Beam Instrumentation – Part II

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Acknowledgements: R. Jones, P. Forck & U. Raich

Overview

- Beam instrumentation are the 'eyes and ears' of accelerators.

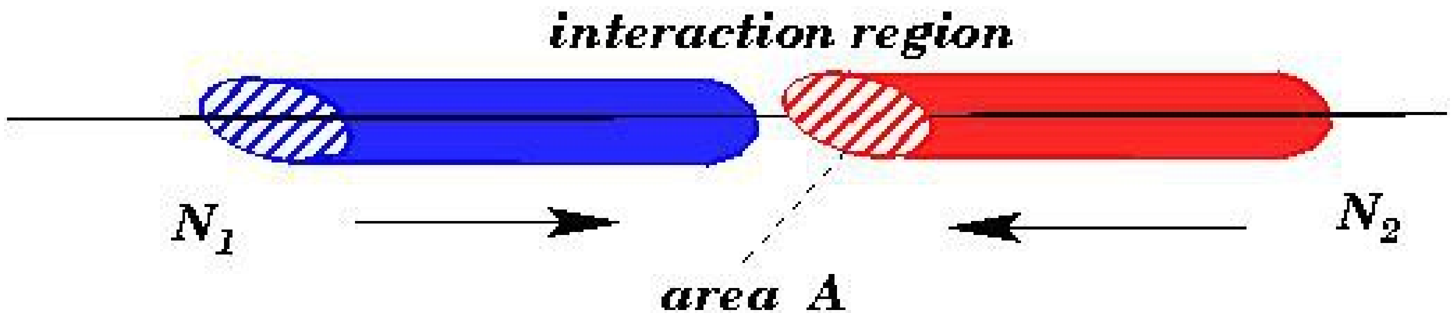
- Part I: electro-magnetic pick-ups (yesterday)
  – Beam intensities: Faraday-Cup, Fast-BCT, DC-BCT, WCM
  – Beam position: position and long. profile: Button-, Strip-line-, and Cavities

- Part II: beam loss and transverse beam profile
  – SEMs, wire scanner, OTR screens, luminescence, synch-light
  – Ionisation chamber, diodes, diamonds, scintillators, (cherenkov)
  – Special ultra-fast devices: electro-optical sampling & streak-camera

- An accelerator can never be better than the instruments measuring its performance!
  → Important skill to assess whether beam observations are 'new/known physics', 'instrumental', or to guide whether/how performance can be improved.

Figure of Merit for most Accelerators

- For a collider – luminosity L_{peak}:



$$L_{peak} \sim \frac{N_1 \cdot N_2}{A} \sim \frac{N_1 \cdot N_2}{\pi \sigma_x \sigma_y}$$

- For a synchrotron-light source – Brilliance B:

$$B \sim \frac{N_{photons}}{A \cdot d\varphi \, d\theta} \sim \frac{N_1 \rightarrow N_1^2}{\pi \sigma_x \sigma'_x \sigma_y \sigma'_y}$$

Increase this → intensity instrumentation

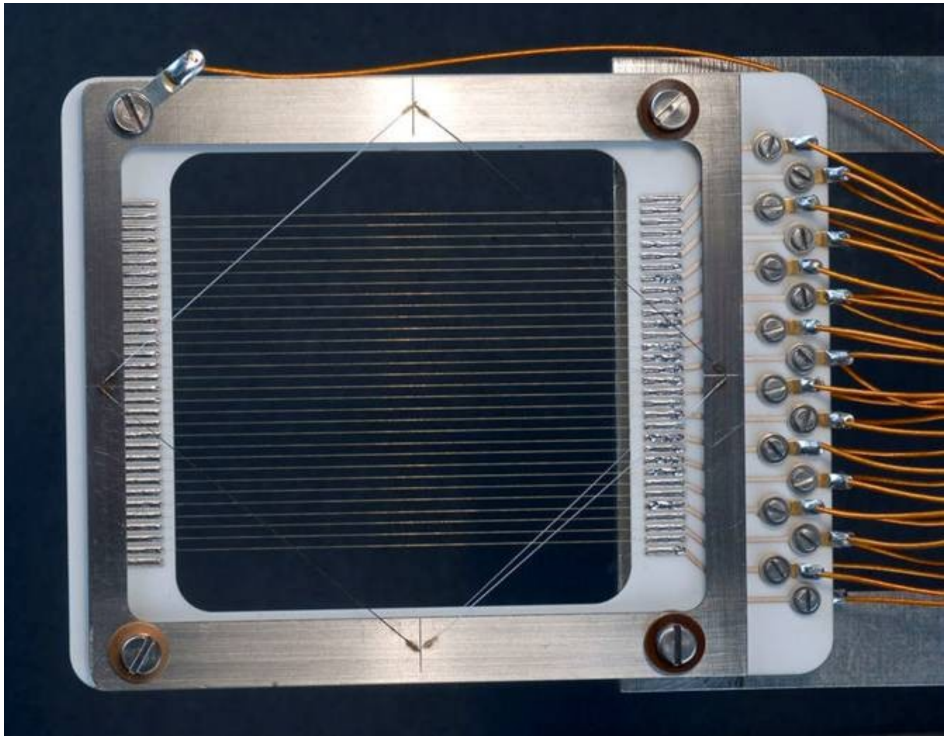
Decrease this → profile instrumentation (todays focus)

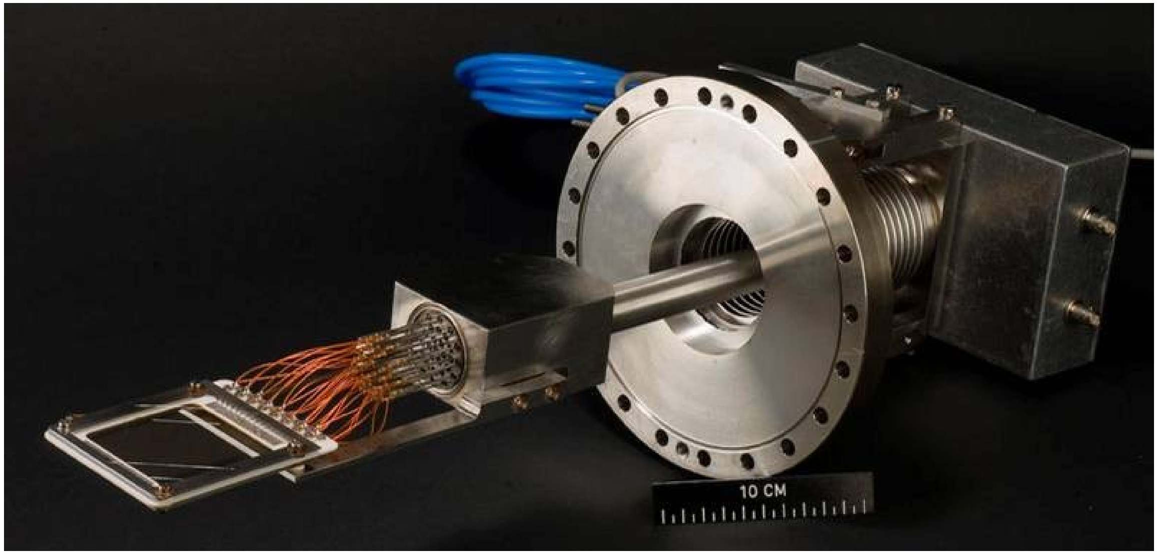
The Typical Instruments

- Beam Intensity
  - Faraday cups, beam current transformers, wall-current monitors
- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionisation and luminescence monitors
  - Femto-second diagnostics for ultra short bunches
- Beam Loss
  - Cherenkov optical fibre, ionisation chambers or pin diodes
- Machine Tune, Chromaticity and Luminosity → diagnostics tutorial

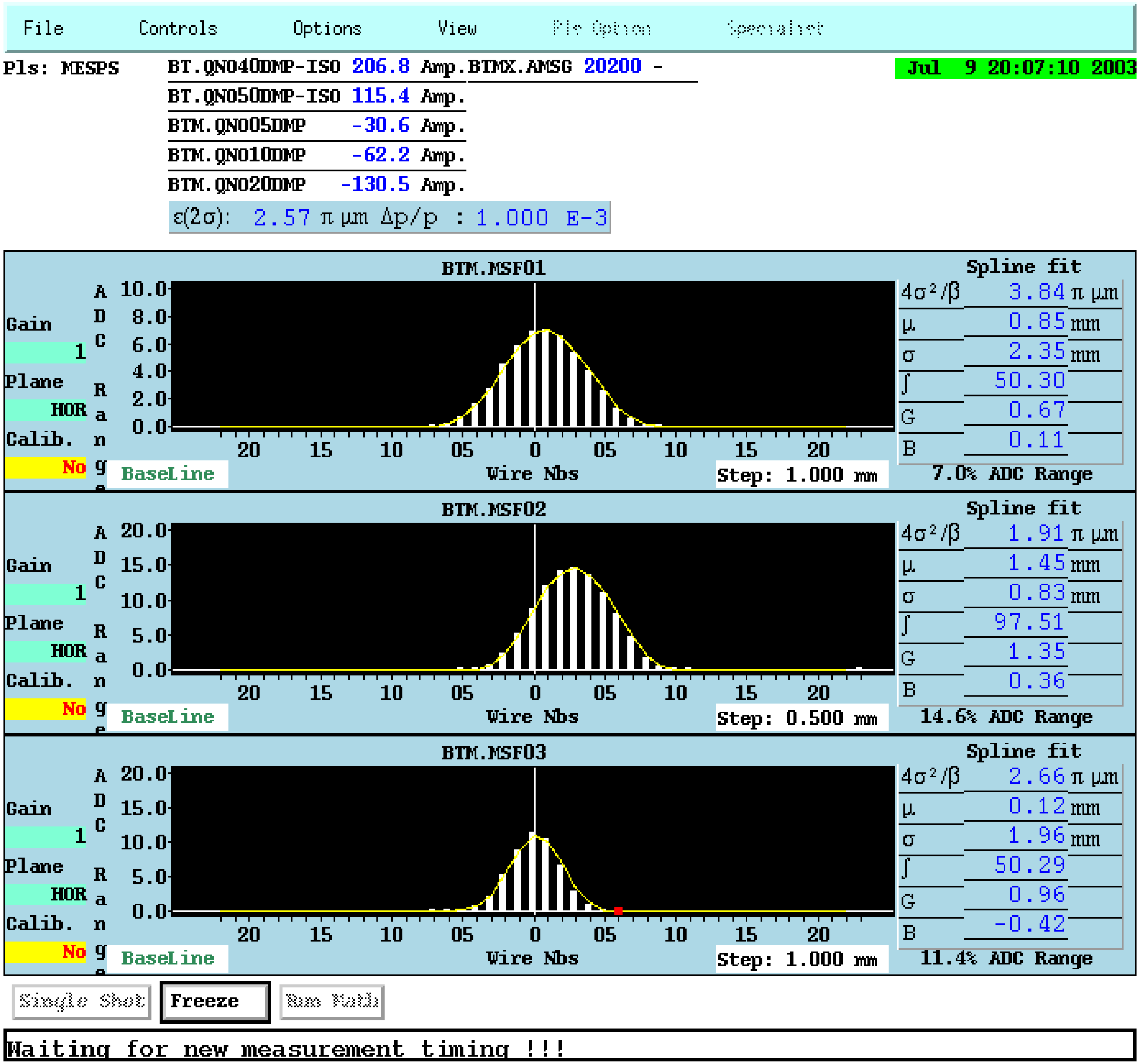
Secondary Emission (SEM) Grids

- When the beam passes through secondary electrons are ejected from the wires
- The liberated electrons are removed using a polarisation voltage
- The current flowing back onto the wires is measured
- One amplifier/ADC chain is used for each wire





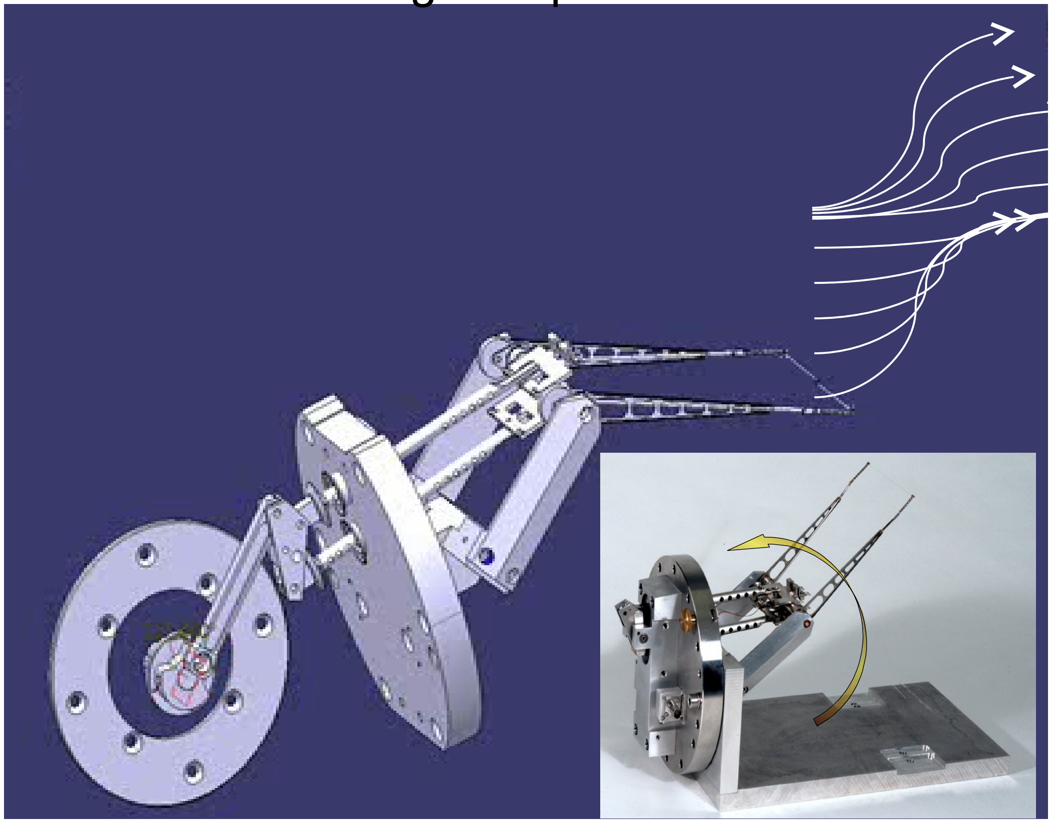
Profiles from SEM grids

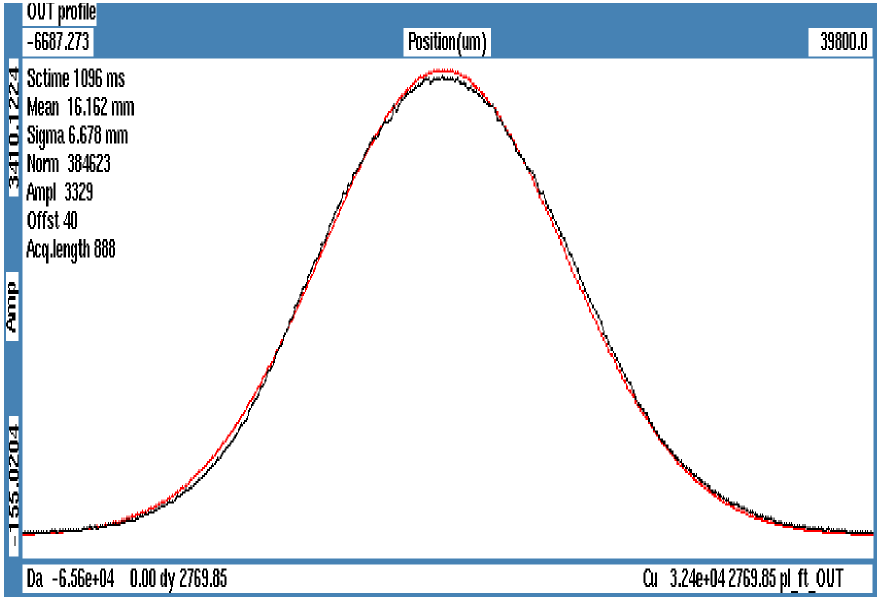


- Charge density measured from each wire gives a projection of the beam profile in either horizontal or vertical plane
- Resolution is given by distance between wires
- Used only in low energy linacs and transfer lines as heating is too great for circulating beams

