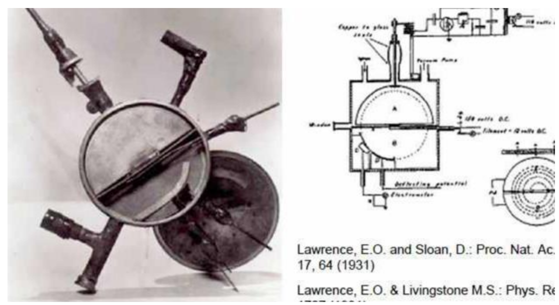
PHY 554

Fundamentals of Accelerator Physics

Lecture 2: History of Accelerators I

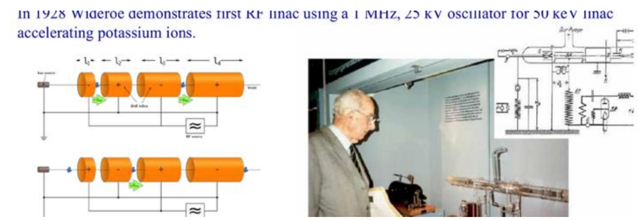


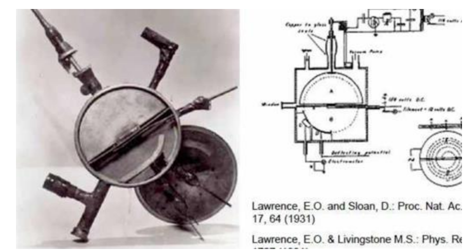
Lawrence cyclotron and early cyclic acceleration concept

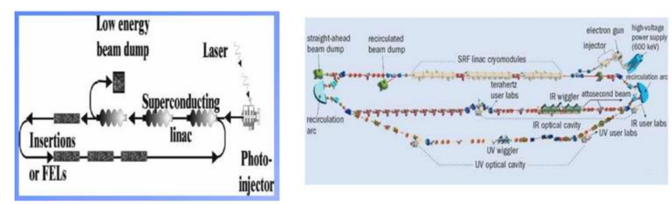
The recurring pattern: a limit appears, then a new acceleration principle bypasses it.

The story we will tell today – chronicle but topical

- Early accelerators were high-voltage devices: useful, but limited by breakdown and size.
- RF linacs replaced the “one huge voltage” problem with many synchronized gaps.
- Cyclic accelerators reused the same RF gap many times; this introduced resonance, rigidity, and focusing.
- Recirculating linacs and ERLs reuse expensive RF structures and, in some cases, recover beam energy.



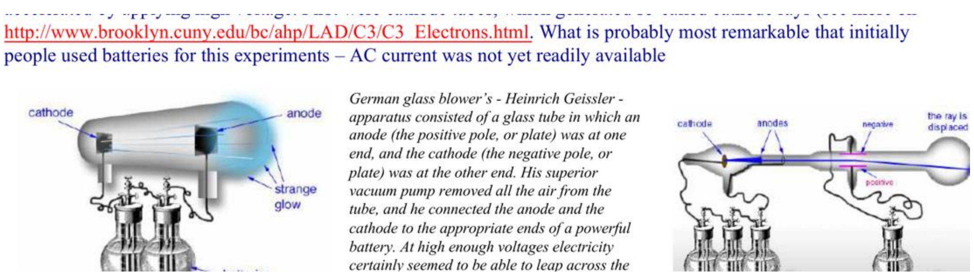




$$\text{acceleration} = \text{fields} + \text{timing} + \text{stability}$$

Historical order is not the main point here; history is used to introduce concepts and vocabulary.

First accelerators: cathode rays and electrostatic tubes



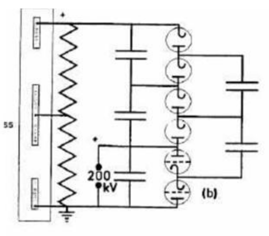
Geissler / Crookes / Thomson tube era

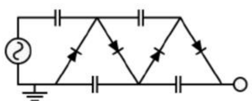
- Cathode-ray tubes generated and accelerated electrons using high voltage.
- Magnetic and electric deflection showed that the rays were charged particles, not waves.
- J. J. Thomson identified the electron in 1897.
- Practical accelerator energies were about 10 keV; the 20th century had to push toward TeV scale.

