Lecture 1

Introduction to Particle Accelerators

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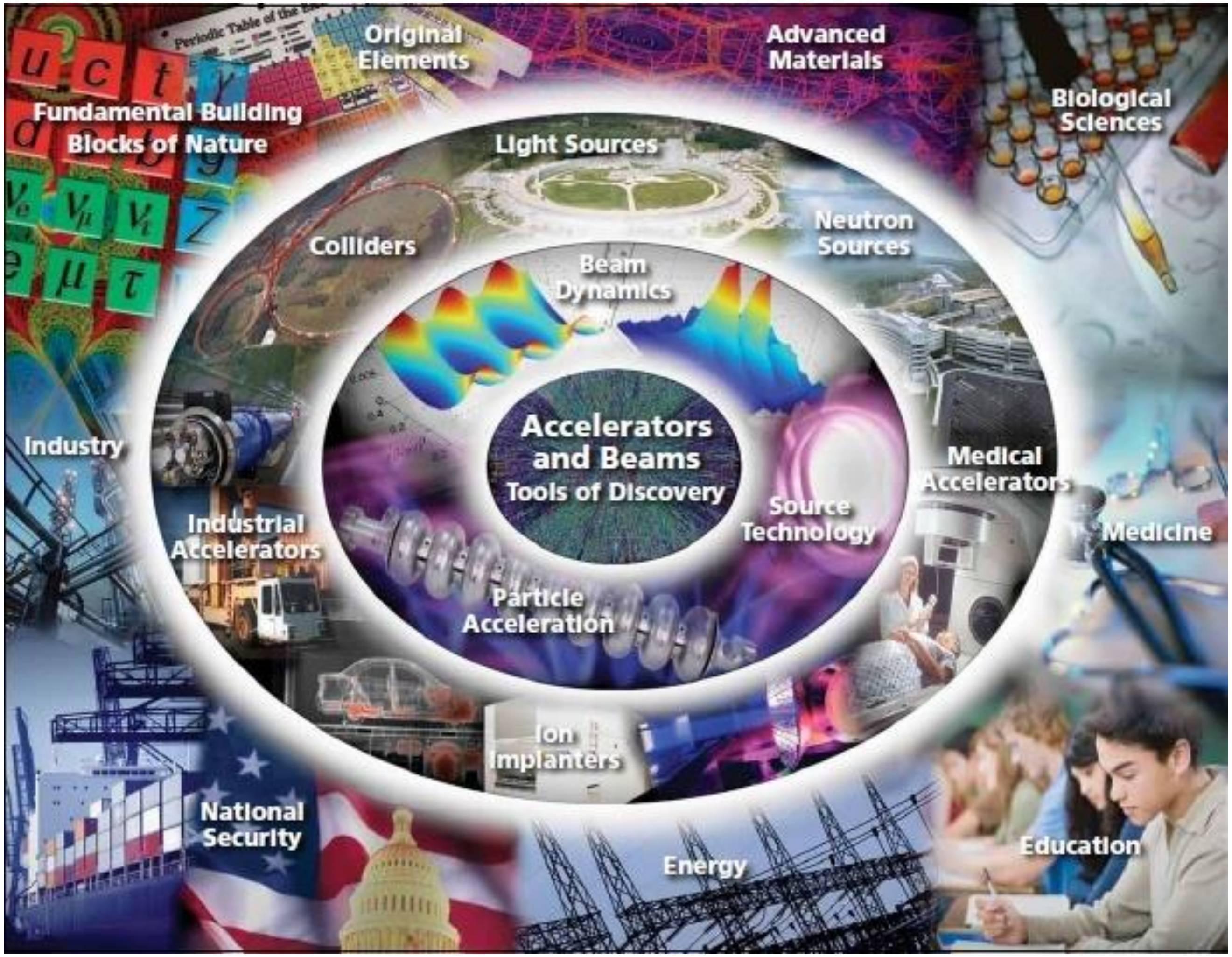
Graduate Accelerator Physics Course
John Adams Institute for Accelerator Science
15 October 2020

JAI Accelerator Physics Course

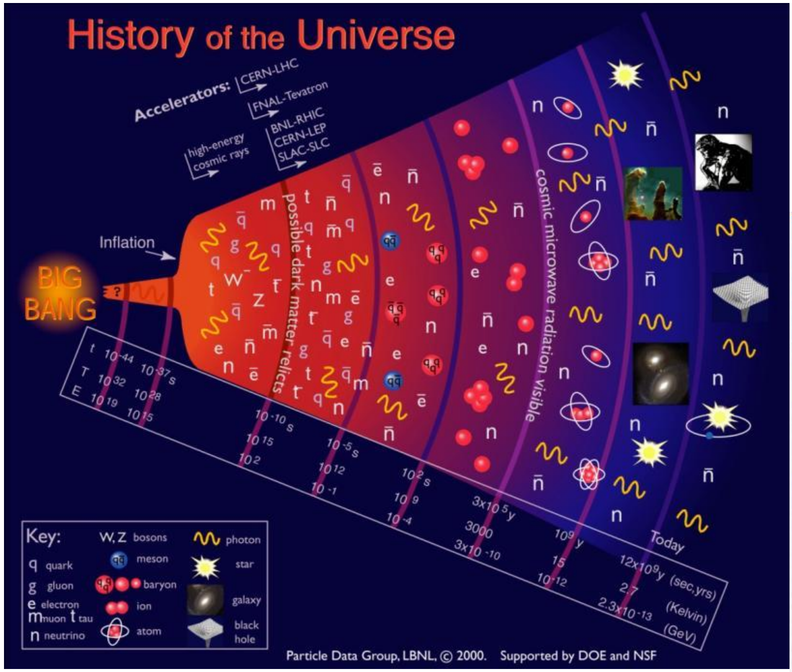
- Delivered over **two Academic Terms**
  - **Term I** (Michaelmas Term 2020)
    - 24 lectures and 6 tutorials
    - First three lectures and first tutorial includes Oxford PP students.
  - **Term II** (Hilary Term 2021)
    - Lectures, tutorials and design Project
- **Course site** is https://indico.cern.ch/category/5869/
  - Includes all lecture / tutorial material, videoconference connection, student handbook etc.
- **Videoconference facility** for remote connection
- Contact Sue Geddes (sue.geddes@physics.ox.ac.uk) for **accommodation** in Oxford college

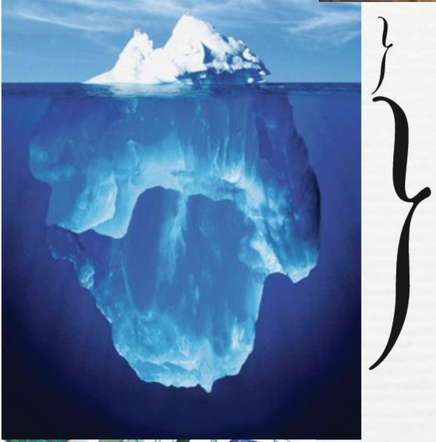
Contact e-mail: Emmanuel.Tsesmelis@cern.ch

Introduction



Particle Accelerators – Study macro and micro world

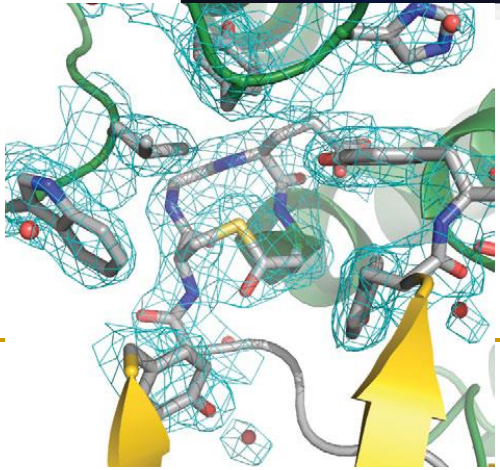


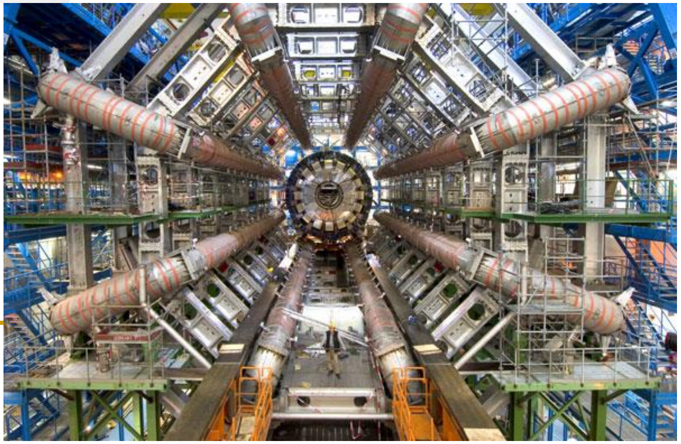


Known Matter

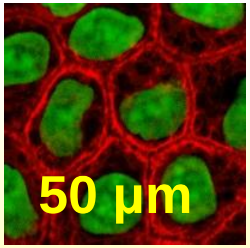
Unknown Matter

DARK MATTER &
DARK ENERGY





The structure of matter…

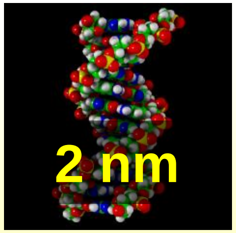


Extra magnification?

CELLS

Twenty
per mm

Microscope



x 25 thousand

DNA

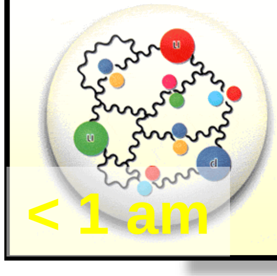
Five hundred
thousand
per mm

Electron microscope

x 1 million

Nucleus

Five hundred
billion
per mm



x 2 thousand

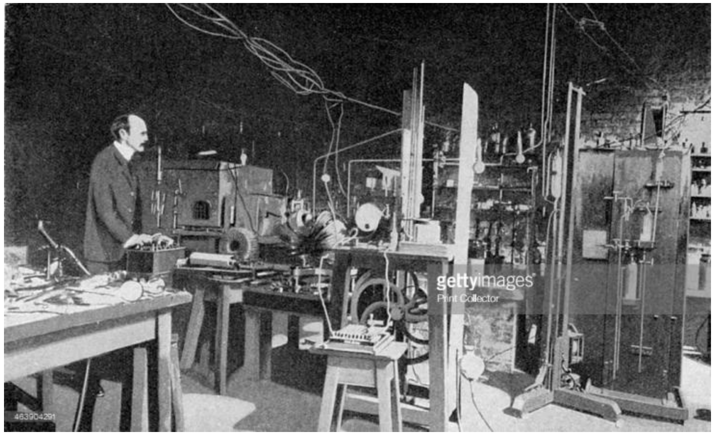
Quarks

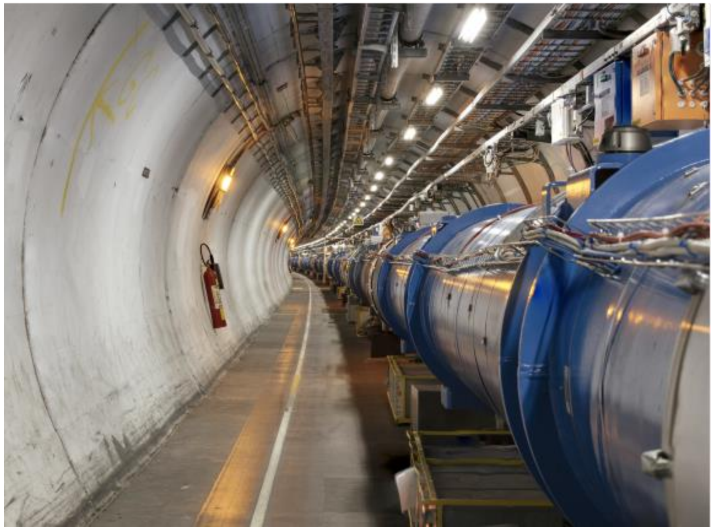
More than one
million billion
per mm

Particle Accelerators

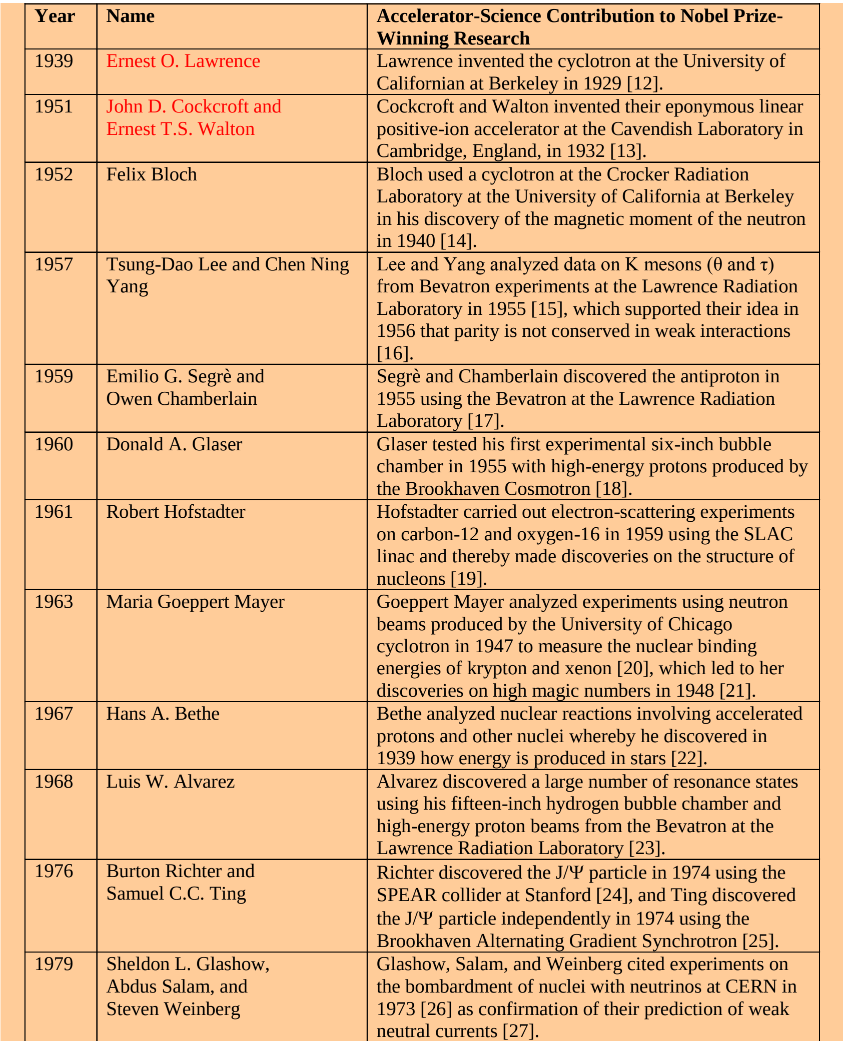
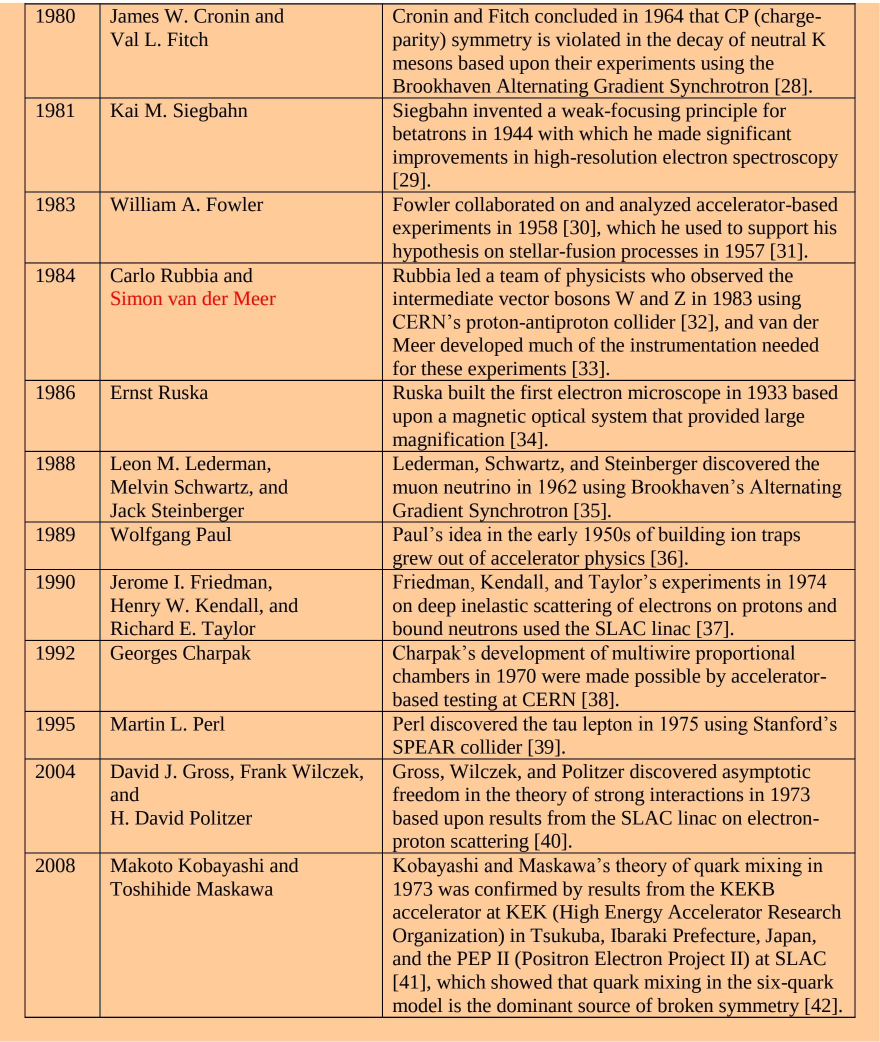
Accelerator Development

