Beam Diagnostics

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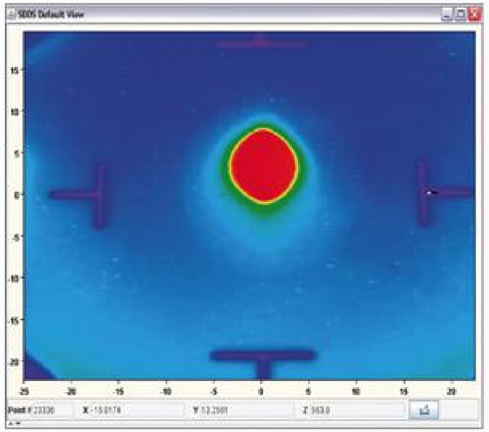
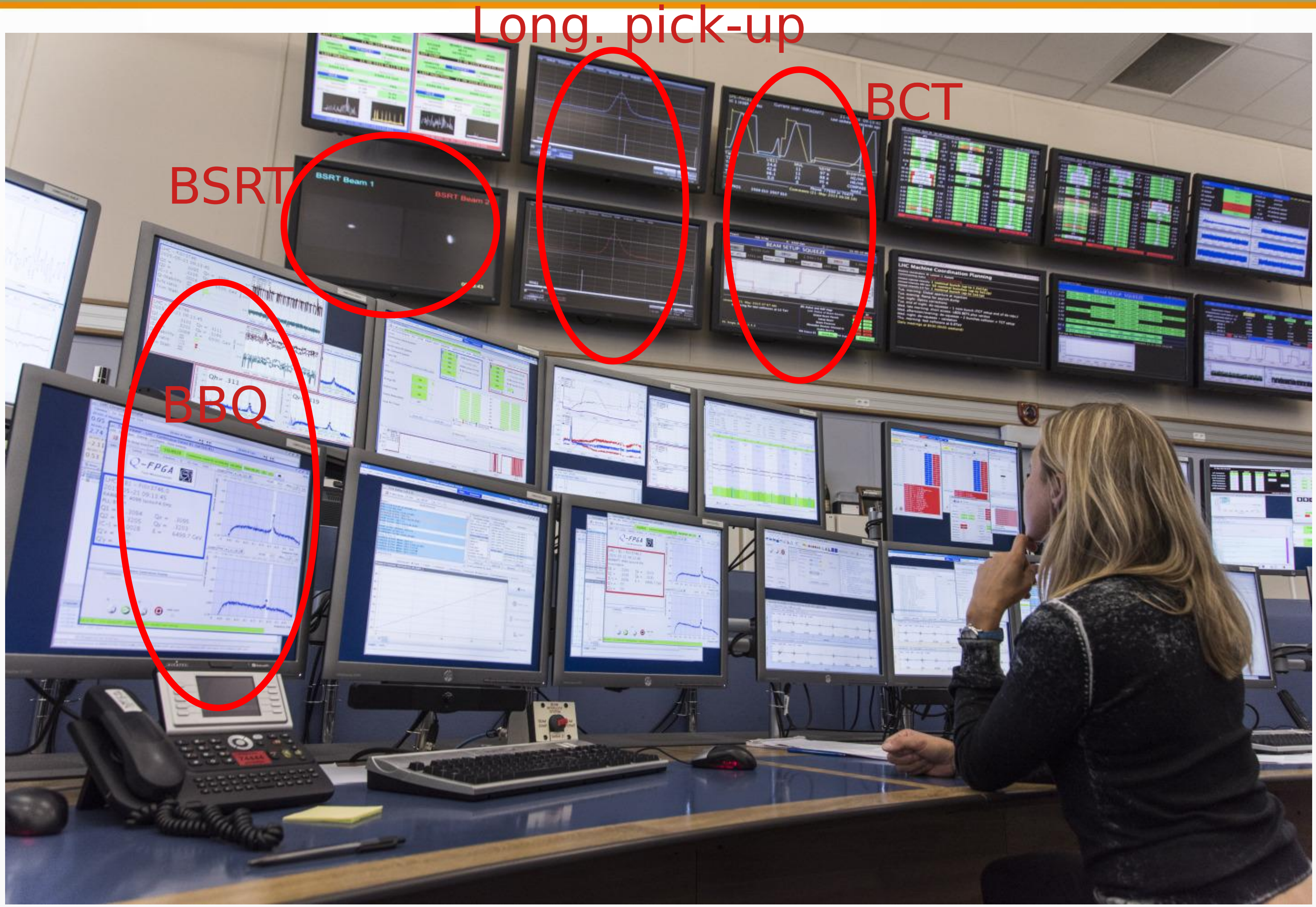
What is beam diagnostics?