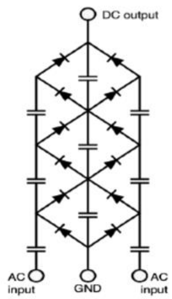
"charged particle + electric field" is already the core of an accelerator.

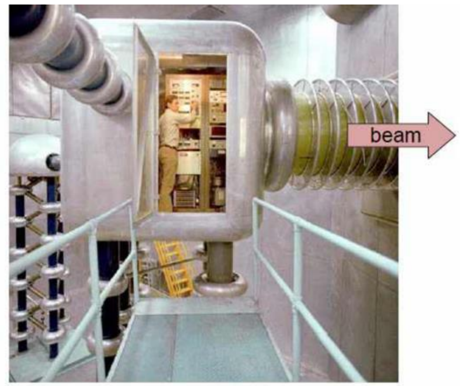
DC gap: $\Delta K = qV$

Electrostatic accelerators: elegant, powerful, and finite



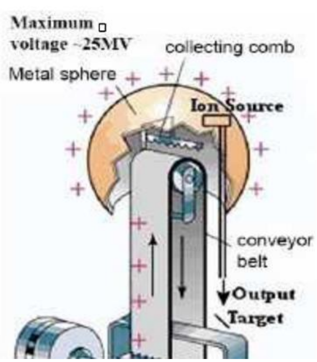






Crockroft-Walton at FNAL accelerates H- to 750keV

- Cockcroft-Walton used a voltage multiplier; 400 kV protons for lithium disintegration reaction in 1932 (later ~ 700 kV or even above 1 MV in some machines).
- Van de Graaff generators reached MV potentials and became reliable nuclear-physics tools.
- Tandems get two boosts from the terminal voltage by changing the ion charge state.
- The single-particle energy scale remains tied to terminal voltage.

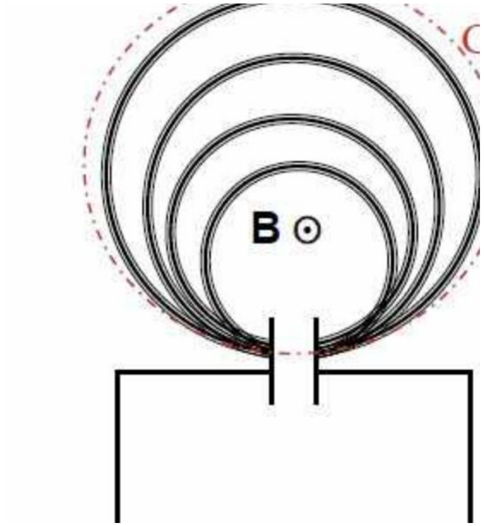


(Photo: CCLRC).

$$K \approx q \times \text{terminal voltage}$$

$$\boxed{A^-} \xrightarrow[\text{accelerate}]{+V} \boxed{\text{stripper}} \quad A^- \to A^{n+} \xrightarrow[\text{accelerate again}]{} \boxed{A^{n+}}$$

Why DC machines hit the roof



- In a static field, a closed path cannot give net acceleration: the field is conservative.
- Each extra MeV requires more terminal voltage, insulation, and physical size.
- Practical breakdown is often of order 10 kV/cm, so a 20 MeV DC accelerator wants tens of meters.
- High-voltage devices are also hazardous; lightning is the natural warning sign.

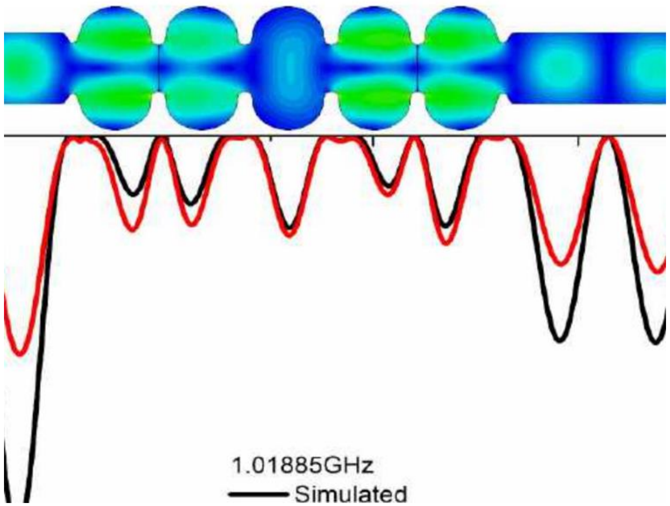
$$\text{static fields:} \quad \Delta E = q\oint E\cdot dl = 0$$

