Lecture 3

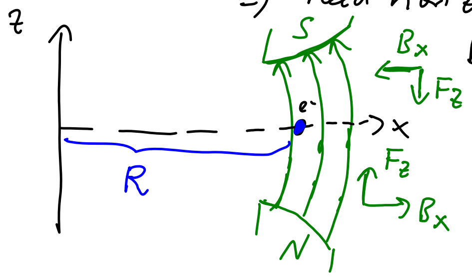
1.4 RF field accelerators
more on weak and strong focusing
1.5 Particle sources and injection
1.6 Accelerators for HEP and energy reach
1.7 Accelerator based light sources
1.8 Accelerators around the world

Weak focusing Synchrotrons (IV)

- for vertical direction

need restoring force: $F_z = -cz$ for focusing in vertical plane

$\Rightarrow$ need horizontal field component



$$\underline{B_x = -c'z} \qquad (c' > 0)$$

from $\vec{\nabla} \times \vec{B} = 0$

$$\frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial x} = \frac{\partial B_z}{\partial r}$$

$\Rightarrow$ need $\frac{\partial B_x}{\partial z} = -c' = \frac{\partial B_z}{\partial r} < 0$

$\Rightarrow$ B_z needs to decrease with increasing r (for e^-)

$\frac{\partial B_z}{\partial r} < 0 \Rightarrow \underline{\underline{n > 0}}$ for vertical focusing

Weak focusing Synchrotrons (V)

$\Rightarrow$ condition for weak focusing in both planes:

$$\boxed{0 < n < 1}$$

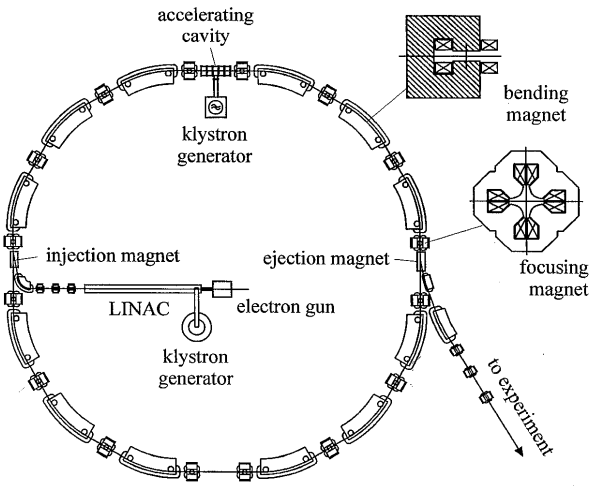
- main issue of weak focusing: large deviations from orbit if R is large $\Rightarrow$ limits energy reach!

$\Rightarrow$ solution: strong focusing!

Strong focusing Synchrotrons

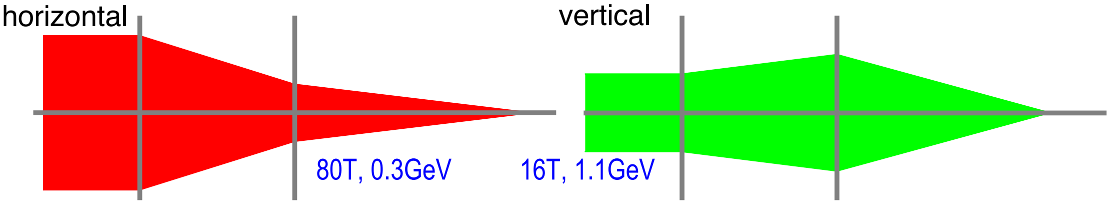
- 1952: Courant, Livingston, Snyder publish about strong focusing
- 1954: Wilson et al. build first synchrotron with strong focusing for 1.1MeV electrons at Cornell, 4cm beam pipe height, only 16 Tons of magnets.
- 1959: CERN builds the PS for 28GeV after proposing a 5GeV weak focusing accelerator for the same cost (still in use)

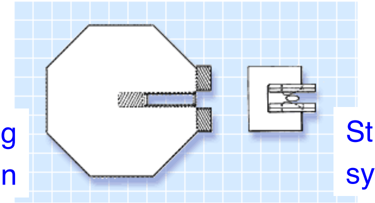
- Key idea: split up machine into series of magnet sectors, in which in alternating order the magnetic field increases strongly with radius (n<<-1) or decreases strongly with increasing radius (n>>+1)
- Alternating series of focusing and defocusing lenses gives overall focusing!



Strong focusing Synchrotrons (II)

Transverse fields defocus in one plane and focus in the other plane.
But two successive elements, one focusing the other defocusing,
can focus in both planes:





- Today: only strong focusing is used. Due to bad field quality at lower field excitations the injection energy is 20-500MeV from a linac or a microtron.

Limits of Synchrotrons

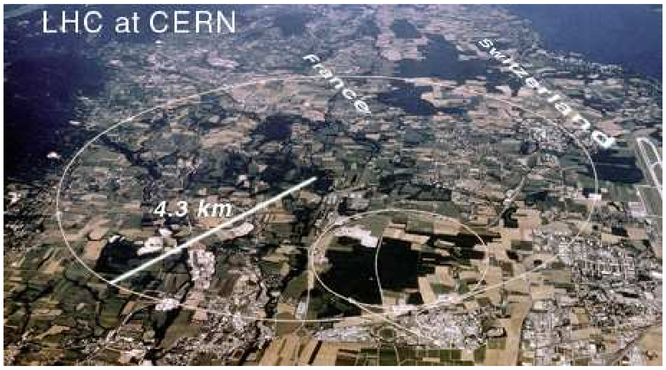
$$R = \frac{p}{qB} \quad \Rightarrow \quad \text{The rings become too long}$$

Protons with p = 20 TeV/c , B = 6.8 T would require a 87 km SSC tunnel
Protons with p = 7 TeV/c , B = 8.4 T require CERN's 27 km LHC tunnel

Electromagnetic power (**Synchrotron radiation**) radiated during transverse acceleration:

$$P_{\text{radiation}} = \frac{c}{6\pi\varepsilon_0} N \frac{q^2}{R^2} \gamma^4$$

Energy needed to compensate radiation becomes too large (for e-)



Electron beam with p = 0.1 TeV/c in CERN's 27 km LEP tunnel radiated 20 MW
Each electron lost about 4GeV per turn, requiring many RF accelerating sections.

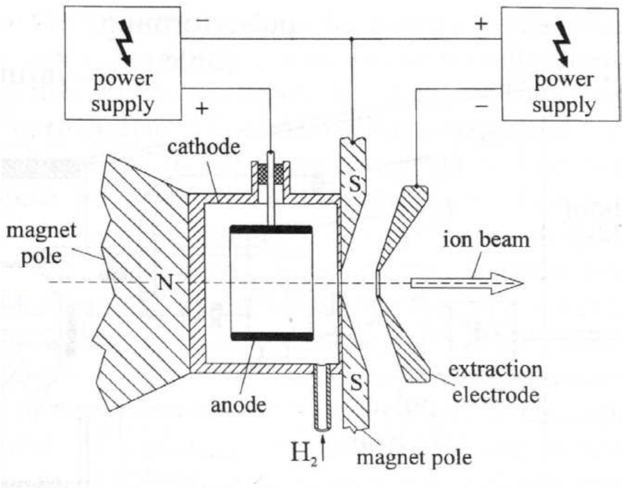
1.5 Particle sources and injection

PIG Ion Source
Diode Electron Source
Triode Electron Source
Other Electron and Position Guns
Injection

PIG Ion Source

Simplest: Phillips Ion Gage
(based on Penning Principle)

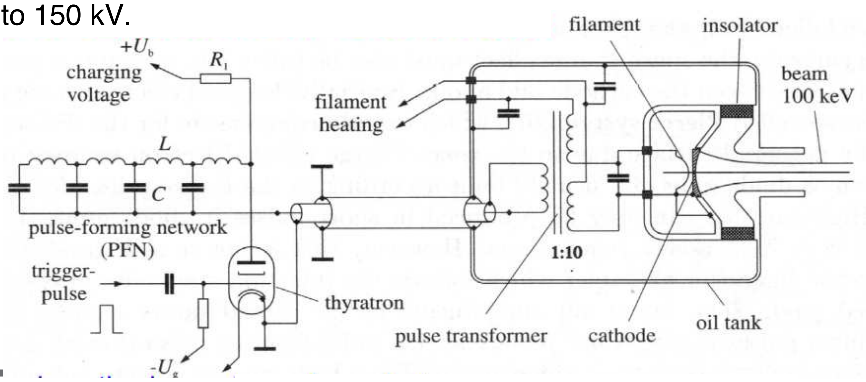
- Magnetic field of about 0.01 T
- Ionization chamber with pressurized gas inserted at <100 Pa (10^{-3} Atm)
- Gas is ionized and remains ionized since electrons are accelerated in the E-field and circle in the B-field
- Positive ions are accelerated through the hole in the cathode to several 100 V.