- Characterised by rapid progress for over a century.
  - From cathode-ray tubes to the LHC.
  - From the discovery of the electron to the discovery of the Higgs boson.
- Advances in accelerators require corresponding advances in accelerator technologies
  - Magnets, vacuum systems, RF systems, diagnostics,...
- But timelines becoming long, requiring:
  - Long-term planning.
  - Long-term resources.
  - Global collaboration.





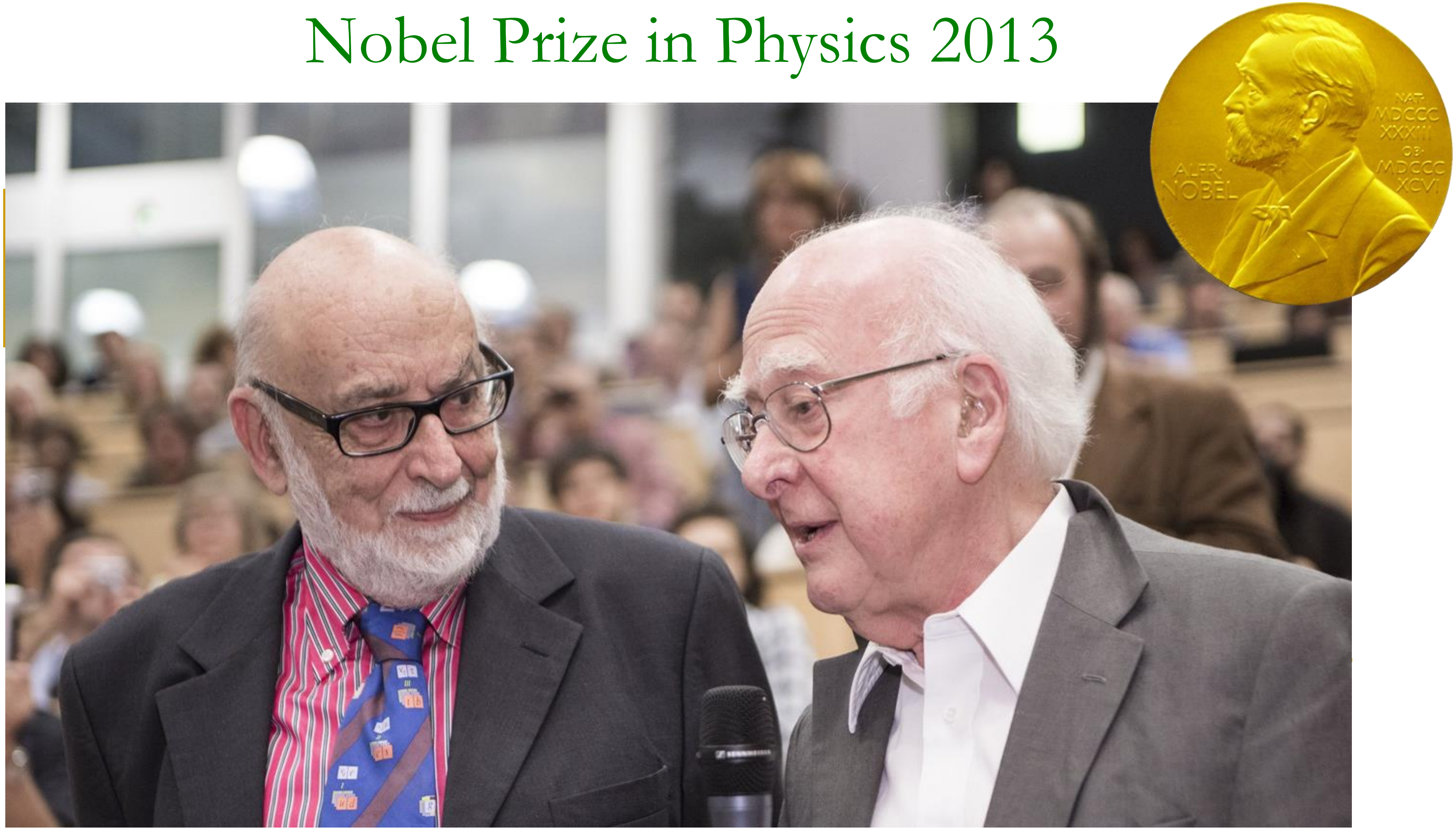
24 (+1) Nobel Prizes in Physics that had direct contribution from accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

A.Chao and E. Haussecker "*Impact of Accelerator Science on Physics Research*", published in ICFA Newsletter, Dec 2010; & submitted to the Physics in Perspective Journal, Dec 2010.

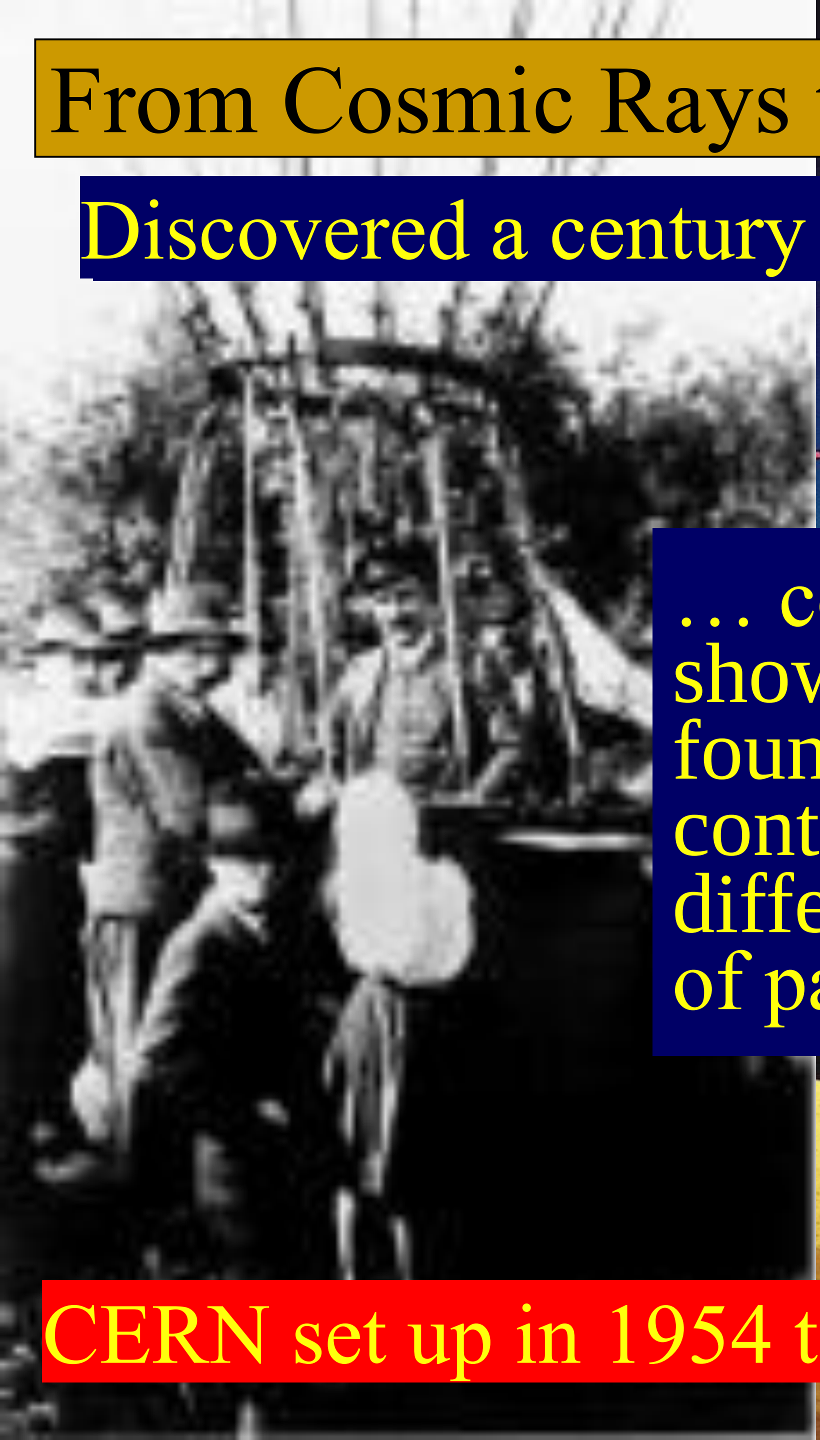
Nobel Prize in Physics 2013

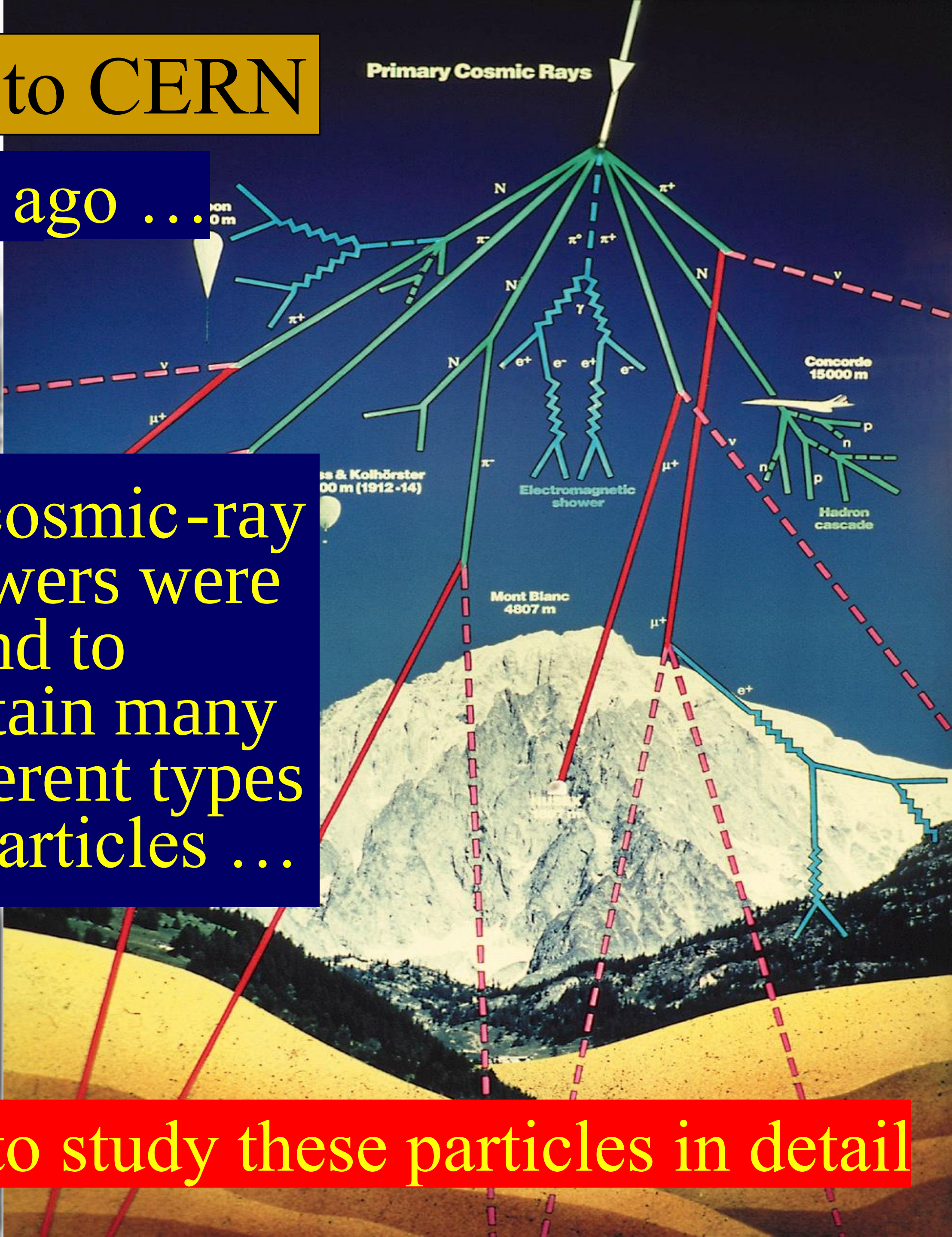


The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

From Cosmic Rays to CERN

Discovered a century ago …





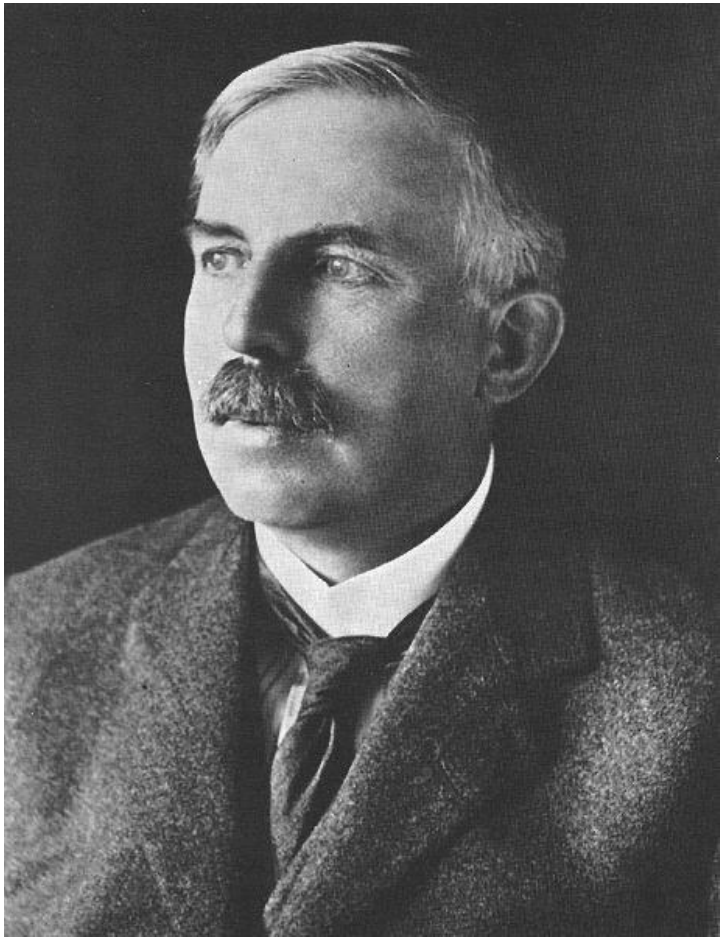
… cosmic-ray showers were found to contain many different types of particles …

