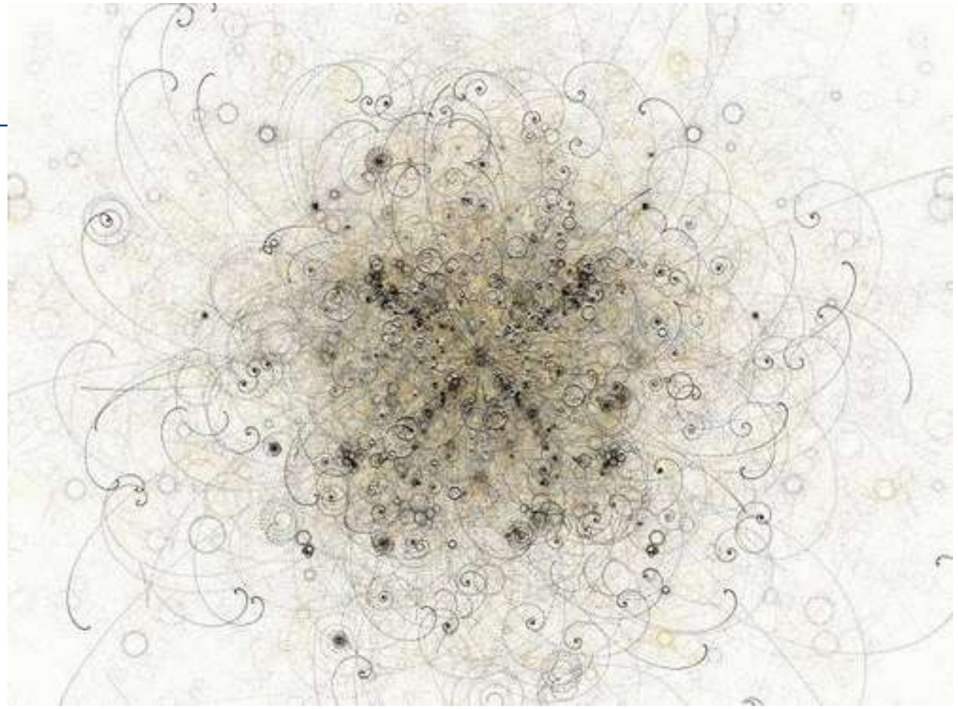
Announcements



Quiz:
- Assorted quizzes from previous weeks: pick up after class
- Next quiz on Friday

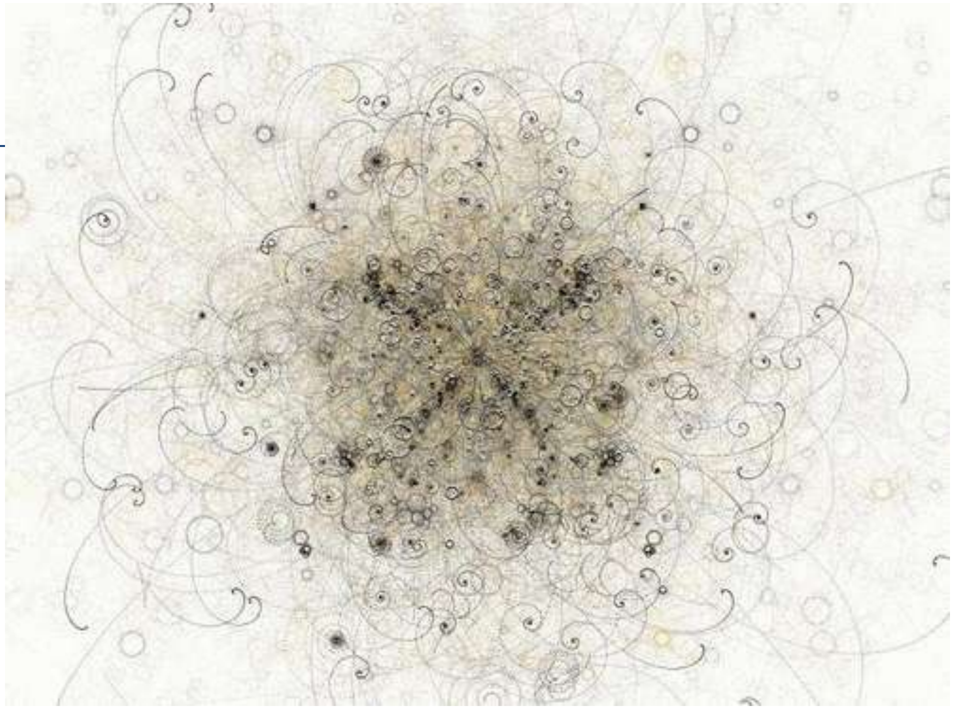
Homework:
Third HW due **Friday** before class on gradescope

Office hours: back to Fridays from 4-5pm

Outline Guidelines: Due February 28th

1. Title
2. Abstract
3. Logical structure of the paper
4. One sentence for each section

Outlines



Due February 28rd at the beginning of class

1. Title
2. Abstract
3. Logical structure of the paper
4. One sentence for each section

Logical structure of paper?

Lab report format:

Intro, Methods, Results, Discussion, Conclusions

Or another structure that is more useful for the topic that you have chosen

The sentence for each section should help me to follow the flow of the structure for your topic

Submit as pdf on gradescope

Worth 1% of class grade: pass/no-pass depending on if you turn in the above on time

I will return them to you after spring break

Cockroft-Walton Generator

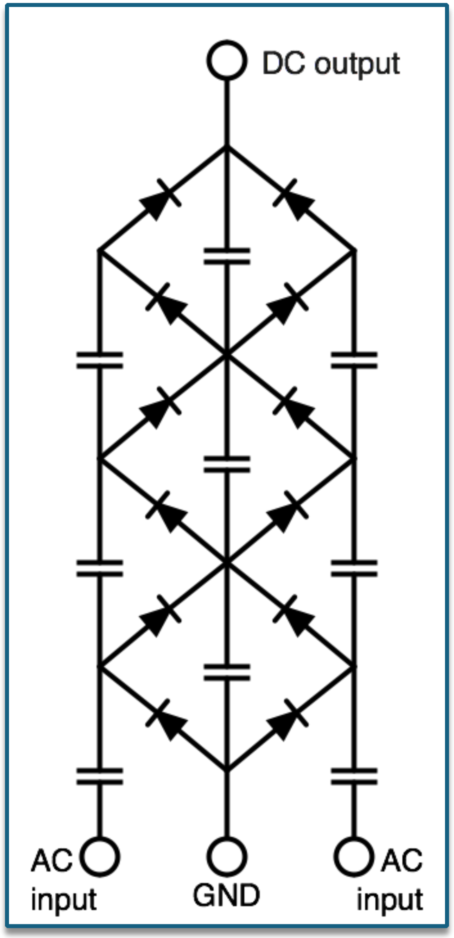
The earliest type of DC accelerator used a Cockroft-Walton generator that produced the high voltages.

- An AC voltage V is applied at the inputs
- Each stage has capacitors that get charged up
- Each state provides a voltage increase of 2 V
  - The first two capacitors charge up to V
- Because of the diodes, the capacitors cannot discharge when the AC voltage goes negative
- A N-stage Cockroft-Walton gives a DC voltage of 2N*V