- Modern ion sources are more complex, and often use high frequency fields for ionization.

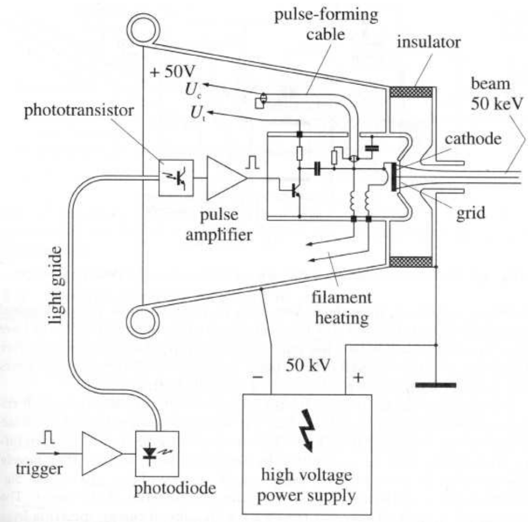
Diode Electron Source

- A **thermionic cathode** produces free electrons
- An earthed anode accelerates them though and aperture into a linac
- The cathode is not flat but curved (**Pierce Cathode**) to produce a force that counters Coulomb explosion of the bunches (the **Space Charge Force**)
- Typical voltages are 100 to 150 kV, typical peak currents are a few Ampere: $I \propto U^{3/2}$
- Due to power limits, only short pulses can be produced (~1 to few μs long)
- A thyratron (gas discharge tube) is used as a fast high current switch and capacitors provide the short pulse
- The pulse from the capacitors is magnified (by about 10) in a transformer to reach the 100 to 150 kV.



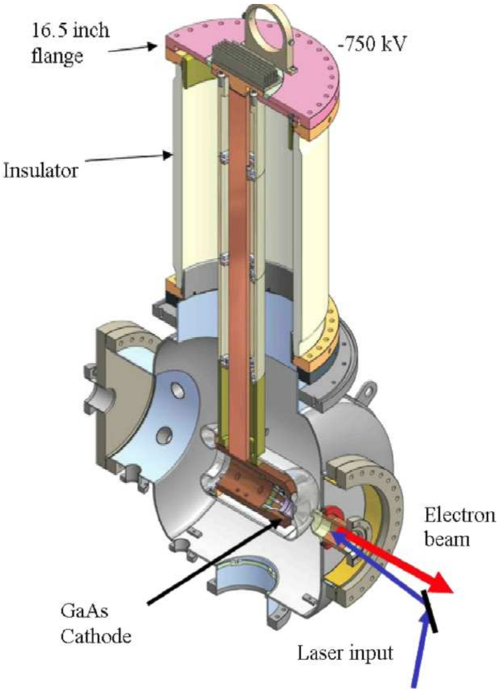
Triode Electron Source

- Use no transformer -> electron pulses (bunches) can be much shorter (>1 ns long)
- A **thermionic cathode** produces free electrons
- A 50 V barrier grid prohibits electrons from leaving the cathode
- An earthed anode accelerates them though an aperture into a linac
- Typical voltages are 50 kV, typical peak currents area a few Ampere.
- The short pulse amplifier is in a Faraday cage at a high potential
- A light guide transports a short trigger pulse to high potential
- The amplified pulse then only has to switch the 50 V of the grid.

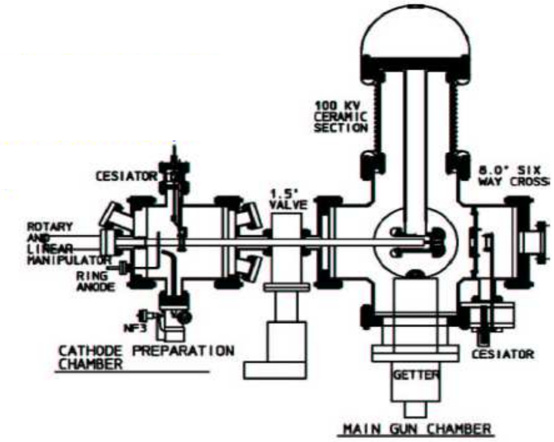


Other Electron Sources (I)

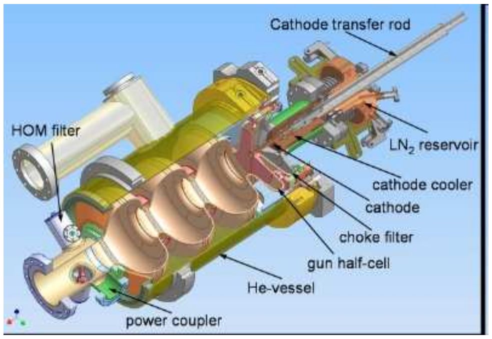
- Laser gun / **photo-cathode systems**:
  - A laser shines on a cathode (metal or semiconductor) which emits photo electrons
  - With GaAs as cathode and with a polarized laser, polarized electrons are produced.
  - Bunches can be as short as a few ps.
  - Peak currents of a few 100 A can be achieved.



Other Electron Sources (II)

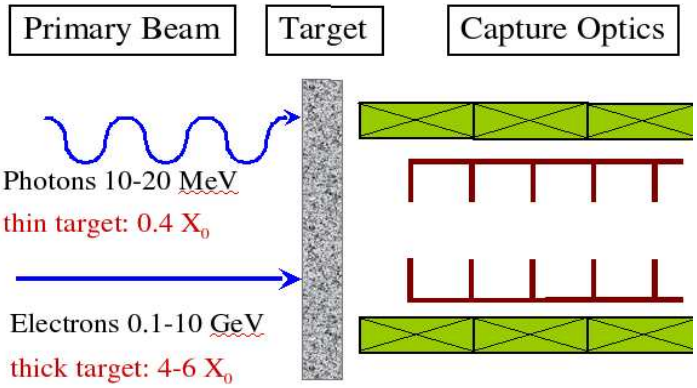


Bunches are accelerated either through an aperture in an anode (**DC gun** like the Cornell ERL gun) or in an RF field in a normal or superconducting cavity (**RF photo-cathode source**).

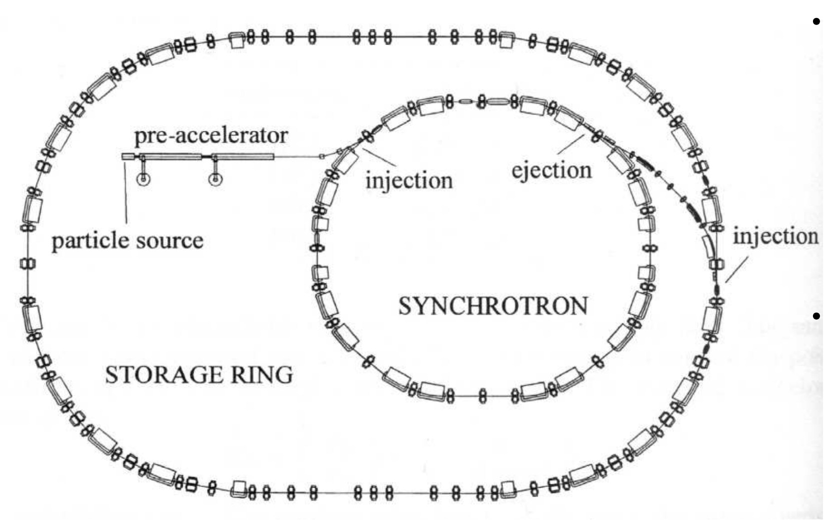


Positron Sources

- Conventional:
  - Electrons are accelerated to several 100 MeV in a linac and hit a tungsten target
  - Pair production leads to e+/e- pairs
  - A following linac has the correct phase to accelerate e+ and decelerate e-
  - Due to multiple collisions in the target, the energy spread is up to several 10 MeV and the beam is very wide. A following damping ring is needed to produce narrow beams.
- Gamma based:
  - Electron beam radiates photons in either a planar or a helical undulator
  - The photons produce then positrons via pair production in a direct conversion process at a rather thin target (0.4-0.5 radiation length).



