Fundamental Concepts of Particle Accelerators

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The Dawn of Particle Accelerator Technology

- Artificial disintegration of atomic nuclei
- First Accelerators
- from DC Acceleration to RF Acceleration
- Problems in RF Acceleration
- Rapid Development of Electronics around World War II (1941 - 1945) or after

First artificial disintegration of atomic nuclei (1)

- Ernest Rutherford's discovery of nuclear disintegration (1917 - 1919)
  - He confirmed that protons were produced in a nitrogen-gas filled container in which a radioactive source emitting alpha particles was placed.

$$\alpha + {}^{14}_{7}\mathrm{N} \rightarrow p + {}^{16}_{8}\mathrm{O}$$

- This provoked strong demand for artificially generate high energy beams to study the nuclear disintegration phenomena in more detail.
- Thus started the race for developing high energy accelerators, and Rutherford himself was a great advocator.

First artificial disintegration of atomic nuclei (2)

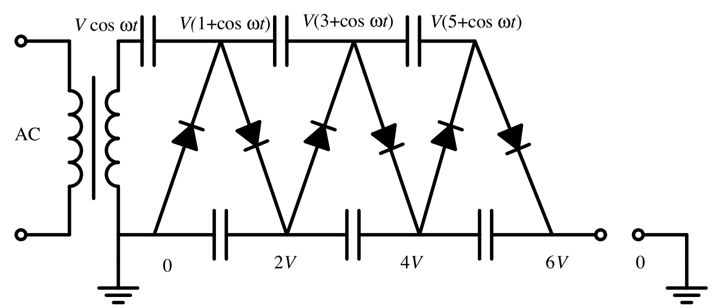
- The first disintegration of atomic nuclei with accelerator beams was achieved at the Cavendish Laboratory in 1932 by John D. Cockcroft and Ernest T. S. Walton, who used 800 kV proton beams from a DC voltage-multiplier.

$$p + {}^{7}_{3}\mathrm{Li} \rightarrow \alpha + \alpha$$

DC HV Accelerators

- DC Generators : two major methods
  - Cockcroft & Walton's 800 kV voltage-multiplier circuit with capacitors and rectifier tubes
  - Van de Graaff's 1.5 MV belt-charged generator (1931)
- Electrostatic accelerators are still in use for the mass spectroscopy, because of their fine and stable tunability of the acceleration voltage.
  - analysis of the ratio $^{14}C/^{12}C$: an important tool for archaeology

Cockcroft & Walton's voltage-multiplier circuit



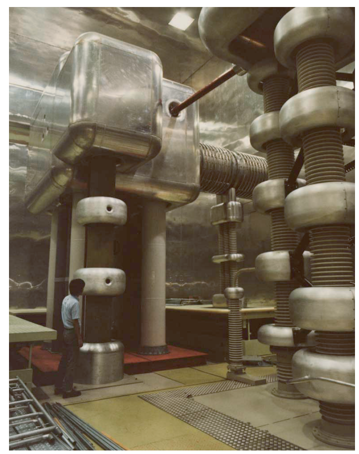
Cockcroft around 1932

See the picture in *From X-rays to Quarks, page 227* by Segrè, E. (W. H. Freeman and Company, 1980) .

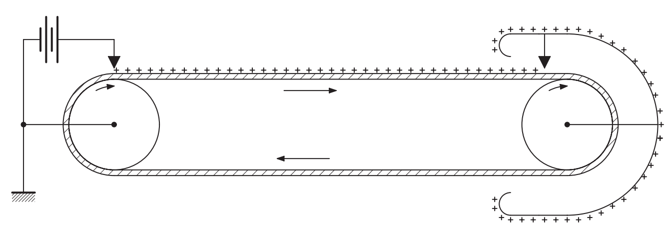
Glass Tube with Beam Acceleration Gaps

Visit the home page :
http://www.daviddarling.info/encyclopedia/C/Cockcroft.html

$750\,\mathrm{keV}$ Cockcroft-Walton Accelerator Used at KEK



Van de Graaff's $1.5\,\mathrm{MV}$ Belt-charged Generator



Limitations in Electrostatic Accelerators

- DC acceleration is limited by high-voltage breakdown (BD).
  - typical BD voltages for a 1cm gap of parallel metal plates

Ambience	Typical BD Voltages
air (1 atm)	$\approx$ 30 kV
SF_6 (1 atm)	$\approx$ 80 kV
SF_6 (7 atm)	$\approx$ 360 kV
transformer oil	$\approx$ 150 kV
UHV	$\approx$ 220 kV

  - no drastic increase in BD limits for much larger plate gaps.

High Voltage Breakdown of a Van de Graaff generator

A demonstration of BD to housing walls.

Search for the key word "van_der_graaf_generator" at
http://en.wikipedia.org/wiki/

Intermediate stage towards RF Acceleration

Use of Faraday's law of induction

- Irrotational electric field due to magnetic flux change, a prelude to RF acceleration [Donald W. Kerst's betatron (1940)]:

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

then

$$\oint_C E_s ds = -\frac{\partial}{\partial t}\iint_S \mathbf{B}\cdot\mathbf{n}\, dxdy = -\frac{\partial}{\partial t}\Phi$$

Kerst's Betatron

Phy. Rev. 60 (1940)

50 D. W. KERST

THE MAGNET

A photograph of the apparatus is shown in Fig. 1.