Faraday's law points to the solution: time-varying fields:

DC electrostatic → RF acceleration → reuse the gap many times

Bottom line: time-varying fields are the solution

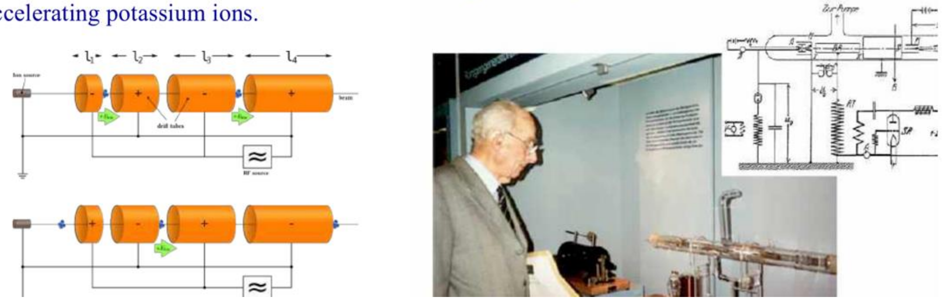
$$\frac{\partial \vec{E}}{c\partial t} = curl\vec{B}; \quad \frac{\partial \vec{B}}{c\partial t} = -curl\vec{E}$$



- Static fields cannot provide net acceleration around a closed path.
- RF cavities naturally contain alternating electric and magnetic fields in vacuum.
- Accelerators exploit timing: the particle samples the accelerating part of the field again and again.
- The rest of the course turns this idea into beam dynamics, RF design, stability, and applications.

Breakthrough: RF fields replace one huge voltage

In 1928 Wideroe demonstrates first RF linac using a 1 MHz, 25 kV oscillator for 50 keV linac accelerating potassium ions.



- Ising proposed time-varying fields in 1924; Wideröe demonstrated a 1 MHz RF linac in 1928.
- Drift tubes shield slow particles while the RF field reverses sign.
- Only the gaps accelerate; N gaps each with voltage V give roughly NqV energy gain.
- The new design variable is phase: the particle must arrive at the right RF time.

$$\text{many small kicks} \rightarrow \text{one large energy gain}$$

New vocabulary: RF phase, synchronous particle, drift tube, cell length.

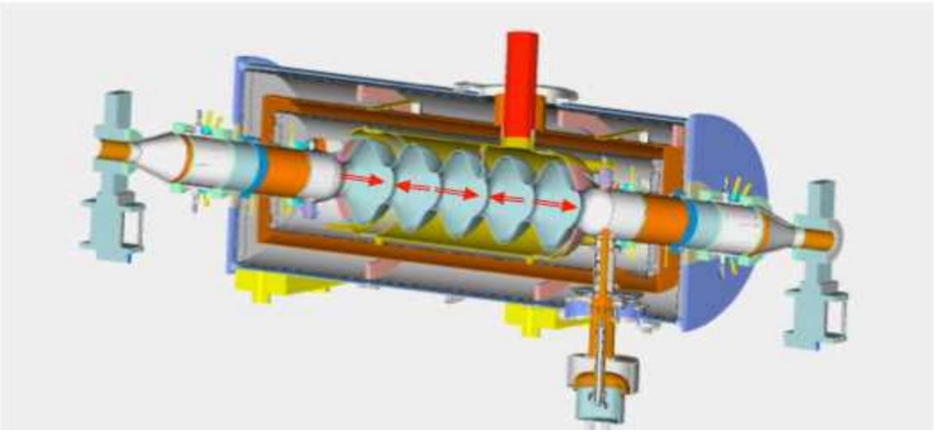
RF linacs grew with RF power and relativistic beams

This "resonant acceleration" becomes easier when particles getting to relativistic velocities, which

- Alvarez drift tubes and later RF structures made resonant acceleration practical.
- High power RF technology from radar development in the World War II was crucial.
- Pulsed electron linacs can reach very high gradients.
- Medical linacs use ~15 MeV electrons to generate treatment photons.
- SLAC's 3.2 km electron linac reached tens of GeV in a single pass.

