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8. Accelerator Measurements
9. RF Systems for Particle Acceleration
10. Luminosity
**Required:**

**Optional:**

**Related material:**

Accelerator Physics has applications in particle accelerators for high energy physics or for x-ray science, in spectrometers, in electron microscopes, and in lithographic devices. These instruments have become so complex that an empirical approach to properties of the particle beams is by no means sufficient and a detailed theoretical understanding is necessary. This course will introduce into theoretical aspects of charged particle beams and into the technology used for their acceleration.

- Physics of beams
- Physics of non-neutral plasmas
- Physics of involved in the technology:
  - Superconductivity in magnets and radiofrequency (RF) devices
  - Surface physics in particle sources, vacuum technology, RF devices
  - Material science in collimators, beam dumps, superconducting materials
Different accelerators

Source
Condenser lenses
Condenser aperture
Sample
Objective lens
Objective aperture
Intermediate lens
Projector lens
Main screen

LHC at CERN

4.3 km

Sources & LINACS
LEIR
PS
PSB
AD
SPS
LHC
A short history of accelerators

- 1862: Maxwell theory of electromagnetism
- 1887: Hertz discovery of the electromagnetic wave
- 1886: Goldstein discovers positively charged rays (ion beams)
- 1894: Lenard extracts cathode rays (with a 2.65um Al Lenard window)
- 1897: JJ Thomson shows that cathode rays are particles since they followed the classical Lorentz force $m\ddot{a} = e(\vec{E} + \vec{v} \times \vec{B})$ in an electromagnetic field
- 1926: GP Thomson shows that the electron is a wave (1929-1930 in Cornell, NP in 1937)
A short history of accelerators

- 1911: Rutherford discovers the nucleus with 7.7MeV $^4$He from $^{214}$Po alpha decay measuring the elastic cross section of $^{197}$Au + $^4$He $\leftrightarrow$ $^{197}$Au + $^4$He.

$$E = \frac{Z_1 e Z_2 e}{4\pi \varepsilon_0 d} = Z_1 Z_2 m_e c^2 \frac{r_e}{d},$$

$$r_e = 2.8\text{fm}, \quad m_e c^2 = 0.511\text{MeV}$$

$d =$ smallest approach for back scattering

- 1919: Rutherford produces first nuclear reactions with natural $^4$He $^{14}$N + $^4$He $\leftrightarrow$ $^{17}$O + $p$

- 1921: Greinacher invents the cascade generator for several 100 keV

- Rutherford is convinced that several 10 MeV are in general needed for nuclear reactions. He therefore gave up the thought of accelerating particles.
Tunneling allows low energies

1928: Explanation of alpha decay by Gamov as tunneling showed that several 100keV protons might suffice for nuclear reactions.

Schroedinger equation:

\[ \frac{\partial^2}{\partial r^2} u(r) = \frac{2m}{\hbar^2} [V(r) - E] u(r), \quad T = \left| \frac{u(L)}{u(0)} \right|^2 \]

The transmission probability \( T \) for an alpha particle traveling from the inside towards the potential well that keeps the nucleus together determines the lifetime for alpha decay.

\[
V(r) = V_0 \frac{R}{r}, \quad L = \frac{V_0}{E} R
\]

\[
T \approx \exp \left[ -2 \int_{R}^{L} \frac{\sqrt{2m[V(r) - E]}}{\hbar} dr \right]
\]

\[
\ln T \approx A - \frac{C}{\sqrt{E}}
\]

\[
10^{-6} \text{s} \approx 3 \mu s
\]

\[
10^{17} \text{s} \approx 3 \text{GYears}
\]
Direct Voltage Accelerators

Resonant Accelerators  Transformer Accelerator

The energy limit is given by the maximum possible voltage. At the limiting voltage, electrons and ions are accelerated to such large energies that they hit the surface and produce new ions. An avalanche of charge carries causes a large current and therefore a breakdown of the voltage.
1930: van de Graaff builds the first 1.5MV high voltage generator

Today Peletrons (with chains) or Laddertron (with stripes) that are charged by influence are commercially available.