For the production of the rapidly changing magnetic field, with the proper dependence on the radius, finely laminated iron pole faces were made from 0.003-inch silicon steel sheets. The return magnetic circuit made from the same material was interleaved for mechanical strength; and the roughly circular central pole pieces were

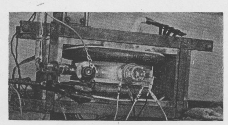
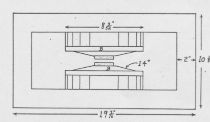


FIG. 1. The induction accelerator. The glass doughnut is between pole faces which are held apart by eccentric wedges.

formed by stacking with different widths of laminations as shown in Fig. 2. Each pole piece was capped by a disk of radially arranged laminations so that perfect circular symmetry was achieved at the pole surfaces (*B*, Fig. 2). The whole pole face was held together by a thick Transite or asbestos board ring about its perimeter, with cement of water glass and flint dust filling the cracks between the laminations and

that the reluctance of the gap was correct. Since the iron particles in these disks are separated, the flux density through them is greater than the average flux density through the disks. This causes the saturation which shrinks the equilibrium orbit down to the target.

Because of the large leakage flux the main coil of the magnet had to be highly subdivided. Two hundred strands of No. 20 double enameled wire were made into a cable approximately 10 yards long which was twisted about ten times and which had its inside wires interchanged with its outside wires several times. This was formed into a 10-turn coil with about $\frac{1}{32}$ inch of insulation between turns. Two such 10-turn coils were made and fitted with large lugs of 1-inch copper tubing. The coils were wrapped with cotton tape, dipped in Bakelite varnish and baked. Figure 3 shows the circuit with the coils connected to a total of eighty 5-microfarad Pyranol condensers which were rated at 660 volts a.c. Energy was supplied to this resonating circuit by a 2-turn primary of stranded enameled wire around the pole pieces. The r.m.s. electromotive force in this primary



Start of Real RF Accelerators

Linear and/or Circular

- Linear accelerator (linac) :
  - Gustaf Ising's proposal (1925)
  - Rolf Wideröe made a prototype of the Ising linac (1928)

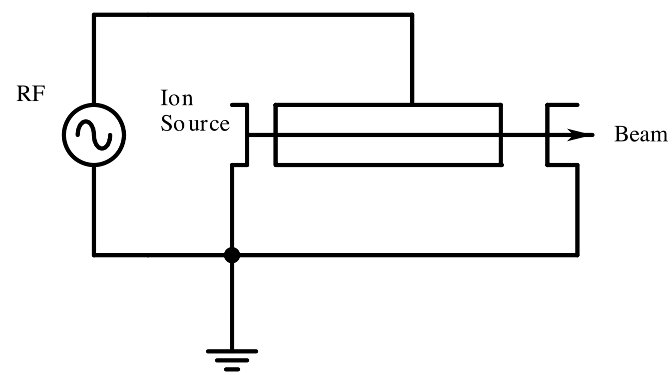
- Multiple RF acceleration in a magnetic field
  - Ernest Lawrence's cyclotron (1931) :

    the first circular accelerator
  - repeated acceleration at the cyclotron frequency :

$$\omega_c = eB_\perp/m$$

The first linac by Wideröe

- $25\,kV$ per gap $\times 2$ with the drift tube
- he convinced the scheme can be repeated indefinitely many times to reach higher beam energies



First Cyclotrons

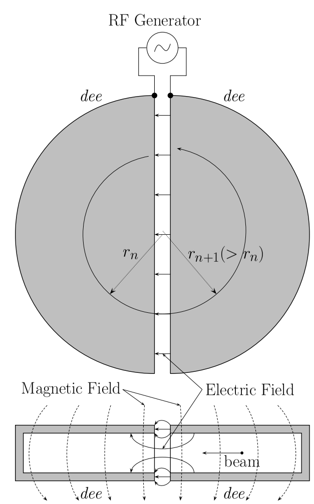
See the picture in *From X-rays to Quarks, page 229* by Segrè, E. (W. H. Freeman and Company, 1980) .

A Riken cyclotron accelerated protons to 9 MeV and deuterons to 14 MeV (1939)

Circular Orbit of Charged Particles in Magnetic Field

Search for the key word "Cyclotron" in
http://en.wikipedia.org/wiki/

Principle of Cyclotron Operation



Problems in RF Acceleration

- Linacs :
  - poor RF sources; electron tube technology was yet in its infancy.
- Cyclotrons :
  - relativistic increase of particle mass
    $\rightarrow$ decrease of ω_c
    $\rightarrow$ asynchronism with RF
- Betatrons :
  - intensity of trapped beam depends critically on the injected beam's positions and angles.
  - analysis of transverse oscillations of particles led to the theory of betatron oscillations of today.

Advances during World War II (1941 - 1945)

- High power microwave tubes for the radars were put to practical use
  - magnetrons and klystrons
- Discovery of the phase stability principle in RF acceleration
  - Vladimir Veksler (1944) and Edwin M. McMillan (1945)
  - cyclotron $\longrightarrow$ synchrocyclotron $\longrightarrow$ synchrotron

The Principle of Phase Stability

- Particles of different energies have
  - differences in velocity and in orbit length;
  - then, particles may be asynchronous with the RF frequency.
- The RF field, however, may have a restoring force at a certain phase, around which asynchronous particles be captured, that is to say bunched.
- This enables a stable, continuous acceleration of the whole particles in a bunch to high energies.
- Circular accelerators based on this principle are called "synchrotron."
- This principle is also applicable to linacs, particularly in low energy range, to bunch continuous beams emitted from a source and to lead bunches to downstream accelerator sections.

Synchrotron Oscillation (1)

- Assume a sinusoidal RF electric field in an RF cavity gap:

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

.