DC: $\sim$1 MV/m RF linacs: 10s of MV/m in pulsed, $\sim$ MV/m in CW

Superconducting RF: low wall loss



- CW accelerators often use superconducting RF because cavity wall losses are much lower.
- Typical CW gradients are more modest than short-pulse demonstrations but are still impressive.
- Electrons become relativistic quickly, so RF cell geometry can be simpler.
- Hadron linacs must handle particles whose velocity changes significantly over the accelerator.

SRF linacs: 10s of MV/m in CW

New terminologies: DC and CW

CW refers to continuous RF operation, not a continuous/unbunched beam

DC machines → DC beam, RF (pulsed or CW) → bunched beam

Why are proton linacs harder than electron linacs?

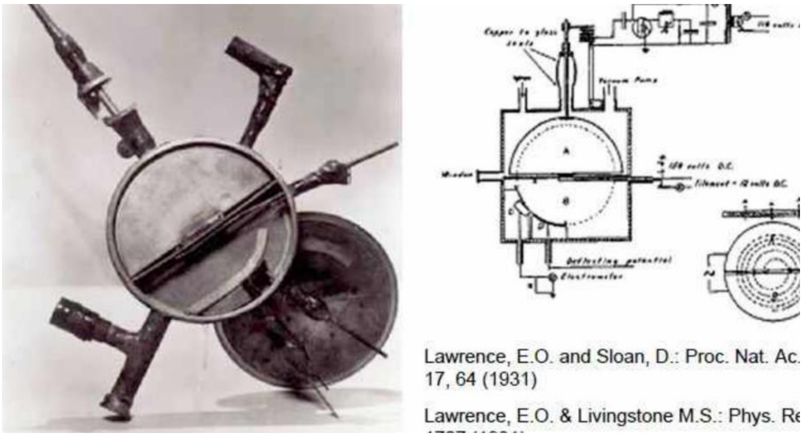
$$\gamma = 1 + K/(mc^2) \qquad \beta = \sqrt{(1 - 1/\gamma^2)}$$

- Electrons: $mc^2 = 0.511$ MeV, so MeV-scale beams are already highly relativistic.
- Protons: $mc^2 = 938$ MeV, so velocity changes substantially through many RF structures.
- Cell length, RF phase, focusing, and matching become more demanding for slow hadrons.

What must change along a linac as β increases?

1. Distance traveled per RF period grows.
2. Focusing strength changes with momentum.
3. Aperture and error tolerances may change along the machine.

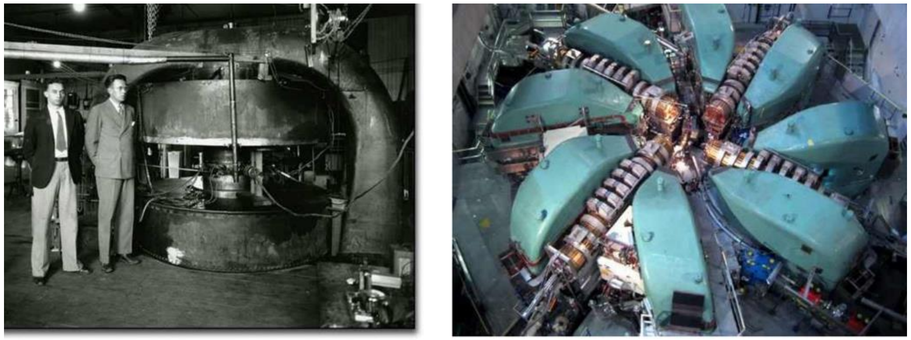
Cyclotron: reuse the same RF gap many times



- Lawrence turned Wideröe's linear idea into a cyclic one: bend particles back through the RF gap repeatedly.
- For non-relativistic particles in a uniform B field, the revolution frequency does not depend on speed.
- This resonance condition made compact, high-current ion acceleration possible.

non-relativistic cyclotron frequency: $f = qB/(2\pi m)$

Cyclotrons in practice: resonance plus corrections



Lawrence with 27” cyclotron in 1932 (left) and a powerful 590 MeV cyclotron built in early 197

- The simple cyclotron is exact only when $\gamma \approx 1$.
- As particles become semi-relativistic, magnet shaping and/or RF changes preserve synchronism.
- PSI accelerates protons from 72 MeV to 590 MeV in 186 turns: about 2.8 MeV per turn.
- A cyclotron is compact because it trades high terminal voltage for many revolutions.

