Beam Diagnostics

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Material in these slides included from

T. Lefevre, E. Bravin, (DITANET instrumentation school 2009)
R. Jones, U. Raich (CAS 2008 & ASP2010 school)
H. H. Braun (CAS 2008), P. Frock (CAS 2008) M. Minty (CAS 2003)

http://cas.web.cern.ch/cas/CAS_Proceedings.html
http://www.liv.ac.uk/ditanet/events/
https://espace.cern.ch/juas/SitePages/Home.aspx

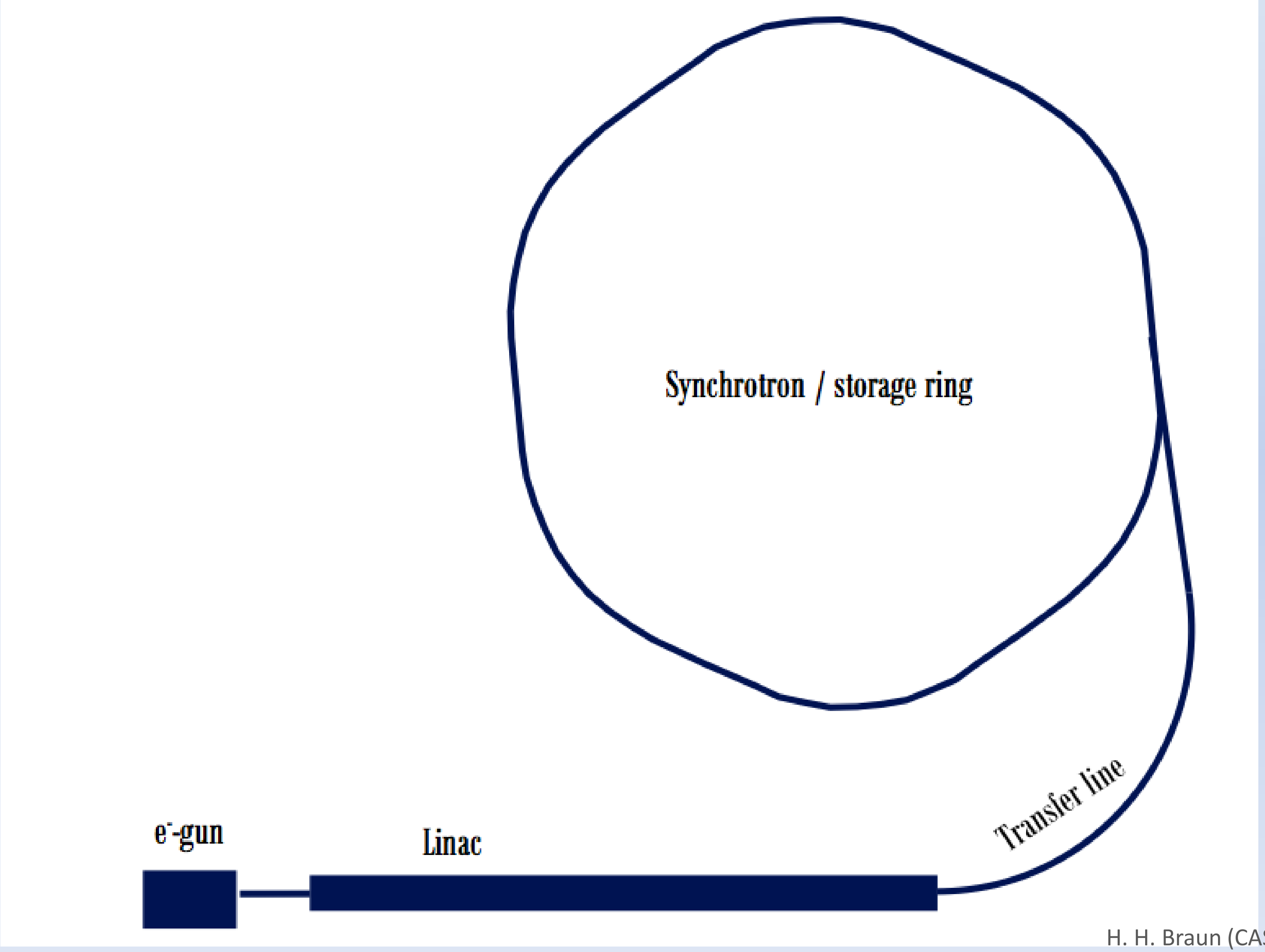
Diagnostics Lecture Outline

- **Why do we need diagnostics**
- **What do we need to measure?**
  - Position
    - Capacitive BPM
  - Current
    - Wall current monitor
    - Faraday Cup
  - Transverse Profile (emittance, TWISS (αβγ) parameters)
    - Intercepting methods
      - » Scanning wires
      - » Radiative screens
      - » Scintillation screens
      - » Cerenkov targets
    - Non intercepting methods
      - » Synchrotron light
  - Longitudinal Profile
    - Streak Camera
    - RF deflector
    - Electro optical techniques
    - RF power measurements and spectroscopy
  - Luminosity Detectors
  - Beam Loss Detectors
- **Discuss diagnostics developments needed for new machines**

First Lecture

Second Lecture

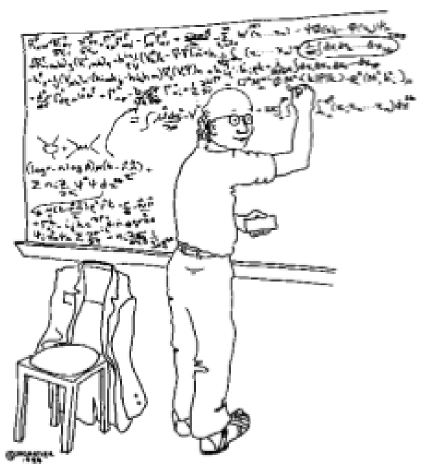
Why do we need diagnostics?



H. H. Braun (CAS 2008)

Why do we need diagnostics?

Accelerator design relies on well established physics !



Magnets, RF cavities

Maxwell's equations

$$\overline{\nabla}\cdot\overline{D} = 4\pi\rho$$

$$\overline{\nabla}\cdot\overline{B} = 0$$

$$\overline{\nabla}\times\overline{E} = -\frac{1}{c}\frac{\partial\overline{B}}{\partial t}$$

$$\overline{\nabla}\times\overline{H} = \frac{4\pi}{c}\overline{J} + \frac{1}{c}\frac{\partial\overline{D}}{\partial t}$$

Beam dynamics

Lorentz Force

$$\vec{F} = e\left(\vec{E} + \vec{\beta}\, c \times \vec{B}\right)$$

Newton's 2nd law + special relativity

$$\frac{d}{dt}\left(\frac{m c\vec{\beta}}{\sqrt{1-\vec{\beta}^2}}\right) = \vec{F}$$

Synchrotron radiation

Lienard-Wiechert potentials and Planck's energy quanta

$$\phi(t) = \frac{e}{4\pi\varepsilon_0}\left\{\frac{1}{r\left(1-\hat{n}\cdot\vec{\beta}\right)}\right\}_{ret}$$

$$\vec{A}(t) = \frac{\mu_0 e}{4\pi}\left\{\frac{\vec{\beta}\, c}{r\left(1-\hat{n}\cdot\vec{\beta}\right)}\right\}_{ret}$$

$$E = \hbar\omega$$

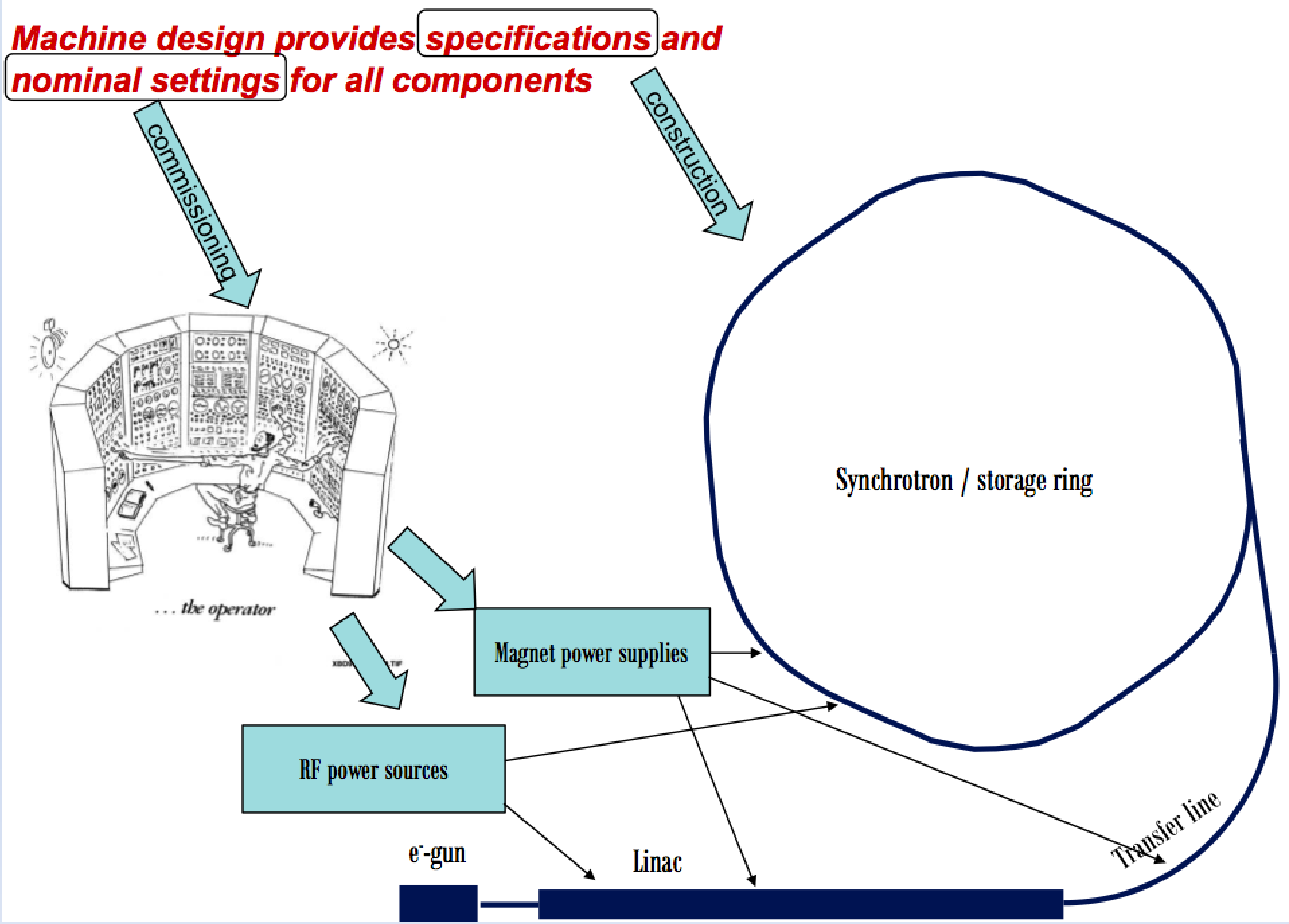
Cathode

Richardson-Dushman equation

$$J = CT^2 e^{\frac{-\Phi}{kT}}$$

H. H. Braun (CAS 2008)

Why do we need diagnostics?



H. H. Braun (CAS 2008)

Protection & monitoring of machine

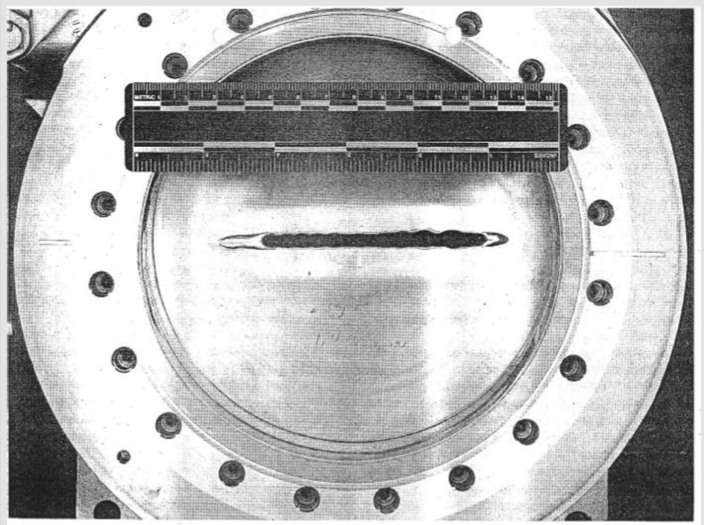
Modern accelerators are expensive, powerful and can contain many components

LHC contains > 1600 superconducting magnets and connections

Collateral damages due to pressure rise

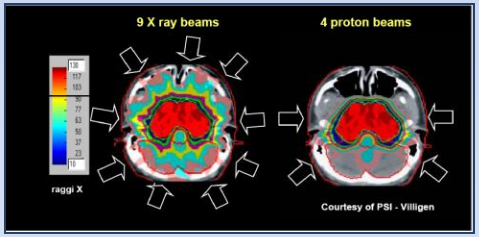
Monitor changes in the temperature and pressure throughout the machine diagnose a problem and correct for it

kW of power from x-rays produced by synchrotron radiation in a light source at BNL

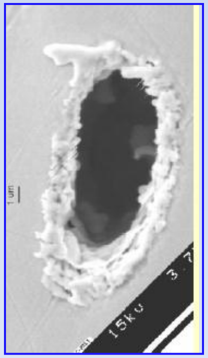


ig. 12. Damaged X-ray ring front end gate valve. The power incident on the valve was approximately 1 kW for a duration estimated to 2–10 min and drilled a hole through the valve plate.

Medical treatment with beams

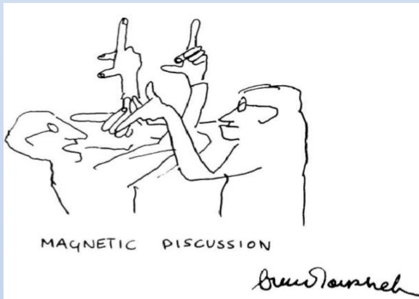


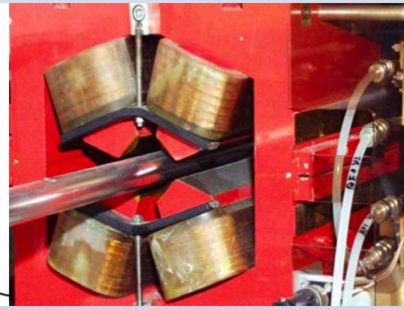
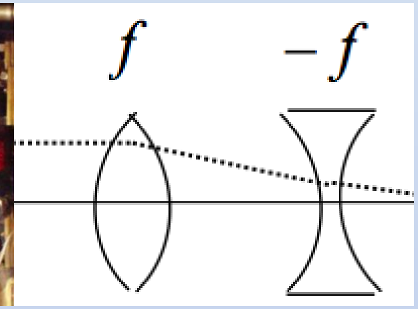
Damage to accelerator components or screens due to **high charge density CTF3 (CERN)**



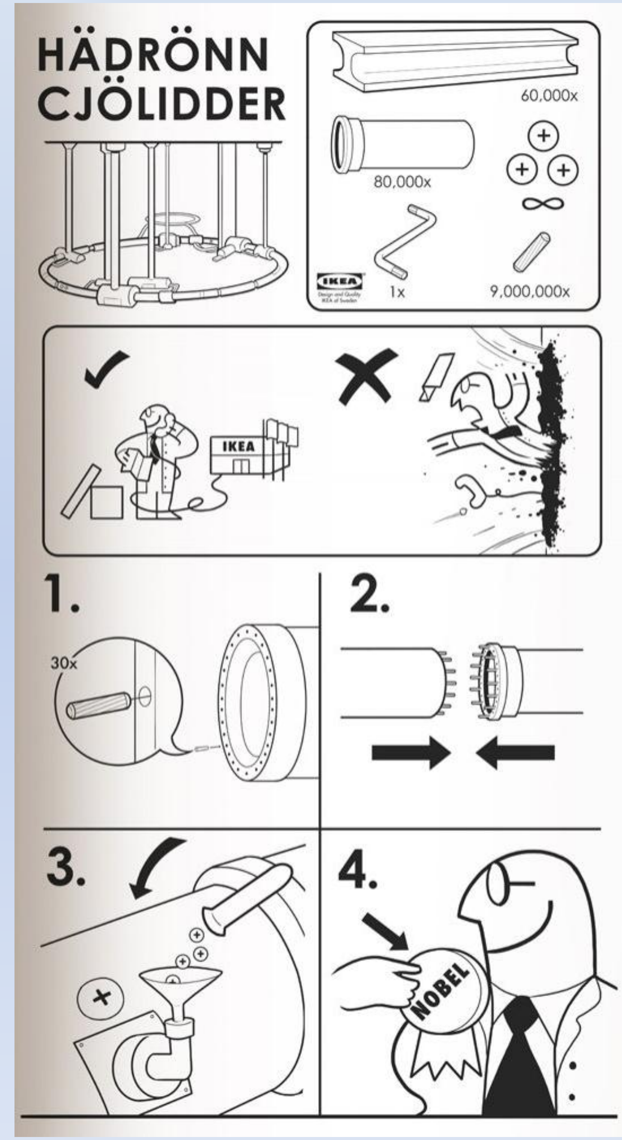
Mistakes during building and integration

- Connect magnet polarity with the wrong polarity



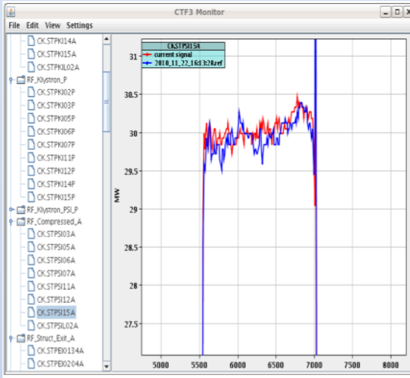



- Cables connected to the wrong equipment
- Wrong values in the controls database .. etc



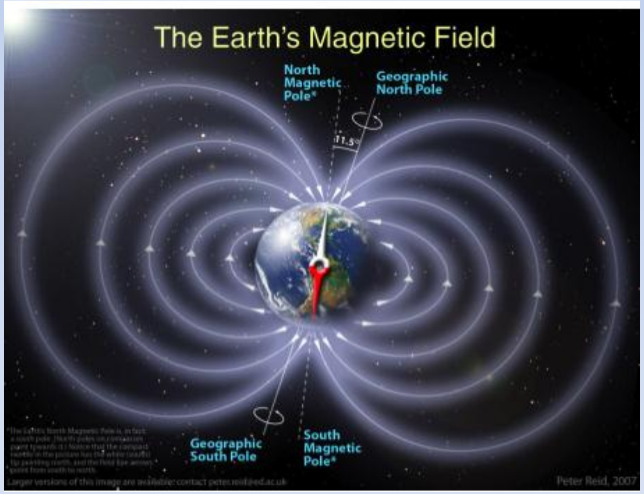
Why do we need diagnostics?

Component tolerances and random errors



- Magnet field has been measured with a finite error
- The survey people have aligned relatively the center of neighboring magnets with a finite transverse and angular (roll) error
- The RF wave amplitude has a ripple due to another ripple from a high voltage power supply
- The resonance frequency of an accelerating structure has drifted due a temperature increase (expansion by a few microns)
- …

Correct for environmental effects



- Earth's magnetic field
- Mechanical vibrations induced by water flow
- Seismic vibrations
- Vibrations due to trains / airplane landing
- Stray fields from neighboring instruments or magnets
- …

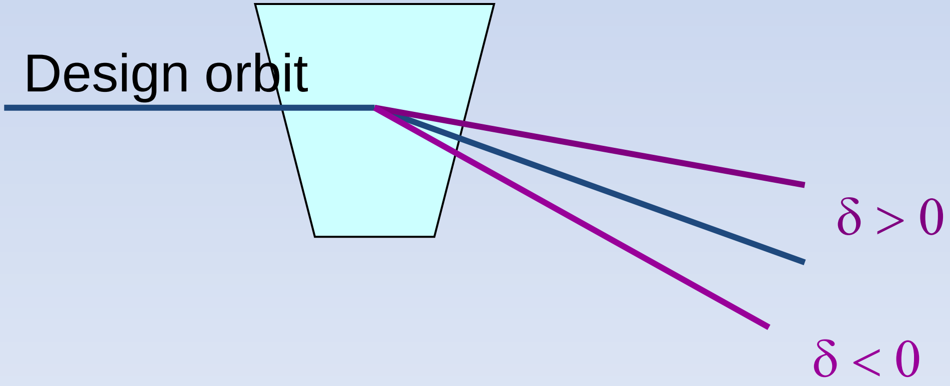
Constantly need to measure and adjust the beam orbit

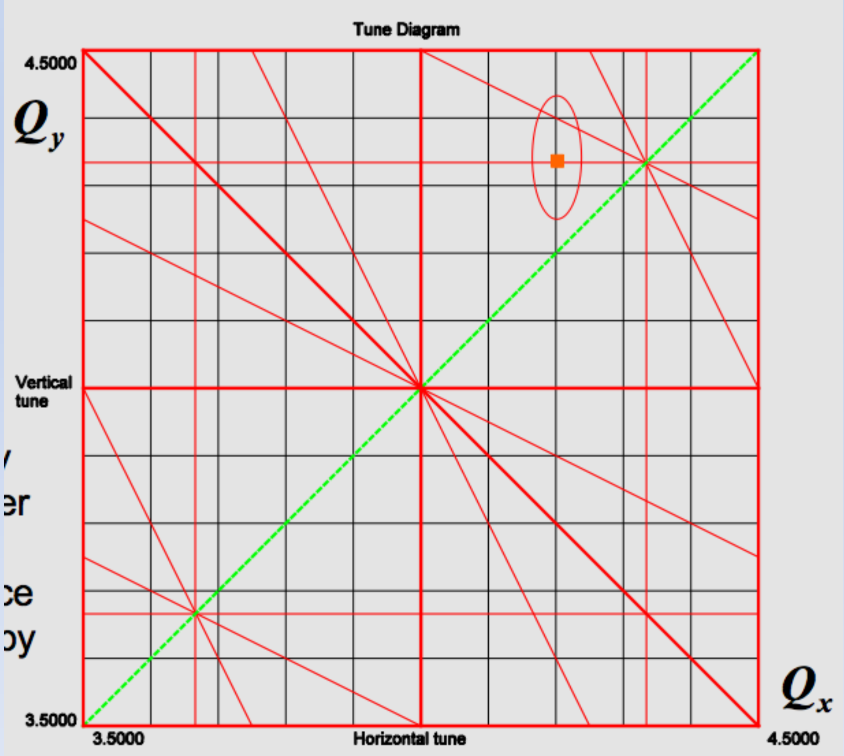
Why do we need diagnostics?

