Introduction of Accelerator

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Outline

1. Ten things about particle accelerators
2. History
3. Basic Physics & Technology
4. Collider & Luminosity

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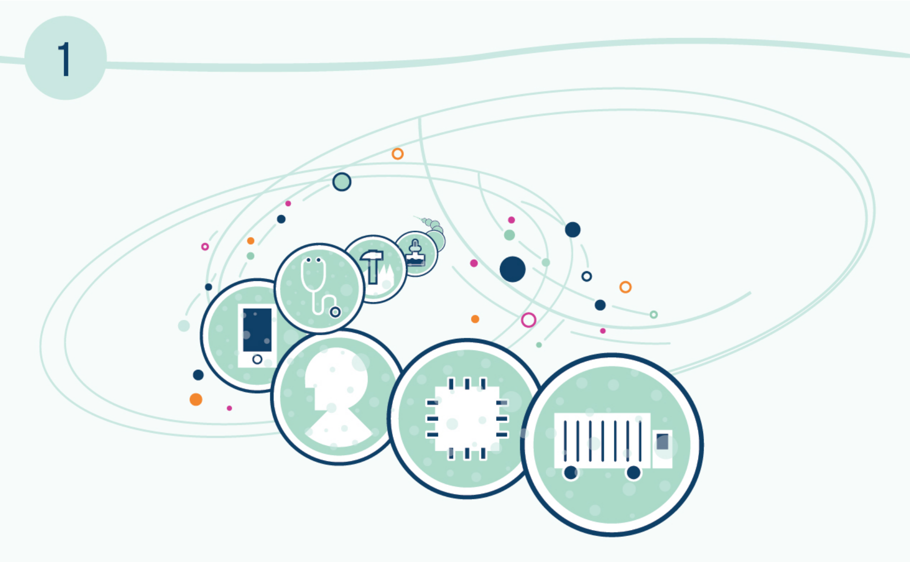
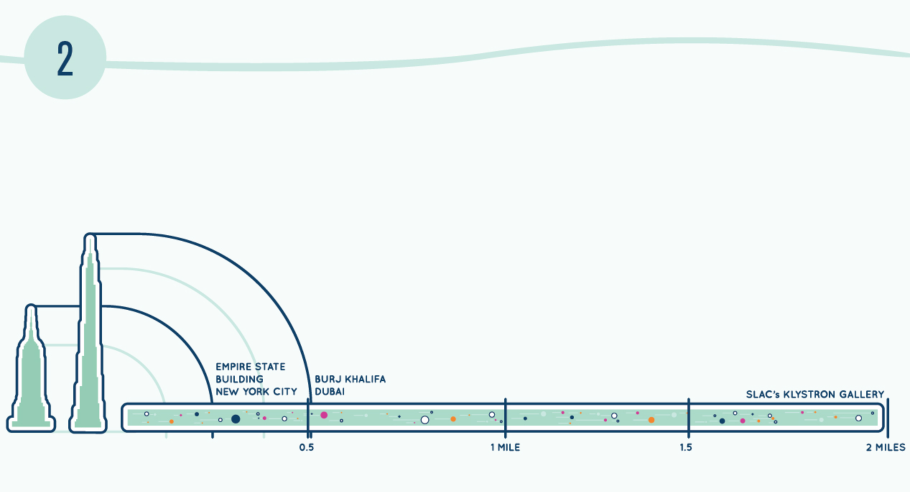
Ten things about particles accelerators

There are more than 30,000 accelerators in operation around the world.



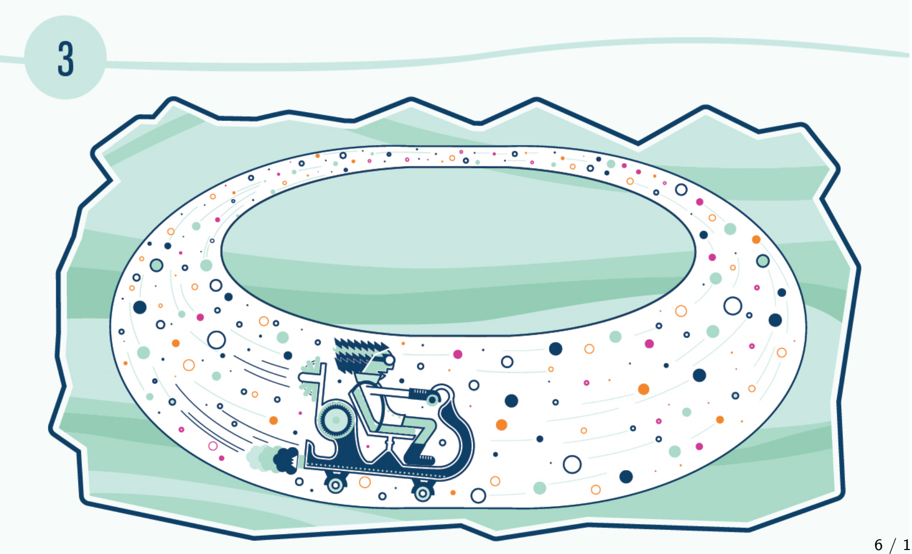
Ten things about particles accelerators

One of the longest modern buildings in the world was built for a particle accelerator.

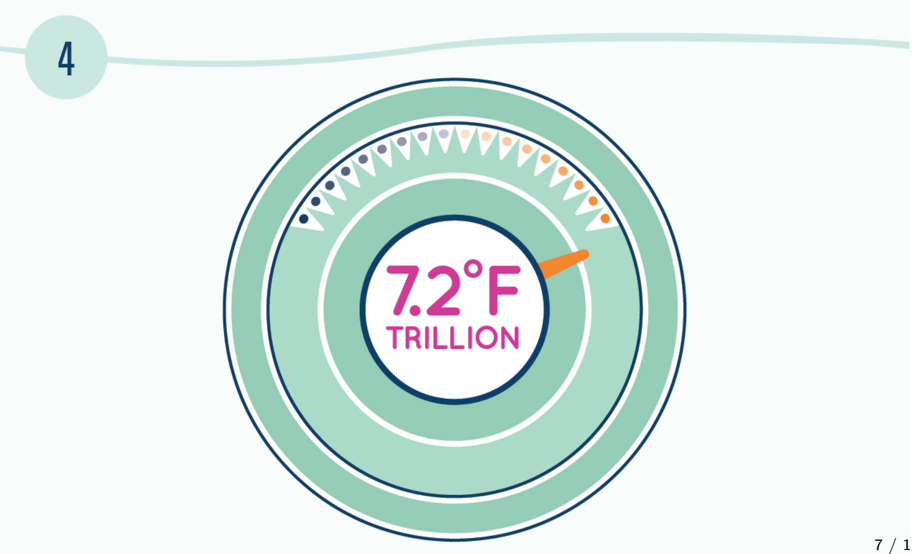


Ten things about particles accelerators

Particle accelerators are the closest things we have to time machines, according to Stephen Hawking.

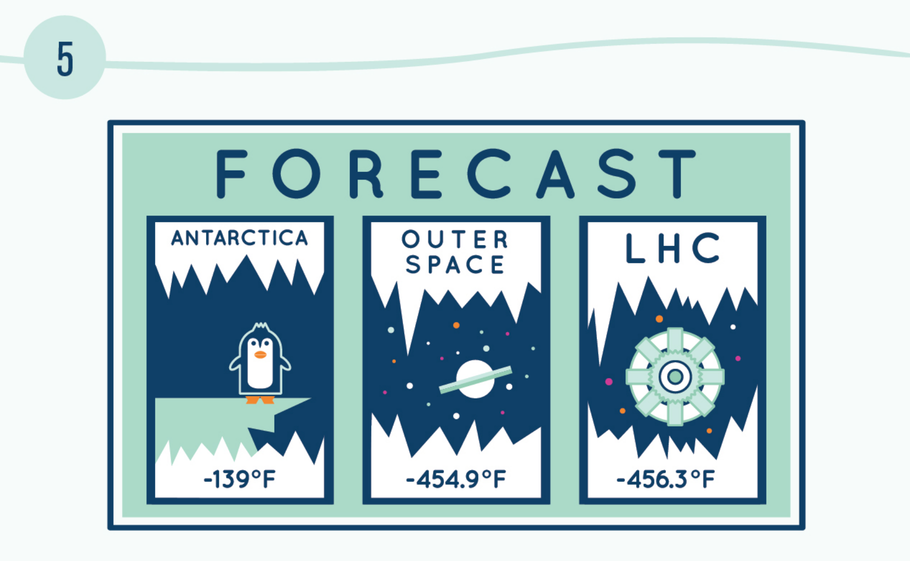


The highest temperature recorded by a manmade device was achieved in a particle accelerator.



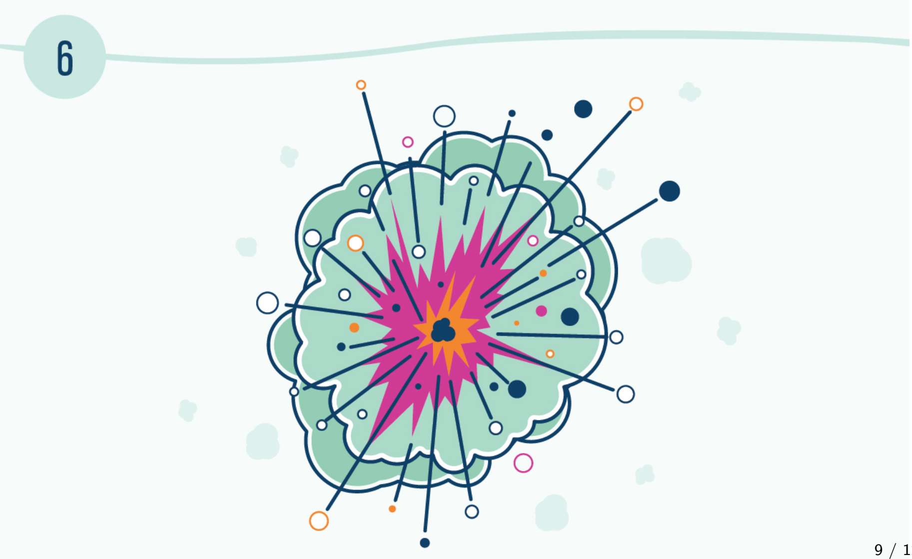
Ten things about particles accelerators

The inside of the Large Hadron Collider is colder than outer space.



Ten things about particles accelerators

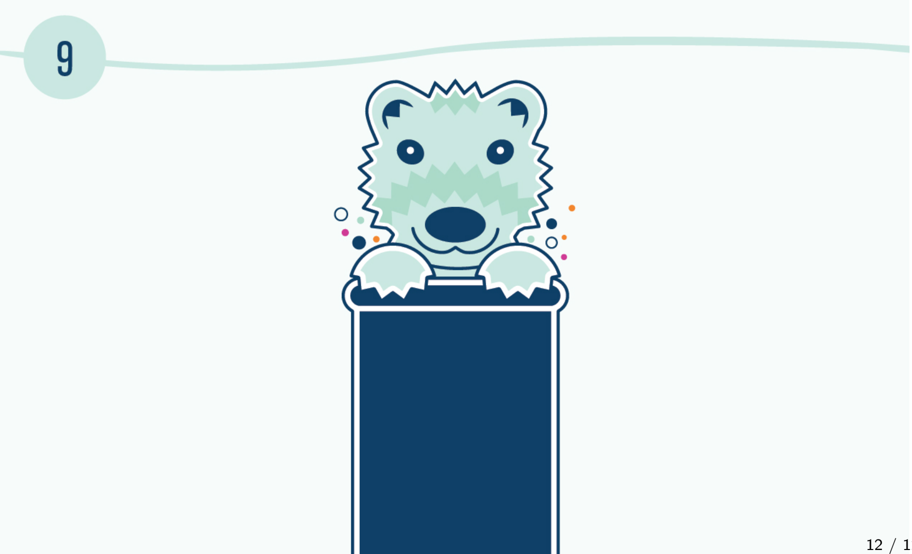
Nature produces particle accelerators much more powerful than anything made on Earth.



Particle accelerators don't just accelerate particles; they also make them more massive.

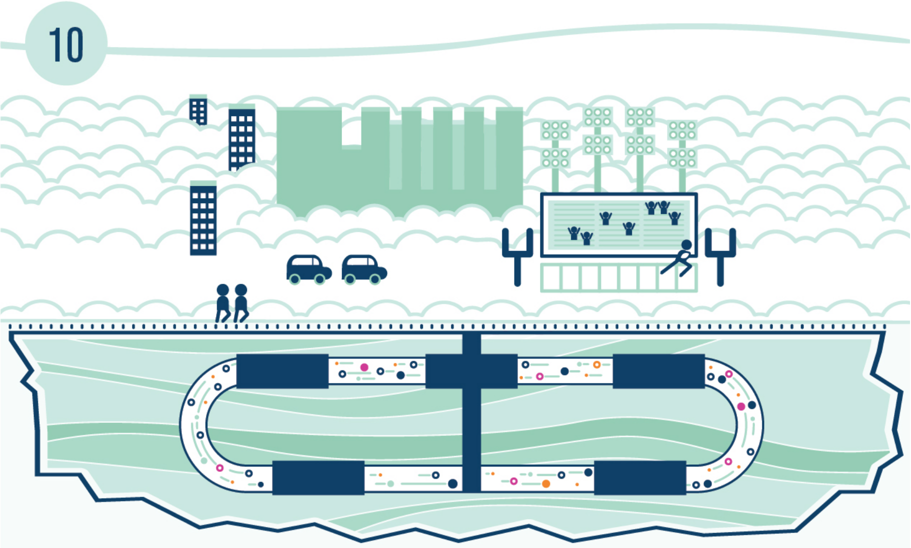
The diameter of the first circular accelerator was shorter than 5 inches; the diameter of the Large Hadron Collider is more than 5 miles.