Wire Scanners

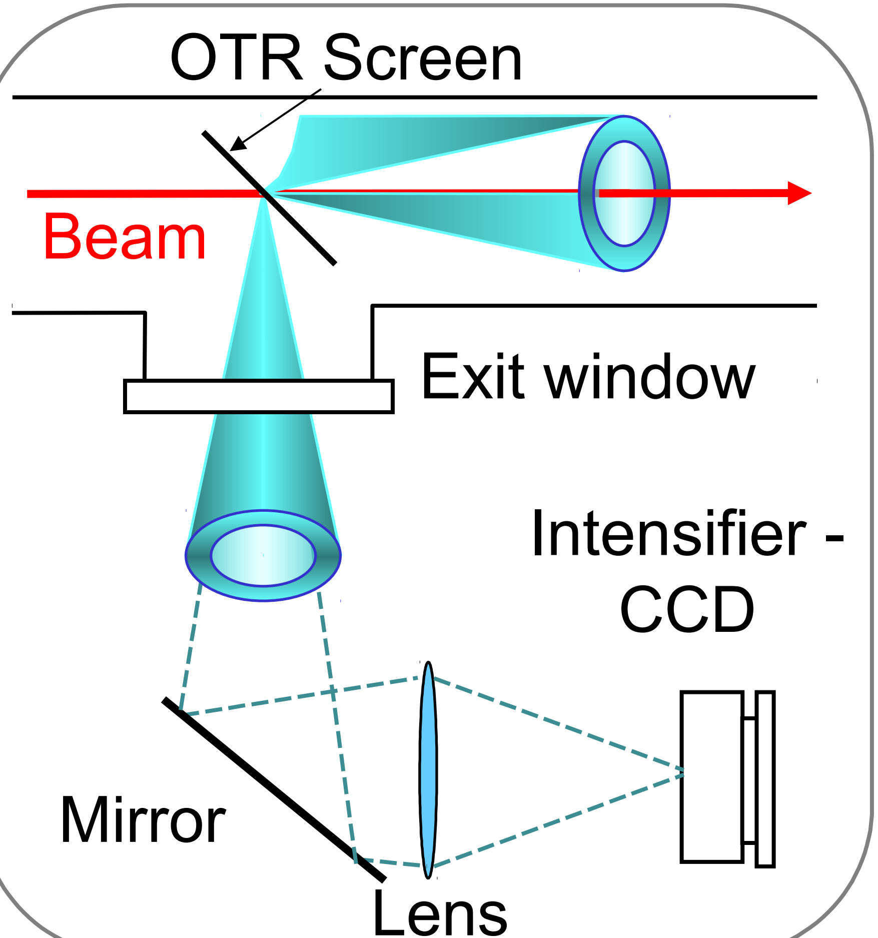
- A thin wire is moved across the beam
  - has to move fast to avoid excessive heating of the wire and/or beam loss
- Detection
  - Secondary particle shower detected outside the vacuum chamber using a scintillator/photo-multiplier assembly
- Secondary emission current detected as for SEM grids
  - Correlating wire position with detected signal gives the beam profile

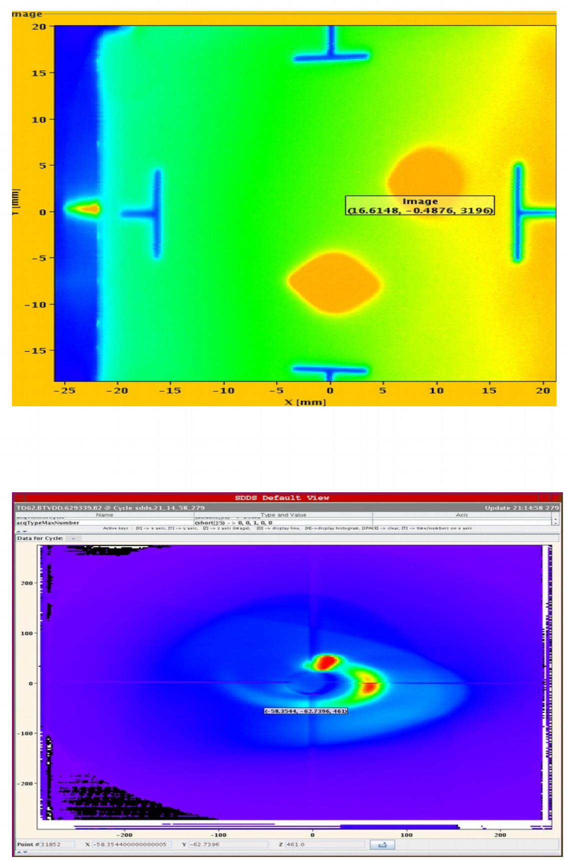




Beam Profile Monitoring using Screens

- Optical Transition Radiation
  - Radiation emitted when a charged particle beam goes through the interface of 2 media with different dielectric constants
  - surface phenomenon allows the use of very thin screens (~10mm)





First full LHC turn 10/9/2008

Un-Captured beam sweeps through he dump line

Profile Monitoring using Screens

- Screen Types
  - Luminescence Screens
    - destructive (thick) but work during setting-up with low intensities
- Optical Transition Radiation (OTR) screens
  - much less destructive (thin) but require higher intensity

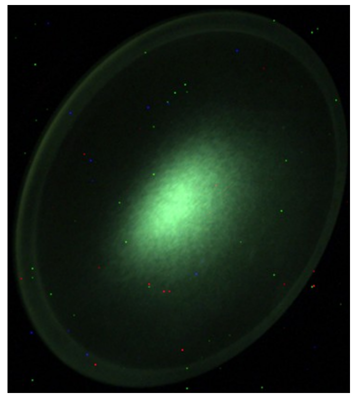
Sensitivities measured with protons with previous screen holder, normalised for 7 px/σ

Type	Material	Activator	Sensitivity
Luminesc.	CsI	Tl	$6\ 10^5$
"	Al_2O_3	0.5%Cr	$3\ 10^7$
"	Glass	Ce	$3\ 10^9$
"	Quartz	none	$6\ 10^9$
OTR [bwd]	Al		$2\ 10^{10}$
"	Ti		$2\ 10^{11}$
"	C		$2\ 10^{12}$
Luminesc. GSI	P43: Gd_2O_2 S	Tb	$2\ 10^7$

Light output from various Scintillating Screens

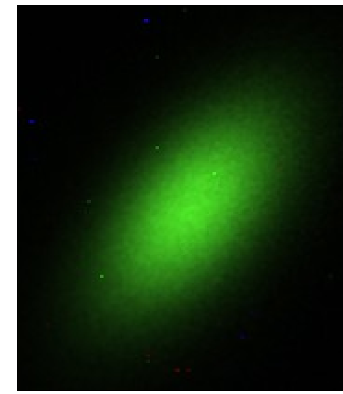
- Example: Color CCD camera

Al_2O_3

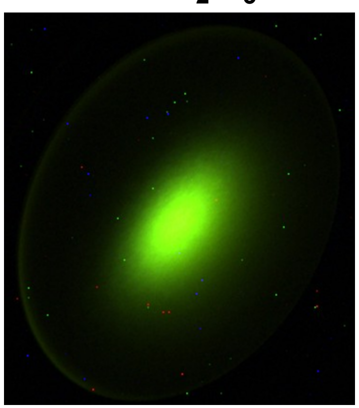


CsI:Tl

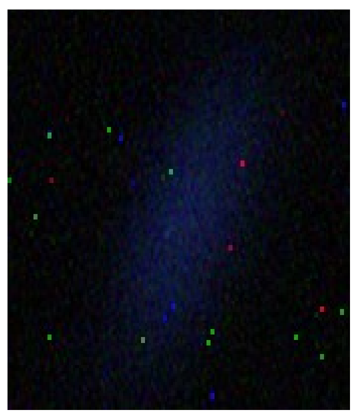
Al_2O_3:Cr



P43

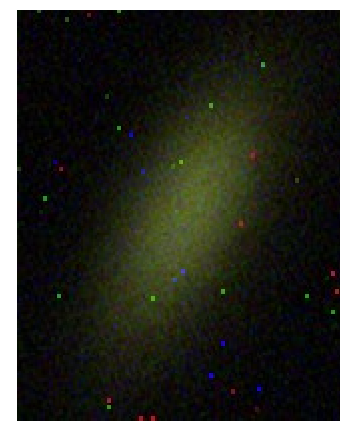


YAG:Ce



Herasil

Quartz:Ce

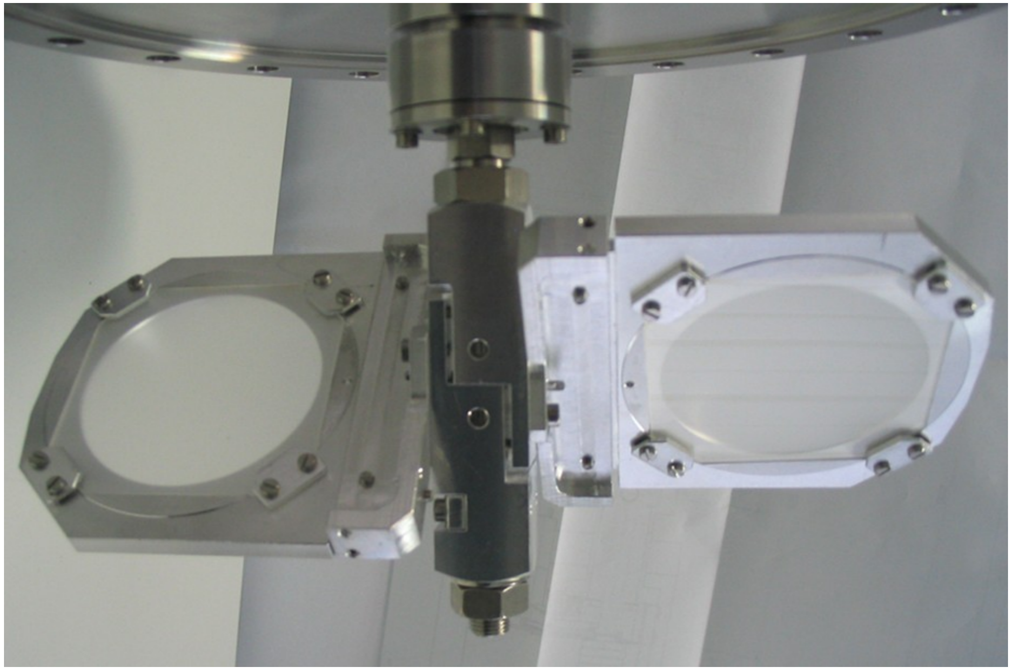


ZrO_2:Mg

– very different light yield i.e. photons per ion‘s energy loss
– different wavelength of emitted light

