Trends in Particle Beam Diagnostics

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CERN Beam Instrumentation Group

Presentation based on:

Trends in Particle Beam Diagnostics

Dr. Rhodri Jones

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Symposium on

Quantum Systems and Research at Accelerators

Cockcroft Institute, UK - May 16th 2012

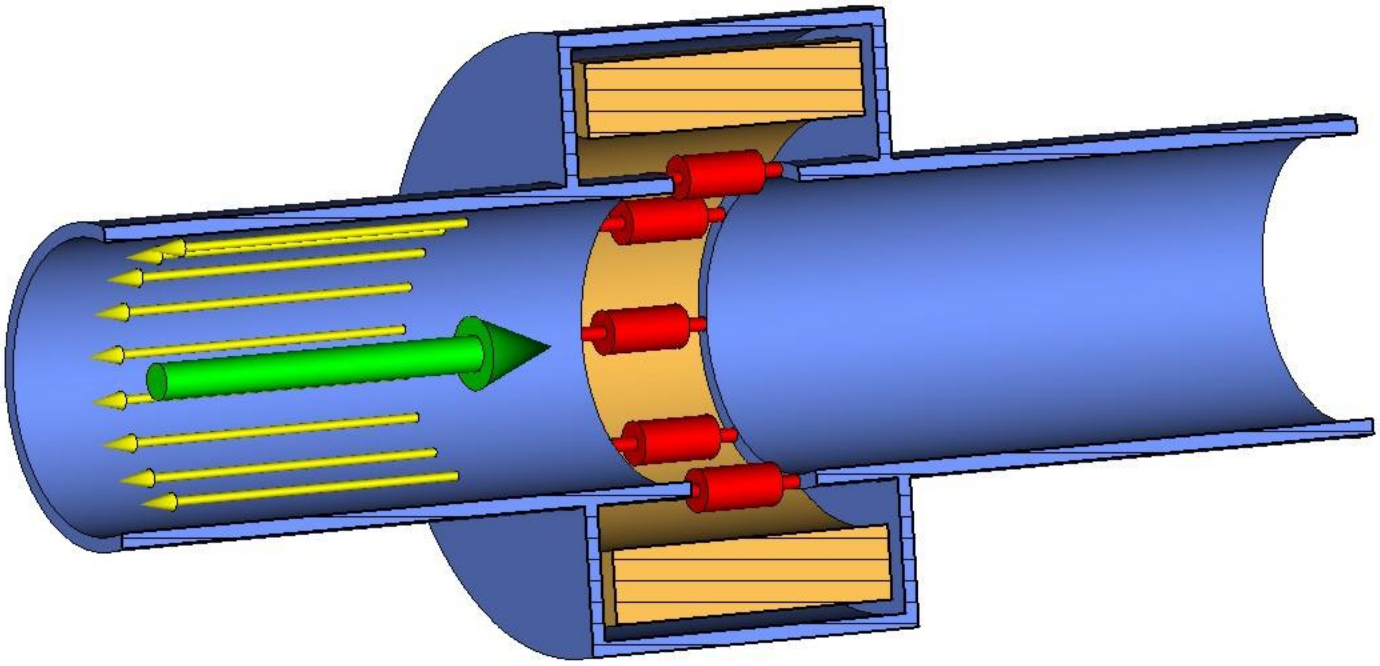
Introduction to Beam Instrumentation

- **Beam instrumentation provides "eyes" for machine operators**
  - The instruments that observe beam behaviour
  - An accelerator can never be better than the instruments measuring its performance!
- **What does work in beam instrumentation entail?**
  - Design, construction & operation of instruments to observe particle beams
  - R&D to innovate or improve existing techniques to fulfill new requirements
  - A combination of many disciplines
    - Applied & Accelerator Physics and a lot of Mechanical, Electronic & Software Engineering
  - A fascinating field of work!
- **What are the main beam parameters measured?**
  - Beam Position to control location of the beam in the accelerator
  - Beam Intensity to measure operational efficiency
  - Beam Loss to ensure safe operation
  - Transverse Beam profiles } to optimise operation
  - Longitudinal Beam profiles }

Trends in Accelerators

- **Bigger, Faster, Better!**
  - High energy machines for particle physics
    - LHC, HL-LHC, HE-LHC (CERN)
    - CLIC/ILC (R&D)
  - High current machines
    - Neutron sources – material science
      - SNS (US), ESS (Sweden), CSNS (China), IFMIF (Japan)
    - Neutrino Production
      - T2K (JPARC, Japan), NuMI/Nova (FNAL, US), CNGS (CERN), Project-X (FNAL, US)
  - High Brightness machines
    - X-ray Free Electron Lasers – probing complex, ultra-small structures
      - LCLS (SLAC, US), European XFEL (DESY, DE)
- **Compact & Exotic!**
  - Rare radioactive isotope machines
    - FAIR (GSI, DE), HIE-ISOLDE (CERN)
  - Anti-matter machines
    - ELENA (CERN), FAIR (GSI, DE)

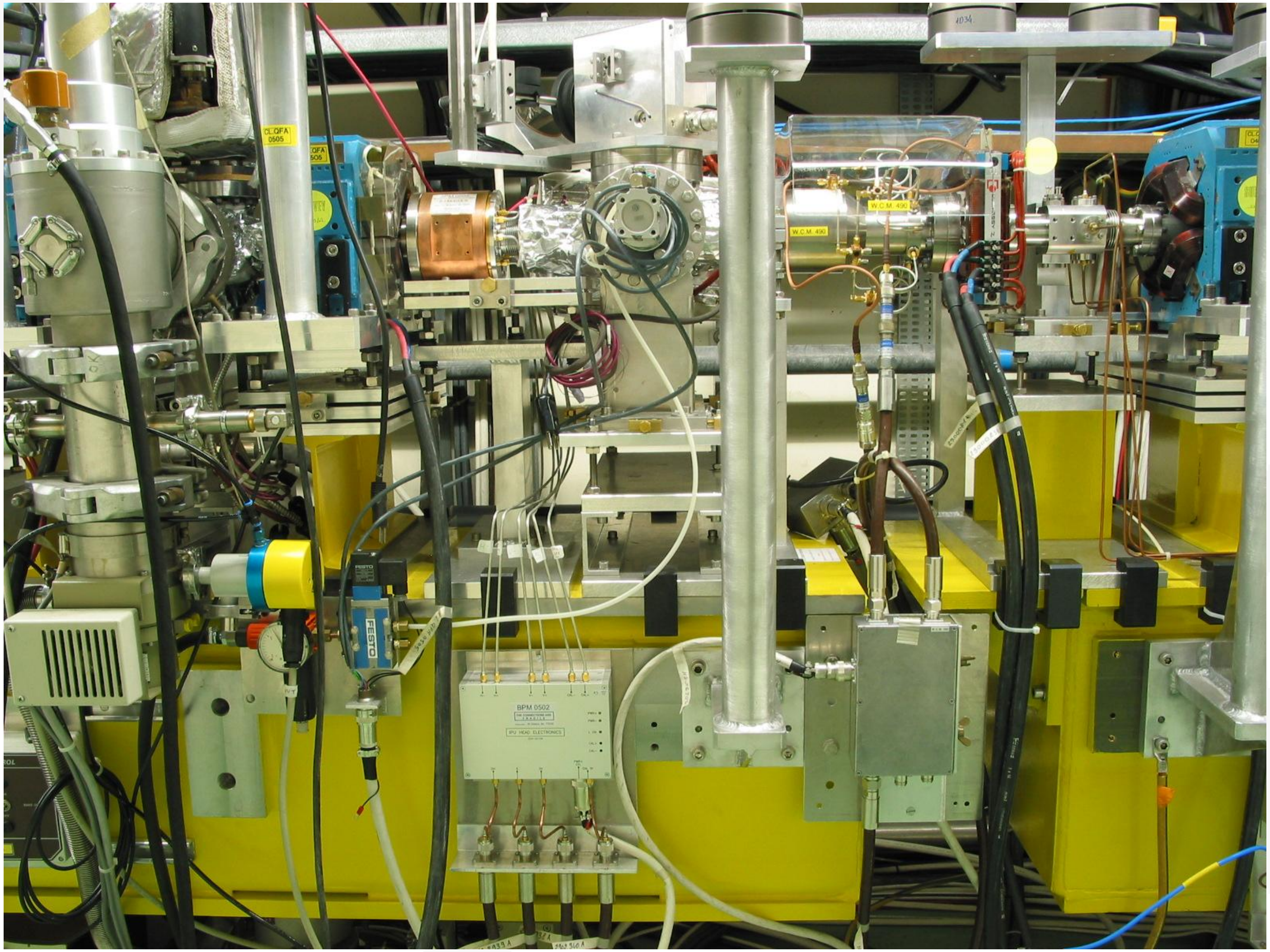
Beam current: Wall Current Monitor (WCM)



- The **BEAM** current is accompanied by its **IMAGE**
- A voltage proportional to the beam current develops on the **RESISTORS** in the beam pipe gap
- The gap must be closed by a box to avoid floating sections of the beam pipe
- The box is filled with the **FERRITE** to force the image current to go over the resistors
- The ferrite works up to a given frequency and lower frequency components flow over the box wall

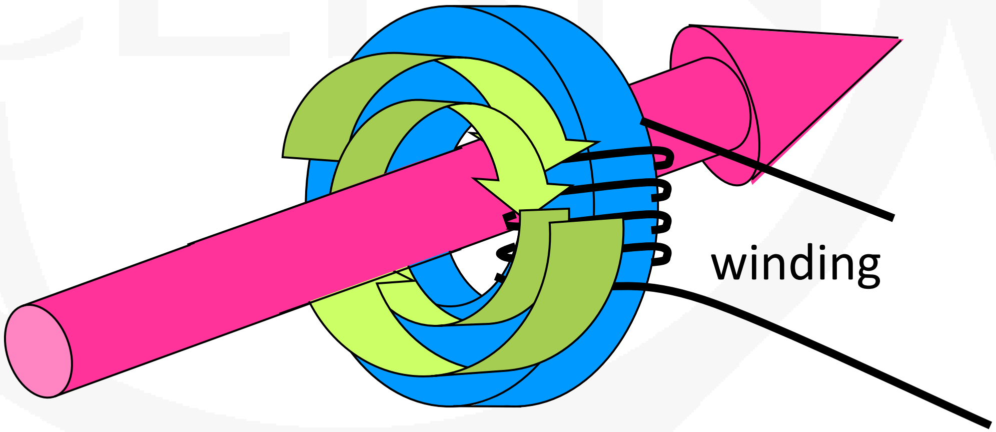
(Very quick) Introduction to BI

Beam current: Wall Current Monitor (WCM)