In the 1970s, scientists at Fermi National Accelerator Laboratory employed a ferret named Felicia to clean accelerator parts.



Ten things about particles accelerators

Particle accelerators show up in unlikely places.



Outline

Motivation

The first motivation was from Ernest Rutherford who desired to produce nuclear reactions with accelerated nucleons.

For many decades the motivation was to get to ever higher beam energies. At the same time, and especially when colliding beams became important, there was a desire to get to ever higher beam current.

In the last three decades there has been motivation from the many applications of accelerators, such as producing X-ray beams, medical needs, ion implantation, spallation sources, and on and on.

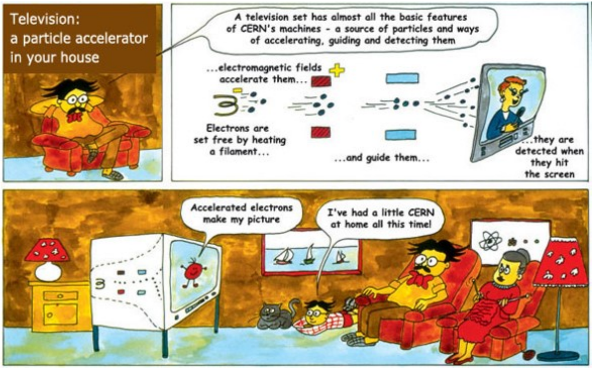
Mechanism of Particle Acceleration

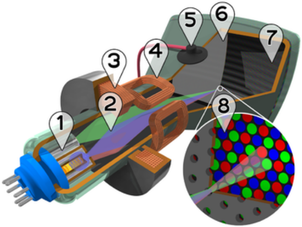
DC voltage acceleration (developed in 1930s)
- Voltage multiplier cascade (Cascade accelerators, Cockcroft and Walton)
- Electrostatic generator (Van de Graaff accelerators)

Resonance acceleration (Gustaf Ising, Sweden, first proposed it in 1924)
- Radio-frequency (RF) Linear accelerators
  (Rolf Wideröe, Norway, built the first linac using an RF accelerating field)
- Radio-frequency quadrupole (RFQ)
  (first proposed by I.M. Kapchinski and V.A. Teplyakov in 1970)
- Cyclic accelerators
  Cyclotron (first one built in 1931)
  Microtron (first proposed in 1944 by V. Veksler and J. Schwinger)
  Synchrocyclotron (first proposed in 1945 by E. McMillan and V. Veksler)
  synchrotron

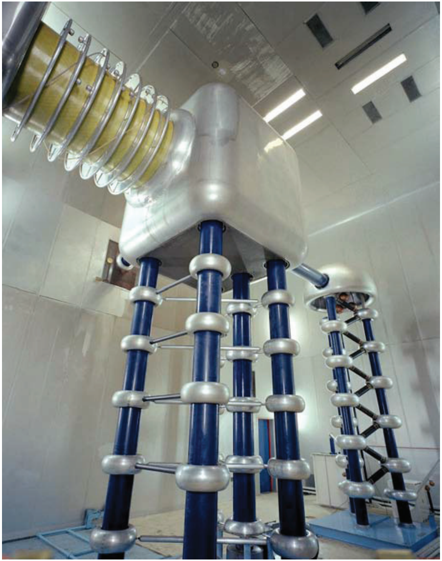
Magnetic induction acceleration
- Betatron (reinvented & built in 1940 by Donald Kerst, but the concept was formulated by R. Wideröe in 1928)
- Induction linac (invented by N.C. Christofilos in 1950s)

Cathode ray tube





1. Three Electron guns (for red, green, and blue phosphor dots)
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inner side of the screen



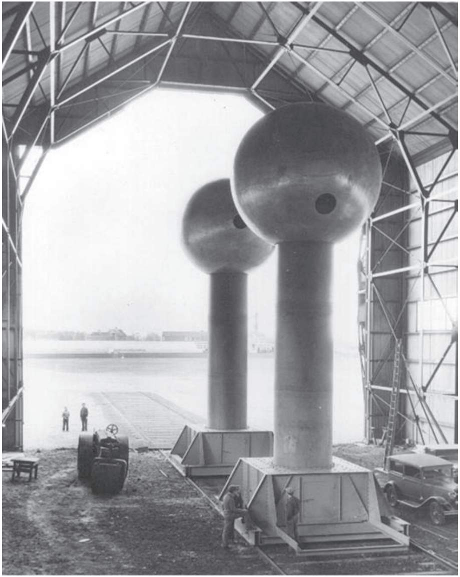
The Cockcroft-Walton pre-accelerator, built in the late 1960s, at the National Accelerator Laboratory in Batavia, Illinois. This very large and expensive installation provided the voltage for the first tiny step in the acceleration of protons to energies of hundreds of GeV.

Cockcroft and Walton induced the nuclear reaction:

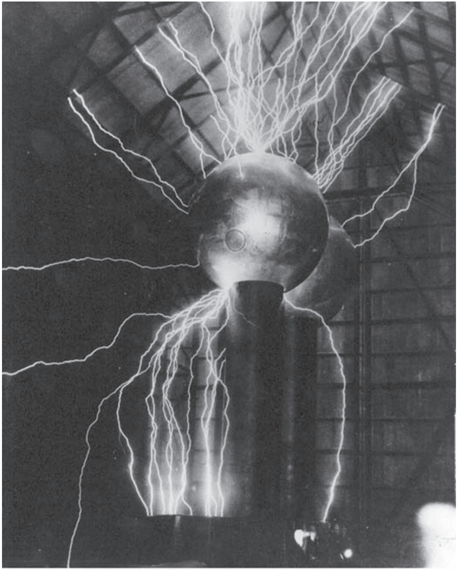
$$Li + p \rightarrow 2He$$

They were honored by receiving the Nobel Prize in 1951.

The Van de Graaff Generator

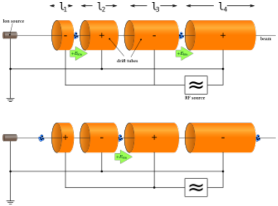


THE GENERATOR IN THE HANGAR AT ROUND HILL

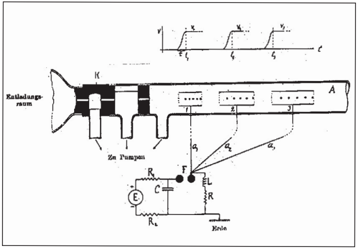


AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)

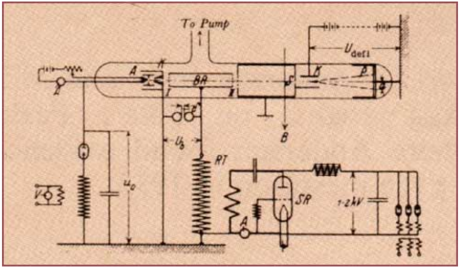
The Early Linear Accelerator



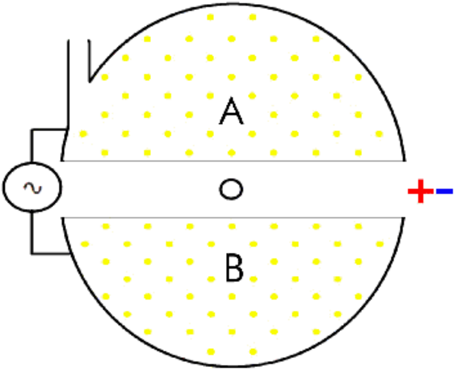
Sketch of the Ising/Widerøe linear accelerator concept, employing oscillating fields (1928)



A drawing, from Ising's original paper of 1924, showing his idea for an RF accelerator. Later Wideroe was able to turn this idea into reality, demonstrating RF acceleration for the first time.



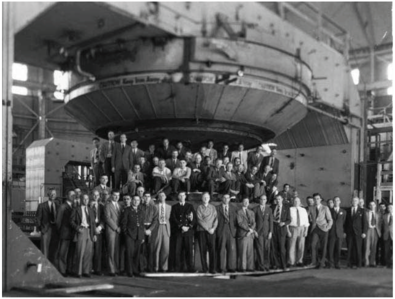
Rolf Wideröe's diagrams describing a method for accelerating ions inspired Ernest Lawrence's invention of the cyclotron.



The first successful cyclotron, the 4.5-inch model built by Lawrence and Livingston.

Lawrence received the Nobel Prize in 1939.

The Largest Cyclotron by Lawrence

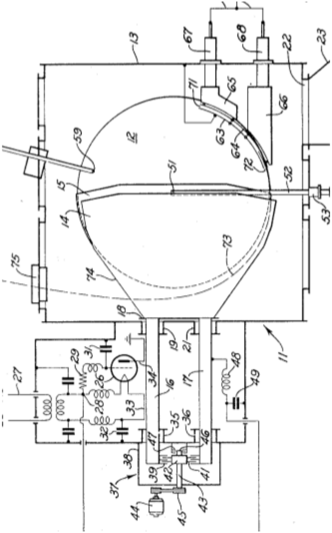


The 184 inch cyclotron built at Univ. of California, Berkeley

[Ref.]: Photography Gallery of Lawrence Berkeley National Laboratory, http://cso.lbl.gov/photo/gallery/

SynchroCyclotron

A synchrocyclotron is a special type of cyclotron, patented by Edwin McMillan, in which the frequency of the driving RF electric field is varied to compensate for relativistic effects as the particles' velocity begins to approach the speed of light. This is in contrast to the classical cyclotron, where this frequency is constant.



Sketch of a synchrocyclotron from McMillan's patent.

Betatron

Donald Kerst and the first betatron (2.3 MeV electrons) he built in Univ. of Illinois in 1940. The betatron had been used by the ***Manhattan Project*** to determine basic properties of thorium, uranium, and plutonium.

[Ref.] http://www.physics.uiuc.edu/history/Timeline/1940s.html

A modern compact betatron, commercially available. The compact betatron is used as a portable x-ray source for the detection of flaws in metal, such as steel beams, ship hulls, pressure vessels, bridges, etc.

[Ref.] http://www.globalxray.com/betatron_photo.html

The Flash X-Ray Facility (FXR), a linear-induction electron beam accelerator built in 1982, at **Lawrence Livermore National Laboratory**, California, USA. It is used to study the detonation process (implosion) of nuclear weapons.

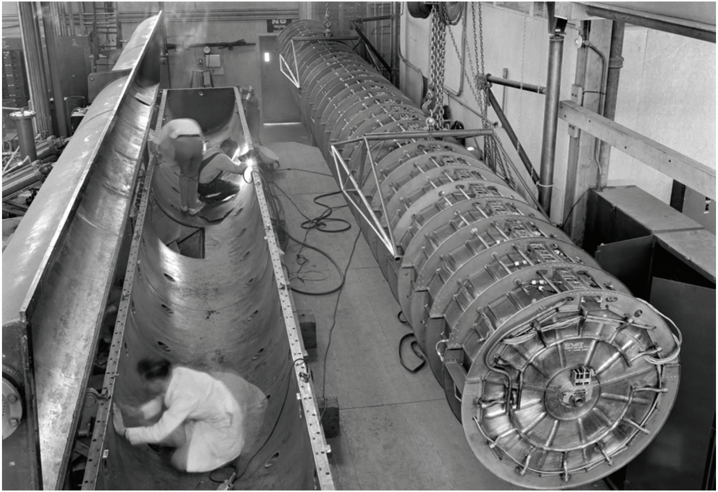
[Ref.] http://www.llnl.gov/str/April02/April50th.html

Nichola C. Christofilos, the inventor of the induction linac (1950s) and the principle of strong focusing.

Christofilos

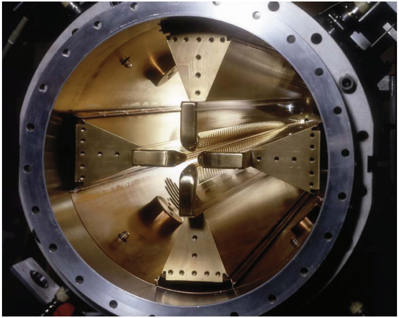
[Ref.] http://www.mlahanas.de/Greeks/new/Christofilos.htm

Protron Linac - Drift Tube Linac



An accelerating tank of the first Alvarez linac, built just after WWII. Since that time many similar linacs have been built all around the world.

Protron Linac - Radio Frequency Quadrupole (RFQ)

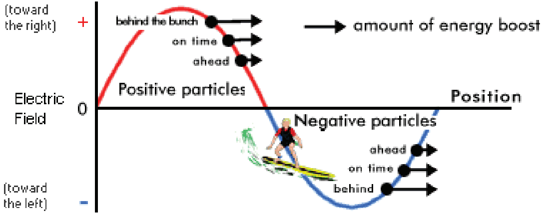


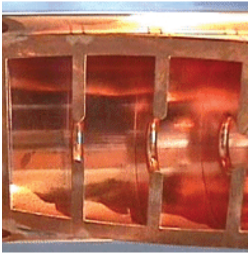
The inside of a Radio Frequency Quadrupole. The RFQ has generally replaced the very large Cockcroft-Waltons as the first stage of injectors into synchrotrons.

