Lecture 1

Introduction to Particle Accelerators

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Graduate Accelerator Physics Course
John Adams Institute for Accelerator Science
16 October 2024

JAI Graduate Accelerator Physics Course

- Delivered over **two Academic Terms**
  - **Term I** (Michaelmas Term 2024)
    - 24 lectures and 6 tutorials
    - First three lectures and first tutorial includes Oxford PP students.
  - **Term II** (Hilary Term 2025)
    - 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

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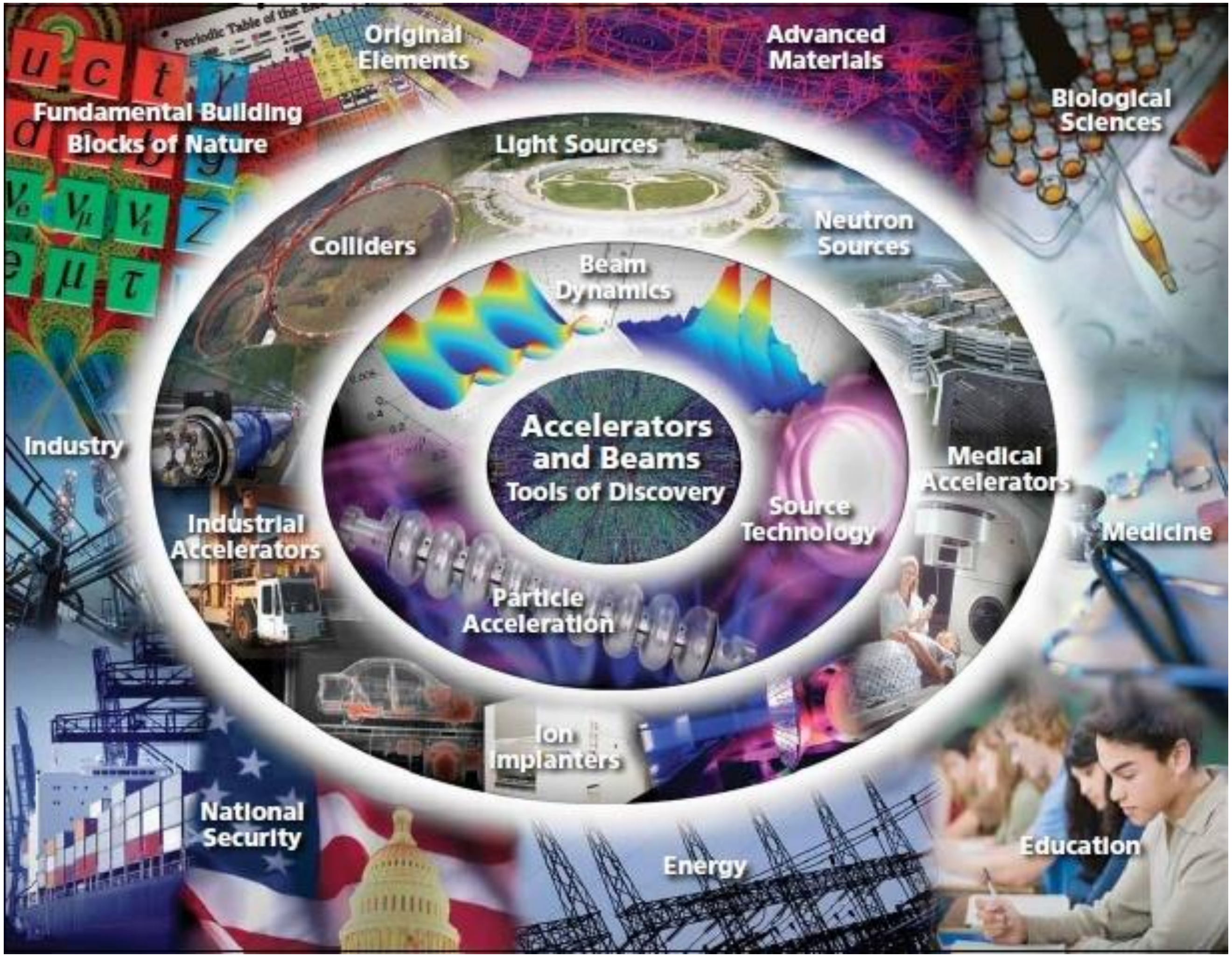
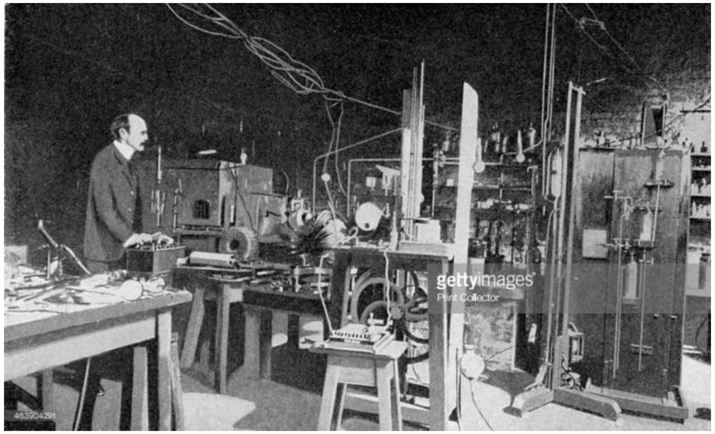
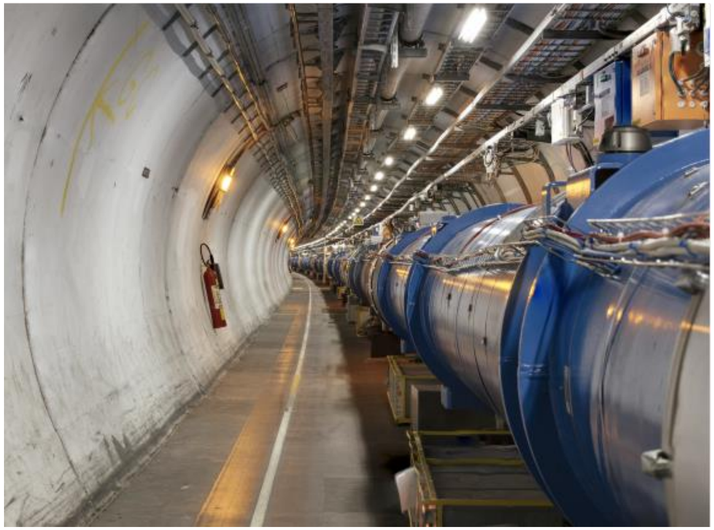
Introduction



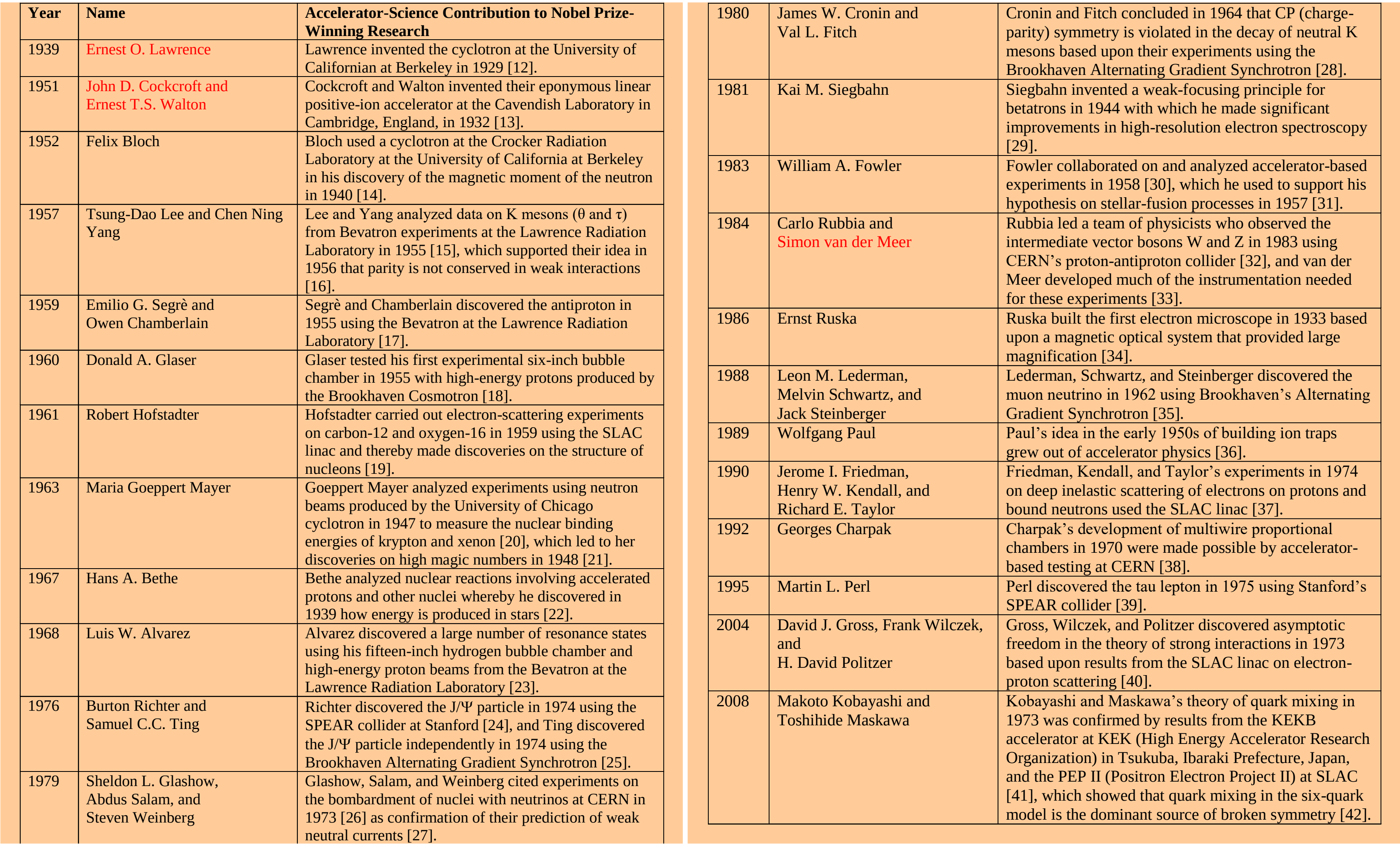
Accelerator Development

- 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.





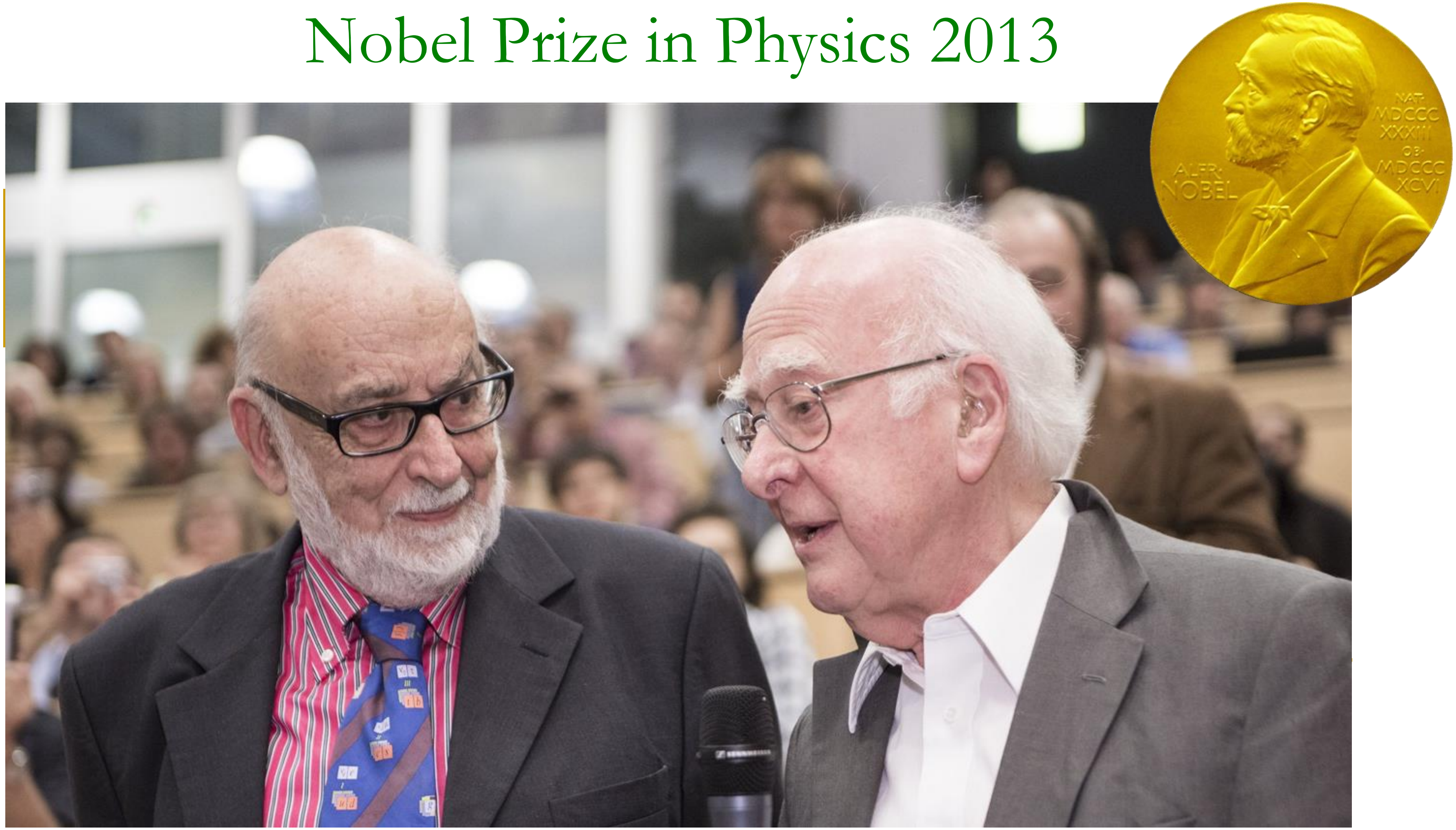
24 (+1) Nobel Prizes in Physics that had direct contribution from accelerators



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].