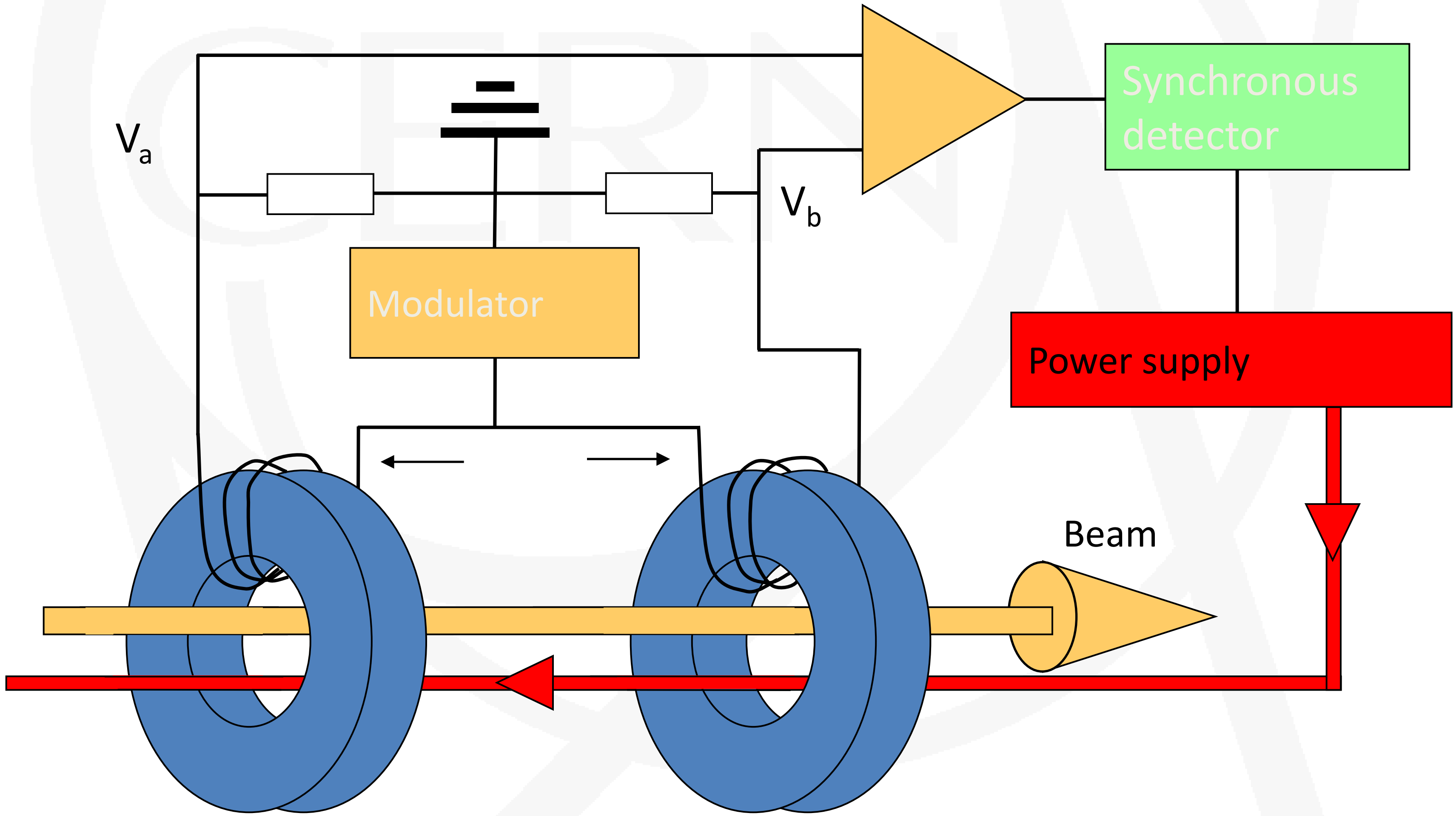
(Very quick) Introduction to BI

Beam current: Fast Beam Current Transformer



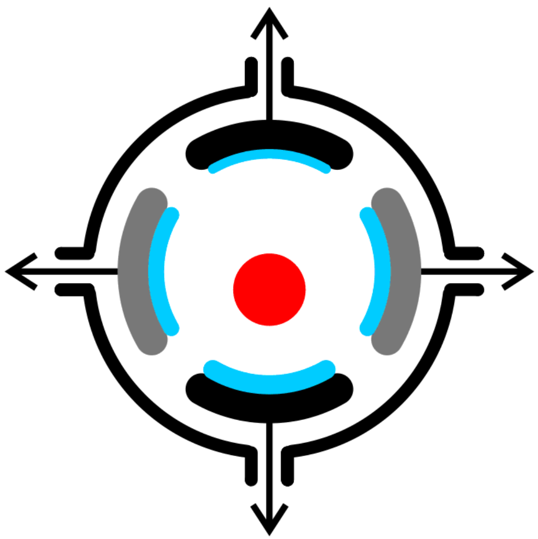
(Very quick) Introduction to BI

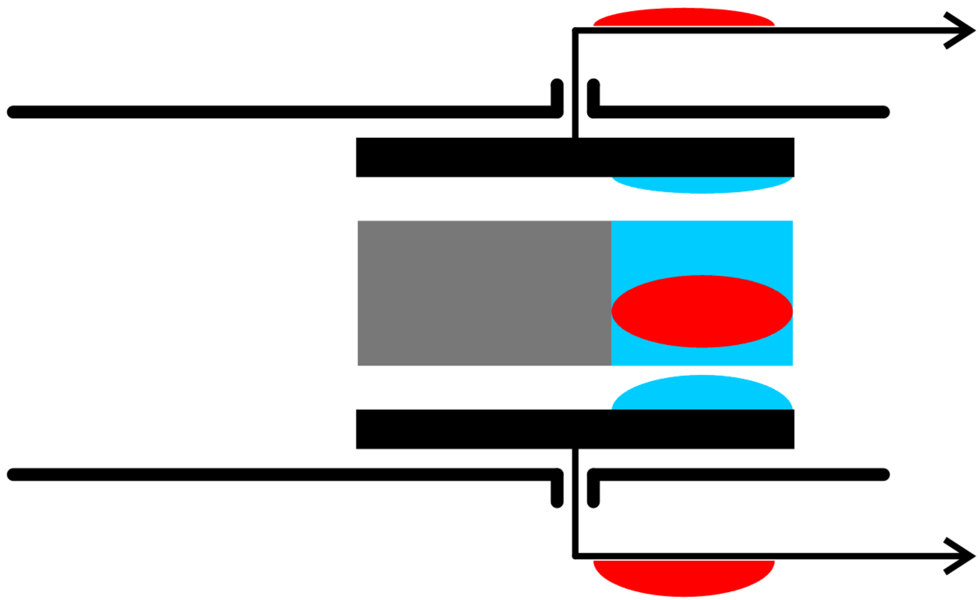
Beam current: DC Beam Current Transformer

