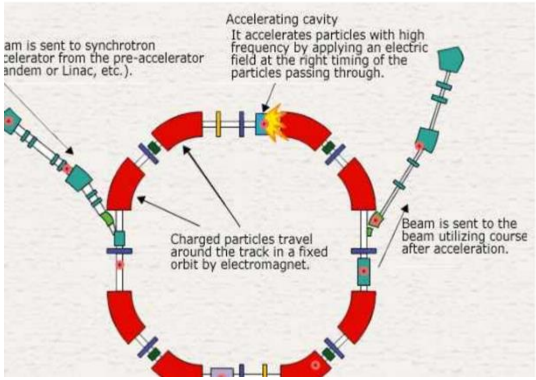
PHY 554

Fundamentals of Accelerator Physics

Lecture 3: History of Accelerators II

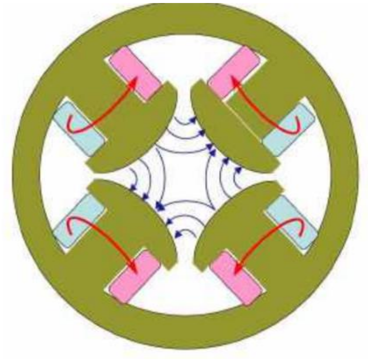


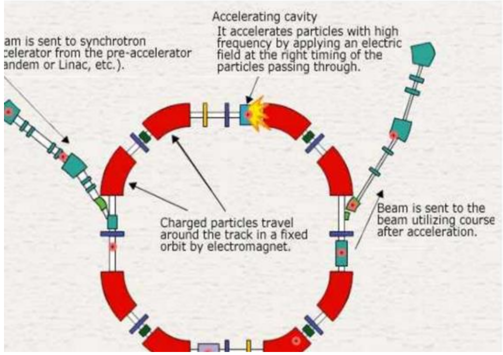
A synchrotron separates bending, RF acceleration, injection, and extraction

Modern machines are built from a small set of ideas: synchronism, focusing, storage, and luminosity.

Today's route: the second half of the accelerator story

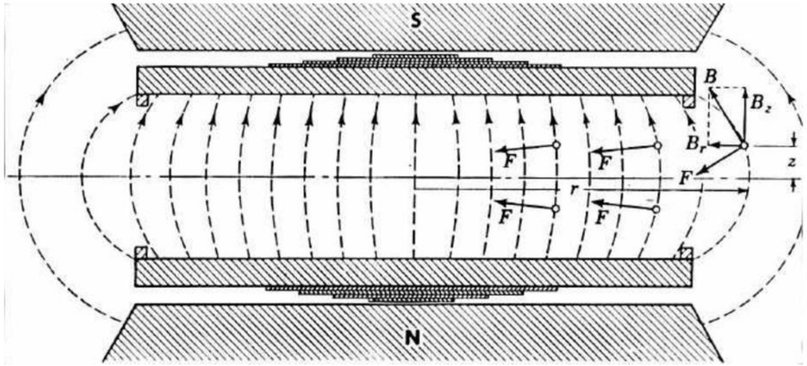
1. Synchrotrons: synchronized RF and ramped magnets.
2. Weak focusing: useful but aperture-hungry.
3. Strong focusing: alternating-gradient optics and the modern accelerator lattice.
4. Storage rings, colliders, luminosity, and light-source brightness.





accelerate → confine → stabilize → collide/store → optimize beam quality

Focusing is not optional



- A perfectly uniform vertical field bends the beam but does not restore vertical errors.
- Small vertical momentum produces a helical trajectory; particles eventually hit the chamber.
- A radial field gradient can provide a returning force, giving stable transverse oscillations.
- These transverse oscillations are historically called betatron oscillations.

Bending and focusing are different jobs.

Weak focusing: useful, but aperture scales badly

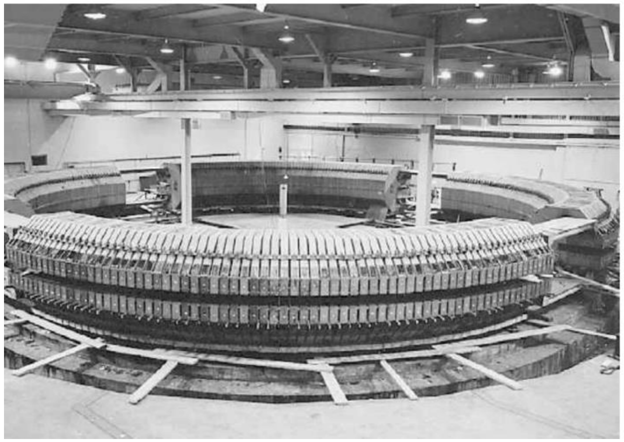
- Define the field index $n = -(\rho/B_0)\, dB_y/dx$.
- Stable weak focusing requires $0 < n < 1$.
- The number of oscillation per turn is less than one oscillation.
- Beam sizes and magnet apertures grow with energy.