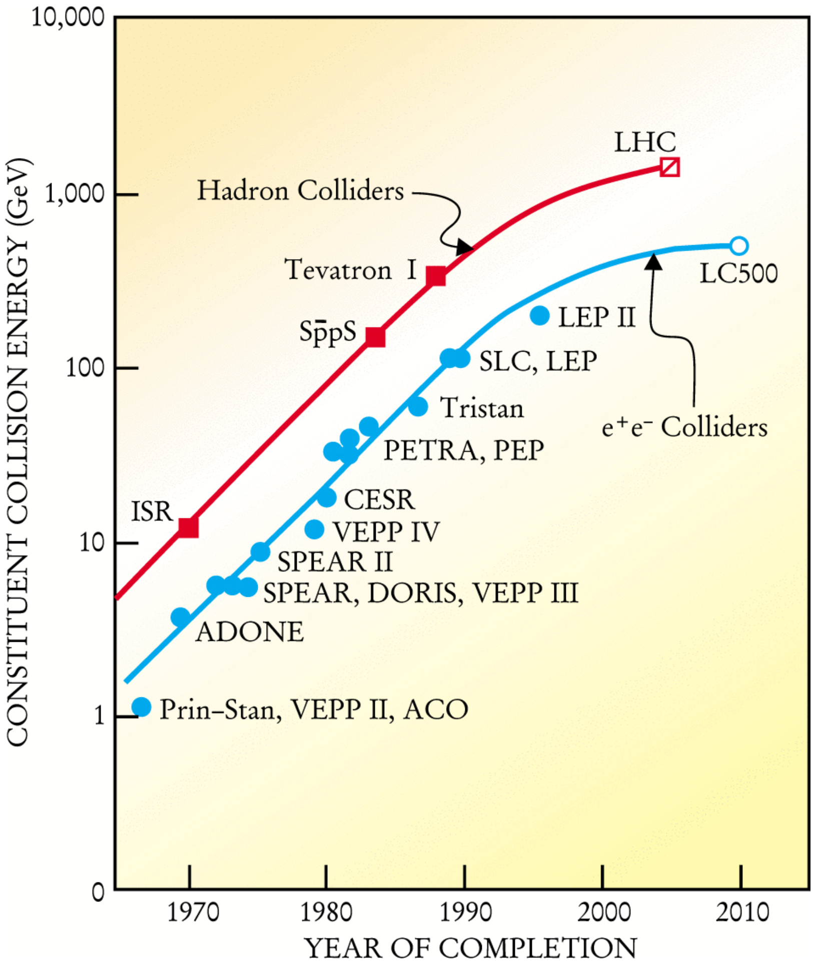
A.Chao and E. Haussecker "*Impact of Accelerator Science on Physics Research*", published in ICFA Newsletter, Dec 2010; & submitted to the Physics in Perspective Journal, Dec 2010.

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".*

Livingston Plot

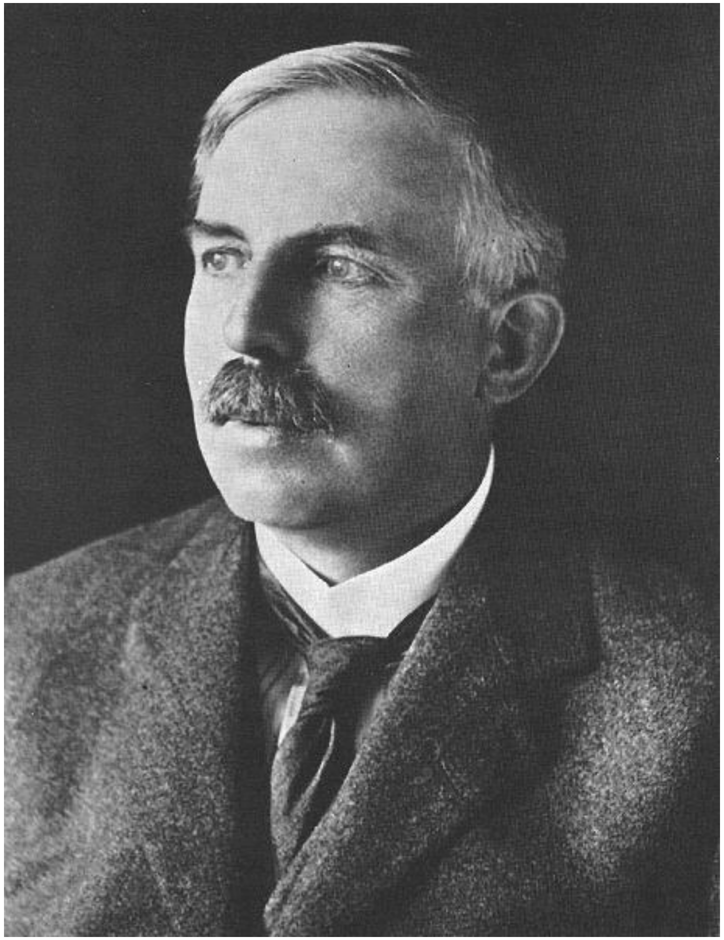


- Around 1950, Livingston made following observation:
  - Plotting energy of accelerator as a function of year of commissioning, on semi-log scale, the energy gain had linear dependence.
- Observations today:
  - Exhibition of saturation effect:
    - New technologies needed.
  - Overall project cost 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.

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".

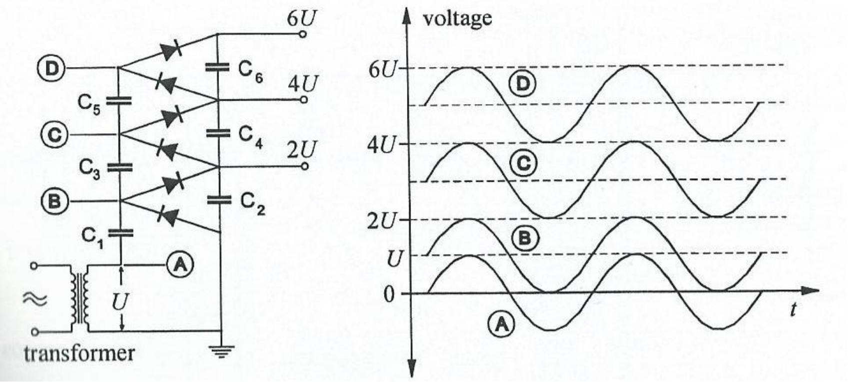


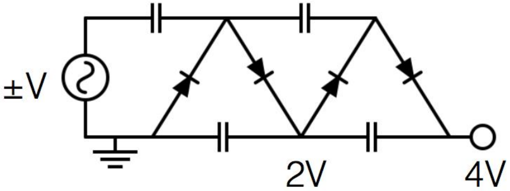
Electrostatic Accelerators
The Cockcroft-Walton

- 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.



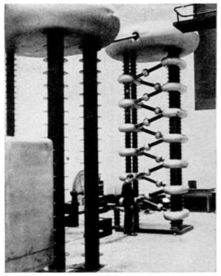


Voltage multiplier circuit

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

Walton and the machine used to "split the atom"

Cavendish Lab, Cambridge



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

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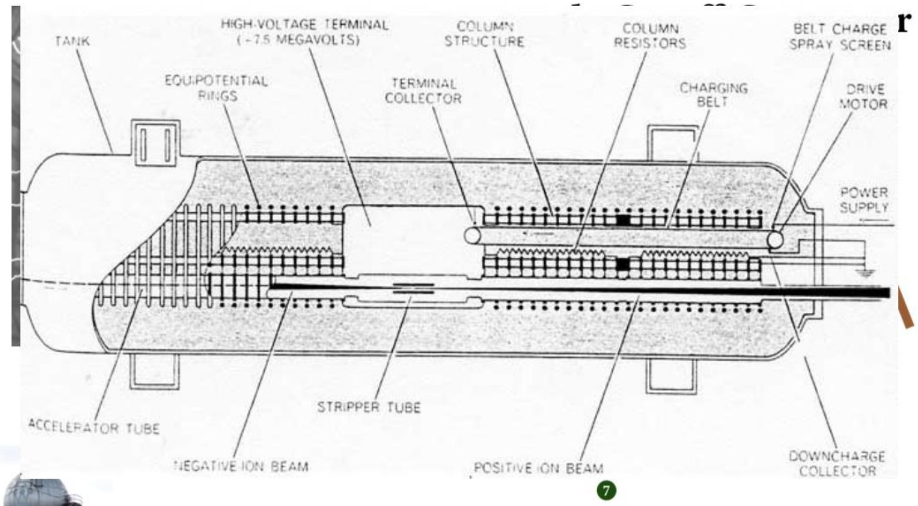
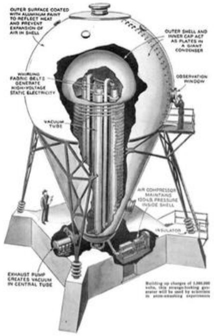
Electrostatic Accelerators – The Van de Graaff

- 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).

Robert Van de Graaff 1929



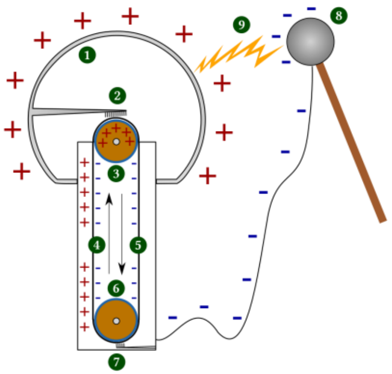
1. hollow metal sphere
2. upper electrode
3. upper roller (for example an acrylic glass)
4. side of the belt with positive charges
5. opposite side of belt, with negative charges
6. lower roller (metal)
7. lower electrode (ground)
8. spherical device with negative charges
9. spark produced by the difference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



The Westinghouse atom smasher, 1937

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

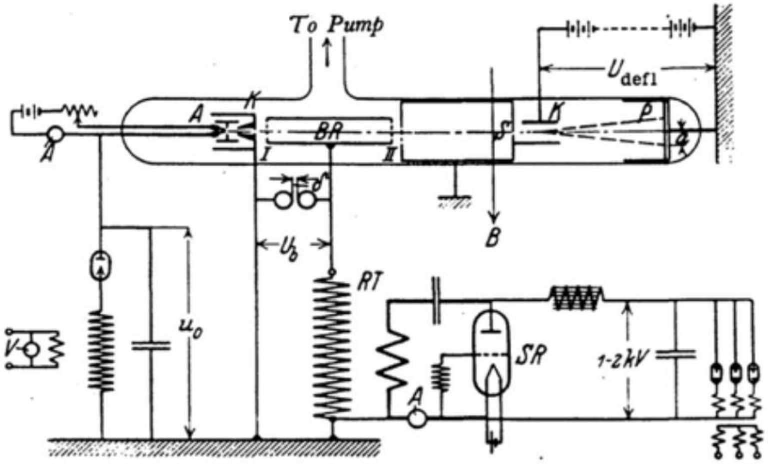
Van de Graaff Generator



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

Linear Accelerators

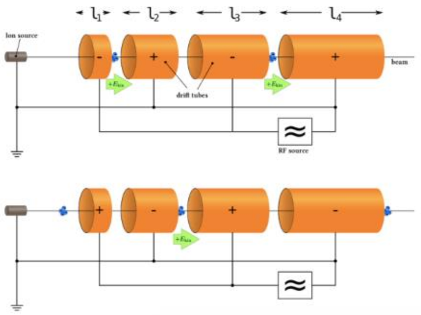
- Rolf Widerøe, 1924
- His PhD thesis was to realise a single drift tube with 2 gaps. 25kV, 1MHz AC voltage produced a 50keV kinetic energy beam.
- First resonant accelerator (patented)



The linear accelerator & it's AC powering circuit

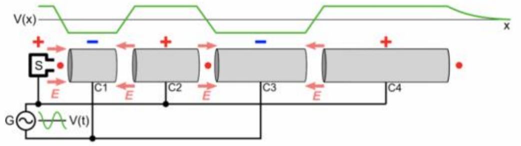
Historical note: He was influenced by Gustav Ising's work, which was never realised in practise as he didn't use an AC source.
Ising, Gustav. *Arkiv Fuer Matematik, Astronomi Och Fysik* **18** (4), 1928

Linear Accelerators



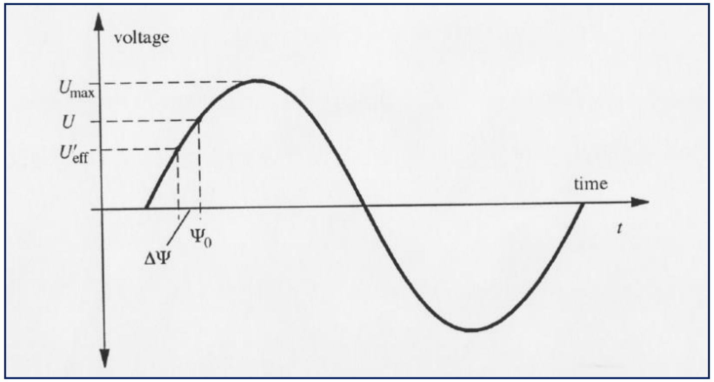
$$l = \beta\lambda_{rf}/2 = v/2f_{rf}$$

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



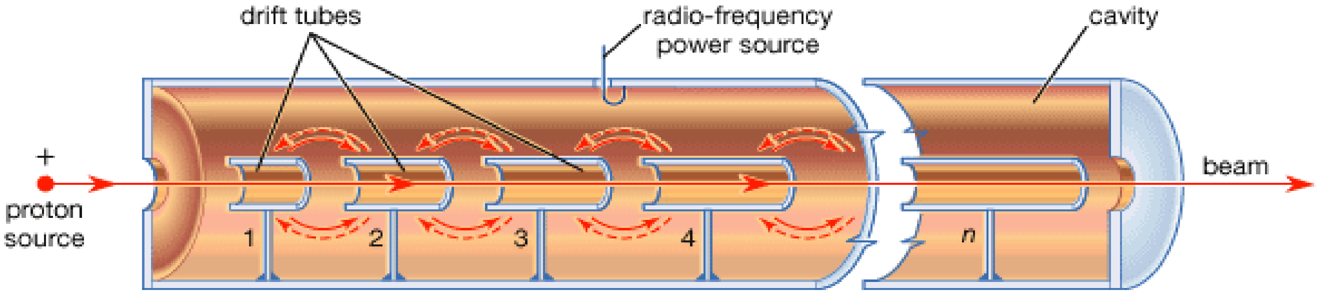
But Wideroe's idea was not quite an RF cavity, Alvarez introduced that…

