Trends in Particle Beam Diagnostics

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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 or Exotic!**
  - Rare radioactive isotope machines
    - FAIR (GSI, DE), HIE-ISOLDE (CERN)
  - Anti-matter machines
    - ELENA (CERN), FAIR (GSI, DE)
  - Medical proton/ion therapy machines

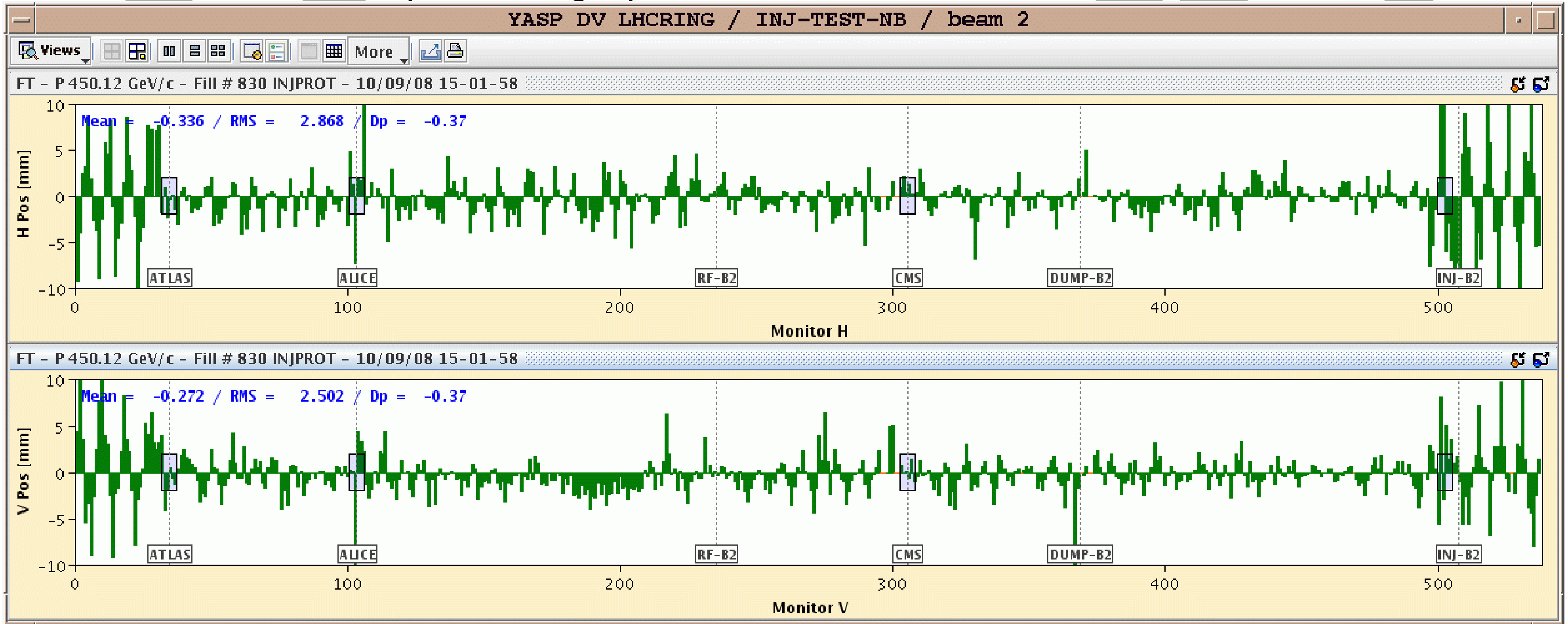
Challenges for Beam Instrumentation

- **Unprecedented request for precision**
  - Positioning down to well below the micron level
- **Treatment of increasingly 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

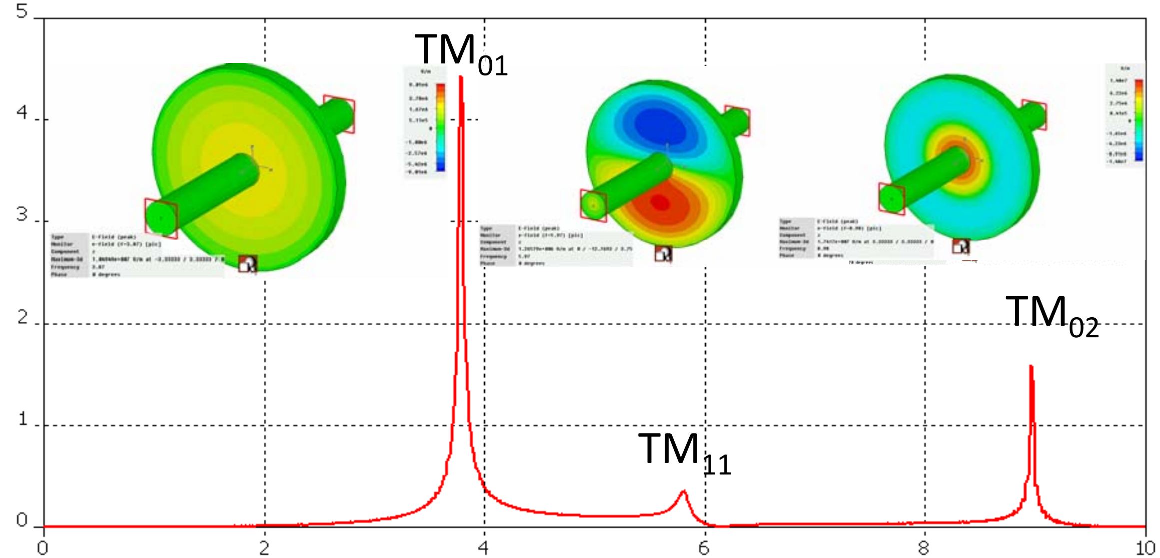
- **Typically one of the largest BI systems**
  - LHC has 1100 BPMs – CLIC drive beam requires 40000! This implies:
    - Precision engineering at low cost
    - Simple, robust, yet very highly performing electronics
      - Digitise as soon as possible (now doable with advances in ADCs & digital treatment systems)
      - Radiation Tolerant (improves S/N, minimises expensive cabling BUT needs 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

Frequency Domain



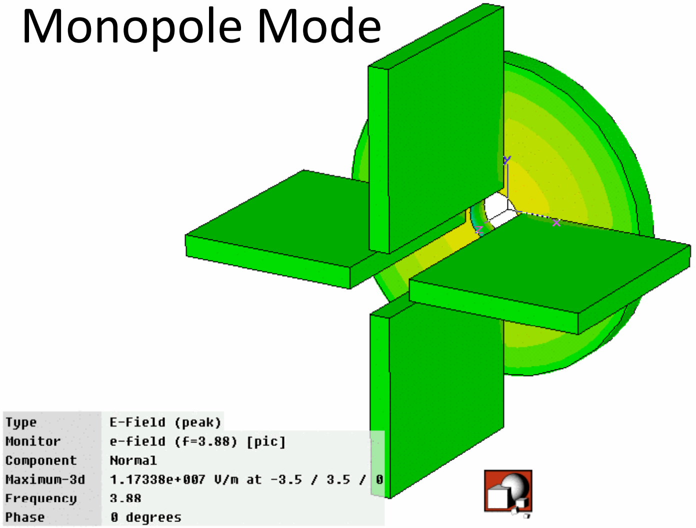
Courtesy of D. Lipka, DESY, Hamburg

U~Q *U~Qr* *U~Q*

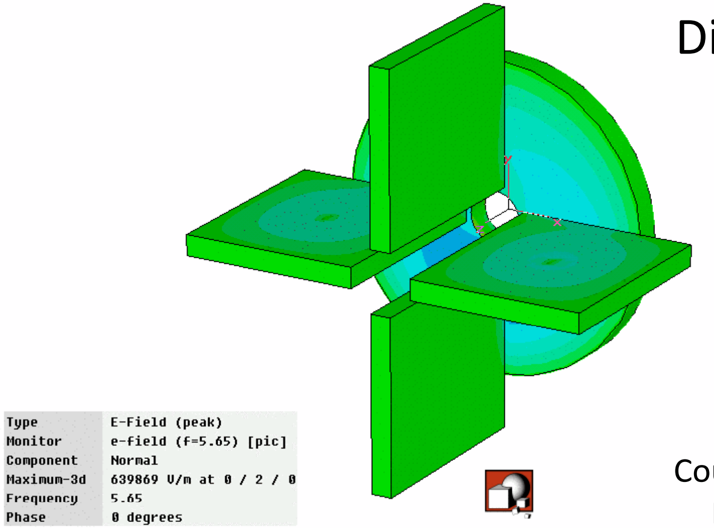
Today's State of the Art BPMs

- **Obtain signal using waveguides that only couple to dipole mode**
  - Further suppression of monopole mode