Scintillating screen in LHC: first turn diagnostic

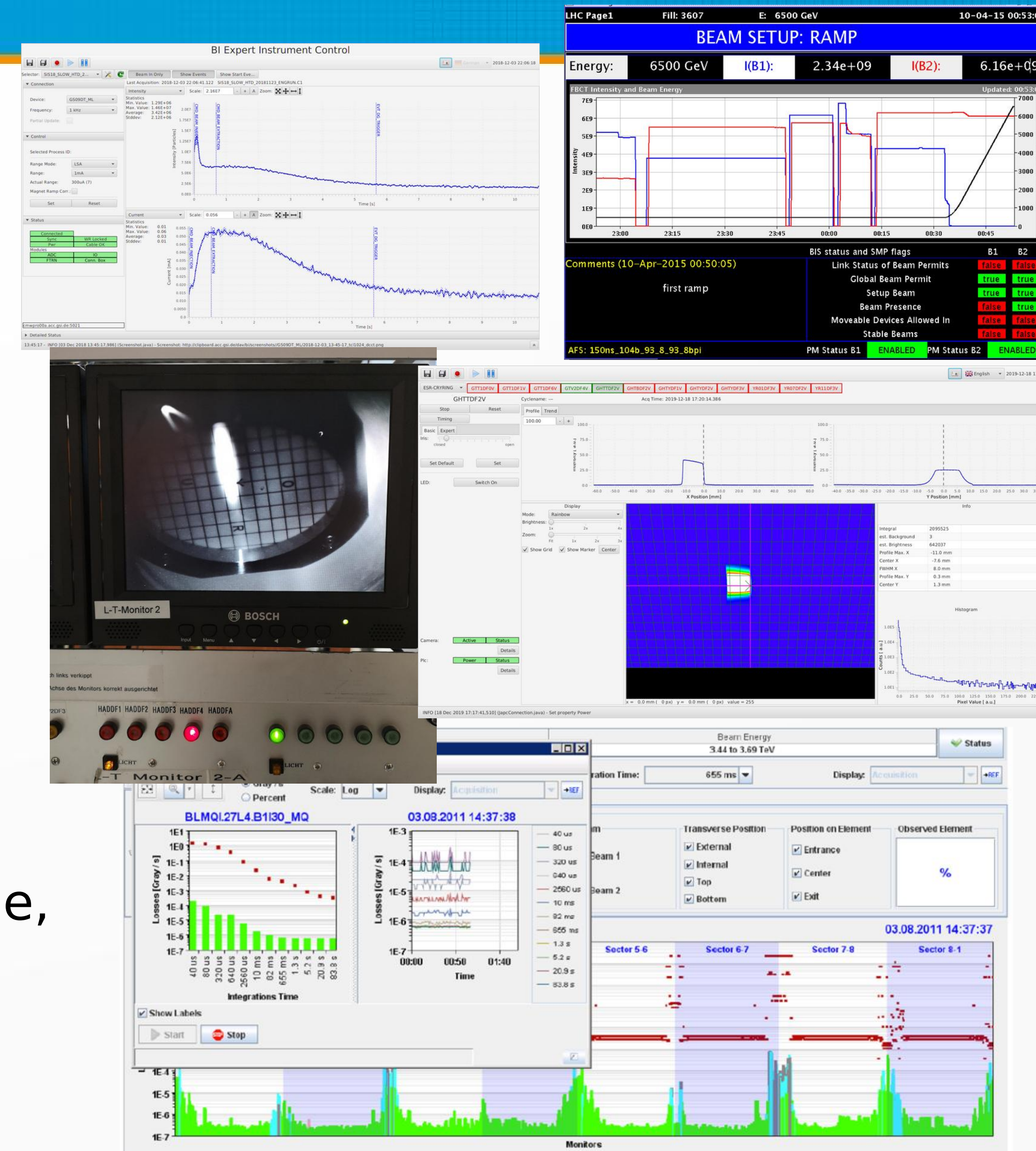
- Let's assume we have this fantastic accelerator, how do we know if it works?
- Does it even produce a beam? Does the beam has right parameters?
- And if, during the operation, the beam suddenly disappears, how do we find out what happened? Is it lost somewhere?
- To answer all these questions you need to measure the beam! And this is a field of beam instrumentation (also called diagnostics).
- Diagnostics is art of seeing!
- Here I will focus on the most important measurements; you need much more to operate particle therapy system.

Control Room



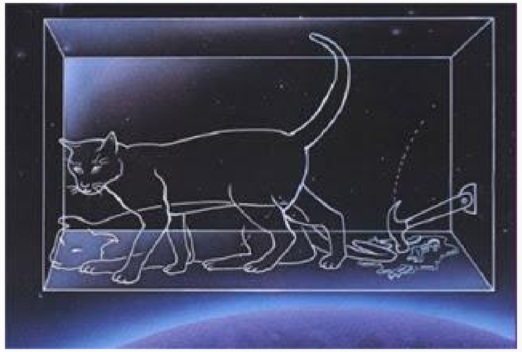
What to measure?

- Beam current.
- Beam position (is beam in the center? is it moving during acceleration?).
- Beam emittance.
- Beam losses.
- Energy, Δp/p.
- Synchrotron: tune, chromaticity.
- Longitudinal profile.
- Other: beam halo, spill structure, divergence, optics errors, orbit feedback scrapers, particle and rigidity selection...