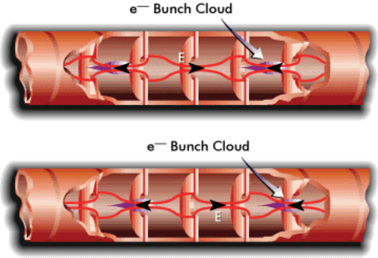
Invented in the Soviet Union by Teplyakov and Kapachinskii in 1970, the Radio Frequency Quadrupole linac (RFQ) was brought to the attention of Western physicists by Joe Manca at Los Alamos. The first RFQ, a “proof of principle”device built at Los Alamos, was small but highly successful.

Electron Linac (disk loaded structure)

Electron Linac (disk loaded structure)





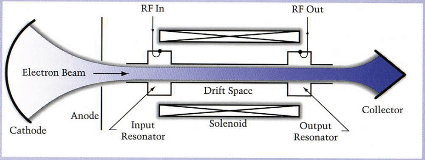


1/20,000,000,000 second later
(notice how far the bunches have moved)

[Ref.] http://www.slac.stanford.edu

High power microwave amplifier:

Klystron Amplifier Principle



Basic klystron arrangement.

THE PRINCIPLE OF THE KLYSTRON AMPLIFIER is shown in the figure above. A heated cathode emits a continuous electron beam of relatively low density. The beam is accelerated and at the same time focused by an electrostatic anode before entering an input resonator that is fed by a low power input signal. There the beam receives a velocity modulation that depends on the input signal. This dependence makes the klystron an amplifier, as opposed to an oscillator. This is critical because it allows control of the multiple klystrons needed in an accelerator. After a drift space, where the beam is focused magnetically, the originally continuous beam is bunched which corresponds to a large rf current. It enters the output resonator where it loses energy to an external load (usually the accelerator). The leftover beam with a strongly reduced kinetic energy is dumped into the collector. The klystron as described would be fully operational, but it would have low efficiency and low gain. High power klystrons have additional idling resonators between the input and output resonators to improve the bunching process.

[Ref.] ***Beam Line, Vol.28 (1998), published by SLAC***

Synchrotron

Cyclotron and betatron are both limited by the relativistic effect

Particles not synchronized with the accelerating voltage as their energy increase.

E.M. McMillan @ Univ. California, USA
V. Veksler @ U.S.S.R.

→ Discovered the principle of ***phase stability***

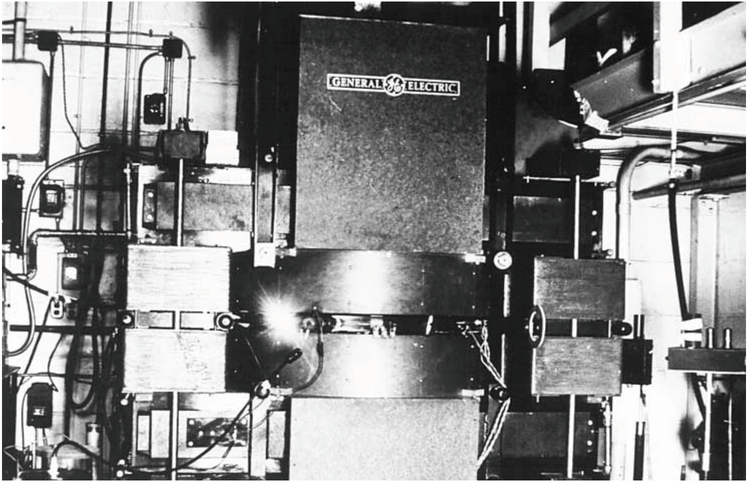
both solved this synchronism problem independently in 1945.
Their solutions were:

1) When the particle energy increases, we can slow down the accelerating voltage, i.e. the accelerating voltage is frequency modulated (decreasing f_{RF}) ⟹ ***synchrocyclotron***

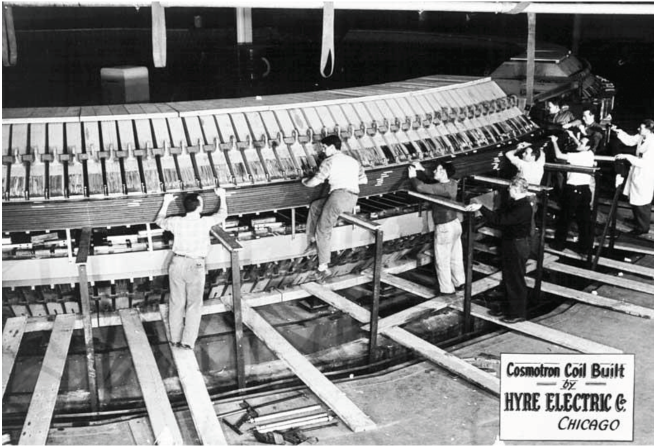
2) The guiding magnetic field be increased in strength as the beam gains energy (the orbit radius kept constant) ⇦ see Eq.(1.5)

The idea of the electron synchrotron!

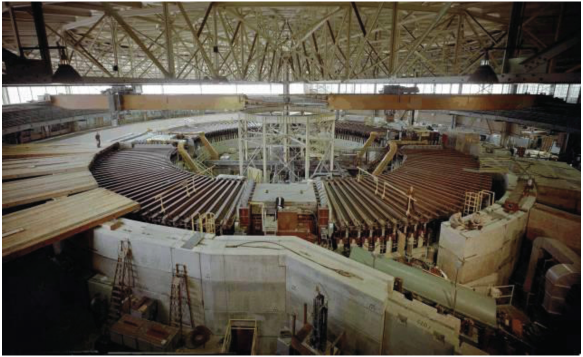
- *J. of Phys.*, U.S.S.R., **9**: 153 (1945), V. Veksler
- *Phys. Rev.*, **68**: 143 (1945), E.M. McMillan



The 300 MeV electron synchrotron built at General Electric Co. in 1940s. The photograph shows the synchrotron radiation emitted from the accelerator.



The 3 GeV Cosmotron was the first proton synchrotron to be brought into operation.



Overview of the Berkeley Bevatron during its construction in the early 1950s. One can just see the man on the left.

Strong Focusing

The invention of strong focusing, in the early 1950's, by Ernie Courant, Hartland Snyder and Stan Livingston, revolutionized accelerator design in that it allowed small apertures (unlike the Bevatron whose aperture was large enough to contain a jeep, with its windshield down).

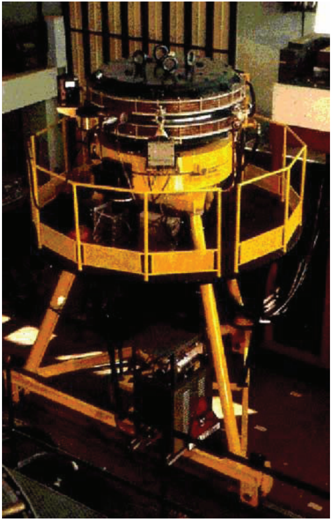
The concept was independently discovered by Nick Christofilos.

An example of strong focusing synchrotron

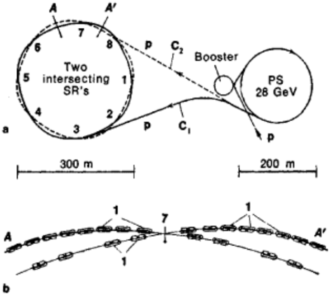
Early Colliders

In the 1950's a number of places, MURA, Novosibirsk, CERN, Stanford, Frascati, and Orsay, developed the technology of colliding beams. Bruno Touschek, Gersh Budker and Don Kerst were the people who made this happen.

Colliders are now the devices employed to reach the highest energies.



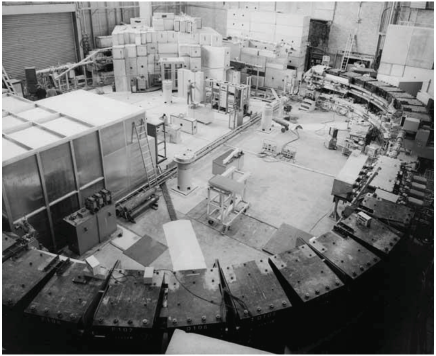
The first electron-positron storage ring, AdA. (About 1960) Built and operated at Frascati, Italy and later moved to take advantage of a more powerful source of positrons in France.



The first proton-proton collider, the CERN Intersecting Storage Rings (ISR), during the 1970's. One can see the massive rings and one of the intersection points.

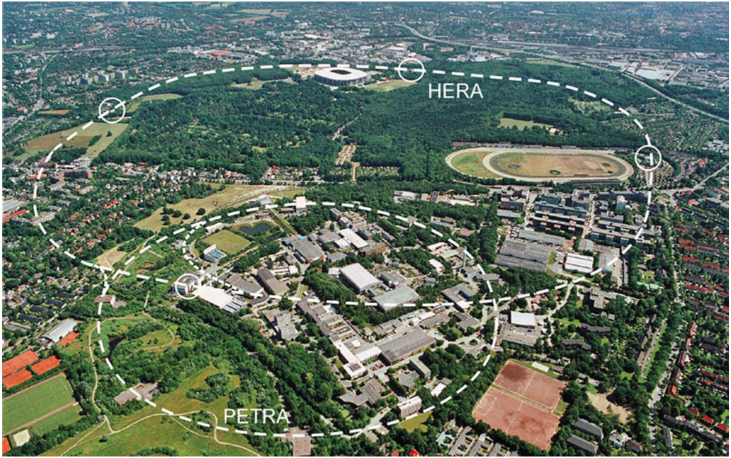
Proton-Antiproton Colliders

It was the invention of stochastic cooling, by van de Meer, that made proton-anti-proton colliders possible.



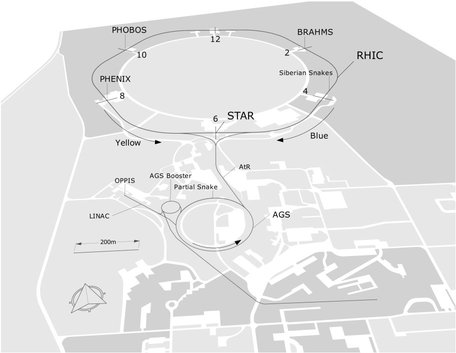
In 1977 the magnets of the "g-2" experiment were modified and used to build the proton-antiproton storage ring: ICE (the Initial Cooling Experiment). The ring verified the stochastic cooling method, and allowed CERN to discover the W and Z.

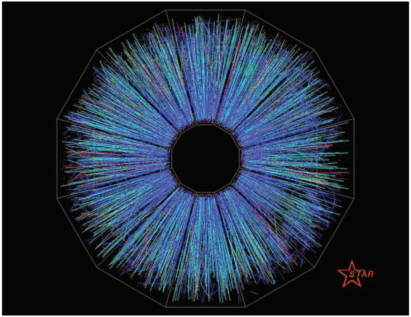
Electron-protron collider



An aerial view of DESY in the city of Hamburg.

Heavy-Ion Colliders

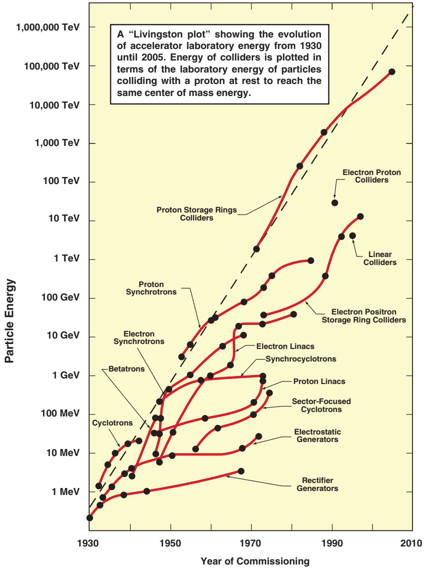




The Relativistic Heavy Ion Collider, RHIC, at Brookhaven National Laboratory, has been used to study nuclear matter under extreme conditions of very high density and very high temperature similar to the conditions in the original Big Bang. Here we see the result of a collision of a nucleus of gold with a nucleus of gold. The temperature, in a collision, rises to 2 trillion degrees Kelvin and as many as 10,000 particles are born in the resulting fireball.

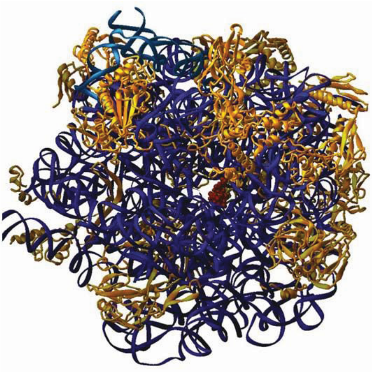
- Livingston chart
  12 orders of magnitudes
  over 70 years.

