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Beam Diagnostics I

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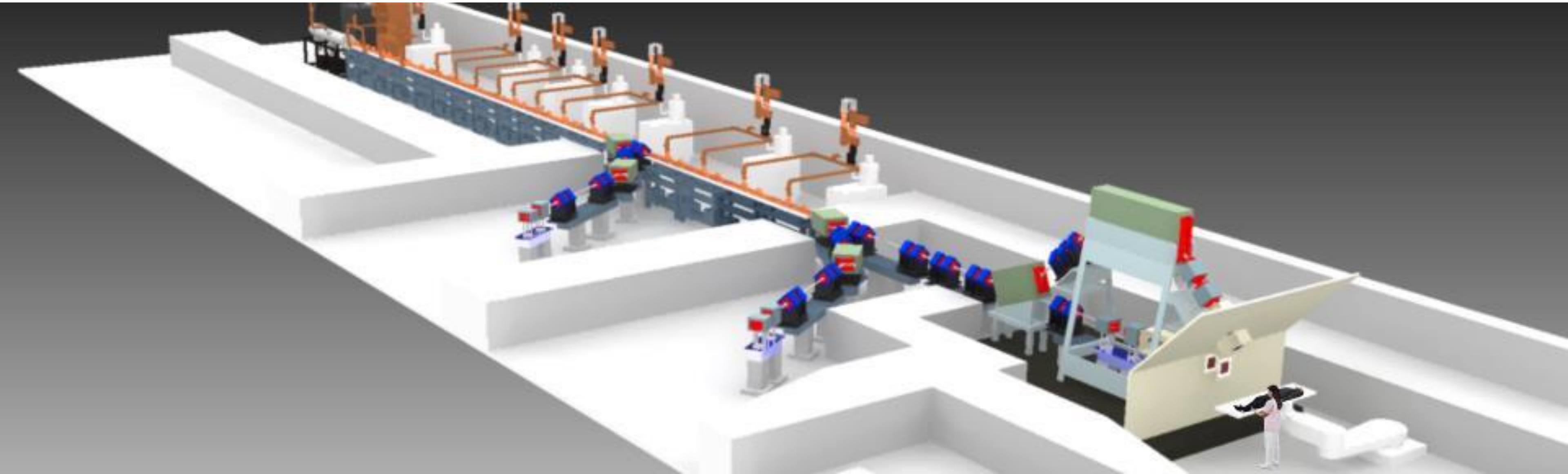

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What is 'Beam Diagnostics'?

- Beam Instrumentation is the 'eyes and ears' of the operators.
- Modern accelerators have thousands of controls. They can't be tuned by trial and error!
- A wide range of instruments are needed to measure different beam properties.

What is ‘Beam Diagnostics’?

- Beam Diagnostics is used in three main ways:

- **Commissioning**
  - When you build an accelerator you need to find settings
  - And fix mistakes…

- **Quality Assurance**
  - Periodically check that the accelerator is performing well

- **Troubleshooting**
  - If there is a problem, we need to identify the source as quickly as possible

…and what it isn't

It has nothing to do with diagnosing the patient…

…does not include radiation monitoring…

…and is generally separate from the 'nozzle' or Beam Delivery System:

What makes a 'good' instrument?

- Instruments have different requirements depending on the beam to be measured and the purpose of the measurement
- Some **figures of merit** which are often useful:
  - **Sensitivity:** how small a signal can be measured?
  - **Accuracy:** how close is the reading to the true value?
  - **Resolution:** what is the smallest change which can be measured?
  - **Dynamic Range:** the ratio between the largest and smallest signals that can be measured.
  - **Measurement speed:** how long does it take to make a measurement?
  - Is the instrument **Destructive** i.e. is the beam still useable afterwards?
  - **Reliability:** the instrument should be 100% available and not give false alarms
  - Is the instrument easy to **calibrate**? Is the calibration stable?

