Introduction to particle accelerators

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3-23 August 2014

Contents

- Basic tools and units
- Acceleration methods and types of machines
  - Electrostatic
  - Time-varying fields
  - Synchrotron radiation
  - Colliders
  - Superconductivity

Acknowledgements & references

- The presentation follows that of Phil Bryant at the CERN Accelerator School
- I have also used material from Frank Tecker's introductory course on RF and longitudinal dynamics at the CERN Accelerator School
- CERN Accelerator School http://cas.web.cern.ch/cas/
- A few books
  - A.W. Chao, K.H. Mess, M. Tigner & F. Zimmermann, Handbook of accelerator physics & engineering, World Scientific, 2013 *(Not a textbook!)*
  - E.J.N. Wilson, An introduction to particle accelerators, Oxford Univ. Press, 2001
  - D.A. Edwards & M.J. Syphers, An introduction to the physics of high-energy accelerators, Wiley, 1993
  - P.J. Bryant & K. Johnsen, The principles of circular accelerators and storage rings, Cambridge Univ. Press, 1993
  - R.W. Hamm & M.E. Hamm, Industrial accelerators and their applications, World Scientific, 2012

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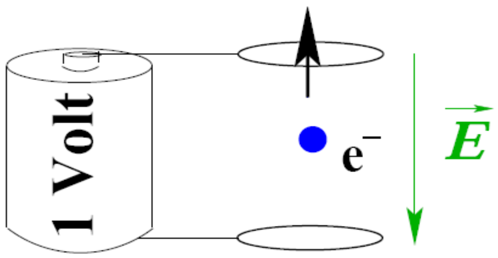
Accelerated particles

- Particle accelerators are machines handling charged particles by means of electromagnetic fields
- Most particle accelerators handle stable particles
  - Leptons: electrons, positrons
  - Hadrons: protons, antiprotons
  - Stable ions
- Exceptions: accelerators for unstable particles
  - Radioactive ion beam accelerators
  - (Future) muon accelerators/colliders

Notations

- In the following, since we will deal a lot with electrical E and magnetic B fields, we decide to use U for the total energy of a particle

Mass-energy units



- 1 eV = energy gained by particle carrying electron charge when accelerated across potential difference of 1 V (1 eV = 1.6 E-19 J)

$$U = mc^2$$

- Since mass and energy are equivalent, rest masses of particles may also be expressed in eV and their multiples

	Electron	Proton
Rest mass [kg]	9.11 E-31	1.67 E-27
Rest mass [MeV]	0.511	938
Electrical charge [Cb]	1.6 E-19	1.6 E-19

Do we need Relativity?

- The motion of a particle is no longer amenable to classical mechanics when the ratio γ of its total mass-energy to its rest mass-energy gets larger than 1

$$\gamma = \frac{U}{U_0} = \frac{m}{m_0}$$

  - Electrons > 0.5 MeV
  - Protons > 1 GeV

- This also corresponds to the case when the velocity of the particle becomes a significant fraction of the velocity of light, i.e. β approaches 1

$$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}}$$

Basic formulae of Special Relativity

- Basic formulae

$$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}}$$

$$\gamma = \frac{U}{U_0} = \frac{m}{m_0} = \frac{1}{\sqrt{1-\beta^2}}$$

$$U = mc^2 = \gamma m_0 c^2$$

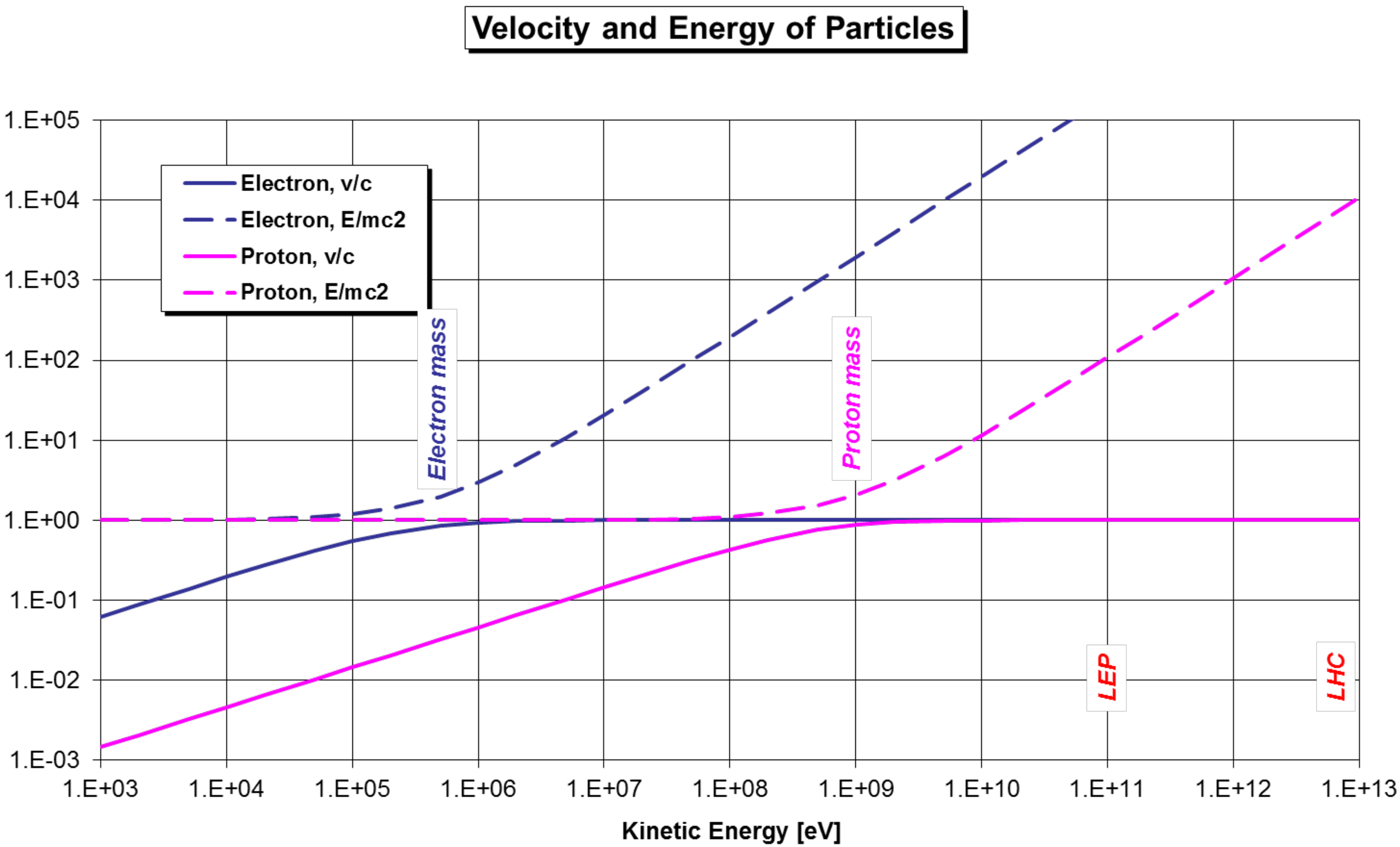
$$p = mv = \frac{U}{c^2}\beta c = \beta\frac{U}{c} = \beta\gamma m_0 c$$

$$U^2 = p^2c^2 + m_0^2c^4$$

- Introducing kinetic energy K

$$U = K + m_0c^2 = \gamma m_0 c^2$$

From classical to relativistic dynamics



Do we need Quantum Mechanics? [1/2]

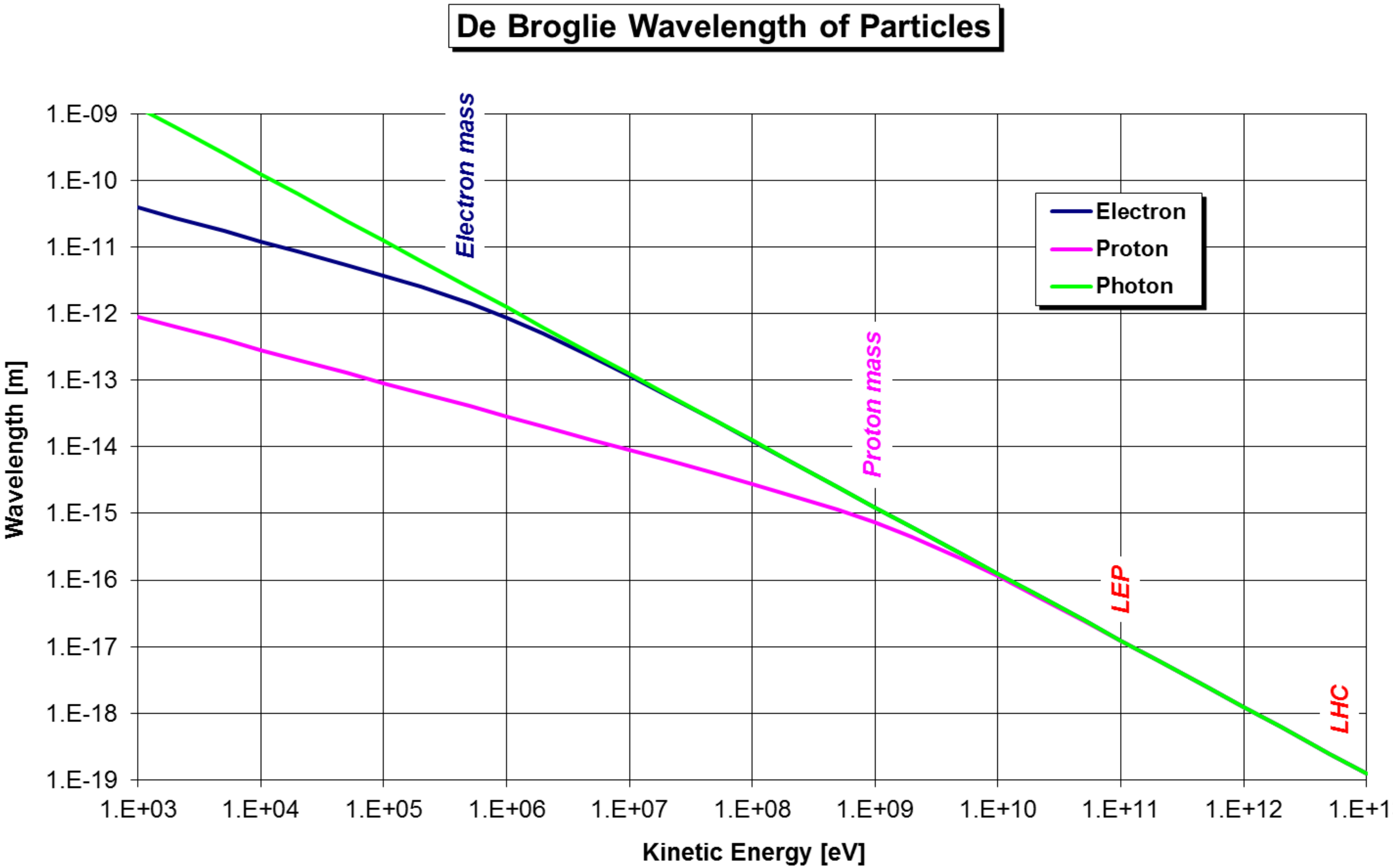
- The de Broglie wavelength λ associated with a particle of momentum p is

$$\lambda = \frac{h}{p} \qquad h \approx 4.14\ 10^{-15}\ \mathrm{eV.}s$$

- For relativistic particles, $U \approx pc$

hence $$\lambda \approx \frac{hc}{U} \qquad hc \approx 1.24\ \mathrm{eV.\mu m}$$

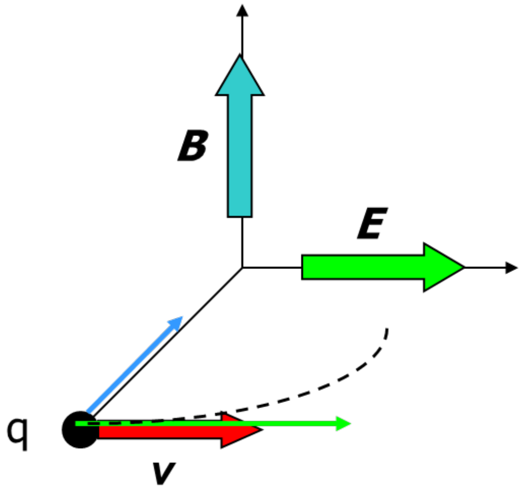
- The de Broglie wavelengths of accelerated particles are very small compared to the size of accelerator structures
- For most purposes, the particles can therefore be seen as “hard points” and their motion treated with classical (relativistic) point mechanics


De Broglie Wavelength of Particles
Wavelength [m]
Kinetic Energy [eV]
1.E-09
1.E-10
1.E-11
1.E-12
1.E-13
1.E-14
1.E-15
1.E-16
1.E-17
1.E-18
1.E-19
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
1.E+09
1.E+10
1.E+11
1.E+12
1.E+13
Electron mass
Proton mass
LEP
LHC
Electron
Proton
Photon

Do we need Quantum Mechanics? [2/2]

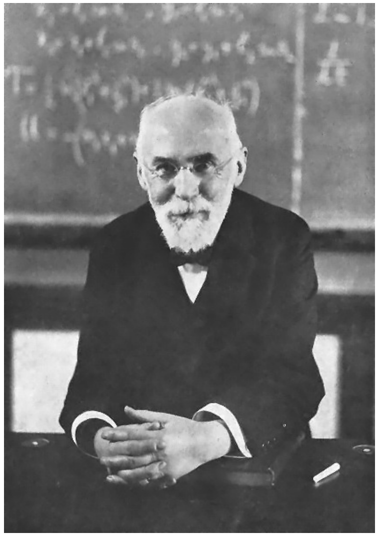
- Quantum behaviour needs however to be considered when looking at specific effects
  - Synchrotron radiation: radiation from the beam is not emitted continuously, but randomly in quanta of discrete energy (photons), thus disturbing the trajectory of the circulating particles; the cumulative effect of many such disturbances introduces a quantum “noise” leading to growth of the beam size
  - Coherent emission from the beams: free-electron laser (FEL), beam monitors using coherent optical transition radiation (OTR)
  - Intra-beam scattering: multiple Coulomb scattering of particles within the beam leads to growth of the beam size; complete model of IBS needs application of quantum scattering theory
  - ...

