Accelerators for Proton Beam Therapy

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What do you want to know?

- Some basics:
  - How do you bend and accelerate a beam?
  - Why go in circles ie. why not just use a linear accelerator?
  - What governs the size of the accelerator?
- A quick look at the 2 technologies in use for existing Proton Beam Therapy facilities:
  - Cyclotron (+ SynchroCyclotron)
  - Synchrotron
- A brief look at gantries: why are they so big?

Forces

- 2 forces available for accelerating a charged particle:
  - Electric (E)
  - Magnetic (B)

$$F = q\vec{E} + q\left(\vec{v} \times \vec{B}\right)$$

- Electric field only accelerates in one direction: no continuous bending.
- Magnetic field only accelerates perpendicular to particle velocity: no linear acceleration.
- Use Electric fields for acceleration, magnetic fields for bending/steering/focussing.
- Can relate magnetic force to centripetal acceleration:

$$F = q\left(\vec{v} \times \vec{B}\right) = \frac{m_0 \gamma v^2}{\rho} = \frac{pv}{\rho}$$

- The *Magnetic rigidity* relates bending radius ρ to momentum p, magnetic field B and charge q:

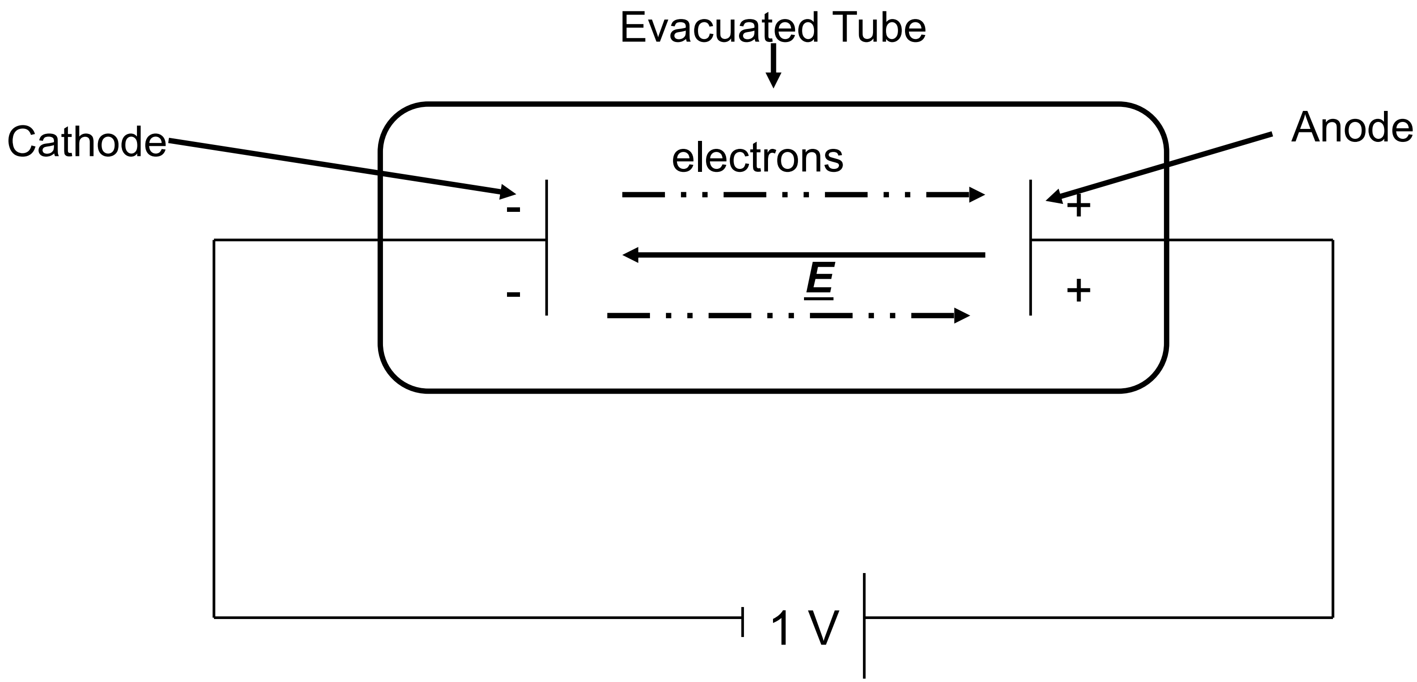
$$B\rho = \frac{p}{q}$$

Acceleration & Bending

- Acceleration comes from *Electric* fields:
  - At low gradients use DC voltage.
  - For high gradients use AC voltage:
    - RF power supply gives alternating field.
    - Automatically gives bunched beam.
- Bending comes from *Magnetic* fields:
  - Magnetic rigidity governs bending radius for given magnetic field.
  - In short, higher particle energy/momentum needs higher magnetic field or larger radius…
- Cyclotrons increase radius, Synchrotrons increase field strength.

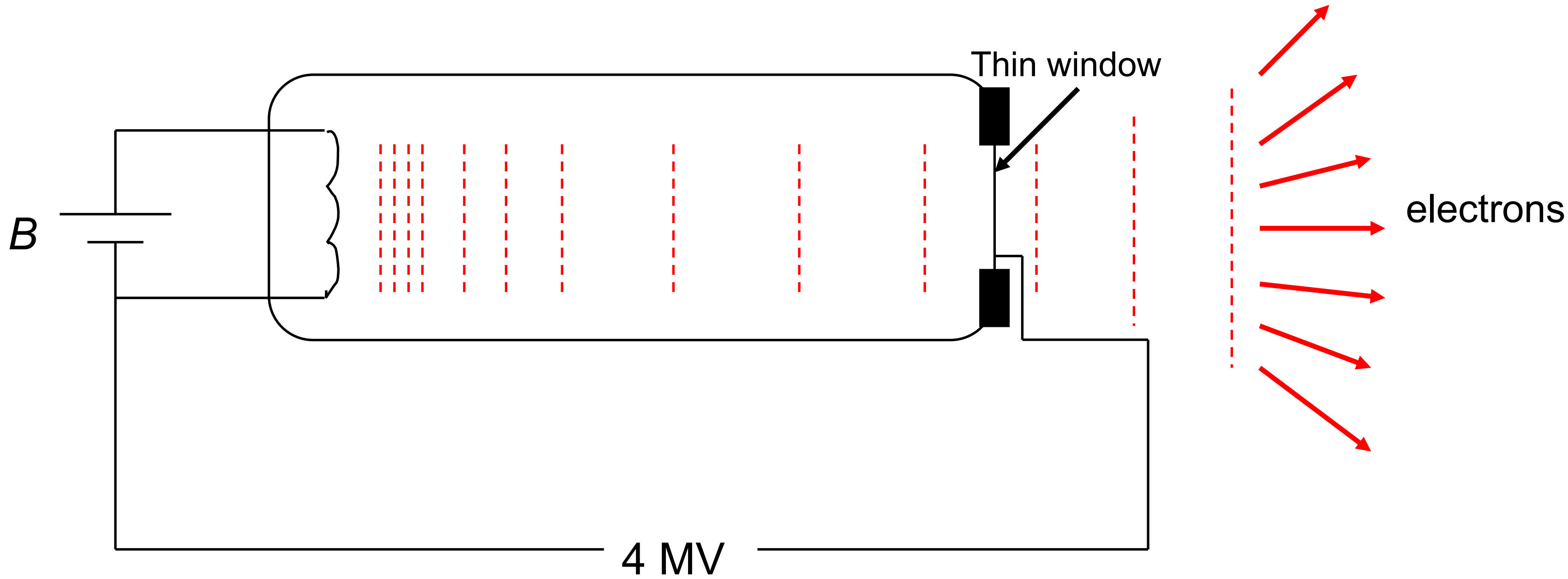
How do you accelerate particles?

Cathode Ray Tube



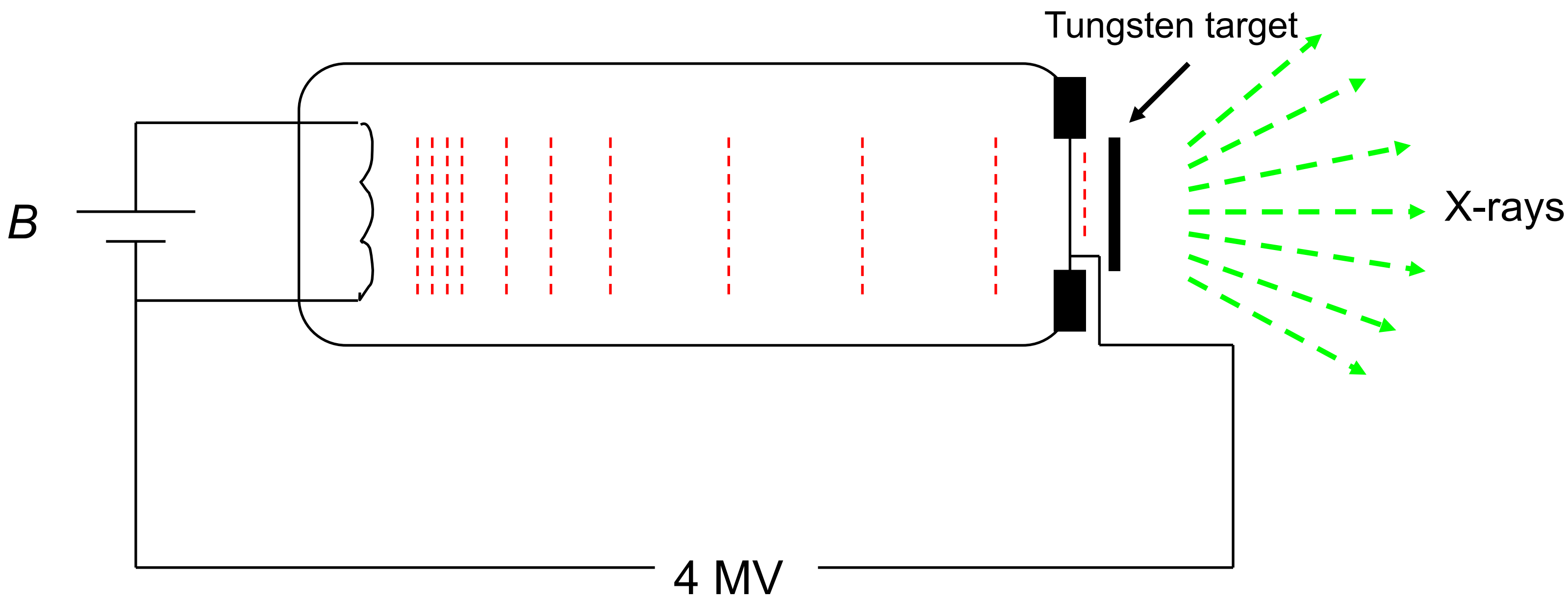
- Electrons flow from cathode to anode via external circuit creating an *Electric Field*, ***E***.
- If electrons are released from the cathode they will be accelerated by E to the anode
- For a potential difference of 1 Volt the electron will gain 1 *electronVolt* of energy.
- Electric Field ***E*** = 1 V/cm = 100 V/m.

Electron Gun



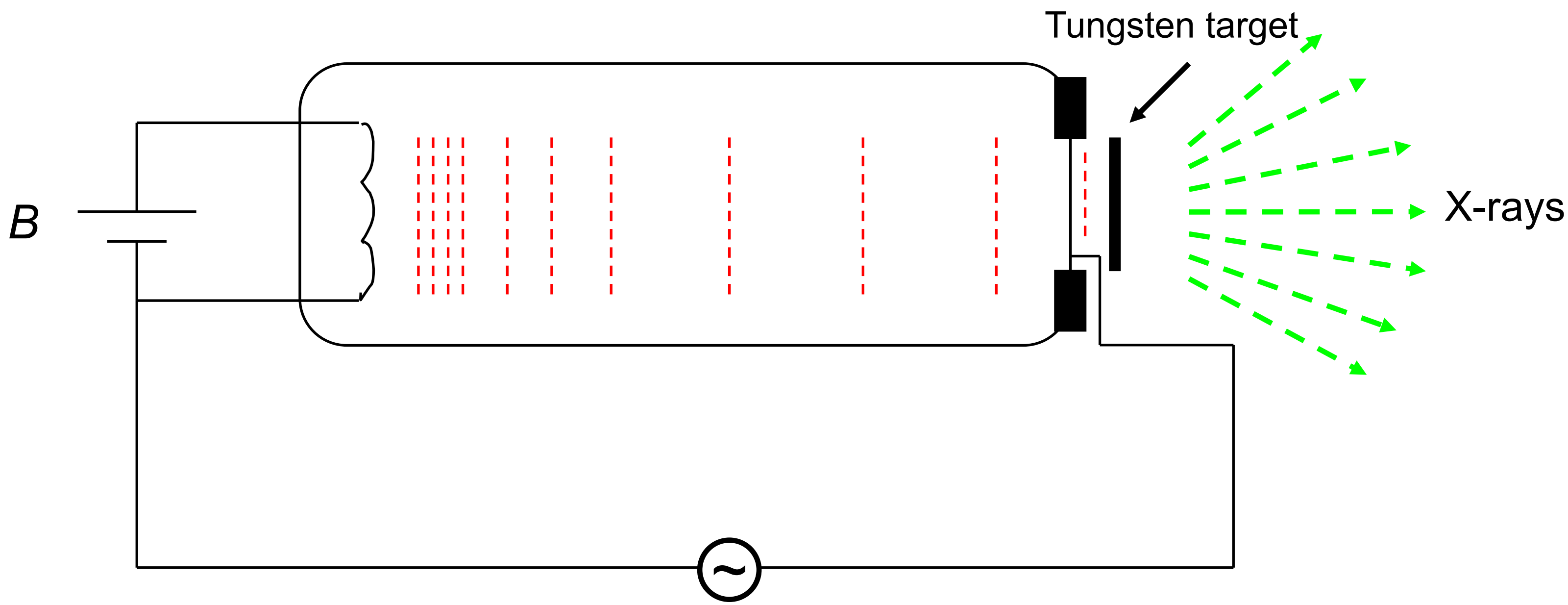
- Replace plate with heated cathode powered by a battery *B*.
- Electrons produced from heated cathode will gain energy 4 MeV.
- Replace anode with thin metal window
- Electrons will pass through with small energy loss

X-Ray Source

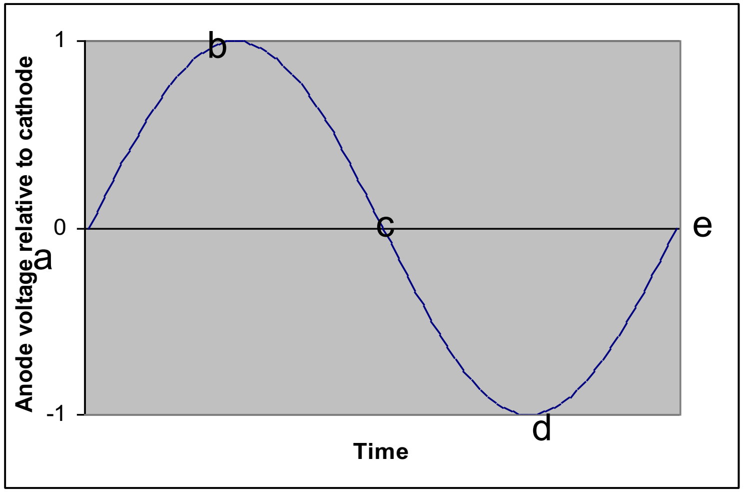


- Add Tungsten target after window:
  - Electrons stop in target.
  - Kinetic energy released as X-ray photons.
  - Energy spectrum of X-rays ranges up to 4 MeV.

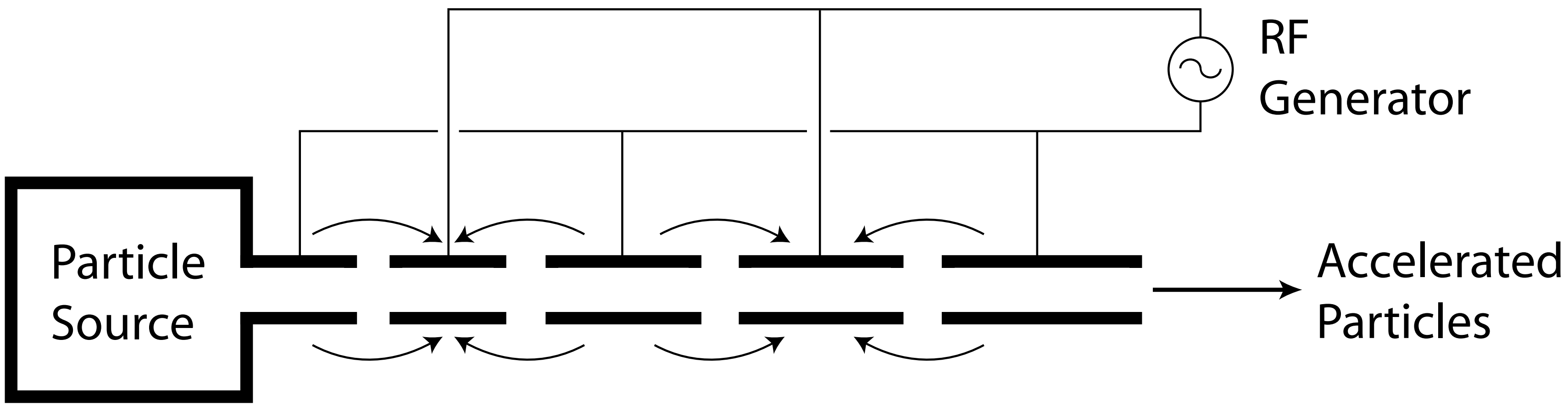
X-Ray Linear Accelerator



- Replace DC accelerating voltage with alternating voltage:
  - Electrons accelerated in *bunches*.
  - Only acceleration between *a*–*c*: maximum at *b*.
  - No acceleration between *c*–*e*.

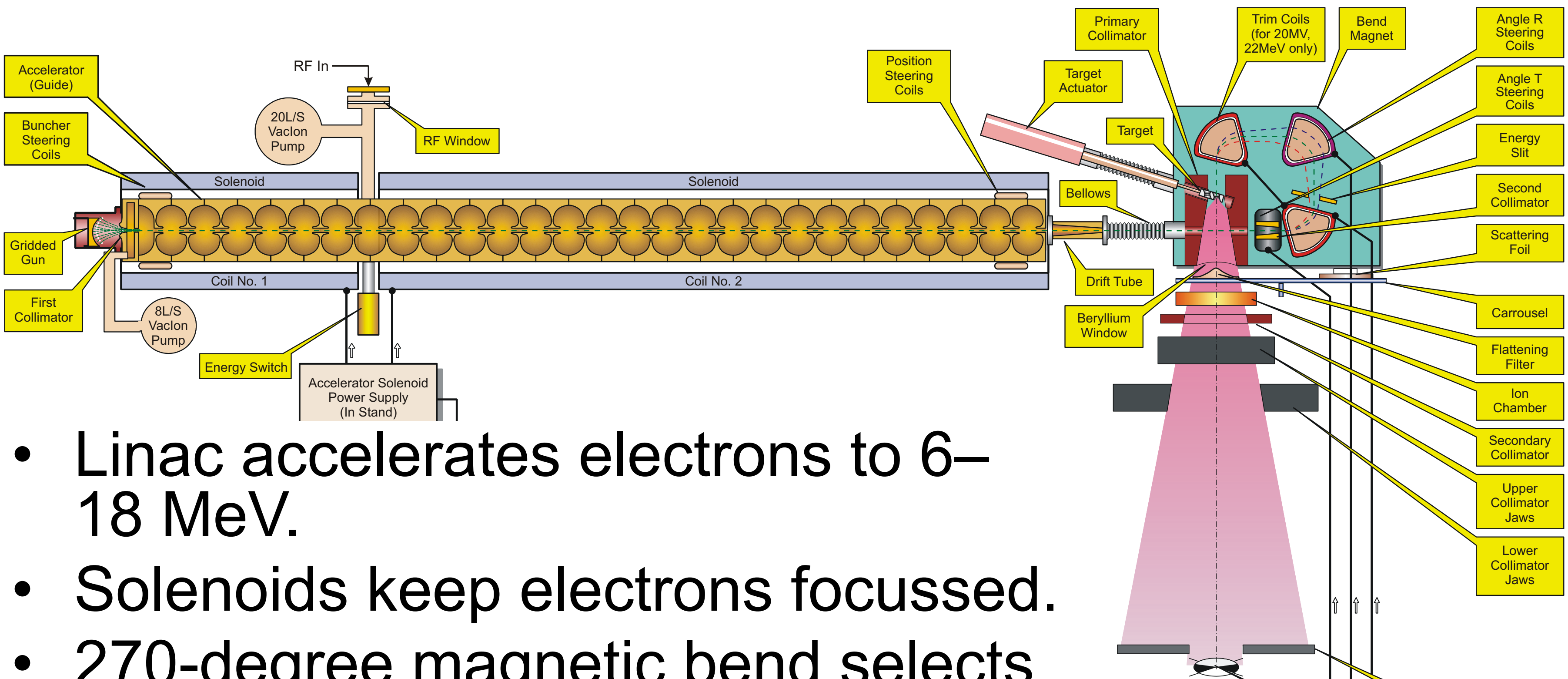


Wideroe Linac



- Instead of having one long cavity, split it up into short *drift tubes*.
- Accelerate in the gaps only: use high frequency (10 GHz for X-ray linac).
- Voltage timed to accelerate particles across every gap.
- For high velocity particles (*eg*. electrons), reduce drift tubes to thin disks…

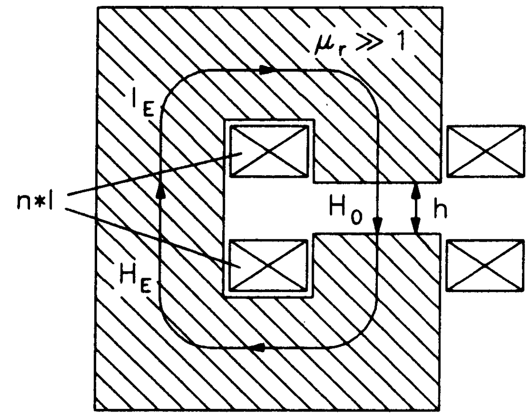
X-Ray Linac Gantry



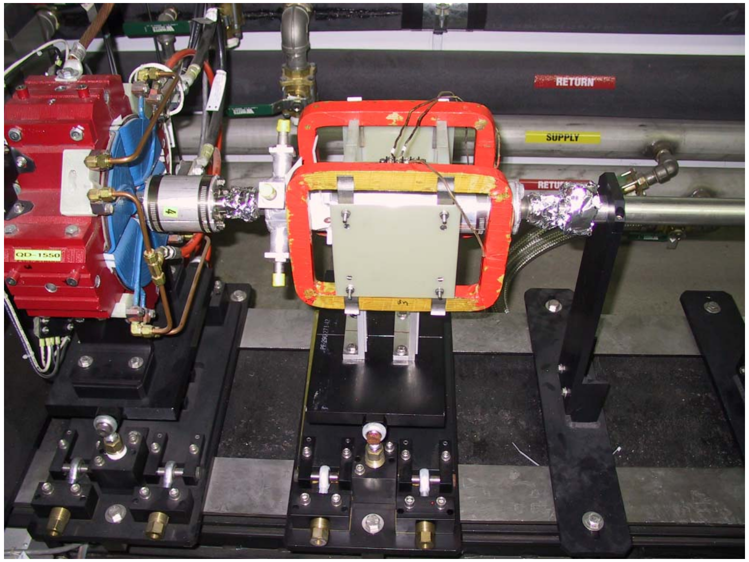
- Linac accelerates electrons to 6–18 MeV.
- Solenoids keep electrons focussed.
- 270-degree magnetic bend selects correct energy.
- Electrons hit Tungsten target and emerge through Beryllium window.

Beam Steering: Dipoles

- Use *q(v x B)* to steer charged particle beam.
- Beam passing through uniform B-field gives uniform deflection.
- B-field produced by dipole magnet:
  - Current flowing in each of 2 coils produces magnetic field.
  - Coupling fields together by placing coils adjacent gives parallel B-field between coils.
  - Wrap coils in iron yoke to provide easy path for return flux.



$$B_0 = \mu_0 \cdot H_0$$
$$= \mu_0 \cdot \frac{n \cdot I}{h}$$

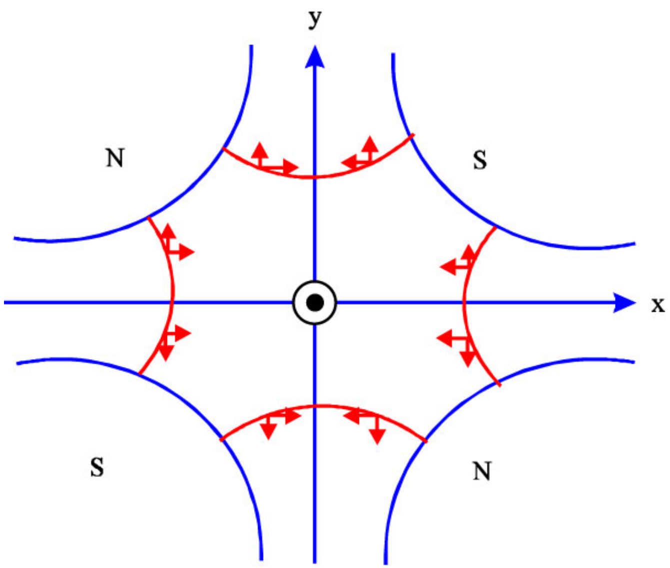


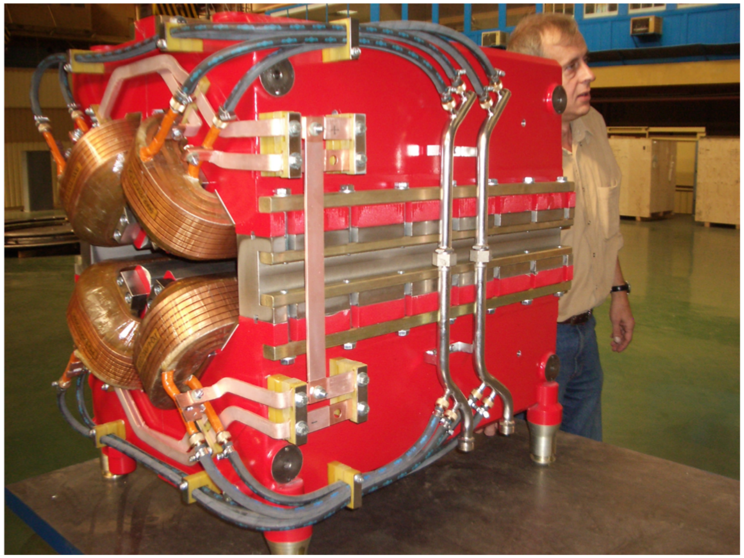
Bea Focussing: Quadrupoles

- Dipoles can steer the beam but not focus it: we need particles that are further off axis to be steered harder.
- A quadrupole magnet is constructed from four poles — two 'North' and two 'South' — that give a B-field that increases as a function of the distance from the centre of the magnet:

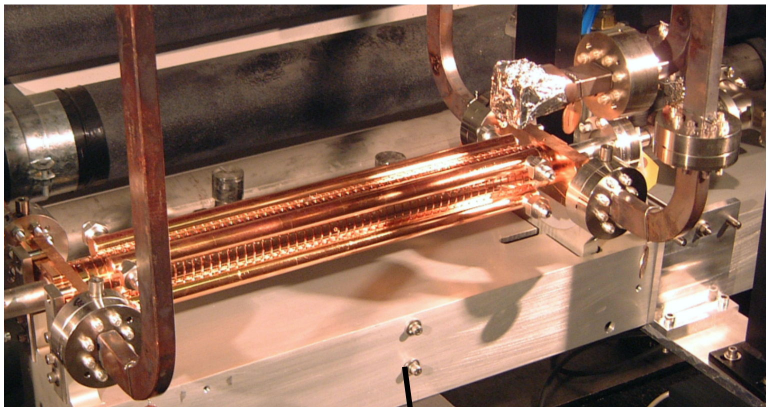
$$B_x \propto y \qquad B_y \propto x$$

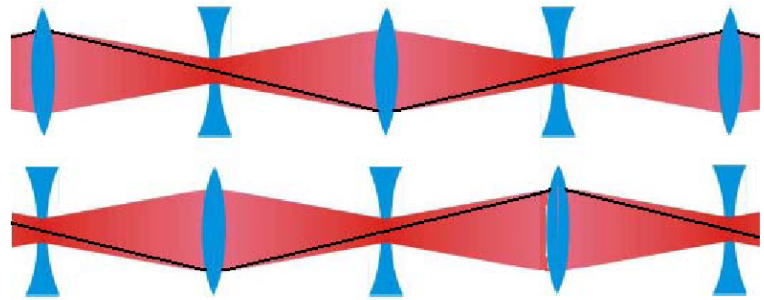
- As such, this gives rise to a dipole field that varies with distance from the centre of the magnet.
- Particles that are further off-axis are steered more strongly back towards the centre, giving an overall focusing effect.
- Quads focus in one plane but defocus in the other: need a FODO lattice…



