Accelerators for Collider Experiments

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Goals and outline

Accelerator science is an exciting area of human knowledge, the high-energy colliders are arguably the most advanced science instruments. My goals are to i) introduce you to the basics of collider-accelerator science and technology; ii) provide some historical insight and highlight future challenges; iii) perhaps convince you that this is a direction worth pursuing in your career.

The lectures are structured along the following plan:

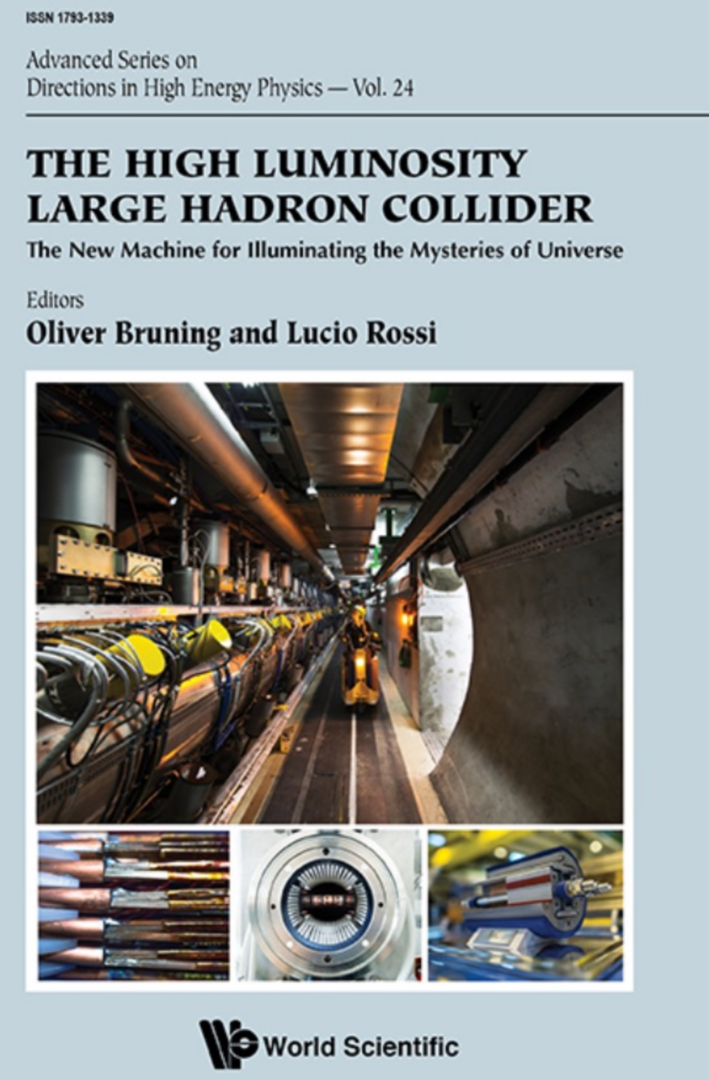
1. Introduction and history
2. Theory and fundamental concepts
3. Key technologies
4. Collider operations
5. Proposals for the future and challenges

Credits

- I am indebted to my Fermilab and CERN colleagues with whom I had a privilege to work on the Tevatron Collider Run-II and LHC programs
- I re-use much of notes and material from V.Shiltsev's previous years' HCPSS lectures

Suggested reading

- Accelerator Physics, S.Y. Lee (World Scientific, 1999)
- CAS - CERN Accelerator School http://cas.web.cern.ch/
- USPAS – US Particle Accelerator School http://uspas.fnal.gov
- Accelerator Physics at the Tevatron Collider (ed. V.Lebedev and V.Shiltsev, Springer, 2014)
- The High Luminosity Large Hadron Collider (ed. O.Brüning and L.Rossi, World Scientific, 2015)



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Directions in High Energy Physics — Vol. 24

THE HIGH LUMINOSITY
LARGE HADRON COLLIDER

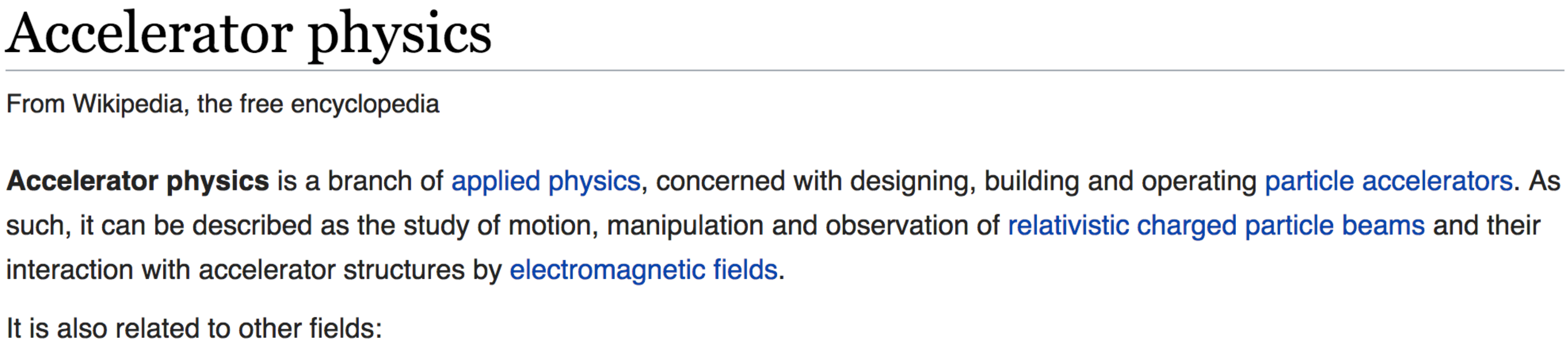
The New Machine for Illuminating the Mysteries of Universe

Editors
Oliver Bruning and Lucio Rossi

World Scientific

1. Introduction and history

Why accelerator science?



Accelerator physics

From Wikipedia, the free encyclopedia

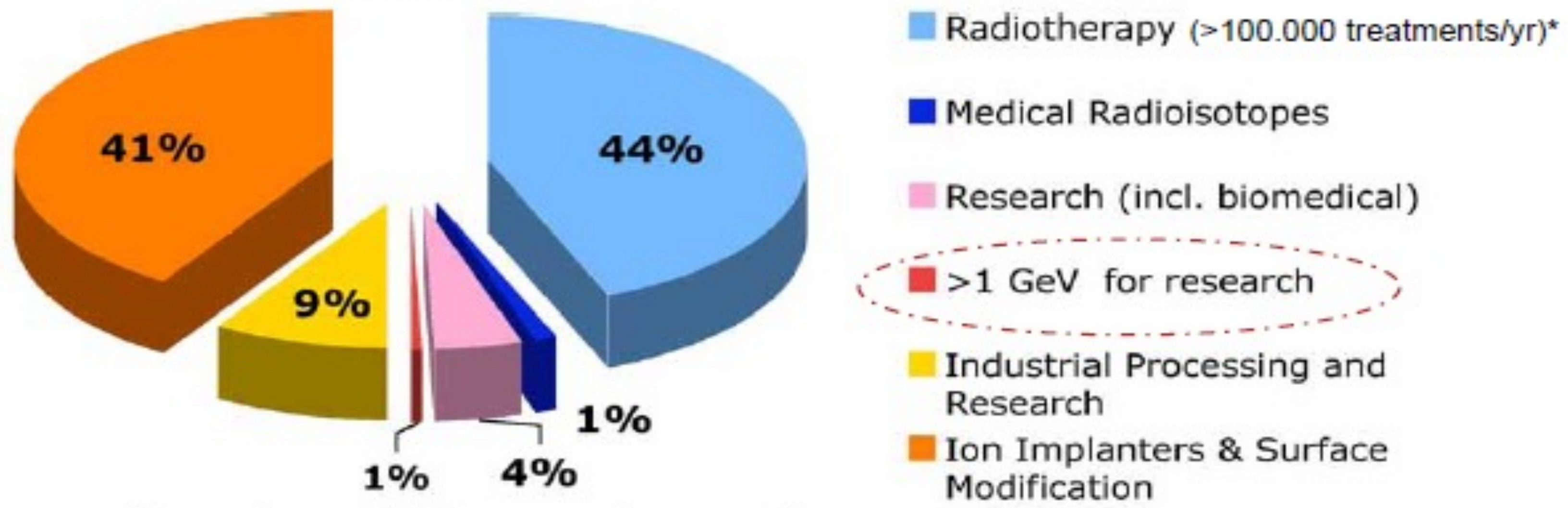
Accelerator physics is a branch of applied physics, concerned with designing, building and operating particle accelerators. As such, it can be described as the study of motion, manipulation and observation of relativistic charged particle beams and their interaction with accelerator structures by electromagnetic fields.