- Assume a synchronous particle pass the gap center at

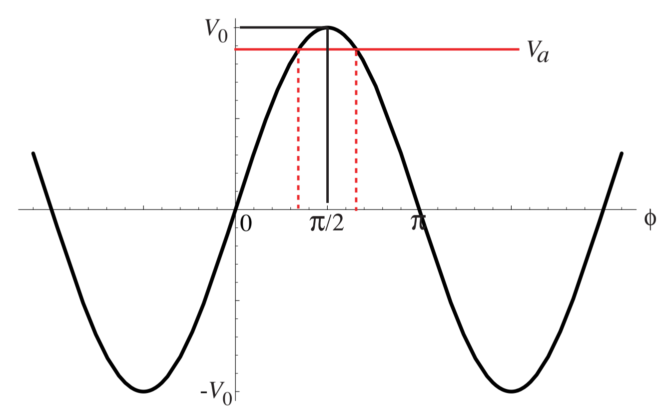
$$\omega t = 0, 2\pi, 4\pi, \ldots$$

and its acceleration voltage be $V_a (< V_0)$.

- Then in one RF period, there are there are two ϕ's which satisfy

$$V_a = V_0 \sin \phi.$$

Sinusoidal RF Wave



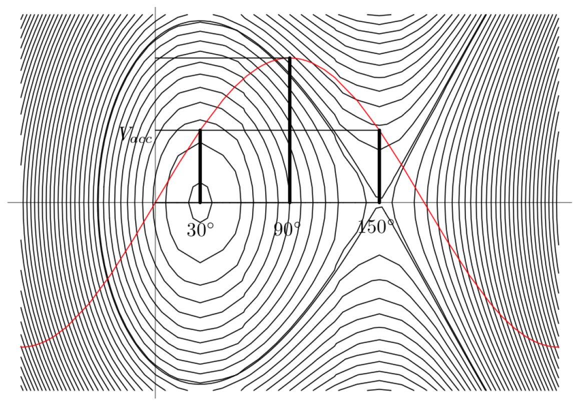
Synchrotron Oscillation (2)

- Only one of the two ϕ's can capture particles, which make oscillations around the phase.
- These oscillations are called synchrotron oscillation and the phase is the synchronous phase ϕ_s.
- Which one is the ϕ_s depends on that the revolution time is longer or shorter for a energy deviation $\Delta E(> 0)$ from the synchronous energy.

Synchrotron Oscillation in an RF Bucket (1)

For the case of $\phi_s = 30°$

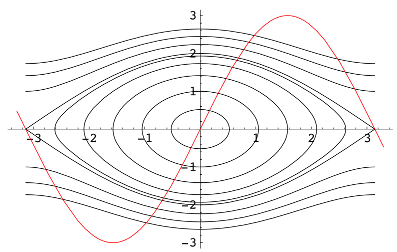
abscissa : $\Delta\phi = \phi_{beam} - \phi_s$, ordinate : $\Delta E = E_{beam} - E_s$

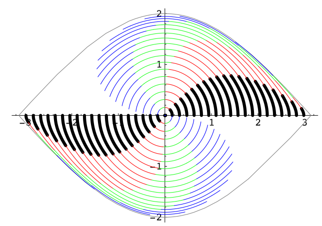


Synchrotron Oscillation in an RF Bucket (2)

For the case of $\phi_s = 0^\circ$

abscissa : $\Delta\phi = \phi_{beam} - \phi_s$, ordinate : $\Delta E = E_{beam} - E_s$





time sequence of motion of particles initially on the abscissa (particles of a larger $\Delta\phi$ move slower or have a smaller ω_s)

Advances in Beam Focusing Technique

- Magnetic, not electric, focusing for high energy particles
- Weak focusing in early cyclotrons and betatrons
- Strong focusing
  - Nicholas C. Christofilos (1950)
  - Ernest D. Courant, M. Stanley Livingston, and Hartland S. Snyder (1952)

Equation of Motion

- In electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$, the equation motion of a particle is

$$\frac{d\mathbf{p}}{dt} = e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

where

$$\mathbf{p} = m\mathbf{v} = \gamma m_0 \mathbf{v}$$

with

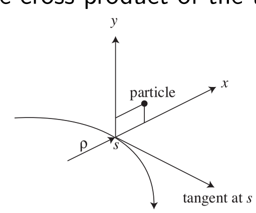
m_0 : rest mass

$\gamma = 1/\sqrt{1-\beta^2}$: Lorentz factor

$\beta = |\mathbf{v}|/c = v/c$

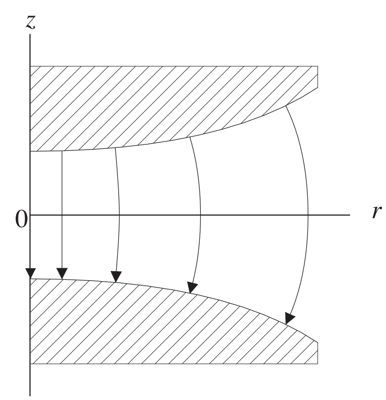
Coordinate System

- In the analysis of beam focusing, it is usually important to describe the equation of motion of particles only for small deviations x and y along the path s of the reference orbit of a synchronous particle
- Thus, a Frenet-Serret frame with respect to the reference orbit is preferred:
  - unit vector tangent to the curve,
  - unit vector in the direction of curvature,
  - and the cross product of the them.