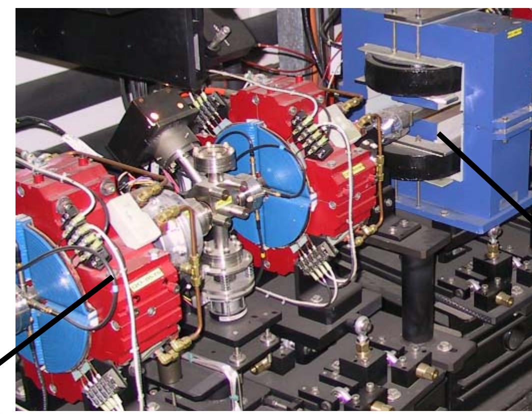


The FODO Lattice

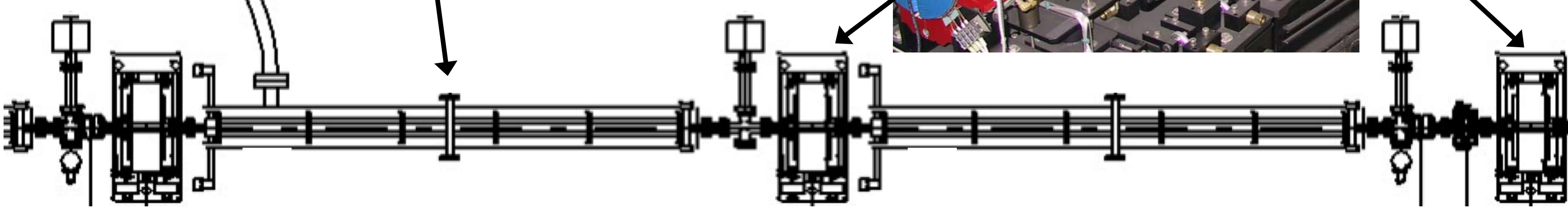




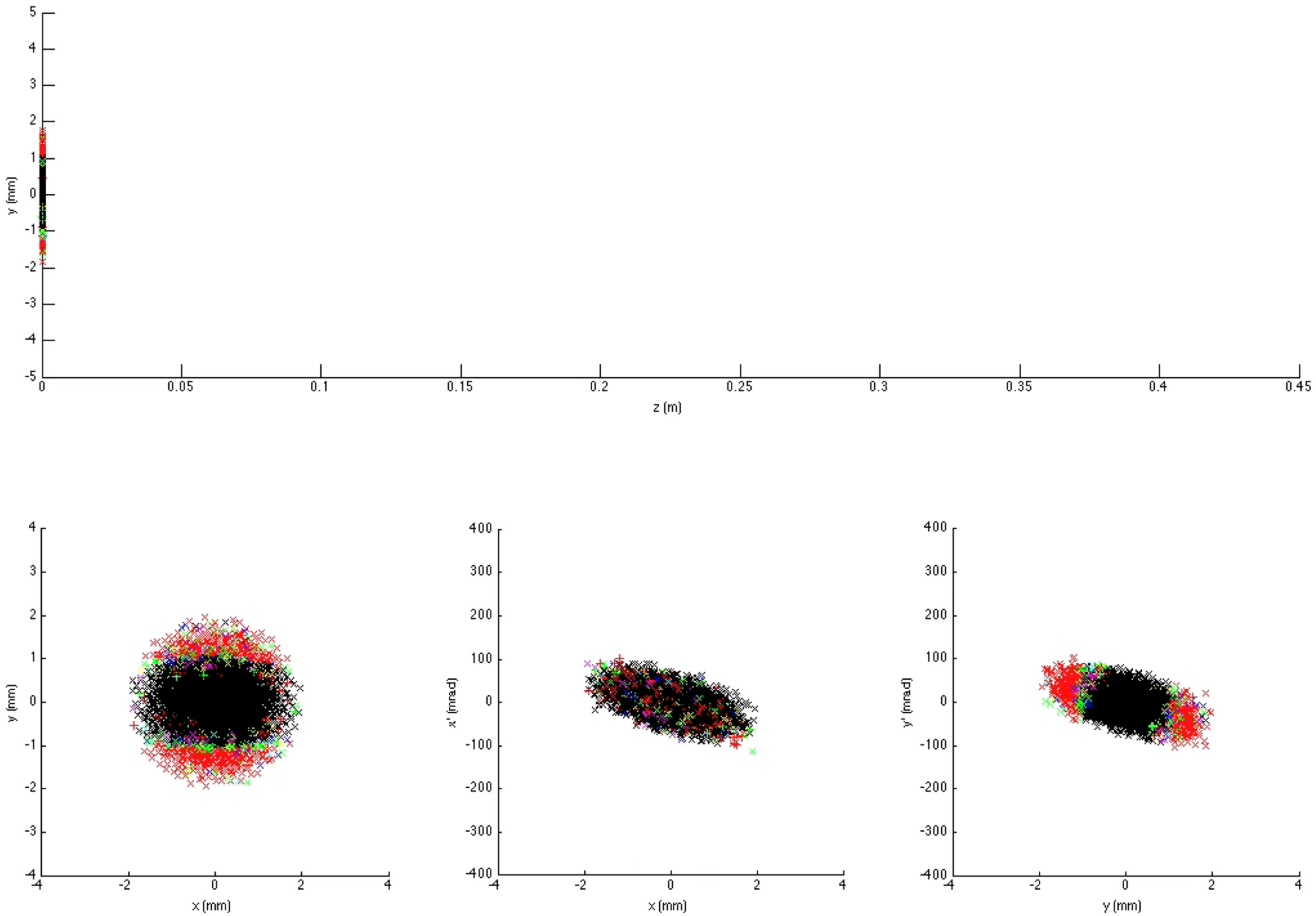
…magnets to focus/bend



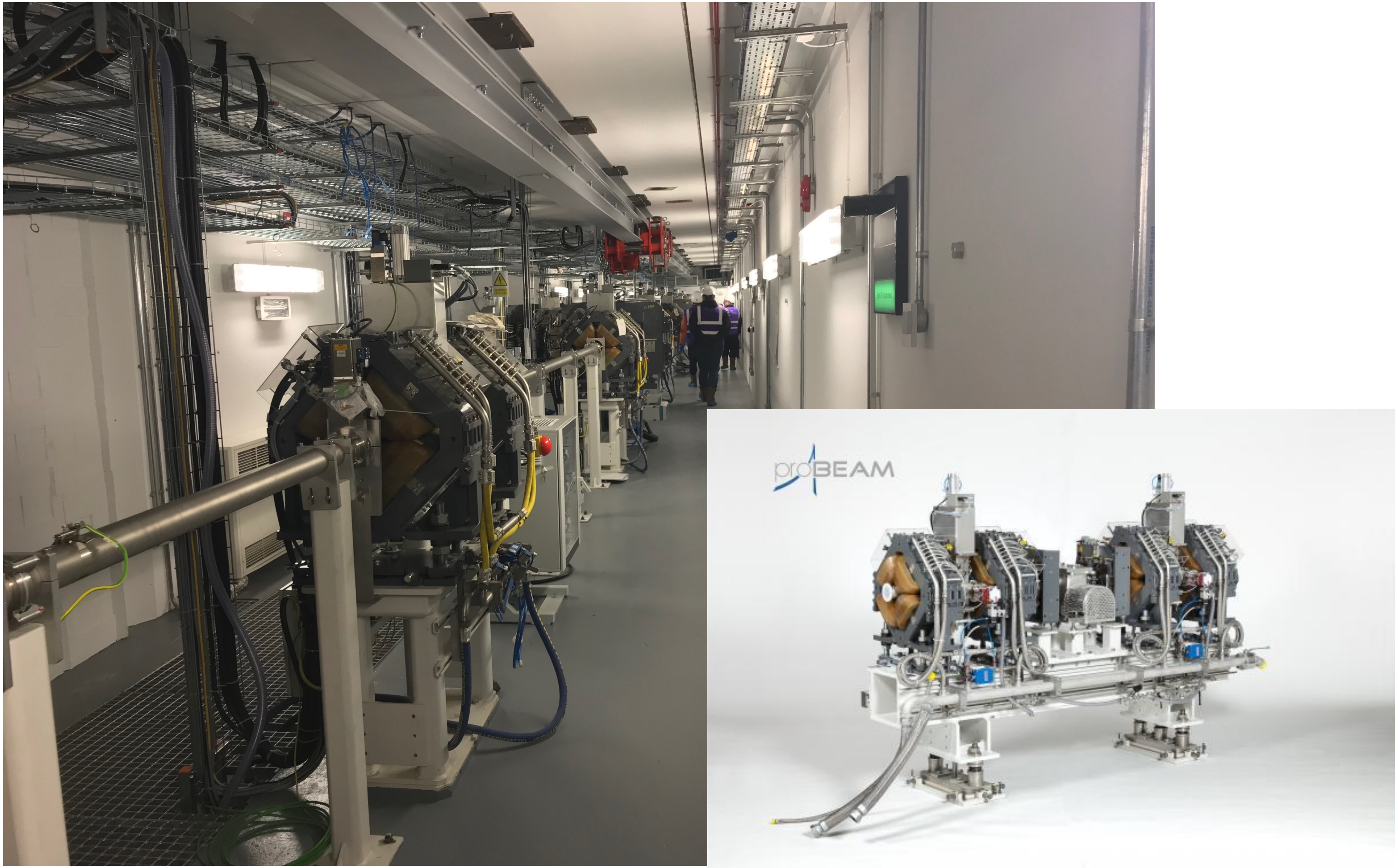
Cavities to accelerate…



Betatron Oscillations



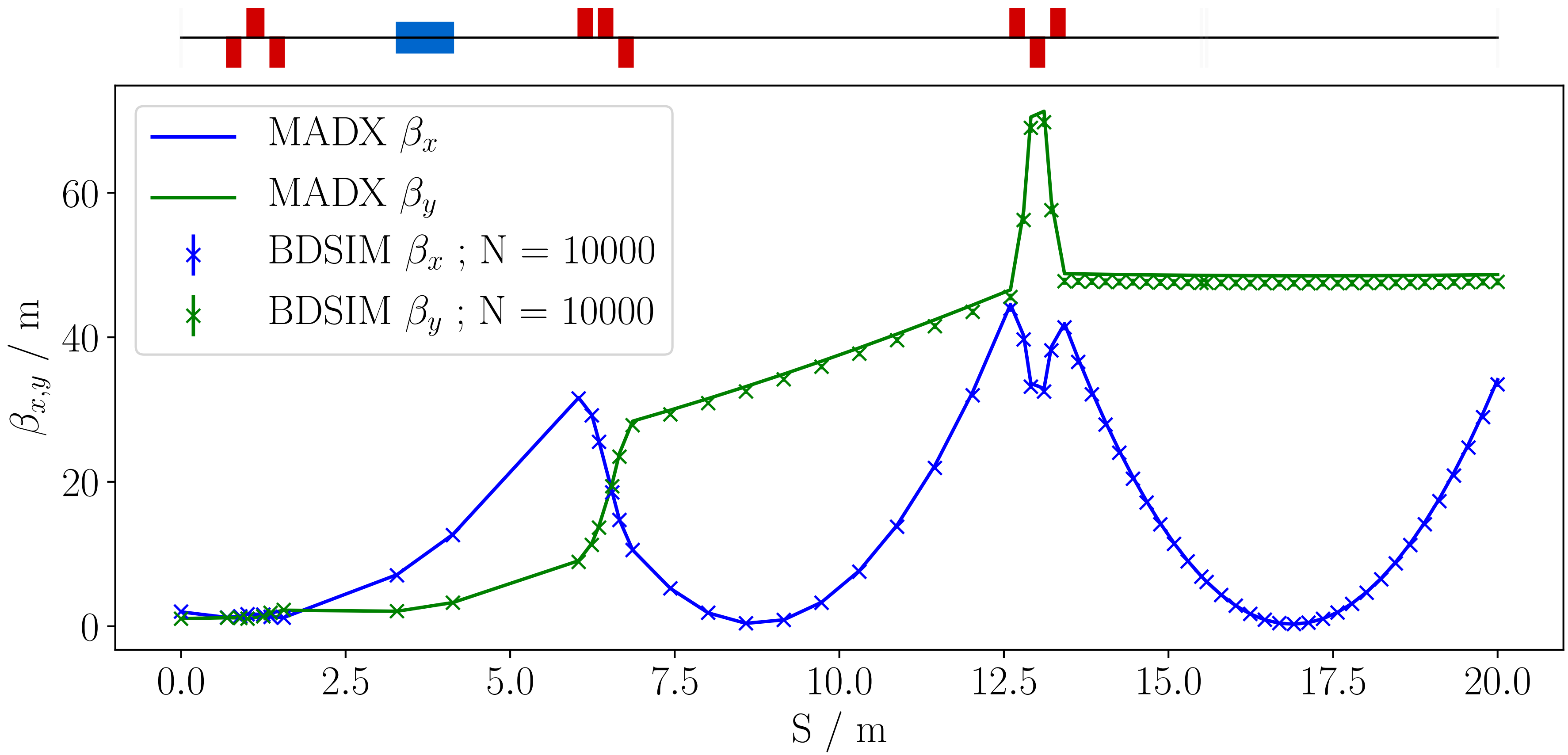
Christie Beam Transport Line



Clatterbridge Twiss Parameters

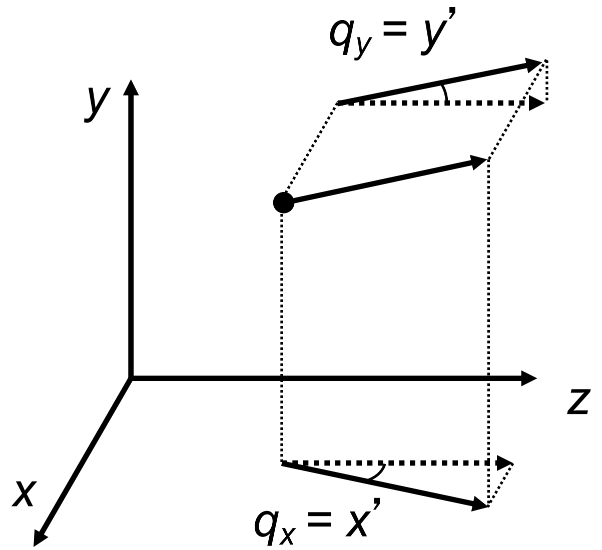
Beta function, $\beta_{x,y}$, describes beam envelope.

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\epsilon_{x,y}}$$



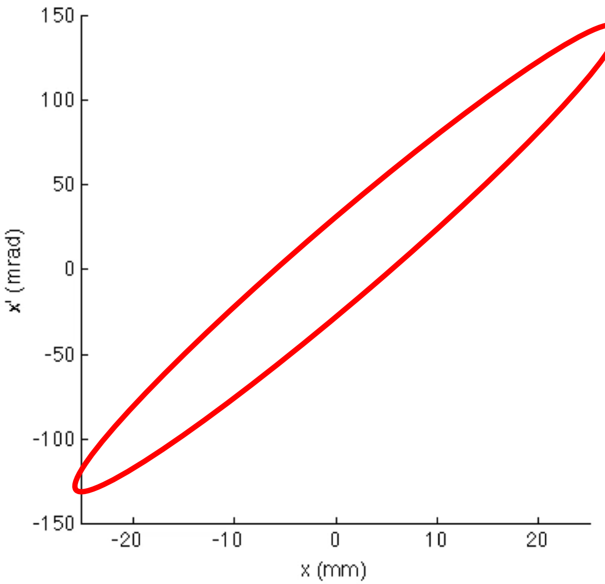
What is Emittance?

Define position of each particle in transverse phase space: $\varepsilon_x(x,x')$, $\varepsilon_y(y,y')$



Each particle has coordinates in 6-D: x, x', y, y', z, E.

Make phase space plot of all particles:



Area of ellipse gives ε_x & ε_y.

Emittance Calculation

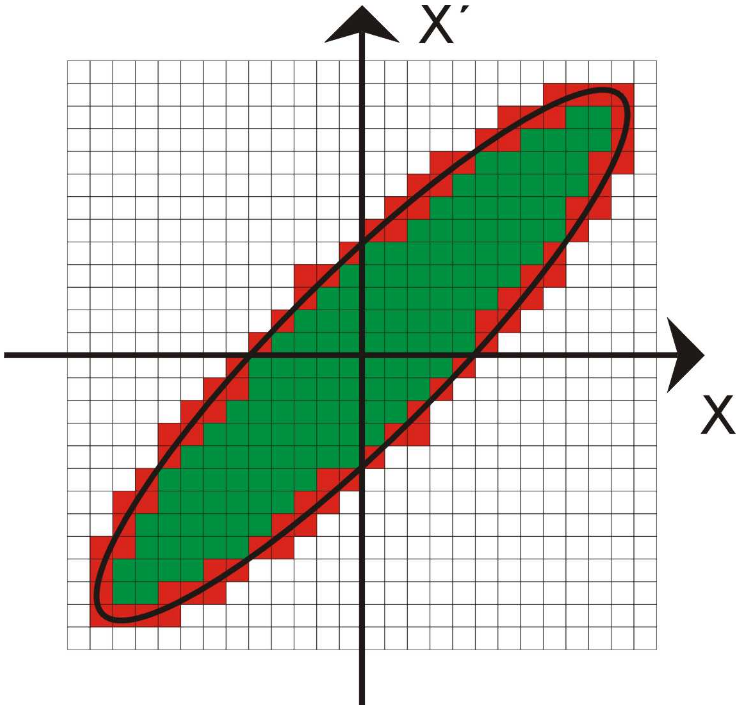
RMS emittance is defined as:

$$\varepsilon_{RMS} = \sqrt{\overline{x}^2 \cdot \overline{x}'^2 - \overline{x}\overline{x}'^2}$$

$$\overline{x}^2 = \frac{\sum_i \rho_i \cdot x_i^2}{\sum_i \rho_i} \qquad \overline{x}'^2 = \frac{\sum_i \rho_i \cdot x_i'^2}{\sum_i \rho_i}$$

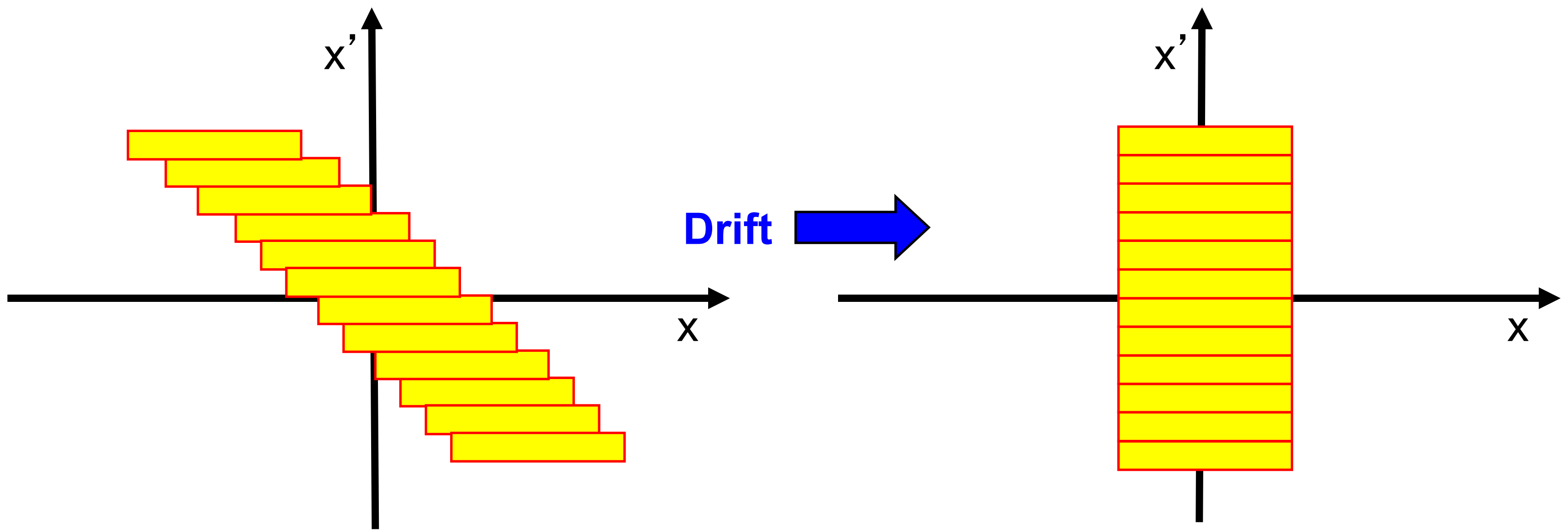
$$\overline{x}\overline{x}'^2 = \frac{\sum_i \rho_i \cdot (x_i x_i')^2}{\sum_i \rho_i}$$

position *x*, angle *x'*, phase space cell density *r*



Emittance is an invariant quantity…

Liouville's Theorem

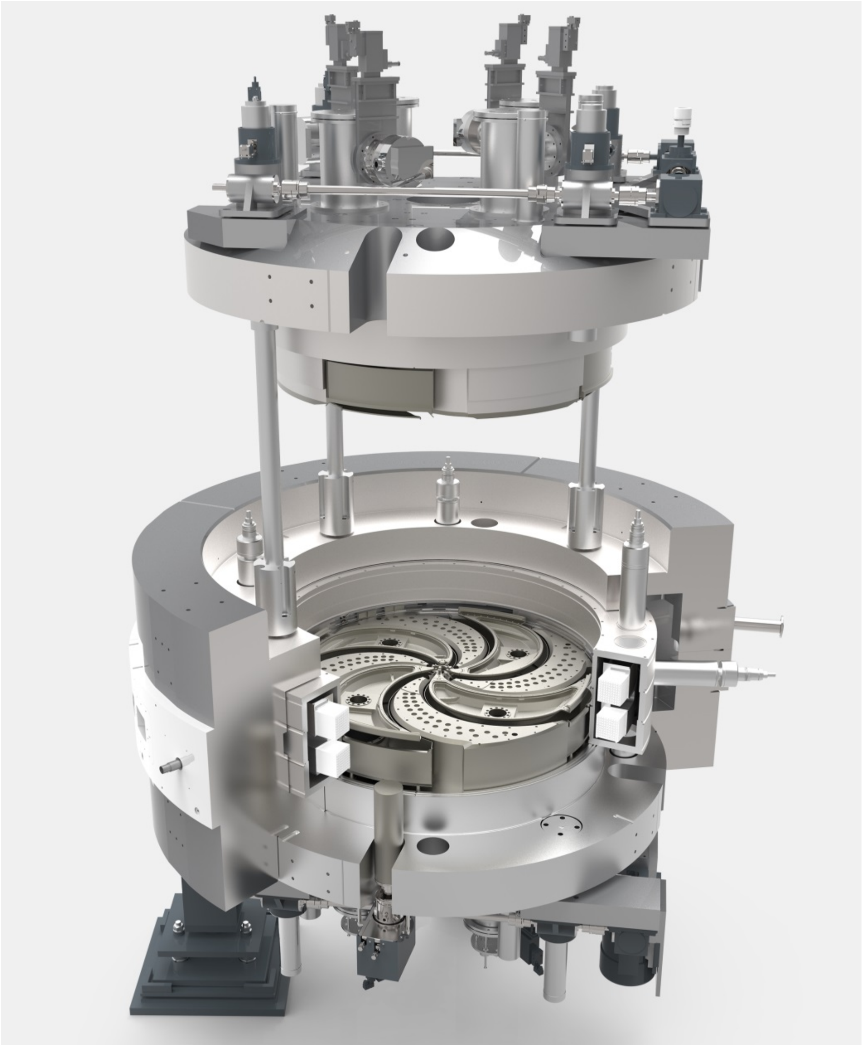


Liouville's Theorem states that, for a "conservative system" (ie. an accelerator beamline), phase space volume is conserved. In other words: things can only get worse! It's very easy to increase the emittance, but difficult (particularly for hadron beams) to make it smaller. Emittance *directly* translates to minimum spot size…

Linear Accelerators

- A first question: why not just use a linear accelerator?
- Linacs have advantages:
  - Good for low energy where velocity is changing rapidly.
  - Powerful: good for continuous (CW) beams.
  - European Spallation Neutron Source (ESS) will use 350 m linac (30 m warm and 320 m SuperConducting) to accelerate 50 mA of protons to 2.5 GeV.
- But there are shortcomings, namely THE COST:
  - Lots of wasted RF power.
  - Can't re-use accelerating structures to accelerate beam in steps.
  - No need for so many protons! 50 mA at 250 MeV gives 12 MW: that would fry an egg…
- Why not try accelerating beam repeatedly through circular orbit…?

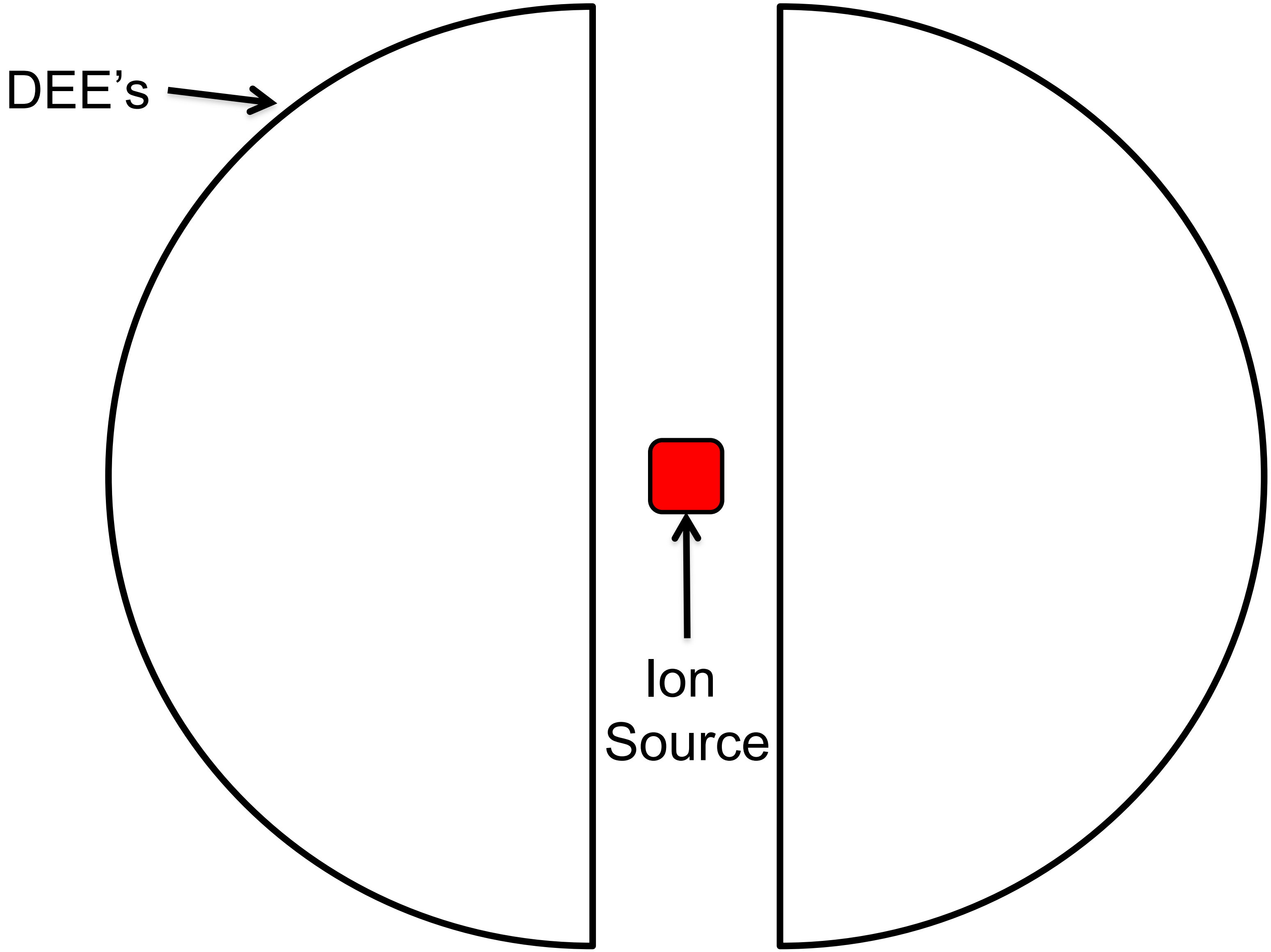
Particle Accelerator: Cyclotron



Cyclotron Basics

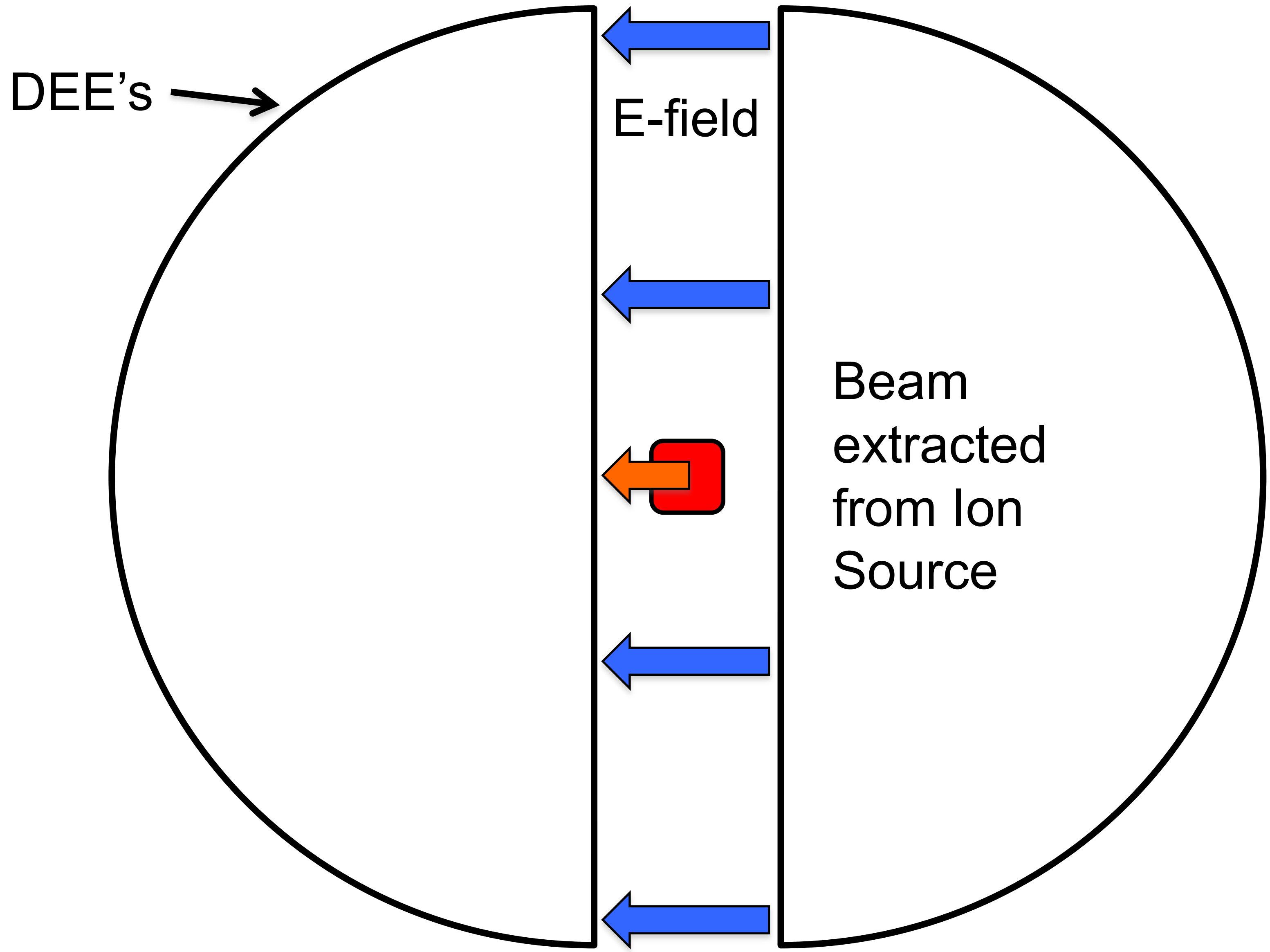
- Cyclotron uses large, **fixed** magnetic field.
- Entire volume is evacuated to allow beam to pass unimpeded.
- Accelerating frequency **fixed**:
  - At low velocity, particles in *synchronous phase*.
  - As velocity increases, need to account for limit of speed of light.
- Cyclotrons *simple* but *only one energy*.
- Ion source in the centre; beam extracted at the edge.