- Used as injectors, for electron cooling, for medical and technical n-source via \( d + t \rightarrow n + \alpha \)
- Up to 17.5 MV with insulating gas (1MPa SF\(_6\))
The Tandem Accelerator

- Two Van de Graaffs, one + one –
- The Tandem Van de Graaff, highest energy 35MeV

1932: Brasch and Lange use potential from lightening, in the Swiss Alps, Lange is fatally electrocuted
The Cockcroft-Walton Accelerator

1932: Cockcroft and Walton used 700keV cascator generator (planned for 800keV) and use initially 400keV protons for $^7\text{Li} + p \rightarrow ^{4}\text{He} + ^{4}\text{He}$ and $^7\text{Li} + p \rightarrow ^7\text{Be} + n$

The Greinacker circuit

transformer

Up to 4MeV, 1A

NP 1951
Sir John D Cockcroft
Ernest T S Walton

Georg.Hoffstaettter@Cornell.edu USPAS Advanced Accelerator Physics 12-23 June 2006
1932: Marx Generator achieves 6MV at General Electrics

After capacitors of around 2uF are filled to about 20kV, the spark gaps or switches close as fast as 40ns, allowing up to 500kA.

Today:
The Z-machine (Physics Today July 2003) for z-pinch initial confinement fusion has 40TW for 100ns from 36 Marx generators
Three historic lines of accelerators

Resonant Accelerators

Direct Voltage Accelerators

Transformer Accelerator

Particles must have the correct phase relation to the accelerating voltage.
The Cyclotron

- 1930: Lawrence proposes the Cyclotron (before he develops a workable color TV screen)
- 1932: Lawrence and Livingston use a cyclotron for 1.25MeV protons and mention longitudinal (phase) focusing
- 1934: Livingston builds the first Cyclotron away from Berkeley (2MeV protons) at Cornell (in room B54)
The cyclotron frequency

\[ F_r = m_0 \gamma \omega_z v = qvB_z \]

\[ \omega_z = \frac{q}{m_0 \gamma} B_z = \text{const} \]

Condition: Non-relativistic particles.
Therefore not for electrons.

- The synchrocyclotron:
  Acceleration of bunches with decreasing
  \[ \omega_z(E) = \frac{q}{m_0 \gamma(E)} B_z \]

- The isocyclotron with constant
  \[ \omega_z = \frac{q}{m_0 \gamma(E)} B_z (r(E)) \]

Up to 600 MeV but this vertically defocuses the beam

1938: Thomas proposes strong (transverse) focusing for a cyclotron
1939: Lawrence uses 60’ cyclotron for 9MeV protons, 19MeV deuterons, and 35MeV 4He. First tests of tumor therapy with neutrons via $d + t \rightarrow n + \alpha$
With 200-800keV d to get 10MeV neutrons.
Modern Nuclear Therapy

The Loma Linda proton therapy facility
Electrons are quickly relativistic and cannot be accelerated in a cyclotron.
In a microtron the revolution frequency changes, but each electron misses an integer number of RF waves.

Today: Used for medical applications with one magnet and 20MeV.
Nuclear physics: MAMI designed for 820MeV as race track microtron.
The microtron condition

- The extra time that each turn takes must be a multiple of the RF period.

\[
\frac{dp}{dt} = qvB \Rightarrow \rho = \frac{dl}{d\phi} = \frac{vdt}{dp / p} = \frac{p}{qB}
\]

\[dp = pd\phi\]

\[\Delta t = 2\pi \left( \frac{\rho_{n+1}}{v_{n+1}} - \frac{\rho_n}{v_n} \right)\]

\[= \frac{2\pi}{qB} \left( m_0\gamma_{n+1} - m_0\gamma_n \right) = \frac{2\pi}{qBc^2} \Delta K\]

\[\Delta K = n \frac{qBc^2}{\omega_{RF}} \text{ for an integer } n\]