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- Instrumentation physicists have to make a **compromise** between these qualities and other limits (cost, space).
- We might have more than one instrument to measure the same property.

Beam Current

- We want to know **how much** beam we have.
- This is called the beam **intensity** or beam **current**
- Integrating over time gives us the beam **charge**

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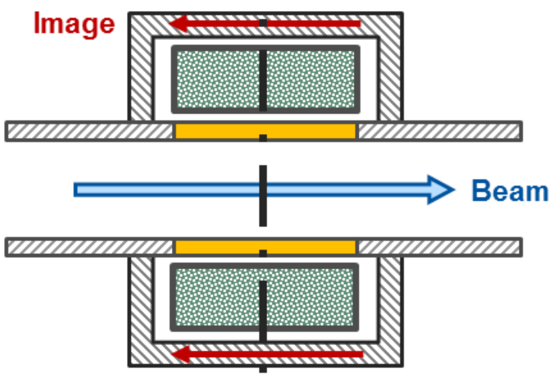
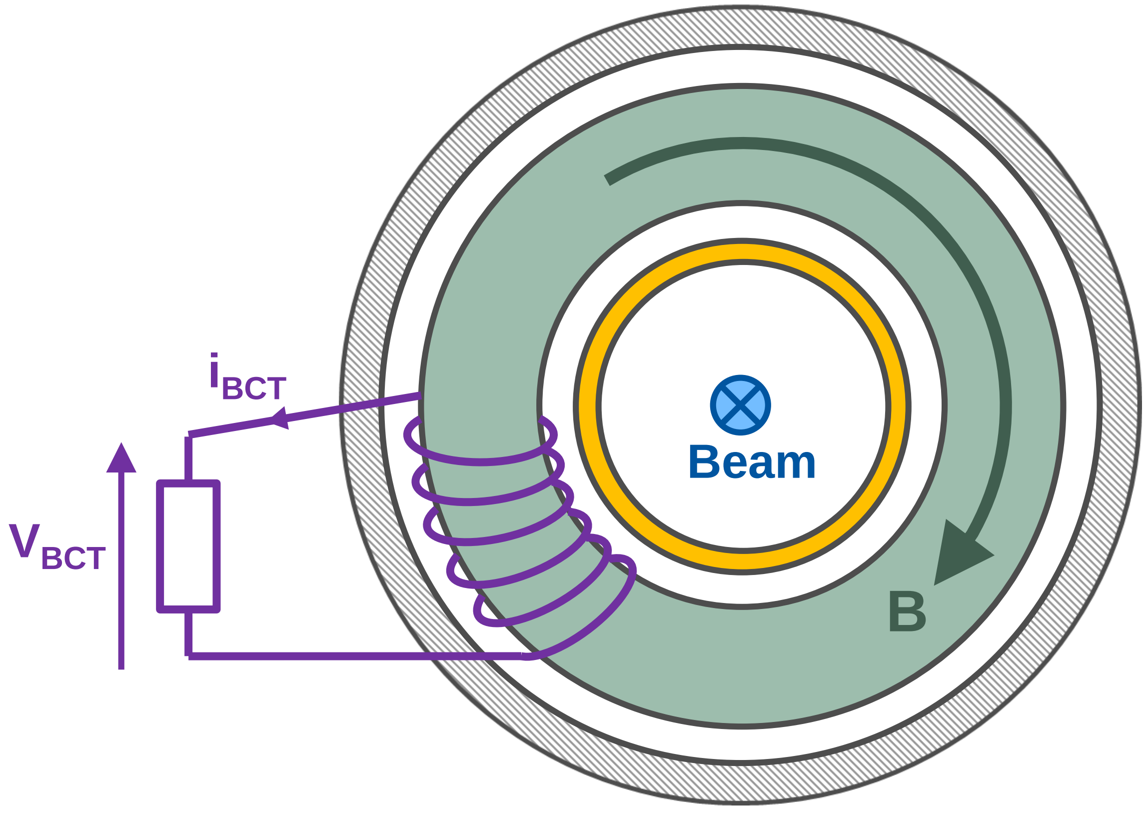
1. Faraday Cup

- The most direct way to measure the beam current: Let the beam hit a conducting block and measure the current flowing to earth.
- Block shaped like a cup to stop particles ‘bouncing off’.
- Use a high-voltage repeller to stop secondary electrons escaping
- Destructive measurement.