N = number of capacitor layers

Diodes that allow current only in one direction

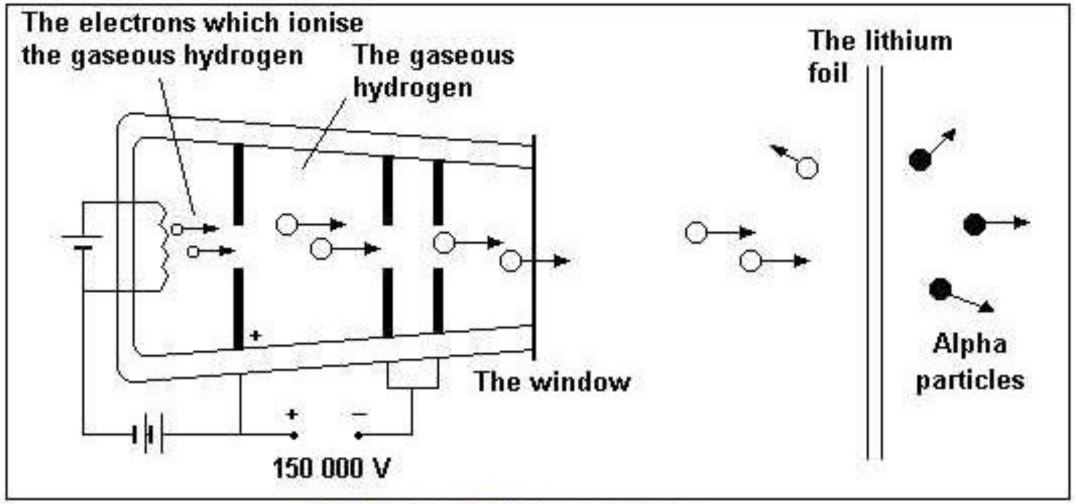
capacitors

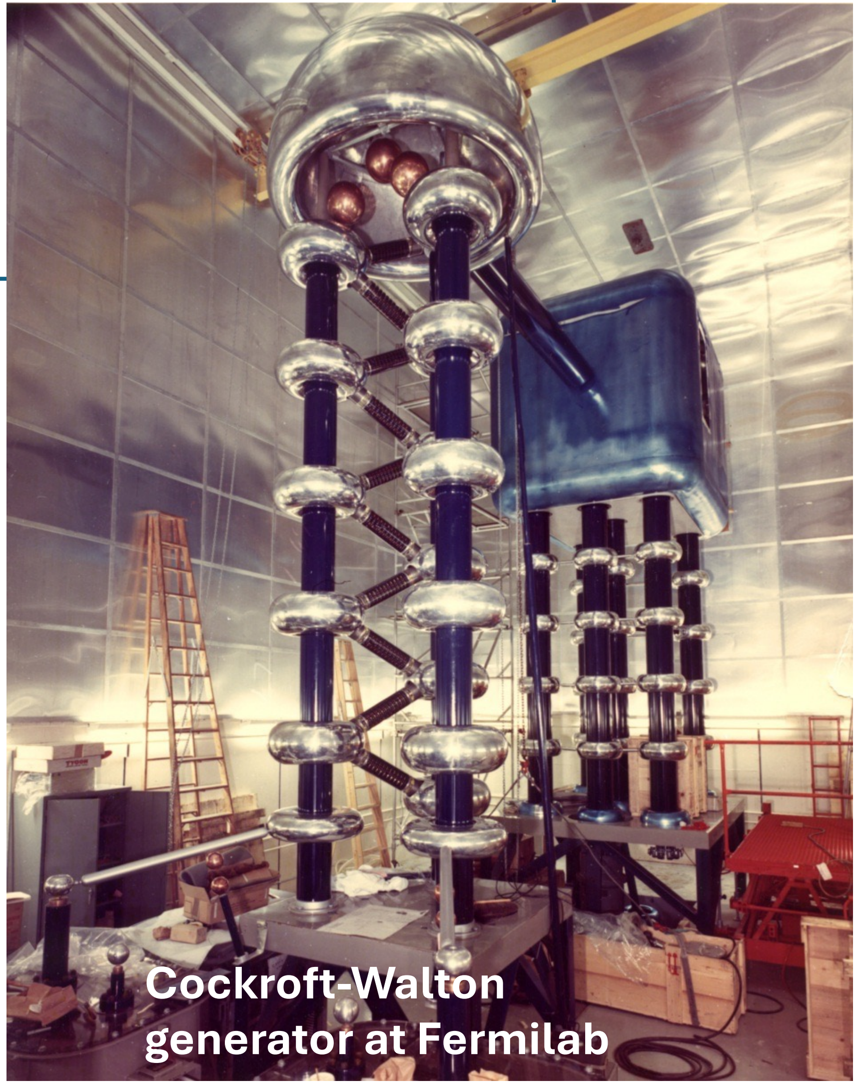


Cockroft Walton at Fermilab

Fermilab used a Cockroft-Walton accelerator as the first stage for decades

- 75 kV input AC voltage
- 5 stages
- 750 kV DC output voltage
- To accelerate negative H ions
- Then strip electrons off



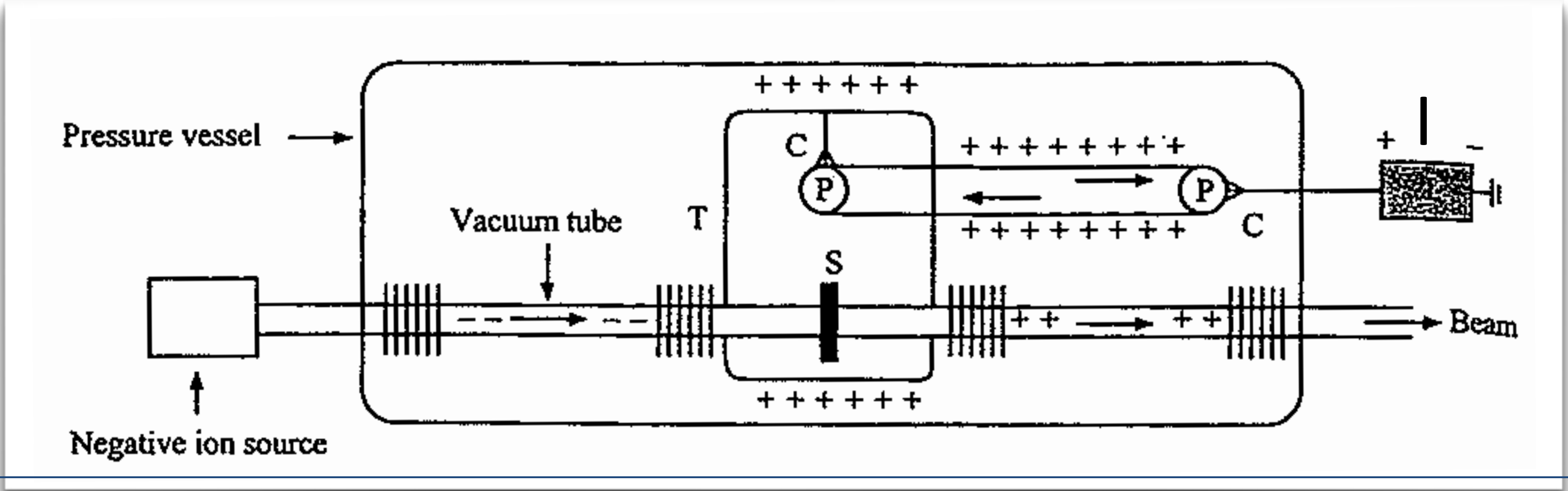


DC Accelerators

The “tandem” Van de Graaff accelerator can double the energy of the simple machine

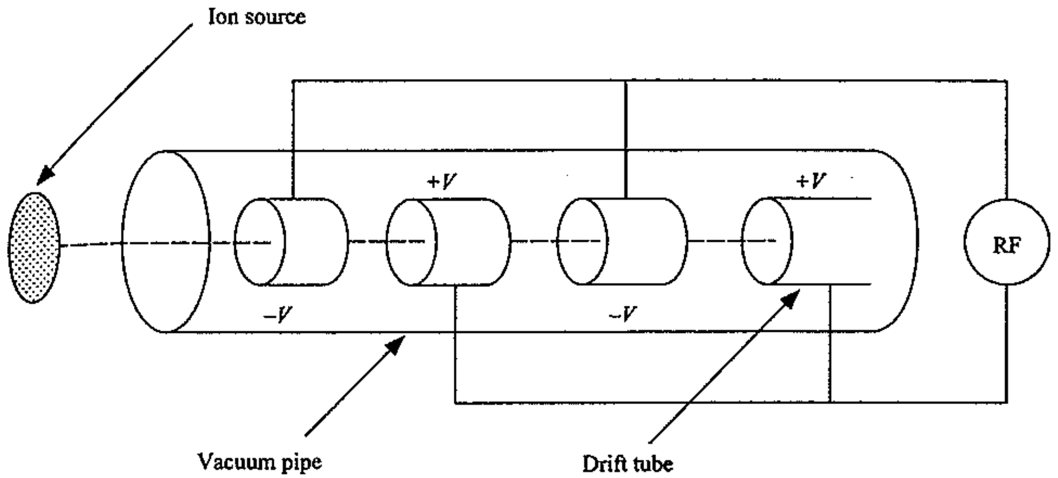
1. a high voltage source at I passes positive ions to a belt via a comb arrangement at C
2. ions are carried on the belt from the first pulley (P) to the second, and sent to another comb in a metal vessel T
3. The charges are transferred to the outer surface which acts as an external terminal
4. Singly-charged negative ions are injected from a source and accelerated along a tube toward T, and two or more electrons are removed in a stripper S. The positive ions can be further accelerated (tandem).

Up to E = ~40 MeV



AC Accelerators: Linac

In a linear accelerator (Linac), particles pass through a series of metal pipes (drift tubes) which are connected successively to alternate terminals of an RF oscillator.



- In between successive drift tubes, the particles are accelerated by the electric field
- The gap between tubes is short so the particles experience the maximum potential difference
- Inside a drift tube, the field switches polarity
    - The particles don't experience a force as long as they are inside a drift tube (Faraday cage)

Why is the length of the tubes different?

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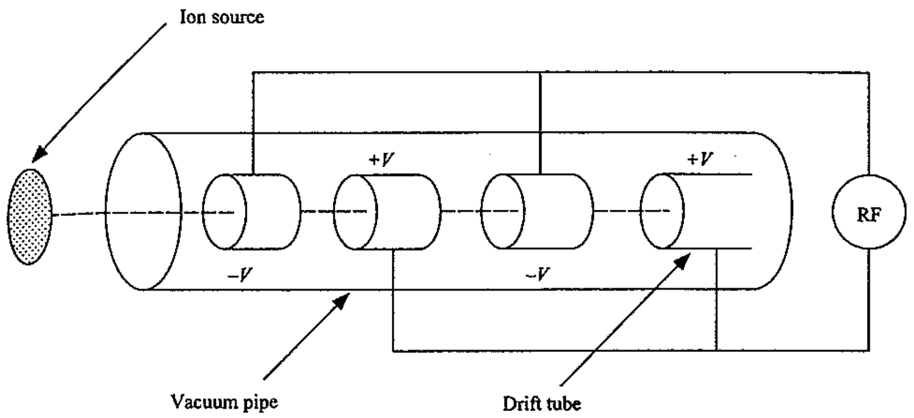