Typical Weak-Focusing Magnetic Field

Cylindrically symmetric magnet poles and magnetic fields of the early cyclotrons



Betatron Oscillations : Weak Focusing

- First order approximation of the field pattern of the previous page

$$B_y = B_0\left(1 - n\frac{x}{\rho} + \dots\right) \quad \text{and} \quad B_x = B_0\left(-n\frac{y}{\rho} + \dots\right),$$

where $n = \frac{dB_y}{B_y} / \frac{d\rho}{\rho}$: the n value

- Equation of motion

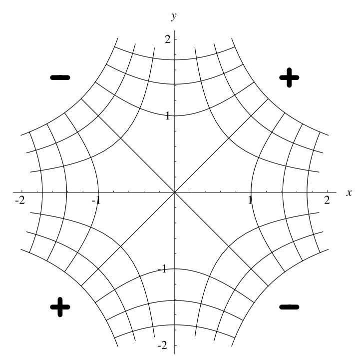
$$\frac{d^2x}{ds^2} + \frac{1-n}{\rho^2}x = 0 \quad \text{and} \quad \frac{d^2y}{ds^2} + \frac{n}{\rho^2}y = 0$$

- Focusing both horizontally and vertically → $0 < n < 1$
- Betatron wavelength

$$\lambda_{\beta,x} = 2\pi\rho/\sqrt{1-n}$$
$$\lambda_{\beta,y} = 2\pi\rho/\sqrt{n}$$

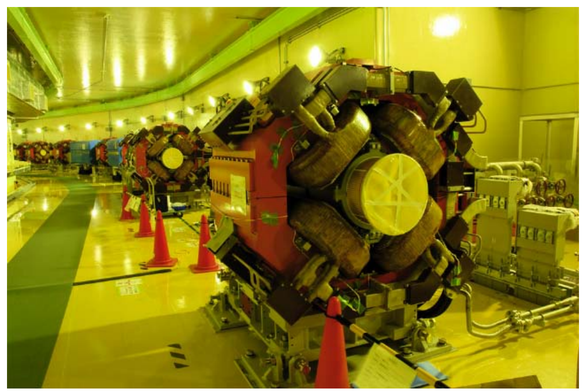
Quadrupole Magnetic Fields for Stronger Focusing

- No limitations for the n value.
- Focusing in one direction, defocusing in the other.
- Later we will see the focusing is superior to the defocusing



Q magnets and B magnets of JPARC RCS synchrotron (1)

http://j-parc.jp/Acc/en/index.html



Q magnets and B magnets of JPARC RCS synchrotron (2)

http://j-parc.jp/Acc/en/index.html

Q magnets and B magnets of JPARC Main Ring (1)

http://j-parc.jp/Acc/en/index.html

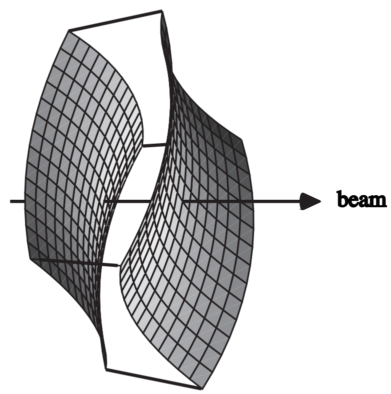
Q magnets and B magnets of JPARC Main Ring (2)

Sextupole magnets are sometimes used.

http://j-parc.jp/Acc/en/index.html

Optical Lens Equivalent of a Quadrupole Magnet

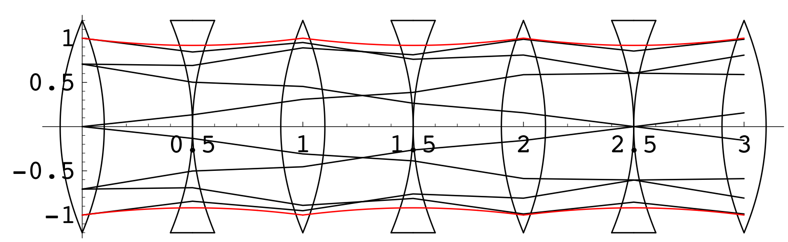
convex lens in one direction and concave lens in the perpendicular direction



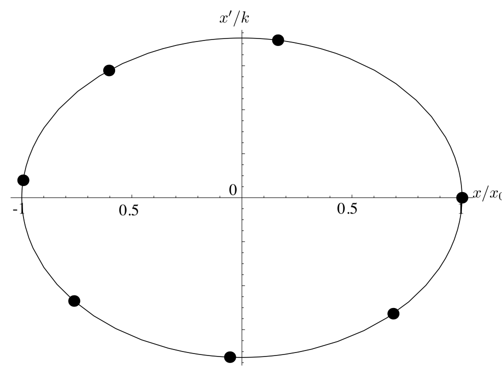
Strong Focusing with a Standard FODO Array

F : focusing Q, D : defocusing Q, O : drift section vspace3mm

- In the following figure, convex lenses are for horizontal focusing and concave lenses for vertical focusing.
- The red curves are beam envelopes for a unit emittance.



Emittance Ellipse for a periodic sequence of Q magnets



$$x^2 + \frac{x'^2}{k^2} = x_0^2 \quad \text{where} \quad k = \frac{1}{L}\sqrt{\frac{L}{f}\left(1 - \frac{L}{4f}\right)}$$

Betatron Oscillations : Strong Focusing (1)

- Use quadrupole magnets with $|n| \gg 1$, but with changing the sign of n alternatively
- Equation of motion

$$\frac{d^2x}{ds^2} + K_x(s)\, x = 0$$

$$\frac{d^2y}{ds^2} + K_y(s)\, y = 0$$

- Focusing/Defocusing forces $K_x(s)$ and $K_y(s)$ are periodic functions for the ring circumference L.
  - They are Mathieu-Hill type functions

Betatron Oscillations : Strong Focusing (2)

- General solution : $x = A_x\sqrt{\beta(s)}\cos(\psi(s) - \psi_0)$ (similar too for y)
  - A_x and A_y are constants proper to each particles and are independent of the position s on the orbit

$$A_x^2 = \frac{4+\beta'^2}{4\beta}x^2 - \beta'\beta x x' + \beta x'^2$$

  - measure a particular particle's $(x,\, x')$ or $(y,\, y')$ for many turns at a position s, the points trace an ellipse on the corresponding phase space.
  - ellipse's direction and eccentricity are functions of s, but area= $\pi A_{x\,(y)}^2$ is conserved
  - the largest area is, roughly speaking, called the emittance of the bunch

Betatron Oscillations : Strong Focusing (3)

- Beta function $\beta_{x\,(y)}(s)$ is defined as the betatron amplitude for $A_{x\,(y)} = 1$:

$$2\beta\beta'' - \beta'^2 + 4\beta^2 K\,(s) = 4.$$

- Phase ψ of betatron oscillation :

$$\psi = \int^s ds/\beta.$$

- Wavelength λ_β of the betatron oscillation : the length corresponding the phase advance $\Delta\psi = 2\pi$.
- Betatron tune $\nu_\beta \equiv L/\lambda_\beta$.