What ultimately limits a cyclotron as γ grows?

With relativistic effect: $f = qB/(2\pi\gamma m)$

Maximum kinetic energy: $K_{max} \propto \sqrt{(qV/mc^2)}$

Proton ~ 20 to 25 MeV

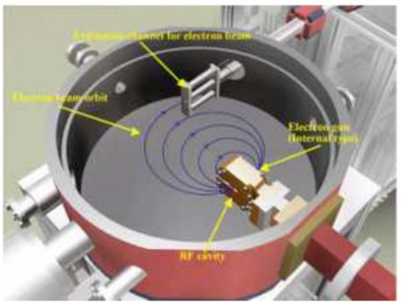
Synchrocyclotron (varies f) or isochronous cyclotron (varies B)

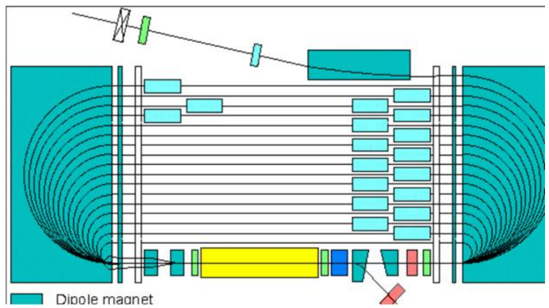
Beam rigidity: the practical language of magnets

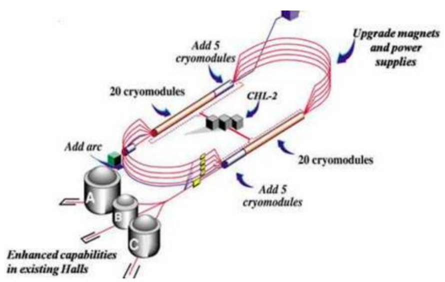
- A magnet does not "know" the particle energy directly; it bends according to momentum per charge.
- Beam rigidity Bρ is the magnetic field × bending radius required for a trajectory.
- Rigidity is one of the most useful quick-estimate quantities in accelerator design.

$$B\rho = p/q \quad \approx \quad p[\mathrm{GeV}/c] \,/\, 0.2998 \ \ \mathrm{T{\cdot}m}$$

Microtrons and recirculating linacs: cyclic ideas for electrons



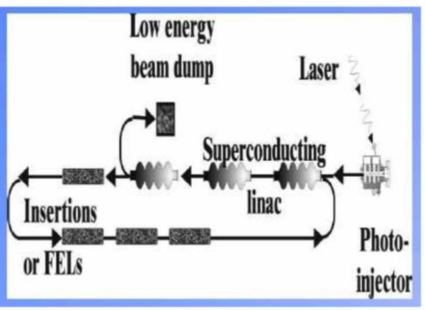


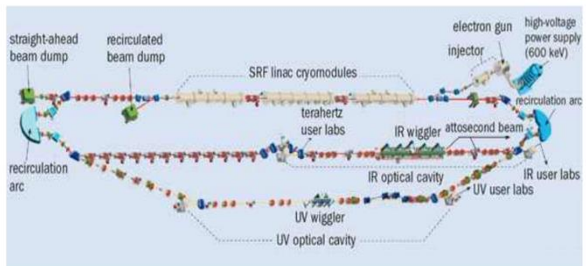


CEBAF, a 12 GeV recirculating SRF linac at Thomas Jefferson Accelerator Facility. On the right and the bottom – SRF accelerating modules.

- A microtron is a resonant cyclic accelerator for relativistic electrons.
- Each pass through the RF cavity changes the path length by an integer number of RF wavelengths.
- Recirculating linacs extend this idea: the same SRF linacs are reused for several energy passes.
- Design idea: spend money on excellent RF once, then pass through it many times.