2. AC beam transformer

- Measure the beam’s magnetic field using the current it induces in a magnetic core
- Needs to be shielded from EM interference





- Use **two** transformers
- Driving coils excited by **equal and opposite** signals
- No net magnetic field if no beam current
- The coils are driven into **saturation**.
- If there is a beam current, one coil goes into saturation more than the other. This gives a measurable net signal.

3. DC beam transformer

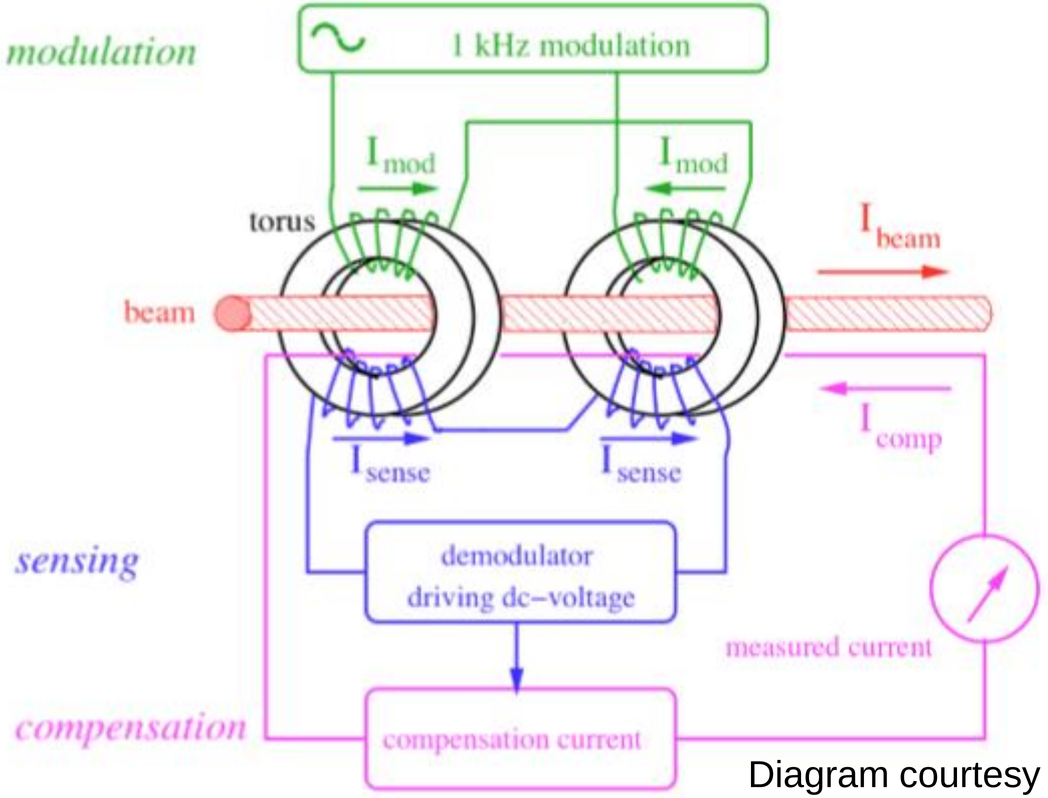


Diagram courtesy of P. Forck

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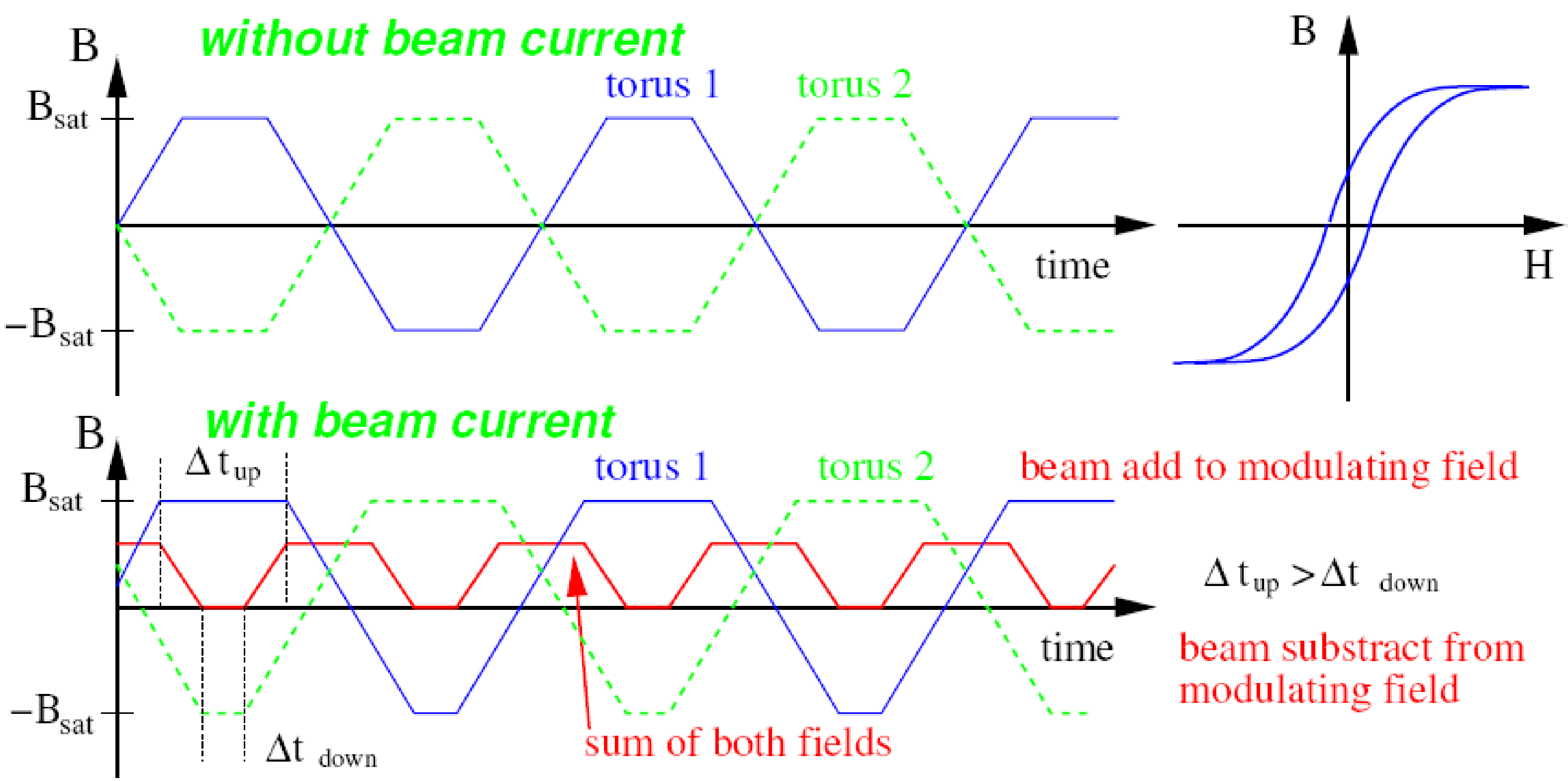
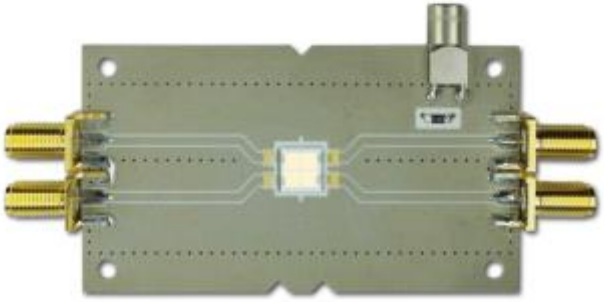