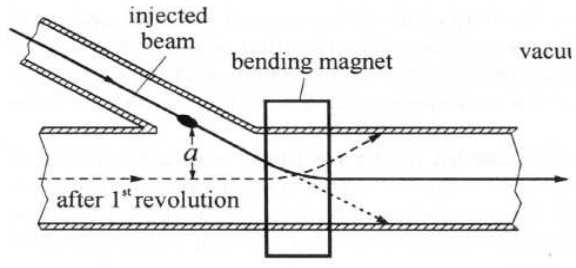
Injection (and Extraction)

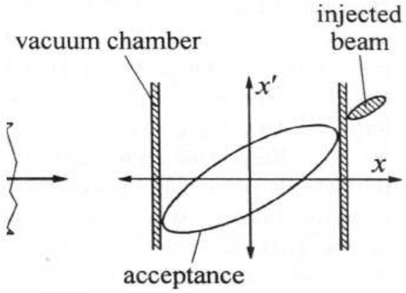


- High energy accelerators are fed by a pre-accelerator chain. For each energy stage, an appropriate accelerator type is used.
- Challenge is to inject beam without disturbing circulating beam!
  -> fast **kicker** (rapid pulsed magnet)!

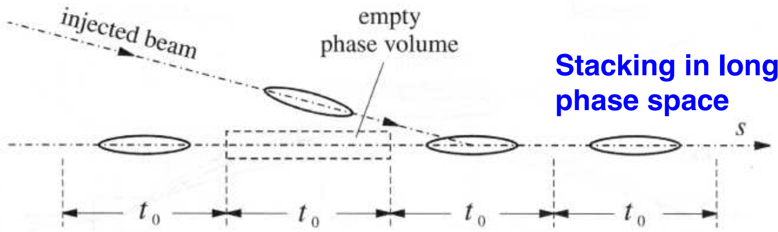
- Particles transfer from one accelerator to the other must have as few particle losses as possible.

Injection: Fast Kicker





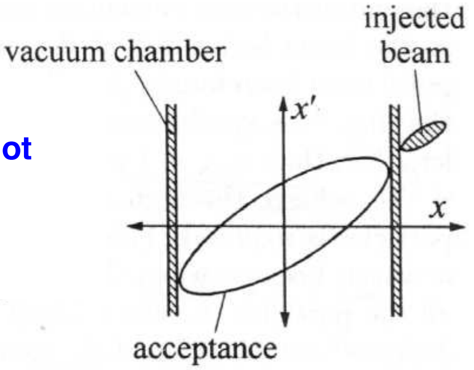
- A fast kicker magnet is needed to bring the injected beam onto the closed orbit, i.e. into the acceptance of the accelerator.
  - In order to not disturb the second turn, the duration of the kick must be less than 2 circulation times (1 μs for a 150 m circumference ring)
  - If the kicker magnet has a fast enough rise time, one can inject many bunches



Stacking in longitudinal phase space

Injection and Liouville's Theorem

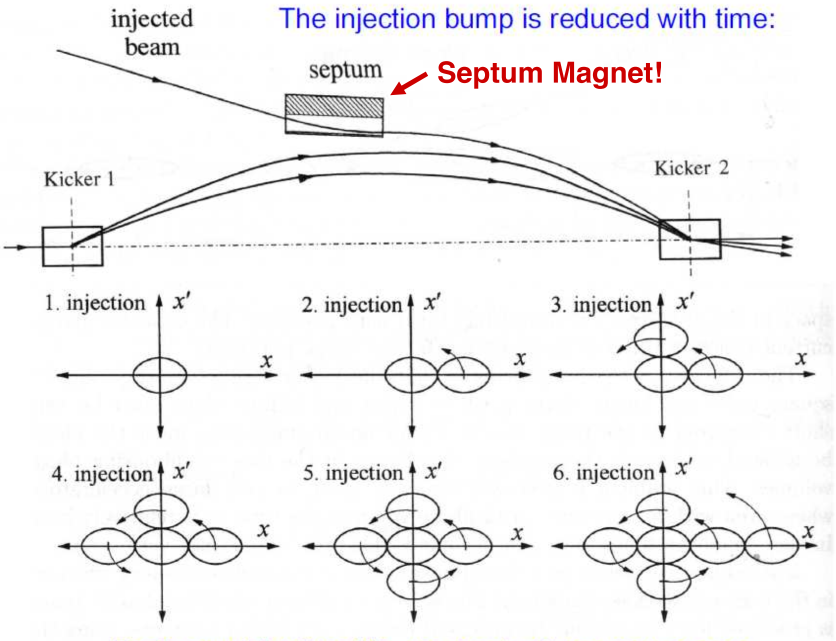
- **Fundamental rule of injection:**
  - **It is not possible to inject particles into an already occupied volume in phase space without losing the particles already present!**
  - **Under influence of conservative forces (Hamiltonian motion): two bunches of identical particles cannot merge in phase space, since the phase space density is conserved.**



- **For protons and ions**
  - **Use phase space painting/ stacking**
  - **Use stripping foils**
- **For electron injection in synchrotrons / storage rings:**
  - **Make use of betatron damping by emission of synchrotron radiation + longitudinal acceleration**

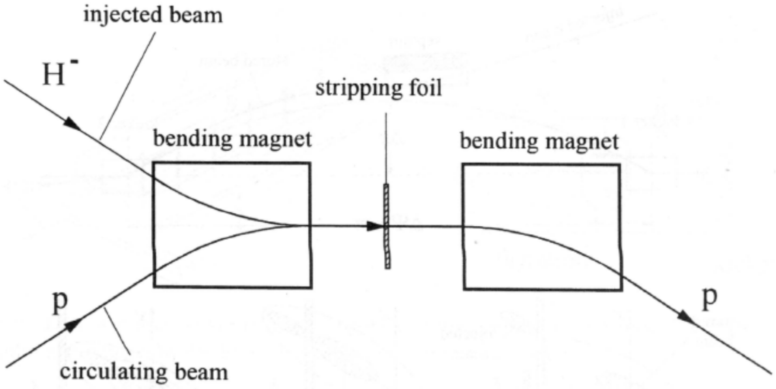
Transverse phase space painting / stacking

The injection bump is reduced with time:



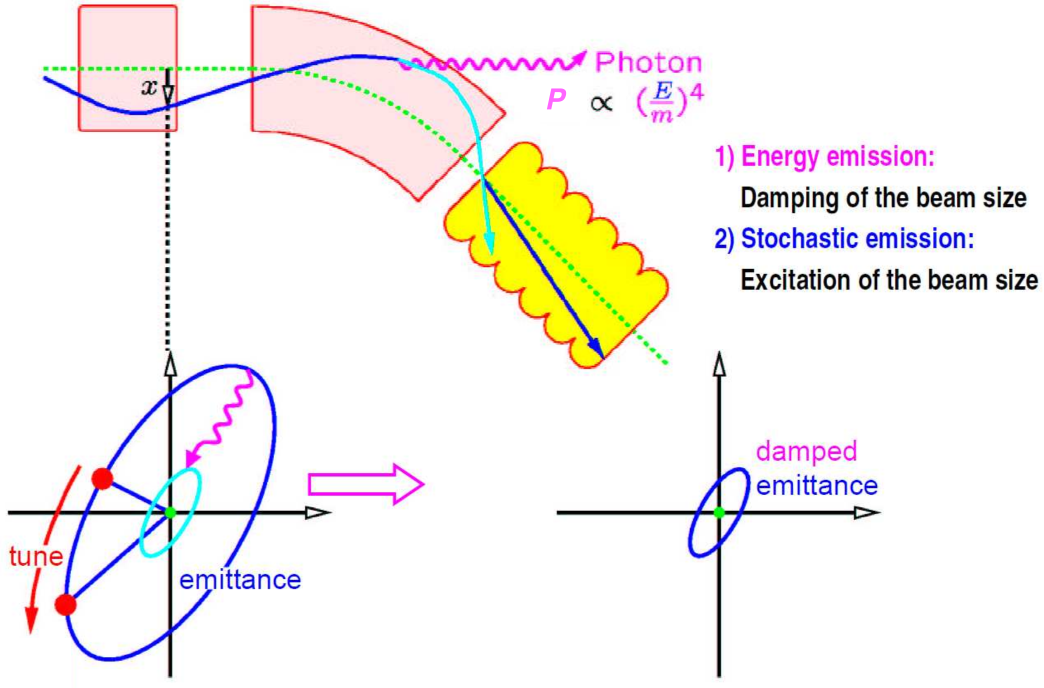
Each new injection fills an empty phase space area.