Electromagnetic force on a moving charge



Lorentz force

$$\vec{F} = \frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B})$$

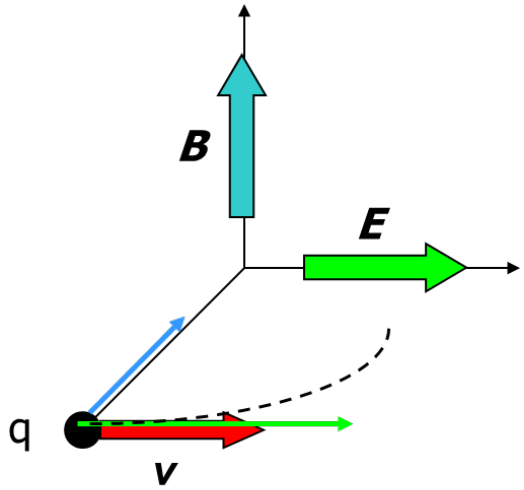


H.A. Lorentz

- First consequence
  - Magnetic force is enhanced w r to electric force by velocity of particle
  - Typical velocity of particle at high energy $v \approx c \approx 3.10^8\ \mathrm{m/s}$
  - Consider a high electric field of 1 MV/m (note that electrical breakdown in air is around 3 MV/m)
  - Consider a moderate magnetic field of 1 T (i.e. half the flux density at saturation in iron) $\left|\vec{v} \times \vec{B}\right| \approx 3.10^8\ \mathrm{V/m} = 300\ \mathrm{MV/m}$
  - The magnetic force is 300 times stronger than the electric force

⇒ Magnets are more efficient than electrostatic devices to act on accelerated particles

Electromagnetic force on a moving charge



Lorentz force

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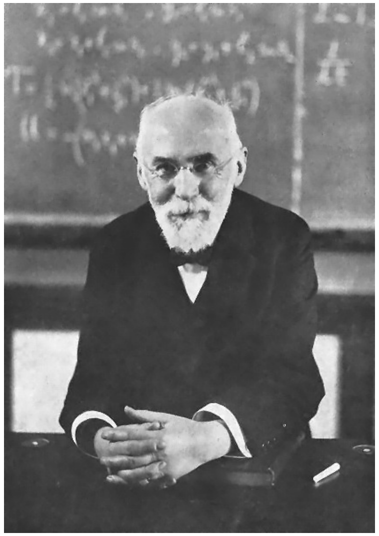


H.A. Lorentz

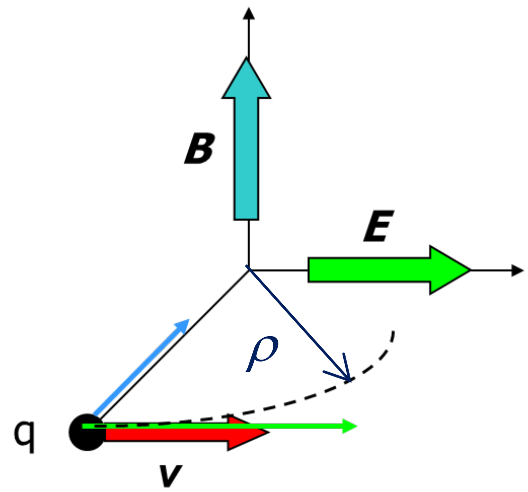
- <u>Second consequence</u>
  - Electrical force is collinear with particle velocity
  - Magnetic force is orthogonal to particle velocity

$$\Delta U = \vec{F}.\vec{v}.\Delta t = \left(e\,\vec{E}.\vec{v} + \underbrace{e\left(\vec{v} \times \vec{B}\right).\vec{v}}_{=\,0}\right)\Delta t$$

⇒ One cannot accelerate, i.e. increase energy of particle by action of magnetic field

⇒ Magnets are used to bend and focus the particle trajectories

Circular orbit in a magnetic field



Lorentz force

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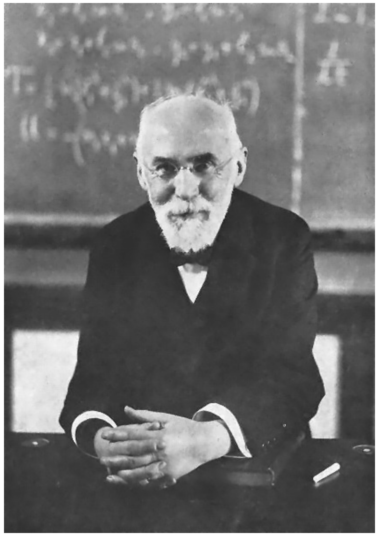

H.A. Lorentz

- In plane normal to $\vec{B}$

$$F = evB = \frac{mv^2}{\rho} = \frac{\gamma m_0 v^2}{\rho}$$

- Hence

$$\frac{p}{e} = B\rho \qquad B\rho[\mathrm{T.m}] \approx \frac{p[\mathrm{GeV/c}]}{0.3}$$

magnetic rigidity

- <u>Example: the LHC</u>
  - Nominal bending field 8.3 T
  - Bending radius 2804 m
  - Nominal momentum ≈ 0.3 x 8.3 x 2804 ≈ 7000 GeV/c

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Methods of acceleration

- We have seen that acceleration needs electric field

- Maxwell

$$\vec{E} = -\vec{\nabla}\varphi - \frac{\partial \vec{A}}{\partial t}$$

J.C. Maxwell

electrostatic (DC)

Cockroft & Walton

Van de Graaf

time-varying (AC)

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

unbunched

Betatron

resonant

Linac

Cyclotron

Synchrotron

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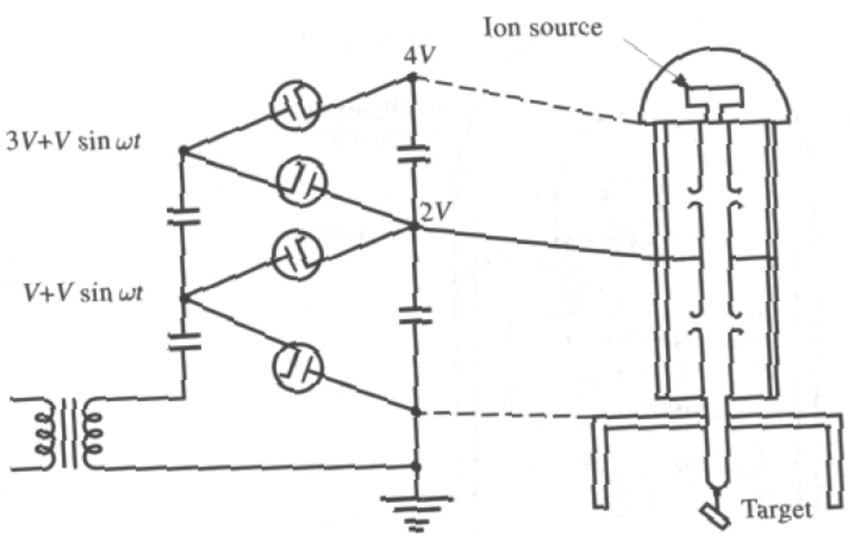
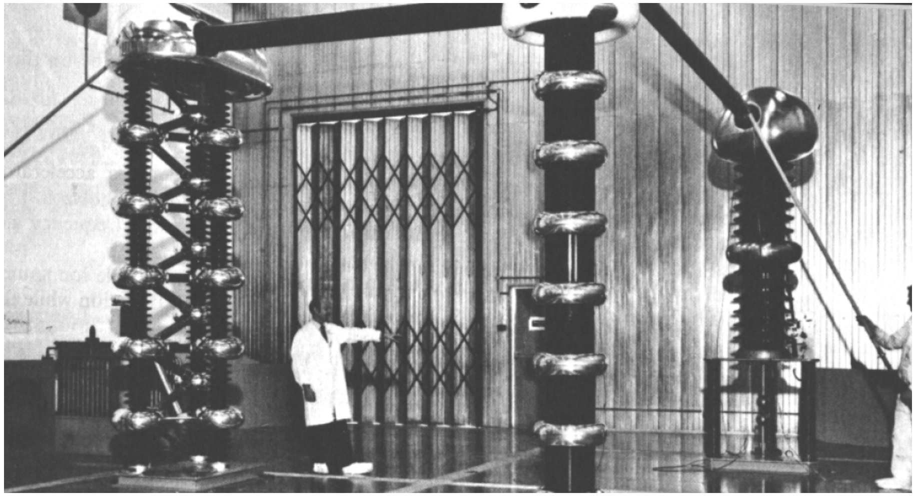
Electrostatic accelerators: Cockroft & Walton



J.D. Cockroft

E.T.S. Walton

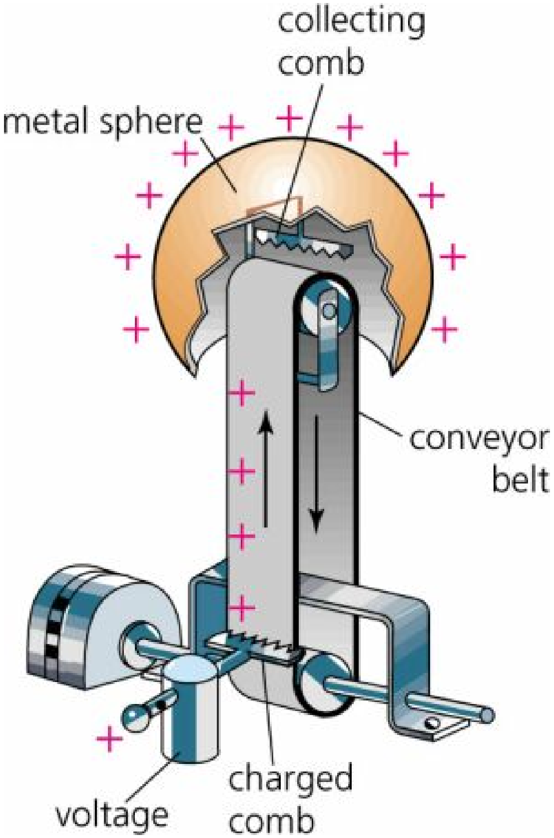


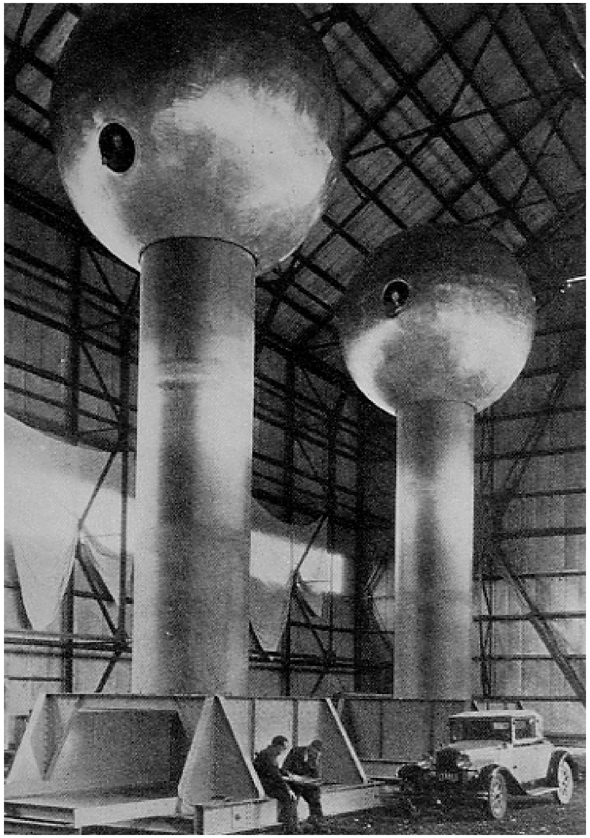
- Voltage multiplication by AC to DC conversion along the ladder
- Theoretical maximum voltage

  $V_{DC} = 2\ N\ V_{AC}$

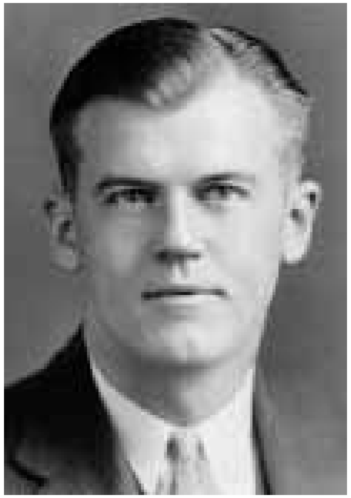
  N number of stages
- In 1932, C&W (Nobel prize 1951) first split the lithium atom with protons from their up-to-600 keV accelerator

Electrostatic accelerators: Van de Graaf





7 MV Van de Graaf at MIT (1933)

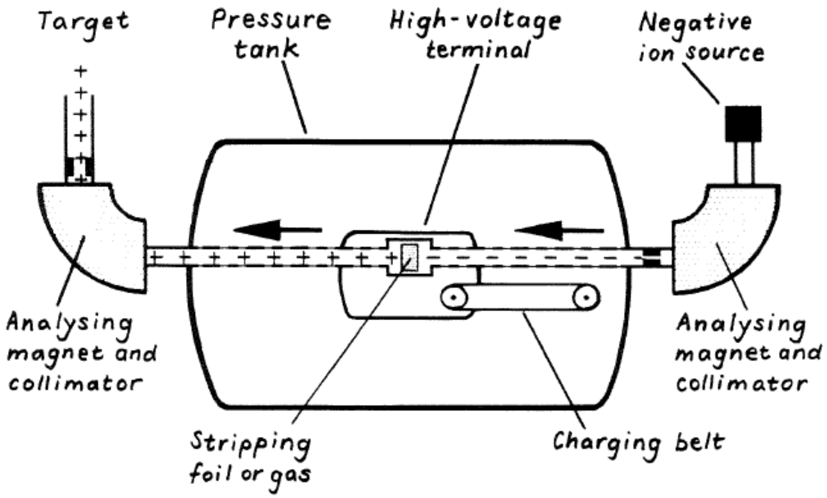


R.J. Van de Graaf

- Electric charges are transported mechanically on an insulating belt
- Stable, continuous beams
- Practical limit 10-15 MV