Energy recovery linacs: reuse the beam energy too

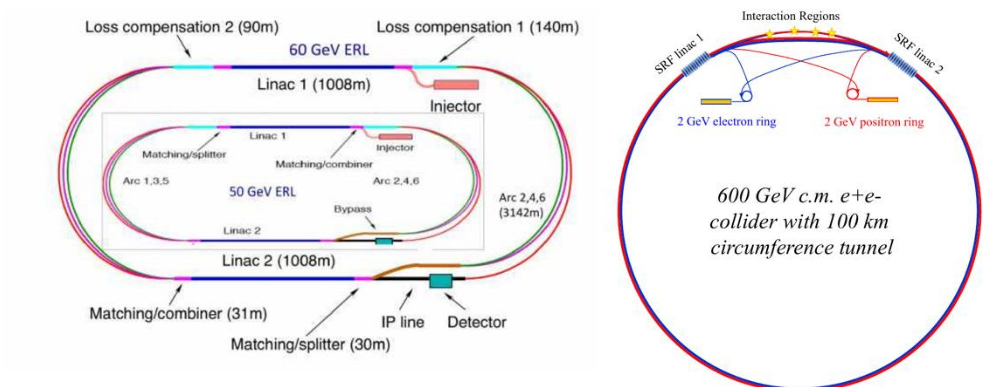




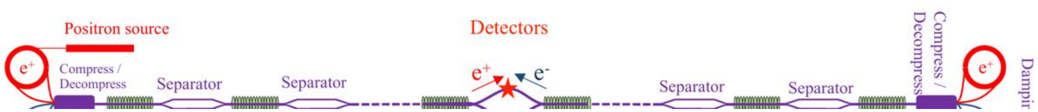
- Tigner's 1965 idea: return used beam to the linac on the decelerating RF phase.
- The beam gives its energy back to the RF fields before being dumped at low energy.
- SRF makes this attractive because the RF system can store energy with low wall loss.
- The difficulty is beam quality and stability: high-Q cavity modes can couple strongly to the beam.

$$\text{accelerate} \rightarrow \text{use beam} \rightarrow \text{decelerate} \rightarrow \text{recover energy}$$

ERLs as a bridge to future collider concepts



60 GeV ERL for LHeC (left) and 2x300 ERLs for future election-position collider (right)



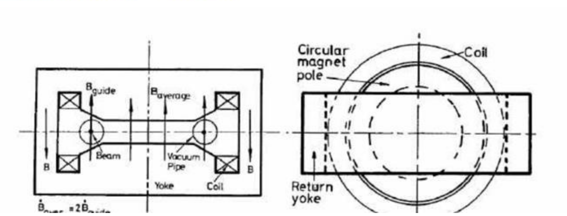
- ERL-based collider concepts try to combine high collision energy with reduced RF power demand.
- Energy recycling is attractive, but collider-quality beams require tight control of emittance, timing, and collective effects.
- The course lesson is not one specific proposal; it is the design logic: recover, recycle, and control phase space.

Betatrons: induction acceleration in a ring

$$e\oint \vec{E}\cdot d\vec{l} = -\frac{e}{c}\frac{d}{dt}\left(\int \vec{H}\cdot d\vec{s}\right)$$

ne idea was written in his lab-book by a young Norwegian student, Wideröe, in 1923 but no
ublished. It included 2:1 rule (see next page). Later he added stability criterion. In 1927 he built a
odel of such betatron but it did not worked – and he turned to RF accelerators where he succeeded!

n **1940 Kernst** re-invented betatron and built a first working 2.2 MeV electron betatron. His larges
etatron reached 300 MeV.