Colliders (1)

- In order to observe the high energy particle reactions : targets in laboratory frame were solely used (fixed target experiment).
- The reaction, however, depends not on the laboratory energy of the projectile from an accelerator, but on the center of mass energy of the projectile and target.
- Touschek' idea to use colliding beams (1960)
- The first collider : AdA (Frascati, 1961)

$$200\,\mathrm{MeV}\ e^- \Rightarrow\Leftarrow 200\,\mathrm{MeV}\ e^+$$

- The collider has become a paradigm of high energy accelerators of today.

Colliders (2) : E_{CM}

- Consider collision of particles of the same rest mass m_0.
- In a fixed target case with the projectile accelerated to $\gamma m_0 c^2$
  - the total energy: $E_T/m_0c^2 = (\gamma + 1)$
  - the total momentum: $p_T/m_0c = \beta\gamma = \sqrt{\gamma^2 - 1}$
  - since $E^2 - c^2p^2$ is a Lorentz invariant,

$$E_{CM}/m_0c^2 = \sqrt{2\gamma + 2} \approx \sqrt{2\gamma}$$

- In a collision of two particles of the same energy $\gamma m_0 c^2$

$$E_{CM}/m_0c^2 = E_T/m_0c^2 = 2\gamma$$

Colliders (3) : Luminosity

- For reaction cross section σ and beam cross section at the collision point S, the probability of reaction for a pair of particles is,

$$\frac{\sigma}{S}$$

- Hence the probability for N_+ and N_- particles at a rate of f times per second

$$f \times N_+ \times N_- \times \frac{\sigma}{S}$$

- Coefficient of σ is the luminosity $\mathcal{L}$

$$\mathcal{L} = f \times \frac{N_+ \times N_-}{S}$$

Synchrotron Radiation (1)

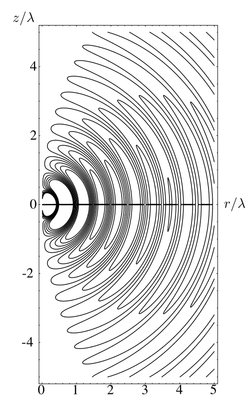
- The synchrotro radiation, SR, is an electric dipole radiation from a charged particle in acceleration $\dot{\mathbf{v}}$
- Radiation power in the rest frame is given by Larmour's formula

$$P = \frac{2r_e m_e}{3c}\left(\frac{d\mathbf{v}}{dt}\right)^2 = \frac{2r_e}{3m_e c}\left(\frac{d\mathbf{p}}{dt}\right)^2$$

where $r_e \equiv e^2/(4\pi\varepsilon_0 m_e c^2) = 2.82 \times 10^{-15}\mathrm{m}$ is the electron's classical radius.

Electric Dipole Radiation : Electric Field Pattern

Radiation pattern (cylindrically symmetric) of an electric dipole at rest



Synchrotron Radiation (2)

- Since P is the ratio of radiated energy to elapsed time, both of which transform in the same manner under Lorentz transformations, P must be an invariant.
- Then $(\ )^2$ in the right hand side of the equation should have the following invariant form

$$(d\mathbf{p}/ds)^2 - (dE/ds)^2 / c^2$$

where ds is the differential of proper time

$$ds = \sqrt{dt^2 - (dx^2 + dy^2 + dz^2) / c^2} = dt/\gamma .$$

Synchrotron Radiation (3)

- Hence in laboratory frame the radiated power is

$$P = \frac{2r_e m_e}{3c}\gamma^2 \left\{ \left[\frac{d(\gamma \mathbf{v})}{dt}\right]^2 - \left[\frac{d(\gamma c)}{dt}\right]^2 \right\}$$

- The radiated energy per turn ΔE for a ring with radius ρ

$$\frac{\Delta E}{m_e c^2} = \frac{4\pi}{3}\frac{r_e}{\rho}\beta^3\gamma^4$$

- A practical formula for $\Delta E(\mathrm{keV})$, $E(\mathrm{GeV})$ and $\rho(m)$

$$\Delta E(\mathrm{keV}) \approx 88.5\left[E(\mathrm{GeV})\right]^4 / \rho(m).$$

Synchrotron Radiation (4)

- Pattern of electric dipole radiation in electron's rest frame $(x',\, y',\, z',\, ct')$

$$dP/d\Omega \propto \sin^2\theta$$

  where Ω being the solid angle and θ the angle from z' axis.
- Transformation to laboratory frame

$$x' = x, \quad y' = y, \quad z' = \gamma\,(z - vt)\,,$$
$$ct' = \gamma\,(ct - vz/c)\,.$$