Monopole Mode



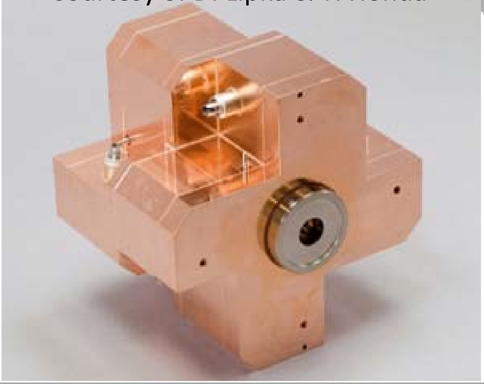
Dipole Mode

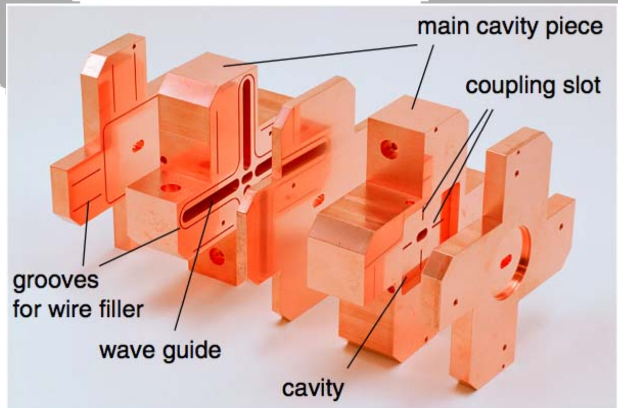


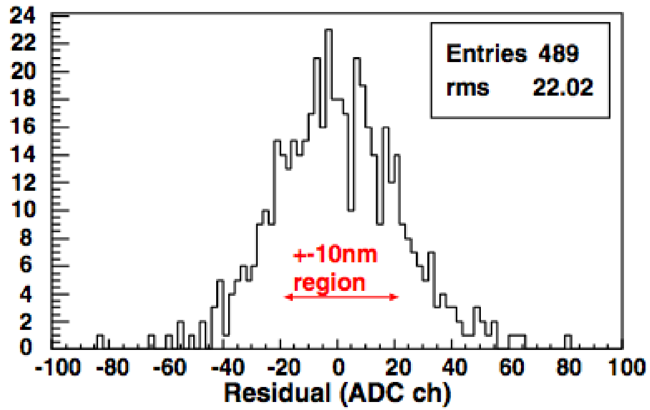
Courtesy of D. Lipka, DESY, Hamburg

- **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 & Y. Honda



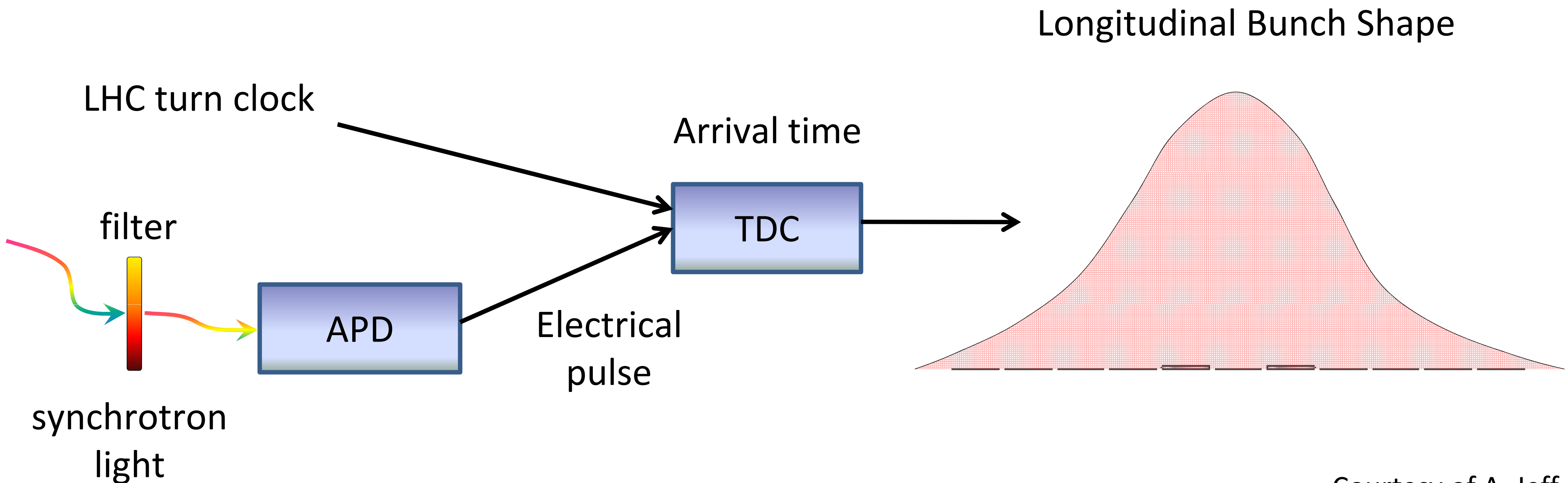




Maximising the Available Data

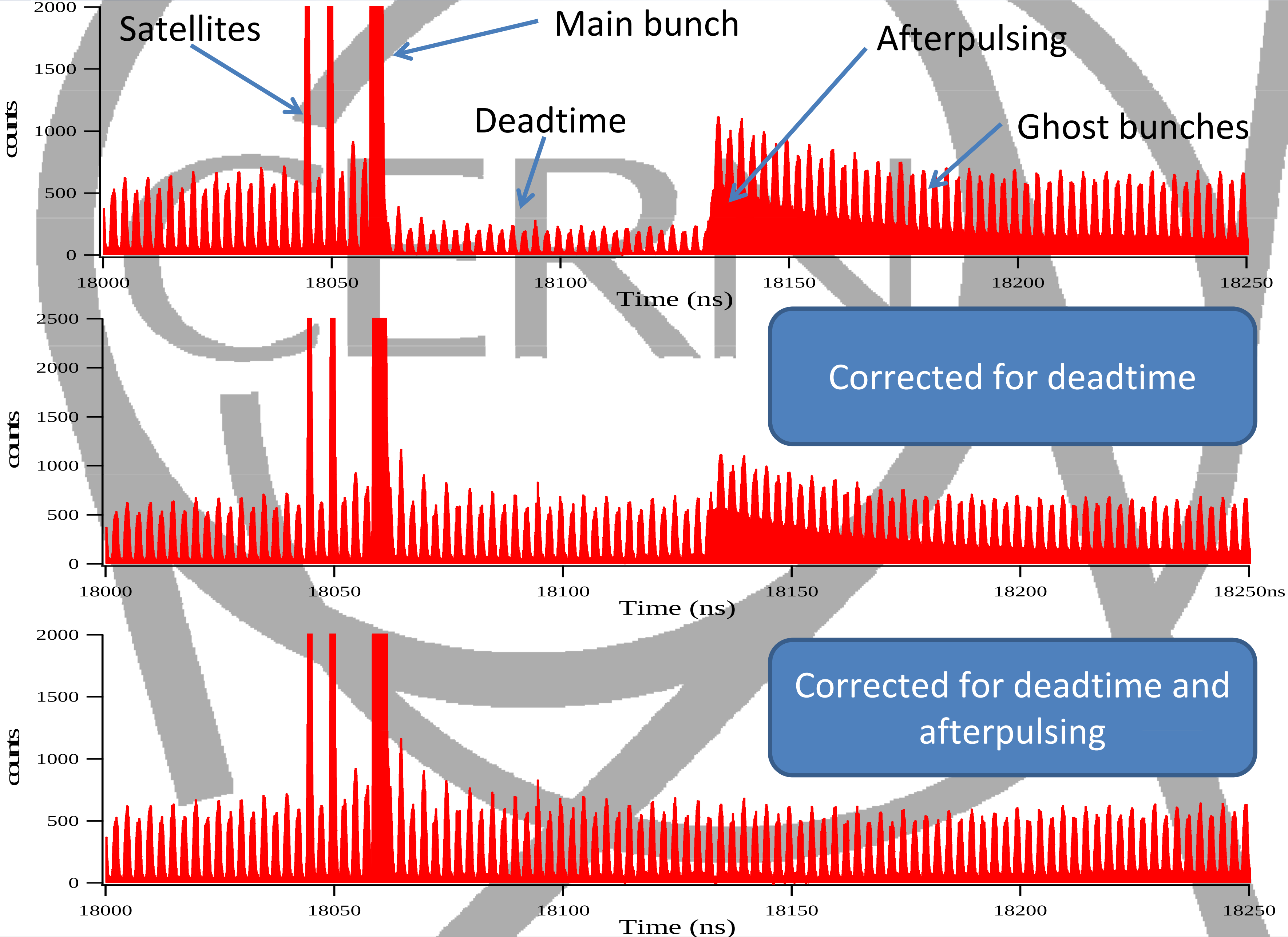
Maximising the Available Data - Example

- **LHC Longitudinal Density Monitor**
  - Aims:
    - Profile of the whole LHC ring with 50ps resolution
    - High dynamic range for ghost charge measurement
  - Method:
    - Single photon counting with Synchrotron light
      - Avalanche photodiode detector
      - 50ps resolution TDC