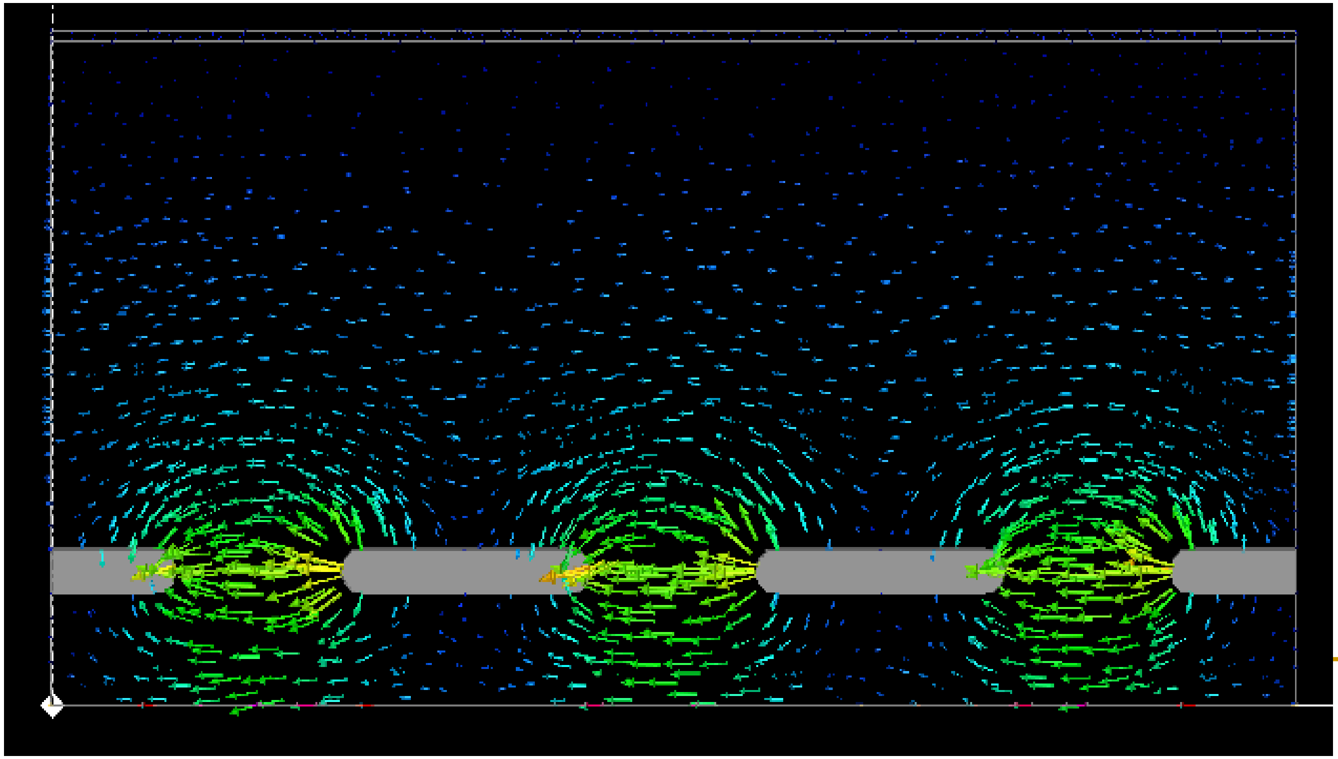
Phase focusing in linacs



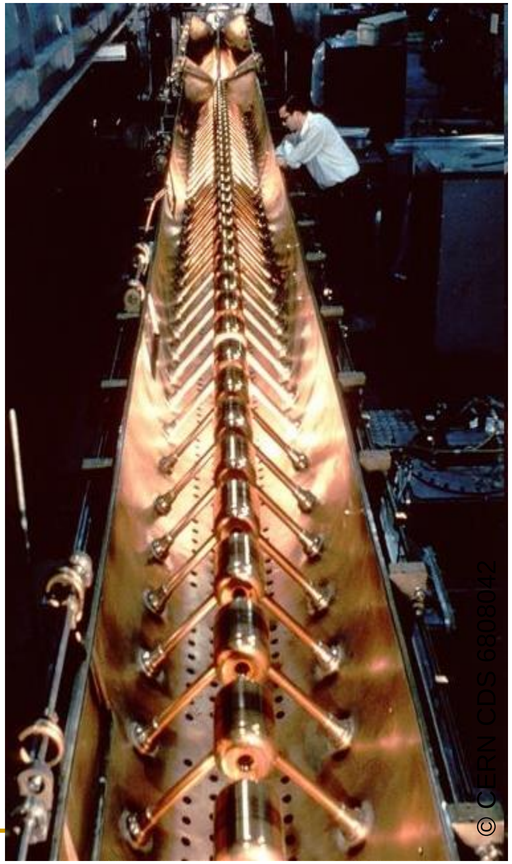
- Principle
  - Use rapidly-changing high frequency voltages instead of direct voltages (Ising)
  - Energy is proportional to number of stages *i* traversed by particle.
  - The largest voltage in entire system is never greater than V_{max}
    - Arbitrary high energies without voltage discharge.

Drift Tube Linac: Higher Integrated Field





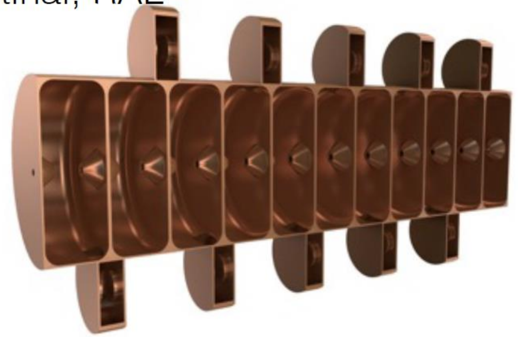
CERN LINAC1



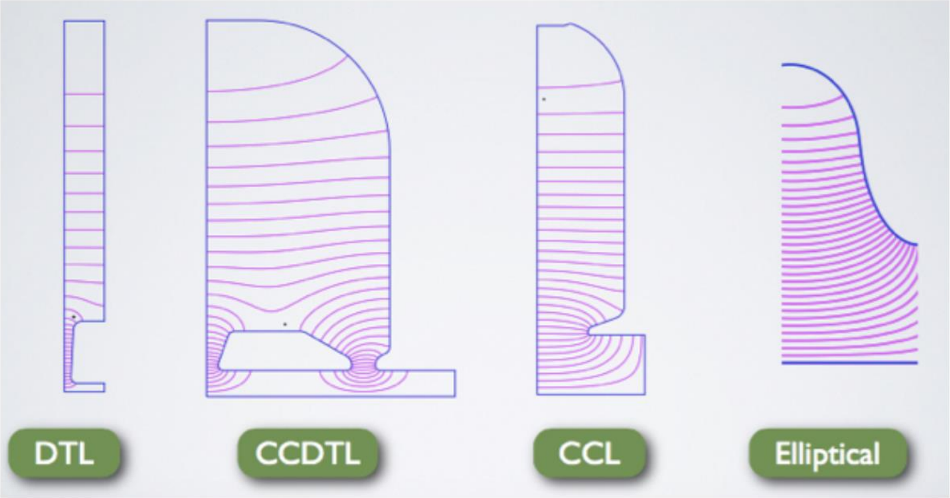
Linac Structures

Images thanks to Ciprian Plostinar, RAL

DTL: Drift Tube Linac



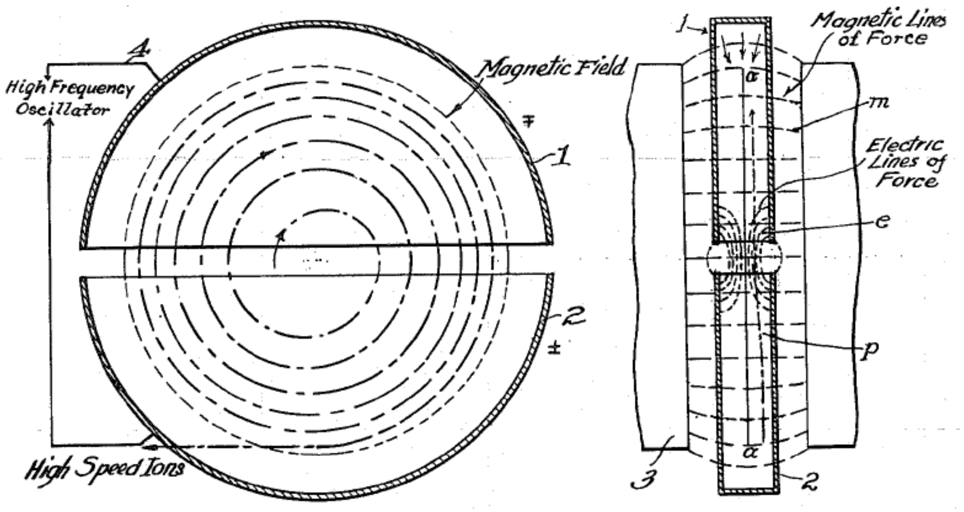
CCL: Coupled Cavity Linac

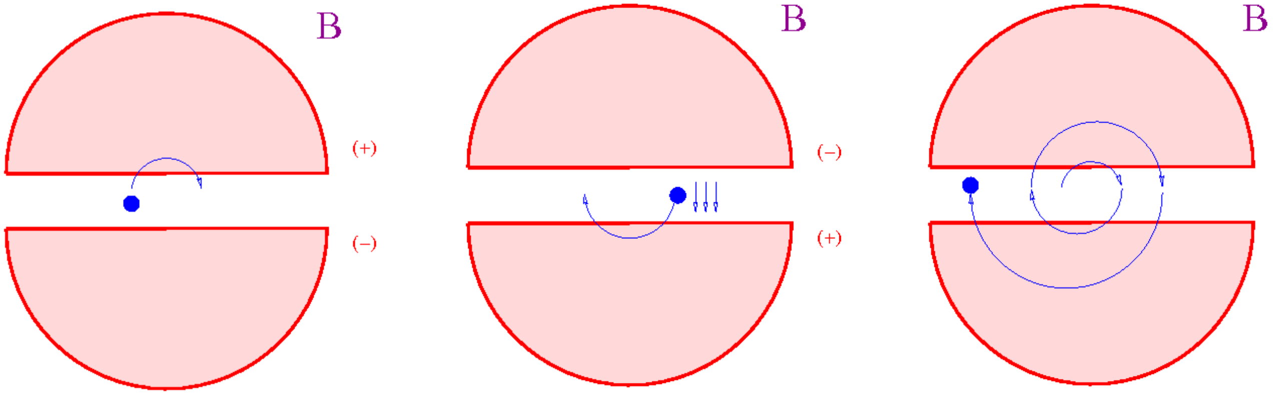


F. Gerigk, CERN

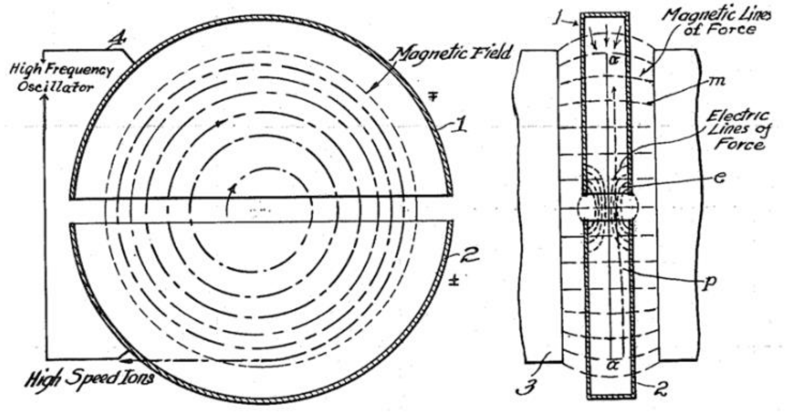
The Cyclotron (1/3)

- 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.

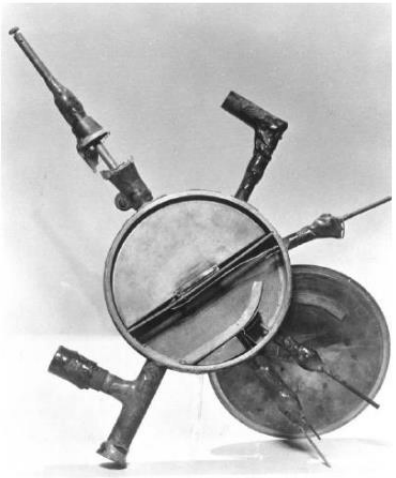




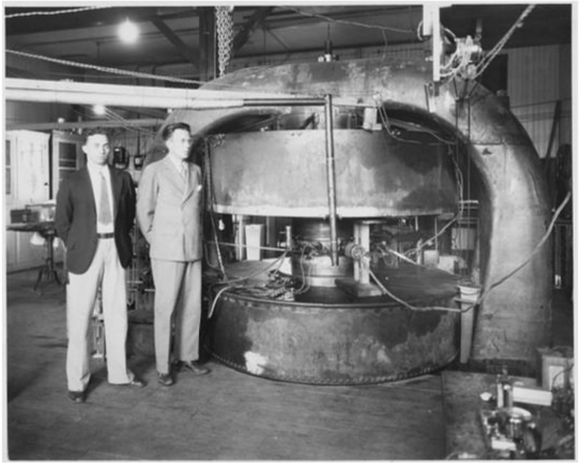
The Cyclotron (2/3)



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

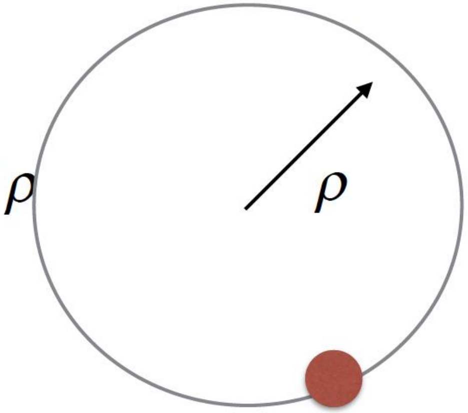
Cyclotron (3/3)

Centrifugal force = magnetic force

$$\frac{mv_\theta^2}{\rho} = qv_\theta B_z$$

Ernest Lawrence

Revolution frequency $\omega_0 = v_\theta / \rho$



Lawrence: "R cancels R!"

Cancelling out rho gives:

$$\omega_0 = qB_z / m$$

$$\rho = mv / qB_z$$

ie. for constant charge q and mass m, and a uniform magnetic field B, the angular frequency is constant. ie. the rf frequency can be constant. The orbit radius is proportional to speed, v.

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

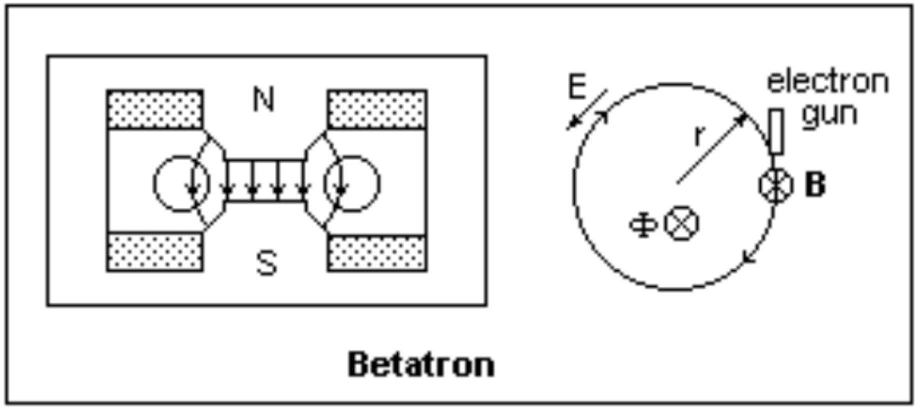


Image: http://mysite.du.edu/~jcalvert/phys/partelec.htm#Tron

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

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

Centripetal force provided by Lorentz force

The Synchrotron - Origins

> "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

With Ernest Rutherford in 1932

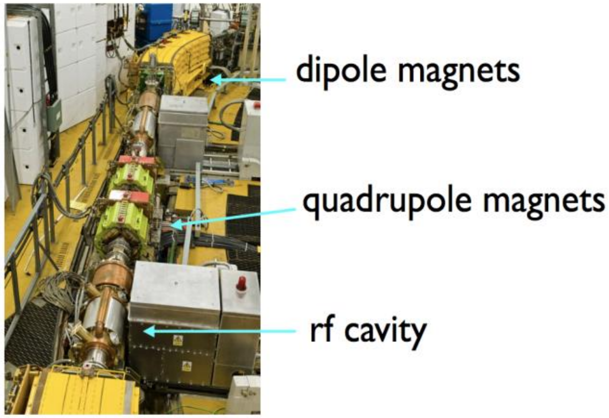
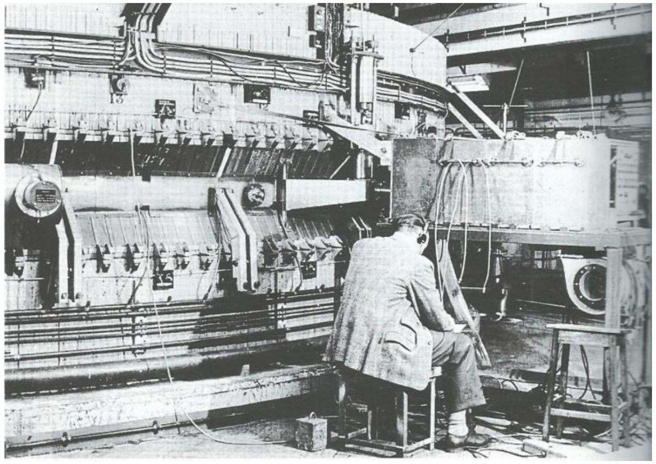