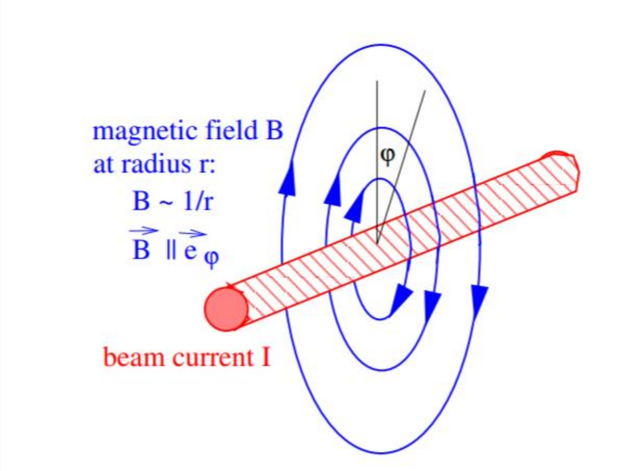
Measurement

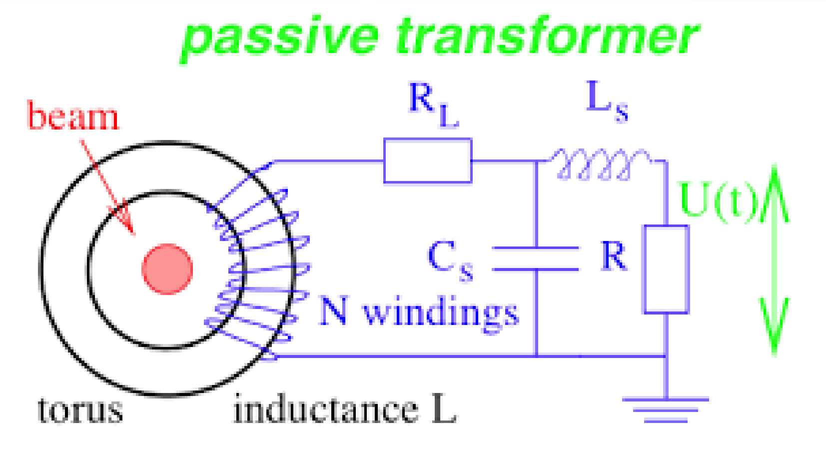
- As far as quantum mechanics is concerned every measurement disturbs the measured system (opening the box kills the cat).
- However for us, if perturbation is very small with respect to particle movement, we say that measurement is not invasive (or non-destructive).
- The main phenomena used in beam measurements:
  - **Electromagnetic induction**
  - **Secondary Electron Emission** (SEM)
  - **Ionization of gases (or solids)**



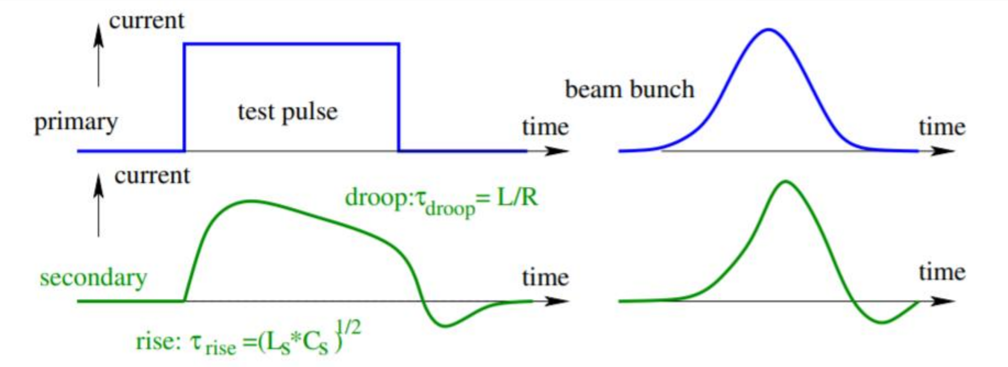
Beam current

- How do we measure current? Good method is induction!
- Such a device is called Beam Current Transformer (BCT).



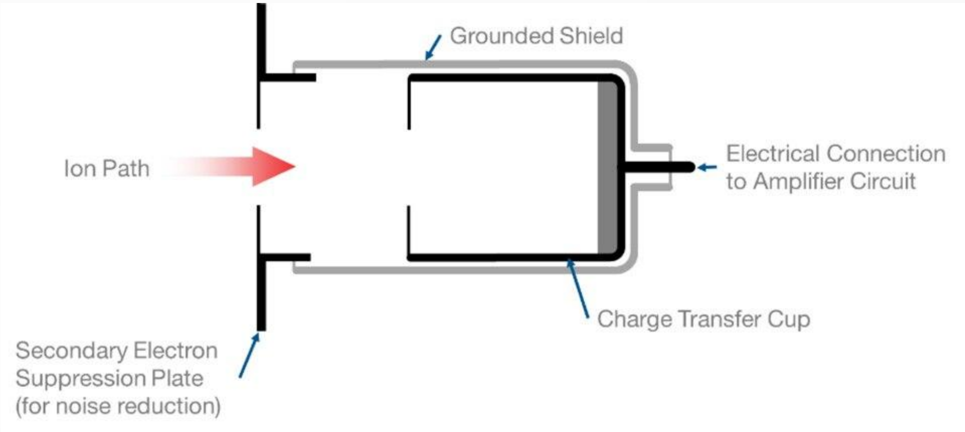


- This way we can measure pulsed beams.
- Nondestructive measurement!



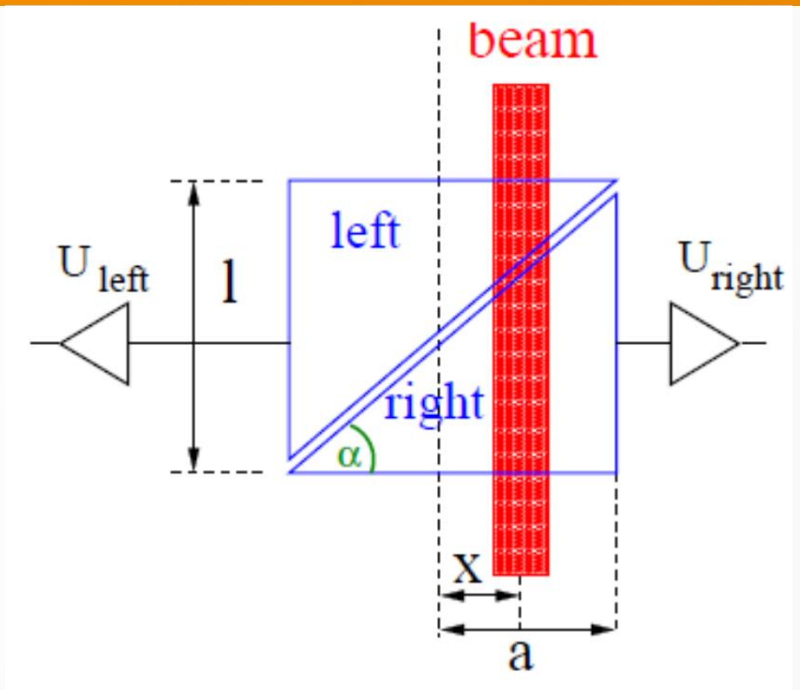
Beam current (II)

- Several versions of Beam Current Transformers exists:
  - Passive transformer – fast but poor sensitivity (~10 μA).
  - Active transformer – sensitive (~0.1 μA), but not so fast.
  - Direct Current (DCCT) – sensitivity ~ 100 μA.
- Another popular way to measure beam current is Faraday cup:
  - Collects beam particles, measures their charge.
  - Sensitivity in range of nA.
  - Destructive measurement.
  - Used up to several MeV/u.