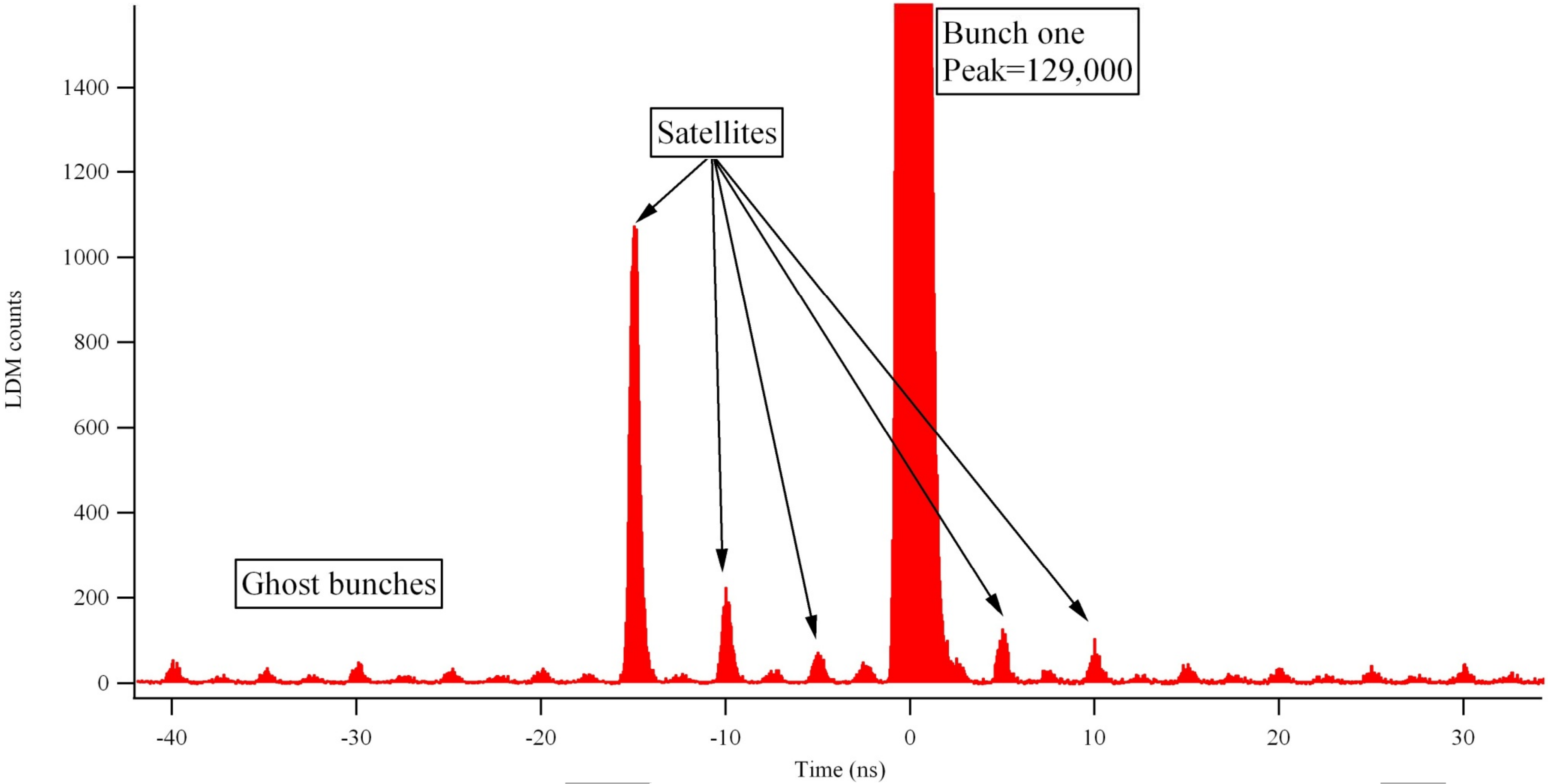
Courtesy of A. Jeff

LDM On-line Correction



LDM Results

- **Results**
  - Able to profile the whole ring within a matter of minutes
  - Critical input for accurate luminosity calibration of the experiments

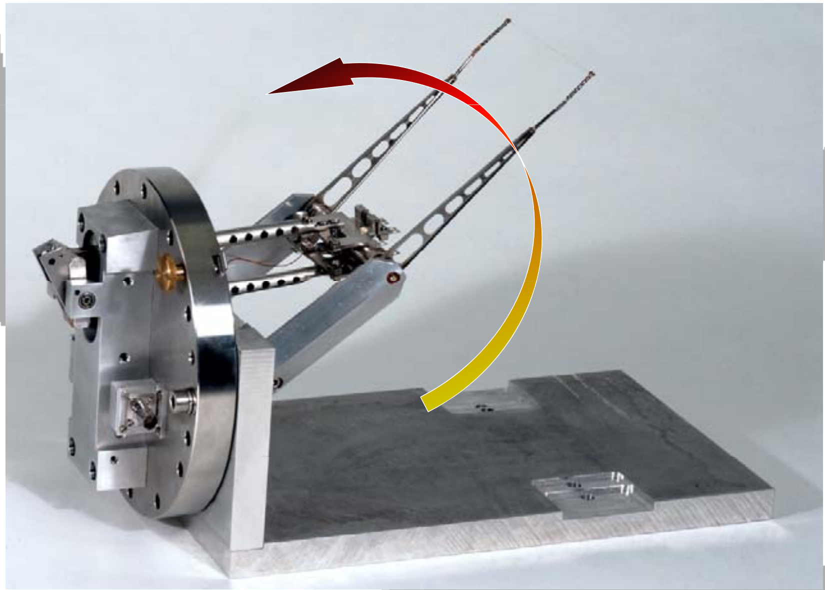


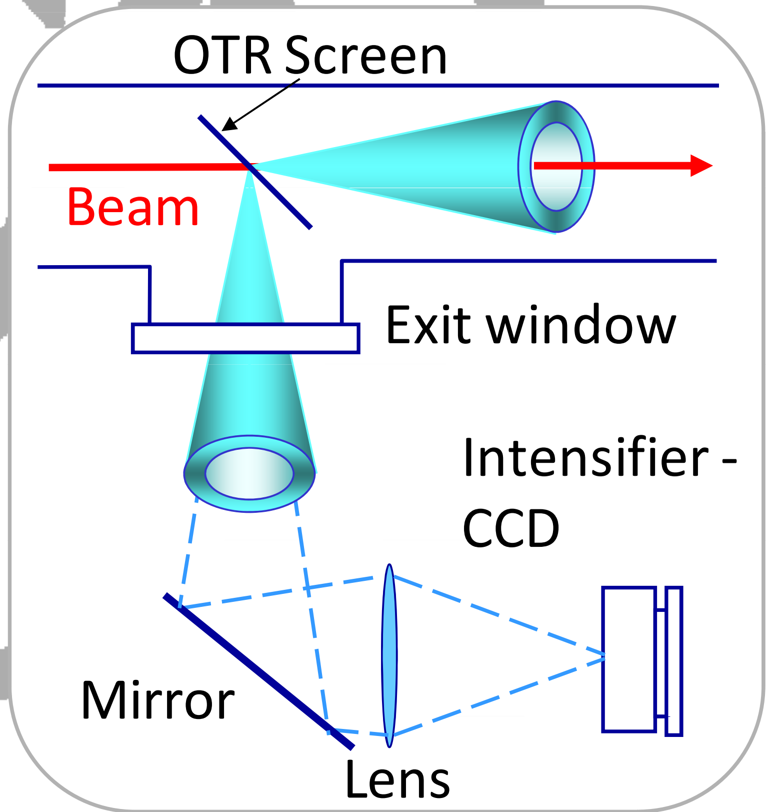
Dealing with high beam powers

Non-invasive measurement techniques

Dealing with High Beam Power - The Issues

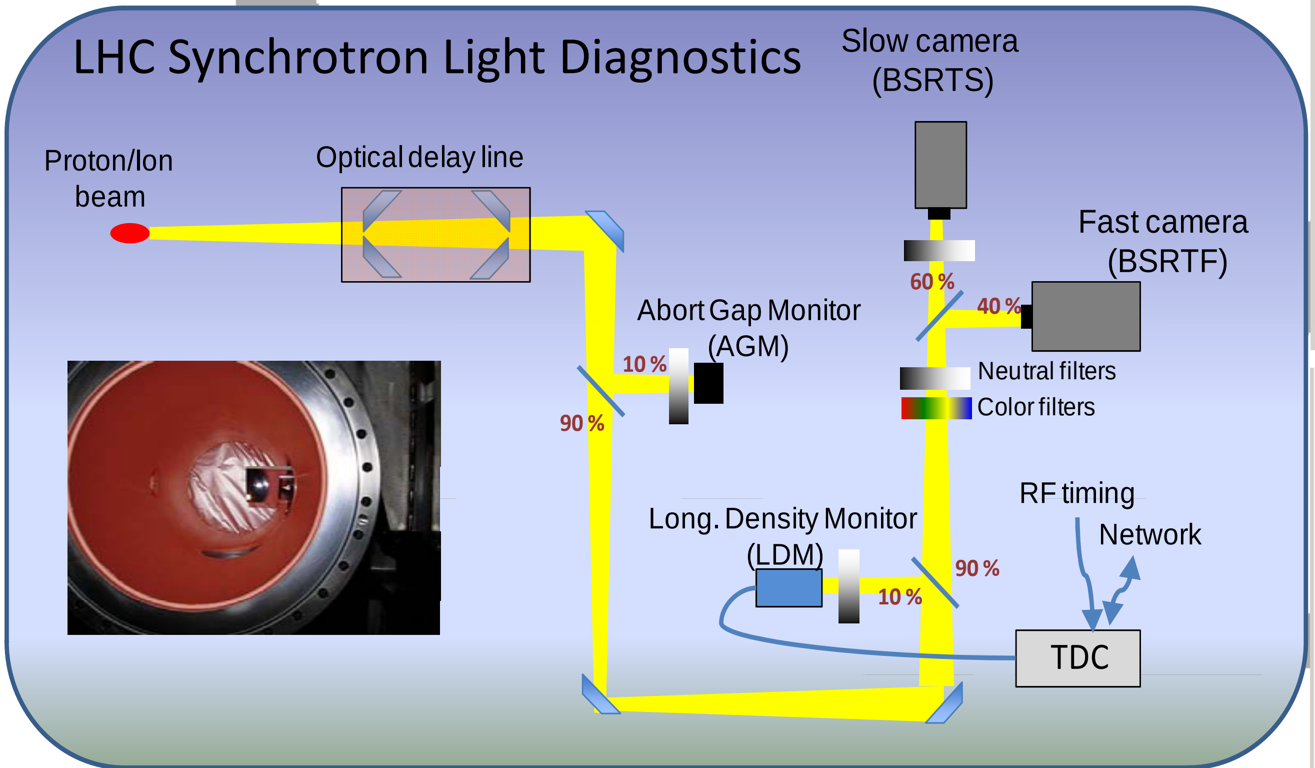
- **Traditional invasive diagnostics no longer suitable**
  - Materials do not withstand energy deposition
    - Burning of holes or breaking of wires
  - Use of superconducting RF structures
    - Risk of contamination on breakage or sputtering of the intercepted material