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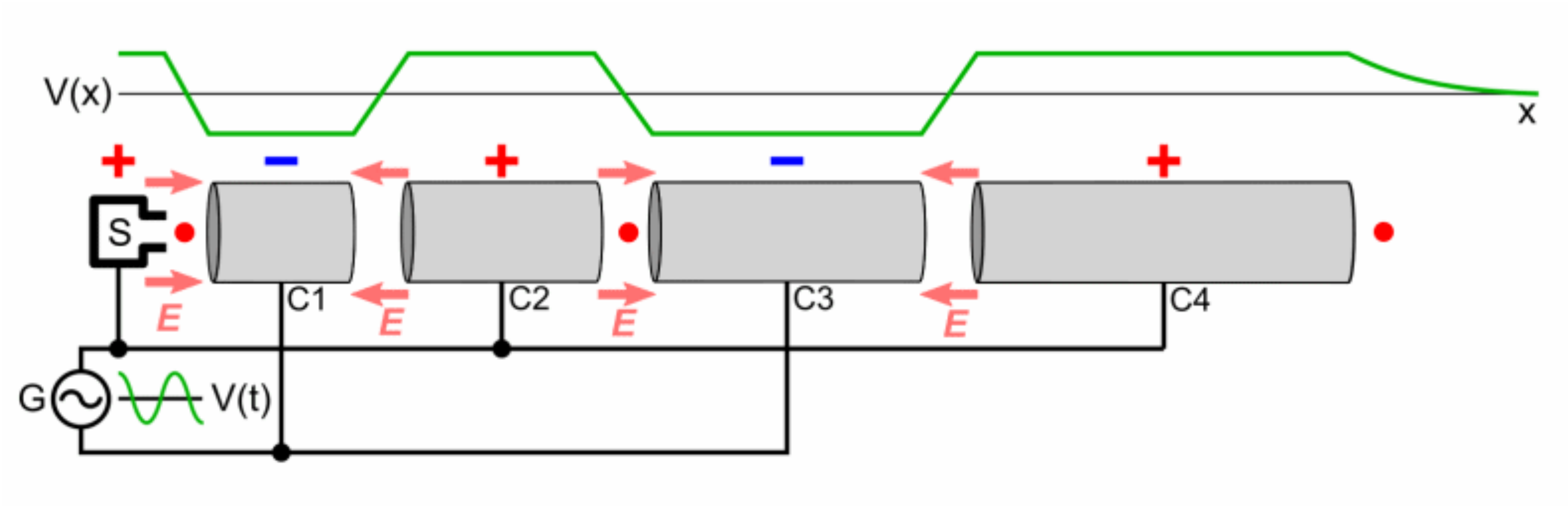
- The gap between tubes is short so the particles experience the maximum potential difference
- Inside a drift tube, the field switches polarity
  - The particles don't experience a force as long as they are inside a drift tube (Faraday cage)
- The length of each tube is adjusted according to the particle's velocity
- Once the particles reach the speed of light c, drift tube length is constant

AC Accelerators: Linac animation



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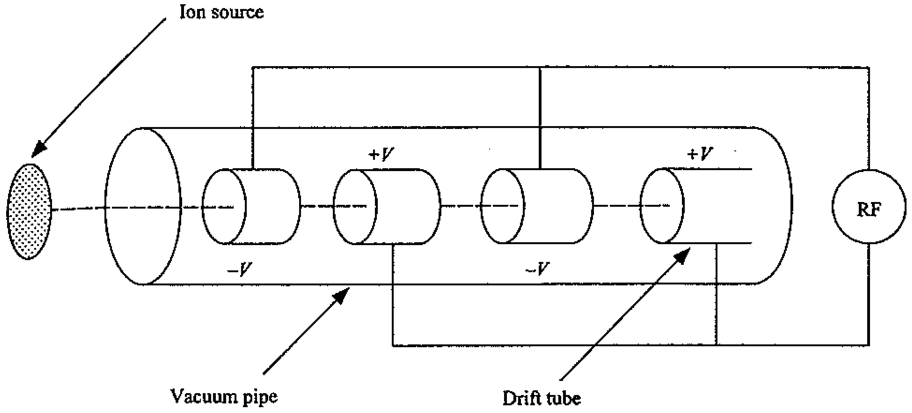
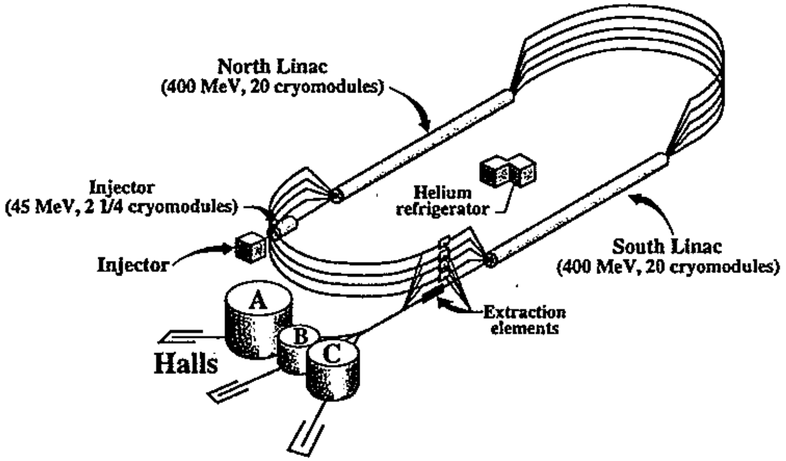


A variety of linacs in USA

- ATLAS (Argonne National Lab.)
  first superconducting linear accelerator
  7-17 MeV/nucleon stable, unstable ions
- SLC (SLAC at Stanford)
  cylindrical metal cavity + magnetic focus lens
  50GeV electrons - 3km long
- CEBAF (Jefferson Lab.)
  two short linacs with bending lines, 0.5-6.0GeV intense electron

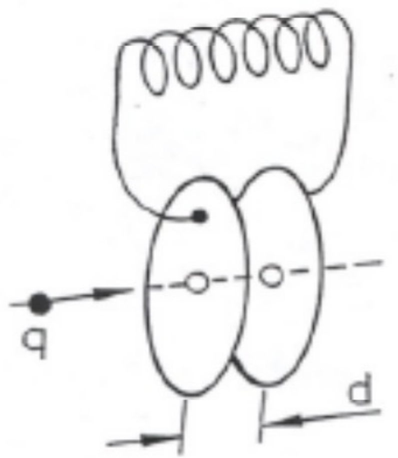
CEBAF



AC accelerating element

- Oscillating LC circuit frequency $\omega = \frac{1}{\sqrt{LC}}$

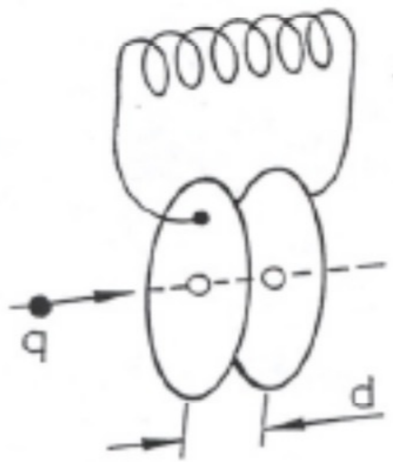
C = capacitance
L = inductance



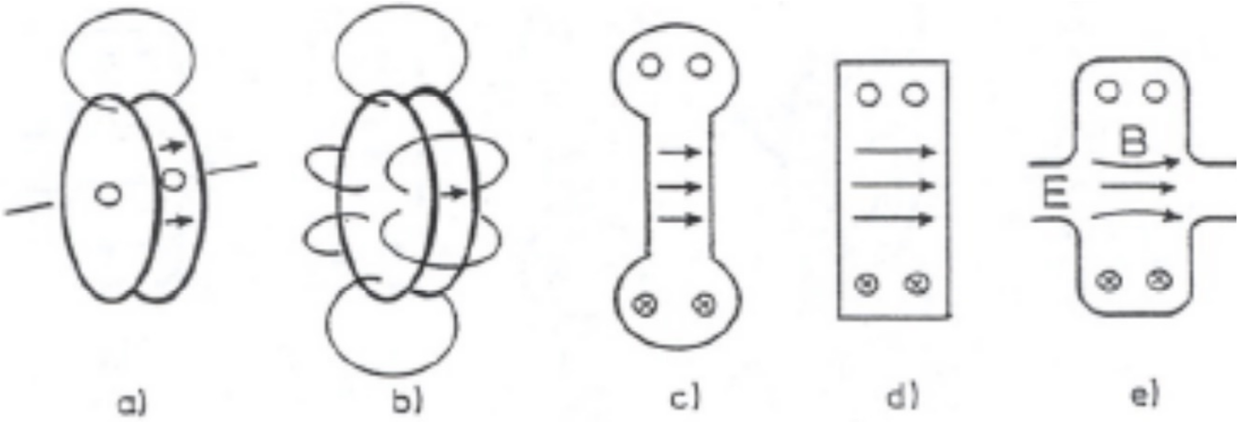
- The cavity will oscillate between electric and magnetic fields - between voltage and current
  - Typically at radio frequencies (RF)
- Charged particle entering the capacitor at the right time will be accelerated

Radio-frequency cavity

- Radio-frequency cavity is a LC circuit
- Outer area contains magnetic field, i.e. current
- Inner area contains capacitor, i.e. voltage
- Start with the LC circuit:



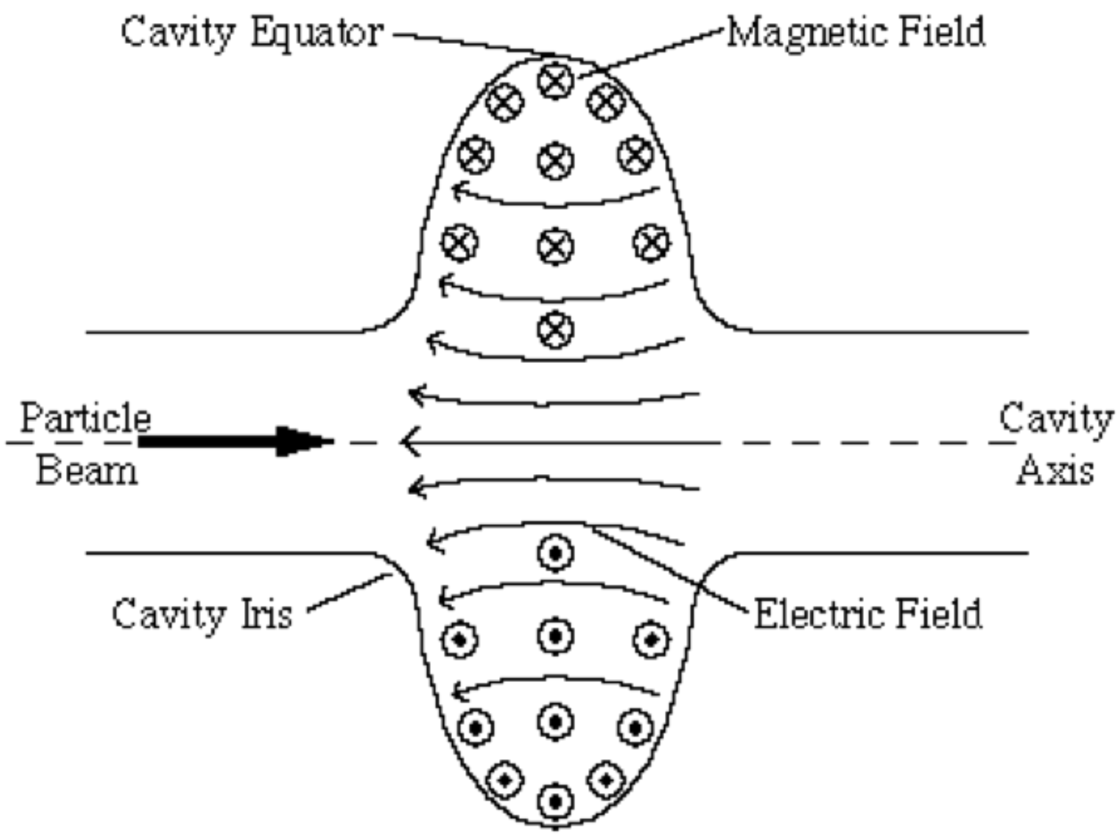
- Then deform to an accelerating cavity:



The smoother the surface the more charge is kept

RF cavity

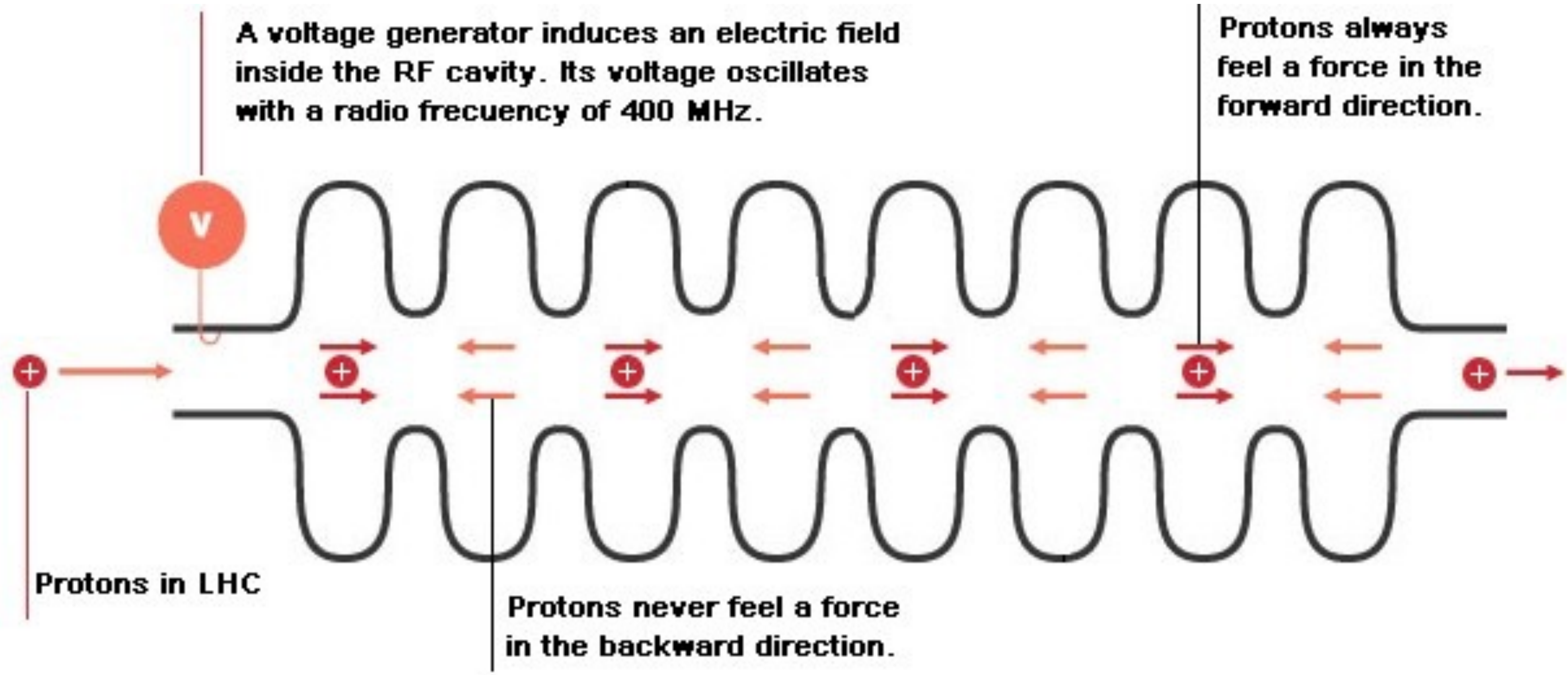
- A cavity is a conductor to which an AC voltage is applied
- The cavity will oscillate between electric and magnetic fields



Example Superconducting RF cavity

- The beam passes from left to right
- A standing wave oscillates in the free space
- A high-powered microwave supplies power to the cavity from the top

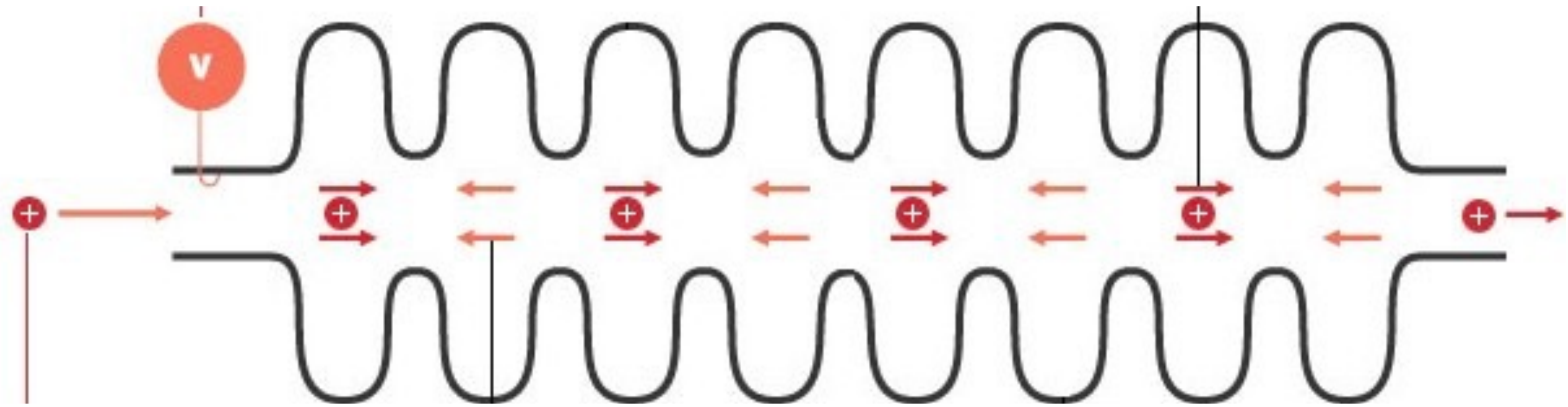
RF cavities at the LHC



- Each cavity contains a standing EM wave
- All cavities are in phase
- f = 400 MHz
- 2 MV per cavity -> 5 MV per meter

Can fill every other cavity with a particle to make a beam!

Distance between successive cavities



- At a given time t, two successive cavities have opposite phase of the electric field
- Path length difference $\lambda/2 = c/2f$
- For the LHC, f =400 MHz, so λ =0.75 m
- Thus the distance between 2 cavities is 0.375 m
- The 8 LHC cavities together are therefore 3 m long