Tandem Van de Graaf

- The DC electric field derives from a potential, therefore the voltage can only be used once for acceleration of a given particle
- The tandem Van de Graaf allows to use the voltage twice, by reverting the charge of the accelerated particle in the center (stripping)



2 x 15 MV tandem Van de Graaf at BNL
To raise electrical breakdown limits, the machine is contained in a SF_6 tank under pressure

Methods of acceleration

- We have seen that acceleration needs electric field
- Maxwell

$$\vec{E} = -\vec{\nabla}\varphi - \frac{\partial \vec{A}}{\partial t}$$

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unbunched

Betatron

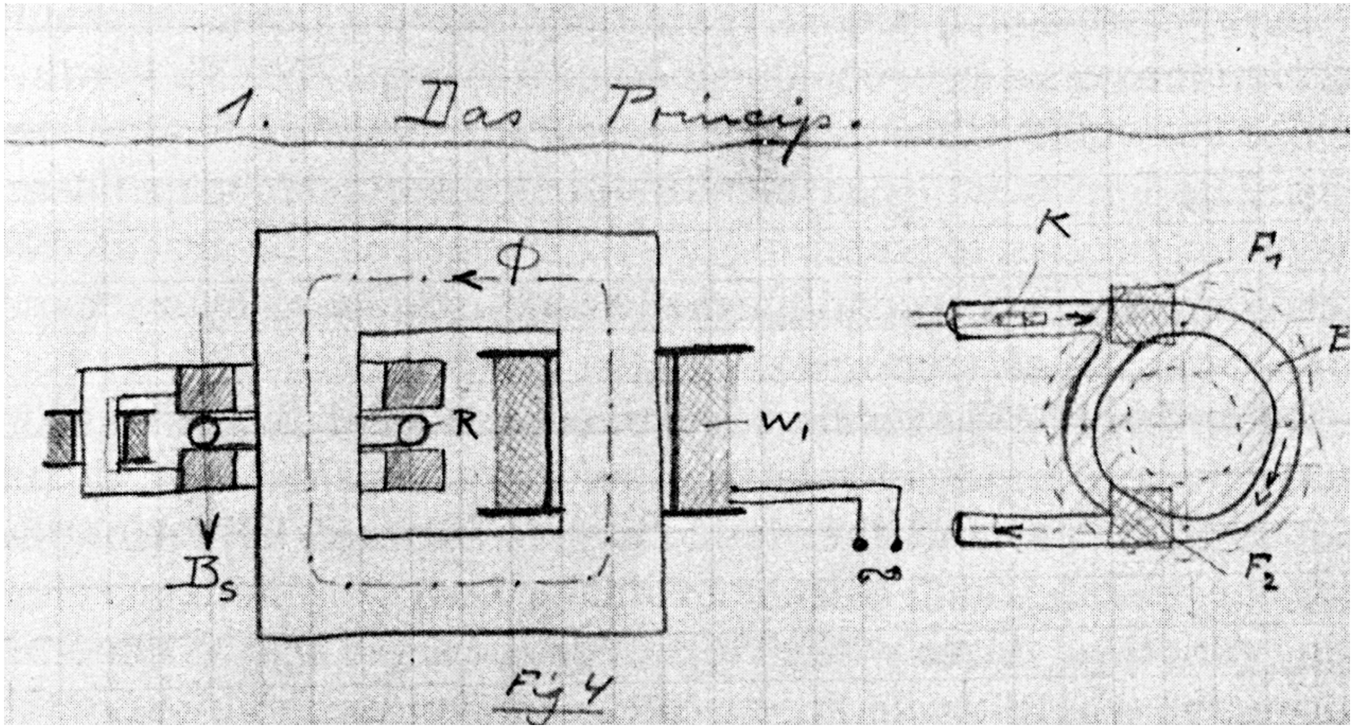
resonant

Linac

Cyclotron

Synchrotron

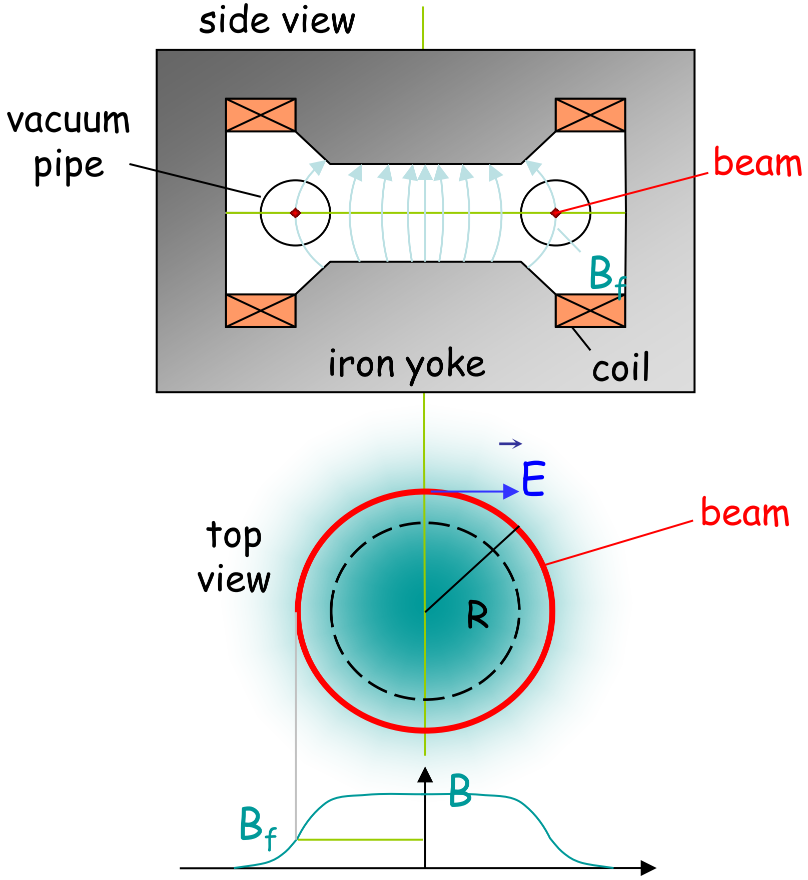
Widerøe's "ray transformer"



R. Widerøe

- The beam acts as secondary winding of a transformer
- Conceptual design by R. Widerøe, PhD student in 1923
- Unsuccessful attempt to build model machine in 1927
- Reinvented as "betatron" by D. Kerst in 1940

Betatron



Donald Kerst with the first betatron, built at University of Illinois in 1940

- Compact, robust accelerator insensitive to relativistic effects, well adapted for electrons up to ~300 MeV
- Used in industry and medicine

Methods of acceleration

- We have seen that acceleration needs electric field

J.C. Maxwell

- Maxwell

$$\vec{E} = -\vec{\nabla}\varphi - \frac{\partial \vec{A}}{\partial t}$$

electrostatic (DC)

Cockroft & Walton

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unbunched

Betatron

resonant

Linac

Cyclotron

Synchrotron

Ising's RF linear accelerator

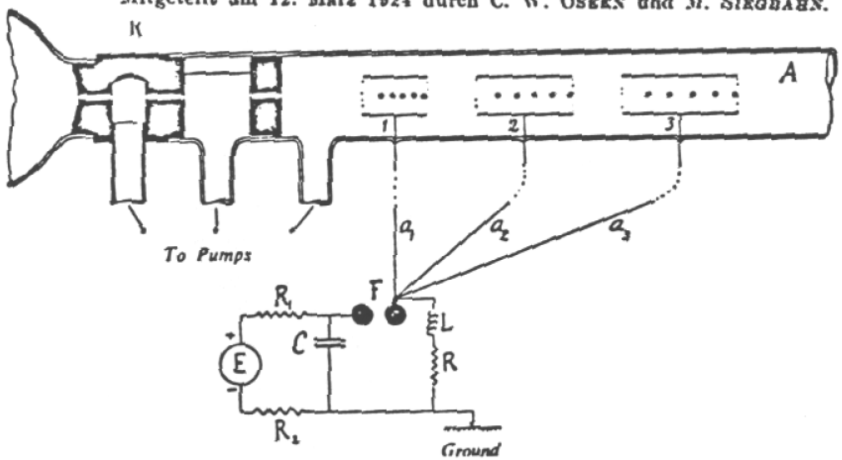
Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl.

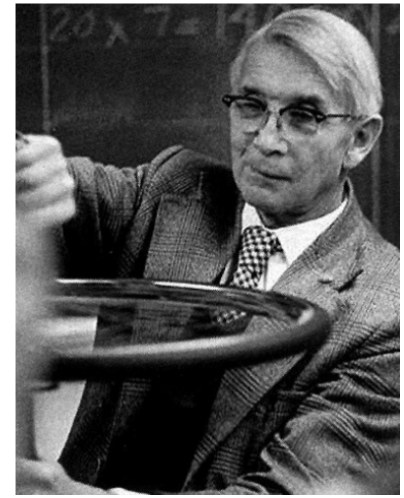
Von

GUSTAF ISING.

Mit 2 Figuren im Texte.

Mitgeteilt am 12. März 1924 durch C. W. Oseen und M. Siegbahn.



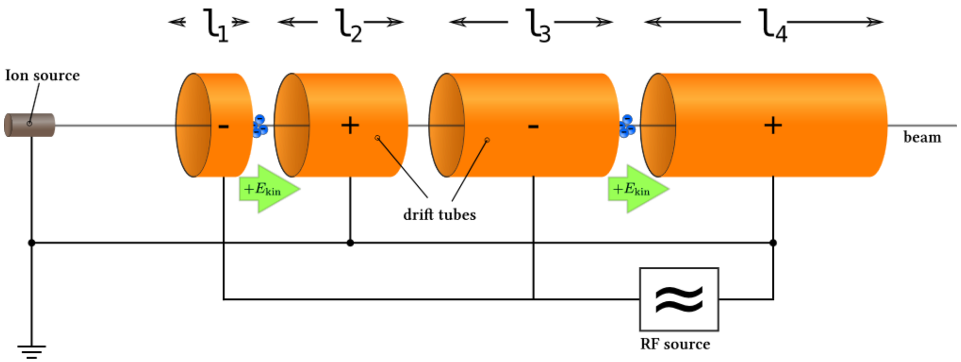


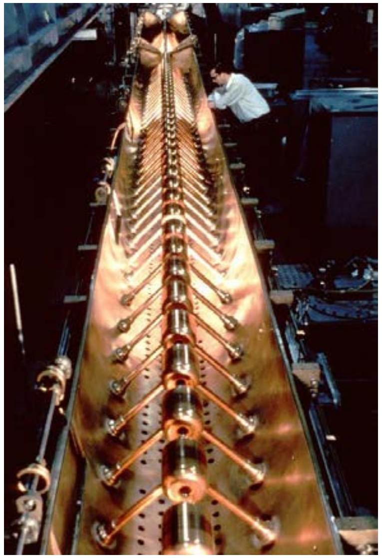
G. Ising

- Electrostatic accelerators are limited in voltage by
  - electrical breakdown ⇒ to go higher, use time-varying fields (RF)
  - flux conservation of electrical field, entailing single-pass acceleration in DC
- In 1924, Ising proposes time-varying fields across drift tubes: the particles can then reach energies above that given by highest voltage in the system
- In 1928, Widerøe builds first demonstration linac using Ising's principle

Alvarez linac

L. Alvarez

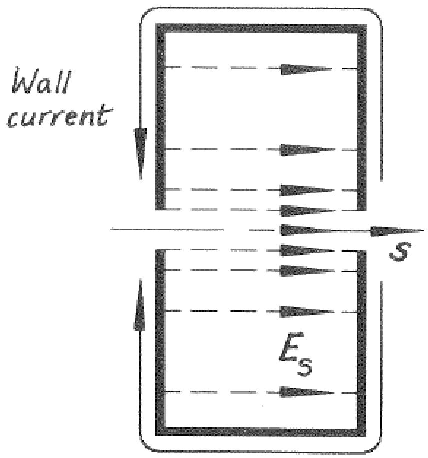


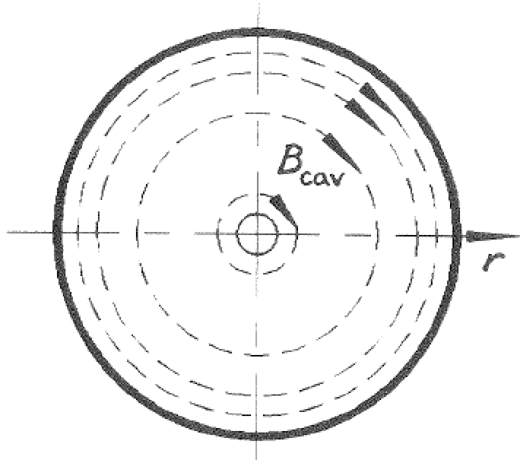


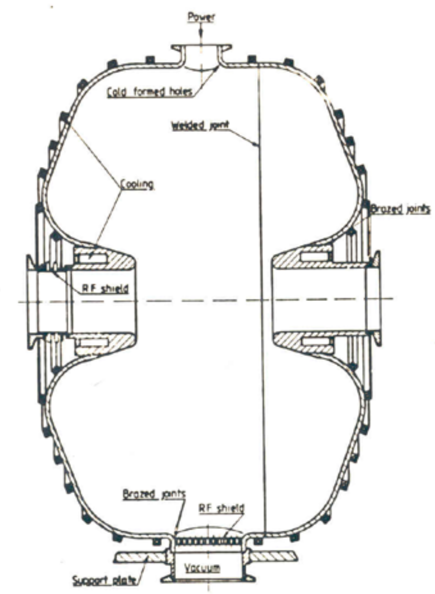
- Synchronism condition $$L = v\frac{T_{RF}}{2} = \frac{v}{2f_{RF}}$$