CERN set up in 1954 to study these particles in detail

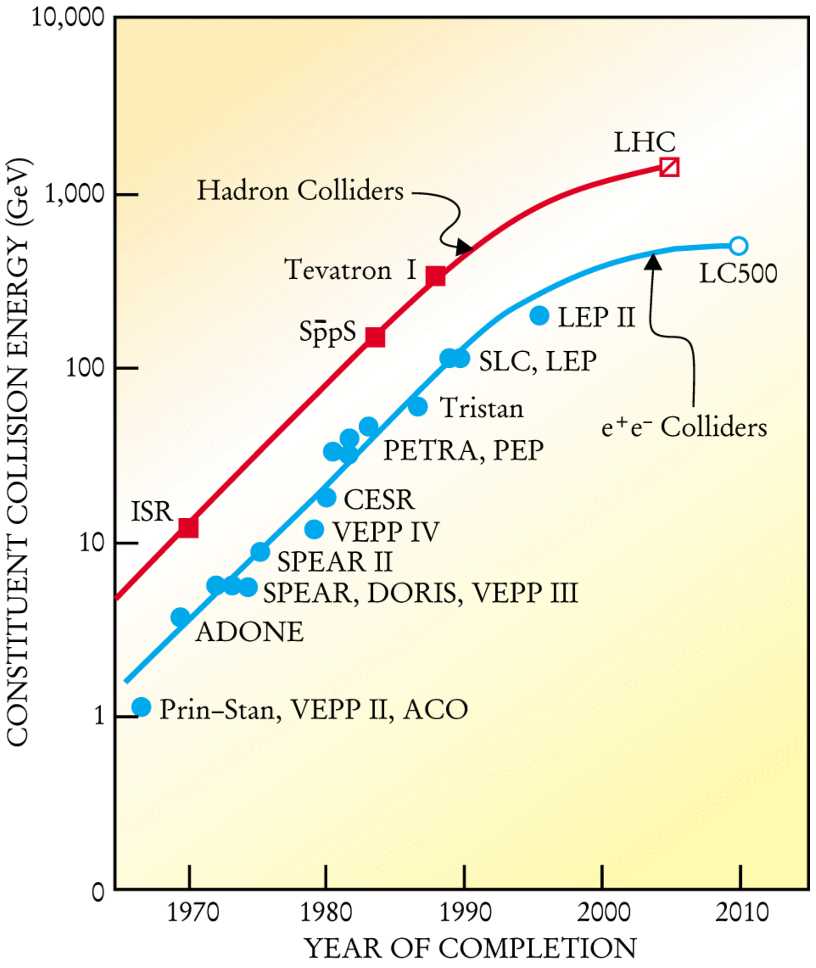
Rutherford fired the starting pistol

At the Royal Society in 1928 he said:

"I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances".



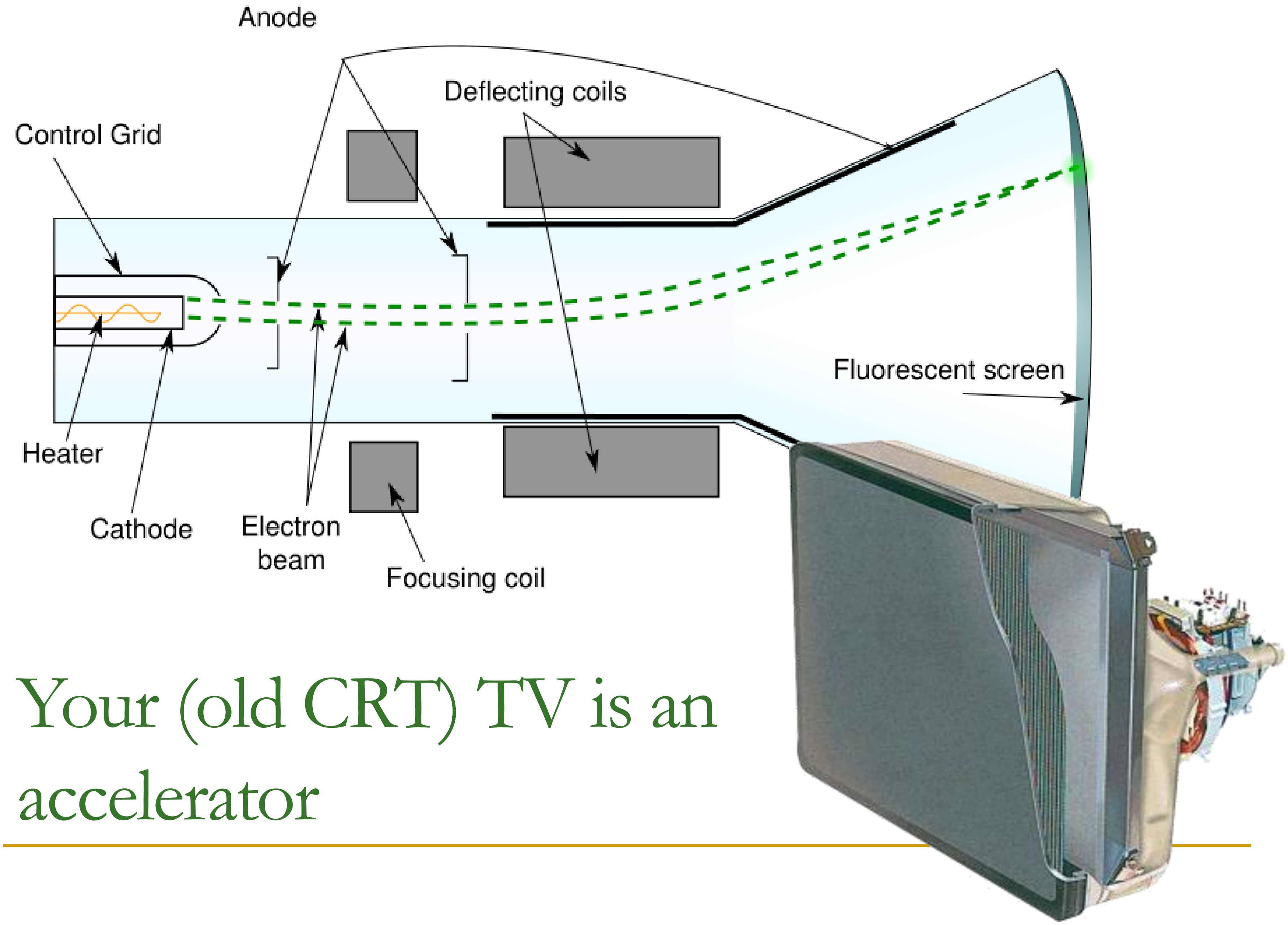
Livingston Plot



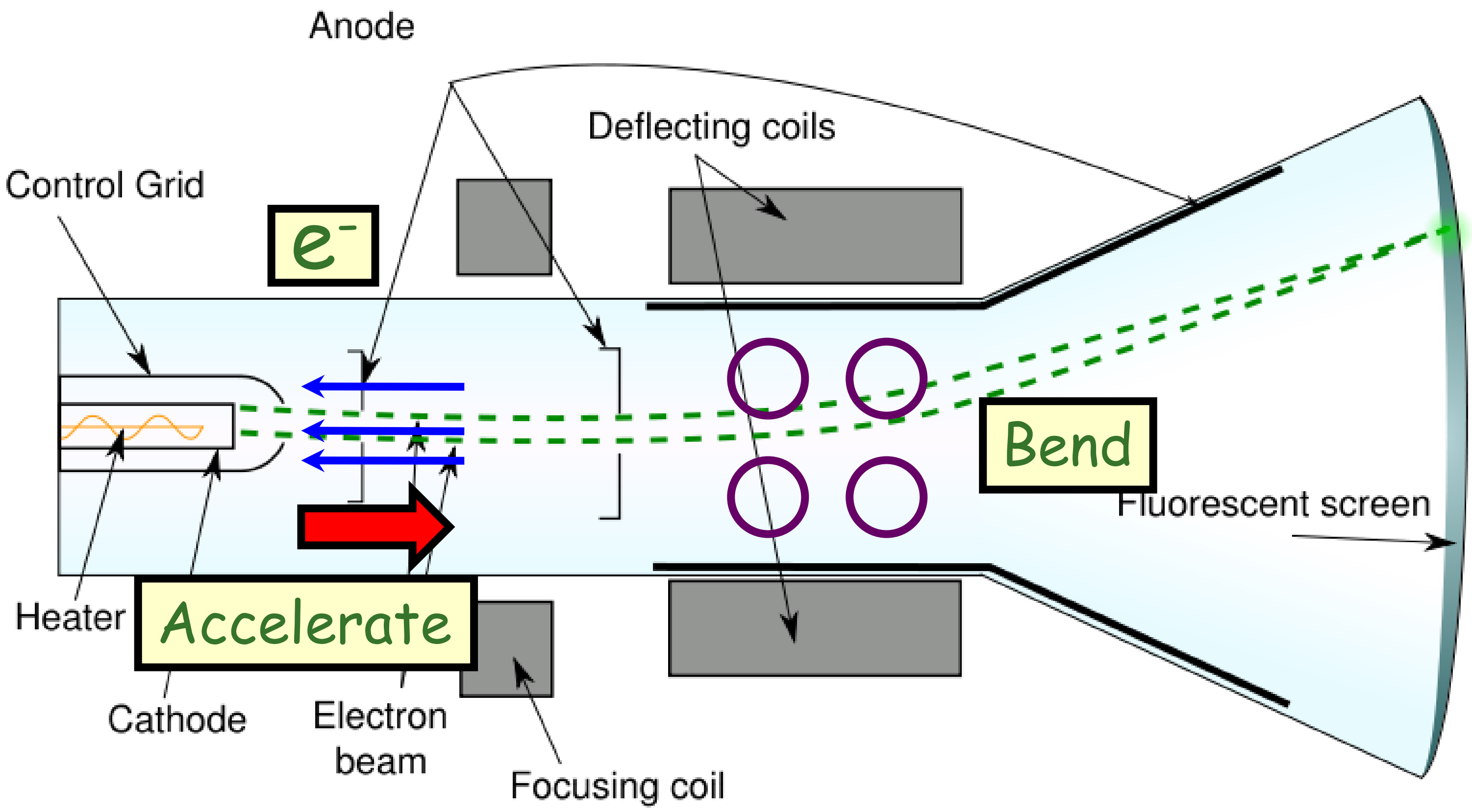
- Around 1950, Livingston made following observation:
  - Plotting energy of accelerator as a function of year of commissioning, on semi-log scale, the energy gain has linear dependence.
- Observations today:
  - Exhibition of saturation effect:
    - New technologies needed.
  - Overall project cost increased
    - Project cost increased by factor of 200 over last 40 years.
  - Cost per proton-proton E_{CM} energy decreased by factor of 10 over last 40 years.

Lightning: requires > MV/m over many tens of meters to initiate it

Your (old CRT) TV is an accelerator



A TV as an Accelerator

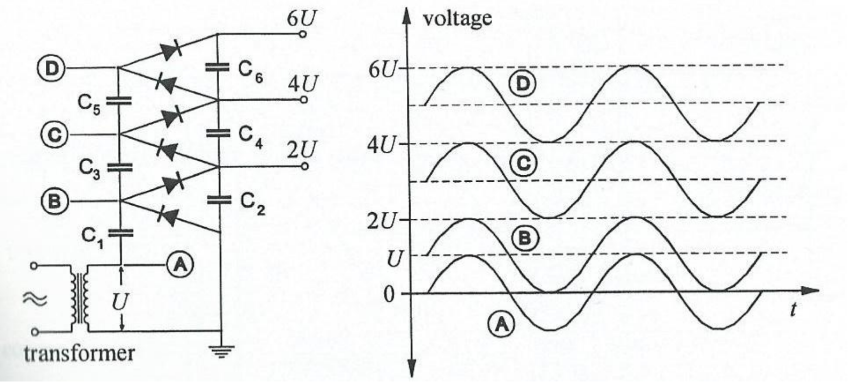


Electrostatic Accelerators
The Cockcroft-Walton

- Based on system of multiple rectifiers.
- Voltage generated by cascade circuit

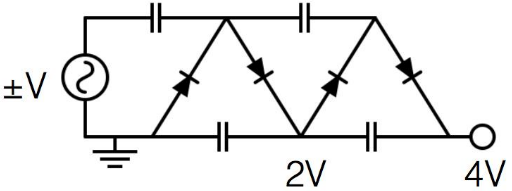
$$U_{\text{tot}} = 2Un - \frac{2\pi I}{\omega C}\left(\frac{2}{3}n^3 + \frac{1}{4}n^2 + \frac{1}{12}n\right)$$

- Modern CWs
    - Voltages up to ~4 MV.
    - Beam currents of several hundred mA with pulsed particle beams of few μs pulse length.



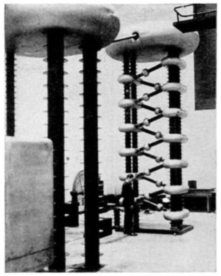
Walton and the machine used to "split the atom"

Cavendish Lab, Cambridge



Voltage multiplier circuit

https://www.youtube.com/watch?v=ep3D_LC2UzU



1.2 MV 6 stage Cockcroft-Walton accelerator at Clarendon Lab, Oxford University in 1948.

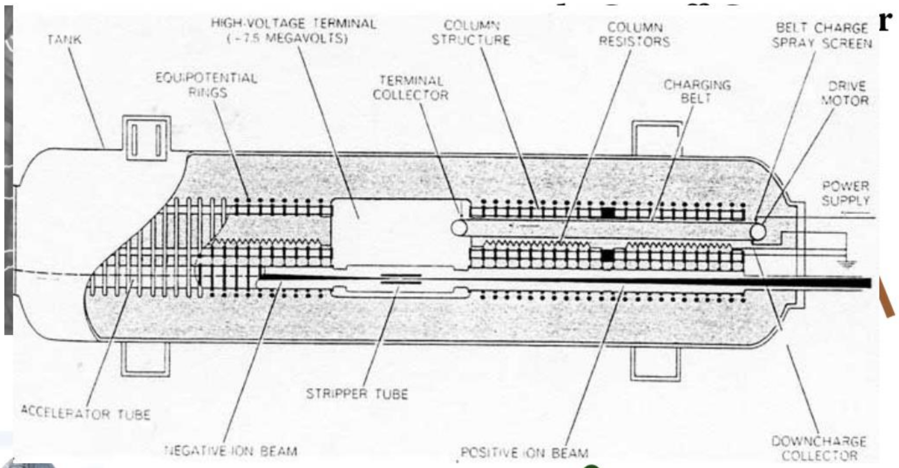
10

Electrostatic Accelerators – The Van de Graaff

- With any electrostatic accelerator, it is difficult to achieve energy higher than ~20 MeV (e.g. due to practical limitations of the size of the vessels).