- A betatron is more accurately an induction accelerator.
- The changing magnetic flux induces an azimuthal electric field that accelerates electrons.
- Wideröe wrote the idea in 1923; Kerst built the first working 2.2 MeV betatron in 1940.
- The name survives in "betatron oscillations," even far beyond betatron machines.

$$q\oint E\cdot dl = -(q/c)\, d\Phi_B/dt$$

The betatron 2:1 condition – Wideroe condition

$$V = -\frac{d\Phi}{dt}$$

$$E = \frac{V}{2\pi r} = \frac{1}{2\pi r}\frac{d\Phi}{dt}$$

$$F = eE = \frac{e}{2\pi r}\frac{d\Phi}{dt}$$

$$\frac{dp}{dt} = \frac{e}{2\pi r}\frac{d\Phi}{dt}$$

$$\boxed{p = \frac{e}{2\pi r}\Phi}$$

Rigidity $p = erB_{orbit}$

$$\Phi = 2\pi r^2 B_{orbit}$$

$$B_{avg} = \frac{\Phi}{\pi r^2}$$

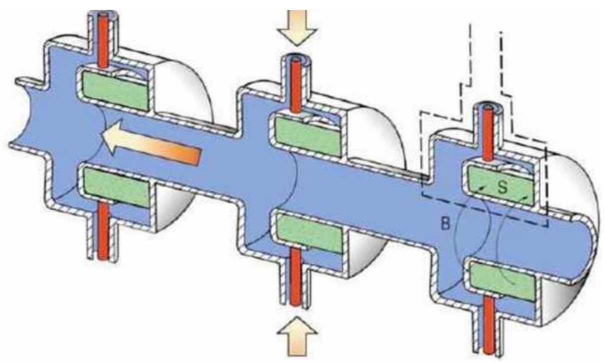
$$\boxed{\mathbf{B_{avg} = 2B_{orbit}}}$$

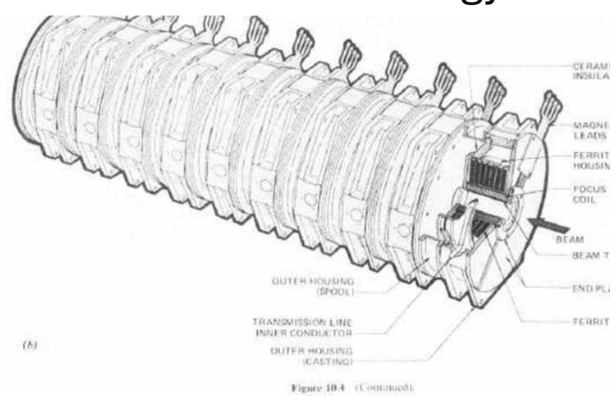
- For a fixed circular orbit, the induced electric field increases the particle momentum.
- At the same time, the orbit momentum must satisfy p = qB(ρ)ρ/c.
- Combining the two conditions gives the famous betatron condition.
- Interpretation: the average vertical magnetic field inside the orbit must be twice the field at the orbit.

- The electromagnet poles of a betatron are specially shaped.
- Center core is made highly permeable to pack more magnetic flux into the middle, while the outer area near the vacuum tube has a wider gap to keep the field half as strong.

Induction linacs: unwrapping the betatron

- A betatron can be "unwrapped" into a linear induction accelerator.
- Toroidal magnetic cores induce longitudinal electric fields in a beam pipe.
- Induction linacs are attractive for high peak current beams.
- They are still limited by induced voltage, pulsed power, and core technology.





same Maxwell idea; different geometry

What to remember from Lecture 2

- Electrostatic accelerators are conceptually simple but limited by terminal voltage and breakdown.
- RF acceleration bypasses the total-voltage problem by synchronizing particles with time-varying fields.
- Cyclotrons introduced cyclic reuse of RF gaps and the practical importance of resonance.
- Beam rigidity $B\rho \approx p[\text{GeV/c}]/0.3$ connects momentum to magnets.
- Microtrons, recirculating linacs, and ERLs reuse RF structures; ERLs also recover beam energy.
- Betatrons use induction; their legacy survives in the term betatron oscillations.

Some take home questions (not homework)

1. Why does DC fail for multi-pass acceleration?
2. What determines the RF phase in a linac?
3. Why does $B\rho$ matter more than energy for magnet design?

Selected references

- P. J. Bryant, “A Brief History and Review of Accelerators,” CERN.
- J. D. Cockcroft and E. T. S. Walton, “Experiments with high velocity positive ions,” Proc. Royal Society A, 1932.
- R. J. Van de Graaff, “A 1,500,000 volt electrostatic generator,” Physical Review, 1931.
- M. S. Livingston, Particle Accelerators: A Brief History, Harvard University Press, 1969.