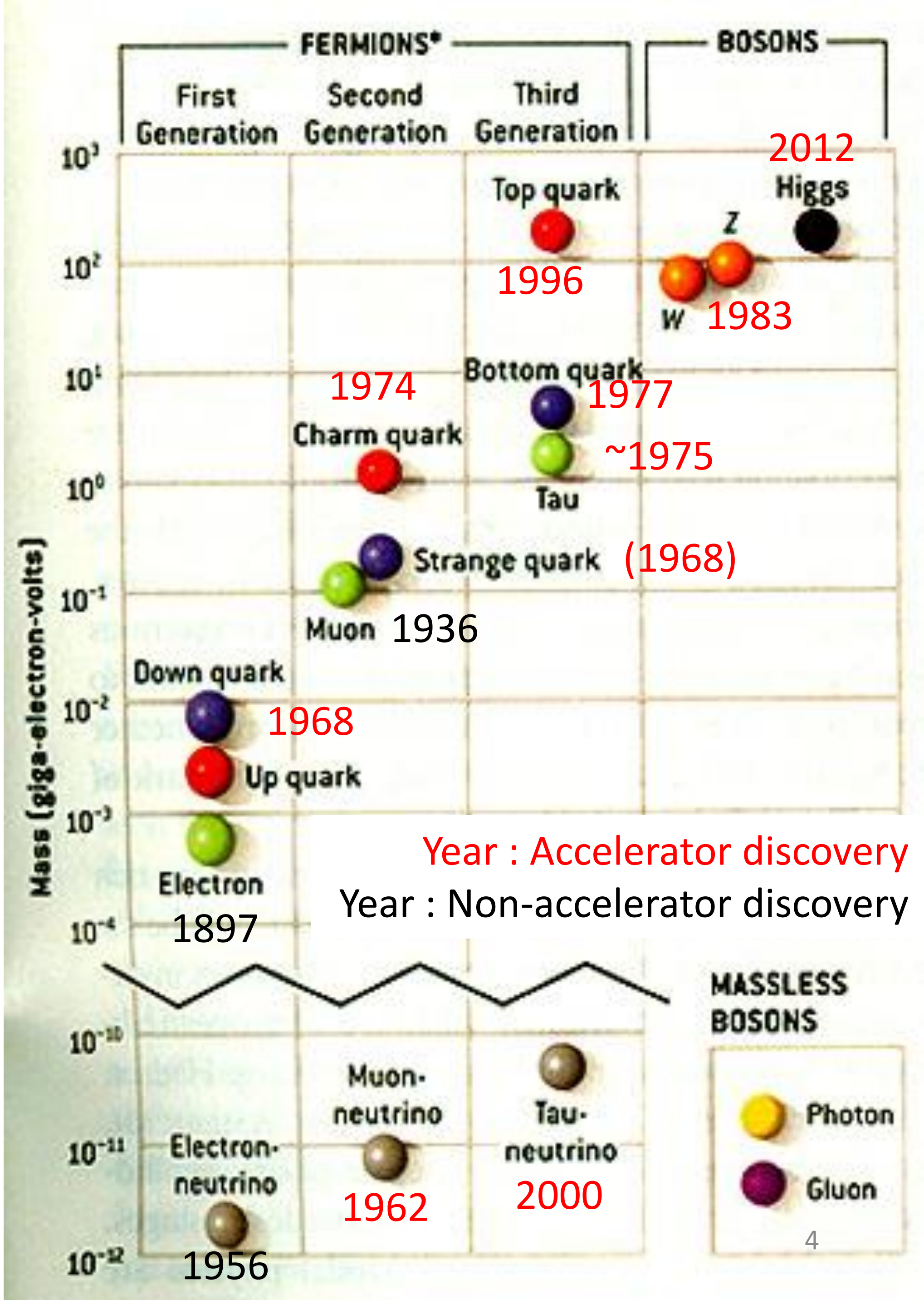
The next big thing? After LHC, high energy, high luminosity, Linear Colliders of several **10 km of length** have been proposed – **why?**



Particle accelerators

Most fundamental particles have been discovered by experiments using beams accelerated by a particle accelerator.

The discovery range has increased as particle accelerators have become more powerful.



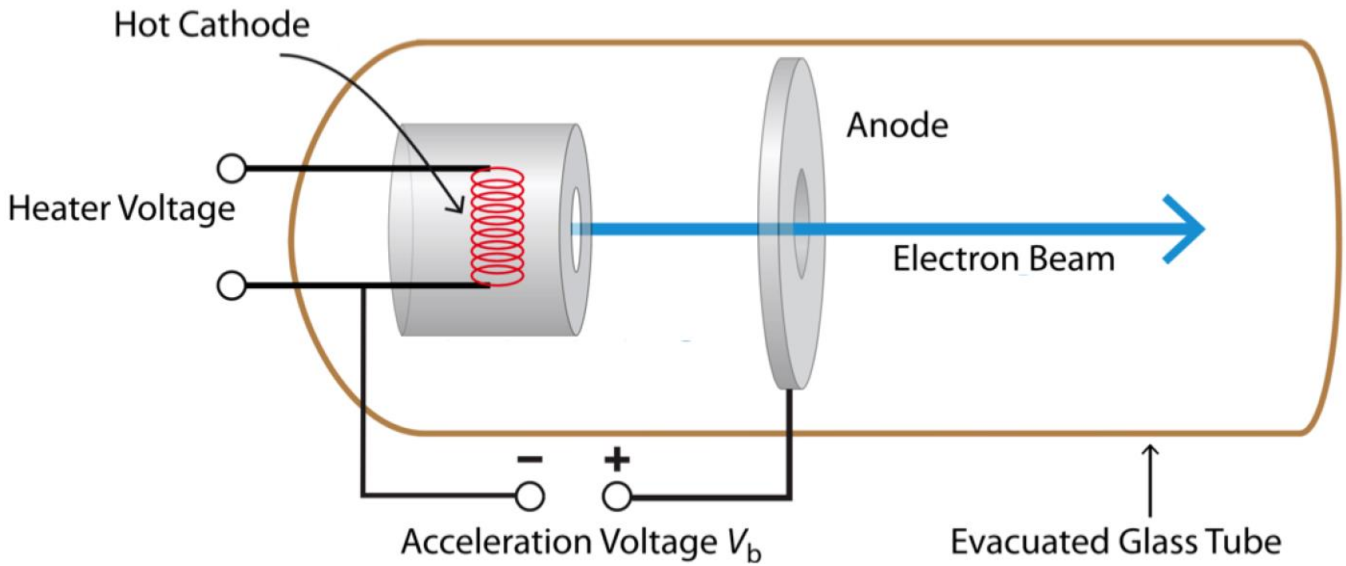
Today's topics

- Particle accelerator basics
- LHC
- Future linear colliders
- Novel accelerator technology

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)

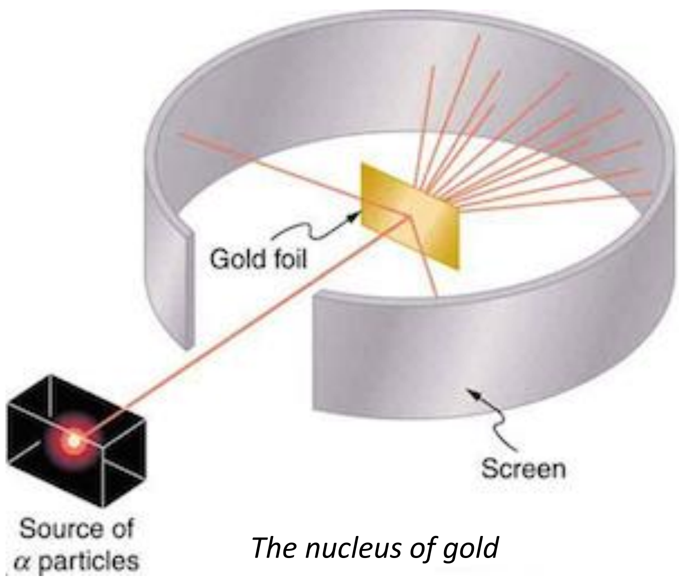


A simple way to make an electron accelerator: electrostatic acceleration with a cathode emitting electrons and an anode, at a higher potential, pulling the electrons towards it.

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

One hundred years back in time : the dawn of particle accelerators

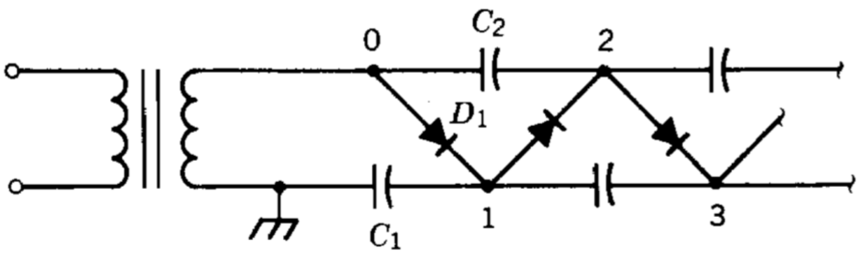
In 1909 E. Rutherford's team, in Manchester, shot alpha-particles from a radioactive source towards a gold foil. The scatter results were surprising. **To explore the tiny, very energetic particles are needed**.



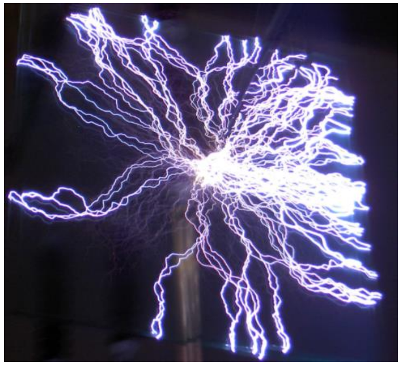
The nucleus of gold

..." 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)

Early 20th Century saw advances in acceleration techniques : multiple stage voltage build-up, for example by **Cockcroft-Walton** multipliers :



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



Cockroft Walton-type accelerator at Fermilab, IL, USA (750 kV)

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

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

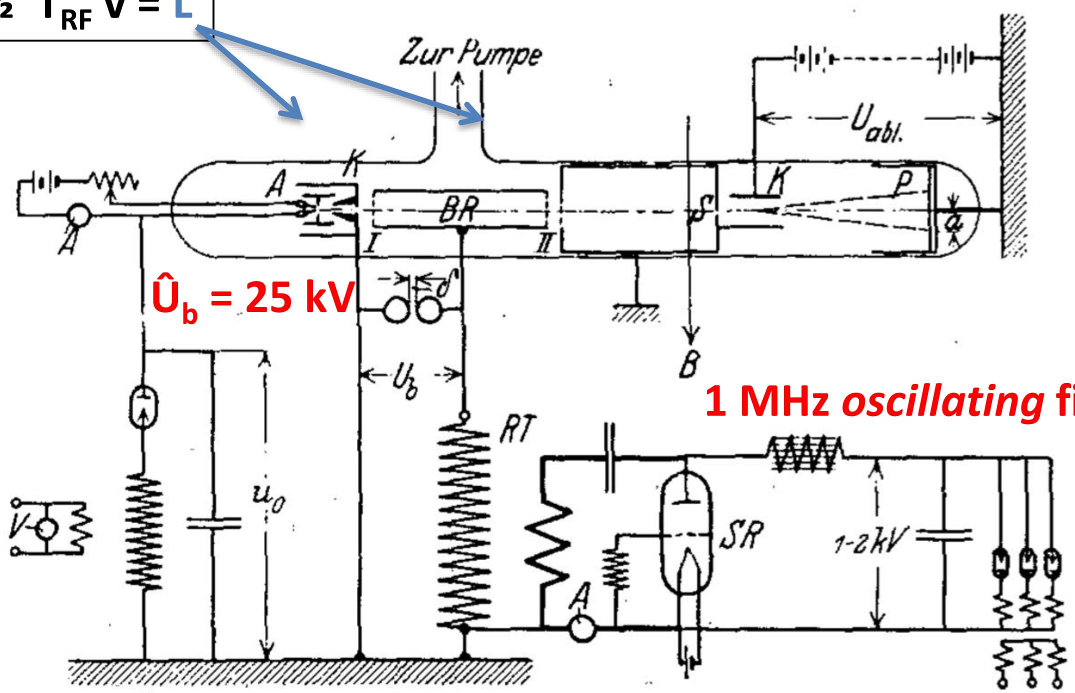


Bild 5. Die verwendete Schaltung.

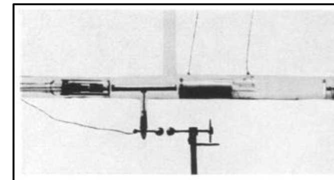
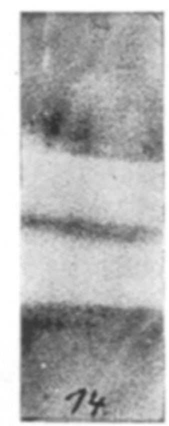


Bild 6. Die Versuchsröhre.



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

Based on an idea (not demonstrated) by **G. Ising**, Arkiv för matematik, astronomi och fysik. **18**, 4 (1924))

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

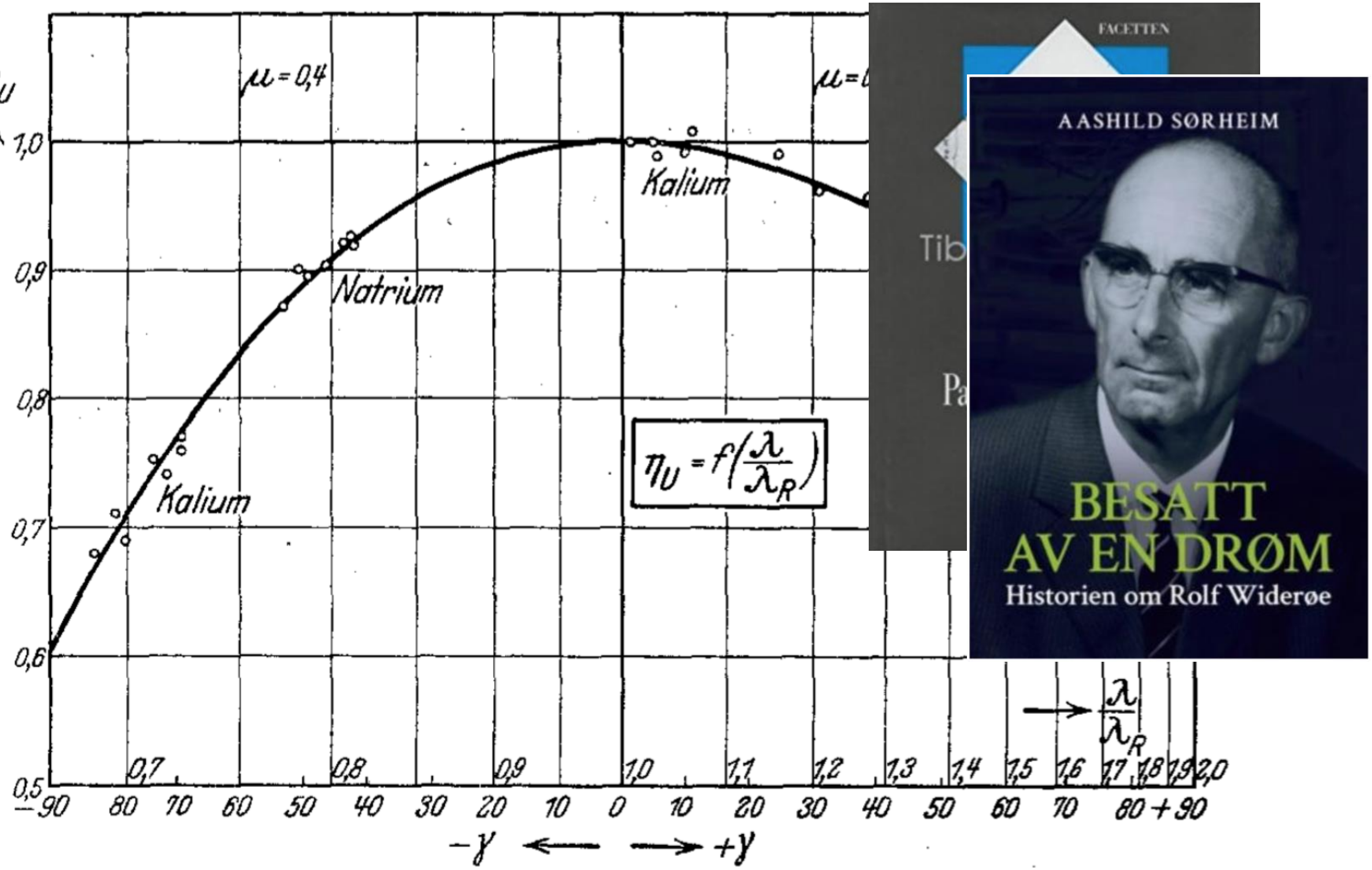


Bild 10. Vergleich der gemessenen mit den berechneten Werten für den Spannungswirkungsgrad bei verschiedenen Wellenlängen.

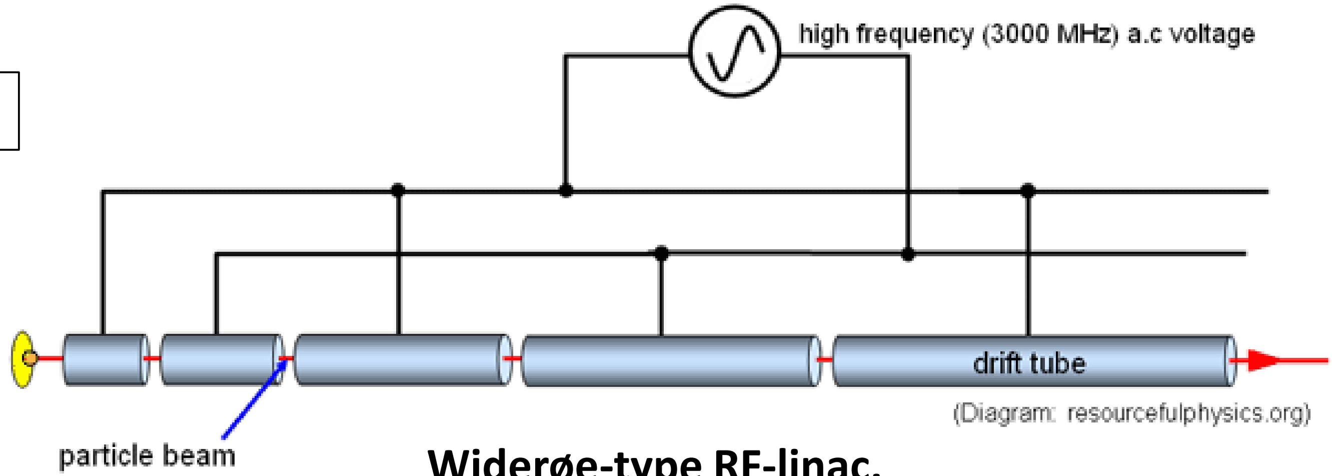
Widerøe accelerated Kalium beams to 50 keV kinetic energy, equal to twice the applied voltage.

This is not possible using electrostatic voltages.

The importance of Widerøe's demonstration:

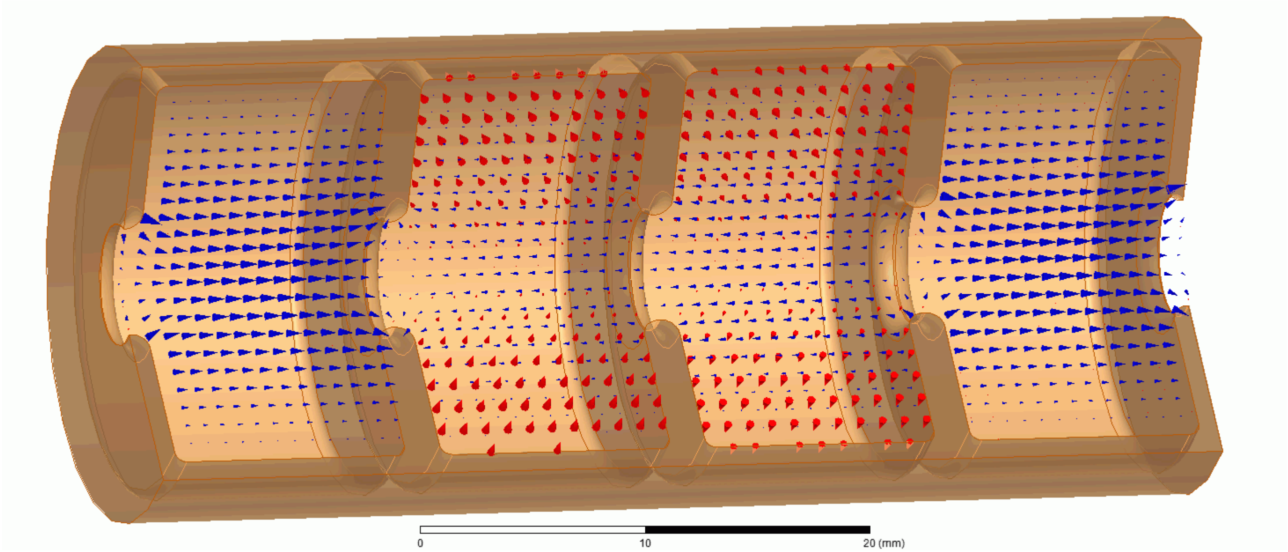
By using time-varying fields, oscillating at radiofrequency **(RF)**, particles can **in principle be accelerated to any energy**, using a limited peak voltage.

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



Widerøe-type RF-linac.

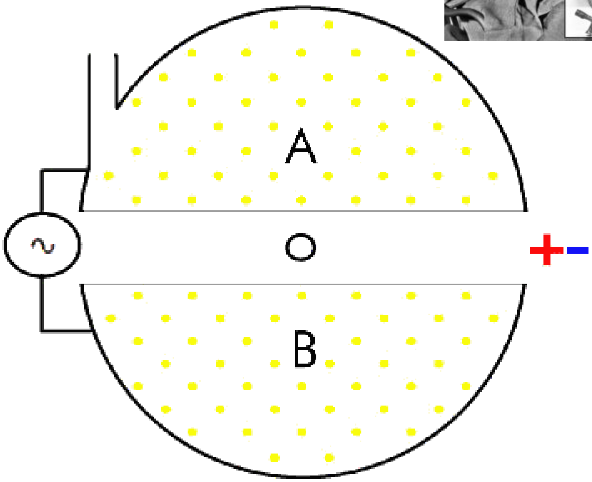
RF-cavities is used in all high-energy particle accelerators today.