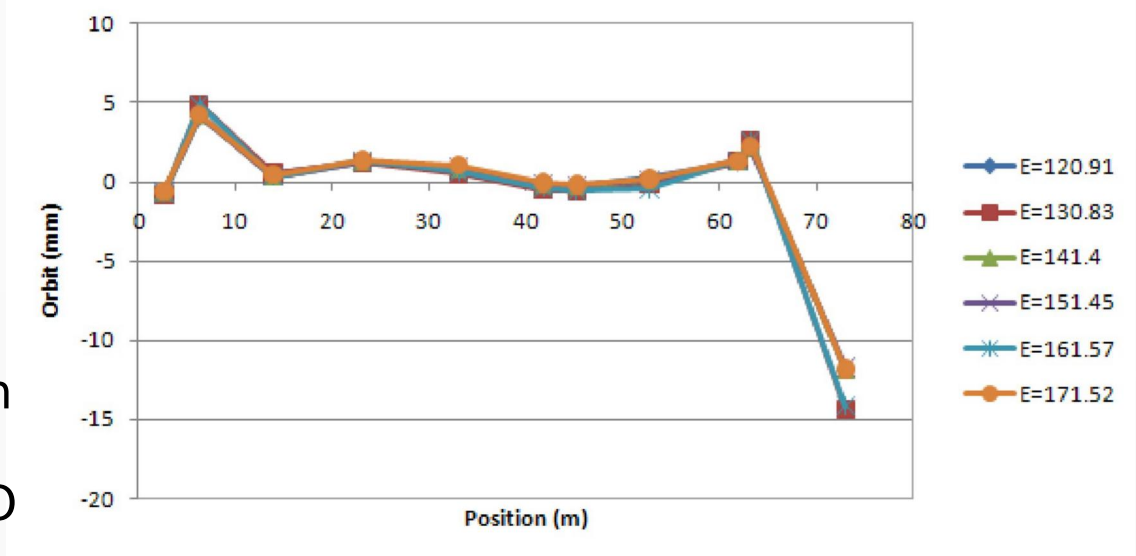


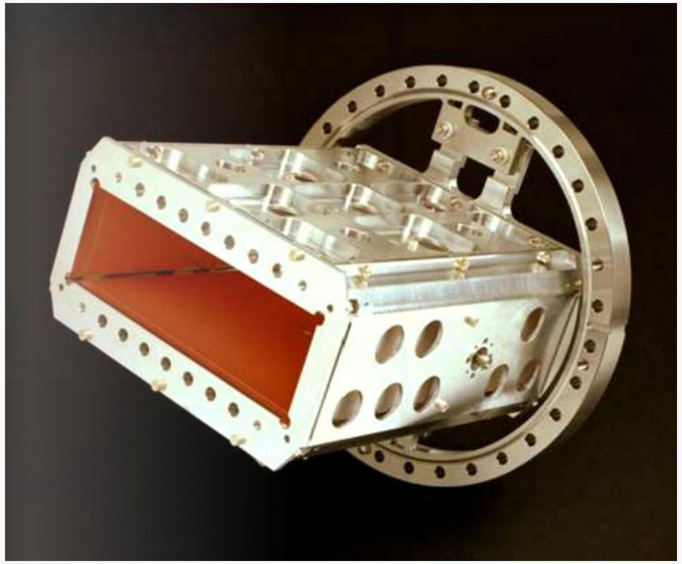
Beam position

- Beam Position Monitor uses signals from 2 antennas (pick-ups) placed on opposite side of the beam.
- Difference of the measured voltages is depends (linearly) on beam position.
- Accuracy ~ 0.1 mm.