Injection of proton beams using stripping foils



- H- ions are injected
- Bending magnet bends them onto the orbit
- Stripping foil removes electrons -> protons circulate in accelerator
- Particles of different charges can be injected into the same phase space!

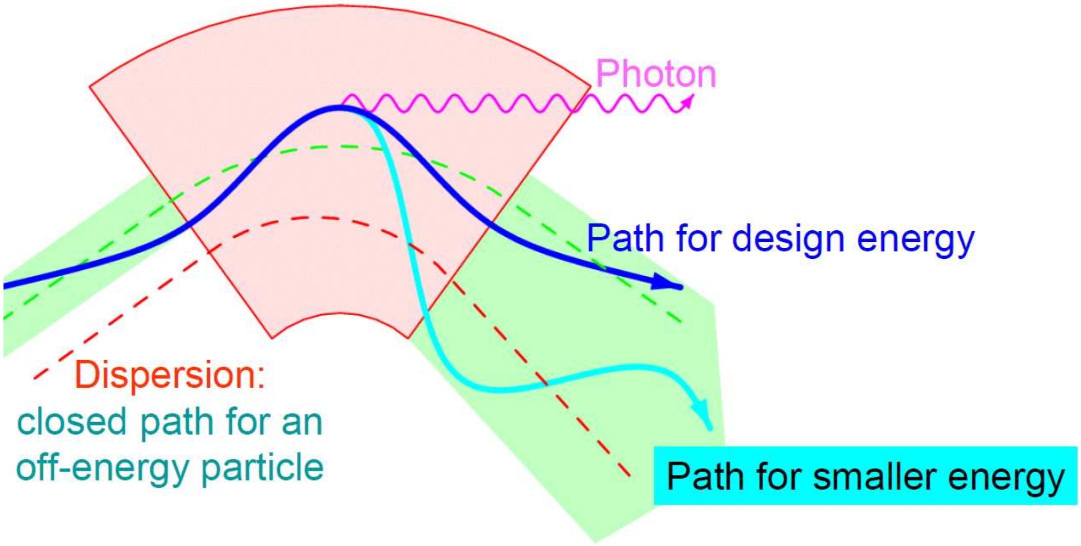
Creation of beam properties in an electron ring



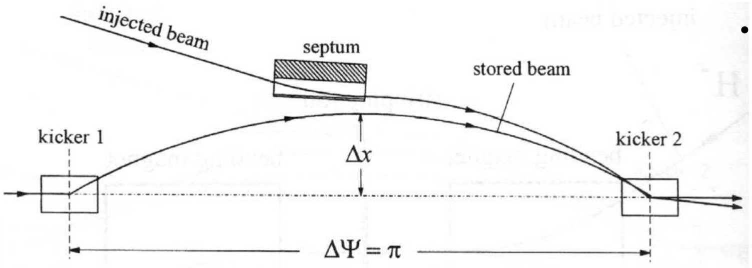
1) Energy emission:
Damping of the beam size
2) Stochastic emission:
Excitation of the beam size

Generation of the emittance

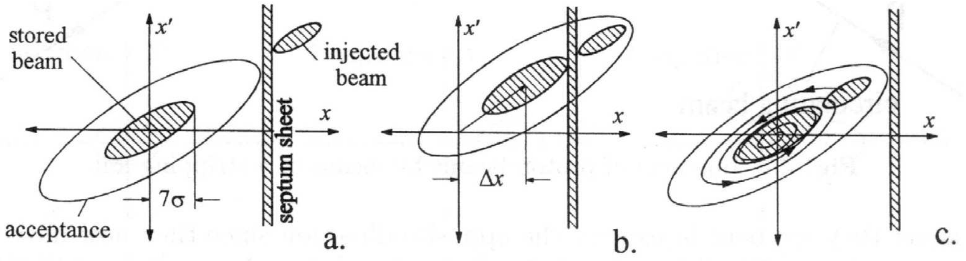
Smaller dispersion → Smaller emittance



Injection into an electron storage ring



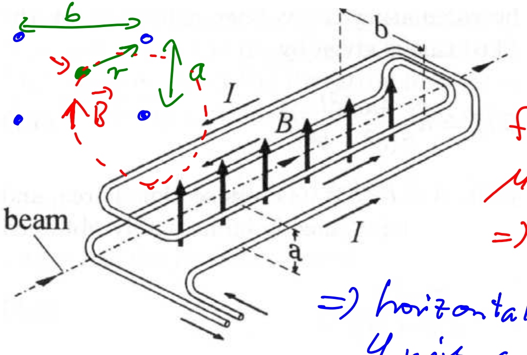
- Make use of transverse damping by synchrotron radiation + subsequent longitudinal acceleration (Liouville's theorem does not hold in presence of synchrotron radiation)!
- An injection bump brings the closed orbit and any existing beam close to the septum magnet -> new bunch is injected next to the existing beam.
- The injection oscillation of the new bunch damps in a few 100 turns due to emission of synchrotron radiation.



>7 σ aperture is needed to not loose beam.

Pulsed kicker magnets (I)

- Short pulses / fast field change: -> use magnet with very small inductance, since otherwise too high voltages would be required. -> use coil with only few turns
- Example with 4 parallel conductors:



distance wire to beam:

$$r = \frac{1}{2}\sqrt{a^2+b^2}$$

field due to wire at this separation

$$\mu_0 I = \oint \vec{B}\cdot d\vec{r} = 2\pi r|B|$$

$$\Rightarrow |B| = \frac{\mu_0 I}{2\pi r} \qquad \vec{B} = \frac{\mu_0 I}{4\pi r}\begin{pmatrix} a/r \\ b/r \end{pmatrix}$$

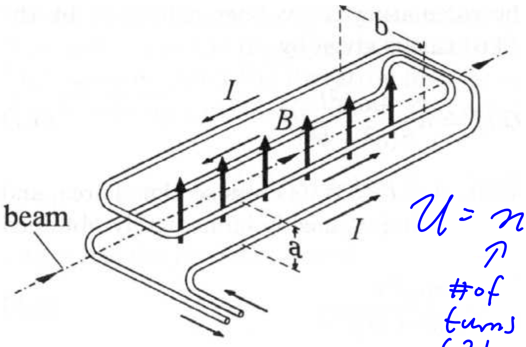
=> horizontal components of fields of the 4 wires cancel out

=> vertical component of net field:

$$B_z = \frac{4\mu_0 b}{\pi(a^2+b^2)} I$$

(neglecting end effects / fringe fields)

Pulsed kicker magnets (II)



Inductance L of the kicker:
voltage generated by the time varying field:

$$U = n \iint \frac{d\vec{B}}{dt} \cdot d\vec{a} = n \frac{4\mu_0 b}{\pi(a^2+b^2)} \frac{dI}{dt} lb$$

$\uparrow$ # of turns (2 here) $\qquad$ A $\uparrow$ $A = l \cdot b$

$$\Rightarrow L = \frac{U}{\dot{I}} = n \frac{4\mu_0 b^2 l}{\pi(a^2+b^2)}$$

Kicker example

a = 0.04m

b = 0.08m

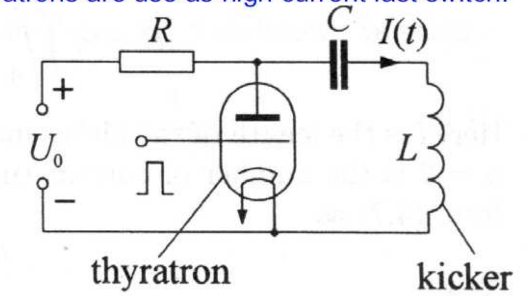
l = 1.0m

E = 5GeV

What current and what voltage is needed to produce a kick angle of

$\varphi = 3\text{mrad}$ in $\tau_{kick} = 1\mu s$

Thyratrons are use as high current fast switch.