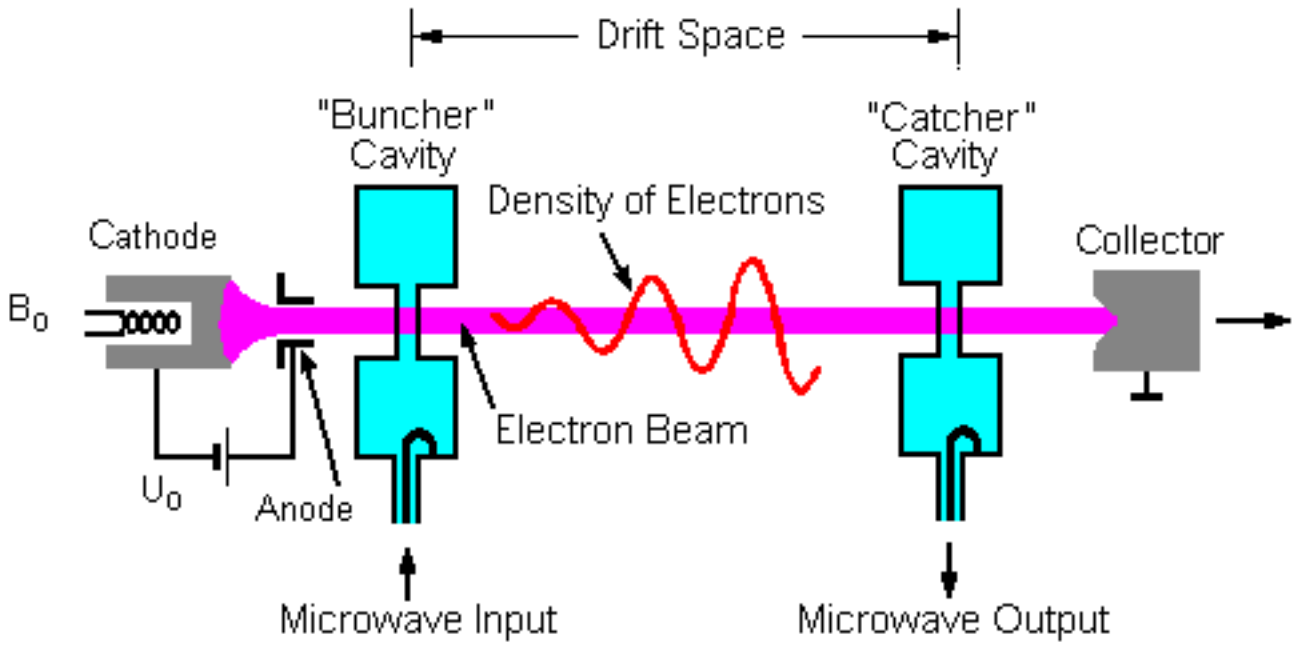
RF cavity at LHC

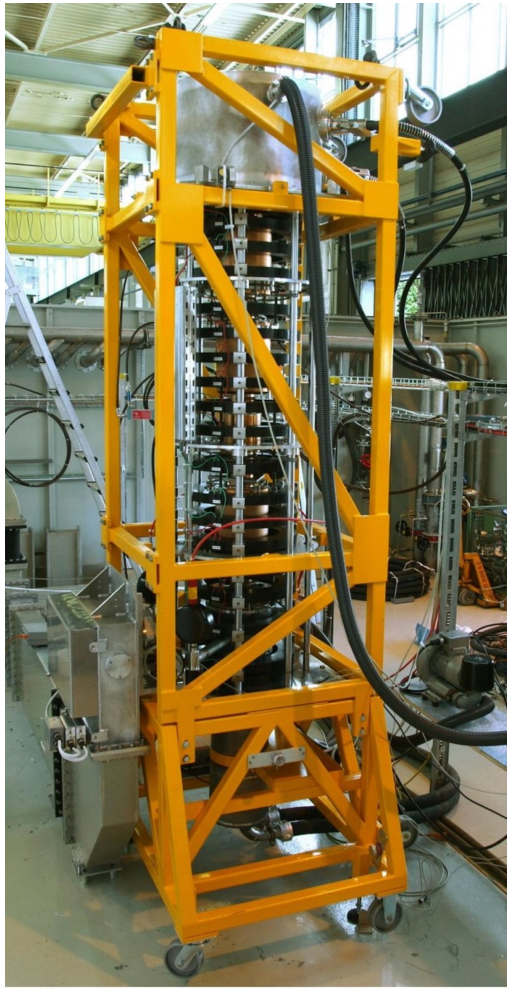
Input radio frequencies

Beam pipe

Klystron

- The microwave power for the accelerator is often provided by a Klystron
- Klystron: electron beam that amplifies microwaves





RF cavity performance

- RF cavities operate at large voltages and high frequencies
- Important to minimize ohmic energy loss
  - Superconducting cavities
  - Room-temperature cavities carefully polished to minimize surface resistance
  - Geometry of cavity to minimize sharp edges, large non-uniform electric fields
- Similarly all wave guides and klystrons optimized to minimize energy loss

Circular accelerators

- In a circular accelerator, the magnetic field B keeps the particles on their circular trajectory

$$\frac{dE}{dt} = \frac{qc^2}{E}\vec{p} \cdot \left(\vec{E} + \vec{v} \times \vec{B}\right)$$

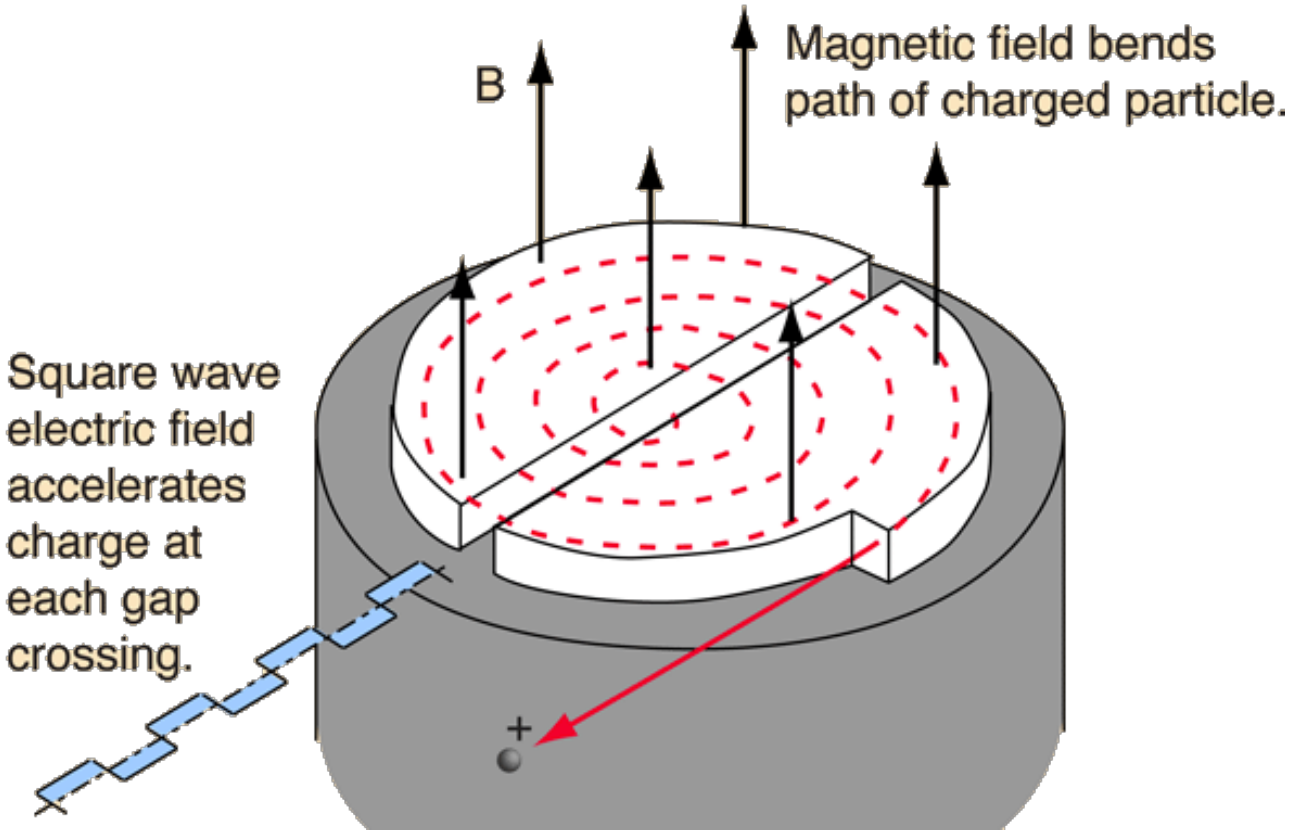
- An electric field is applied to accelerate the particles
  - Often only once per turn

Circular accelerators: Cyclotron

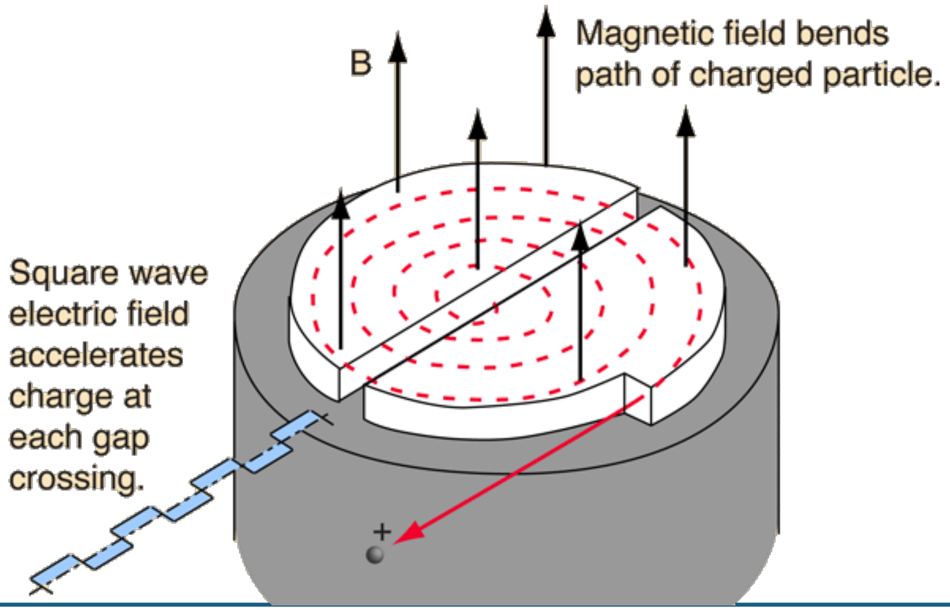
For a low-energy nuclear physics experiments, cyclic accelerators, called cyclotrons, are used.
They are also used to produce beams for medical application, including proton beam radiation therapy.

1. Charged particles are injected into the machine near its center.
2. Uniform magnetic field bends path of charged particles.
3. The ions are accelerated each time they pass across the gap with an RF field.