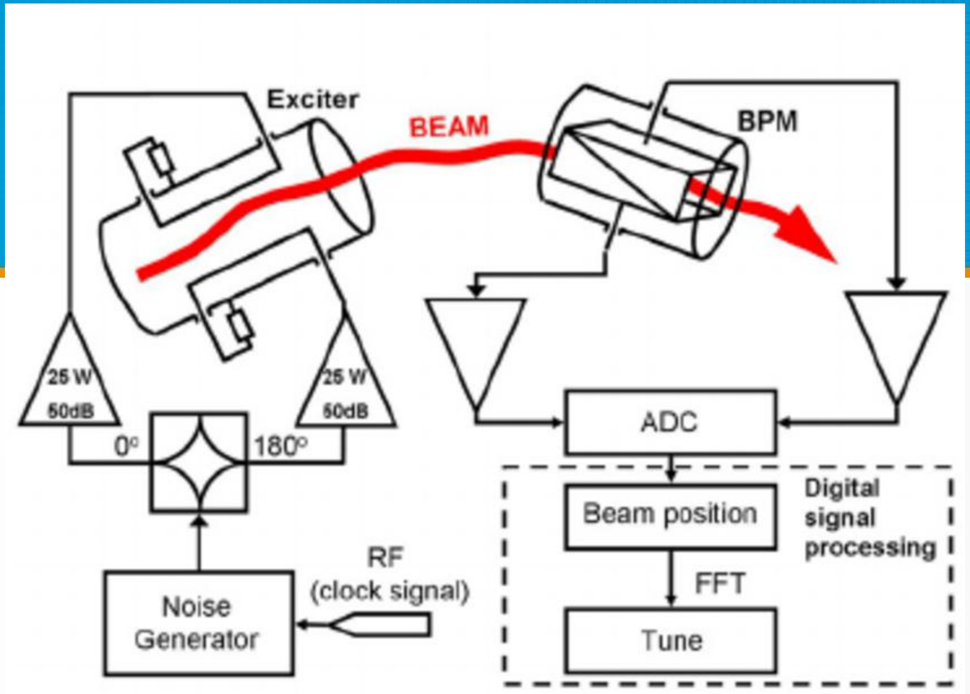
Beam orbit in synchrotron, source: CNAO

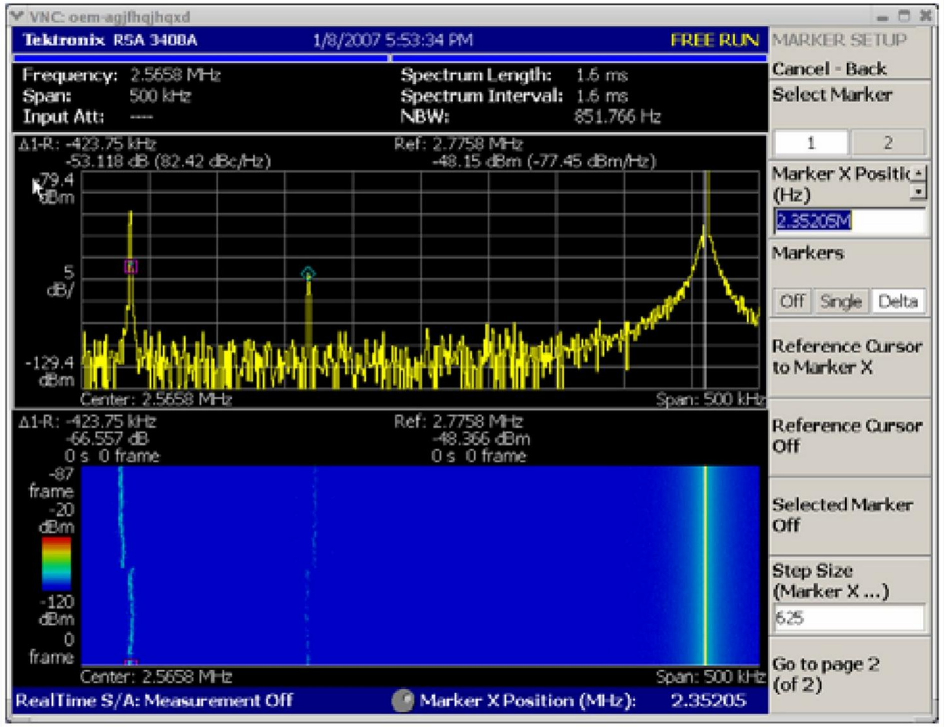


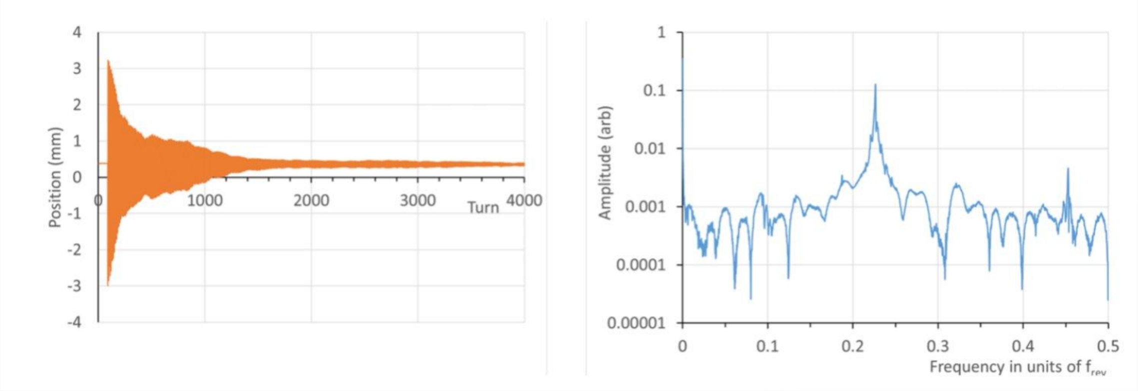


Tune

- Tune measurement a particular oscillation frequency of the beam in a synchrotron.
- Frequency is measured by converting time-series to frequency spectra using Fourier Transform.
- In order to get the enough signal the beam is often excited using fast kicker.
- A commercial spectrum analyzer can be used for signal processing.