- Acceleration occurs in the gaps between the drift tubes
- First practical linac (200 MHz, 32 MeV) built by L. Alvarez at Berkeley in 1946
- As particle velocity increases, the drift tubes get longer $\Rightarrow$ lost length
- This can be contained by increasing $f_{RF} \Rightarrow$ increased power loss
- To limit power loss, enclose the system into a resonant cavity

RF cavities

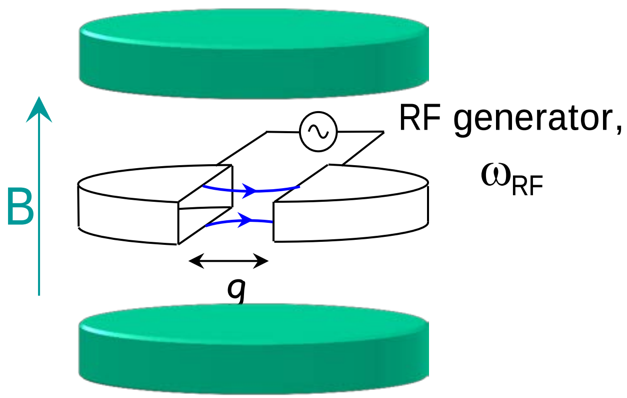


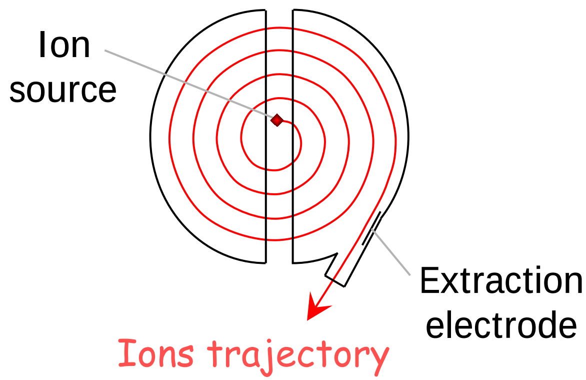


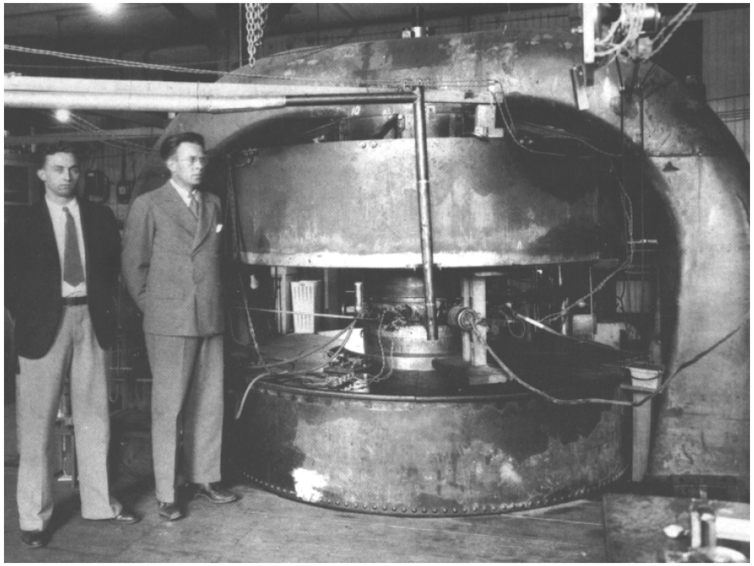


- To limit power loss, the electromagnetic fields are enclosed in a cavity with resonant frequency matching that of the RF generator: “pillbox” cavity
- The electromagnetic power is now constrained to the resonant volume
- However, Joule losses occur in the cavity wall
  – Use low-resistance materials (copper) or superconductors
  – Water cooling
- Local design features
  – Rounded shape to optimize field distribution and reduce losses
  – Avoid sharp edges to limit electron emission

Lawrence & Livingston's Cyclotron







S. Livingston & E.O. Lawrence (1933)

Synchronism $2\pi\rho = vT_{RF} = v/f_{RF}$

Cyclotron frequency $\omega_{RF} = \dfrac{eB}{m_0\gamma}$

- "Folded-in" linac: the electrodes are the "dees" immersed in magnetic field
- Orbits are spirals as particles gain energy at each gap crossing
- Constant magnetic field means constant frequency at $\gamma = 1$, no exact synchronism for relativistic particles

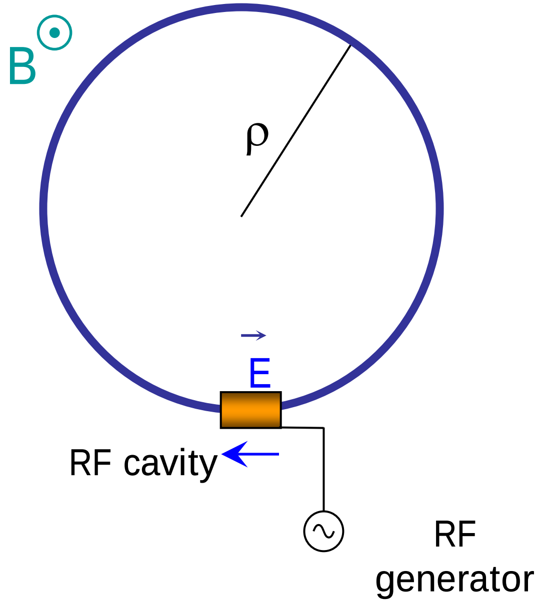
High-energy cyclotrons

TRIUMF 520 MeV proton cyclotron
(Vancouver, Canada)

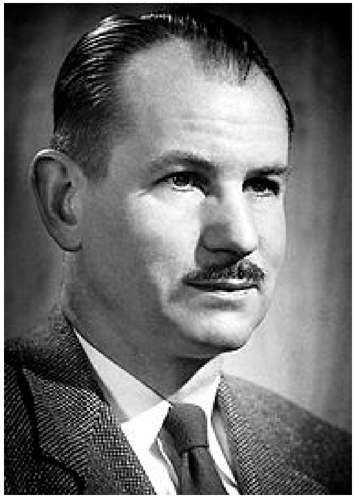
Poles of the 600 MeV ion superconducting cyclotron
(Catania, Italy)

- Cyclotrons face two types of limitation at higher energy
  - Loss of isochronism in the relativistic regime
  - Large size of the magnet
- Possible solutions to overcome these limitations
  - Synchro-cyclotrons
  - Shaping of the magnet poles (sectored magnet) ⇒ isochronism and focussing
  - Superconducting magnets ⇒ higher field ⇒ higher energy at given radius

Synchrotron



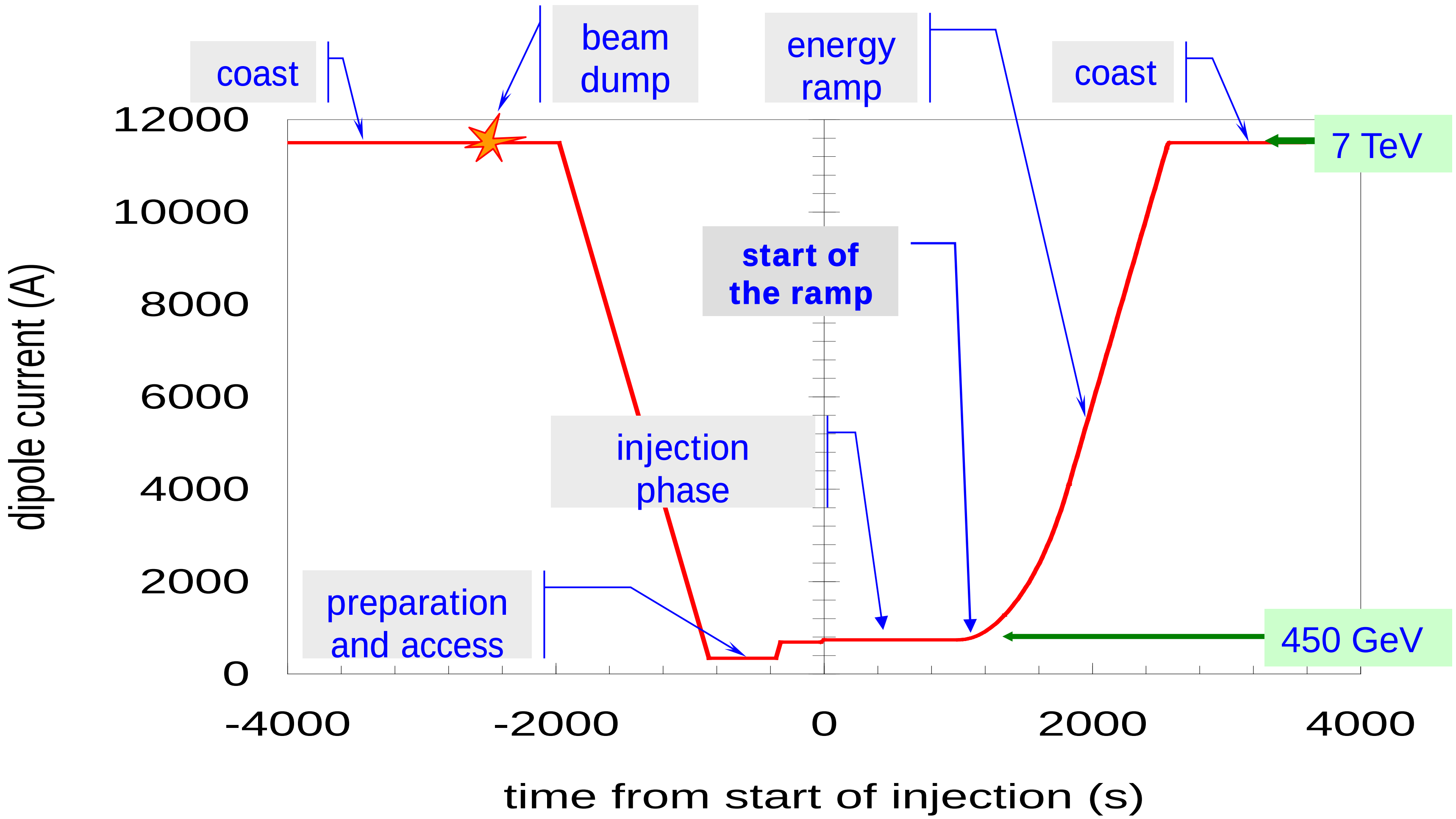

M. Oliphant


E. McMillan

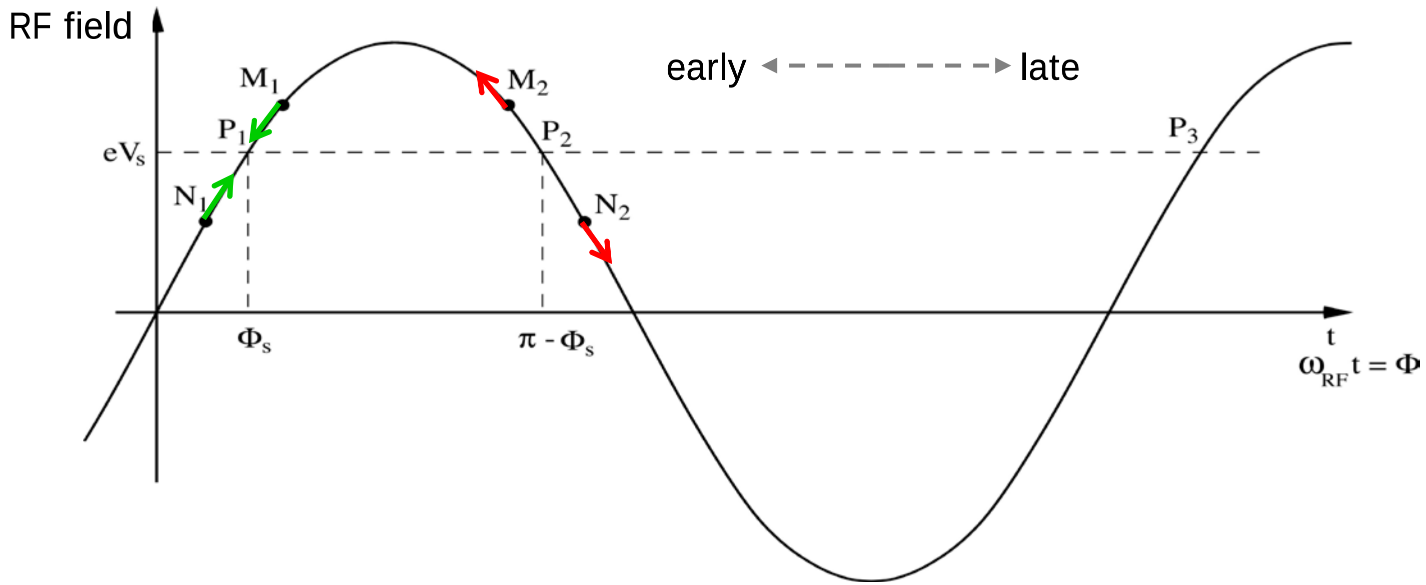

V. Veksler

- In 1943, M. Oliphant proposed the concept of synchrotron, developed by E. McMillan and V. Veksler who solved the issue of "phase stability" (see later)
- Constant orbit during acceleration: to keep particles on closed orbit, B must increase in time
- Revolution frequency must increase during acceleration (non-relativistic)
  $\frac{2\pi\rho}{v} = T = \frac{1}{f}$
- RF frequency is a multiple of revolution frequency $f_{RF} = hf$