It is also related to other fields:

- Microwave engineering
- Optics
- Mechanics and mathematical physics
- Computer technology
- Plasma physics
- Material science
- …

The field of accelerators is vast, research machines ~1%

Number of accelerators worldwide ~ 26,000



Annual growth is several percent

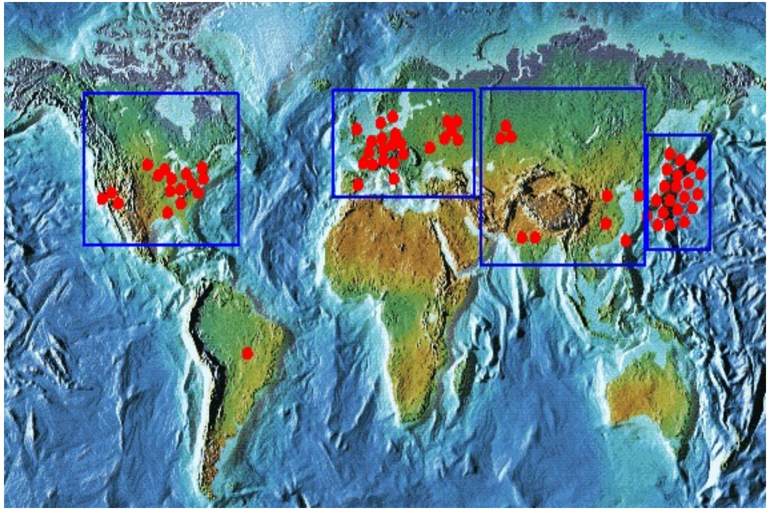
Sales >3.5 B$/yr

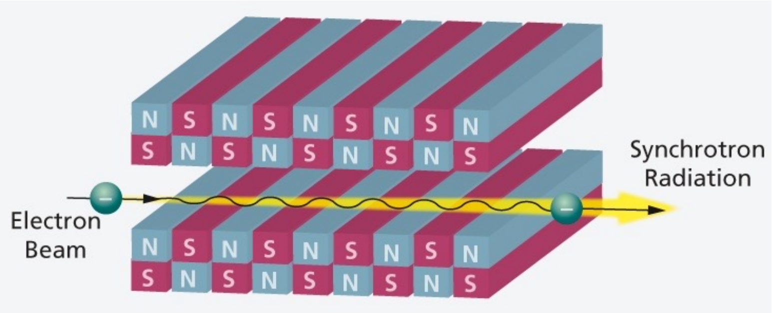
Value of treated good > 50 B$/yr **

Industrial accelerators

- Radioisotope production
- Medical treatment
- Electron welding
- Food sterilization
- Catalyzed polymerization
- Waste treatment
- …

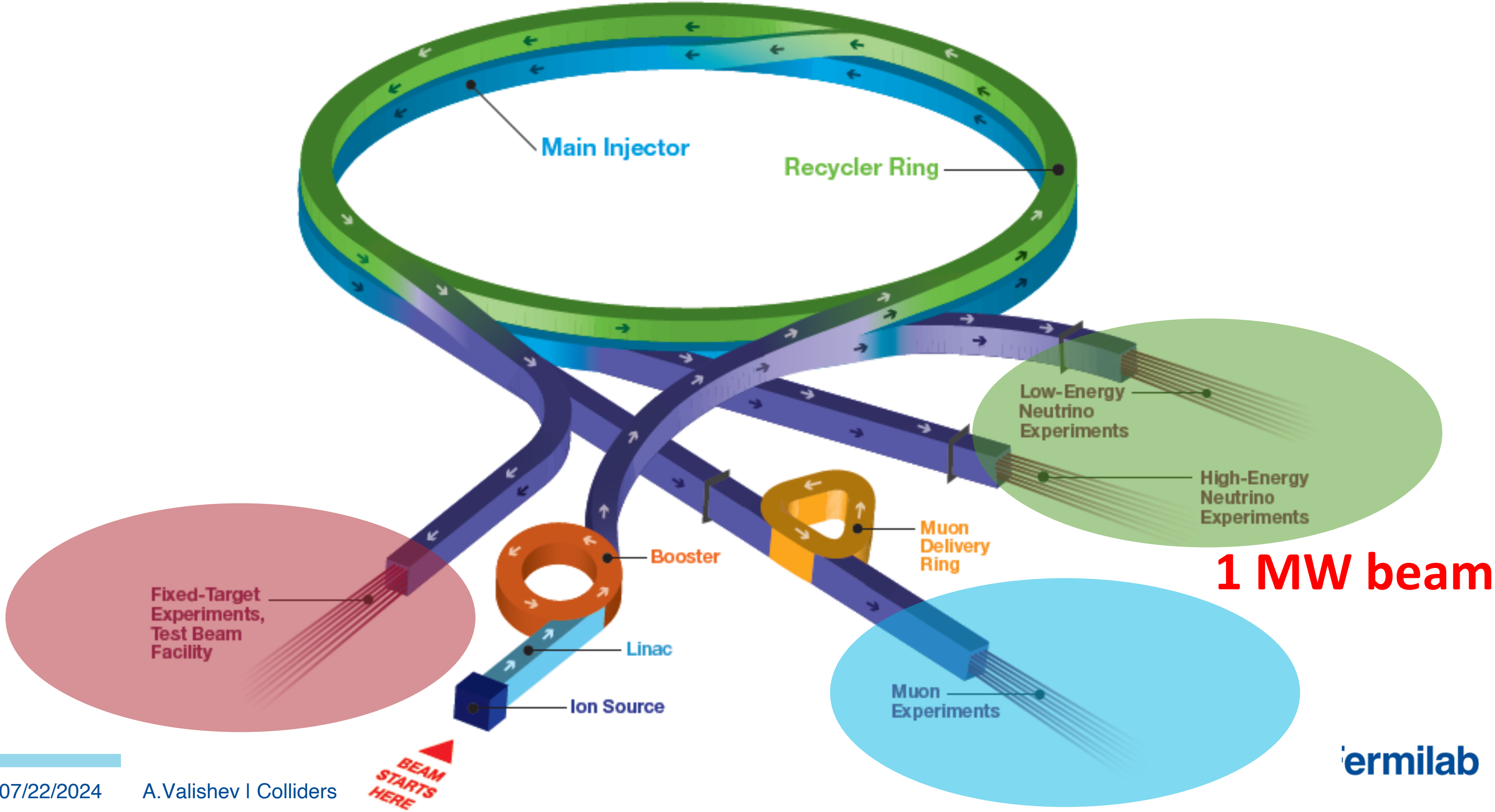
Light sources





- Electron beam passes through alternating-sign magnetic field, an “undulator” to create synchrotron radiation (typically X-ray)
- Many applications in biophysics, material science, industry
- Machines continuously improve beam brightness and light coherence

Accelerators for basic research - Fermilab Accelerator Complex



1 MW beam

Collider concept

- The (only) reason is *energy*

$2E$

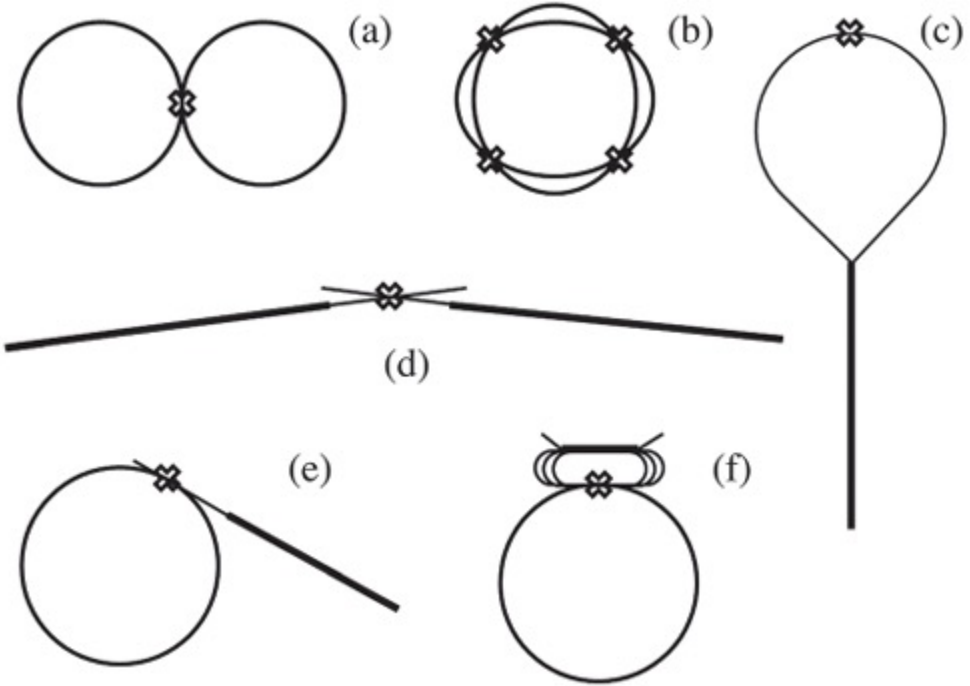
$\sqrt{2mc^2E}$

- To get to the 14 TeV CM energy of the LHC with a single beam on a stationary proton would require that beam to have an energy of 100,000 TeV!
- The idea was first given serious consideration by the Norwegian engineer and inventor Rolf Wideröe, who in 1943 filed a patent for the collider concept (and received the patent in 1953)
- "…It is estimated that [since then] accelerator science has influenced almost 1/3 of physicists and physics studies and on average contributed to physics Nobel Prize-winning research every 2.9 years." Haussecker and Chao, Physics in Perspective 13, 146 (2011)