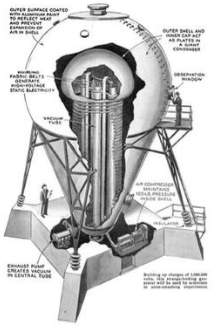
- Tandem is version with charge exchange in middle.

Robert Van de Graaff



⑦

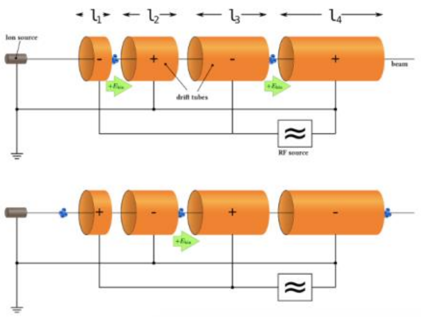
1. hollow metal sphere
2. upper electrode
3. upper roller (for example an acrylic glass)
4. side of the belt with positive charges
5. opposite side of belt, with negative charges
6. lower roller (metal)
7. lower electrode (ground)
8. spherical device with negative charges
9. spark produced by the difference of potentials



The Westinghouse atom smasher, 1937

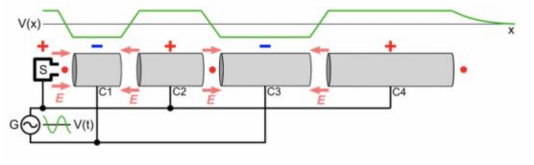
"Van de Graaff Generator" by Omphalosskeptic - Own work. Licensed under CC BY-SA 3.0 via Commons

Linear Accelerators



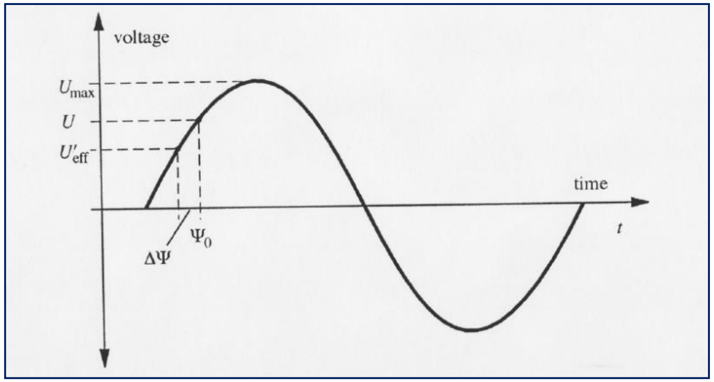
$$l = \beta\lambda_{rf} / 2 = v / 2 f_{rf}$$

- For high energy, need high frequency RF sources
- Weren't available until after WWII



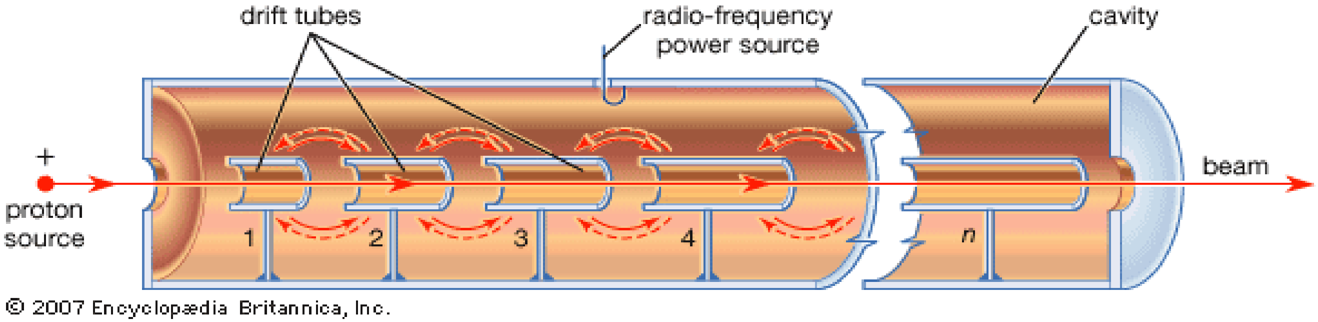
But Wideroe's idea was not quite an RF cavity, Alvarez introduced that…

Phase focusing in linacs



- Principle
  - Use rapidly-changing high frequency voltages instead of direct voltages (Ising)
  - Energy is proportional to number of stages *i* traversed by particle.
  - The largest voltage in entire system is never greater than V_{max}
    - Arbitrary high energies without voltage discharge.

Drift Tube Linac: Higher Integrated Field



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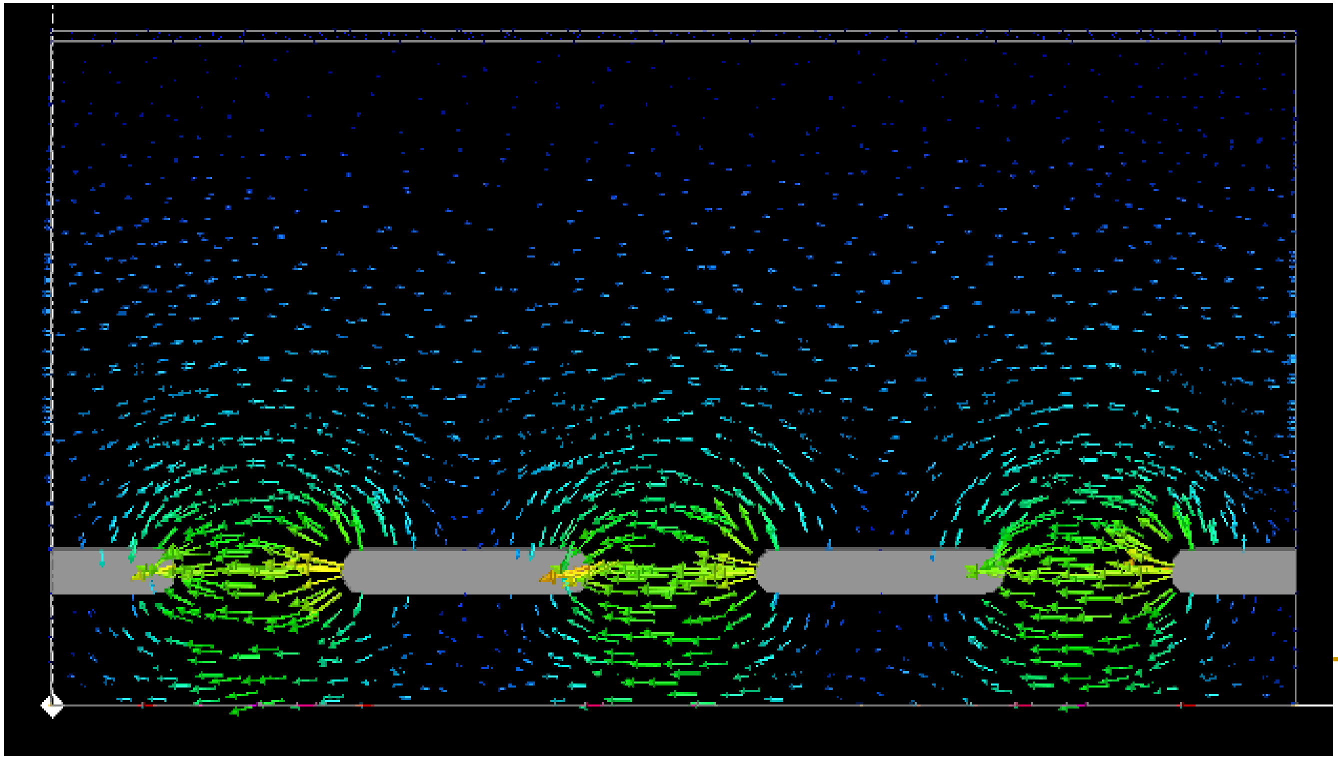
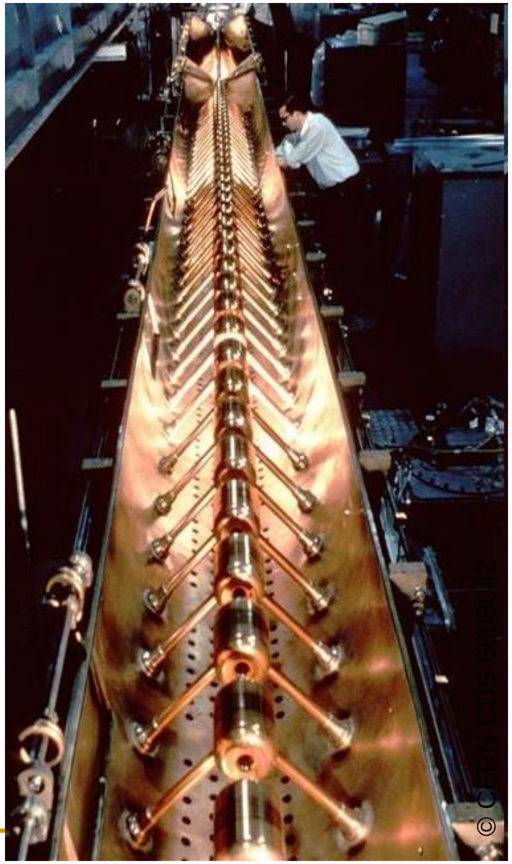


CERN LINAC1



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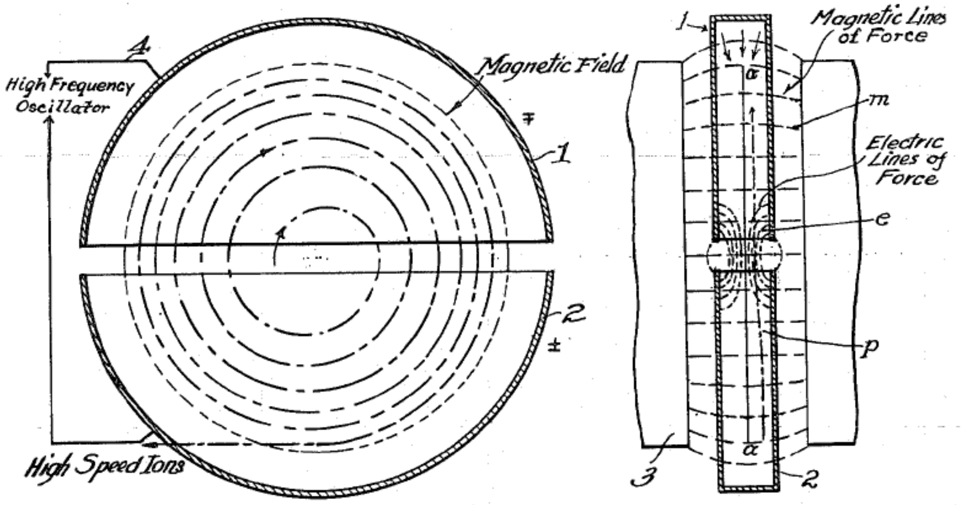
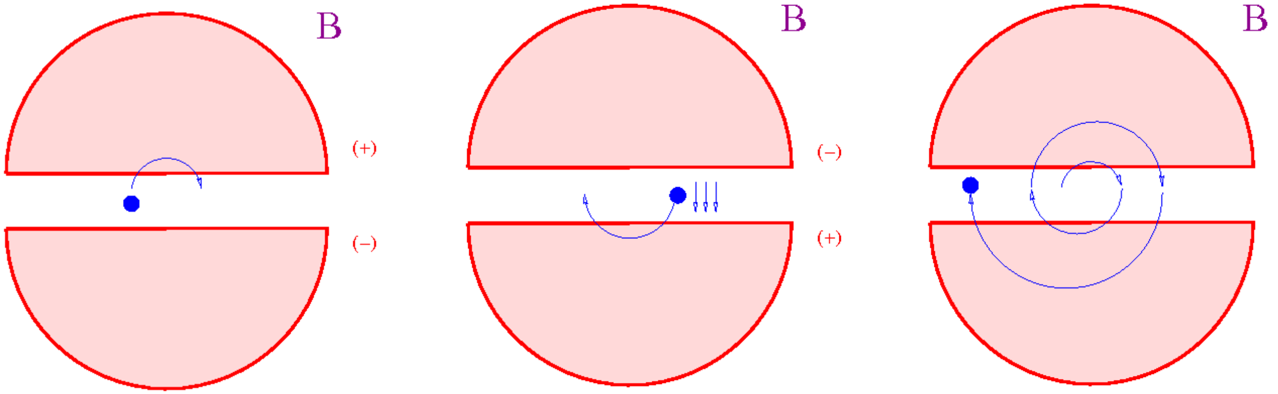
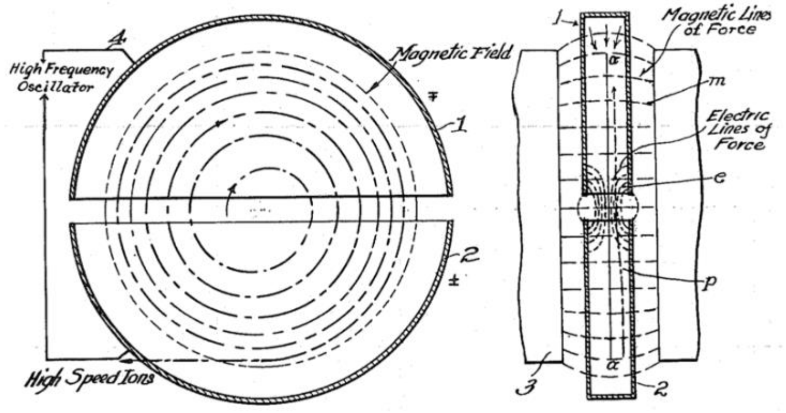
The Cyclotron

- In 1929-1930 Lawrence designed a “cyclotron”, a circular device made of two electrodes placed in a magnetic field.
- Cyclotrons can accelerate (e.g.) protons up to hundreds of MeV.