B=1T, n=1, and f_{RF}=3GHz leads to 4.78MeV

This requires a small linear accelerator.
non-relativistic:

\[ K_n = nqU_{\text{max}} \sin \psi_0 = \frac{1}{2} m v_n^2 \]

\[ l_n = \frac{1}{2} v_n T_{RF} = \frac{1}{2} \beta_n \lambda_{RF} \propto \sqrt{n} \]

Called the \( \pi \) or the \( 1/2\beta\lambda \) mode
1933: J.W. Beams uses resonant cavities for acceleration

Traveling wave cavity:
\[ v_{\text{phase}} = \frac{\omega}{k} = v_{\text{particle}} \quad \text{Here } v = c \text{ for electrons} \]

\[ E(t, s) \approx E_{\text{max}} \sin(\omega t - ks) \]

Standing wave cavity:
\[ \frac{\omega}{k} = v_{\text{particle}} \]

\[ E(t, s) \approx E_{\text{max}} \sin(\omega t) \sin(ks) \]
\[ E\left(\frac{s}{v_{\text{particle}}}, s\right) \approx E_{\text{max}} \sin^2(ks) \]
\[ \pi \text{ or the } 1/2\beta \lambda \text{ mode} \]

Transit factor (for this example):
\[ \langle E \rangle = \frac{1}{\lambda_{RF}} \int_0^{\lambda_{RF}} E\left(\frac{s}{v_{\text{particle}}}, s\right) ds \approx \frac{1}{2} E_{\text{max}} \]
The Alvarez Linear Accelerator

$2\pi$ or the $\beta \lambda$ mode

Needs only one power input coupler and walls do not dissipate energy.
1945: Veksler (UDSSR) and McMillan (USA) realize the importance of phase focusing.

\[ \Delta K = qU(t) = qU_{\text{max}} \sin(\omega(t - t_0) + \psi_0) \]

Longitudinal position in the bunch:

\[ \sigma = s - s_0 = -v_0(t - t_0) \]

\[ \Delta K(\sigma) = qU_{\text{max}} \sin(-\frac{\omega}{v_0}(s - s_0) + \psi_0) \]

\[ \Delta K(0) > 0 \quad \text{(Acceleration)} \]

\[ \Delta K(\sigma) < \Delta K(0) \text{ for } \sigma > 0 \implies \frac{d}{d\sigma} \Delta K(\sigma) < 0 \quad \text{(Phase focusing)} \]

\[ qU(t) > 0 \]
\[ q \frac{d}{dt} U(t) > 0 \]

\[ \psi_0 \in (0, \frac{\pi}{2}) \]

Phase focusing is required in any RF accelerator.
1970: Kapchinskii and Teplyakov invent the RFQ
Three historic lines of accelerators

Direct Voltage Accelerators  Resonant Accelerators

- 1924: Wideroe invents the betatron
- 1940: Kerst and Serber build a betatron for 2.3MeV electrons and understand betatron (transverse) focusing (in 1942: 20MeV)

**Betatron:**
\[ R=\text{const, } B=B(t) \]

Whereas for a cyclotron:
\[ R(t), B=\text{const} \]

No acceleration section is needed since
\[
\oint E \cdot d\vec{S} = -\int \int_A \frac{d}{dt} \vec{B} \cdot d\vec{a}
\]

![Diagram of a betatron and cyclotron](image)
The Betatron Condition

Condition: \[ R = \frac{-p_\phi(t)}{qB_z(R,t)} = \text{const.} \]

Given \( \oint \vec{E} \cdot d\vec{s} = -\iint_A \frac{d}{dt} \vec{B} \cdot d\vec{a} \)

\[ E_\phi(R,t) = -\frac{1}{2\pi R} \int \frac{d}{dt} B_z(r,t) r dr d\varphi = -\frac{R}{2} \left\langle \frac{d}{dt} B_z \right\rangle \]

\[ \frac{d}{dt} p_\phi(t) = qE_\phi(R,t) = -q \frac{R}{2} \left\langle \frac{d}{dt} B_z \right\rangle \]

\[ p_\phi(t) = p_\phi(0) - q \frac{R}{2} \left[ \langle B_z \rangle(t) - \langle B_z \rangle(0) \right] = -RqB_z(R,t) \]

\[ B_z(R,t) - B_z(R,0) = \frac{1}{2} \left[ \langle B_z \rangle(t) - \langle B_z \rangle(0) \right] \]

Small deviations from this condition lead to transverse beam oscillations called betatron oscillations in all accelerators.