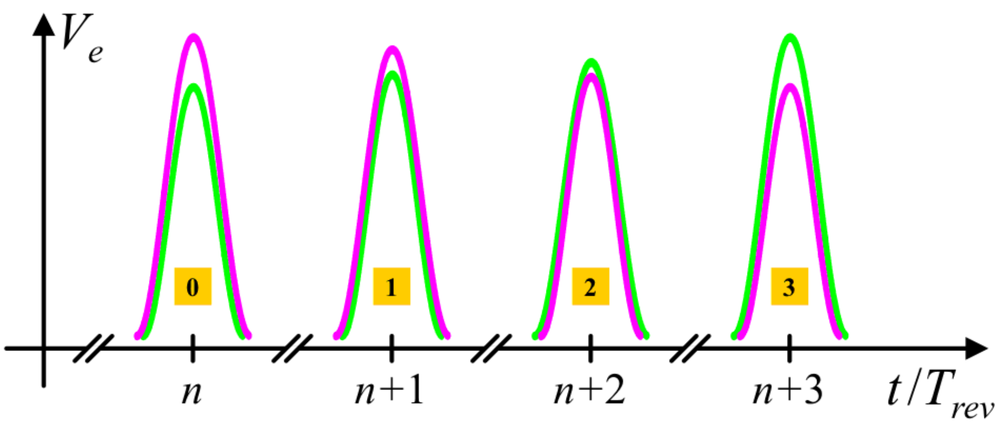


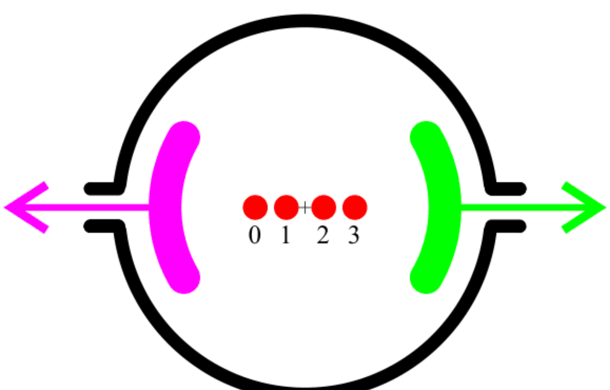
(Very quick) Introduction to BI

Beam position: Beam Position Monitor









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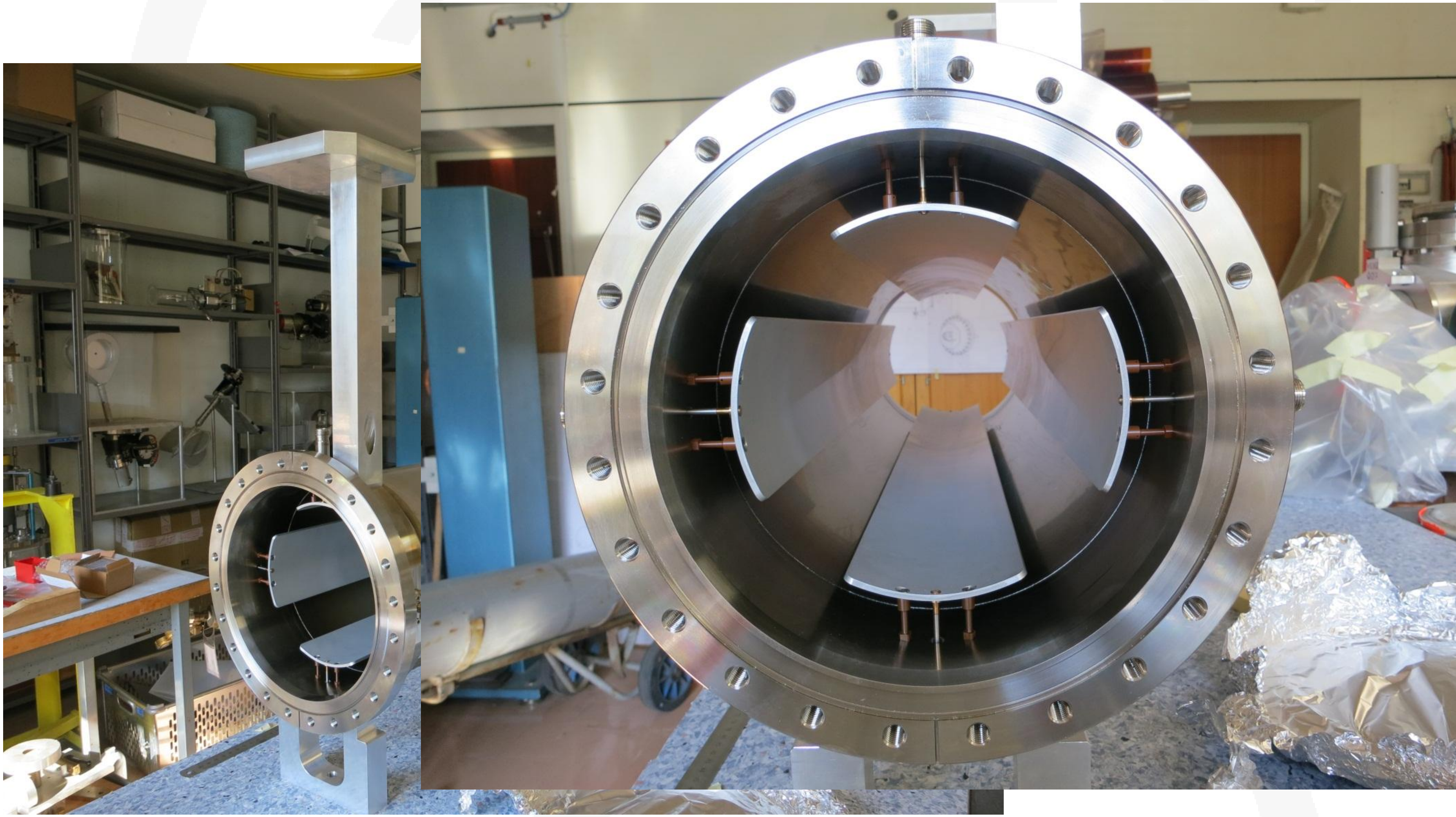

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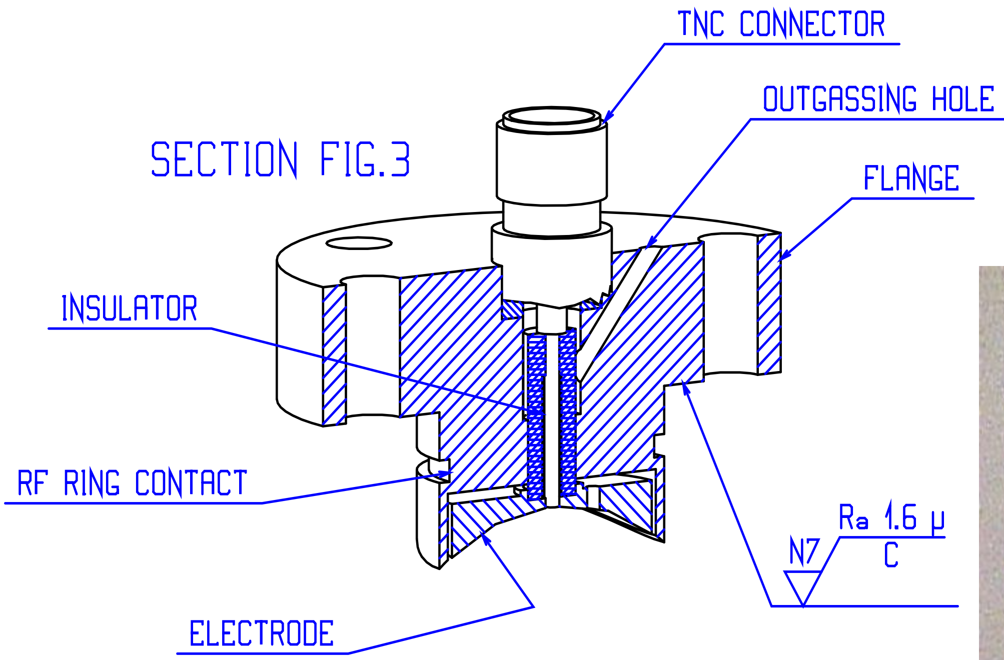
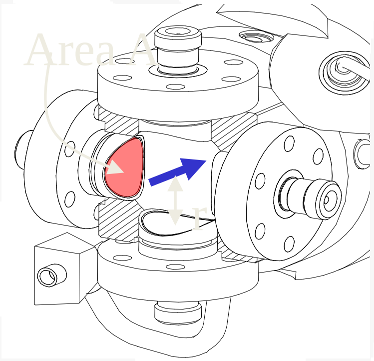
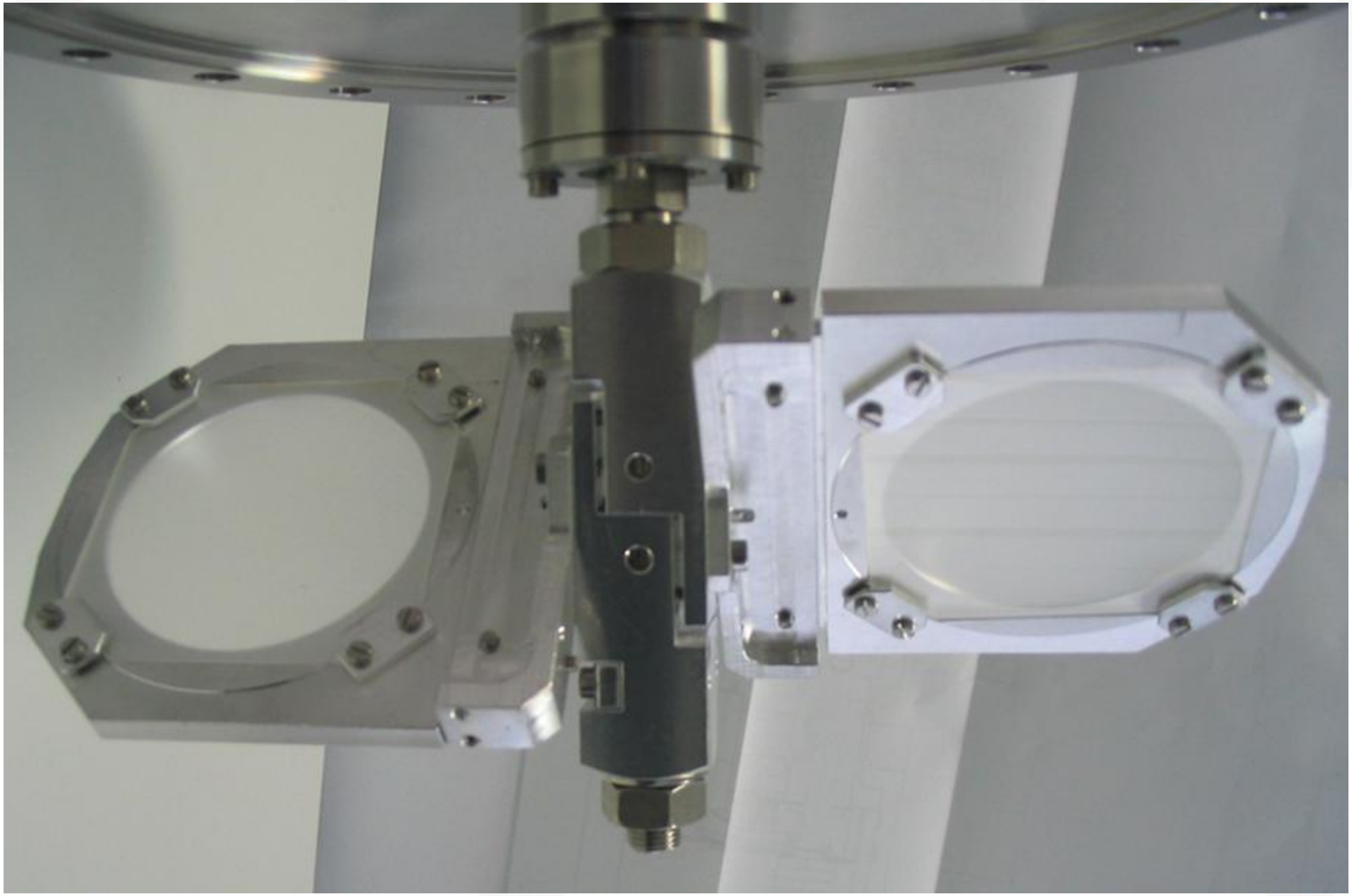
Beam position: Beam Position Monitor