Cyclotron Acceleration (1)

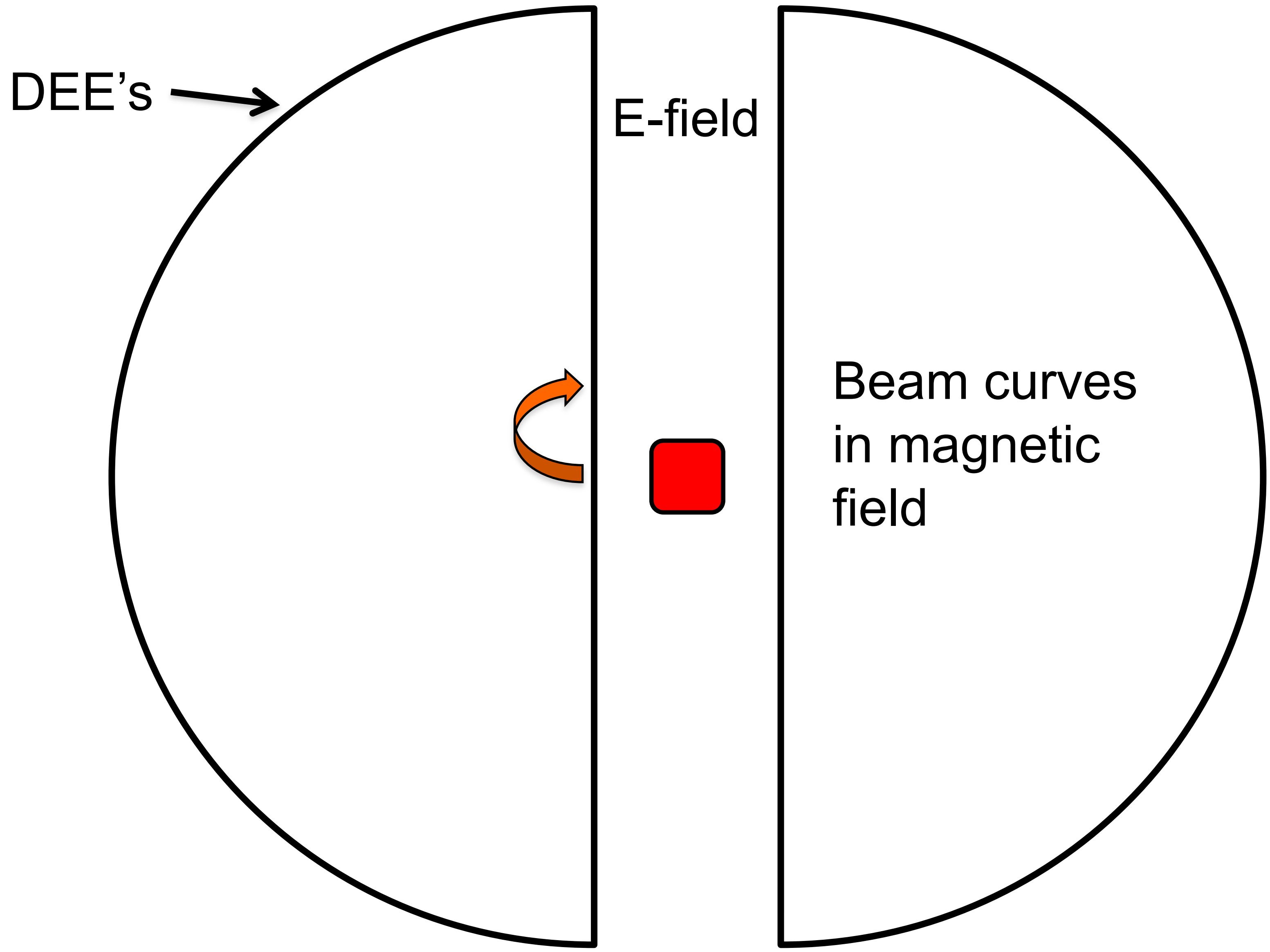


Cyclotron Acceleration (2)

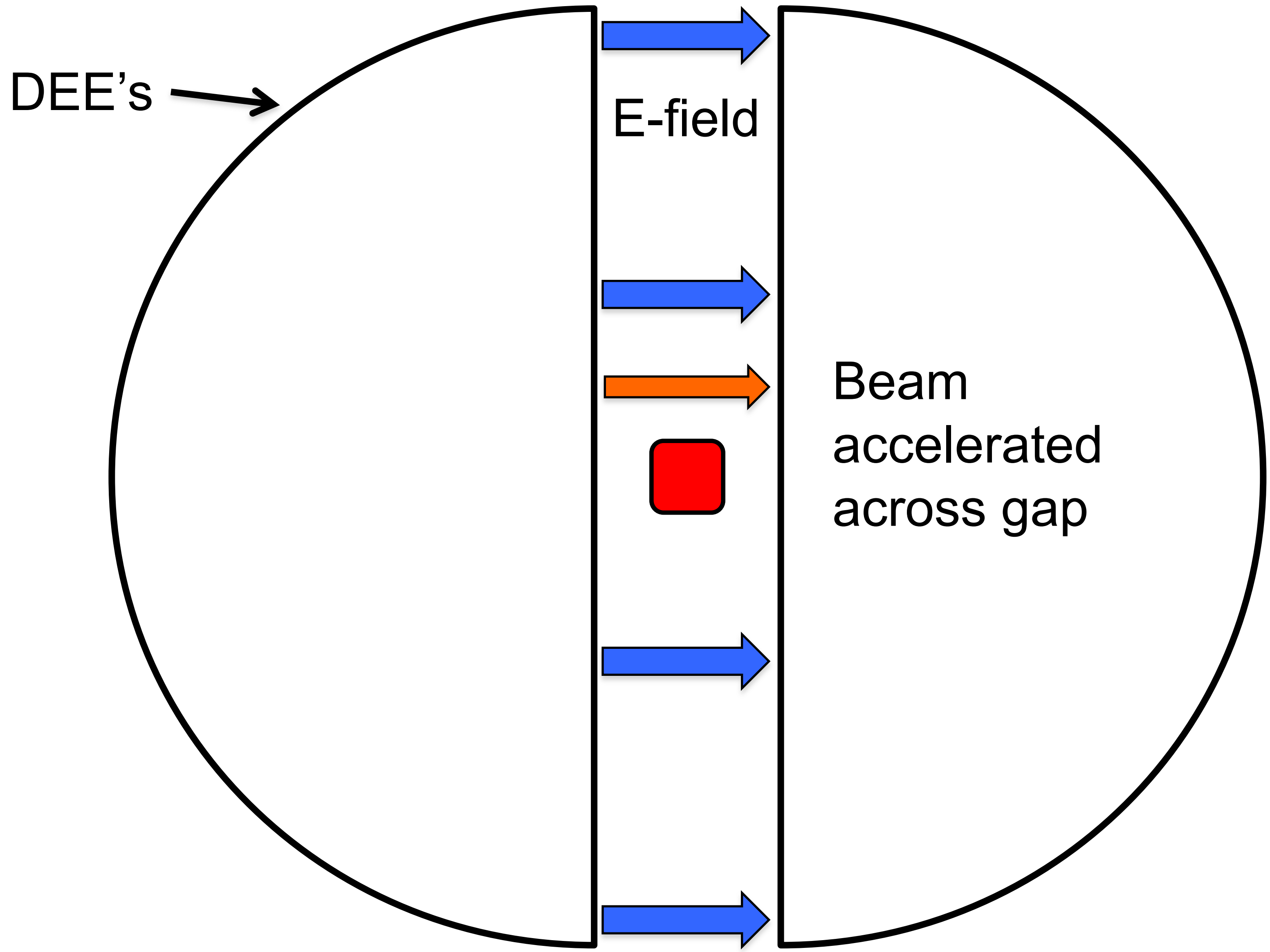
UCL



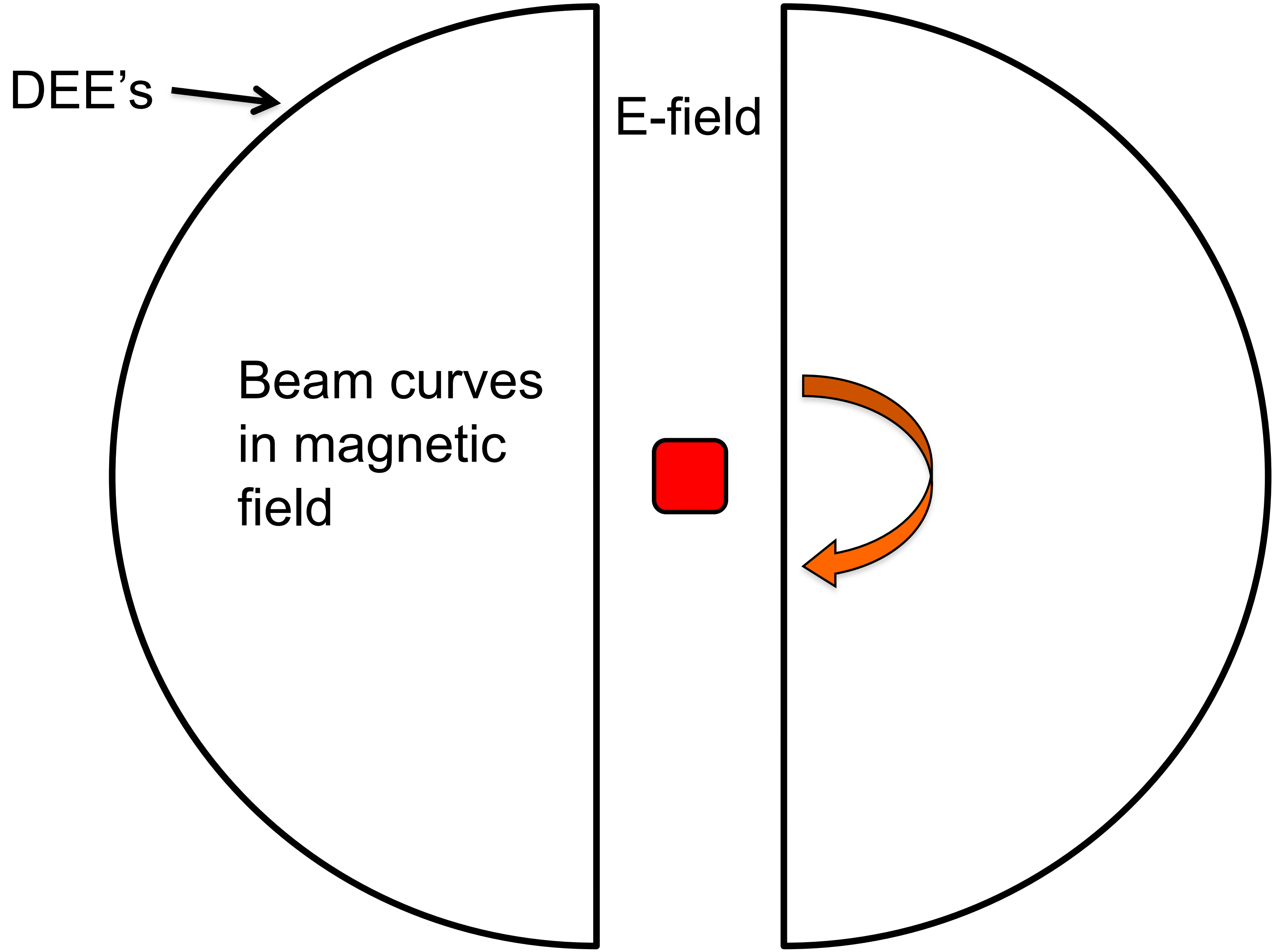
Cyclotron Acceleration (3)



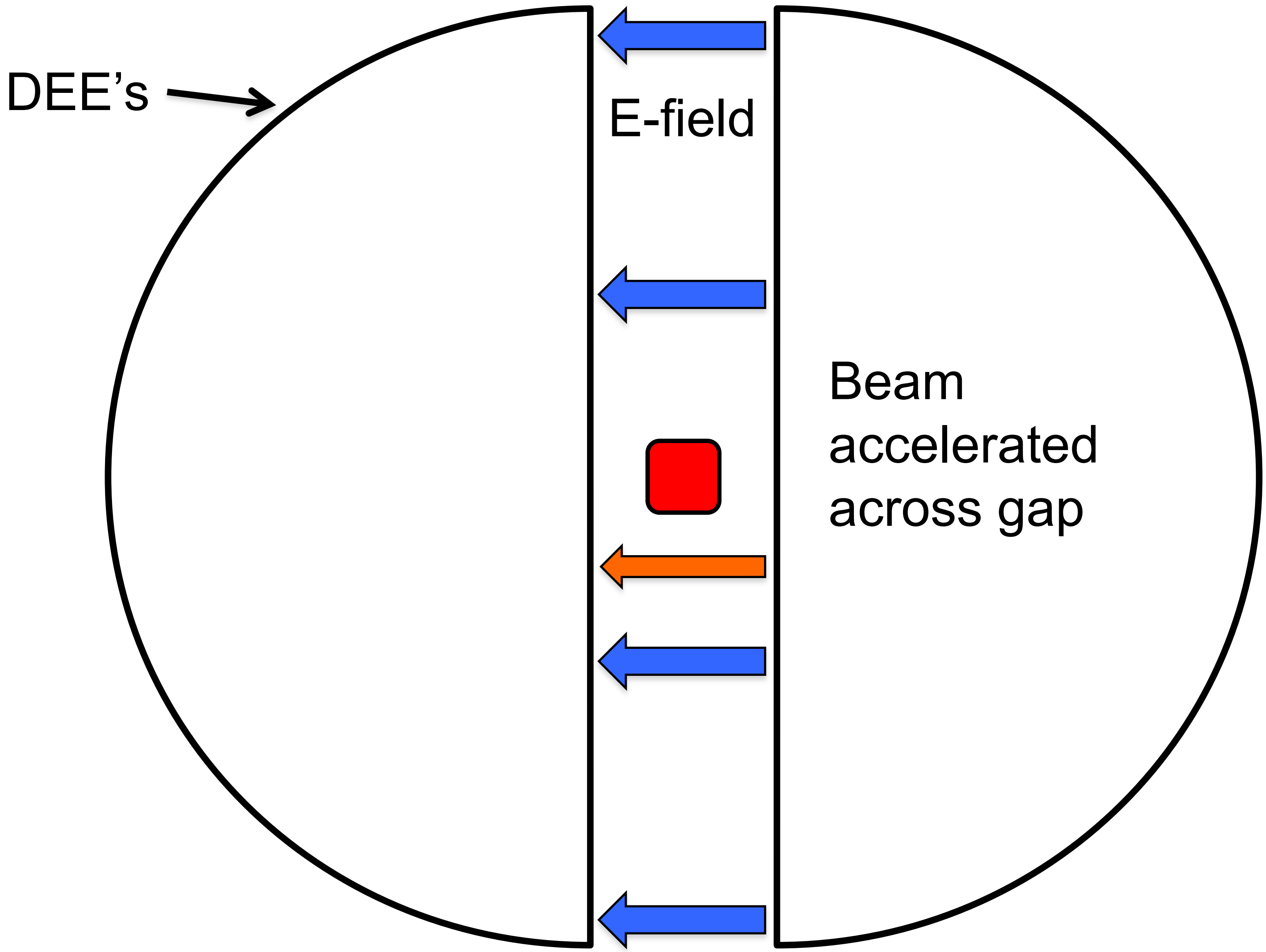
Cyclotron Acceleration (4)



Cyclotron Acceleration (5)

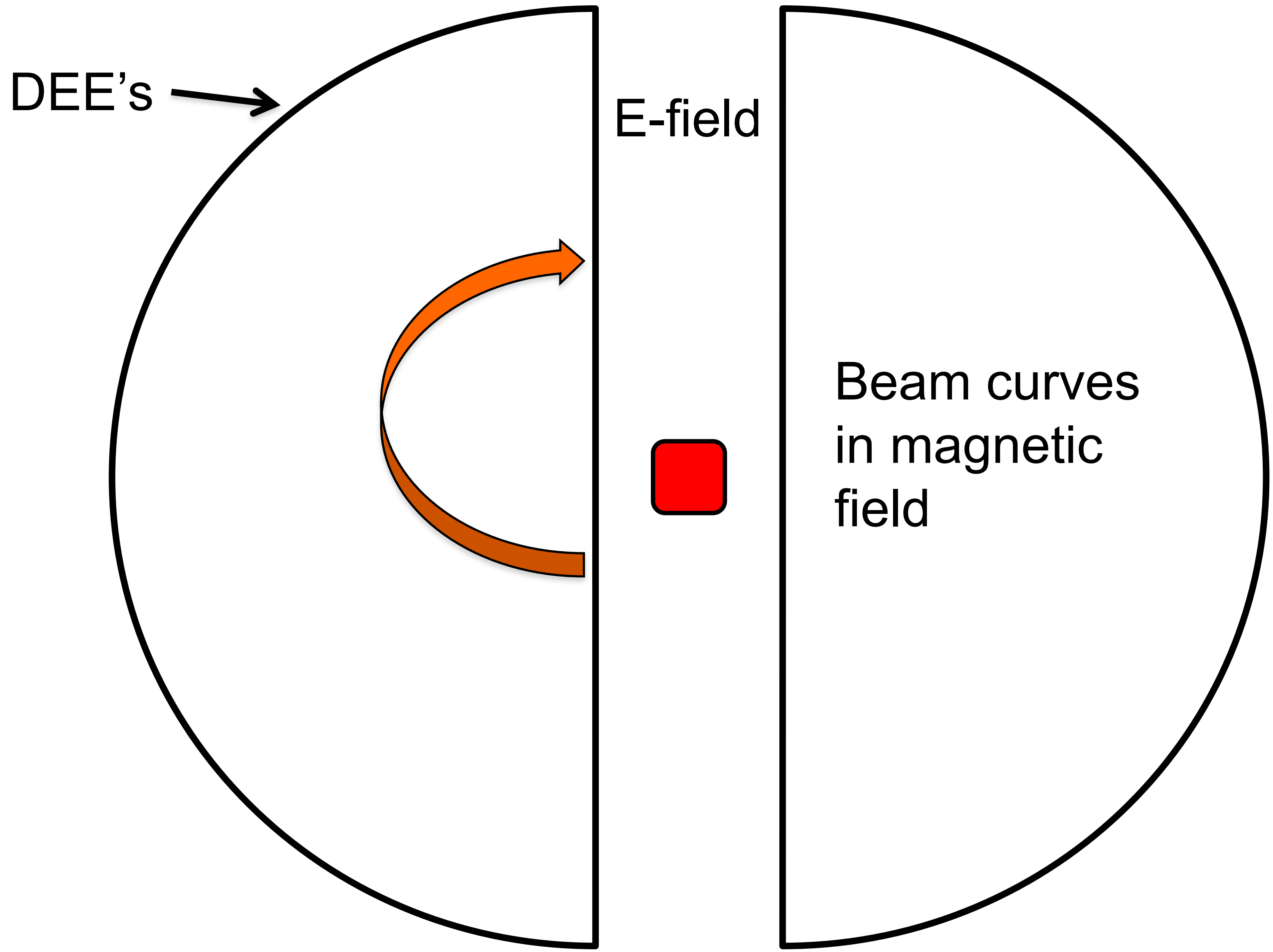


Cyclotron Acceleration (6)



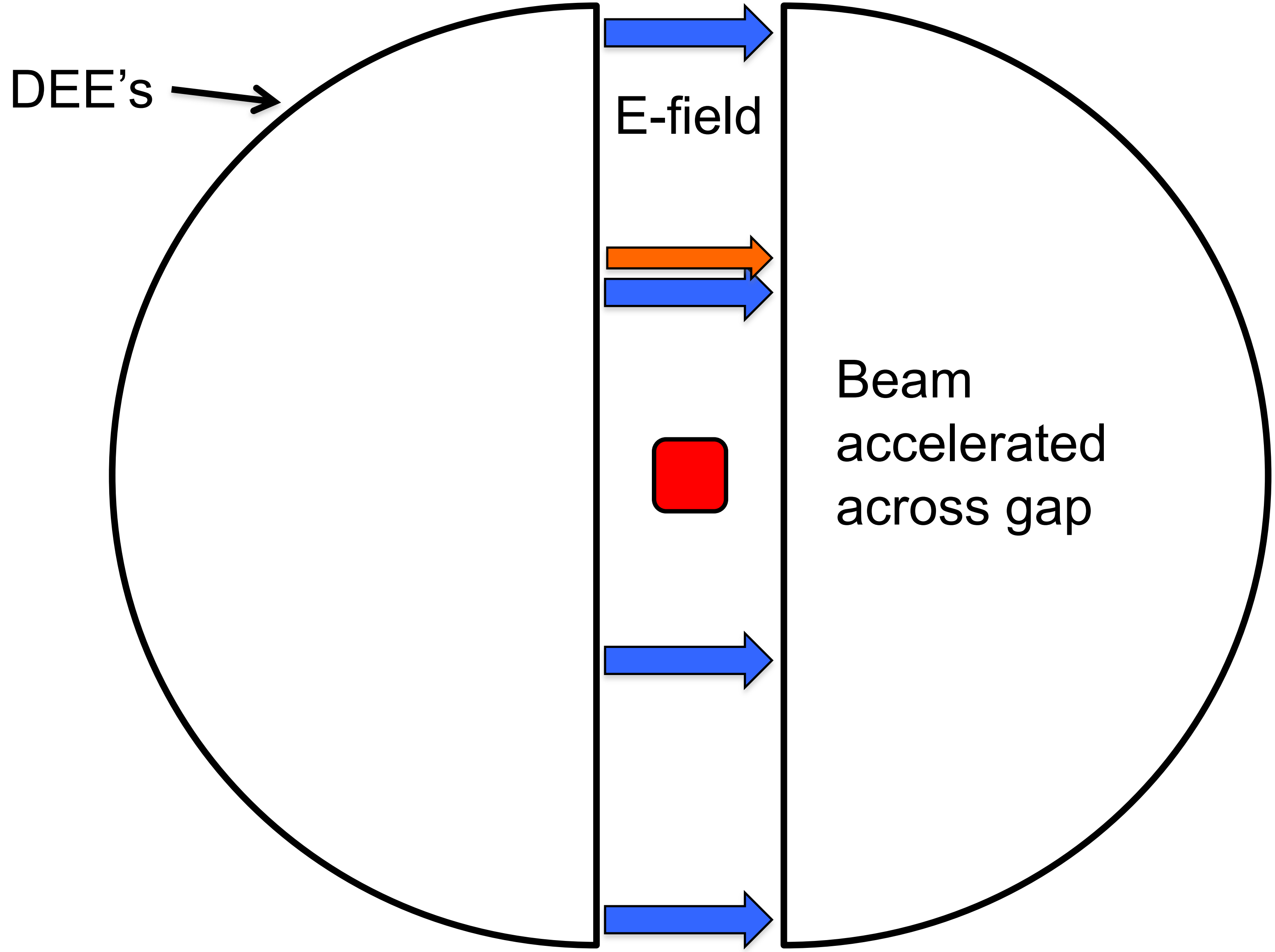
Cyclotron Acceleration (7)

UCL

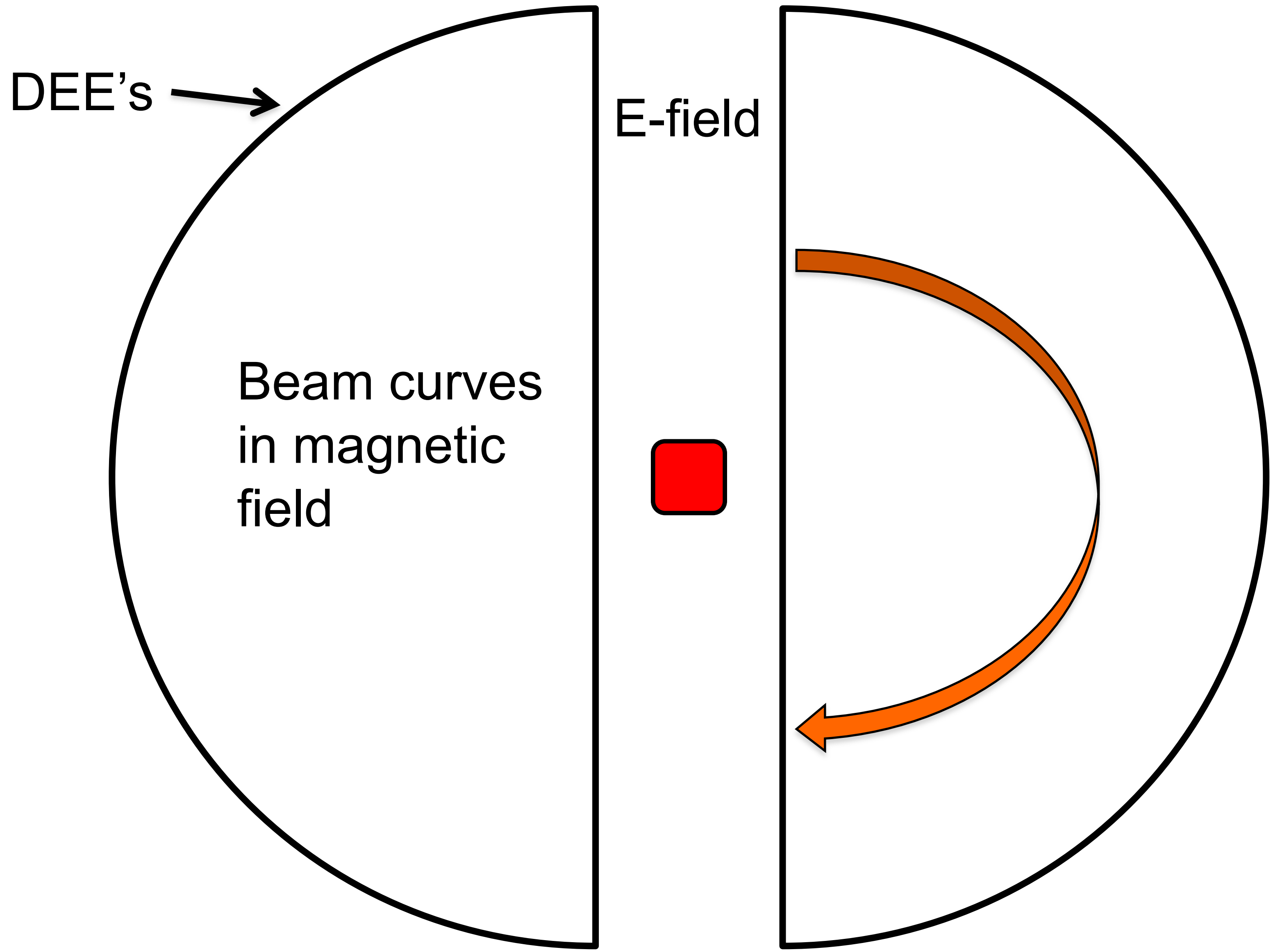


Cyclotron Acceleration (8)

UCL



Cyclotron Acceleration (9)



Cyclotron Acceleration (10)

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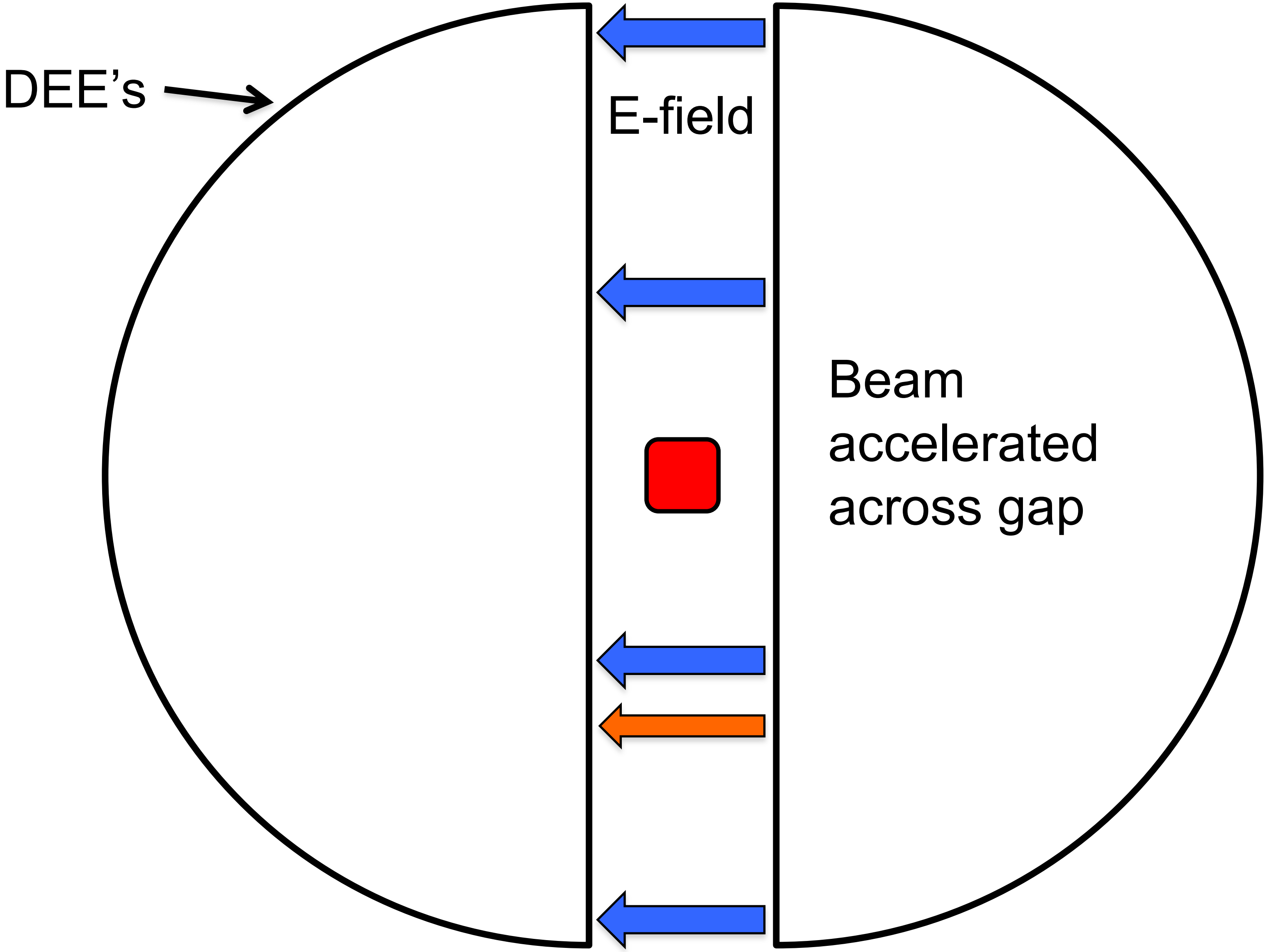

Cyclotron Acceleration (11)

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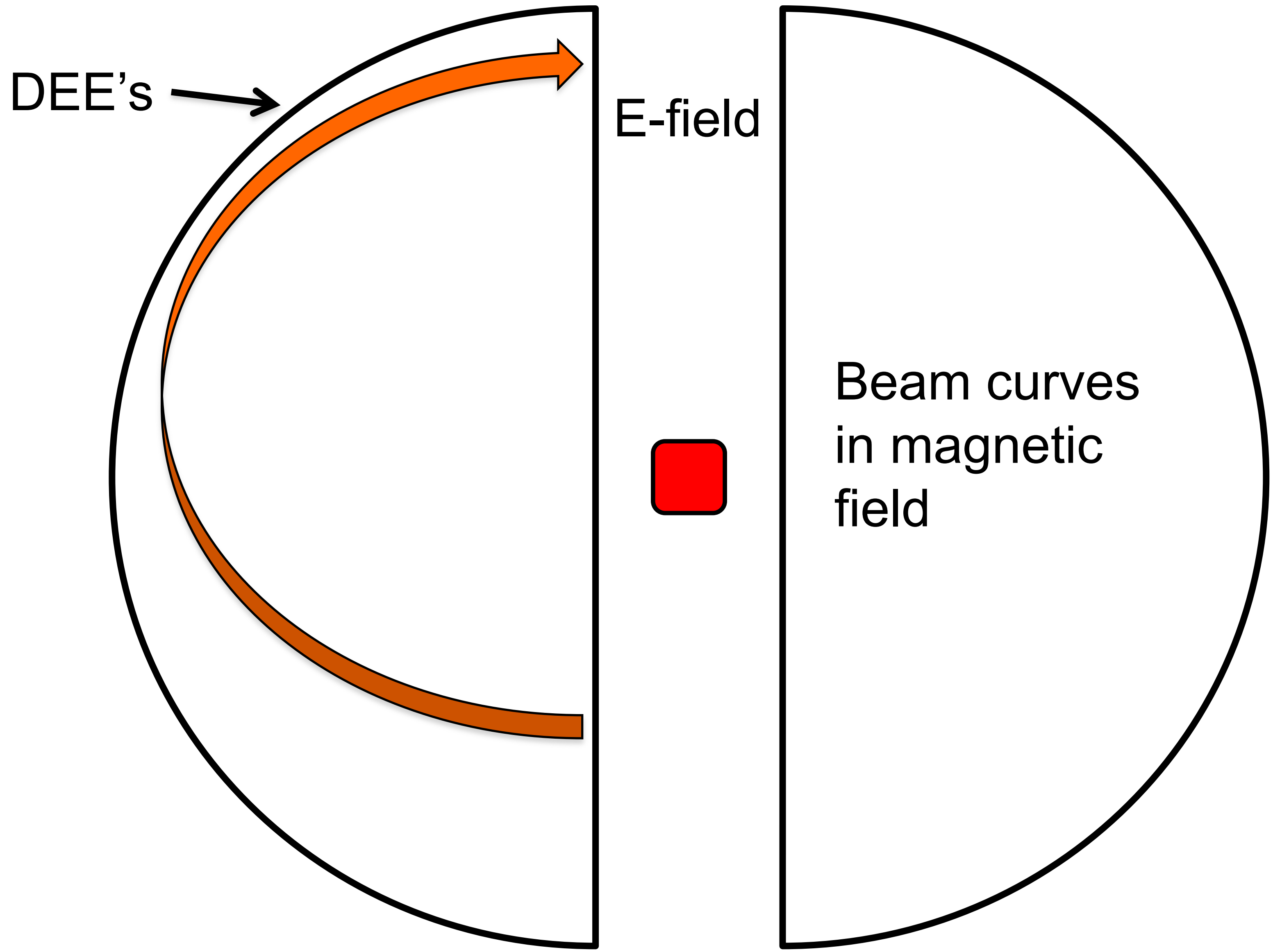
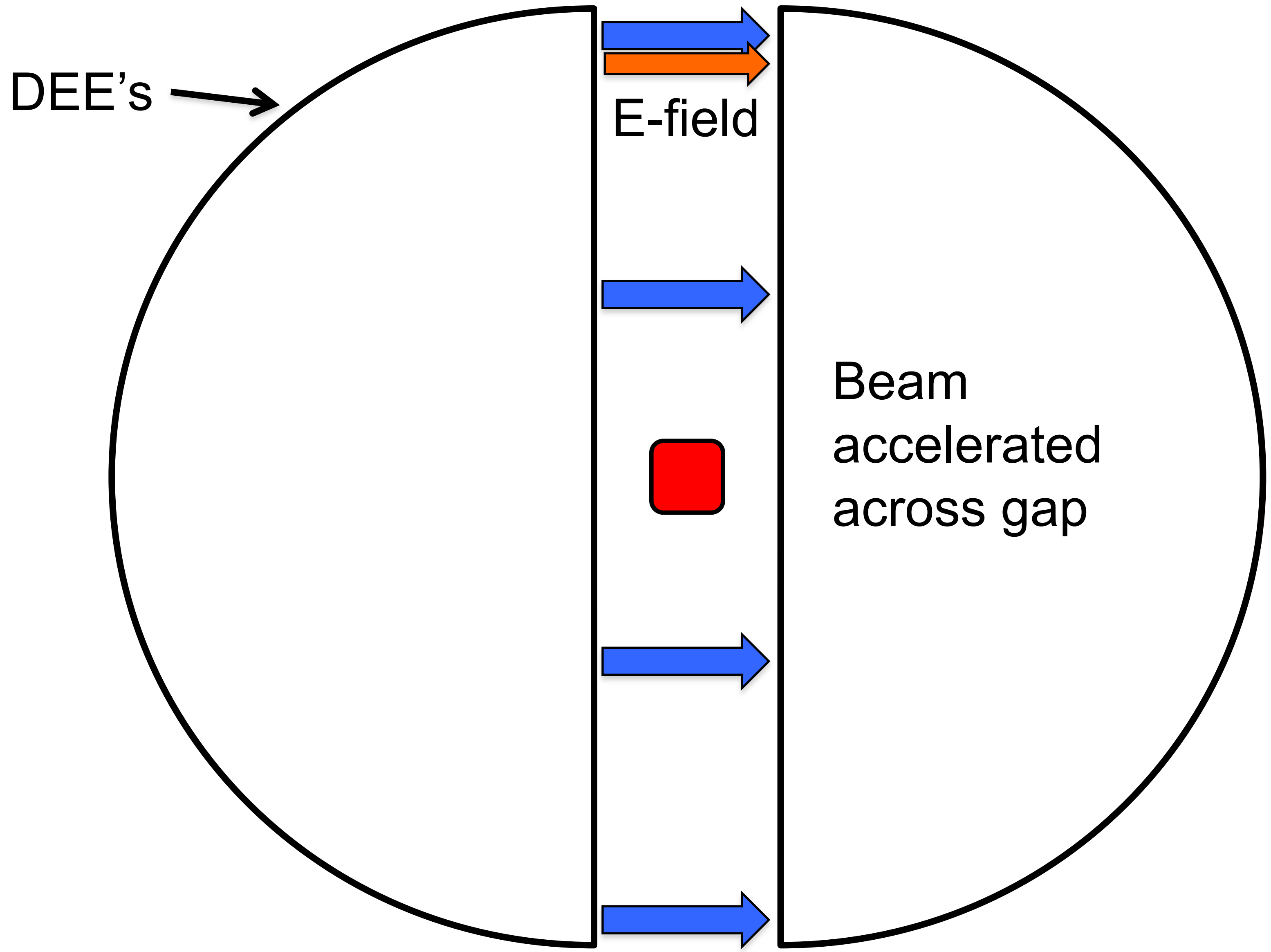
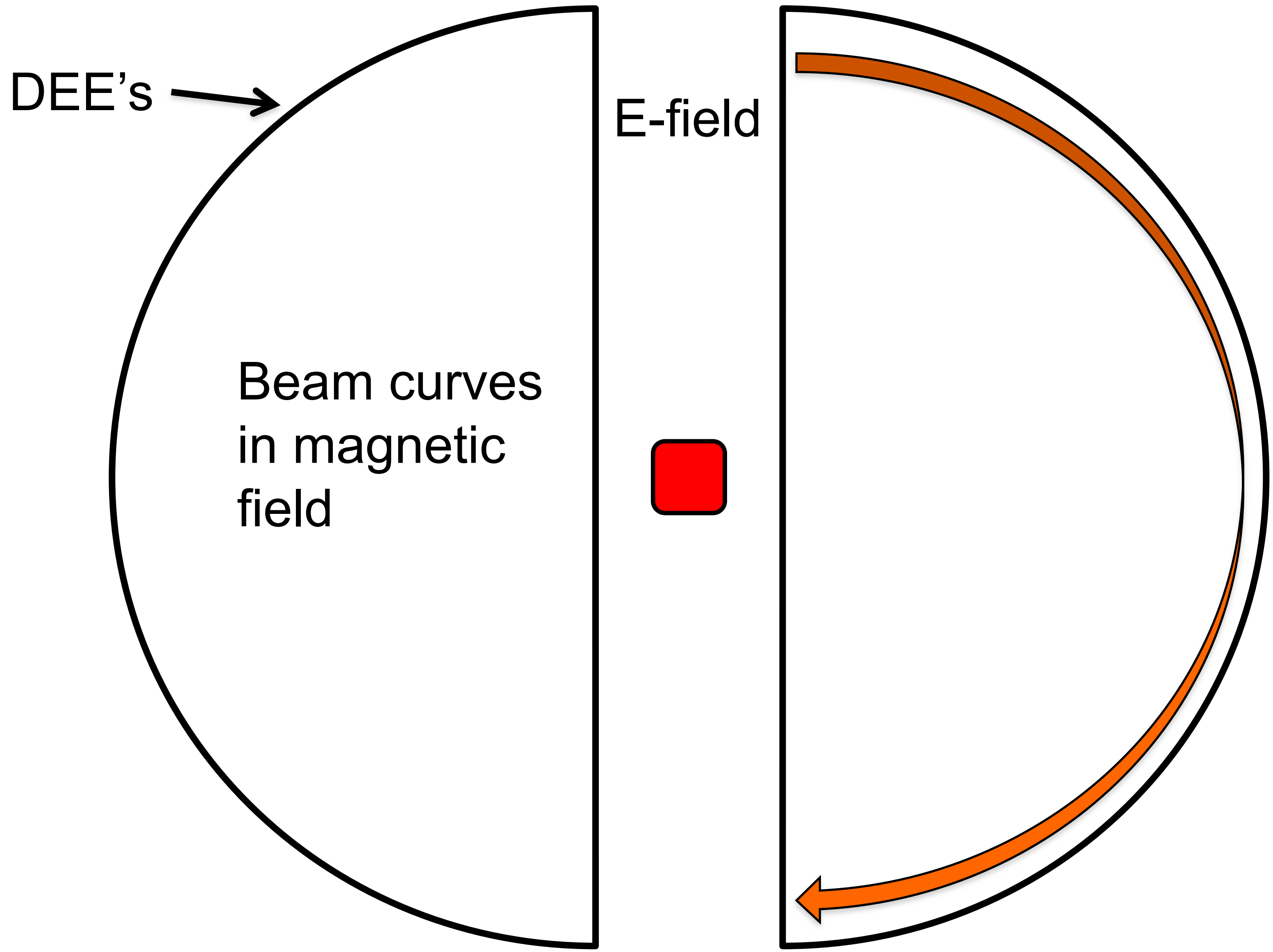