- Today: Betatrons with typically about 20MeV for medical applications
• 1945: Veksler (UDSSR) and McMillan (USA) invent the synchrotron
• 1946: Goward and Barnes build the first synchrotron (using a betatron magnet)
• 1949: Wilson et al. at Cornell are first to store beam in a synchrotron (later 300MeV, magnet of 80 Tons)
• 1949: McMillan builds a 320MeV electron synchrotron

- Many smaller magnets instead of one large magnet
- Only one acceleration section is needed, with

\[ R = \frac{p(t)}{qB(R,t)} = \text{const.} \]

\[ \omega = 2\pi \frac{\nu_{\text{particle}}}{L} n \]

for an integer \( n \) called the harmonic number
Rober R Wilson, Architecture

Science Ed Center, FNAL (1990)

Robert R Wilson
USA 1914-2000

Wilson Hall, FNAL
Broken symmetry

Mobius strip

Tractricious

π lines

Hyperbolic obelisk

Rober R Wilson, Cornell & FNAL
1952: Operation of the Cosmotron, 3.3 GeV proton synchrotron at Brookhaven: Beam pipe height: 15cm.

Natural ring focusing:

Vertical focusing + Horizontal defocusing + ring focusing

Focusing in both planes

The Cosmotron
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)

Transverse fields defocus in one plane if they 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

\[ \rho = \frac{p}{qB} \implies \text{The rings become too long} \]

Protons with \( p = 20 \text{ TeV/c} \), \( B = 6.8 \text{ T} \) would require a 87 km SSC tunnel
Protons with \( p = 7 \text{ TeV/c} \), \( B = 8.4 \text{ T} \) require CERN’s 27 km LHC tunnel

\[ P_{\text{radiation}} = \frac{e}{6\pi\varepsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \downarrow \]

Energy needed to compensate
Radiation becomes too large

Electron beam with \( p = 0.1 \text{ TeV/c} \) in CERN’s 27 km LEP tunnel radiated 20 MW
Each electron lost about 4 GeV per turn, requiring many of RF accelerating sections.
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 (designed for 8GeV)

Advantage:
More center of mass energy

Drawback:
Less dense target
The beams therefore must be stored for a long time.
Ellements of a Collider

- Saving one beam while injection another
- Avoiding collisions outside the detectors.
- Compensating the forces between $e^+$ and $e^-$ beams
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 radiation.
Further Development of Colliders

- 1981: Rubbia and van der Meer use stochastic cooling of antiportons 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
- 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 being build at CERN
Special Relativity

\[ E = mc^2 \]

Four-Vectors:

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

Examples:

\[ X^\mu \in \{ct, x, y, z\} \]

\[ P^\mu \in \left\{ \frac{1}{c} E, p_x, p_y, p_z \right\} \]

\[ \Phi^\mu \in \left\{ \frac{1}{c} \phi, A_x, A_y, A_z \right\} \]

\[ J^\mu \in \left\{ c \rho, j_x, j_y, j_z \right\} \]

\[ K^\mu \in \left\{ \frac{1}{c} \omega, k_x, k_y, k_z \right\} \]

\[ X^\mu \in \{ct, x, y, z\} \implies X^\mu X_\mu = (ct)^2 - \vec{x}^2 = \text{const.} \]

\[ P^\mu \in \left\{ \frac{1}{c} E, p_x, p_y, p_z \right\} \implies P^\mu P_\mu = \left( \frac{E}{c} \right)^2 - \vec{p}^2 = (m_0 c)^2 = \text{const.} \]
Available Energy

\[ \frac{1}{c^2} E_{\text{cm}}^2 = \left( P_1^\mu + P_2^\mu \right)_{\text{cm}} \left( P_1^\mu + P_2^\mu \right)_{\text{cm}} \]
\[ = \left( P_1^\mu + P_2^\mu \right) \left( P_1^\mu + P_2^\mu \right) \]
\[ = \frac{1}{c^2} \left( E_1 + E_2 \right)^2 - \left( p_{z1} - p_{z2} \right)^2 \]
\[ = 2 \left( \frac{E_1 E_2}{c^2} + p_{z1} p_{z2} \right) + \left( m_{01} c \right)^2 + \left( m_{02} c \right)^2 \]