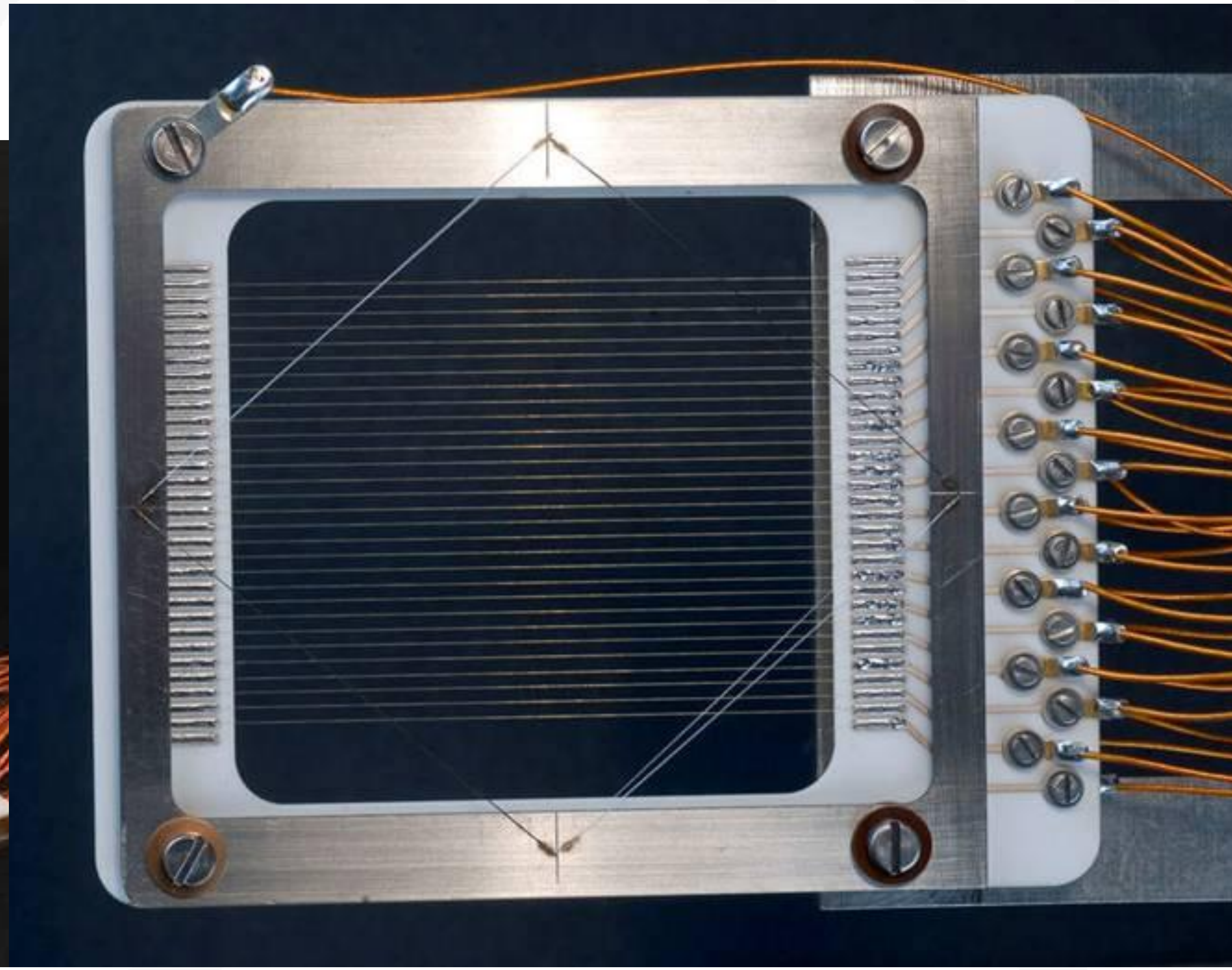
(Very quick) Introduction to BI

Beam profile: Screens



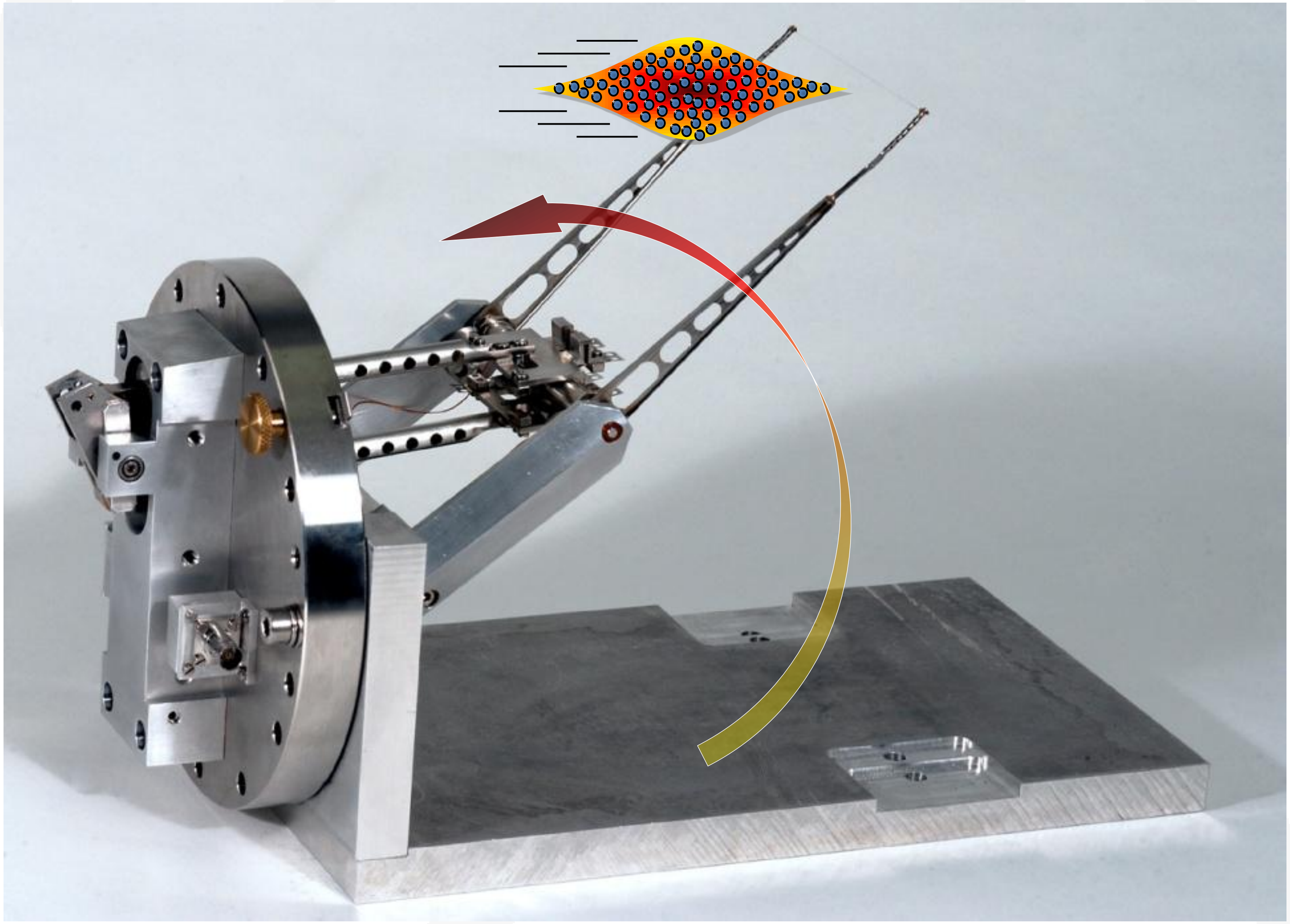
(Very quick) Introduction to BI

Beam profile: Secondary emission grids



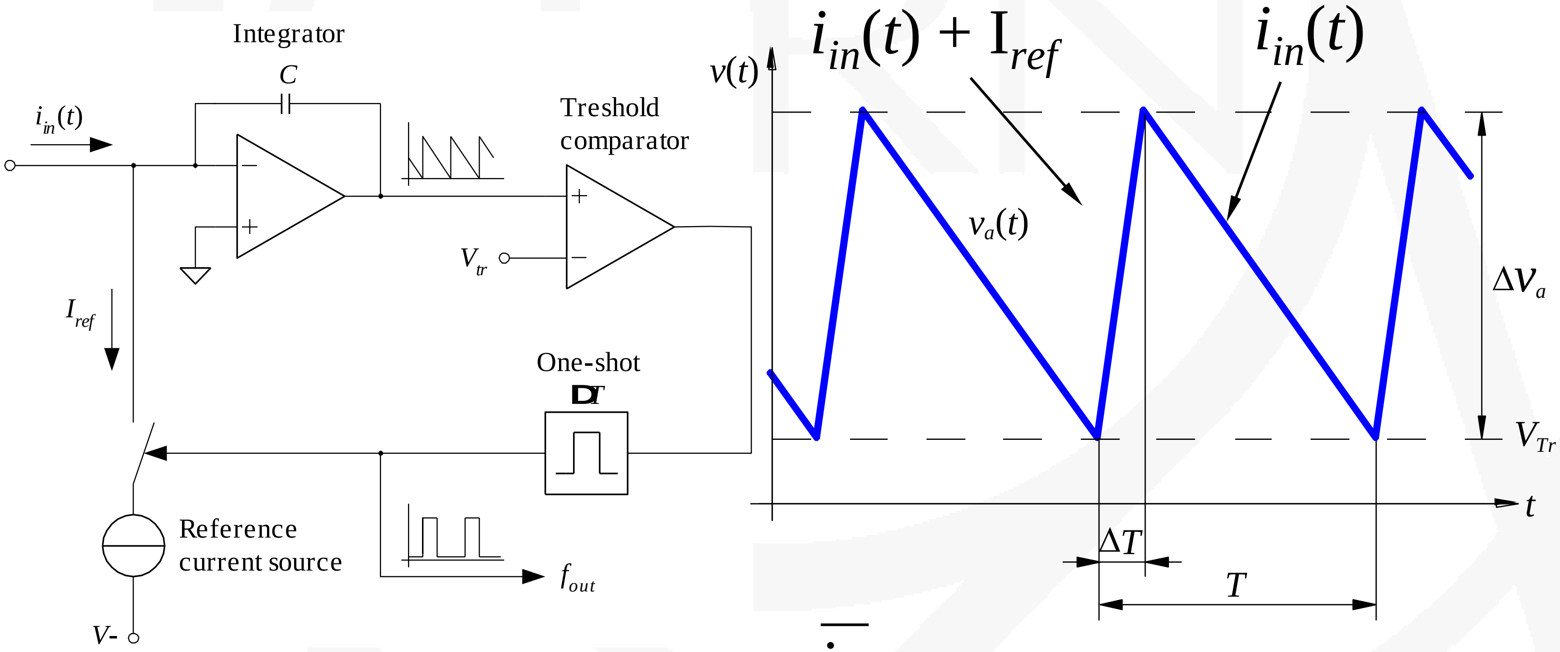
(Very quick) Introduction to BI

Beam profile: Wire scanner



(Very quick) Introduction to BI

Beam loss: Ionisation chamber



$$f = \frac{\overline{i_{in}}}{I_{ref}\,\Delta T}$$

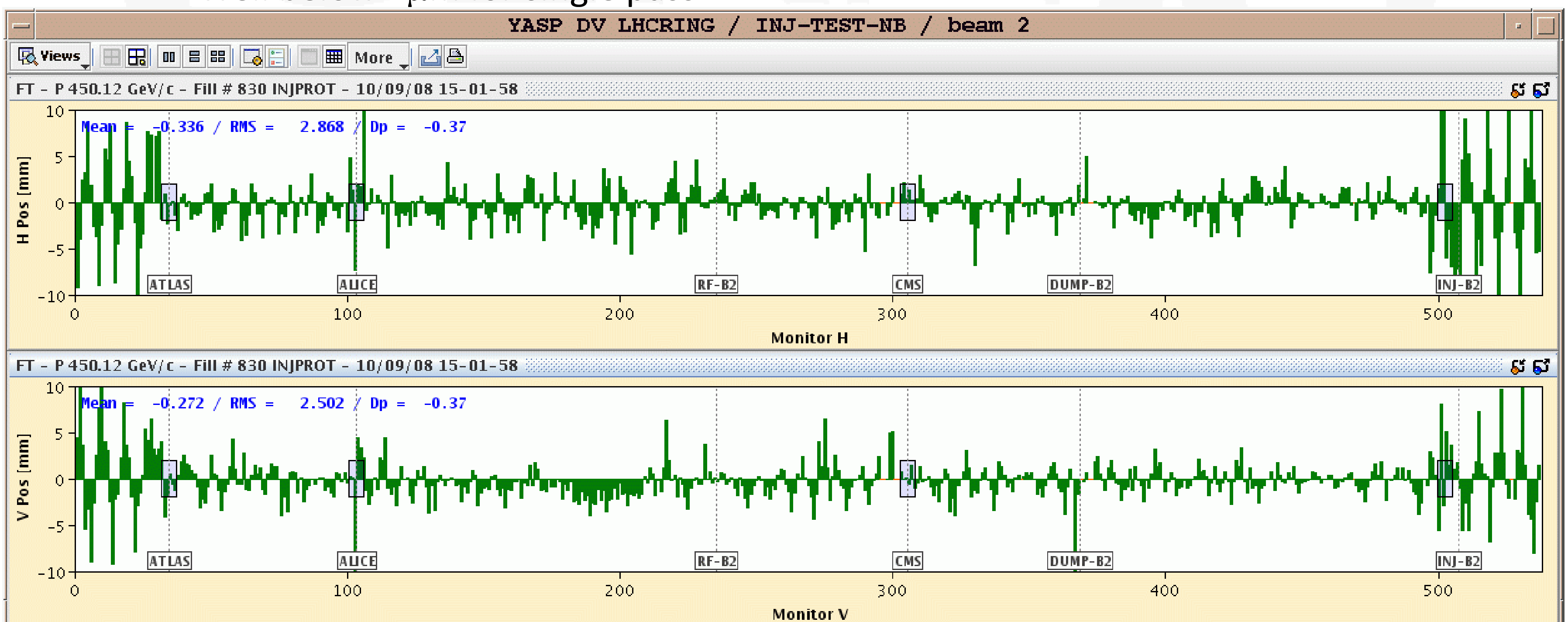
Challenges for Beam Instrumentation

- **Unprecedented request for precision**
  - Positioning down to well below the micron level
- **Treatment of more and more data**
  - Bunch by bunch measurements for all parameters
- **Dealing with high beam powers**
  - Non-invasive measurement techniques
  - Robust and reliable machine protection systems
- **Dealing with the ultra-fast**
  - Measurements on the femto-second timescale
- **Dealing with the ultra-low**
  - Measurement of very small beam currents

The Quest for Unprecedented Precision

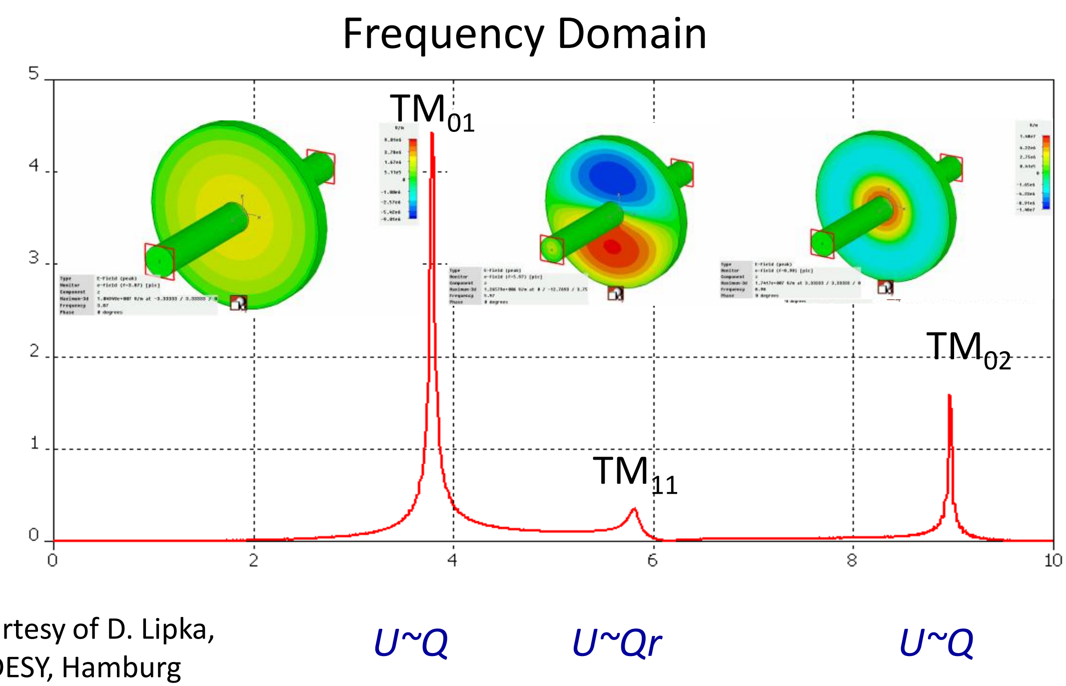
Beam Position Monitoring – The Challenges