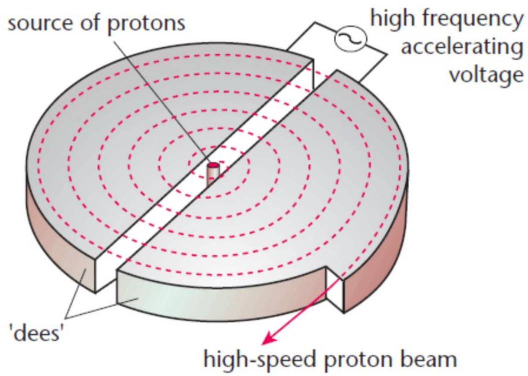


Later development: enclose RF-fields in metal cavities (RF cavities)

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

Cyclotrons :

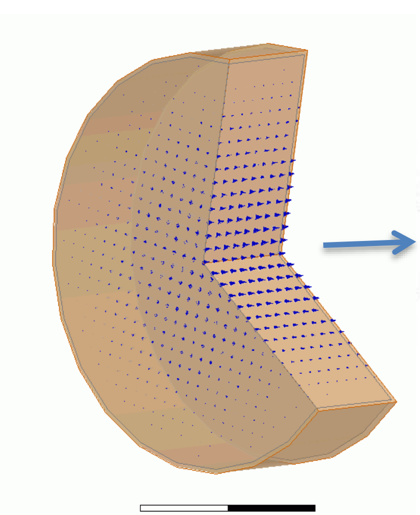


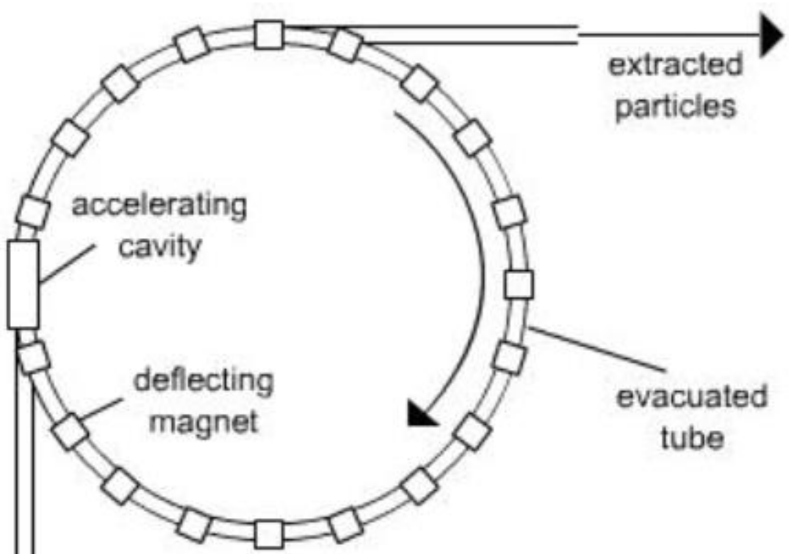


Norway's only research accelerator

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

Synchrotrons :





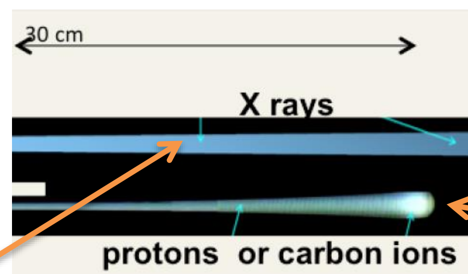
The CERN Proton-Synchrotron (1959, 628 m)
28 GeV (28 billion volts)

In parallel with the particle physics development, particle accelerators have been adopted for **important uses in the society.**

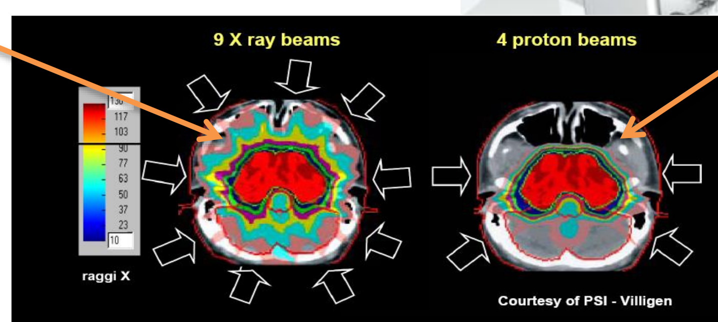
A well known use is **cancer radiotherapy**. In radiotherapy electrons are accelerated by about **10 million volts**. The electron energy is then converted into X-rays.

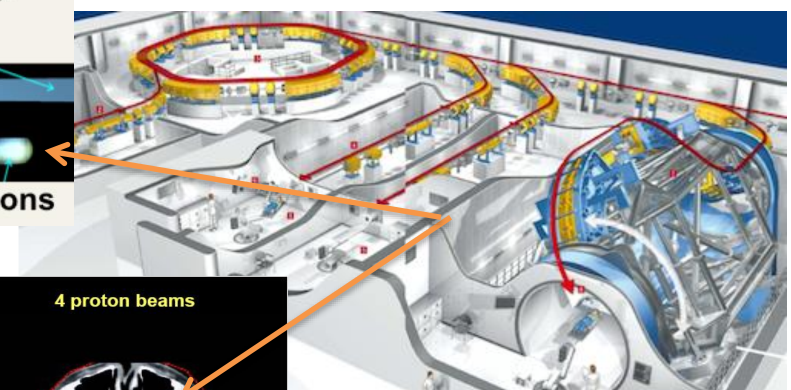
Several types of tumors may be treated more efficiently, with less damage to healthy tissue, by using heavy charged particles, protons or ions – particle therapy. Again, a "spin off" from **the development of RF accelerators for high energy physics.**

Standard radiotherapy (Elekta)



Radiation in tissue





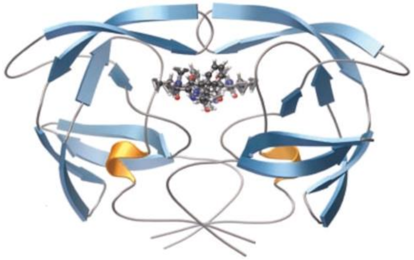
Ion therapy center (Heidelberg)

Accelerators are also uses to create **very powerful microscopes**. X-ray light is used for example in **life sciences (understanding proteins, DNA, viruses), and material sciences (solar cells, batteries)**. Advancement in these fields is possible due to the very brilliant light accelerators can produce.

Particle accelerators would also be an important part of **a future accelerator driven Thorium power plant**.

The ideas to use accelerators for these purposes came **only after accelerators had been invented.**

The European synchrotron X-ray light source in Grenoble (ESRF).



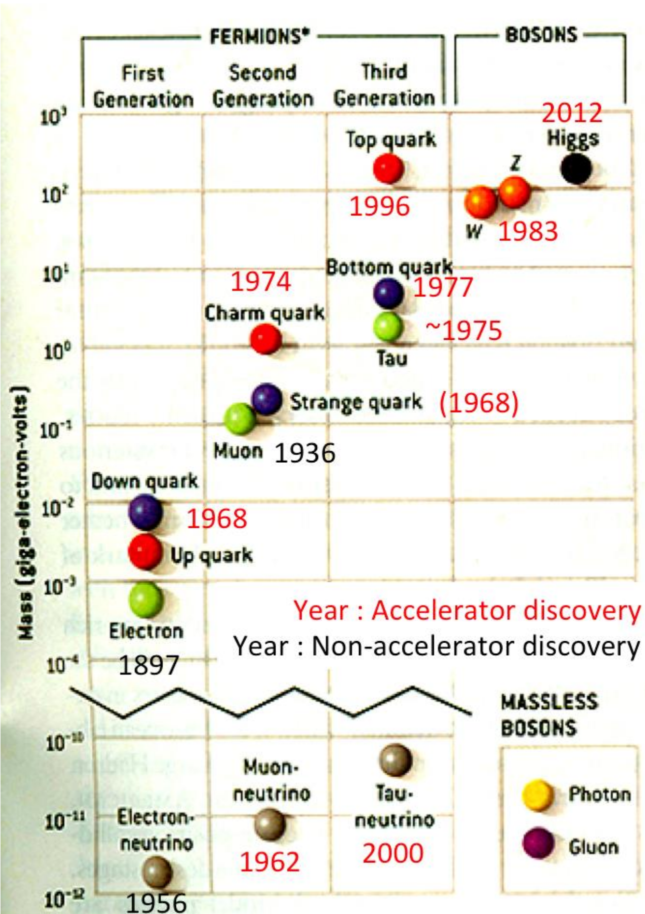
Structure of a protein of HIV-1, as studied in light sources

Fictional future Thorium power plant (TV2)

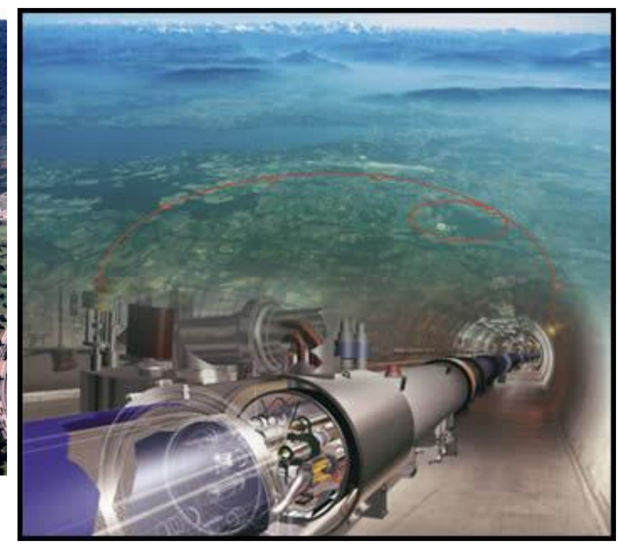
The **development of particle accelerators** has been driven by the quest for the understanding of the **fundamental origins of matter**.

A million volt … a billion volt … 14 trillion volt (LHC)

To study fundamental particles and forces ever **larger and more powerful RF particle accelerators have been constructed** in Russia, Asia, the US and at CERN in Switzerland**.**

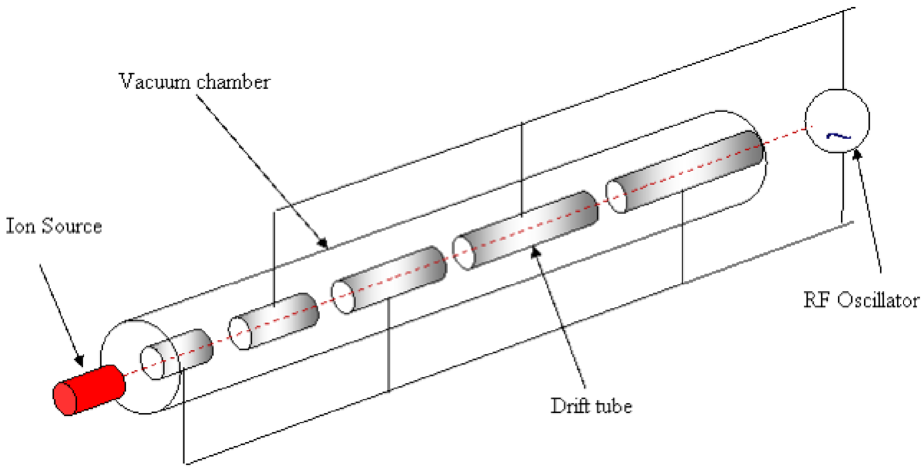


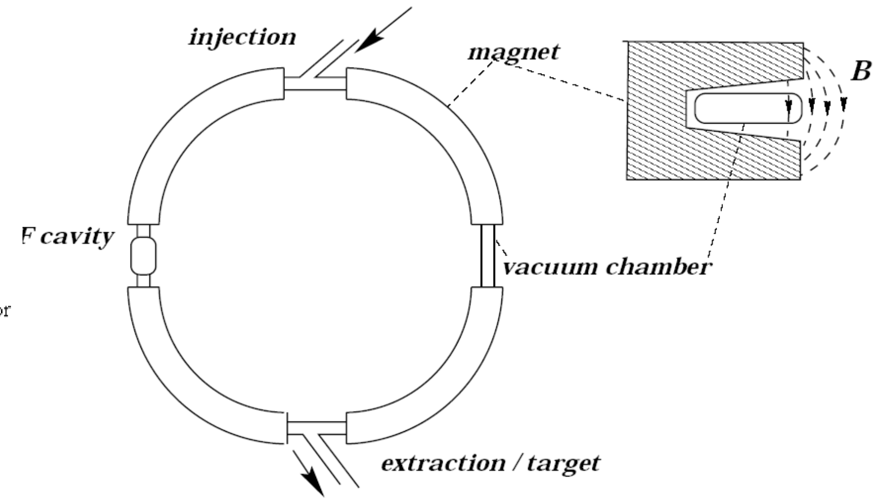
The Stanford Linear Accelerator
(1966, 3 km)
50 GeV electrons and positrons



*The **Large Hadron Collider**, CERN*
(2008, 27 km)
14 TeV protons

Accelerators: circular and linear





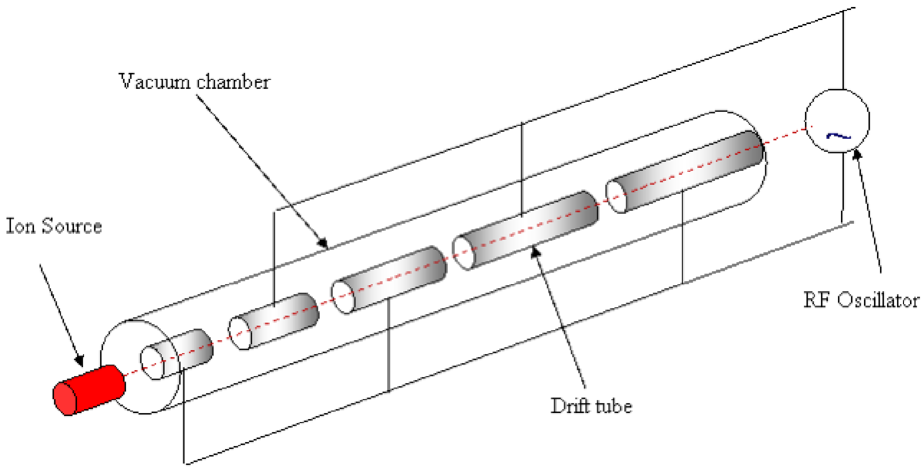
Purpose of particle accelerators: steer, shape and modulate energy of charged particle beams.

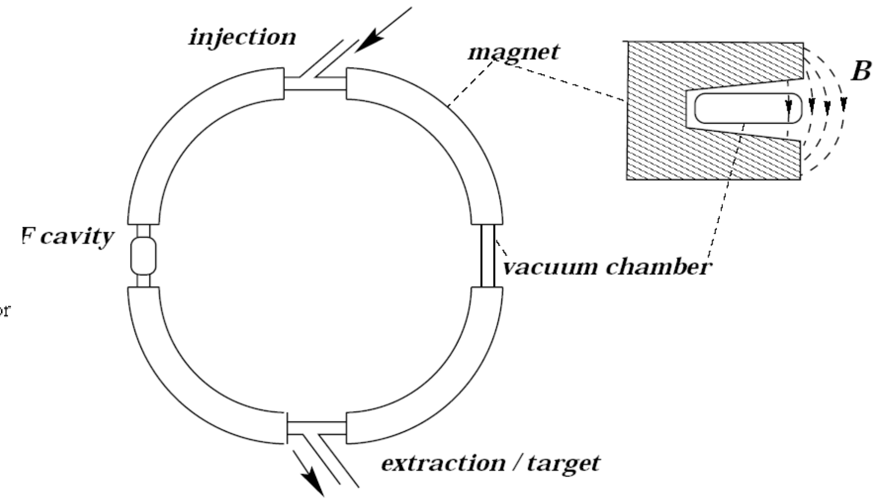
Dynamics of motion governed by the Lorentz force equation :

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

- $F_B \perp v$: **only F_E does work** and provides energy gain
- F_E or F_B for deflection? When $v \approx c$, $1\ \mathrm{T} \sim 3{\cdot}10^8$ V/m. **F_B preferred** for high velocity particles.

Accelerators: circular and linear





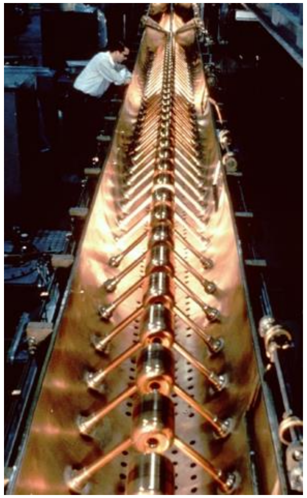
Advantages rings :

- re-uses the same RF cavity
  - Often cheapest and simplest way to reach high energy
- Re-use of circulating charge : colliders and light source

Disadvantages rings :

- Requires strong bending fields
- Energy loss through synchrotron radiation (challenge for high energy)
- Injection/extraction may be challenging
- Lower instability limitations (many-turn instabilities)

Example of linear Accelerators



Electron linacs are built different from proton linacs. The ultra-relativistic velocities means very small space-charge and phase velocities very close to **c**.

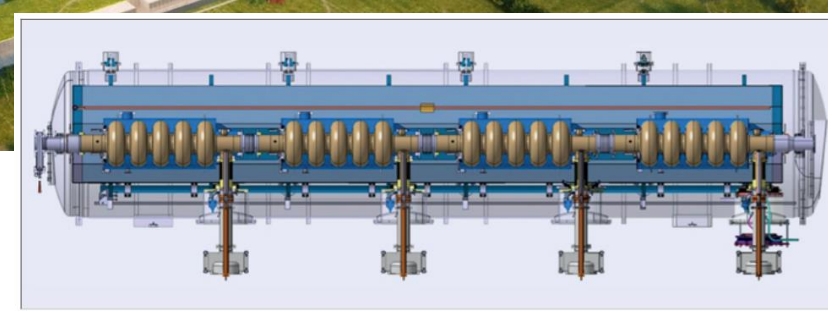


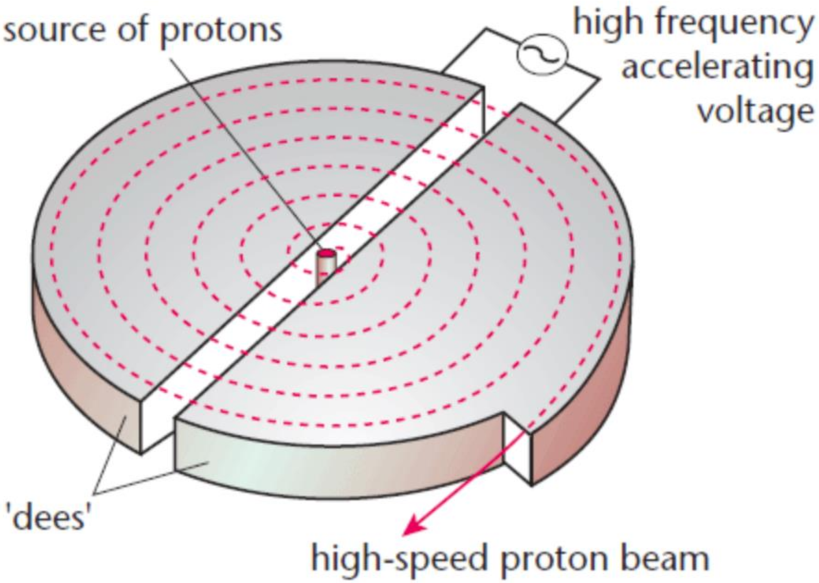
Fig. 3. Preliminary design of a high-beta cryomodule from IPN Orsay and CEA Saclay.

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

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

The cyclotron

- Cyclotron:
  - constant B field
  - Fixed frequency RF field in gap
  - radius increases proportionally to energy
  - limit: relativistic energy, RF out of synch
  - More compact and simpler than the synchrotron



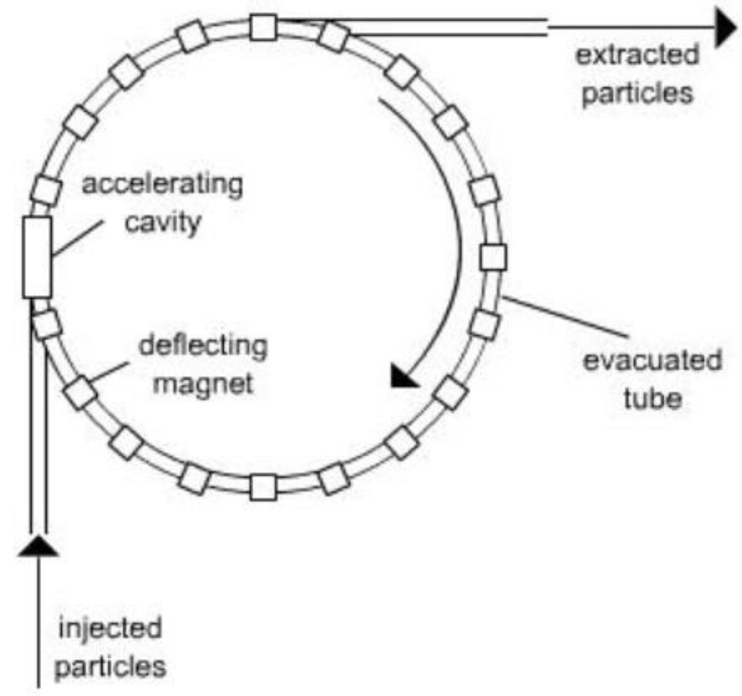
- Synchro-cyclotron : time-varying RF freq,
- Isochronous cyclotron : r-varying magnetic field

- Advantages: Compact, Continuous current, high average power
- Usages : nuclear physics, medicine isotope, ion therapy

Norway's only research accelerator

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

The synchrotron

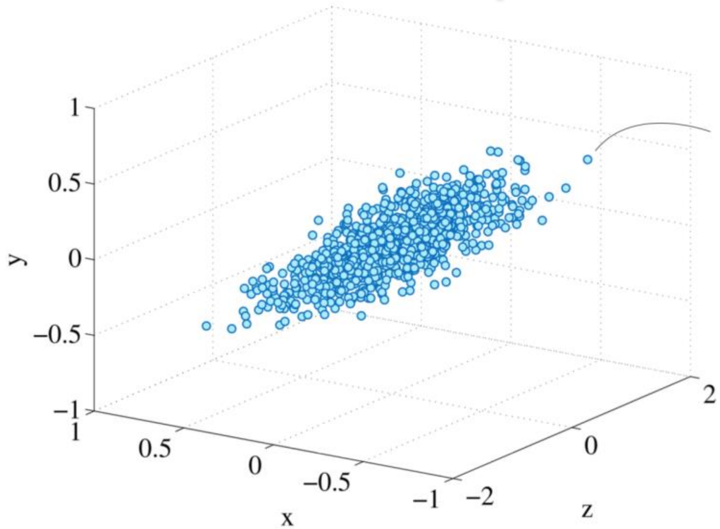


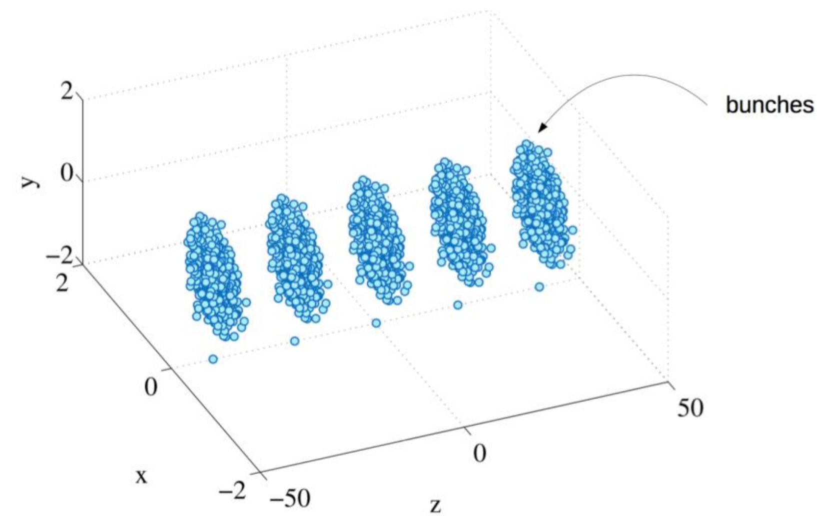
- High energy on small footprint
- Acceleration by RF cavities
- Piece-wise circular motion (bending field, F_B)
- Bending magnets with a homogenous field, with field strength synchronized with the particle energy :

$$F_B = m\frac{v^2}{\rho} \Rightarrow \frac{1}{\rho} = \frac{qB}{p} \Leftrightarrow \frac{1}{\rho}[m^{-1}] \approx 0.3\frac{B[T]}{p[GeV/c]}$$

- The RF frequency stays locked to the revolution frequency of a particle
- Used for most colliders to date (**LHC**, Tevatron, HERA, LEP, SPS, PS …), Synchrotron Light Sources, hadron therapy ...

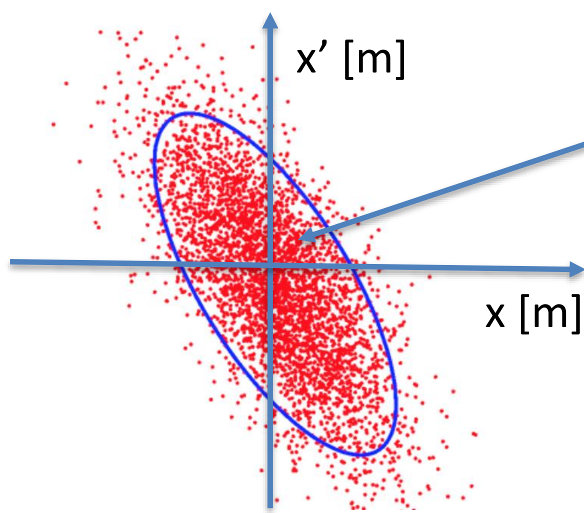
Description of particle beams





$$\psi = \psi(x, x', y, y', z, E)$$ $x' = p_{x}/p$

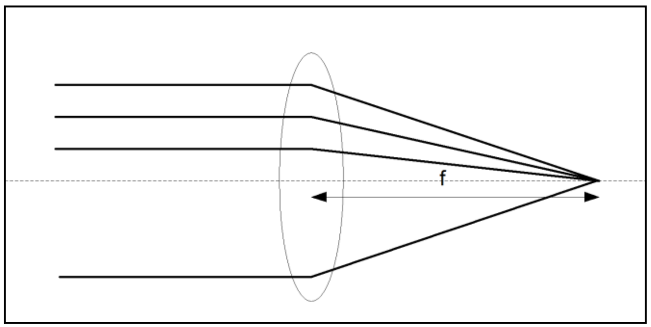
Particle beam: 6D distribution, two transverse planes + one longitudinal plane.