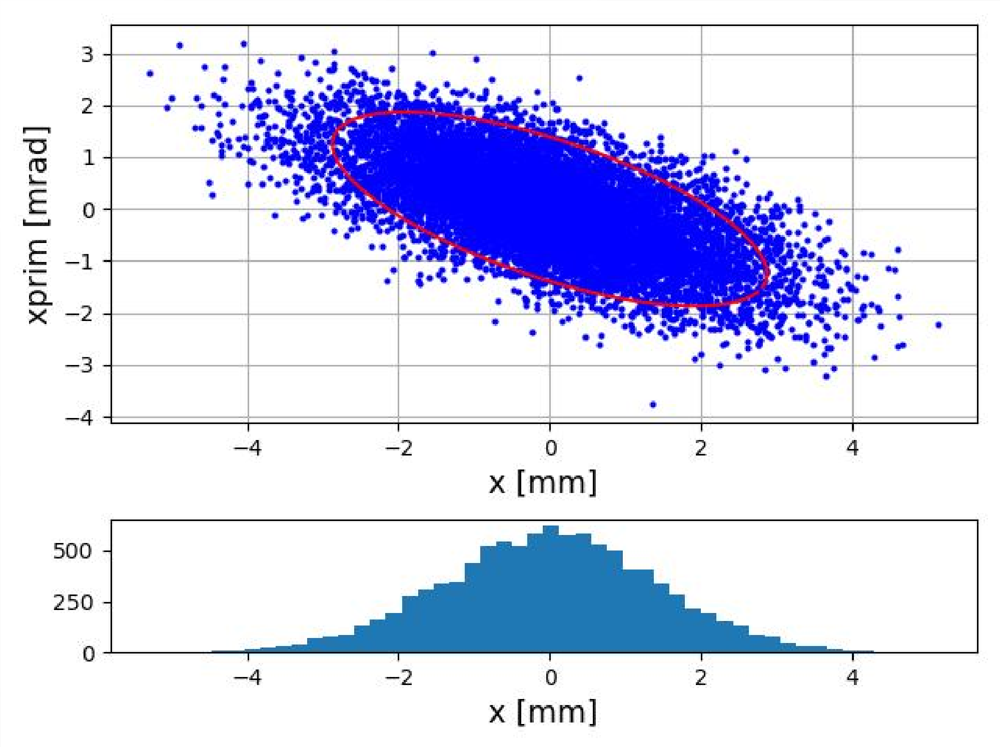


Beam emittance (I)

- Transverse emittance is a volume of the transverse phase space occupied by beam particles.
- In case of regular, gaussian beams it can be reconstructed from beam size and Twiss beta function:

$$\sigma = \sqrt{\beta\varepsilon + D^2(\frac{\Delta p}{p})^2}$$

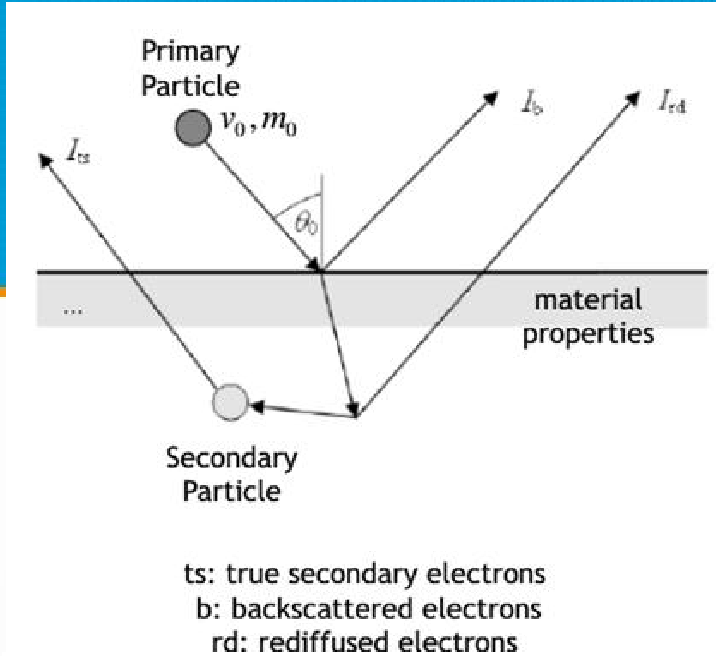
- It is good to measure in dispersion-free region.

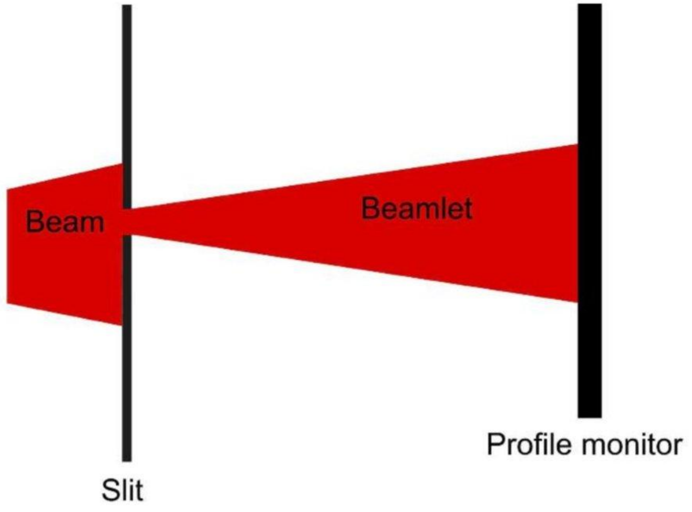


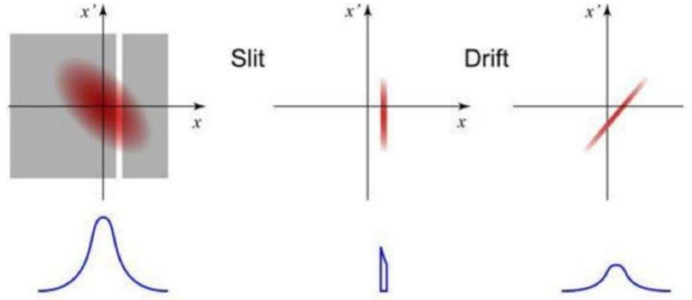
Recap: emittance shrinks with beam energy

Emittance at low energies: nongaussian beams

- Secondary Emission (SEM) is emission of low energy electrons from metallic surfaces.
- It is a surface phenomena, electrons are emitted from the 10 nm layer of the metal ('skin effect').
- Number of emitted electrons (so current) is proportional to beam intensity.
- Slit is used to select an investigated part of the beam profile – for each slit position we measure beamlet (part of the beam) divergence.
- It is called slit-grid system.
- Measurement is destructive.