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

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

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

\[ E_1 \gg m_{01} c^2; E_2 \gg m_{02} c^2 \quad \Rightarrow \quad E_{\text{cm}} = 2 \sqrt{E_1 E_2} \]
Energy that would be needed in a fixed target experiment versus the year of achievement

\[ E_1 = \frac{E_{cm}^2}{2m_{02}c^2} \]

Comparison:

highest energy cosmic rays have a few \(10^{20}\) eV
Example: Production of the pbar

1954: Operation of Bevatron, first proton synchrotron for 6.2GeV, production of the antiporton by Chamberlain and Segrè

\[ p + p \rightarrow p + p + p + \bar{p} \]

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

\[ (4m_{p0} c)^2 < \frac{1}{c^2} E_{cm}^2 = 2\frac{E_1 m_{p0}}{c^2} + (m_{p0} c)^2 + (m_{p0} c)^2 \]

\[ 7m_{p0} c^2 < E_1 \]

\[ K_1 = E_1 - m_0 c^2 > 6m_{p0} c^2 = 5.628 \text{ GeV} \]
Example: c-cbar states

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

$$\frac{1}{c^2} E_{cm}^2 = 2\left(\frac{E_1 E_2}{c^2} + p_{z_1} p_{z_2}\right) + (m_{01}c)^2 + (m_{02}c)^2$$

$$E_1 = E_2 \implies E_{cm}^2 = 4E^2$$

Energy per beam: $K = E - m_0c = 1547\text{MeV}$

Beam energy needed for an equivalent fixed target experiment:

$$\frac{E_{cm}^2}{c^2} = 2[Em + (mc)^2]$$

$$K = E - m_{0e}c^2 = \frac{E_{cm}^2 - 4(m_{0e}c^2)^2}{2m_{0e}c^2} = 9.4\text{TeV}$$
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: TANTALOS, first dedicated storage ring for synchrotron radiation

Dale Corson
Cornell’s 8th president
USA 1914 –
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 (4th Generation): Construction of Free Electron Lasers (FELs) driven by LINACs
# Sort by Location