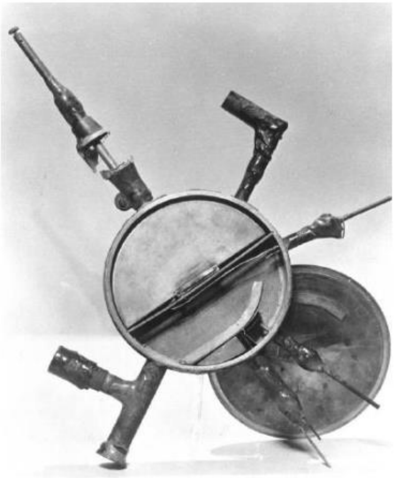




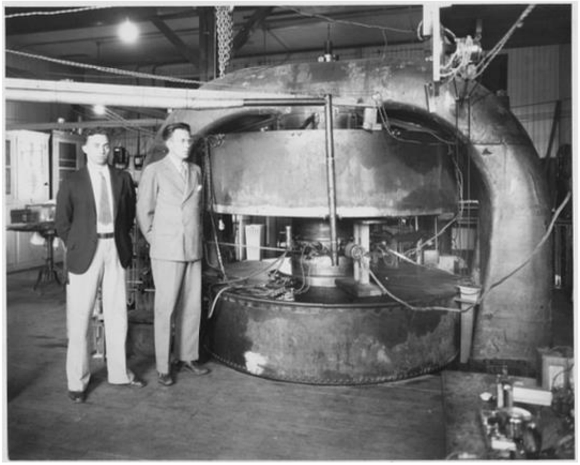
The Cyclotron



The Cyclotron, from E. Lawrence's 1934 patent



The first cyclotron



We will discuss cyclotron focusing in Transverse Dynamics I

E. Lawrence & M. Stanley Livingston

The Betatron

- Like a transformer with the beam as a secondary coil
- Usually used for relativistic electrons (so different from a cyclotron).
- Max energy achieved 300 MeV
- Accelerating field produced by a changing magnetic field that also serves to maintains electrons in a circular orbit of fixed radius as they are accelerated

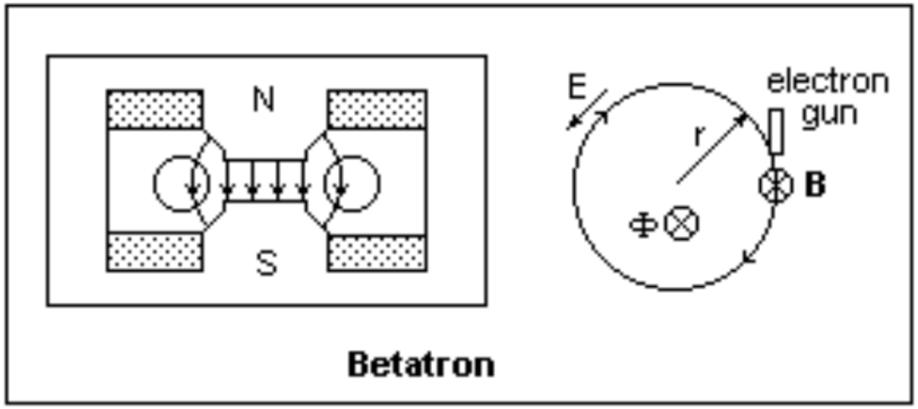


Image: http://mysite.du.edu/~jcalvert/phys/partelec.htm#Tron

Equate Faradays law on induction & Lorentz force law gives…

$$B_{orbit} = \frac{\Phi}{2\pi r^2} \Rightarrow B_{orbit} = \frac{\bar{B}}{2}$$

since $\bar{B} = \frac{\Phi}{\pi r^2}$

http://physics.princeton.edu/~mcdonald/examples/betatron.pdf

Mark Oliphant & the Synchrotron

"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field...which would be varied in such a way that the radius of curvature remains constant as the particle gains energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes."

Mark Oliphant, Oak Ridge, 1943

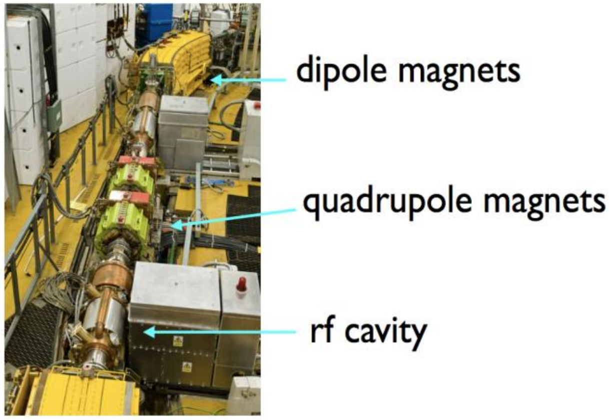
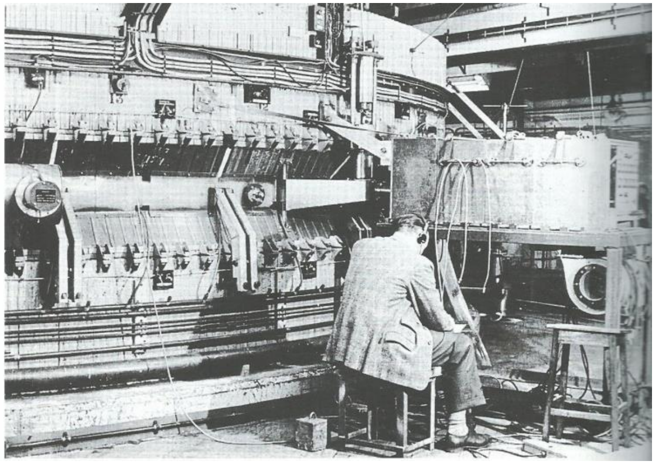


Image courtesy of ISIS, STFC

With Ernest Rutherford in 1932



1 GeV machine at Birmingham University

The Synchrotron

- From

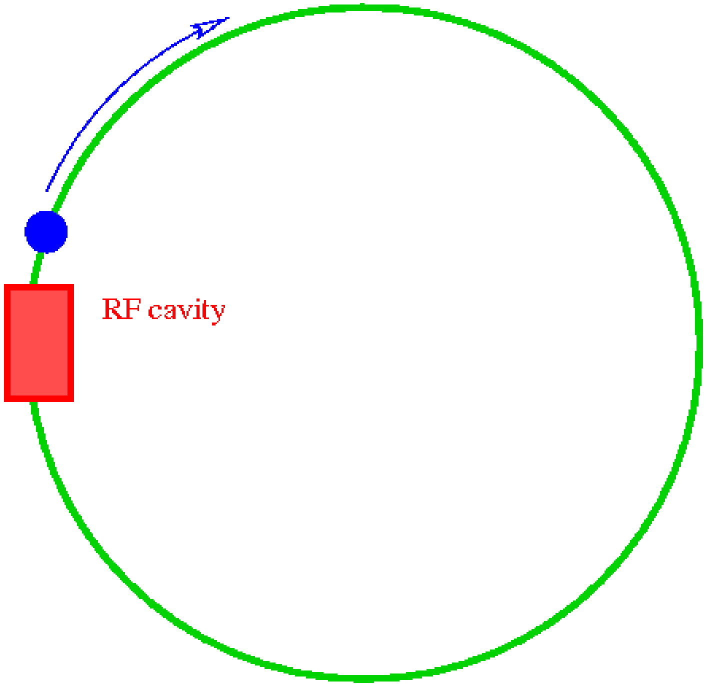
  $R = E / (ecB)$

  E/B kept constant since R is fixed.

  B increases synchronously with rising *E*

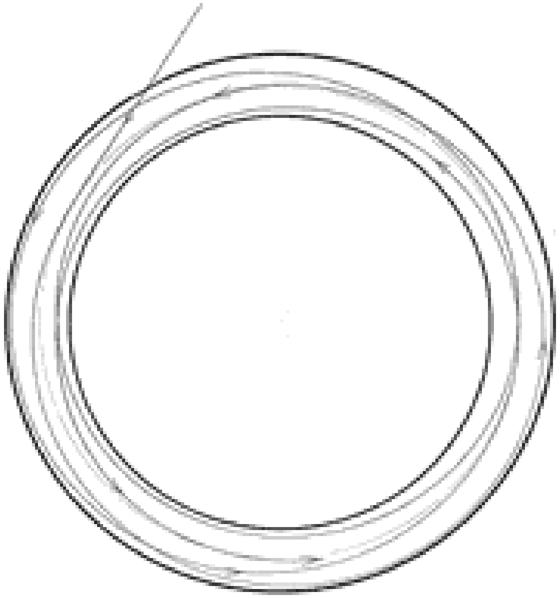
- Synchrotrons, such as LHC, can accelerate to much higher energies.

- Limitation of synchrotrons (especially for electrons) is due to “synchrotron radiation”.



Focusing

- Focusing is needed to confine the orbits.
- First accelerators had “weak focusing” – focusing period is larger than the perimeter.

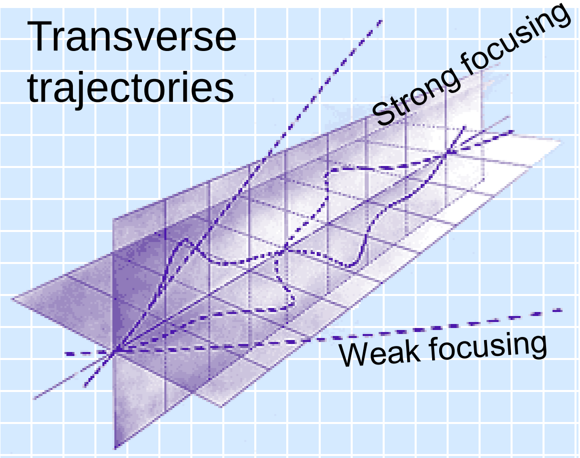


Weak focusing accelerator

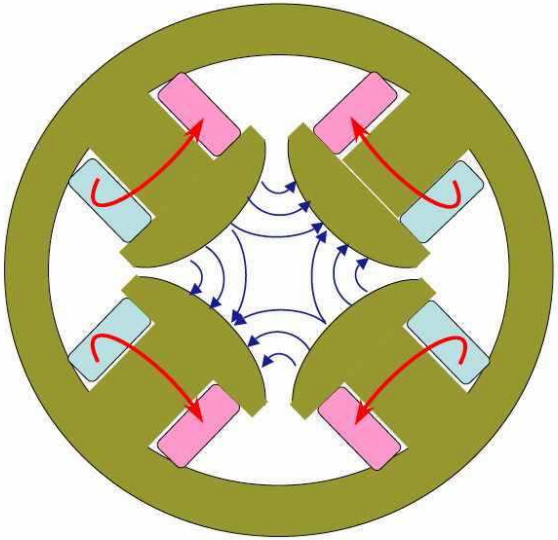
10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful of its time. Its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world.

sergeydolya.livejournal.com

- “Strong focusing” alternates focusing-defocusing forces (provided by quadrupoles) to give overall focusing in both X & Y planes.



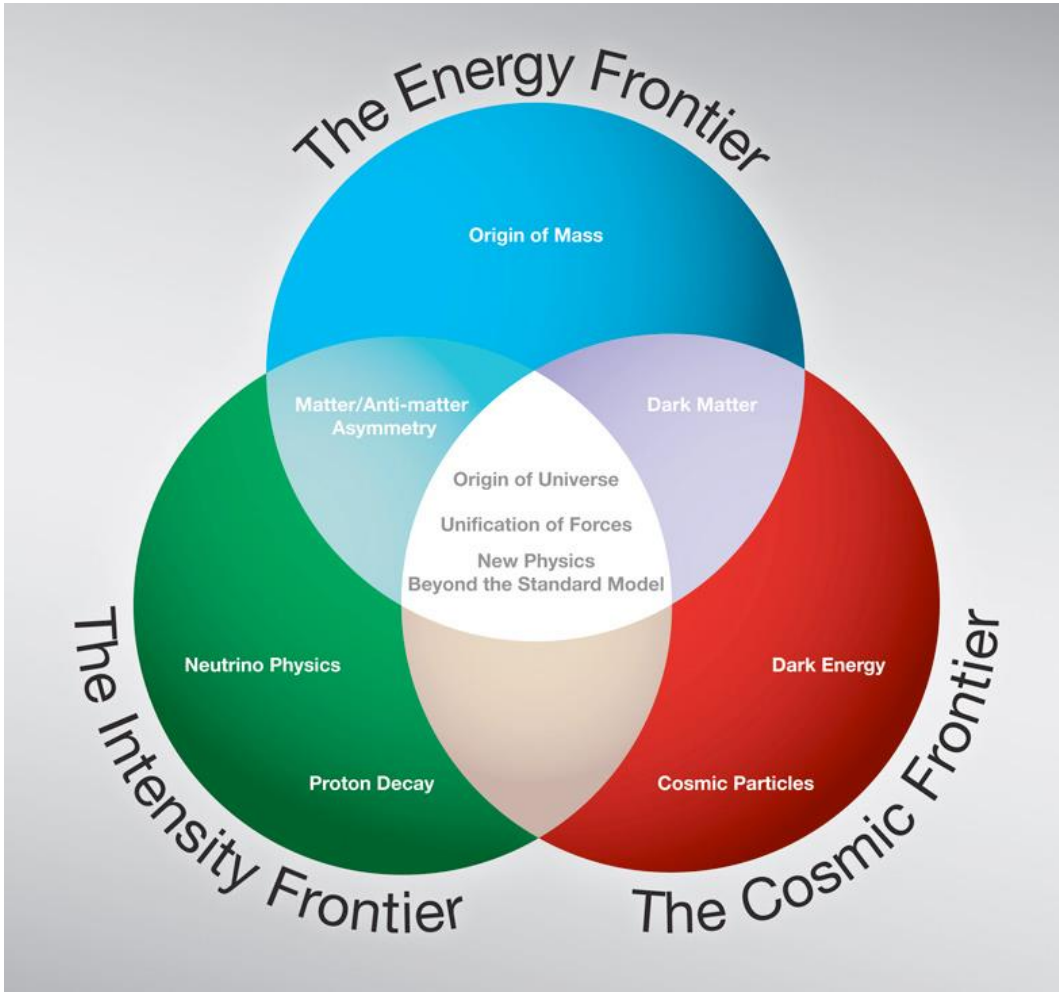
Strong focusing allows use of more compact magnets, thus achieving many times larger energy with the same cost.