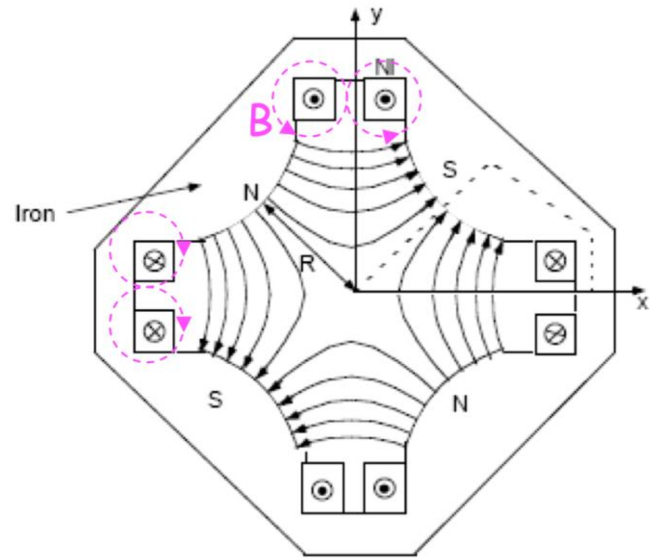


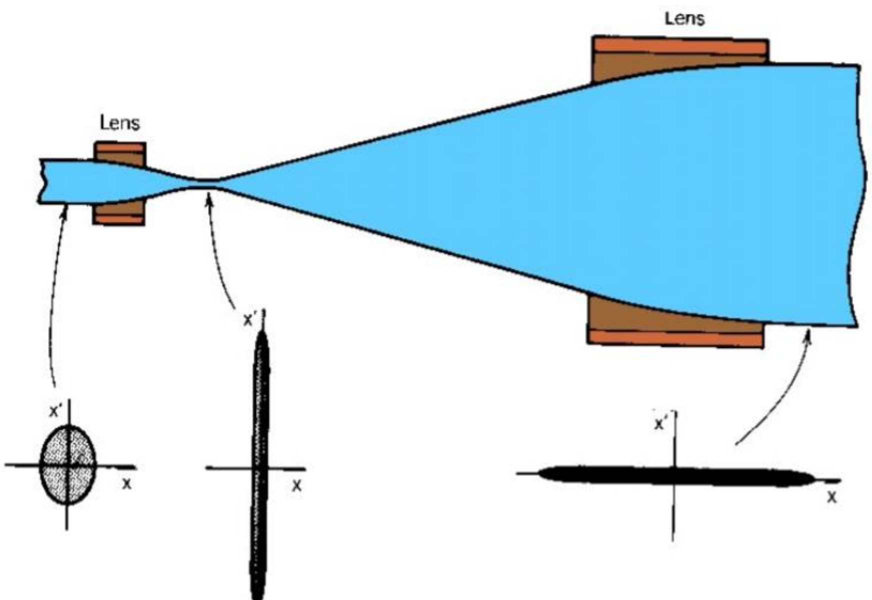
- Phase-space area is conserved under beam transport
- Metric of how well the beam can be focused, named **emittance**

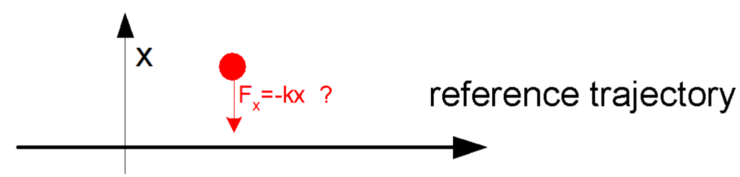
Focusing of particle beams

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









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

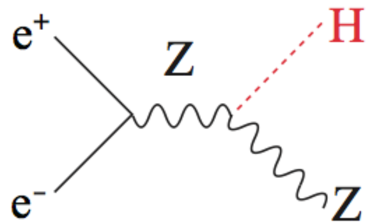
Lattice

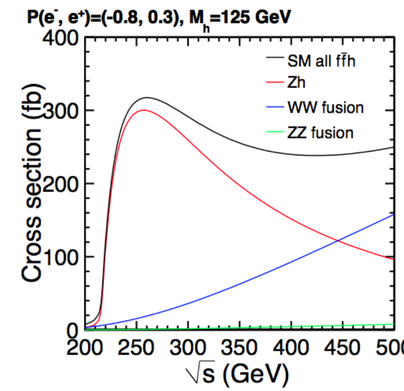
Beam quality: emittance

Luminosity

- High energy is not enough, production rate are as important, because the events we are looking for are rare.
- The probability for particle physics processes to occur are quantified by "**cross section**", σ, an **area**, with units in "barns", b = 10^{-28} $m^{2.}$
- The higher the cross section, and the more collisions per second, the higher reaction rate **R** for a given process is :

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





- *The proportional factor, $\mathcal{L}$, called the luminosity* [$cm^{-2}s^{-1}$], depends on the colliding beam parameters as :

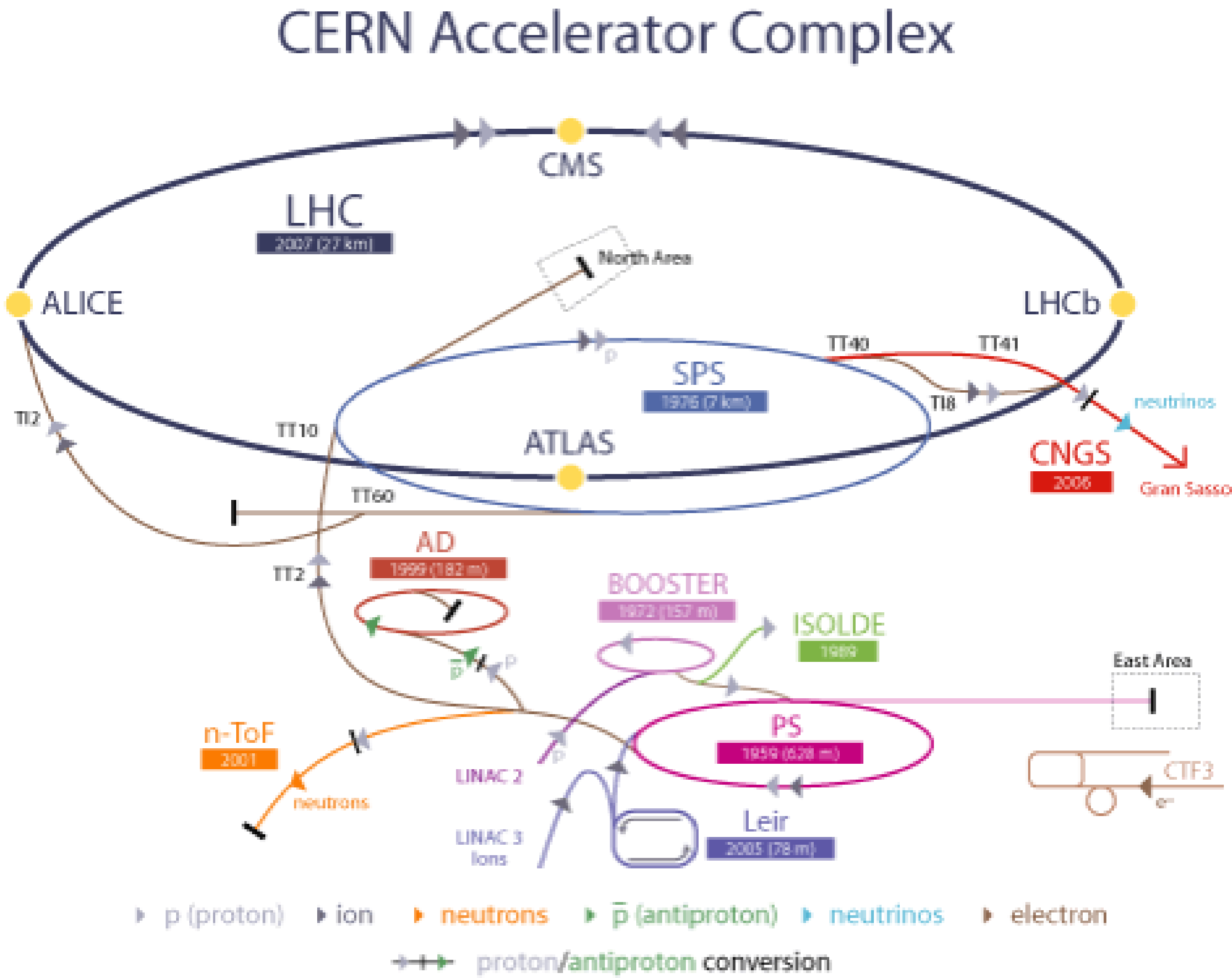
$$L = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

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

The Large Hadron Collider

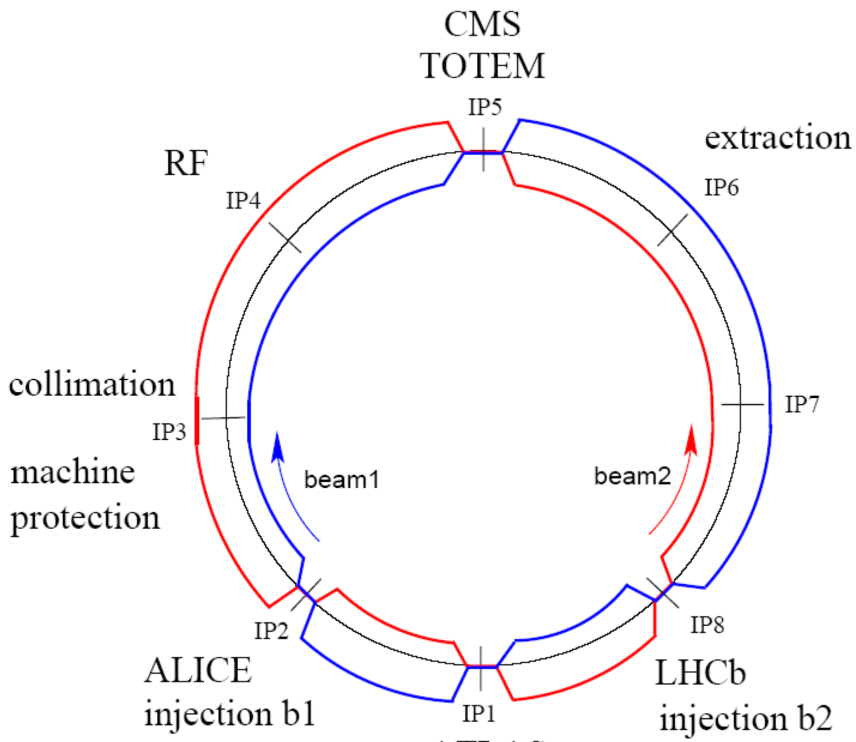
LHC and the CERN accelerator complex

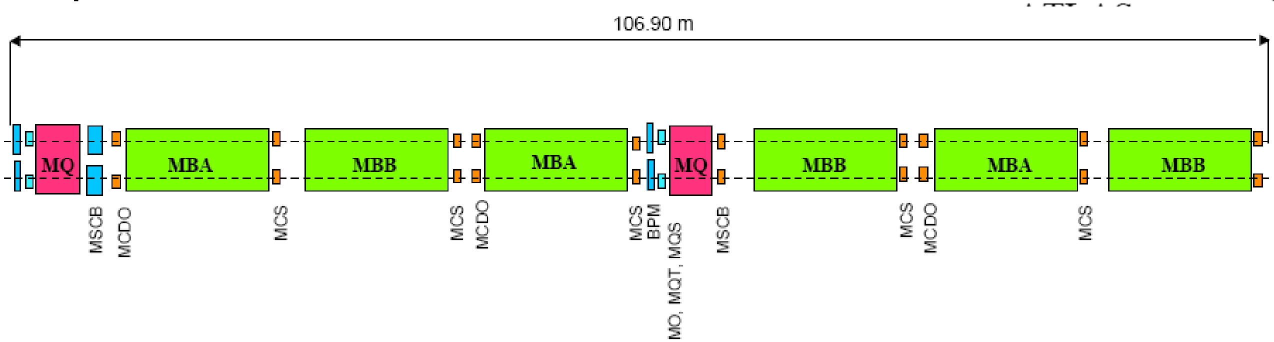
- LHC is responsible for accelerating protons from 450 GeV up to 7000 GeV
- 450 GeV protons injected into LHC from the SPS
- PS injects into the SPS
- LINACs injects into the PS
- The protons are generated by a proton source where a H_2 gas is heated up to provide protons
- The limitations in the earlier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



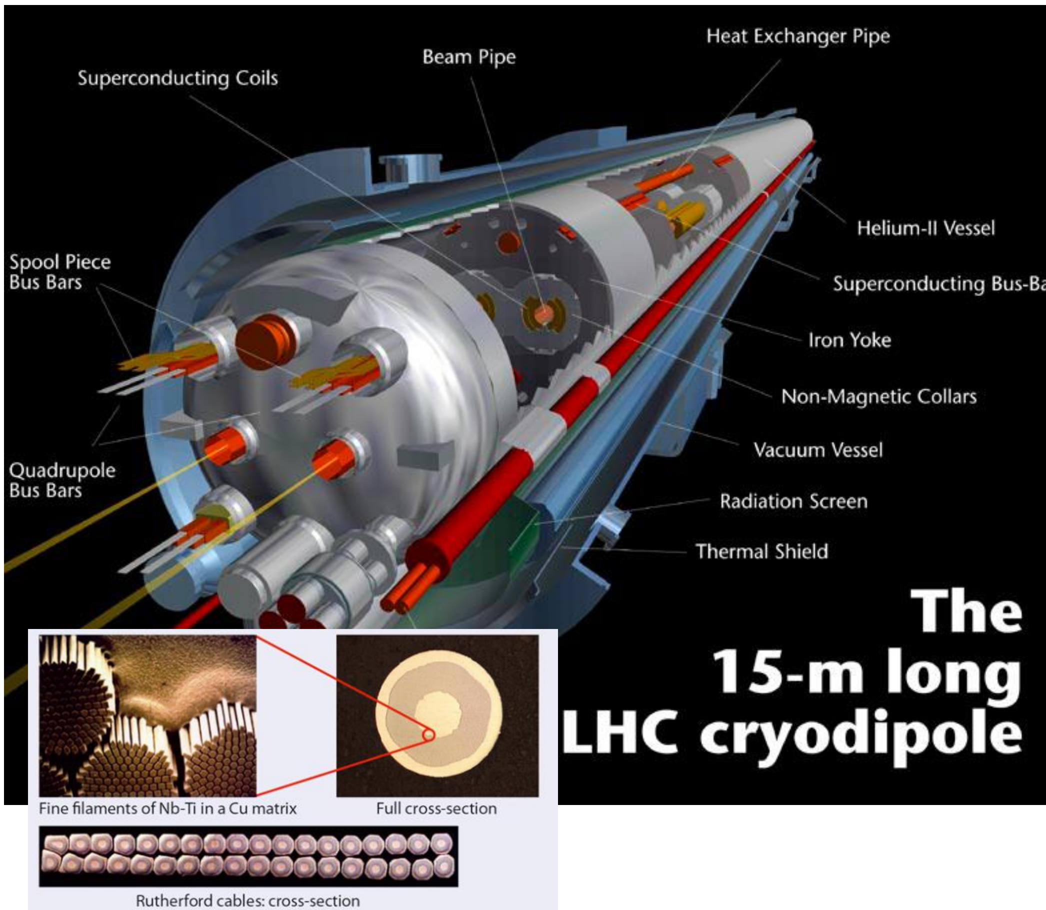
LHC layout

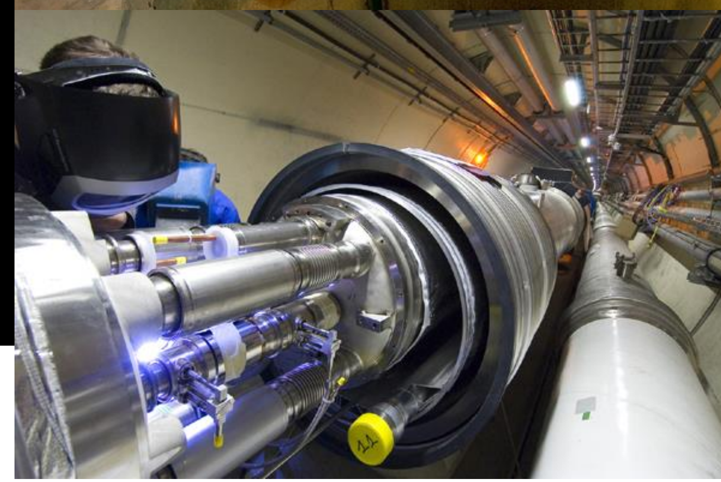
- Circumference = 26658.9 m
- Four interactions points, where the beams collide, and massive particle physics experiments record the results of the collisions (ATLAS, CMS, ALICE, LHCb)
- Eight straight sections, containing the IPs, around 530 m long
- Eight arcs with a regular lattice structure, containing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





LHC bending magnets

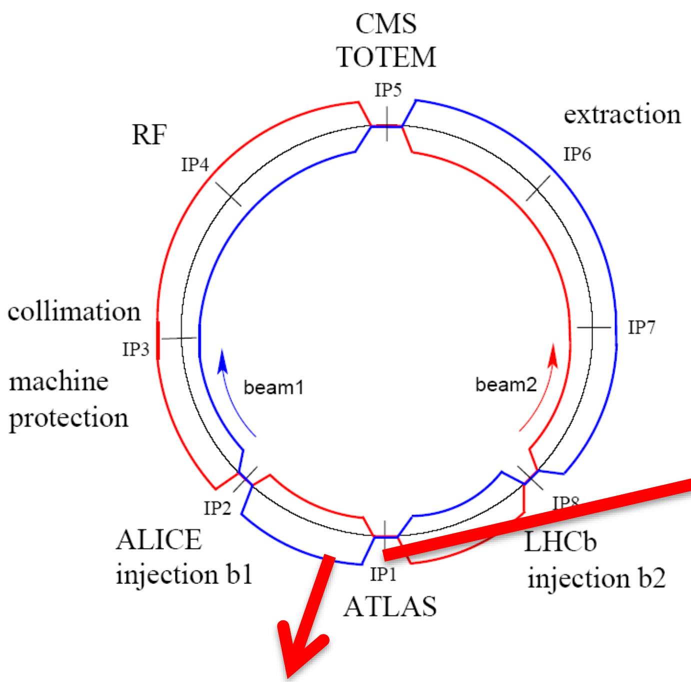




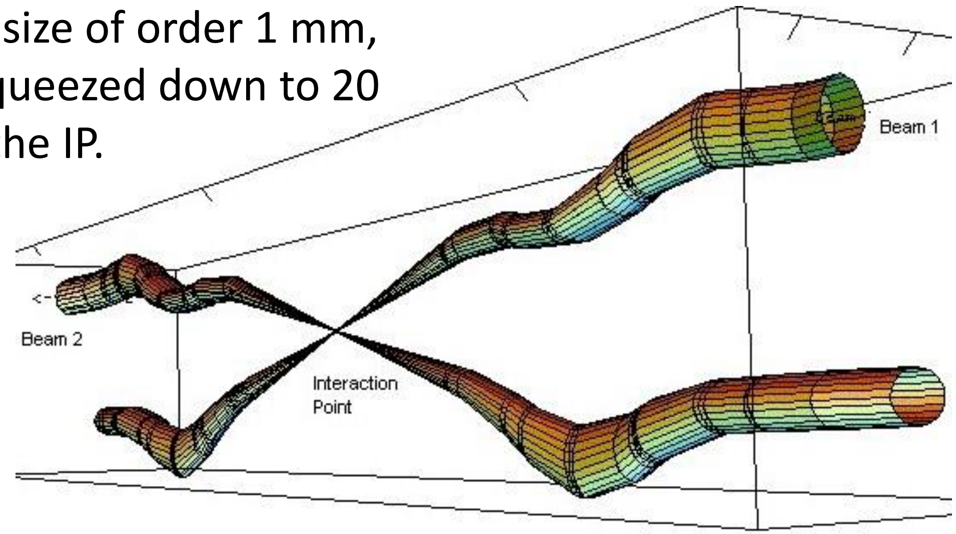
8.3 T maximum field (allows for 7 TeV per proton beam). Generated by a current of 12 kA in the superconducting Rutherford coils.

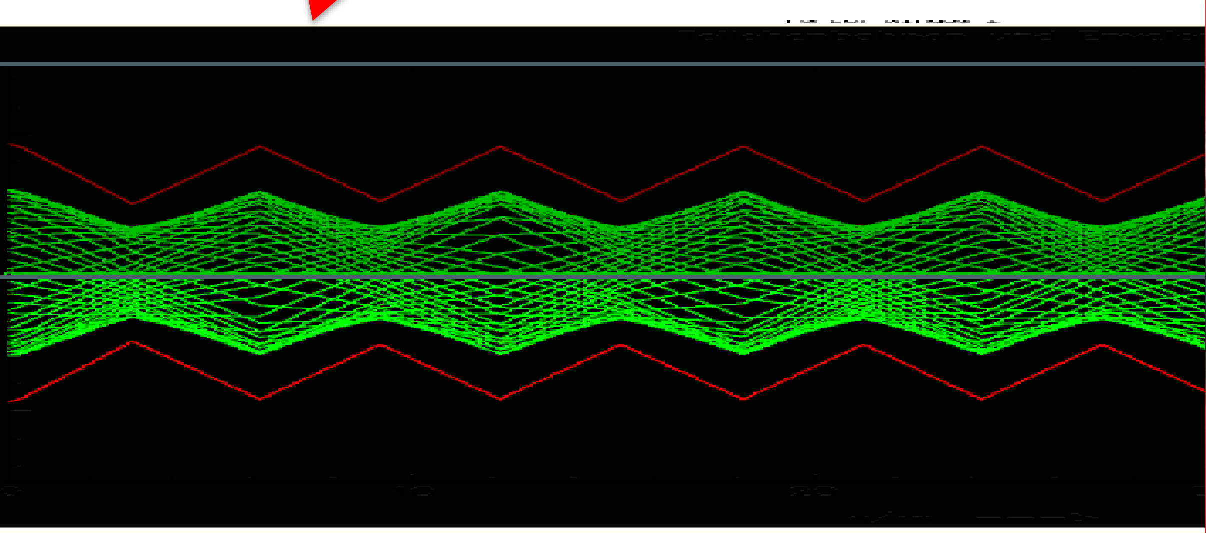
Developments for higher energy hadron colliders (HE-LHC, FCC) : Nb_3Sn, HTS

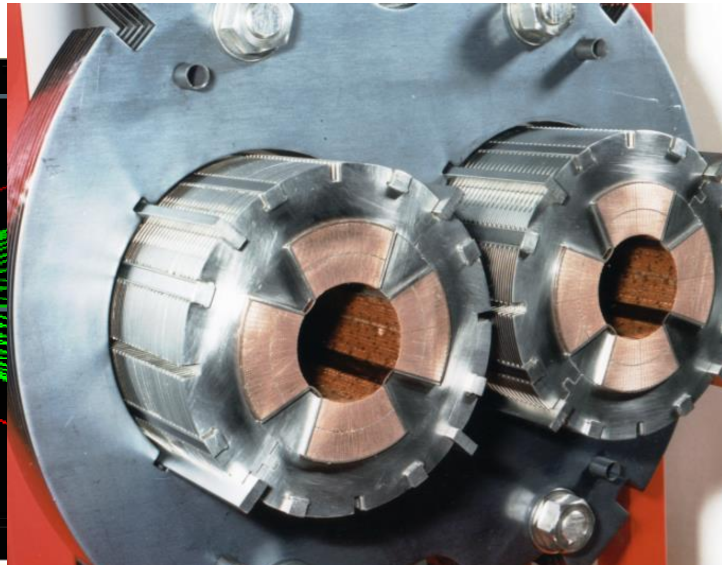
LHC beam focusing



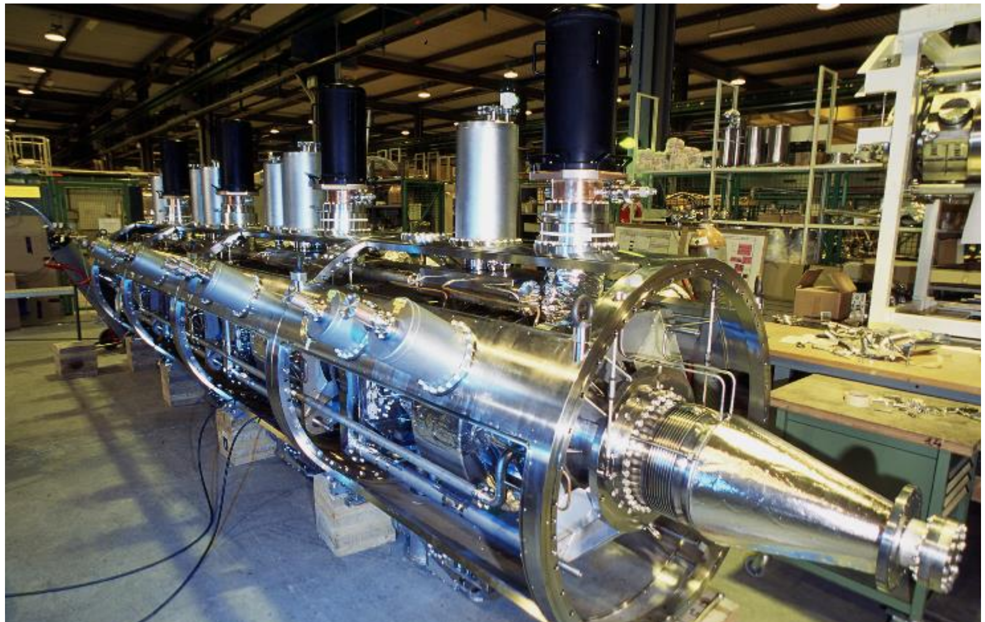
The beam is kept focused in arcs to size of order 1 mm, then squeezed down to 20 um at the IP.