Image courtesy of ISIS, STFC



1 GeV machine at Birmingham University

Synchrotrons - Principles

- From

  $R = E / (ecB)$

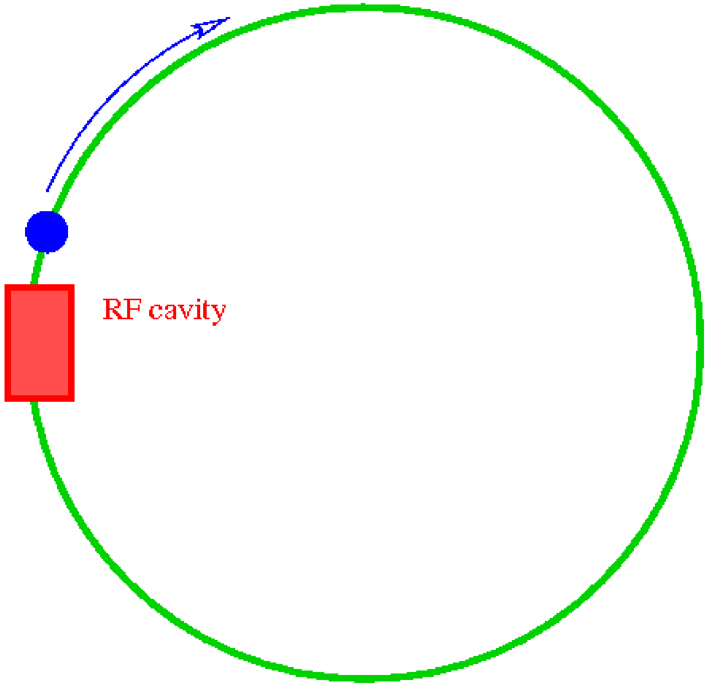
  E/B kept constant since R is fixed.

  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”.

R = radius of curvature
E = particle energy
B = magnetic field



Beam Optics

- Physical fundamentals for beam steering & focusing.
- Fix particle trajectory and then repeatedly steer diverging particles back onto ideal trajectory.
- Performed by EM fields (***E*** and ***B***) satisfying Lorentz Force

$$F = e(\mathbf{E} + v \times \mathbf{B}) = \dot{p}$$

- Lorentz force = centrifugal force

$$F_x = -e v_s B_z$$

$$F_r = m v_s^2 / R$$

$$\frac{1}{R(x,z,s)} = \frac{e}{p} B_z(x,z,s)$$

Magnetic Rigidity

- ✓ The force **evB** on a charged particle moving with velocity **v** in a dipole field of strength **B** is equal to its mass multiplied by its acceleration towards the centre of its circular path.
- ✓ This is:

$$F = evB = \frac{mv^2}{\rho}$$

Radius of curvature

Like for a stone attached to a rotating rope

- ✓ Which can be written as:

$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

Momentum
P=mv

- ✓ **Bρ** is called the **magnetic rigidity**, and in the correct units obtain:

Bρ = 33.356·p [KG·m] = 3.3356·p [T·m] (if p is in [GeV/c])

Energy & Momentum

- Einstein's relativity formula: $E = mc^2$

Total energy:
kinetic + rest mass

  - For a mass at rest this will be: $E_0 = m_0 c^2$

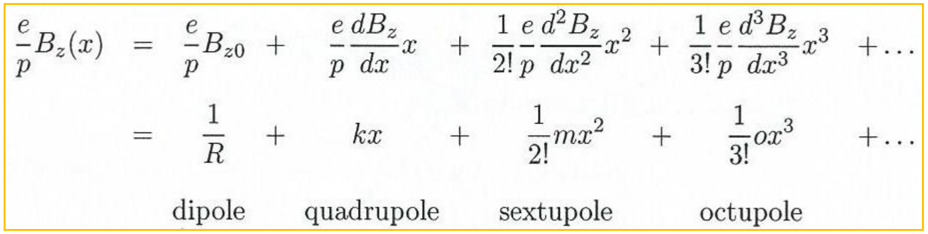
Rest mass

Rest energy

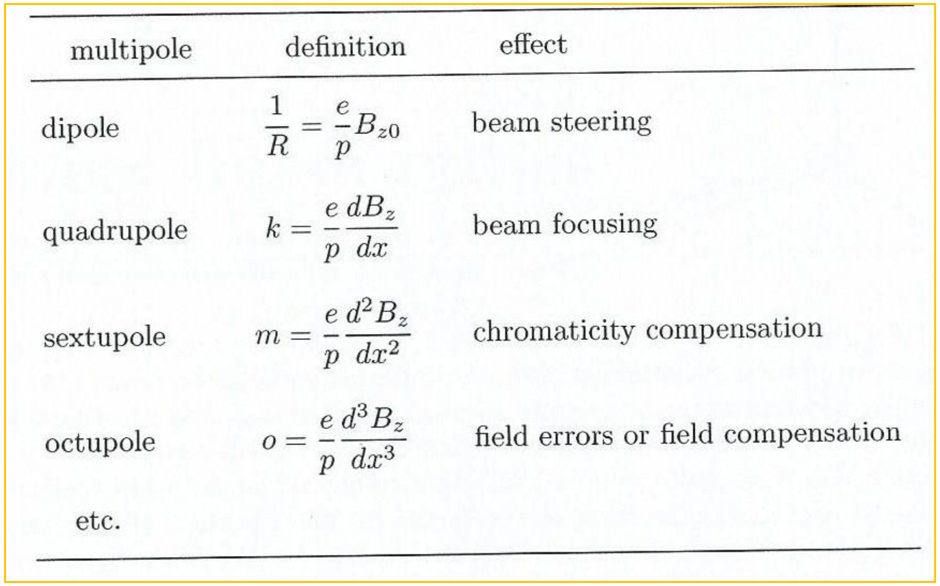
  - Define: $\gamma = \frac{E}{E_0}$ as being the ratio between the total energy and the rest energy.
  - Then the mass of a moving particle is: $m = \gamma m_0$
  - Define: $\beta = \frac{v}{c}$, then can write: $\beta = \frac{mvc}{mc^2}$
  - $p = mv$, which is always true and gives: $\beta = \frac{pc}{E}$ *or* $p = \frac{E\beta}{c}$

Multipoles in Beam Steering

- Magnetic field around beam is sum of multipoles.
  - Each has different effect on particle path.
- Linear beam optics refers to use of only dipoles and quadrupoles for beam steering.

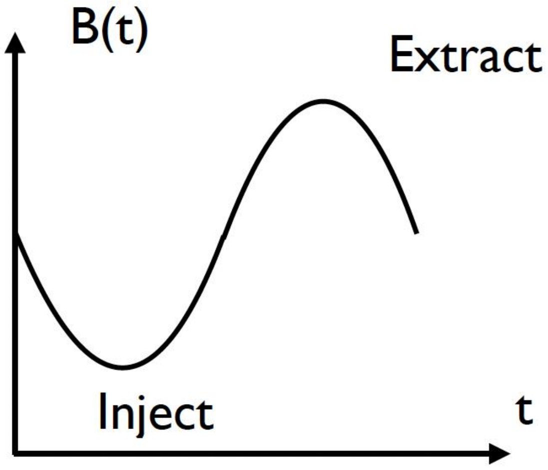


$$\begin{aligned}\frac{e}{p}B_z(x) &= \frac{e}{p}B_{z0} + \frac{e}{p}\frac{dB_z}{dx}x + \frac{1}{2!}\frac{e}{p}\frac{d^2B_z}{dx^2}x^2 + \frac{1}{3!}\frac{e}{p}\frac{d^3B_z}{dx^3}x^3 + \dots \\ &= \underbrace{\frac{1}{R}}_{\text{dipole}} + \underbrace{kx}_{\text{quadrupole}} + \underbrace{\frac{1}{2!}mx^2}_{\text{sextupole}} + \underbrace{\frac{1}{3!}ox^3}_{\text{octupole}} + \dots\end{aligned}$$



multipole	definition	effect
dipole	$\frac{1}{R} = \frac{e}{p}B_{z0}$	beam steering
quadrupole	$k = \frac{e}{p}\frac{dB_z}{dx}$	beam focusing
sextupole	$m = \frac{e}{p}\frac{d^2B_z}{dx^2}$	chromaticity compensation
octupole	$o = \frac{e}{p}\frac{d^3B_z}{dx^3}$	field errors or field compensation
etc.		

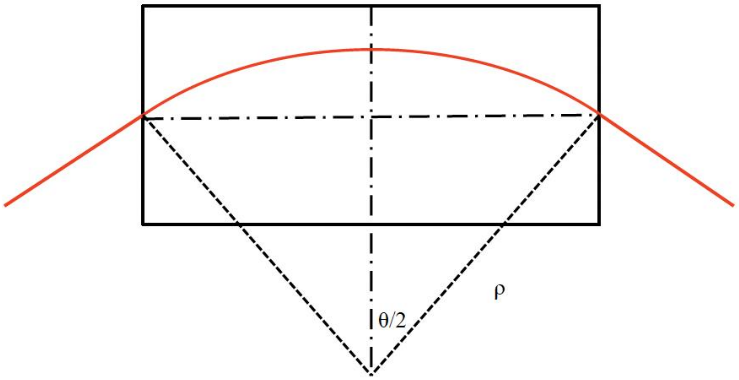
Synchrotrons- Bending Magnets



Typical synchrotron magnet cycle

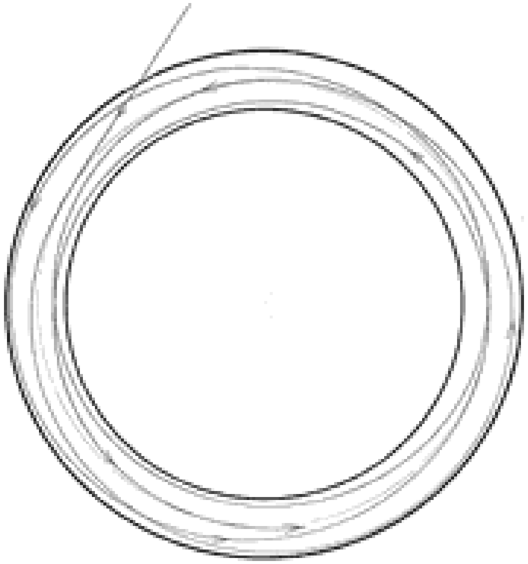
Bending angle in dipole magnet

$$\sin(\theta/2) = \frac{B(t)L}{2(B(t)\rho)} \qquad \theta \approx \frac{B(t)L}{p(t)/q}$$



Synchrotrons - Focusing

- Focusing is needed to confine the orbits.
- First accelerators had “weak focusing” – focusing period is larger than the perimeter.
  - Vertical focusing comes from the curvature of the field lines when the field falls off with radius.
  - Horizontal focusing from the curvature of the path.
  - Negative field gradient defocuses horizontally & must not be so strong as to cancel path curvature effect

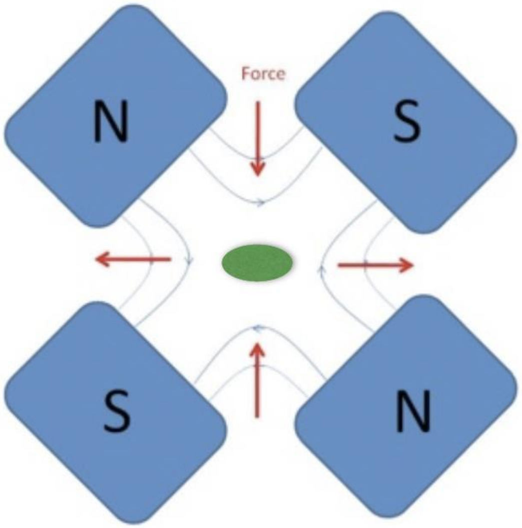


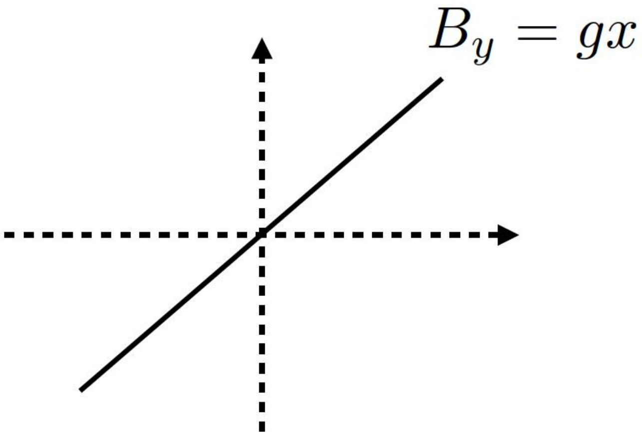
Weak focusing accelerator

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

Synchrotron – Focusing Magnets



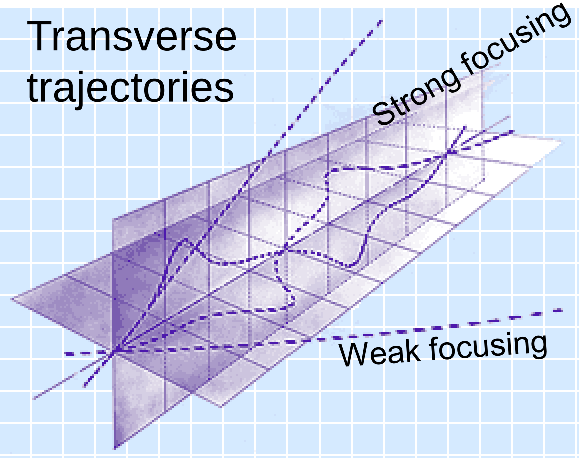


$$B_y = gx$$

$$k = \frac{g}{p/q} \qquad \frac{1}{f} = \frac{L(dB(t)/dx)}{p(t)/q}$$

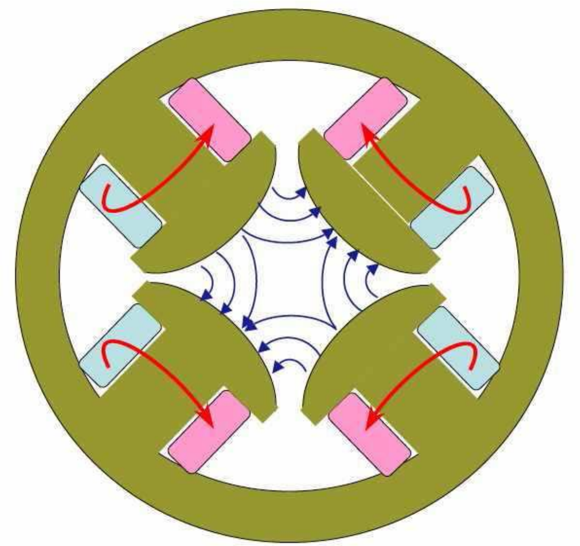
‘normalised gradient’ of quad

- “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.