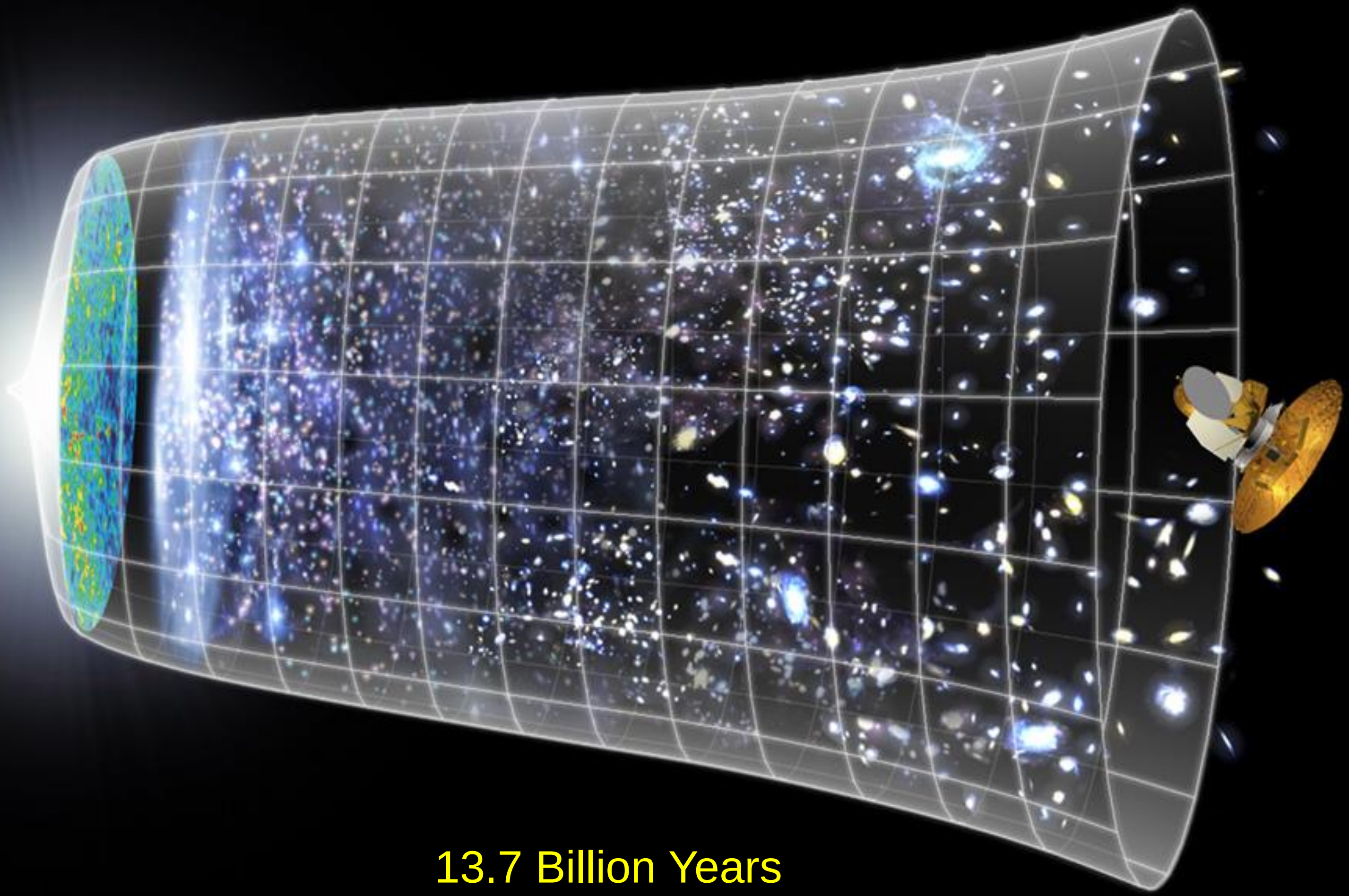
200-m diameter ring, weight of magnets 3,800 tons

CERN's Proton Synchrotron, was the first operating strong-focusing accelerator.

The Three Frontiers



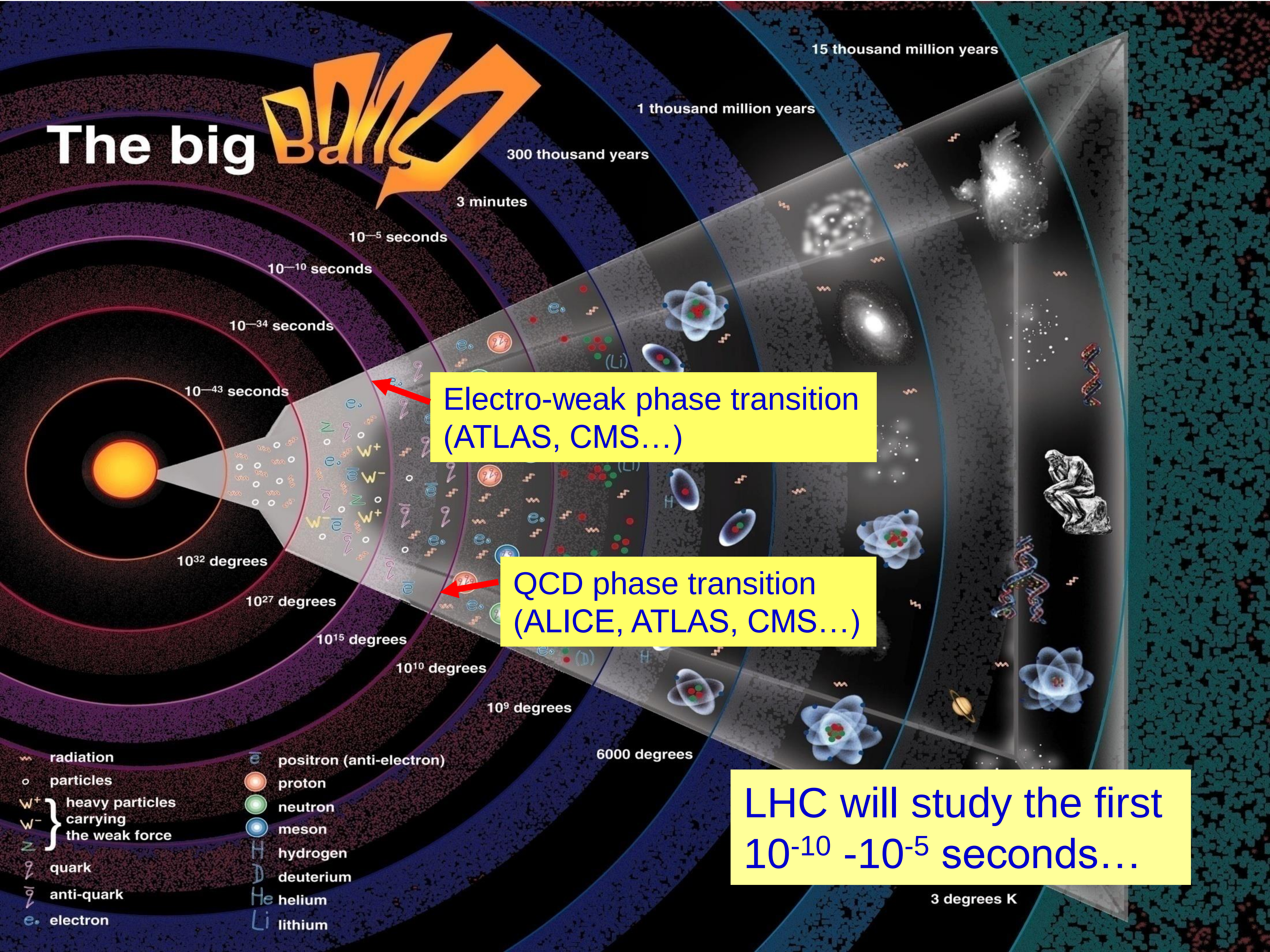
Evolution of the Universe



Big Bang

13.7 Billion Years

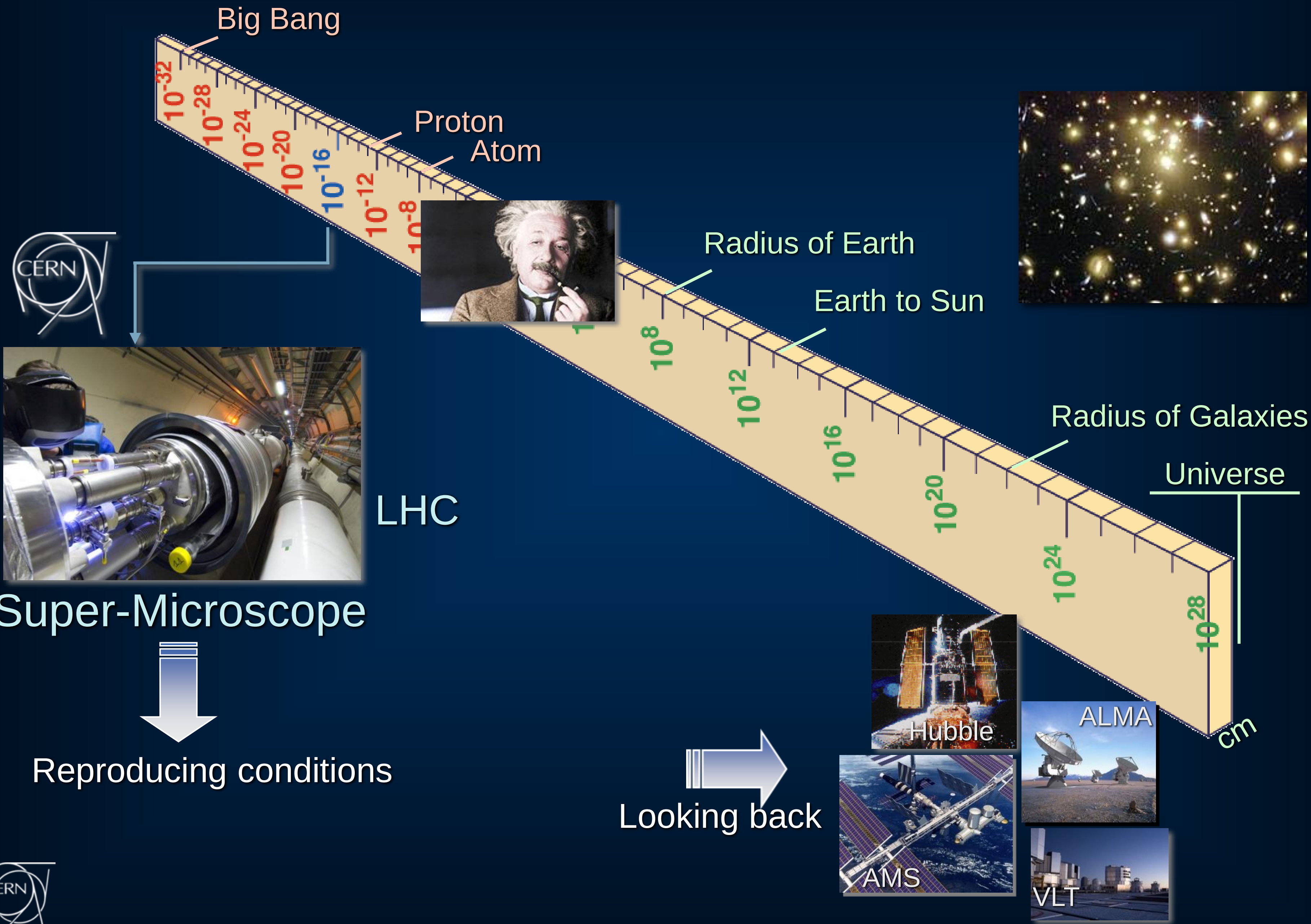
10^{28} cm



Electro-weak phase transition
(ATLAS, CMS…)

QCD phase transition
(ALICE, ATLAS, CMS…)

LHC will study the first 10^{-10} -10^{-5} seconds…

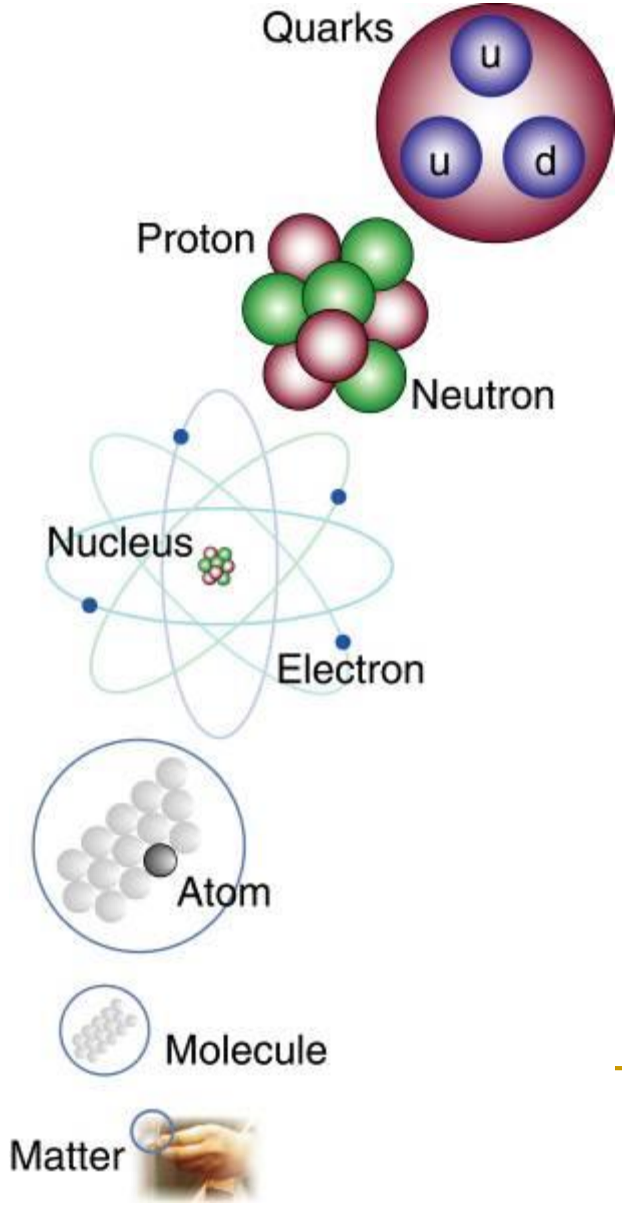


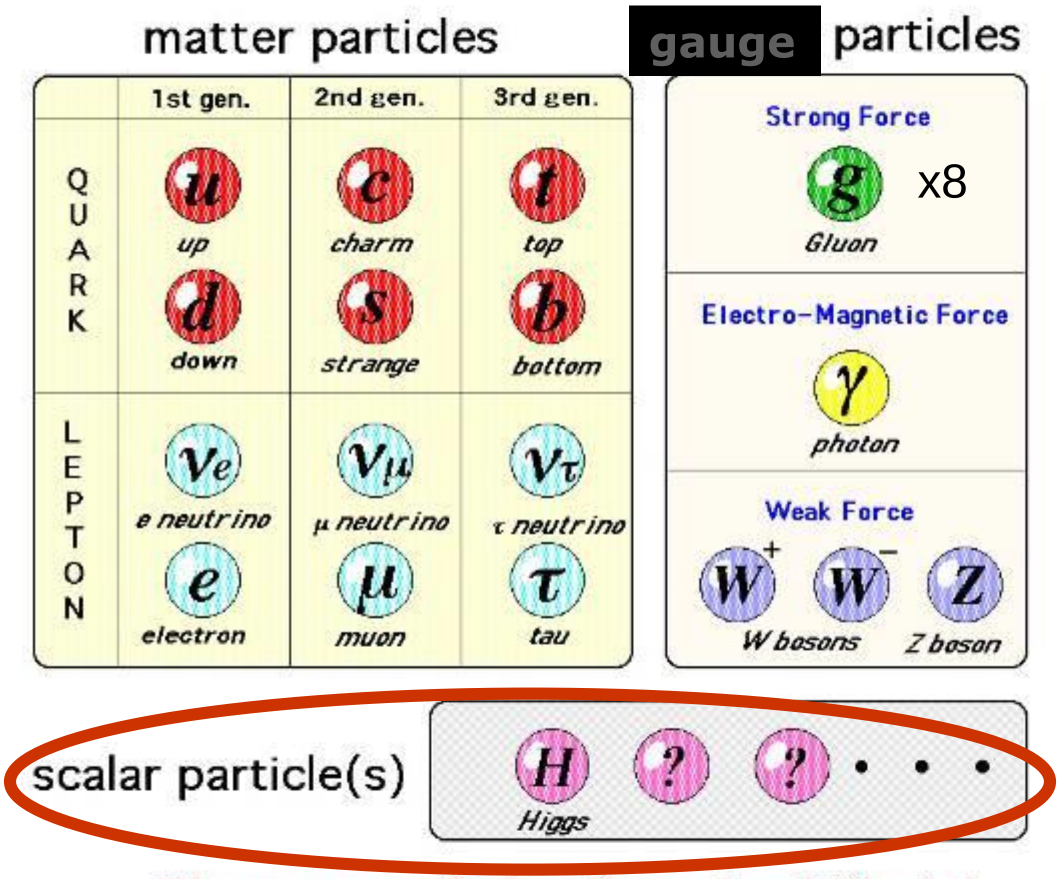
Super-Microscope

Reproducing conditions

Looking back

The Study of Elementary Particles & Fields and their Interactions





matter particles

	1st gen.	2nd gen.	3rd gen.
QUARK	*u* up	*c* charm	*t* top
	d down	*s* strange	*b* bottom
LEPTON	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino
	e electron	*μ* muon	*τ* tau

gauge particles

Strong Force
g Gluon x8
Electro-Magnetic Force
γ photon
Weak Force
W^+ W^- W bosons; *Z* Z boson

scalar particle(s)

H Higgs ? ? • • •

Elements of the Standard Model

Why Colliders?