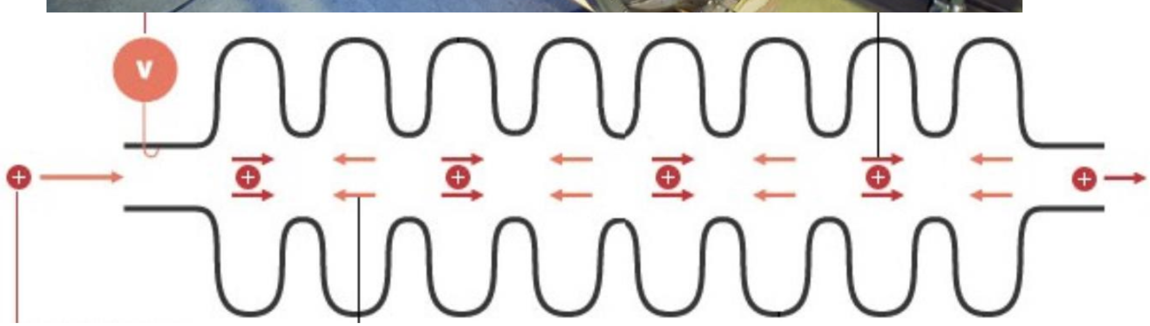






LHC cavities





- 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 nominal **parameters**

Particle type	p, Pb
Proton energy E_p at collision	7000 GeV
Peak luminosity (ATLAS, CMS)	1×10^{34} cm^{-2}s^{-1}
Circumference C	26 658.9 m
Bending radius ρ	2804.0 m
RF frequency f_{RF}	400.8 MHz
# particles per bunch n_p	1.15×10^{11}
# bunches n_b	2808, 25 ns spacing

Future Linear Colliders

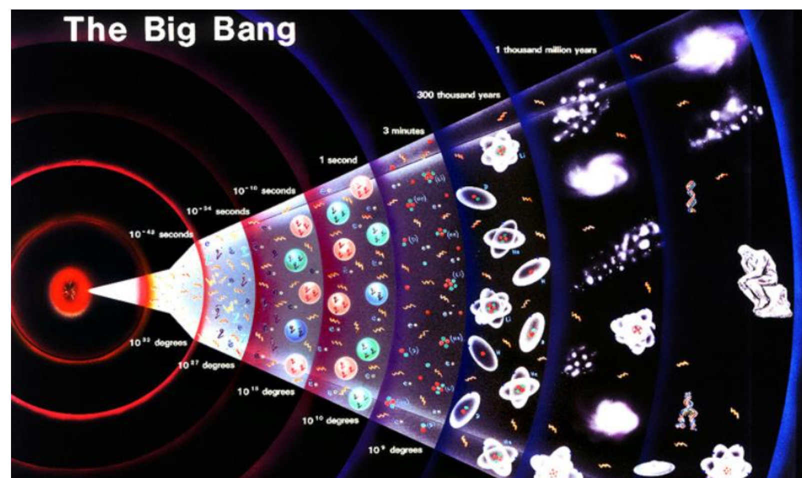
After LHC and the TeV-scale: Are we done?

The 27 km LHC discovered the long elusive Higgs Boson. However, a large number of important questions remain :

The Standard Model of particle physics points describes several types of particles. **Why?** Is there only one fundamental building block? Most of the matter observed in the universe are of an unknown type. **What is this dark matter? What did the universe look like just after the Big Bang?**

Particle physics at the energy frontier – the TeV scale (and beyond) : requires advances in accelerator science.

Dark Matter?

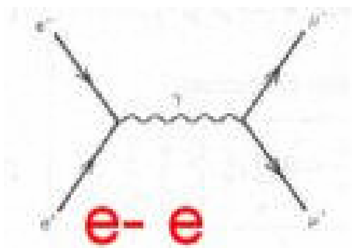


More energetic collisions: closer towards the Big Bang

Collider: hadron versus lepton

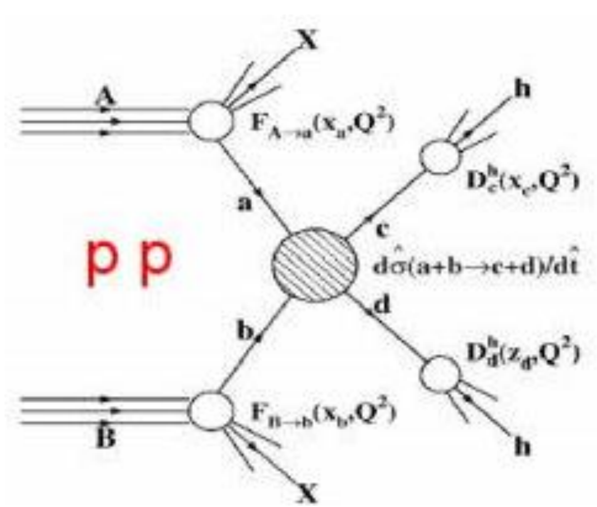
Lepton collisions: elementary particles (leptons, muons…)

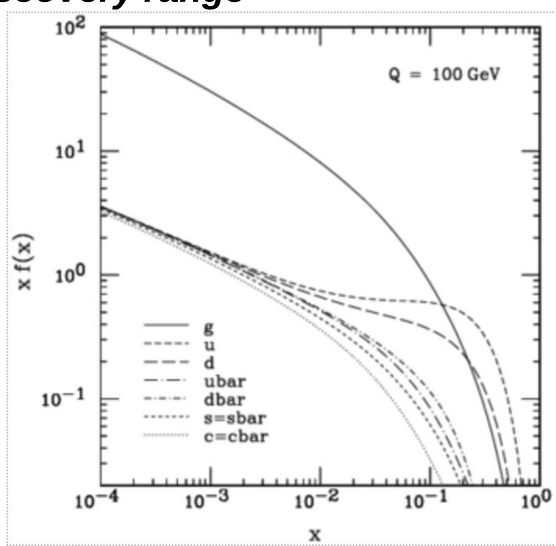
- Collision process known
- Well defined energy
- ***Lepton collisions*** $\Rightarrow$ ***precision measurement***



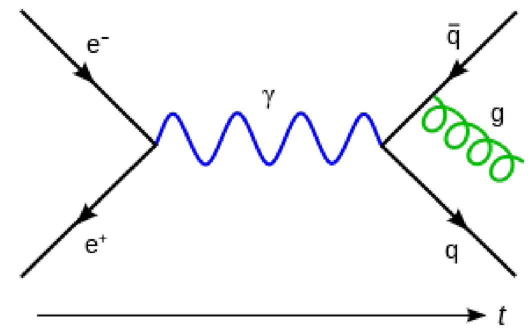
Hadron collisions: compound particles (protons, ions…)

- Mix of quarks, anti-quarks and gluons: variety of processes
- Parton energy spread
- ***Hadron collisions*** $\Rightarrow$ ***large discovery range***

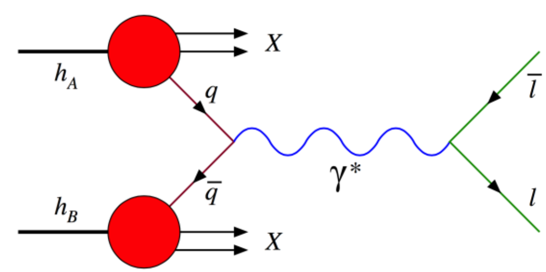




Hadron production from lepton collisions



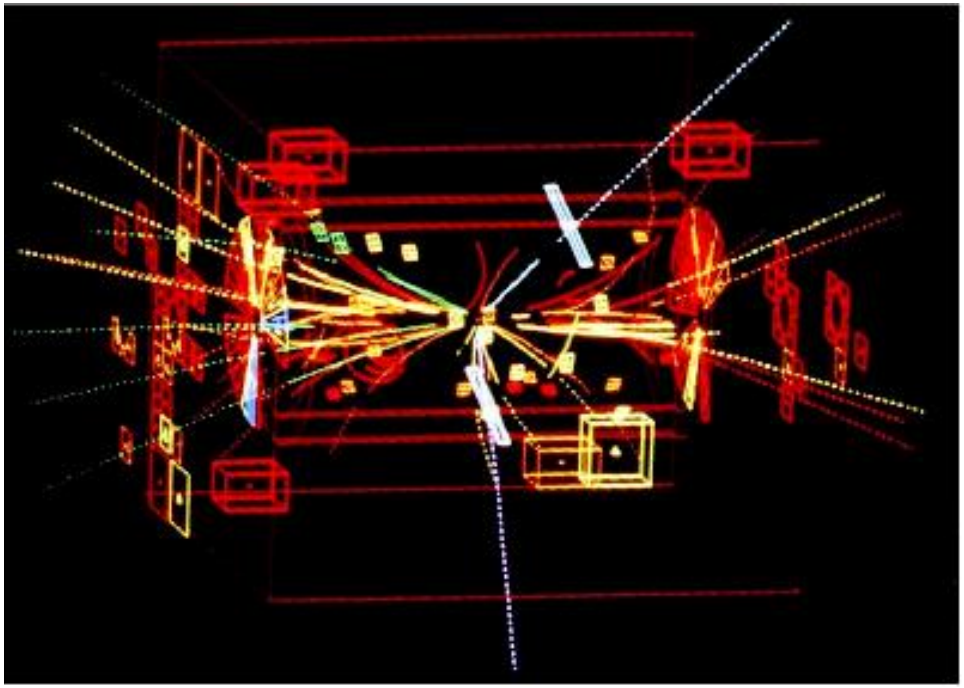
Lepton production from hadron collisions



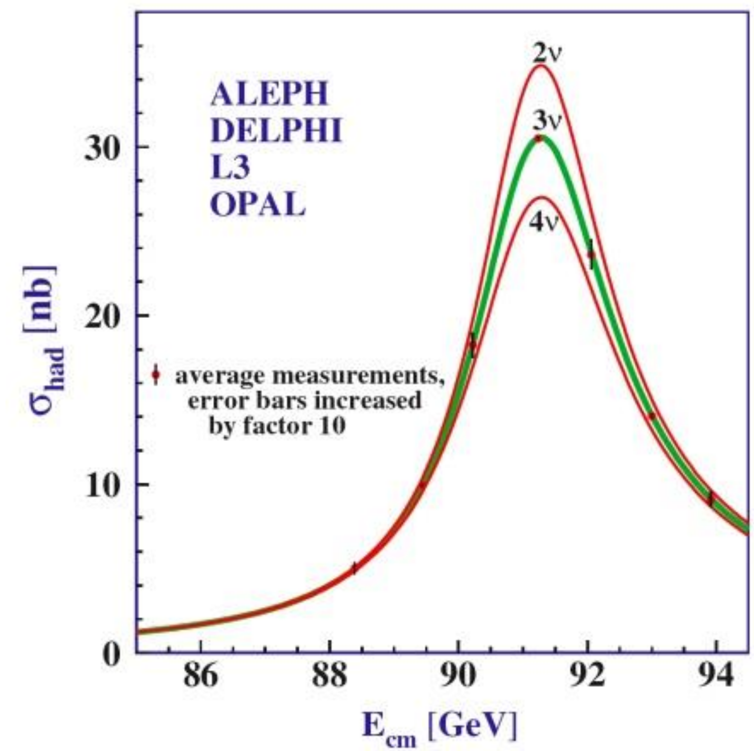
"If you know what to look for, collide leptons, if not collide hadrons"

SppS versus LEP

1983

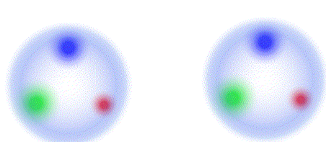


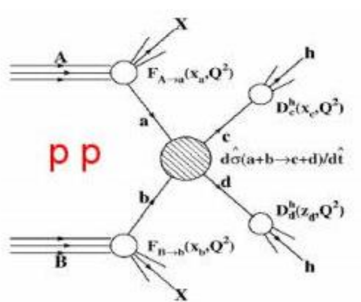
1983

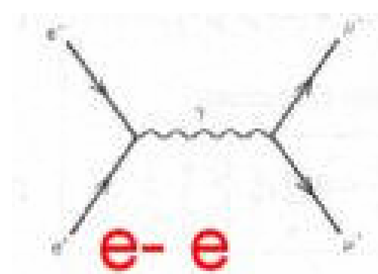


Hadron collider SppS, √s=540 GeV, $W^{+/-}$ and Z^0 discovery

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



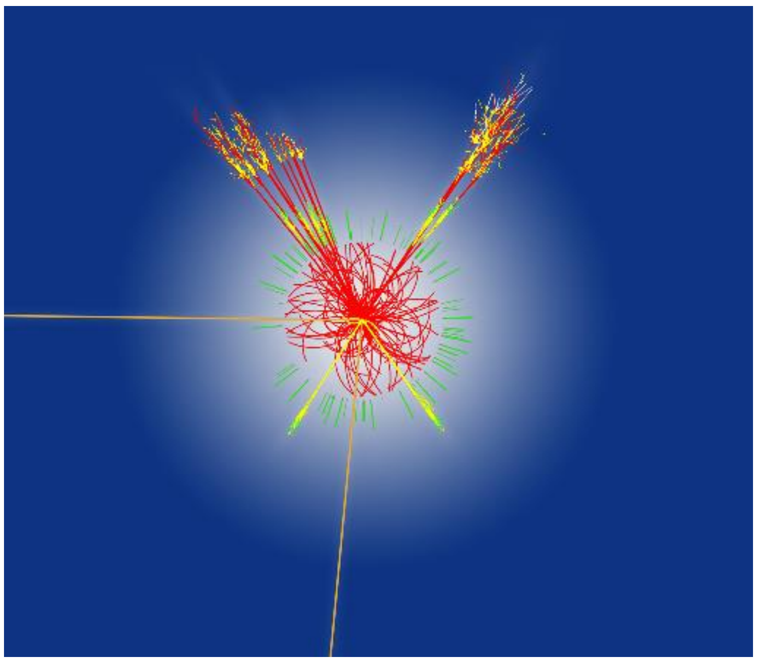




LHC versus future colliders

Analogy: Higgs physics

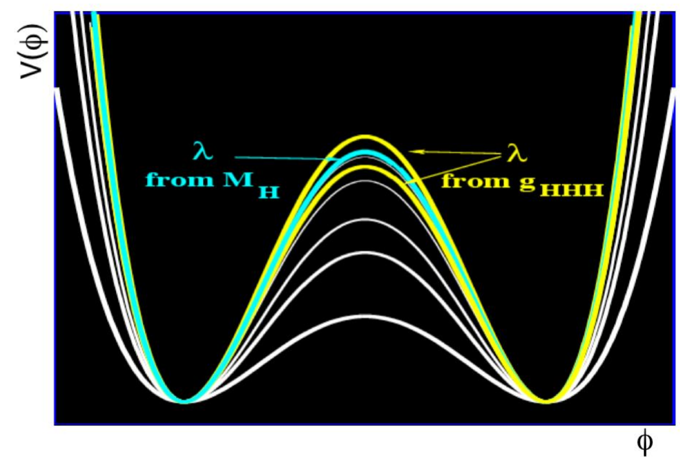
Standard Model Higgs:
- scalar spin-0 particle
- specific form of scalar potential :



ATLAS and CMS@LHC, discovery of the Higgs boson confirmed in 2012. LHC continues to study properties of the Higgs boson. For example coupling coefficients. Precision numbers are key.

Linear collider : can perform complementary, model independent Higgs physics.

$$V(\eta) = \lambda v \eta^3 + \frac{1}{4}\lambda\eta^4$$



Linear Collider: Precision measurements if the trilinear **HHH-coupling** (Courtesy of M. Battaglia)

Energy limitation in collider rings

Synchrotron radiation power loss :

Any charged particle undergoing acceleration radiates, and looses energy.

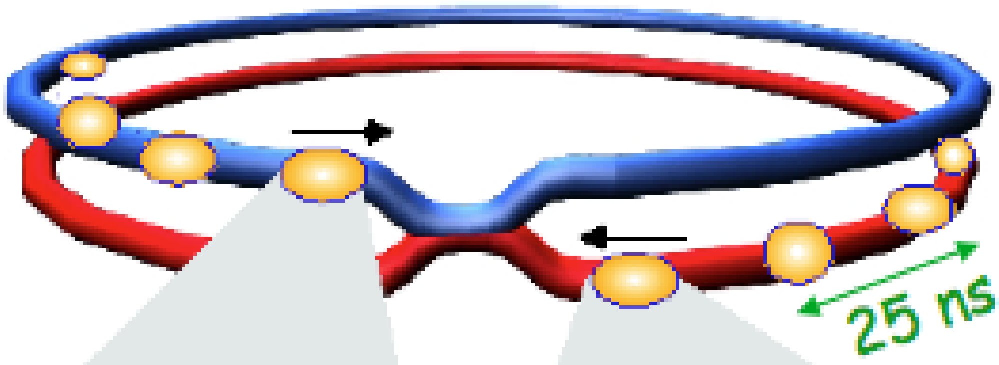
$$\boxed{P_e = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}}$$

- **Limiting factor** for the LEP energy ($E_{cm,max}$ = 209 GeV)
- Total **cost scaling** for rings, as you scale energy **: ~E^2**
- With linear acceleration : ~E with respect to E^2 for rings
- **TeV e- e+ collisions**: circular colliders not a practical option. The main driver for linear collider research.

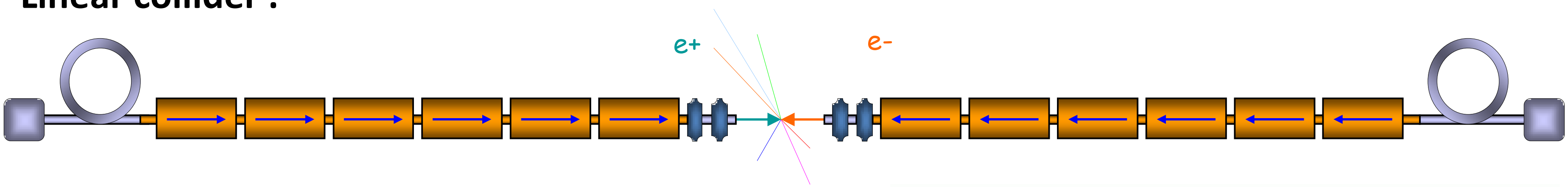
A linear collider ?

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

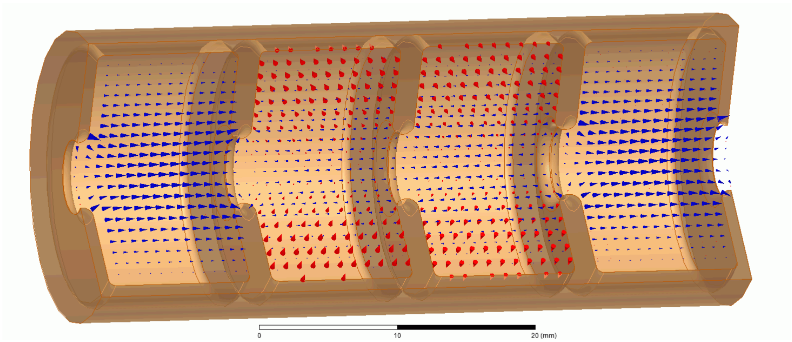
Circular collider :



Linear collider :

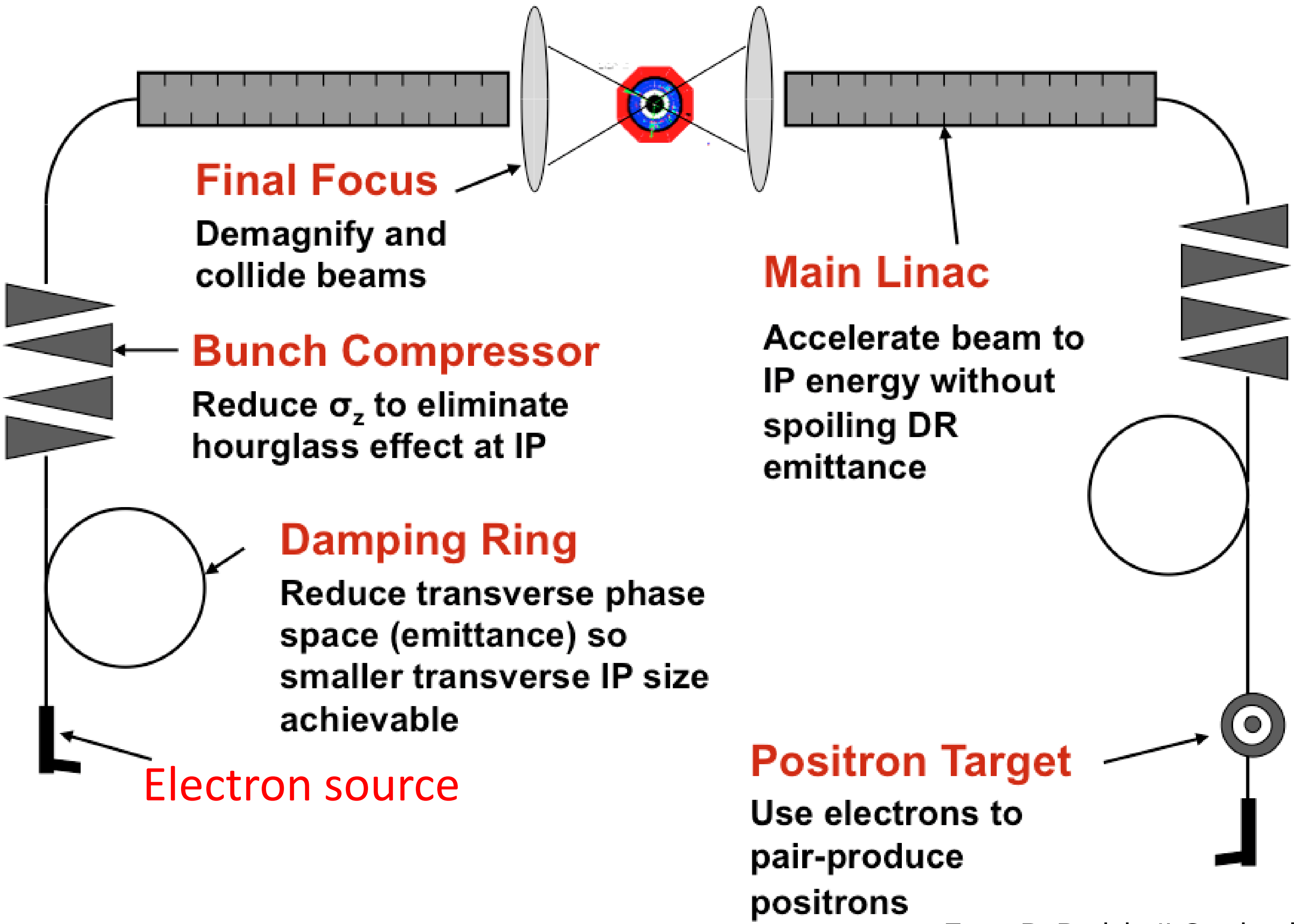


Length of a linear collider: Each cavity accelerates each bunch only once. Collider length is driven by how large electric field can be sustained in a metallic cavity.