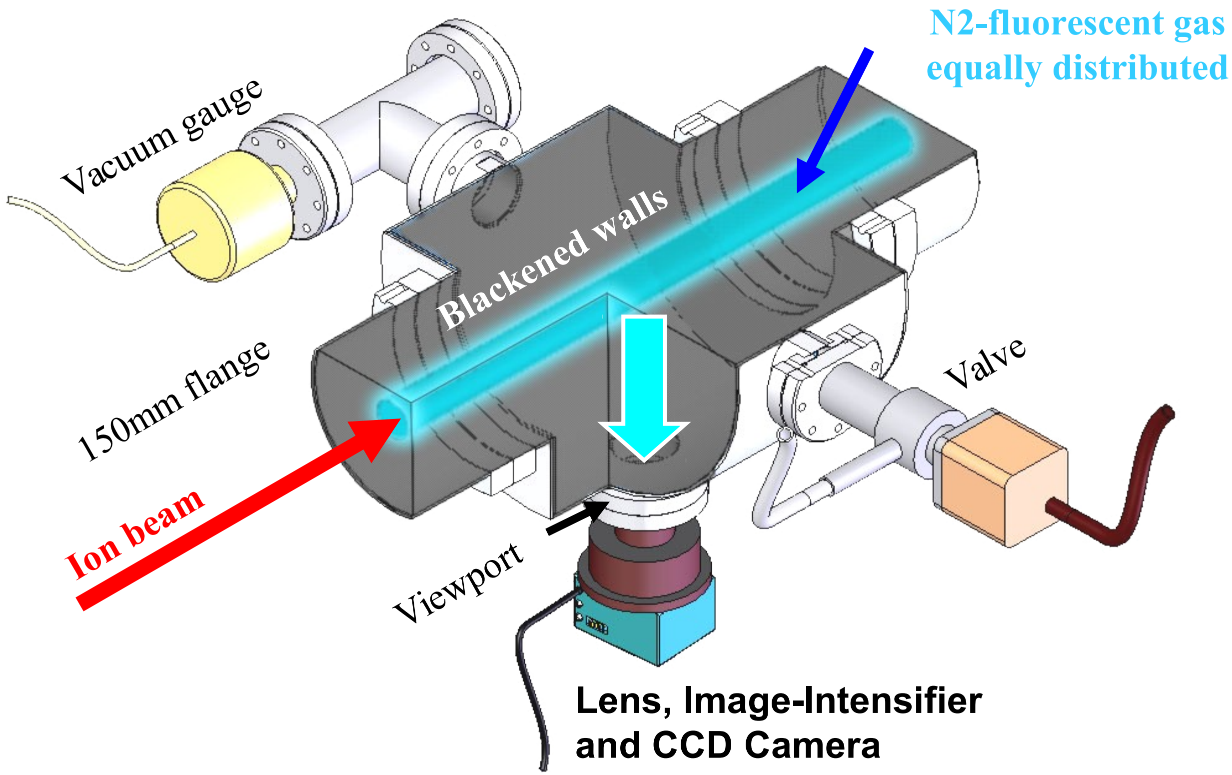
Profile Monitoring using Screens

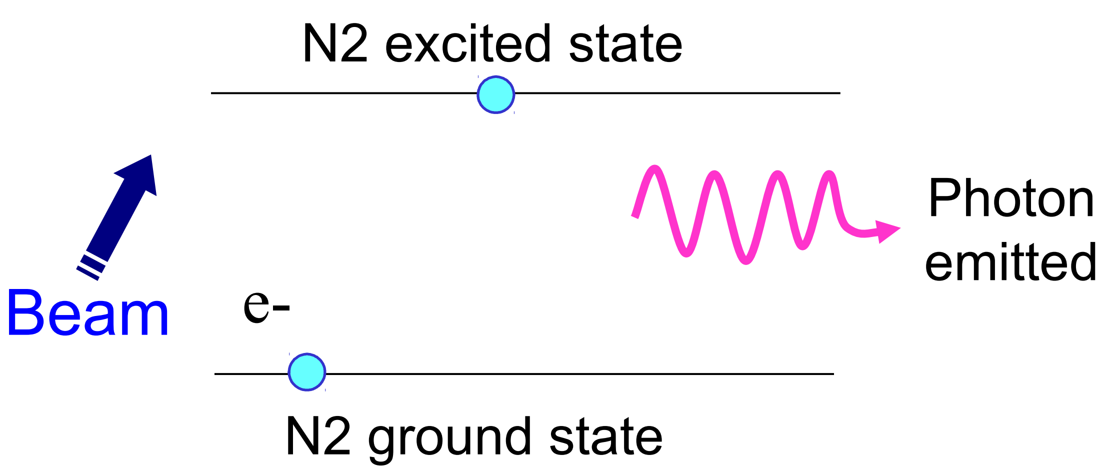
- Usual configuration
  - Combine several screens in one housing e.g.
    - Al_2O_3 luminescent screen for setting-up with low intensity
    - Thin (~10um) Ti OTR screen for high intensity measurements
    - Carbon OTR screen for very high intensity operation



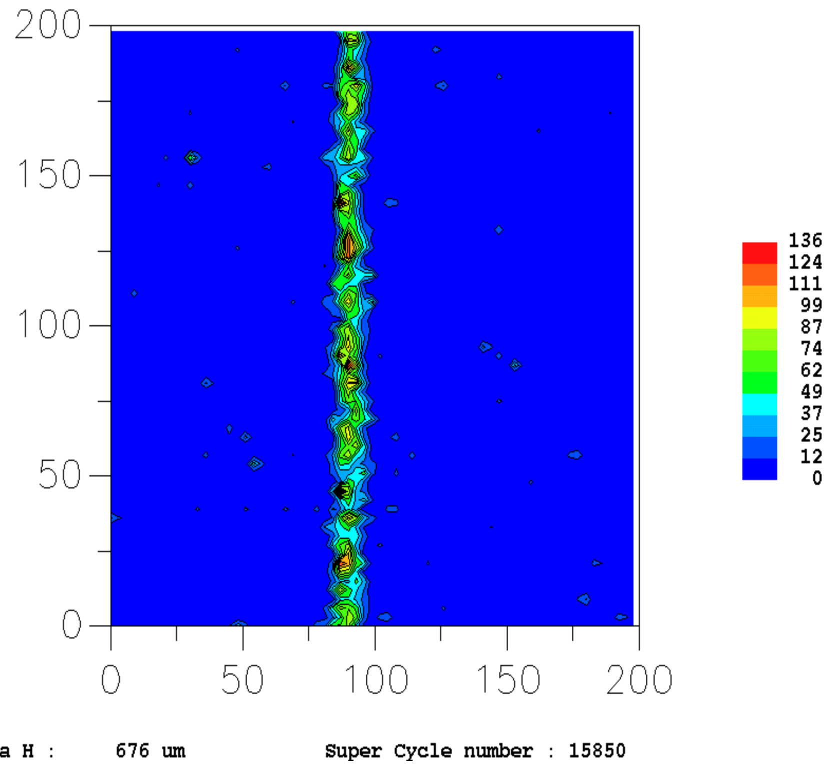
- Advantages compared to SEM grids
  - allows analogue camera or CCD acquisition
  - gives two dimensional information
  - high resolution: ~ 400 x 300 = 120’000 pixels for a standard CCD
  - more economical
    - Simpler mechanics & readout electronics
  - time resolution depends on choice of image capture device
    - From CCD in video mode at 50Hz to Streak camera in the GHz range

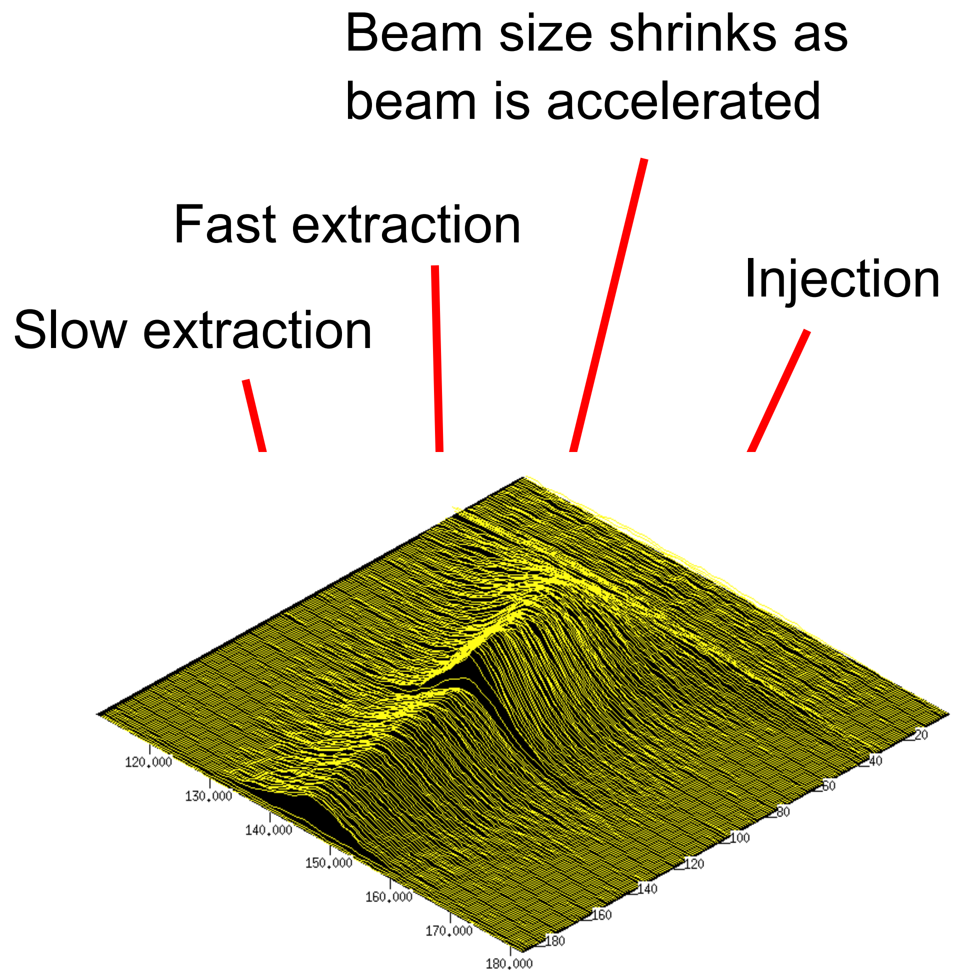
Luminescence or Rest-Gas-Ionisation Profile Monitor