Verification of optics model with beam based measurements

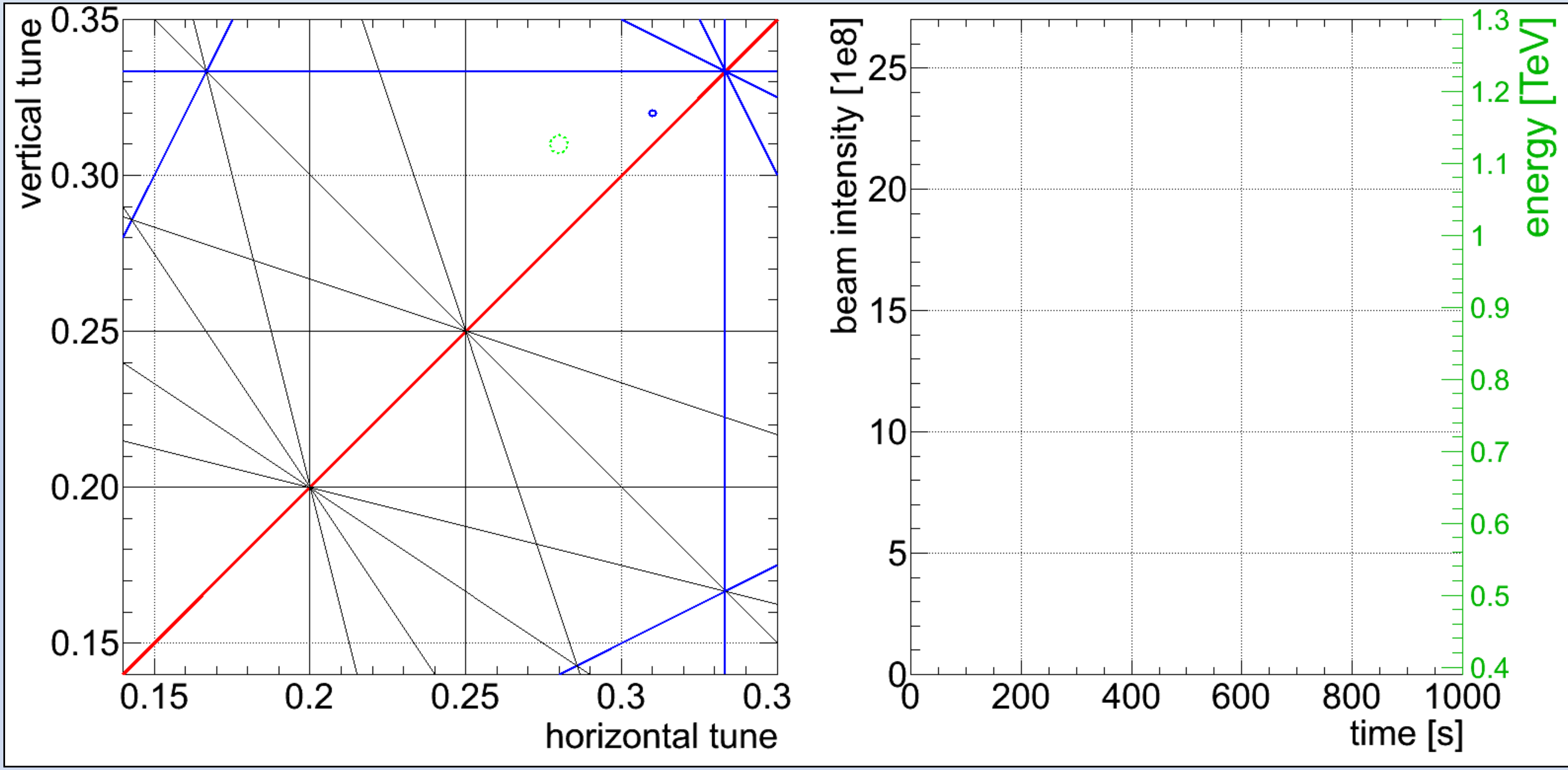
- Measure the difference between predicted trajectory / angle and measured trajectory
- Measure the dispersion pattern in the machine
- Keeping the beam within < 100 um for many hours (billions of km) in a modern storage ring
- Verify you are staying away from a tune resonance
- Understand why you loose the beam …
- Etc …

$$x_{\max}(s) = |D_x(s) \cdot \delta| + \sqrt{\varepsilon_x \beta_x(s)}$$





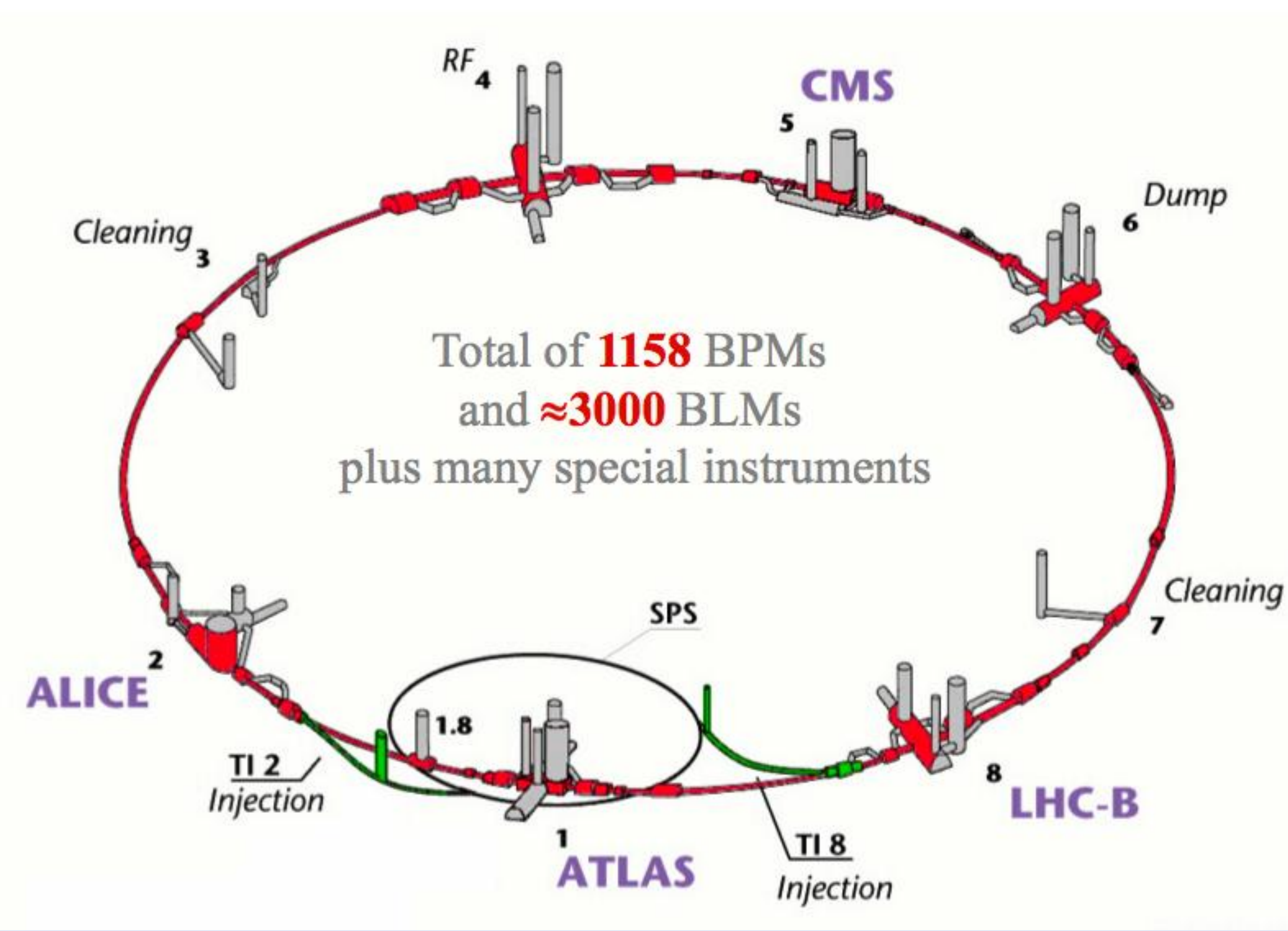
LHC Ramp Commissioning



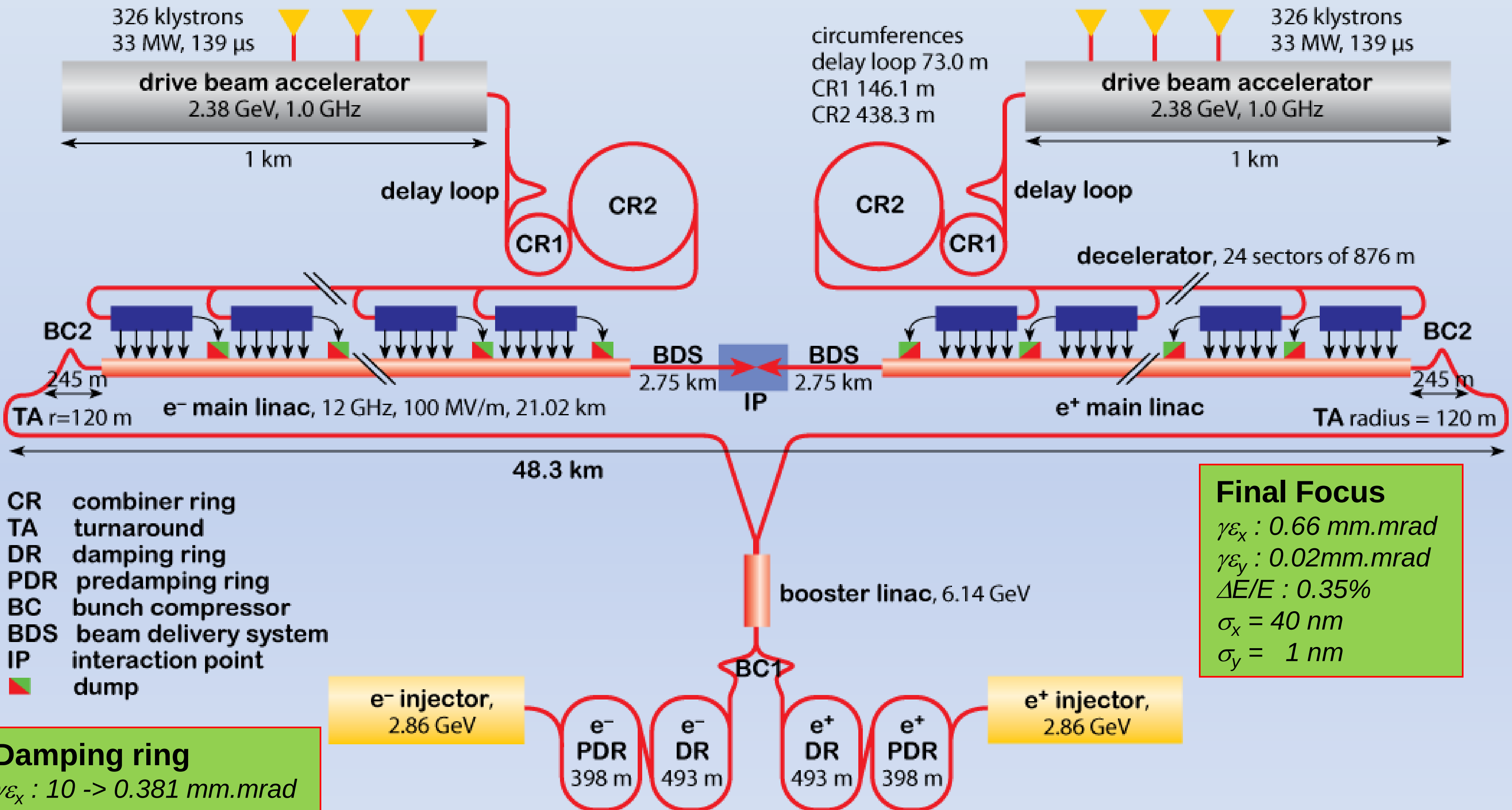
- Tune diagnostics throughout the ramp
  - Early ramps had poor tune control
  - Beam loss observed every time tune crossed resonance line

R. Jones

LHC Beam Diagnostics



Instrumentation for CLIC



Final Focus

- $\gamma\varepsilon_x$: 0.66 mm.mrad
- $\gamma\varepsilon_y$: 0.02mm.mrad
- $\Delta E/E$: 0.35%
- σ_x = 40 nm
- σ_y = 1 nm

Damping ring

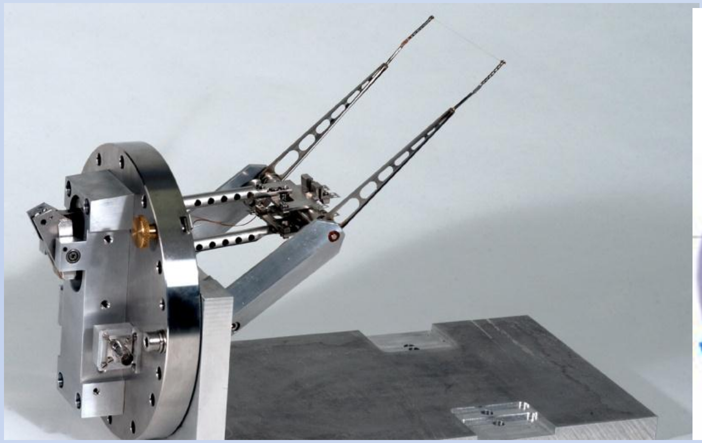
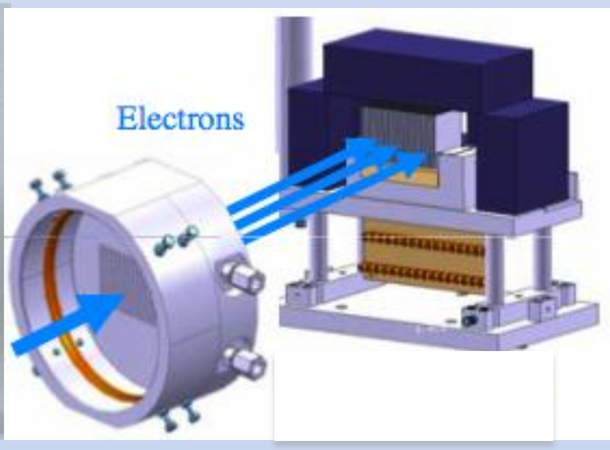
- $\gamma\varepsilon_x$: 10 -> 0.381 mm.mrad
- $\gamma\varepsilon_y$: 10 -> 0.004 mm.mrad
- $\Delta E/E$: 0.134%
- σ_z : 1.5mm (5ps)

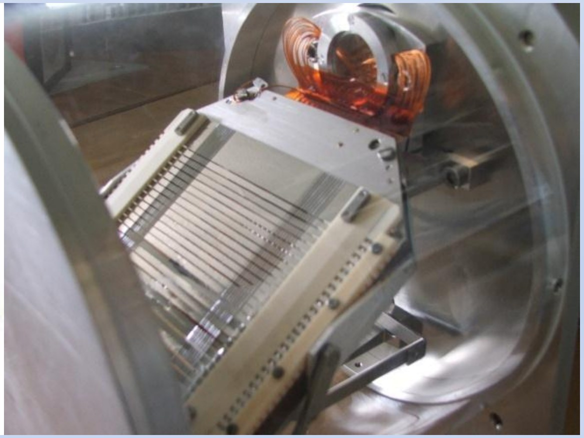
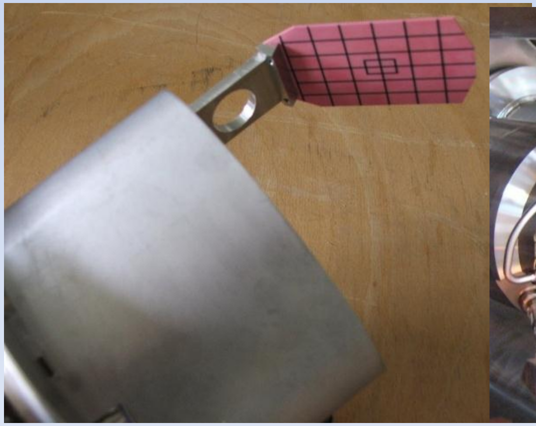
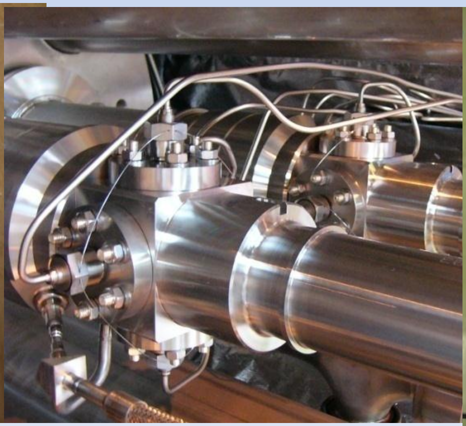
More than 200kms of beamline requiring > **50 000 instruments**

T. Lefevre

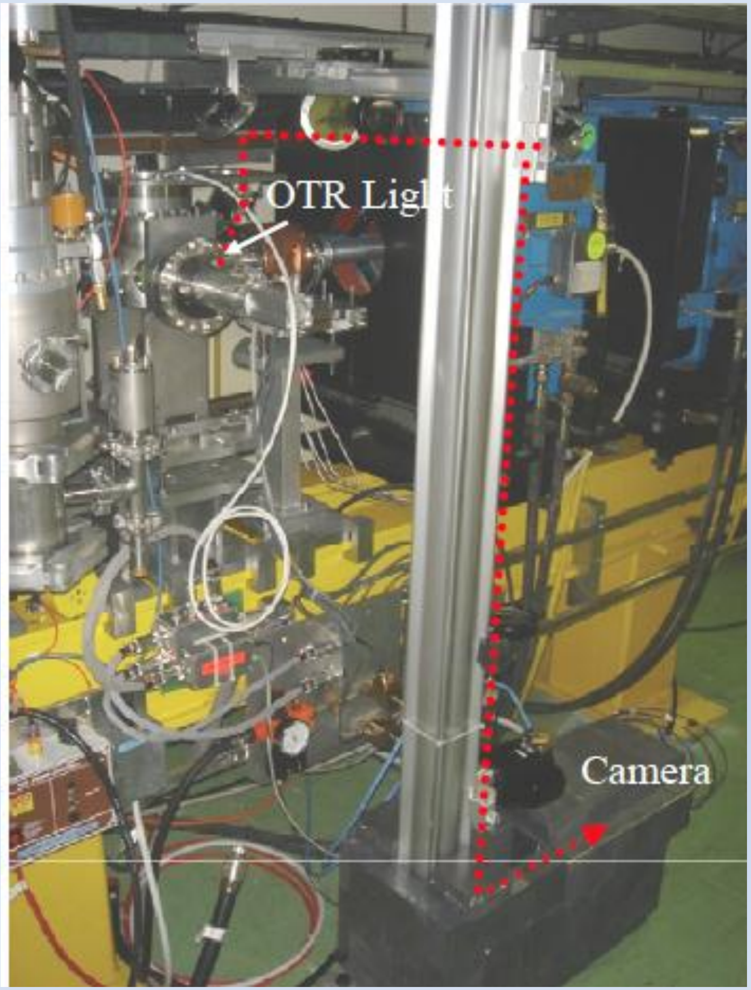
What do we need to measure?

➡ Position; Current; Energy; Transverse Profile (emittance and TWISS parameters); Longitudinal Profile (Bunch length, Bunch shape, Bunch spacing); Beam Loss …

What skills are needed?



C. Welsch

- Beam Instrumentation == "eyes" of the machine operators
  - i.e. 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 find new or improve existing techniques to fulfill new requirements
  - A combination of the following disciplines
    - Applied & Accelerator Physics;
      - Material science, thermodynamics, Electro-magnetism, Optics, Mechanics, Electronics, Nuclear Physics, Controls and Software engineering …
  - A multi-disciplinary field!

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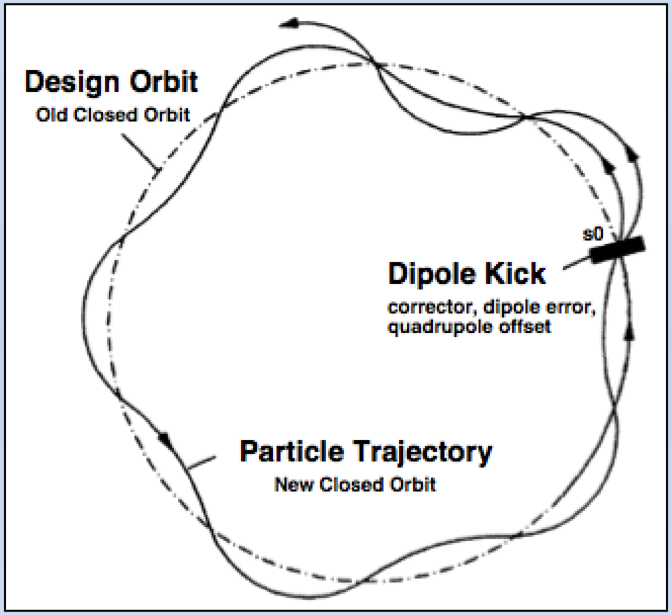
- **Discuss diagnostics developments needed for new machines**

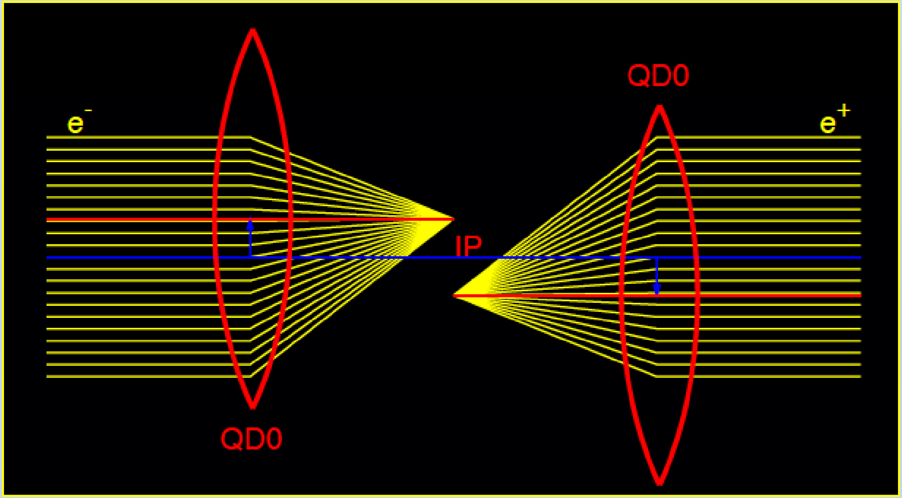
First Lecture

Second Lecture

Position Measurements

- In a modern storage ring particles travel billions of km within < 100 µm of the ideal orbit
- In linear colliders nano-beams from independent accelerators must be made to collide
- Must employ stability principles for beam dynamics and accurate components and diagnostics

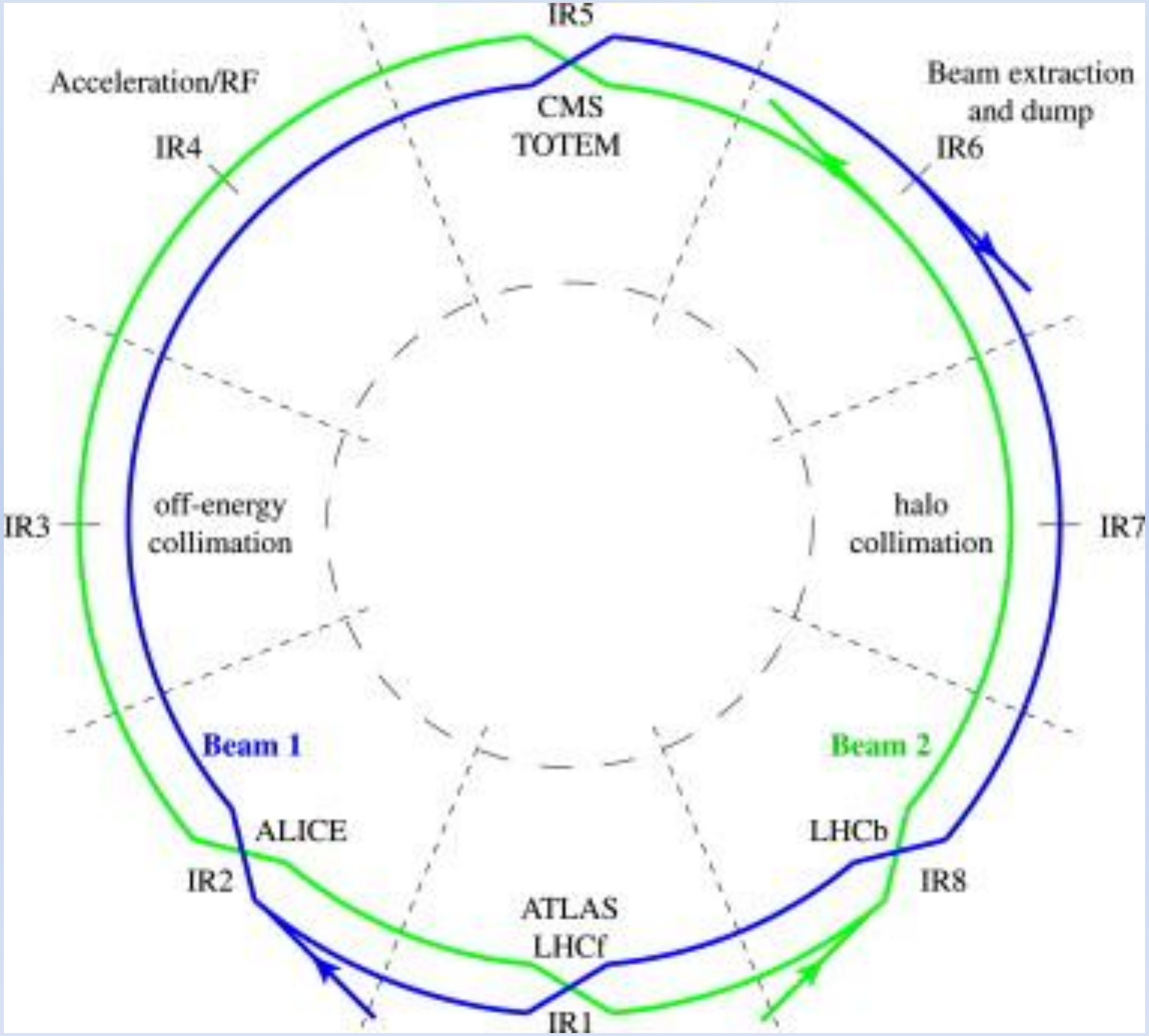




QD0 should be stabilized to 0.15 nm for frequencies above 4 Hz

- At the SLS 73 "button" BPMs measure orbit deviations to better than 1 µm @ 4 kHz sampling rate.
- LHC BPM resolution ~ 5µm (depending on location in machine & measurement purpose)
- CLIC BPMs, resolution requirements:
  - 100µm (injectors) down to **3 nm (at IP)**

LHC Beam Diagnostics

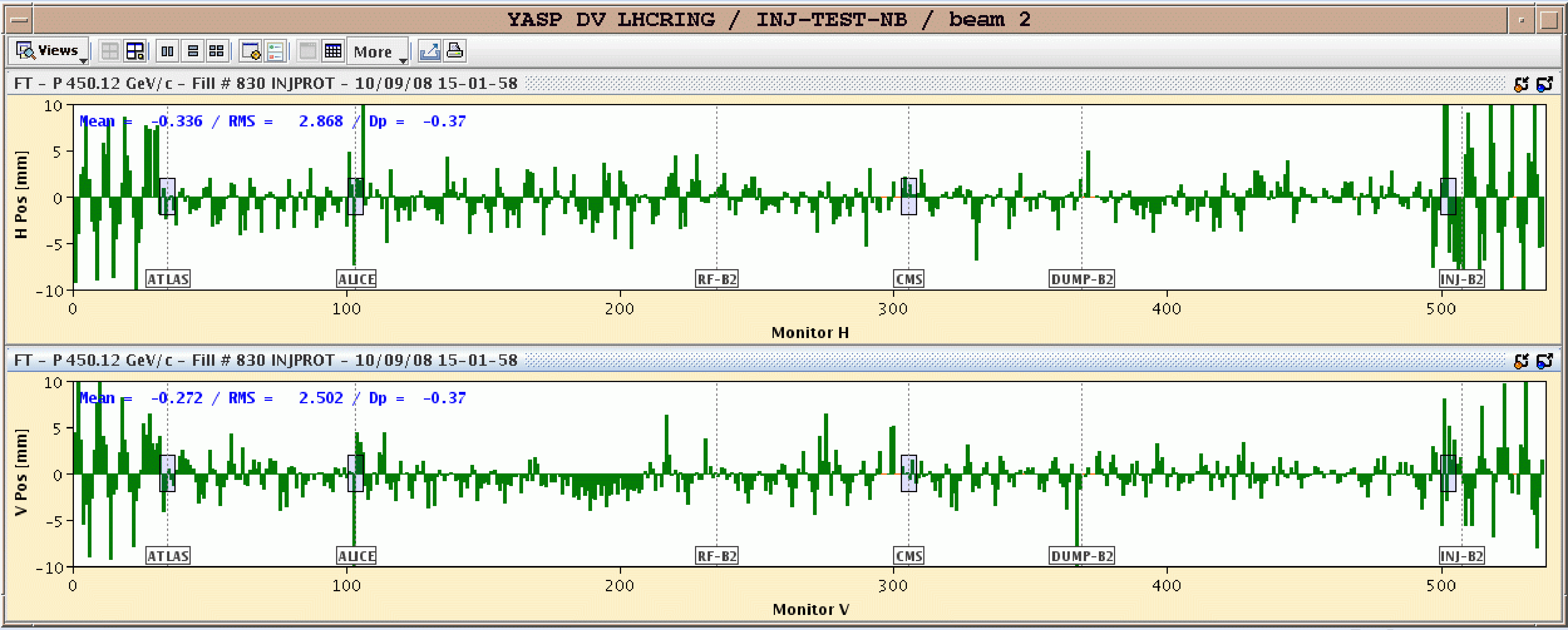


Position Measurement for Beam Threading

- Threading the beam round the LHC ring
  - One beam at a time, one hour per beam.
  - Collimators were used to intercept the beam (1 bunch, 2×10^9 protons)
  - Beam through 1 sector (1/8 ring)
    - correct trajectory, open collimator and move on.