Collider types

I. Particle species:
  - electron-electron, electron-positron
  - proton-proton, proton-antiproton
  - electron-proton, electron-ion, ion-ion

II. Geometry:
  - Circular (30 built)
  - Linear (1 built)
  - Combination



Rate of collisions, statistics and Luminosity

- Luminosity (L) is a machine property that describes the relationship between the rate of events (R) and number of events (N) for a process with given cross-section (σ)

$$R = L\times\sigma \qquad N = \sigma\times\int L\,dt$$

- Customary unit for Luminosity is cm^{-2}s^{-1}
- Standard unit of cross section is “barn”=10^{-24} cm^{2}
- Integrated luminosity is usually in barn^{-1}
  - nb^{-1} = 10^{9} b^{-1}, fb^{-1}=10^{15} b^{-1}, etc.)

$$b^{-1} = (1s)\times(10^{24}cm^{-2}s^{-1})$$

- Record instantaneous luminosities:

– Electron-positron: SuperKEKB	471 × 10^{32} cm^{-2}s^{-1}
– Proton-antiproton: Tevatron	4.3 × 10^{32} cm^{-2}s^{-1}
– Proton-proton: LHC	222 × 10^{32} cm^{-2}s^{-1}
– Proton-electron: HERA	0.75 × 10^{32} cm^{-2}s^{-1}

First colliders

Lighter particles, electrons and/or positrons are easier to handle and collide

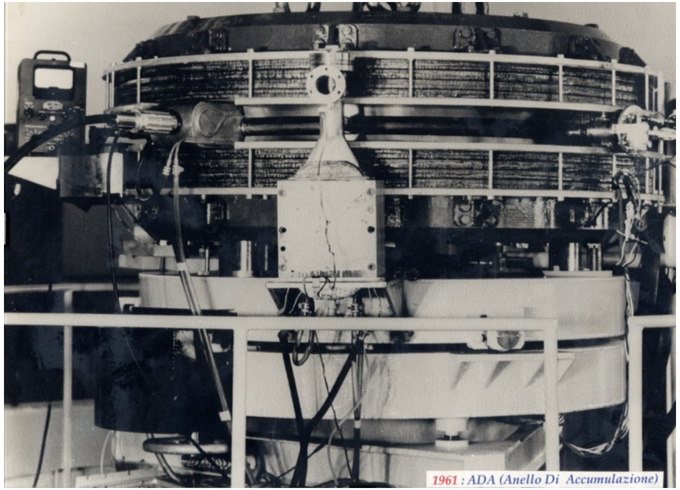
VEP-1 (Встречные Электронные Пучки)

at BINP, Novosibirsk, USSR

130MeV e-/e-
1963 construction complete
May 19, 1964 luminosity

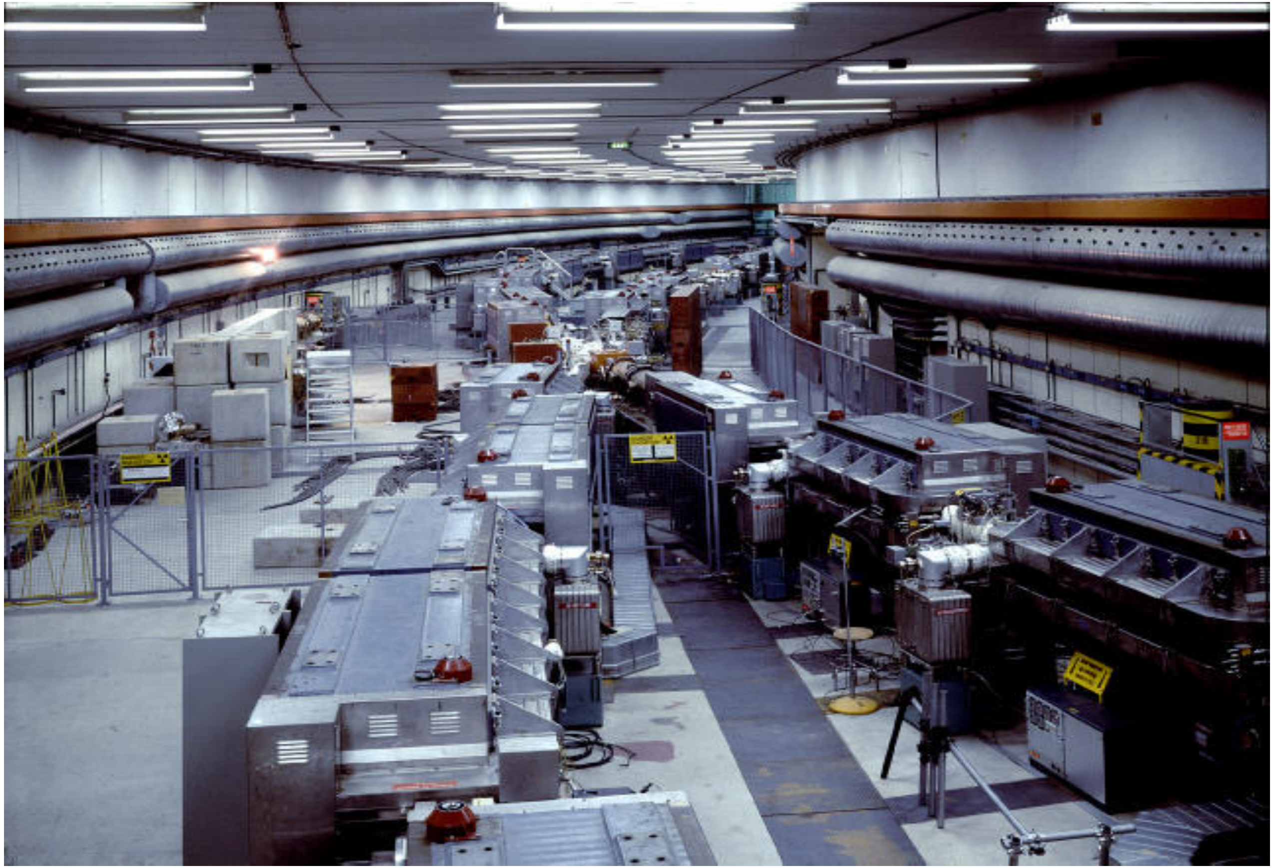
ADA (Anello Di Accumulazione)

at INFN, Frascati, Italy



250 MeV e+/e-
1961 construction complete
May-June, 1964 luminosity

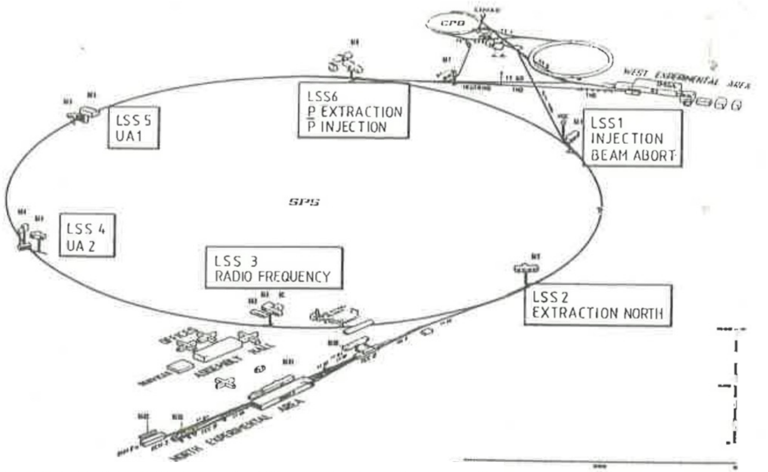
First proton collider – CERN Intersecting Storage Rings (ISR) - 1971

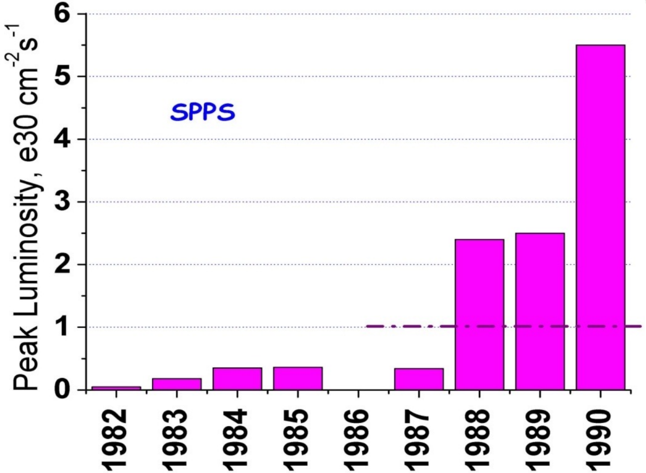


- 31 GeV + 31 GeV colliding proton beams.
- Highest CM Energy for 10 years
- Set a luminosity record that was not broken for 28 years!