A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

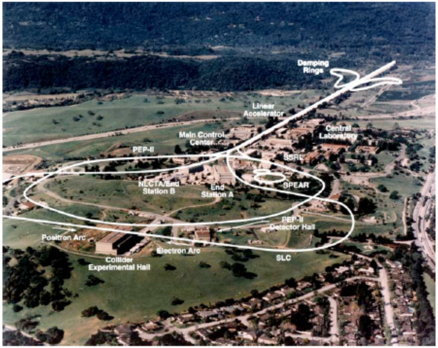


Synchrotron X-Ray Sources

At first (about 1970's), accelerators built for high-energy physics were used parasitically, but soon machines were specially built for this important application. There are more than 50 synchrotron radiation facilities in the world. In the US there are machines in Brookhaven (NSLS), Argonne (APS), SLAC: SPEAR and the LCLS, and at LBL (ALS).



This intricate structure of a complex protein molecule structure has been determined by reconstructing scattered synchrotron radiation.

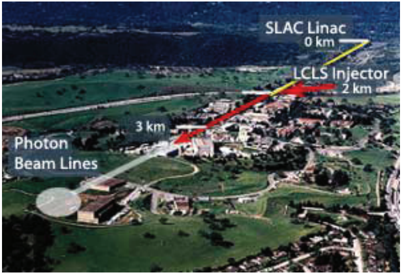


T he SLAC site showing its two-mile long linear accelerator, the two arms of the SLC linear collider, and the large ring of PEP II. This is where the LCLS is being located.

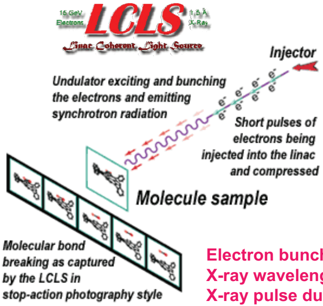
Linear Coherent Light Source

Forth Generation Light Source (X-ray FEL)

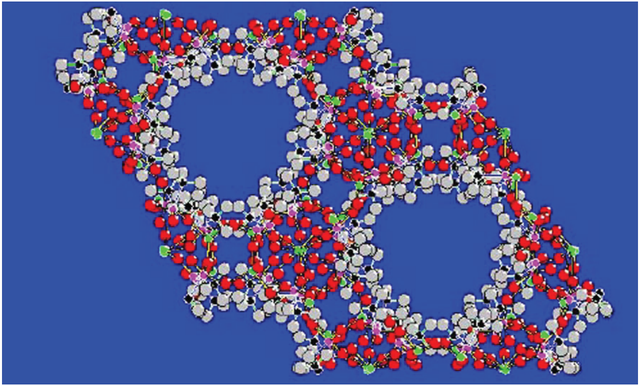
FEL: free electron laser



http://www-ssrl.slac.stanford.edu/lcls/

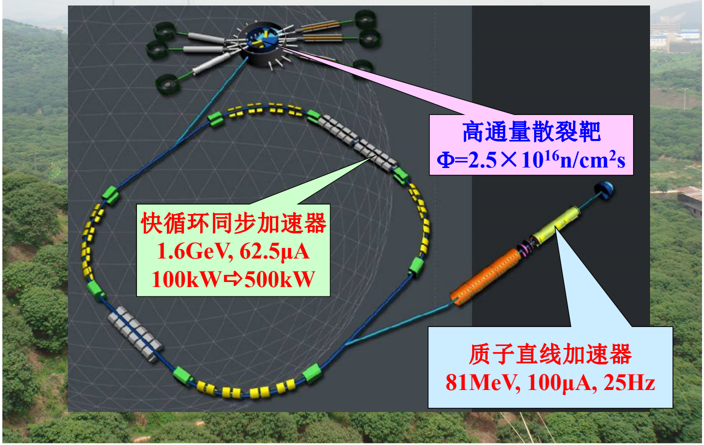


Electron bunch length: 0.023 mm, 15 GeV electron beam
X-ray wavelength: 0.15 – 1.5 nm
X-ray pulse duration: 100 femtosecond – 100 attosecond



A picture taken at the British neutron facility ISIS showing a hybrid microporous organic-inorganic solid. Neutron diffraction is particular in its sensitivity to light elements such as hydrogen, deuterium, carbon, nitrogen and oxygen, and thus provides an ideal tool for structural studies of such materials. Synchrotron radiation, on the other hand, is sensitive to heavy elements, so the two approaches are complementary.

中国散裂中子源 (CSNS)



Special Nuclear Energy Program in CAS

- **TMSR**

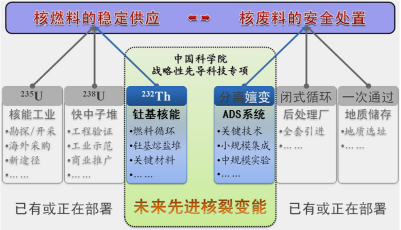
  - Diversify Nuclear fuel source

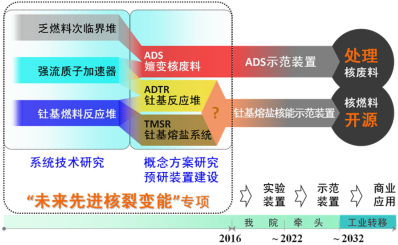
- **ADS**

  - Transmutation of Long lived Nuclear fuel waste

- ~2032,

  - Industrial demo facility





Prehistory

- 1883 Maxwell equations
- 1887 Hertz E&M wave.
- 1890-1930 cathode ray tubes are the first accelerators
- 1911 Rutherford -particle beam experiment
- 1912 Schott's synchrotron radiation classical analysis. 1946 Schwinger's synchrotron raditation quantum analysis

The beginning

The years around 1930 can be marked as the starting point of the accelerator era. Lord Ernest Rutherford can be regarded as the first person to push the development of particle accelerators.

- 1923 Wiederoe, betatron principle,
- 1928 Wiederoe, rf linac, 50 kV potassium ions
- 1930 Cockcroft & Walton, 400 kV rectifier high voltage
- 1931 Van de Graff, electrostatic charging device
- 1932 Lawrence 1.25 MeV cyclotron

The evolution

- 1939 klystrons, Hansen and Varian brothers
- 1940 Kerst betatron 2.3 MeV
- 1941 betatron stability principle, Kerst & Serber
- 1945 phase stability principle, McMillan & Veksler
- 1948 Alvarez 32 MeV drift tube proton linac
- 1952 strong focusing principle, Christofilos, Courant, Snyder, Livingston

Phase stability and strong focusing principles marked a revolutionary period and the beginning of modern era of accelerator physics.

The evolution

- 1958 Christofilos induction linac
- 1960 first electron storage ring collider, Touschek
- 1966 electron cooling, Budker
- 1966 SLAC linac
- 1969 first proton storage ring ISR
- 1970 RFQ, Kapchinskij & Teplyakov
- 1972 stochastic cooling, Van de Meer
- 1985 first linear collider SLC

Letter to the editor

(ICFA BD Newsletter, no. 53, December 2010)

1.1 Influence of Accelerator Science on Physics Research

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Abstract:
We evaluate accelerator science in the context of its contributions to the physics community. We address the problem of quantifying these contributions and present a scheme for a numerical evaluation of them. We show by using a statistical sample of important developments in modern physics that accelerator science has influenced 28% of post-1938 physicists and also 28% of post-1938 physics research. We also examine how the influence of accelerator science has evolved over time, and show that on average it has contributed to a physics Nobel Prize-winning research every 2.9 years.

- **This letter carried out an extensive survey of a large body of literature from Nobel Prize committee and laureates – a total of 331 documents (a stack of 60 cm high).**
- **From 1939 (when Ernest Lawrence received a Nobel Prize for his invention of the cyclotron) to 2009, nearly 30% of the Nobel Prizes in Physics had a direct contribution from accelerators.**
- **On the average, accelerator science contributed to a Nobel Prize in Physics every 3 years.**

25 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 in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].
2013	Francois Englert and Peter W. Higgs	Englert's and Higgs's theory of the Higgs particle in 1960s was confirmed by the ATLAS and CMS experiments at CERN's LHC in 2012.

Frontiers

- High energy
- High luminosity
- High brightness
- Applications

Acceleration Mechanism (G. Mourou)

In Existence Now

The Large Hadron Collider (LHC), CERN.

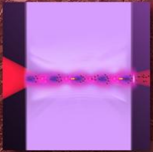
** 27kms toroidal tunnel*

** 175m underground*

** 1 billion proton collisions per second*

** 1 - 14 TeV*

27 kilometres



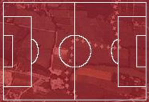
In Development Now

Laser Wakefield Acceleration visible light

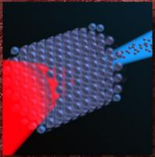
** electron/positron collider*

** 100m in length*

** 1 GeV/cm*



100 metres



In The Future

Zeptosecond X-ray Driver

** laser induced solid crystal wakefield*

** electron, muon, ion collider*

** 1cm in length*

** 1 TeV/cm*

1 centimetre

IZEST International Zeta-Exawatt Science Technology

International Year of Light 2015

Outline

Technologies used in modern accelerators

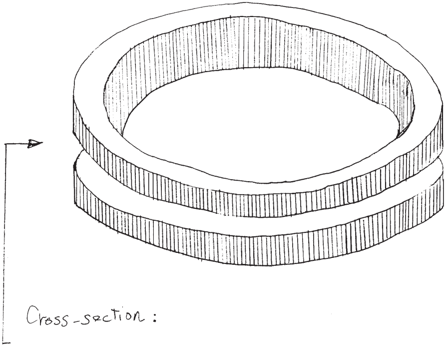
- large scale vacuum
- high power microwave
- superconducting (magnets, microwave) technology
- computer control
- very strong/very high precision magnets
- large scale scientific project management (very important)
- accelerator physics (beam dynamics) (beam physics)
- ...

How to design a storage ring

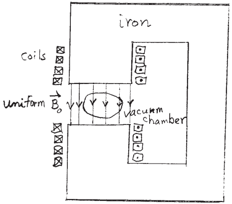
- charged particles
- Lorentz force

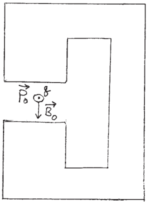
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- why magnetic field, not electric field



Cross-section:

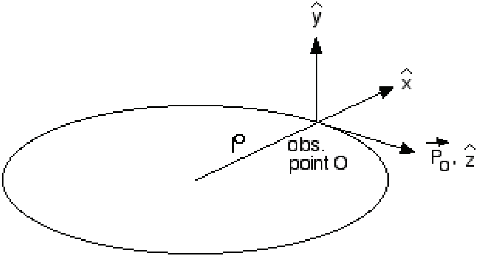




$$\vec{F} = q\vec{v} \times \vec{B}$$

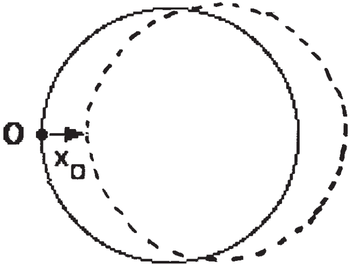
Stability Principle

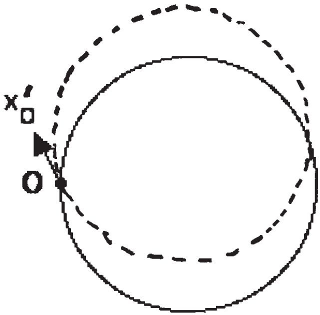
A stable storage ring must also store nonideal particles with “slight deviations” from the ideal conditions, i.e. the accelerator must have a finite acceptance around the ideal condition. Otherwise it is not a stable accelerator.



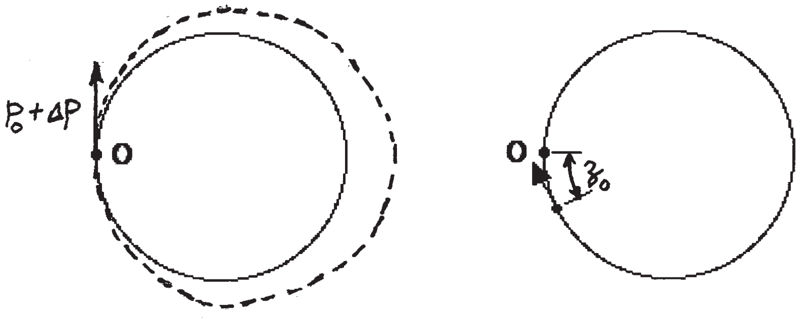
Motion must be stable for particles with all these six kinds of initial deviations: $x_0, x'_0, \Delta P_0, z_0, y_0, y'_0$.