## Europe

<table>
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<tr>
<th>Code</th>
<th>Description</th>
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<td>AGOR</td>
<td>Accelerateur Groningen-ORsay, KVI Groningen, Netherlands</td>
</tr>
<tr>
<td>ANKA</td>
<td>Ångströmquelle Karlsruhe, Karlsruhe, Germany (Forschungsgruppe Synchrotronstrahlung (FGS))</td>
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<tr>
<td>ASTRID</td>
<td>Aarhus Storage Ring in Denmark, ISA, Aarhus, Denmark</td>
</tr>
<tr>
<td>BESSY</td>
<td>Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung, Germany (BESSY1 status, BESSY II status)</td>
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<tr>
<td>BIP</td>
<td>Budker Institute for Nuclear Physics, Novosibirsk, Russian Federation (VEPP-2M collider, VEPP-4M collider (status))</td>
</tr>
<tr>
<td>CERN</td>
<td>Centre Européen de Recherche Nucléaire, Geneva, Switzerland (LEP &amp; SPS Status, LHC, CLIC, PS-Division, SLD-Division)</td>
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<td>COSY</td>
<td>Cooler Synchrotron, IFP, FZ Jülich, Germany (COSY Status)</td>
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<td>CYCLONE</td>
<td>Cyclotron of Louvain-la-Neuve, Louvain-la-Neuve, Belgium</td>
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<td>DELTA</td>
<td>Dortmund Electron Test Accelerator, U of Dortmund, Germany (DELTA Status)</td>
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<td>DESY</td>
<td>Deutsches Elektronen Synchrotron, Hamburg, Germany (HERA, PETRA and DORIS status, TESLA)</td>
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<td>ELBE</td>
<td>Electron source with high brilliance and low emittance, FZ Rossendorf, Germany</td>
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<td>ELETTRA</td>
<td>Trieste, Italy (ELETTRA status)</td>
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<td>ELSA</td>
<td>Electron Stretcher Accelerator, Bonn University, Germany (ELSA status)</td>
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<tr>
<td>ESRF</td>
<td>European Synchrotron Radiation Facility, Grenoble, France (ESRF status)</td>
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<td>GANIL</td>
<td>Grand Accélérateur National d’Ions Lourds, Caen, France</td>
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<tr>
<td>GSI</td>
<td>Gesellschaft für Schwerionenforschung, Darmstadt, Germany</td>
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<tr>
<td>IHEP</td>
<td>Institute for High Energy Physics, Moscow, Moscow region, Russian Federation</td>
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<tr>
<td>INFN</td>
<td>Istituto Nazionale di Fisica Nucleare, Italy, LNF - Laboratori Nazionali di Frascati (CIFNE, other accelerators), LNL - Laboratori Nazionali di Legnaro (Tandem, CN Van de Graaff, AN 2000 Van de Graaff, LNS - Laboratori Nazionali del Sud, Catania, Superconducting Collider &amp; Van de Graaff Tandem)</td>
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<td>ISIS</td>
<td>Rutherford Appleton Laboratory, Oxford, U.K (ISIS Status)</td>
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<tr>
<td>JIL</td>
<td>Institut für Lehre und Forschung, Jülich, Germany</td>
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<tr>
<td>JINR</td>
<td>Joint Institute for Nuclear Research, Dubna, Russian Federation (U-200, U-400, U-40CM, Storage Ring, LHE Synchrophasotron (Nucleotron))</td>
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<tr>
<td>JYFL</td>
<td>Jyväskylän Yliopiston Yksiköt Lapin Laitos, Jyväskylä, Finland</td>
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<tr>
<td>KTH</td>
<td>Kungliga Tekniska Högskolan (Royal Institute of Technology), Stockholm, Sweden (Alfén Lab electron accelerators)</td>
</tr>
</tbody>
</table>
### Accelerators of the World

| LMU      | Accelerator of LMU and TU Muenchen, Munich, Germany |
| LURE    | Laboratoire pour l'Utilisation du Rayonnement Electromagnétique, Orsay, France (DCI, Super-ACO status, CLIC) |
| MANI    | Max-Planck-Institut, Mainz, Germany |
| MAPP-Lab| Lund University, Sweden |
| MIST    | Max-Planck-Institut, Stockholm, Sweden (CRYRING) |
| NICHEF  | National Institut voor Kernfysica en Hoge-Energiefysica, Amsterdam, Netherlands (AmIFS closed) |
| FSI     | Paul Scherrer Institute, Villigen, Switzerland (FSI status, SLS under construction) |
| S-DALINAC| Darmstadt University of Technology, Germany (S-DALINAC status) |
| SRS     | Synchrotron Radiation Source, Daresbury Laboratory, Warrington, UK (SRS Status) |
| TSL     | The Svedberg Laboratory, Uppsala University, Sweden (CELSIUS) |
| TSR     | Heavy-Ion Test Storage Ring, Heidelberg, Germany |

### North America

| BEPC    | Beijing Electron-Positron Collider, Beijing, China |
| KEK     | National Laboratory for High Energy Physics (Nishina Kenzo), Tsukuba, Japan (KEK-1, KEK-2, KEK-3) |
| NSC     | Nuclear Science Centre, New Delhi, India (16 UD Pelletron Accelerator) |
| PLS     | Pohang Light Source, Pohang, Korea |
| RIKEN   | Institute of Physical and Chemical Research (Riken Joukan), Saitama, Japan |
| SNS     | Spallation Neutron Source, Oak Ridge, Tennessee |
| SRC     | Spallation Neutron Source, Oak Ridge, Tennessee |