First proton-antiproton collider - Super Proton–Antiproton Synchrotron

- Initial energy 270GeV / beam
  - Later raised to 315 GeV
- First collisions in 1981
- Discovery of W and Z in 1983
  - 1984 Nobel Prize in Physics (Rubbia and Van der Meer)
- Protons from SPS were used to produce antiprotons
- Antiprotons were injected in the opposite direction and accelerated

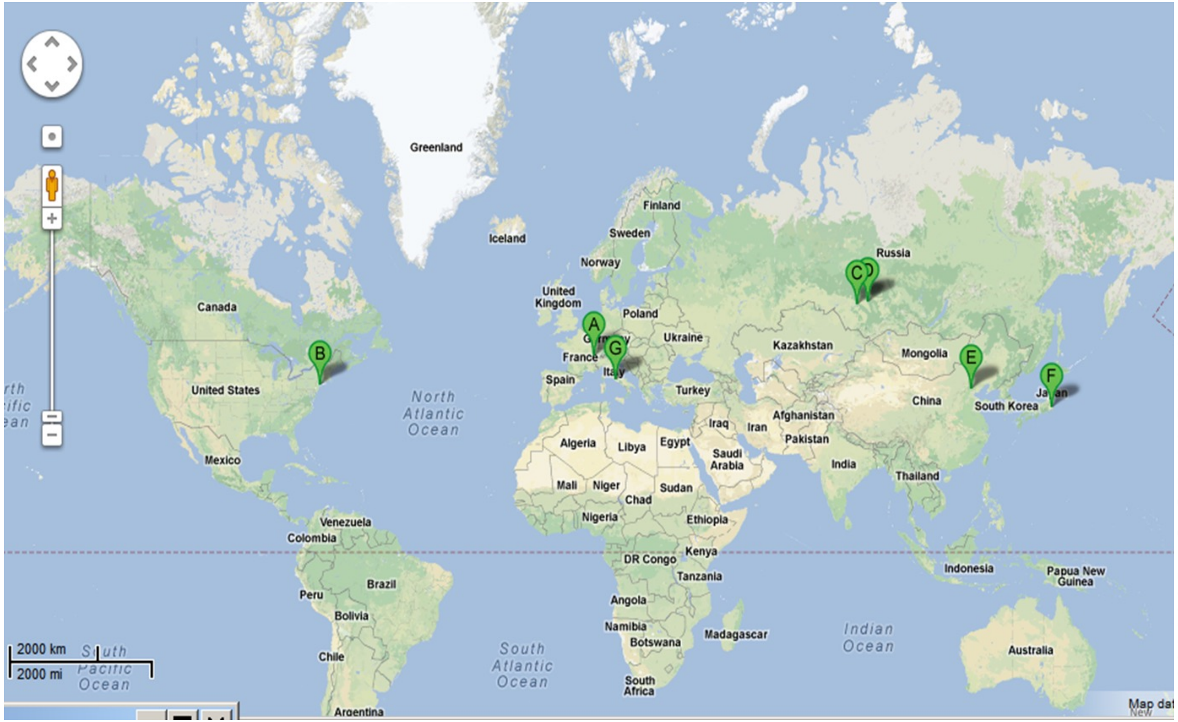


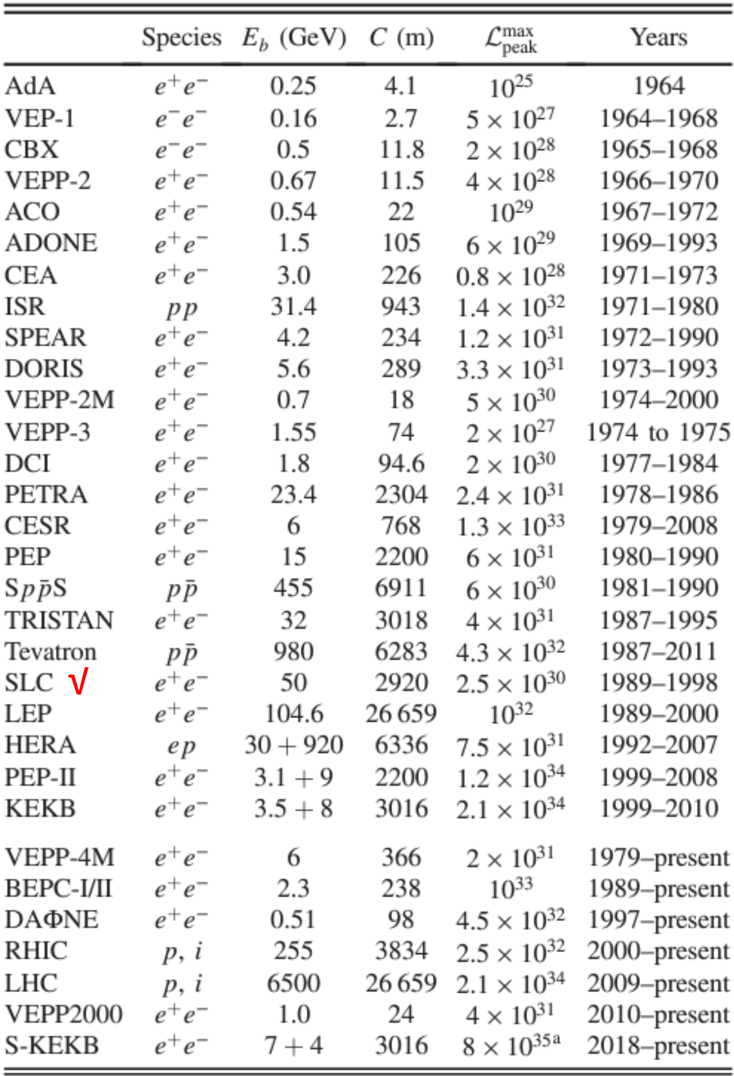


First superconducting synchrotron - Tevatron

- 1968 – Fermilab Construction Begins
- 1972 – Beam in Main Ring (normal magnets)
  - Plans soon began for a superconducting accelerator to share the tunnel
- 1985 – First proton-antiproton collisions in Tevatron
  - Most powerful accelerator in the world for the next quarter century
- 1995 – Top quark discovery
- 2011 – Tevatron shut down after successful LHC startup