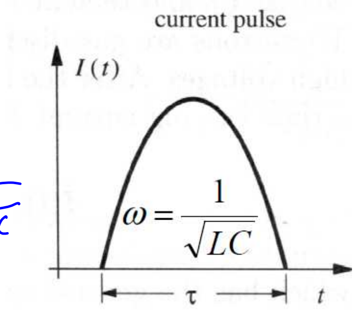
$$B_y = \frac{4\mu_0 b}{\pi(a^2+b^2)} I = \frac{p}{e}\frac{\varphi}{l} \Rightarrow \underline{I = 3127\text{A}}$$

$$L = \frac{U}{\dot{I}} = n \frac{4\mu_0 b^2 l}{\pi(a^2+b^2)} = 2.56\mu H$$

$$\omega = \frac{\pi}{\tau_{kick}} = \frac{1}{\sqrt{LC}}$$

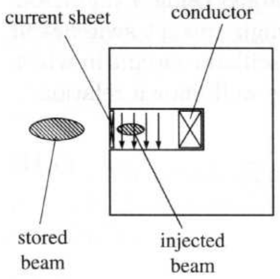
$$C = \left(\frac{\tau_{kick}}{\pi}\right)^2 \frac{1}{L} = 39.6nF$$

$$\hat{U} = L\hat{\dot{I}}_{max} = \omega L\hat{I}_{max} \underline{= 25.1\text{kV}}$$



Septum magnet

Current sheet septum magnet

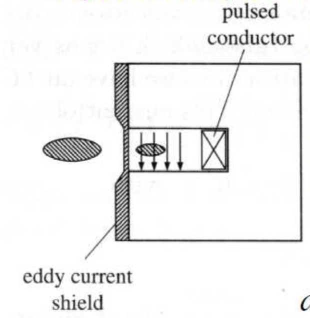


Key: shield circulating beam from kick field!

The sheet has to carry the same current as the conductor. Its width is only a few mm.

For a few μs pulses, cooling is usually not required.

Eddy current septum magnet

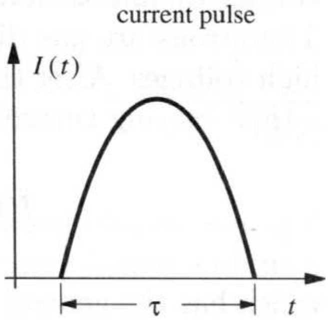


Eddy currents shield the stored Beam from the changing field.

It has to be significantly wider than the skin depth:

$$d_s = \sqrt{\frac{2}{\omega\sigma\mu_r\mu_0}}$$

$$d_s^{(Cu)} = 0.66\text{mm for } 50\mu\text{s}$$



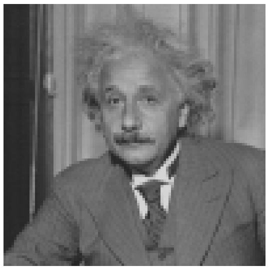
1.6 Accelerators for particle physics and energy reach

Available Energy

Colliding Beam Accelerators

Special Relativity

$E = mc^2$



Albert Einstein, 1879-1955
Nobel Prize, 1921
Time Magazine Man of the Century

Four-Vectors:
Quantities that transform according to the Lorentz transformation when viewed from a different inertial frame.

Examples:

Contravariant coordinates	Covariant coordinates
$X^\mu \in\{ct, x, y, z\}$	$X_\mu \in\{ct, -x, -y, -z\}$
$P^\mu \in\{\frac{1}{c}E, p_x, p_y, p_z\}$	$P_\mu \in\{\frac{1}{c}E, -p_x, -p_y, -p_z\}$
$\Phi^\mu \in\{\frac{1}{c}\phi, A_x, A_y, A_z\}$	$\Phi_\mu \in\{\frac{1}{c}\phi, -A_x, -A_y, -A_z\}$
$J^\mu \in\{c\rho, j_x, j_y, j_z\}$	$J_\mu \in\{c\rho, -j_x, -j_y, -j_z\}$

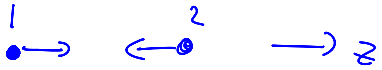
Calculating the Minkowski norm of a four-vector gives a Lorentz invariant quantity:

$$X^\mu \in\{ct, x, y, z\} \quad \Rightarrow \quad X^\mu X_\mu = (ct)^2 - \vec{x}^2 = \text{const.}$$

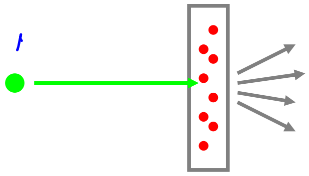
$$P^\mu \in\{\tfrac{1}{c}E, p_x, p_y, p_z\} \Rightarrow \quad P^\mu P_\mu = \left(\frac{E}{c}\right)^2 - \vec{p}^2 = (m_0 c)^2 = \text{const.}$$

Available Energy

$$\begin{aligned}
\tfrac{1}{c^2}E_{\text{cm}}^2 &= (P_1^\mu + P_2^\mu)_{\text{cm}}(P_{1\mu} + P_{2\mu})_{\text{cm}} \\
&= (P_1^\mu + P_2^\mu)(P_{1\mu} + P_{2\mu}) \\
&= \tfrac{1}{c^2}(E_1 + E_2)^2 - (p_{z1} - p_{z2})^2 \\
&= 2\left(\frac{E_1 E_2}{c^2} + p_{z1}p_{z2}\right) + (m_{01}c)^2 + (m_{02}c)^2
\end{aligned}$$

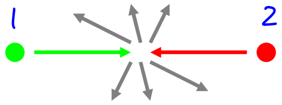


Operation of synchrotrons: fixed target experiments where some energy is in the motion of the center off mass of the scattering products



$$E_1 >> m_{01}c^2, m_{02}c^2; p_{z2} = 0; E_2 = m_{02}c^2 \quad \Rightarrow \quad E_{\text{cm}} = \sqrt{2E_1 m_{02}c^2}$$

Operation of colliders:
the detector is in the center of mass system



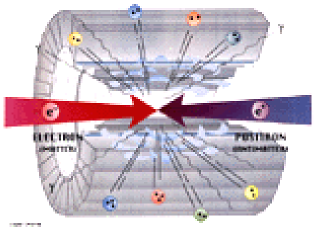
$$E_1 >> m_{01}c^2; E_2 >> m_{02}c^2 \quad \Rightarrow \quad E_{\text{cm}} = 2\sqrt{E_1 E_2}$$

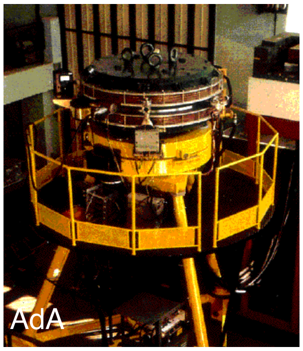
Colliding Beam Accelerators

- 1961: First storage ring for electrons and positrons (AdA) in Frascati for 250MeV
- 1972: SPEAR electron positron collider at 4GeV. Discovery of the J/Psi at 3.097GeV by Richter (SPEAR) and Ting (AGS) starts the November revolution and was essential for the quarkmodel and chromodynamics.
- 1979: 5GeV electron positron collider CESR

Advantage:

More center of mass energy





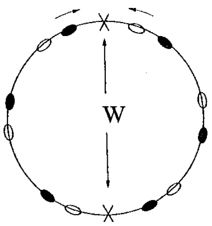
Drawback:

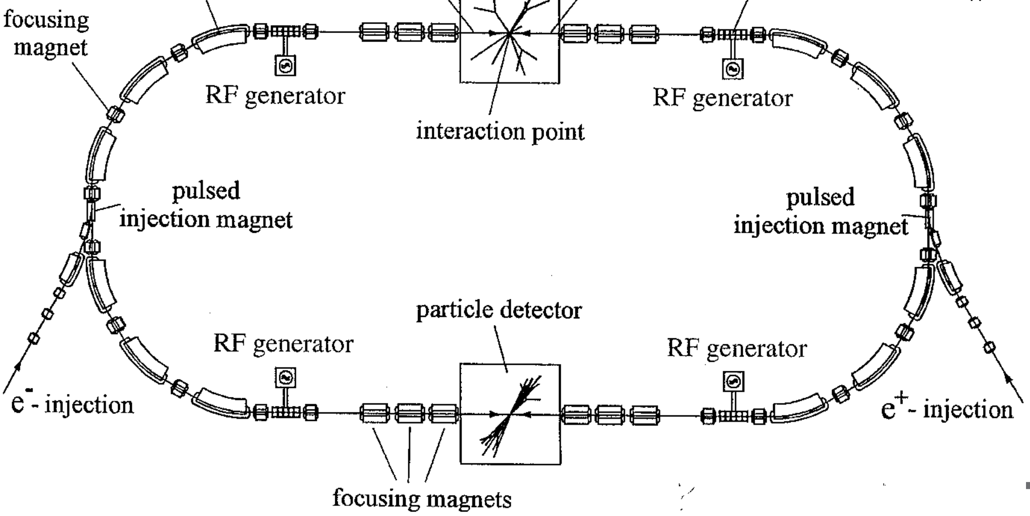
Less dense target

The beams therefore must be stored for a long time.

Elements of a Collider

- Saving one beam while injection another (e+ and e- can be stored in the same pipe!)
- Avoiding collisions outside the detectors.
- Compensating the forces between e^+ and e^- beams





Storage Rings

To avoid the loss of collision time during filling of a synchrotron, the beams in colliders must be stored for many millions of turns.

Challenges:

- Required vacuum of pressure below 10^{-7} Pa = 10^{-9} mbar, 3 orders of magnitude below that of other accelerators.
- Fields must be stable for a long time, often for hours.
- Field errors must be small, since their effect can add up over millions of turns.
- Even though a storage ring does not accelerate, it needs acceleration sections for phase focusing and to compensate energy loss due to the emission of synchrotron radiation.

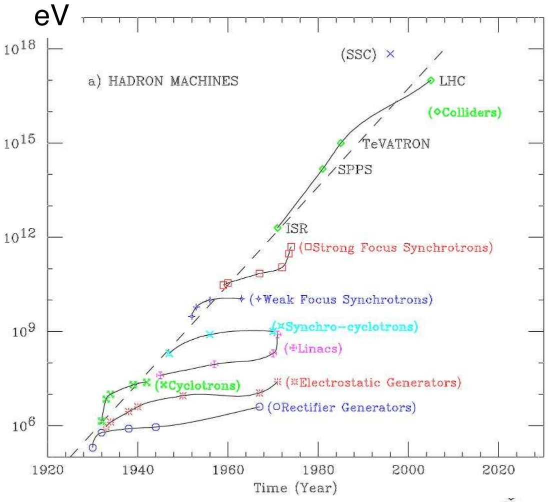
Further Development of Colliders

- 1981: Rubbia and van der Meer use stochastic cooling of anti-protons and discover W+,W- and Z vector bosons of the weak interaction
- 1987: Start of the superconducting TEVATRON at FNAL
- 1989: Start of the 27km long LEP electron positron collider (up to 200 GeV)
- 1990: Start of the first asymmetric collider, electron (27.5GeV) proton (920GeV) in HERA at DESY
- 1998: Start of asymmetric two ring electron positron colliders KEK-B / PEP-II
- Today: 27km, 7 TeV proton collider LHC at CERN

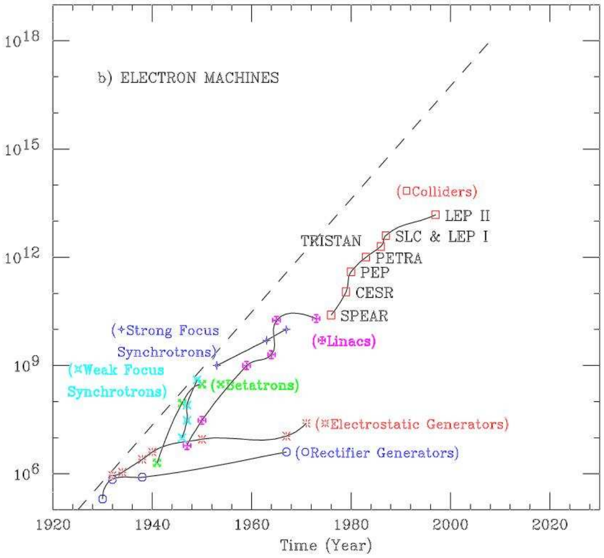
NP 1984
Carlo Rubbia
Italy 1934 -

NP 1984
Simon van der Meer
Netherlands 1925 -

The Livingston Chart



Comparison:
highest energy cosmic rays
have a few 10^{20}eV



Energy that would be needed in a fixed target experiment versus the year of achievement

$$E_1 = \frac{E_{\mathrm{cm}}^2}{2m_{02}c^2}$$

Example: Production of the pbar

- 1954: Operation of Bevatron, first proton synchrotron for 6.2GeV, production of the anti-proton by Chamberlain and Segrè (fixed target!)

$$p + p \quad \mapsto \quad p + p + p + \overline{p}$$

$$\tfrac{1}{c^2} E_{\mathrm{cm}}^2 = 2\left(\frac{E_1 E_2}{c^2} + p_{z1} p_{z2}\right) + (m_{01}c)^2 + (m_{02}c)^2$$

$$(4m_{p0}c)^2 < \tfrac{1}{c^2} E_{\mathrm{cm}}^2 = 2E_1 m_{p0} + (m_{p0}c)^2 + (m_{p0}c)^2$$

$$7m_{p0}c^2 < E_1$$

$$\underline{K_1} = E_1 - m_0c^2 > 6m_{p0}c^2 \; \underline{= 5.628\,\mathrm{GeV}}$$

NP 1959
Emilio Gino Segrè
Italy 1905 – USA 1989

NP 1959
Owen Chamberlain
USA 1920 - 2006

Example: c-cbar states

- 1974: Observation of $c - \bar{c}$ resonances (J/Ψ) at Ecm = 3095MeV at the e$^+$/e$^-$ collider SPEAR

$$\tfrac{1}{c^2} E_{\text{cm}}^2 = 2\left(\frac{E_1 E_2}{c^2} + p_{z1} p_{z2}\right) + (m_{01}c)^2 + (m_{02}c)^2$$

$$E_1 = E_2 \quad \Rightarrow \quad E_{\text{cm}}^2 = 4E^2$$

Energy per beam: $K = E - m_0 c \underline{= 1547\text{MeV}}$

Beam energy needed for an equivalent fixed target experiment: $\dfrac{E_{cm}^2}{c^2} = 2[Em + (mc)^2]$

NP 1976
Burton Richter
USA 1931 -

$$K = E - m_{0e}c^2 = \frac{E_{cm}^2}{2m_{0e}c^2} - 2m_{0e}c^2 \underline{= 9.4\text{TeV}}$$

NP 1976
Samuel CC Ting
USA 1936 -

1.7 Accelerator based light sources

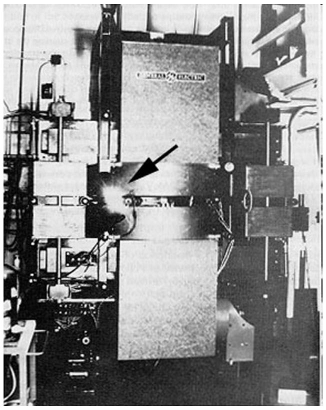
Rings for Synchrotron Radiation

- 1947: First detection of synchrotron light at General Electrics.
- 1952: First accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1968: TANTALUS (University of Wisconsin), first dedicated storage ring for synchrotron radiation