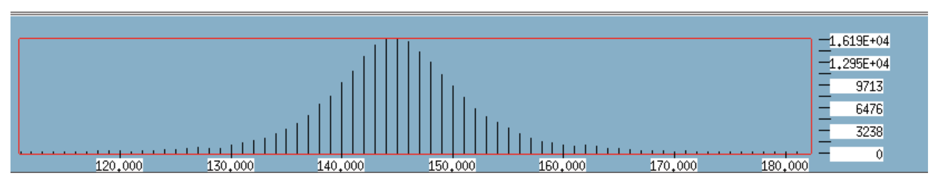




Luminescence or Rest-Gas-Ionisation Profile Monitor





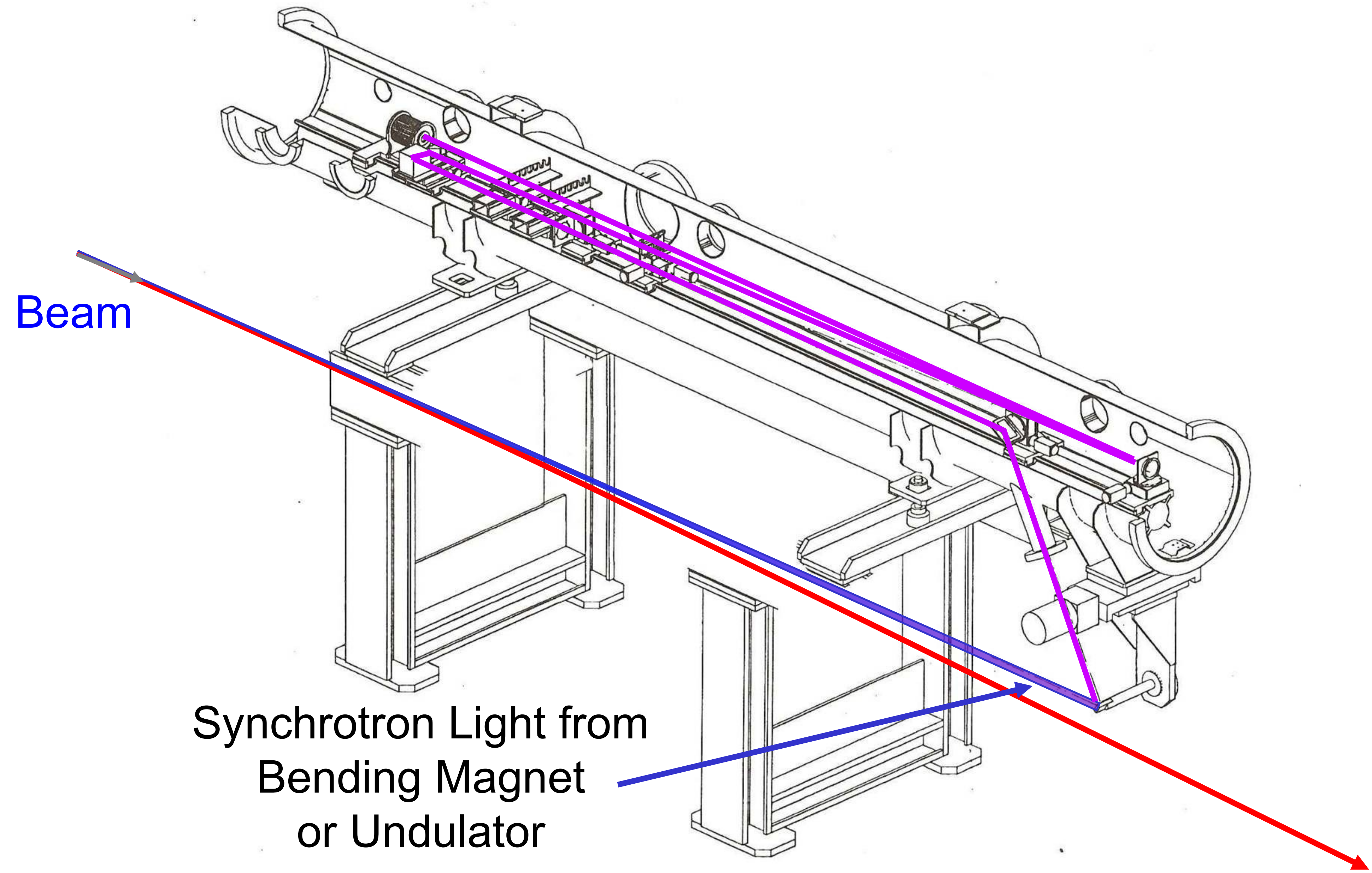


CERN-SPS Measurements

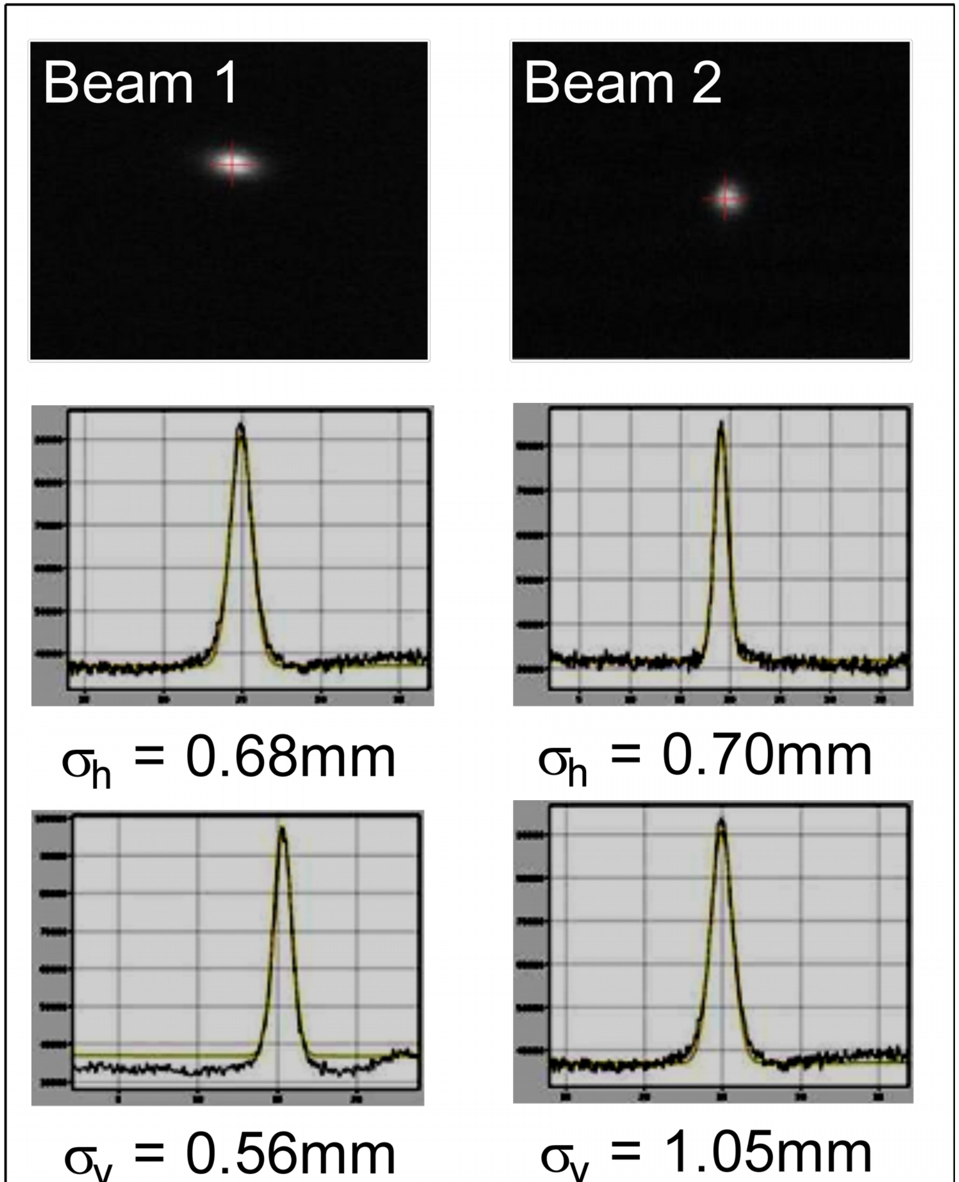
Profile Collected every 20ms

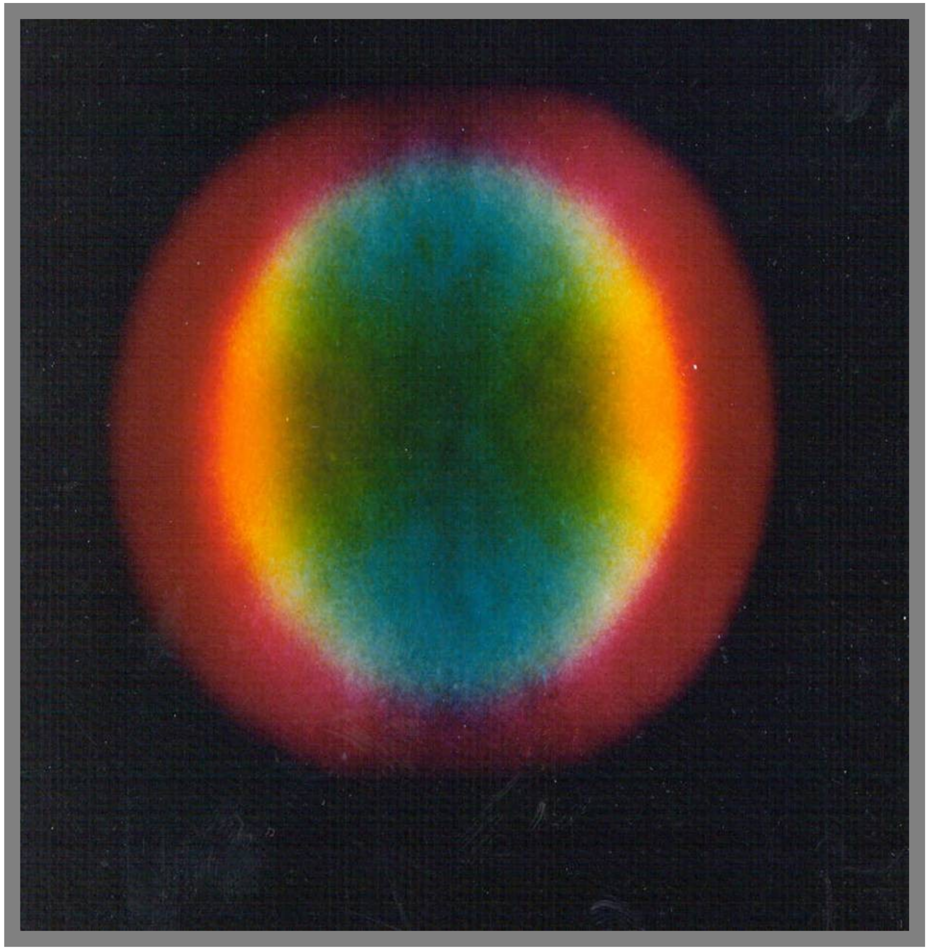
Local Pressure at ~5×10-7 Torr

The Synchrotron Light Monitor



The Synchrotron Light Monitor





Measuring Short Bunch-Lengths

- Hadron accelerators:
  - $\sigma_t \approx$ 0.1 … 250 ns ↔ bunch lengths of few cm to tens of m (!!)
    → Electro-magnetic pick-ups, e.g. wall-current- or strip-line monitors

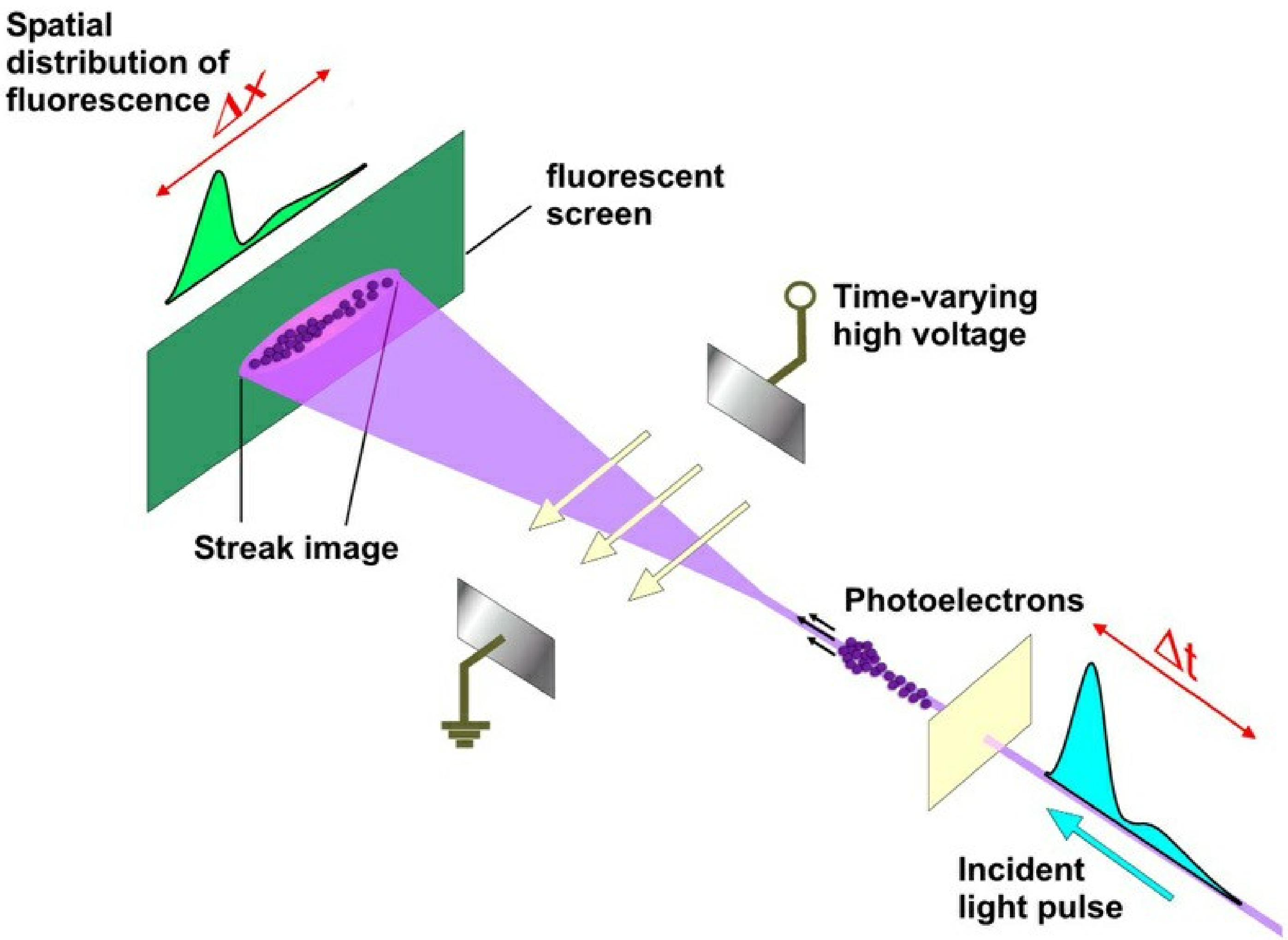
- Next Generation FELs & Linear Colliders
  - Use ultra short bunches to increase brightness or improve luminosity

- Q: How does one measure such short bunches?

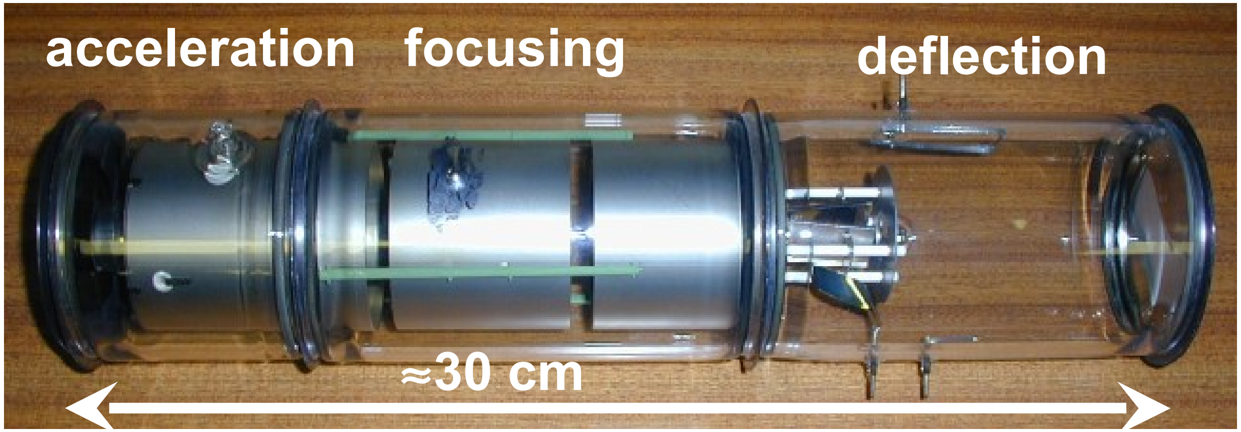
p+ @ PSB	~250 ns
p+ @ LHC	0.1-1 ns
H- @ SNS	100ps
e- @ ILC	500fs
e- @ CLIC	130fs
e- @ XFEL	80fs
e- @ LCLS	<75fs

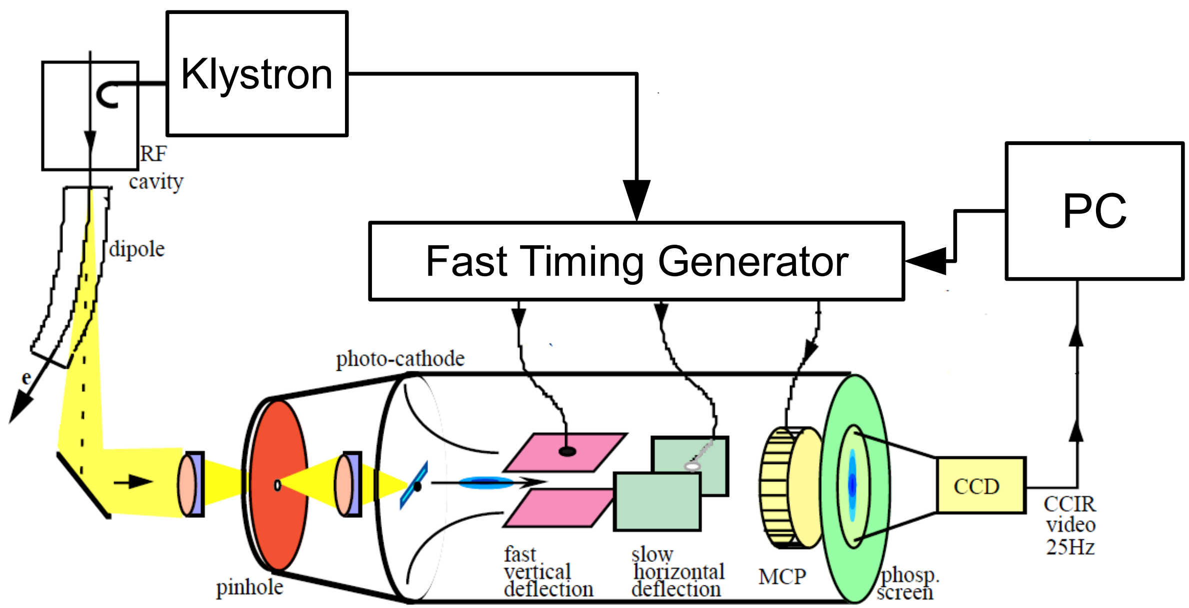
Streak-Camera Principle

- Idea: a mini accelerator or inverse cathode ray tube (old TV)
  - typical resolution: σ_t~1 ps (Hamamatsu FESCA-200 σ_t=0.2 ps)