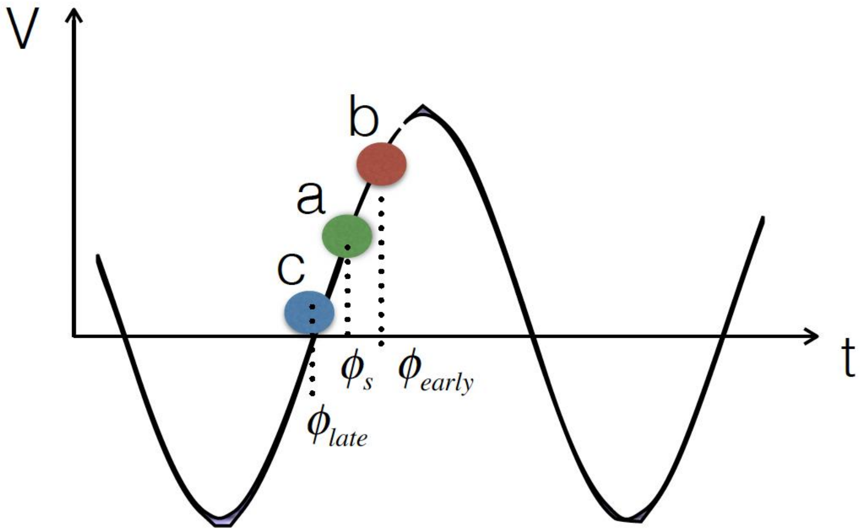
Synchtroton – Phase Stability

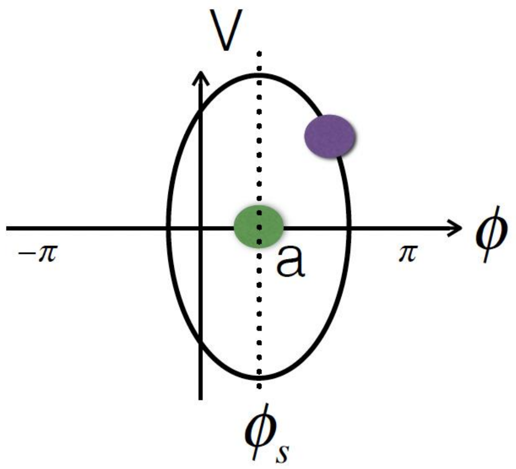
a - synchronous

b - arrives early, sees higher voltage, goes to larger orbit -> arrives later next time

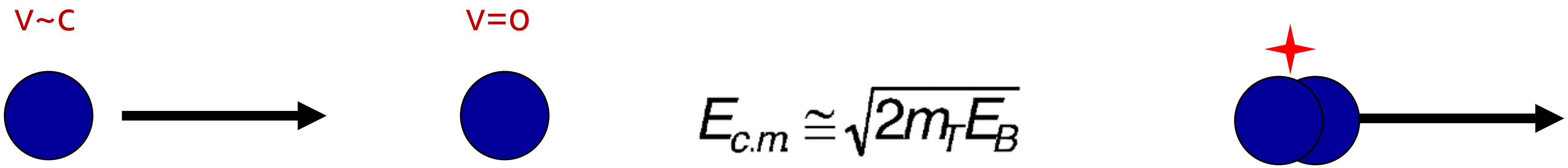
c - arrives late, sees lower voltage, goes to smaller orbit -> arrives earlier next time

$$V = V_0 \sin(2\pi f_a + \phi_s)$$





Why Colliders?



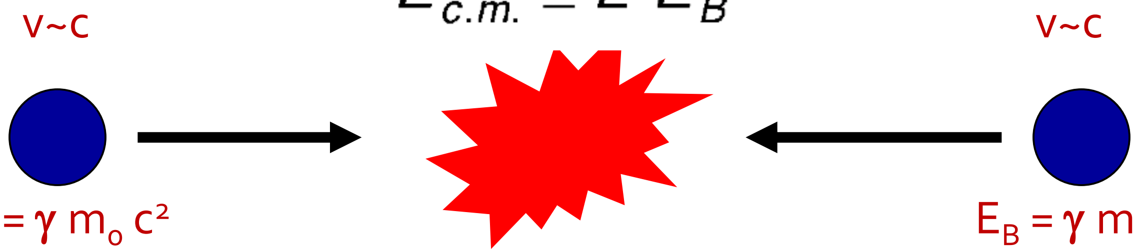
$$E_{c.m} \cong \sqrt{2 m_T E_B}$$

$E_B = \gamma\, m_o\, c^2$

$P_B = \gamma\, m_o\, v$

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

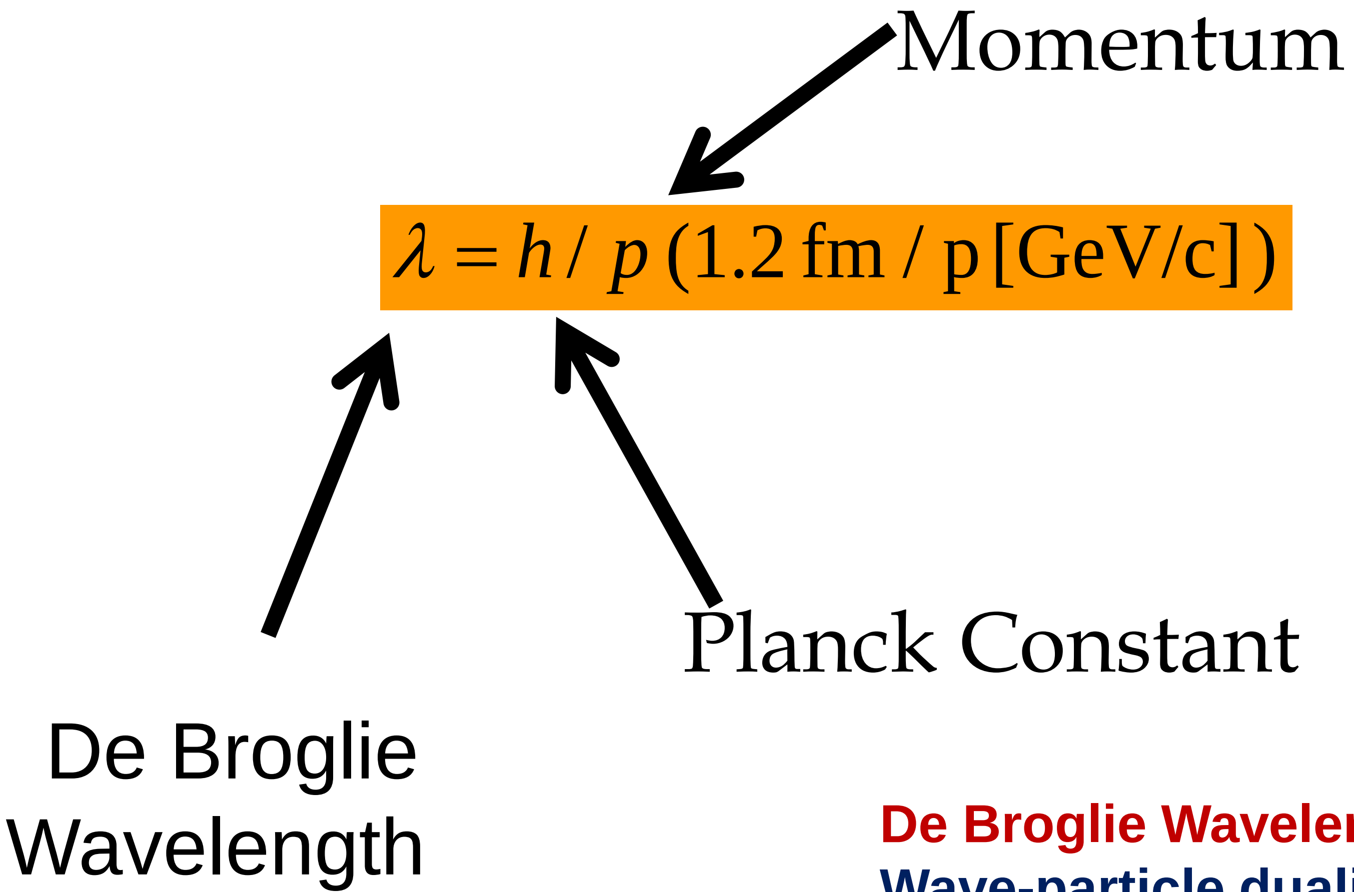
$$E_{c.m.} \cong 2\ E_B$$



$E_B = \gamma\, m_o\, c^2$

$E_B = \gamma\, m_o\, c^2$

De Broglie Wavelength



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

Luminosity

Particle colliders designed to deliver two basic parameters to HEP user.

- Measure of collision rate per unit area.
- Event rate for given event probability (“cross-section”):

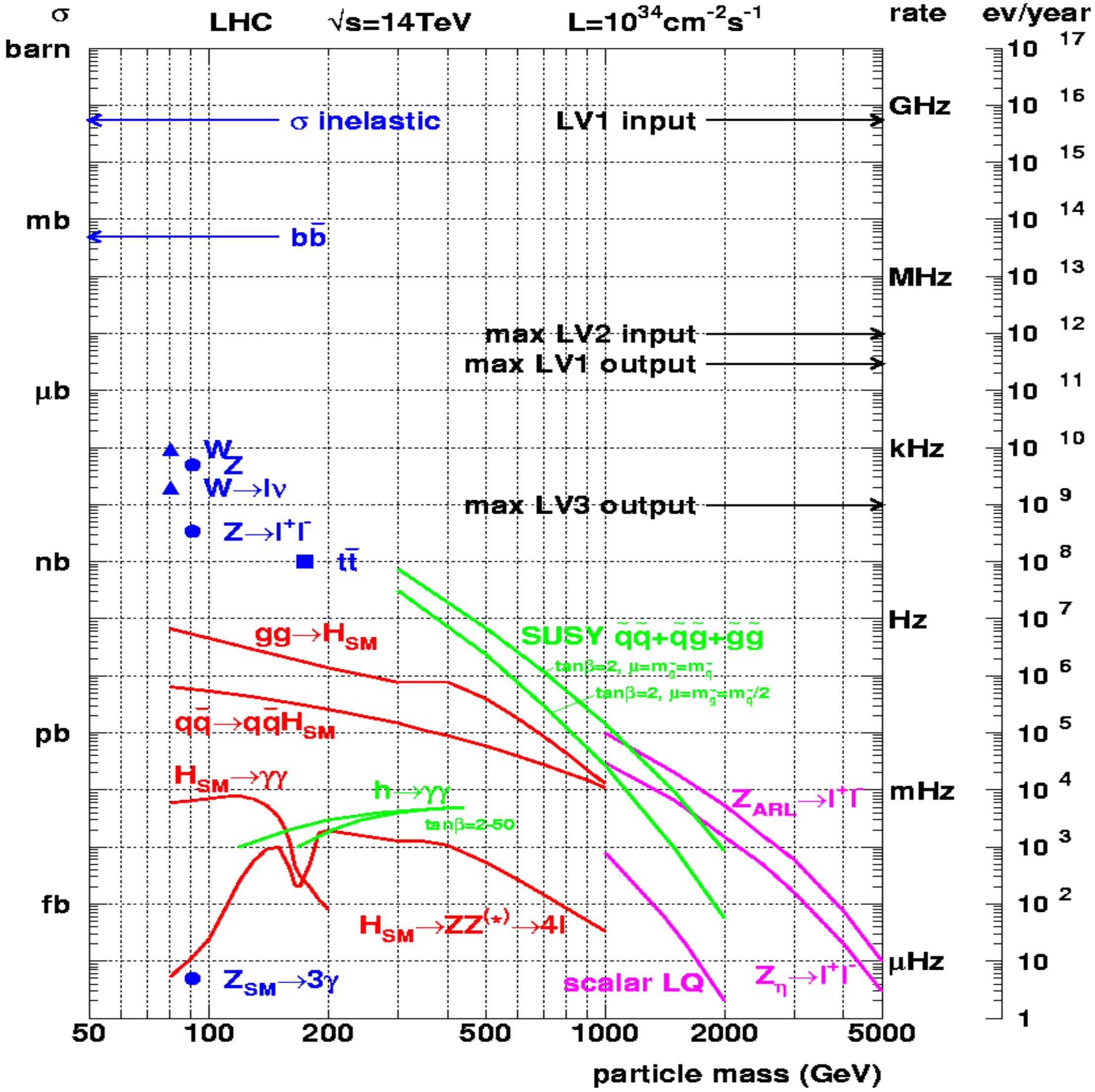
For a Collider, instantaneous luminosity L is given by

$$\boxed{R = \mathscr{L}\,\sigma}$$

- → Require intense beams, high bunch frequency and small beam sizes at IP.

$$\boxed{\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}}$$

Cross-sections at the LHC



"Well known" processes. Don't need to keep all of them …

New Physics!!

We want to keep!!

Collider Types

- Hadron Colliders
  - Desire high energy
    - Only ~10% of beam energy available for hard collisions producing new particles
      - Need *O*(10 TeV) Collider to probe 1 TeV mass scale.
      - High-energy beam requires strong magnets to store and focus beam in reasonable-sized ring.
  - Desire high luminosity
    - Use proton-proton collisions.
      - High bunch population and high bunch frequency.
    - Anti-protons difficult to produce if beam is lost
      - *c.f.* SPS Collider and Tevatron

Collider Types

- Lepton Colliders (e+e-)
  - Synchrotron radiation is the most serious challenge
    - Energy loss of a particle per turn

$$\boxed{u = \underbrace{\frac{4\pi}{3}\frac{r}{\left(m_0c^2\right)^3}}_{C} E^4 \int \frac{1}{\rho^2} d\rho \quad = -\frac{CE^4}{\rho}}$$

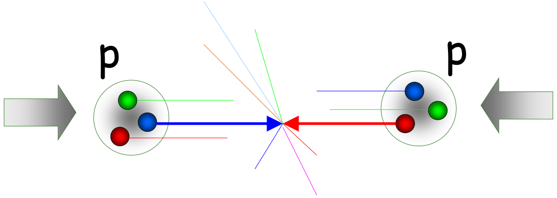
    - Emitted power in circular machine is

$$P_{SR}[\mathrm{kW}] = \frac{88.5\, E^4[\mathrm{GeV}]\, I[\mathrm{A}]}{\rho[\mathrm{m}]}$$

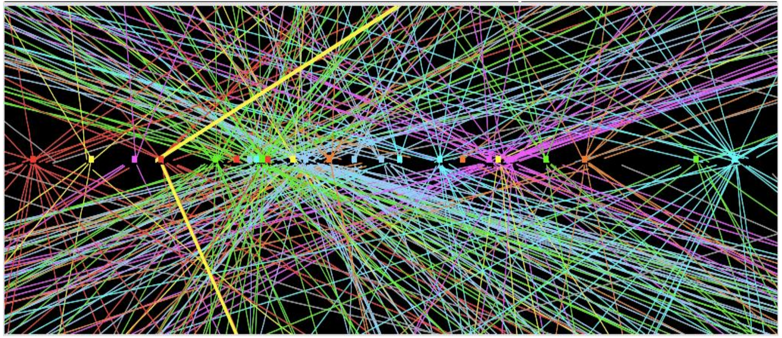
    - For collider with E_{CM} = 1 TeV in the LHC tunnel with a 1 mA beam, radiated power would be 2 GW
      - Would need to replenish radiated power with RF
      - Remove it from vacuum chamber
  - Approach for high energies is Linear Collider.