Bending field vs time in the LHC



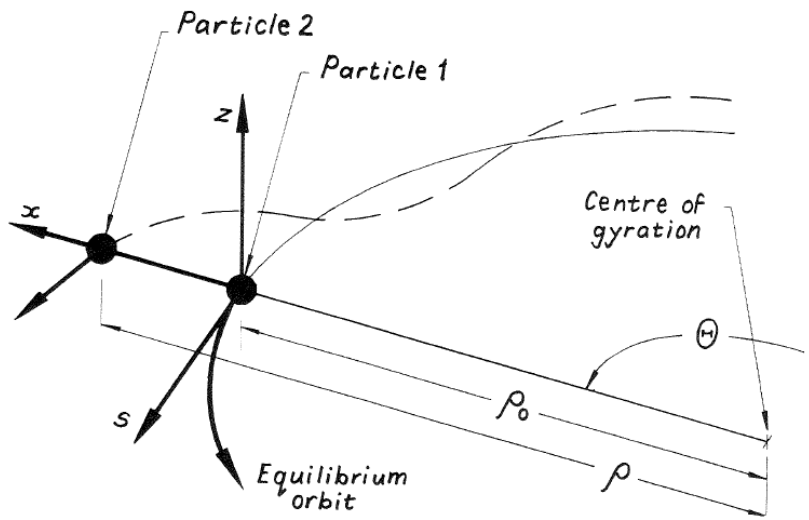
Notion of phase stability



- In certain range, acceleration by RF field results in early arrival of particle at next turn: for stability, this particle should undergo less acceleration
- Operating point P2 is unstable
  - Late particle N2 sees lower acceleration and gets even later
  - Early particle M2 sees higher acceleration and gets even earlier
- Operating point P1 is stable

⇒ *Lectures on Beam dynamics*

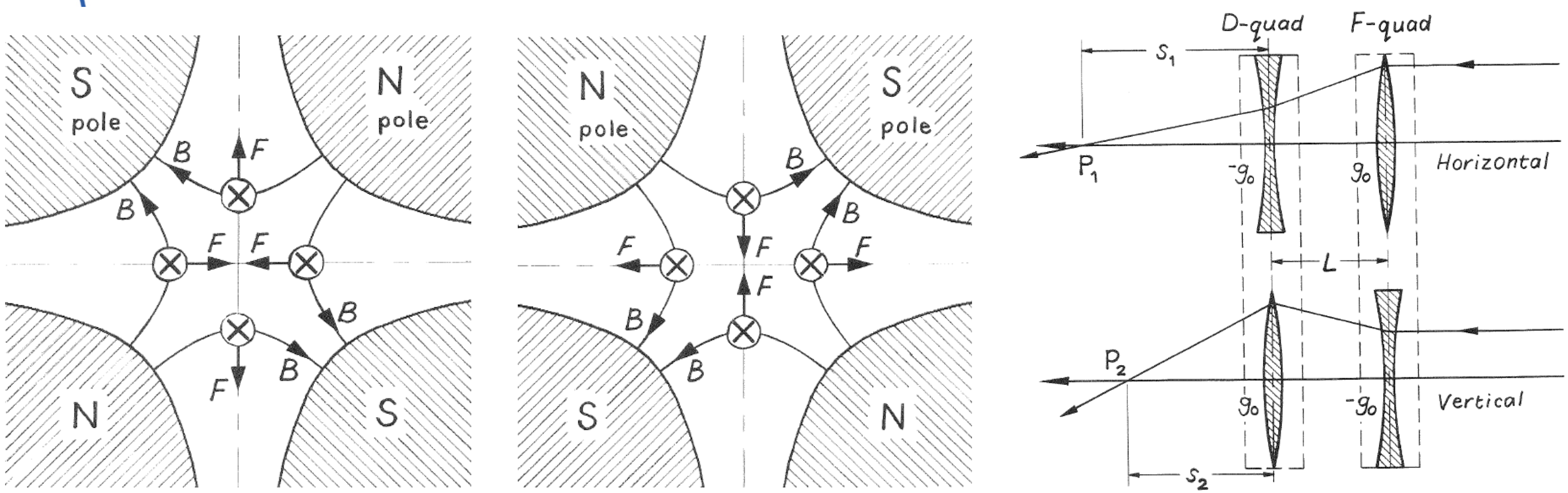
Notion of transverse focussing



- Consider a particle of momentum p in a circular accelerator, with a deviation $x = \rho - \rho_0$ with respect to the equilibrium orbit, of radius ρ
- The quantity $B\rho$ is an invariant $B\rho = B_0\rho_0 = \frac{p}{e}$
- Focussing can be obtained by increasing the field seen by the particle, i.e. introducing a field gradient $\partial B / \partial x$
- The field gradient can be obtained by shaping the pole pieces of the magnets, as well as by the natural divergence of field lines at their edges

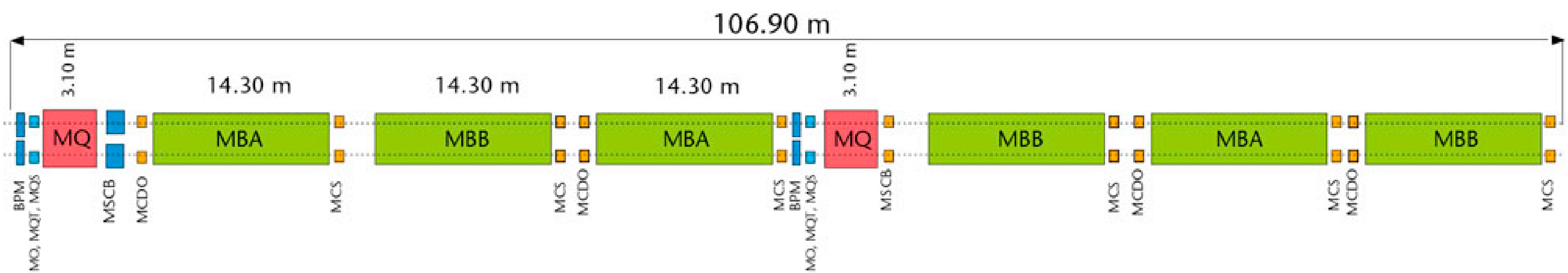
⇒ Lectures on Beam dynamics

Strong focussing by alternating gradients



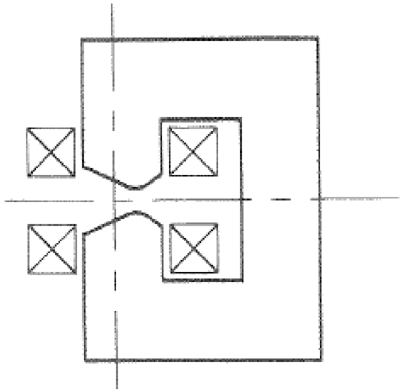
- Increasing the strength of the field gradient can be achieved by using quadrupole magnets
- However, the constant field in the current-free region of the magnet aperture satisfies $\vec{\nabla} \times \vec{B} = 0$, implying $\partial B_z / \partial x = \partial B_x / \partial z$: focussing in one plane, defocussing in the other
- In 1952, E. Courant and H. Snyder propose alternating-gradient strong focussing: a string of alternately focussing and defocussing quadrupoles of equal or similar gradient is globally focussing
- All modern synchrotrons are strong-focussed

Schematic layout of one LHC cell (23 periods per arc)

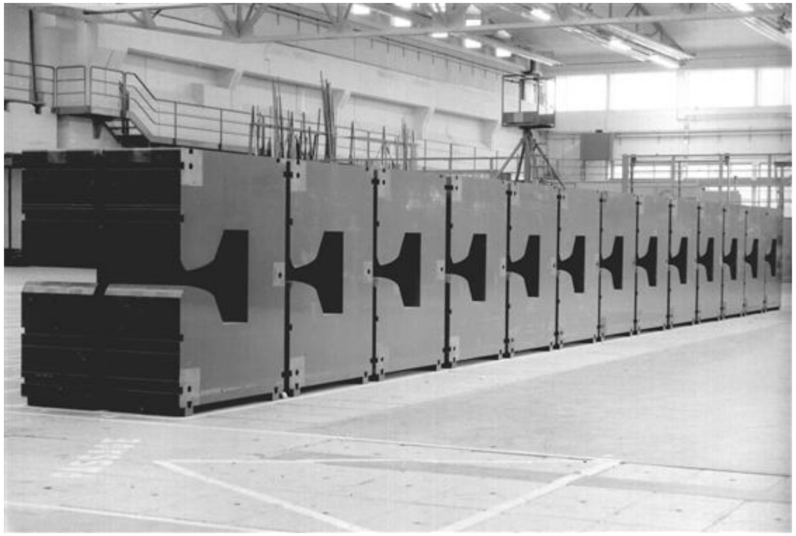


MQ: Lattice Quadrupole
MO: Landau Octupole
MQT: Tuning Quadrupole
MQS: Skew Quadrupole
MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
BPM: Beam position monitor
MBA: Dipole magnet Type A
MBB: Dipole magnet Type B
MCS: Local Sextupole corrector
MCDO: Local combined decapole and octupole corrector

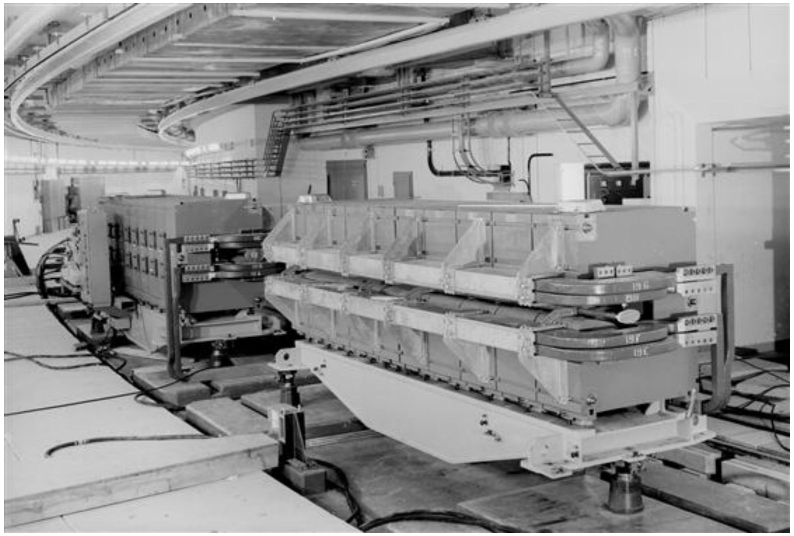
Combined-function magnets



- The gap, and hence the magnetic field, vary across the horizontal aperture
- This superimposes a gradient (quadrupole term) onto the bending (dipole) field

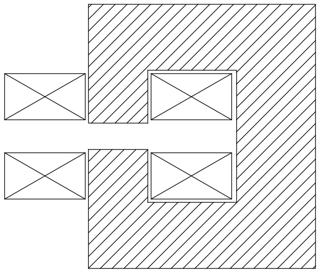


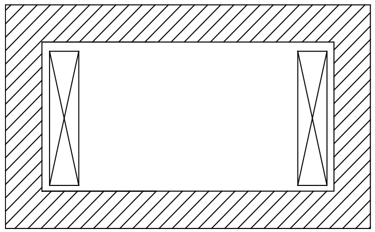
Combined-function yoke blocks for the CERN PS magnets

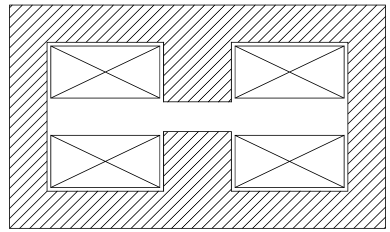


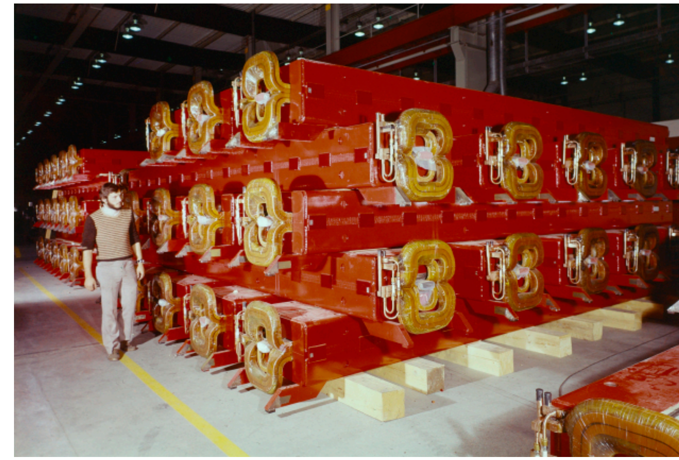
Magnets installed in the PS tunnel: note the arrangement to produce alternating-gradient focussing