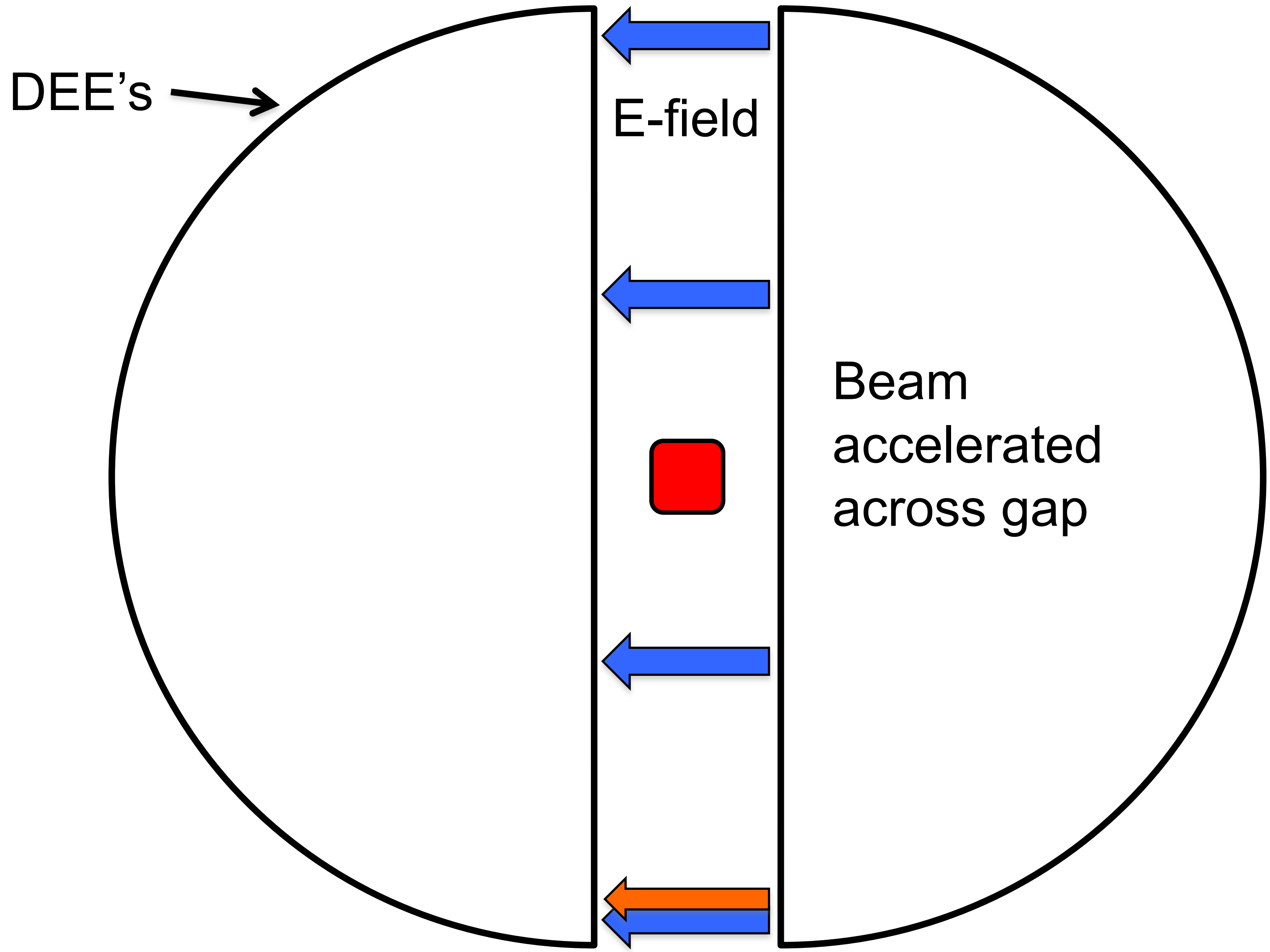
Cyclotron Acceleration (12)



Cyclotron Acceleration (13)

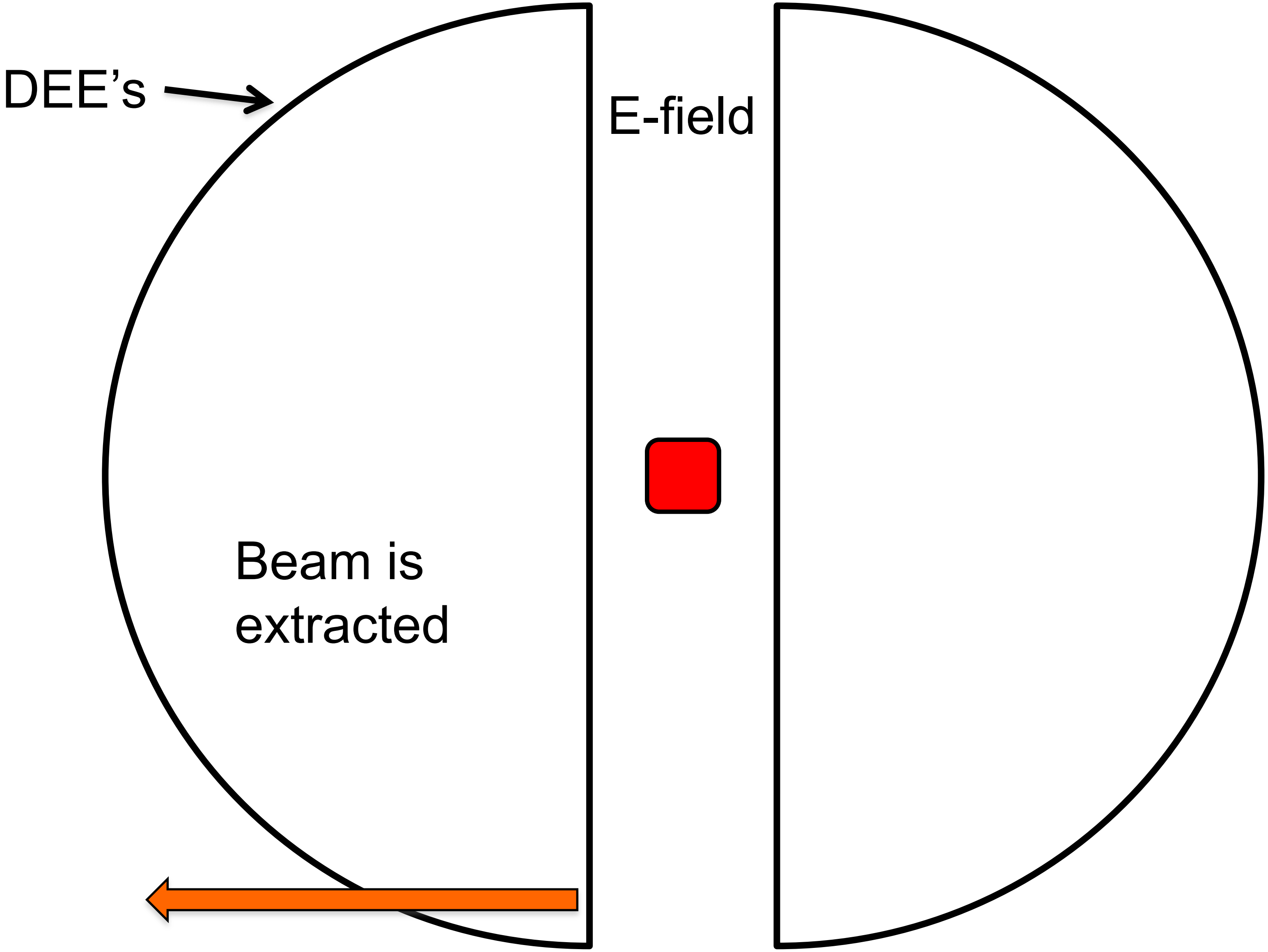


Cyclotron Acceleration (10)

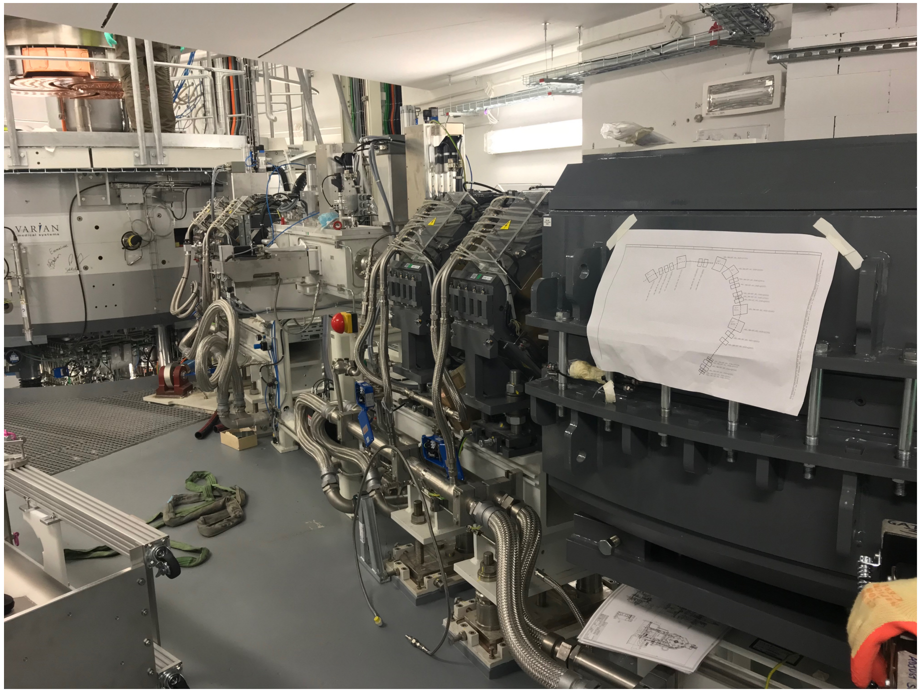


Cyclotron Acceleration (15)

UCL

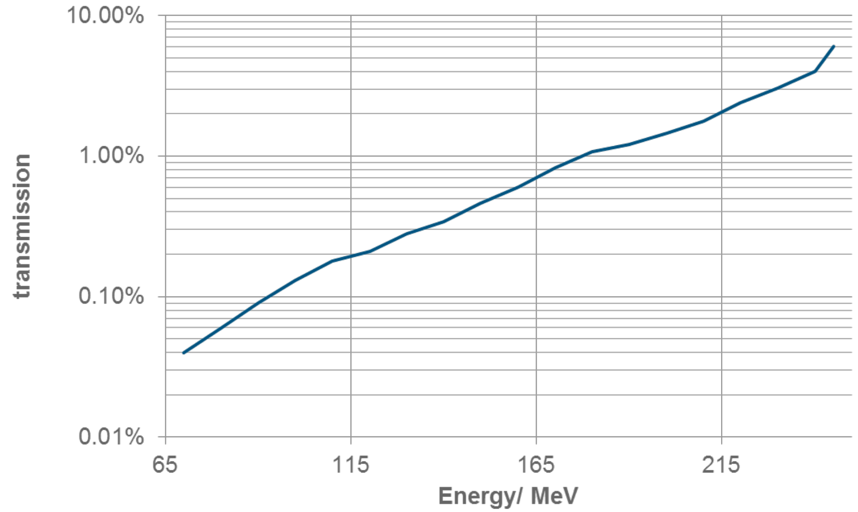


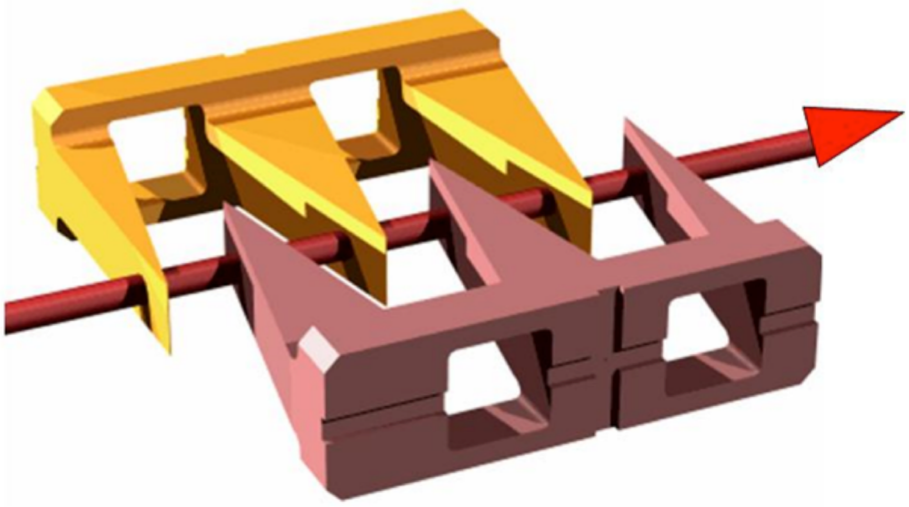
Varian Cyclotron: The Christie



Energy Selection

- Cyclotrons produce *single energy*.
- We need range of energies for treatment.
- To reduce energy, beam passes through variable absorbers ("*wedges*").
- Like linac bend, series of bending magnets select correct energy: *Energy Selection System* (ESS).





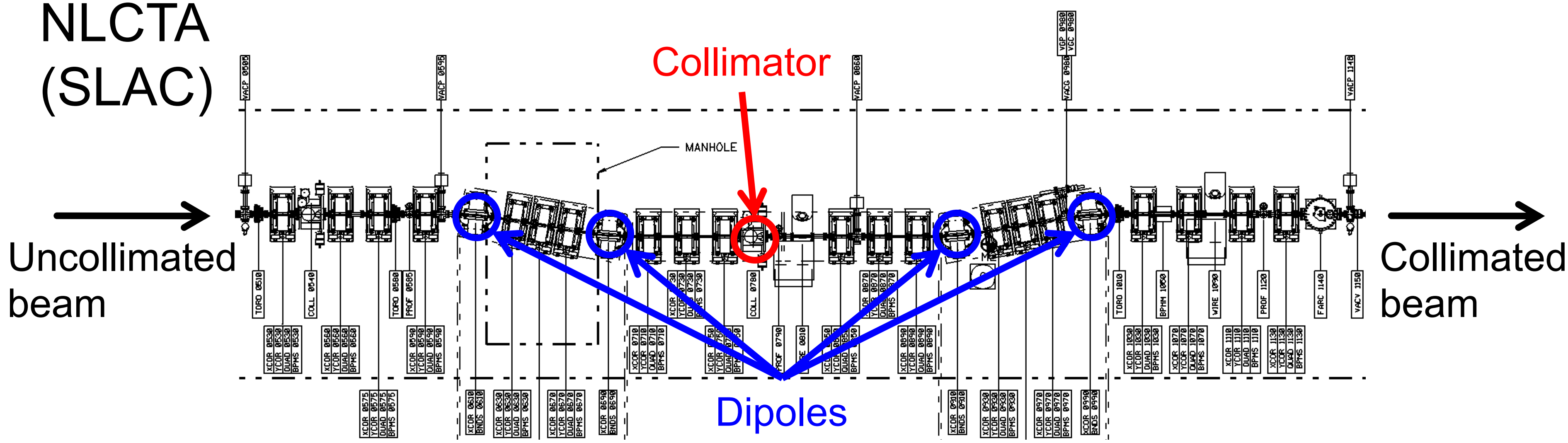
Aside: Energy Spectrometer

- Chicane used at NLCTA to measure beam energy.
- Chicane introduces dispersion into beam:

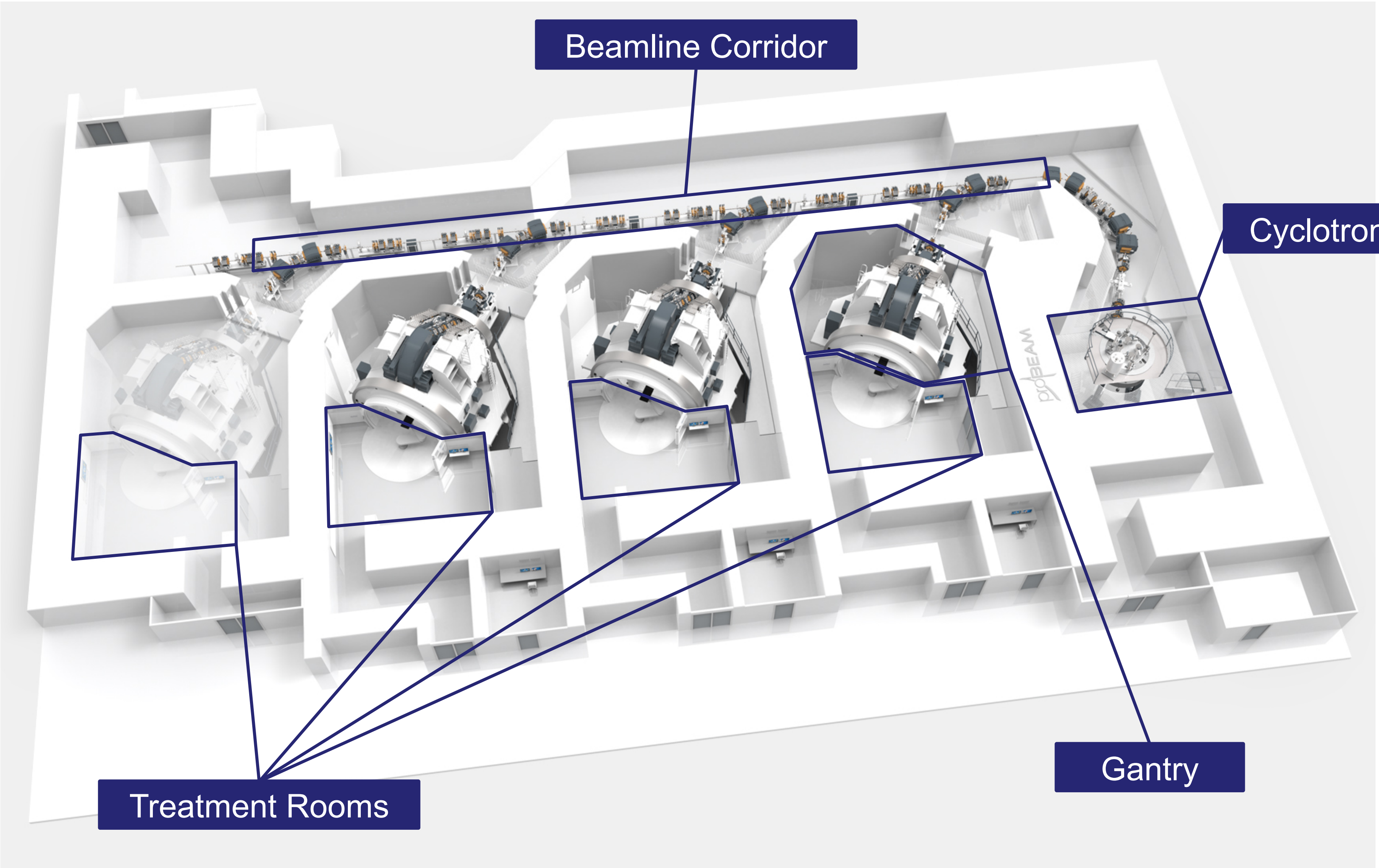
$$\Delta x = D_x \frac{\Delta p}{p}$$

- Beam centroid, as measured by BPM, gives energy.
- Collimator allows energy selection.

NLCTA (SLAC)



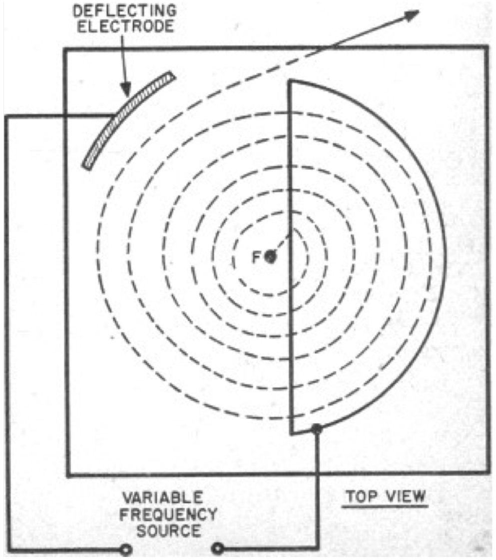
UCLH Proton Therapy Facility



Images courtesy of Varian/UCLH

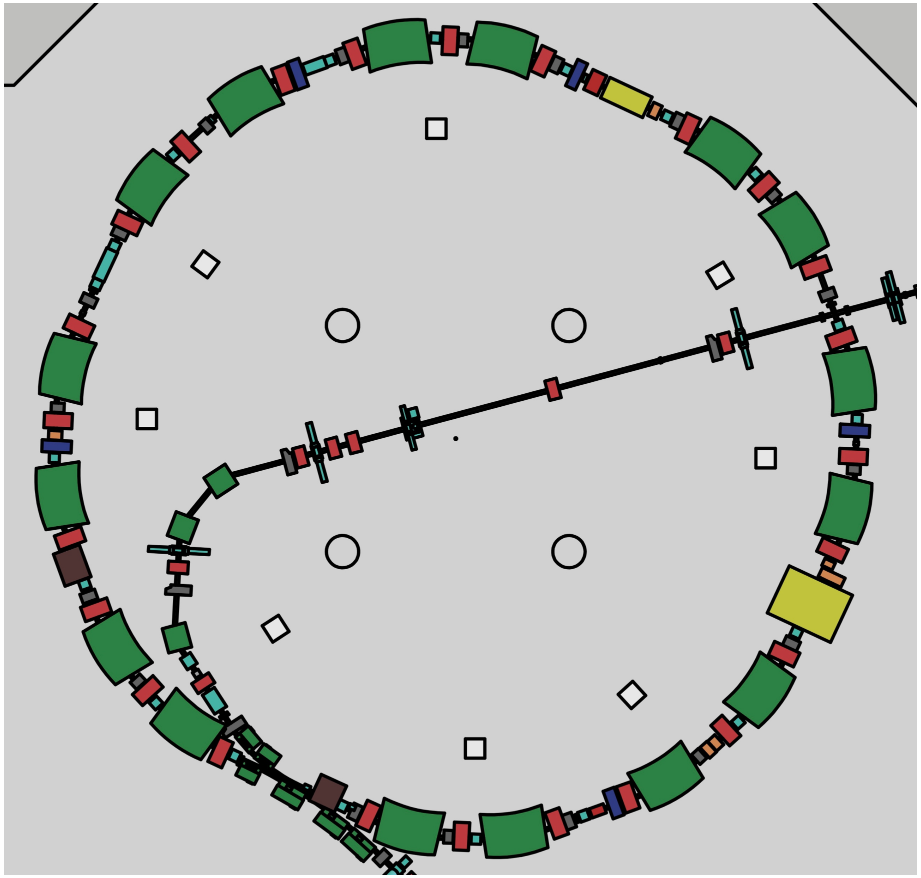
Synchrocyclotrons

- SynchroCyclotron makes Cyclotron more compact.
- Still keep magnetic field fixed, but change RF frequency as particle approaches speed of light.
- Number of revolutions by particle not fixed, so voltage can be much smaller:
  - Only one DEE used because high gradient not required.
  - Magnets closer together, so higher magnetic field.
  - Gives compact accelerator.
- BUT because RF varies, can't extract continuous current:
  - Fewer protons…

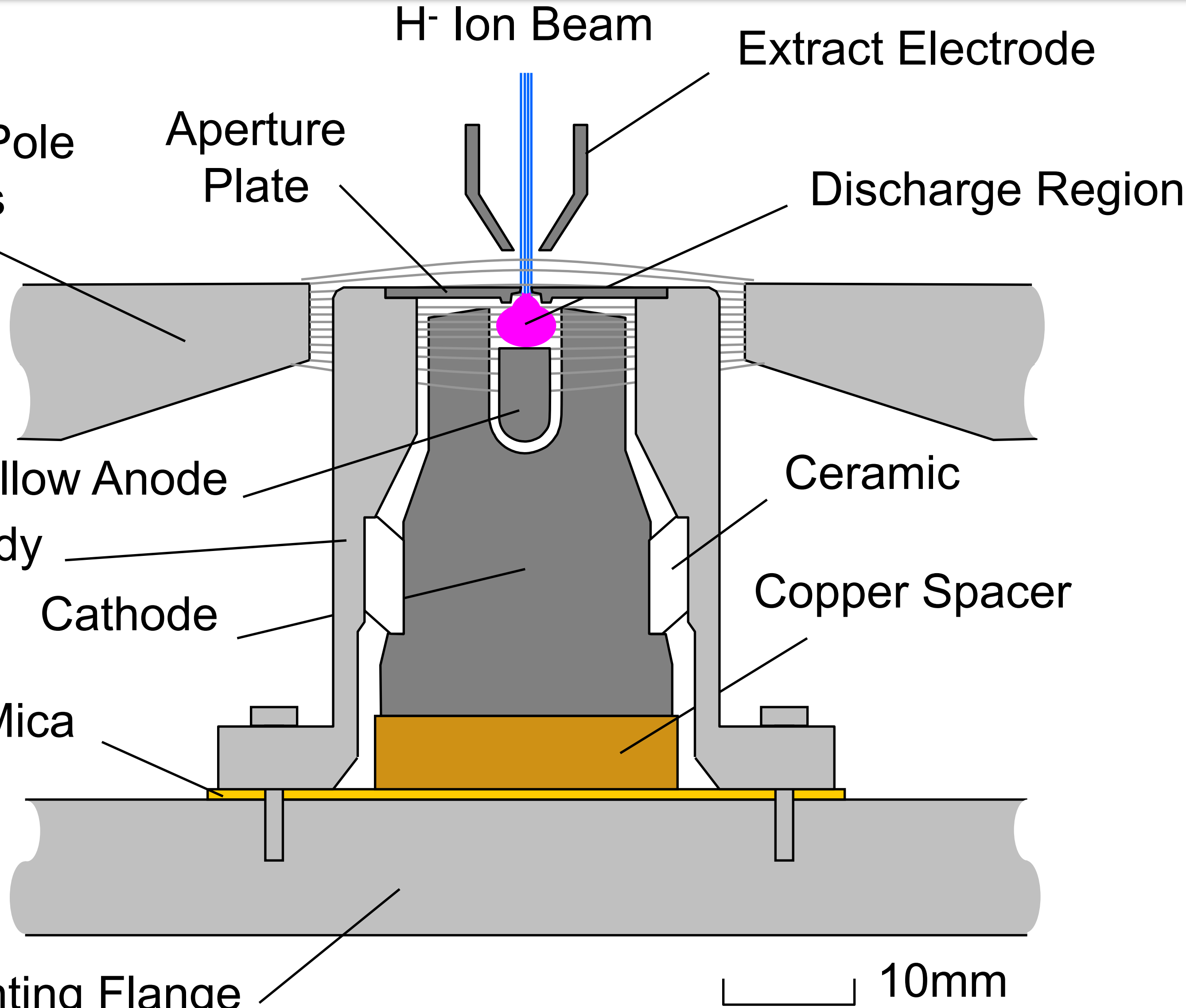


Synchrotrons

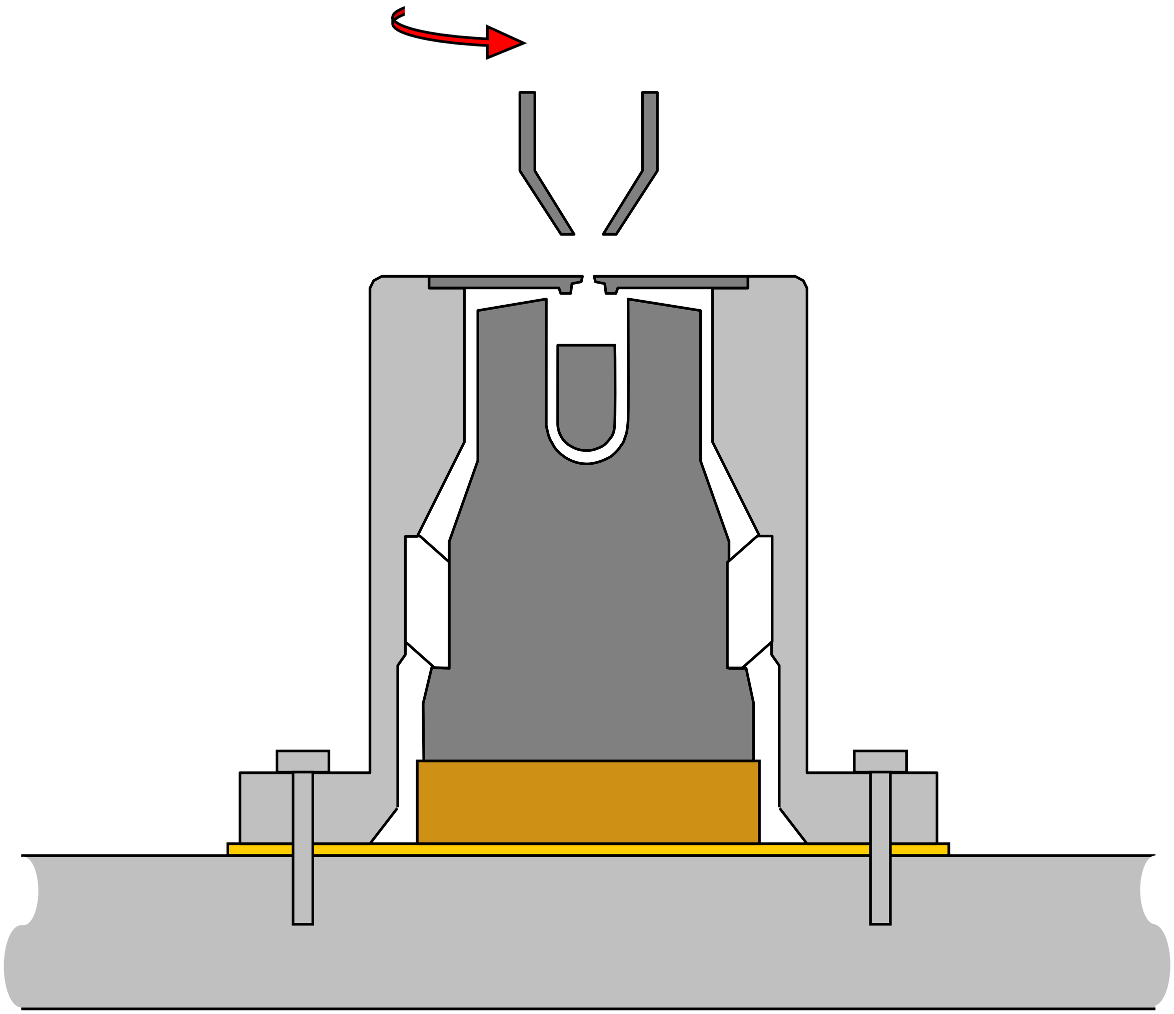
- Synchrotrons take opposite approach:
  - Fix particle radius.
  - Increase magnetic field.
  - Adjust RF frequency to match particles as they get faster.
  - *Synchro*tron because strength of magnetic field and frequency, amplitude and phase of RF and focussing strength of the lenses have to be *synchronised*.
- Dipole magnets to bend particles round in circle, and to inject and extract the beam.
- RF electric fields to accelerate particles – particle passes accelerating cavities many times.
- Instead of large single vacuum chamber, evacuated volume much smaller:
  - Narrow beam pipe with discrete components.
  - Focussing magnets contain 99.9% of injected beam (more like 50% for cyclotrons!)
- Normally consist of short straight accelerating/focussing/diagnostic sections, separated by bending sections with dipoles.
- B = 0 not possible and therefore a non-zero initial energy is necessary: chain of accelerators.