Collider Characteristics

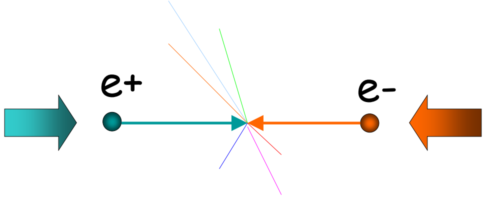
- Hadron collider at the frontier of physics
  - Huge QCD background
  - Not all nucleon energy available in collision



ATLAS Z → μμ event from 2012 data with 25 reconstructed vertices

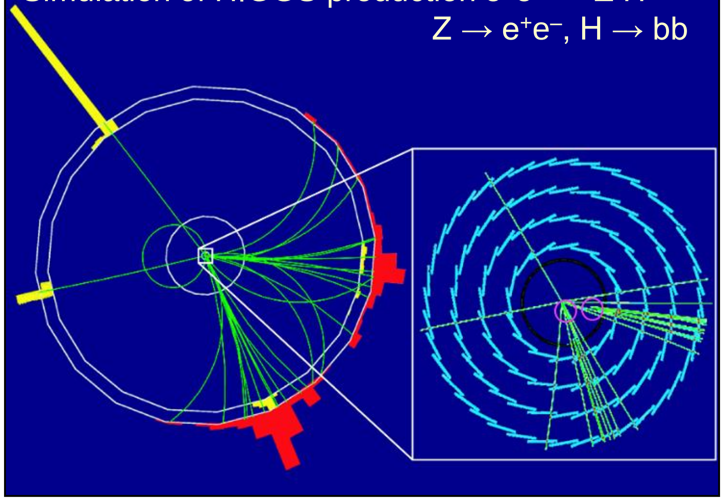


- Lepton collider for precision physics
  - Well defined initial energy for reaction
  - Colliding point like particles

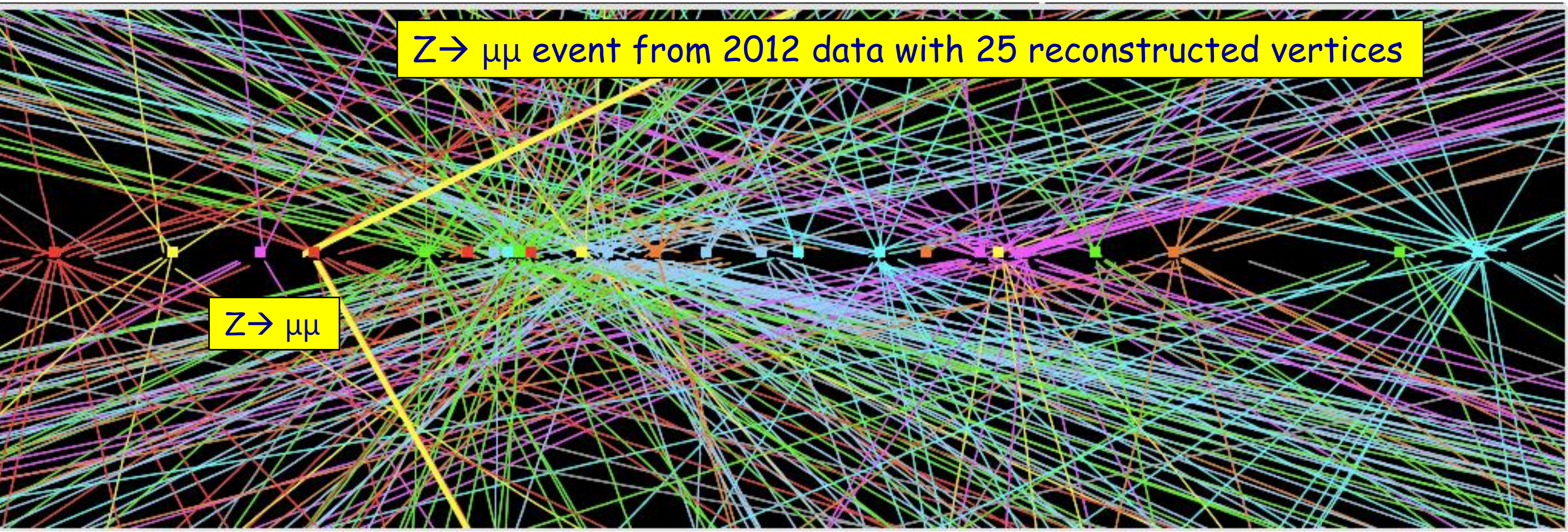


Simulation of HIGGS production $e^+e^- \rightarrow Z\,H$

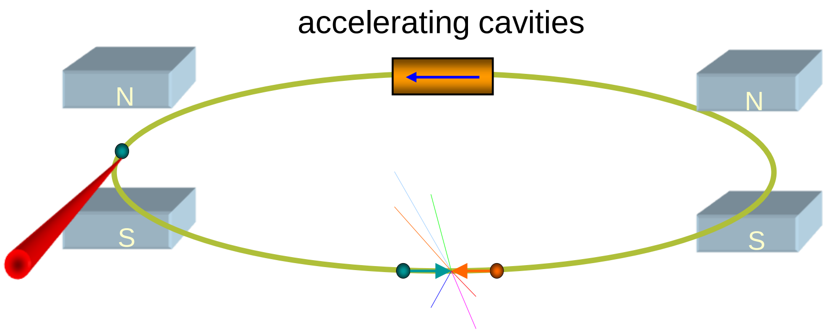
$Z \rightarrow e^+e^-$, $H \rightarrow bb$



The Higgs is hiding in thousands of trillions interactions…



Circular versus Linear Collider

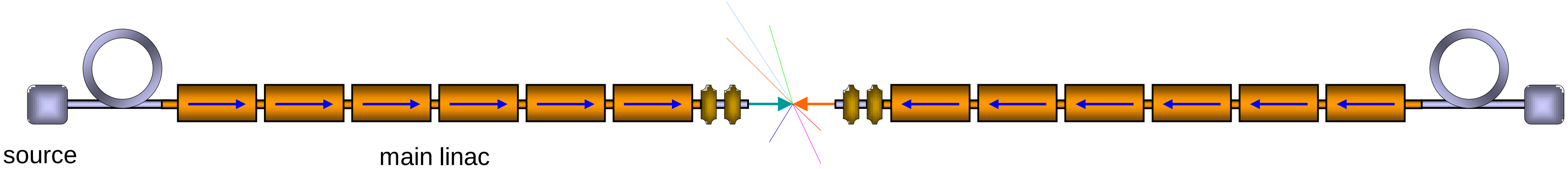


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses (E^4/m^4R)



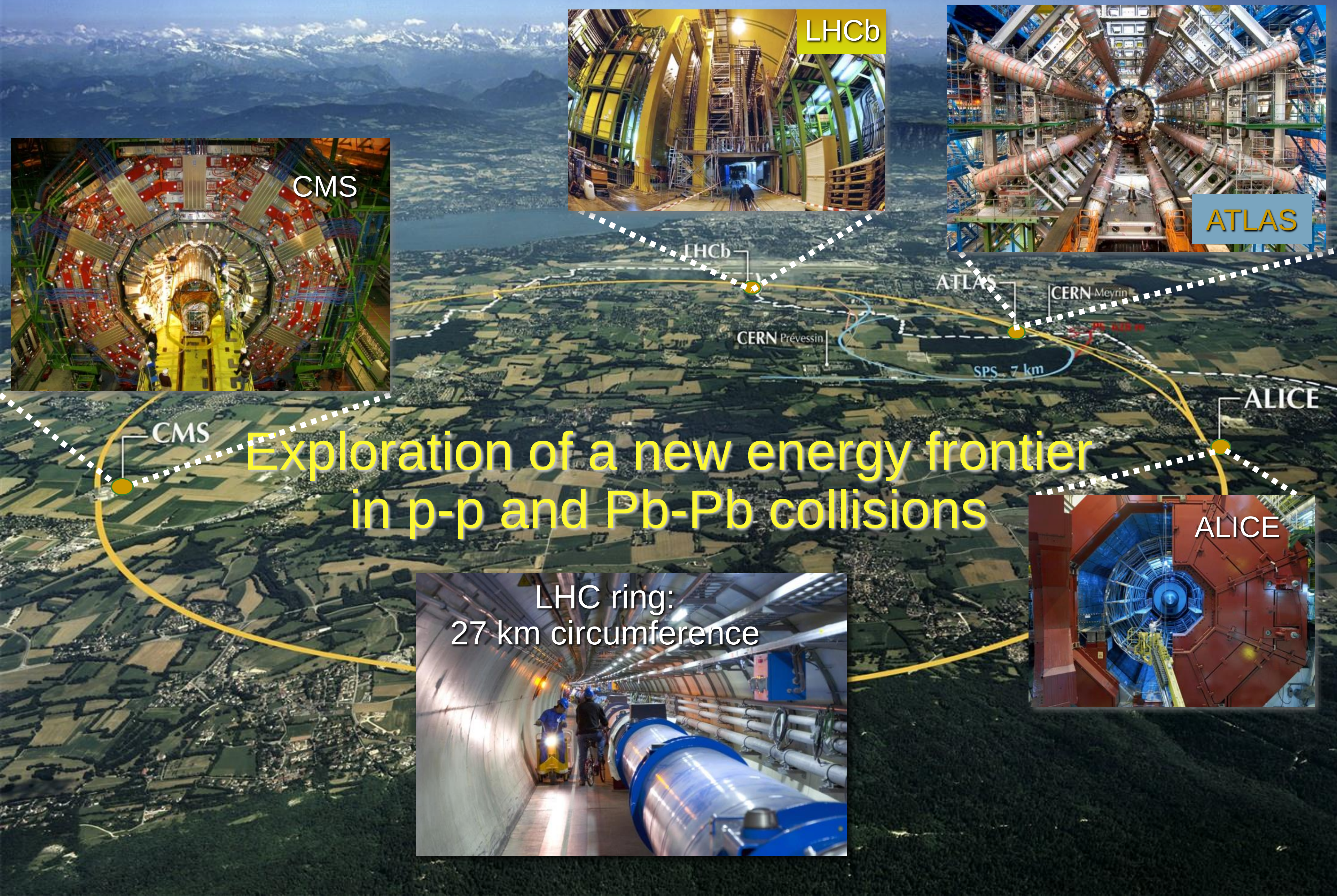
Linear Collider

few magnets, many cavities, single pass beam

higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

A New Era in Fundamental Science



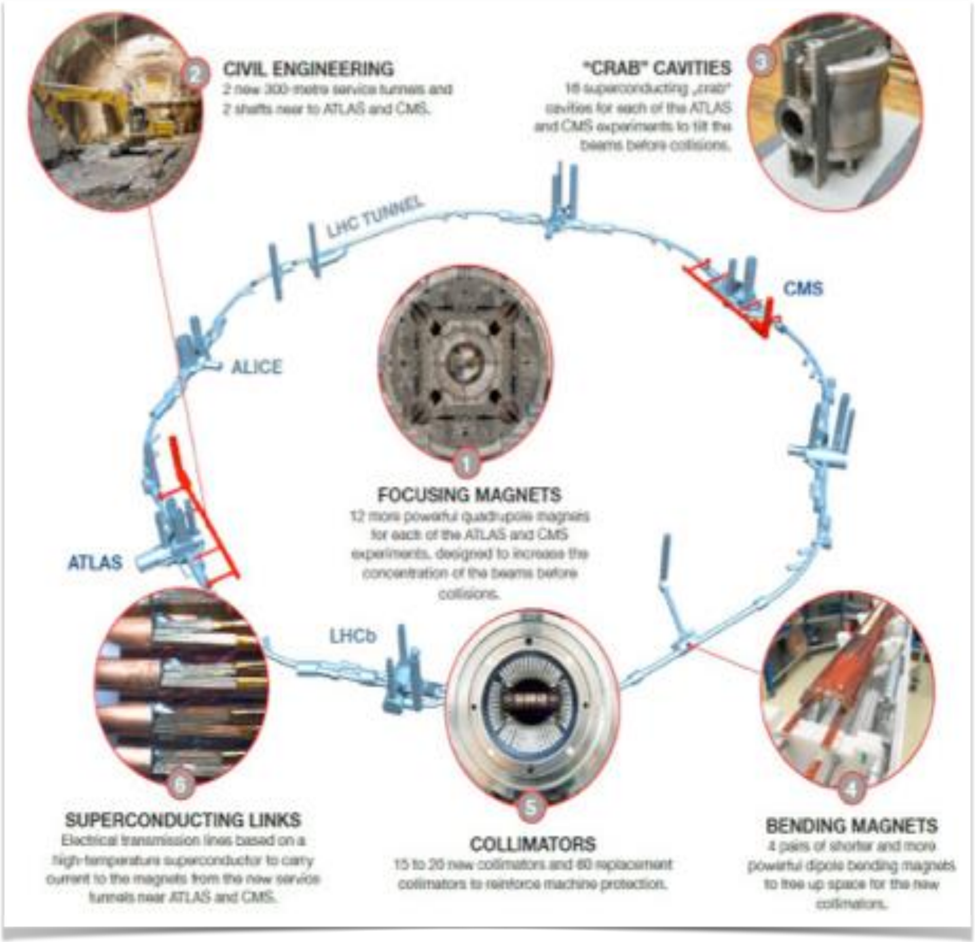
Exploration of a new energy frontier in p-p and Pb-Pb collisions

LHC ring:
27 km circumference

Upgrade to the High-Luminosity LHC is under way

- The HL-LHC will use new technologies to provide 10 times more collisions than the LHC.
- It will give access to rare phenomena, greater precision and discovery potential.
- It will start operating in 2030, and run until approx. 2041.

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.