- **Typically one of the largest BI systems**
  - LHC has 1000+ BPMs – CLIC drive beam requires 40000! This implies:
    - Precision engineering at low cost
    - Simple, robust, yet very highly performing electronics
      - Digitise as soon as possible (now doable with advances in ADCs & digital treatment systems)
      - Radiation Tolerant (minimises expensive cabling BUT requires significant testing time)
  - XFEL's and Linear Colliders increasingly asking for very high resolution
    - Well below 1μm for single pass



Improving the Precision for Next Generation Accelerators

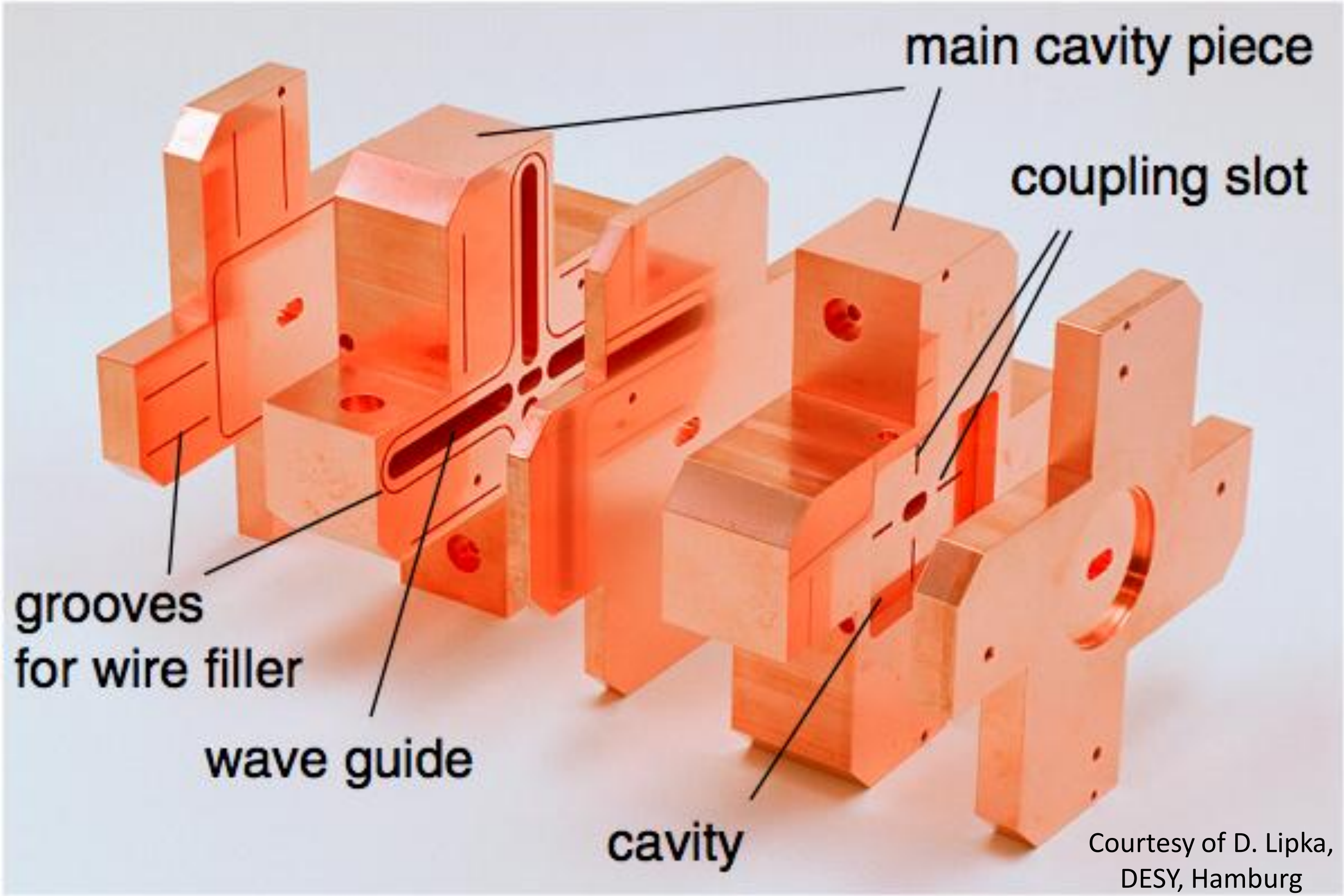
- **Standard BPMs give intensity signals - need to subtract them to obtain a difference which is proportional to position**
  - Difficult to do electronically without some of the intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
- **Solution – cavity BPMs allowing sub micron resolution**
  - Design the detector in such a way as to only collect only the difference signal
    - Dipole Mode TM_{11} proportional to position & shifted in frequency with respect to monopole mode