ISIS Ion Source



ISIS Ion Source



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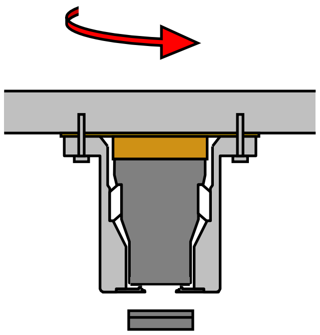

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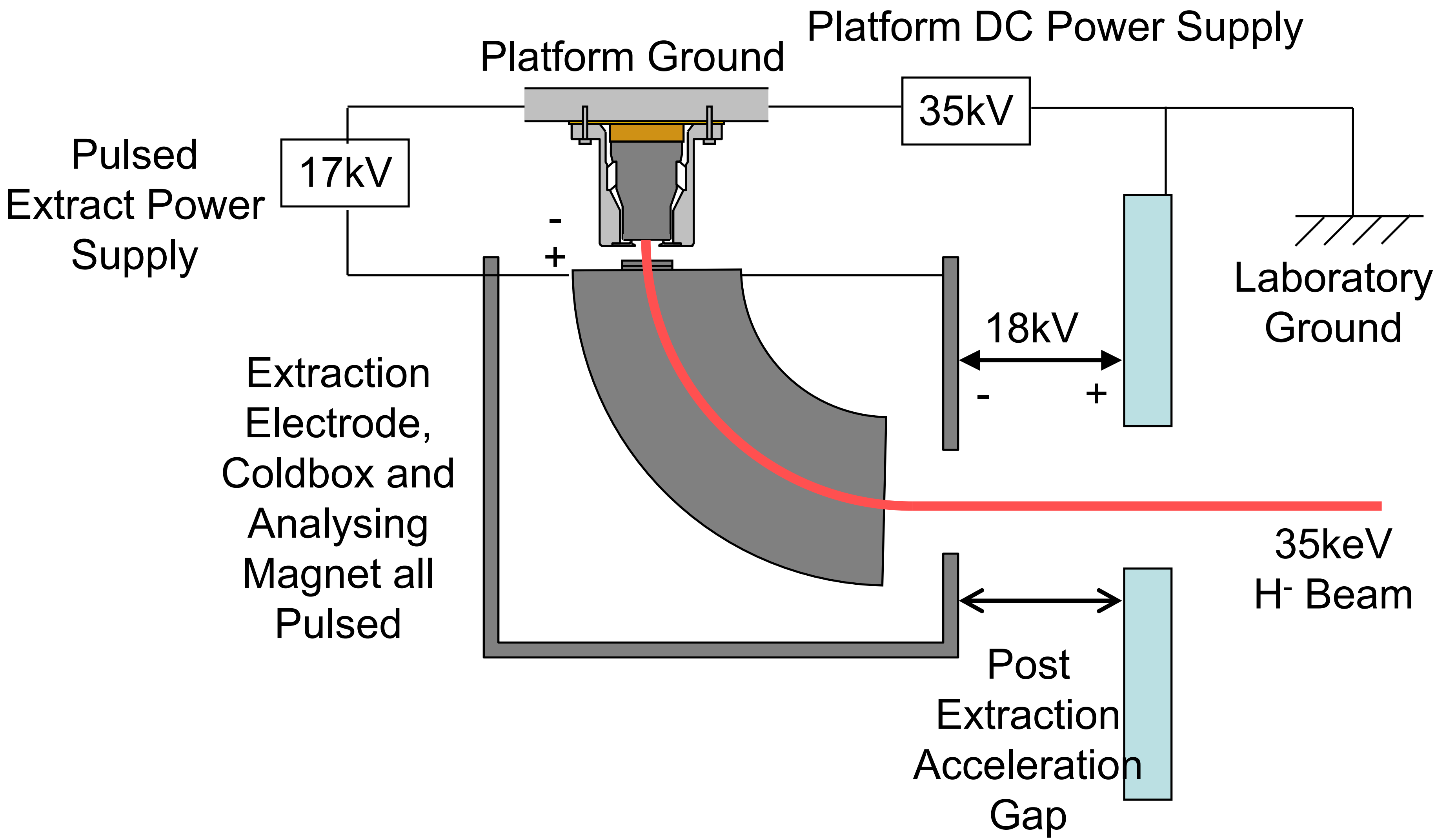
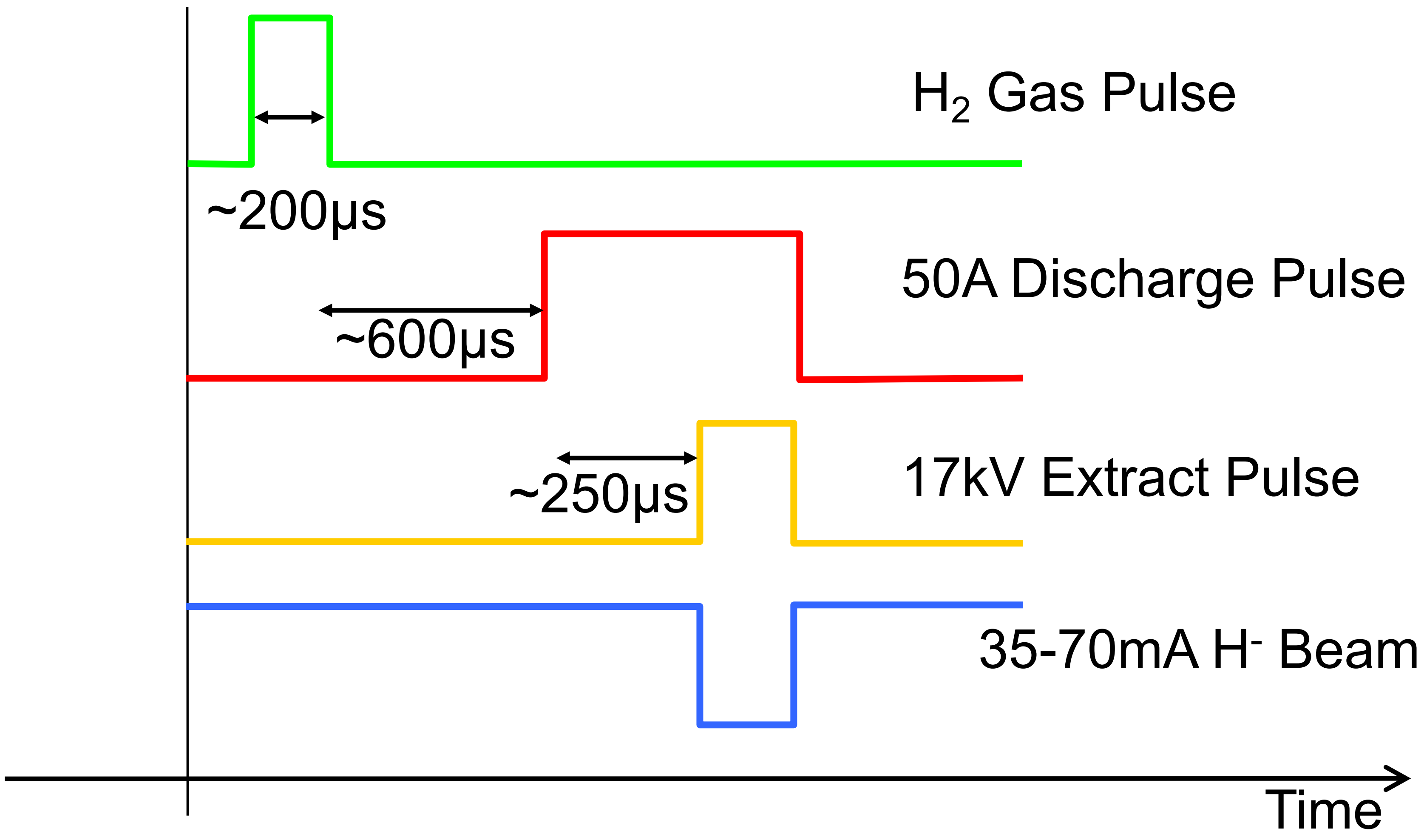
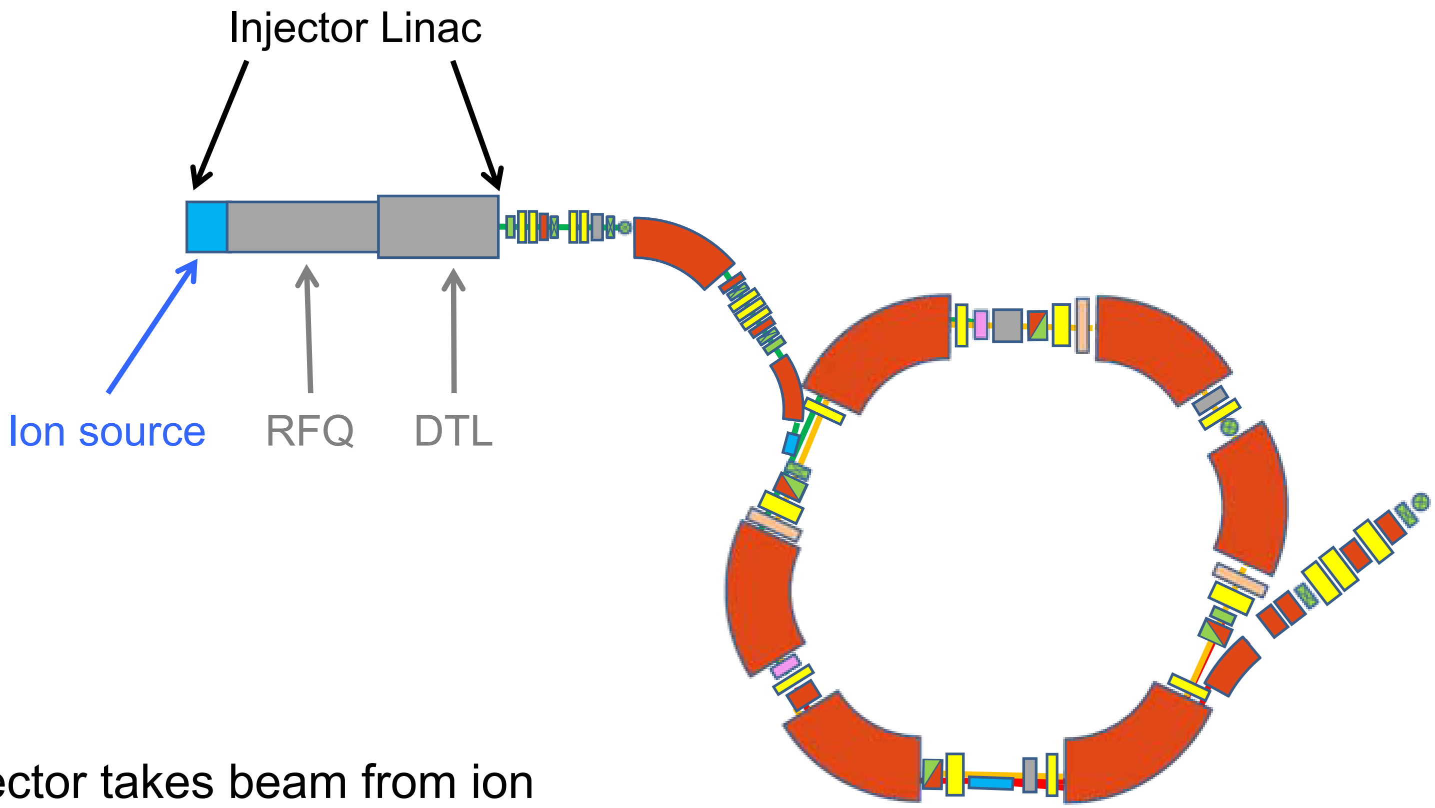


Ion Source Mode of Operation



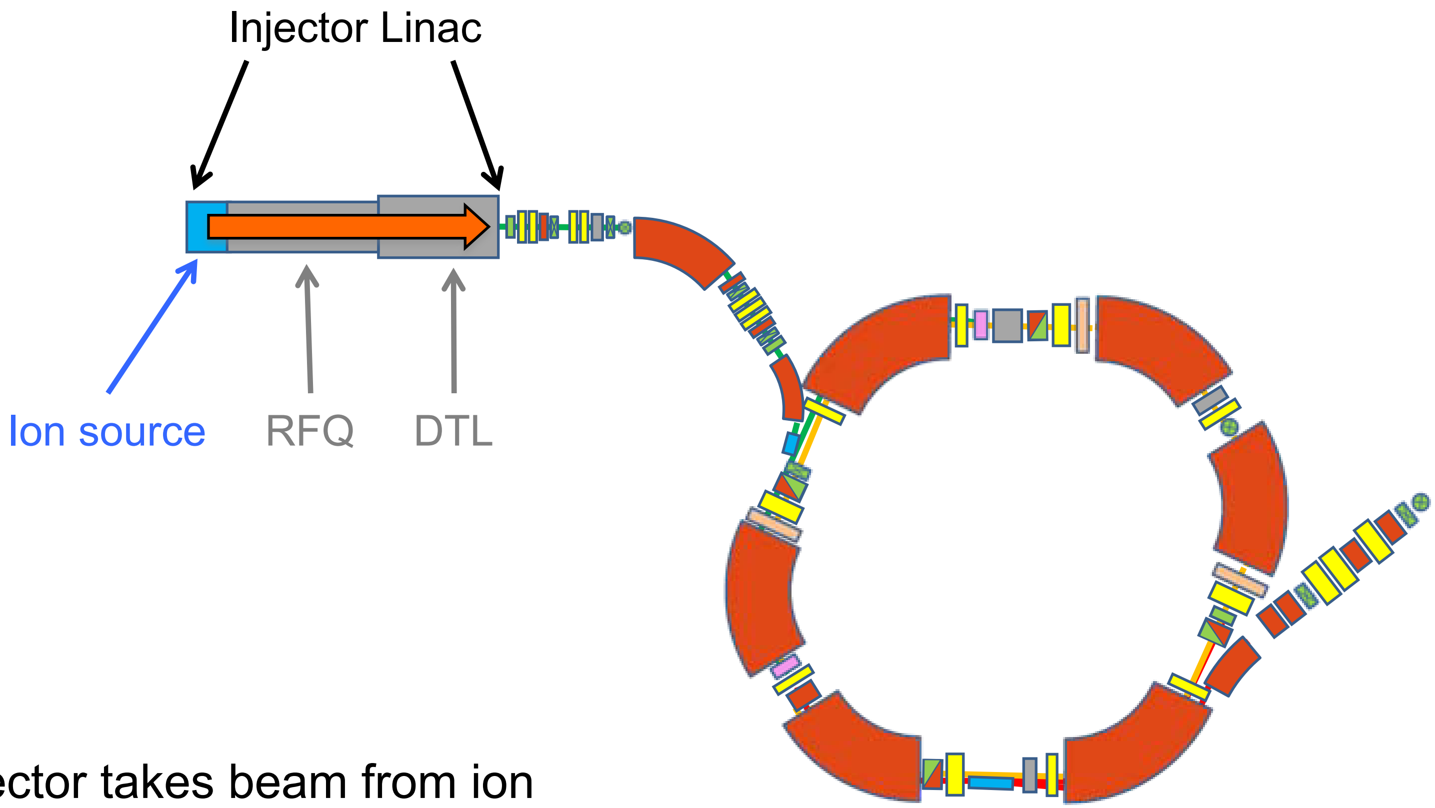
Synchrotrons: Injector



Injector takes beam from ion source, focuses it down to correct size and accelerates it to 7 MeV.

Need to do this with a linac as space charge within beam requires rapid acceleration and continuous focussing.

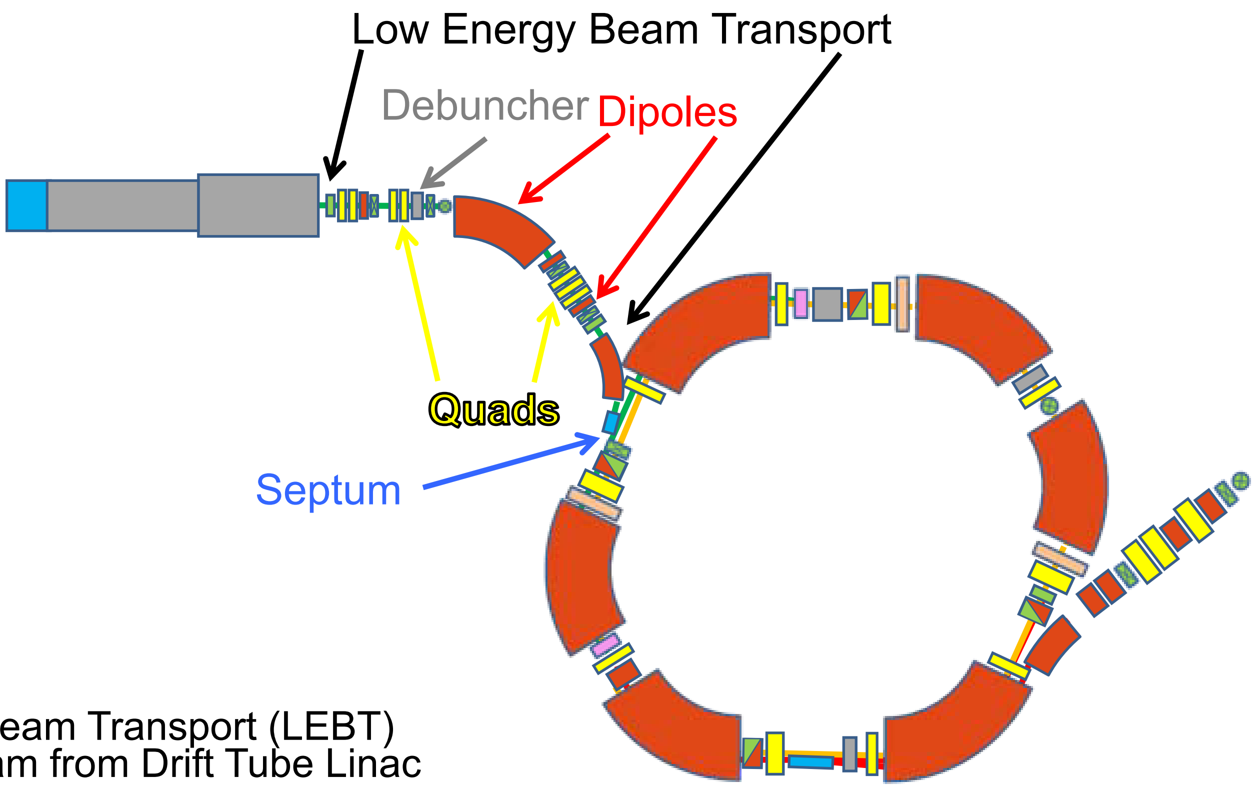
Synchrotrons: Injector



Injector takes beam from ion source, focuses it down to correct size and accelerates it to 7 MeV.

Need to do this with a linac as space charge within beam requires rapid acceleration and continuous focussing.

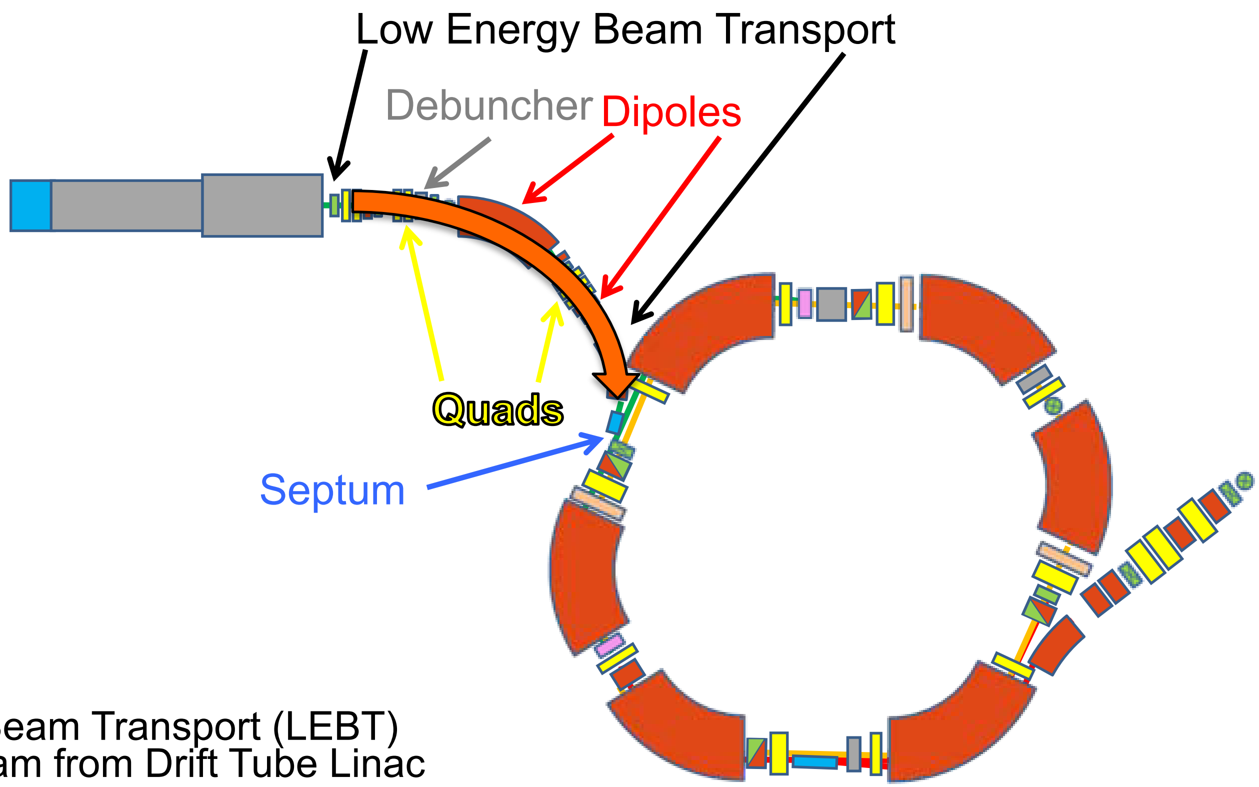
Synchrotrons: LEBT



Low Energy Beam Transport (LEBT) transports beam from Drift Tube Linac (DTL) exit to synchrotron injection.

Consists of several quadrupole doublets for focusing, steering dipoles, beam position monitors and a debuncher to match the beam to synchrotron frequency.

Synchrotrons: LEBT



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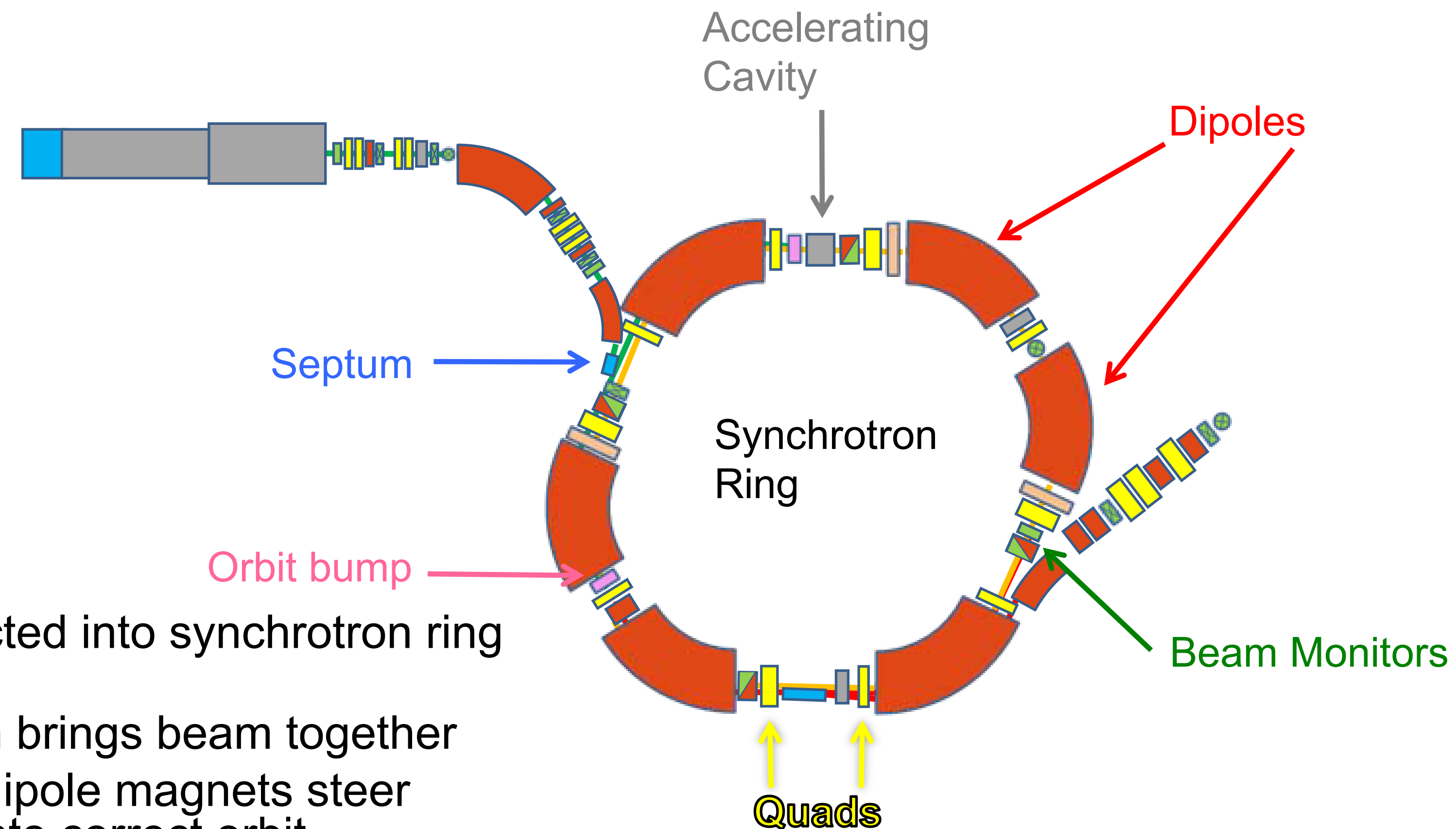
Consists of several quadrupole doublets for focusing, steering dipoles, beam position monitors and a debuncher to match the beam to synchrotron frequency.

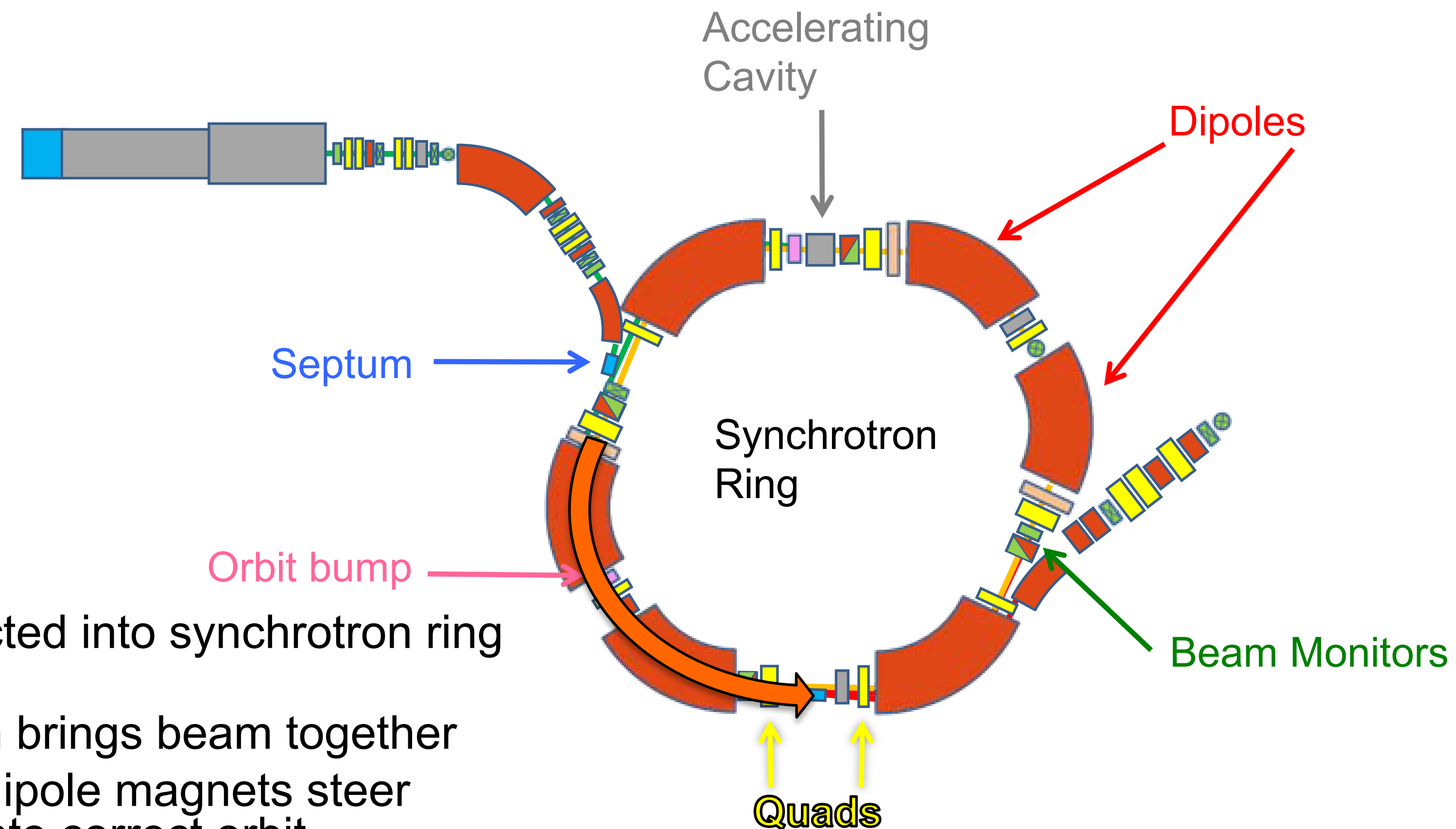
Synchrotrons: Acceleration (1)



Beam injected into synchrotron ring in stages:

- Septum brings beam together
- Bump dipole magnets steer beam into correct orbit.
- Dipoles steer beam in a circle.
- Quadrupoles keep beam on correct trajectory.