Dale Corson

Cornell's 8th president

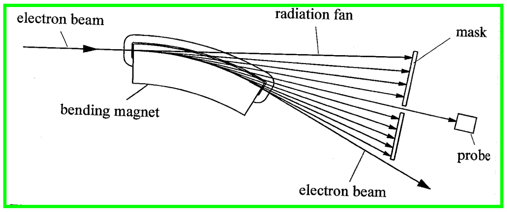
USA 1914 –

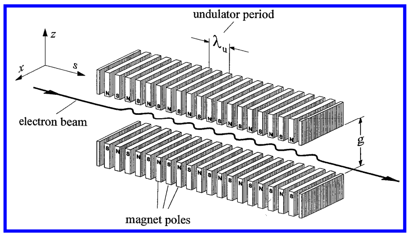


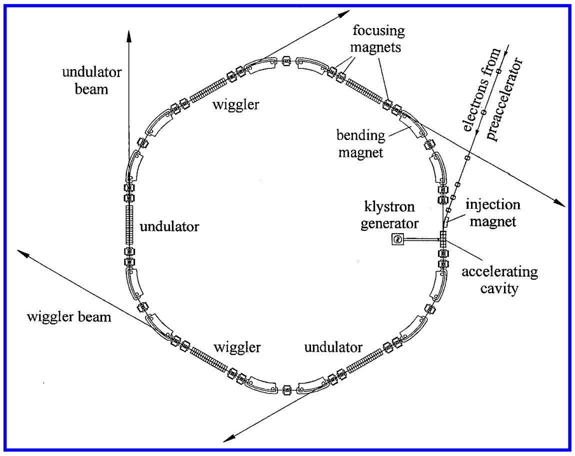
General Electric synchrotron accelerator built in 1946

3+ Generations of Light Sources

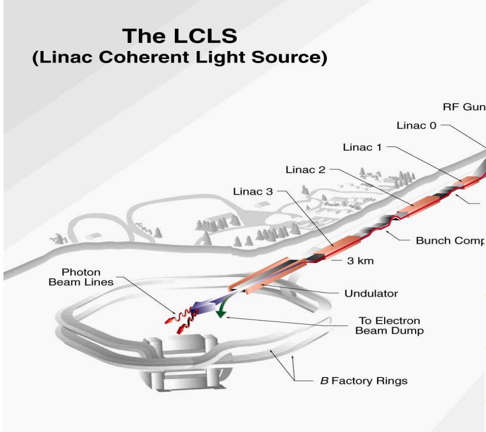
- **1st Generation** (1970s): Many HEP rings are parasitically used for X-ray production
- **2nd Generation** (1980s): Many dedicated X-ray sources (light sources)
- **3rd Generation** (1990s): Several rings with dedicated radiation devices (wigglers and undulators)
- Today: Construction of Free Electron Lasers (FELs) driven by LINACs (**4th Generation**) and Energy-Recovery-Linacs (ERLs)



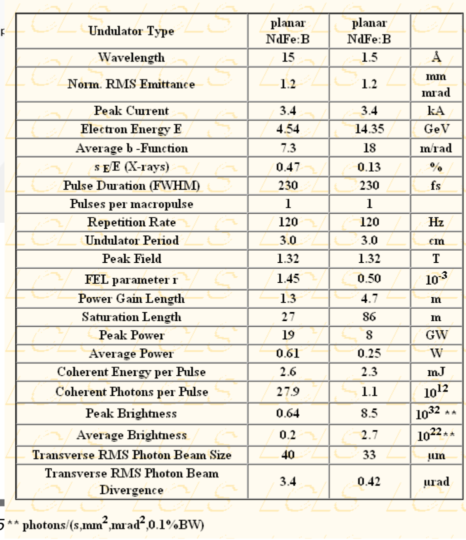




Free Electron Lasers: LCLS

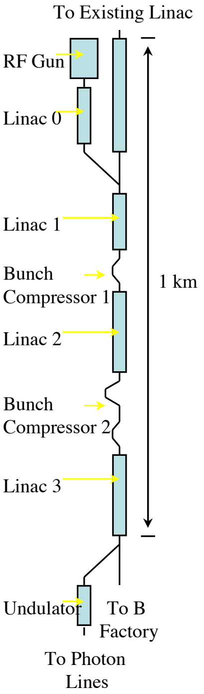


The Linac Coherent Light Source is the world's first hard X-ray free-electron laser, located at the U.S. Department of Energy's SLAC National Accelerator Laboratory in Menlo Park, California.



Undulator Type	planar NdFe:B	planar NdFe:B	
Wavelength	15	1.5	Å
Norm. RMS Emittance	1.2	1.2	mm mrad
Peak Current	3.4	3.4	kA
Electron Energy E	4.54	14.35	GeV
Average b -Function	7.3	18	m/rad
s E/E (X-rays)	0.47	0.13	%
Pulse Duration (FWHM)	230	230	fs
Pulses per macropulse	1	1	
Repetition Rate	120	120	Hz
Undulator Period	3.0	3.0	cm
Peak Field	1.32	1.32	T
FEL parameter r	1.45	0.50	10^{-3}
Power Gain Length	1.3	4.7	m
Saturation Length	27	86	m
Peak Power	19	8	GW
Average Power	0.61	0.25	W
Coherent Energy per Pulse	2.6	2.3	mJ
Coherent Photons per Pulse	27.9	1.1	10^{12}
Peak Brightness	0.64	8.5	10^{32} **
Average Brightness	0.2	2.7	10^{22}**
Transverse RMS Photon Beam Size	40	33	µm
Transverse RMS Photon Beam Divergence	3.4	0.42	µrad

** photons/(s,mm^2,mrad^2,0.1%BW)



1.8 Accelerators around the world

Accelerators of the World

Europe

AGOR	Accelerateur Groningen-ORsay, KVI Groningen, Netherlands
ALBA	Synchrotron Light Facility *(under construction)*, Barcelona, Spain
ANKA	Ångströmquelle Karlsruhe, Karlsruhe, Germany (Forschungsgruppe Synchrotronstrahlung (FGS))
BESSY	Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung, Germany
CERI	Centre d'Etudes et de Recherches par Irradiation C.N.R.S, Orléans, France
CERN	Centre Europeen de Recherche Nucleaire, Geneva, Suisse (LHC, PS-Division, SL-Division)
COSY	Cooler Synchrotron, IKP, FZ Jülich, Germany (COSY Status)
CYCLONE	Cyclotron of Louvain la Neuve, Louvain-la-Neuve, Belgium
DELTA	Dortmunder ELekTronenspeicherring-Anlage, Zentrum für Synchrotronstrahlung der Technischen Universität Dortmund, Germany
DESY	Deutsches Elektronen Synchrotron, Hamburg, Germany (XFEL, PETRA III, FLASH, ILC)
ELBE	ELectron source with high Brilliance and low Emittance, Forschungszentrum Dresden - Rossendorf e.V. (FZD), Germany
ELETTRA	AREA Science Park, Trieste, Italy
ELSA	Electron Stretcher Accelerator, Bonn University, Germany (ELSA status)
ESRF	European Synchrotron Radiation Facility, Grenoble, France
GANIL	Grand Accélérateur National d'Ions Lourds, Caen, France (GANIL, SPIRAL2)
GSI	Gesellschaft für Schwerionenforschung, Darmstadt, Germany
HISKP	Helmholtz-Institut für Strahlen- und Kernphysik, Bonn, Germany (Isochron Cyclotron)
IHEP	Institute for High Energy Physics, Protvino, Moscow region, Russian Federation
INFN	Istituto Nazionale di Fisica Nucleare, Italy, LNF - Laboratori Nazionali di Frascati (DAFNE, DAFNE beam test facility) LNL - Laboratori Nazionali di Legnaro (Tandem, CN Van de Graaff, AN 2000 Van de Graaff), LNS - Laboratori Nazionali del Sud, Catania, (Superconducting Cyclotron)
ISA	Institute for Storage Ring Facilities (ASTRID, ASTRID2, ELISA), Aarhus, Denmark
ISIS	Rutherford Appleton Laboratory, Oxford, U.K.
JINR	Joint Institute for Nuclear Research, Dubna, Russian Federation (U-400, U-400M, LHE Synchrophasotron / Nuclotron)
JYFL	Jyväskylän Yliopiston Fysiikan Laitos, Jyväskylä, Finland
MLL	Maier-Leibnitz-Laboratorium: Accelerator of LMU and TU Muenchen, Munich, Germany
MAMI	Mainzer Microtron, Mainz U, Germany
MAX-Lab	Lund University, Sweden
MPI-HD	Max Planck Institut für Kernphysik, Heidelberg, Germany
MSL	Manne Siegbahn Laboratory, Stockholm, Sweden (CRYRING)
RUBION	Zentrale Einrichtung für Ionenstrahlen und Radionuklide, Universität Bochum, Germany
SLS	Paul Scherrer Institut PSI, Villigen, Switzerland
SRS	Synchrotron Radiation Source, Daresbury Laboratory, Daresbury, U.K. (Closed since Aug. 18th, 2008)
TSL	The Svedberg Laboratory, Uppsala University, Sweden