Courtesy of D. Lipka, DESY, Hamburg

Today's State of the Art BPMs

- **Prototype BPM for ILC Final Focus**
  - Required resolution of 2nm (yes nano!) in a 6×12mm diameter beam pipe
  - Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)



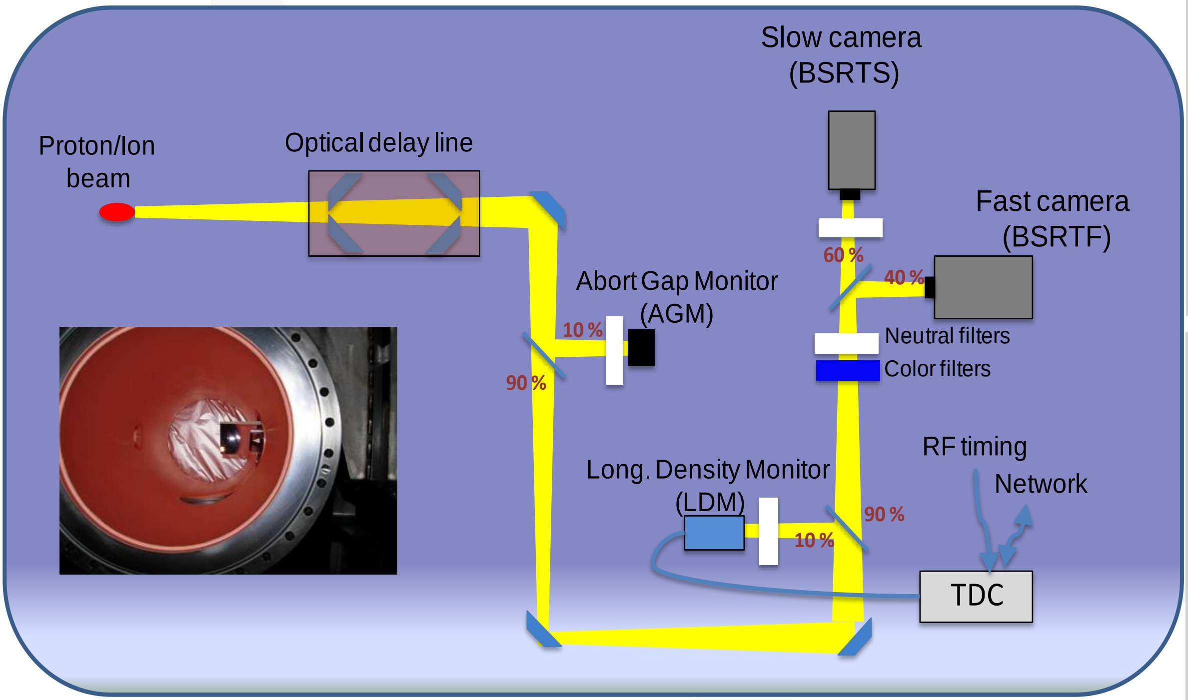
Courtesy of D. Lipka, DESY, Hamburg

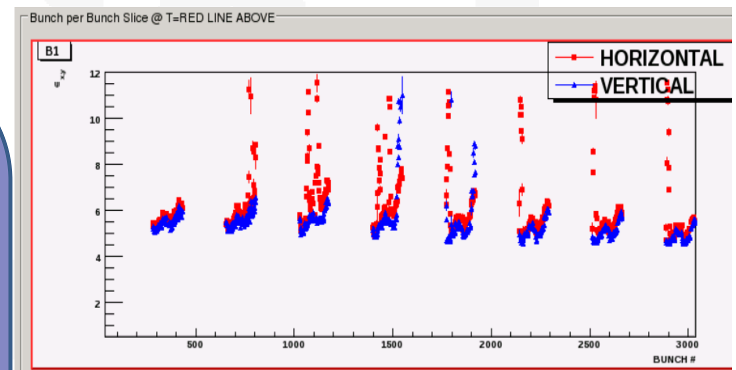
Dealing with high beam powers

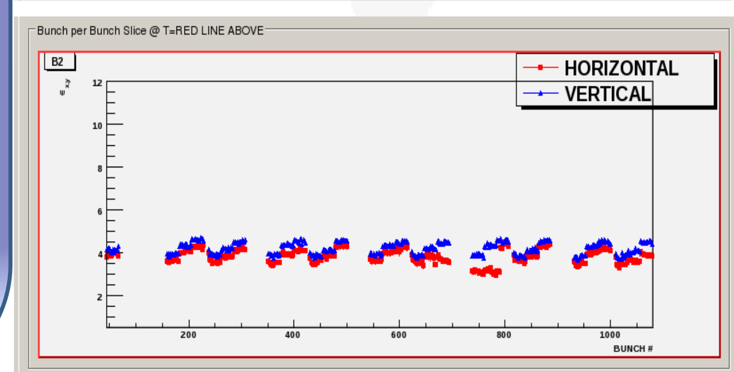
Non-invasive measurement techniques

Measuring the Size of High Power Beams

- **Synchrotron Light Diagnostics**
  - Only for electron & very high energy proton/ion machines (LHC)
  - Difficult to get absolute calibration
    - Image correction factors typically bigger than the beam size!
  - Additional challenges lie in fast cameras & signal treatment chains for bunch by bunch measurement

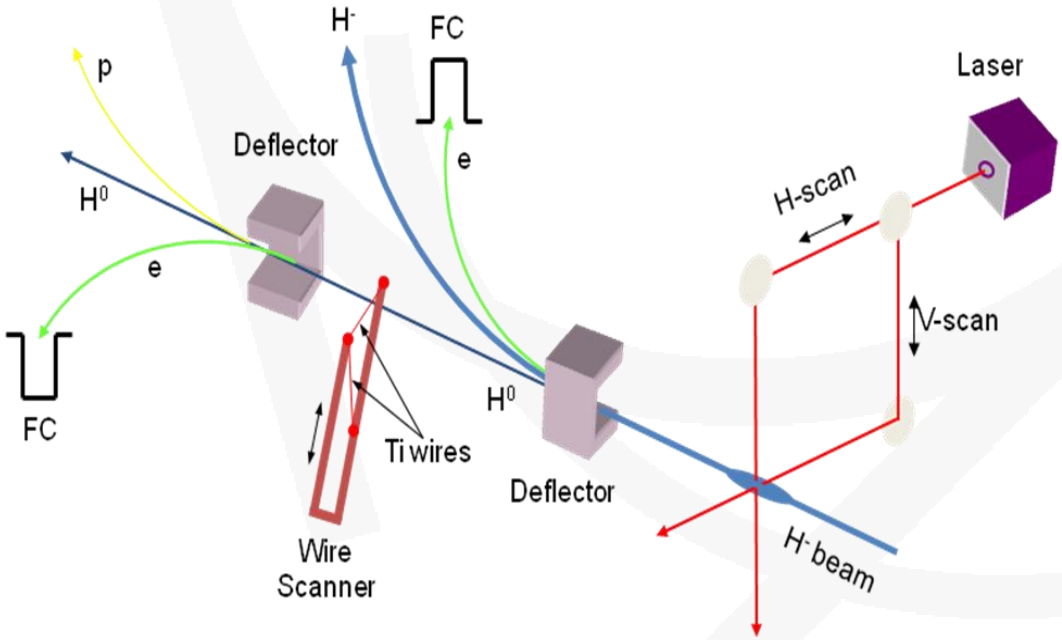


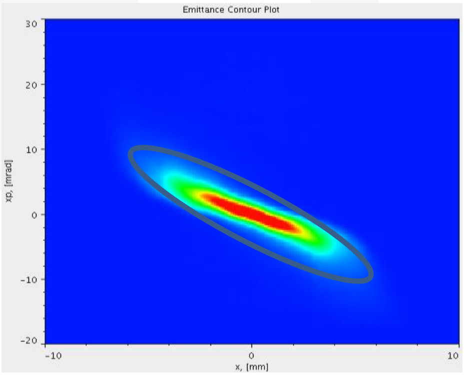


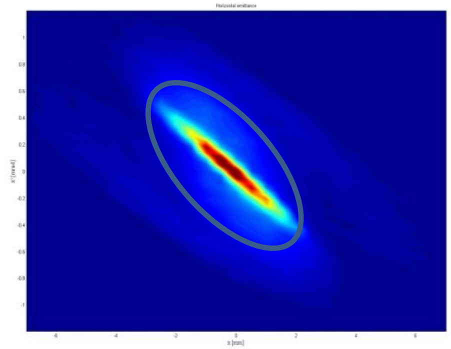


Non-Invasive Beam Size Measurement

- **Laser wire scanner**
  - Good candidate for H^- & electrons
  - Needs to be made into turn-key instrument
    - Reliable laser system
    - Laser distribution to multiple measurement stations