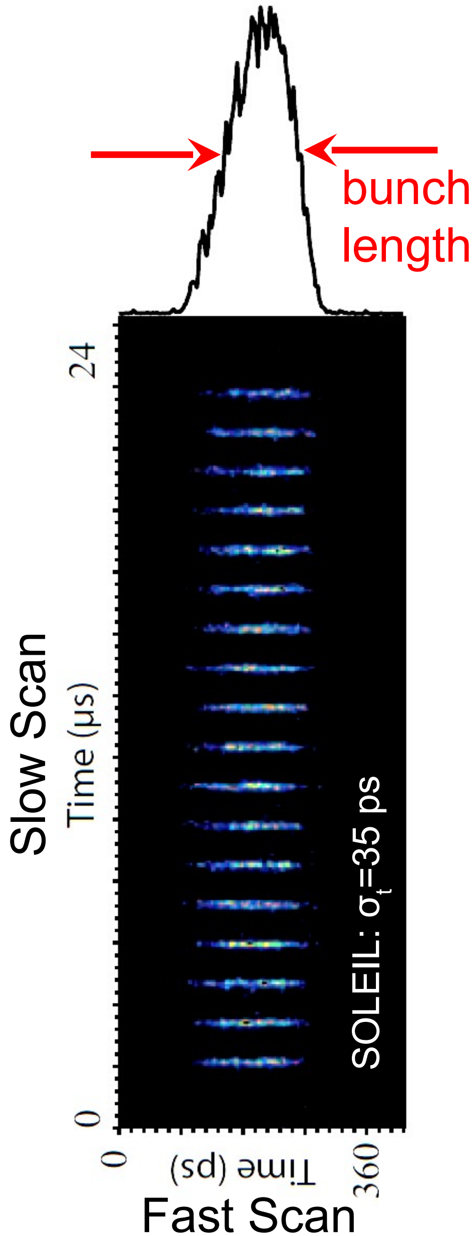


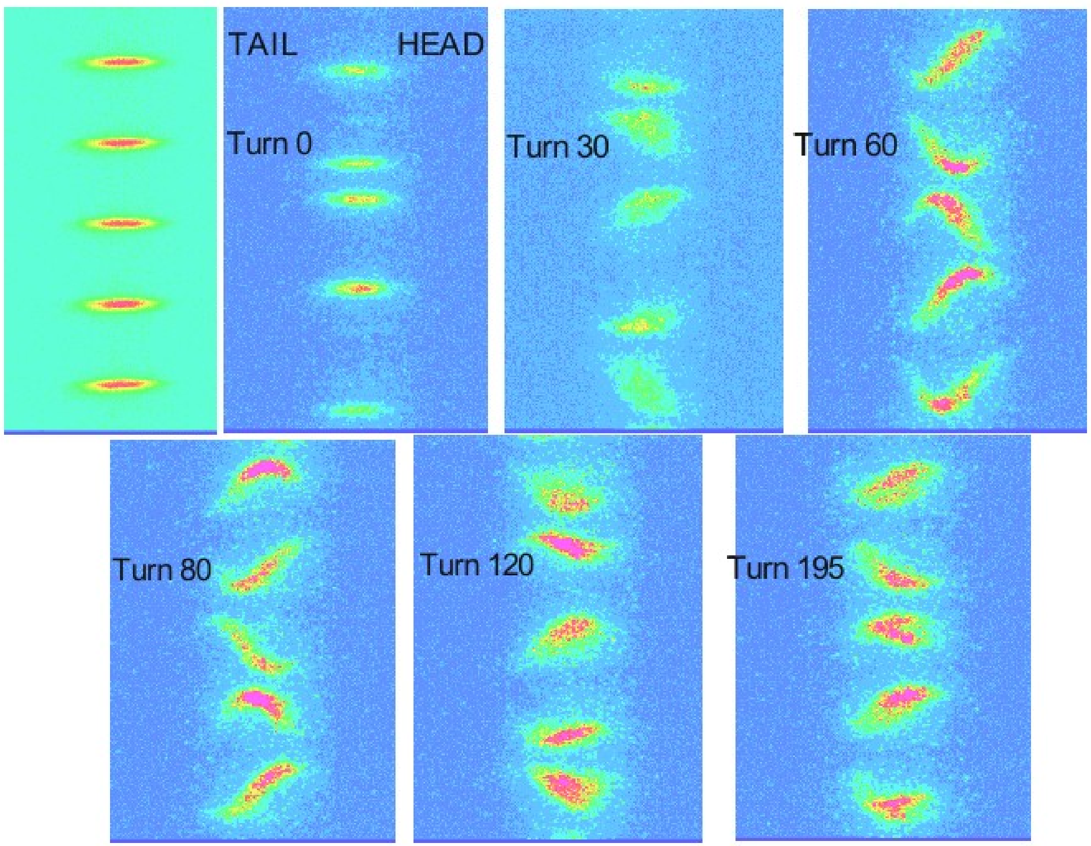
Streak Camera Realisation





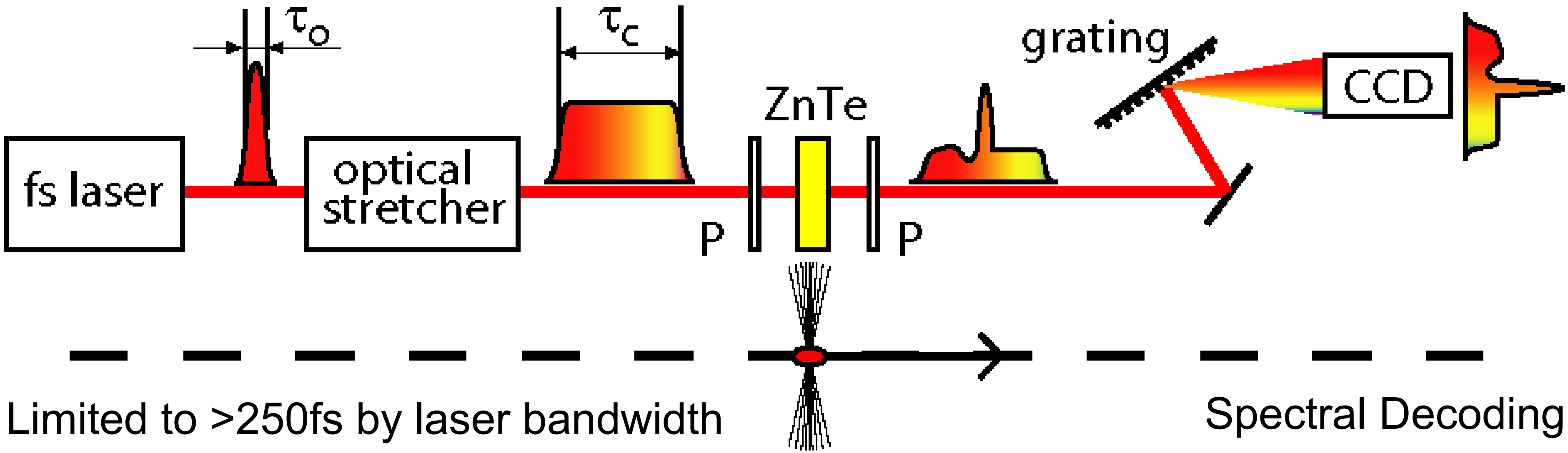
Streak Camera Results

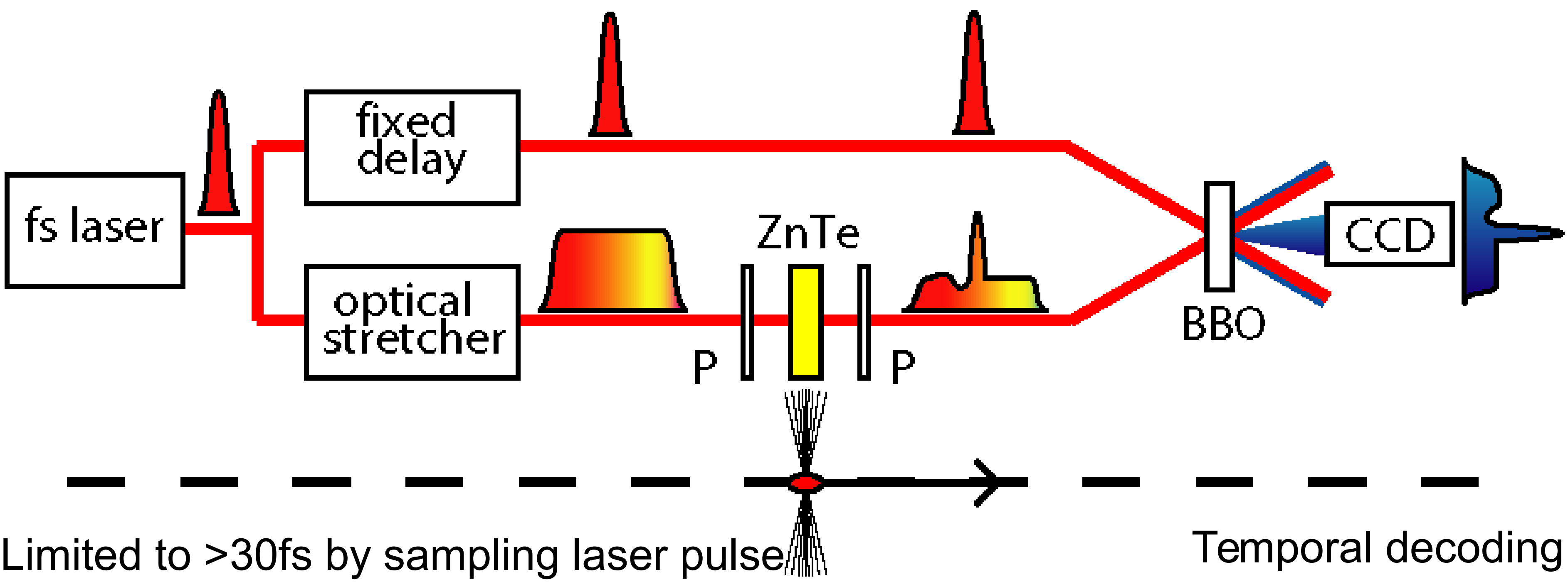




APS kicker-induced synchro-betatron motion
courtesy Bingxin Yang, ANL

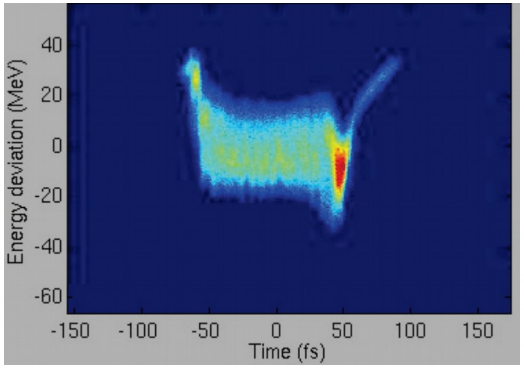
Electro-Optic Sampling – Non Destructive

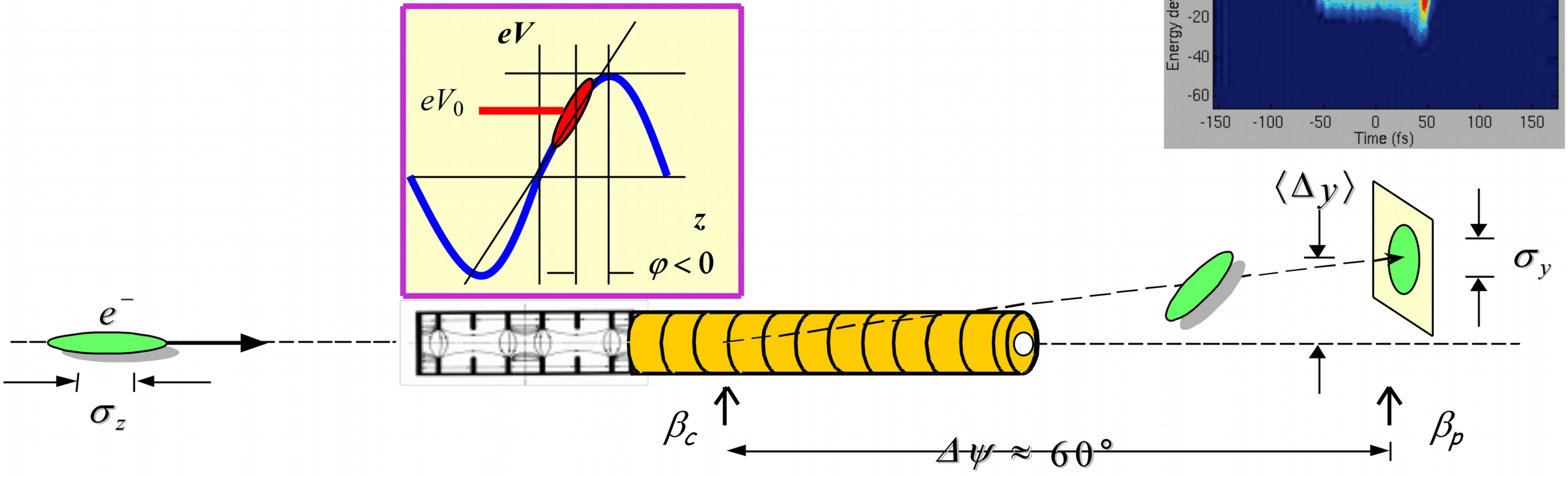




Transverse Deflecting Cavity

- Working principle very similar to streak camera
  - ie. without photo luminescent screen causing a slow photo-response
  - destructive measurement → typ. placed in dedicated diagnostics sections
- State-of-the-art bunch length resolutions[1]: $\sigma_t \approx 1.3$ fs





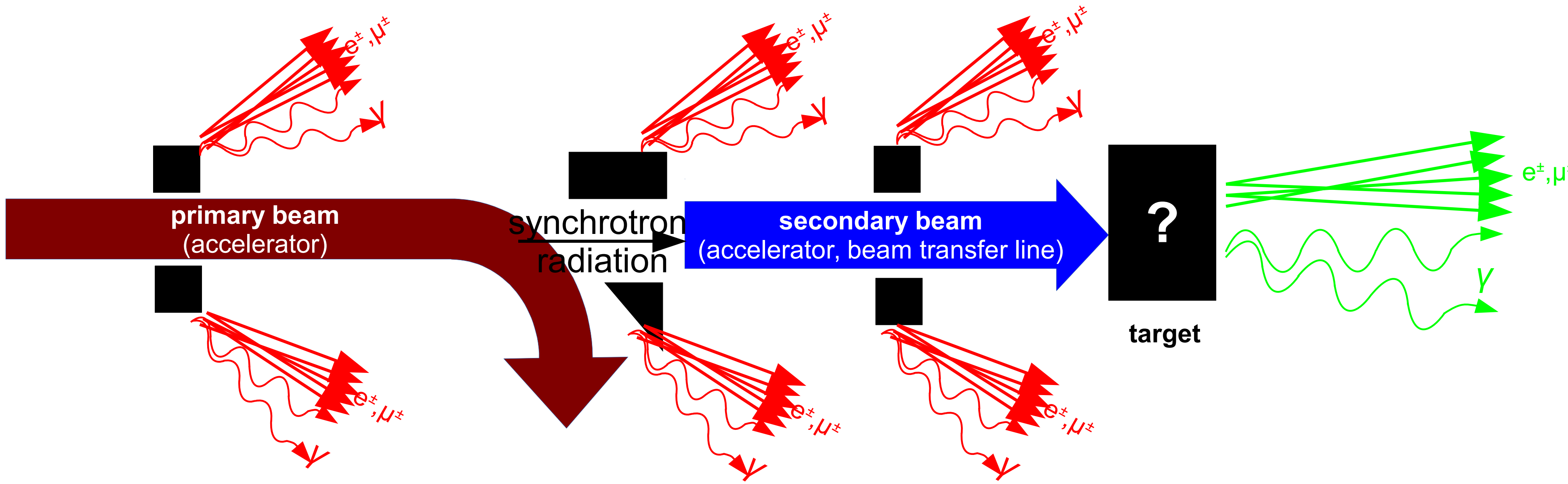
[1]Patrick Krejcik,"Commissioning the New LCLS X-band Transverse Deflecting Cavity with Femtosecond Resolution", IBIC'13, http://www.ibic2013.org/prepress/talks/tual2_talk.pdf