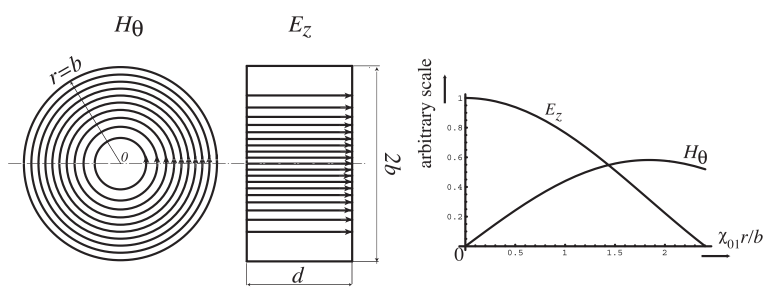
- Angles of axes x' and y' with respect to z axis are $\sim 1/\gamma$.
  - forward radiation power is within a cone of a full angle of $\sim 2/\gamma$.
  - electron is observable for an arc length of $\sim 2\rho/\gamma$.
  - doppler effect shortens the wavelength by $(1 - v/c) \sim 1/2\gamma^2$.
- Critical wavelength (Schwinger-Jackson's definition)

$$\lambda_c \equiv 4\pi\rho/3\gamma^3$$

Accelerating Cavity (1)

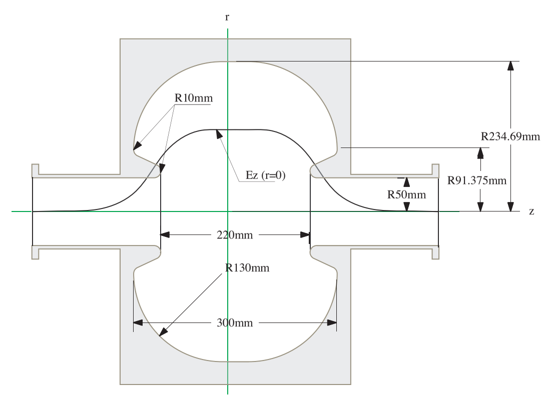
There are many types of accelerating cavity, which, however, basically are variations of a cylindrical cavity (or pillbox cavity),

- operating on the fundamental TM_{010} mode.



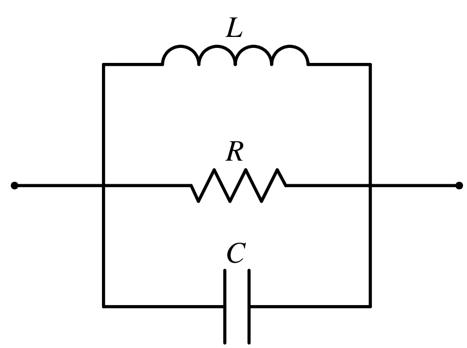
Accelerating Cavity (2)

Single-Cell Accelerating Cavity for Photon Factory Storage Ring
($f_{RF} = 500\,\mathrm{MHz}$, $V_{peak} = 0.7\,\mathrm{MV}$)



Accelerating Cavity (3)

Global behavior of a resonant cavity is well described by an equivalent circuit comprising three parameters L, C, R.



Accelerating Cavity (4)

- first of all, the resonant frequency and the Q value are derived from the following two equations :
$$\omega_0 = 1/\sqrt{LC} \quad \text{and} \quad Q = \omega_0 RC.$$
- one more independent relation is required to determine the three parameters L, C, $\mathrm{and} R$.
- for this sake, we choose the peak acceleration voltage along the beam orbit
- this choice is reasonable, because it satisfies the energy conservation of the (EM fields + beam) system.
$$\iiint_V \mathbf{J} \cdot \mathbf{E} dV + \iint_S (\mathbf{E} \times \mathbf{H}) \cdot \mathbf{n} dS = 0.$$
($\mathbf{J}$: beam current distribution, $\mathbf{E} \times \mathbf{H}$: Poynting vector, V : cavity volume, S : cavity surface)

High Gradient Electric Fields and Breakdown

- Kilpatrick's empirical rule
- Fowler-Nordheim's theory for field emission
- Surface damage on an X-band copper structure
- Weak discharge: multipacting

Kilpatrick Criterion

W. D. Kilpatrick, Rev. Sci. Instr. **28** (1957) 824

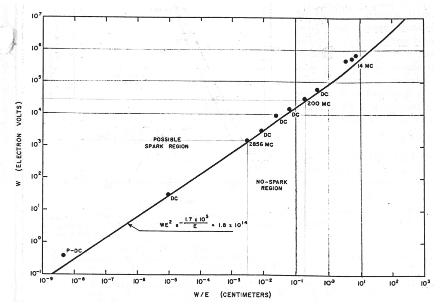


FIG. 1. W is the maximum ion energy at the cathode, in electron volts. For dc, W corresponds to the applied voltage, and W/E is the gap spacing for plane parallel fields. For rf, W is a function of frequency and gap (see text).

* This work was done under the auspices of the U. S. Atomic Energy Commission.
[1] W. D. Kilpatrick, "Sparking and x-rays in a mercury-pumped vacuum system," UCRL-1907 (August, 1952).

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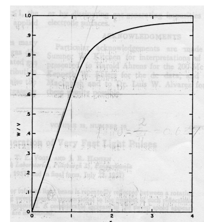


FIG. 3. Graph for ion transit-time correction. For plane parallel fields, $V^*=(g/\lambda)^2 M_0 c^2/eq$. For computing the maximum cathode ion energy, where $\nabla\cdot E$ is not $=0$, the calculation of W or V^* is without reference.