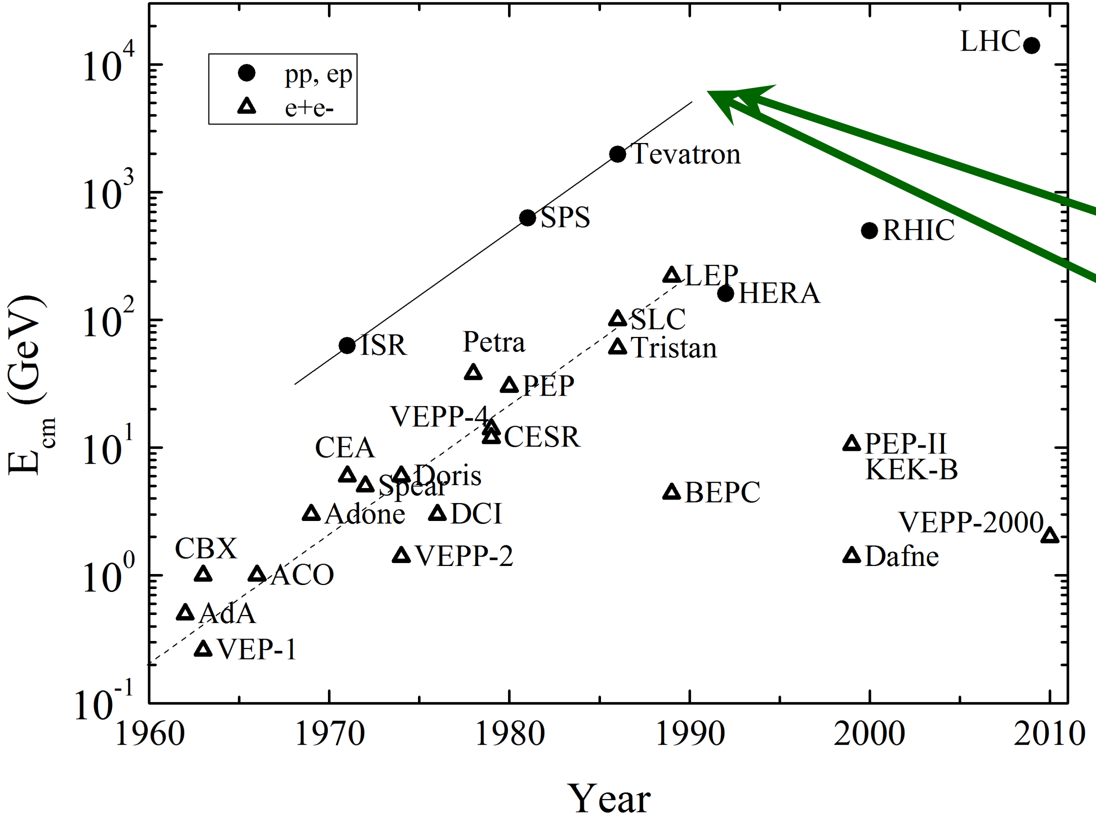
Colliders – 31 built, 7 in operation

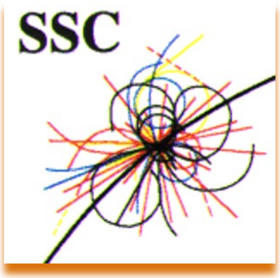




	Species	E_b (GeV)	C (m)	$\mathcal{L}_{\text{peak}}^{\text{max}}$	Years
AdA	e^+e^-	0.25	4.1	10^{25}	1964
VEP-1	e^-e^-	0.16	2.7	5×10^{27}	1964–1968
CBX	e^-e^-	0.5	11.8	2×10^{28}	1965–1968
VEPP-2	e^+e^-	0.67	11.5	4×10^{28}	1966–1970
ACO	e^+e^-	0.54	22	10^{29}	1967–1972
ADONE	e^+e^-	1.5	105	6×10^{29}	1969–1993
CEA	e^+e^-	3.0	226	0.8×10^{28}	1971–1973
ISR	pp	31.4	943	1.4×10^{32}	1971–1980
SPEAR	e^+e^-	4.2	234	1.2×10^{31}	1972–1990
DORIS	e^+e^-	5.6	289	3.3×10^{31}	1973–1993
VEPP-2M	e^+e^-	0.7	18	5×10^{30}	1974–2000
VEPP-3	e^+e^-	1.55	74	2×10^{27}	1974 to 1975
DCI	e^+e^-	1.8	94.6	2×10^{30}	1977–1984
PETRA	e^+e^-	23.4	2304	2.4×10^{31}	1978–1986
CESR	e^+e^-	6	768	1.3×10^{33}	1979–2008
PEP	e^+e^-	15	2200	6×10^{31}	1980–1990
S$p\bar{p}$S	$p\bar{p}$	455	6911	6×10^{30}	1981–1990
TRISTAN	e^+e^-	32	3018	4×10^{31}	1987–1995
Tevatron	$p\bar{p}$	980	6283	4.3×10^{32}	1987–2011
SLC √	e^+e^-	50	2920	2.5×10^{30}	1989–1998
LEP	e^+e^-	104.6	26 659	10^{32}	1989–2000
HERA	ep	30 + 920	6336	7.5×10^{31}	1992–2007
PEP-II	e^+e^-	3.1 + 9	2200	1.2×10^{34}	1999–2008
KEKB	e^+e^-	3.5 + 8	3016	2.1×10^{34}	1999–2010
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979–present
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989–present
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997–present
RHIC	p, i	255	3834	2.5×10^{32}	2000–present
LHC	p, i	6500	26 659	2.1×10^{34}	2009–present
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010–present
S-KEKB	e^+e^-	7 + 4	3016	$8 \times 10^{35\text{a}}$	2018–present

Colliders – the glorious past





2. Theory and fundamental concepts

Units and variables

- For the most part, accelerator physicists use SI units except for
  - Energy: eV, keV, MeV, GeV, etc.
    - Speaking of beam energy, we usually mean the kinetic energy K
  - Mass: eV/c^2
  - Momentum: eV/c
  - Luminosity: $cm^{-2}s^{-1}$

$$p = \gamma m v$$

$$E = \gamma m c^2$$

$$\mathrm{K} = E - mc^2$$

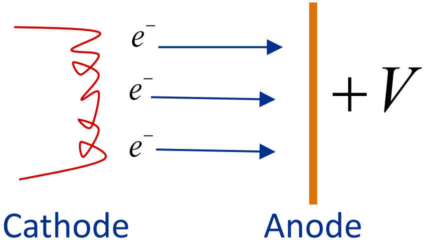
$$E = \sqrt{(mc^2)^2 + (pc)^2}$$

$$\beta = \frac{pc}{E} \qquad \gamma = \frac{E}{mc^2} \qquad \beta\gamma = \frac{pc}{mc^2}$$

Particle acceleration

- The simplest way to accelerate charged particles is through static electric field

$$K = eEd = eV$$



- This method is limited by the magnitude of electric field
  - CRT display ~keV
  - X-ray tube ~10keV
  - Van de Graaf ~MeV
- How to overcome this limitation?
  - Alternate fields to keep particles in accelerating fields
    - Radio Frequency (RF) acceleration

$$V = V_0 \sin(\omega t)$$

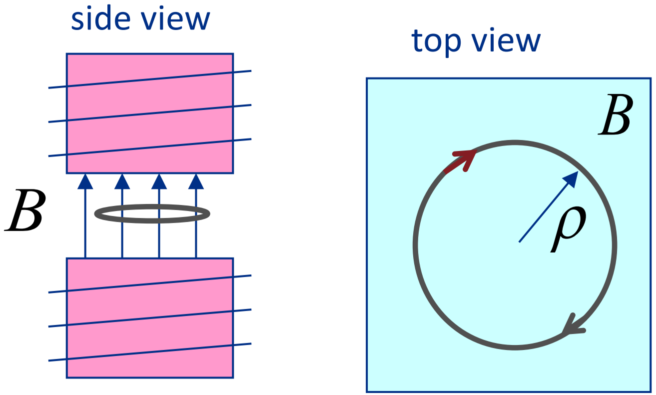
  - Bend particles so they see the same accelerating field over and over
    - cyclotron, betatron, synchrotron

Making a ring – bending magnetic field

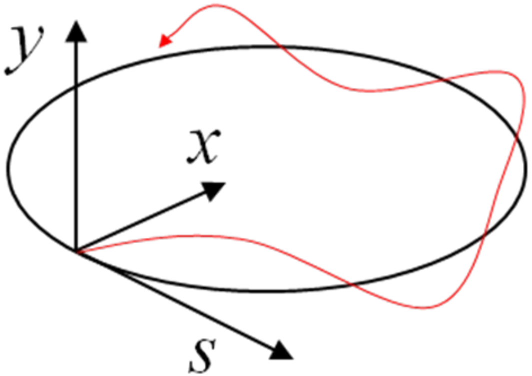
- The Lorentz force for a particle in electromagnetic field is

$$\vec{F} = \frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v}\times\vec{B}\right) \qquad \vec{p} = \gamma m\vec{v}$$

- Particle of unit charge in a uniform magnetic field will move in a circle of radius $\rho = \frac{p}{eB}$
- If all magnetic fields are scaled with the momentum as particles accelerate, the trajectories remain the same
  - Synchrotron [Veksler (1944), McMillan (1945)]
- Beam "rigidity" is defined as $(B\rho)[T\cdot m] = \frac{p[eV/c]}{c[m/s]}$
- This is all good for a single particle, but we want a beam!
  - Particles inside of the beam have different momenta
  - Hence, we need focusing



Beam focusing in accelerators

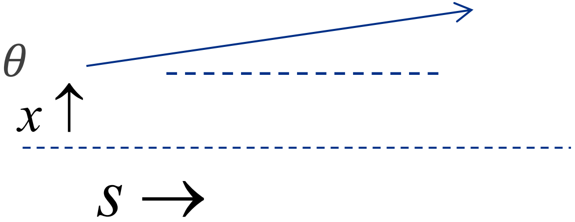


$$H = c\left[m^2c^2 + \left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right)^2\right]^{\frac{1}{2}}$$

$$H' \approx \frac{p_x^2 + p_y^2}{2} + \frac{K_x(s)x^2}{2} + \frac{K_y(s)y^2}{2}$$

$$\begin{cases} x'' + K_x(s)x = 0 \\ y'' + K_y(s)y = 0 \end{cases}$$

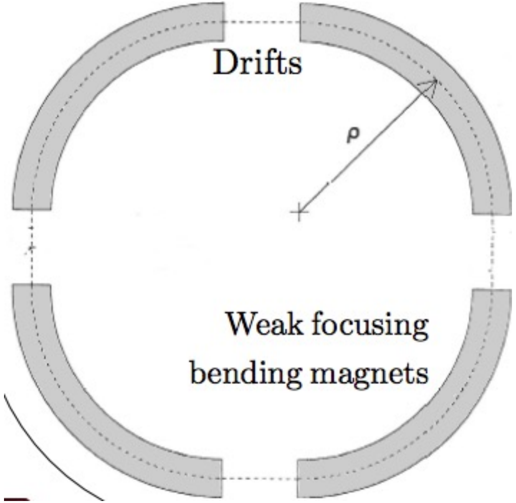
$$x' = \frac{dx}{ds} = \theta$$



$$K_{x,y}(s + C) = K_{x,y}(s)$$

- **Equilibrium orbit** – closed circular trajectory of the particle with ideally matched energy
- **Beam** – particles which have a spread in coordinates, momenta (both transverse x,y) and longitudinal (s)
  - **Beam emittance** – volume in phase space
- Need to contain beam particles
  - Focusing with Lorentz force from magnets and accelerating structures
    - Longitudinal focusing – synchrotron principle

Transverse beam focusing – *weak focusing*



Weak focusing (betatron, early synchrotrons)