If there exist deviation in x_0 and x_0'

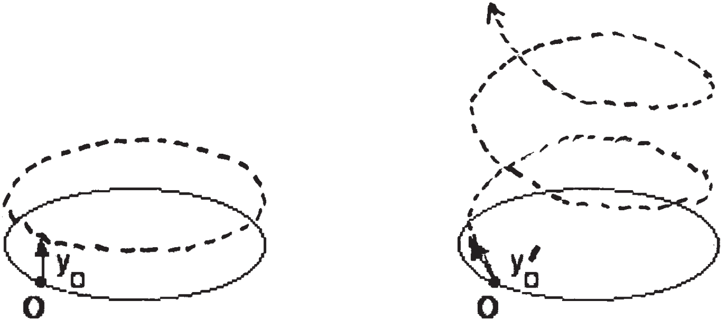




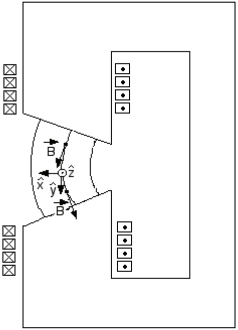
If there exist deviation in P_0 and z_0

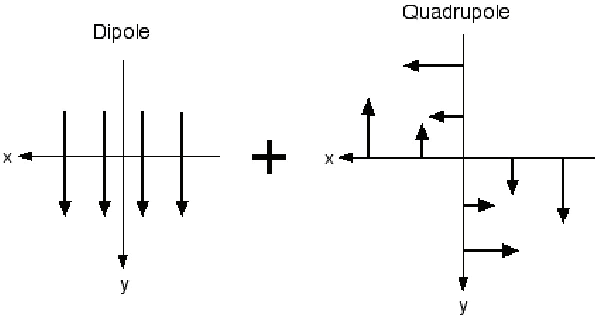


If there exist deviation in y_0 and y_0'



Weak focusing Magnet



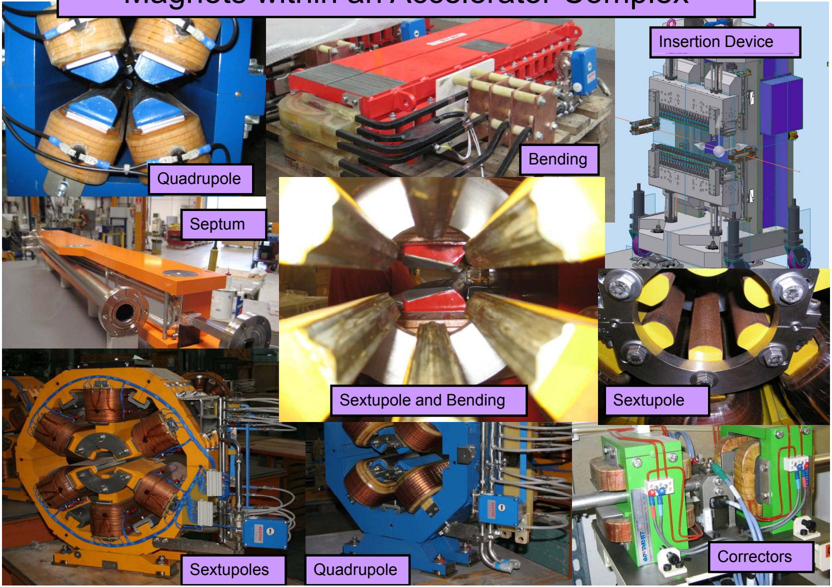


$$\vec{B} = B_0 \hat{y} + G(y\hat{x} + x\hat{y})$$

2-D Magnetostatics

- iron-dominated, uses iron pole face to shape the magnetic field. Because the iron typically saturates when the magnetic field reaches beyond 2 Tesla or so, iron-dominated magnets typically has maximum pole tip field less than 2 Tesla.
- current-dominated, uses little iron and is most likely using superconducting wires to carry the large currents. The superconducting current-dominated magnets typically reach 4-10 Tesla.

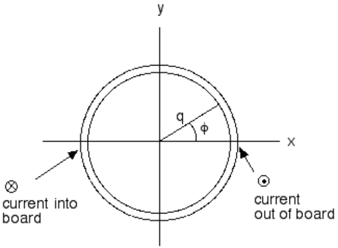
Magnets within an Accelerator Complex



$\cos\theta$ Magnet

Consider a cylindrical infinitely-thin sheet of current distribution

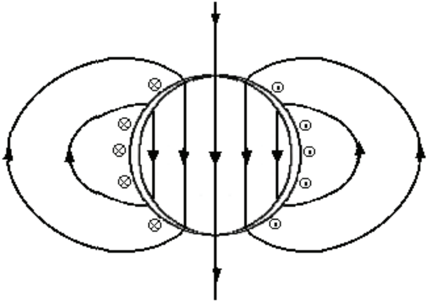
$$J(q,\phi) = \frac{I_0}{2a}\delta(q-a)\cos\phi$$



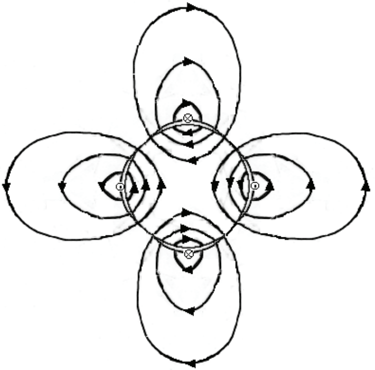
where a is the current-carrying cylinder radius. The right half of the sheet ($\cos\phi > 0$) carries current out of the board. There are no currents at the north and the south poles.

$$B_y + iB_x = \frac{\mu_0 I_0}{4}\begin{cases} -\frac{1}{a} & , \sqrt{x^2+y^2} < a \\ \frac{a}{z^2} & , \sqrt{x^2+y^2} > a \end{cases}$$

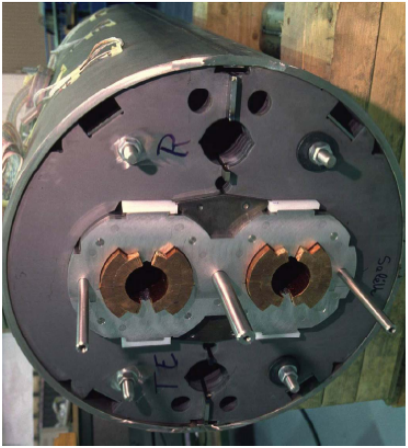
$\cos\theta$ and $\cos 2\theta$ magnet field

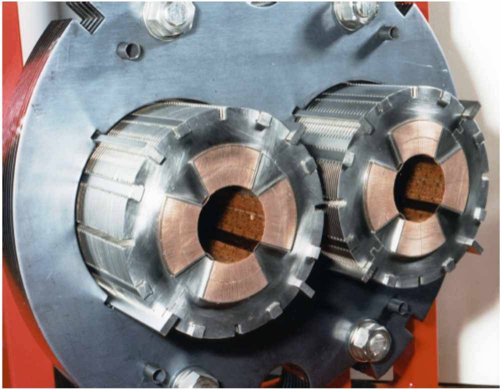


cos θ dipole



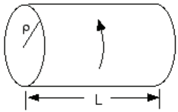
cos 2θ quadrupole

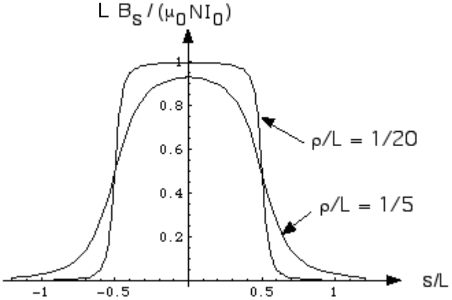


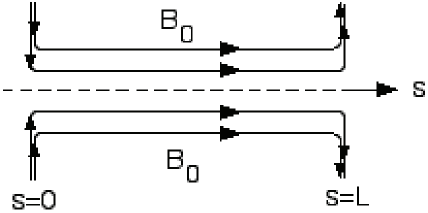


Another common magnet not of a multipole type is the solenoid. It is no longer a 2-D system.

Solenoid

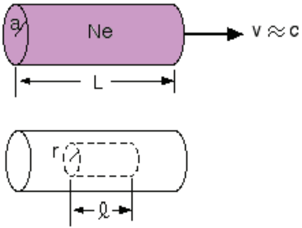






Beam Field & Space Charge

Consider a cylindrically shaped beam with uniform distribution moving in the z-direction as shown below:



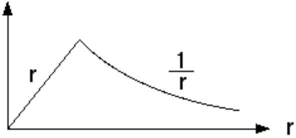
- Appling the Gauss's law,

$$E_r = \begin{cases} \frac{Ne}{2\pi\epsilon_0 a^2 L} r, & (r < a) \\ \frac{Ne}{2\pi\epsilon_0 L}\frac{1}{r}, & (r > a) \end{cases}$$

- Applying Ampere's law,

$$B_\theta = \begin{cases} \frac{\mu_0 v Ne}{2\pi a^2 L} r, & (r < a) \\ \frac{\mu_0 v Ne}{2\pi L}\frac{1}{r}, & (r > a) \end{cases}$$

$$B_\theta = \frac{v}{c^2} E_r$$



The Lorentz force experienced by a particle in the beam due to the space charge fields it sees,

$$\vec{F} = \frac{Ne^2}{2\pi\epsilon_0 a^2 L\gamma^2} r\hat{r}$$

This almost-perfect cancellation between the electric and the magnetic forces is very important for relativistic particles, without which most accelerators will not work.

Design of an accelerator

Having provided a design trajectory, and made sure that there are focusing in x,y, and z, there seems to be nothing left to do. But that is not true. We still have to examine the stability of the beam particles in much more detail.

Single-particle stability. This is one very important area of accelerator physics, i.e. single-particle nonlinear dynamics

Multi-particle stability. There is a second significant part of accelerator physics. It is called multi-particle collective beam instability effects, sometimes also called collective beam instabilities, coherent beam instabilities, beam instabilities, or simply instabilities.

Linear Betatron Motion

- Hill's Equation

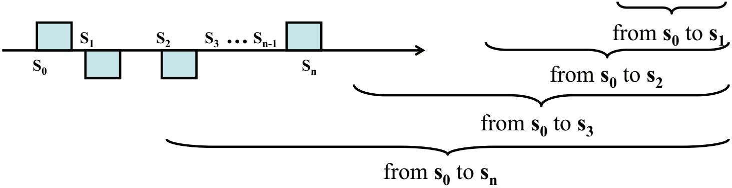
$$u'' + K_u(s)u = 0$$

- Matrix Form

$$\begin{pmatrix} u \\ u' \end{pmatrix} = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix} \begin{pmatrix} u_0 \\ u'_0 \end{pmatrix} \equiv M \begin{pmatrix} u_0 \\ u'_0 \end{pmatrix}$$

- a beamline with n elements

$$\mathcal{M}(s_n|s_0) = \mathcal{M}(s_n|s_{n-1}) \ldots \mathcal{M}(s_3|s_2) \cdot \mathcal{M}(s_2|s_1) \cdot \mathcal{M}(s_1|s0)$$



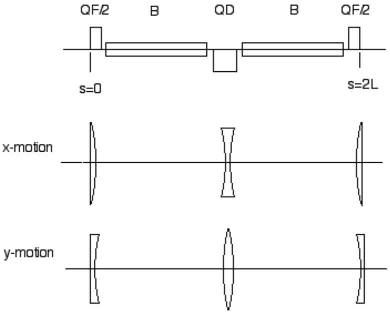
$\Longrightarrow$

$$\begin{pmatrix} u_n \\ u'_n \end{pmatrix} = M(s_n|s_0) \begin{pmatrix} u_0 \\ u'_0 \end{pmatrix}$$

On matrix formalism

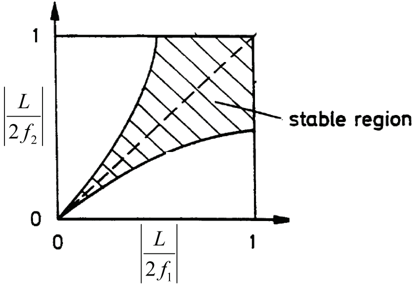
Mathematics	Accelerator physics
linear system	• vectors for phase space coordinate and transfer matrices • separability of beam properties (vector) and accelerator properties (transfer matrix)
matrix multiplication	beamlines
non-commutative	can't switch magents around
similarity transformation	observation of beam dynamics at different locations
eigenvalues	tunes (i.e. natural frequencies)
eigenvalues and trace are invariant under similiarity transformations	• tunes don't change with observation location • stability/instability of beam dynamics doesn't change with observation location
symplecticity	• Hamiltonian dynamics • conservation of phase space
normal form	• Courant-Snyder analysis • β function

FODO



$$M_x = \begin{pmatrix} 1 - 2\frac{L}{f^*} & 2L\left[1 - \frac{L}{2f_2}\right] \\ -\frac{2}{f^*}\left[1 - \frac{L}{2f_1}\right] & 1 - 2\frac{L}{f^*} \end{pmatrix}$$

where $\dfrac{1}{f^*} = \dfrac{1}{2f_1} + \dfrac{1}{2f_2} - \dfrac{L}{4f_1 f_2}$



Trying too hard to speed up only slows you down!

Twiss Functions (Courant-Snyder Parameters)

The solution of Hill's Equation

$$u'' + K(s)u = 0, \qquad K(s+L) = K(s)$$

can be represented in Courant-Snyder formalism

$$u(s) = \sqrt{2J\beta(s)}\cos(\psi(s) + \psi_0)$$

We define α function,

$$\alpha(s) = -\frac{1}{2}\beta'(s)$$

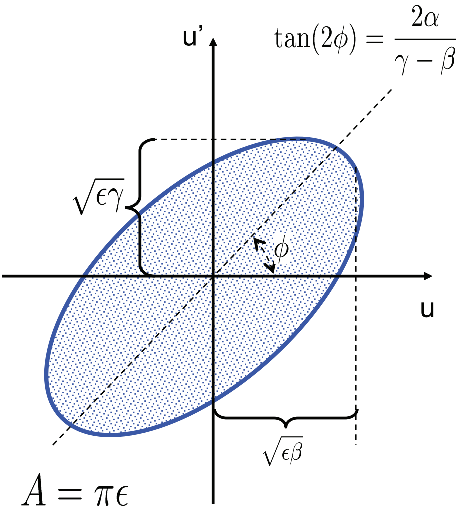
The unit of β is meter, and α is dimensionless.