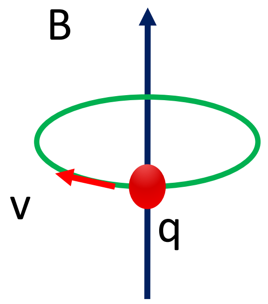
With each kick across the gap the particle moves faster, so has a larger bending radius



Circular accelerators: Cyclotron



Cyclotron frequency (ω_c)



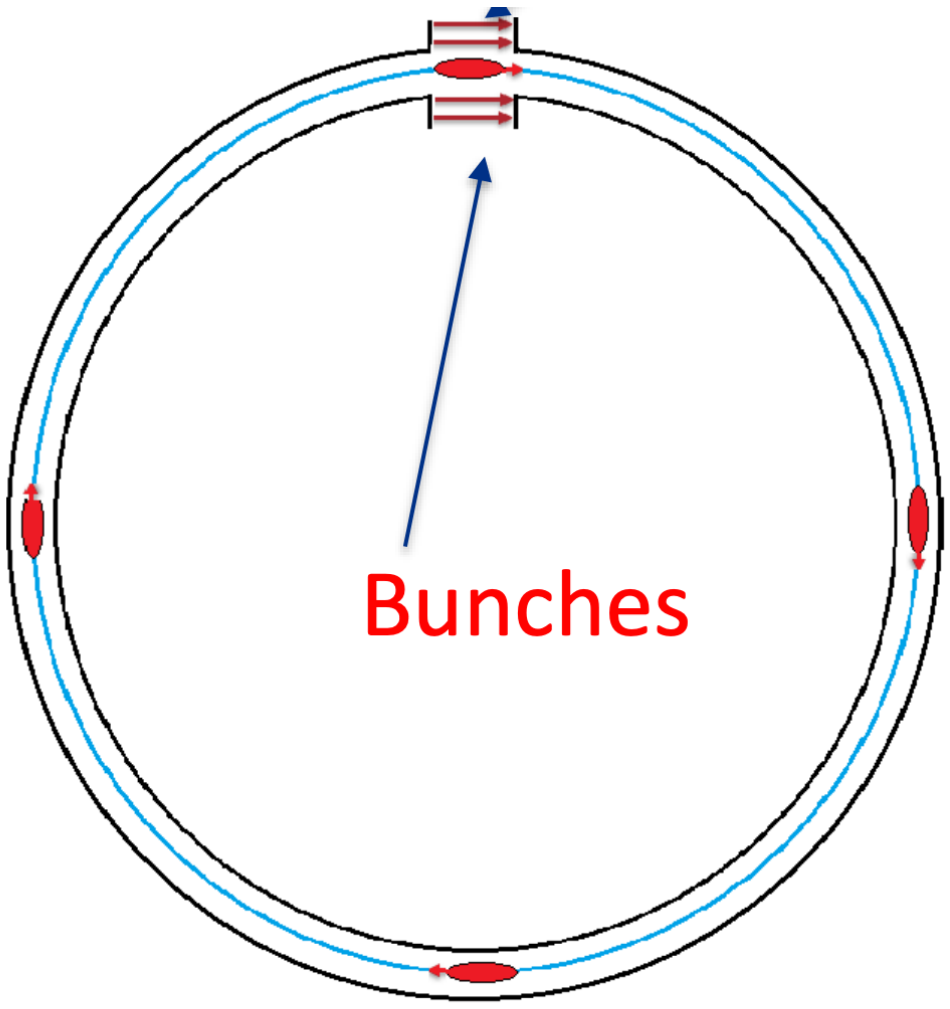
$$\frac{mv^2}{r} = qvB$$

$$v = \frac{qBr}{m}$$

Time for rotation: $t = 2\pi r/v = \dfrac{2\pi m}{qB}$

$$\omega_c = 2\pi f = 2\pi/t = \frac{qB}{m}$$

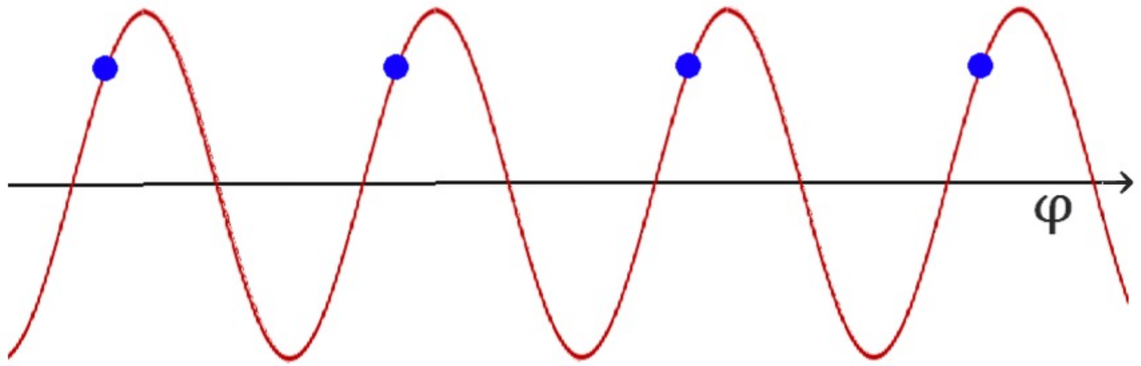
Circular accelerator: Synchrotron



- Accelerate bunches of particles
- Each bunch passes by the acceleration gap once per turn
- Electric field in the gap
$$E = E_0 \cos\omega t$$
- The angular frequency ω is determined by the ring geometry
$$\omega = \Omega N$$
  - Ω is the ring revolution frequency
  - N is the harmonic number, also the number of available bunches (buckets)

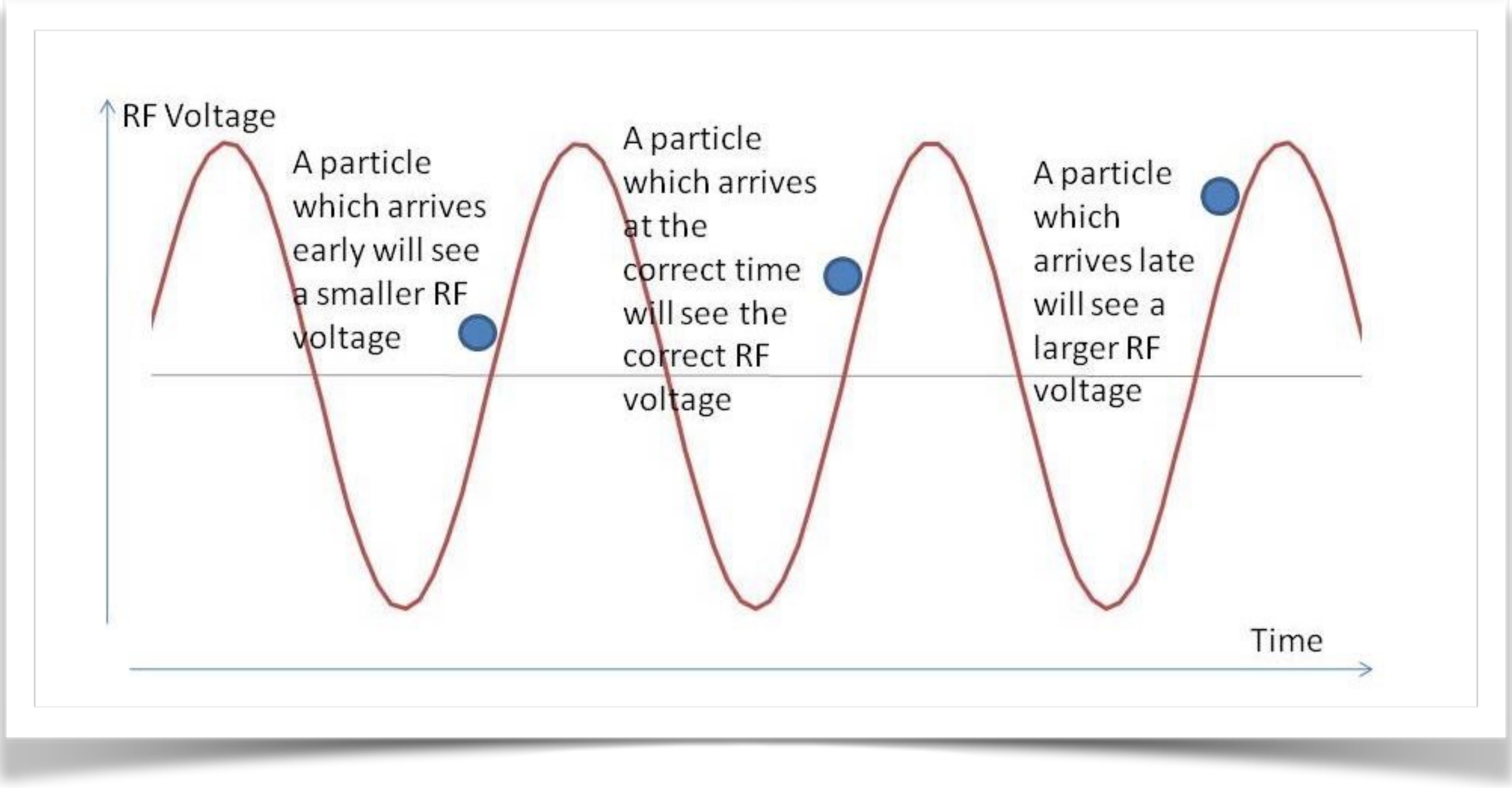
Synchrotron

- Circular accelerator with an acceleration gap
- RF frequency in the acceleration gap tuned to circumference of ring
- All charged particle bunches should reach the center of the acceleration gap at the same phase φ → Synchronous
- Voltage that accelerates each bunch $V = V(\varphi) = V_0 cos(\varphi)$
- Need $-\pi/2 < \varphi < \pi/2$ for acceleration