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

Linear collider parts

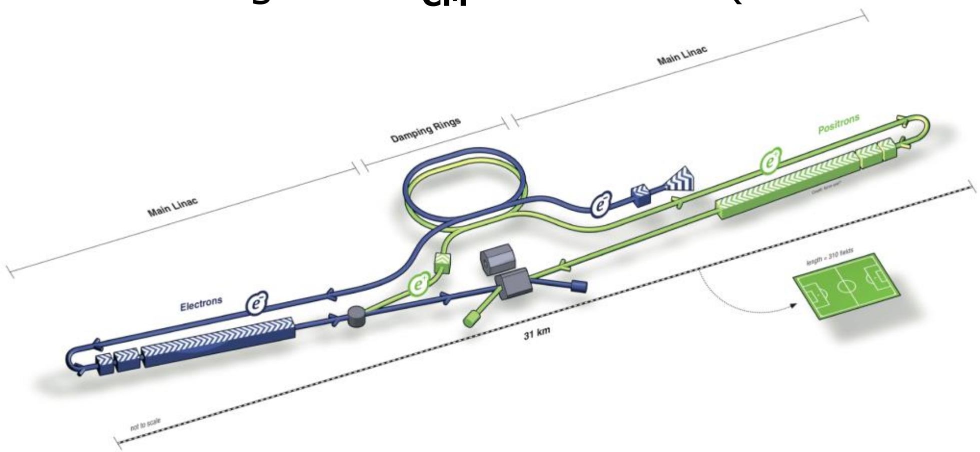


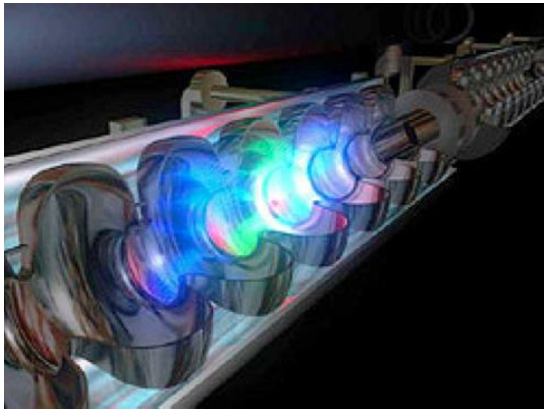
From B. Barish, ILC school 2012

Linear Collider Projects

The International Linear Collider, ILC

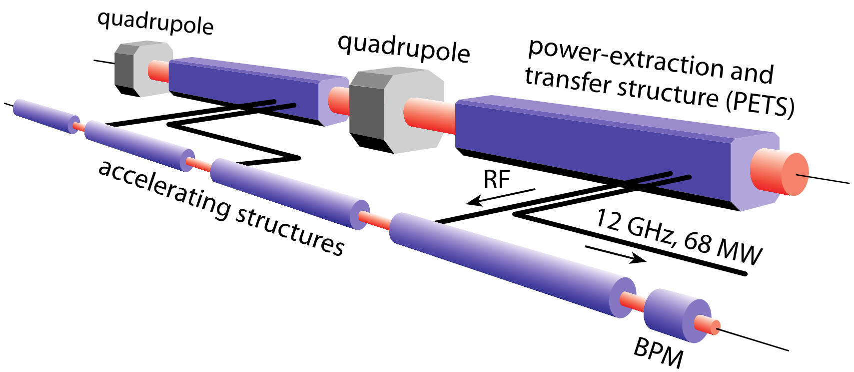
Main linac technology: **super conducting RF 1.3 GHz SW cavities**, **31.5 MV/m**
Nominal design for $\mathbf{E_{CM} = 0.5}$ **TeV** (250 GeV to 1 TeV)

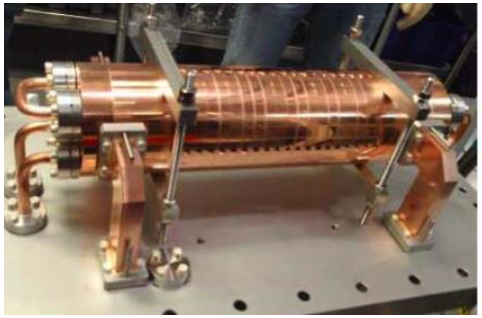


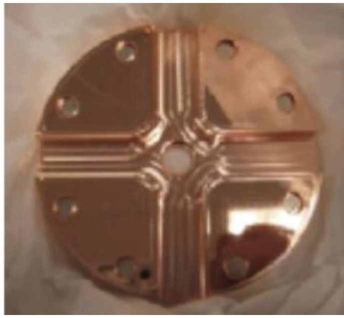


The Compact Linear Collider, CLIC

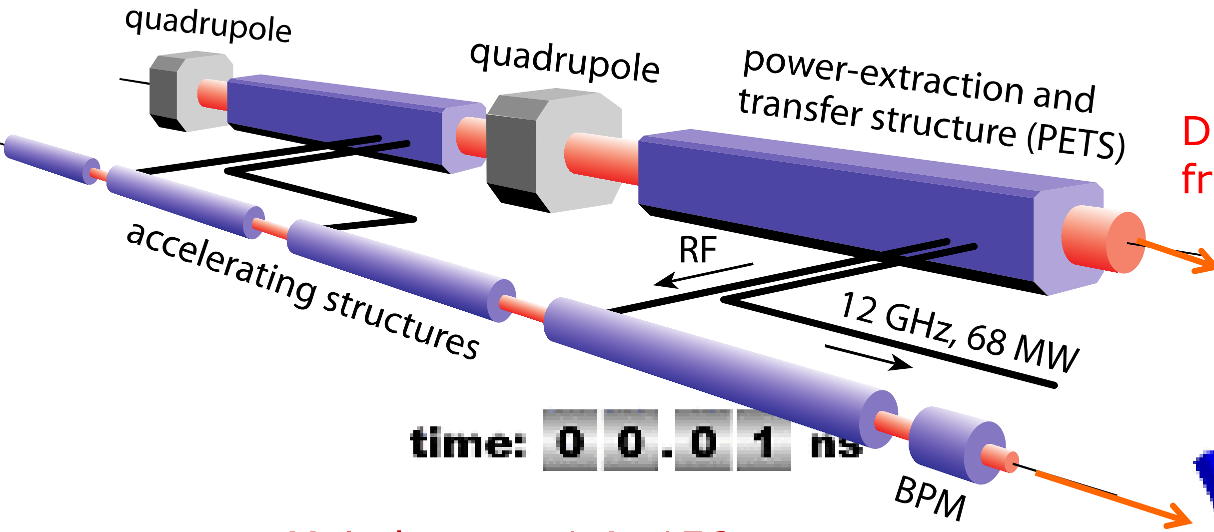
Main linac technology: two-beam scheme**. Normal conducting Cu RF 12 Ghz TW cavities, 100 MV/m**. Nominal design for $\mathbf{E_{CM} = 3}$ **TeV** (375 GeV to 3 TeV)







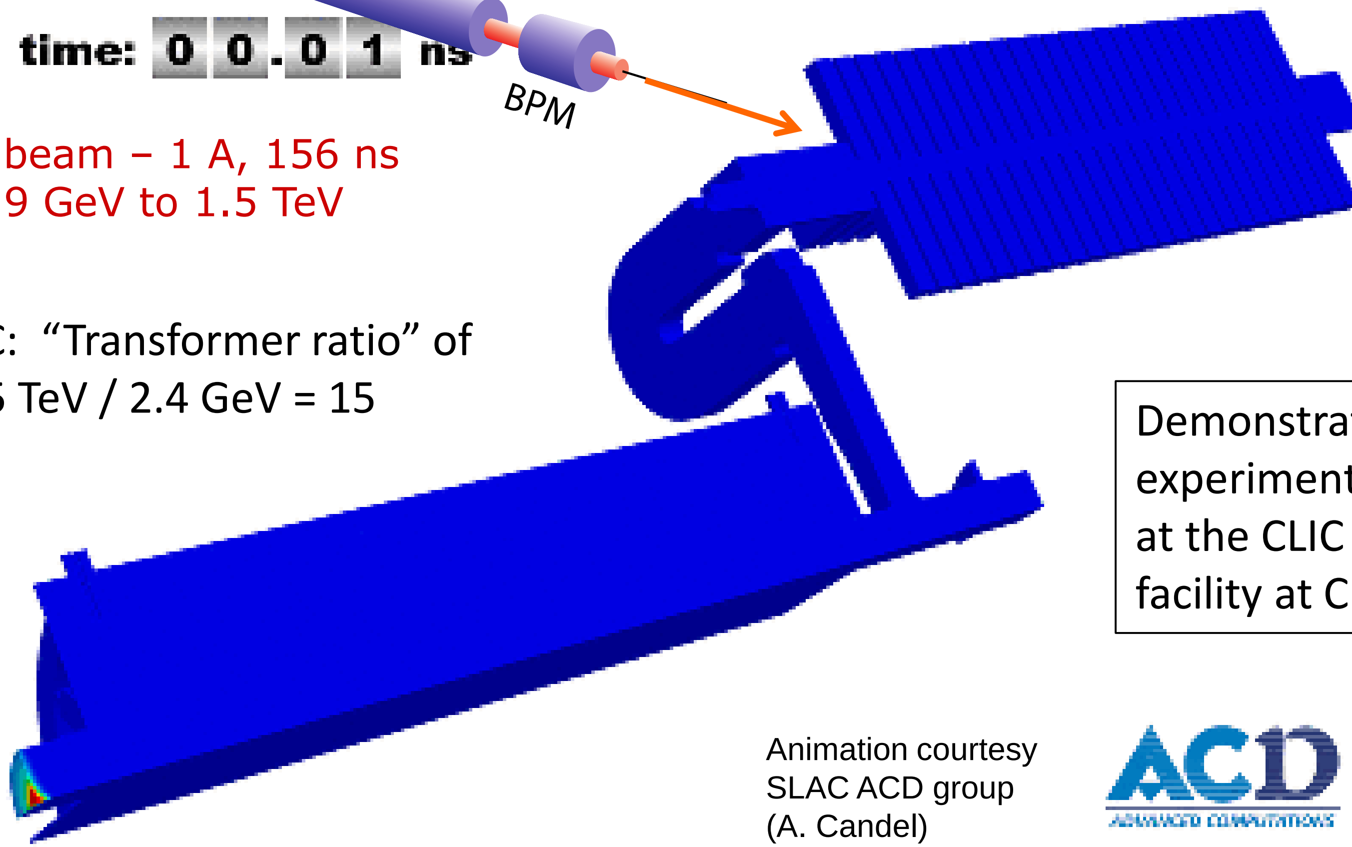
The CLIC Two-Beam scheme



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

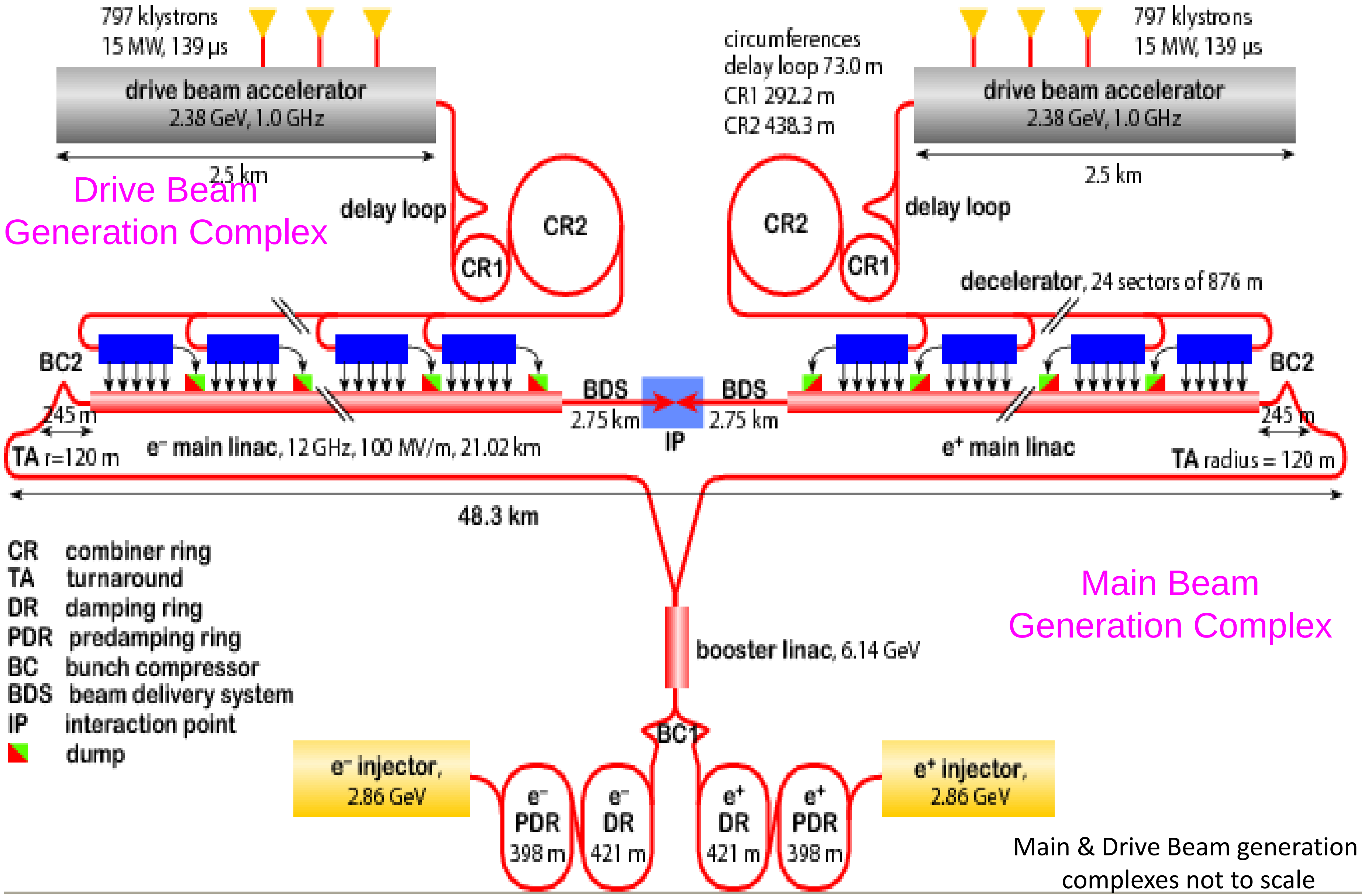
CLIC: “Transformer ratio” of
~1.5 TeV / 2.4 GeV = 15



Demonstrated experimentally at the CLIC Test facility at CERN.

Animation courtesy
SLAC ACD group
(A. Candel)

CLIC : a multi-TeV LC option



Main & Drive Beam generation complexes not to scale

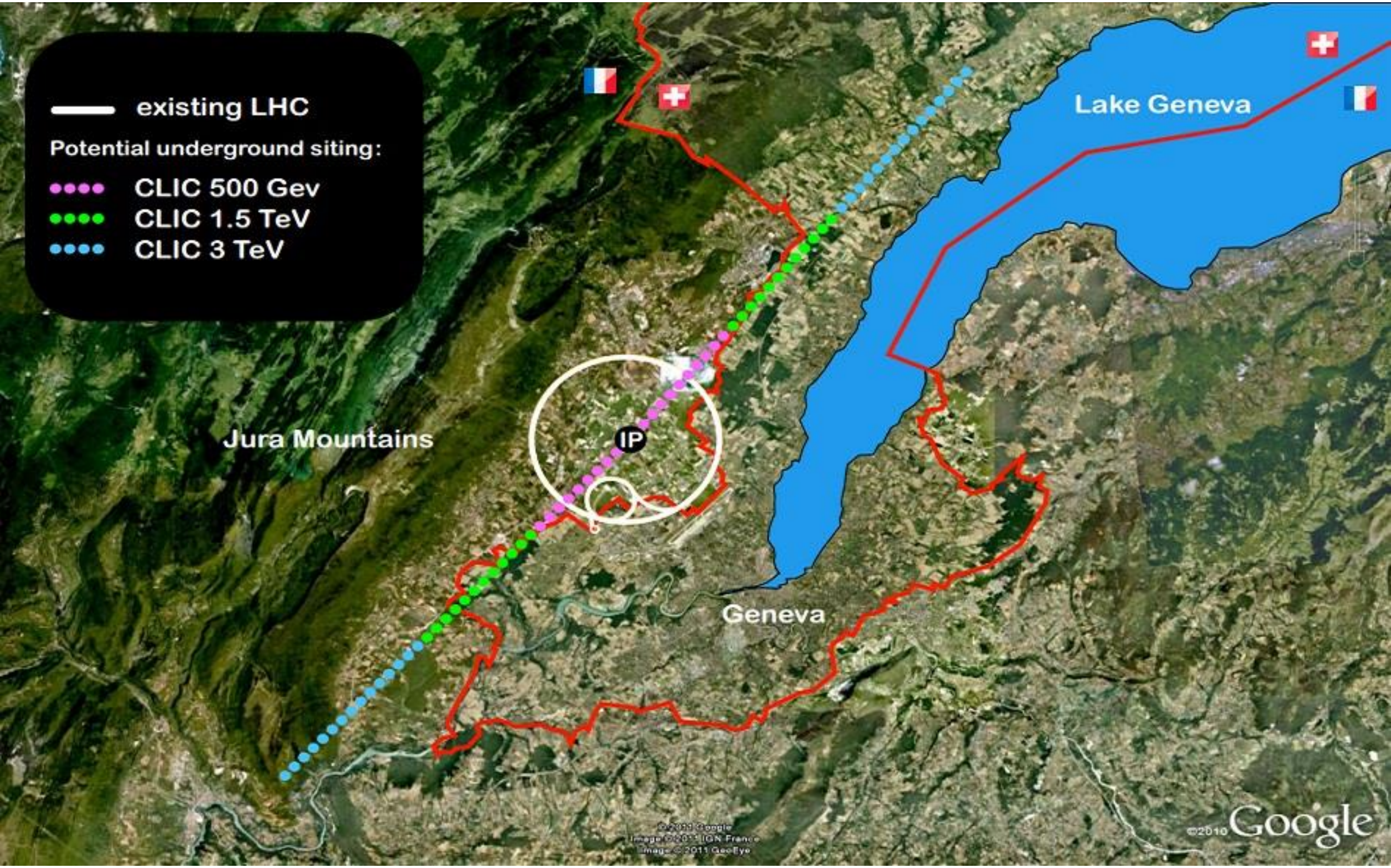
The CLIC collaboration

ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETHZurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)

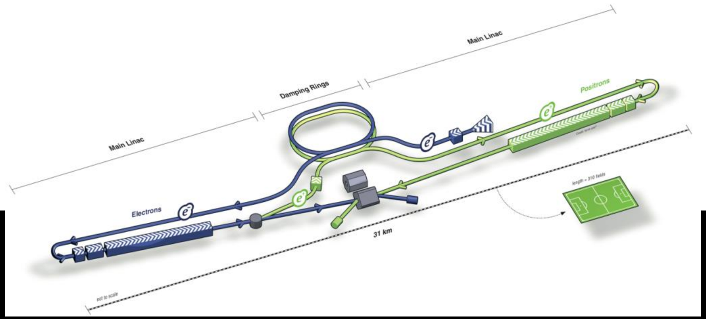
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
IHEP (China)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute/Oxford (UK)

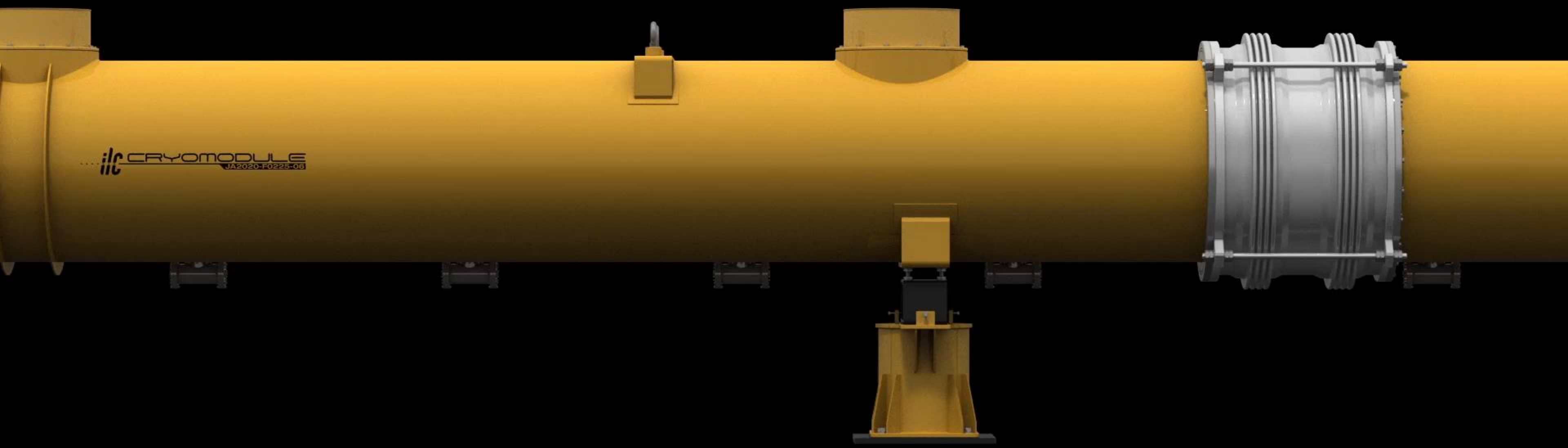
John Adams Institute/RHUL (UK)
JINR (Russia)
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NIKHEF/Amsterdam (Netherland)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Patras University (Greece)

Polytech. University of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
Uppsala University (Sweden)
UCSC SCIPP (USA)


existing LHC
Potential underground siting:
CLIC 500 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
©2010 Google

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.