Separated-function magnets



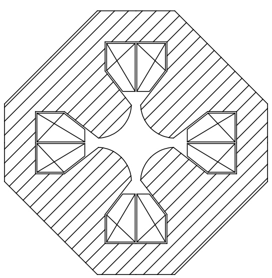


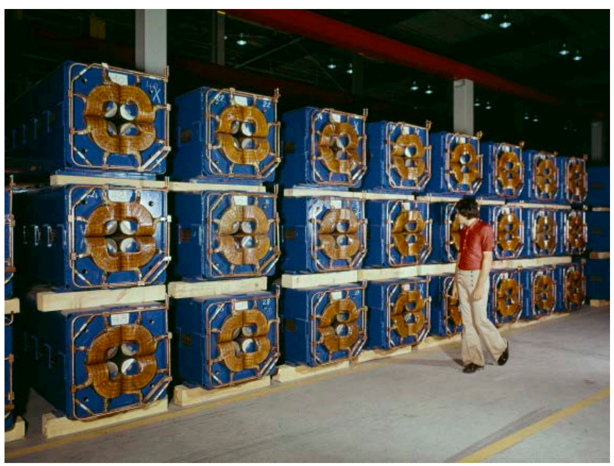




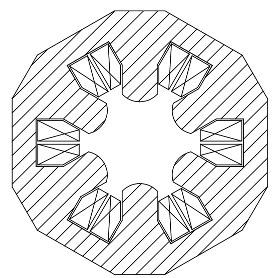
Dipoles

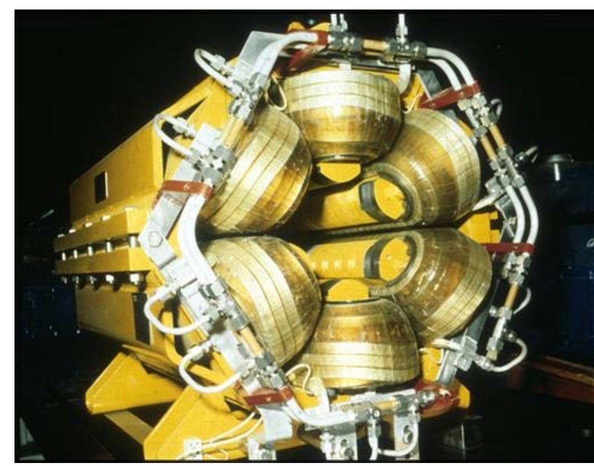
C-shaped | Window-frame | H-type





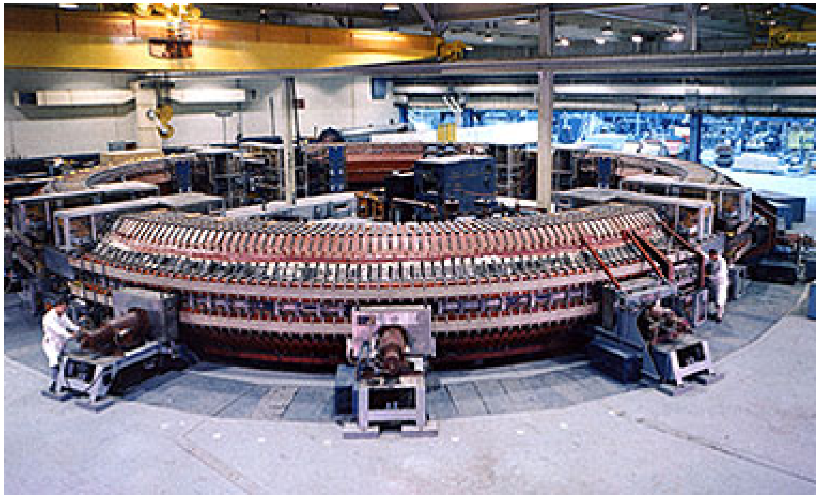
Quadrupoles



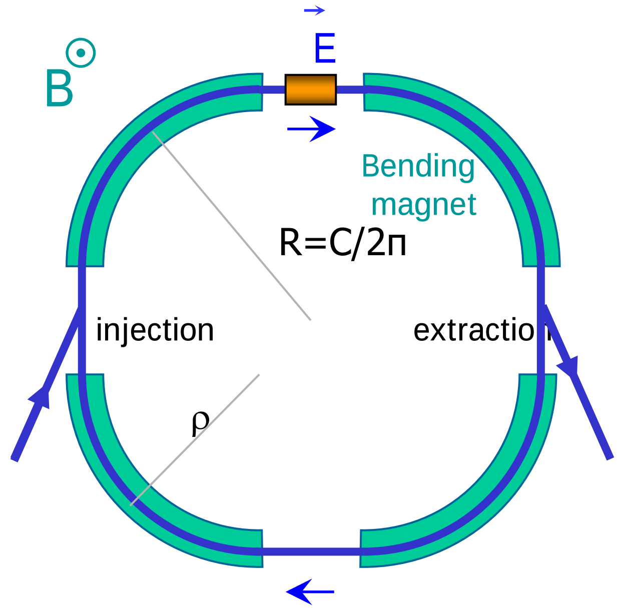


Sextupoles

Synchrotrons



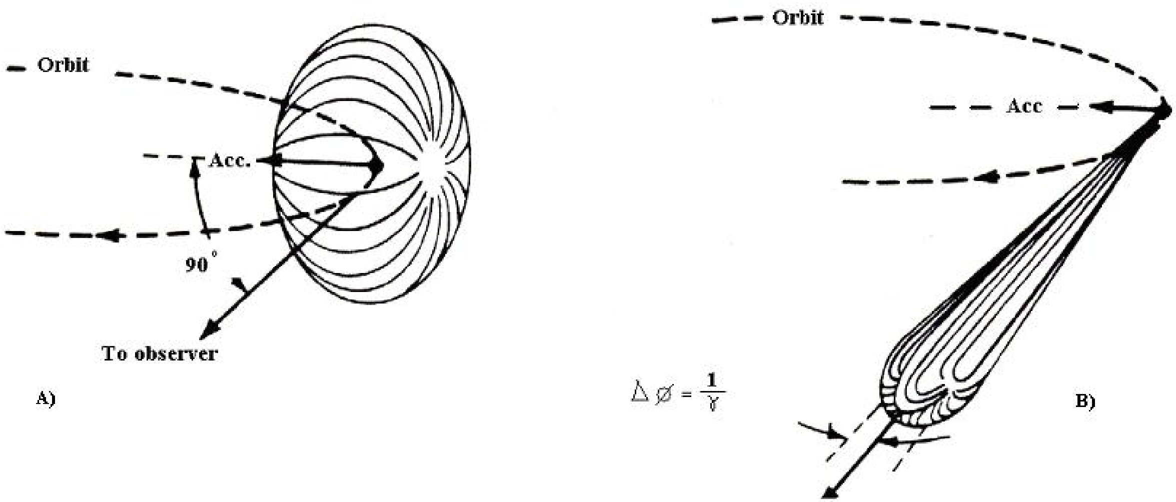
3 GeV Cosmotron at BNL
weak focussing, combined function magnets

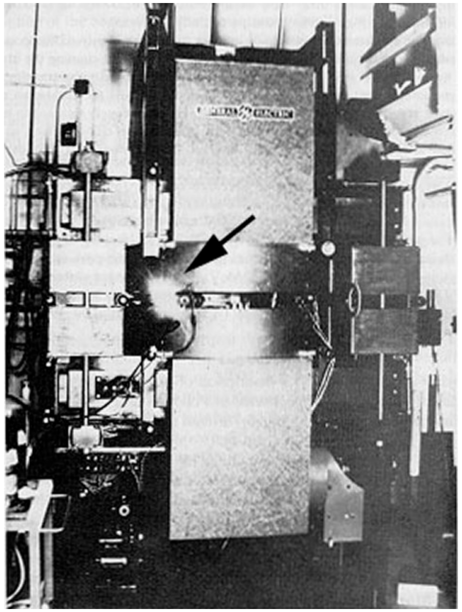


28 GeV PS at CERN
strong focussing, combined function magnets

400 GeV SPS at CERN
strong focussing, separated function magnets

Synchrotron radiation





Synchrotron radiation from the GE 70 MeV synchrotron (1947)

- Accelerated charges emit electromagnetic radiation
- In particular, a charge subject to centripetal acceleration due to motion across a magnetic field emits “synchrotron” radiation
- For a fast moving charge in the laboratory frame, the radiation is emitted tangent to the trajectory, over a narrow cone of half-aperture $1/\gamma$
- First observed at the 70 MeV synchrotron of the GE Research Labs in 1947

Synchrotron radiation [2/2]

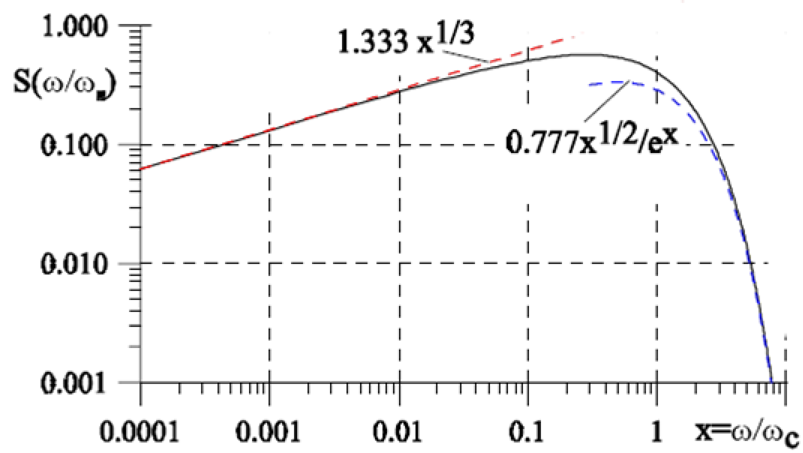
- Instantaneous power $$P = \frac{cC_\gamma}{2\pi}\frac{U^4}{\rho^2}$$

  with $C_\gamma = \frac{4\pi}{3}\frac{r_e}{(mc^2)^3}$ for electrons

- Energy loss per turn (constant B) $$W_{turn} = C_\gamma \frac{U^4}{\rho}$$

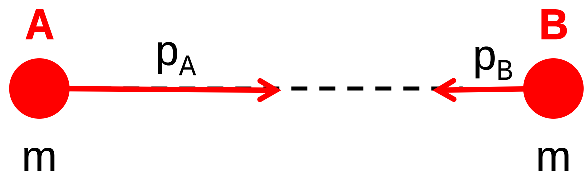
- From a bending magnet, emission in a continuous spectrum, the median of which is the "critical photon energy" $$\mathcal{E}_c = \frac{3}{2}\hbar c\frac{\gamma^3}{\rho}$$

Normalized frequency spectrum



⇒ Lectures on Synchrotron light

Fixed-target vs head-on collisions



- Relativistic invariant $(\Sigma m)^2 c^4 = (\Sigma U)^2 - (\Sigma p)^2 c^2$
- In the laboratory frame $4m^2c^4 = (U_A + U_B)^2 - (\overrightarrow{p_A} + \overrightarrow{p_B})^2 c^2$
- Let U^* be the total energy available in the collision
- In the center-of-mass frame $\overrightarrow{p^*} = \overrightarrow{p_A} * + \overrightarrow{p_B} * \equiv 0$

$$4m^2c^4 = {U^*}^2$$

$${U^*}^2 = (U_A + U_B)^2 - (\overrightarrow{p_A} + \overrightarrow{p_B})^2 c^2$$

- Fixed-target $p_B = 0 \; ; \; U_B = mc^2$

$${U^*}^2 = {U_A}^2 - {p_A}^2 c^2 + m^2c^4 + 2U_A mc^2$$

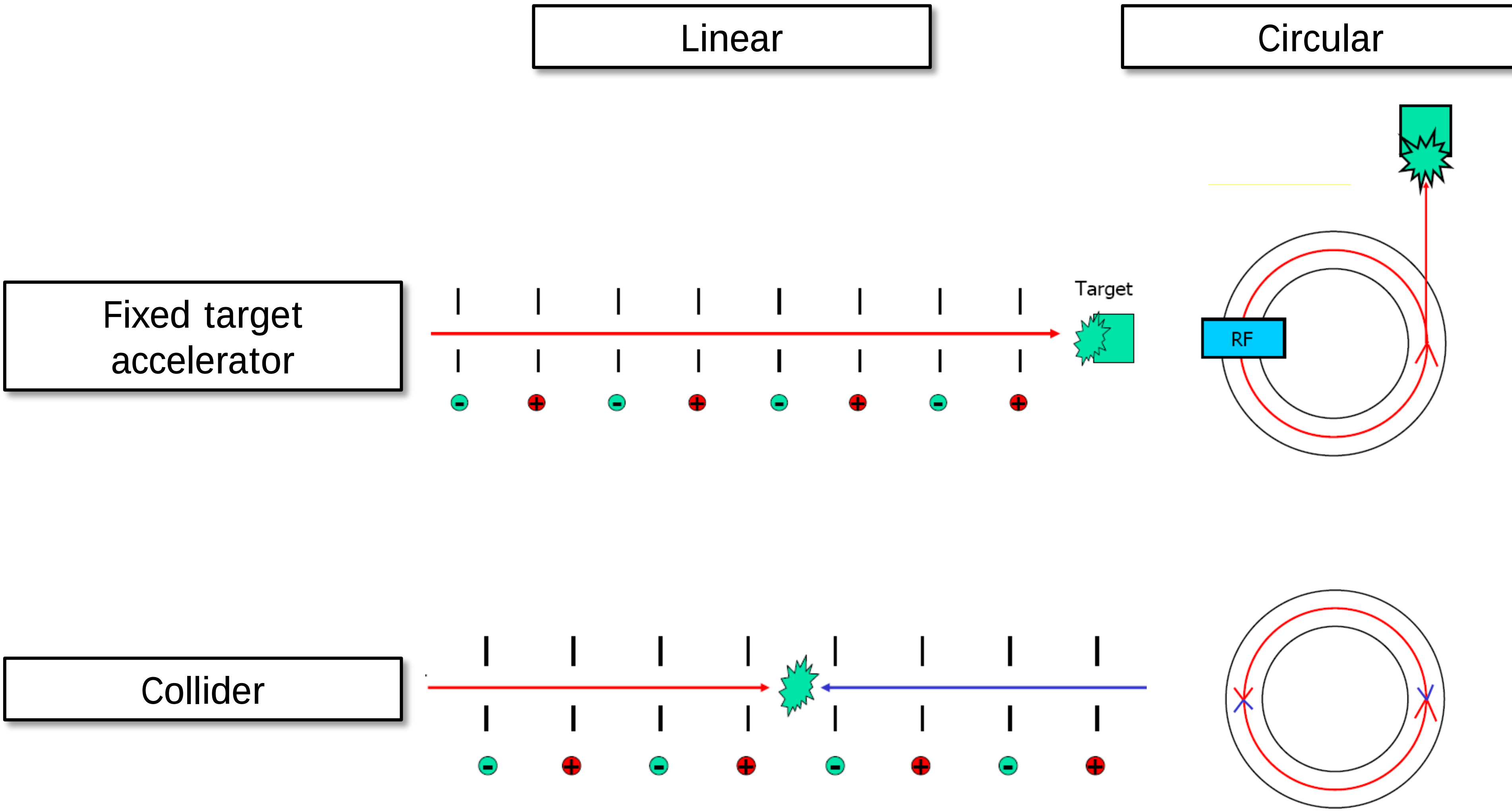
$${U^*}^2 = 2m^2c^4 + 2U_A mc^2 \approx 2U_A mc^2$$

$$U^* \approx \sqrt{2U_A mc^2}$$

- Head-on collision

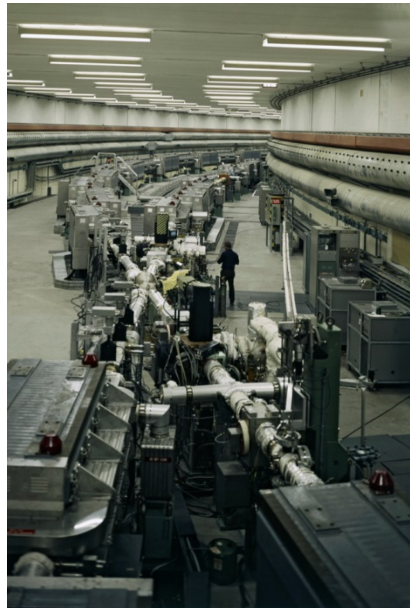
$$U^* = U_A + U_B$$

Accelerators vs colliders



Particle colliders [1/2]