The Typical Instruments

- Beam Intensity
  - Faraday cups, beam current transformers, wall-current monitors
- Beam Position
  - electrostatic or electromagnetic pick-ups and related electronics
- Beam Profile
  - secondary emission grids and screens
  - wire scanners
  - synchrotron light monitors
  - ionisation and luminescence monitors
  - Femto-second diagnostics for ultra short bunches
- Beam Loss
  - Cherenkov optical fibre, ionisation chambers or pin diodes
- Machine Tune, Chromaticity and Luminosity $\rightarrow$ diagnostics tutorial

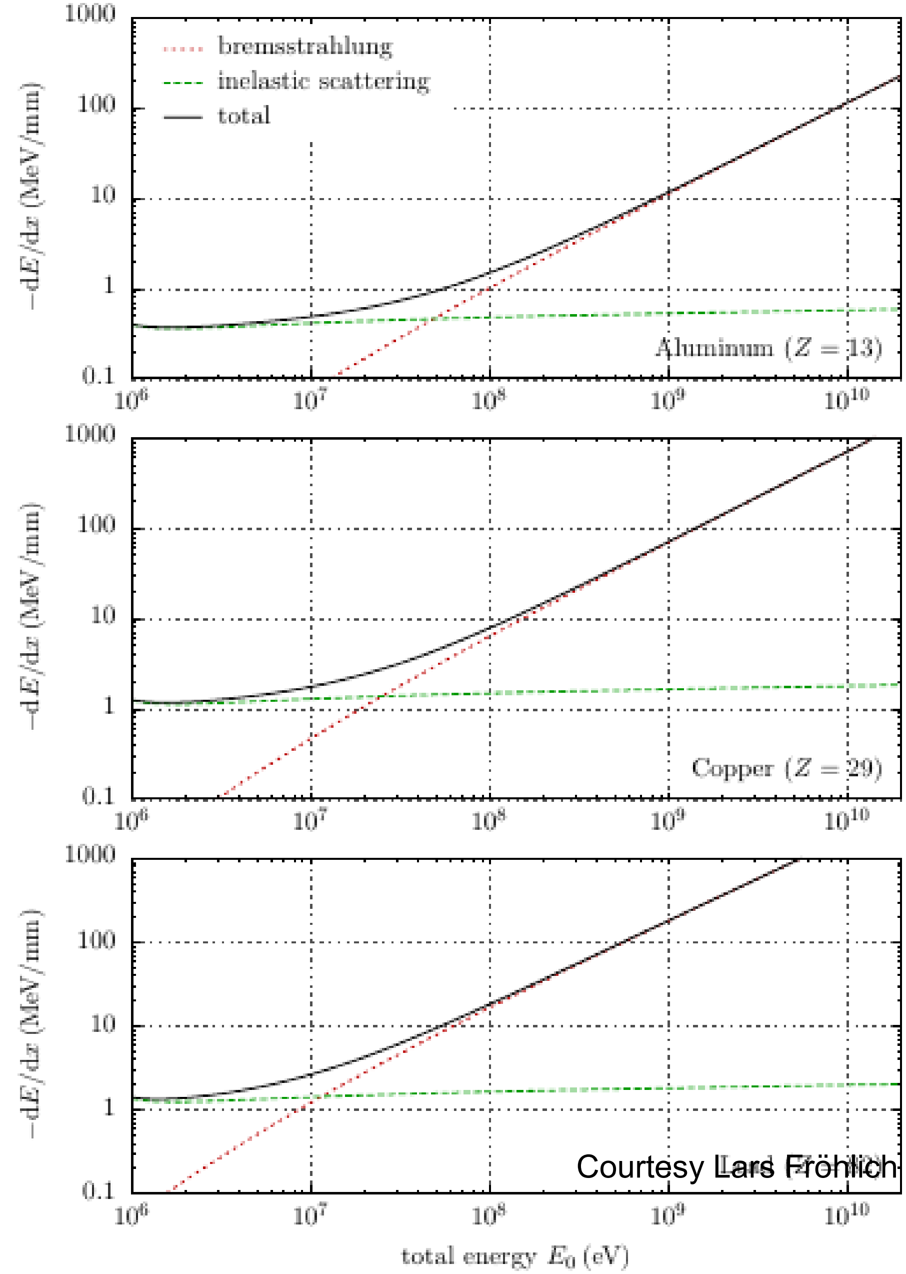
Beam Loss Monitoring – Requirements I/II

- Life isn't perfect so aren't accelerators



1) Machine Protection Protection:
   - interlock signal for fast (& safe) beam extraction to protect sensitive devices (e.g. quenches in super-conducting magnets, de-magnetisation of undulators)
2) Beam diagnostics:
   - optimize transmission to the target.
   - Beam alignment to prevent unnecessary activation and complicated material handling → ALARA principle (As Low As Reasonably Achievable accelerator operation philosophy)
3) Accelerator physics:
   - using these sensitive particle detectors.

Energy Loss of Particles in Matter



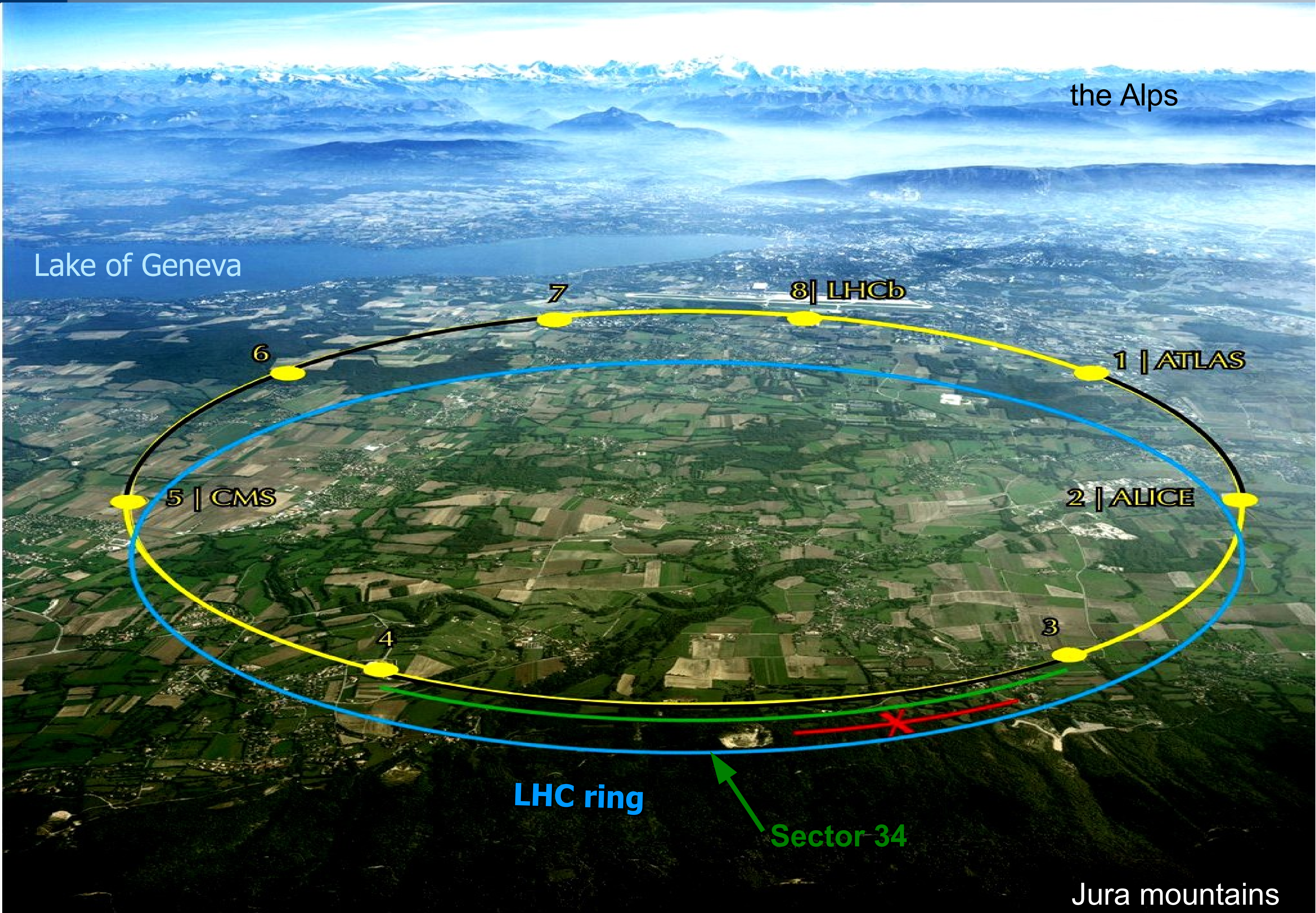
Courtesy Lars Fröhlich

Beam Loss Monitoring – Requirements II/II

- Beam Loss Types:
  - Irregular or fast losses by malfunction of devices (magnets, cavities etc.)
    → BLM as online control of the accelerator functionality and interlock generation.
  - Intermediate
  - Slow regular losses
    - e.g. by lifetime limits or due to collimator → BLM used for alignment.
    - ALARA: As Low As Reasonably Achievable → minimise unnecessary activation of the machine complicating material handling

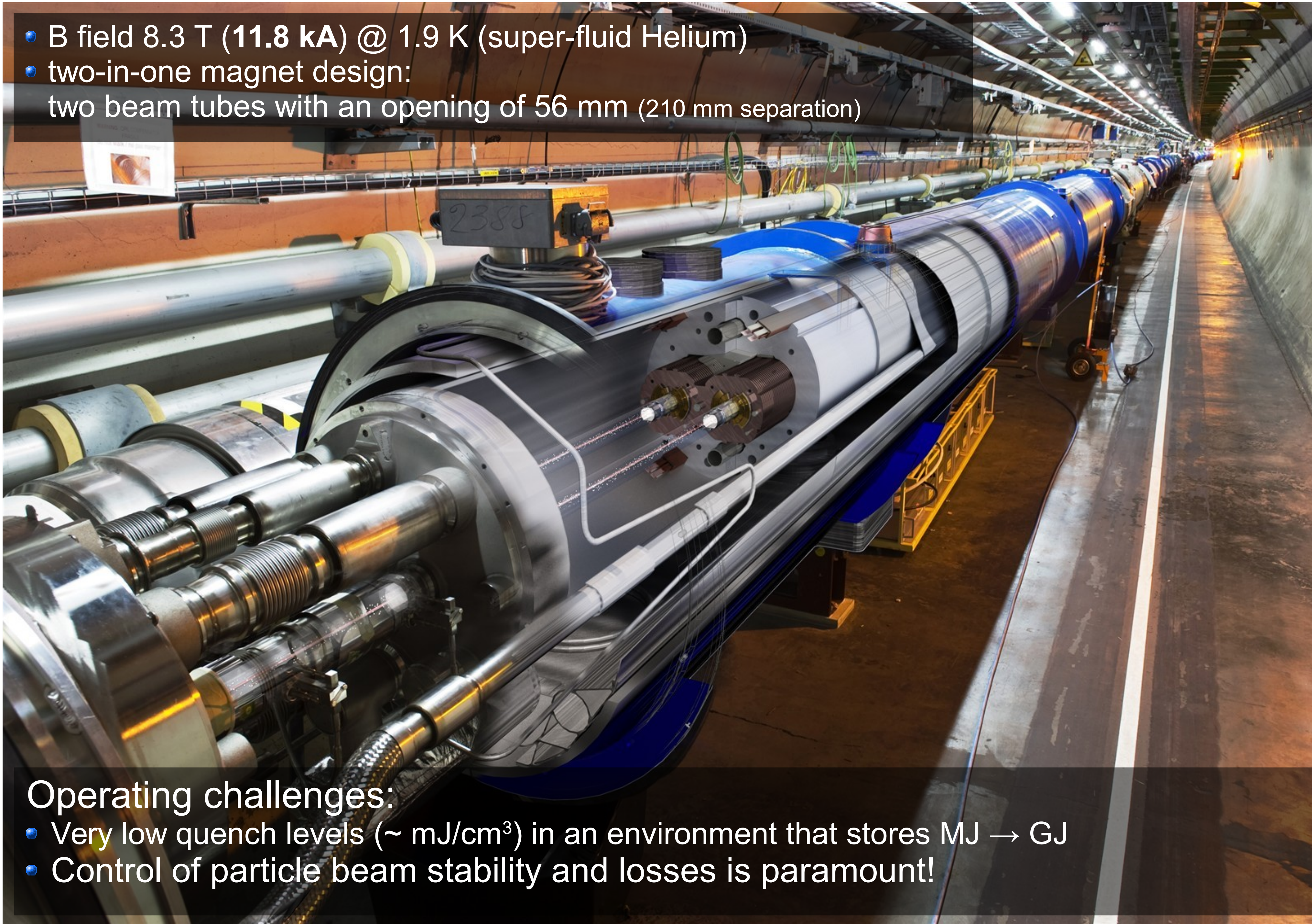
- Requirements for BLM:
  - High sensitivity to detect behaviour of beam halo e.g. at collimator
  - Large dynamic range:
    - low signal during normal operation, but very large signal in case of malfunction
    - detectable without changing the full-scale-range, e.g. scintillators from 10^2...10^7/s in counting mode.