Summary:

Main parameters characterizing
a high-energy physics accelerator

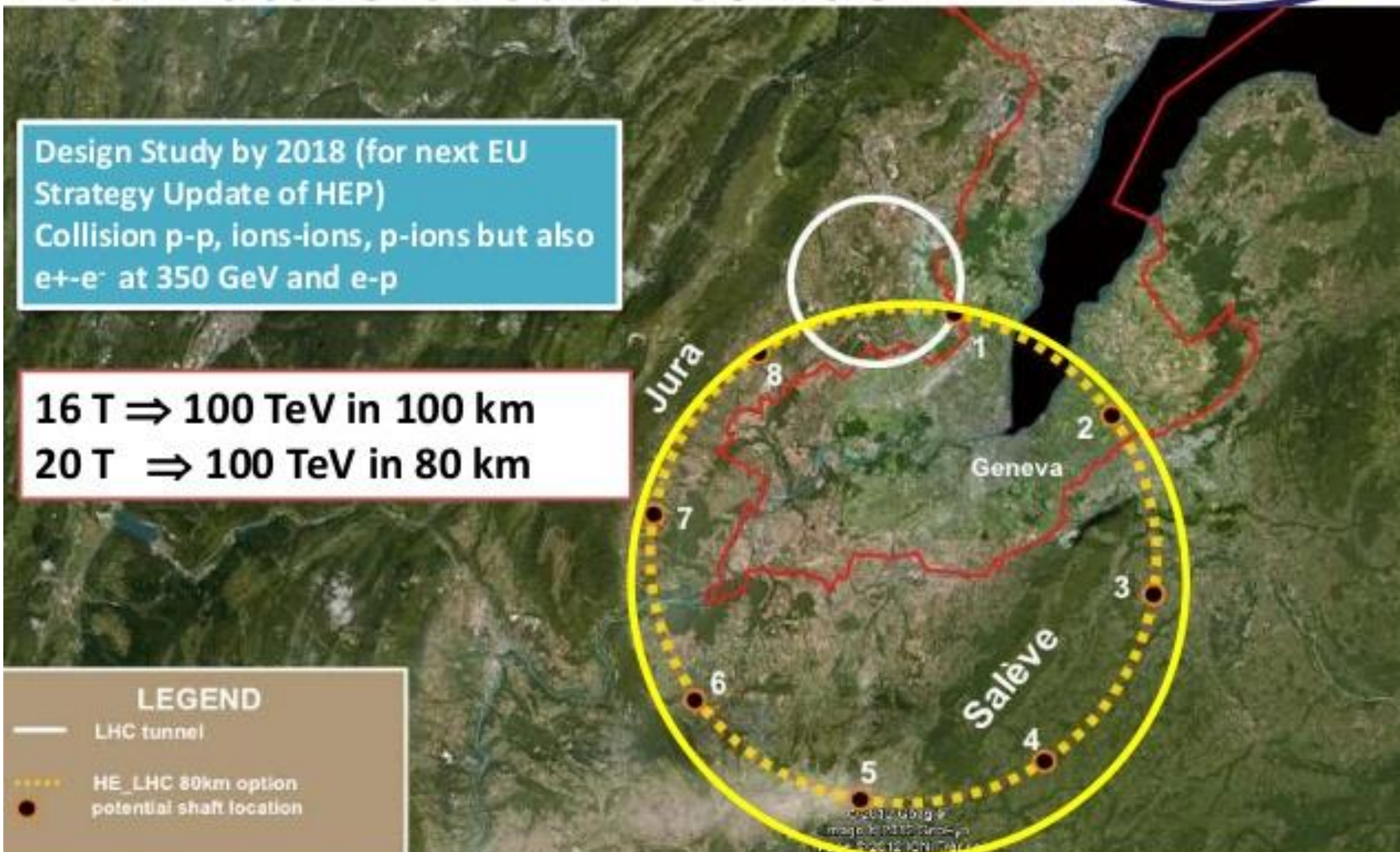
- Particle type
- Energy spectrum
- Emittance
- Focusing
- Charge per time
- Time structure
- …

Luminosity

New project under consideration:
FCC: Future Circular Collider

Design Study by 2018 (for next EU Strategy Update of HEP)
Collision p-p, ions-ions, p-ions but also e^+-e^- at 350 GeV and e-p

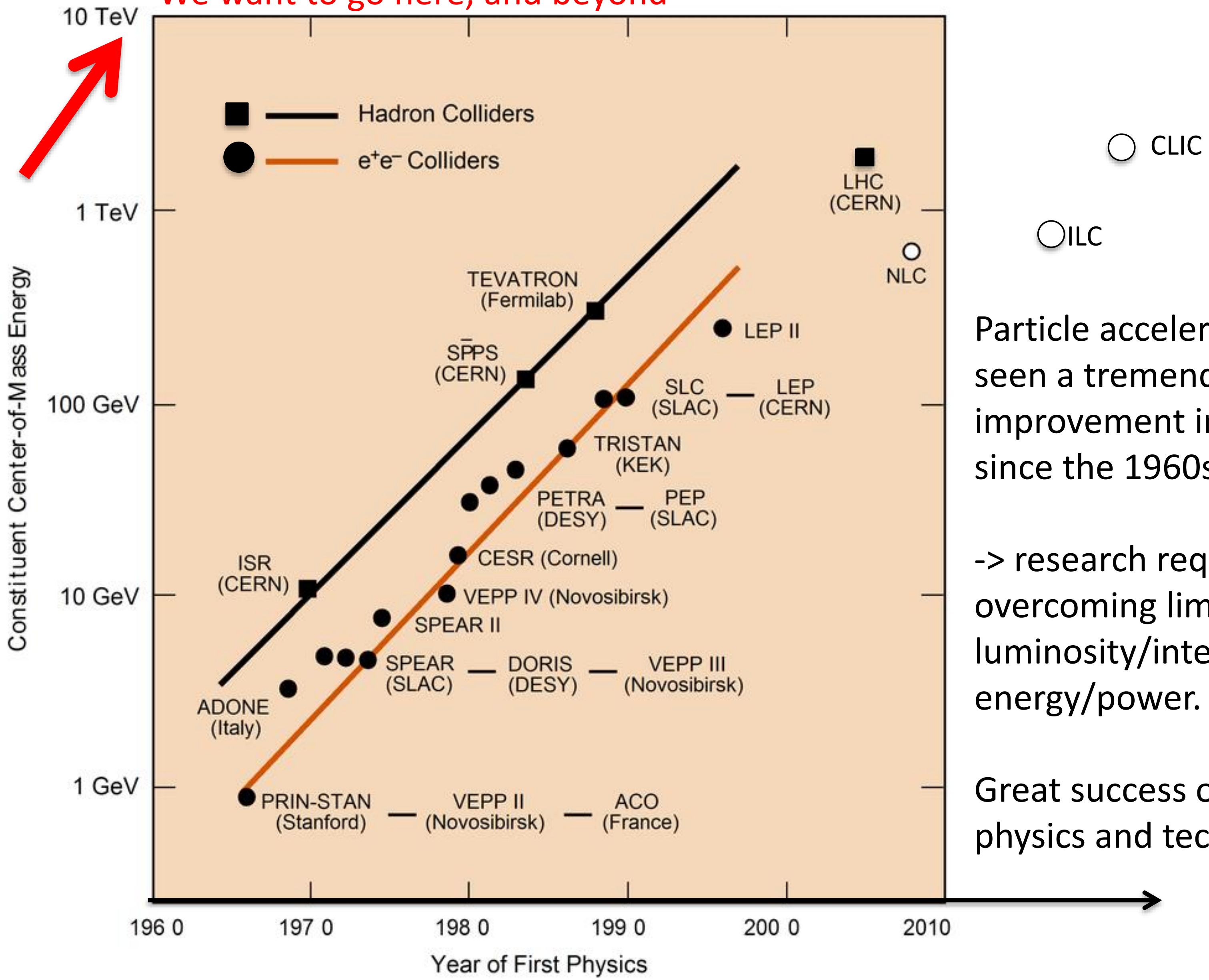
16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km



Novel Acceleration Techniques

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.

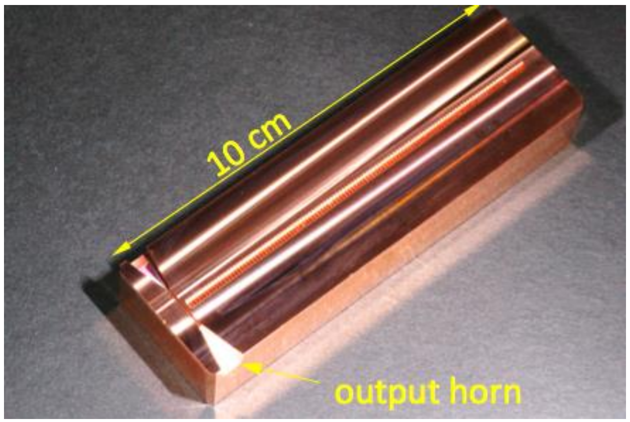
Great success of accelerator physics and technology.

Novel accelerator research

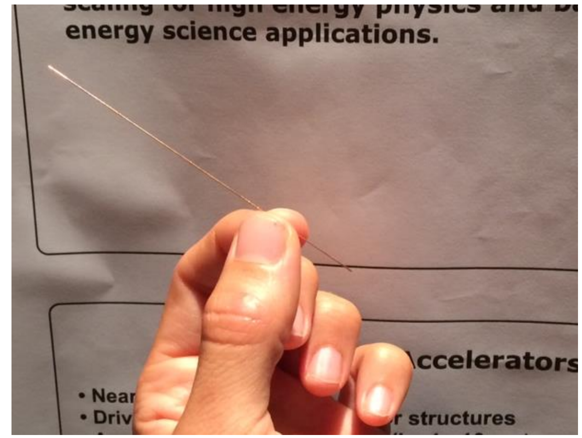
Cutting edge accelerator physics research, with the objective of **overcoming limitations** of conventional accelerator technology.

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

116 GHz structure (SLAC)



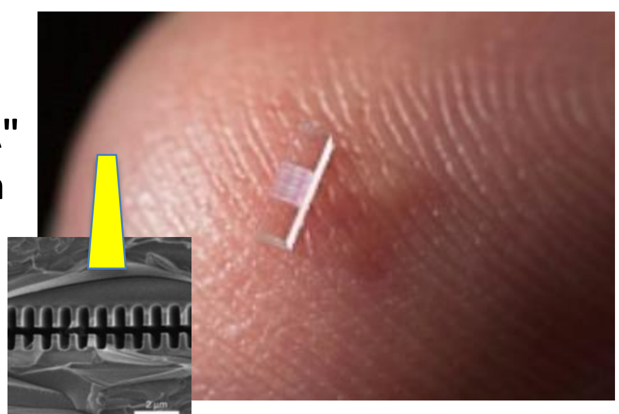
Dielectric structures



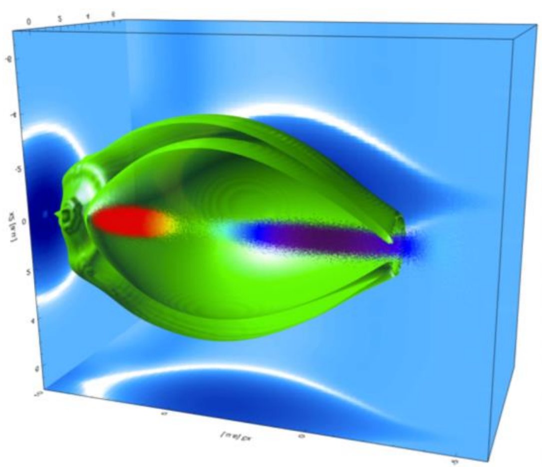
SiO_2

~1.0 THz,
1-10GV/m

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



Feed of laser beam into Si structure



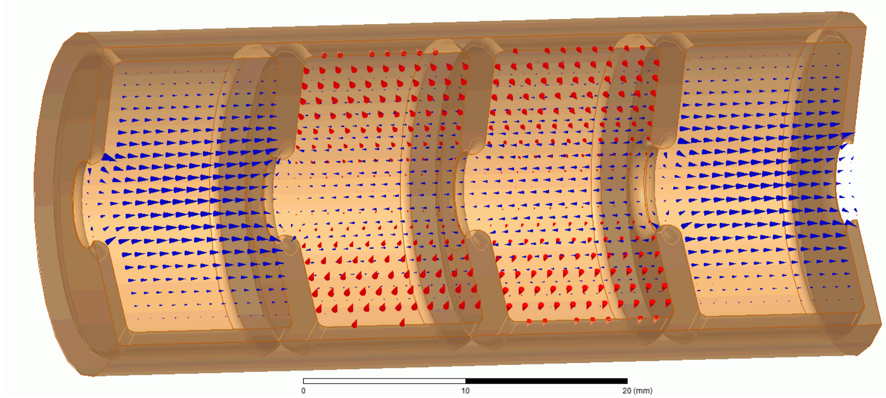
Plasma wakefield acceleration

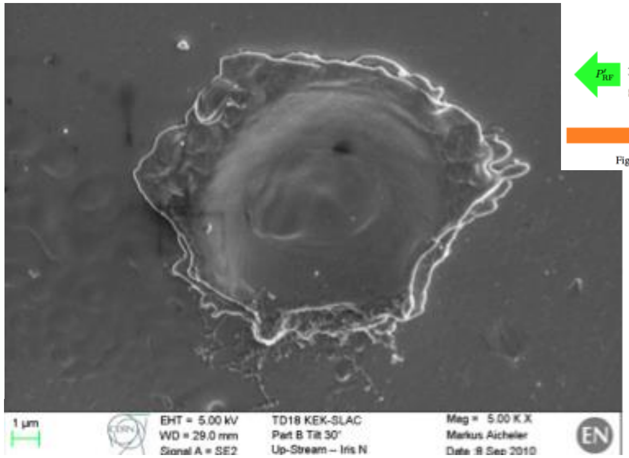
The topic here.

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.*





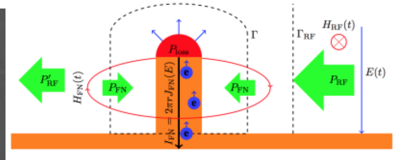
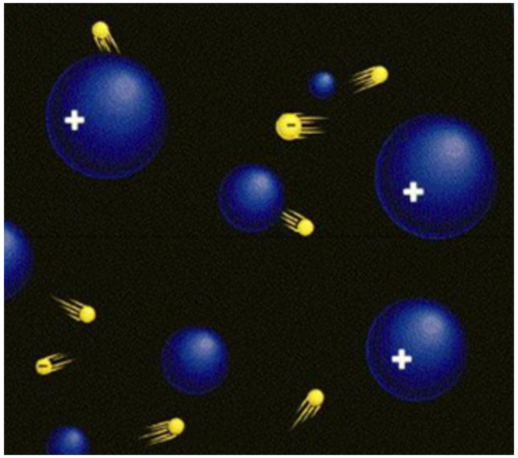


Figure 4.3.: Power flows around a field emitter tip in an RF cavity.

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 $n_0 = n_e = n_{ion}$:

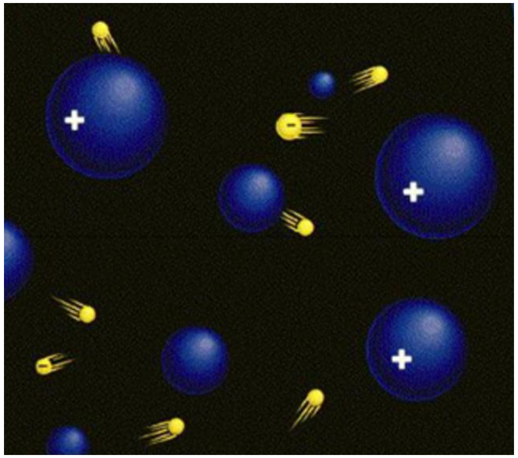
Scale of electrical fields (1D) :

Gauss' law:

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

Plasma electron frequency :

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



Assume wave solutions:

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

Apply Gauss' law:

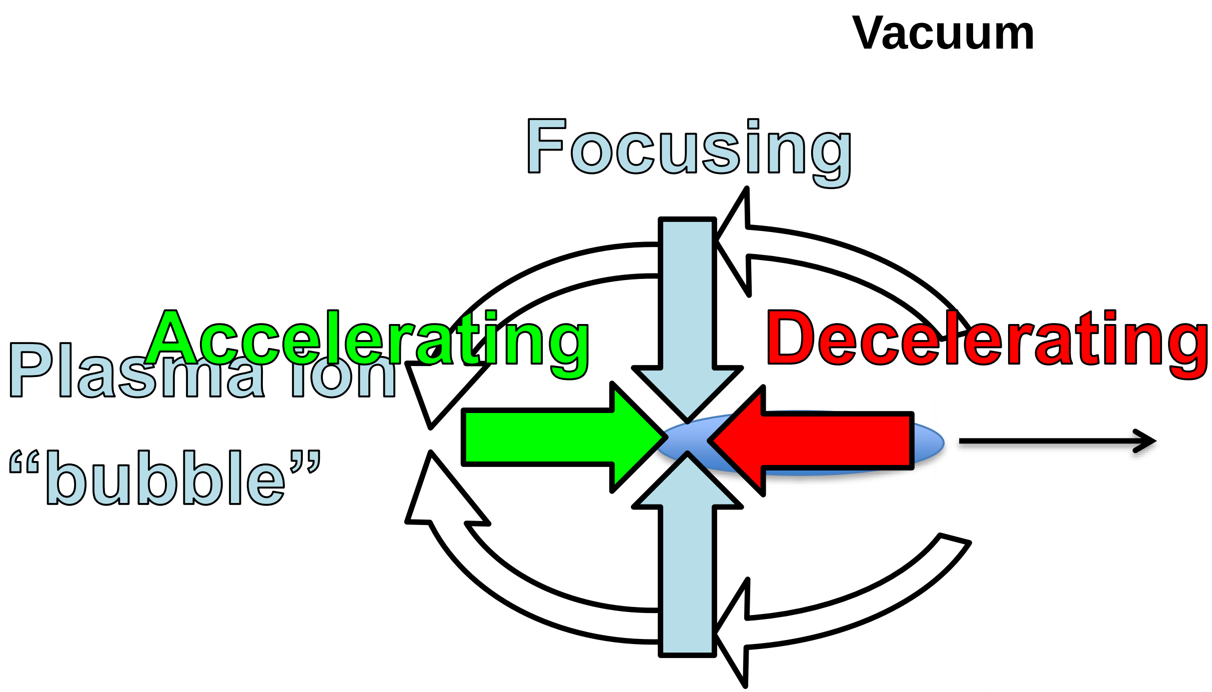
$$\frac{e n_0}{\varepsilon_0} = E_0 \frac{\omega_p}{c} \Rightarrow \boxed{E_{WB} = \frac{e c n_0}{\varepsilon \omega_{0p}}} \sim \sqrt{n_0}$$

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

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

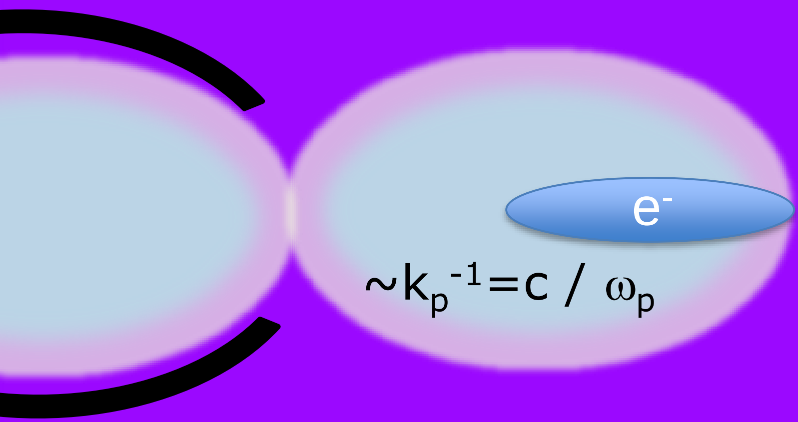
n_0 = 1e17/cm3 : **E_{WB} = 30 GV/m**

Plasma Wakefield acceleration



A driver (here: electron beam) propagates to the right into a neutral plasma.

Plasma Wakefield acceleration



Typical scales :

n_0 ~ 10^{14}-10^{18}/cm3

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

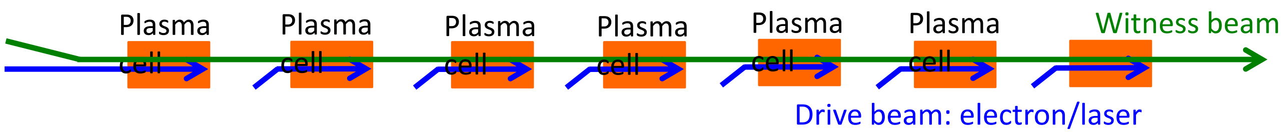
Length : $k_p^{-1} = \lambda_p/2\pi$ ~ **5-500 μm** ~ $\sqrt{n_0}$

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)

Towards TeV beams

While GeV acceleration in plasmas has been demonstrated for with both lasers and electron beams, reaching TeV scales requires **staging** of many drivers and plasma cells. **Challenging.**



A possible witness beams:

Electrons: 10^{10} particles @ 1 TeV

~few kJ

Existing driver beams options :

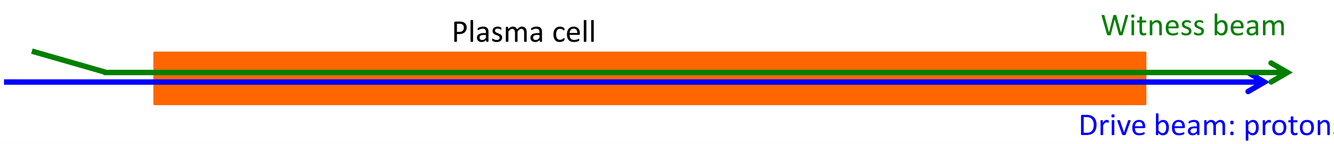
Lasers: up to 40 J/pulse

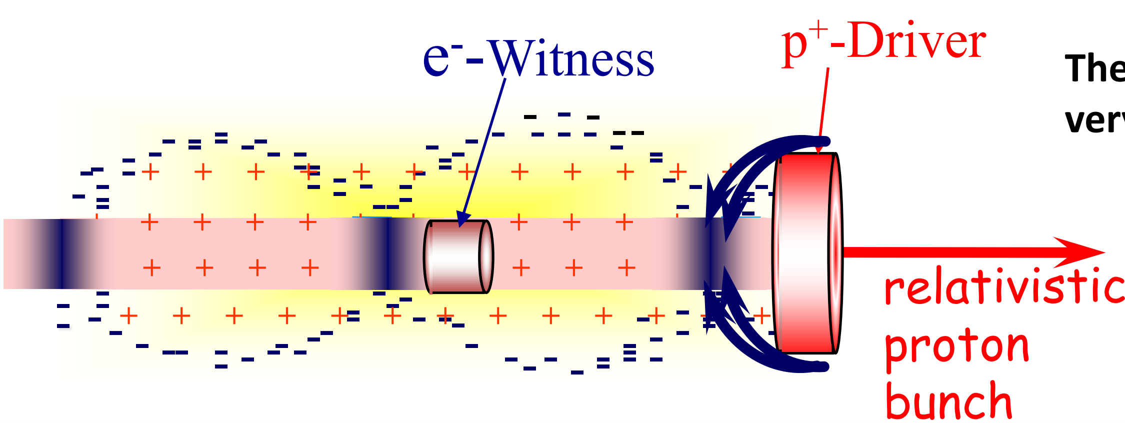
Electron driver: up to 60 J/bunch

Proton driver: **SPS 19 kJ/bunch**, LHC **300 kJ/bunch**

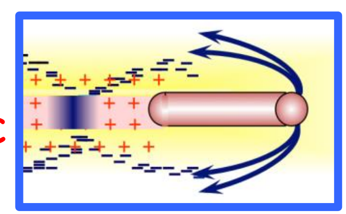
Proton drivers: large energy in proton bunches → can consider **single stage TeV acceleration**:

- A single SPS/LHC bunch could produce an ILC bunch in a single proton driven PWA stage.





The wake of short proton drivers (~k_p^{-1}) is very similar to that of electrons drivers.



Long term hope? Linear collider based on PWFA?

Numerous challenges. **Jury still out** if a colliders based on PWFA is feasible/advantageous.

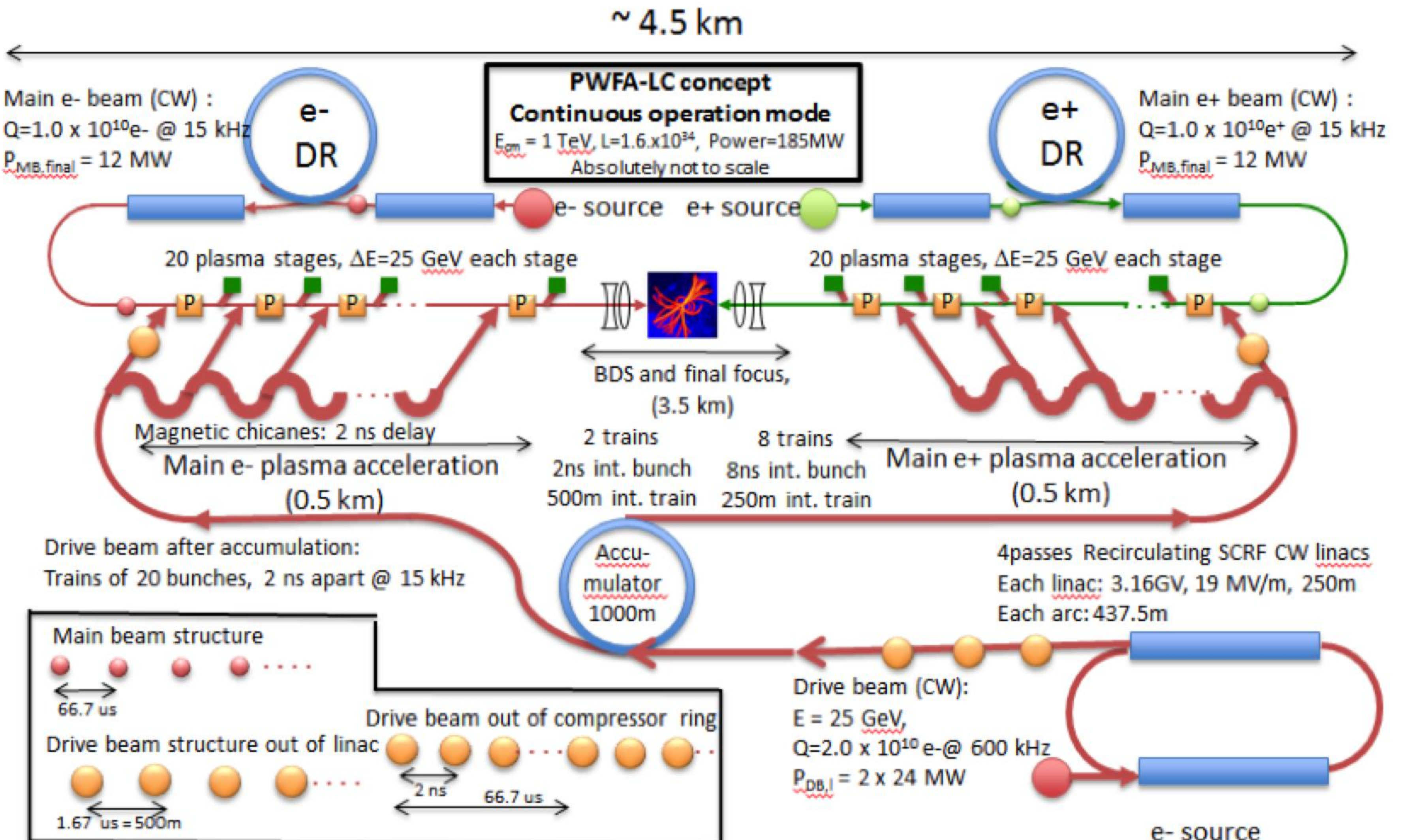


Figure 1: Illustration of a PWFA-LC layout for 1TeV.