Twiss parameters, emittance and beam sizes

- Twiss parameters and emittance determine the size and shape of the beam at some observation point

$$
\begin{aligned}
\langle x^2 \rangle &= \beta_x \langle J_x \rangle \\
\langle x x' \rangle &= -\alpha_x \langle J_x \rangle \\
\langle x'^2 \rangle &= \gamma_x \langle J_x \rangle
\end{aligned}
$$

$$\epsilon_x = \langle J_x \rangle$$



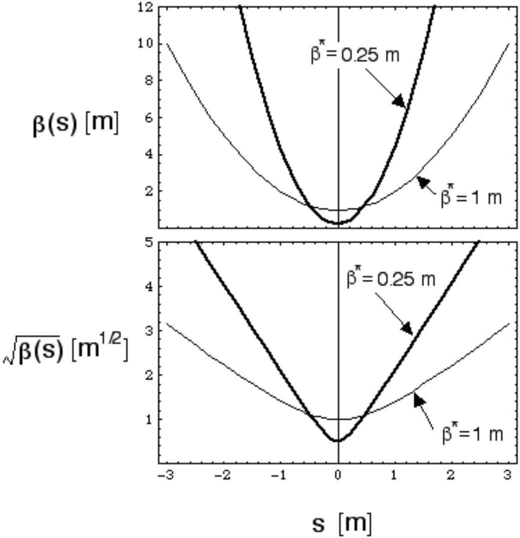
Betatron tune

The quantity Φ is related to another important quantity *betatron tune* per period,

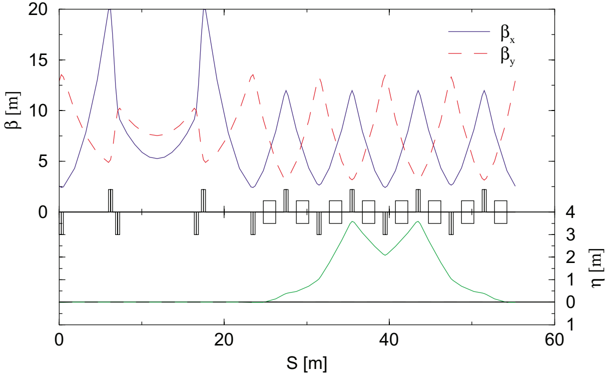
$$\boxed{\nu = \frac{\Phi}{2\pi} = \frac{1}{2\pi}\int_s^{s+L}\frac{dt}{\beta(t)} = \frac{1}{2\pi}\oint\frac{ds}{\beta(s)}}$$

β function in a drift space

$$\beta(s) = \beta(0) + \frac{s^2}{\beta(0)}$$



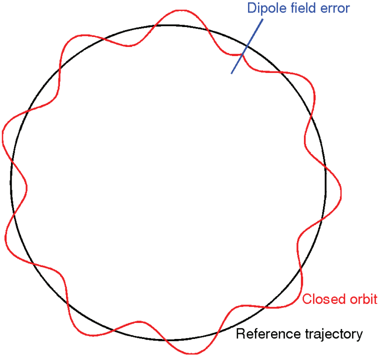
β functions in one period



- The β-functions are necessarily positive, and they are periodic with the lattice period, as evidenced by the fact that their values are equal at the two end-points.

Closed orbit distortion

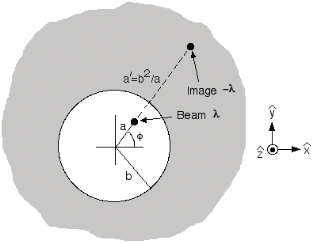
$$u(s) = \theta \frac{\sqrt{\beta_0 \beta(s)}}{2 \sin \pi\nu} \cos(\pi\nu - |\psi(s) - \psi(s_0)|)$$



A dipole field error causes a distortion of the closed orbit. There is a “kink” in the closed orbit at the location of the dipole field error.

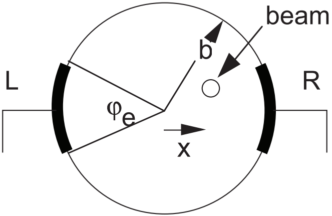
Image Current & Beam Position Monitor

Consider a beam moving inside a perfectly conducting metal pipe in the z-direction. The pipe has a circular transverse cross-section with radius b. Let the beam be represented as an infinitely long moving line charge with linear density λ. The beam is displaced transversely by $\vec{a} = (a\cos\phi, a\sin\phi)$ relative to the axis of the pipe.



We can calculate the surface charge Σ on the conducting pipe wall,

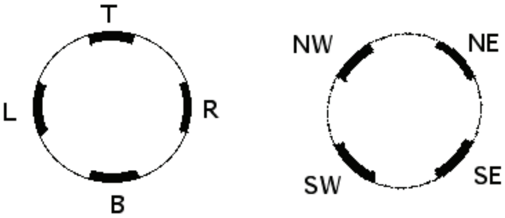
$$\Sigma(\theta) = -\frac{\lambda}{2\pi b}\frac{b^2 - a^2}{a^2 + b^2 - 2ab\cos(\phi - \theta)}$$

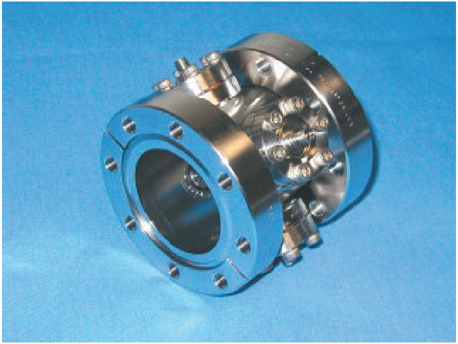


The signal seen by the stripline is obtained by integrating the wall current it carries. One then combines the signals L and R to extract the horizontal beam position,

$$\frac{R - L}{R + L} = \frac{2x}{b}\frac{\sin(\psi_e/2)}{(\psi_e/2)}$$

Image Current & Beam Position Monitor (Cont.)





Dispersion Function

A closed orbit solution of x for the off-momentum particle can be written as

$$x(s) = D(s)\delta$$

where $D(s)$ is called the dispersion function. In other words, we have defined

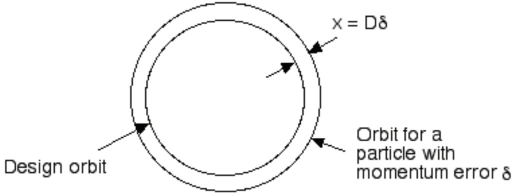
$$\begin{pmatrix}\text{dispersion} \\ \text{function}\end{pmatrix} = \frac{\begin{pmatrix}\text{closed orbit distortion for} \\ \text{a particle with momentum error } \delta\end{pmatrix}}{\delta}$$

The general solution for x of an off-momentum particle is given by

$$x(s) = x_\beta(s) + D(s)\delta$$

Dispersion Function (Cont.)

- Dispersion in a uniform magnetic field



In uniform magnetic field, D = R

- Dispersion in FODO cells

$$\langle D \rangle \approx \frac{R}{\nu_x^2}$$

Example

A storage ring with $R = 100$ m and $\nu_x \approx 10$, we will have $\beta_x \approx 10$ m and $D \approx 1$m. A particle with momentum error of $\delta = 1\%$ has a dispersive orbit of $D\delta = 1$ cm.
To appreciate the strong suppression effect on dispersion, one should consider a particle moving in a uniform magnetic field. Recalling that the dispersion function $D = R$ in that case, a particle with 1% momentum error will have an orbit as large as 1 m.

Chromaticity

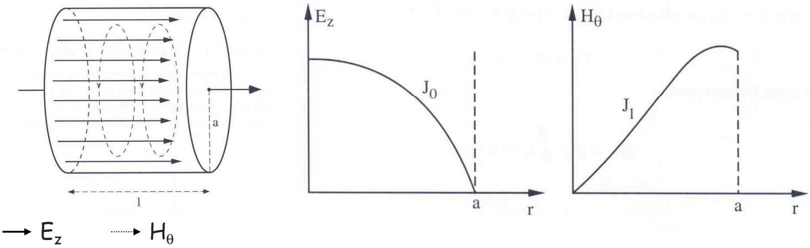
For an off-momentum particle, its momentum deviation δ induces **dipole perturbations** that gives rise to a closed orbit distortion, which we have now discussed in terms of a **dispersion function**. We have been calling such beam dynamical effects caused by momentum deviation *chromatic effects*. Now we discuss another important chromatic effect related to δ-dependent quadrupole perturbations. Basically what happens is the following. Higher momentum particles ($\delta > 0$) have higher rigidity, and therefore experience weaker effect due to magnetic fields. Dispersion comes from the weakened dipoles. The weakened quadrupoles will introduce chromaticities, i.e. the betatron tunes will depend on δ,

$$\nu_{x,y}(\delta) = \nu_{x,y}(0) + \xi_{x,y}\delta$$

where the parameters $\xi_{x,y}$ are the chromaticities.

Pill box cavity

A simplified model of the RF cavity is a pill box cavity with length L and radius R.



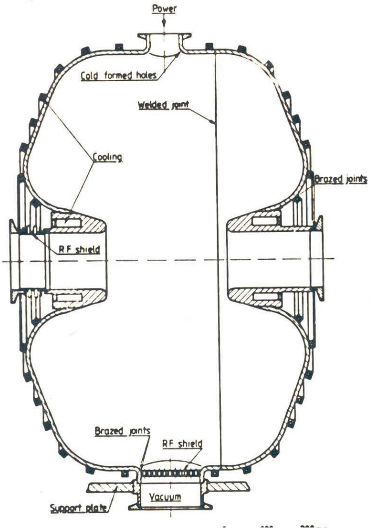
$$E_z(r) = E_0 J_0(\frac{\omega}{c} r) \cos \omega t$$

$$B_\theta(r) = -\frac{E_0}{c} J_1(\frac{\omega}{c} r) \sin \omega t$$

The mode frequency,

$$\omega = 2.405 \frac{c}{R} \qquad [example : R = 30cm, f = 400MHz]$$

A more realistic pill-box cavity



The design of a pill-box cavity can be sophisticated in order to improve its performances:

-A nose cone can be introduced in order to concentrate the electric field around the axis,

-Round shaping of the corners allows a better distribution of the magnetic field on the surface and a reduction of the Joule losses. It also prevent from multipactoring effects.

A good cavity is a cavity which efficiently transforms the RF power into accelerating voltage.

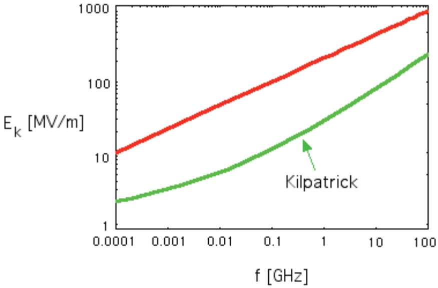
Break Down

The peak field in a cavity in vacuum is limited by breakdown. One often uses the *Kilpatrick limit* (1953) to determine where the breakdown might occur. It is an empirical relation derived from data taken before the era of ultra-highvacuum technology. The maximum field E_k [MV/m] at any frequency f [GHz] according to this criterion is determined by the following equation:

$$f = 0.00164 E_k^2 \exp(-8.5/E_k)$$

The breakdown limit increases as the RF frequency is increased. This is one reason why linear colliders tend to push for technologies of higher frequency RF systems.
Today, with ultra-high-vacuum technology, much higher fields are often achieved. Indeed a more recent fit (although more studies are being carried out in this active research area) gives

$$E_k[\text{MV/m}] = 220(f[\text{GHz}])^{1/3}$$



Principle of phase stability

We assume the longitudinal voltage across an RF cavity is

$$V = V_0 \sin(\omega_{\mathsf{rf}} t + \phi_s)$$

where ϕ_s is the RF phase angle relative to the synchronous particle. The RF frequency ω_{rf} is an integral multiple of the revolution frequency ω_0, i.e.

$$\omega_{\mathsf{rf}} = h\omega_0$$

where h is the harmonic number. Note that we have ignored the r-depedentce of V here because we consider on-axis field with r = 0.
As mentioned, h has to be exactly an integer. Otherwise we will lose the synchronism and lose the ability to accelerate the beam. One might ask how exactly does this condition have to be fulfilled? What if, for example, $\frac{\omega_{\mathsf{rf}}}{\omega_0} = 200.000001$? If this were the case, then after $\frac{1}{2} \times 10^6$ turns, the RF voltage will get out of phase with the beam's arrival time, and we will be decelerating the beam! Since a beam is to be stored much longer than $\frac{1}{2} \times 10^6$ turns, any tiny mismatch of frequencies must not be allowed.