Fowler-Nordheim's Law

R. H. Fowler and L. Nordheim, Proc. Roy. Soc. **A 119** (1928) 173
J. W. Wang and G. A. Loew, **SLAC-PUB-7684** (1997)

- DC field emission current density $j_F\,[\mathrm{A/m^2}]$:

$$j_F = \frac{1.54 \times 10^{-6} \times 10^{4.52\phi^{-0.5}} E^2}{\phi} \exp\left(-\frac{6.53 \times 10^9 \phi^{1.5}}{E}\right)$$

  - microscopic surface gradient $E\ [\mathrm{V/m}]$
  - metal work function $\phi\ [\mathrm{eV}]$

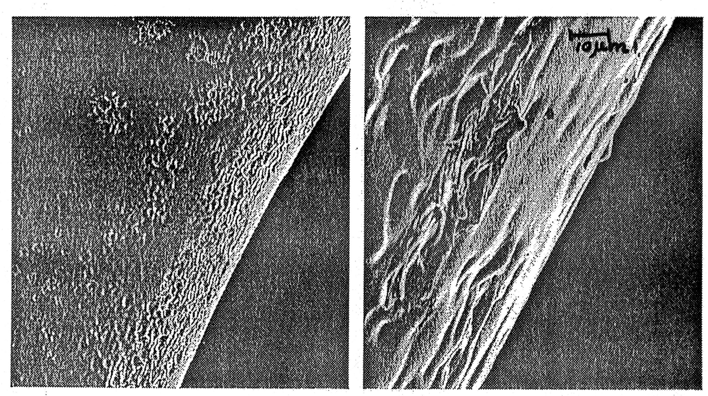
- Averaged over one RF cycle, j_F is modified as:

$$\bar{j}_F = \frac{5.7 \times 10^{-12} \times 10^{4.52\phi^{-0.5}} E^{2.5}}{\phi^{1.75}} \exp\left(-\frac{6.53 \times 10^9 \phi^{1.5}}{E}\right)$$

- Field enhancement factor β : $E = \beta E_{macro}$

Surface Damage on the Iris of an X-band Linac Structure

R. E. Kirby, SLAC-PEL, 2000



11/6/00 Robert E. Kirby, SLAC-PEL 2

Multipacting : a weak discharge phenomenon

A. J. Hatch and H. B. Williams, Phys. Rev. 112 (1958) 581

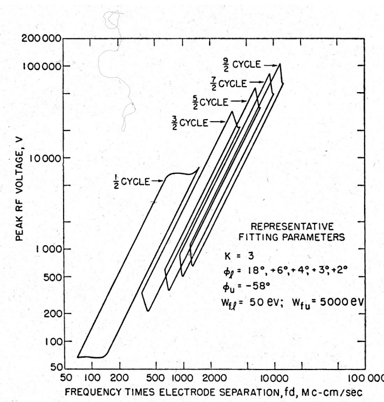


FIG. 1. Multiple mode multipacting theory, ½- through 9/2-cycle modes, $n = 1, 2, 3, 4, 5$.

Superconductor and RF

- Niobium is mostly used, which is a Type II superconductor
  - critical temperature $T_c = 9.2\mathrm{K}$
  - critical field $H_c = 2 \times 10^3 \mathrm{Oe}$
  - in meissner state for $H \leq H_{c1} = 1.7 \times 10^3 \mathrm{Oe}$
  - in normal state for $H \geq H_{c2} = 2.3 \times 10^3 \mathrm{Oe}$
- Maxwell equations + London equations
  - London's penetration depth λ_L
    - about $50\,\mathrm{nm}$ for niobium
  - coherent length ξ_0
    - about $40\,\mathrm{nm}$ for niobium
  - wall losses do still exist, although very small, which are caused by normal electrons

Equations for Superconducting State

- Maxwell's equations:

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \quad \text{and} \quad \nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}$$

- London equations:

$$\mathbf{J}_s = -j\frac{n_s e^2}{\omega m_e}\mathbf{E} \quad \text{and} \quad \nabla \times \mathbf{J}_s = -\frac{n_s e^2}{m_e}\mu_0 \mathbf{H}$$

- Field equations:

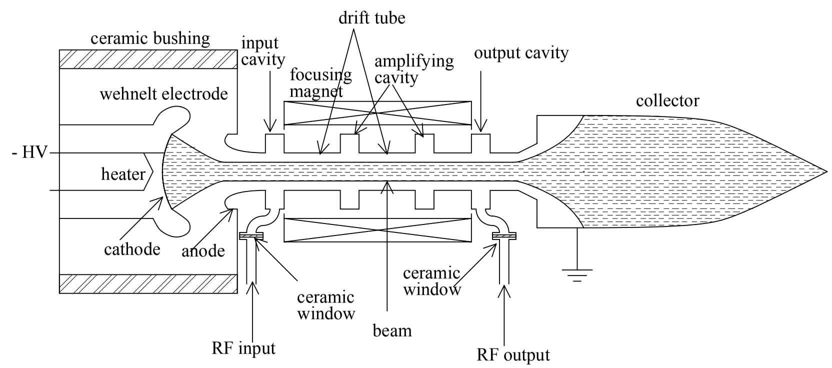
$$\nabla^2 (\mathbf{J}, \mathbf{E}, \mathbf{H}) = \left(\lambda_L^{-2} + j\omega\sigma\mu_0 - \omega^2 \varepsilon_0 \mu_0\right)(\mathbf{J}, \mathbf{E}, \mathbf{H})$$

- London's penetration depth: $\lambda_L = \sqrt{m_e / n_s e^2 \mu_0}$

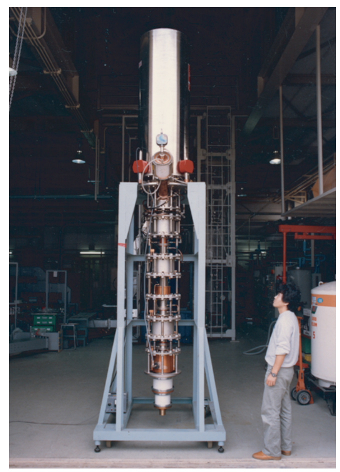
Klystron (1)

- Also an accelerator with decelerating electric fields
- Perveance μ_p
  - Child-Langumuir law for space-charge limited flow
    - $\mu_p \propto I/V^{3/2}$
    - *cf.* M. Reiser:
      Theory and Design of Charged Particle Beams,
      John Wiley & Sons, 1994.
- Efficiency vs. perveance
  - *cf.* R. B. Palmer and R. Miller: SLAC-PUB-4706, September 1988.