For harmonic oscillation solution:

$$0 < n < 1 \qquad \nu_x = \sqrt{(1-n)} \qquad \nu_y = \sqrt{n}$$

Weak focusing – beam size scales with machine size.

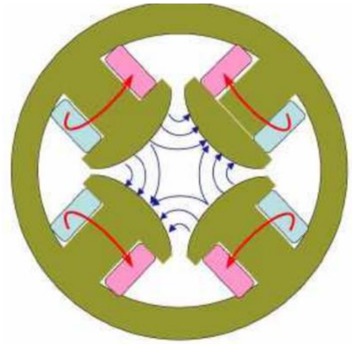
Weak-focusing synchrotrons became enormous

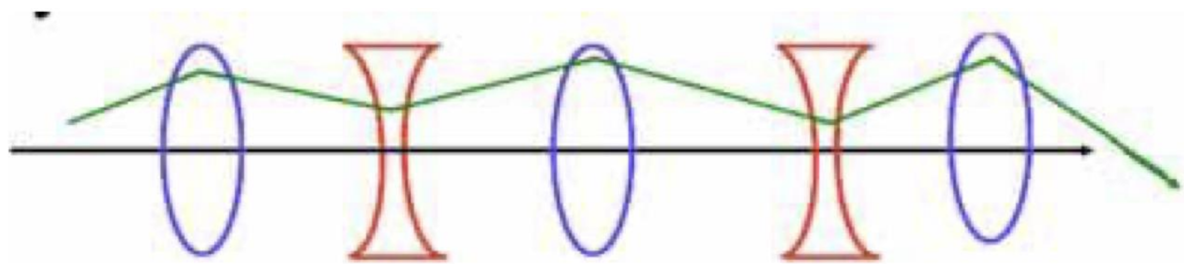


- Weak focusing made early synchrotrons possible, but it demanded very large apertures.
- For a fixed angular error, orbit deviation scales roughly with machine radius.
- Vacuum chambers became so large that people could stand inside them.
- A new focusing principle was needed for higher-energy rings.

This is a dead end that strong focusing solved.

Strong focusing: alternating-gradient optics

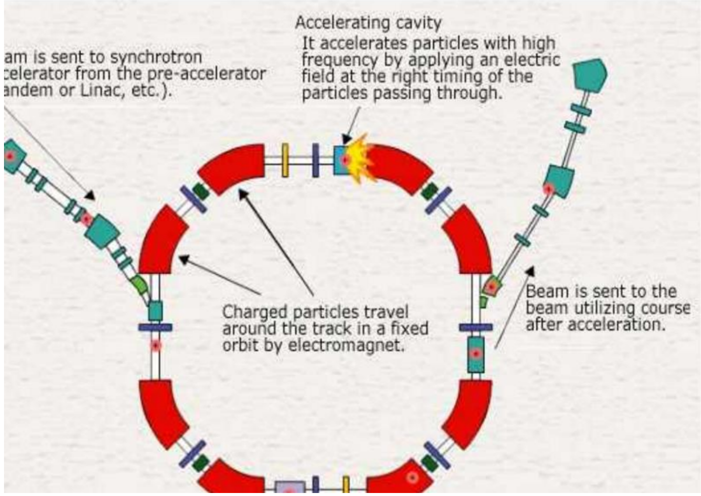




quadrupole field: $B_x = G\,y, \quad B_y = G\,x$

- A quadrupole focuses in one transverse plane and defocuses in the other.
- A separated focusing lens and defocusing lens can focus in both planes over a period.
- Christofilos proposed strong focusing; Courant, Livingston, and Snyder developed the theory at BNL.
- Modern accelerators use strong focusing to shrink apertures from meters to centimeters or millimeters.

Synchrotrons: separated magnets plus synchronized RF



- By the 1940s, DC, RF, and induction acceleration had all been demonstrated.
- Solid-core magnets became impractical at large size and high energy.
- Synchrotrons use separated bending magnets and RF cavities distributed around a ring.
- Magnets ramp with beam energy; RF gives turn-by-turn acceleration.

Synchrotron ≠ storage ring: a synchrotron accelerates from injection to extraction.