Principle of phase stability (2)

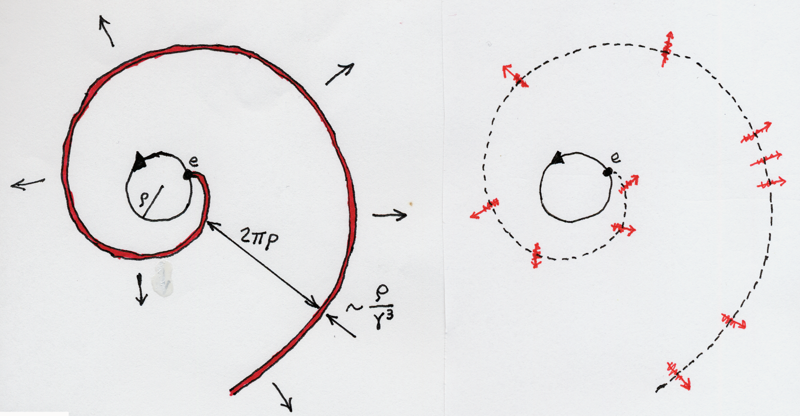
This difficulty was resolved by the important **phase stability principle** of McMillan and Veksler in 1945. What happens is that under some condition of stability, the beam will settle this problem by itself! In particular, the phase stability principle states the following two statements:

1. You first choose your ω_{rf} . Once ω_{rf} is chosen, the beam —at least its synchronous particle —will adjust its revolution frequency ω_0 in such a way that it becomes exactly equal to $\omega_{\text{rf}}/200$ even though its initial ω_0 is slightly off.
2. A particle with slight deviations in z, δ from the synchronous particle will oscillate around the synchronous particle, and these deviations will not grow indefinitely with time.

The phase stability is an extremely important principle in accelerator physics. Together with the strong focusing principle, they provide the two foundations for all modern accelerators, phase stability addressing the longitudinal dynamics while strong focusing addressing the transverse dynamics of the particle motion.

A snapshot of the synchrotron radiation

In the classical picture, synchrotron radiation is described as a continuous emission of electromagnetic waves. In quantum mechanics, however, we understand that the radiation consists really of a large number of discrete photons, each carrying an energy of $u = \hbar\omega$.



Equilibrium Beam Parameters

$$\text{equilibrium beam emittance} = \frac{\text{quantum excitation}}{\text{radiation damping}}$$

- energy spread σ_δ

$$\sigma_\delta^2 = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} \frac{\gamma^2}{(2+\mathcal{D})\rho}$$

- bunch length σ_z

$$\sigma_z = \frac{c|\eta|}{\omega_s} \sigma_\delta$$

- horizontal emittance

$$\epsilon_x = \frac{\sigma_{x\beta}^2}{\beta_x} \approx \frac{2R}{\nu_x^3} \sigma_\delta^2$$

- horizontal beam size

$$\sigma_{x\beta} \approx \sqrt{2} \frac{R}{\nu_x^2} \sigma_\delta$$

Example

With $R = 30$ m and $E_s = 5$ GeV, we had $\sigma_\delta = 0.8 \times 10^{-3}$. If $\nu_x \approx 5$, then $\sigma_{x\beta} \approx 1.3$ mm

Outline

Luminosity: Definition

The luminosity is the number of events produced by the collisions, per second, for events with a cross section of one square centimeter.

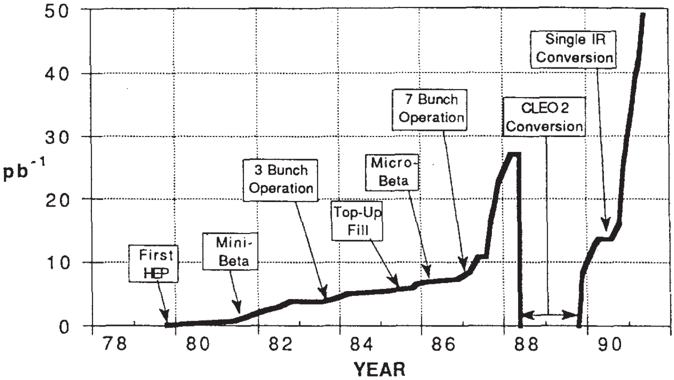
Since a typical cross section unit is one nanobarn (1 nb – $10^{-33} cm^2$), a luminosity $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$ only produces one such event per second, in which case the luminosity is said to be one inverse nanobarn per second.

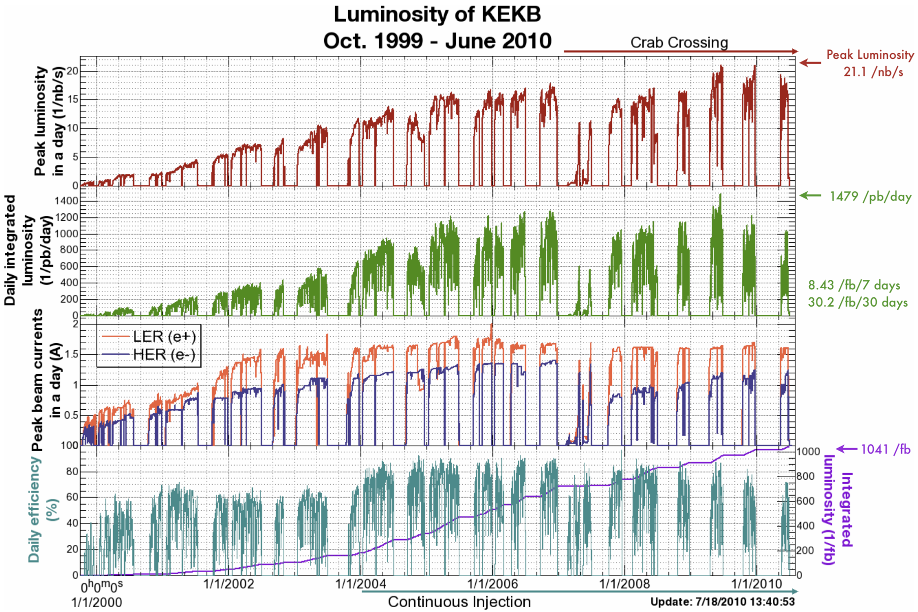
The figure that one quotes as luminosity is in general the peak luminosity of the machine, expressed in $cm^{-2} s^{-1}$ which mostly interests machine designers.

Integrated Luminosity

Luminosity integrated over a week , or at least several runs is what physicists are interested in; it is often measured in inverse picobarn. Note

that one inverse picobarn is one thousand times larger than one inverse nanobarn. In MKS unit: 1 pb$^-1 = 10^{40}$ m$^-2$.





Luminosity of KEKB
Oct. 1999 - June 2010
Crab Crossing
Peak Luminosity
21.1 /nb/s
1479 /pb/day
8.43 /fb/7 days
30.2 /fb/30 days
1041 /fb
Peak luminosity in a day (1/nb/s)
Daily integrated luminosity (1/pb/day)
Peak beam currents in a day (A)
LER (e+)
HER (e-)
Daily efficiency (%)
Integrated luminosity (1/fb)
0h0m0s 1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
1/1/2010
Continuous Injection
Update: 7/18/2010 13:40:53

Table 1. Electron-positron circular colliders in the world. S/D = single/double ring.

Collider	Location	Scheme	Beam Energy (GeV)	Luminosity ($10^{30}cm^{-2}s^{-1}$)	Year
AdA	Frascati	S	0.25	$\sim 10^{-5}$	1962
ACO	Orsay	S	0.5	0.1	1966
Adone	Frascati	S	1.5	0.6	1969–1993
SPEAR	SLAC	S	4	12	1972–1990
VEPP-2/2M	BINP	S	0.7	13	1974–
DORIS	DESY	D	5.6	33	1974–1993
DCI	Orsay	D	1.8	2	1976–2003
PETRA	DESY	S	19	30	1978–1986
VEPP-4M	BINP	S	7	50	1979–
CESR	Cornell	S	6	1,300	1979–2002
PEP	SLAC	S	15	60	1980–1990
TRISTAN	KEK	S	32	37	1986–1994
BEPC	IHEP	S	2.2	13	1989–2005
LEP	CERN	S	46	24	1989–1994
DAΦNE	Frascati	D	0.7	150	1997–
LEP2	CERN	S	105	100	1995–2000
PEP-II	SLAC	D	3.1 / 9	12,000	1999–2008
KEKB	KEK	D	3.5 / 8	21,100	1999–2010
CESR-c	Cornell	S	1.9	60	2002–2008
VEPP-2000	BINP	S	0.5	120	2006–
BEPCII	IHEP	D	2.1	710	2007–

Beam-Beam Parameter

- the achieved beam-beam parameter ξ with collision is defined as

$$\xi_u = \frac{N r_e}{2\pi\gamma} \frac{\beta_u^0}{\sigma_u(\sigma_x + \sigma_y)}$$

  where β^0 is nominal beta function without collision, and σ is disturbed beam size with collision.

- Do not consider the finite bunch length and finite crossing angle, the bunch luminosity can be represented as

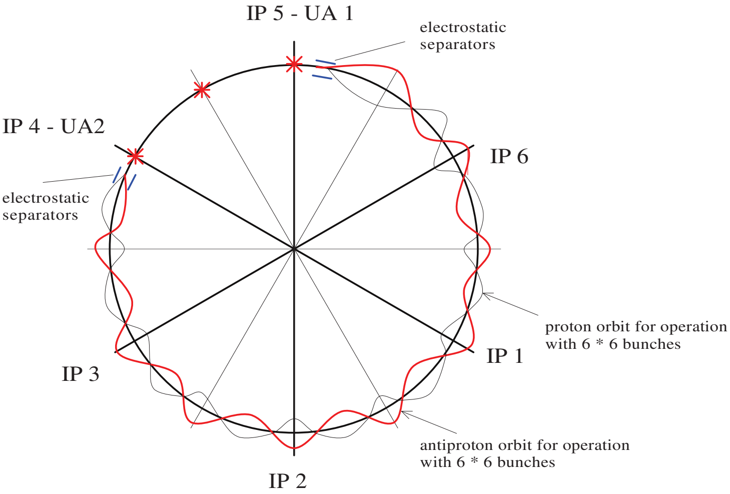
$$L = \frac{N^2 f_0}{4\pi\sigma_x\sigma_y}$$

  where σ is disturbed beam size with collision.

- when beam $\sigma_y \ll \sigma_x$, the achived ξ_y can be represented by lum,

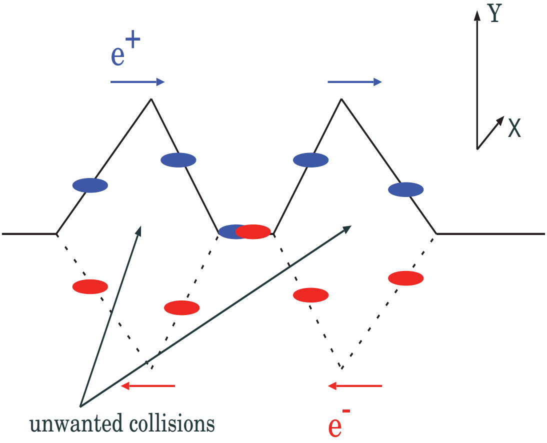
$$\xi_y = \frac{2 r_e \beta_y^0}{N\gamma} \frac{L}{f_0}$$

Beam separation with a Pretzel scheme



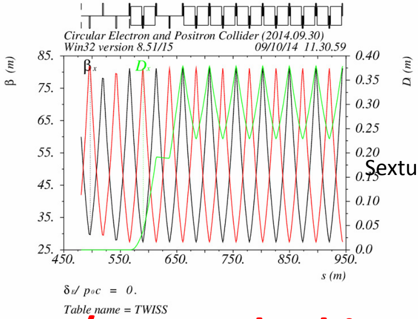
Short bunch trains in LEP

To avoid a separation around the whole machine, the bunches can be arranged in so-called trains of bunches following each other closely. In that case a separation with electrostatic separators is only needed around the interaction regions. Such a scheme was used in LEP in the second phase.