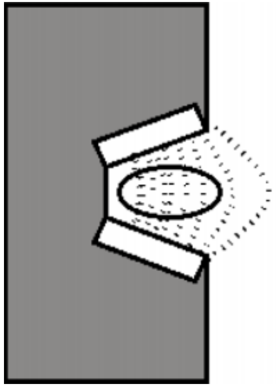
- Bending magnet does the focusing
- Azimuthally uniform transverse magnetic field $B_y(x) = B_0 + \frac{\partial B_y}{\partial x} x$
- To satisfy the Maxwell equations $x'' + (1 - n)x = 0$

$$y'' + n\, y = 0$$

- Stability criterion $0 < -\frac{\rho}{B_0}\frac{\partial B_y}{\partial x} < 1$
- Betatron tune and betatron function

$$x = \sqrt{J_x \beta_x}\cos(Q_x \tfrac{s}{\rho}) \qquad Q_x = \sqrt{1-n} \qquad \beta_x = \frac{\rho}{\sqrt{1-n}}$$

- RMS Beam size $\sigma_x = \sqrt{\varepsilon_x \beta_x}$
  - Beta-function – determined by focusing properties
  - Emittance – intrinsic beam property



Limitations of weak beam focusing

- No room for insertion devices – all circumference occupied by gradient magnet
- Cannot achieve small beam size
  - Limited beam brightness
  - Requires huge beam aperture = cost

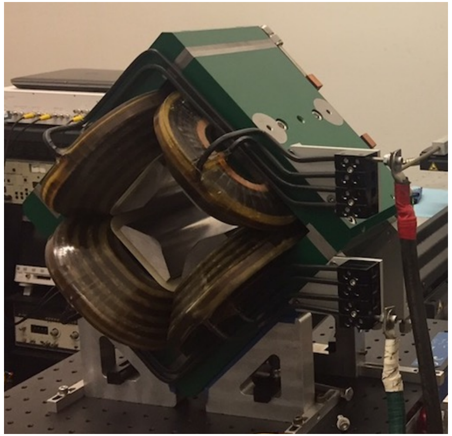
$$\beta_x = \frac{\rho}{\sqrt{1-n}} = \frac{\rho}{Q_x}$$


sergeydolya.livejournal.com

Dubna Synchrophasotron 1957

- E=10 GeV, Protons
- ρ = 30 m
- Vacuum chamber 2 × 0.36 m
- Magnet weight 36,000 ton

Transverse beam focusing – *strong focusing*



a.k.a alternating-gradient focusing

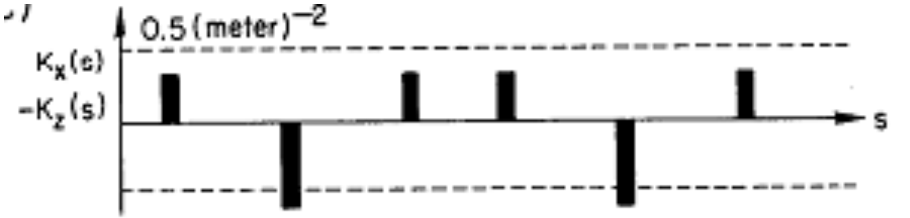
- N.Christofilos (1949, unpublished);
- Courant, Livingston, Snyder (1952)

28GeV CERN PS (1958), 30GeV BNL AGS (1960)

$$\begin{cases} x'' + K_x(s)x = 0 \\ y'' + K_y(s)y = 0 \end{cases}$$

$$K_{x,y}(s+C) = K_{x,y}(s)$$

piecewise constant alternating-sign fns

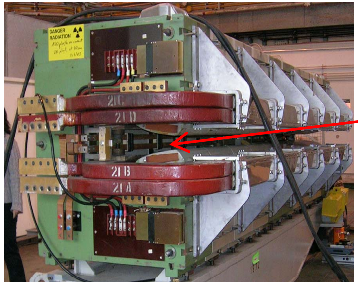


--Magnet lattice and focussing functions in the normal cells of a particular guide field.

- Quadrupole is focusing in one direction and defocusing in cross-plane
- A combination of quadrupoles with alternating signs can be made stable in both x and y

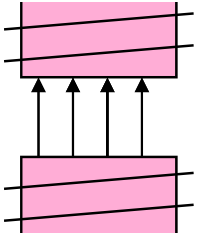
Implementation of strong focusing

- Strong focusing was originally implemented by building magnets with non-parallel pole faces to introduce a linear magnetic gradient



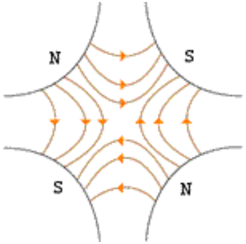
$$B_y(x) = B_0 + \frac{\partial B_y}{\partial x}x$$

=



dipole

+

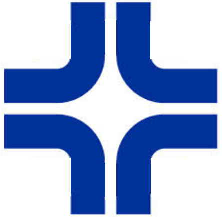


quadrupole

- Later synchrotrons were built with physically separate dipole and quadrupole magnets. The first “separated function” synchrotron was the Fermilab Main Ring (1972, 400 GeV)

dipole

+



quadrupole

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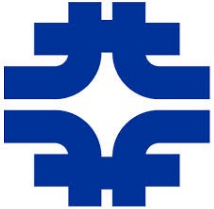
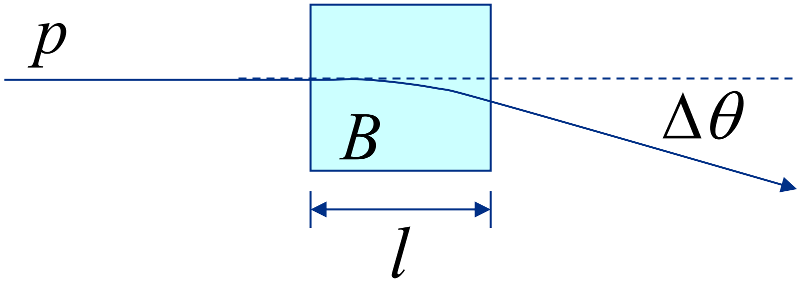
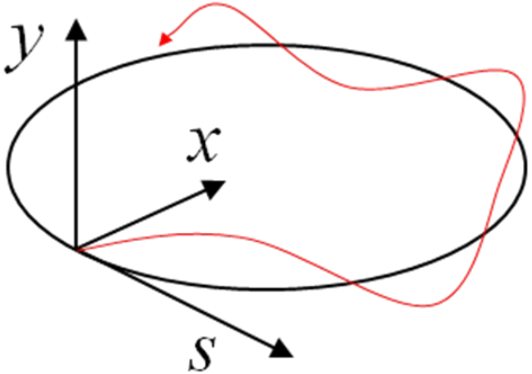


Fermilab

Thin-lens approximation



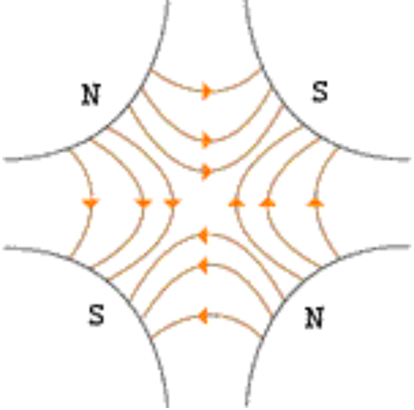


$$x' = \frac{dx}{ds} = \theta$$

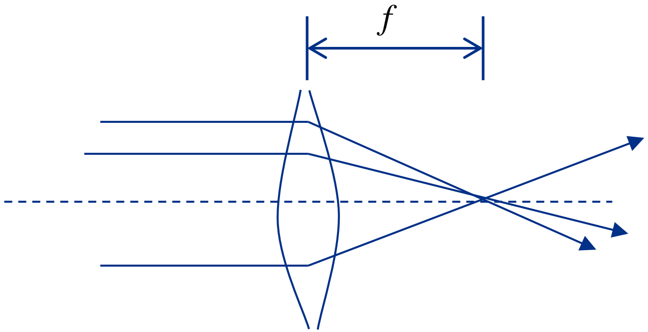
$$p_\perp \approx qvBt = \frac{qvBl}{v} = qBl$$

- If the path length through a transverse magnetic field is short compared to the bend radius of the particle, then we can think of the particle receiving a transverse “kick”, which is proportional to the integrated field
- The particle trajectory will be bent by a small angle $\Delta\theta \approx \frac{p_\perp}{p} = \frac{Bl}{B\rho}$
- In this “thin lens approximation”, a dipole is the equivalent of a prism in classical optics

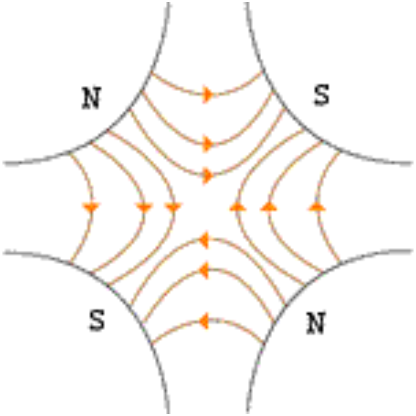
Quadrupole magnet as thin lens



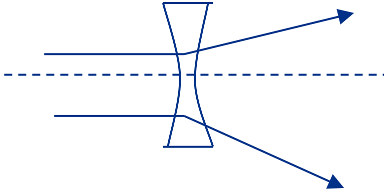
- $B_y = \frac{\partial B_y}{\partial x} x \qquad B_x = \frac{\partial B_x}{\partial y} y$
- $\vec{\nabla} \times \vec{B} = 0 \rightarrow \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} = B'$
- A charged particle passing through the magnet along the axis (i.e. perpendicular to page) off center in horizontal plane will experience a kick proportional to the displacement
- $\Delta\theta \approx -\frac{B_y l}{B\rho} = -\frac{B' l}{B\rho} x$
- Similar to a thin lens with focal length $f = \frac{x}{\Delta\theta} = \frac{B\rho}{B' l}$