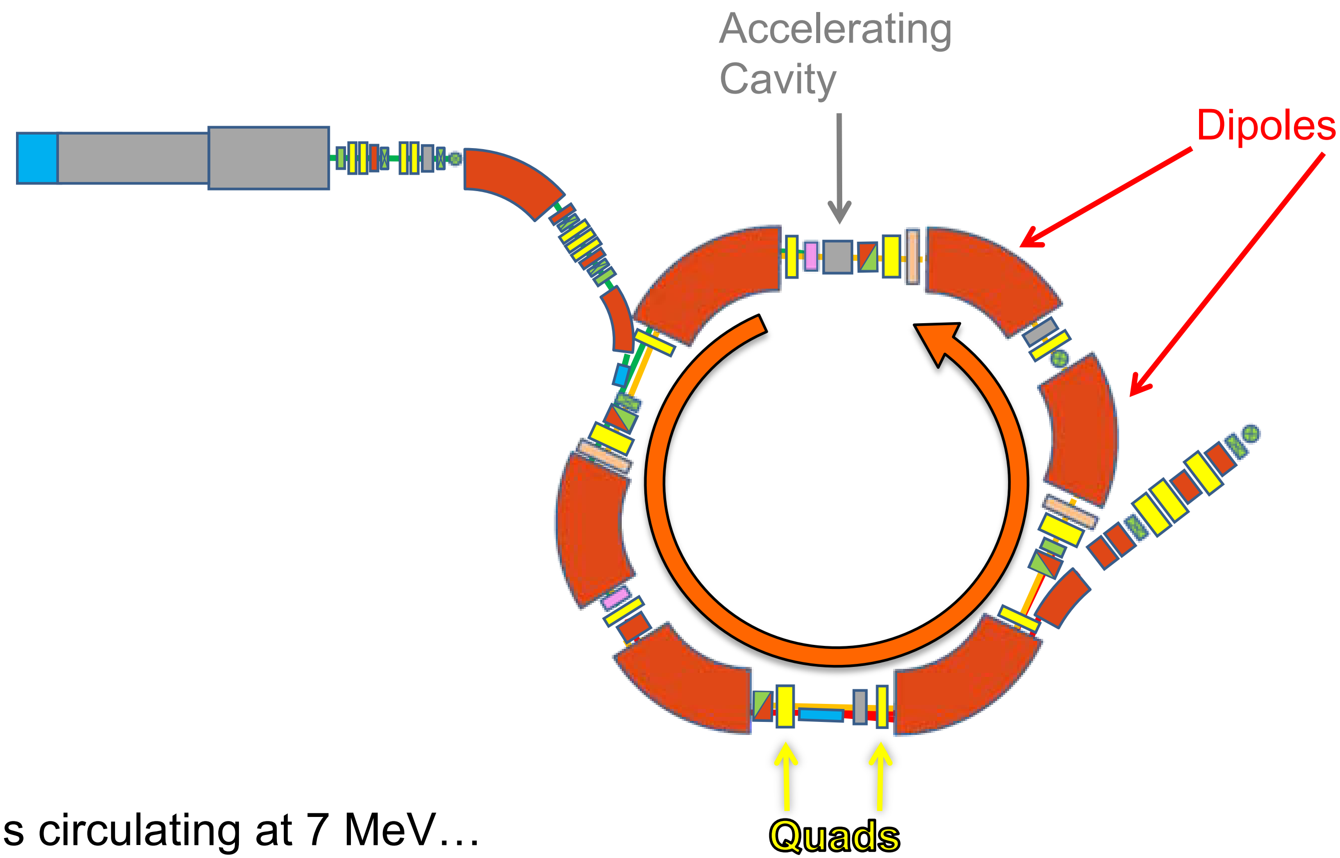
Synchrotrons: Acceleration (1)



Beam injected into synchrotron ring in stages:

- Septum brings beam together
- Bump dipole magnets steer beam into correct orbit.
- Dipoles steer beam in a circle.
- Quadrupoles keep beam on correct trajectory.

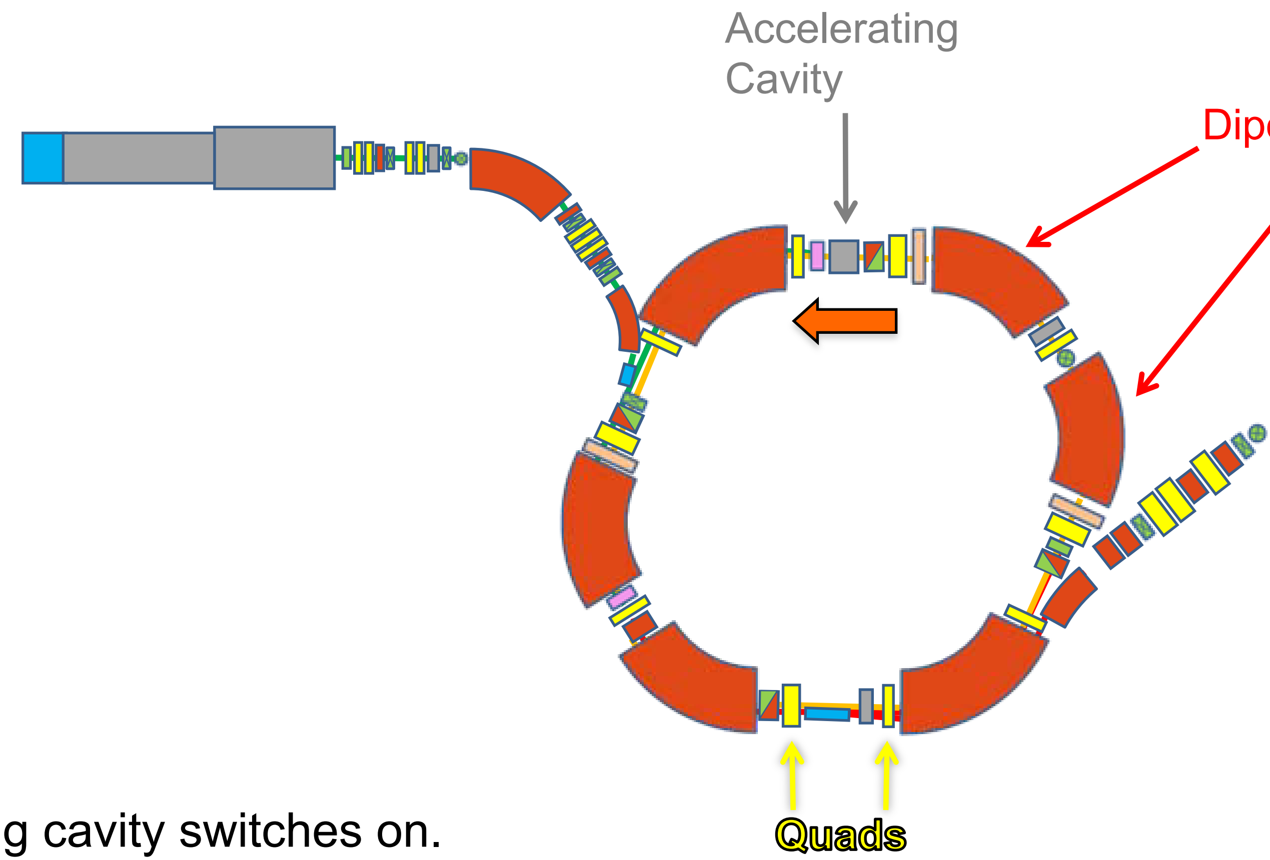
Synchrotrons: Acceleration (2)



Beam begins circulating at 7 MeV…

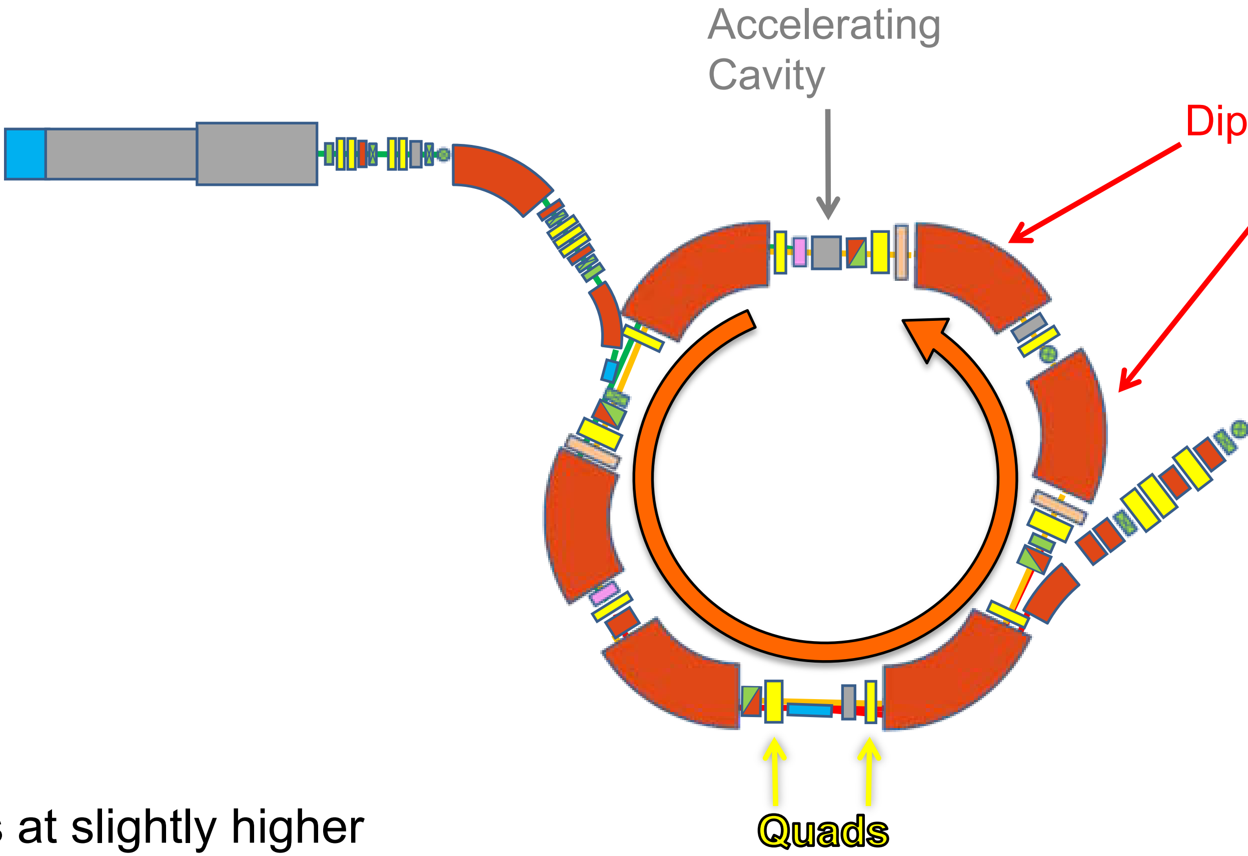
Synchrotrons: Acceleration (3)

UCL



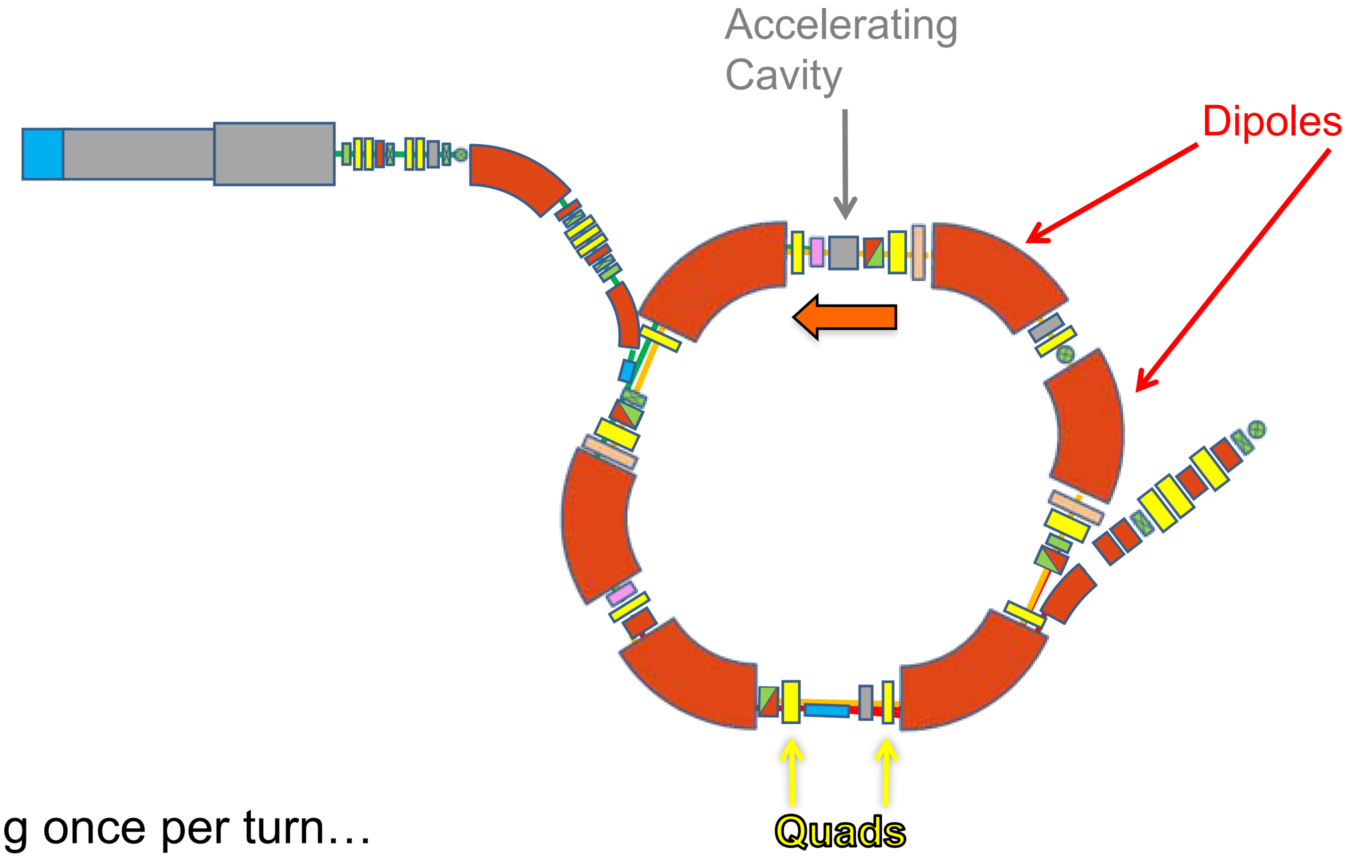
Accelerating cavity switches on.
Beam accelerated once per turn…

Synchrotrons: Acceleration (4)



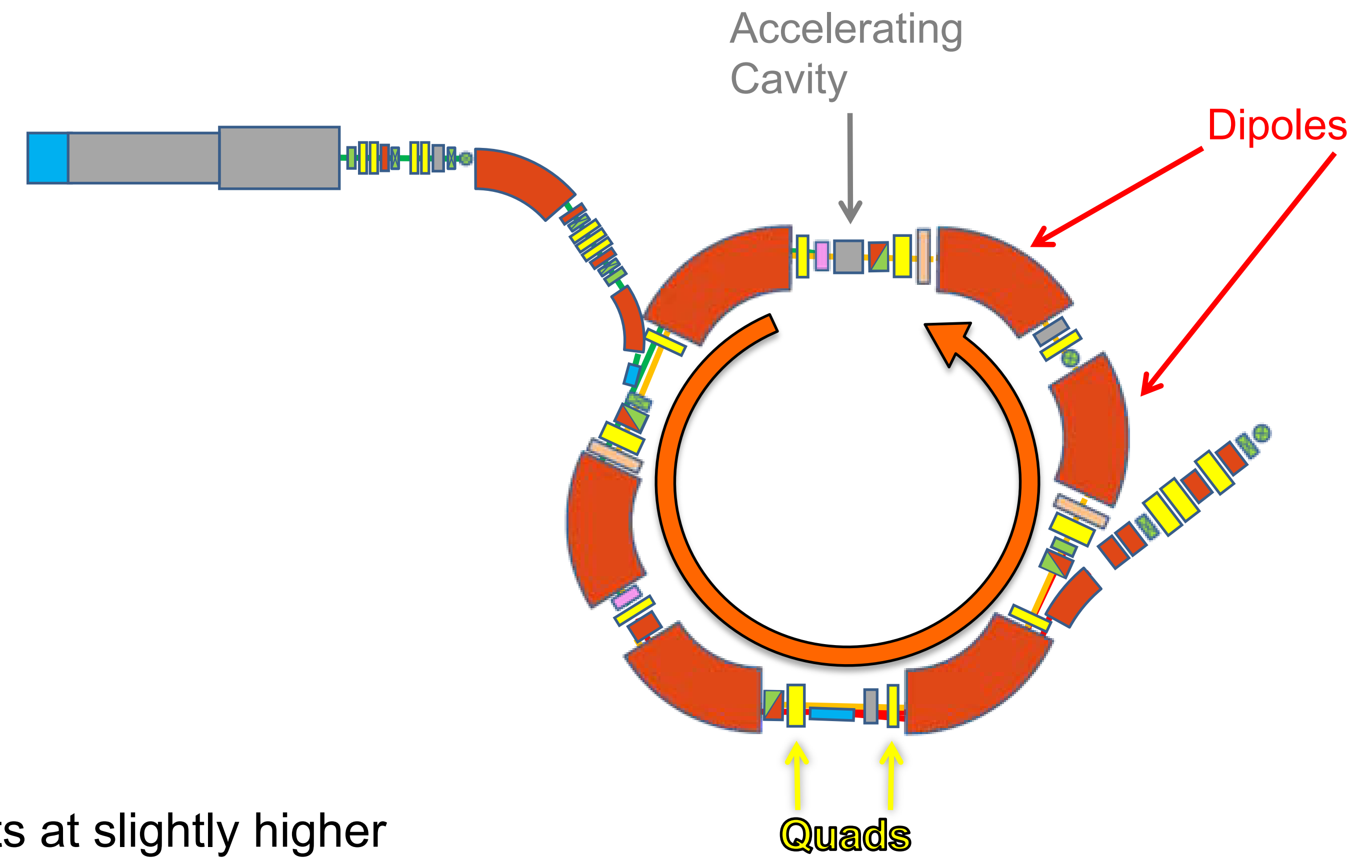
Beam orbits at slightly higher energy…

Synchrotrons: Acceleration (5)



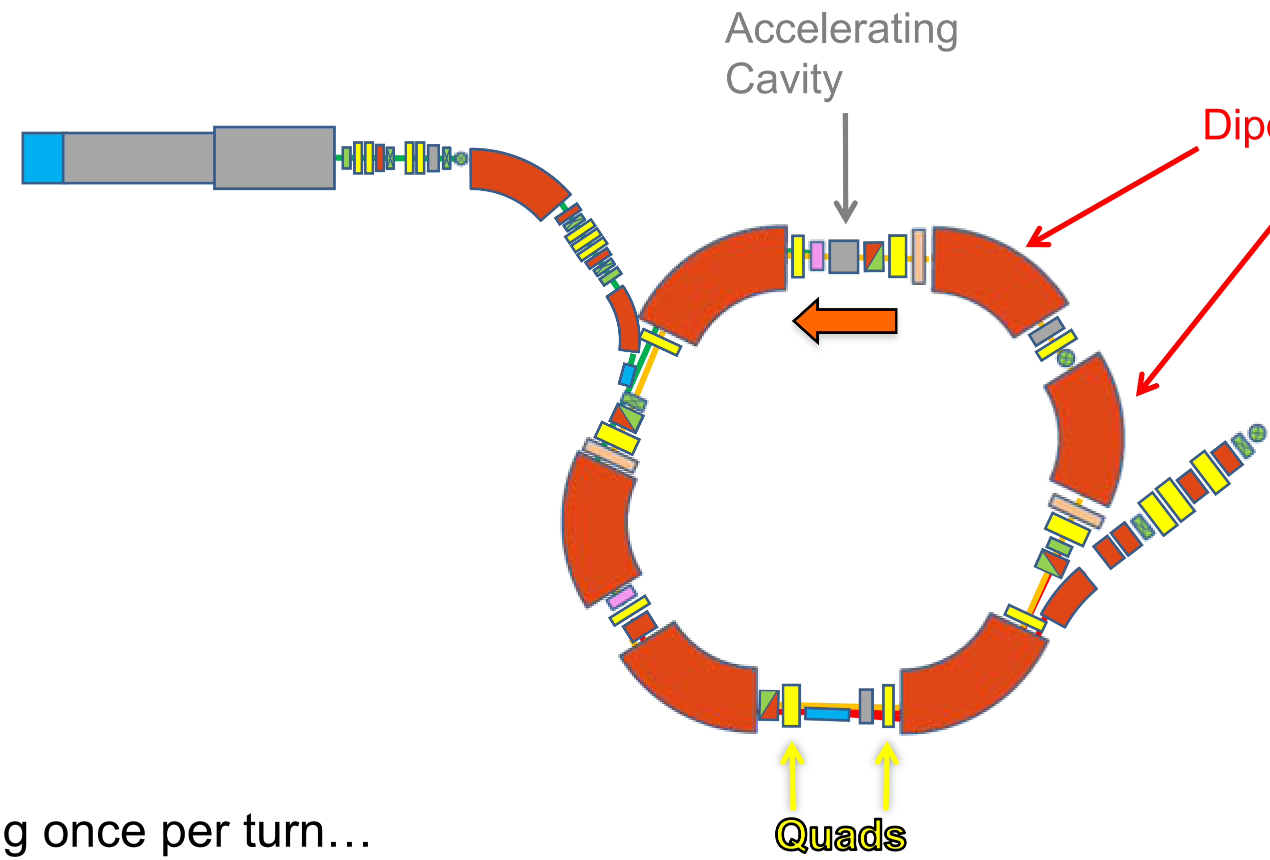
Accelerating once per turn…

Synchrotrons: Acceleration (6)



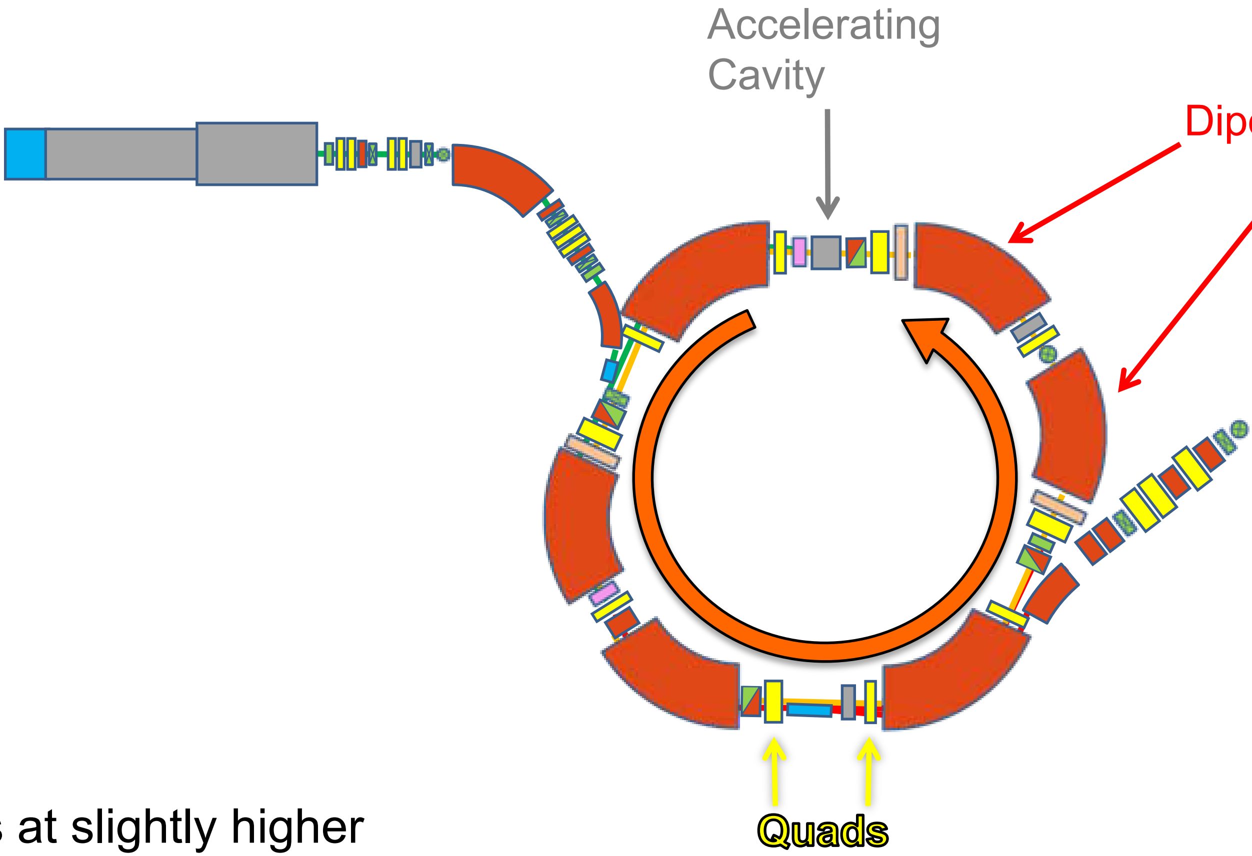
Beam orbits at slightly higher energy…

Synchrotrons: Acceleration (7)



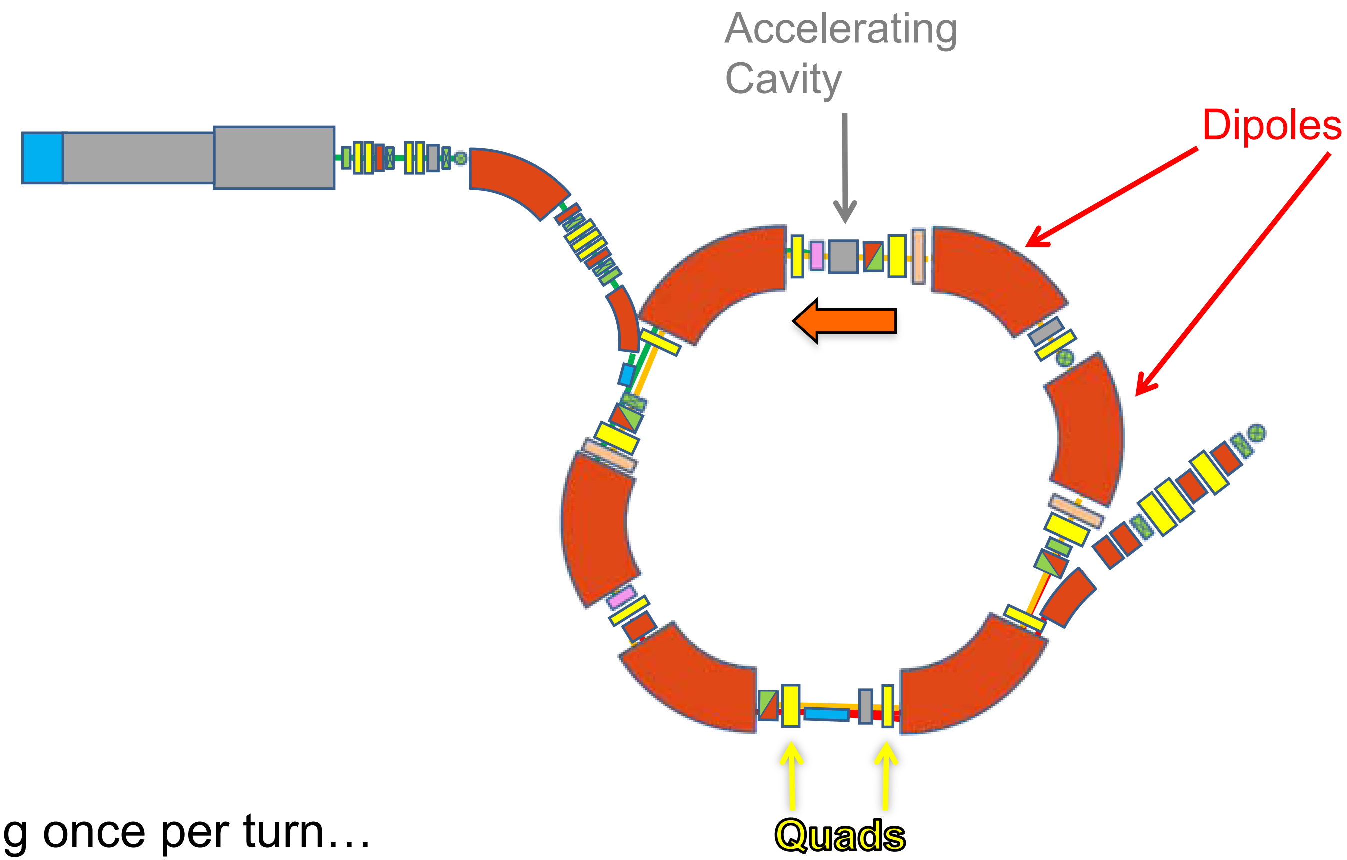
Accelerating once per turn…

Synchrotrons: Acceleration (8)