The Large Hadron Collider LHC
Installed in the LEP tunnel, 27 km, Depth of 70-140 m



27 km Circumference – 1232 LHC dipole magnet

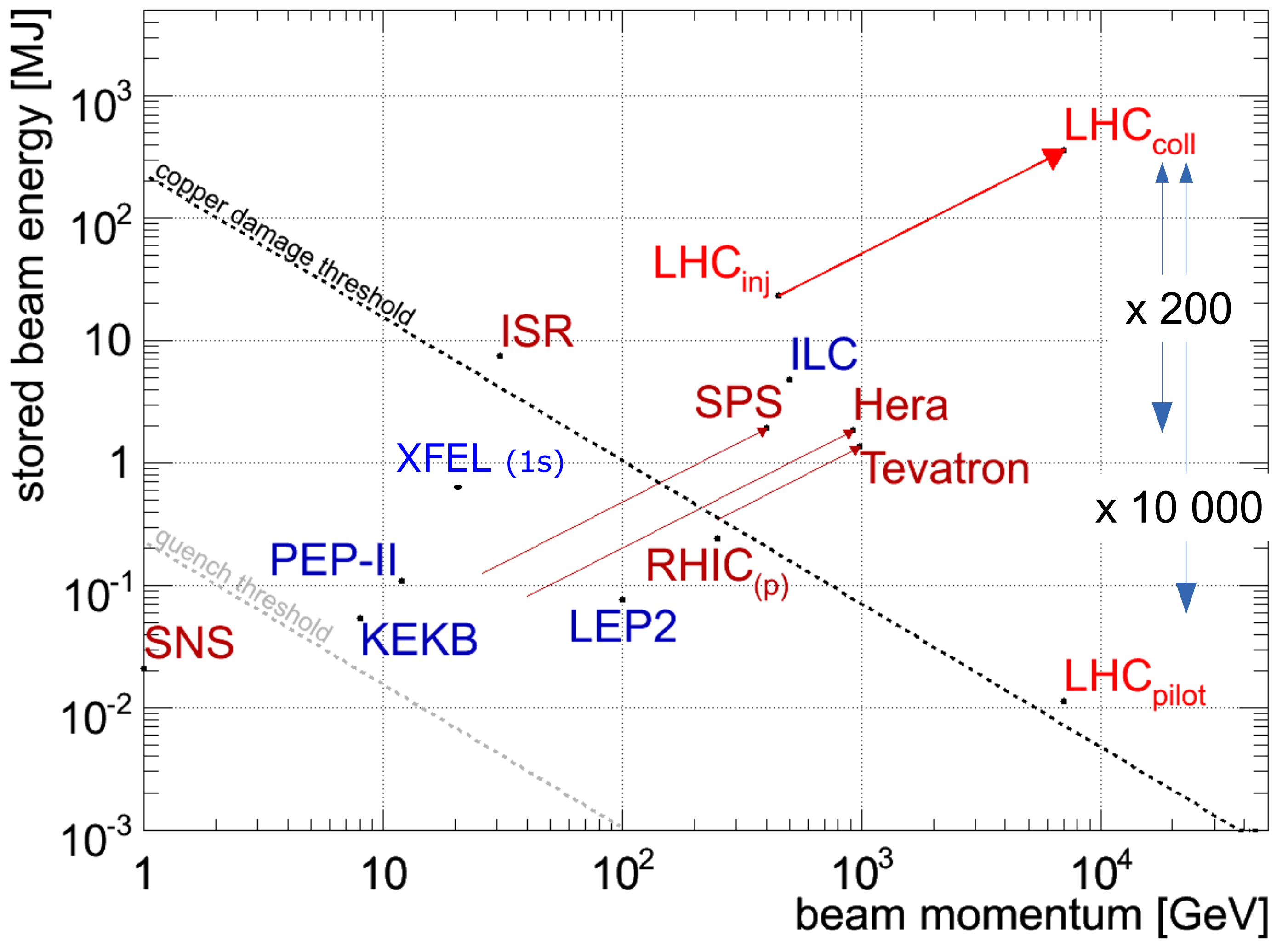
- B field 8.3 T (**11.8 kA**) @ 1.9 K (super-fluid Helium)
- two-in-one magnet design:
  two beam tubes with an opening of 56 mm (210 mm separation)



Operating challenges:

- Very low quench levels (~ mJ/cm^3) in an environment that stores MJ → GJ
- Control of particle beam stability and losses is paramount!

Stored Beam Energies



Quench Levels	Units	*Tevatron*	*RHIC*	*HERA*	*LHC*
Instant loss **(0.01 - 10 ms)**	[mJ/cm³]	4.5	18	2.1 - 6.6	87
Steady loss **(> 100 s)**	[mW/cm³]	75	75		5.3

Maximum LHC Energy of 7 TeV

- LHC superconducting dipoles may loose superconducting state ("quench")

  minimum quench energy E_{MQE} @7 TeV for t~10 – 20 ms

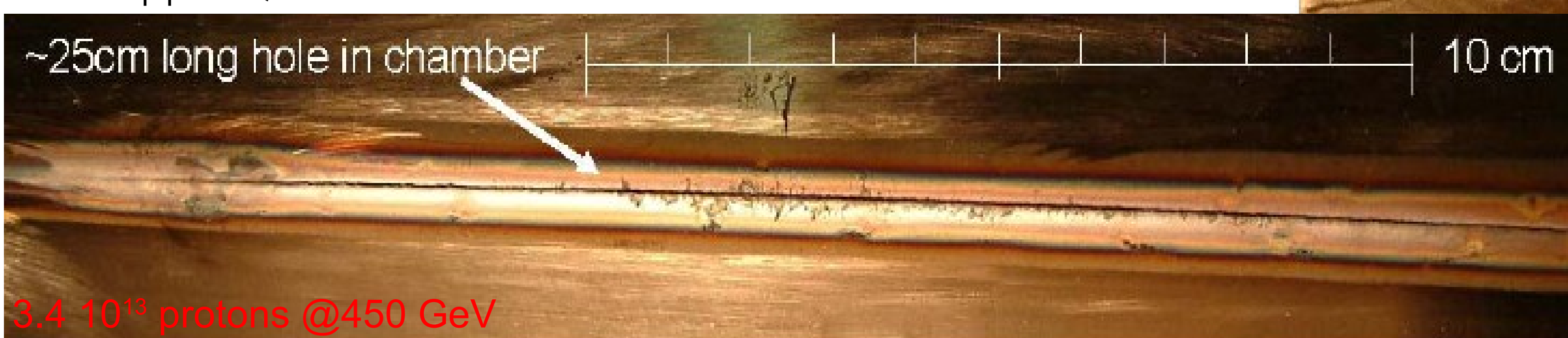
  $$E_{MQE} < 30 \text{ mJ/cm}^{-3} \quad \text{vs.} \quad E_{stored} = 350 \text{ MJ/beam}$$

  → sufficient to quench all magnets and/or may cause serious damage

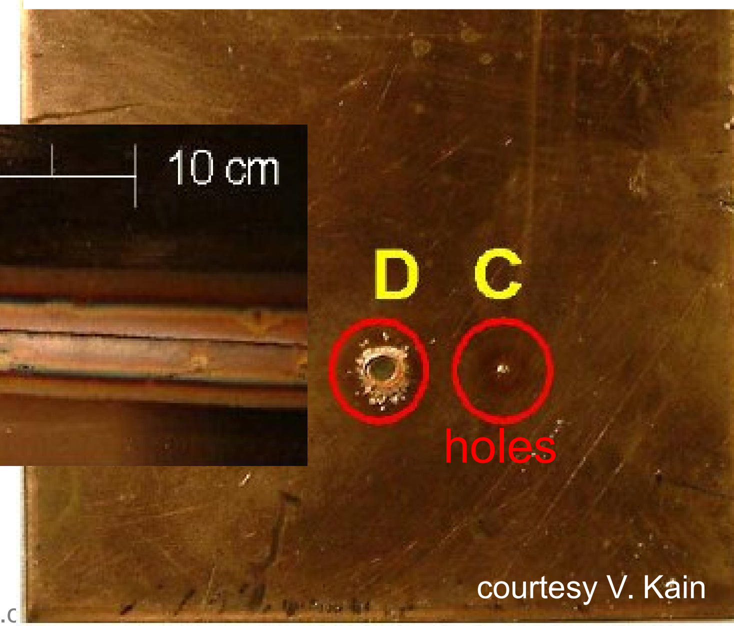
  - requires excellent control of particle losses

Example: un-controlled vs. controlled energy release

Vacuum pipe of QTRF in TT40



C = 5.4 10^{12} protons @ 450 GeV
D = 7.9 10^{12} protons @ 450 GeV

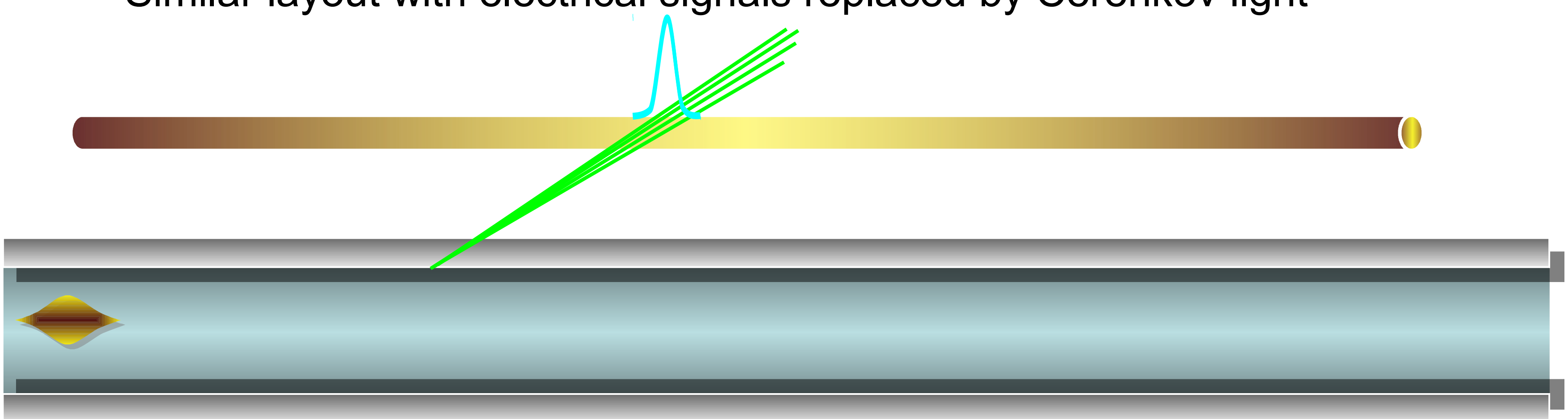


for details see: Chamonix XIV:
"Damage levels - Comparison of Experiment and simulation" and PAC'05

Beam Loss Detectors

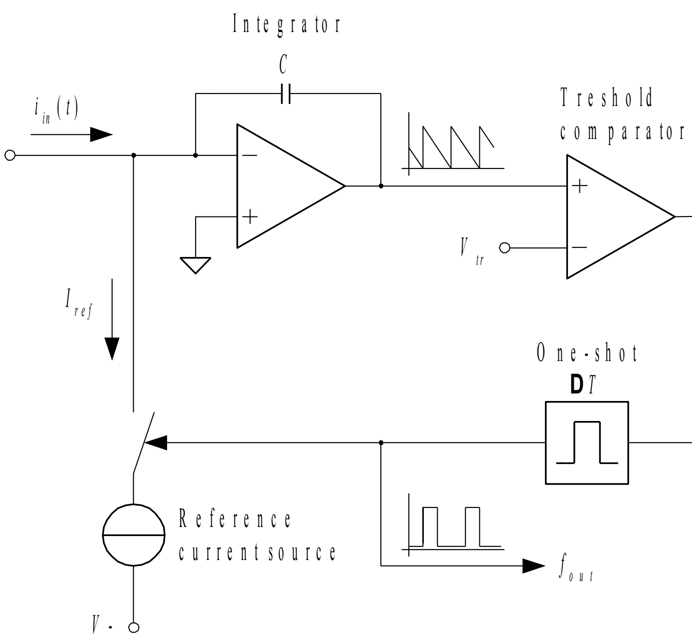
- Role of a BLM system:
  - Protect the machine from damage
  - Dump the beam to avoid magnet quenches (for SC magnets)
  - Diagnostic tool to improve the performance of the accelerator

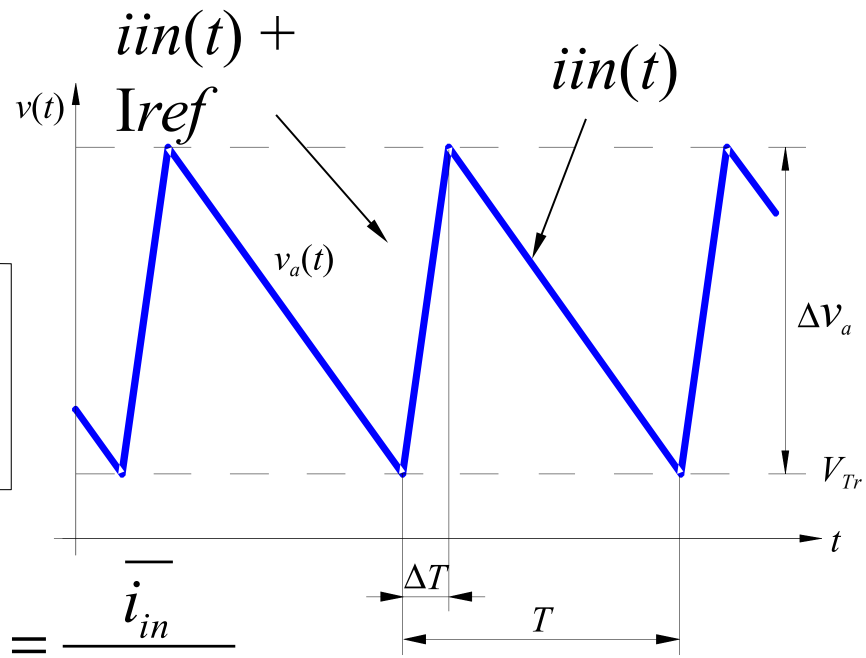
- Common types of monitor
  - Long ionisation chamber (charge detection)
    - Up to several km of gas filled hollow coaxial cables
    - Position sensitivity achieved by comparing direct & reflected pulse
      - e.g. SLAC – 8m position resolution (30ns) over 3.5km cable length
    - Dynamic range of up to 10^4
  - Fibre optic monitors
    - Similar layout with electrical signals replaced by Cerenkov light