J.P.Delahaye, E. Adli et al., White Paper input to US Snowmass Process 2013. **arxiv 1308.1145**

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

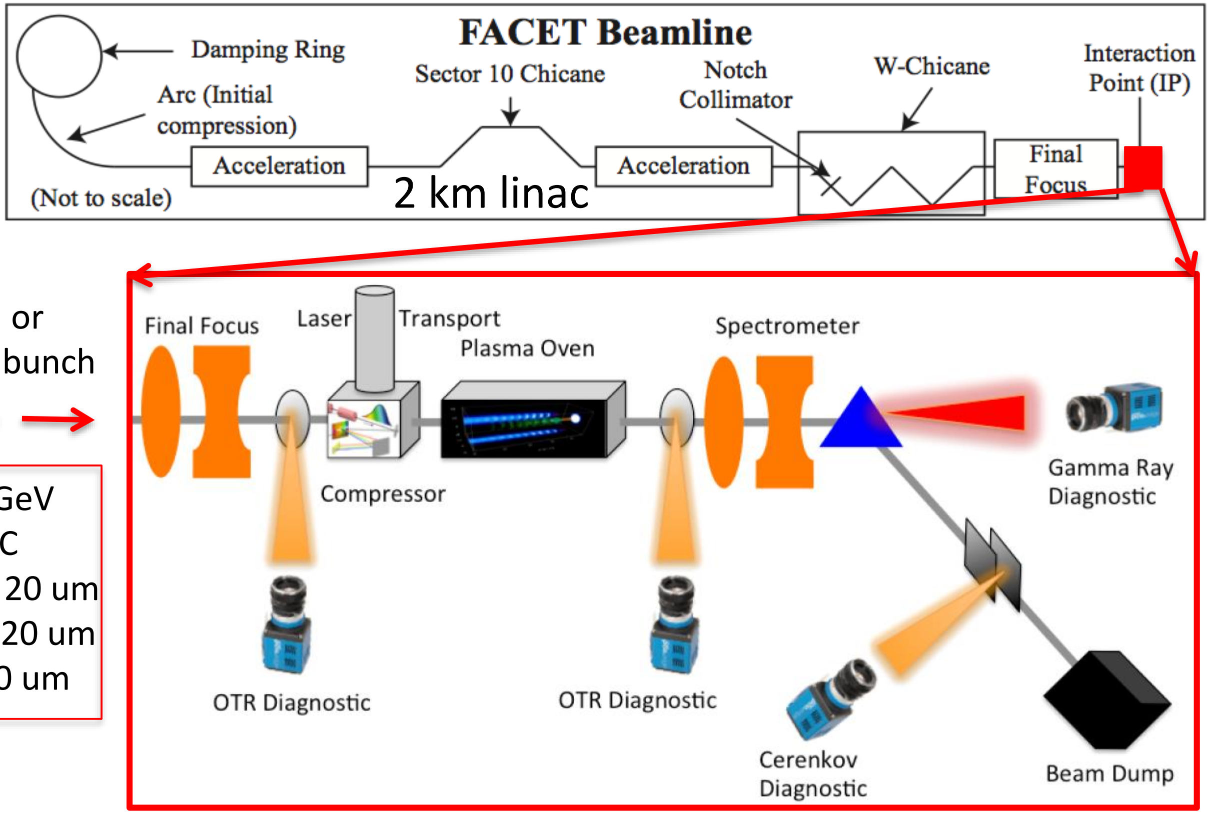
AWAKE TEDX:
https://www.youtube.com/watch?v=5Ryp6UTCeUo

Development of novel accelerators

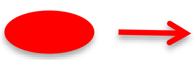
Currently a large experimental R&D effort to develop novel accelerators based on plasma and other technologies :

1. Meter scale plasmas ✓
1. High gradients ✓
1. Low energy spread ✓
1. High efficiency ✓
1. Multi GeV e^+ PWFA ✓
1. Emittance preservation

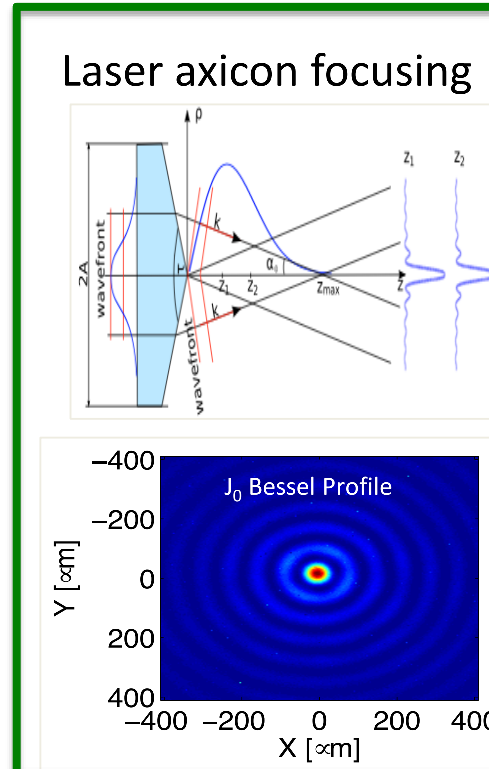
Development of novel accelerators



Electron, or Positron bunch

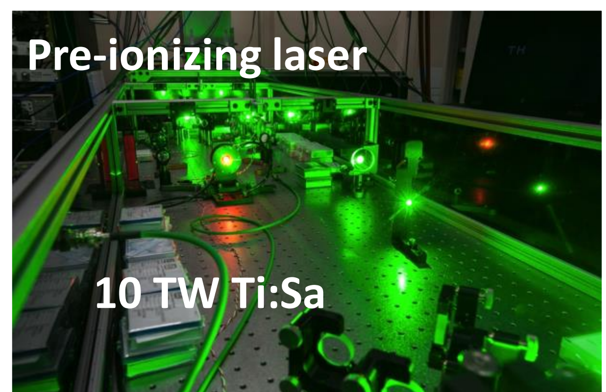


$E = 20$ GeV
$Q = 3$ nC
$\sigma_{z,min} = 20$ um
$\sigma_{r,min} = 20$ um
$\varepsilon_n \sim 100$ um

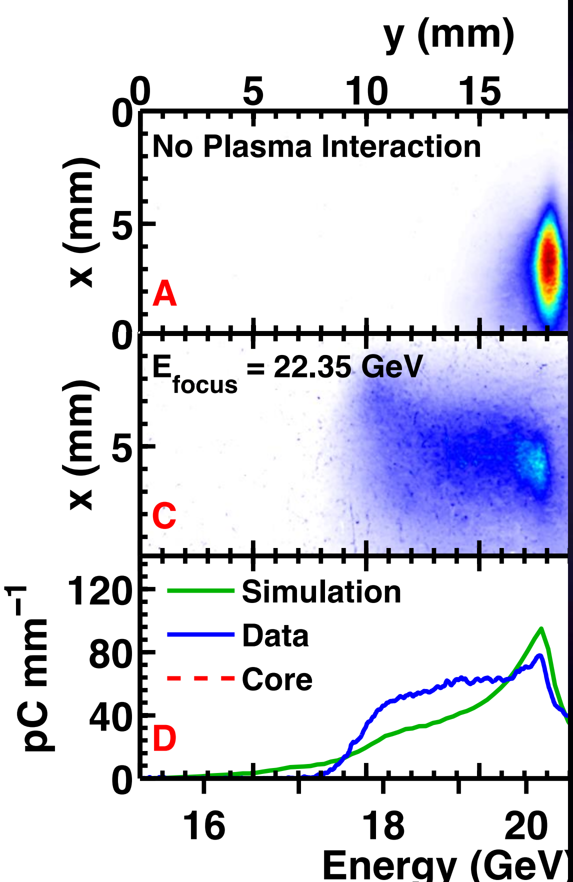


Plasma densities, n_0, 10^{16}-10^{17}cm^{-3}

~ 1 m length



FACET two-bunch results



2013

n in

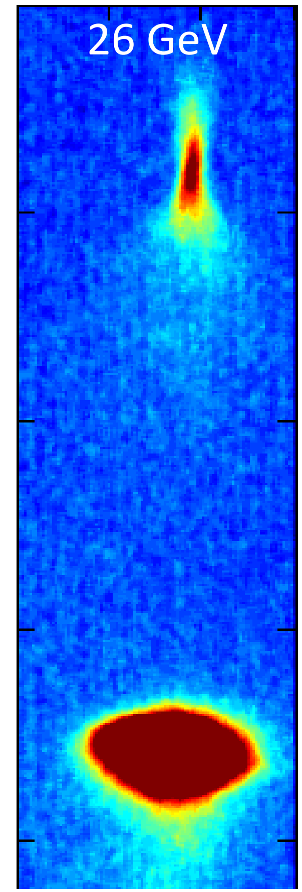
d Li

sfer

3%).

in

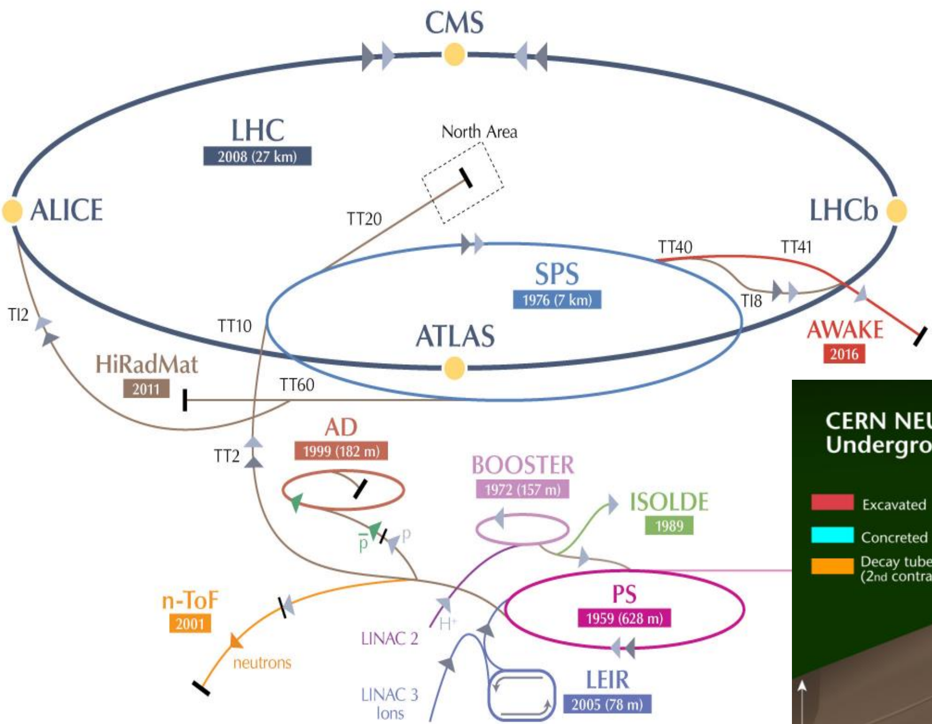
1.3 m plasma



2014

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

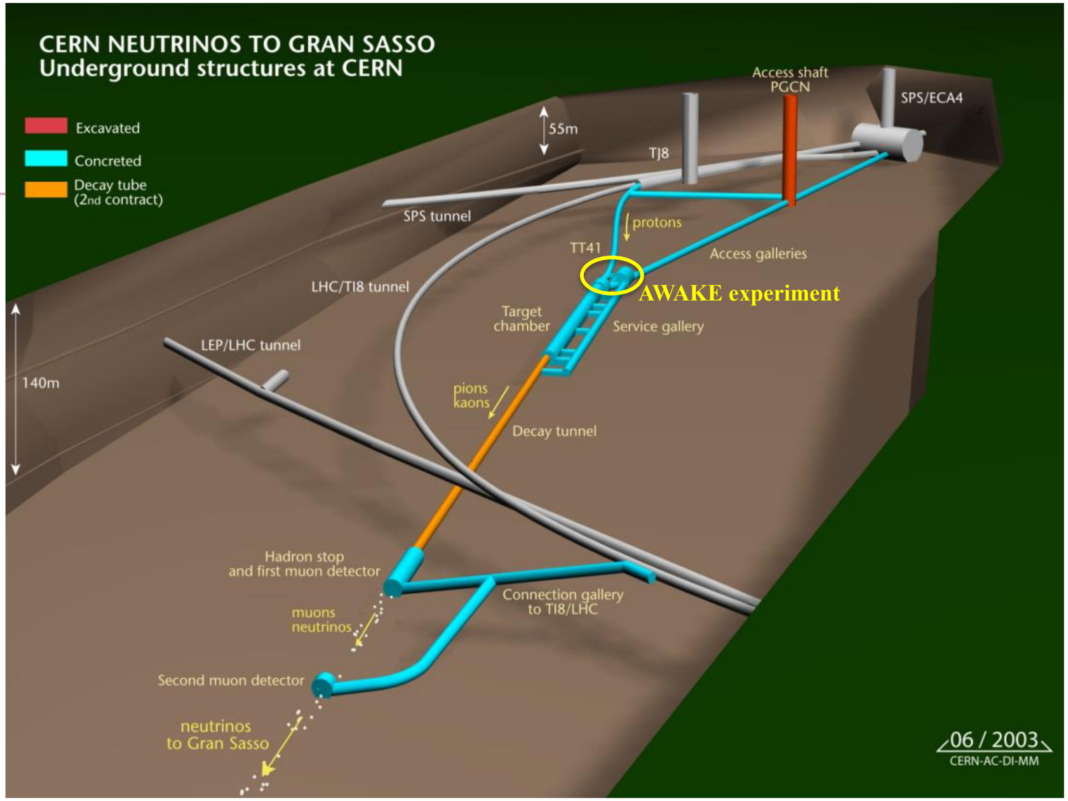
AWAKE: plasma wakefield at CERN



AWAKE is installed in

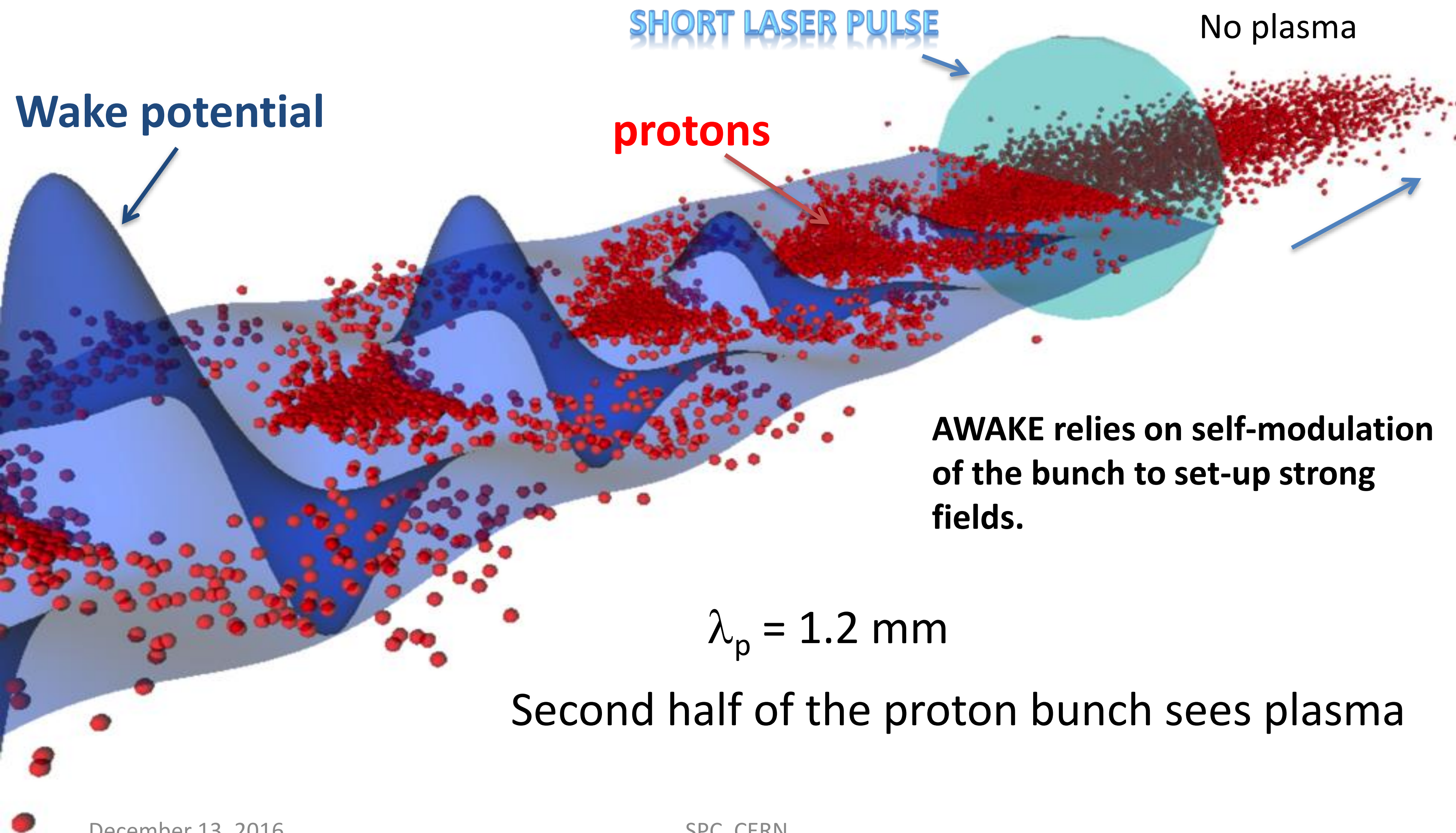
CNGS Facility (CERN Neutrinos to Gran Sasso)

→ CNGS physics program finished in 2012



A. Caldwell et al., "Path to AWAKE: Evolution of the concept", Nucl. Instrum. Meth. A829 (2016) 3-16; E. Gschwendtner et al. [AWAKE Collaboration], "AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN," Nucl. Instrum. Meth. A829, 76 (2016).

Seeded self-modulation instability of a long proton bunch in plasma

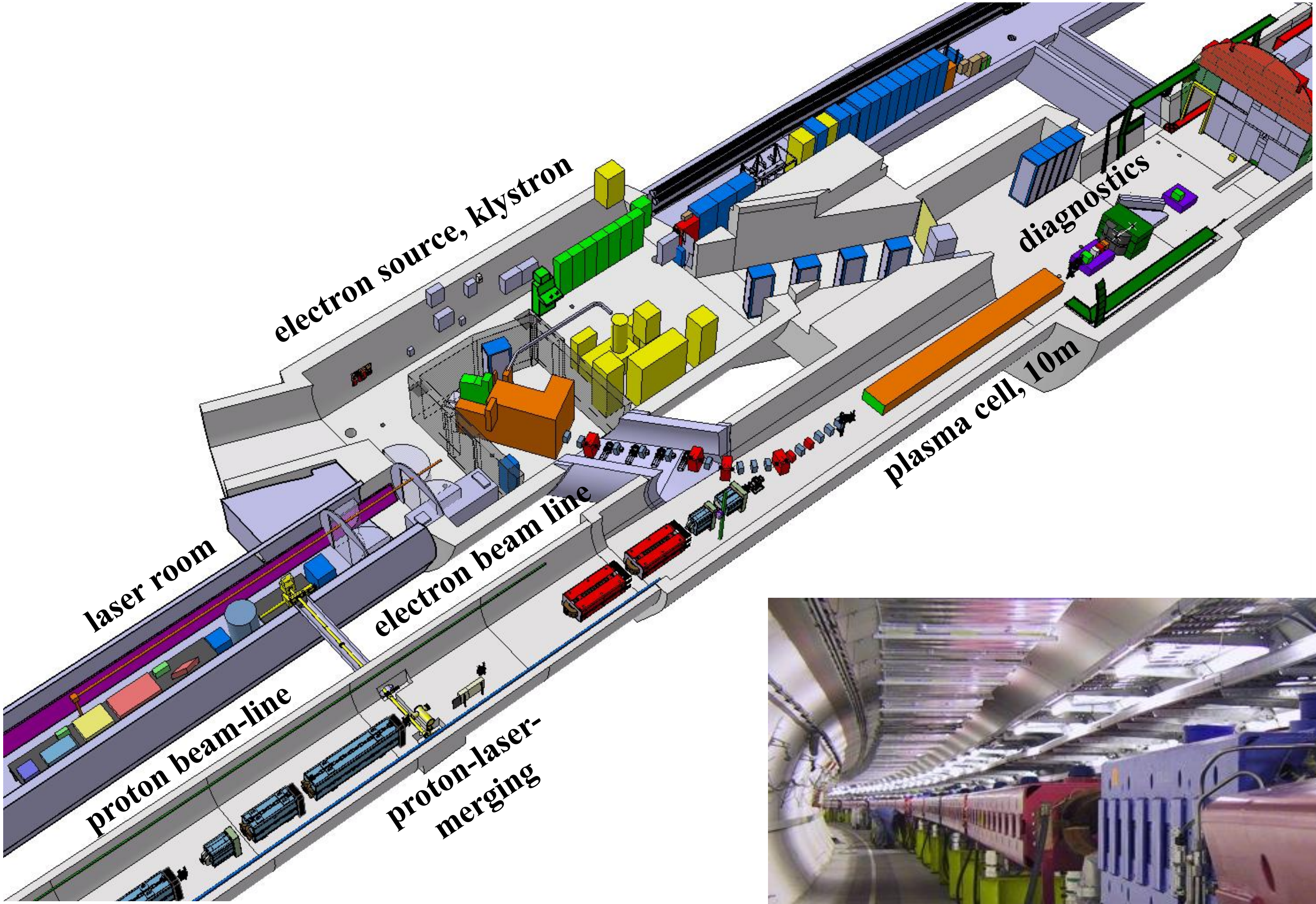


AWAKE relies on self-modulation of the bunch to set-up strong fields.