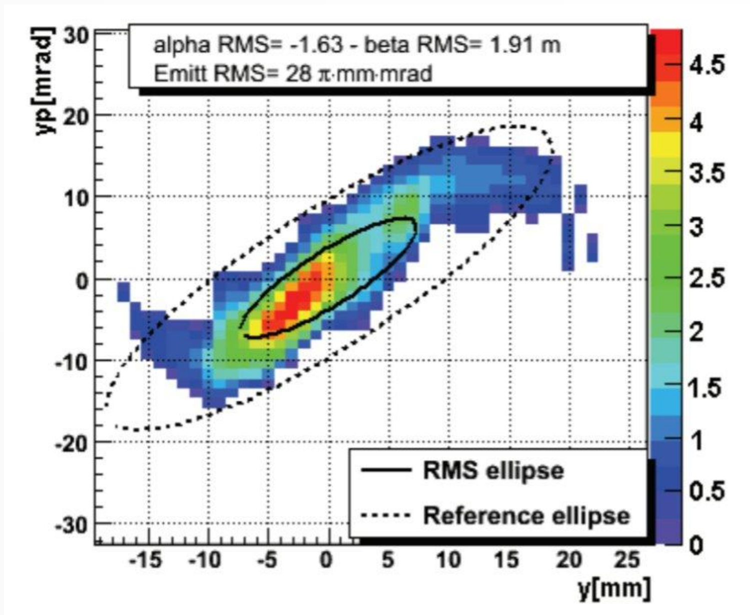




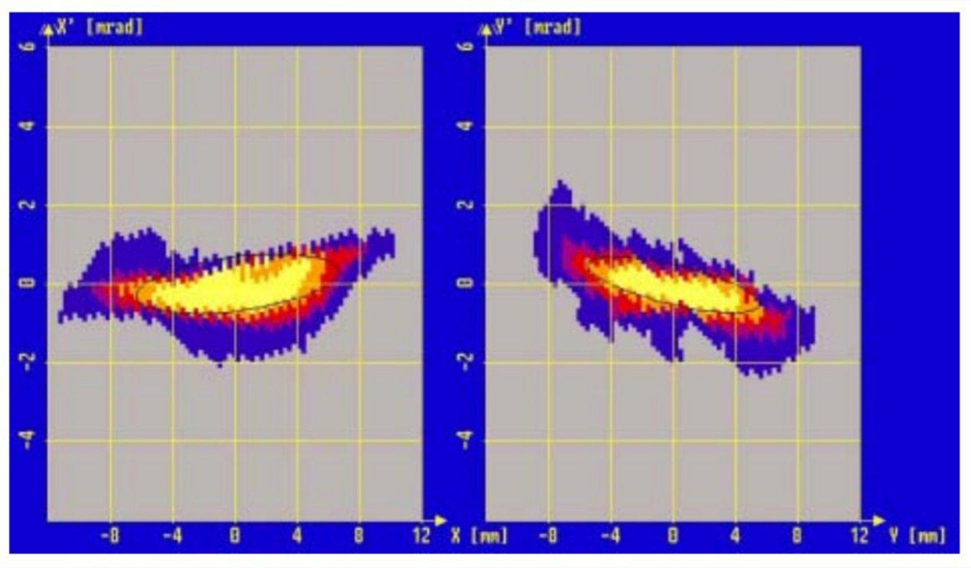


Emittance at low energies: nongaussian beams

- Examples



CNAO, after source

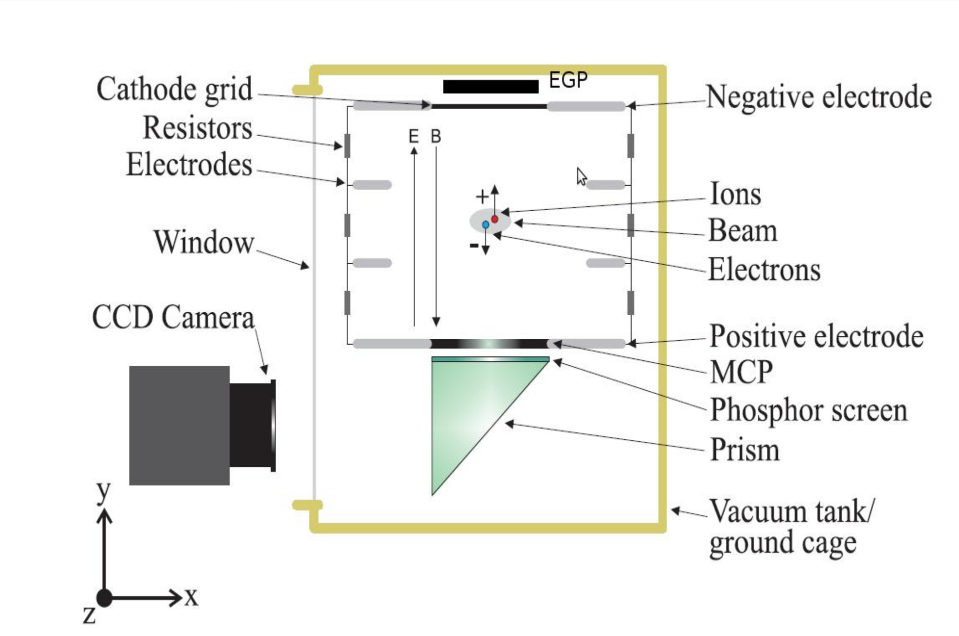


GSI, UNILAC, U@11 MeV/u

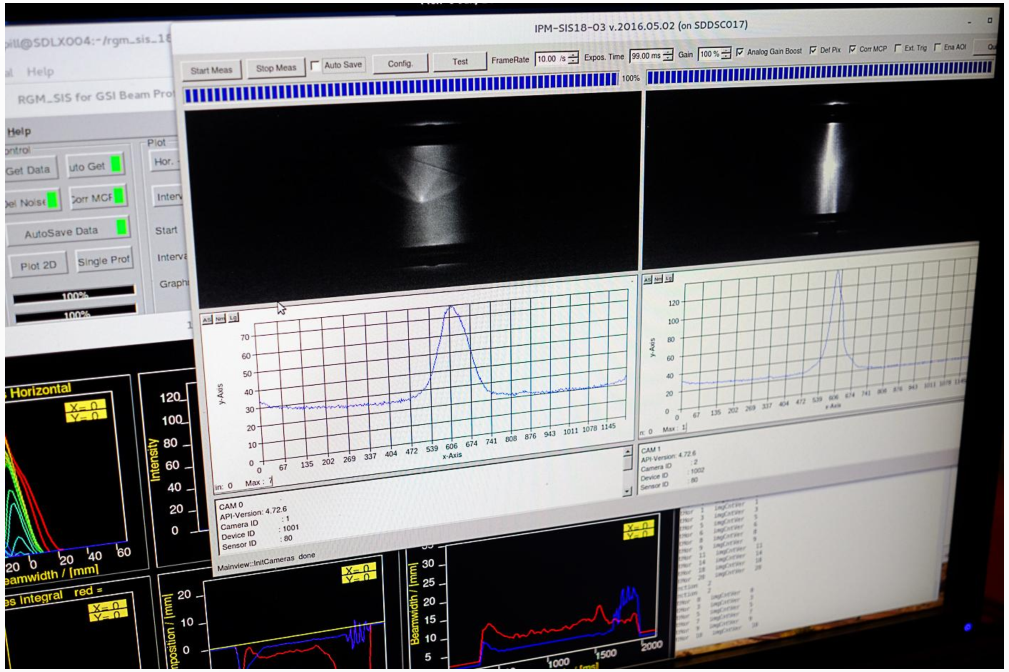
- Sometimes (eg. CNAO) a single moving wire (wire scanner) is used instead of grid of wires.

Emittance at high energies

- At high energies it is enough to measure beam size to determine emittance.
- Devices: SEM grids, Multi-Wire Proportional Chambers, scintillating screens, beam scrapping with current measurement, Wire Scanners, Ionization Profile Monitors (IPM).
- IPM principle:

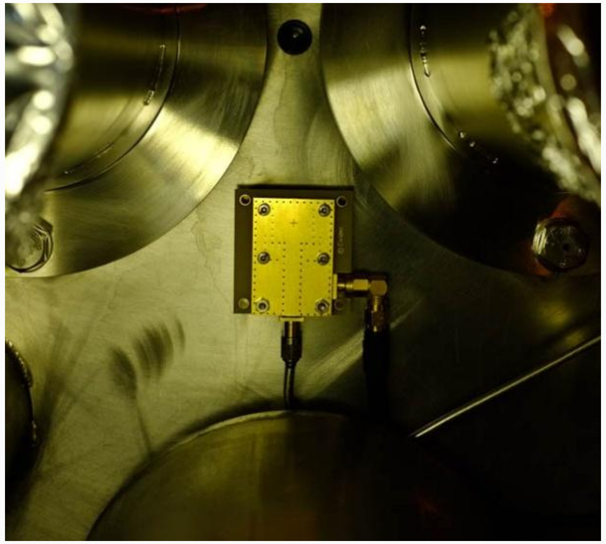


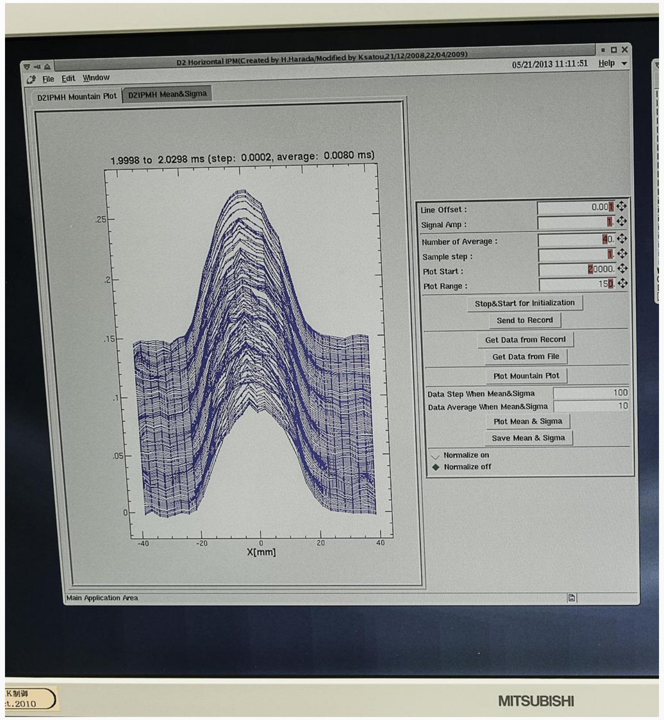
GSI SIS18 beam



Conclusions

- Instrumentation allows to measure what is in the machine; this feedback is necessary to reach design performance
- Main measured quantities: beam current, position, emittance, tune
- Main physics processes used by instruments: electromagnetic coupling, secondary electron emission, gas ionization
- There are non-invasive and destructive measurements





Acknowledgments:
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- JUAS school, P. Forck lectures and handouts
https://www.esi-archamps.eu/Thematic-Schools/Discover-JUAS
- CAS school on instrumentation:
https://cas.web.cern.ch/schools/tuusula-2018

Thank you for your attention!

Please contact me if you have questions concerning this lecture: mariusz.sapinski@cern.ch

HITRI plus
Heavy Ion Therapy Research Integration

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