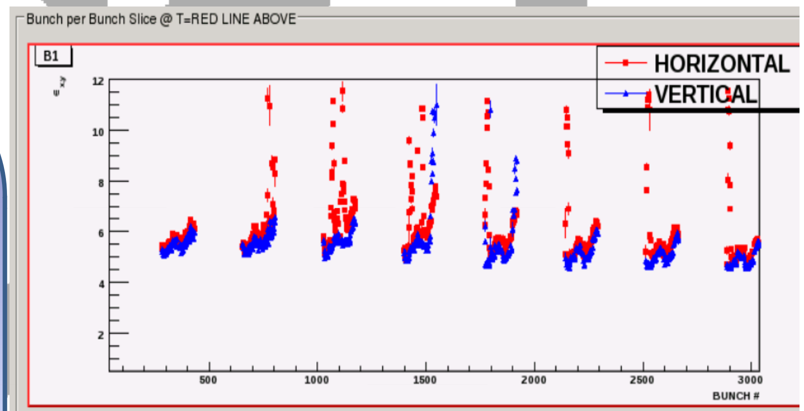


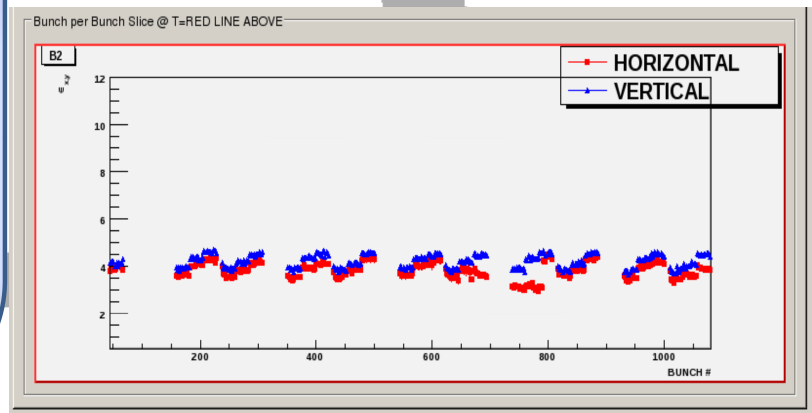


Measuring the Size of High Power Beams

- **Synchrotron Light Diagnostics**
  - Only for electron & very high energy proton/ion machines (LHC)
    - Difficult to separate the light from the beam for linear accelerators
  - 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

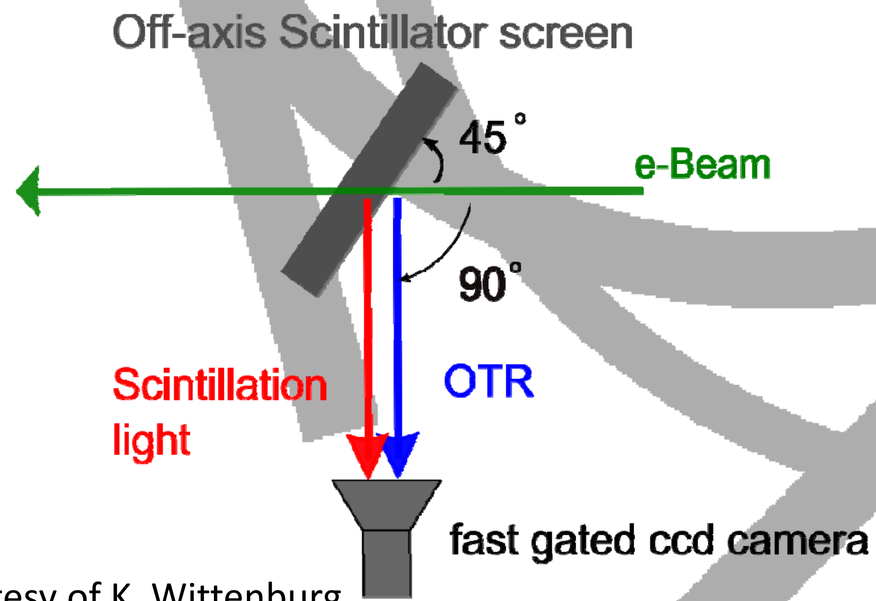




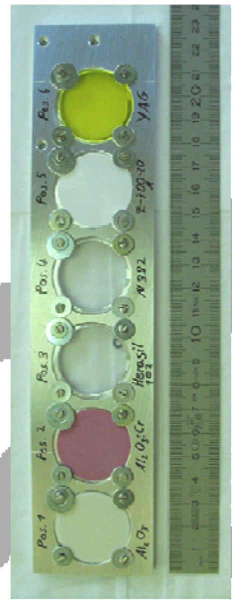


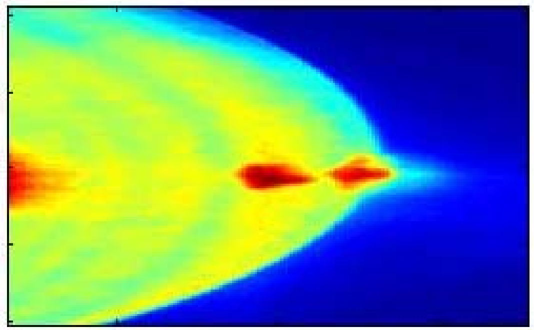
Measuring the Size of Intense Bunches

- **Standard OTR not an option for short intense bunches (main issue for LCLS)**
  - Signal swamped by Coherent OTR from micro-bunching within the main bunch
- **One proposal is to go to luminescent Screens**
  - There will still be COTR at polished surfaces
  - Resolution might be a problem
- **Investigation of temporal suppression of COTR**
  - Scintillation screen + fast gated camera
  - Proof-of-principle at FLASH, DESY
- **Resolution of scintillation screens needs study**
  - Synergy with ion beam diagnostics
  - Similar studies ongoing for FAIR