Klystron (2)


ceramic bushing
input cavity
drift tube
focusing magnet
amplifying cavity
output cavity
collector
wehnelt electrode
- HV
heater
cathode
anode
ceramic window
ceramic window
beam
RF input
RF output

500 MHz-1 MW CW Klystron for KEKB

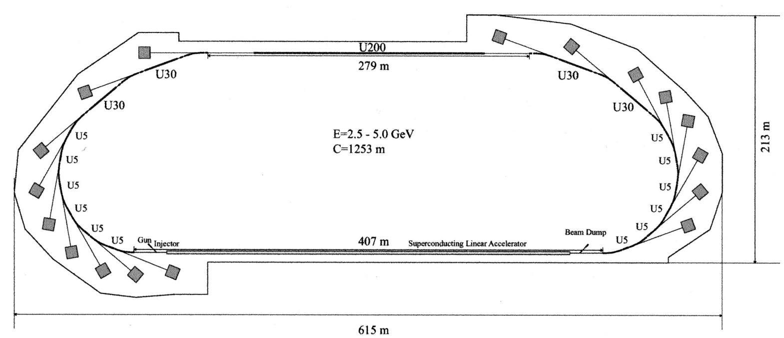


Future Accelerators

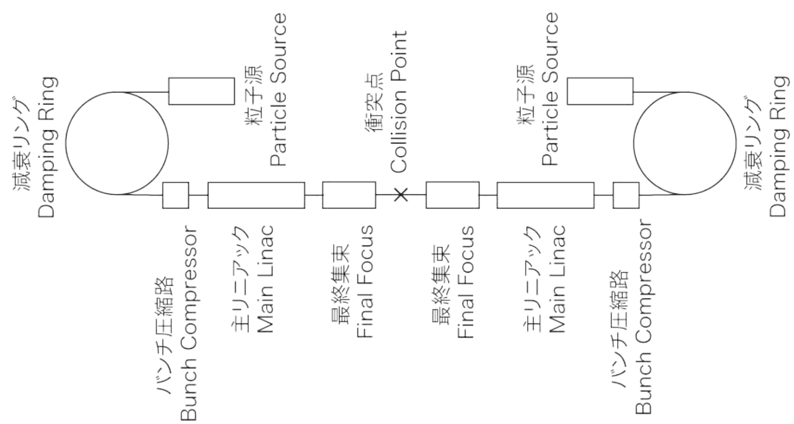
- ERL: Energy Recovery Linac
- LC : Linear Collider
- μ-μ Collider and/or μ-Factory
- Laser-plasma acceleration

KEK-PF-ERL : A Future Plan

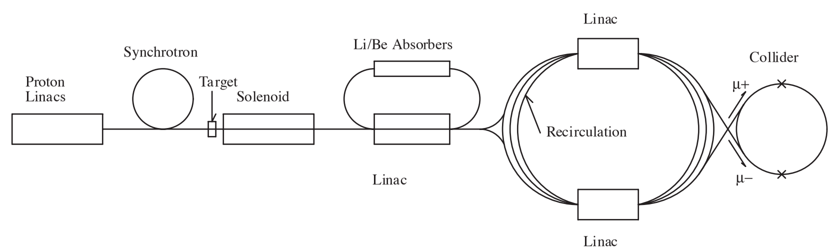
- An SR source with a superconducting linac energy-recovered by returned electron beams



Linear Collider: schematic layout



μ-μ Collider



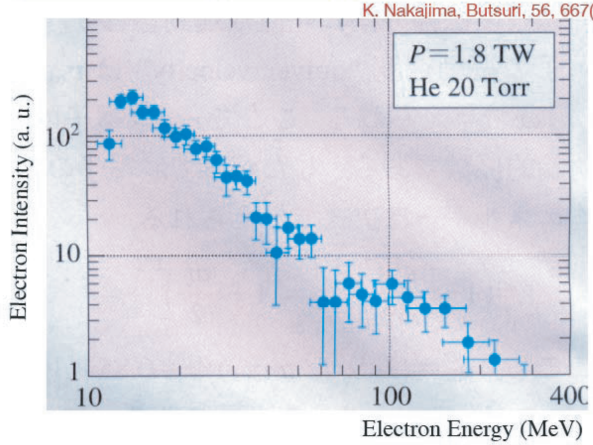
Laser Plasma Acceleration (1)

cf. C. Joshi and T. Katsouleas's article in Physics Today, June 2003, p.47.

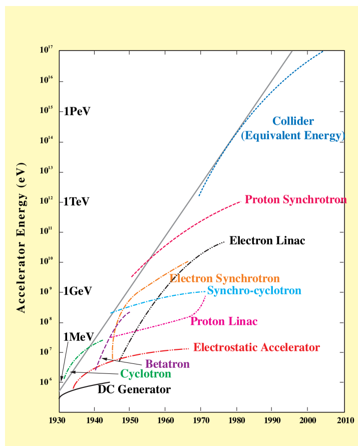
Laser Plasma Acceleration (2)

Electron Energy Gain by Laser Wake Field

K. Nakajima, Butsuri, 56, 667('01)



Livingston Chart



- Originally given by M. S. Livingston & J. P. Blewett: "Particle Accelerators, p.6", MacGraw Hill, 1962
- Energies for the colliders are equivalent values for the fixed target system
- Maximum beam energy ever achieved
  - Electron Synchrotron : 2×100 GeV (2000, CERN LEP)
  - Proton Synchrotron : 2×7 TeV (2010, CERN LHC) http://lhc.web.cern.ch/lhc/
- Electron-positron linear collider 2×500 GeV? (2025 or later?)

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References (2)

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