4. ‘Semi-Interceptive’ instruments

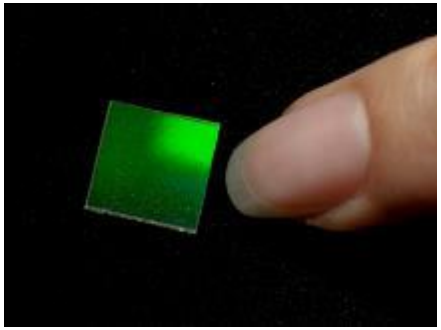
- Instruments can be inserted into the beam path during treatment if their effect is sufficiently small
- Must be **very thin** and use **low-Z** materials
  - typically few hundred µm water equivalent in beam path
- More scattering can be accepted closer to isocenter

Ionisation Chamber

Diamond or silicon

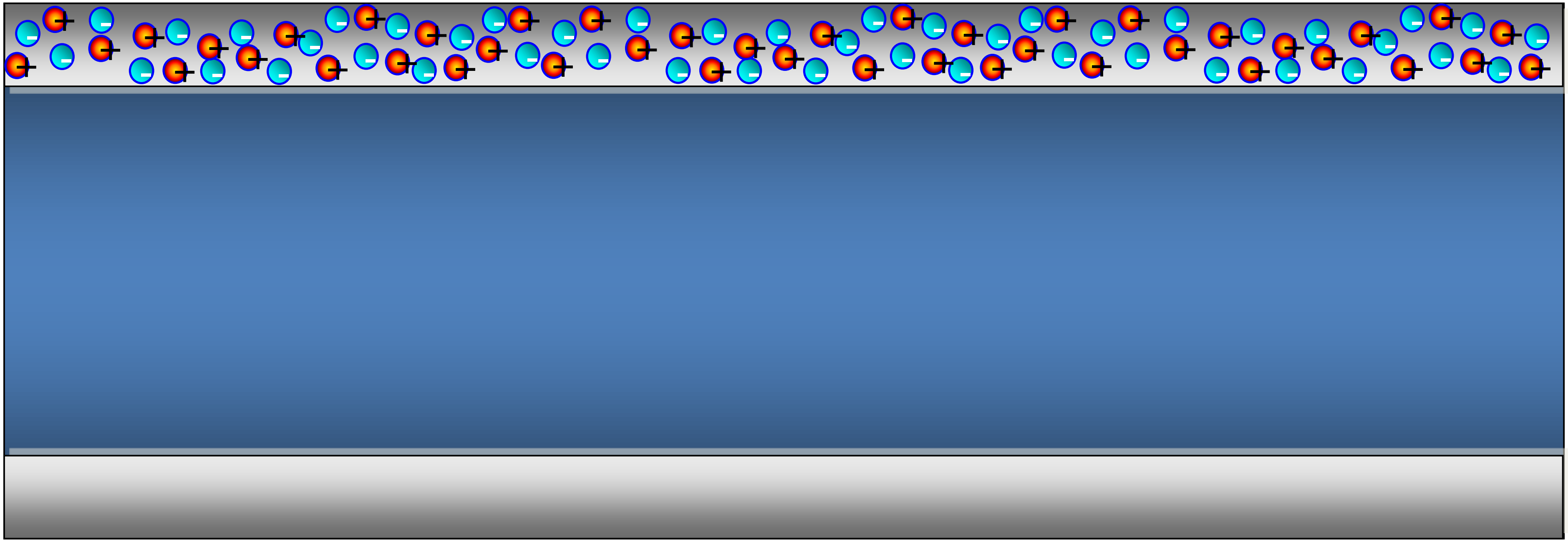


Scintillator

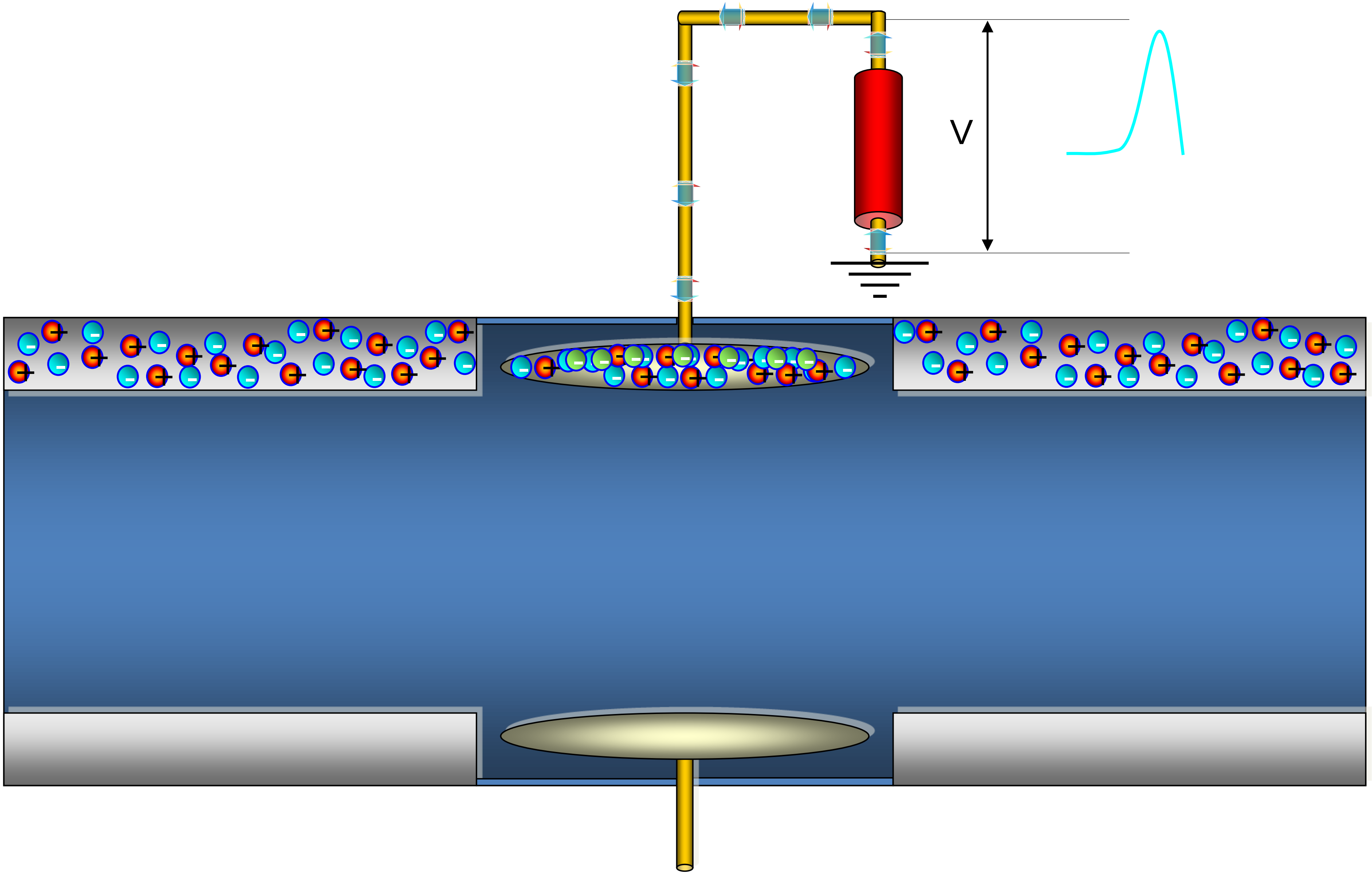


Beam Position

- Since the beam is charged, it has an electric field.
- The electric field affects the beam pipe.
- The beam pipe is a conductor – free electrons can be pushed around by the beam's electric field