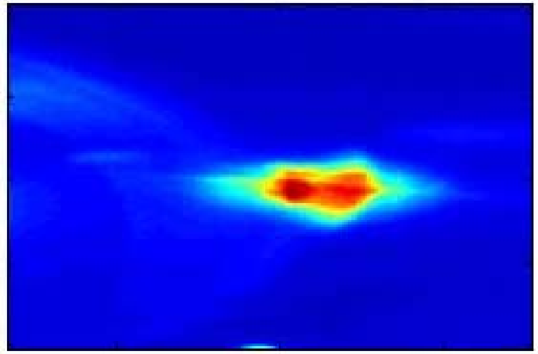


Courtesy of K. Wittenburg

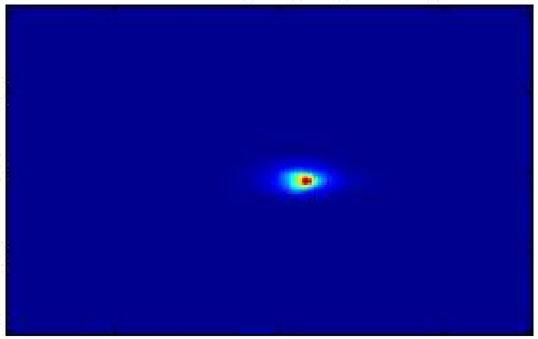




Al coated Si OTR screen, COTR light, Coherent SR



LuAG screen, COTR & scintillation light

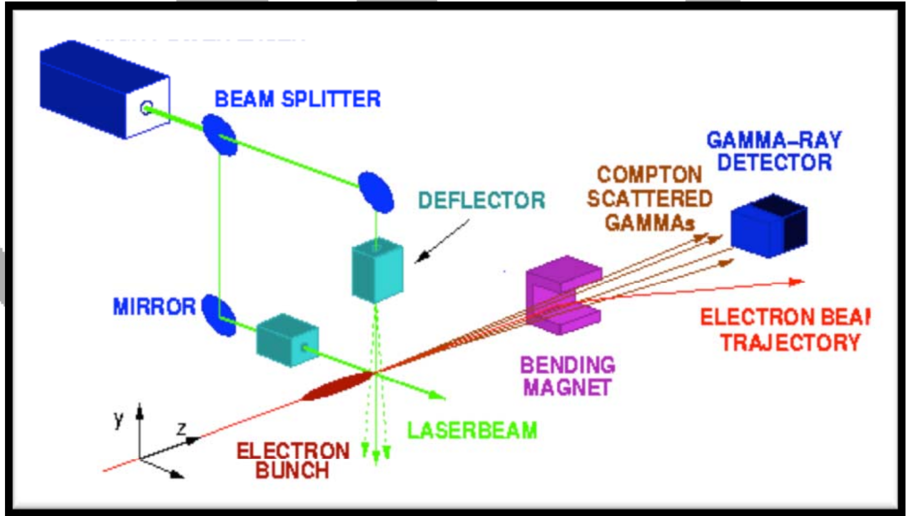


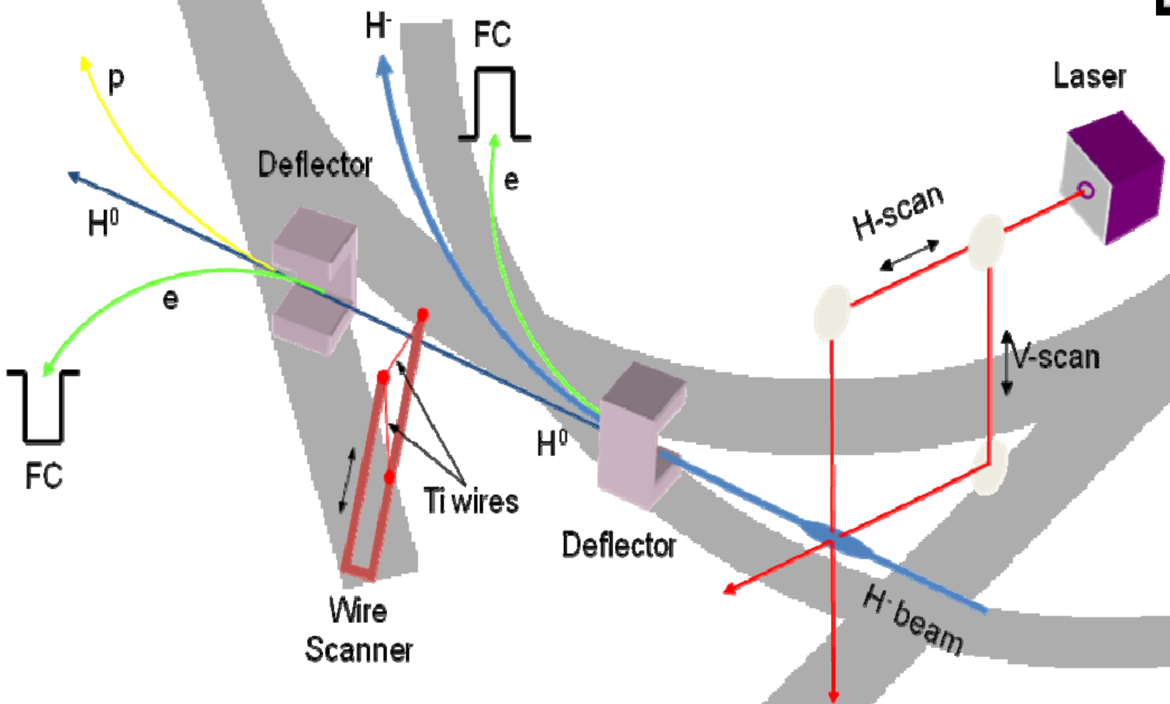
LuAG screen +100ns delay Only scintillation light

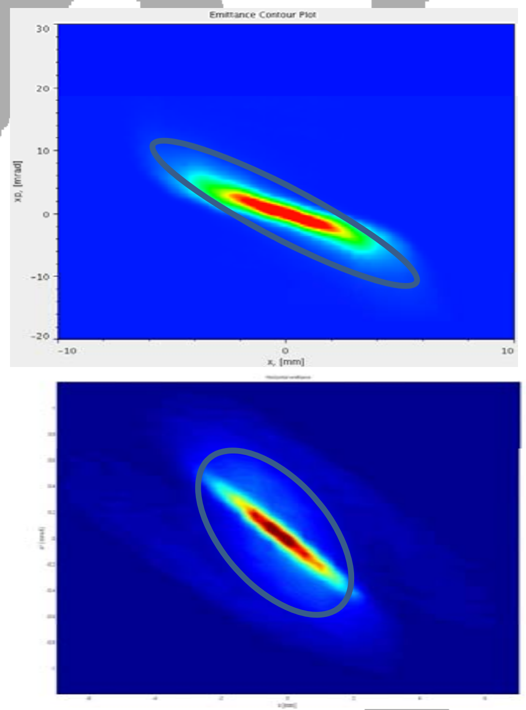
Courtesy of M. Yan

Non-Invasive Beam Size Measurement

- **Laser wire scanner**
  - Good candidate for H^- & electrons
    - Can measure down to micron level
  - Needs conversion to turn-key instrument
    - Reliable laser system
    - Laser distribution to multiple measurement stations