BPM availability ~ 99%

Beam 2 threading



R. Jones

Transfer matrix between two points

The transfer matrix between two arbitrary point in the machine

$$\begin{pmatrix} x \\ x' \end{pmatrix}_2 = M_{1\to 2} \begin{pmatrix} x \\ x' \end{pmatrix}_1$$

Measure:

- **Position**
- **Angle**

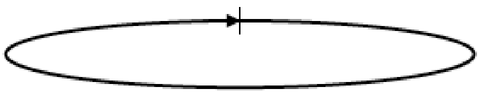
With beam position monitor at point 1 (2) using at least 2 beam position monitors

Adjust machine parameters

Stability of transverse (betatron) oscillations

The transfer matrix of a beamline that consists of elements with individual matrices M_1 , M_2 , ... M_n $\mathbf{M_{tot} = M_n \cdot \ ... \ \cdot M_2 \cdot M_1}$ (N.B. the order in which matrices are multiplied!)

- Full turn matrix M



$$\begin{pmatrix} x \\ x' \end{pmatrix}_n = M^n \begin{pmatrix} x \\ x' \end{pmatrix}_0$$

- After n turns must remain finite for arbitrarily large n

L. Rivkin

Position Measurement for Beam Threading

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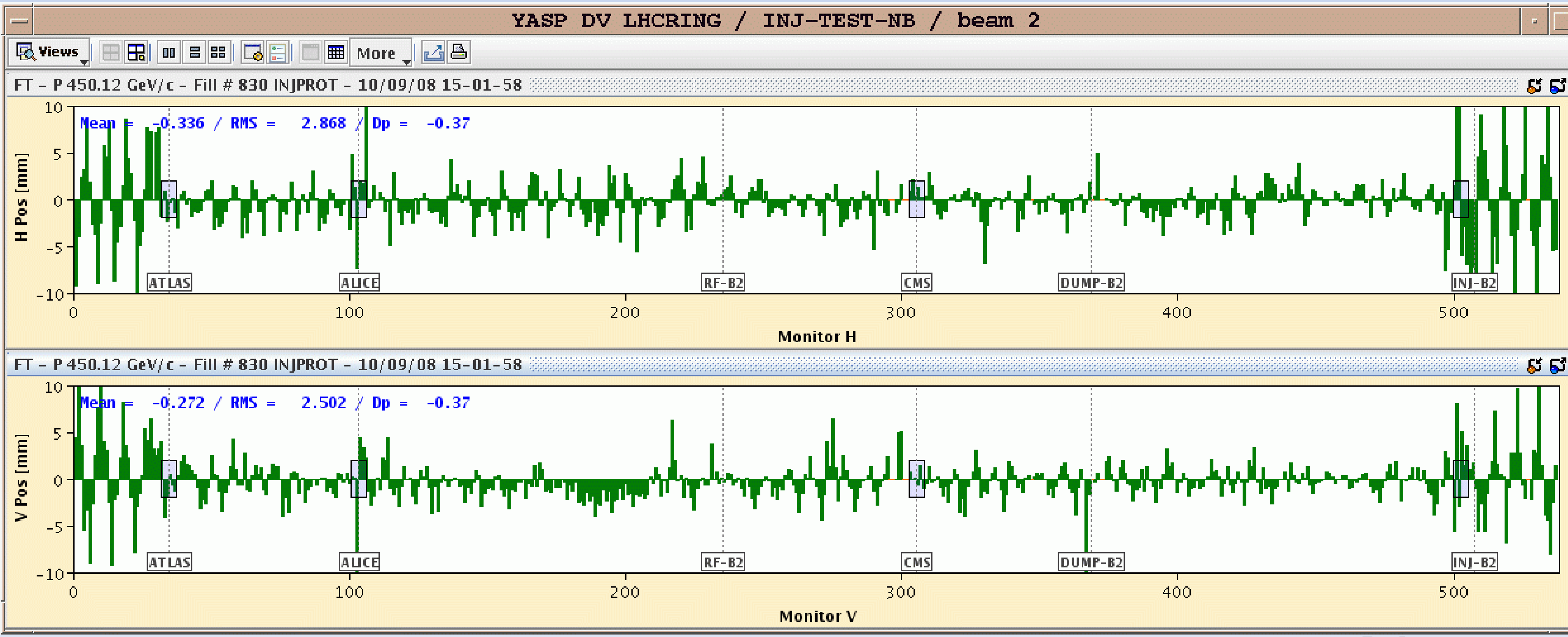
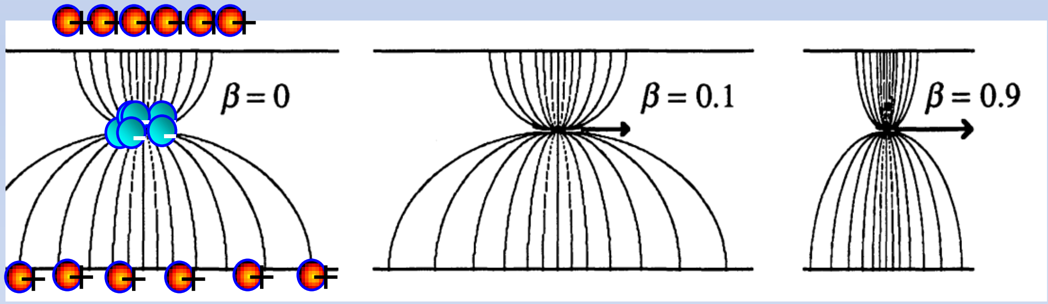


R. Jones

Physics : Electricity and magnetism

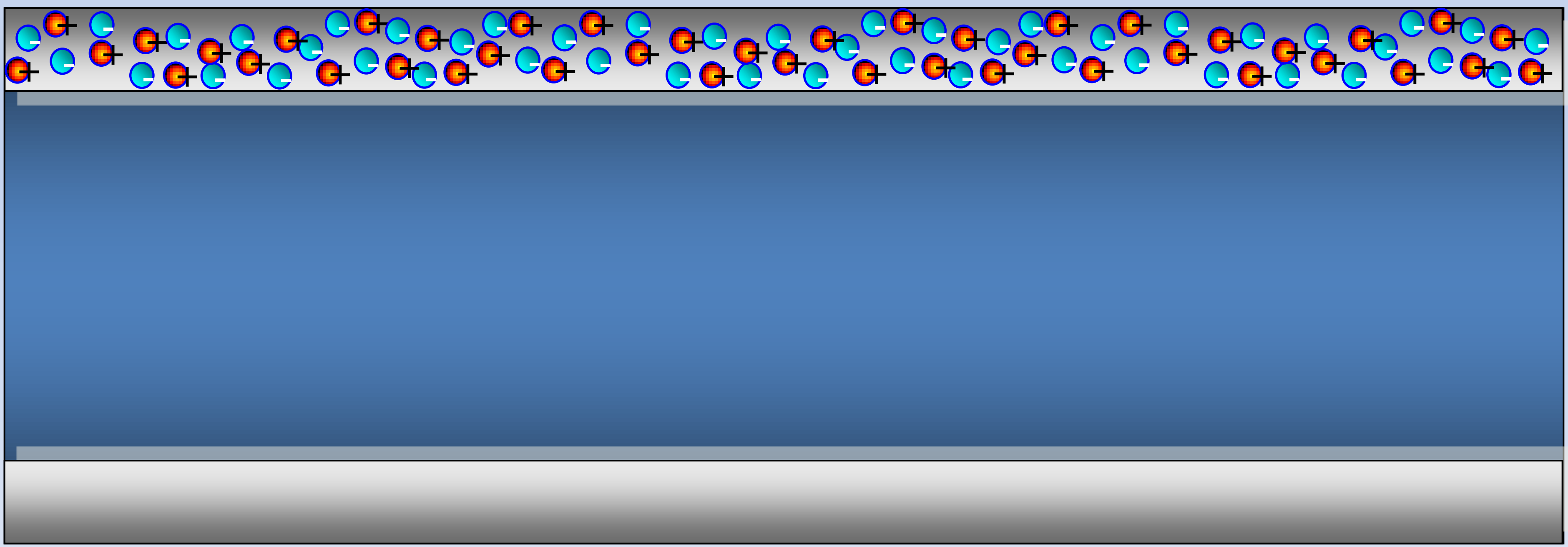
- Relativistic beams:
  - Measure the relative difference in the strength of the electric field (image charge density on beam pipe) moving in disk with and at right angles to the beam's velocity direction
  - (other method's too – e.g. cavity BPMs)



+ electronics

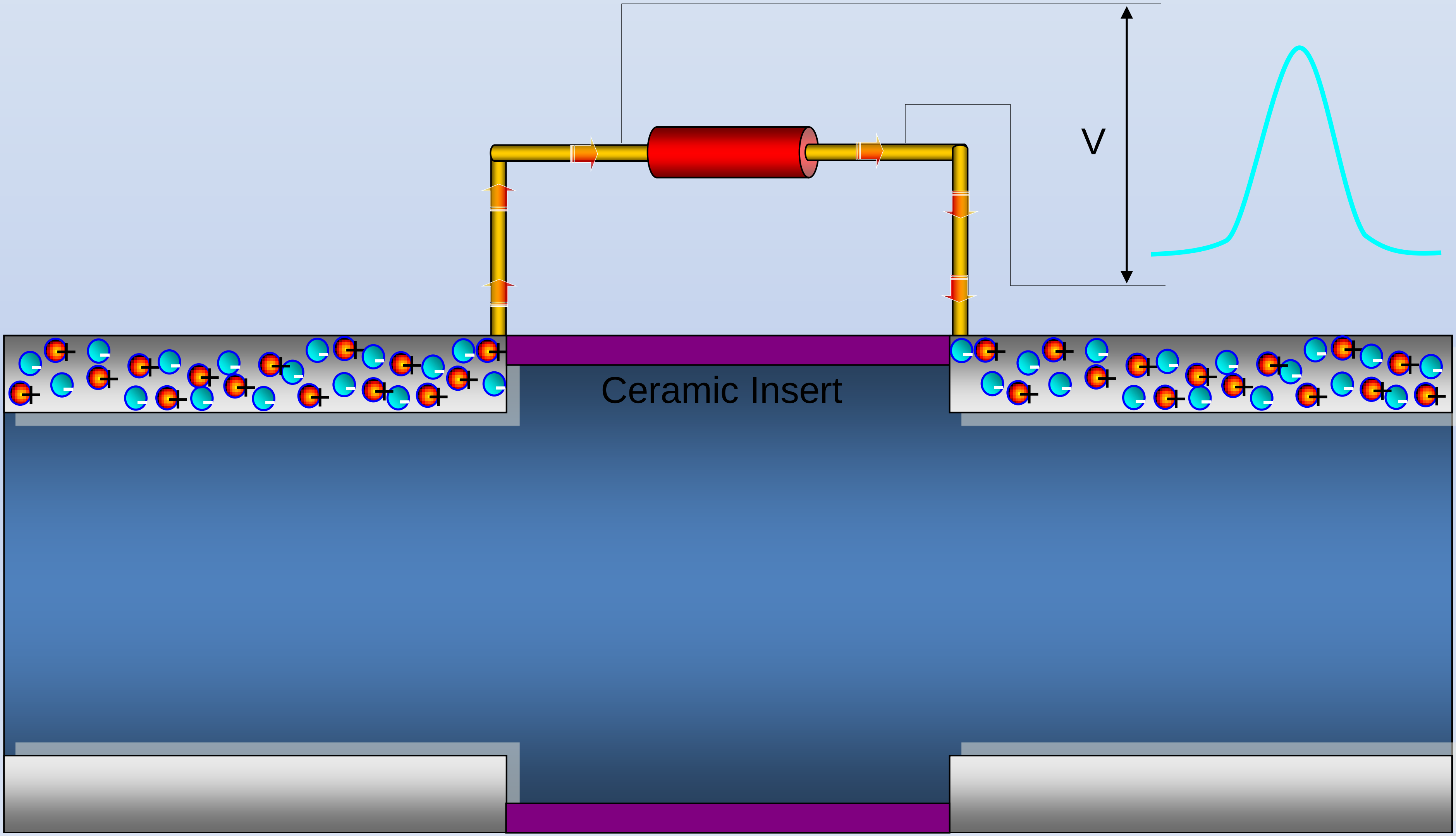
Basic principle exploited in inductive and electrostatic BPMs and wall current monitors

Measuring Beam Position – The Principle



Slide by R. Jones

Wall Current Monitor – The Principle



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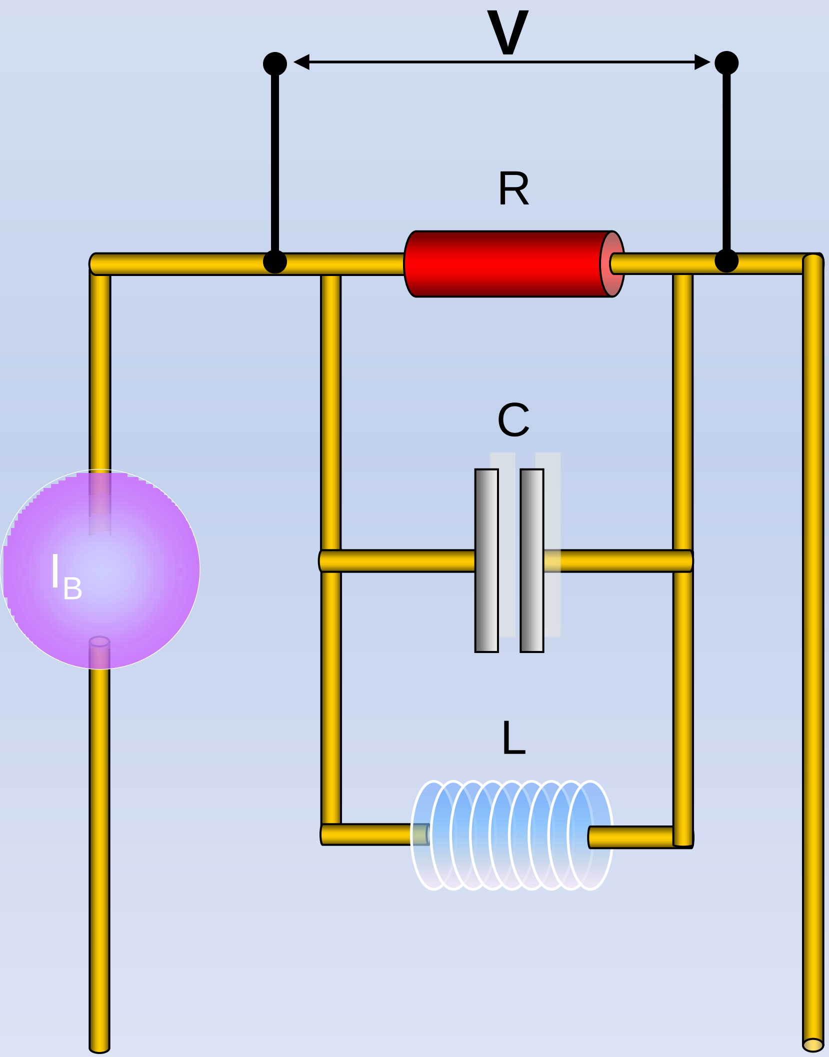
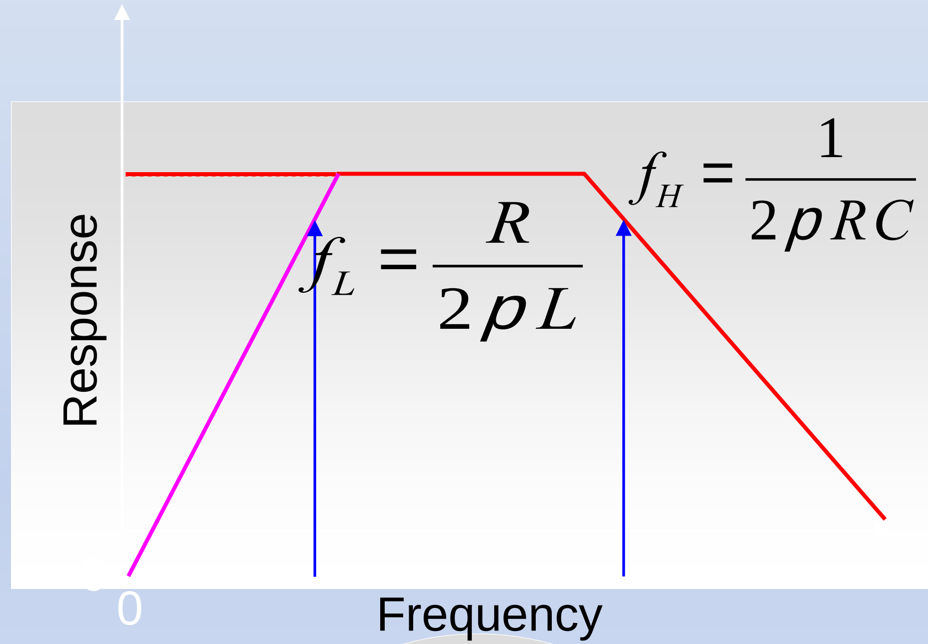
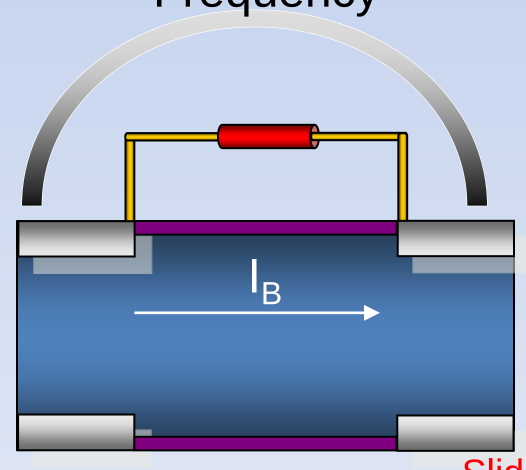
Wall Current Monitor – Beam Response







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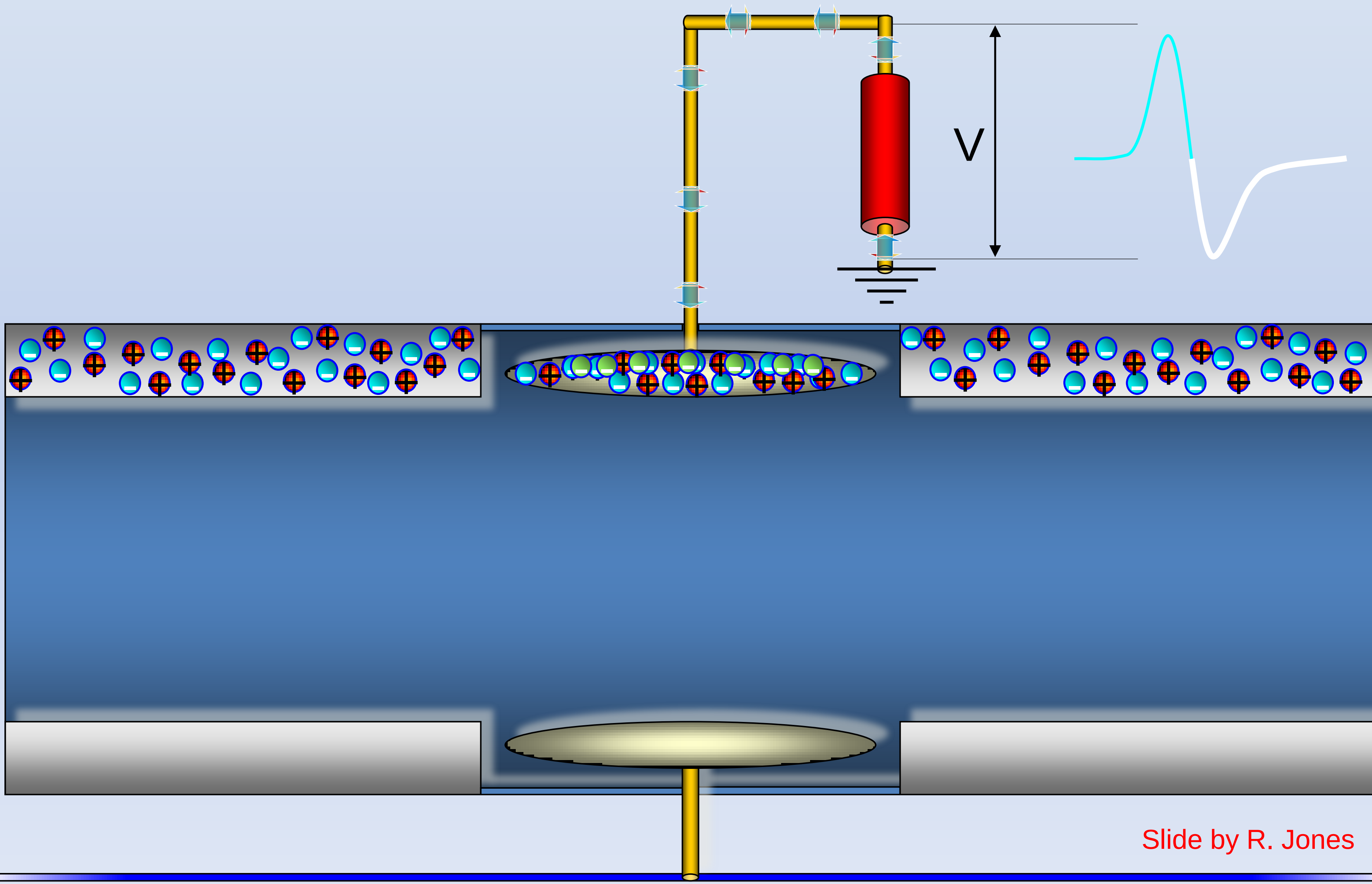
Principle of Signal Generation of electrostatic / capacitive BPMs