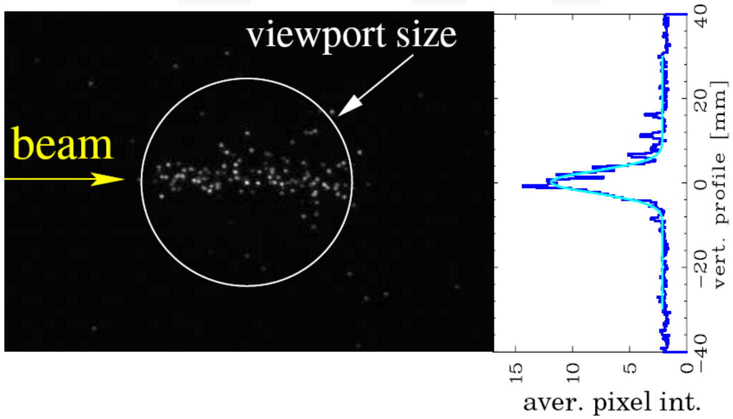


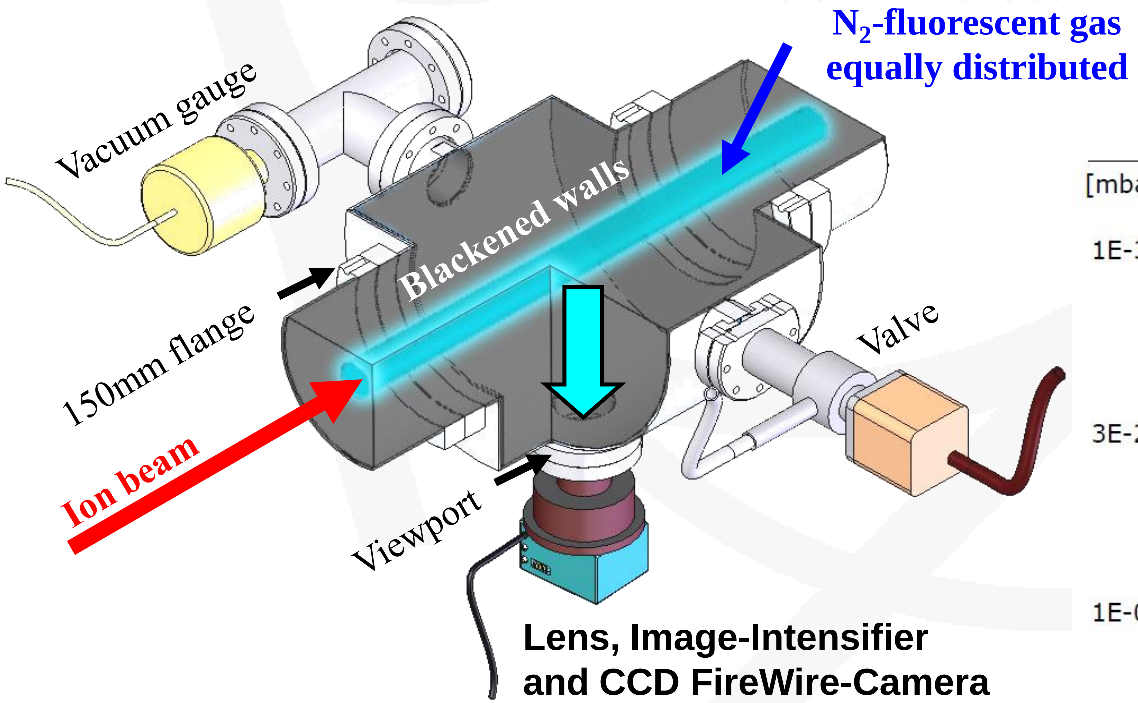


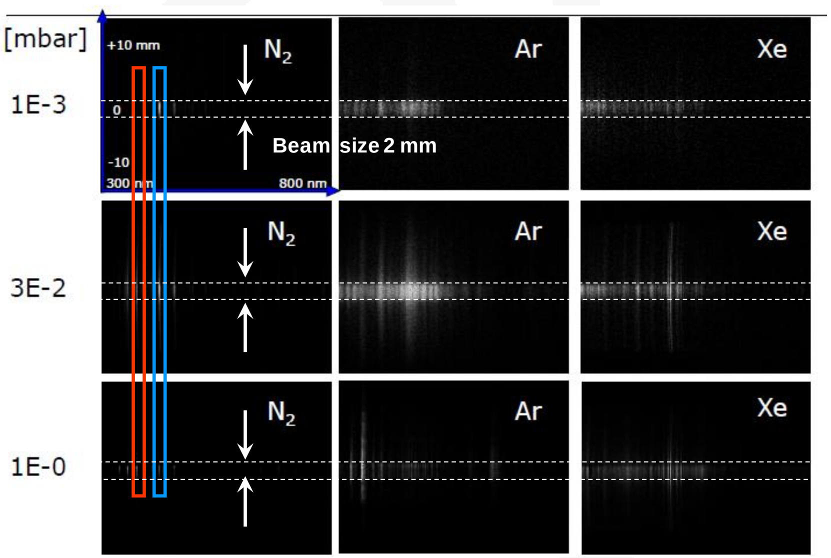


Non-Invasive Beam Size Measurement

- **Beam Induced Fluorescence**
  - Issues
    - Sensitivity to radiation
    - Low signal yield ⇒ vacuum bump







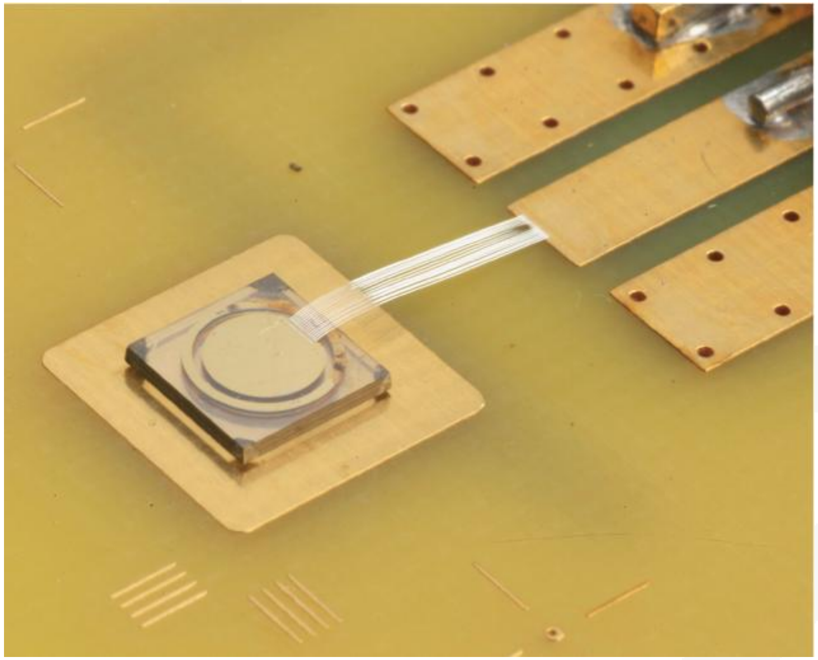
Challenges for Beam Instrumentation

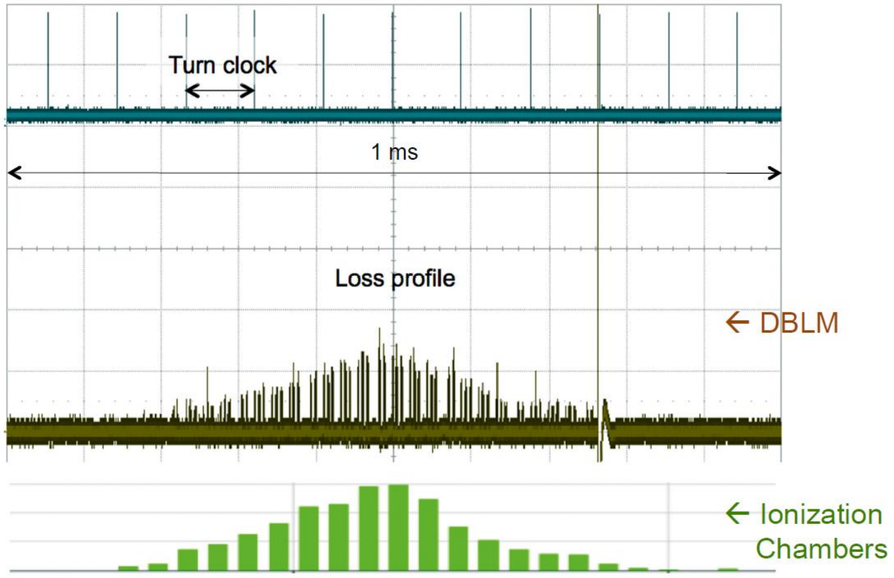
Dealing with high beam powers

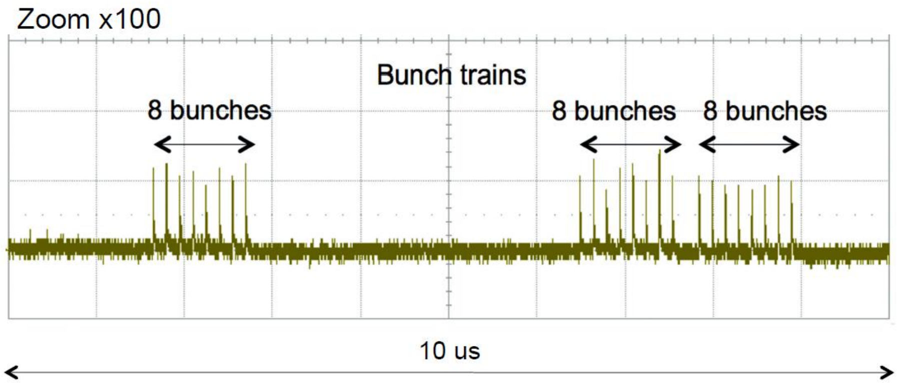
Robust and Reliable Machine Protection Systems

Beam Loss Monitors – New Materials

- **Diamond Detectors**
  - Fast & sensitive
  - Used in LHC to distinguish bunch by bunch losses
  - Investigations now ongoing to see if they can work in cryogenic conditions