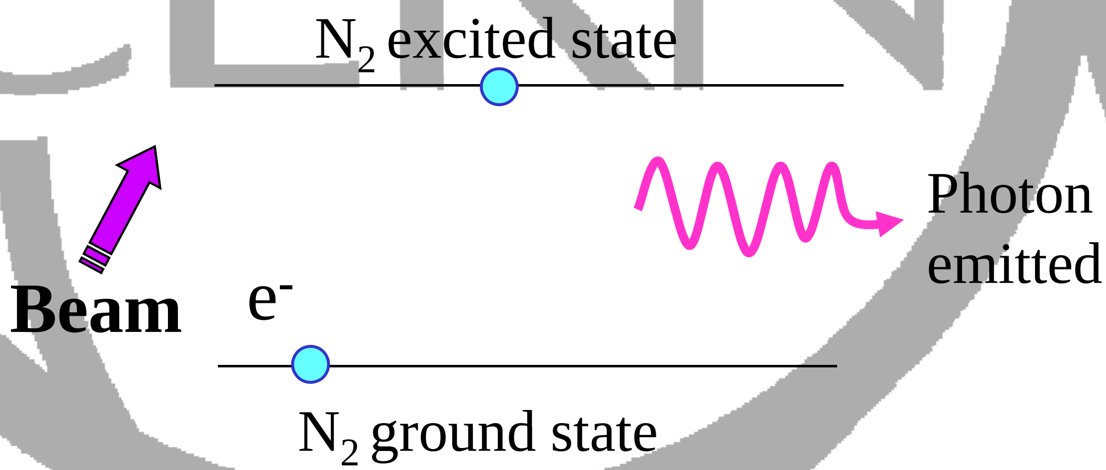




Courtesy of A. Alexandrov

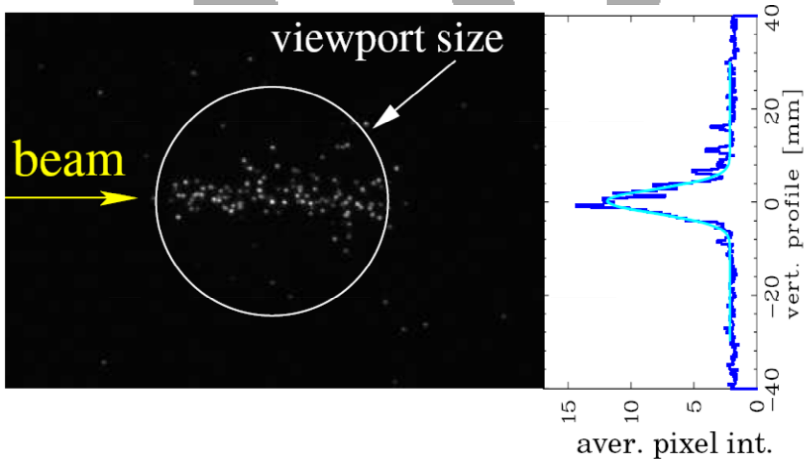
Non-Invasive Beam Size Measurement

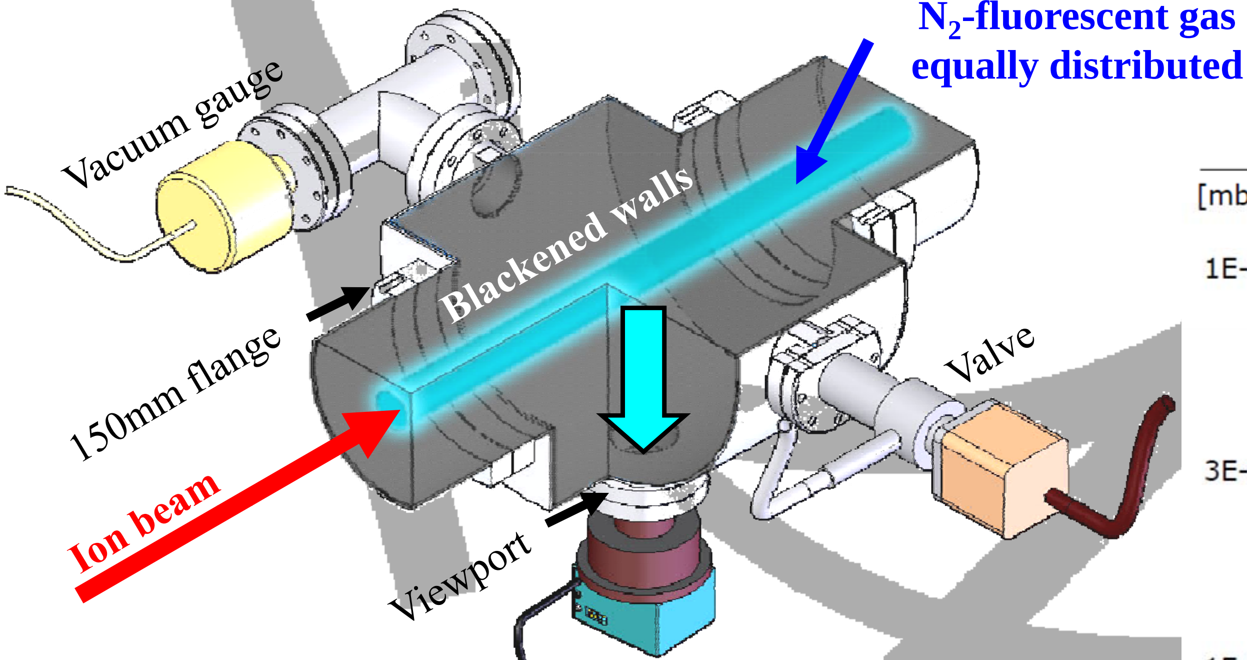
- **Beam Induced Fluorescence**



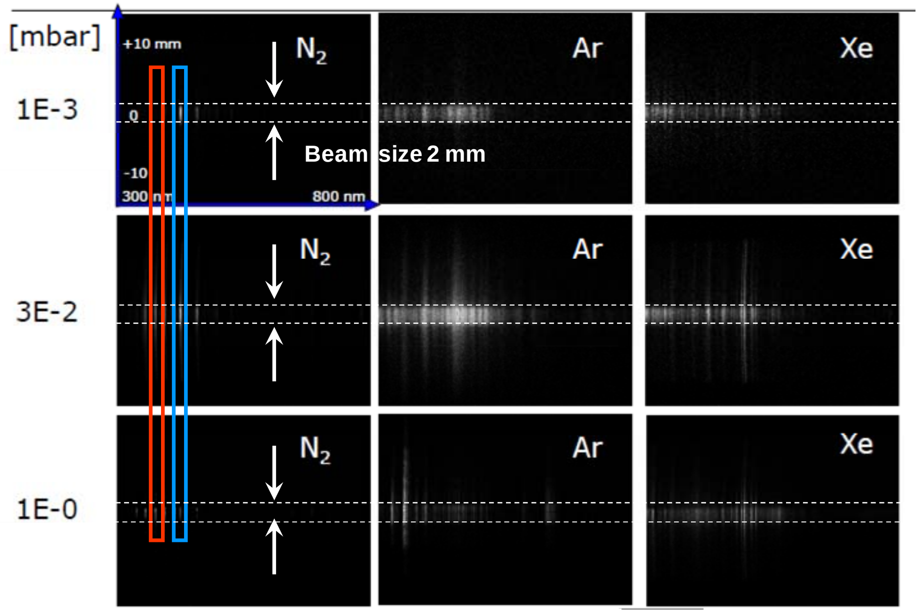
Non-Invasive Beam Size Measurement

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





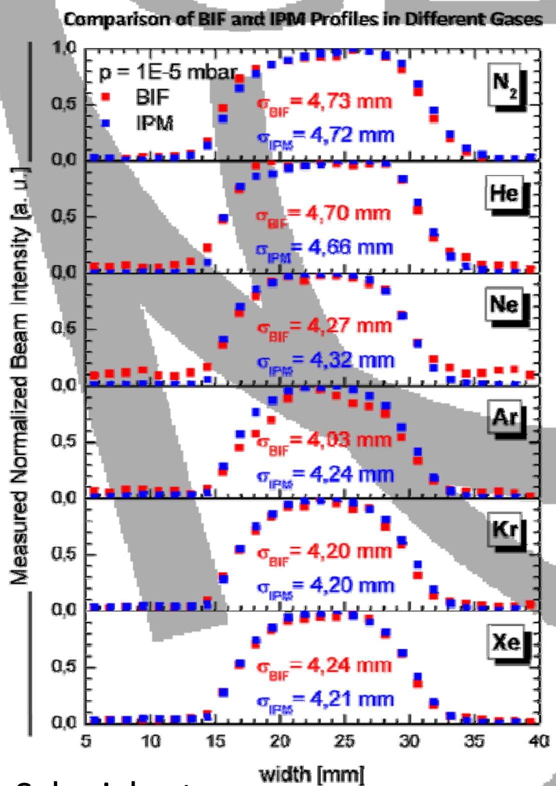
Lens, Image-Intensifier
and CCD FireWire-Camera

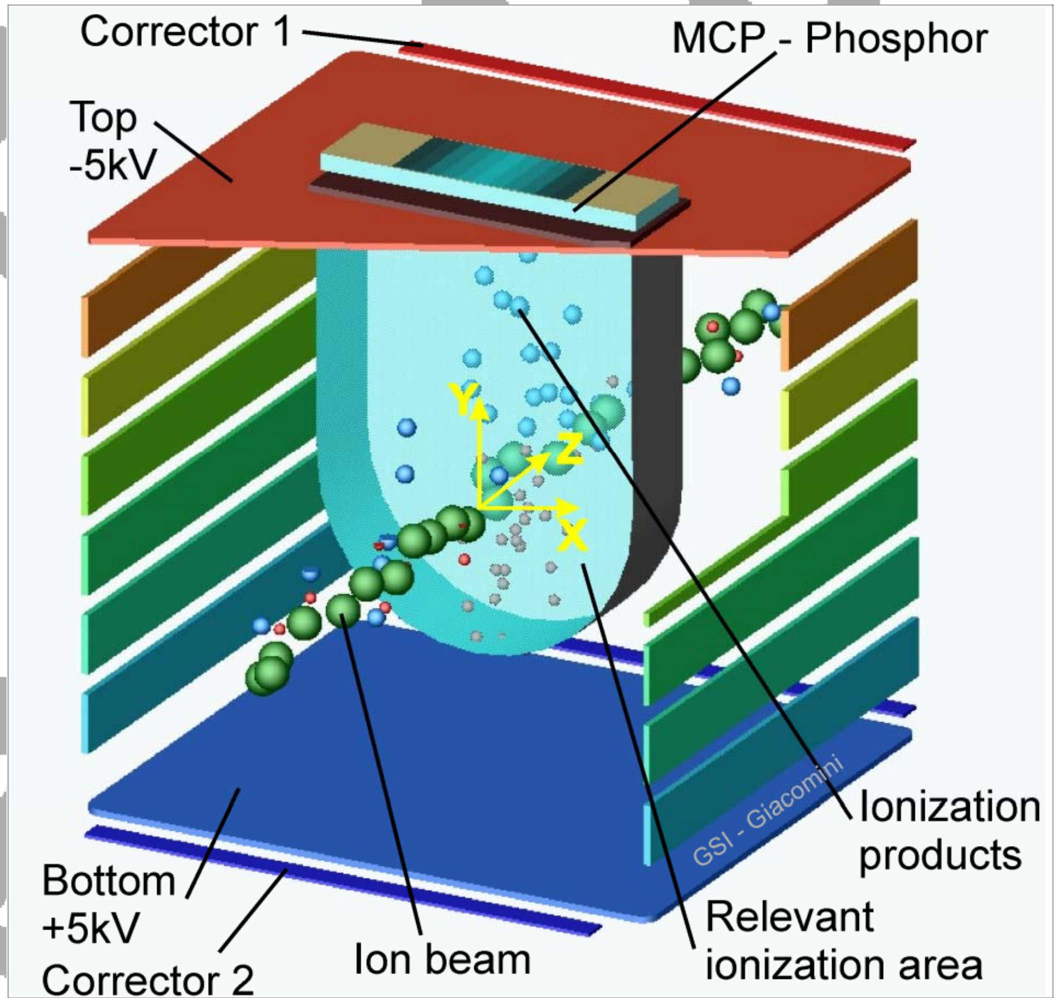


Courtesy of M. Schwickert

Non-Invasive Beam Size Measurement

- **Residual Gas Ionisation**
  - Some 10 times more sensitive than BIF
  - More complicated to build
    - High voltage network
    - Guiding magnetic field
  - Image broadening due to space charge
  - Ageing of detectors an issue