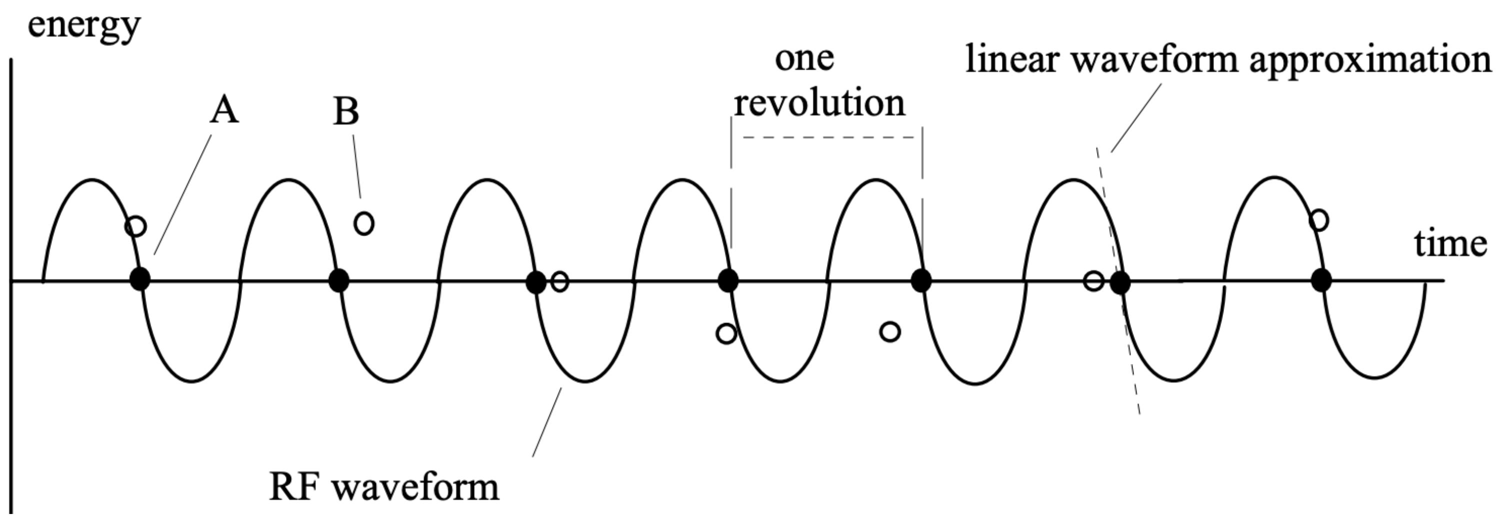
Synchrotron orbits

Cyclic accelerators used in particle physics are called synchrotrons.
The operation is similar to that of a linear accelerator, but synchrotrons have a near circular orbit → auto-phasing



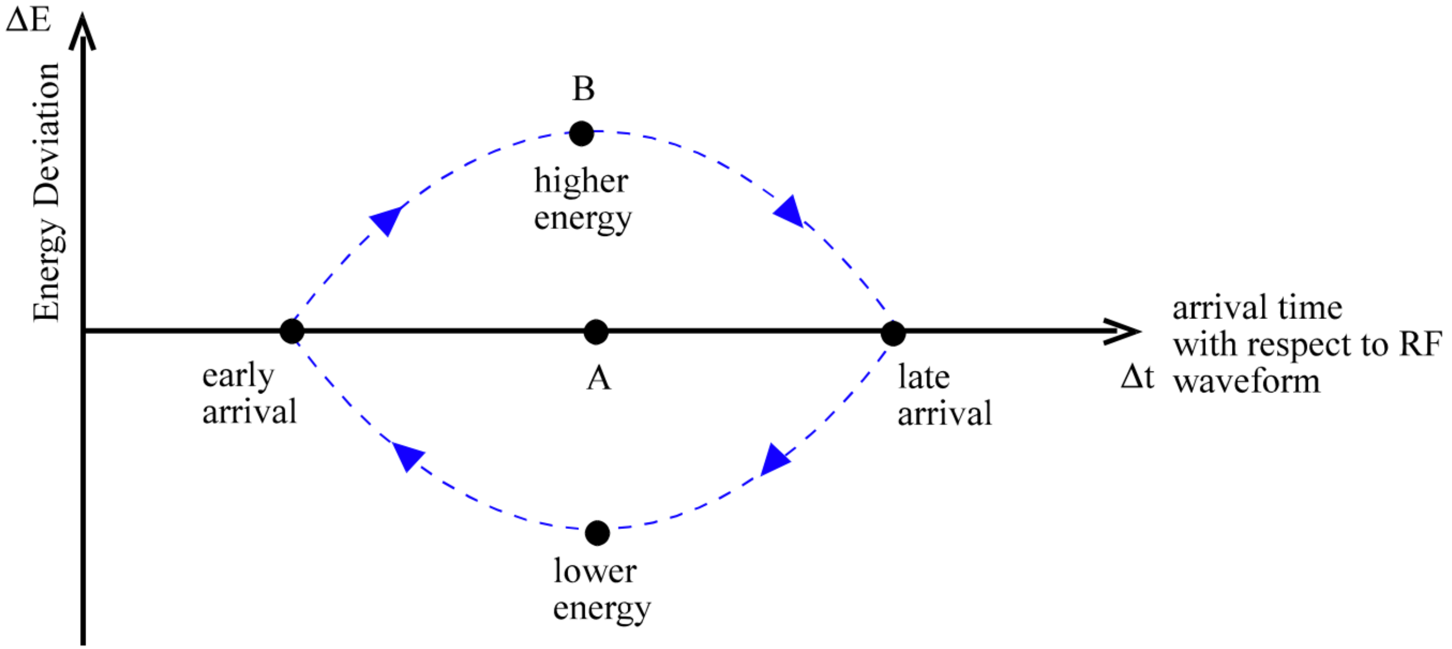
Longitudinal phase space

- Two particles A and B in the same bunch
- A is synchronous with the accelerator cavity frequency
- B is initially at the same time as A, but has higher energy
  - So B travels at a larger radius around the circle and arrives later than A at the second turn
  - Then B gets a negative energy contribution and then travels on a smaller circle orbit - and so on



Longitudinal phase space

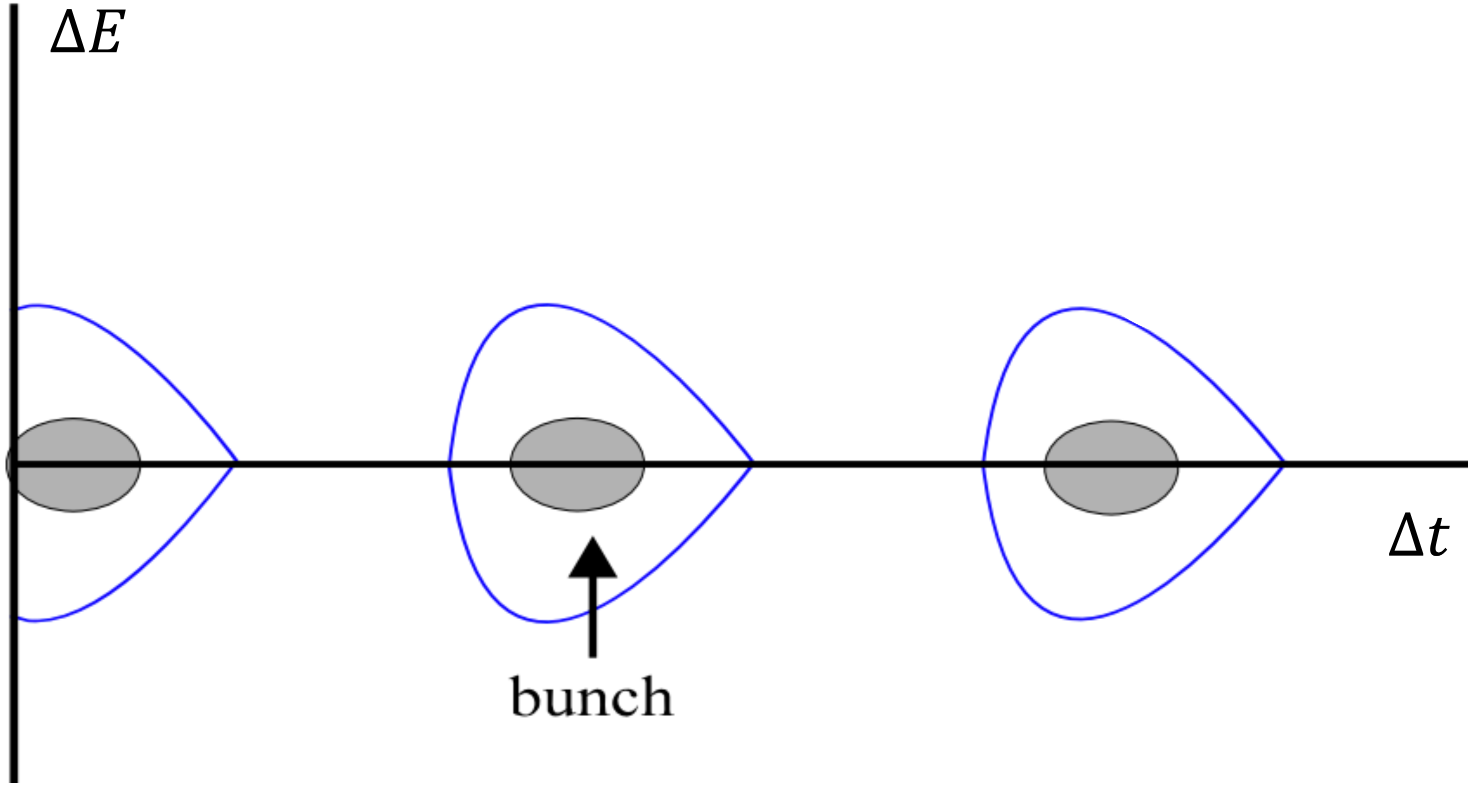
- Arrival time Δt and corresponding energy gain ΔE can be visualized in a 2d phase-space plot