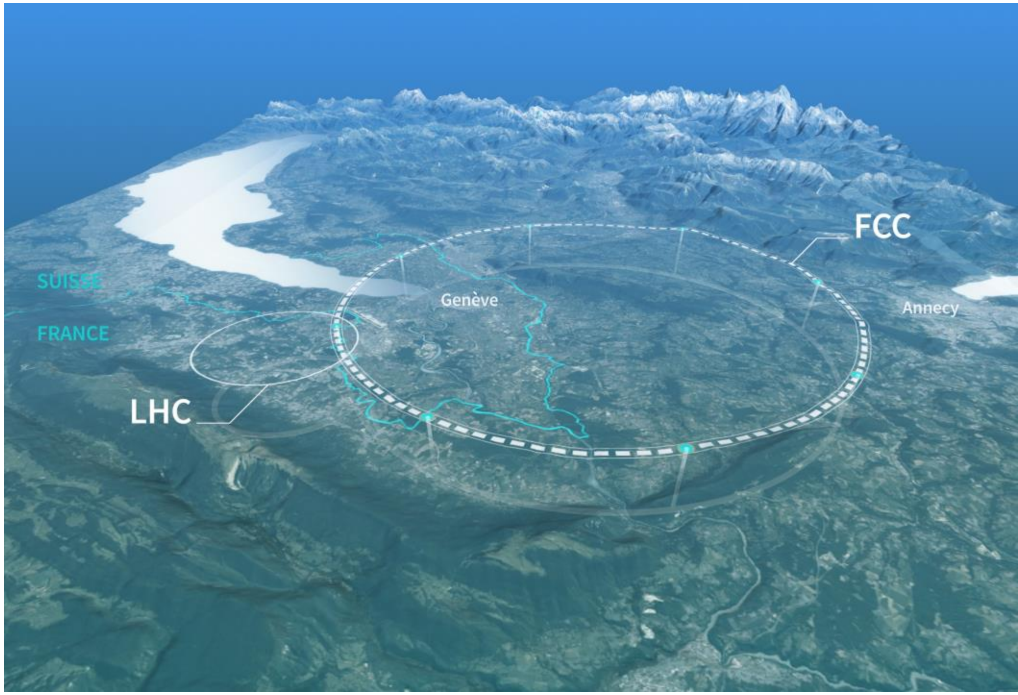
BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

- 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

Preparing CERN’s Future

Driven by the **2020 Update of the European Strategy for Particle Physics**

- Technical and financial feasibility study of a Future Circular Collider (report in 2025)
- Accelerator R&D to develop technologies for FCC and for alternative options
- Detector and computing R&D
- Maintain and expand a compelling scientific diversity programme
- Continue to support other projects around the world



FUTURE
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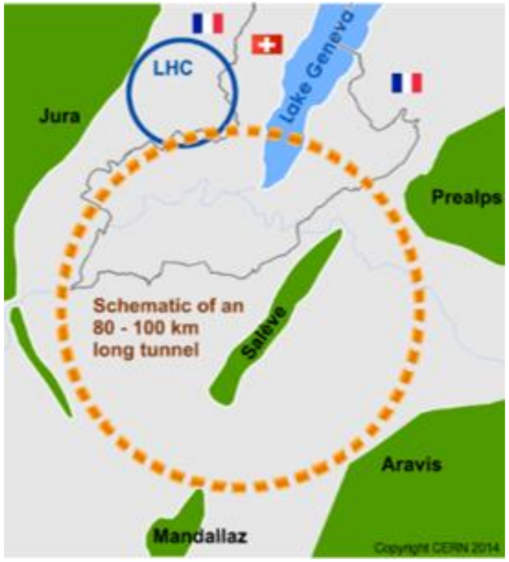
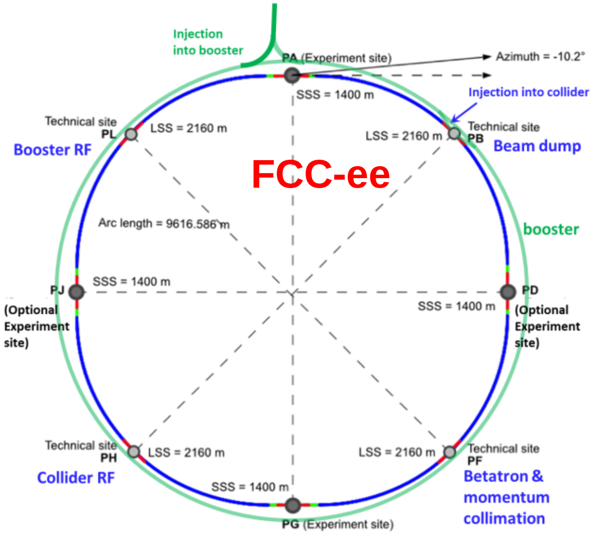
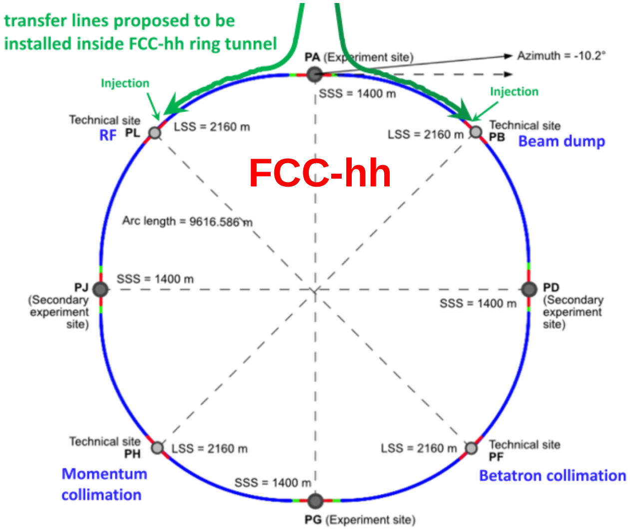
FCC Integrated Programme

Comprehensive long-term programme maximising physics opportunities

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- Highly synergetic and complementary programme boosting the physics reach of both colliders
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







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FCC-ee Main Machine Parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

4 years
5 x 10^{12} Z
LEP x 10^5

2 years
> 10^8 WW
LEP x 10^4

3 years
2 x 10^6 H

5 years
2 x 10^6 tt pairs

Design and parameters to maximise luminosity at all working points:

- Allow for 50 MW synchrotron radiation per beam.
- Independent vacuum systems for electrons and positrons
- Full energy booster ring with top-up injection, collider permanently in collision mode

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

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FCC-hh Main Machine Parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significant amount of time for high-field magnet R&D, aiming at highest possible collision energies

- Target field range for cryo-magnet R&D

Formidable challenges:

☐ high-field superconducting magnets: 14 - 20 T
☐ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
☐ stored beam energy: ~ 9 GJ → machine protection
☐ pile-up in the detectors: ~1000 events/xing
☐ optimization of energy consumption: → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

☐ Direct discovery potential up to ~ 40 TeV
☐ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
☐ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, Zγ, μμ)
☐ Final word about WIMP dark matter

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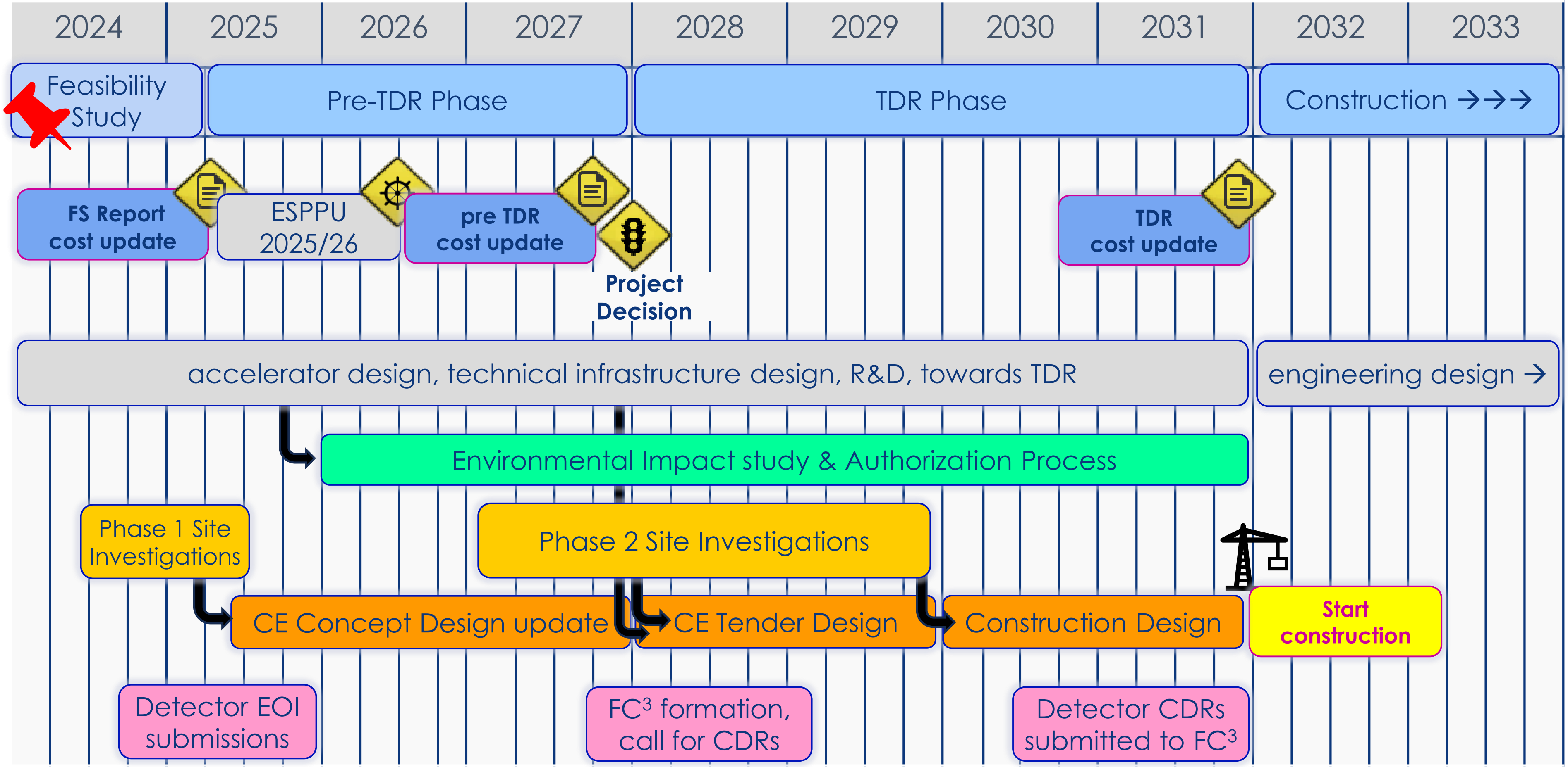
Projected Timeline to Start of Construction



2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033

Feasibility Study

Pre-TDR Phase

TDR Phase

Construction →→→

FS Report cost update

ESPPU 2025/26

pre TDR cost update

Project Decision

TDR cost update

accelerator design, technical infrastructure design, R&D, towards TDR

engineering design →

Environmental Impact study & Authorization Process

Phase 1 Site Investigations

Phase 2 Site Investigations

CE Concept Design update

CE Tender Design

Construction Design

Start construction

Detector EOI submissions

FC^3 formation, call for CDRs

Detector CDRs submitted to FC^3

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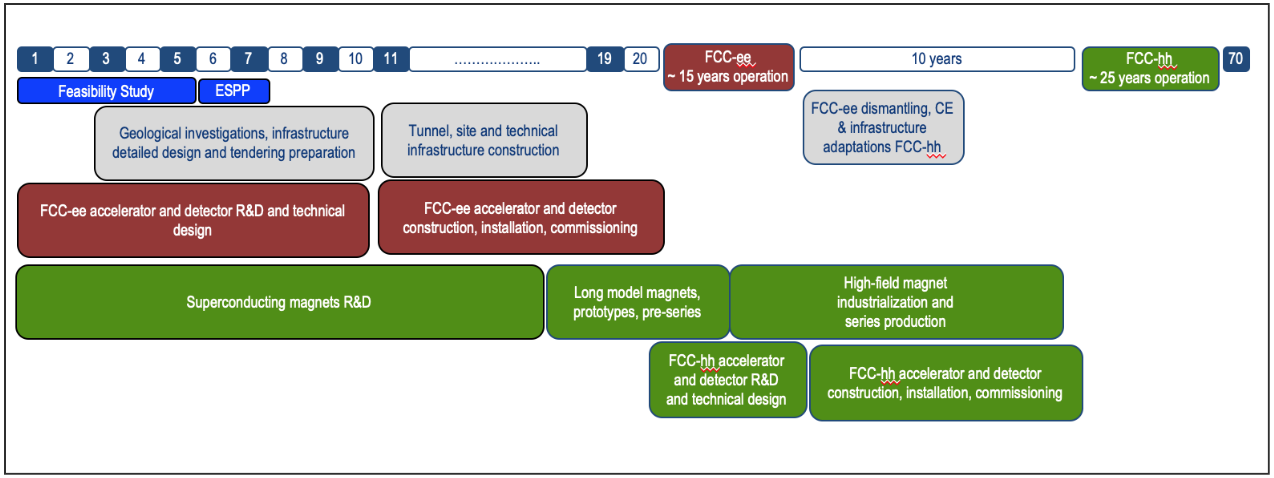
FCC Integrated Programme - Timeline



Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

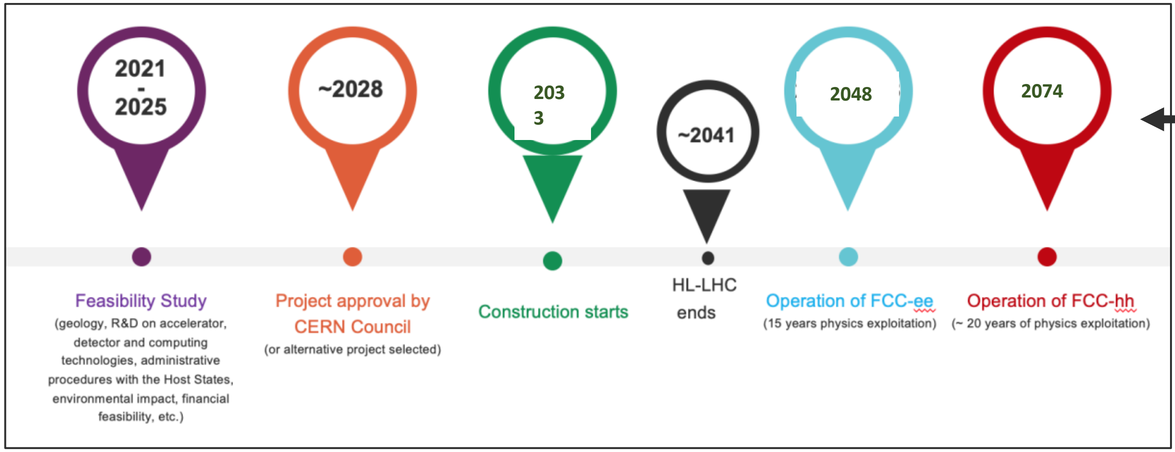
High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018

FCC construction can proceed in parallel with HL-LHC operation.