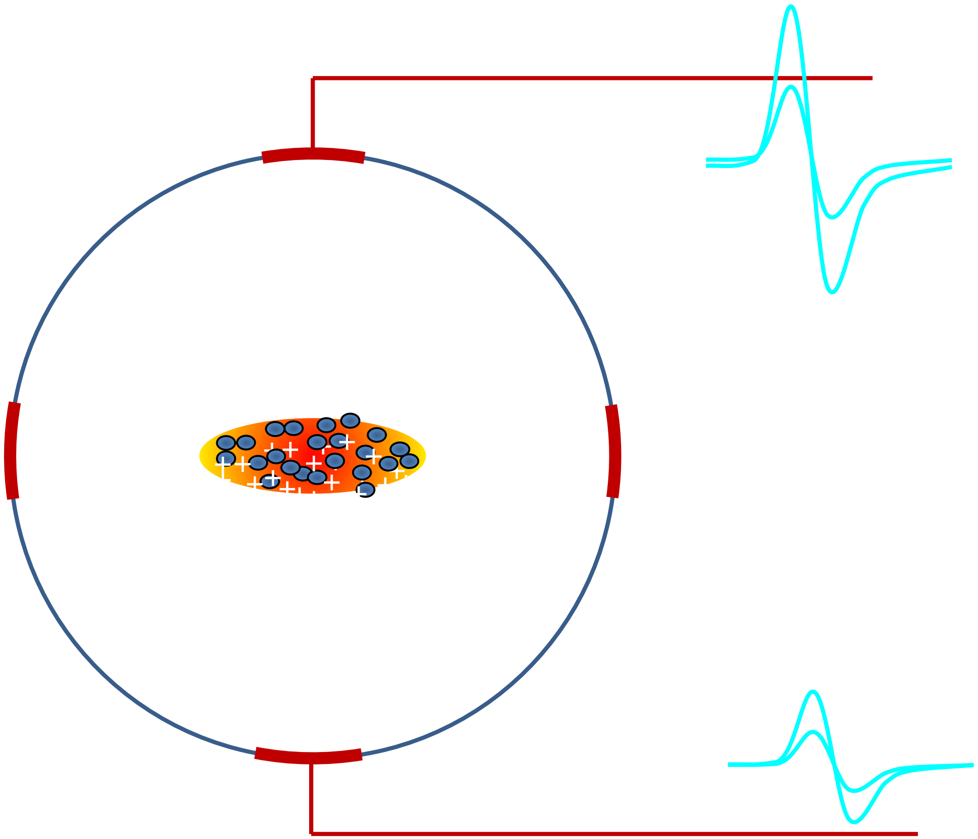


Beam Position



Beam Position

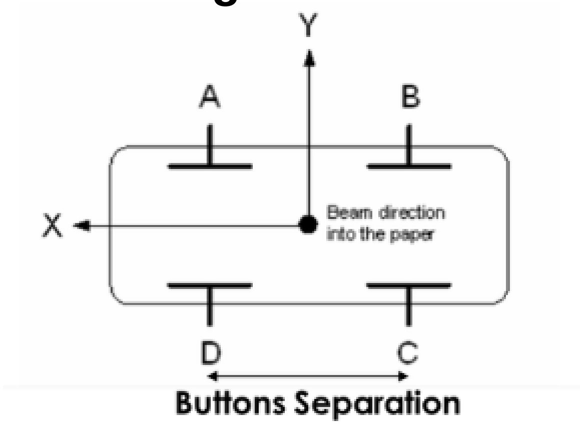
- The pick-up will generate a larger signal if it is closer to the beam.
- So having several pick-ups arranged around the beam pipe will let us determine the beam position.
- We look at the **sum** and the **difference** of opposite pick-ups, to get a position measurement that is independent of the beam intensity.