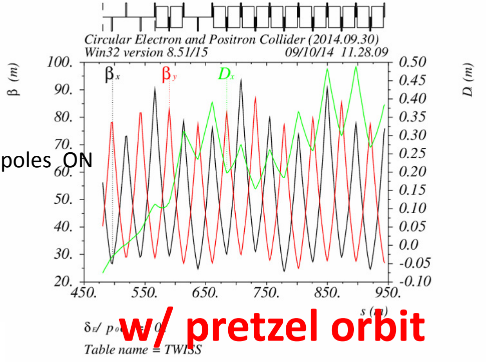
Issues with pretzel orbit

- Pretzel orbit has effects on:
  - Beta functions, thus tune
  - Dispersion function, thus emittance
  - Dynamic aperture



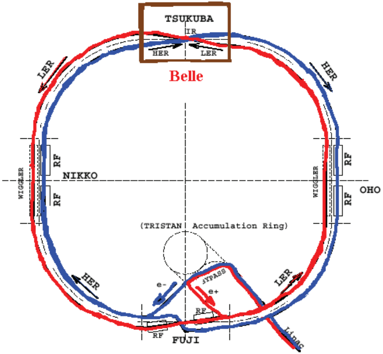
w/o pretzel orbit

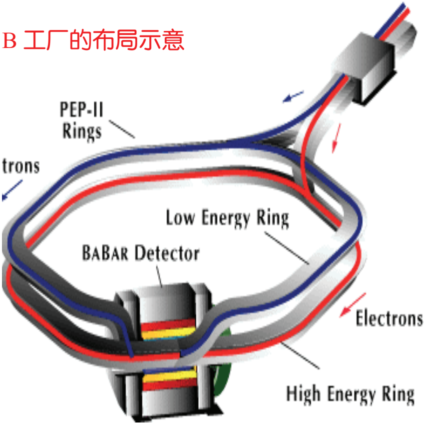
Sextupoles ON

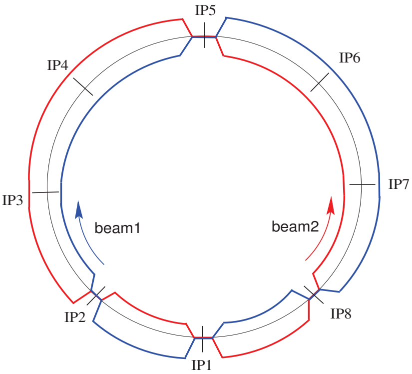


w/ pretzel orbit

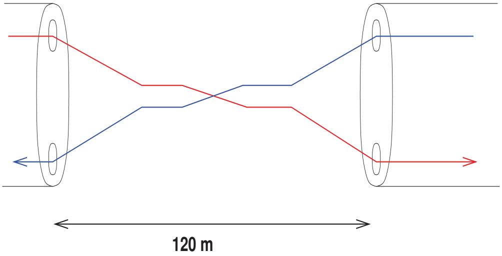
KEKB 和 PEPII 两个 B 工厂的布局示意图







Schematic layout of the LHC collision points and beams



Cross over between inner and outer vacuum chamber in the LHC (schematic)

Interaction Region

To achieve high luminosity low beta values are required at the interaction point.

The assembly of elements used to achieve this, starting from the regular lattice, is called the interaction region. It usually includes, starting from the interaction point: a quadrupole doublet, a matching section, a dispersion suppressor, and a set of skew quadrupoles in order to compensate the effect of the detector solenoid.

In the case of double rings a set of beam separators is required. When the separation is made in the vertical plane a vertical dispersion matching is required. In the case of the B-factory this must be done separately for two different energies, and with elements common to the two beams close to the interaction point. The solutions proposed should be transparent enough that the experimenter can understand, measure, and correct possible imperfections.

How to Achieve High Luminosity - Ordinary

For flat lattices with $\sigma_y^*/\sigma_x^* \ll 1$ and $\epsilon_y/\epsilon_x \ll 1$, the luminosity

$$\mathcal{L} = f_0 \frac{\pi\gamma^2}{r_e^2} \frac{\epsilon_{x0}}{\beta_y^*} \xi_x \xi_y S$$

where,

- f_0, the revolution frequency; r_e, the classical electron raidus; γ, the relativistic factor
- ϵ_{x0}, the natural emittance; β_y^*, the vertical beta function at IP
- ξ_x/ξ_y, the beam-beam parameter
- S, the luminosity geometrical suppression factor

Since ξ_x/ξ_y are generally limited to values < 0.05, high luminosity requires:

- short bunches
- small β_y^*, the so-called "mini-beta insertion"
- large horizontal emittance

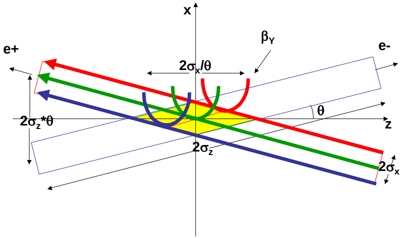
A new collision scheme?

Summary from Oide's talk at 2005 2nd Hawaii SuperBF Workshop

- Present design of SuperKEKB hits fundamental limits in the beam-beam effect and the bunch length (HOM & CSR).
- Higher current is the only way to increase the luminosity.
- Many technical and cost issues are expected with a new RF system.
- **We need a completely different collider scheme.....**

Crab Waist in 3 Steps

1. Large Piwinski's angle $\Phi = tg(\theta)\sigma_z/\sigma_x$
2. Vertical beta comparable with overlap area $\beta_y \approx \sigma_x/\theta$
3. Crab waist transformation $y = xy'/(2\theta)$

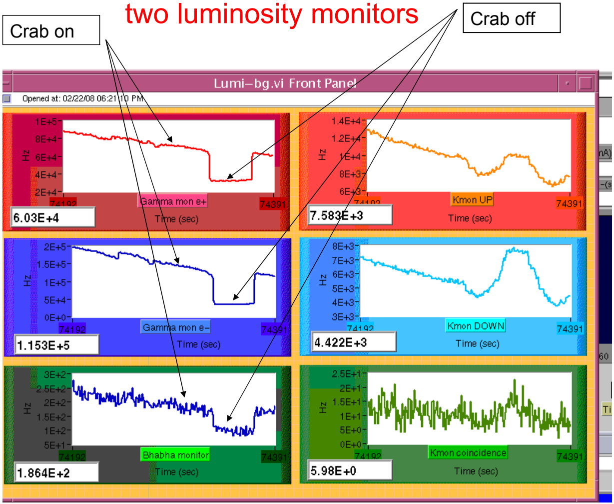


Crabbed waist is realized with a sextupole in phase with the IP in X and at $\pi/2$ in Y

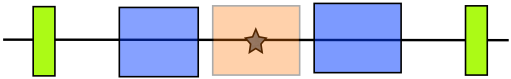
1. *P.Raimondi, 2° SuperB Workshop, March 2006*

2. *P.Raimondi, D.Shatilov, M.Zobov, physics/0702033*

Success of Crab-Waist Scheme



Crab waist and IR nonlinearity



$$\mathcal{M}_{IR} = e^{-axy^2} e^{-H_{Q's}} e^{-H_{Sol}} e^{-H_{BB}} e^{-H_{Sol}} e^{-H_{Q's}} e^{-axy^2}$$

$$\neq$$

$$e^{-H_{Q's}} e^{-H_{Sol}} e^{-xp_y^2/2\phi} e^{-H_{BB}} e^{-xp_y^2/2\phi} e^{-H_{Sol}} e^{-H_{Q's}}$$

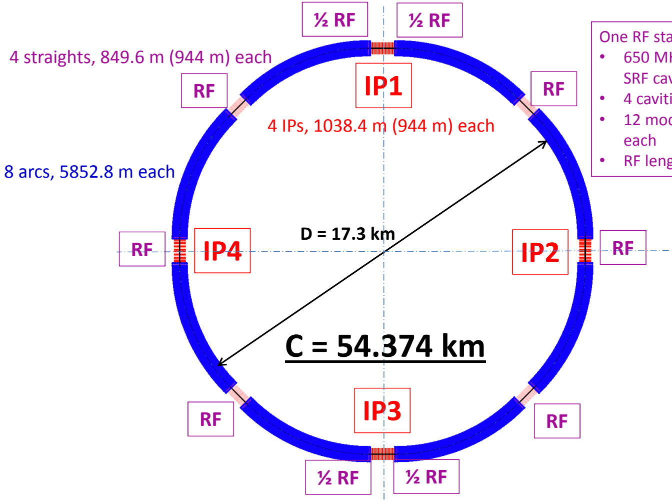
- Strong dynamic aperture degradation is seen by crab sextupole installation (H. Koiso).
- We do not know how to handle the nonlinear terms of Q's and Solenoid located at very high β.
- Crab waist is an option in (the) future for Super KEKB.

Parameters of SuperKEKB, CEPC, LHC and FCC

	SuperKEKB		CEPC	FCC-ee	LHC	FCC-hh
circumference (L[m])	3016		54,000	100,000	26658	100000
energy (E[GeV])	4(e+)	7(e-)	120	120	7,000	50,000
emittance (ε_x [nm])	3.2	4.6	1	0.9	0.5	0.041
emittance (ε_y [nm])	0.0086	0.012	0.001	0.5		
β_x^*[m]	0.032	0.025	0.8	1.2	0.55	0.55
β_y^*[m]	0.00027	0.0003	0.003	0.0012	0.55	0.55
rms bunch length [m]	0.006	0.005	0.001	0.001	0.0755	0.0755
bunch population N_p (10^{10})	9.0	6.5	3.9	6	11.5	10
number of bunches	2500	2500	48	1046	2808	13338
bunch spacing [ns]	4	4	3750	320	50	25
crossing angle/2 [mrad]	41.5		0	0-10	0.15	-
luminosity (10^{34} cm^{-2}s^{-1})	80		2	10	1	10


S363
S251
S266
S048
山海关区
G1
秦皇岛市
高能所
G102
抚宁县
S267
G205
2013 DigitalGlobe
2013 Mapabc.com
2013 TerraMetrics
Google earth

CEPC Lattice Layout (September 24, 2014)

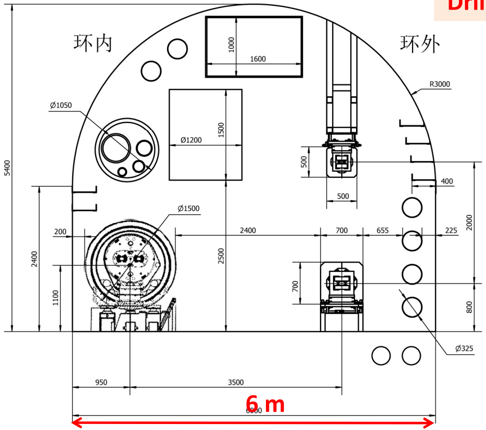


One RF station:

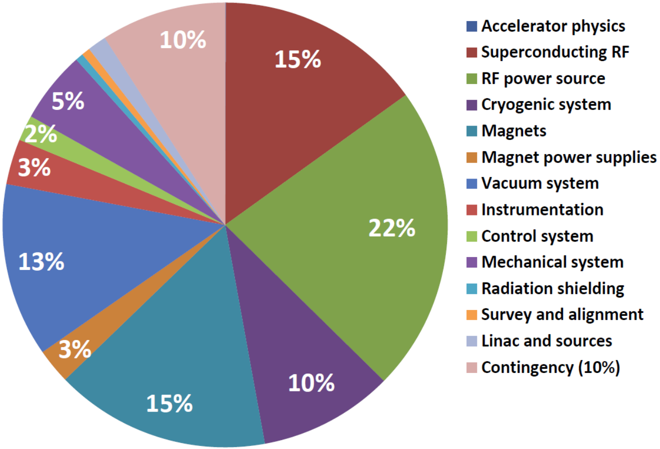
- 650 MHz five-cell SRF cavities;
- 4 cavities/module
- 12 modules, 10 m each
- RF length 120 m

Tunnel Cross Section – SPPC + CEPC Magnets

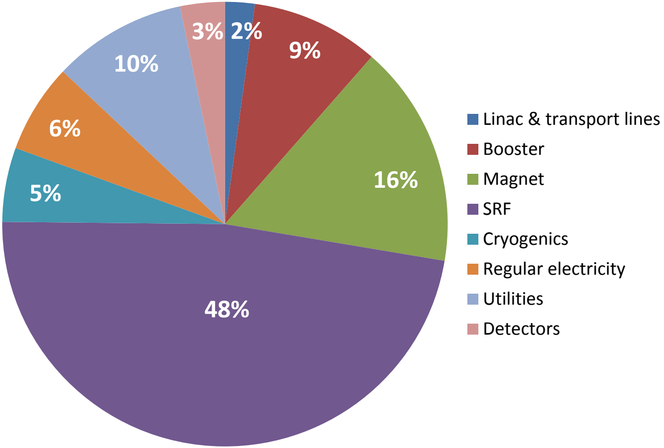
Drill/Blast Method



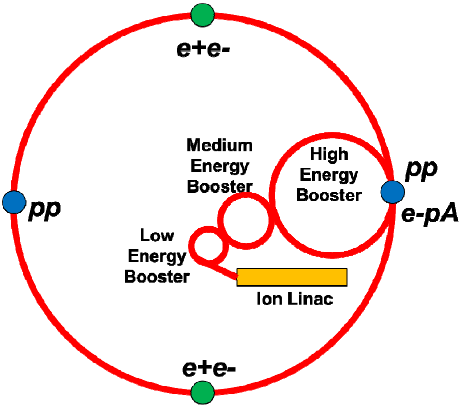
CEPC Relative Cost Estimate



Relative Power Consumption



Upgrade to SPPC



Main Technical Challenges for SPPC

- Accelerator technology
  - SC magnet (increasing performance and decreasing costs)
  - Synchrotron radiation and beam screen (reducing power consumption)
  - Collimation (machine protection)
- Accelerator physics
  - IR design, low β_y^* , dynamic aperture
  - Synchrotron radiation, heat load and radiation damage lifetime
  - Beam-beam
  - e-cloud
  - Impedance and instabilities
  - Ground motion
  - MDI and background
  - Machine reliability
  - Cooling
- Non-technical:
  - Government strategic plan for S/T investment
  - Support from both HEP and non-HEP scientists

CEPC-SPPC

Preliminary Conceptual Design Report

March 2015

300 authors
from 57 institutions
in 9 countries

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Fuqing Chen[1] (陈福庆), Geng Chen[4] (陈耿), Jiaxin Chen[1] (陈佳鑫),

- **Pre-CDR is easy**
- **CDR is hard. Because we leave all hard things to CDR!**
- **A long worklist (total 37) by Weiren Chou**

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- . . .