AdA at Frascati



ISR at CERN

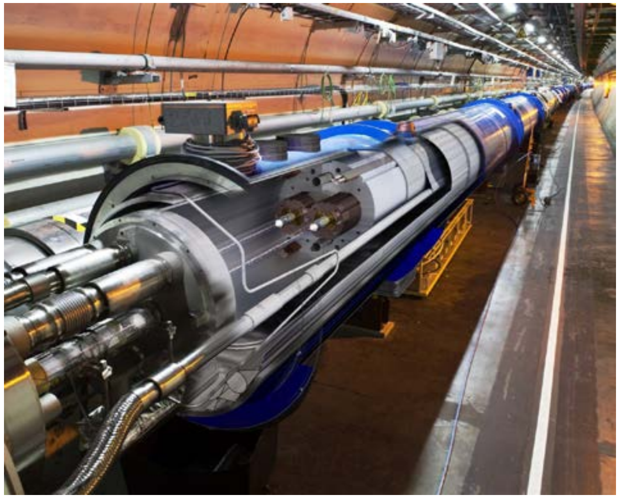
TeVatron at Fermilab

- 1943, R. Widerøe patents the concept of colliding beams in storage rings
- 1961, the first electron-positron storage ring AdA is built in Frascati
- 1971, CERN starts operating the ISR, first proton-proton collider
- 1982, the CERN SPS is converted into a proton-antiproton collidre
- 1987, the TeVatron at Fermilab is converted into a proton-antiproton collider
- 1987, the SSC, a 40 TeV proton-proton collider, is approved for construction in the USA. The project was subsequently cancelled in 1993.

Particle colliders [2/2]

LEP at CERN

HERA at DESY



LHC at CERN

- 1989, CERN starts operating the 26.7 km, high-energy electron-positron collider
- 1989, SLAC starts operating the SLC, first linear collider converted from the linac
- 1991, HERA at DESY becomes the first proton-electron collider
- 1999, RHIC at BNL becomes the first heavy-ion collider
- 2008, CERN starts operation of the LHC, 14 TeV proton-proton collider
- 2012, design studies are published for electron-positron linear colliders, ILC and CLIC
- 2014, CERN launches design study for Future Circular Colliders (100 km circumference)

Luminosity

- The performance of a collider is characterized not only by the collision energy, but also by the luminosity, which is a measure of the event rate
- For colliding beams, the luminosity is defined as the ratio of the event rate $\dot{\mathcal{N}}$ for a given interaction to the cross-section Σ of that interaction

$$\mathcal{L} = \frac{\dot{\mathcal{N}}}{\Sigma}$$ expressed in $cm^{-2}.s^{-1}$

- For head-on collisions of bunches of N particles at frequency f_{col}

$$\mathcal{L} = \frac{N^2 f_{col}}{4\pi\sigma_x\sigma_y} = \frac{N^2 n f_{rev}}{4\pi\sigma_x\sigma_y}$$

with: $f_{col} = n f_{rev}$, n number of bunches

σ_x and σ_y measure of beam size at collision

- For round beams, introducing emittance ϵ and beta function β^* at collision

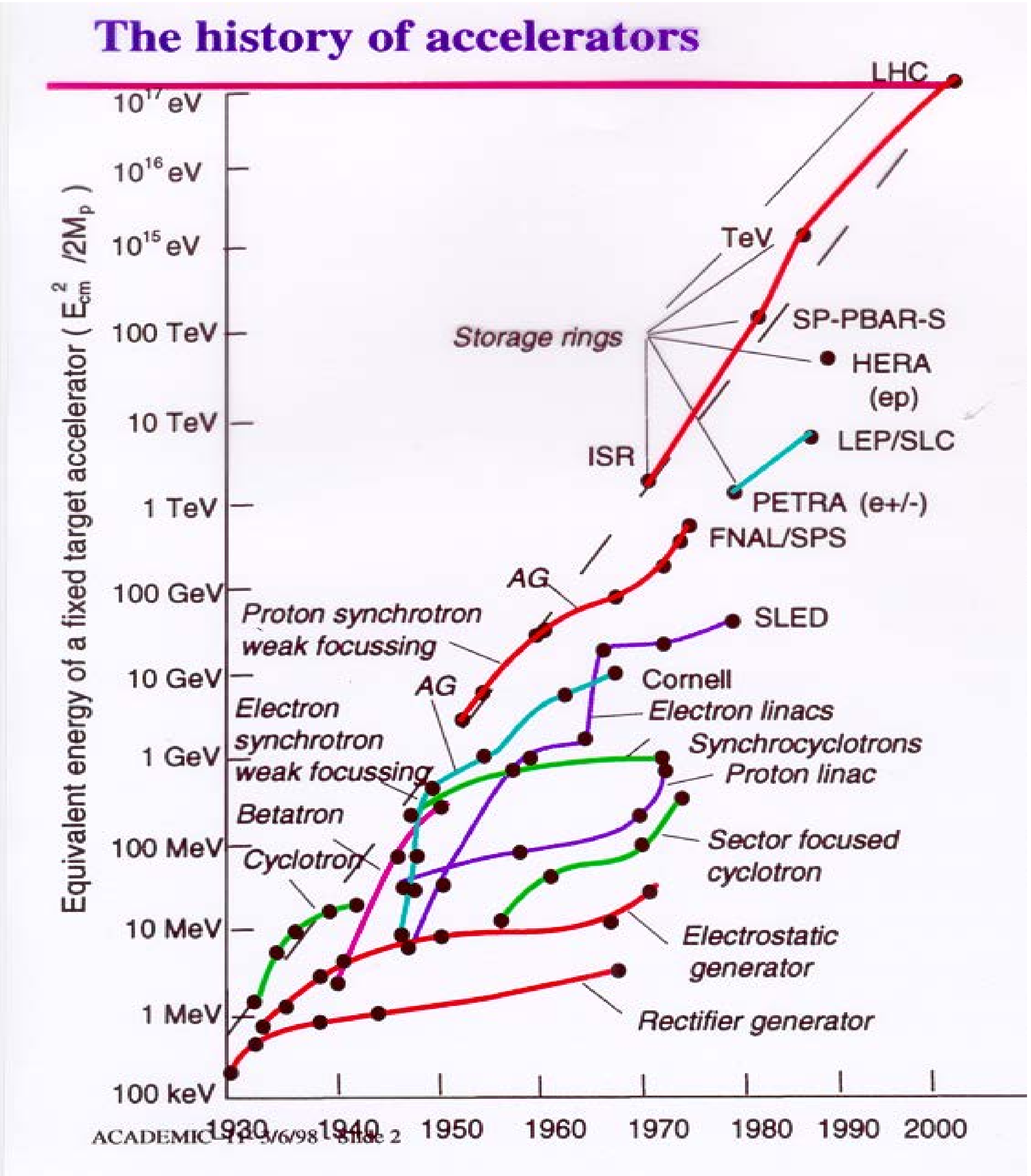
$$\mathcal{L} = \frac{N^2 n f_{rev}}{4\pi\epsilon\beta^*}$$

$\Rightarrow$ For higher luminosity

- increase bunch population
- increase collision frequency $\Rightarrow$ number of bunches
- reduce β^* $\Rightarrow$ “low-beta” insertions

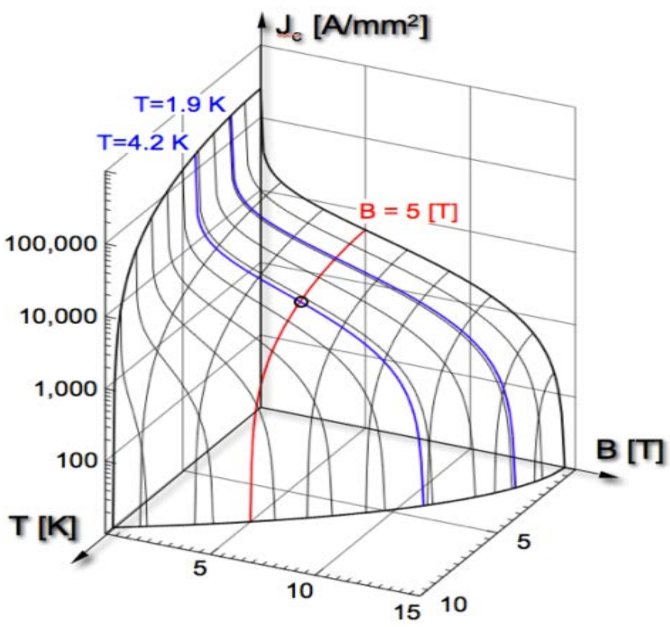
«Livingston diagram» shows

- sustained exponential development for more than 70 years
- progress achieved through repeated jumps from saturating to emerging technologies
- all high-energy machines since the 1970s are colliders



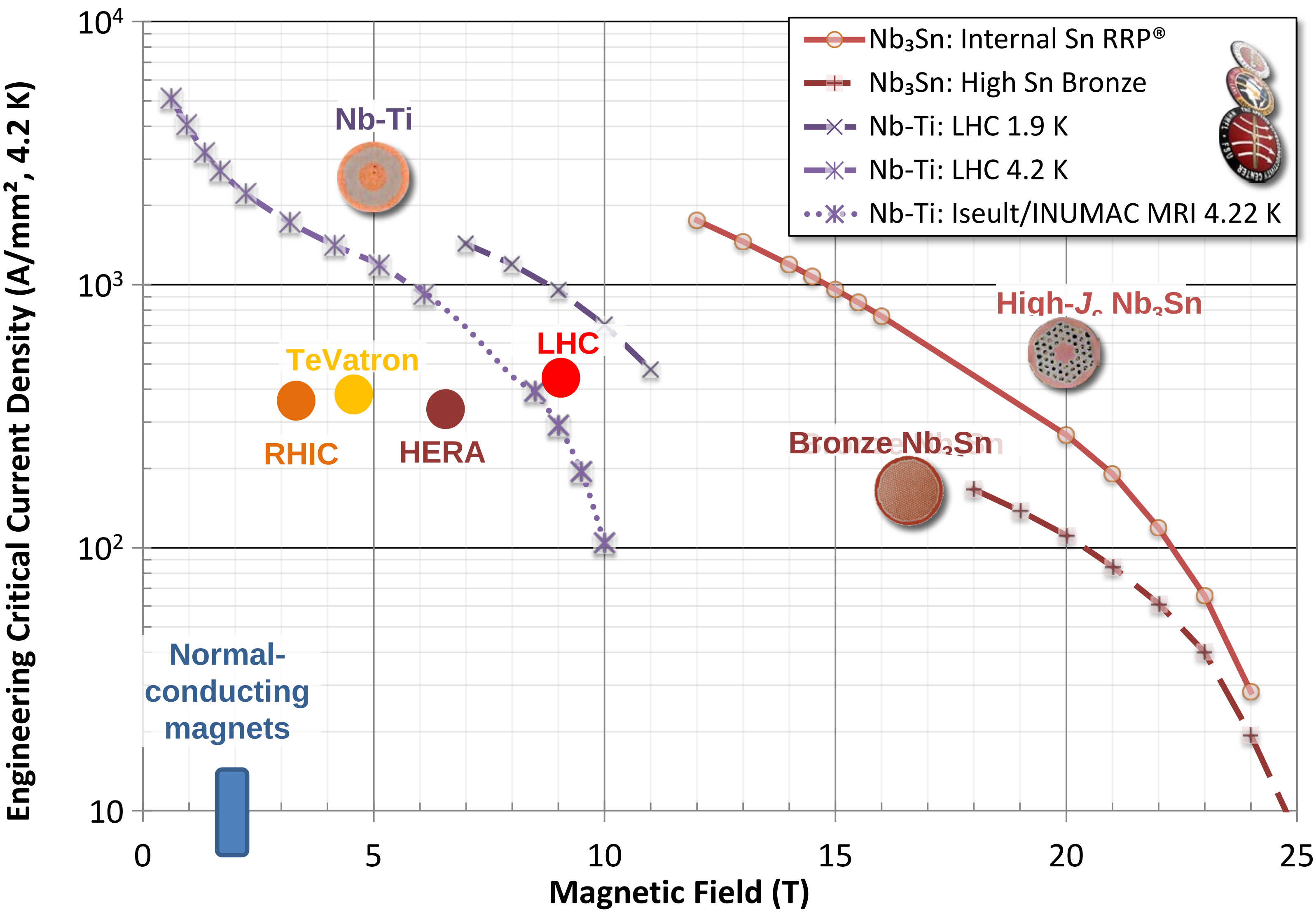
Superconductivity

- Superconductivity, entailing nil (DC) or low (AC) electrical resistance, has become a key technology for high-energy particle accelerators
  - Allowing to design high-field, high current density magnets operating above the saturation of iron,
  - Allowing to build high-field, low-loss RF cavities (low wall resistance)
  - Reducing overall electrical consumption of the machines