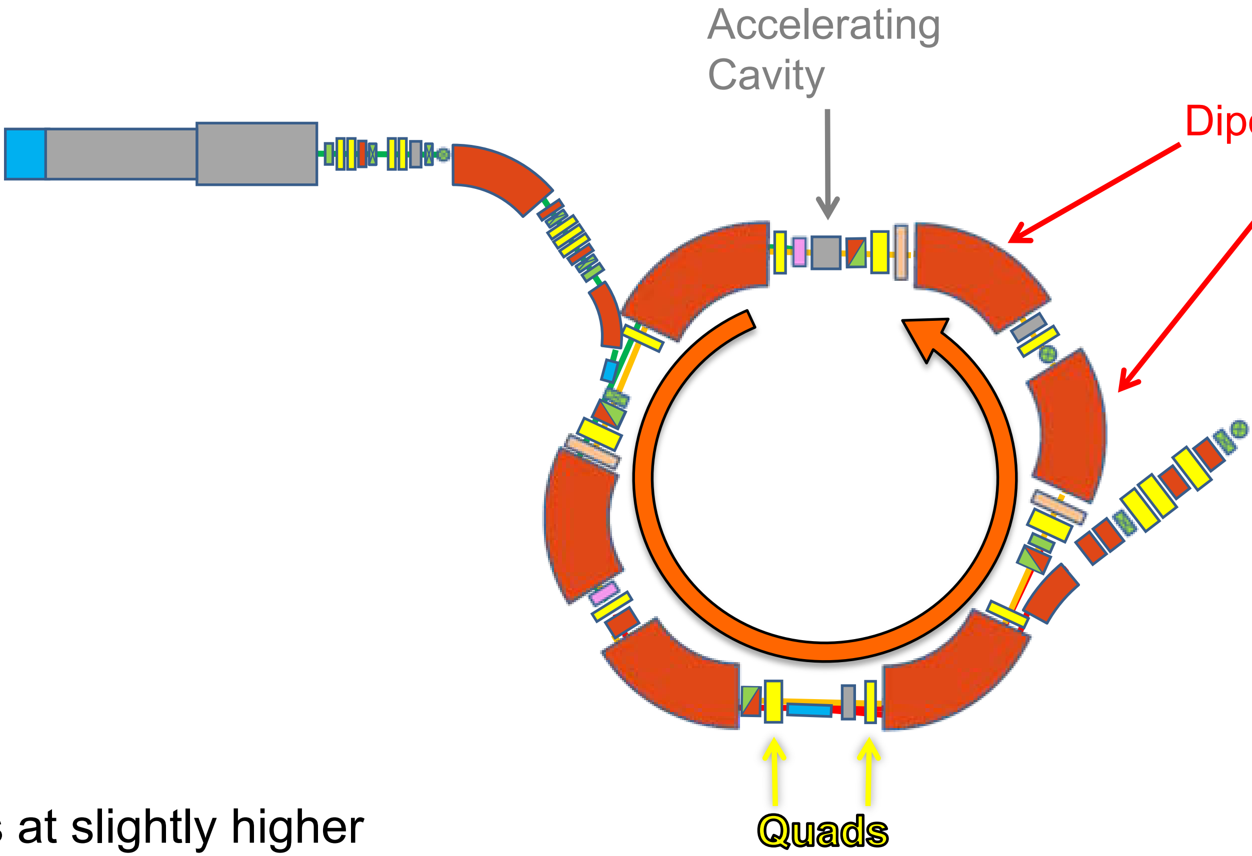
Beam orbits at slightly higher energy…

Synchrotrons: Acceleration (9)



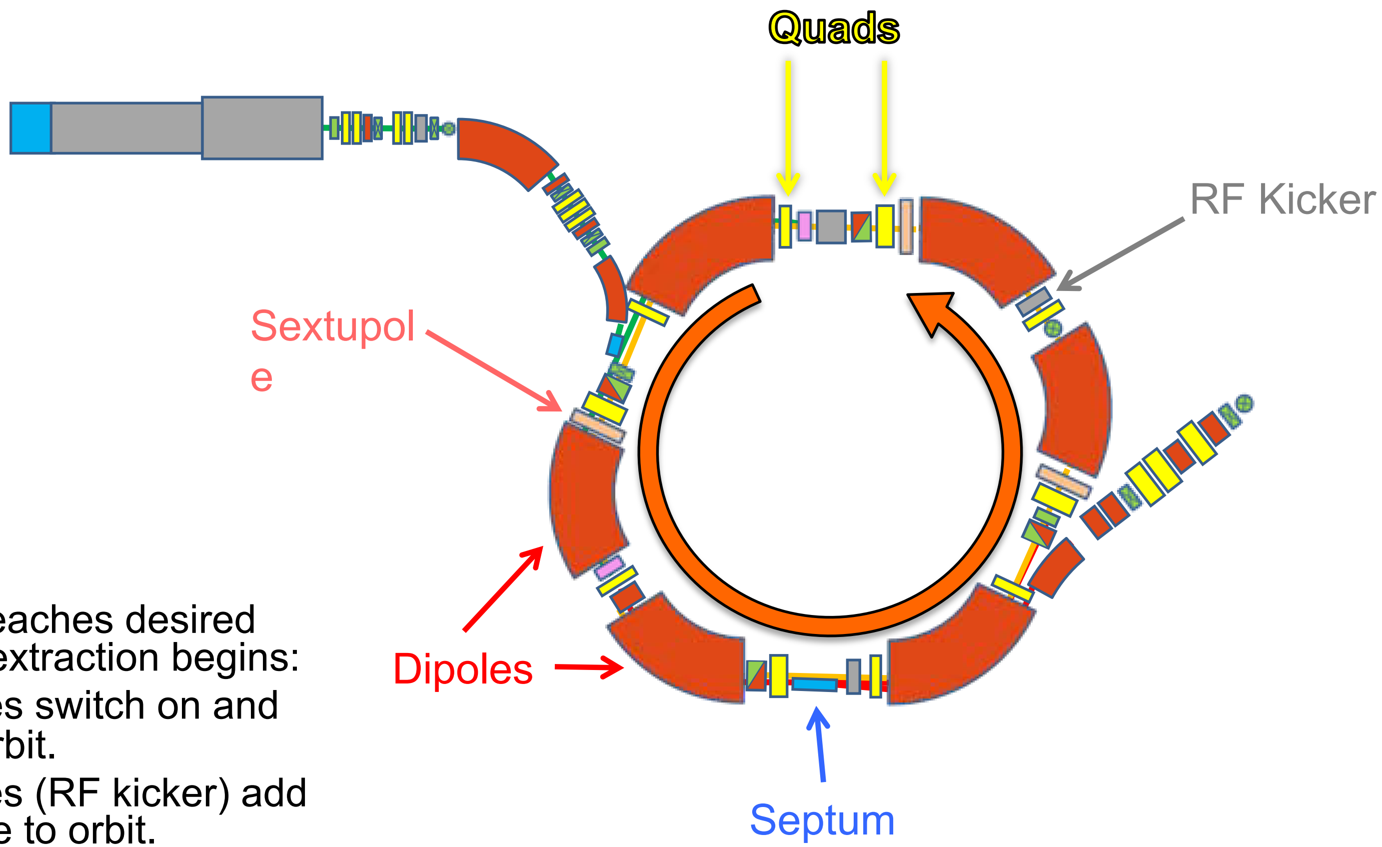
Accelerating once per turn…

Synchrotrons: Acceleration (10)



Beam orbits at slightly higher energy…

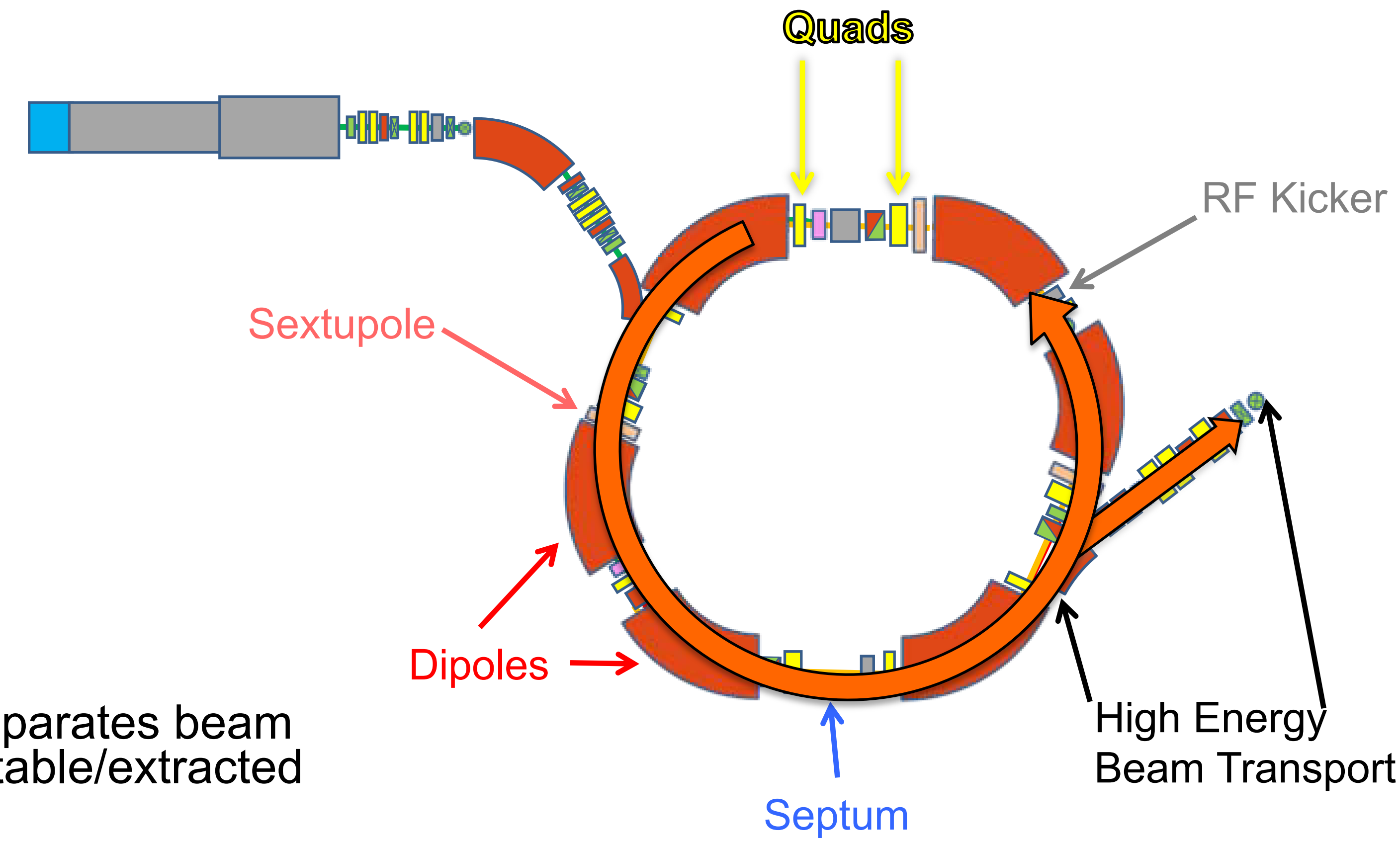
Synchrotrons: Extraction (1)



Once beam reaches desired energy, slow extraction begins:

- Sextupoles switch on and change orbit.
- RF cavities (RF kicker) add resonance to orbit.
- Some beam now outside stable orbit.

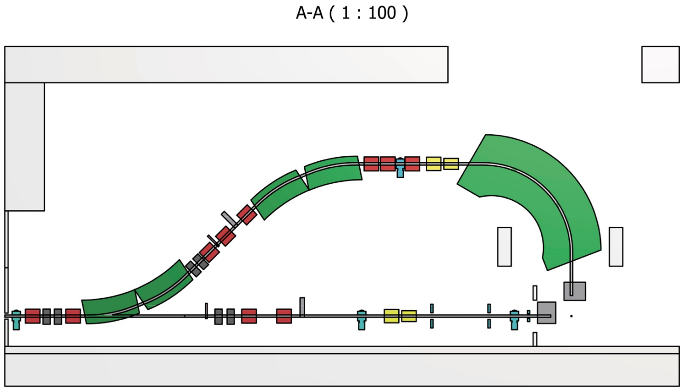
Synchrotrons: Extraction (2)

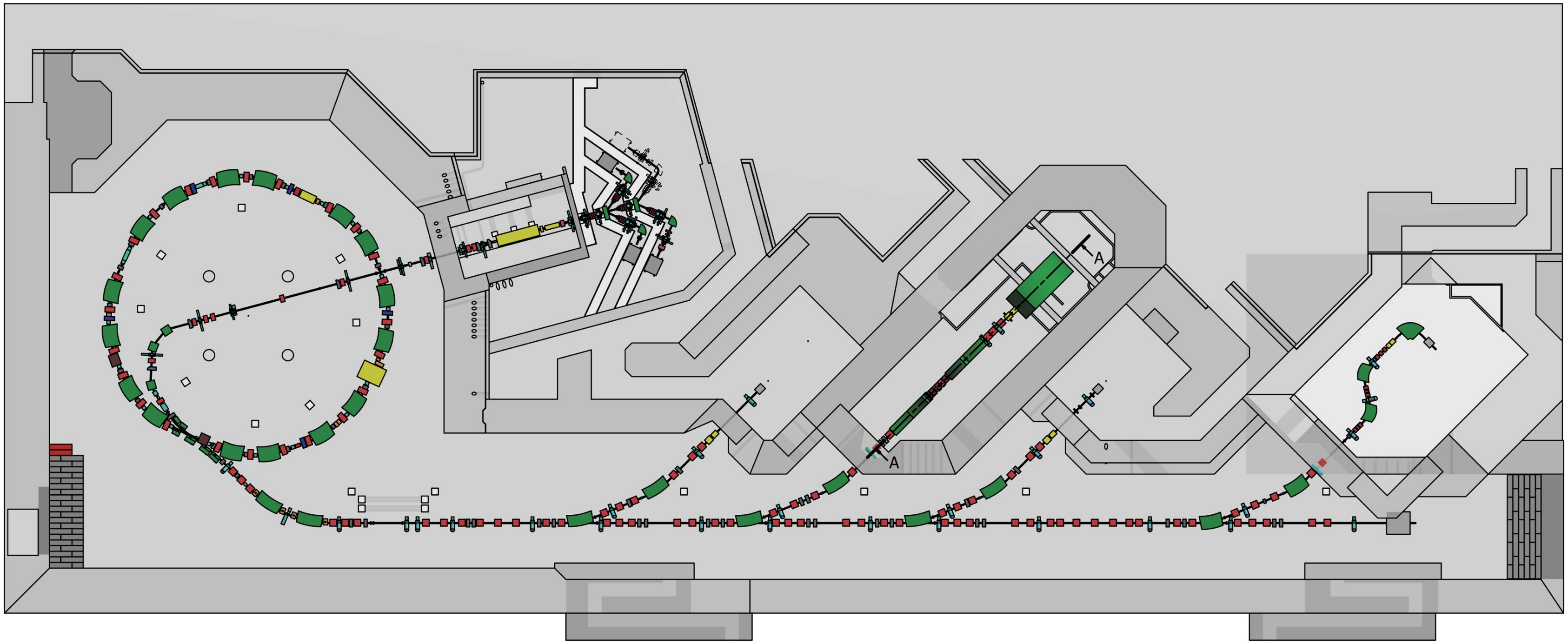


Septum separates beam between stable/extracted orbits.

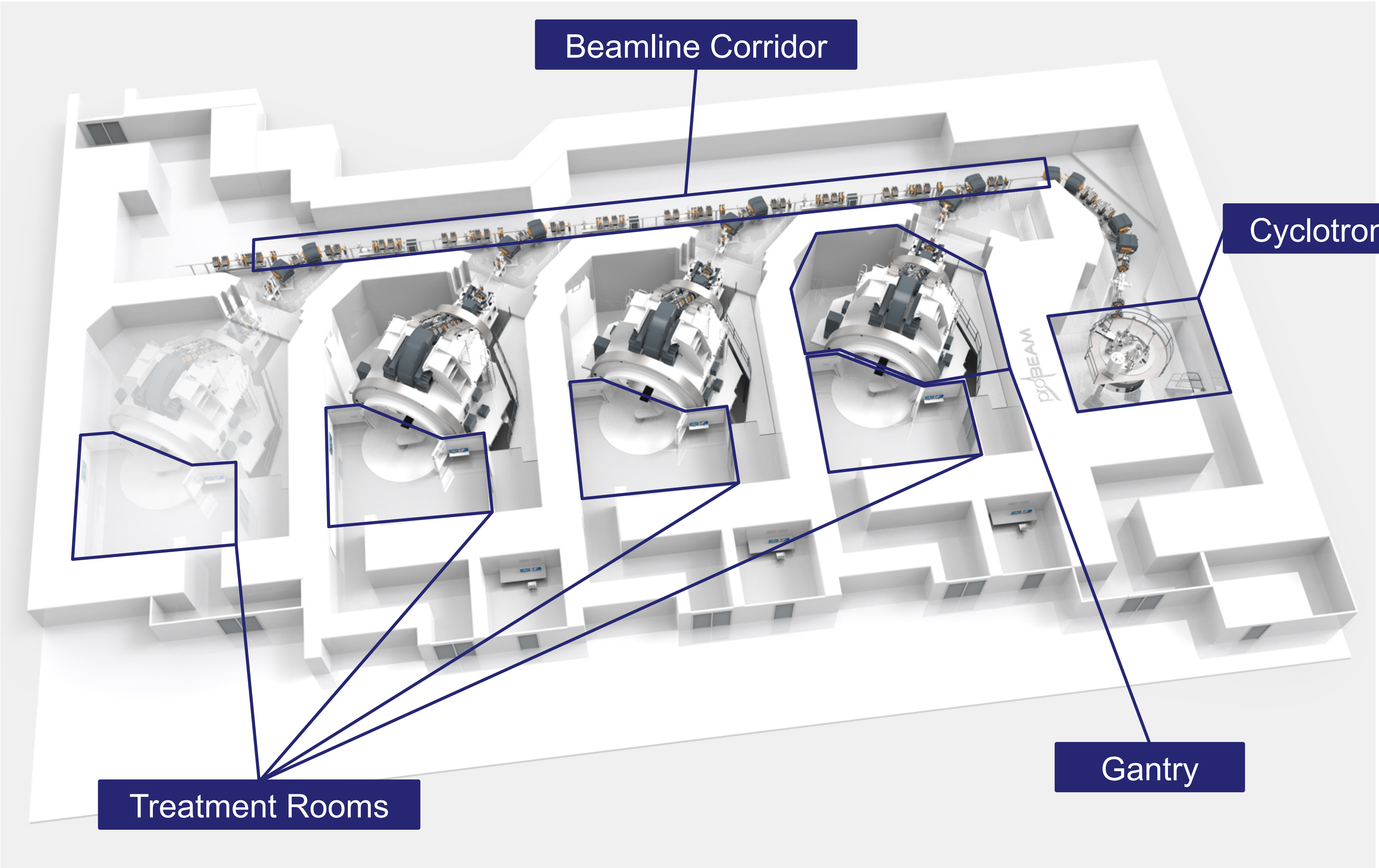
Extracted passes into High Energy Beam Transport (HEBT) and on to gantries.

MedAustron





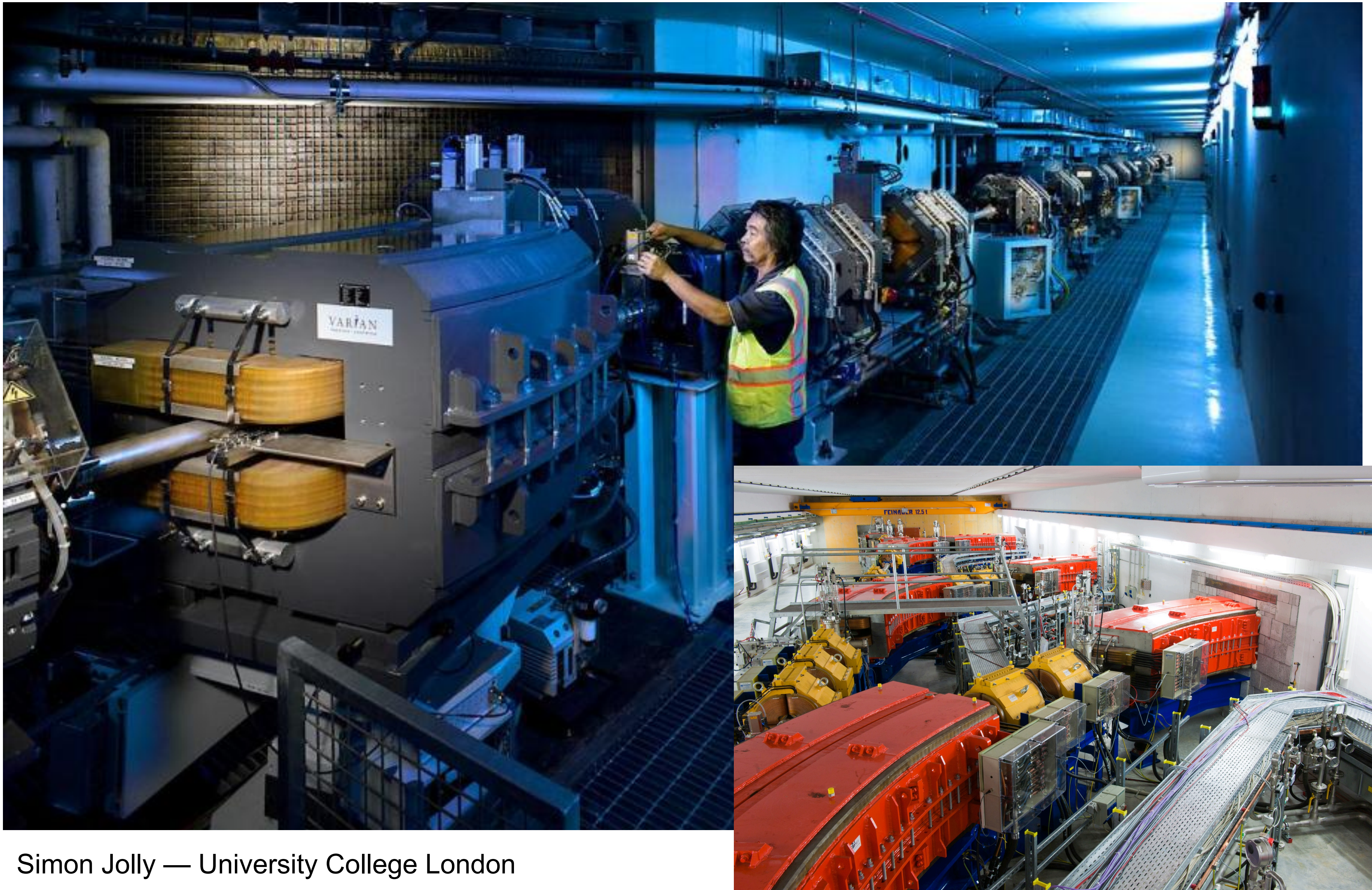
UCLH Proton Therapy Facility



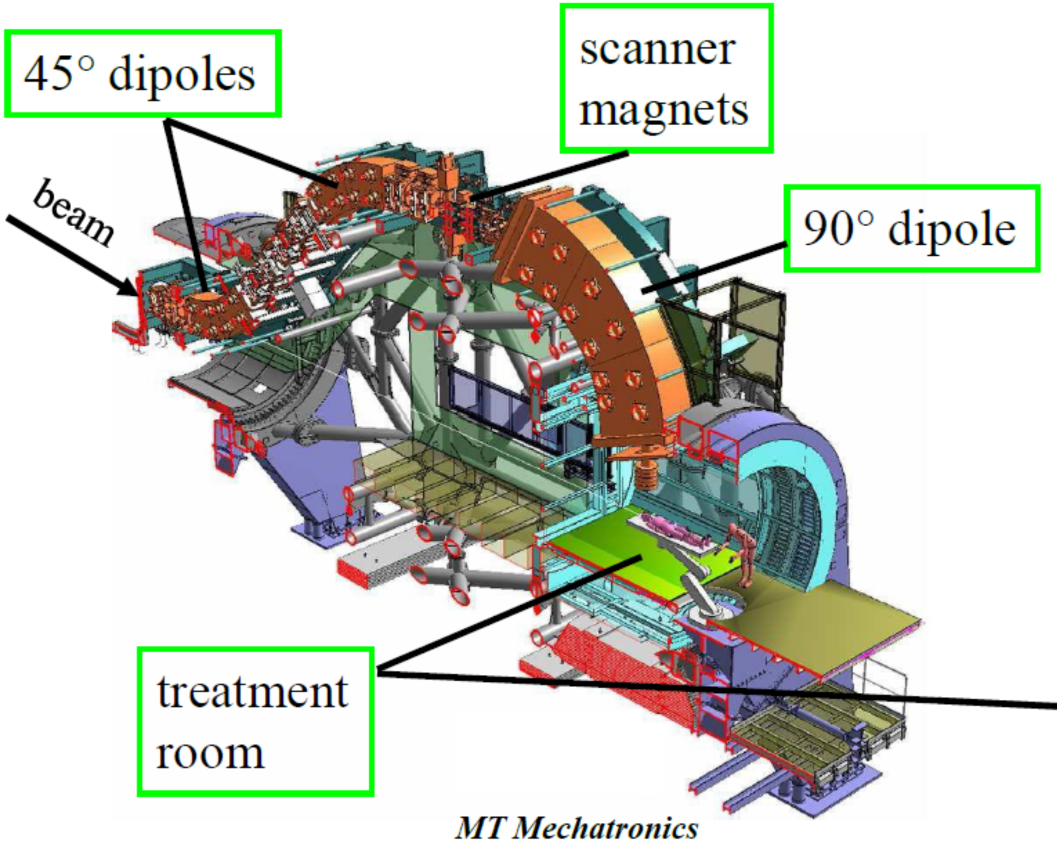
Images courtesy of Varian/UCLH

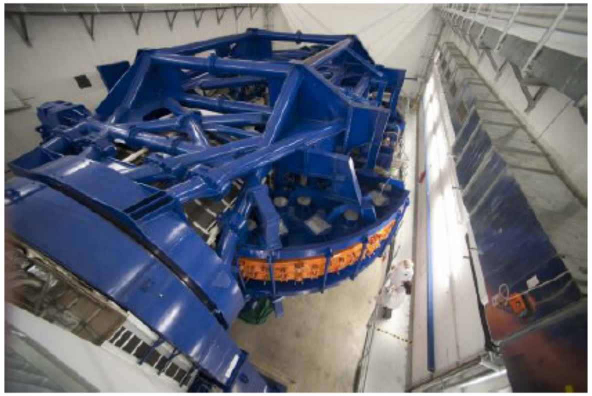
Beam Transport Line

UCL



Gantries

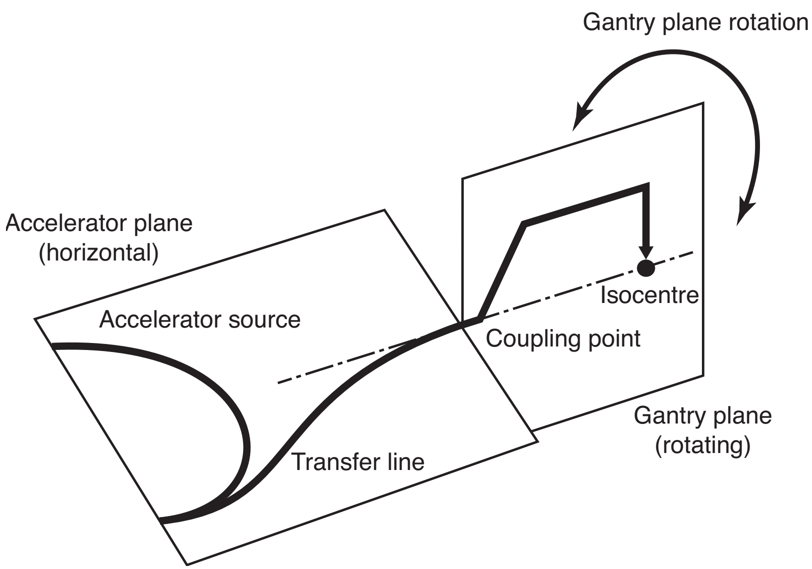


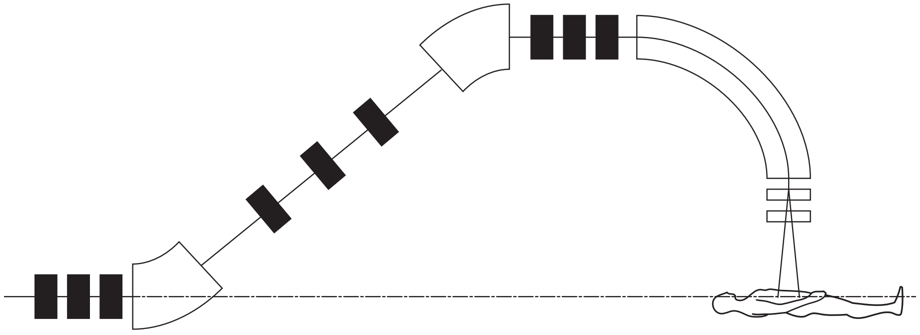


- Gantries deliver beam from accelerator to patient.
- Essentially standard beamline but mounted to rotating assembly.
- Delivers beam from any angle: patient stationary.
- Big beasties: "compact" gantries 11 m in diameter; carbon gantry 22 m long x 13 m diameter!

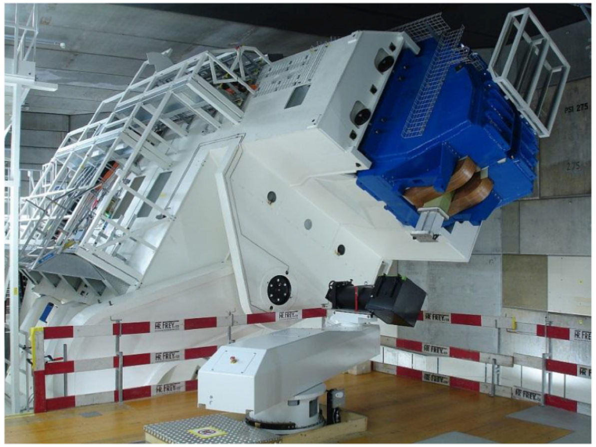
Gantries

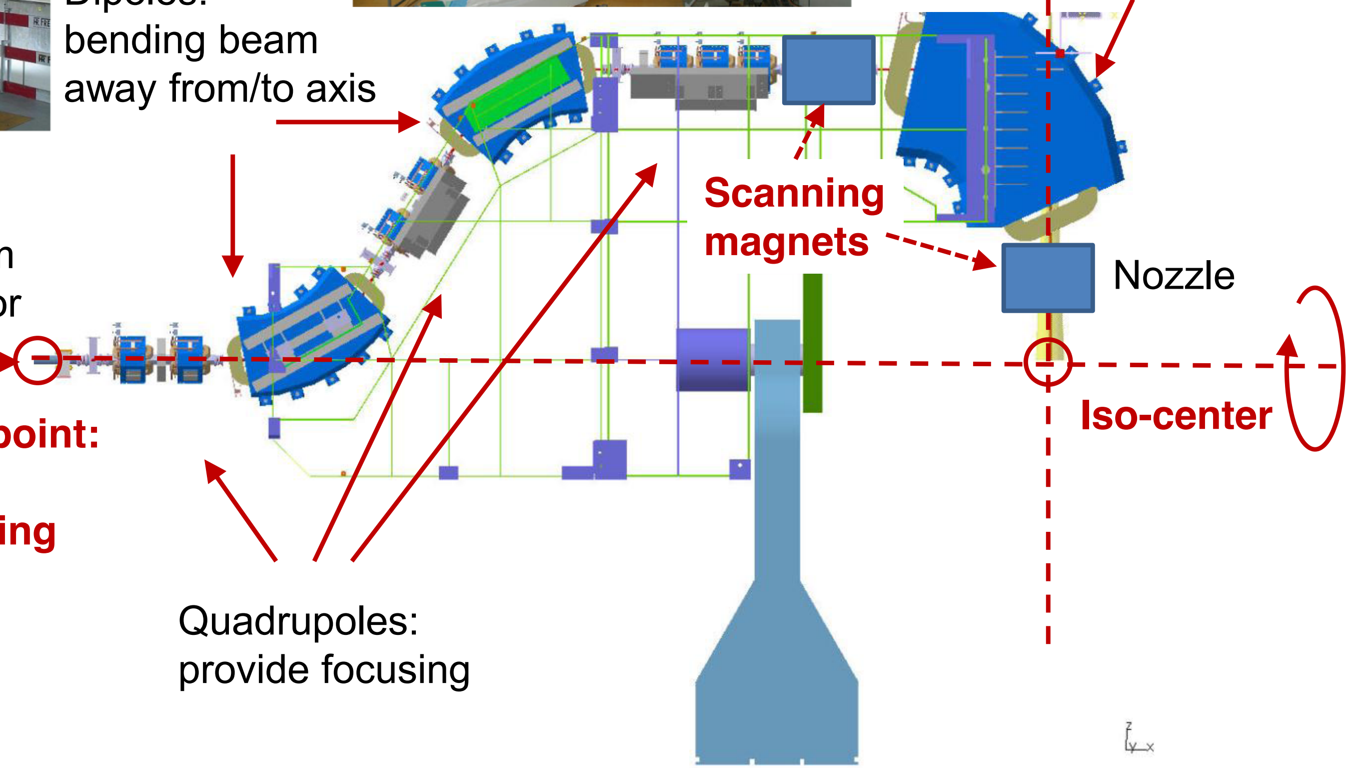
- Gantries deliver beam from accelerator to patient.
- A rotating beam transport line:
  - Virtually always a single axis.
  - Focuses and directs particle beam to desired location in target volume, at any angle.
  - Gantry rotation + patient table rotation = full solid angle coverage.
- Patient is supine and stationary: setup before beam delivery on robotic couch.
- Components:
  - Mechanical structure and drive.
  - Beamline components: dipoles, quadrupoles, correctors, vacuum, diagnostics.
  - Nozzle: scattering or scanning.
  - Infrastructure.
- Large structures! Frequently above 200 tonnes, 10 m diameter.