Accelerators of the World

North America

88" Cycl.	88-Inch Cyclotron, Lawrence Berkeley Laboratory (LBL), Berkeley, CA
ALS	Advanced Light Source, Lawrence Berkeley Laboratory (LBL), Berkeley, CA (ALS Status)
ANL	Argonne National Laboratory, Chicago, IL (Advanced Photon Source APS [status], Intense Pulsed Neutron Source IPNS, Argonne Tandem Linac Accelerator System ATLAS)
BNL	Brookhaven National Laboratory, Upton, NY (AGS, ATF, NSLS, RHIC)
CAMD	Center for Advanced Microstructures and Devices
CESR	Cornell Electron-positron Storage Ring, Cornell University, Ithaca, NY (CESR Status)
CHESS	Cornell High Energy Synchrotron Source, Cornell University, Ithaca, NY
CLS	Canadian Light Source, U of Saskatchewan, Saskatoon, Canada
CNL	Crocker Nuclear Laboratory, University of California Davis, CA
FNAL	Fermi National Accelerator Laboratory , Batavia, IL (Tevatron)
IAC	Idaho accelerator center, Pocatello, Idaho
ININ	National Institute for Nuclear Research, Mexico
IUCF	Indiana University Cyclotron Facility, Bloomington, Indiana
JLab	aka TJNAF, Thomas Jefferson National Accelerator Facility (formerly known as CEBAF), Newport News, VA
LAC	Louisiana Accelerator Center, U of Louisiana at Lafayette, Louisiana
LANL	Los Alamos National Laboratory
MIBL	Michigan Ion Beam Laboratory, University of Michigan
NSCL	National Superconducting Cyclotron Laboratory, Michigan State University
ORNL	Oak Ridge National Laboratory Oak Ridge, Tennessee
PBPL	Particle Beam Physics Lab (Neptune-Laboratory, PEGASUS - Photoelectron Generated Amplified Spontaneous Radition Source)
SLAC	Stanford Linear Accelerator Center, (SLC - SLAC Linear electron positron Collider, SSRL - Stanford Synchrotron Radiation Laboratory)
SNS	Spallation Neutron Source, Oak Ridge, Tennessee
SRC	Synchrotron Radiation Center, U of Wisconsin - Madison
SURF III	Synchrotron Ultraviolet Radiation Facility, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland
TRIUMF	Canada's National Laboratory for Particle and Nuclear Physics, Vancouver, BC (Canada)
UNAM	Universidad Nacional Autónoma de México, Mexico

South America

LNLS	Laboratorio Nacional de Luz Sincrotron, Campinas SP, Brazil
TANDAR	Tandem Accelerator, Buenos Aires, Argentina

Accelerators of the World

Asia

BEPC	Beijing Electron-Positron Collider, Beijing, China
HLS	Hefei Light Source, Univ. of Science & Technology of China, Hefei city, China
INDUS	Centre for Advanced Technology CAT, INDORE, India
KEK	National Laboratory for High Energy Physics ("Koh-Ene-Ken"), Tsukuba, Japan (KEK-B, PF,)
NSC	Nuclear Science Centre, New Delhi, India (15 UD Pelletron Accelerator)
PLS	Pohang Light Source, Pohang, Korea
RIKEN	Institute of Physical and Chemical Research ("Rikagaku Kenkyusho"), Hirosawa, Wako, Japan
SESAME	Synchrotron-light for Experimental Science and Applications in the Middle East, Jordan (under construction)
SPring-8	Super Photon ring - 8 GeV, Japan
SRRC	Synchrotron Radiation Research Center, Hsinchu, Taiwan
VECC	Variable Energy Cyclotron, Calcutta, India
BINP	Budker Institute of Nuclear Physics, Novosibirsk, Russia (VEPP-3, VEPP-4M, VEPP-2000)

Africa

NAC	National Accelerator Centre, Cape Town, South Africa

Australia

Australian Synchrotron	Melbourne, Victoria, Australia

Accelerators of the World

Sorted by Accelerator Type

Electrons

Stretcher Ring/Continuous Beam facilities

ELSA (Bonn U), JLab, MAMI (Mainz U), MAX-Lab, SLAC

Synchrotron Light Sources

ALBA, ANKA (FZK), ALS (LBL), APS (ANL), ASTRID (ISA), Australian Synchrotron, BESSY, CAMD (LSU), CHESS (Cornell Wilson Lab), CLS (U of Saskatchewan), DELTA (U of Dortmund), ELBE (FZD), Elettra, ELSA (Bonn U), ESRF, HASYLAB (DESY), HLS, INDUS (CAT), MAX-Lab, LNLS, NSLS, PF (KEK), PLS, SESAME, SLS (PSI), SPEAR (SSRL, SLAC), SPring-8, SRC (U of Wisconsin), SRRC, SRS, SURF III (NIST)

Other

IAC, Neptune, PEGASUS UNAM,

Protons

88" Cyclotron (LBL), CERI, CNL (UC DAVIS), COSY (FZ Jülich), IPNS (ANL), ISL (HMI), ININ, ISIS, IUCF, LHC (CERN), NAC, PS (CERN), PSI, RHIC (BNL), SPS (CERN), TRIUMF, TSL

Light and Heavy Ions

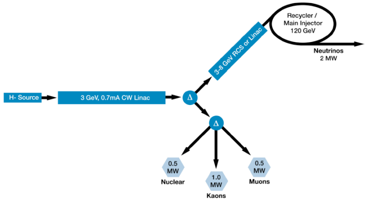
88" Cyclotron (LBL), AGOR, ASTRID, CNL (UC DAVIS), (ISA), ATLAS (ANL), CERI, CRYRING (MSL), CYCLONE, GANIL, GSI, HISKP, ININ, ISL (HMI), IUCF, JYFL, LAC, LHC (CERN), LHE Synchrophasotron / Nuclotron (JINR), LNL (INFN), LNS (INFN), Maier-Leibnitz-Laboratorium, MIBL, MPI-HD, NAC, NSC, ORNL, PSI, RHIC (BNL), RUBION, SBSL, SNS, SPS (CERN), TANDAR, TSL, U-400 / U-400M (JINR), UNAM, VECC

Collider

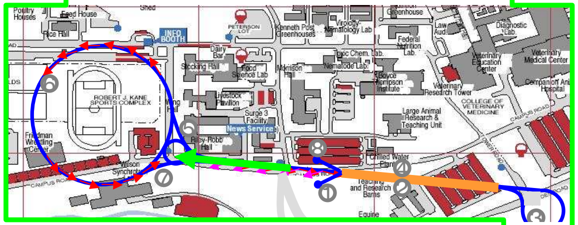
BEPC, CESR, DAFNE (LNF), HERA (DESY), LHC (CERN), PEP-II (SLAC), SLC (SLAC), KEK-B (KEK), RHIC (BNL), TESLA (DESY), Tevatron (FNAL), VEPP-3, VEPP-4M, VEPP-2000 (BINP)

The Future

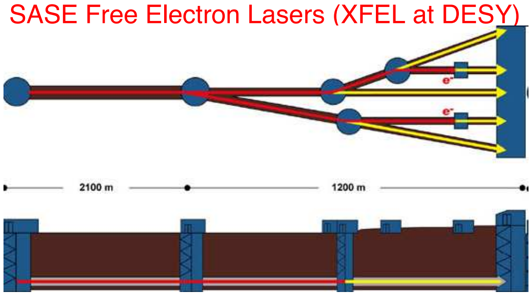
Project-X at Fermilab



Energy Recovery Linacs



SASE Free Electron Lasers (XFEL at DESY)



Linear Colliders