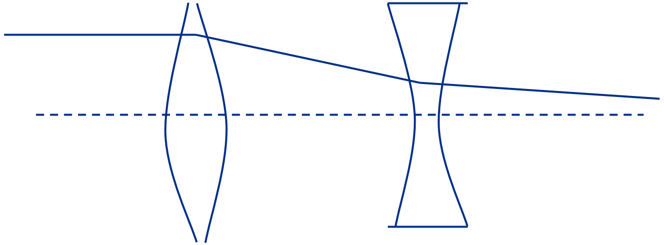
Quadrupole lens in cross plane

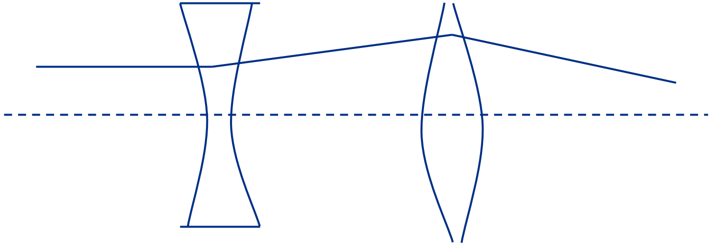


- $\vec{\nabla}\times\vec{B} = 0 \rightarrow \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} = B'$
- If the lens is focusing in horiz. plane, it will be defocusing in y!



- Placing focusing and defocusing lenses in pairs or other combinations can achieve net focusing in both planes regardless of the order





Transfer maps

- The simplest magnetic lattice consists of a sequence of quadrupole lenses and drifts between them
- Quadrupole magnet transforms the pair (x, x') as:
  - $x = x_0$
  - $x' = x'_0 - \frac{1}{f} x_0$

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} x \\ x' \end{bmatrix}_0$$

- For the drift:
  - $x = x_0 + Lx'_0$
  - $x' = x'_0$

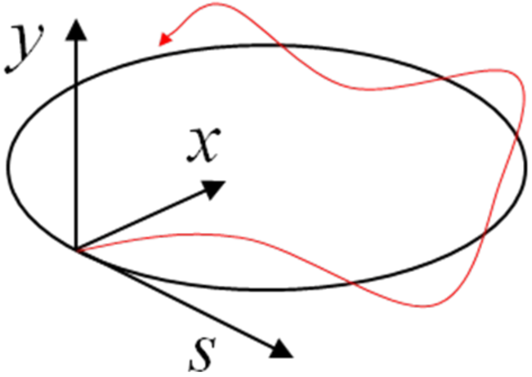
$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ x' \end{bmatrix}_0$$

- FODO cell:

$$M = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ +\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix}$$

- For a periodic system, stability criterion $|Tr[M]| < 2$

Betatron motion



$$H = c\left[m^2c^2 + \left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right)^2\right]^{\frac{1}{2}}$$

$$H' \approx \frac{p_x^2 + p_y^2}{2} + \frac{K_x(s)x^2}{2} + \frac{K_y(s)y^2}{2}$$

$$\begin{cases} x'' + K_x(s)x = 0 \\ y'' + K_y(s)y = 0 \end{cases}$$

$$K_{x,y}(s+C) = K_{x,y}(s)$$

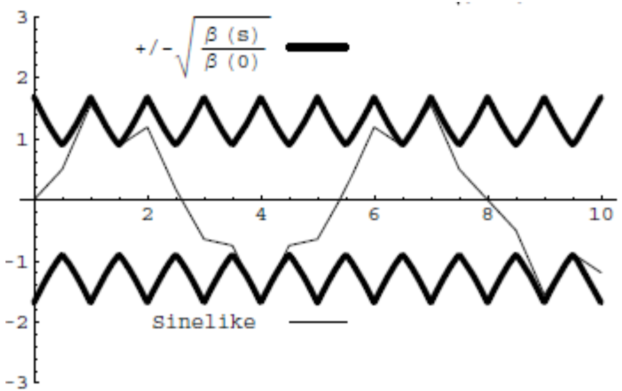
$$x(s) = A\sqrt{\beta(s)}\cos(\psi(s) + \psi_0)$$

$$\psi(s) = \int_0^s \frac{d\varsigma}{\beta(\varsigma)}$$

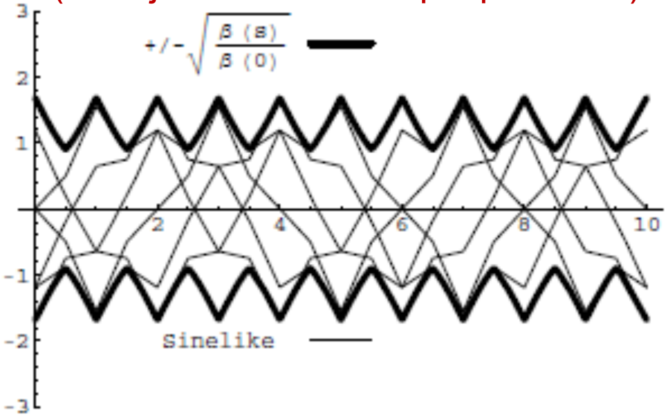
- Particle motion around closed orbit can be described in terms of initial conditions and the periodic '*amplitude function*' (*lattice function*, *β-function, betatron function*)
- Particles execute pseudo-harmonic oscillations (i.e. with variable wavelength)
- Note: β units are [length], hence amplitude A is $\sqrt{[length]}$

Conceptual understanding of lattice functions

- Betatron function represents the bounding envelope to the motion of particles in the beam, not the particle motion itself



Normalized particle trajectory

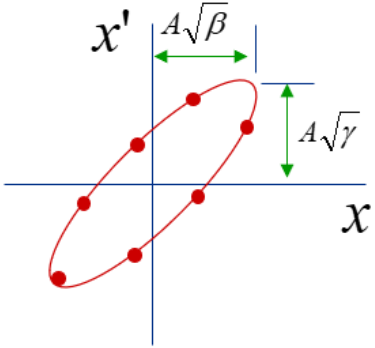


Trajectories over multiple turns
(or trajectories of multiple particles!)

- Features:
  - Closely spaced strong quadrupoles → small β → small aperture, many wiggles
  - Sparsely spaced weak quadrupoles → large β → large aperture, few wiggles

Characterizing particle ensemble - Emittance

- A particle returning to the same point in a ring over many turns traces an ellipse, defined by the β-function and two additional parameters, α and γ



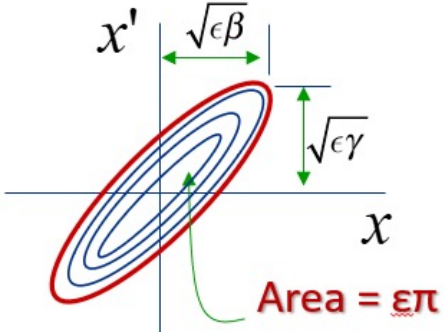
$$\beta x'^2 + 2\alpha x x' + \gamma x^2 = A^2 = constant$$

$$\alpha = -\frac{1}{2}\frac{d\beta}{ds} \qquad \gamma = \frac{1+\alpha^2}{\beta}$$

NOT to be confused with relativistic β and γ!