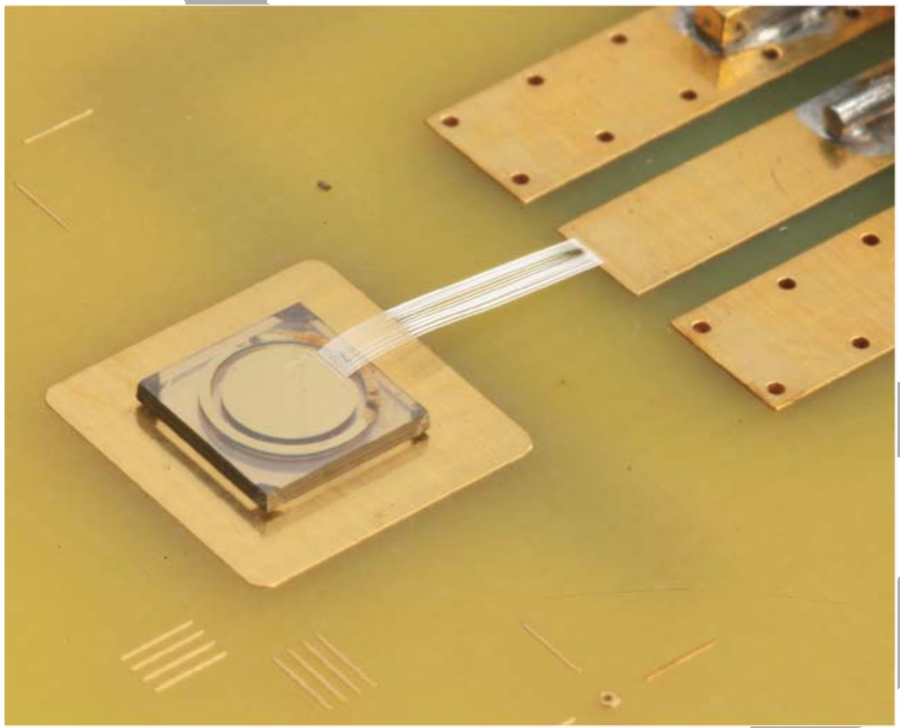
Courtesy of M. Schwickert

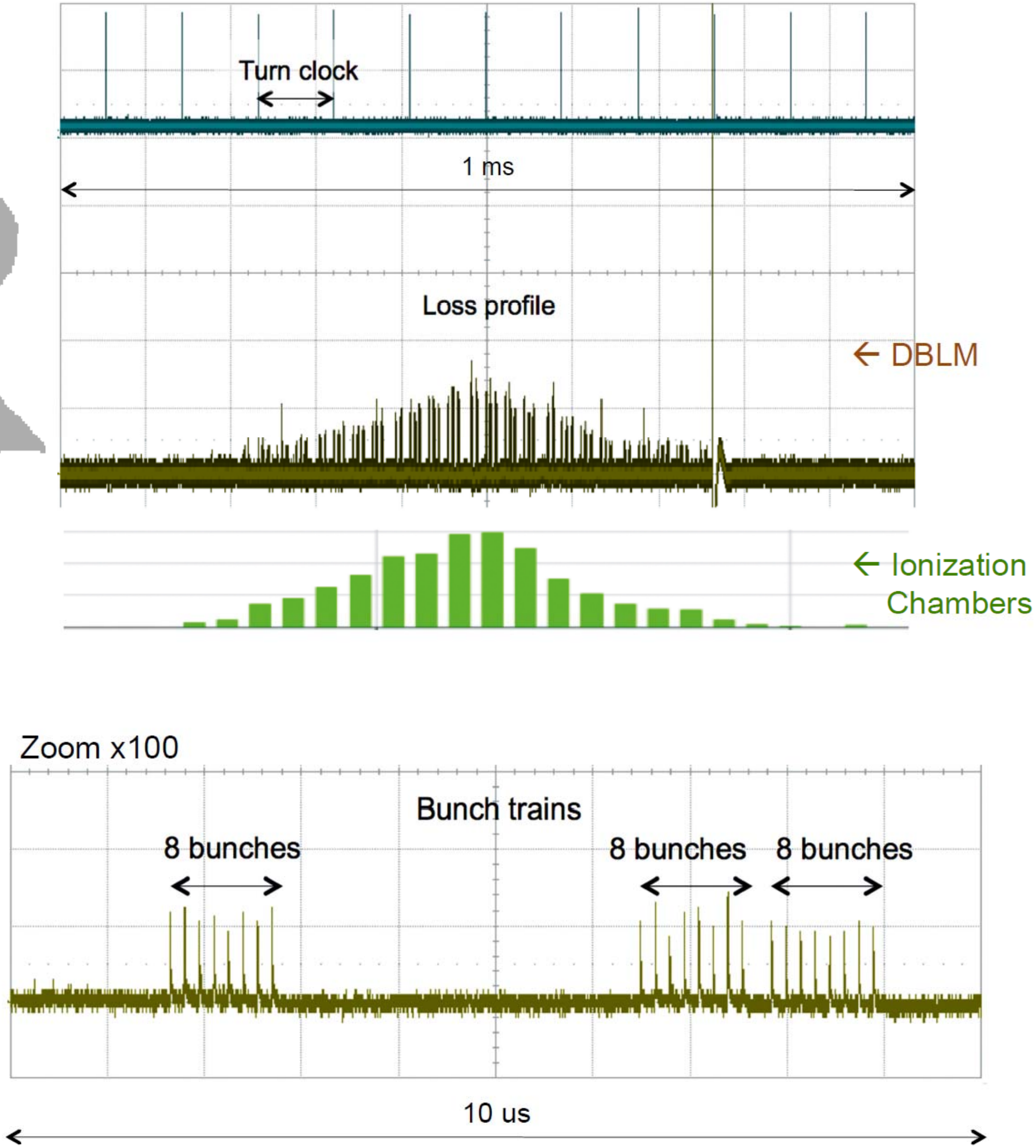
Dealing with high beam powers

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





Courtesy of E. Griesmayer

Challenges for Beam Instrumentation

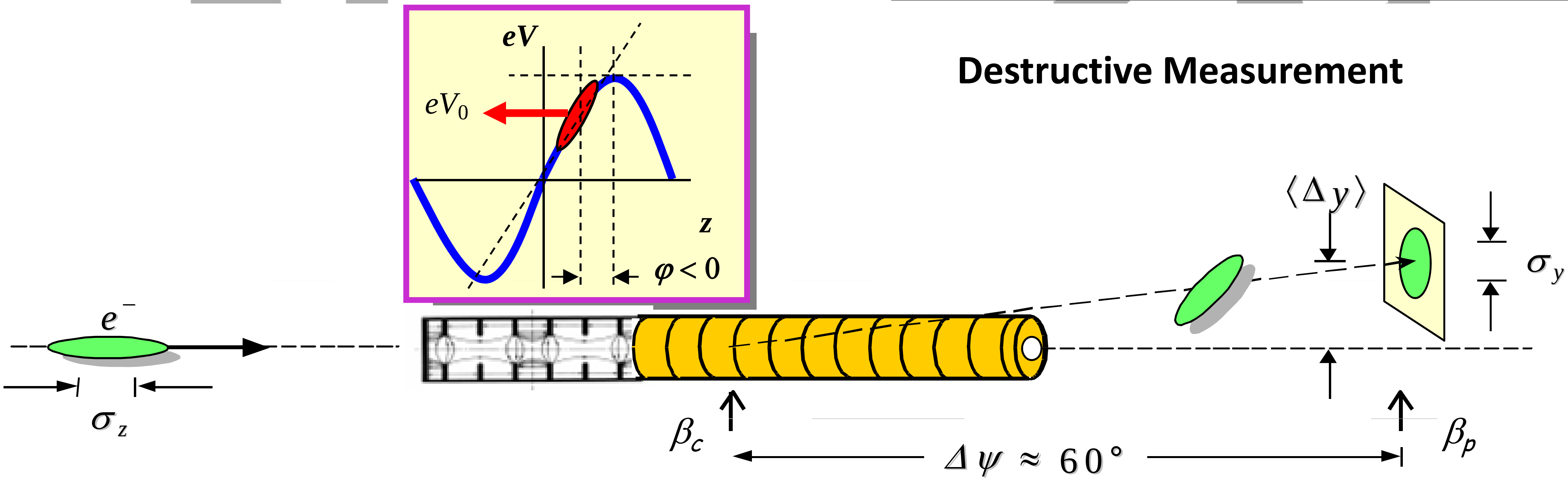
Dealing with the ultra-fast

Measurements on the femto-second timescale

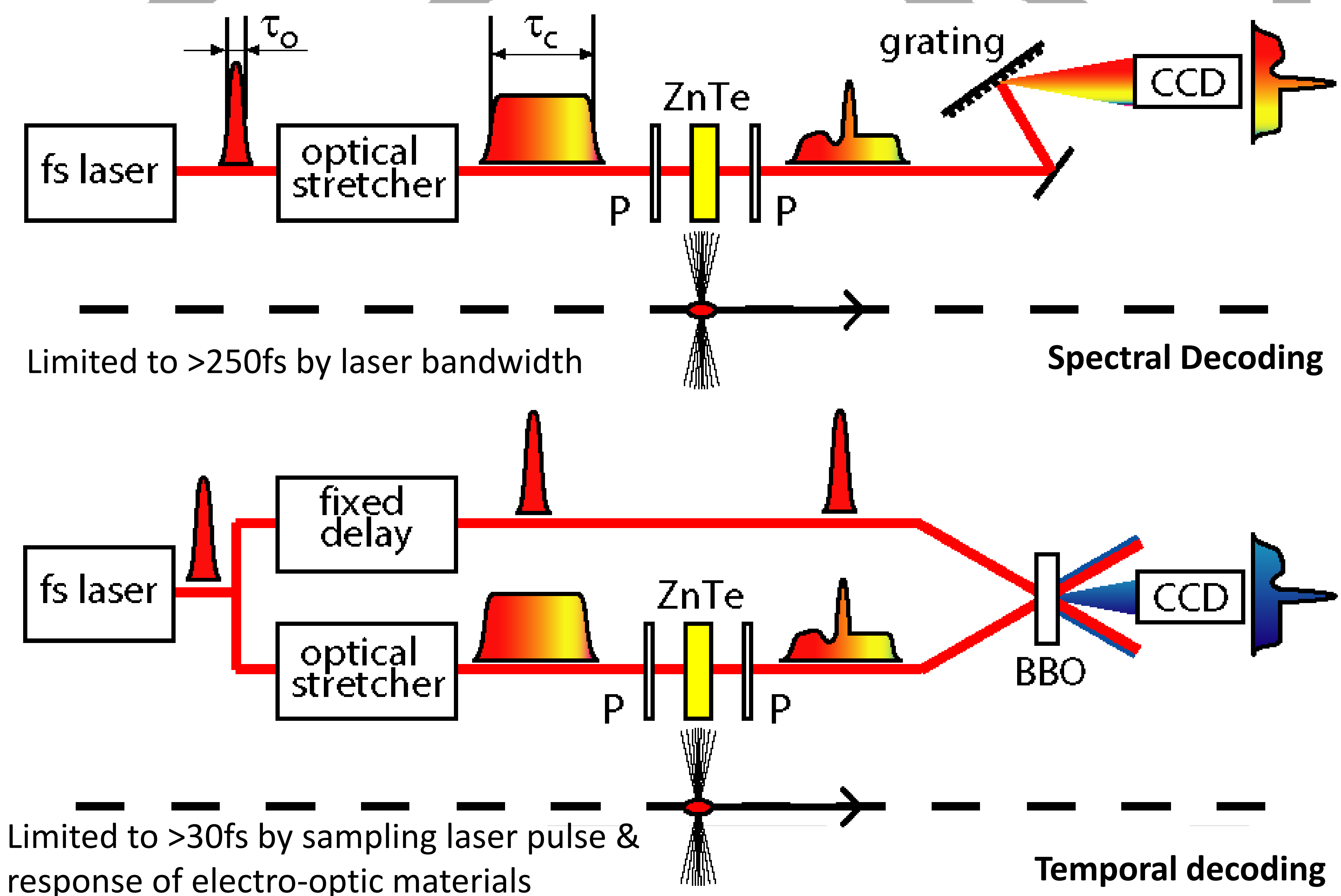
Ultra-Short Bunch Length Diagnostics

- **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

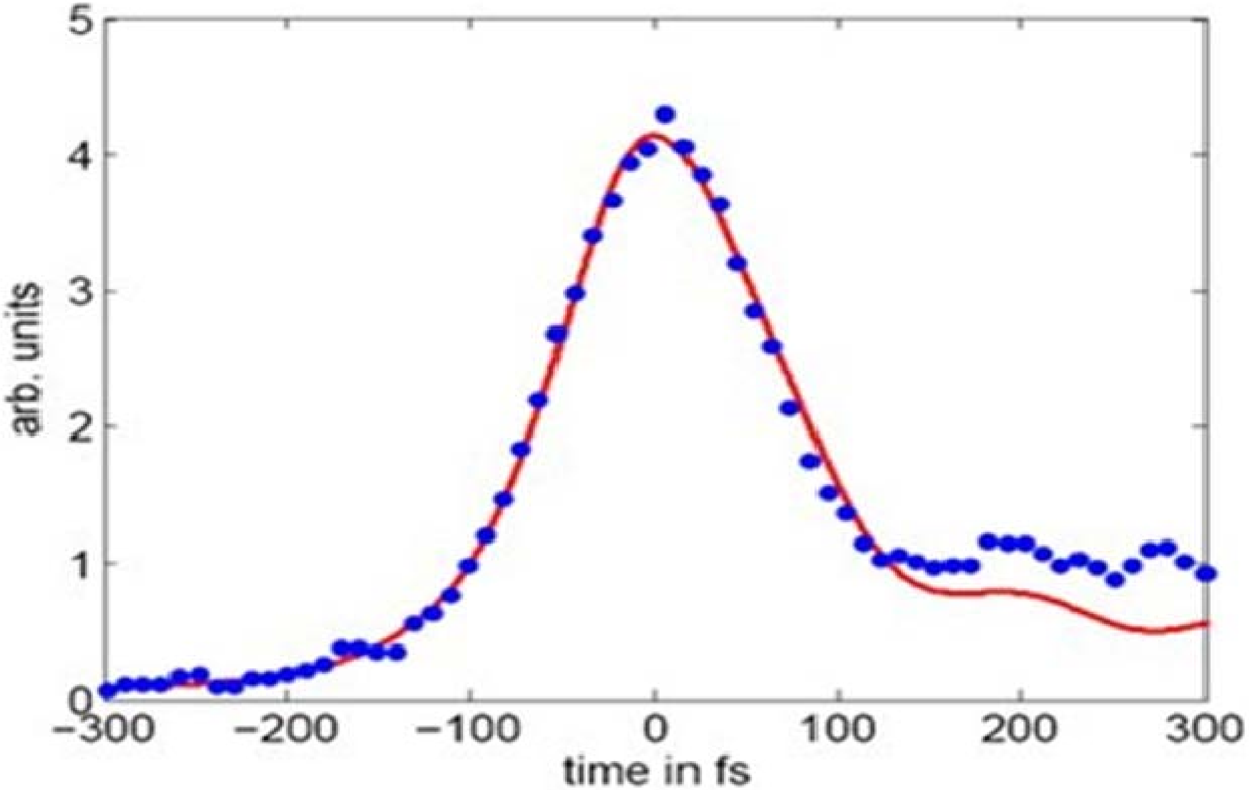


Non Destructive – Electro-Optic Sampling



Non Destructive – Electro-Optic Sampling

- **Shortest measured electron bunch profile**
  - 79.3 ± 7.5 fs at DESY FLASH
  - Using 65um thick GaP crystal



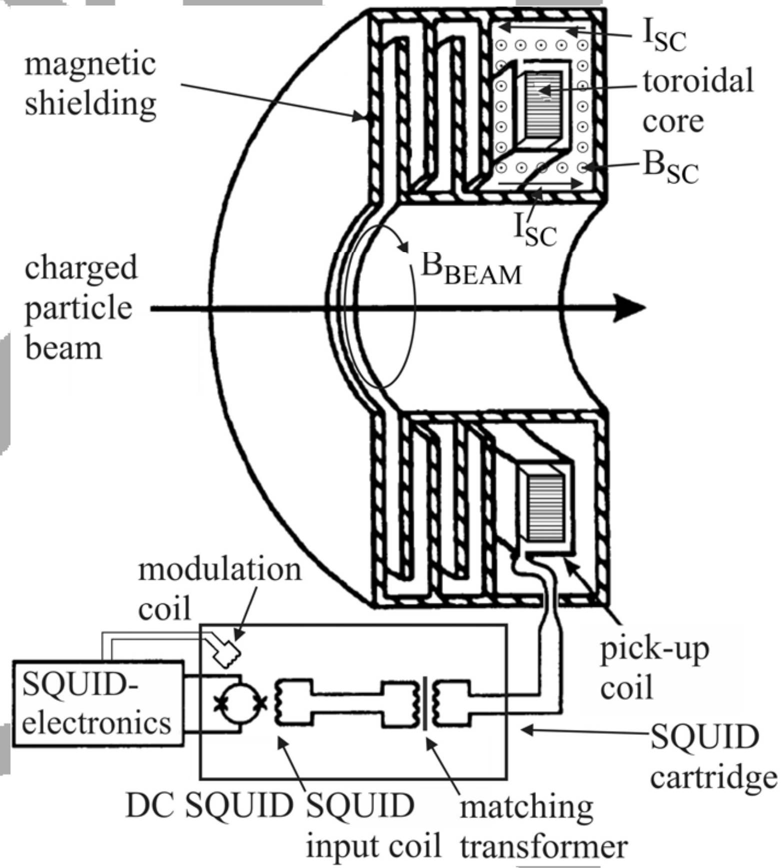
Courtesy of A. Gillespie

Dealing with the ultra-low

Measurement of very small beam currents

Measuring very low Intensity Beams

- **Measuring rare ions and antiprotons**
  - Currents well below 1μA resolution of traditional Direct Current Beam Transformers
- **Superconducting QUantum Interference Devices**
  - Can overcome the limits of conventional systems
  - Both low and high temperature versions have been developed
- **Challenges**
  - Shielding the detector from stray fields
    - Earth's magnetic field ~ 50μT
    - Field produced by 100 nA beam at 10 cm ~ 0.2 pT !
  - Making the system compact
- **Cryogenic Current Comparator (CCC)**
  - Charged particle beam induces screening currents
  - Toroidal pick-up coil of niobium with ferromagnetic core is used to measure magnetic field
  - Signal from coil is fed through a superconducting transformer for impedance matching to the input coil of the readout DC SQUID.



Conclusion

- **Particle Beam Diagnostic systems are continually evolving to meet the requirements of**
  - ever more powerful and sophisticated 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
  - Was already underway between the major accelerator laboratories worldwide
  - Now strengthened and extended to universities and industry via European Networks