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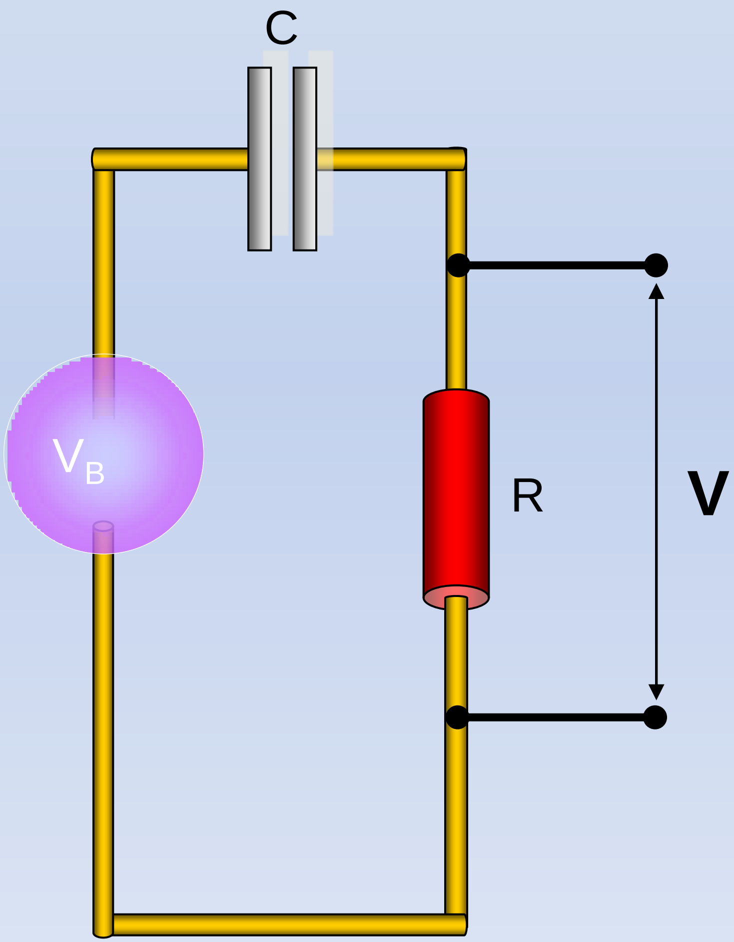
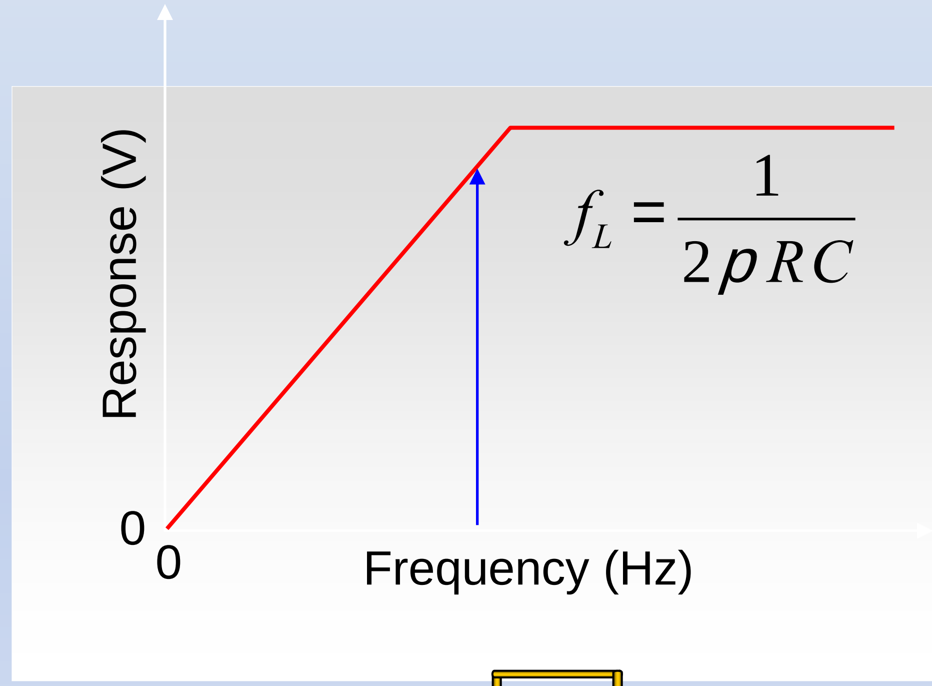
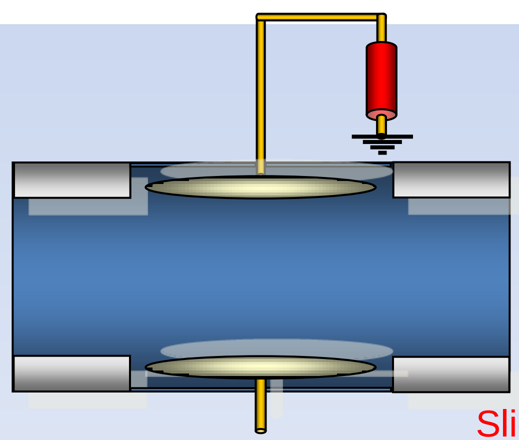
Electrostatic Monitor – Beam Response







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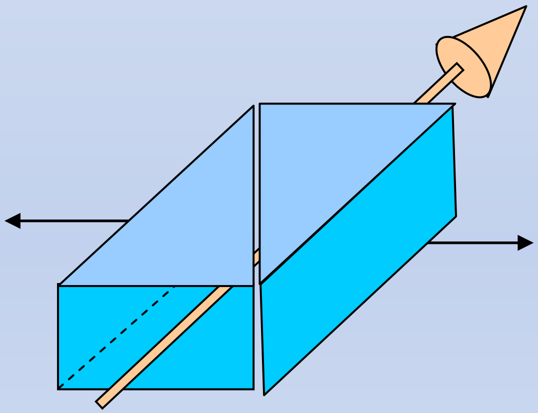
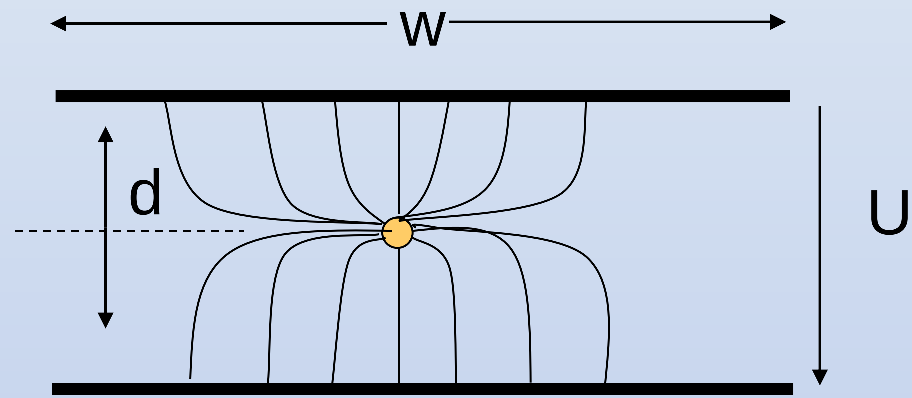
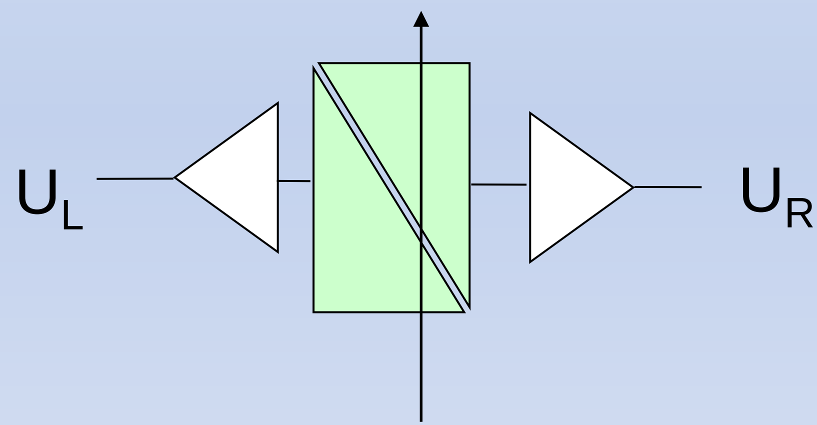
Shoebox pick-up

Bunch length should be smaller than the shoebox length, w to be linear







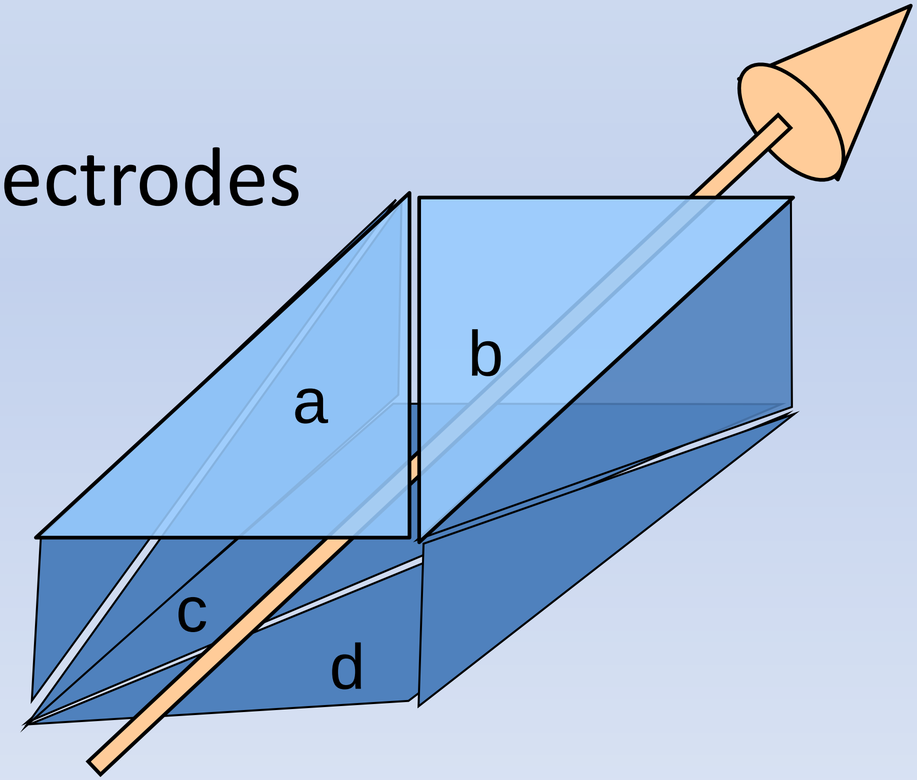
Linear cut through a shoebox

$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{D}{S}$$

R. Jones

Doubly cut shoebox

- Can measure horizontal and vertical position at once
- Has 4 electrodes



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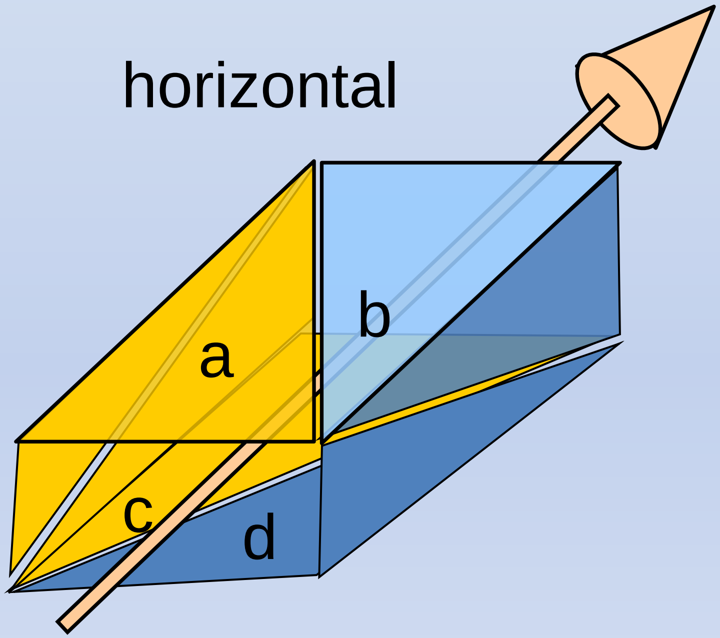
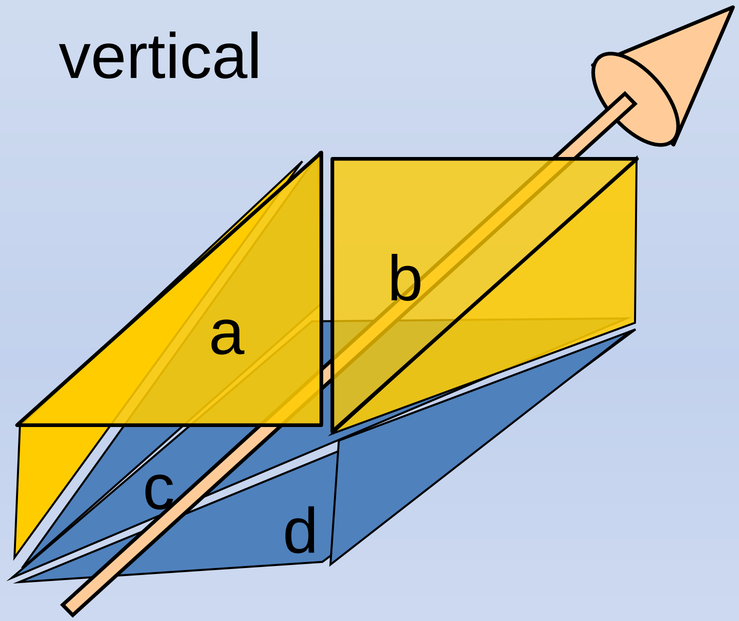
Simultaneous horizontal and vertical measurement

horizontal



$$X = \frac{(U_a + U_c) - (U_b + U_d)}{\Sigma U}$$

vertical



$$Y = \frac{(U_a + U_b) - (U_c + U_d)}{\Sigma U}$$

Slide by R. Jones

BPM position calculation

Important Effects:

- Non-linearity
- Geometrical center ≠ electrical center
- Errors in difference of small numbers
  - Amplification before sum and difference
- System bandwidth –
  - Convolution of the transfer impedance and frequency response of the cables, amplifier, filters, ADC
- Saturation
- Sampling resolution of ADC
- Noise on electronics
- Average position measurement or single shot
- Goodness of calibration circuit
- Cross talk between adjacent electrodes

$$X = \frac{1}{S_x}\frac{(U_a + U_c) - (U_b + U_d)}{SU} + d_x$$

$$Y = \frac{1}{S_y}\frac{(U_a + U_b) - (U_c + U_d)}{SU} + d_y$$

Important Concepts:

- Accuracy, Resolution, Analog Bandwidth, Acquisition bandwidth, Dynamics range, Signal-to-noise ratio

Digital Signal Processing

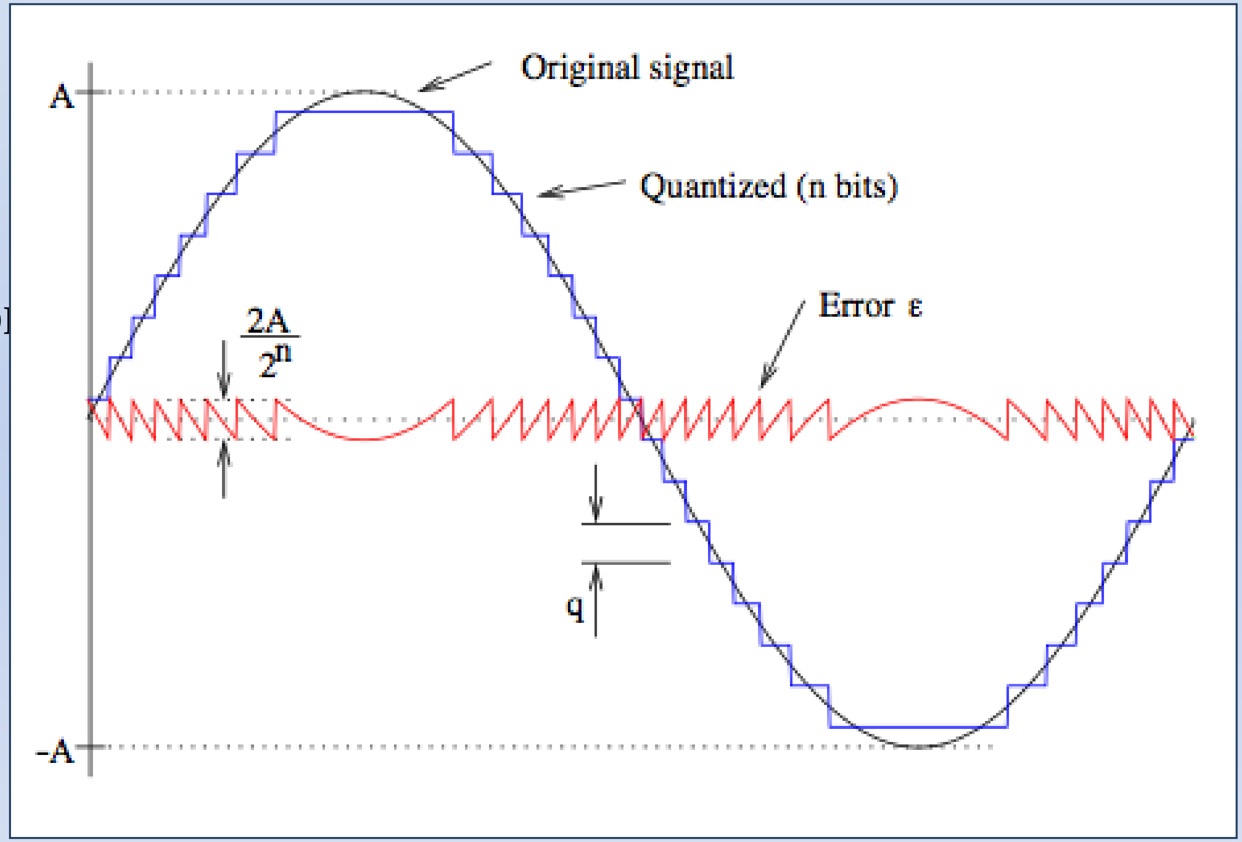
Excellent Lecture “Analog to Digital“ at CAS2008 School by Belleman

Amplitude Quantization

$$q = \frac{2A}{2^n} = A.2^{-(n-1)}$$

Maximum quantization error

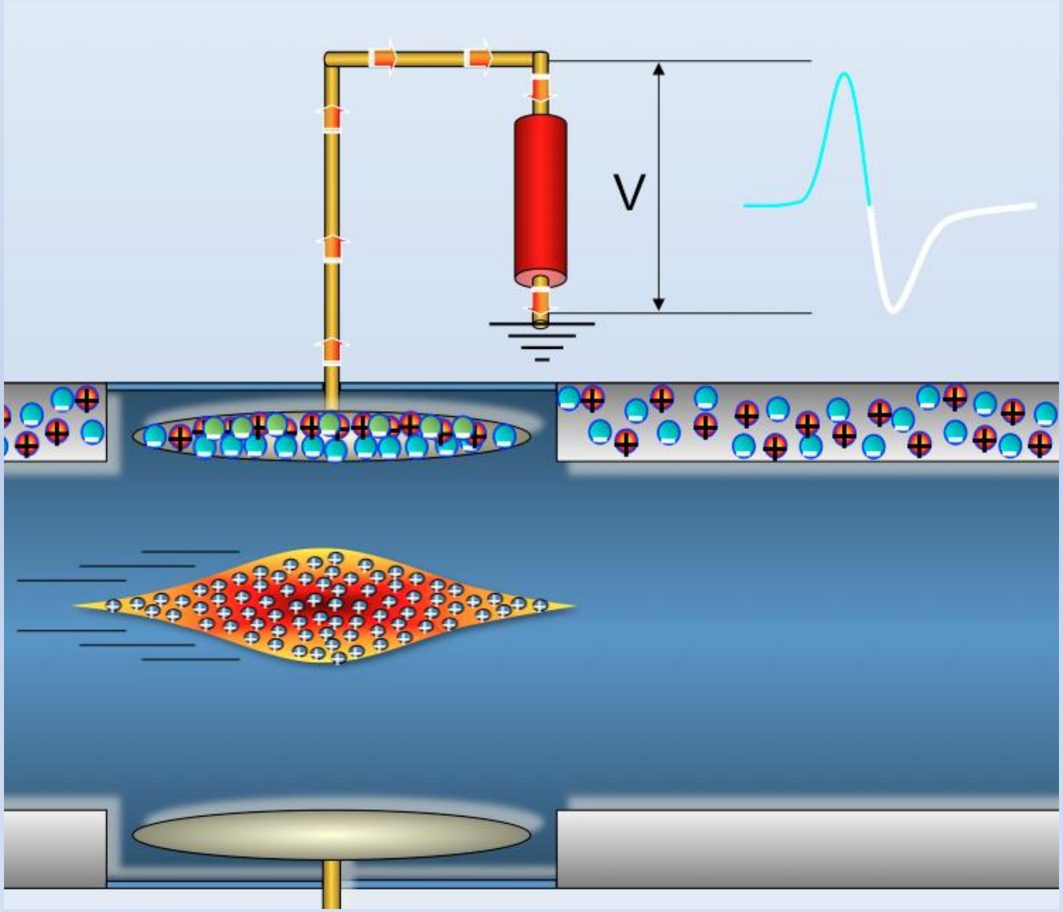
$$e = \frac{\pm q}{2} = A \cdot 2^{-n}$$



- Digital electronics - contributes to the resolution
- Appears now in most diagnostics
- Important subject in itself – requires dedicated lecture

Current Measurements, cont ..

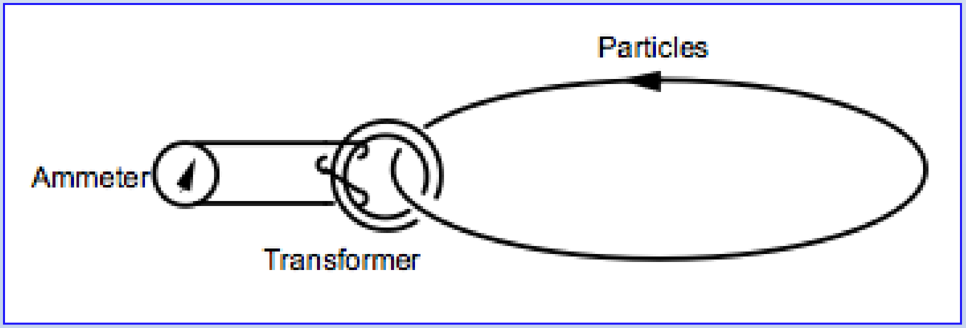
From this BPM signal – how do you measure the current?

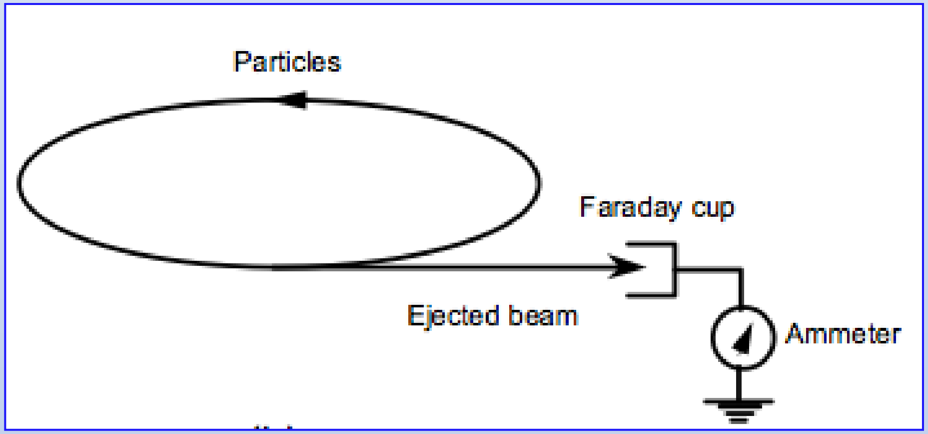


Any other way to measure the current? ….

Current Measurements, cont ..