$\lambda_p = 1.2$ mm

Second half of the proton bunch sees plasma

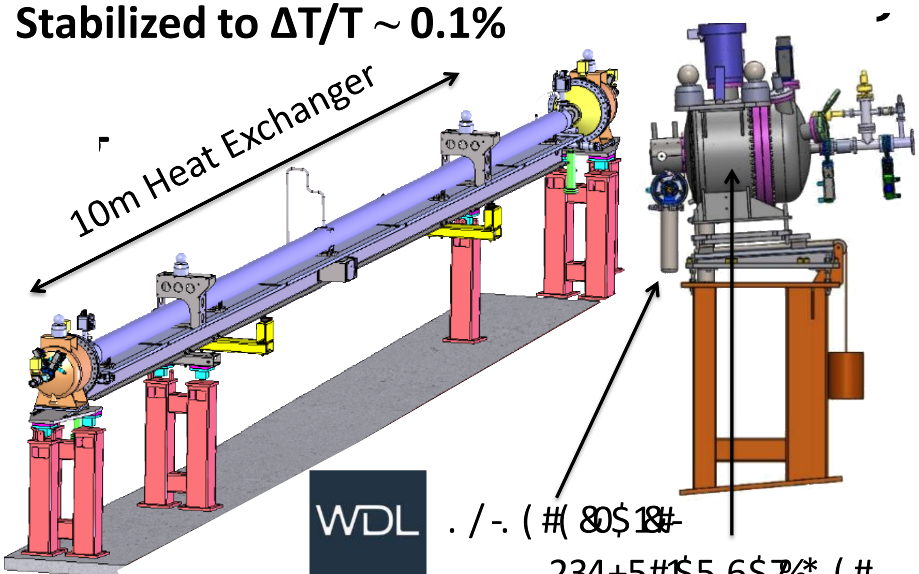
AWAKE Overview

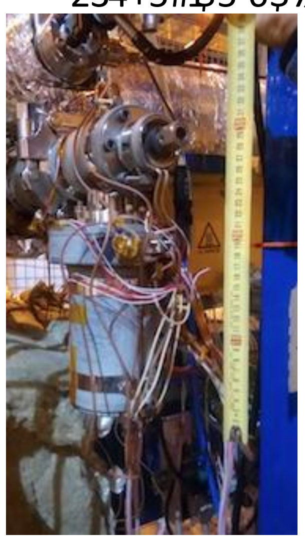


The 10 m AWAKE Rb vapour cell

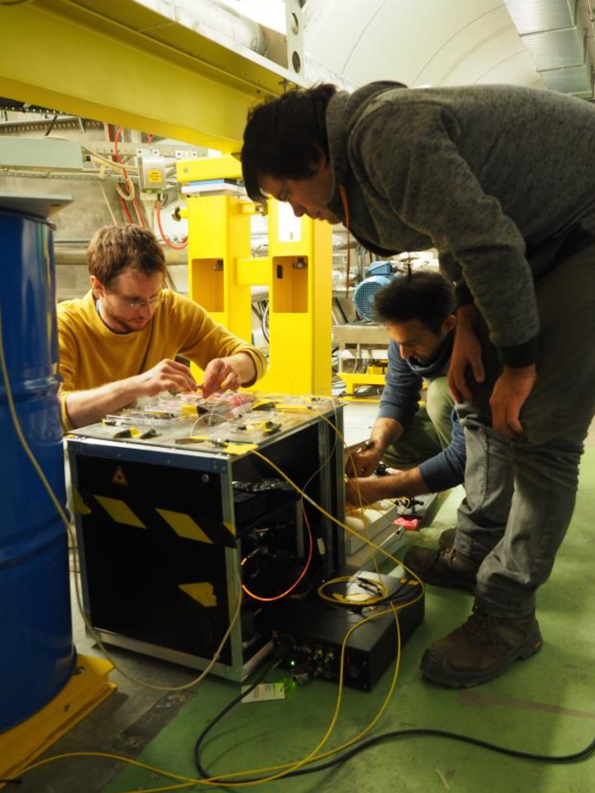
E. Oz and P. Muggli, Nucl. Instr. Meth. Phys. Res. A 740 (11) 197 (2014)

Stabilized to ΔT/T ~ 0.1%





The AWAKE experiment

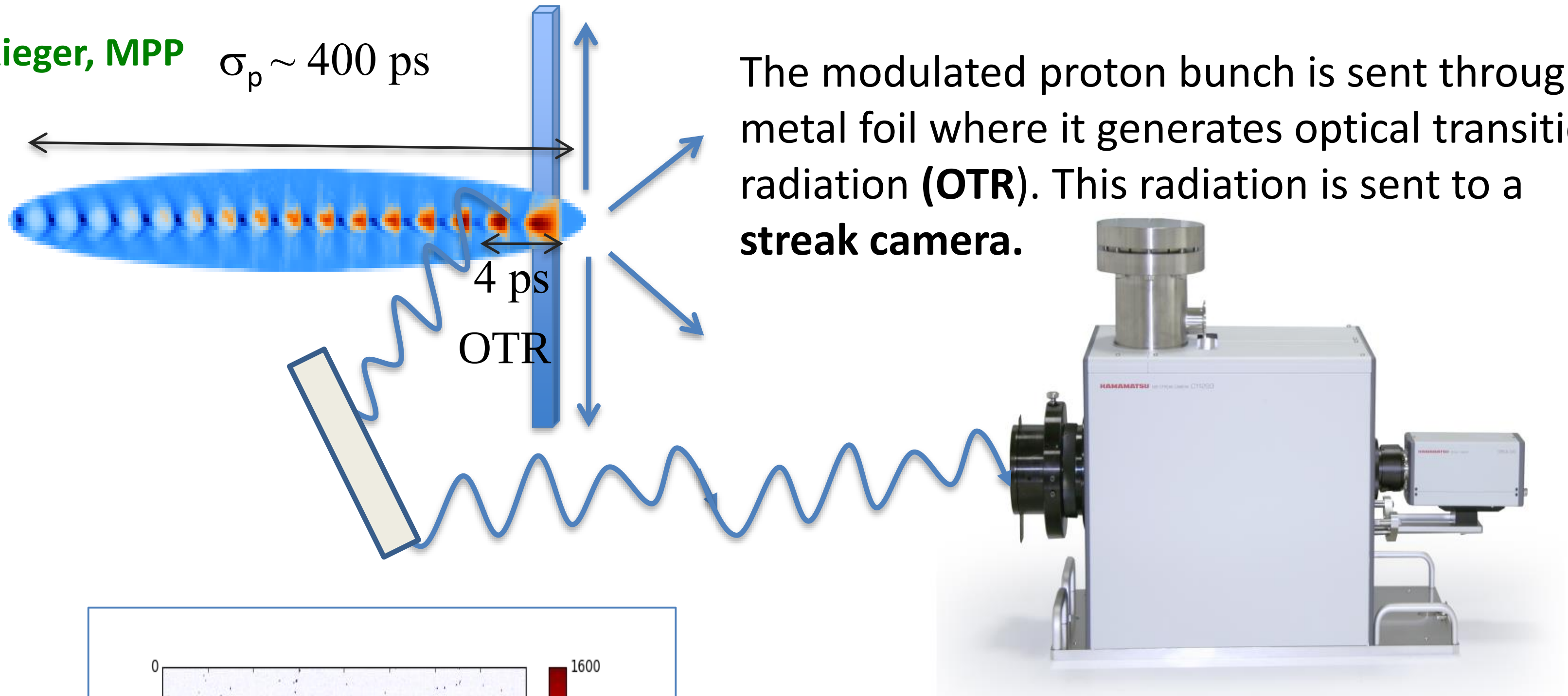




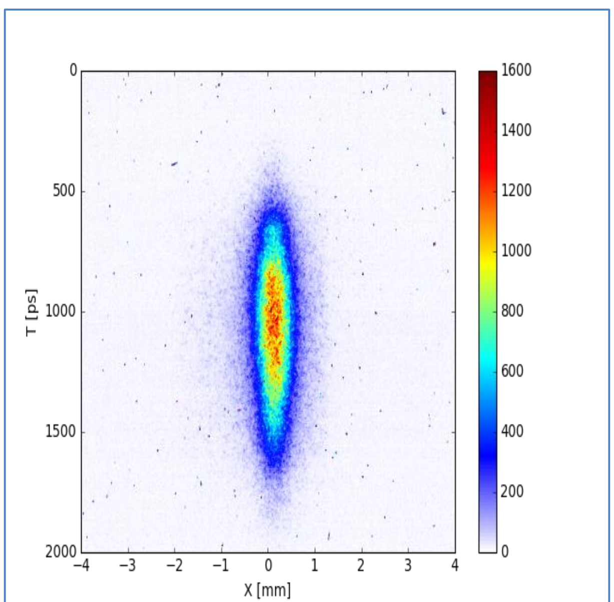


SMI measurements I: streak camera

K. Rieger, MPP



The modulated proton bunch is sent through a metal foil where it generates optical transition radiation **(OTR)**. This radiation is sent to a **streak camera.**

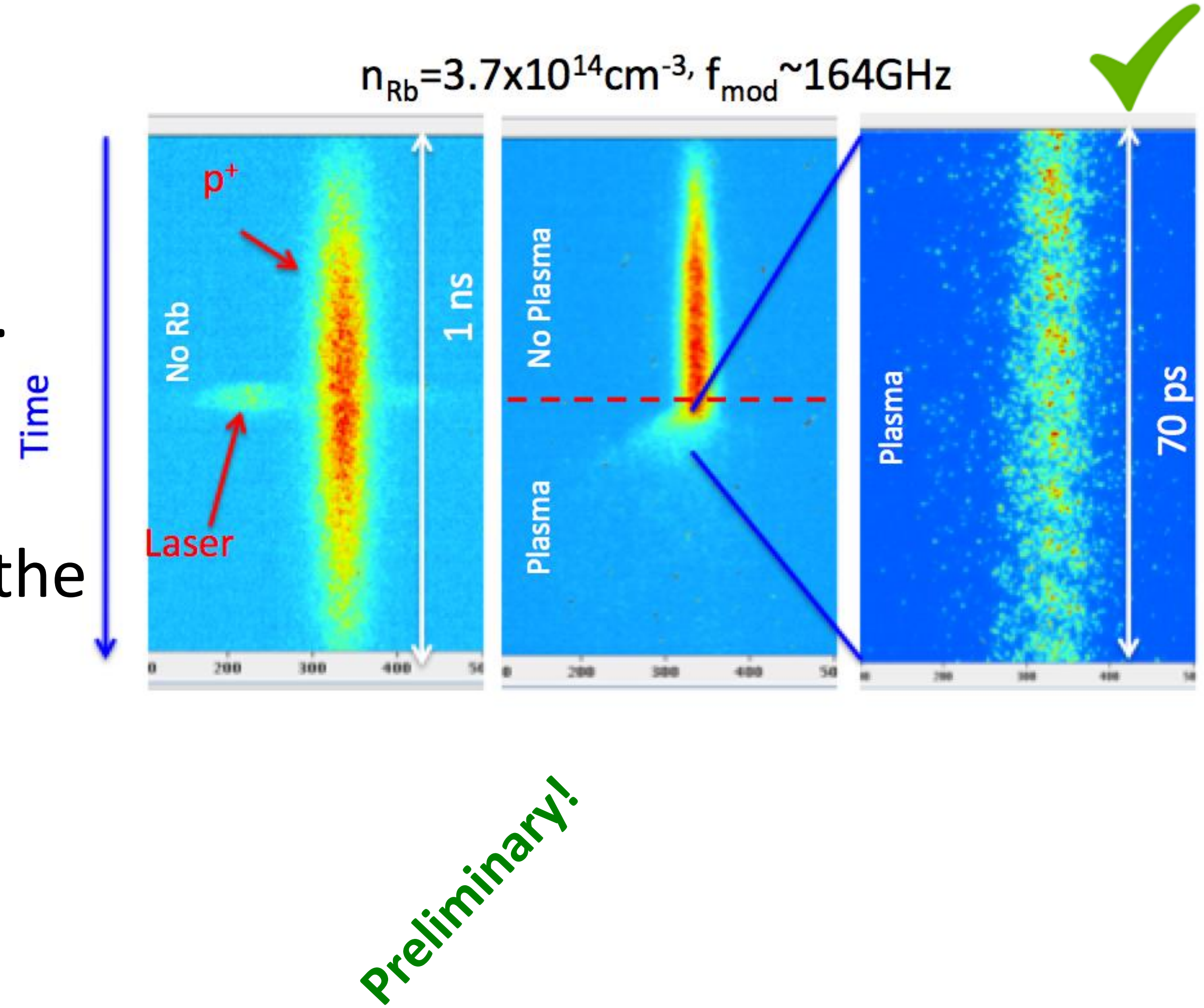


Left: the 12 cm SPS bunch as measured with the streak camera without plasma in the beamline. The bunch is typically straight with no visible structure.

Success! Observation of Seeded SMI

The laser pulse ionizes the plasma about mid-way through the beam.

Observed microbunching at the seeded beam undergoes in the region trailing the plasma.



K. Rieger, MPP

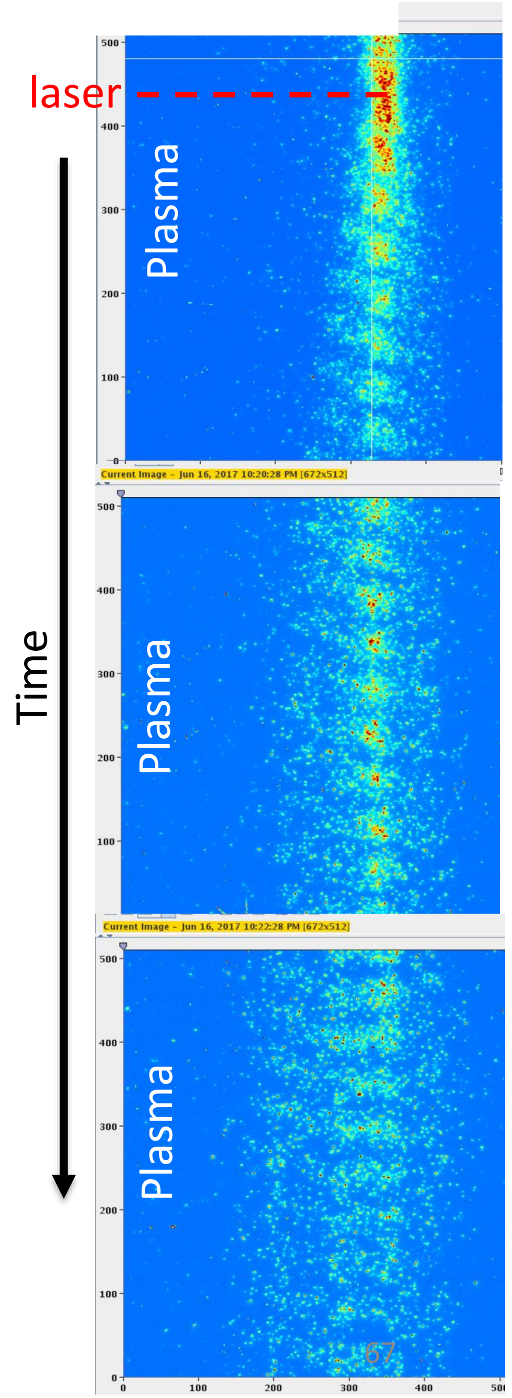
Observation of Seeded SMI

We scan the timing of the streak camera relative to the position of laser ionizations to attempt to observe the total number of microbunches in the beam.

Persistent microbunching is a good indication that the seeding is working and that a large amount of energy is transferred to the plasma wake.

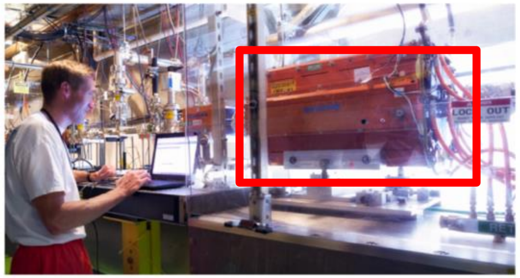
Preliminary!

K. Rieger, MPP



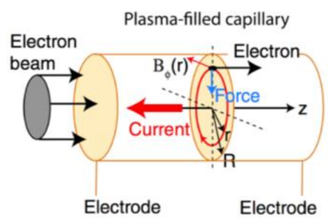
Teaser: compact focusing

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

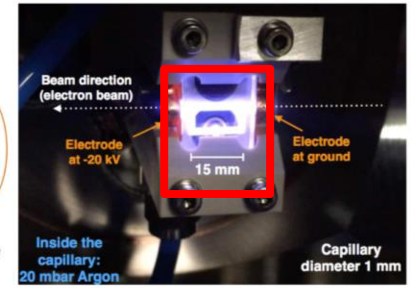


100 cm

c) Principle of an active plasma lens

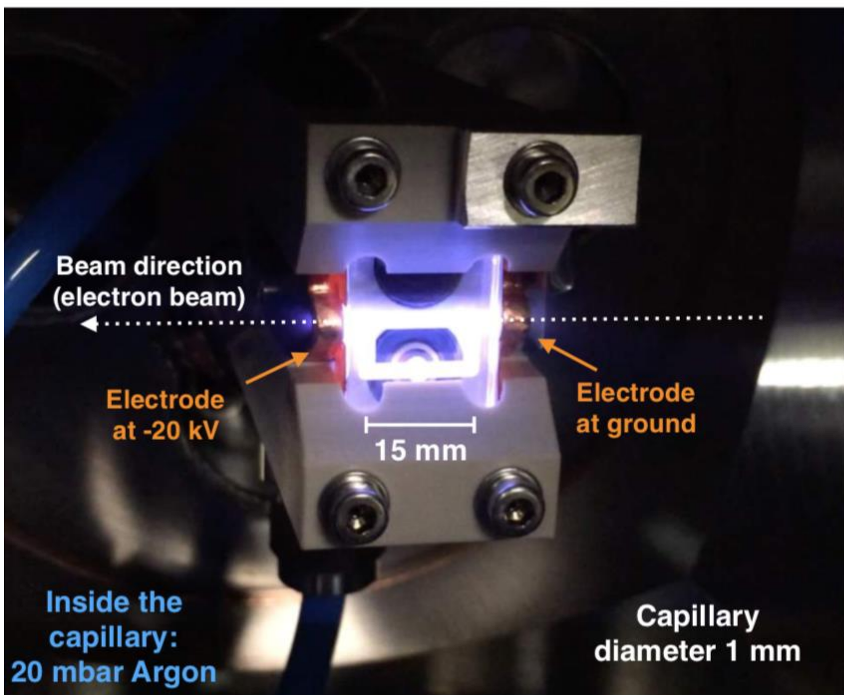


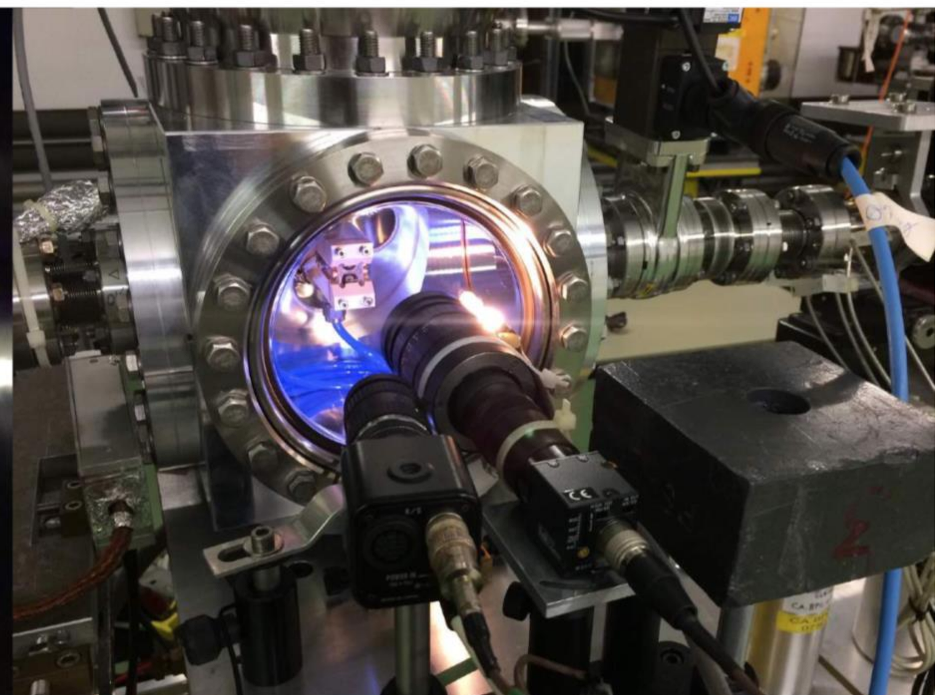
b) The Oslo active plasma lens focusing device



15 mm

The Oslo Plasma Lens Experiment at CLEAR (CERN)

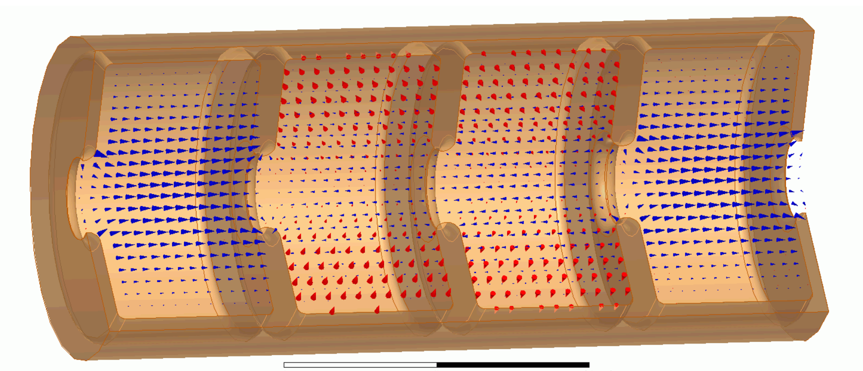




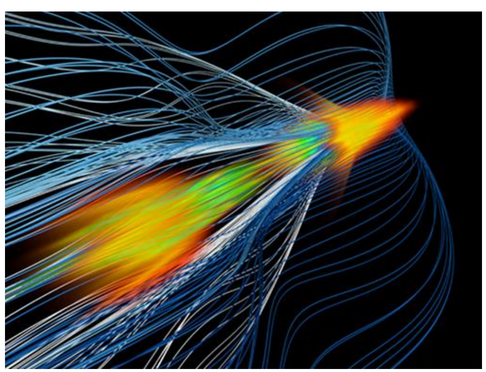
- An experiment to test the operation and characteristics of an active plasma lens.

Summary

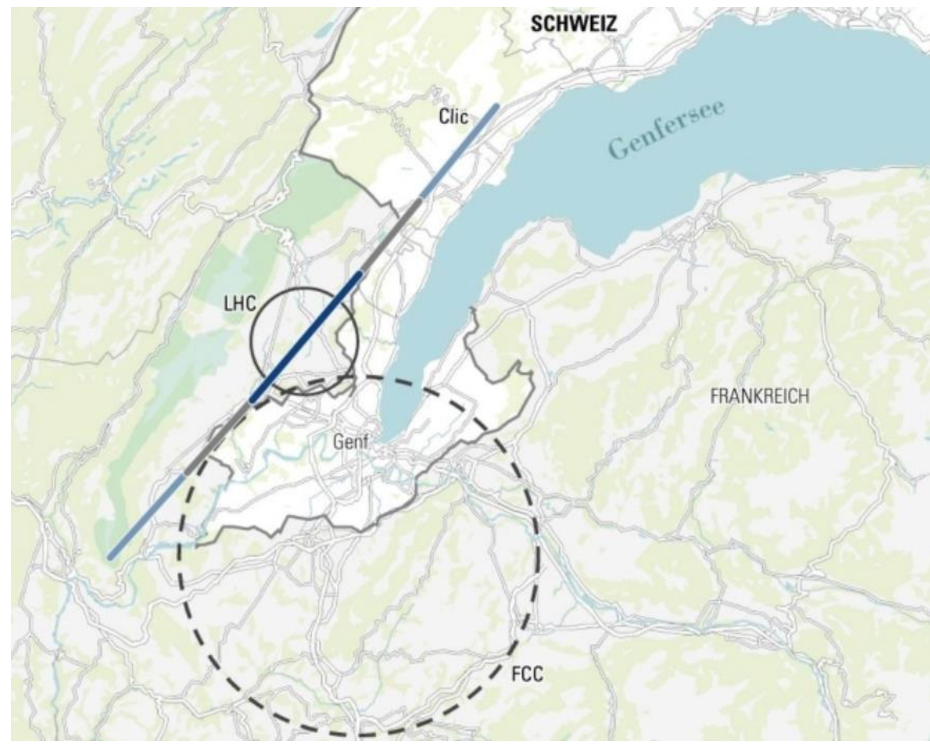
The compact linear collider, CLIC



CLIC 100 MV/m accelerating structure



Plasma wave with accelerating fields



Size of possible future particle colliders, compared to the LHC

Extra

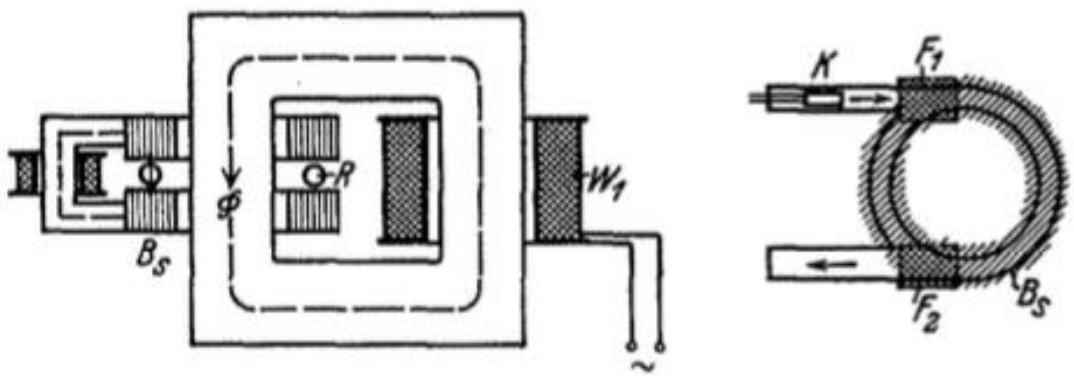
R. Wideröe, Archiv für Elektrotechnik, July 1928, **21**, 4, pp 387–406 :

Sidestep: documented in the same 1928 paper is another invention of Widerøe (which he did not demonstrate): the beam transformer or **betatron accelerator.**

IV. Der Strahlentransformator.

1. Das Prinzip.

In Bild 11 ist die Wirkungsweise des Strahlentransformators schematisch gezeigt. Die Primärwicklung W_1 treibt einen Wechselfluß Φ durch den Eisenkern des Transformators. Als Sekundärwicklung dient die Hochvakuumröhre R. Der Elektronenstrahl wird mittels der Glühkathode K erzeugt und in die Kreisröhre R geführt.



$\dot{B}_s = ½ \langle \dot{B} \rangle$

Bild 11. Wirkungsweise des Strahlentransformators.

Magnetic coils with **time varying fields** provides both focusing and acceleration (through magnetic induction) at the same time. Elegant and compact. Used to accelerate electrons up to few **10s of MeV** at hospitals, including Radiumhospitalet, until the 1980s (now linear RF accelerators are used almost everywhere).

The ESS accelerator is about 600 m long, and accelerates protons to 2 GeV