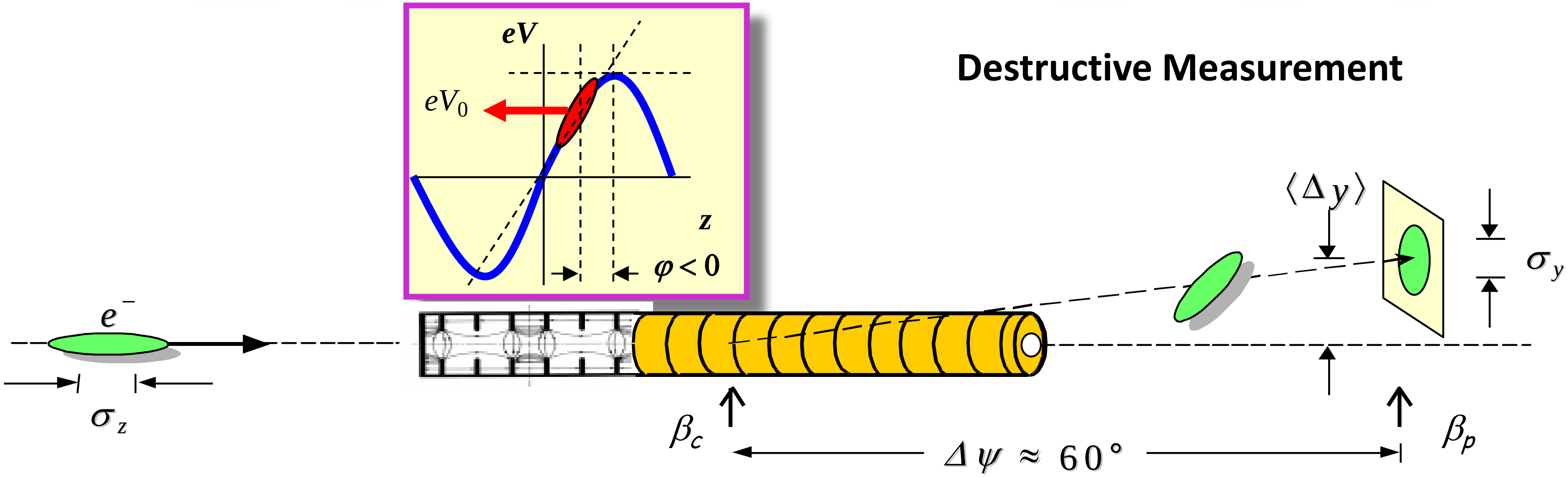
Dealing with the ultra-fast

Measurements on the femto-second timescale

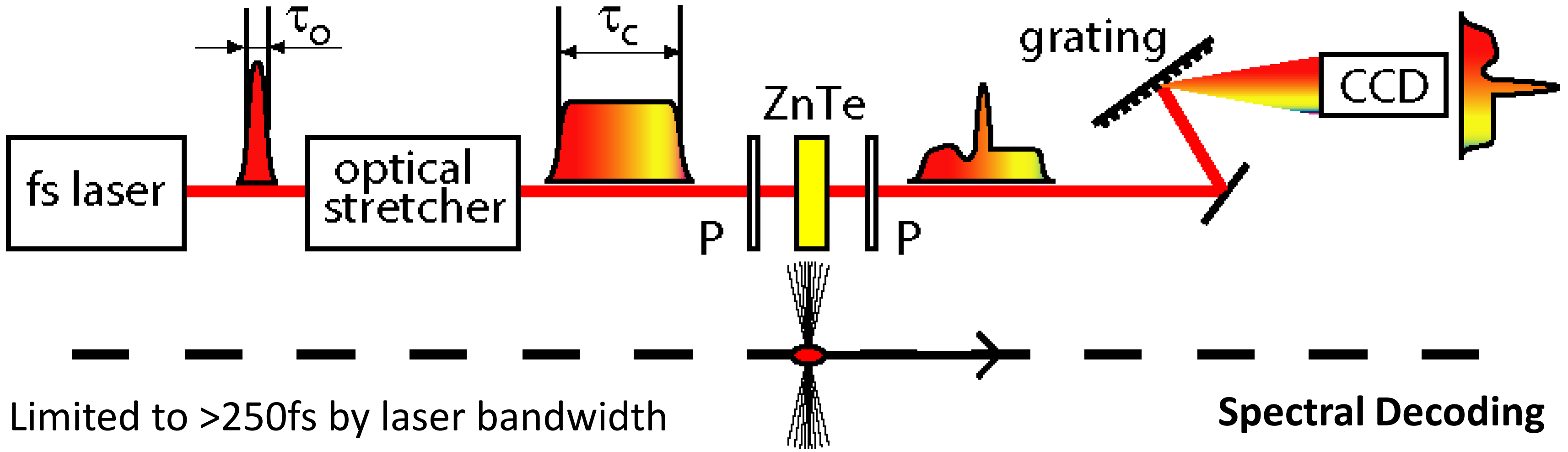
Ultra-Short Bunch Length Diagnostics

- **Next Generation FELs & Linear Colliders**
  - Use ultra short bunches to increase brightness or improve luminosity
- **How do we currently measure such short bunches?**
  - Transverse deflecting cavity

p^+ @ LHC	250ps
H^- @ SNS	100ps
e^- @ ILC	500fs
e^- @ CLIC	130fs
e^- @ XFEL	80fs
e^- @ LCLS	75fs

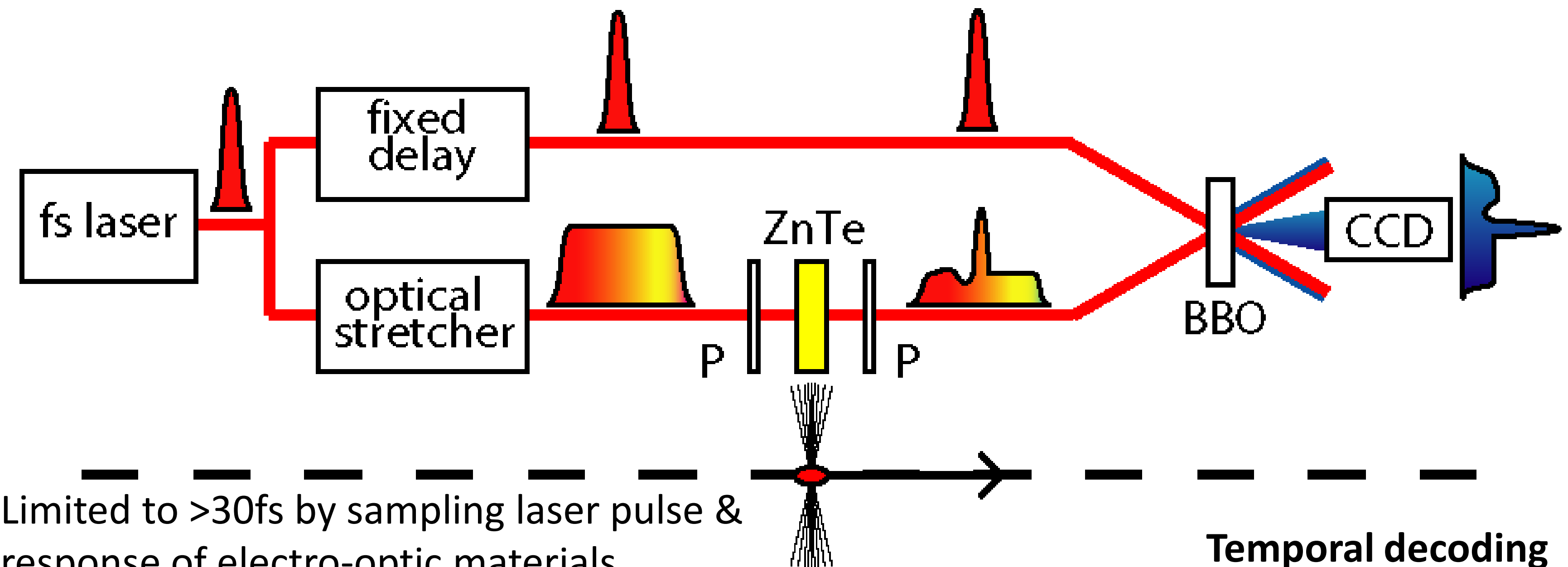


Non Destructive – Electro-Optic Sampling



Limited to >250fs by laser bandwidth

Spectral Decoding



Limited to >30fs by sampling laser pulse & response of electro-optic materials

Temporal decoding

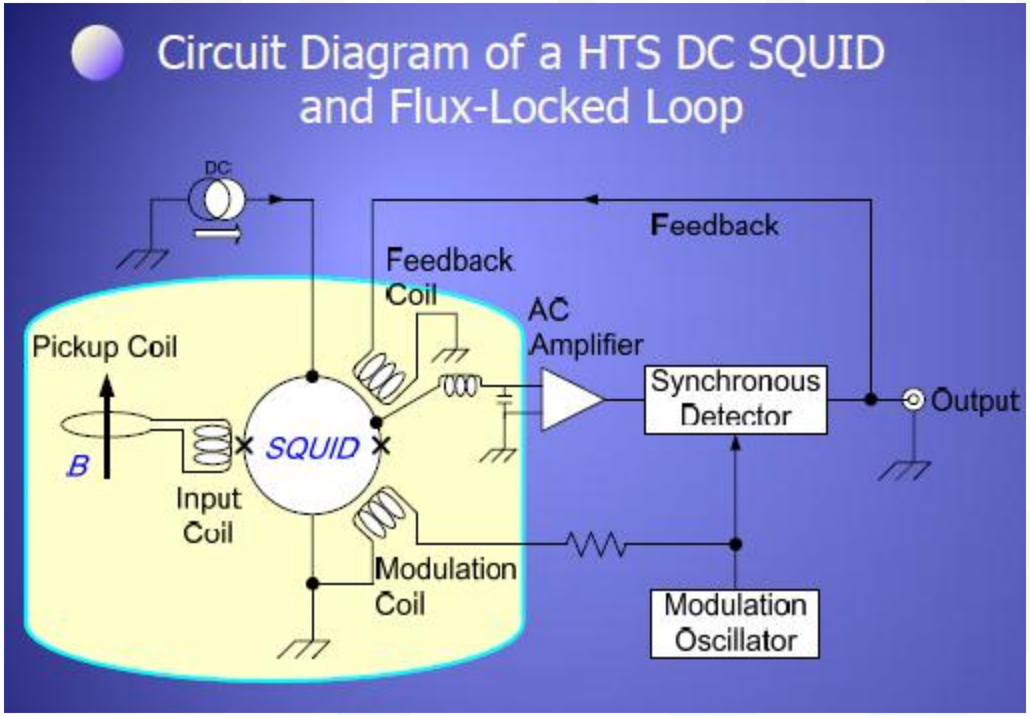
Challenges for Beam Instrumentation

Dealing with the ultra-low

Measurement of very small beam currents

SQUID-based zero-flux systems

- **Idea similar to DCCT, but a SQUID is used to detect very small magnetic fields**
- **Allows nA beam current measurement**



Courtesy of T. Watanabe

Conclusion

- **Particle Beam Diagnostic systems are continually evolving to meet the requirements of**
  - ever more powerful accelerators
  - ever more demanding specifications
- **Many synergies between the developments required for all types of new accelerator facilities**
  - Ideal subject for collaboration on an international level
  - Already underway between the major accelerator laboratories worldwide
  - Now strengthened and extended to universities and industry via European Networks