Rate at which charge passes a fixed point



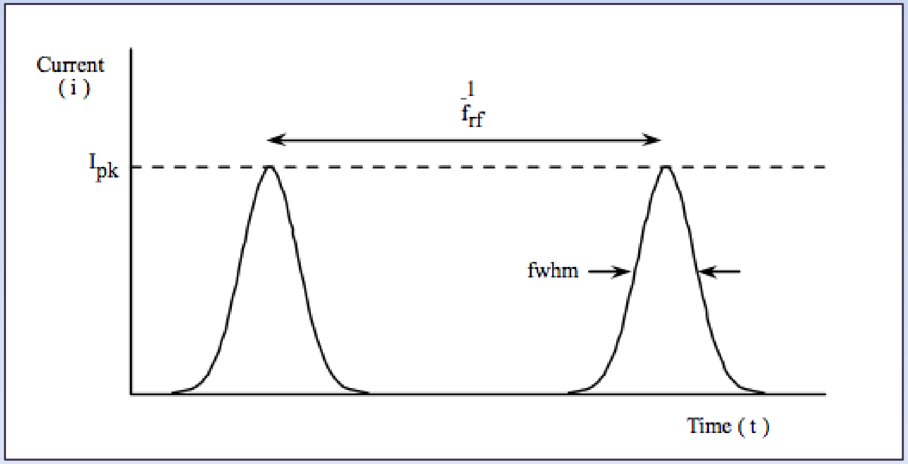


DC current transformer

(Measures magnetic field produced by the current)

Faraday cup

(measured the total beam charge)

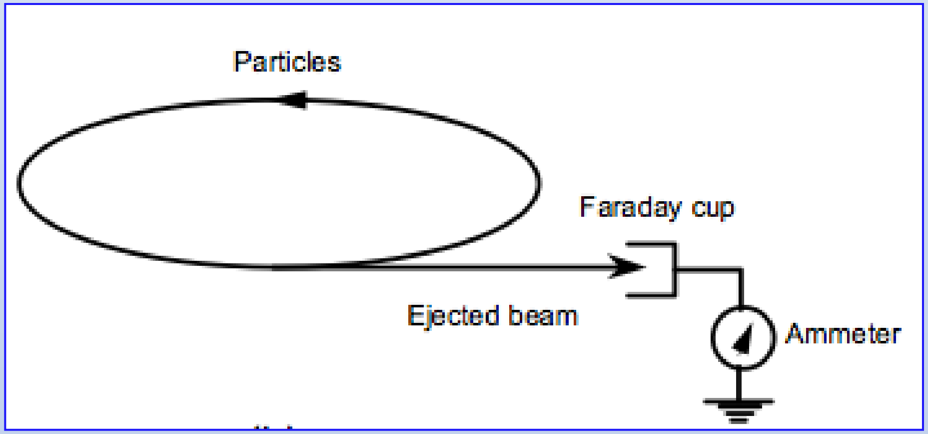


Current Measurement – Faraday Cup

- At very low energies and low intensities the Faraday Cup is an often used device for intensity measurements.

- It acts as a beam stopper and is therefore fully destructive

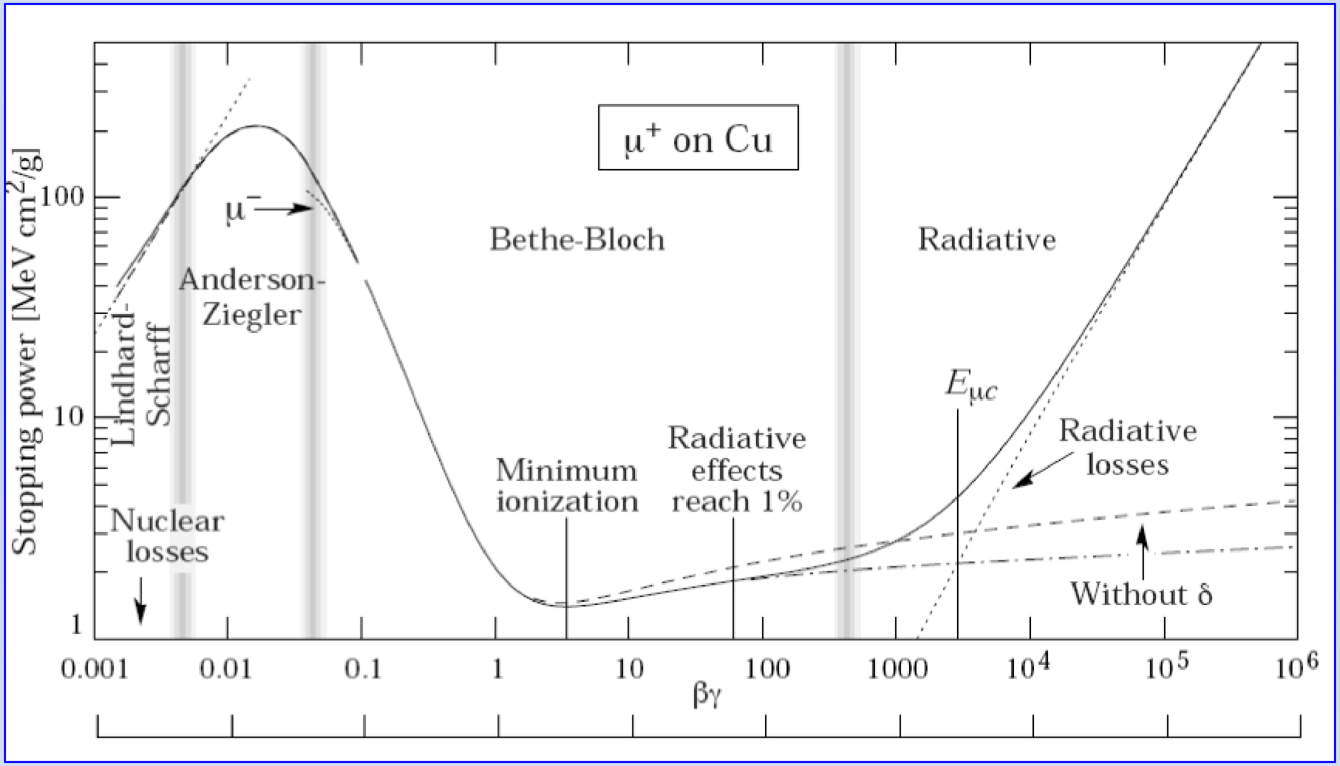
- Very low intensities down to a few pA can be measured, even for a DC beam, with low noise current to voltage amplifiers

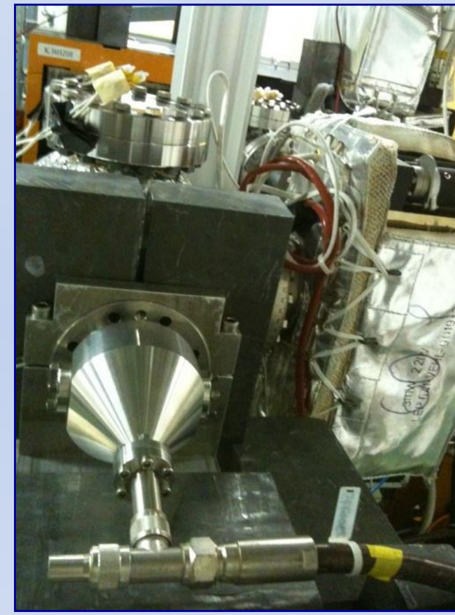


Current Measurement – Faraday Cup

Physics : Understanding particles interact with matter

Measure directly the stopped charge as a current in a metallic block
To measure the full charge ➔ must stop the full beam





Bethe Bloch formula: Stopping Power dE/dz /ρ

Current Measurement – Faraday Cup – Electron Beam

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \frac{Z_T}{A_T} \rho \frac{Z_p^2}{\beta^2}\left[\ln\frac{2m_e c^2 \gamma^2 \beta^2}{I} - \beta^2\right]$$

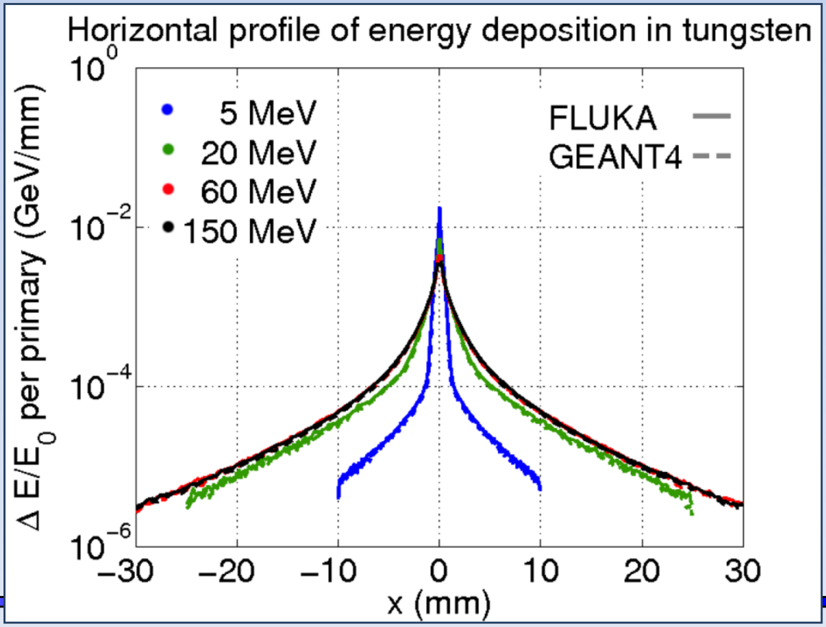
Variables in design:

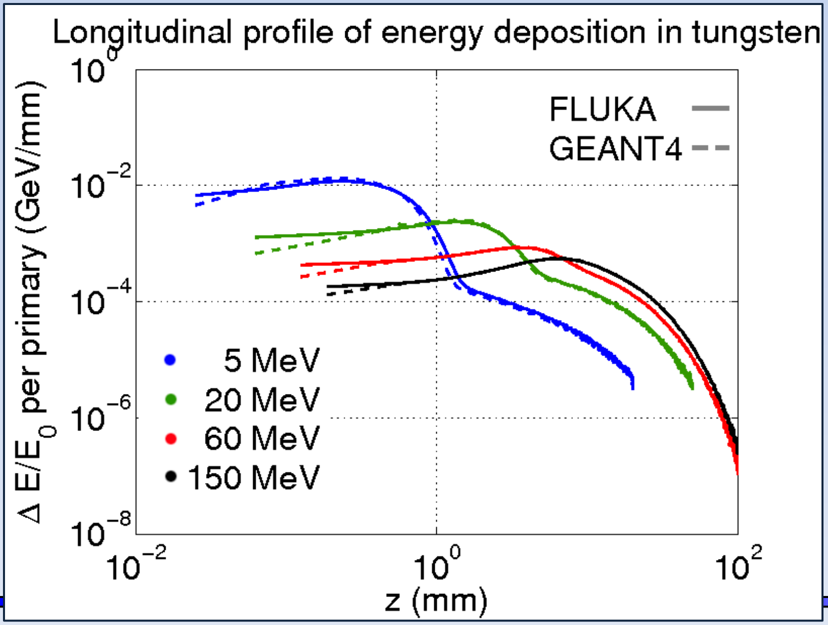
- ρ: material density
- A_T and Z_T: the atomic mass and nuclear charge
- Z_p: particle charge
- β: the particles velocity and γ $\quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$

Detector Size:

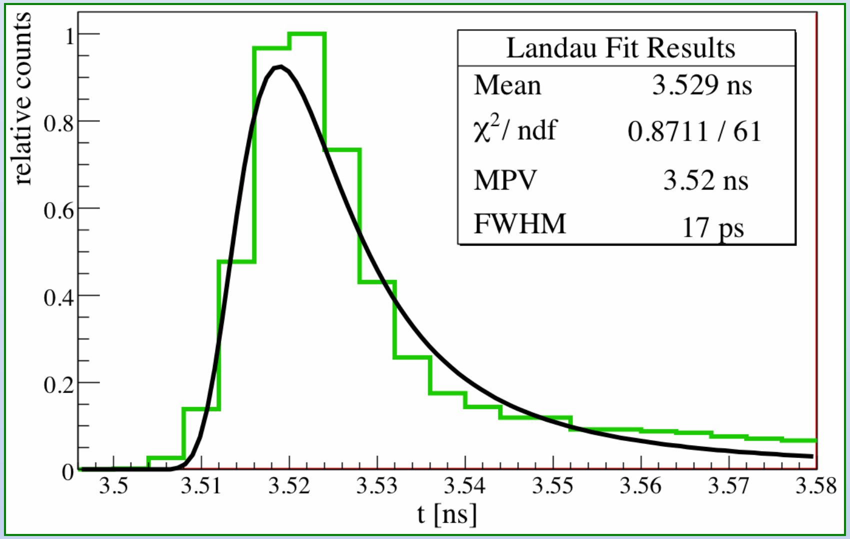
Chose conducting material to fully the particles and contain the beam shower

Example for various electron beam energies into a tungsten sample

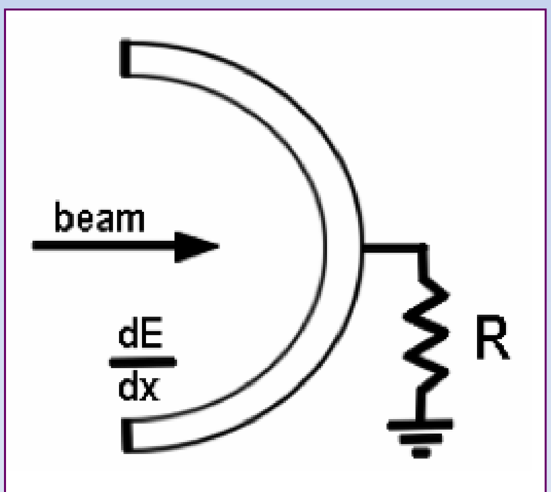




Current Measurement – Faraday Cup – Electron Beam



Simulation of time to stop particles GEANT 4

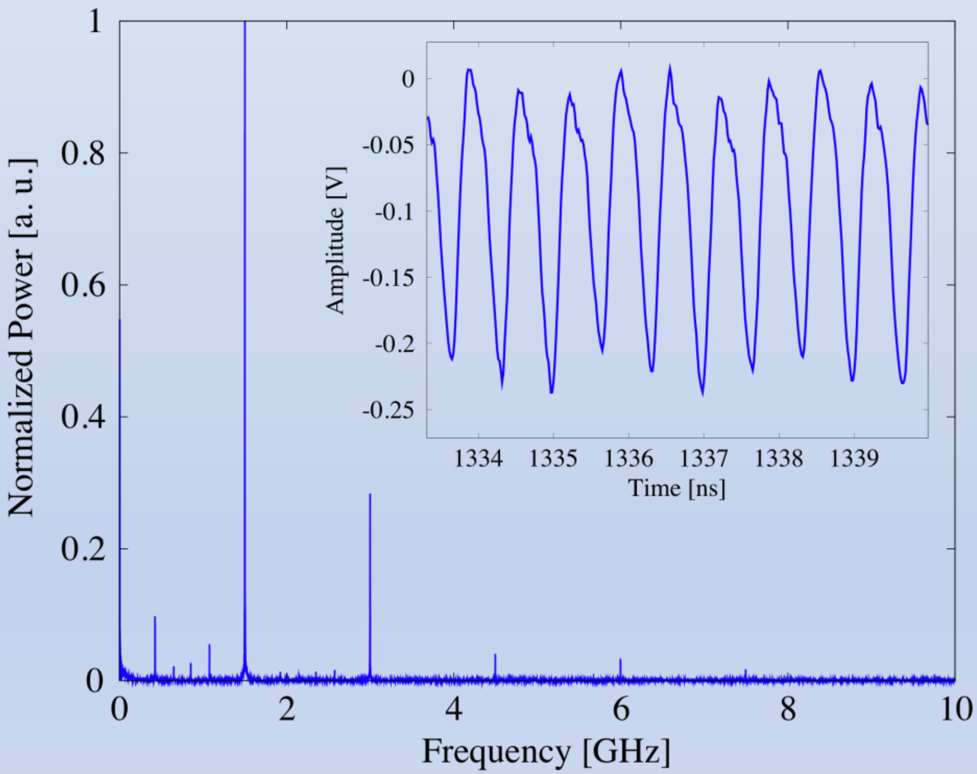


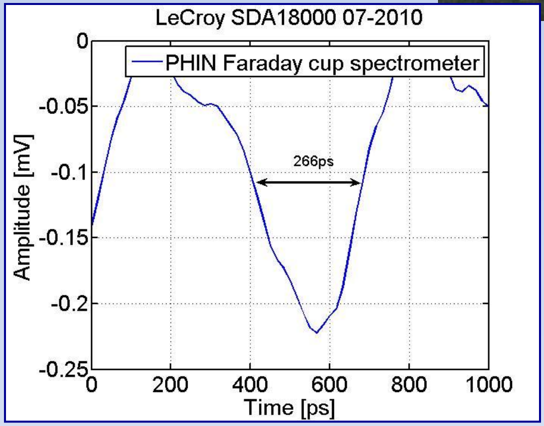
- Beam charge converted into a current
- The voltage measured across resistor R to ground

The time response ➔ design of signal transmission line:

- Resistance R
- The capacitance C of the cables (~ 100pF/m)
- The inductance H of the cables (µH/m)
- The length of the cable
- Bandwidth of connectors
- Sampling rate of ADC / scope

Current Measurement – Faraday Cup – Electron Beam

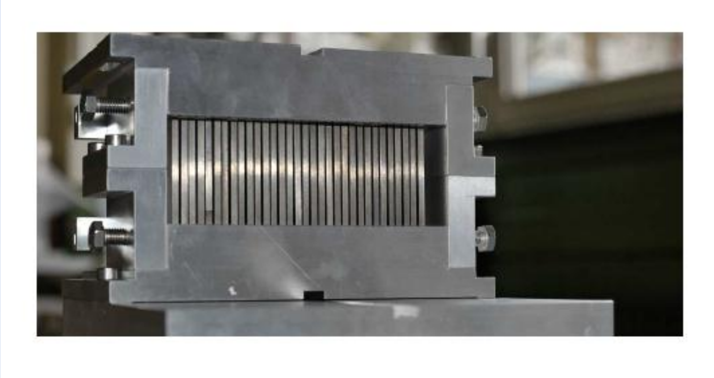


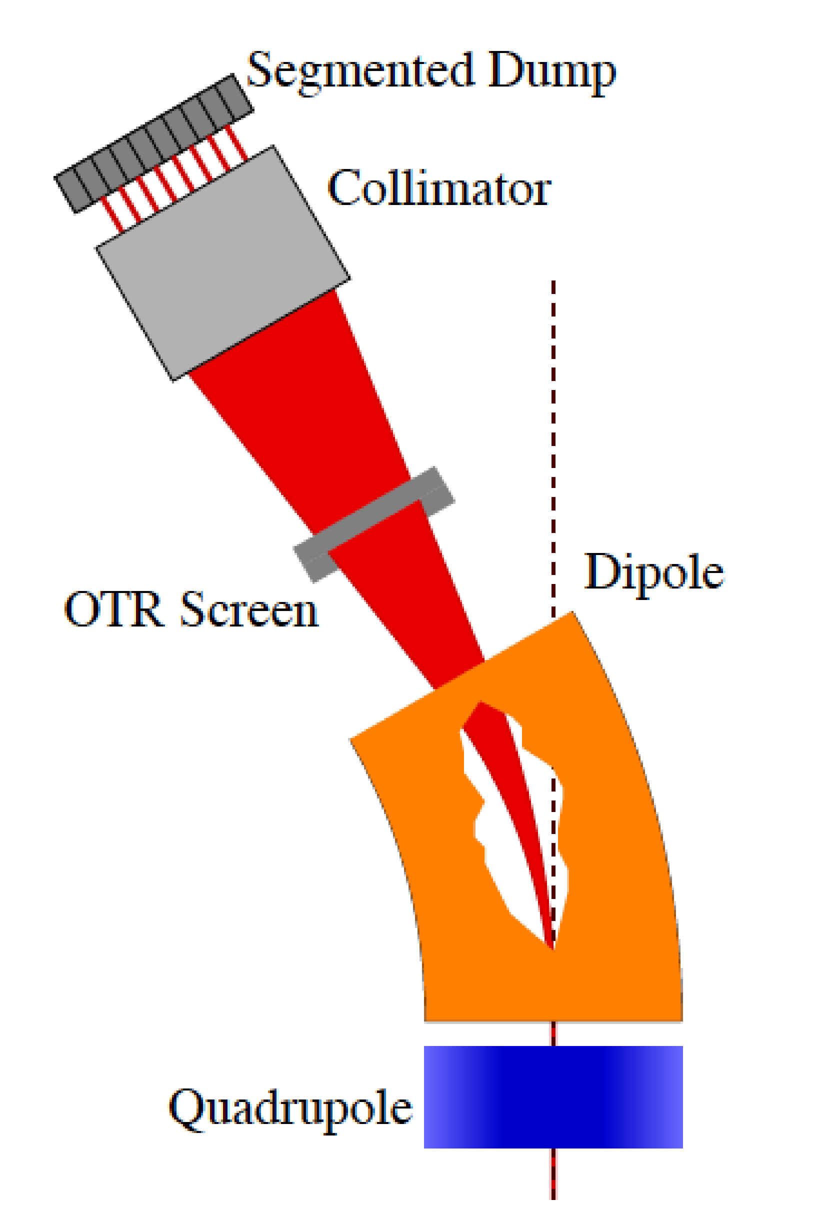


Scope Trace:

- Bunch current
- Bunch spacing
- Bunch length (in reality it is shorter, limited by the time resolution of the Faraday cup + RC circuit by cables … need better diagnostics for bunch length measurement

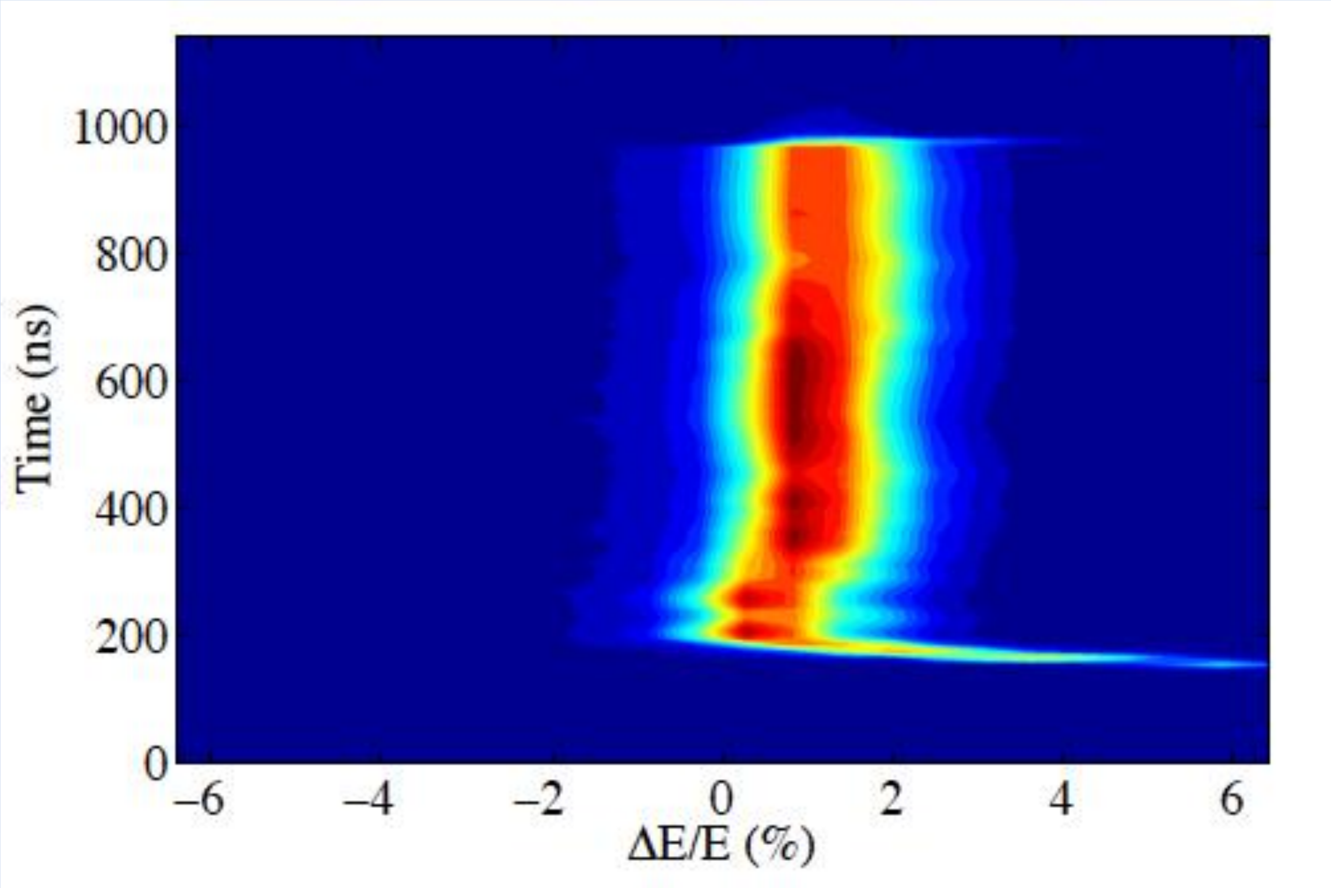
What if you segmented the faraday cup, and put it after a dipole magnet?