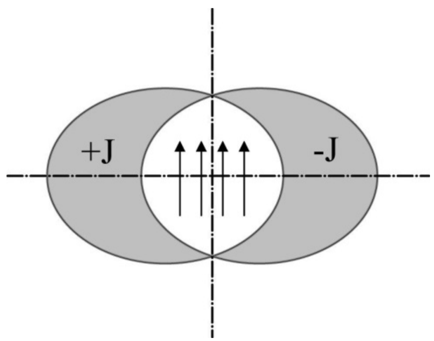
- The superconducting state only occurs in a limited domain of (low) temperature, magnetic field and current density, limited by the «critical surface» of the material
- Superconducting magnets produce high field with high current density
- The working point must remain below the «critical surface» of the superconductor
- Operating at lower temperature increases the working range in the magnet design plane (J_c,B)

Superconductivity to produce high magnetic fields

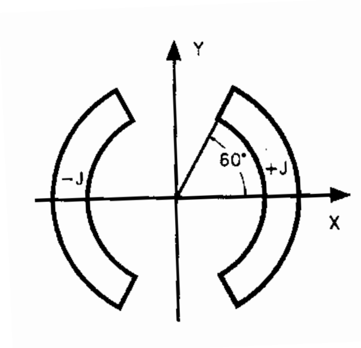


Superconducting magnets

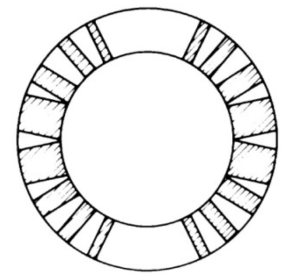
- In a superconducting magnet, the field is given by the current distribution in the windings (Biot & Savart's law).
- When present, the iron only acts as a flux return yoke



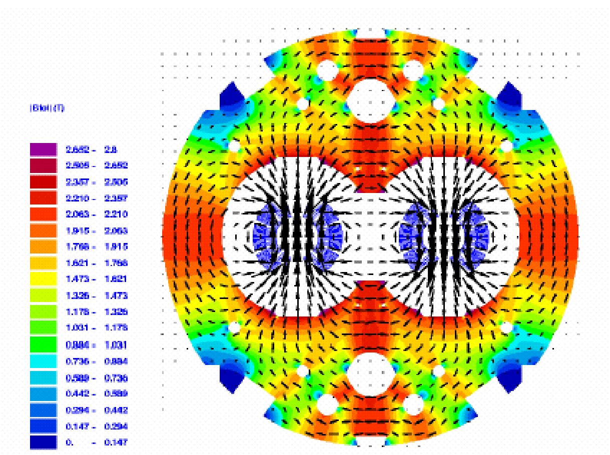
Intersecting ellipses

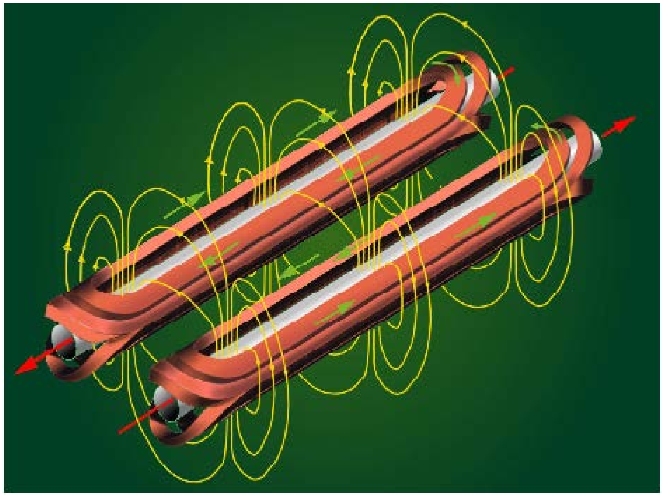


"cos θ"



« block » approximation





Magnet power consumption

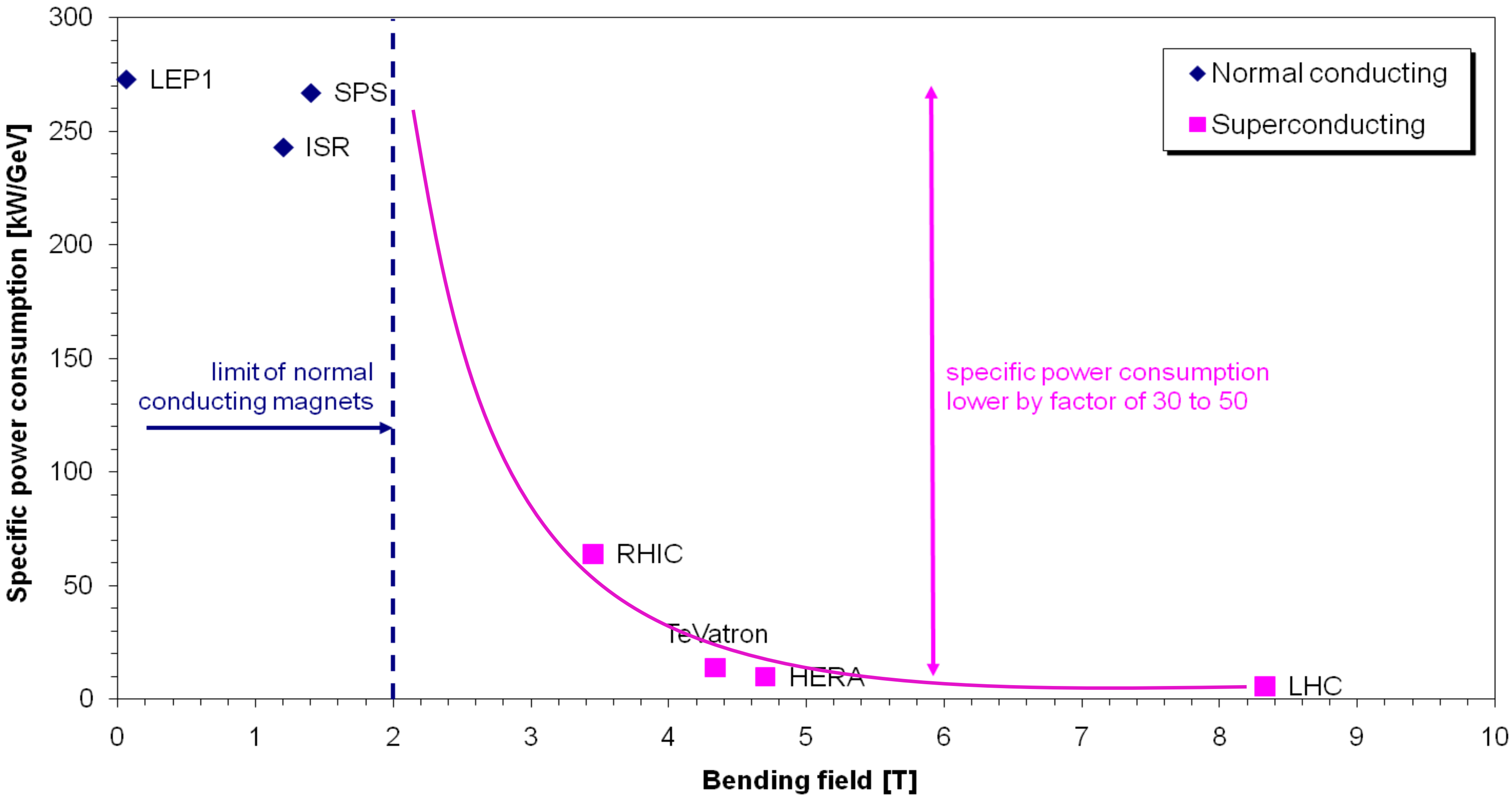
- Normal conducting (copper)
  - Power dissipation per unit length $P/L \sim \rho_{Cu}\, jB$
  - Total power dissipation $P \sim \rho_{Cu}\, jB\rho \sim \rho_{Cu}\, jBp$
- Superconducting
  - Total power (refrigeration) $P \sim L \sim \rho$

  -> independent of magnetic field

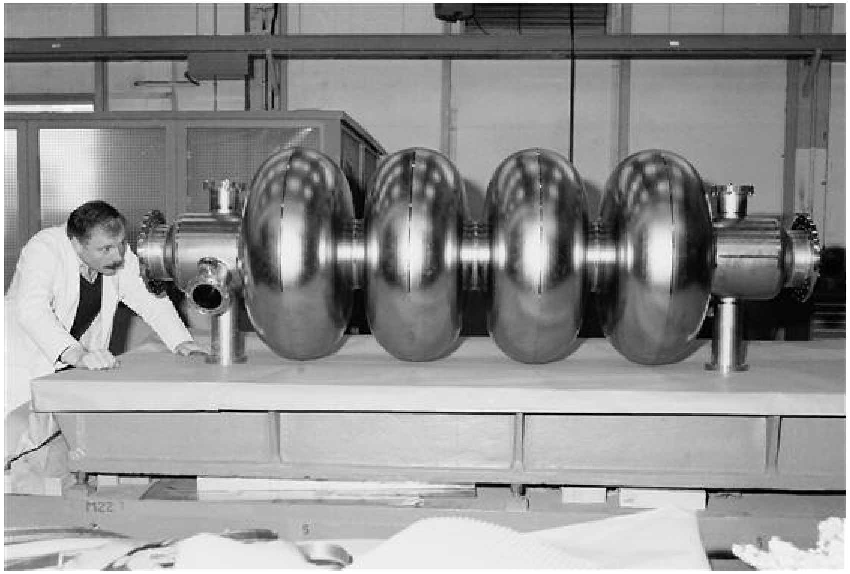
	Normal conducting	Superconducting (LHC)
Magnetic field	1.8 T (limited by iron saturation)	8.3 T (limited by critical surface of Nb-Ti)
Field geometry	Defined by pole pieces	Defined by windings
Current density in windings	10 A/mm^2	400 A/mm^2
Electromagnetic forcess	20 kN/m	3400 kN/m
Electrical power from grid	10 kW/m	2 kW/m

Superconductivity to reduce power consumption

Superconductivity and higher fields break the canonical
~ 250 kW/GeV specific power consumption of conventional synchrotron magnets

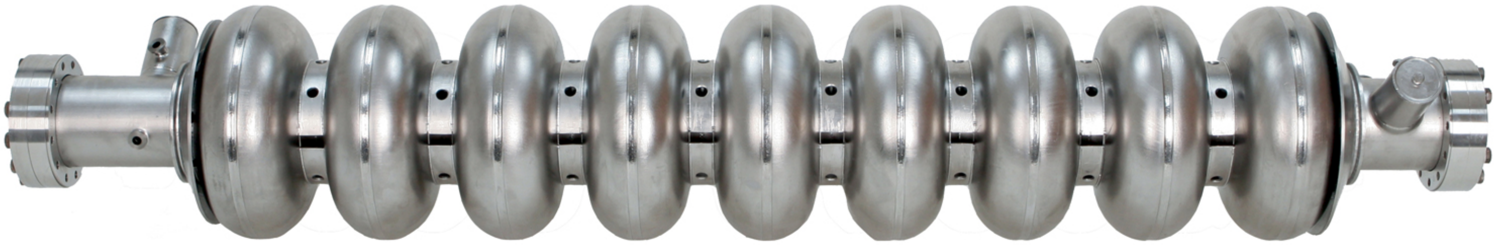


Superconductivity: RF cavities



4-cell, 352 MHz Nb on Cu cavity for LEP2

400 MHz Nb on Cu cavities in LHC tunnel



9-cell, 1.3 GHz Nb prototype cavity for the ILC

RF cavity power consumption

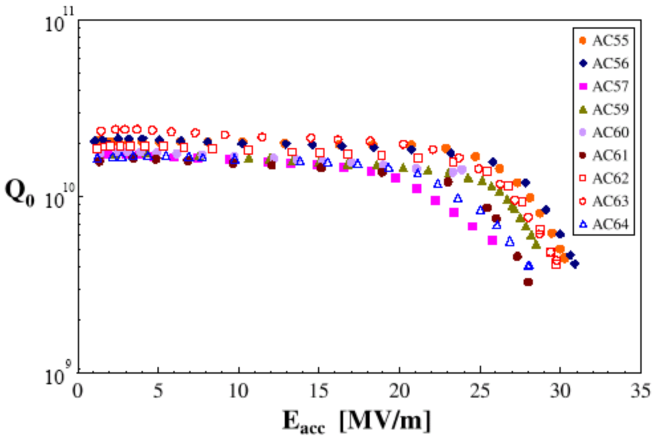
- Power dissipation in RF cavity
  - Power per unit length $P/L \sim R_s E^2/\omega$
  - *Q* factor of resonator $Q \sim 1/R_s$

  -> to reduce power dissipation, need high Q at high field

  -> superconductivity allows very high Q values

  -> the power is however dissipated at low temperature: the electrical consumption must take into account the efficiency of cryogenic refrigeration

SC cavities Nb at 1.5 GHz



Typical Q values for cavities at 500 MHz, 1 MV/m

Cavity	Normal conducting (Copper)	Superconducting
Q	4. 10^4	4. 10^9
P at 4.2 K [W/m]	-	0.7
P at 290 K [W/m]	35'000	350

La recherche est le démiurge qui remodèle sans cesse la face du monde. Elle pourvoit en techniques nouvelles le champ de la pratique quotidienne. Elle augmente l'emprise de l'homme sur la nature et fait de lui un agent actif de transformation du monde.

Cheikh Anta Diop

Perspectives de la Recherche Scientifique en Afrique (1974)