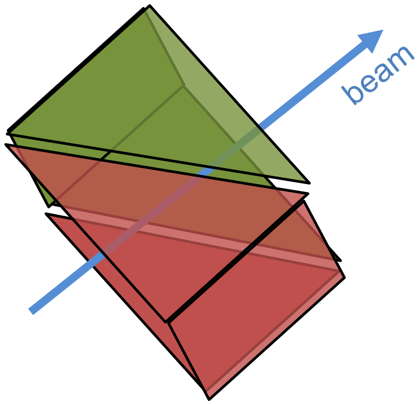
- Different pick-up geometries exist

Button BPM

Diagonal BPM



Shoebox BPM



- Signals are generally small so read-out electronics must be carefully thought out to reduce noise.
- We want to know $\frac{A-C}{A+C}$: Quantisation error can be an issue
- Beam position in a cyclotron is more complicated (overlapping turns)

Beam Energy

- The depth of the Bragg peak depends on the beam energy
- We have to know the energy if we want to treat the right bit of the patient

There are two approaches to beam energy in hadron therapy:

- Produce beam at a fixed (maximum) energy and then reduce it as required by inserting material in the beam path

or

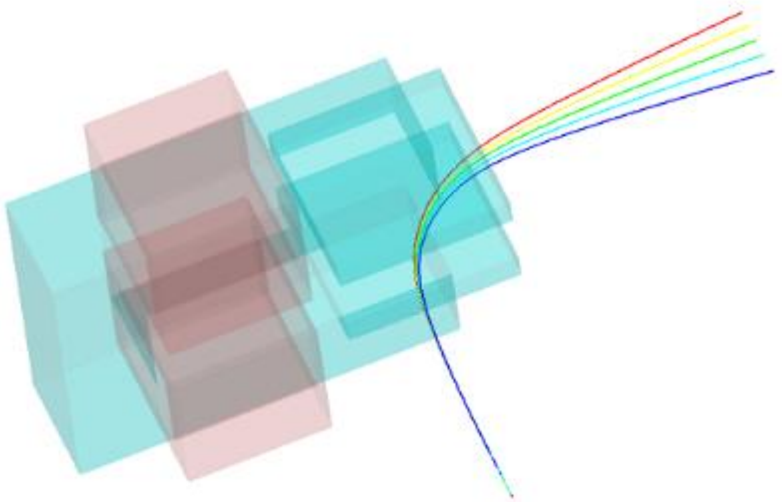
- Change the energy of the beam from one shot to the next

1. Spectrometer

- It is known that the bending radius of a charged particle depends on momentum:

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

- If your accelerator is circular you get ρ for free
- If not you need to build a spectrometer



- Pass the beam through a strong bending magnet.
- Measure trajectory using BPMs
- Particles with **higher** energy are bent **less** and vice versa.

2. Time-of-Flight

- Simply measure the speed of the particles by timing them between two points.
- Three regimes depending on energy range:

‘non-relativistic’ $ke = \frac{1}{2}mv^2$ ← Not many accelerators in this regime…

‘relativistic’ $ke = E_0 \frac{1}{\sqrt{1 - v^2/c^2}}$

‘ultra-relativistic’ $v \approx c$ ← TOF not useful here…

- Time of flight of a 230 MeV proton over a 5m baseline is 28ns
- Need ~picosecond timing for ~100keV energy resolution

Conclusion

- The perfect instrument hasn’t been invented yet
- Beam diagnostics is the art of finding the best compromise for each property you want to measure

- Beam Diagnostics costs money and takes up accelerator space…
- … but running an accelerator without them would be like designing a car without a windscreen.

Thanks for your Attention