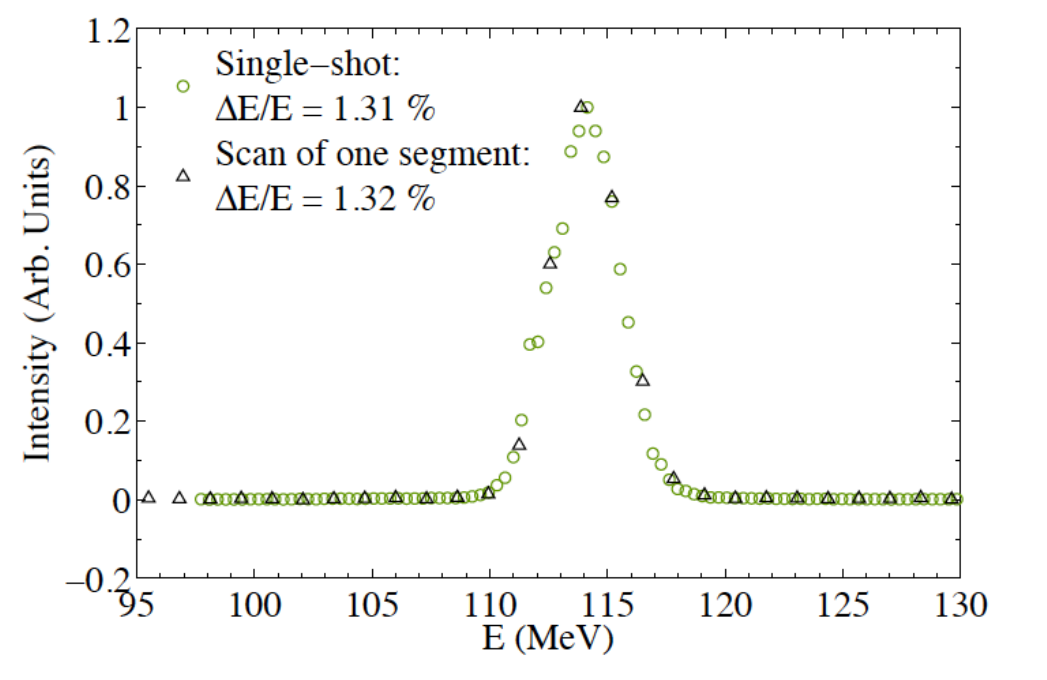
M. Olvegaard et al Nuclear Instruments and Methods in Physics Research A, Volume 683, p. 29-39.

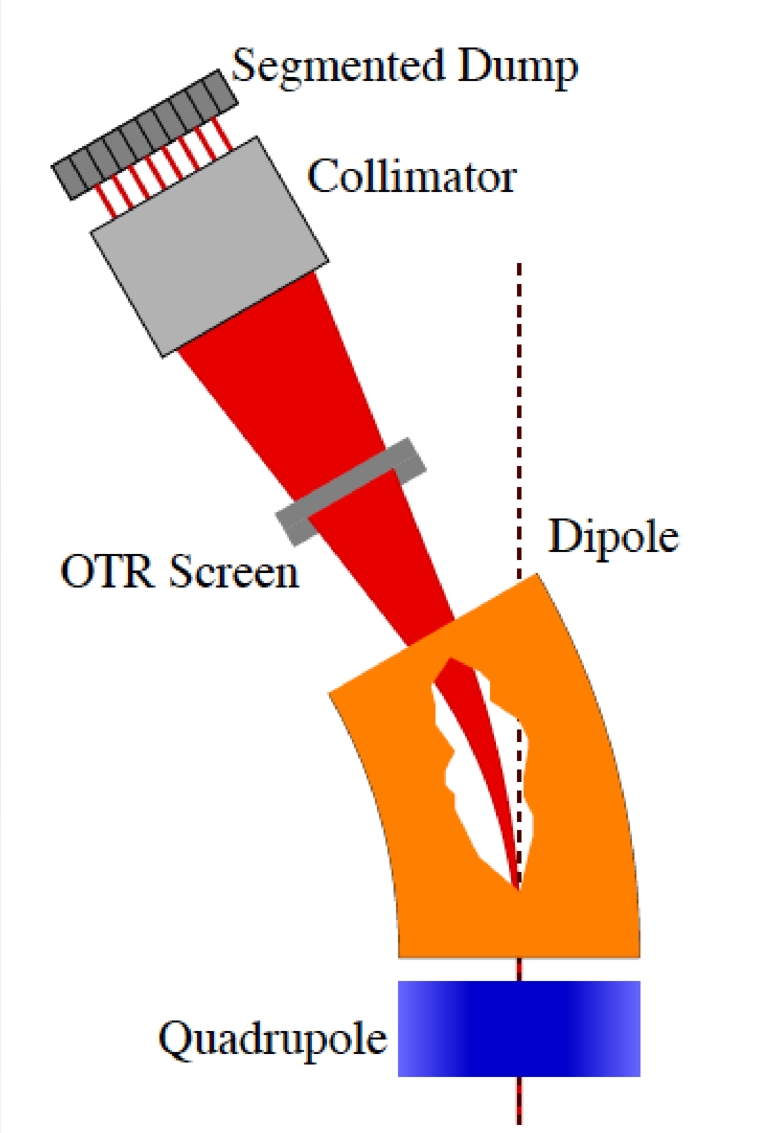
Measure current as a function of x- position



Project onto the X axis,

Know the calibration of dipole magnet
Measure the average **central energy & energy spread**





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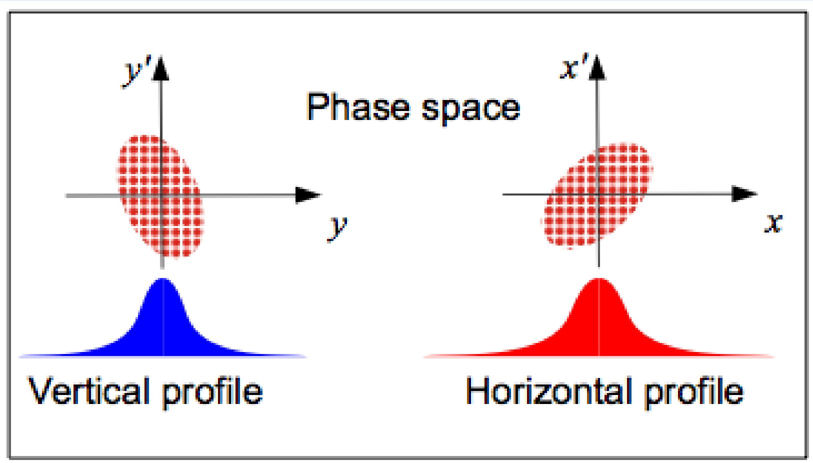
Transverse Phase Space and Beam Profile



$$x' = \frac{\partial x}{\partial s}$$

$$y' = \frac{\partial y}{\partial s}$$

s is the longitudinal co-ordinate

$\varepsilon_{x(y)} =$ area in [x(y); x'/(y')] plane occupied by beam particles divided by π

$$\varepsilon_x^{rms} = \frac{1}{\beta_x(s)}\left[\sigma_x^2(s) - \left(D(s)\frac{\Delta p}{p}\right)^2\right]$$

$$\varepsilon_y^{rms} = \frac{1}{\beta_y(s)}\left[\sigma_y^2(s)\right]$$

measure: $\sigma_x^2(s_i)$

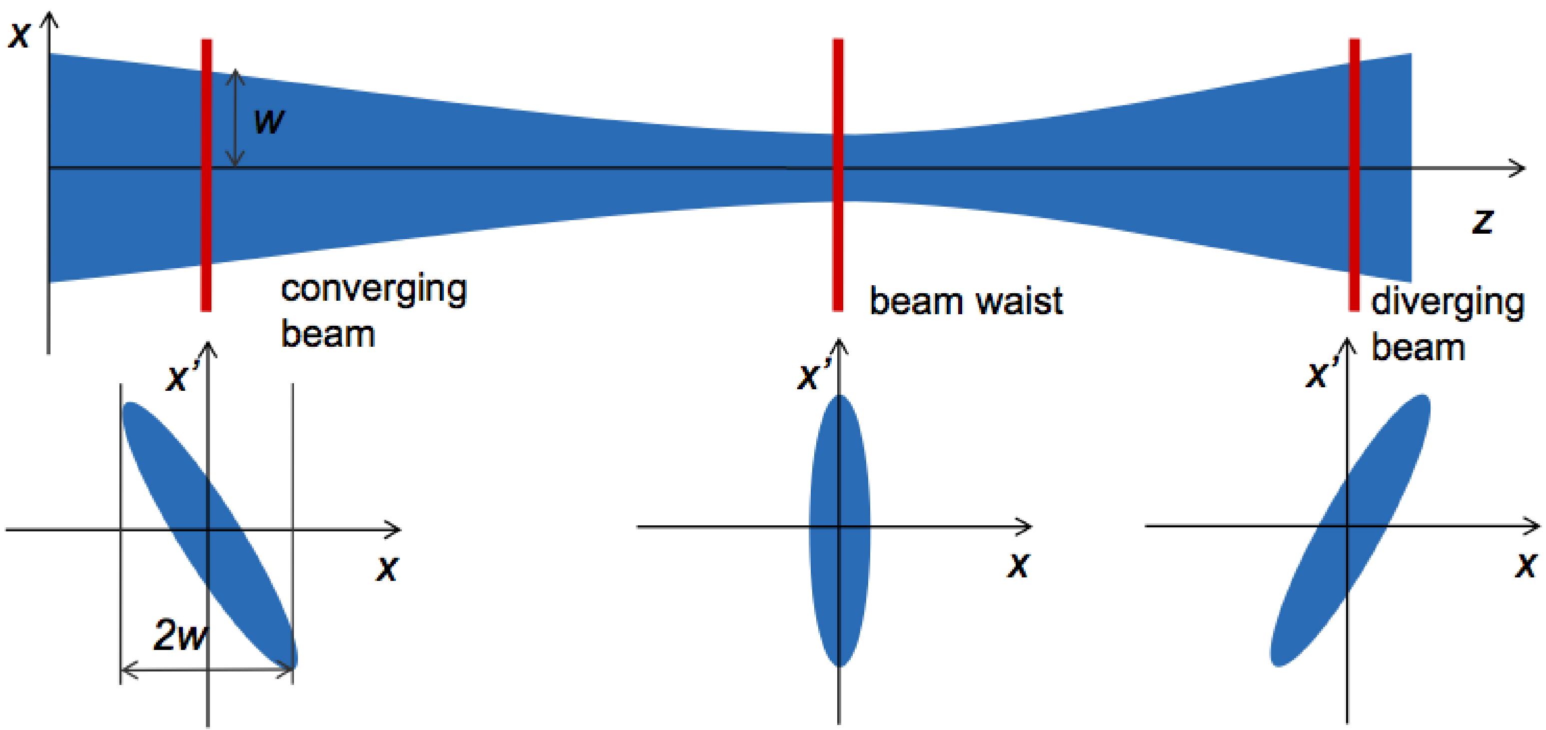
know the optics: $\beta_x(s_i); D(s)\frac{\Delta p}{p}$

calculate the emittance

DITANET school - Transverse profiles - E. Bravin

Transverse Profile

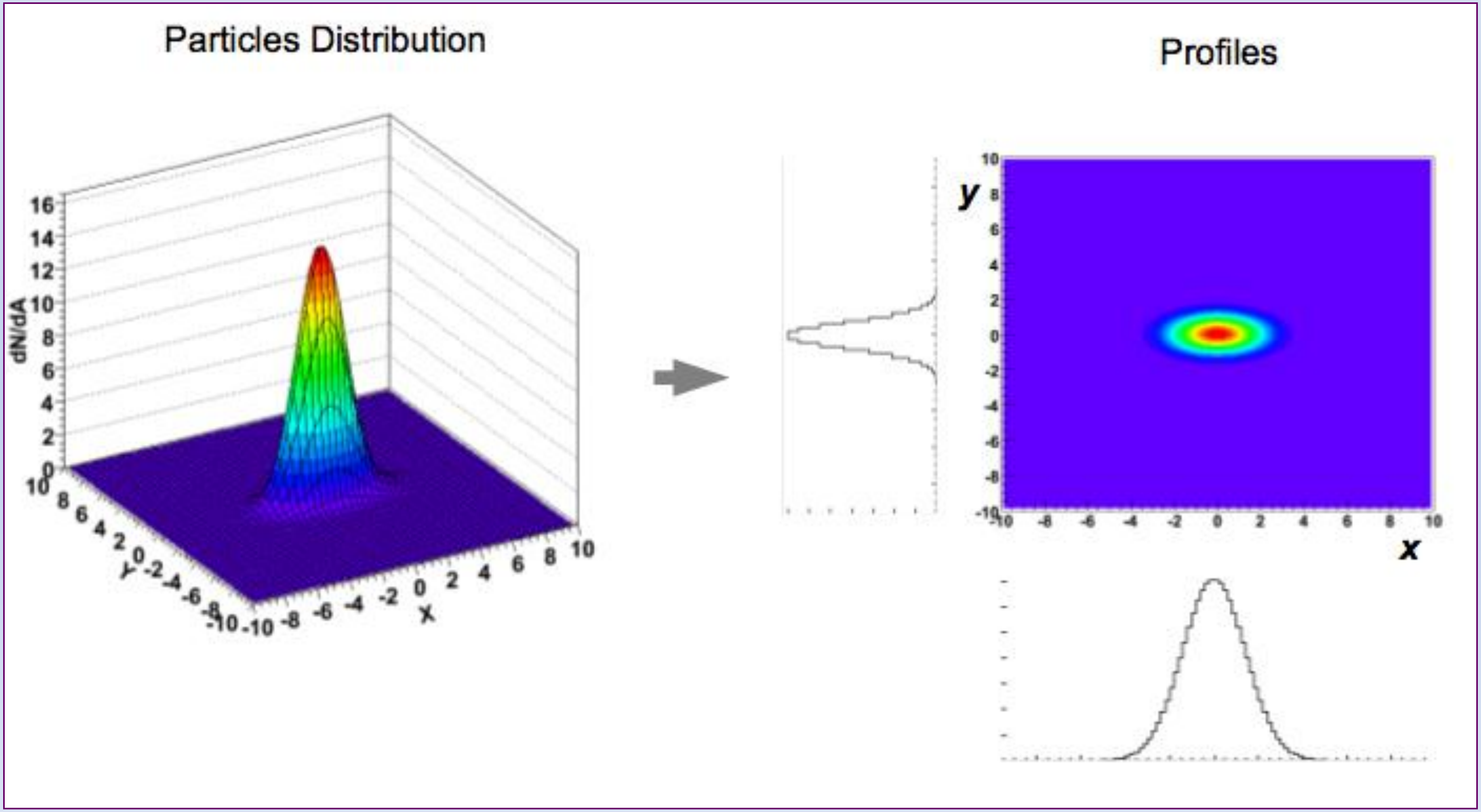
Beam envelope along beamline



Along a beamline the orientation and aspect ratio of beam ellipse in *x*, *x'* plane varies, but area $\pi\varepsilon$ remains constant

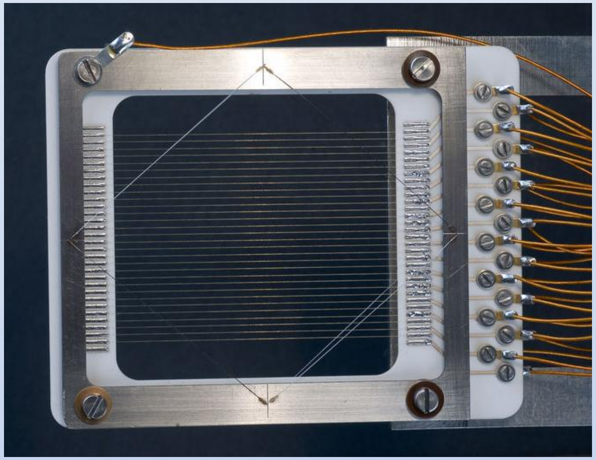
H. H. Braun (CAS 2008)

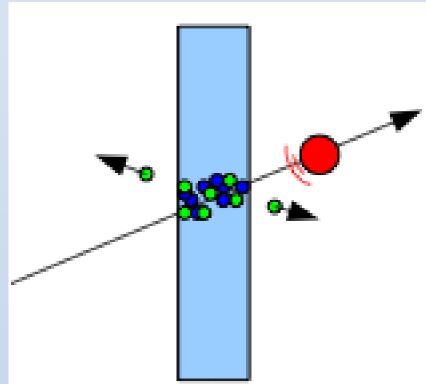
Transverse Profile Measurement

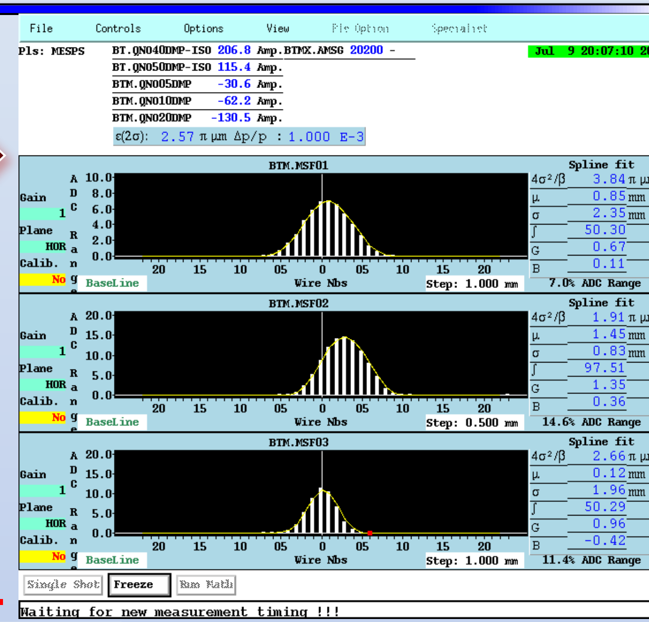


DITANET school - Transverse profiles - E. Bravin

SEM (secondary emission) grids







Detector:
SEM grid (parallel wires)

Physics process:
Secondary emission or e-

Complex mechanical assembly:

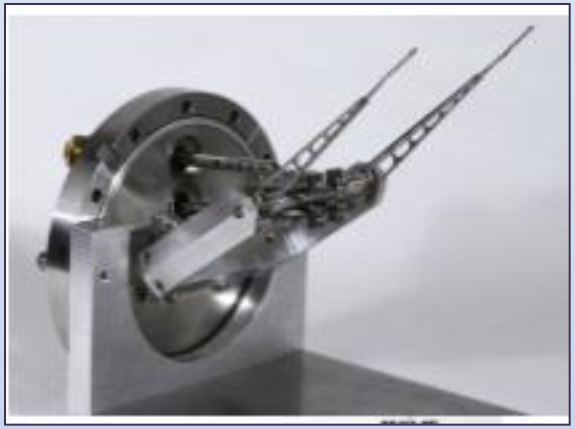
- Insert grid into the beam, in vacuum
- Single shot
- Profile scale determined by wire position
- Profile sampling determined by distance between wires, wire thickness
- Wires stretched tight

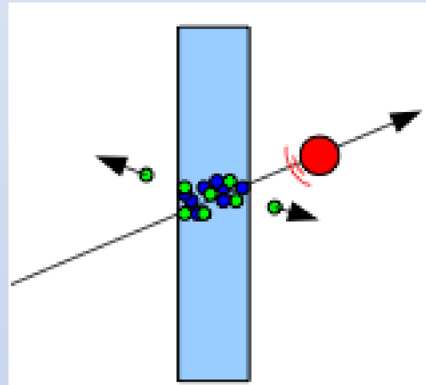
Wire signal detection:

- Current flowing back onto the ribbons is measured
- Electrons ejected are taken away by polarization voltage
- One amplifier / ADC per channel

Single shot profile

Wire scanner





Detector:
Wire Scanner

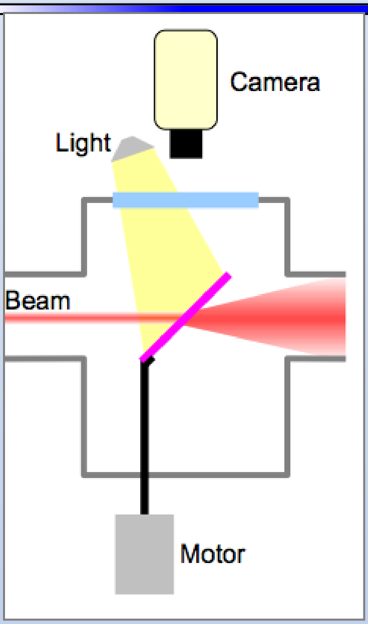
Physics process:
Secondary emission or e-

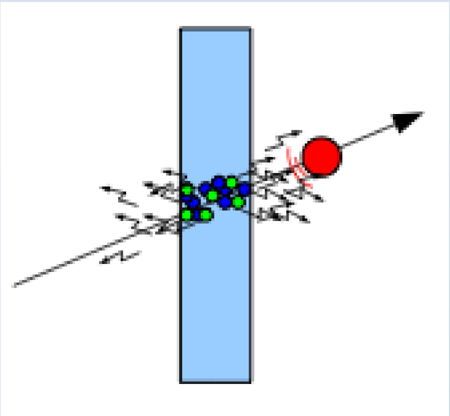
Reconstruct transverse profile

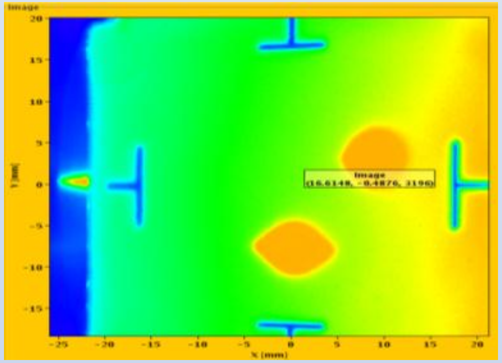
Complex mechanical assembly:
- Scan wire, across beam, in vacuum
- Speeds up to 20 m/s!
- Profile scale determined by wire position
- Profile sampling determined by speed of the wire w.r.t. frequency of beam
- Perturbs the beam, not suited to follow the emittance evolution

Wire signal detection:
- Either measure the current from wire
- Or deflect (capture) secondary electrons, create photons, image the photons

Scintillating screen







First full turn as seen by the BTV 10/9/2008

Single shot profile

Detector:

Insert screen + optical system

Physics process:

Scintillation, photons are emitted due to the excitation, and de-excitation of atomic states

Image detection:

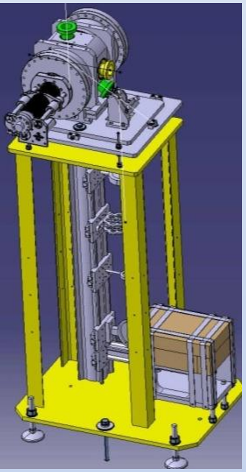
- Image the light of the screen
- Multiple scattering in screen increase beam size
- Emission of photons ns to micro seconds
- Calibrate optical system with known target
- Correct for optical aberrations (screen 45 degrees)

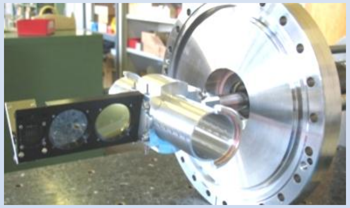
Type	Composition	Decay Time	
		Decay of Light Intensity	
		from 90 % to 10 % in	from 10 % to 1 % in
P 43	Gd_2O_2S:Tb	1 ms	1,6 ms
P 46	$Y_3Al_5O_{12}$:Ce	300 ns	90 µs
P 47	Y_2SiO_5:Ce,Tb	100 ns	2,9 µs
P 20	(Zn,Cd)S:Ag	4 ms	55 ms
P 11	ZnS:Ag	3 ms	37 ms

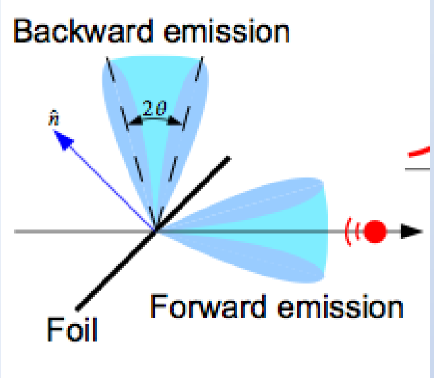
1 MeV e^- on *5µm* P43 yields ~ *60 ph.*

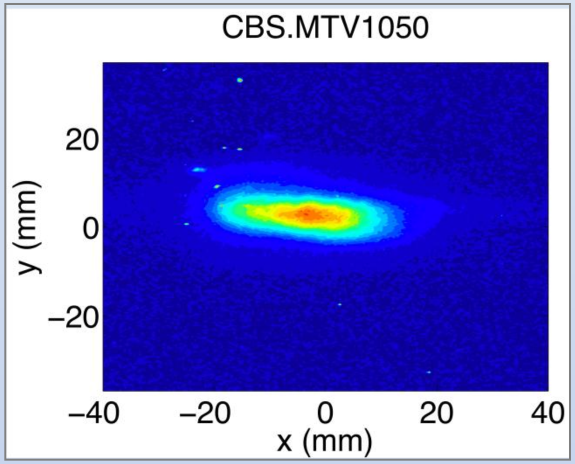
Mechanical assembly move screen into vacuum chamber:

Transition Radiation









Detector:

Insert radiator
(e.g. thin Al foil / SiC wafer) +
optical system

Physics process:

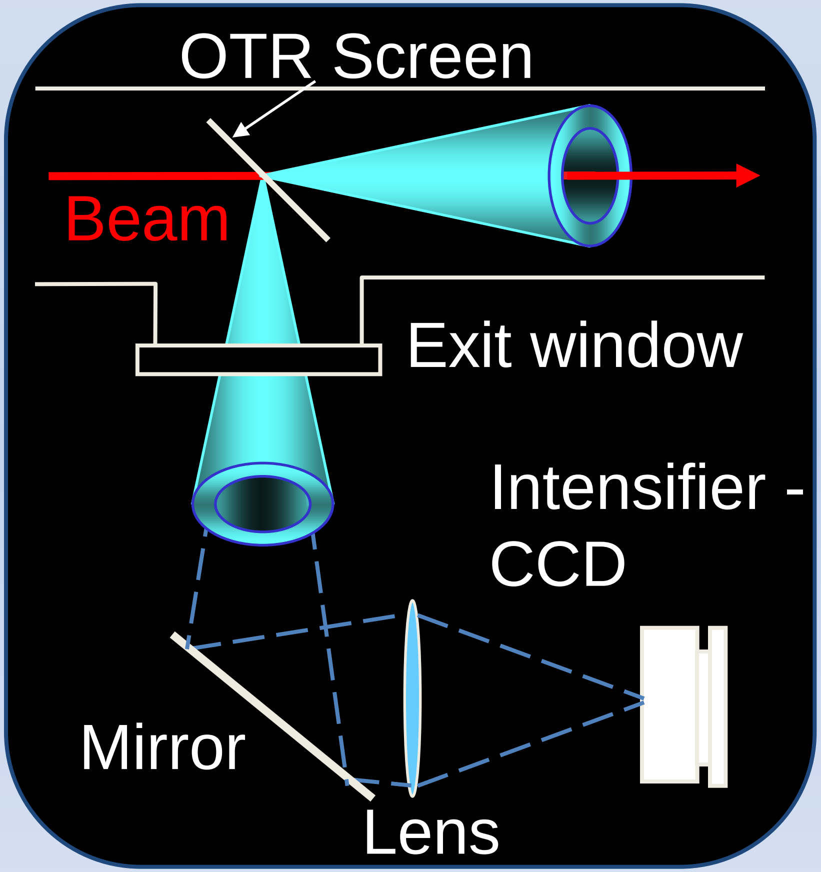
Radiation emitted when a charged particle crosses a material with a different dielectric constant

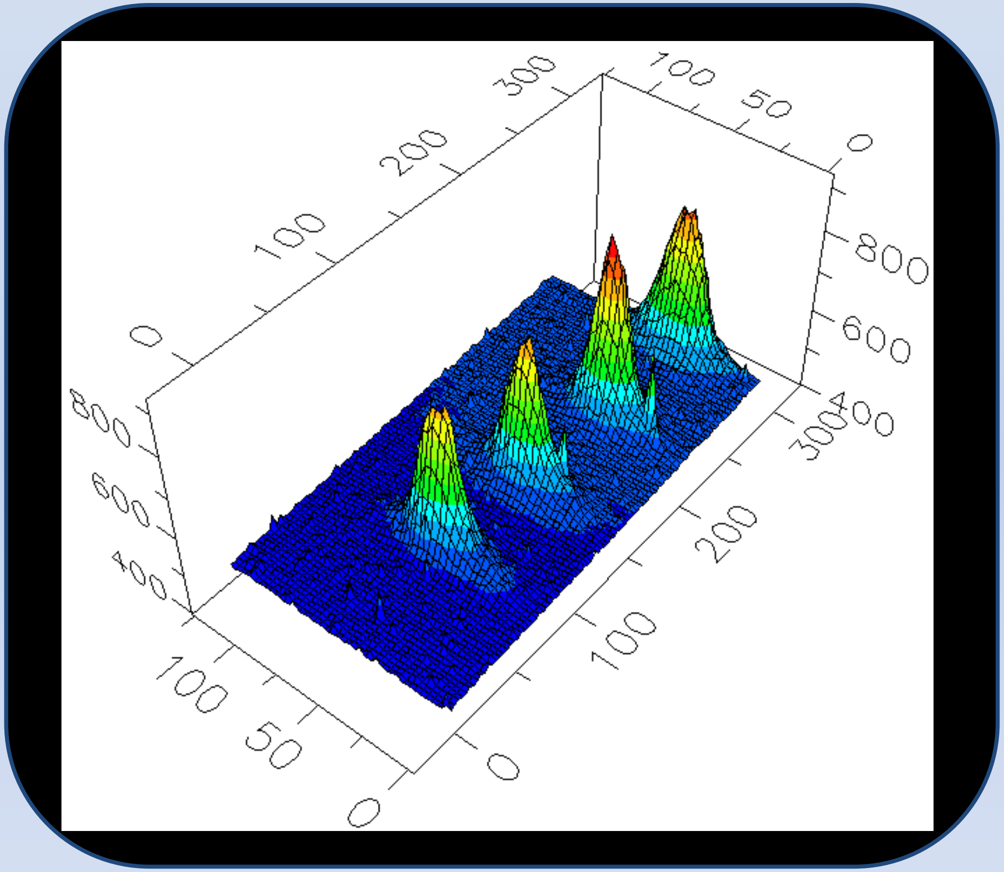
$$\frac{d^2 W}{d\,\Omega\, d\,\omega} \approx \frac{N q^2}{\pi^2 c}\left(\frac{\theta}{\gamma^{-2}+\theta^2}\right)^2$$

Image detection:

- Image the light at the focus of the screen
- Screen can be thin & emission instantaneous
- Angular pattern of emission depends on beam energy
- Thermal damage to screen charge density > 10^6nC/cm^2
- Number of photos emitted depends on electron energy ~0.3 photons/electron (50 MeV), 0.001 photon/electon (100 keV) [400 – 600 nm]

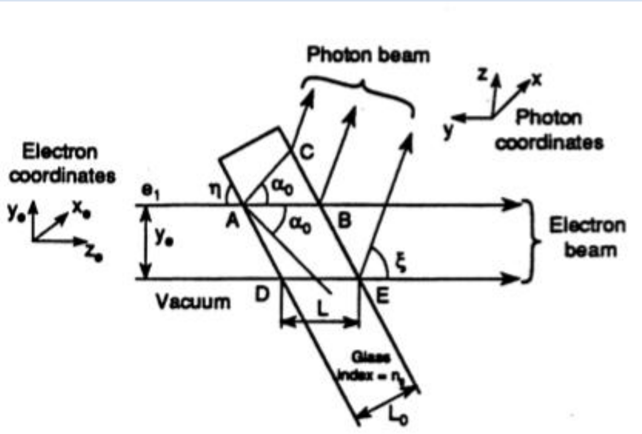
Transition Radiation

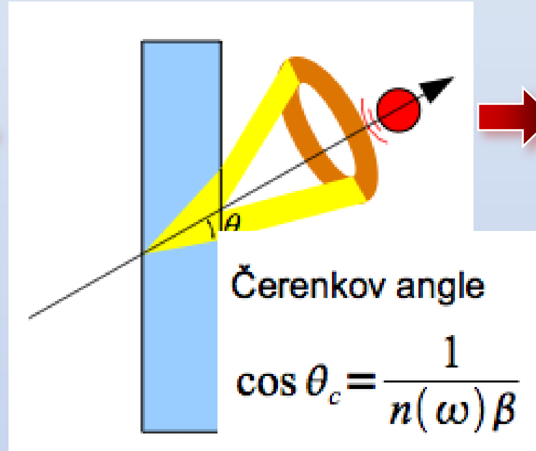




R. Jones

Cerenkov Radiation





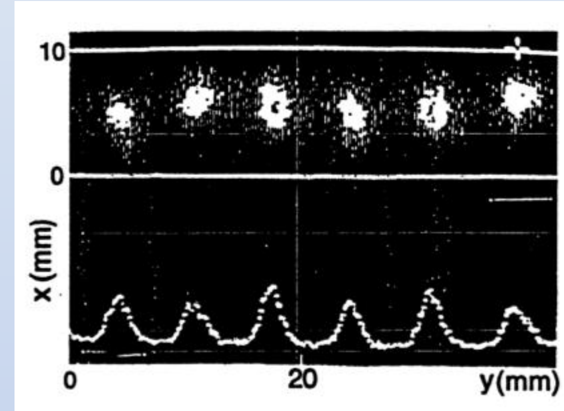


Fig. 1c The transverse distribution of each bunch

Detector:

Insert radiator, with index of refraction matching beam energy requirements, with correct optical system

Physics process:

Radiation emitted when a charged particle crosses a material, when

$$b.n(W) > 1$$

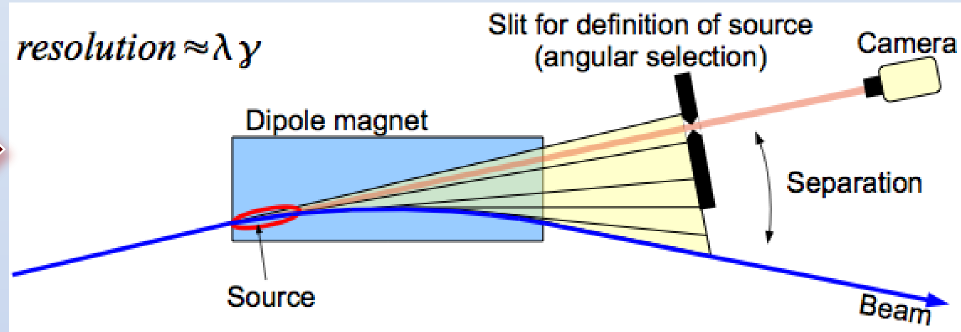
Radiation has a defined angular distribution, not very suitable for transverse imaging

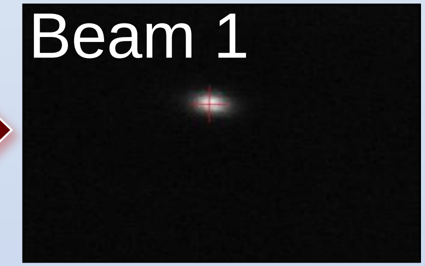
Image detection:

- Threshold effect
- Fast emission – charged beam polarizes material, then de-excites back to ground state
- Emitted light travels slower than charged particles (source dispersion)
- Good light production yield-
  Sent to Streak Camera

$$\frac{d^2N}{dx\,d\omega} = \frac{\alpha z^2}{c}\sin^2\theta_c(\omega) = \frac{\alpha z^2}{c}\left(1 - \frac{1}{\beta^2 n^2(\omega)}\right)$$

Synchrotron Light





Detector:

Extract light from a dipole magnet (or undulator or wiggler)

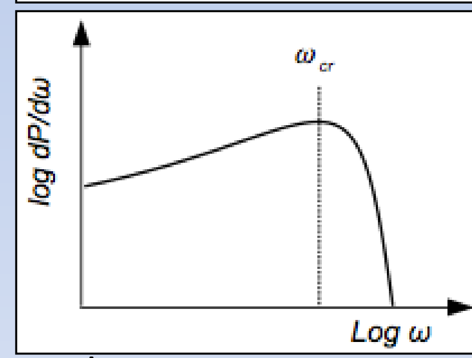
Optical system + camera /PMT

Physics process:

Charge particles emit electromagnetic radiation when accelerated

Synchrotron radiation: change in direction

$$P = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{ce^2\gamma^4}{\rho^2}$$

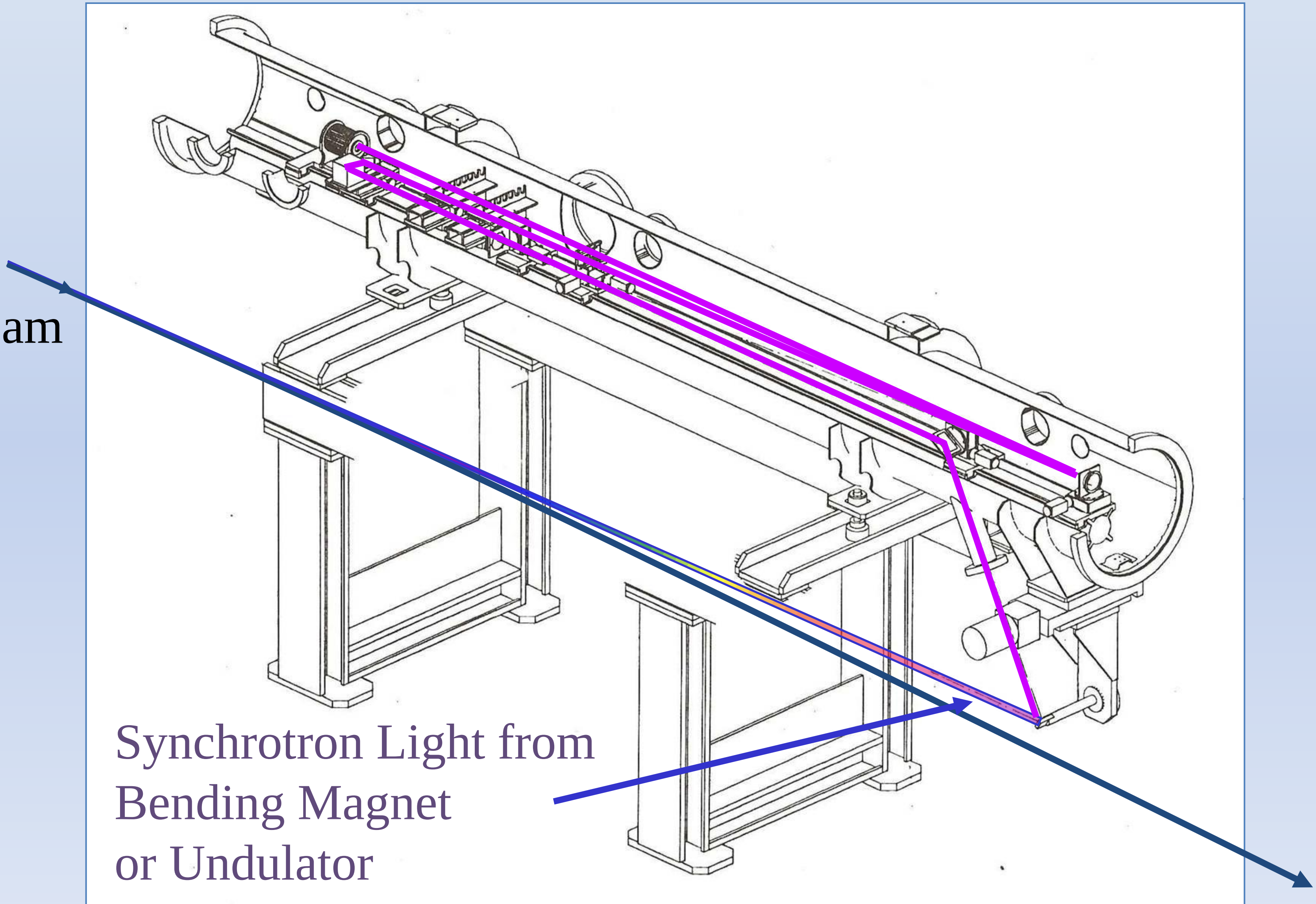


$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$

Image detection:

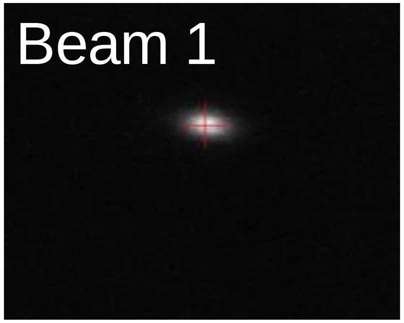
- Image the light from the entrance or entrance edge of the magnet - higher frequency components, edge radiation
- Must implement a "virtual" target to image the source of the radiation in the magnet
- Resolution limited by diffraction

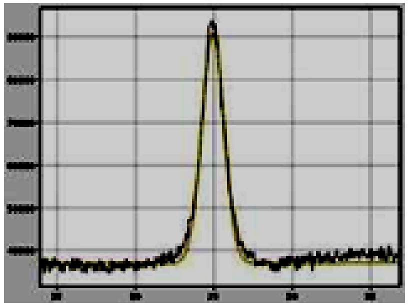
The Synchrotron Light Monitor

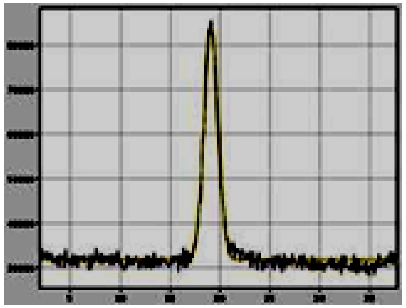


Rhodri Jones

The Synchrotron Light Monitor

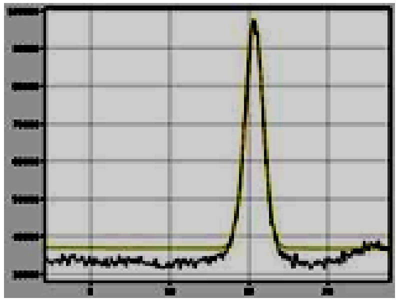


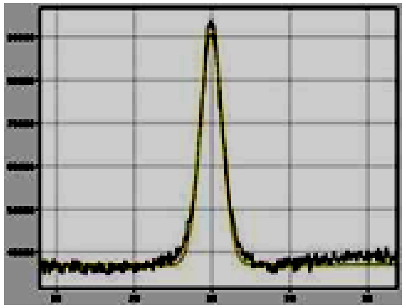




σ_h = 0.68mm

σ_h = 0.70mm



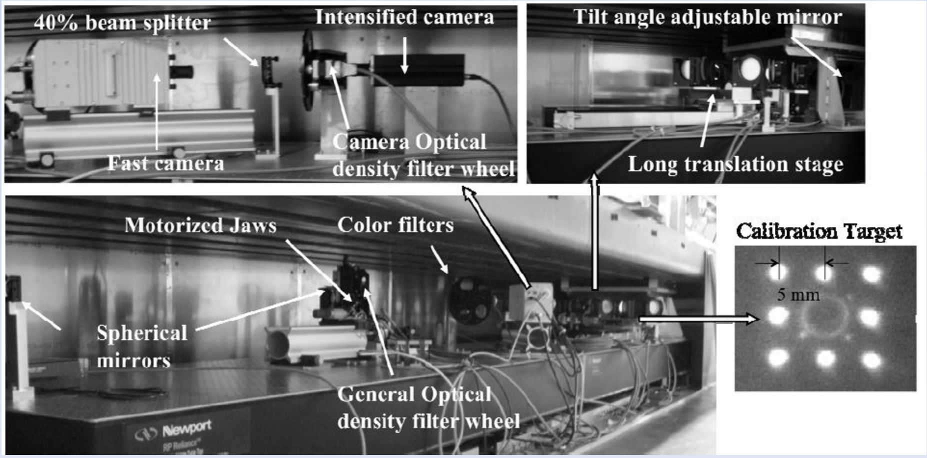


σ_v = 0.56mm

σ_v = 1.05mm

Important instrument design:

1. Simulation:
   - Synchrotron radiation source
   - Optical line transport through all lenses, mirrors, filters
   - Camera response
2. Calibration target.
3. Remote control of all devices
4. Filters for variable bunch intensity



Diagnostics Lecture Outline

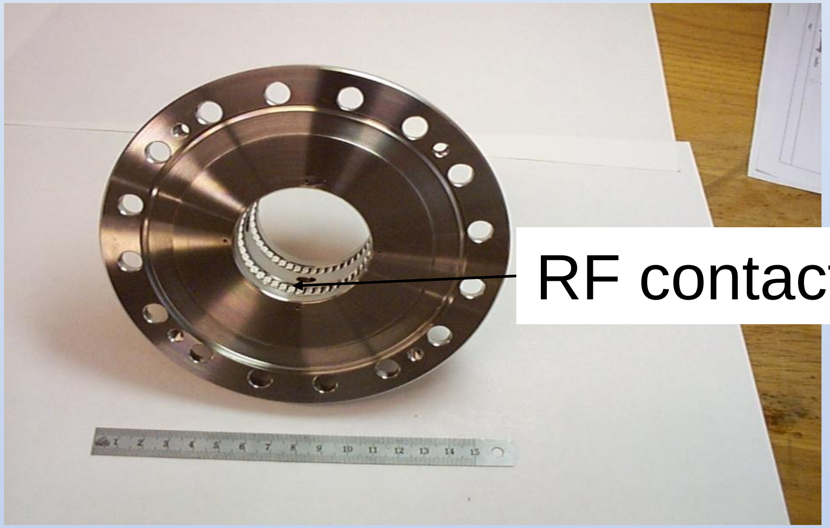
- **Why do we need diagnostics**
- **What do we need to measure?**
  - Position
    - Capacitive BPM
  - Current
    - Wall current monitor
    - Faraday Cup
  - Transverse Profile (emittance, TWISS (αβγ) parameters)
    - Intercepting methods
      - » Scanning wires
      - » Radiative screens
      - » Scintillation screens
      - » Cerenkov targets
    - Non intercepting methods
      - » Synchrotron light
  - Longitudinal Profile
    - Streak Camera
    - RF deflector
    - Electro optical techniques
    - RF power measurements and spectroscopy
  - Luminosity Detectors
  - Beam Loss Detectors
- **Discuss diagnostics developments needed for new machines**