Synchronism: the RF and the orbit must stay locked

- The particle revolution period must match an integer number of RF periods.
- Hadron synchrotrons must vary RF frequency as velocity changes during acceleration.
- Electron synchrotrons can often inject at already relativistic speeds, making frequency control easier.
- Ramping magnets is an engineering limit; synchronizing the RF is a beam-dynamics requirement.

$$T_0 = C/v = n\ T\_RF = n/f\_RF$$

1. B field follows momentum.
2. RF frequency follows time of flight.
3. RF phase provides stable acceleration.

More details in RF section of the course.

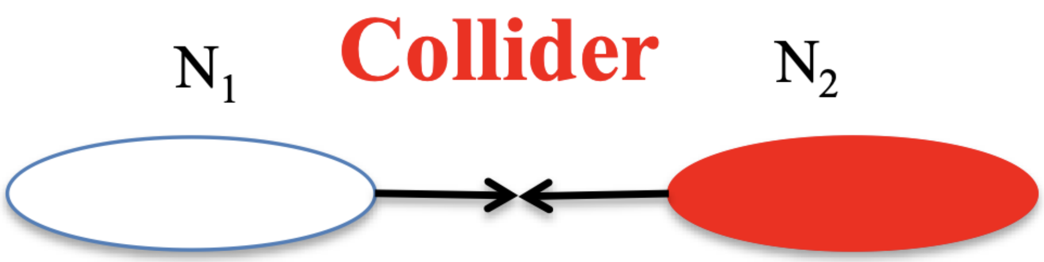
Storage rings and colliders: store beams, then collide them

- Storage rings became possible because synchrotron technology, ultra-high vacuum, superconducting magnets, and RF matured together.
- A single ring can collide particle-antiparticle beams traveling in opposite directions.
- Two intersecting rings allow collisions of more general beam species, as in RHIC and the LHC.
- The key energy advantage is center-of-mass energy, not laboratory beam energy.

$$\text{collider geometry:}\ \ E\_CM = E_1 + E_2$$

1. Beam lifetime: hours to days.
2. Ultra-high vacuum: reduce scattering.
3. Collisions: maximize overlap density.
4. Detectors: sit at interaction points.

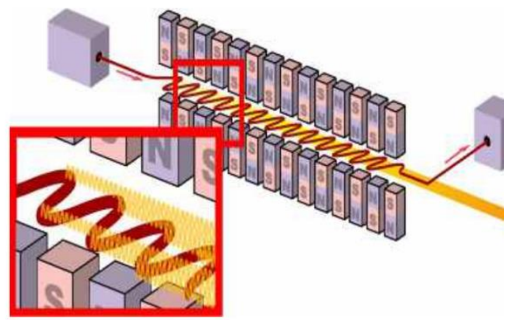
Luminosity: why colliders were not obviously easy



- Event rate is R = σL: cross-section times luminosity.
- Fixed targets have enormous areal densities, so early skeptics doubted colliders could compete.
- Colliders win with many particles per bunch, high collision frequency, and very small transverse beam size.
- Beam quality and optics enter through the overlap area.