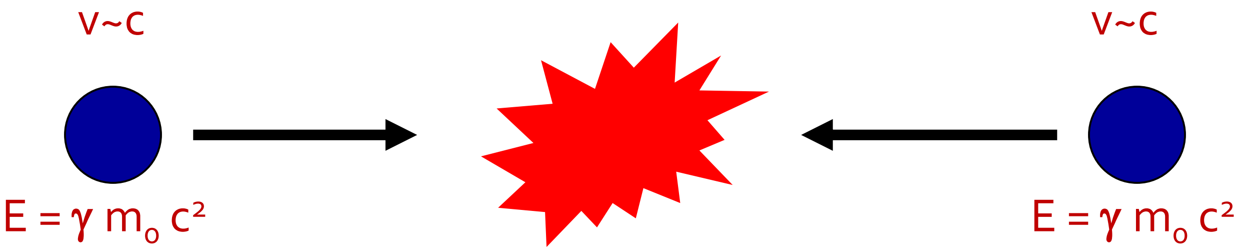
v~c

v=0

$E = \gamma m_0 c^2$

$P = \gamma m_0 v$

Only a tiny fraction of energy converted into mass of new particles
(due to energy and momentum conservation)



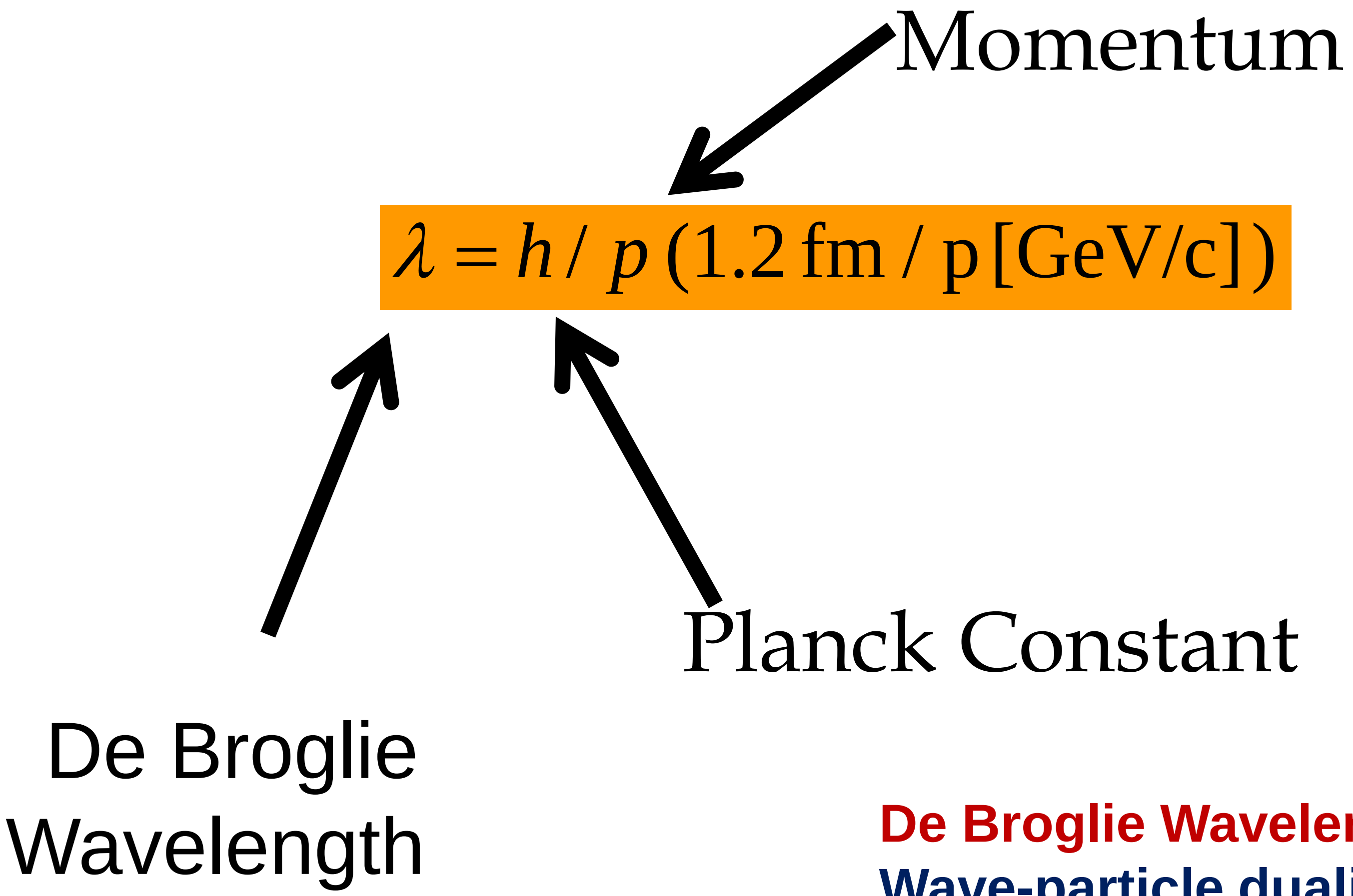
v~c

v~c

$E = \gamma m_0 c^2$

$E = \gamma m_0 c^2$

Key Equation



Momentum

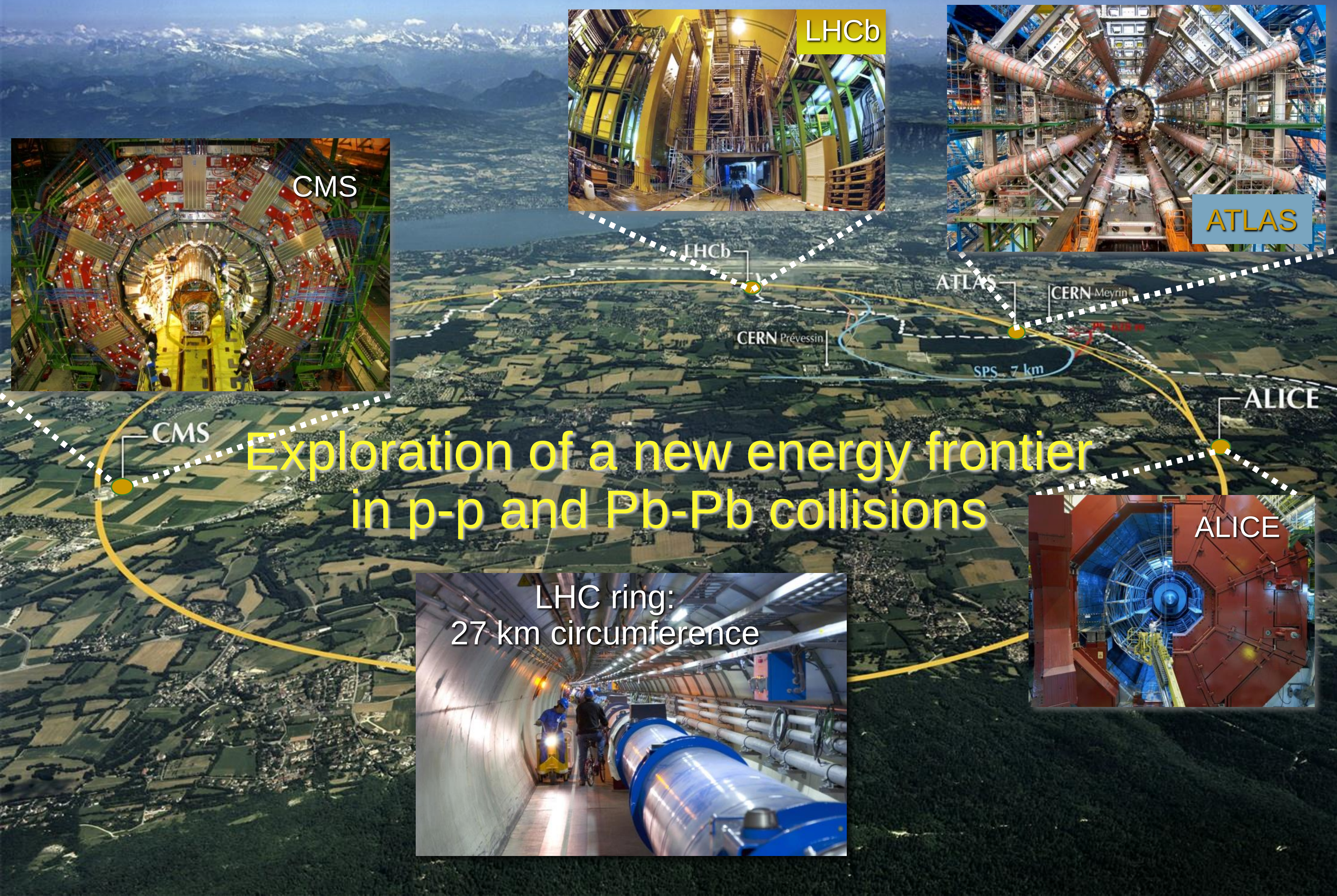
$$\lambda = h / p \; (1.2\,\mathrm{fm} / \mathrm{p}\,[\mathrm{GeV/c}])$$

Planck Constant

De Broglie
Wavelength

De Broglie Wavelength
Wave-particle duality;
For higher E, probe shorter distances inside matter

A New Era in Fundamental Science

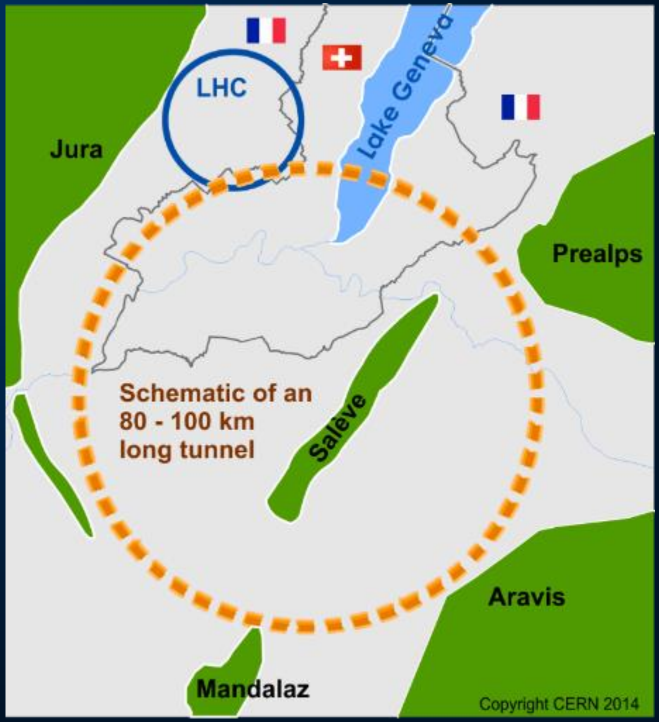


Exploration of a new energy frontier in p-p and Pb-Pb collisions

LHC ring:
27 km circumference

Future of Particle Physics at CERN

- European Strategy for Particle Physics. Road map for particle physics, updated by CERN Council in June 2020.
  Priorities include:
- Full exploitation of LHC physics potential. Successful completion of high-luminosity upgrade of accelerators and experiments.
- Electron-positron Higgs factory as highest priority next collider.
- Ramping up R&D on advanced accelerator technologies.
- Investigation of feasibility of a future 100 TeV hadron collider at CERN with electron-positron Higgs factory as possible first stage. Prepare plan for the next strategy update (~2026).
- Support long-baseline neutrino projects in Japan and US, and high-impact Scientific Diversity Programme, complementary to high-energy colliders.



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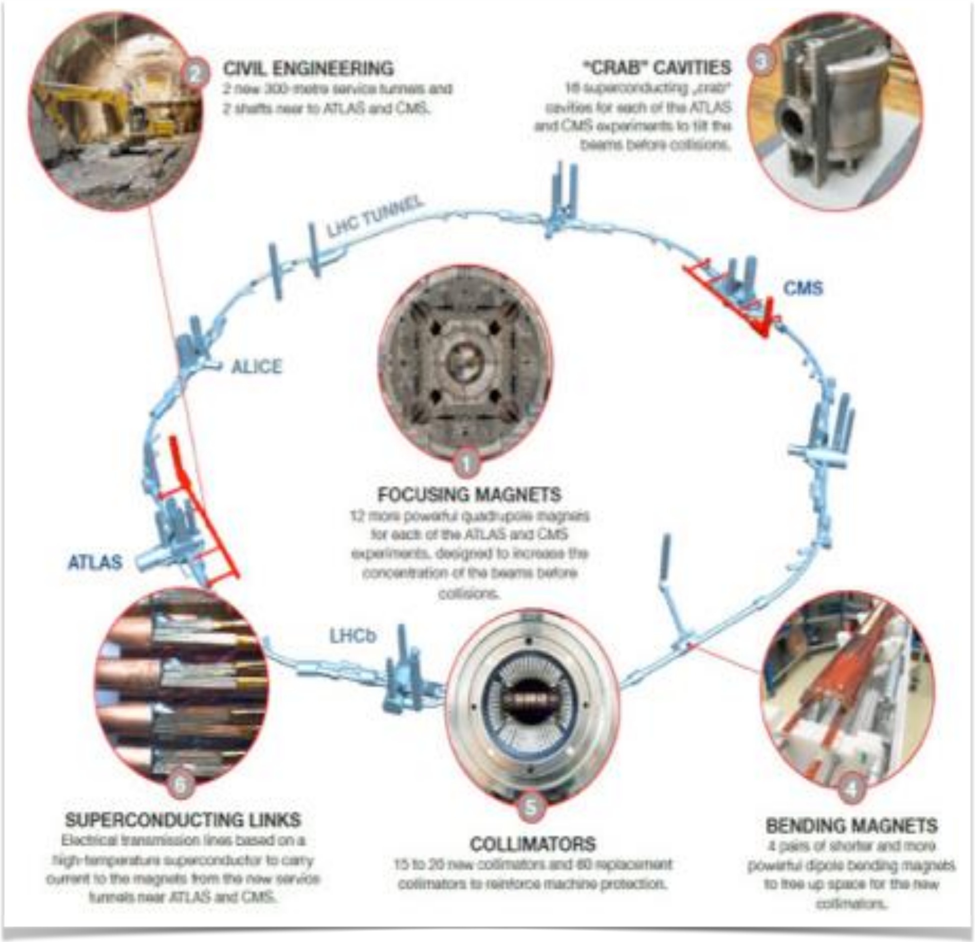
High-Luminosity LHC (HL-LHC)



CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

- New quadrupole magnets near the interaction points
- New 11 Tesla short dipole magnets
- Collimation upgrade
- Crab Cavities
- Accelerator safety upgrade
- Major interventions on 1.2 km of the LHC

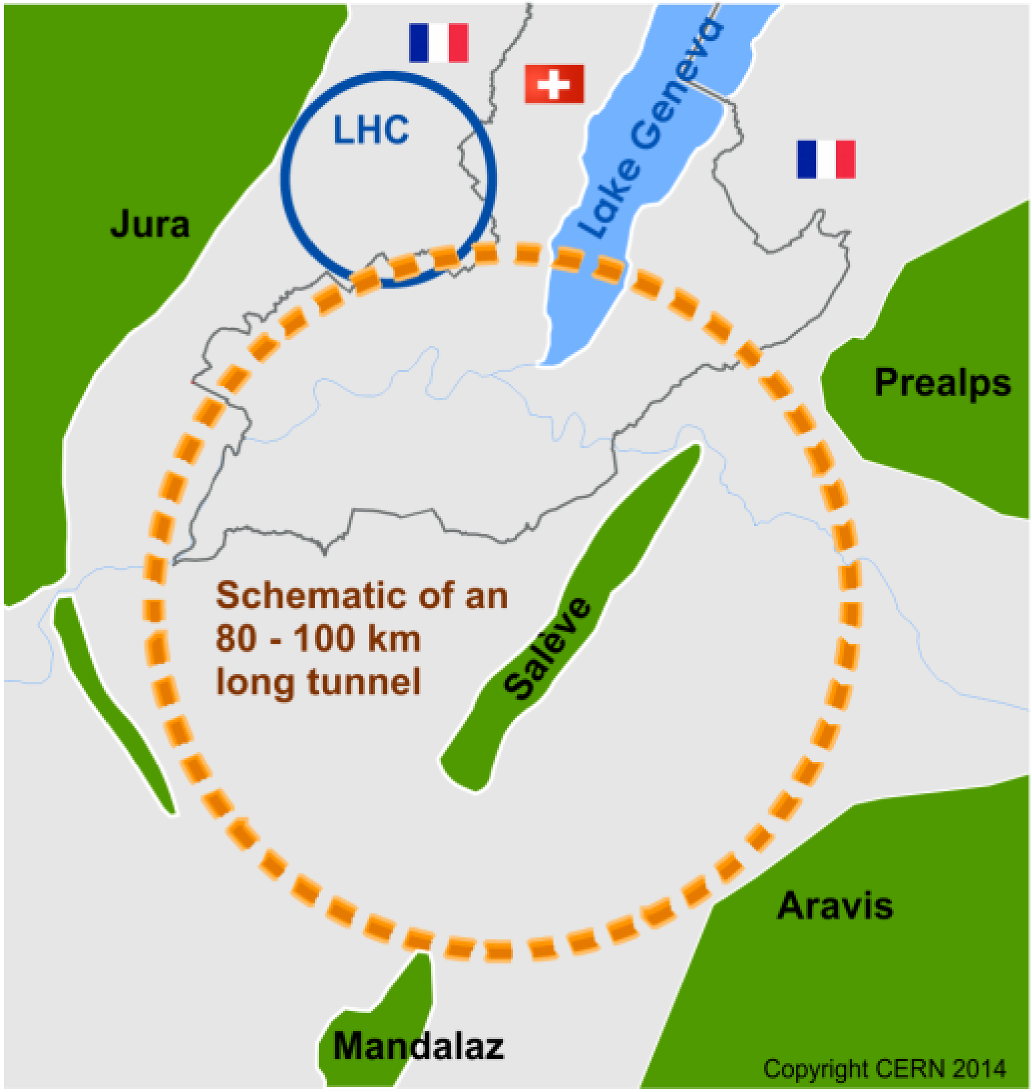
Future Circular Collider Study (FCC)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)** → defining infrastructure requirements

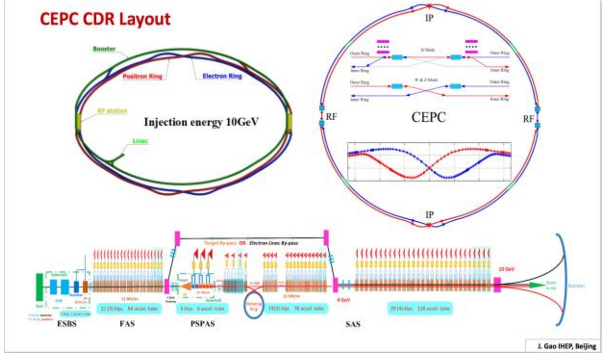
~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



CEPC/SppC

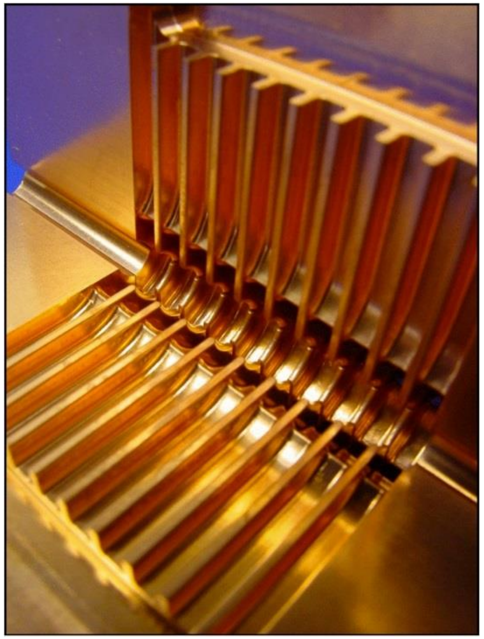
- CEPC
  - Circular Electron Positron Collider
  - 50 -70 km ring, up to 100 km?
  - 90-250 GeV
  - Z and Higgs factory



- SppC
  - Super proton-proton Collider
    with centre-of-mass energies > 100 TeV
  - Discovery machine in the same ring as CEPC

Linear Colliders

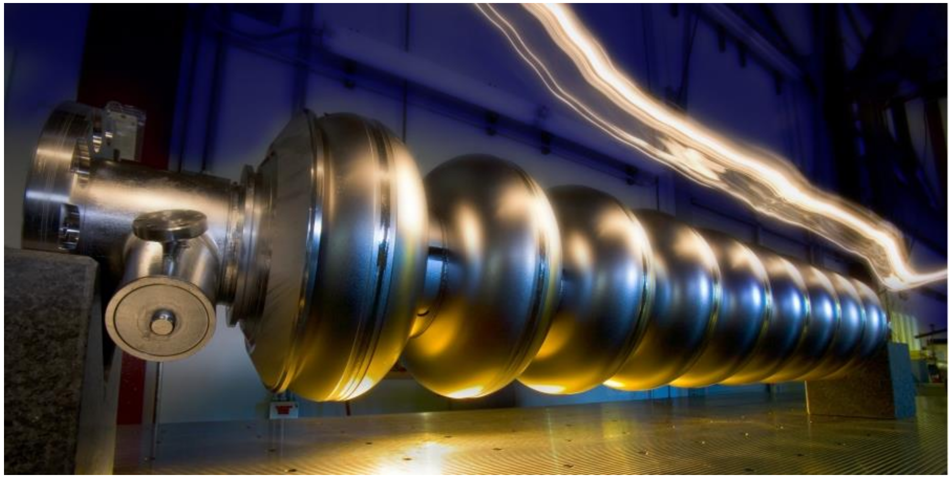
CLIC



- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m
- √s up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

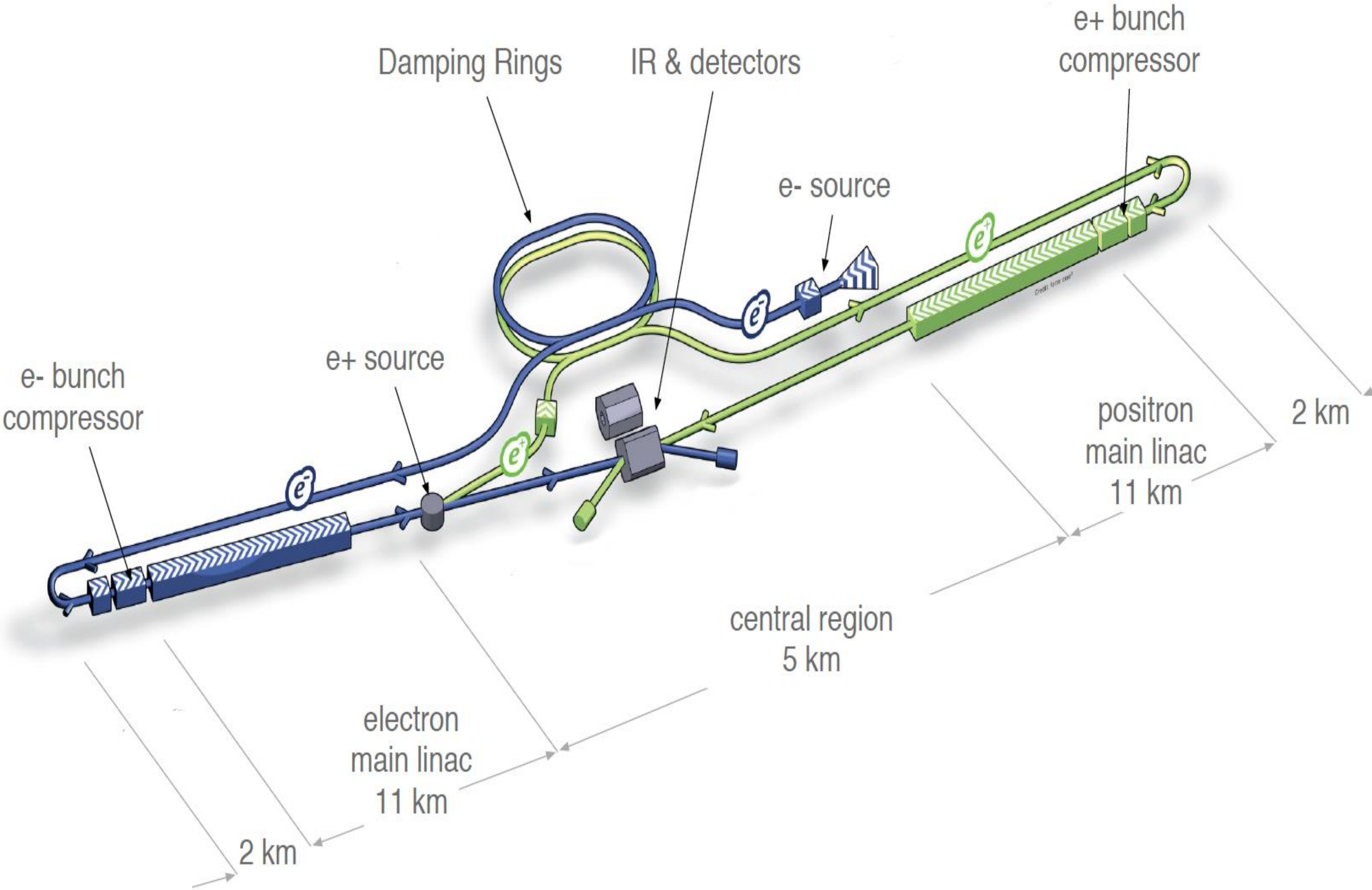
Linear e^+e^- colliders
Luminosities: few 10^{34} cm^{-2}s^{-1}

ILC



- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- √s ≤ 500 GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

The International Linear Collider (ILC)



Damping Rings

IR & detectors

e+ bunch compressor

e- source

e+ source

e- bunch compressor

positron main linac 11 km

2 km

central region 5 km

electron main linac 11 km

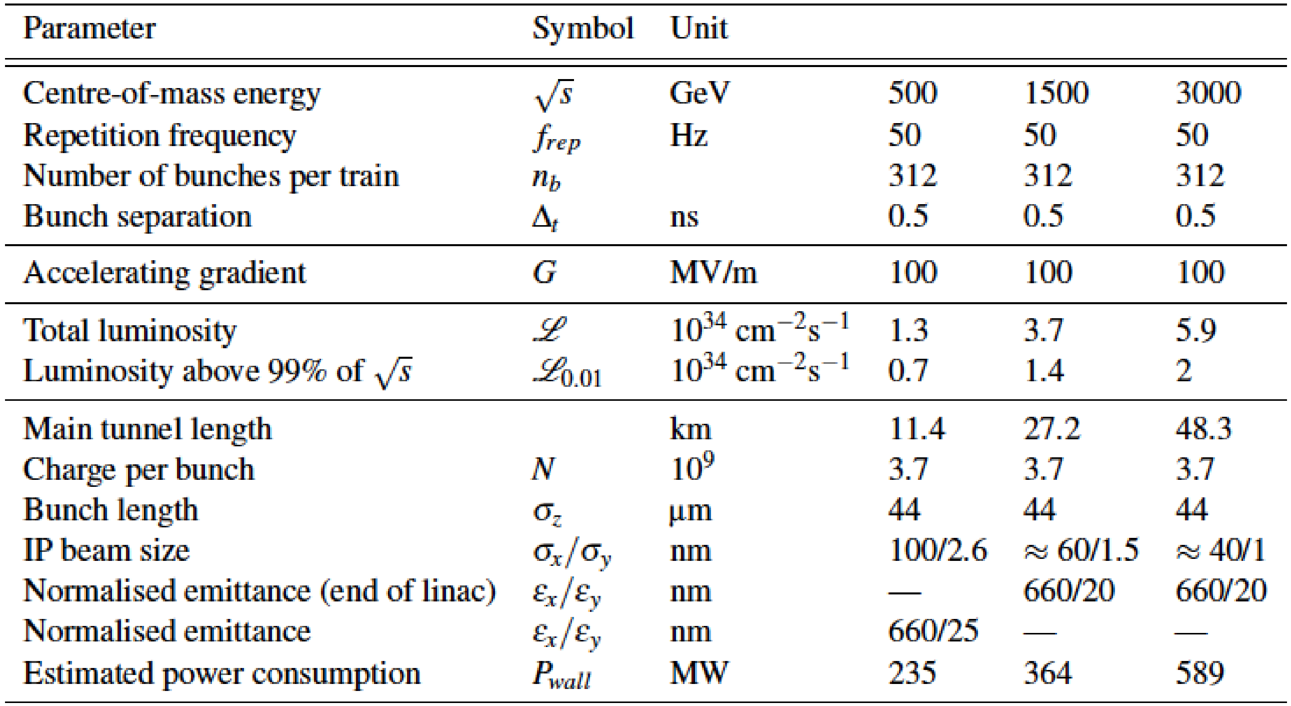
2 km

CLIC Implementation

← Possible lay-out near CERN

Note: the design is currently being re-optmised, e.g. to include 350 GeV as the first stage

↓ CLIC parameters



Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	≈ 60/1.5	≈ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

Bibliography

- *Unifying Physics of Accelerators, Lasers and Plasma*, Andrei Seryi, CRC Press, 2015
- *The Physics of Particle Accelerators – An Introduction*, Klaus Wille, OUP, 2000
- *An Introduction to Particle Accelerators*, Edmund Wilson, OUP, 2001
- *Engines of Discovery*, Andrew Sessler & Edmund Wilson, World Scientific, 2006
- *Engines of Discovery Revised & Expanded Edition*, Andrew Sessler & Edmund Wilson, World Scientific, 2014