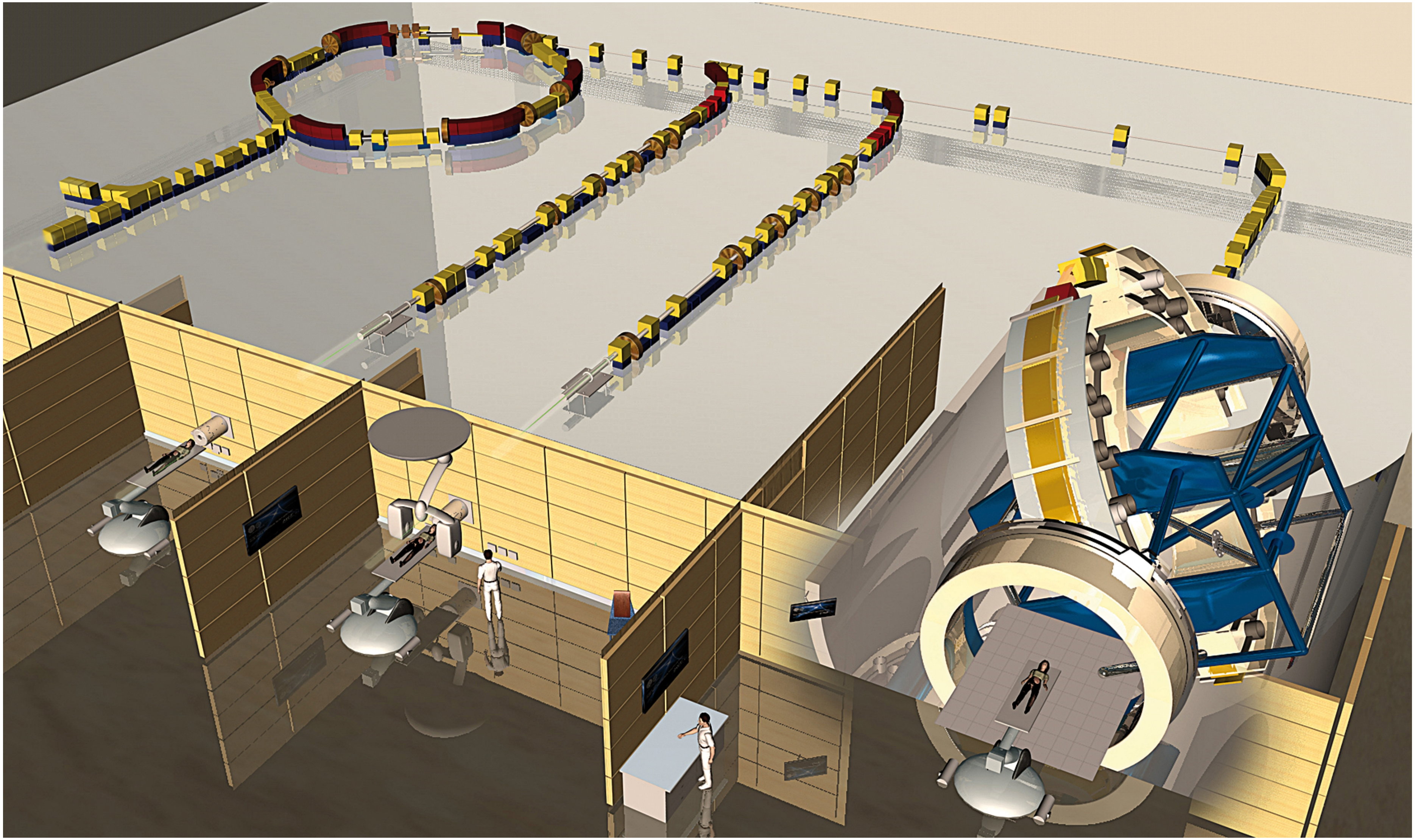
PSI Gantry 2



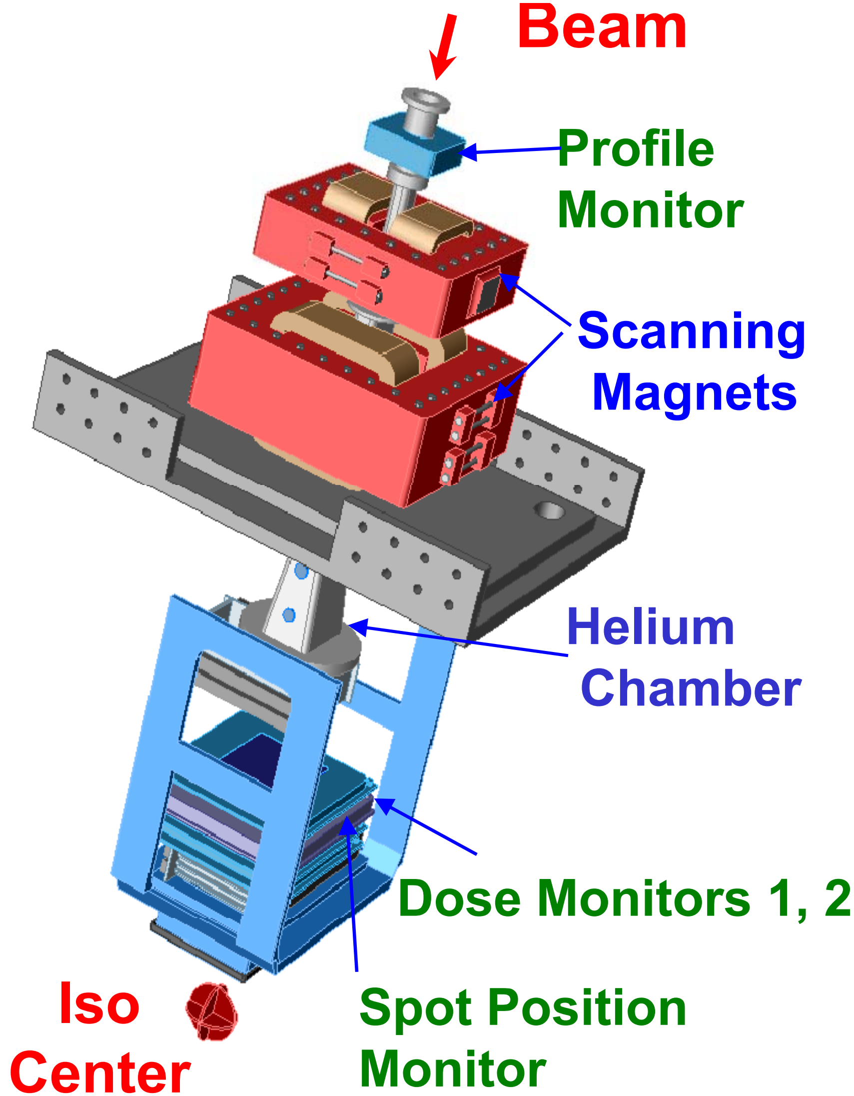

Last bending dipole:
bends beam into plane of
rotation and iso-center
Dipoles:
bending beam
away from/to axis
Particle
beam from
accelerator
Scanning
magnets
Nozzle
Iso-center
Coupling point:
junction
fixed/rotating
beamline
Quadrupoles:
provide focusing

Heidelberg Gantry: 13 m x 22 m

Heidelberg Ion Therapy Centre

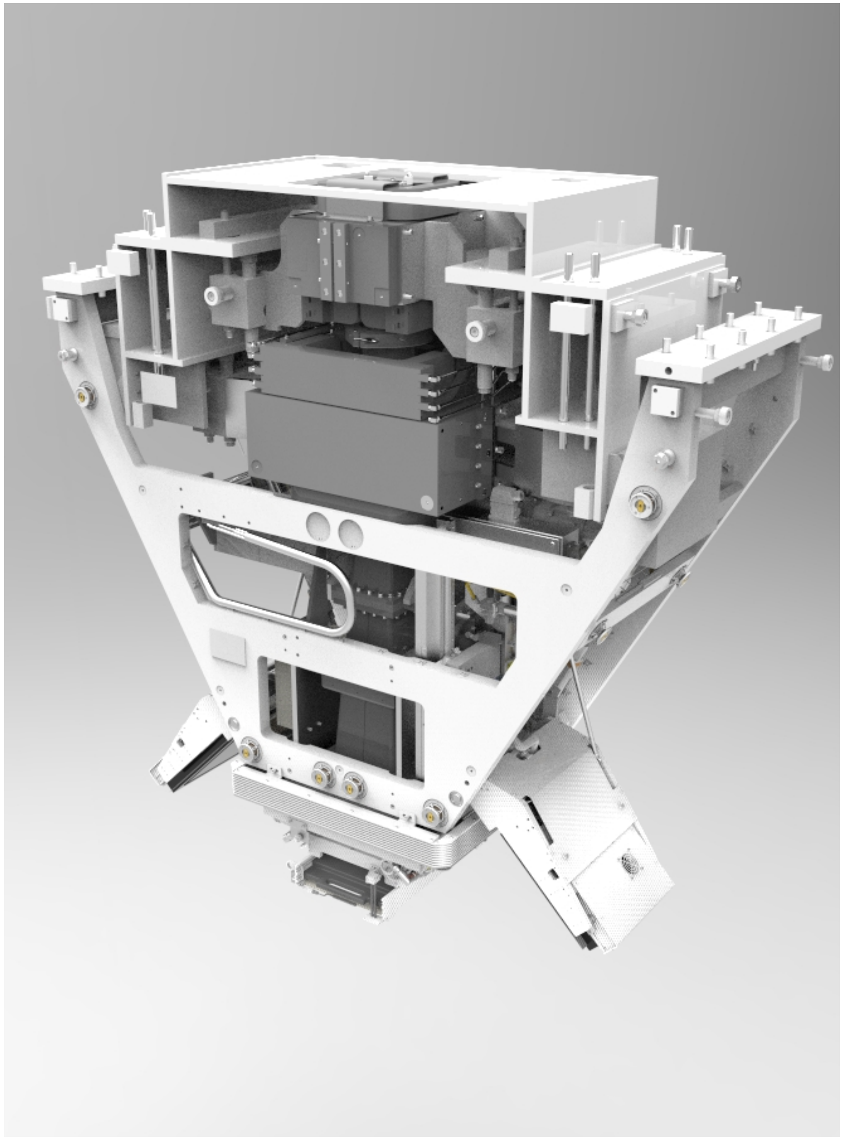


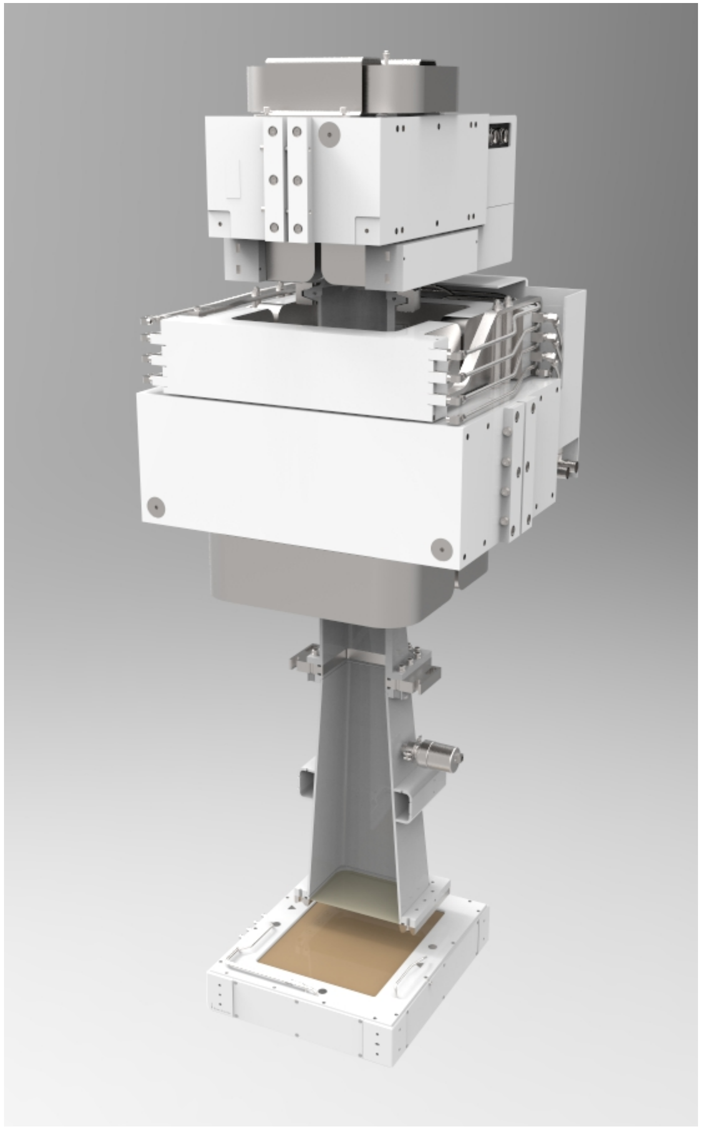
Hitachi Scanning Nozzle



Profile Monitor (PRM)	Parallel plate ionization chamber Wire pitch: 0.5 mm
Helium Chamber	Pressure: approx. 1 bar
1st Scanning Magnet	Scan in Y direction +/-15 cm at isocenter Scan velocity 6 m/s Water-cooled
2nd Scanning Magnet	Scan in X direction +/-15 cm at isocenter Scan velocity 6 m/s Water-cooled
Spot Position Monitor (SPM)	Parallel plate ionization chamber Wire pitch: 2 mm
Main Dose Monitor	Parallel plate ionization chamber Electrode gap: 2 mm
Sub Dose Monitor	Parallel plate ionization chamber Electrode gap: 2 mm

Varian Nozzle





Accelerator Diagnostics Or: what the hell is going on…?

Accelerator Diagnostics

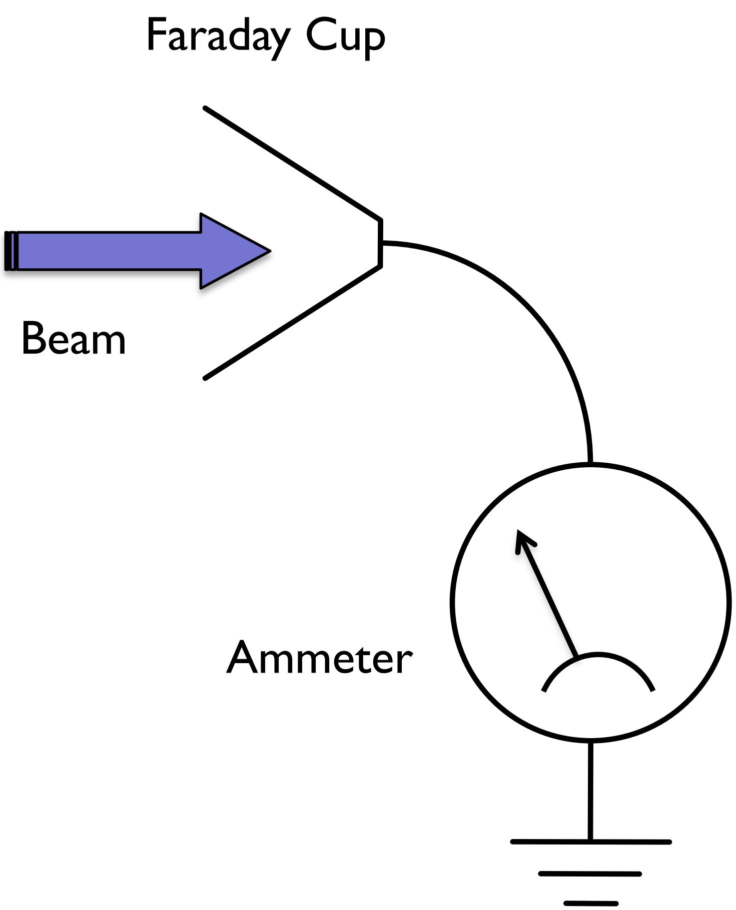
- Many different ways to measure all the parameters of the beam.
- What do we want to measure?
  - Beam Charge (and Current).
  - Beam Position (and Direction).
  - Beam Size (and Shape): transverse and longitudinal.
  - Emittance: transverse and longitudinal (energy).
- How can we make these measurements?
  - Destructive: beam does not survive measurement “undamaged”.
  - Non-destructive: beam parameters largely unaffected.
  - Ideally, all measurements would be non-destructive! Sadly, destructive measurements are usually better…

Beam Current Measurement

- Measurement of the beam charge/current is about the simplest you can make.
- Easy to make highly accurate measurements of beam charge, and non-invasive measurements that have a negligible effect on the beam.
- We will look at:
  - Destructive: Faraday Cup.
  - Non-destructive: Toroid (current transformer).

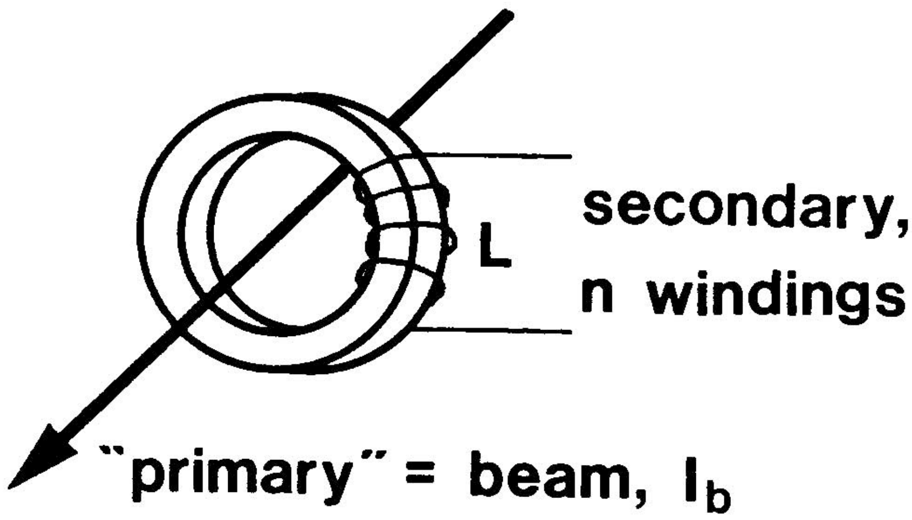
The Faraday Cup

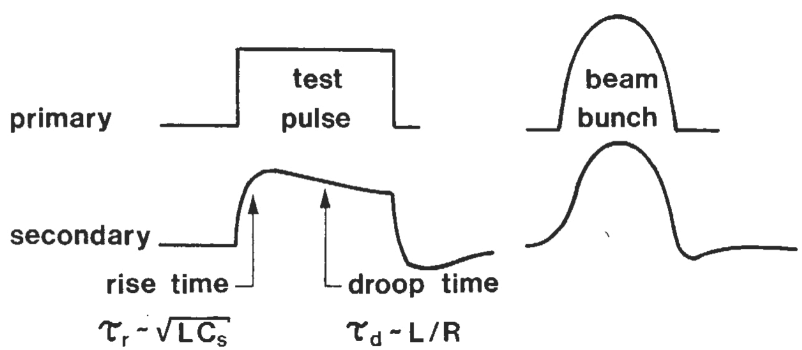
- Beam charge is absorbed by conducting collector.
- Charge drawn off cup and discharged to ground.
- Discharge current measured by ammeter.
- Very good measurement: absolutely linear measurement of beam charge & current.
- Current measurement limited by time resolution of system.
- Shortcomings:
  - Destructive.
  - Needs to be thick enough to stop beam (not good for high energies).
  - Might need cooling.
  - Need to collect secondaries (*eg*. electrons) to accurately measure all charge.



Toroids (Current Transformers)

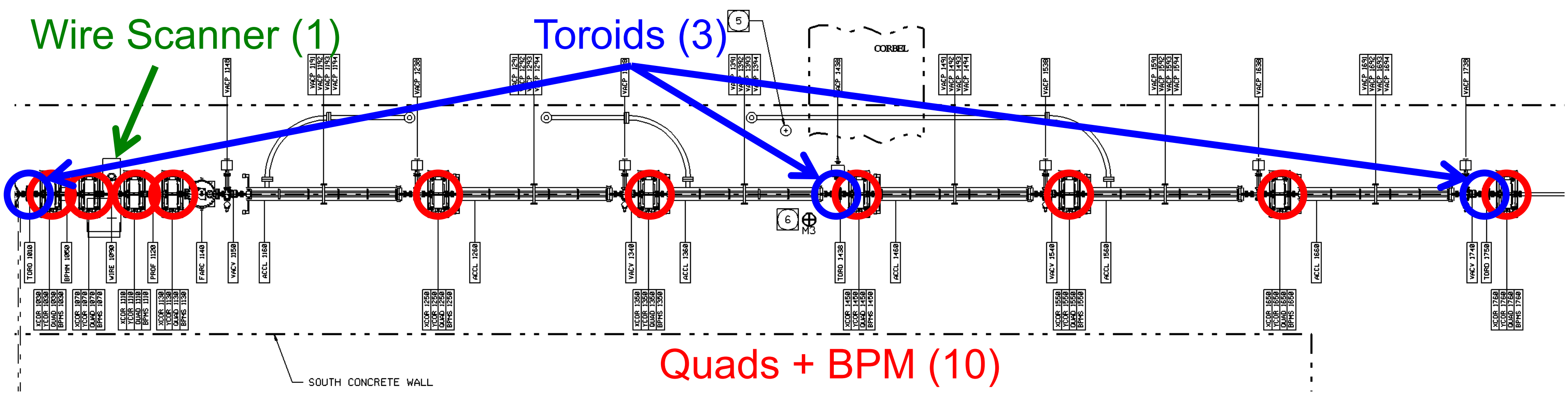
- Works like a transformer where the beam is the primary winding.
- B-field around beam couples inductively to toroid core and induces a current in the secondary windings.
- Iron core and secondary windings sit inside beampipe.
- Broadband more difficult than narrowband:
  - Inherently AC-coupled, so bandwidth defined by inductance.
  - Better for bunched beams, since you can tune resonance to bunch spacing.
  - To increase bandwidth, signal droop needs to be compensated for: either using driving amplifier or compensate after digitisation.
- See www.bergoz.com for more info and technical details.





Beam Position Monitors

- Beam position monitors (BPM’s) are the most common diagnostic used in accelerators.
- Normally installed at regular intervals along beamline eg. inside quads.
- 3 main types: cavities, buttons and striplines.



NLCTA (SLAC)

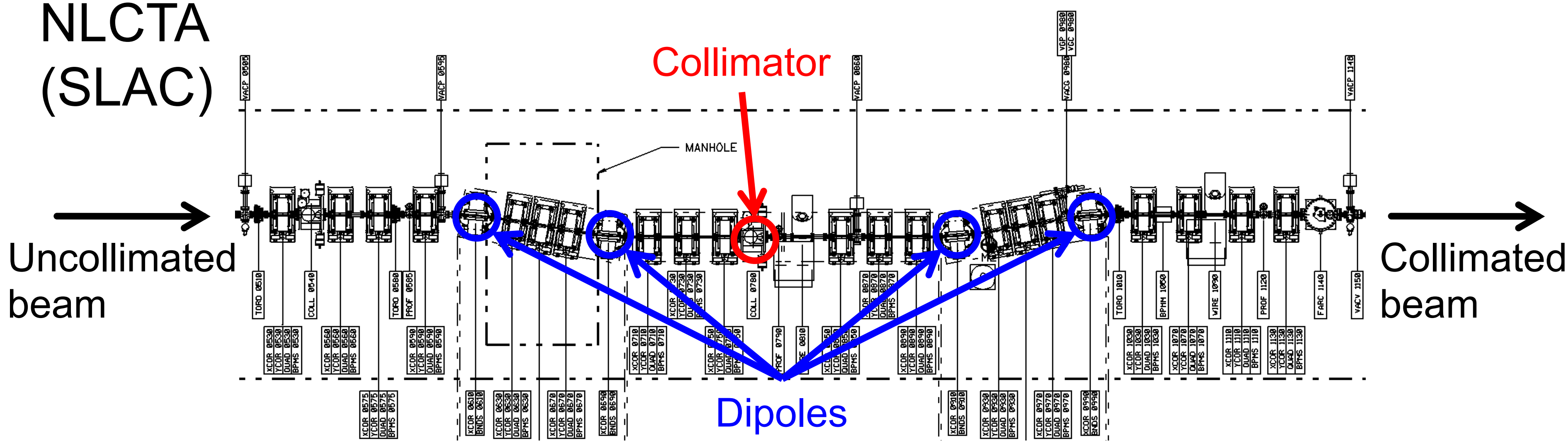
Energy Spectrometer

- Chicane used at NLCTA to measure beam energy.
- Chicane introduces dispersion into beam:

$$\Delta x = D_x \frac{\Delta p}{p}$$

- Beam centroid, as measured by BPM, gives energy.
- Collimator allows energy selection.

NLCTA (SLAC)

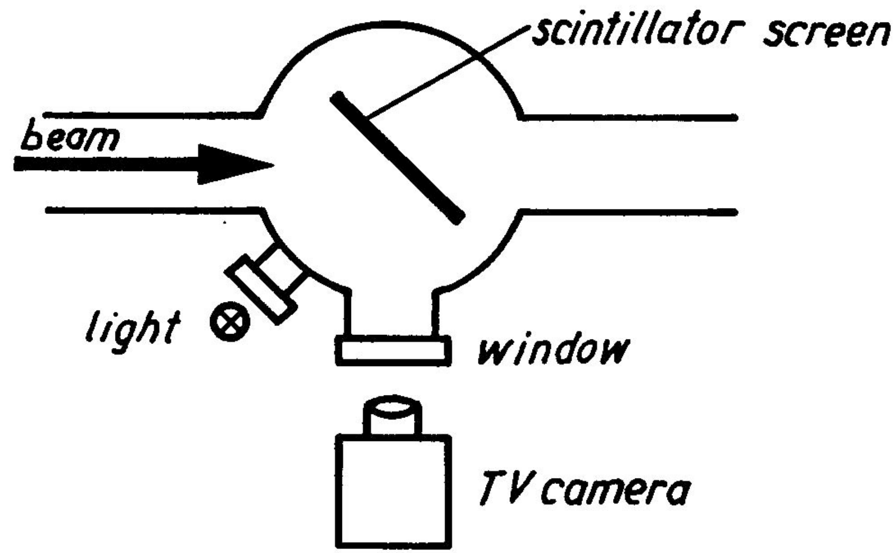


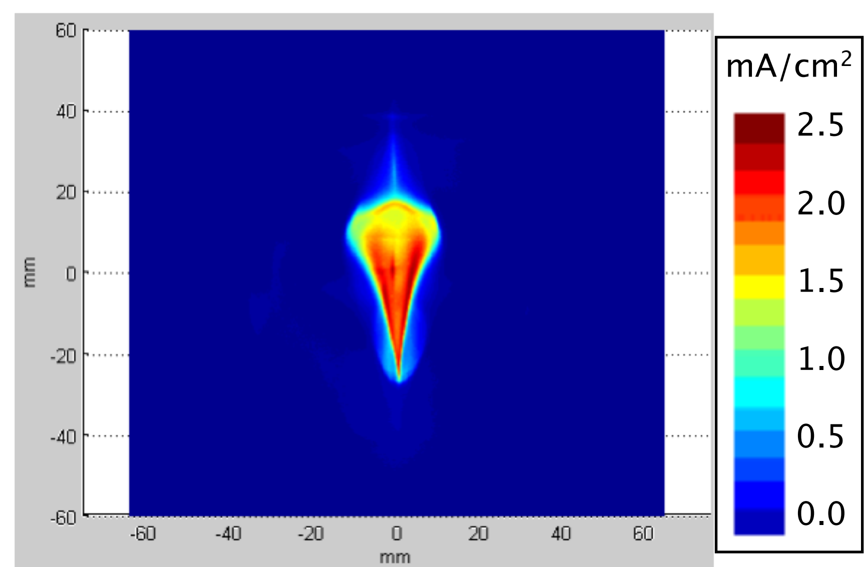
Beam Profile Measurements

- Beam profile measurements are conceptually the simplest measurements to make:
  - What is the beam size/shape at a given location?
- At first glance, this is easy: put a scintillating screen in the way of the beam and watch it glow…
- However, what happens if we want a non-destructive measurement…?
- As before, need to make a trade-off: more destructive measurements give more information.
  - Destructive: scintillators.
  - "Slightly" destructive (or non-non-destructive): wire scanner, ionisation chamber.
  - Non-destructive: Beam Induced Flourescence (BIF), laserwire.
- CERN, for example, use ALL of these at various stages in the LHC accelerator chain.

Scintillators

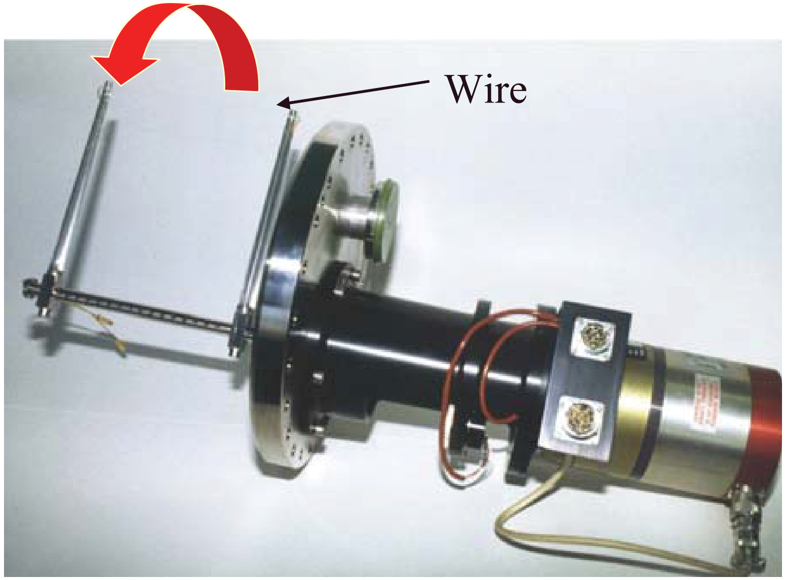
- Movable scintillator screen intercepts beam.
- CCD camera + intensifier mounted outside beampipe at 90° to image beam.
- Graticule marked on scintillator gives calibration.
- Cr-doped Al2O3 (ruby) common, but replaced by YAG:Ce and LYSO.
- Scintillator thickness means trade-off:
  - Fully absorbed beam means linear response: destructive (beam stop), scint burn-out.
  - Thin scintillator only absorbs fraction of beam energy: may be nonlinear, need to make assumptions about beam geometry.

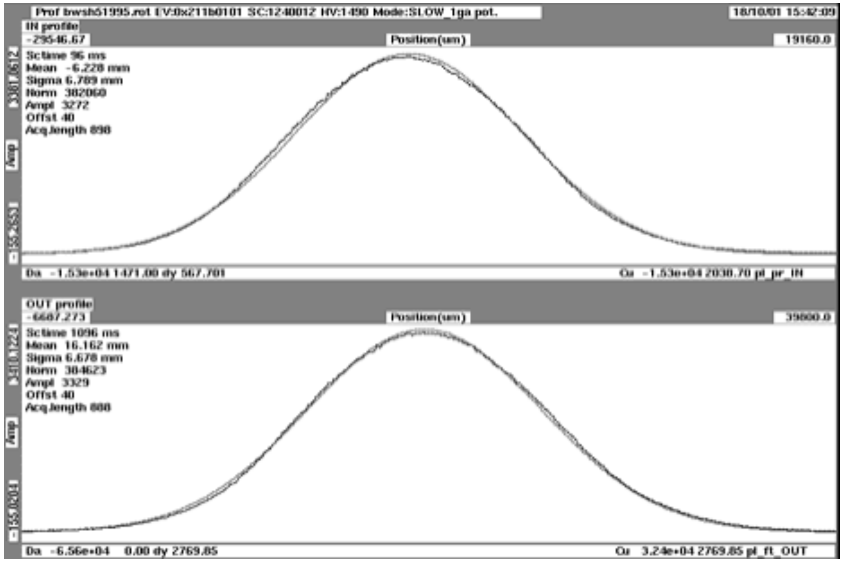




Wire Scanners

- Highly consistent method of measuring 1-D transverse beam profile: most common profile measurement method.
- Thin wire (some tens of microns in diameter) mounted on a fork that sweeps through the beam at high speed.
- Current produced by secondary emission of electrons within wire (like SEM grids): measure current as a function of wire position.
- For high current beams, measure flux of secondary particles created as the beam interacts with the wire (measured with radiation detector downstream of wire).





Ionisation Chamber

- Very simple "particle counting" detector.
- Detector filled with gas between anode/cathode plates.
- Charged particle creates electron-hole pairs which drift towards anode/cathode: count electrons to measure number of particles.
- If you make *both* plates cathodes you can string anode wires in the gap:
  - Electrons pulled to nearest wire.
  - Gives 1-D profile measurement from amount of charge collected on each wire.