$L = f\_c\, N_1 N_2 / A$ and A is the area of overlap

Light sources: accelerators as microscopes

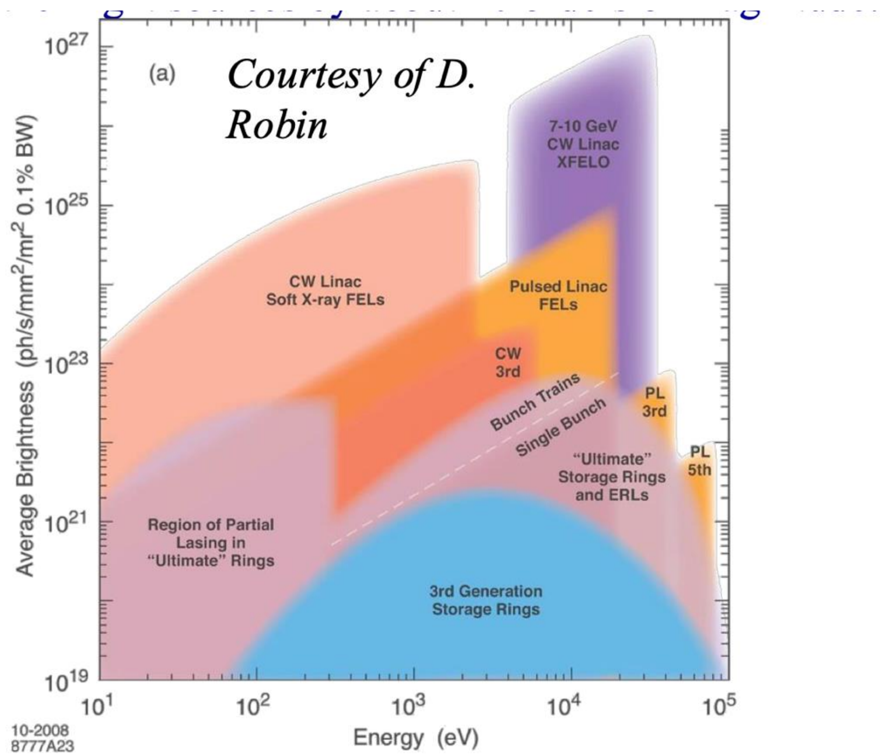


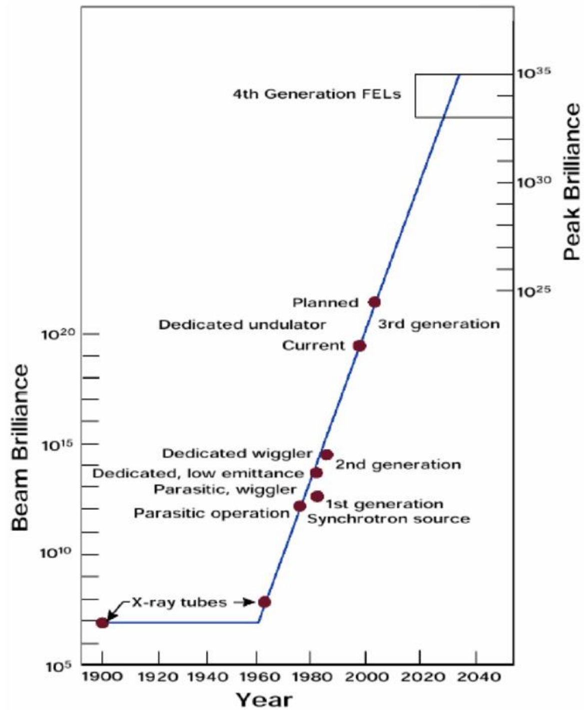
- Electrons radiate when bent in dipoles, wigglers, and undulators.
- Most storage-ring light sources operate in soft-X-ray and X-ray regimes using GeV electron beams.
- Undulators turn transverse oscillation into narrow-band, high-brightness photon beams.
- Free-electron lasers use a collective interaction between the electron beam and radiation field.

$$\lambda_c \sim \rho/\gamma^3 \qquad \lambda_{rad} \sim \lambda_u/\gamma^2$$

Figure of merit shifts from energy to photon-beam quality.

Brightness: the figure of merit for light sources





Average spectral brightness of light sources (left) and equivalent of the Livingston plot for light sources

$$B = \dot{N}\_ph \,/\, (A\,\Omega \cdot \Delta E/E)$$

- Brightness counts photons per second, source area, solid angle, and spectral bandwidth.
- High brightness means many photons are delivered into a small phase-space volume.
- FELs can produce laser-like X-ray beams with extremely high peak brightness.

SUMMARY

What to remember from Lecture 3

- Betatron's legacy survives in the term betatron oscillations.
- Synchrotrons synchronize RF, magnet fields, and particle time of flight while ramping energy.
- Weak focusing works but drives huge apertures at high energy.
- Strong focusing is the central invention that makes modern compact high-energy rings possible.
- Colliders are judged by luminosity as well as center-of-mass energy; light sources by brightness.

1. Why does $\langle B \rangle = 2B$ matter in a betatron?
2. What does the RF need to synchronize to in a synchrotron?
3. Why does alternating-gradient focusing work?
4. Why is luminosity not just beam current?

Selected references

- E. M. McMillan, “The synchrotron - a proposed high-energy particle accelerator,” Physical Review, 1945.
- V. Veksler, Journal of Physics USSR, 1945.
- D. W. Kerst, “The acceleration of electrons by magnetic induction,” Physical Review, 1942.
- E. D. Courant and H. S. Snyder, “Theory of the alternating-gradient synchrotron,” Annals of Physics, 1958.
- E. D. Courant, M. S. Livingston, and H. S. Snyder, “The strong-focusing synchrotron,” Physical Review, 1952.
- Course notes: PHY 554 Lectures 2 & 3, “History of Accelerators.”

Homework #1: Lab report I, due next Monday 9/7/26 before class

Install the code Elegant, run the provided .lte and .ele files.

Answer the following questions (10 pts, each 2 pts):

1. What is the total length of the accelerator?
2. What is the central momentum of the beam?
3. What are the beam sizes (for x and y) at the start of the accelerator?
4. What are the maximum and minimum beam sizes (for x and y) along the accelerator?
5. How does quadrupole in the lattice file affect these beam sizes?