- An ensemble of particles can be characterized by a bounding ellipse, known as the “emittance” (definitions vary: RMS, 95%, 99%)

$$\beta x'^2 + 2\alpha x x' + \gamma x^2 = \epsilon$$



Beam size and adiabatic damping

- Using the Gaussian definition of the emittance, the rms beam size is

$$\sigma_x = \sqrt{\epsilon\beta_x}$$

- Emittance is constant at a constant energy, but as particles accelerate, the emittance decreases

$$\epsilon \propto \frac{1}{\beta\gamma}$$

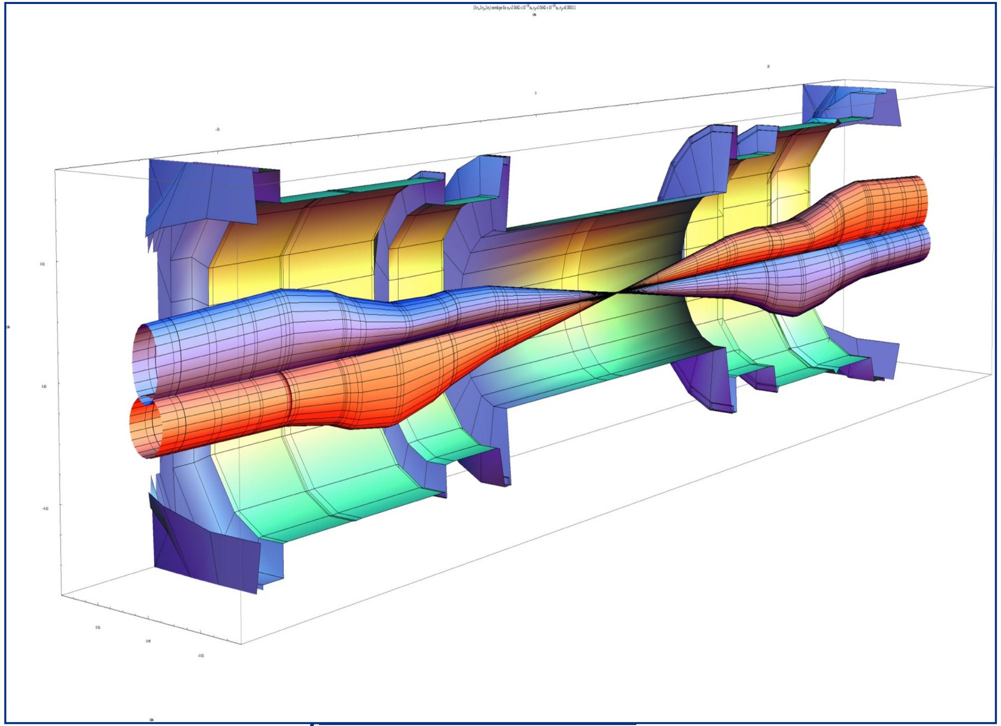
Relativistic β and γ
(yes, it is confusing)

- This is known as “adiabatic damping”. We therefore define a “normalized emittance” (measure of truly conserved adiabatic invariant $\Delta p \times \Delta x$)

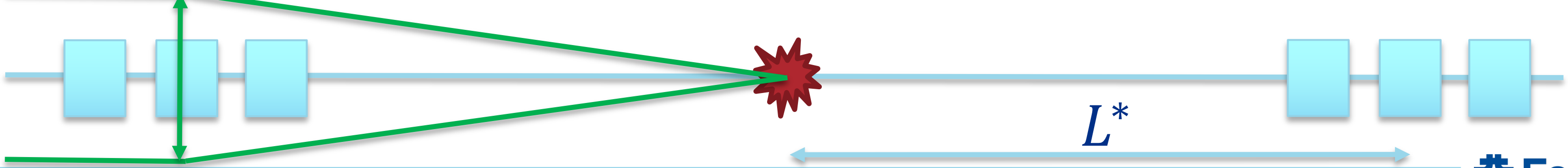
$$\epsilon_N = \beta\gamma\epsilon$$

Strong focusing - features

- Beta-function and consequently beam size can be small
- Beam size varies along the ring – there are maxima and minima
- For example, in the final focus of the LHC
- $\beta^* = 30$ cm
- β_{max} =4.5 km



$$\sigma^* = \sqrt{\varepsilon\beta^*} \approx 15\mu m \qquad \sigma_L = \sigma^*\sqrt{1 + L^{*2}/\beta^{*2}} \approx 2\ mm$$



Betatron frequency and betatron tune

- As particles go around a ring, they will undergo a number of betatron oscillations Q

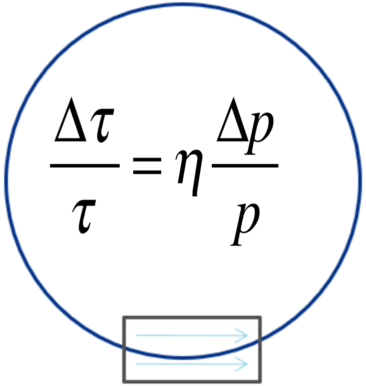
$$Q = \frac{1}{2\pi} \oint \frac{ds}{\beta(s)}$$

- Q is referred to as the ‘betatron tune’
- For the Tevatron, Q=20.58. For the LHC, Q=64.31
  - Integer part relates to aperture
  - Fractional part is related to beam stability
- Betatron frequency

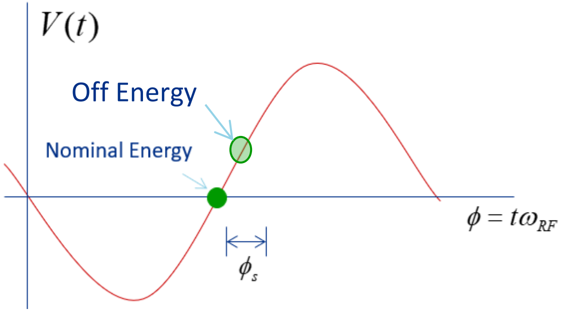
$$f_\beta = Q f_0 = Q \frac{1}{T}$$

Longitudinal motion and phase stability

- Similar to transverse (betatron) oscillations and envelope, the beam can be focused longitudinally w.r.t. the ‘reference’ particle
- This is achieved by phasing the RF cavities such that the ‘reference’ particle will see no accelerating voltage, while the more energetic particles will receive less acceleration
- Frequency of accelerating RF voltage is an integer of the revolution frequency $f_{RF} = hf_0$
  - Allows for multiple ‘buckets’ (i.e. bunches) along the ring
  - In the LHC, h=35,640
    - Not every ‘bucket’ is occupied by a bunch, LHC operates with 2,808 bunches per beam
    - LHC bunch length is 15 cm



$$\frac{\Delta\tau}{\tau} = \eta \frac{\Delta p}{p}$$



Putting it all together – collider Luminosity

- For equal intensity round beams with Gaussian profile

$$L = f\frac{N_b^2}{4\pi\sigma^2}R$$

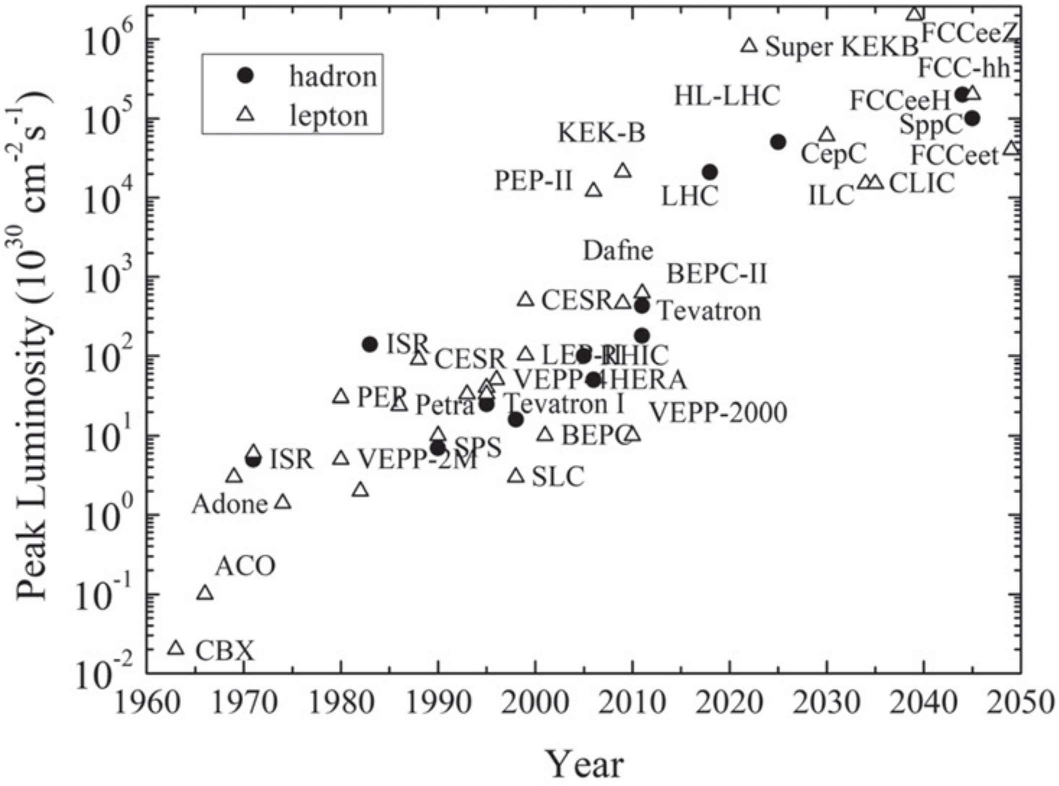
- Here f-collision frequency, N_b-number of particles per bunch, σ-beam size, R-geometrical factor determined by e.g. crossing angle

- Substituting $\sigma^2 \approx \frac{\beta^* \epsilon_N}{\gamma}$

$$L = f_0\frac{1}{4\pi}nN_b^2\frac{\gamma}{\beta^* \epsilon_N}R$$

- n- number of bunches, β^*- beta-function at the collision point

Luminosities of colliders (Δ-lepton colliders, •-hadron colliders)



Summary

Today, we reviewed

- The evolution of the field
- Basics of creating tightly-focused beams suitable for collisions
- Luminosity scaling

Plan for tomorrow:

3. Key technologies
4. Collider operations
5. Proposals for the future and challenges

Questions?