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

Project approval by CERN Council
(or alternative project selected)

Construction starts

HL-LHC ends

Operation of FCC-ee
(15 years physics exploitation)

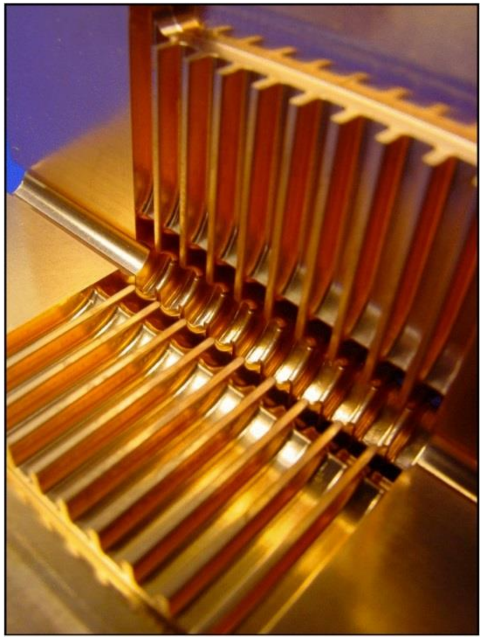
Operation of FCC-hh
(~ 20 years of physics exploitation)

“Realistic” schedule taking into account:
- ☐ past experience in building colliders at CERN
- ☐ approval timeline: ESPP, Council decision
- ☐ that HL-LHC will run until 2041

Can be accelerated if more resources available

Linear Colliders

CLIC

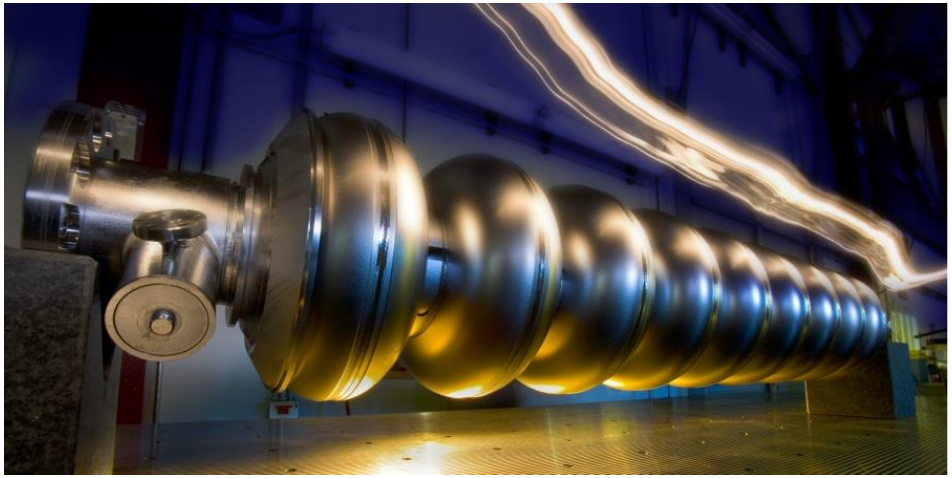


- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m
- √s up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

Linear e^+e^- colliders

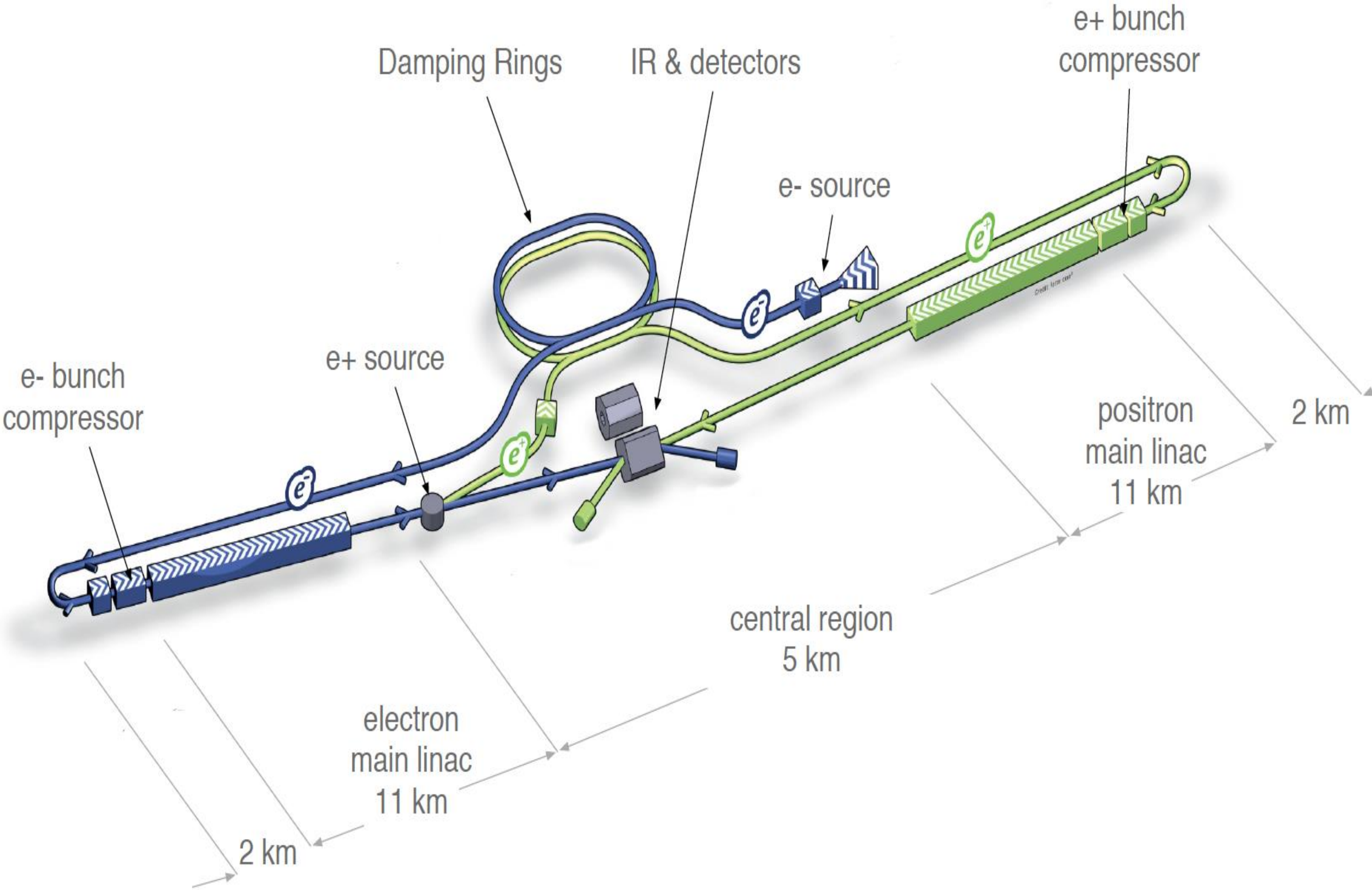
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

ILC

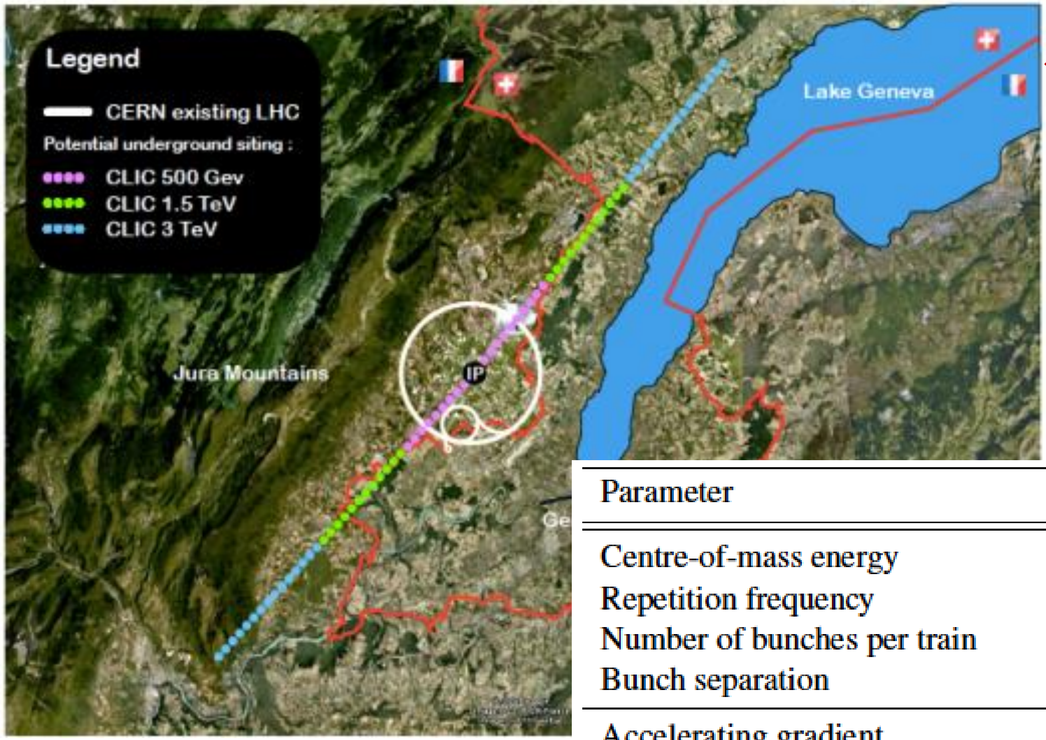


- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- √s ≤ 500 GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

The International Linear Collider (ILC)



CLIC Implementation



← Possible lay-out near CERN

↓ 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)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

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

Physics with Muon Beams

- Muon Beams and the Neutrino Sector

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu$$

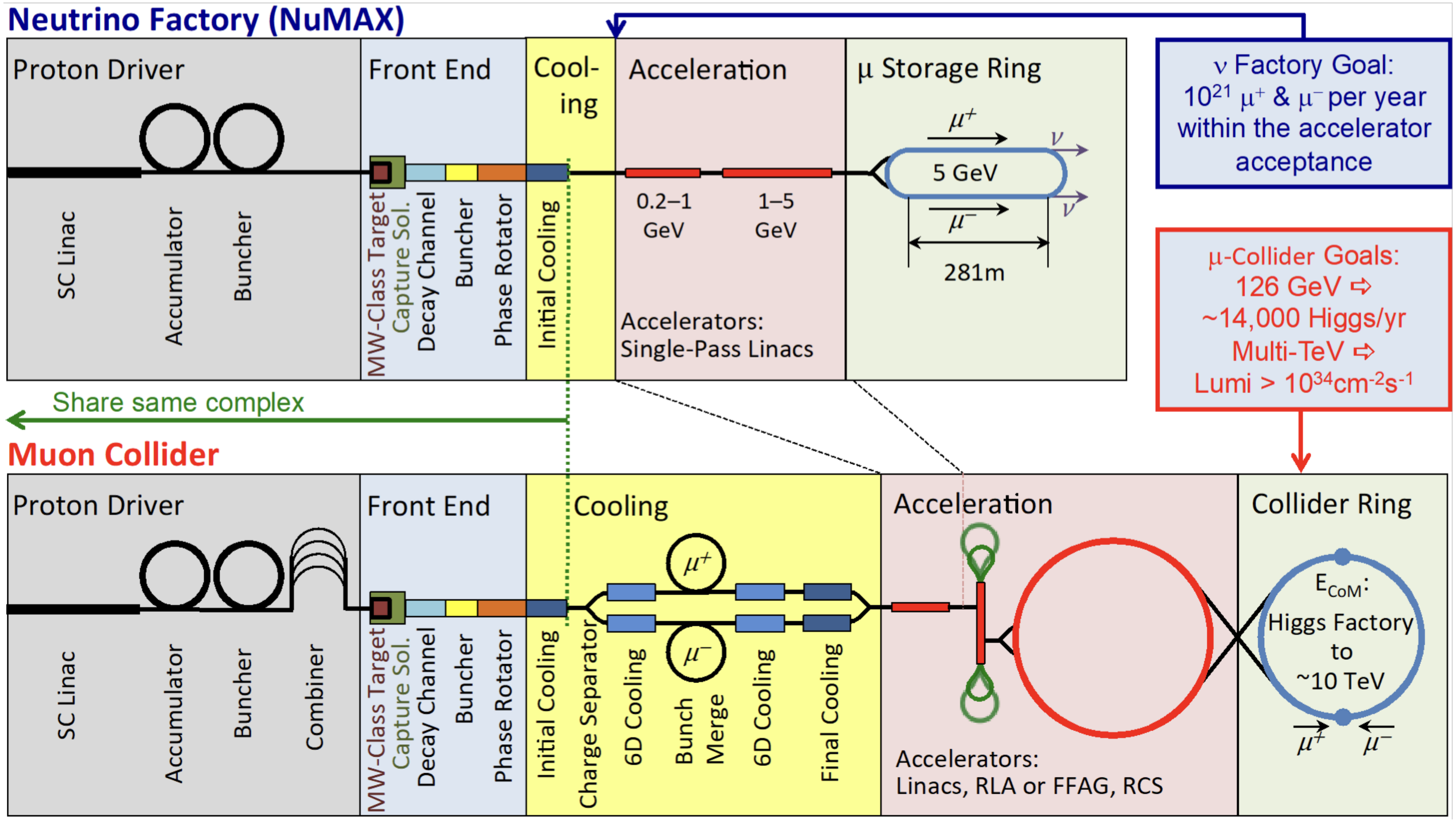
Produces high energy neutrinos

  - Decay kinematics well known
  - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable wrong-sign μ
- Muon Beams and the Energy Frontier
  - Point particle makes full beam energy available for particle production.
    - Couples strongly to Higgs sector
  - Muon Collider has almost no synchrotron radiation
    - Narrow energy spread
    - Fits on existing laboratory sites

Muon Beam Challenges

- Muons created as tertiary beam (p → π → μ)
  - Low production rate
    - Need target that can tolerate multi-MW beam
  - Large energy spread and transverse phase space
    - Need solenoidal focusing for the low-energy portions of the facility
      - Solenoids focus in both planes simultaneously,
    - Need ionisation cooling, high-acceptance acceleration system & decay ring.
- Muons have short lifetime (2.2 μs at rest)
  - Mean distance travelled in the lab frame from production to decay
    - L = (p/mc) c tau with momentum p, mass m, lifetime at rest tau
  - Puts premium on rapid beam manipulations
      - High-gradient RF cavities (in magnetic field)
- Decay electrons give backgrounds in Collider detectors and instrumentation & heat load to magnets

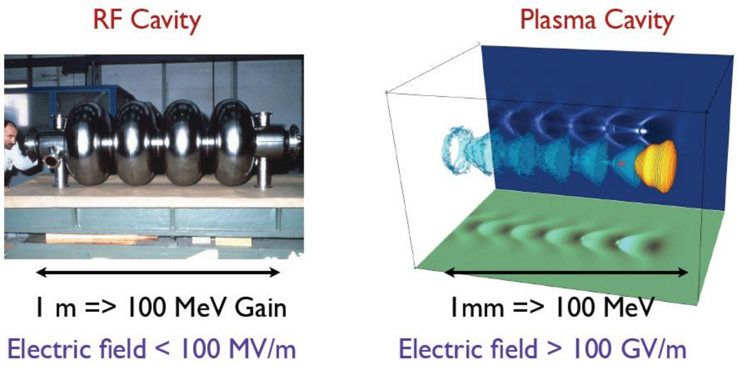
Muon Accelerator Synergies



ν Factory Goal:
10^{21} μ^+ & μ^- per year
within the accelerator
acceptance

μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

Plasma Accelerators



V. Malka *et al.*, Science **298**, 1596 (2002)

e.g. AWAKE at CERN

Demonstration experiment to verify novel technique of p-driven plasma wakefield acceleration

Plasma accelerators:

Transform transverse fields into longitudinal fields.

Significantly higher accelereating gradients than conventional RF.

Laser driven

e- driven

p driven

Dielectric wakefields

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