### Asia

| ERL     | Electron Ring Accelerator, Osaka, Japan |
| KEK     | National Accelerator Facility, Tsukuba, Japan |
| NSC     | Nuclear Science Centre, New Delhi, India |
| PLS     | Pohang Light Source, Pohang, Korea |
| RIKEN   | Institute of Physical and Chemical Research (Riken Joukan), Saitama, Japan |
| SNS     | Spallation Neutron Source, Oak Ridge, Tennessee |
| SRC     | Spallation Neutron Source, Oak Ridge, Tennessee |

### Africa

| NAC     | National Accelerator Centre, Cape Town, South Africa |

### North America

| BNL     | Brookhaven National Laboratory, Upton, NY (AGS, AFW, ALS, RHIC) |
| CERN    | Center for Advanced Microstructures and Devices |
| CHES    | Cornell High Energy Synchrotron Source, Cornell University, Ithaca, NY |
| CLS     | Canadian Light Source, Saskatoon, Canada |
| CESR    | Cornell Electron-positron Storage Ring, Cornell University, Ithaca, NY (CESR Status) |
| FNAL    | Fermi National Accelerator Laboratory, Batavia, IL (Tevatron) |
| IAC     | Idaho Accelerator Center, Post Falls, Idaho |
| IUCL    | Indiana University Cyclotron Facility, Bloomington, Indiana |
| JLab    | Japan Atomic Energy Research Institute (Japan-KEK), Tokai, Japan |
| LBL     | Lawrence Berkeley Laboratory, Berkeley, CA (ALS Status) |
| LANL    | Los Alamos National Laboratory |

### South America

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

### Sorted by Accelerator Type

#### Electrons

### Stretcher Ring/Continuous Beam facilities

| ELSA, ESS, JLab, KNL, MAMI, MAC, NIKHEF, NIRF, PSI (SLS), S-DA-LINAC, TH-Darmstadt, SLC |
Synchrotron Light Sources

ANKA (FZK), ALS (LBL), APS (ANL), ASTRID (ISA), BESSY, CAMD (LSU), CHESS (Cornell Wilson Lab), CLS (U of Saskatchewan), DELTA (U of Dortmund), ELBE (FZ Rossendorf), Elettra, ELSA (Bonn U), ESRF, HASYLAB (DESY), LURE, MAX-Lab, LNLS, NSLS (BNL), PF (KEK), UVSOR (IMS), PLS, S-DALINAC (TH Darmstadt), SESAME, SLS (PSI), SPEAR (SSRL, SLAC), SPring-8, SRC (U of Wisconsin), SRRC, SRS (Daresbury), SURF II (NIST)

Other

Alfén Lab (KTH), IAC

Protons

88" Cyclotron (LBL), CELSIUS (TSL), COSY (FZ Jülich), IPNS (ANL), ISL (HMI), ISIS, IUCF, LHC (CERN), NAC, PS (CERN), PSI, SPS (CERN)

Light and Heavy Ions

88" Cyclotron (LBL), AGOR, ASTRID (ISA), ATLAS (ANL), CELSIUS (TSL), CRYRING (MSL), CYCLONE, EN Tandem (ORNL), GANIL, GSI, ISL (HMI), IUCF, JYFL, LAC, LHC (CERN), LHE Synchrophasotron / Nuclotron (JINR), LMUTUM, LNL (INFN), LNS (INFN), NAC, NSC, PSI, RHIC (BNL), SBSL, SNS, SPS (CERN), TANDAR, TSR, U-200 / U-400 / U-400M / Storage Ring (JINR), VECC

Collider

BEP, CESR, DAIFNE (LNF), HERA (DESY), LEP (CERN), LHC (CERN), PEP / PEP-II (SLAC), SLC (SLAC), KEK-B (KEK), TESLA (DESY), Tevatron (FNAL), VEPP-2M, VEPP-4M (BINP)
The Future

Energy Recovery Linacs

SASE Free Electron Lasers

Linear Colliders

To Existing Linac
RF Gun
Linac 0
Linac 1
Bunch Compressor 1
Linac 2
Bunch Compressor 2
Linac 3
Undulator
To B Factory
To Photon Lines

1 km