Beam Loss Detectors

- Common types of monitor (cont)
  - Short ionisation chamber (charge detection)
  - Typically gas filled with many metallic electrodes and kV bias
  - Speed limited by ion collection time - tens of microseconds
  - Dynamic range of up to 10^8

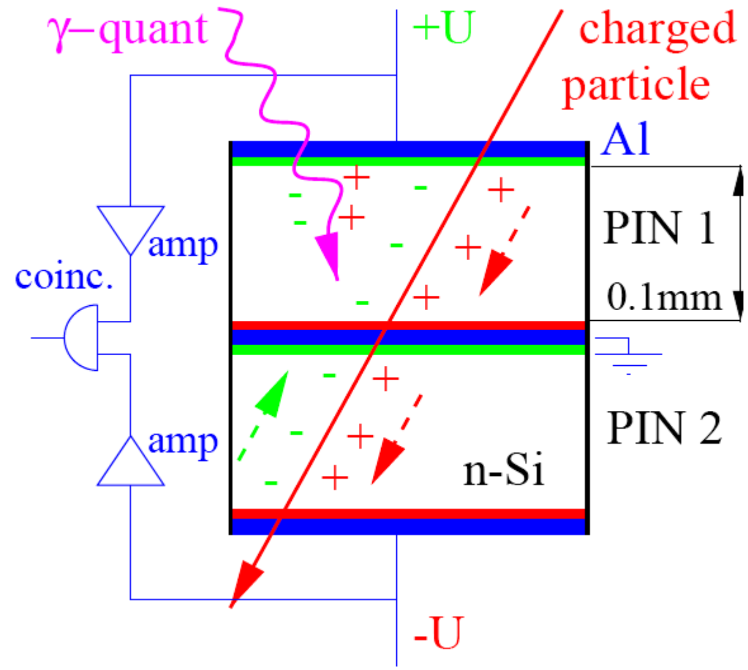


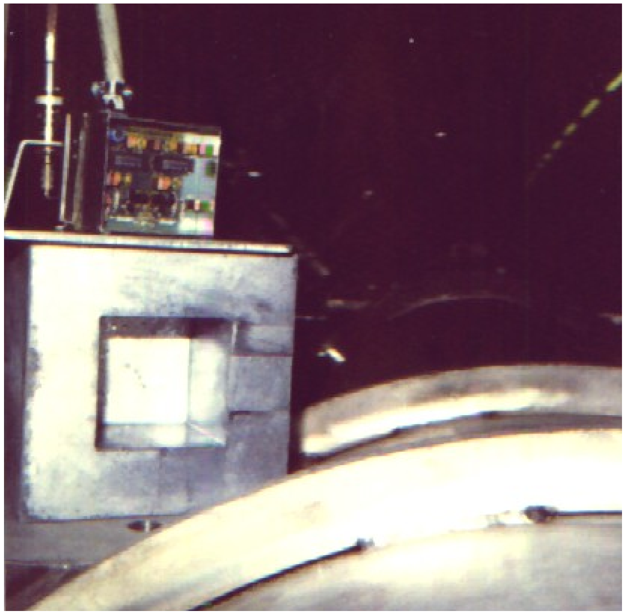


$$f = \frac{\overline{i_{in}}}{I_{ref}\Delta T}$$

Beam Loss Detectors

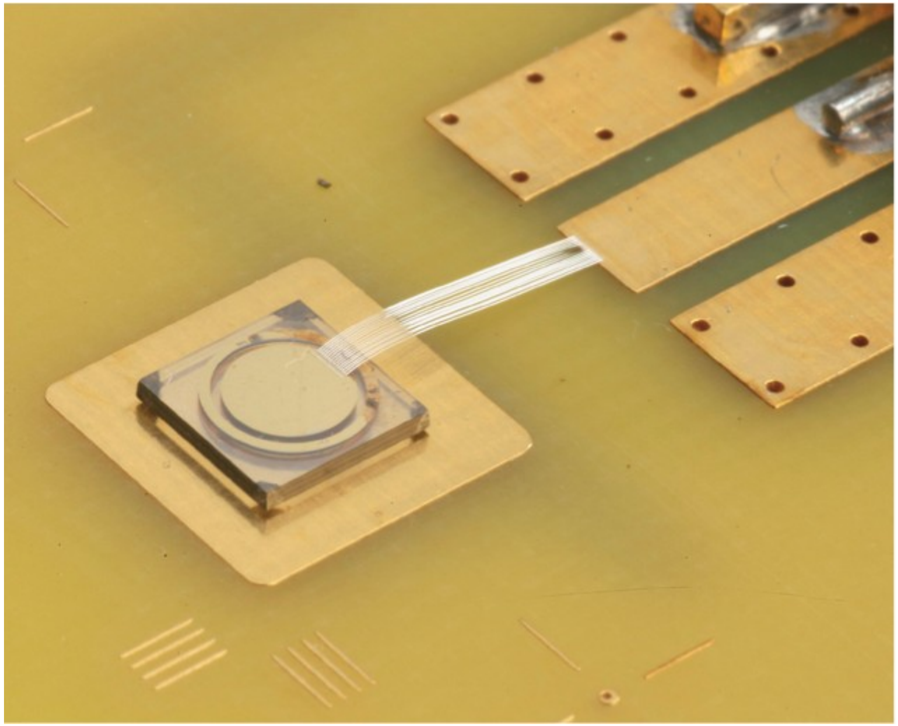
- Common types of monitor (cont)
  - PIN photodiode (count detection)
    - Detect MIP crossing photodiodes
    - Count rate proportional to beam loss
    - Speed limited by integration time
    - Dynamic range of up to 10^9

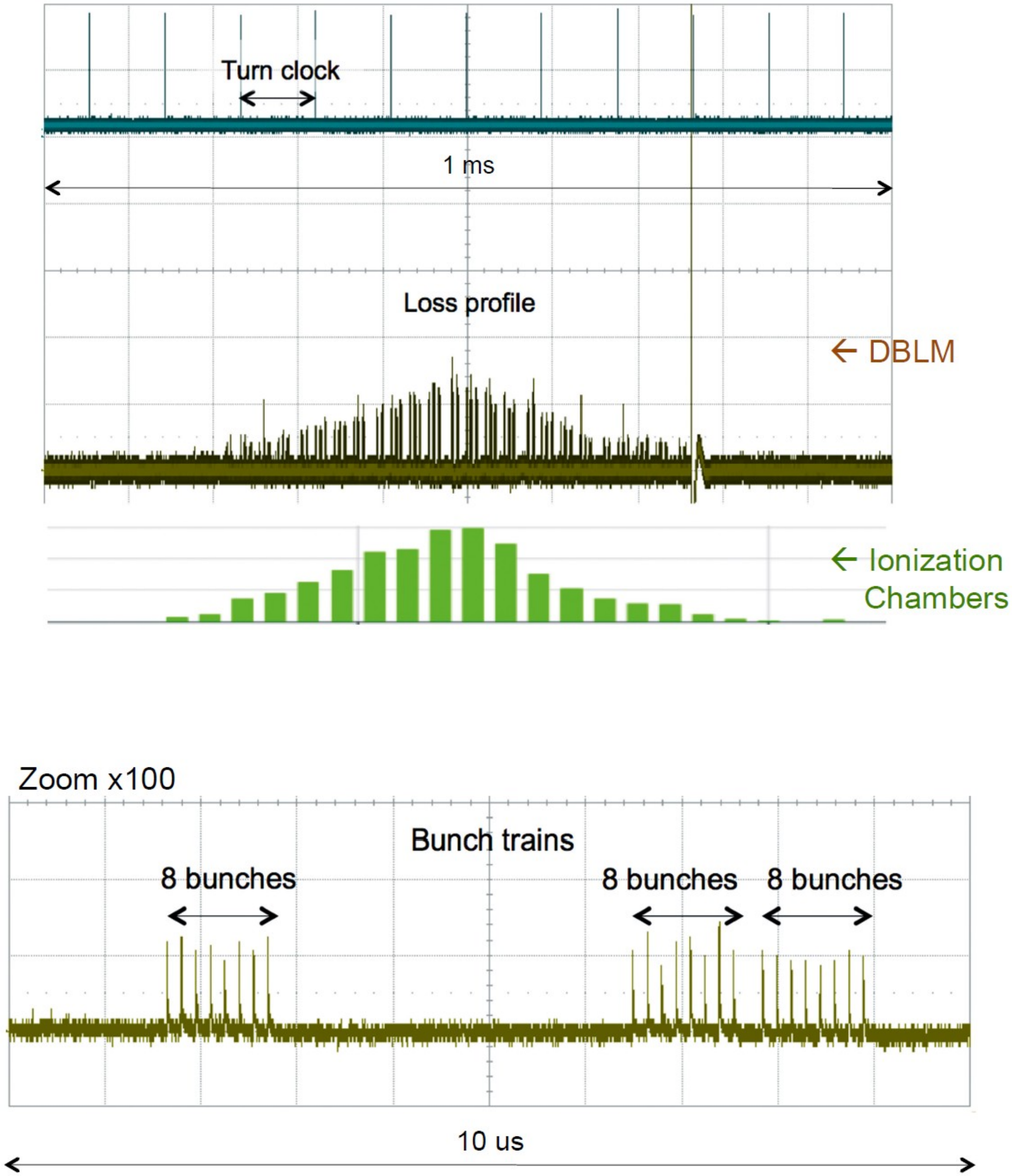




Beam Loss Detectors – New Materials

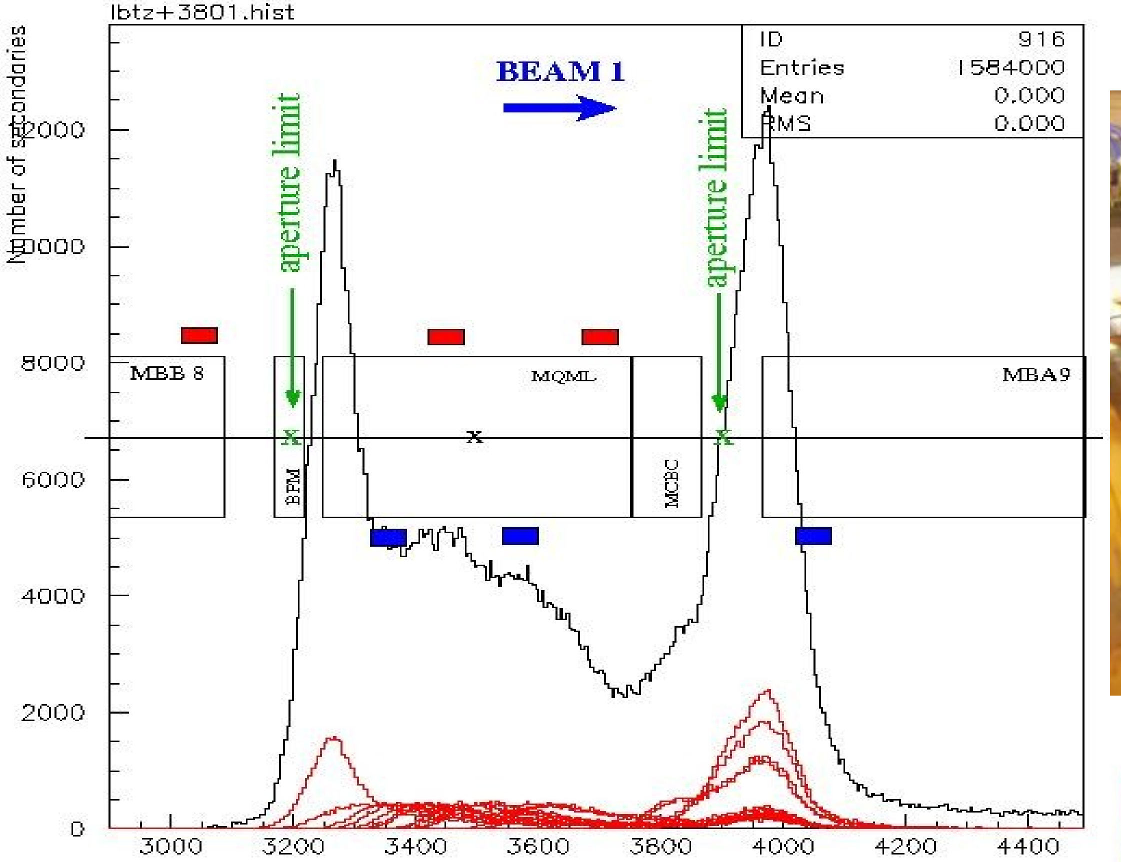
- Diamond Detectors (CVD)
  - Fast & sensitive
  - Used in LHC to distinguish bunch by bunch losses
  - Investigations now ongoing to see if they can work in cryogenic conditions

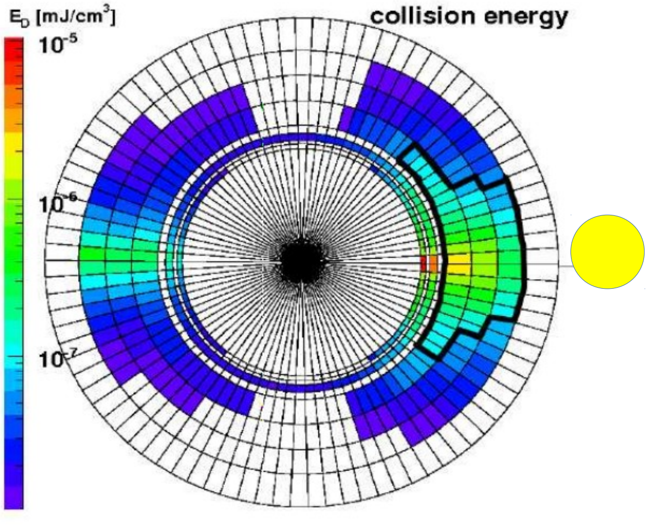




Courtesy of E. Griesmayer

BLM Threshold Level Estimation





Summary

- Beam instrumentation are the 'eyes and ears' of accelerators.
- Part I: electro-magnetic pick-ups
  - Beam intensities: Faraday-Cup, Fast-BCT, DC-BCT, WCM
  - Beam position: position and long. profile: Button-, Strip-line-, and Cavities
- Part II: beam loss and transverse beam profile
  - SEMs, wire scanner, OTR screens, luminescence, synch-light
  - Special ultra-fast devices: electro-optical sampling & streak-camera
  - Cherenkov fibre, Ionisation chamber, diodes, diamonds, scintillators
- An accelerator can never be better than the instruments measuring its performance!
  → Important skill to assess whether beam observations are 'new/known physics', 'instrumental', or to guide whether/how performance can be improved.