- All particles that are in stable orbits must be inside this envelope (bucket)
- A synchrotron has a fixed number of buckets (= harmonic number)
  - Not all are occupied (bunches)

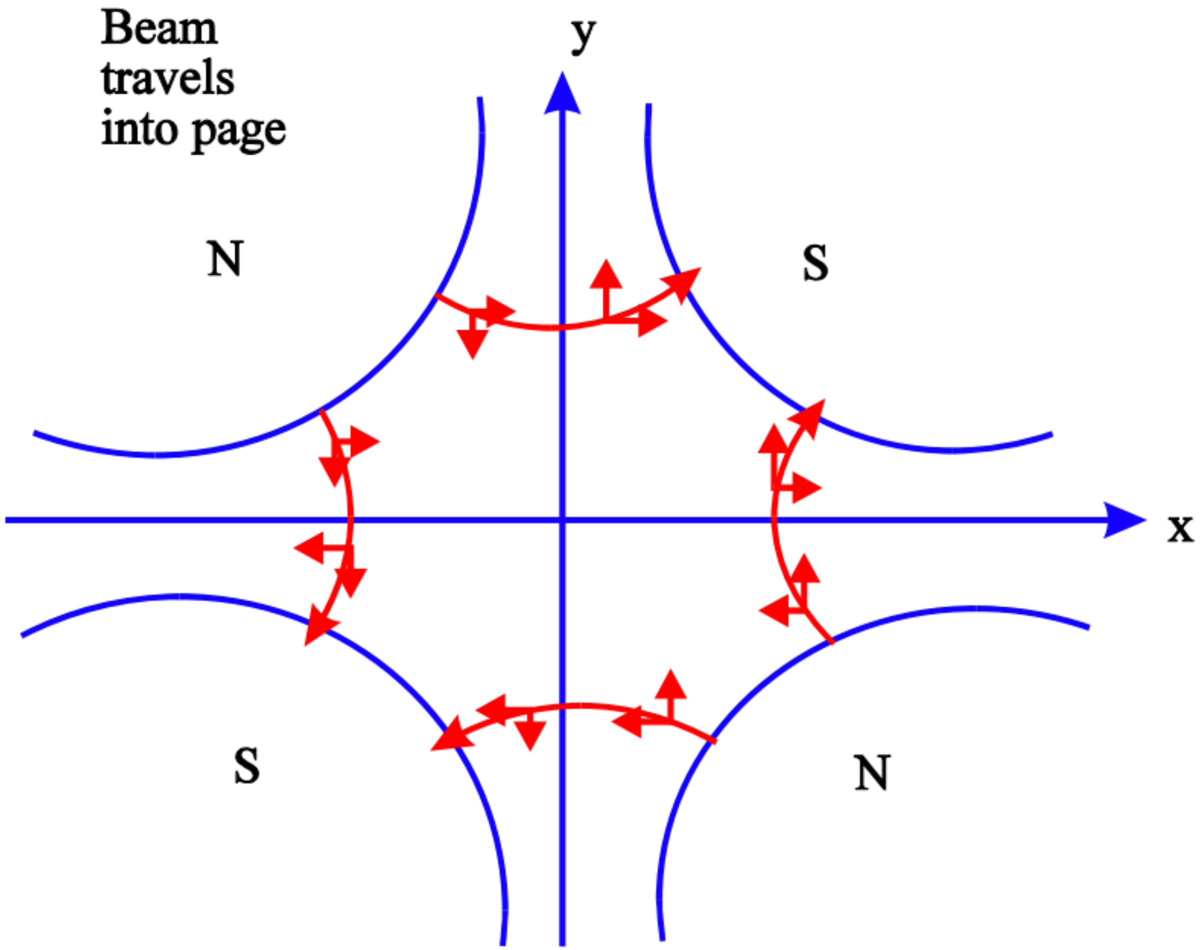
Longitudinal phase space

- In an accelerating system, the effect is the same but the phase space bucket is not symmetric



Synchrotron transverse beam stability

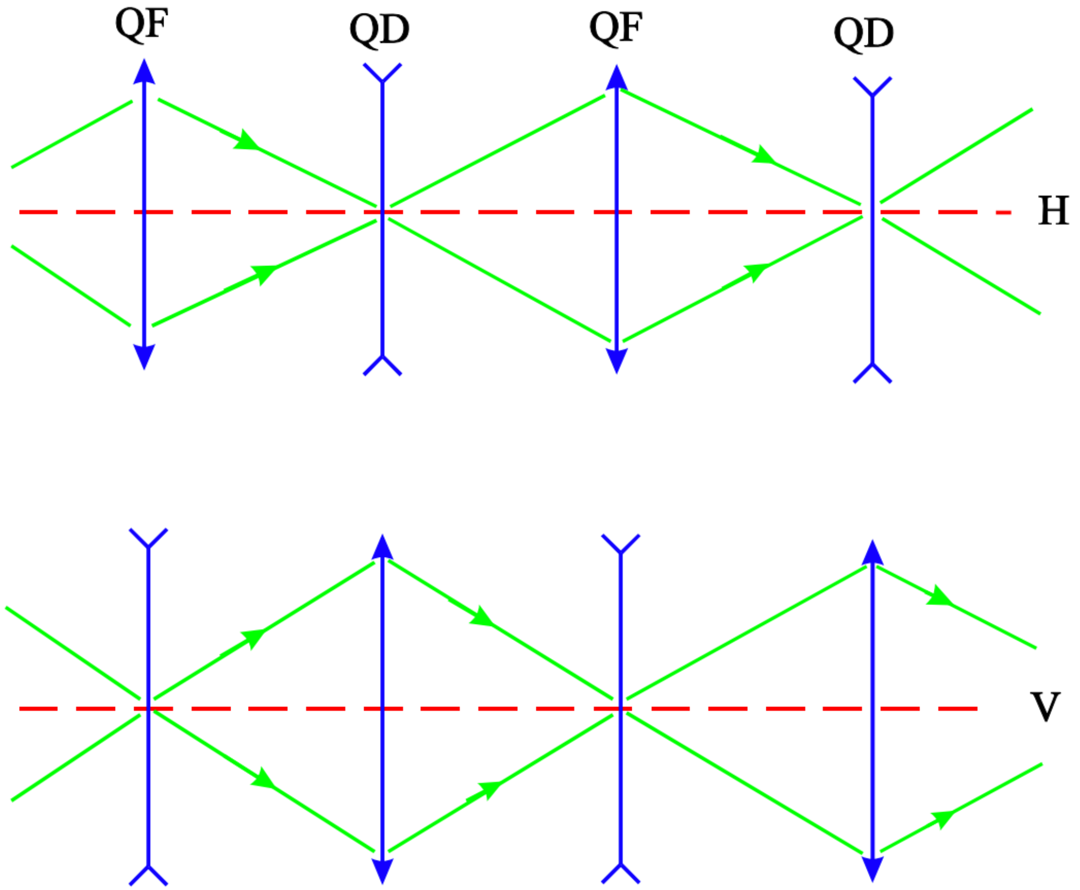
- Quadrupole magnets to keep particles in orbit in the transverse direction
- Series of quadrupoles to keep beam focused



Focusing in y direction

De-focusing in x direction

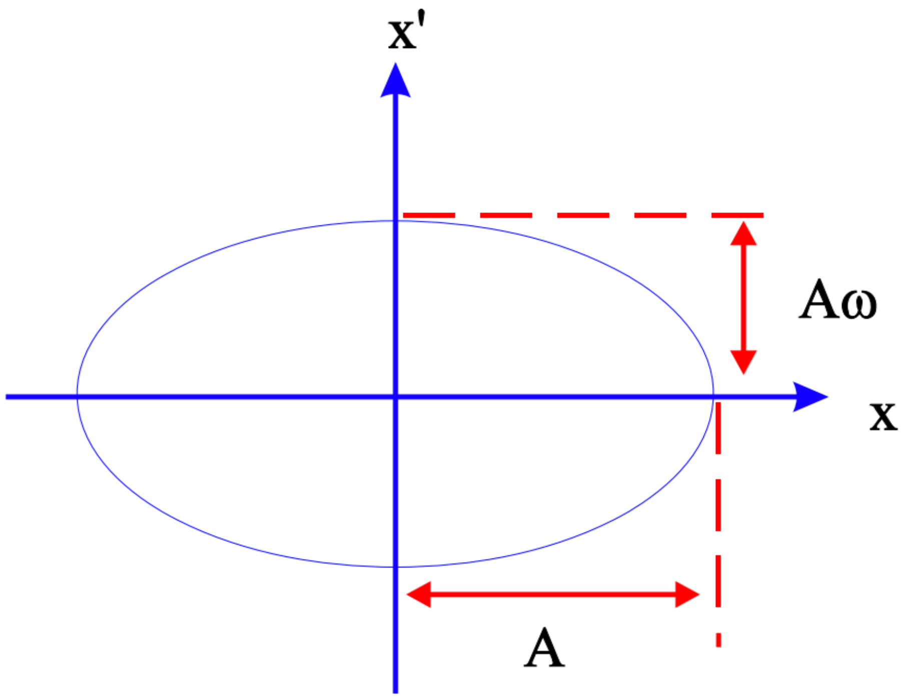
Quadrupoles act like lenses



- Series of focusing and de-focusing lenses
- Particles that are off-axis will undergo Betatron oscillations: bulging/flattening of bunch shape to keep particles together

Transverse phase space

- In the horizontal and vertical planes (transverse to the beam), each particle is described by
  - x = displacement from the central orbit
  - x' = angle with respect to the central orbit



$$x = A\cos\omega t + \phi$$

$$x' = -A\omega\sin\omega t + \phi$$