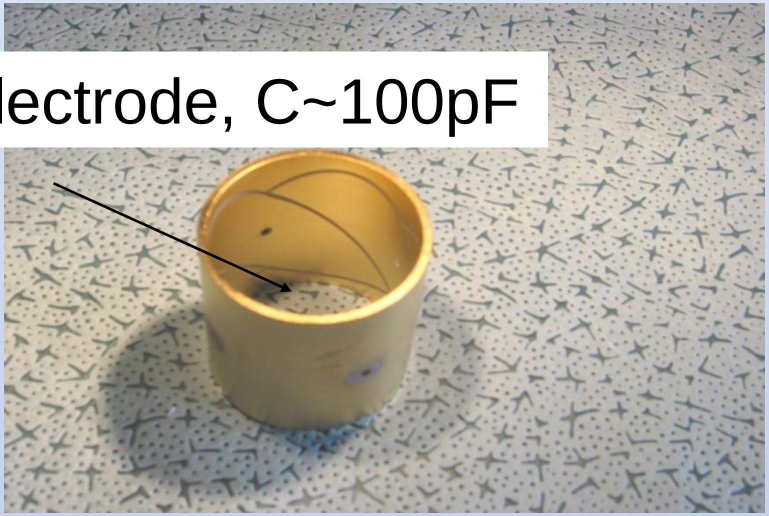
First Lecture

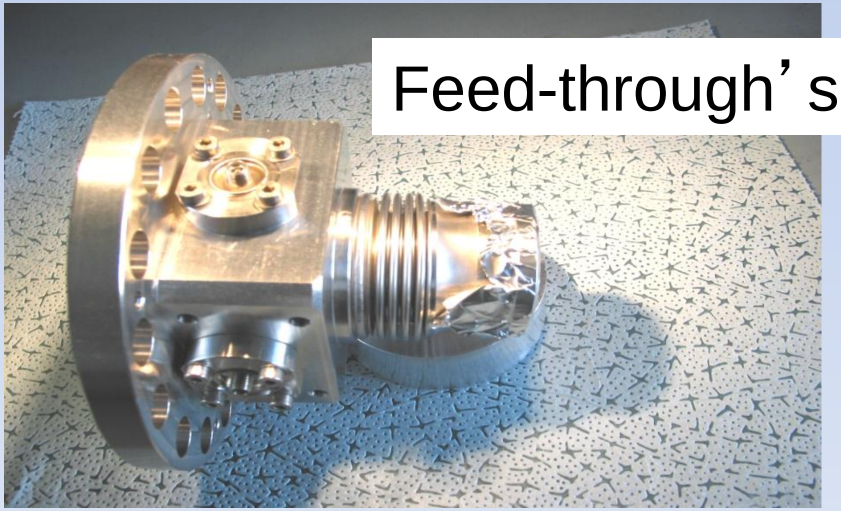
Second Lecture

Measure current as a function of x- position

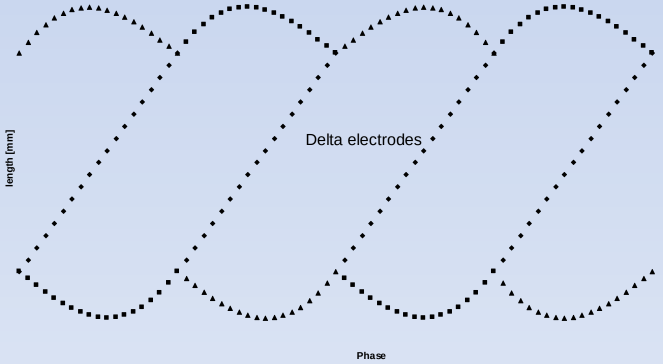
Electrostatic Pick-up (BPE) – CTF3





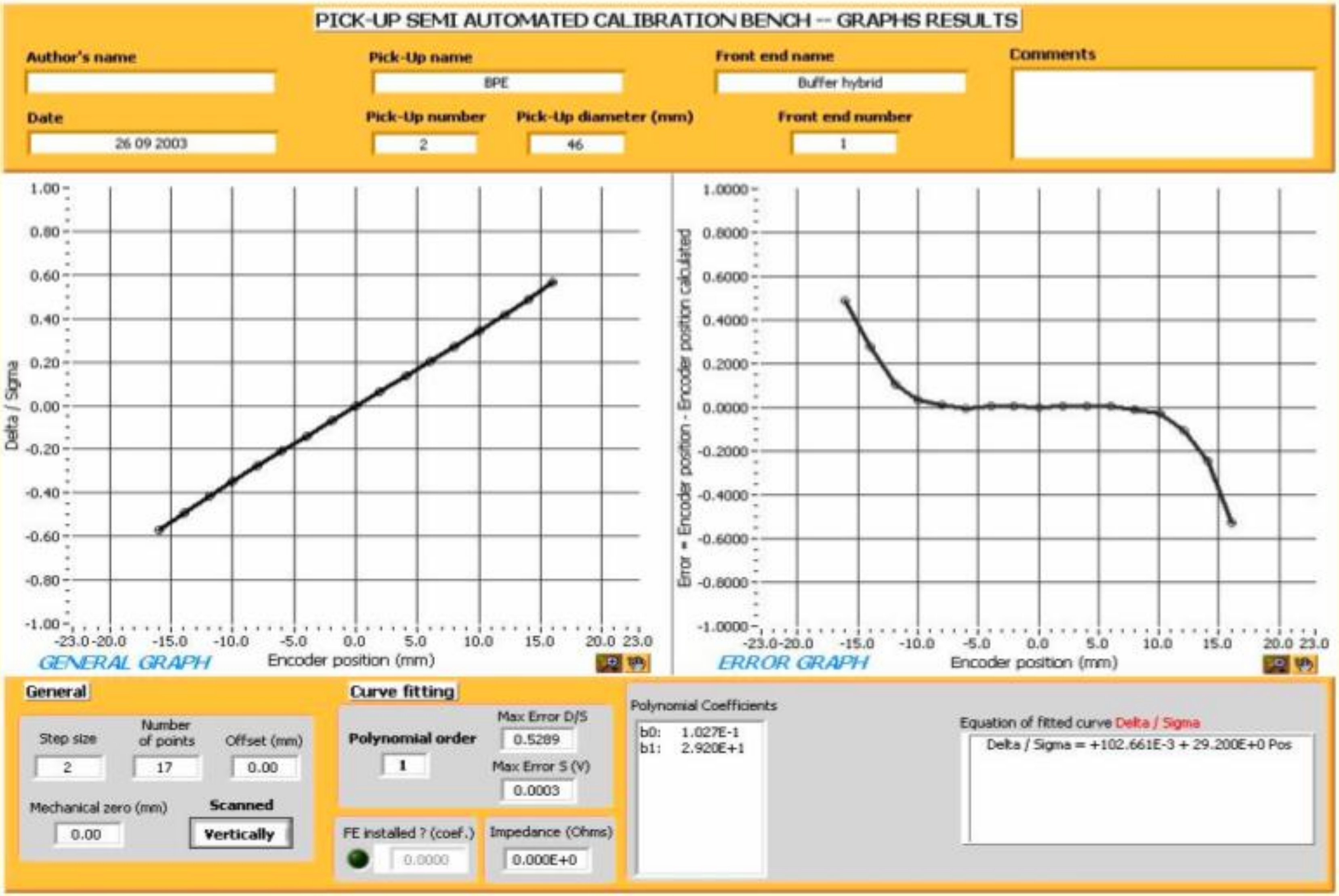


$$\hat{V}(t) = \frac{1}{v} \times \frac{l_{eff}}{C_{Elec}} i(t)$$

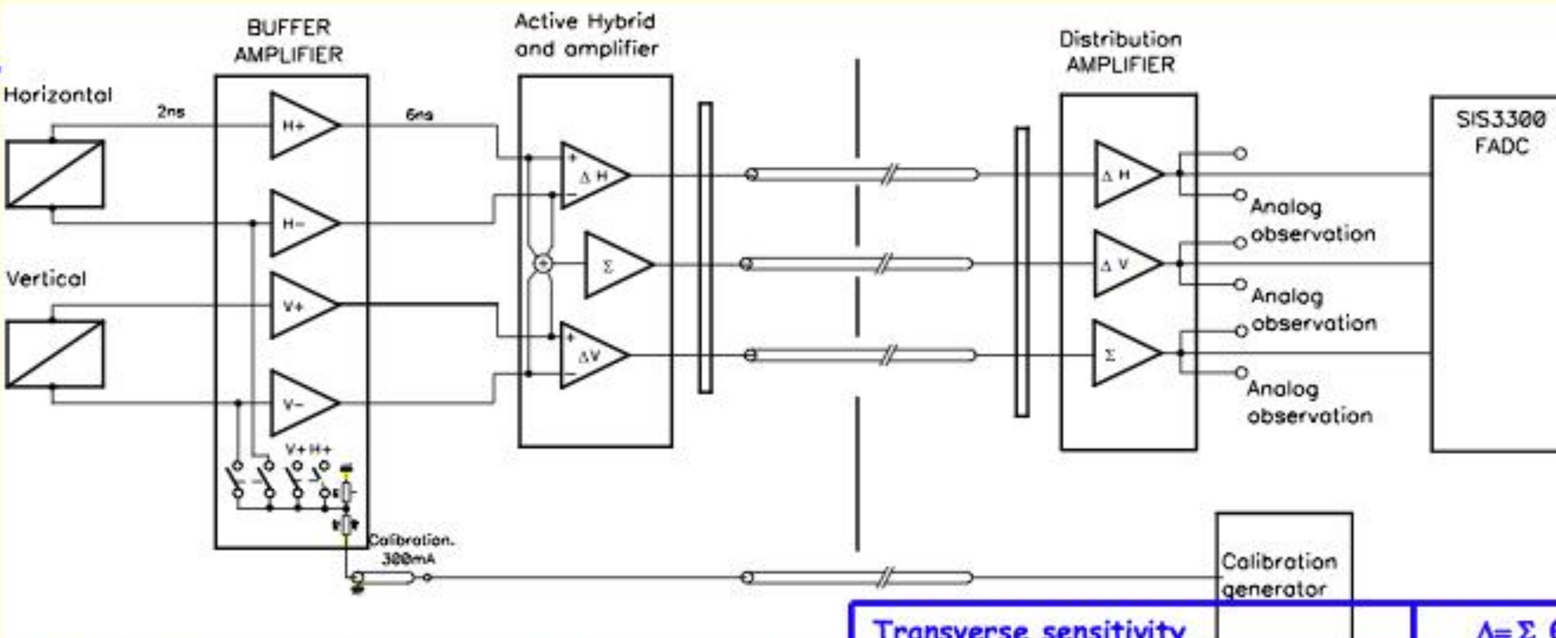


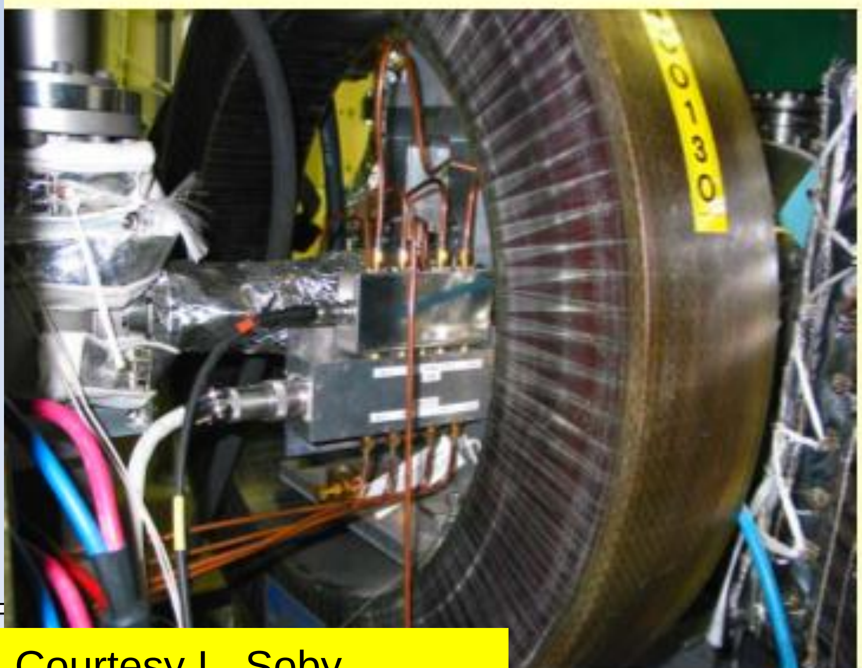
Developed by L. Søby, CERN

Electrostatic PU



Electrostatic PU





Courtesy L. Soby

Transverse sensitivity	Δ=Σ @ ~10mm
Resolution	10um /20um
Relative precision (±10mm)	0.2%
Longitudinal coupling impedance	0.17 / 1.7 ohm
Resolution	12mA / 1.2mA
Absolute precision (I)	~ 1%
Low frequency cut off	1kHz
High frequency cut off	200MHz
Calibration	Yes
ID / Length	46mm / 130mm
Number of feedthroughs	4
Flange types	DN40CF / DN100CF
Max. bake-out temperature	130 °C

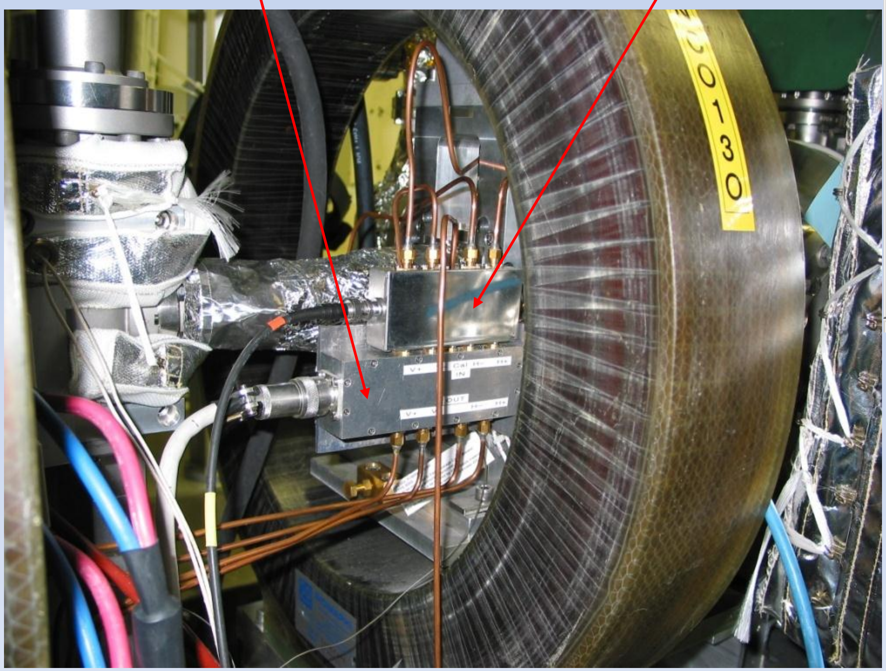
Electrostatic PU (BPE)

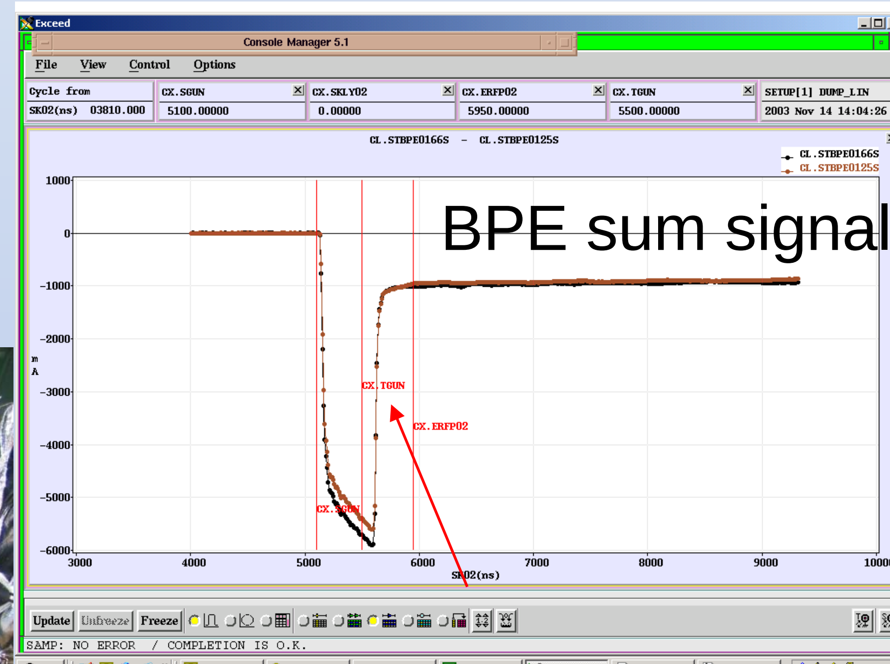
$$F_{Low} = \frac{1}{2 \cdot \pi \cdot R_L \cdot C_{Elec}}$$

CTF3 bunch spacing 3 GHz >> F_low

Buffer amplifier, R_L=1MΩ

HT bias



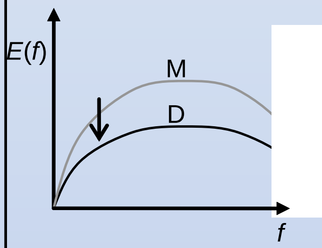
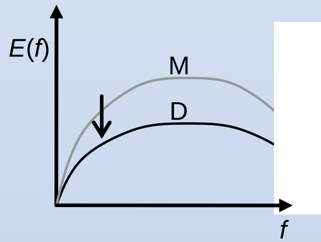
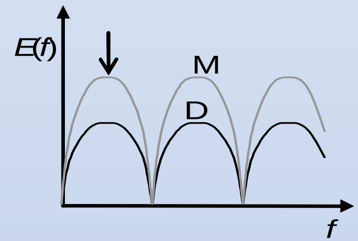
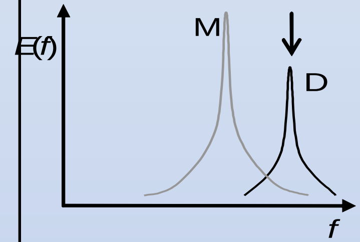


BPE sum signals

Electrodes charging up due to beam halo!

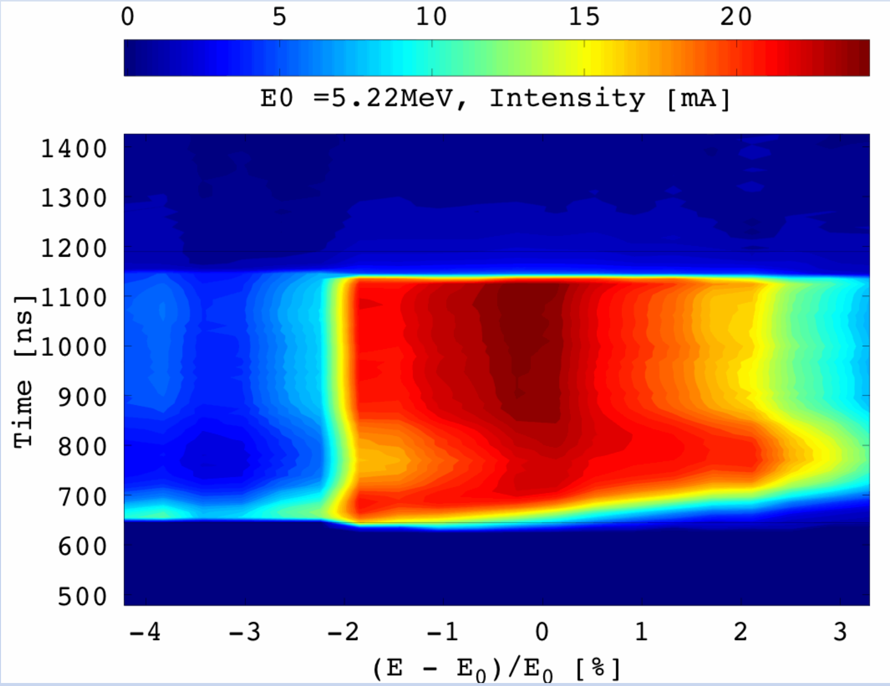
Courtesy L. Soby

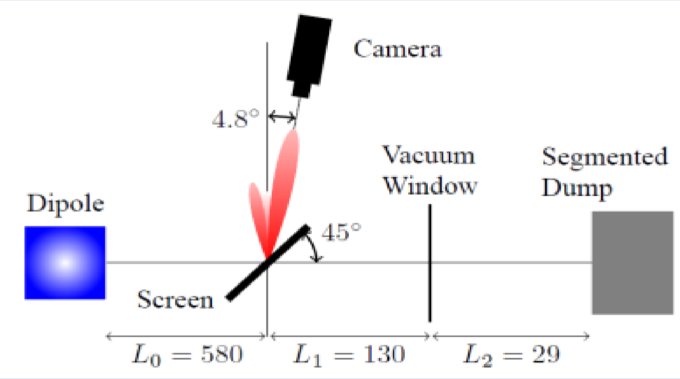
Comparison of different BPM types

Pickup	Transformer	Button	Matched Stripline	RF Cavity
Spectrum				
Monopole Mode Suppression	Modal (hybrid) / electronics	Modal (hybrid) / electronics	Modal (hybrid) / electronics	Modal (coupler), frequency,
Typical RMS Noise, 10pC, *20mm pipe*	>50µm	>100µm	~60µm	<1µm
Typical Electronics Frequency	0.1…200MHz	300…800MHz	300…800MHz	1-12GHz
Pictures				

H. H. Braun (CAS RF 2010)

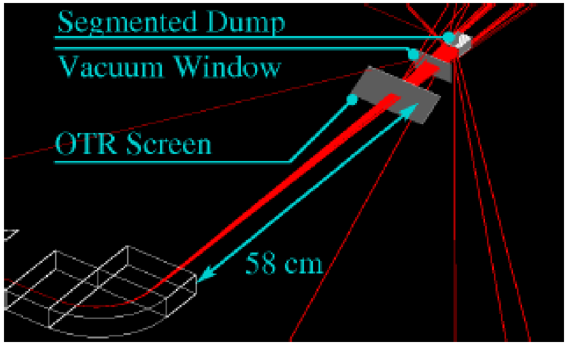
Current Measurement- Segmented Dump –Electron Beam



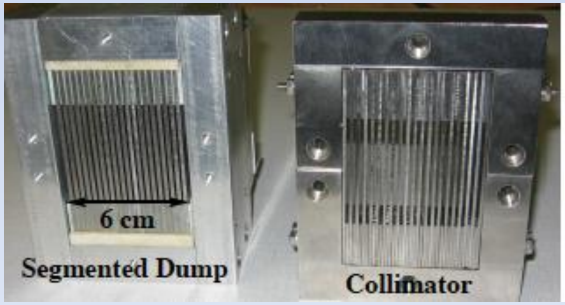


PHIN Spectrometer

- Segmented dump at 78 cm
- OTR screen at 58 cm



Measure profile in a dispersive region → energy spectrum



Daniel Egger

Beam Intensity - Toroids

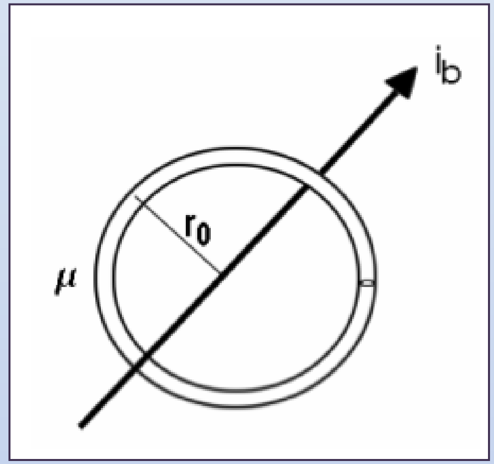
$$\oint B \cdot dl = \mu I_{enc}$$

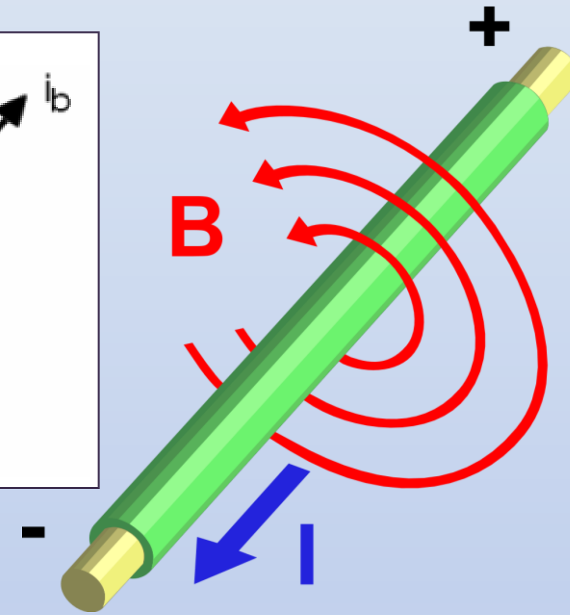
Ampere's Law

If r_0 is thicker than the toroid

$$B = \langle B_n \rangle = \frac{\mu I_b}{2\pi r_0}$$

$$\varepsilon = \frac{\partial \Phi}{\partial t}, \text{ where } \Phi = \oint B \cdot da$$





$$\varepsilon = \frac{\mu A}{2\pi r_0} \frac{\partial i_b}{\partial t}$$

Faraday's law of induction

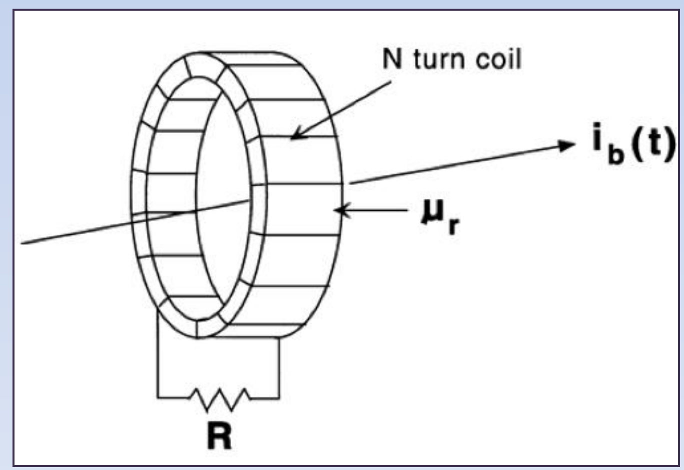
Lenz's law

Coil is wound around the core

This coil senses the induced emf, and acts to appose the magnetic field induced by the beam

Add a resistor in series ➔

$$V_r = I_r R = (I_b / N) R$$



What about the bandwidth of this signal?

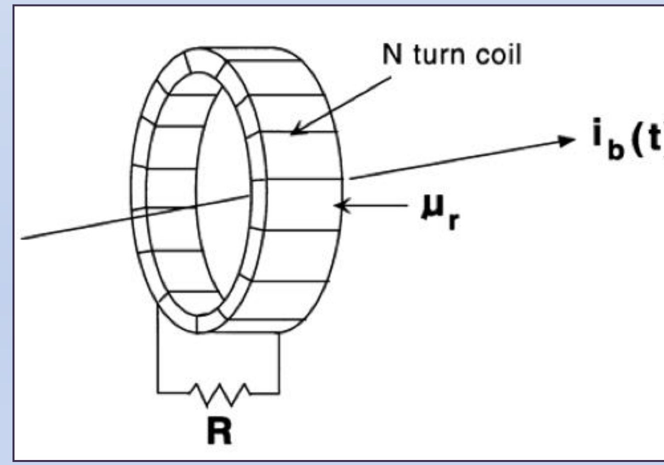
Beam Intensity - Toroids

$$\varepsilon = \frac{\partial \phi}{\partial t}, \text{ where } \phi = \oint B \cdot da$$

$$\varepsilon = \frac{\mu A}{2\pi r_0} \frac{\partial i_b}{\partial t}$$

Faraday's law of induction

Lenz's law



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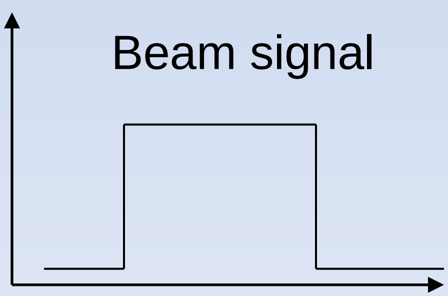
Add a resistor in series ➔

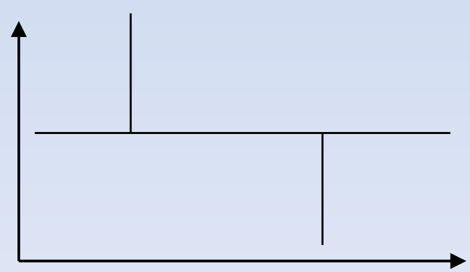
$$V_r = I_r R = (I_b/N)R$$

What about the bandwidth of this signal?

Beam signal



Transformer output signal



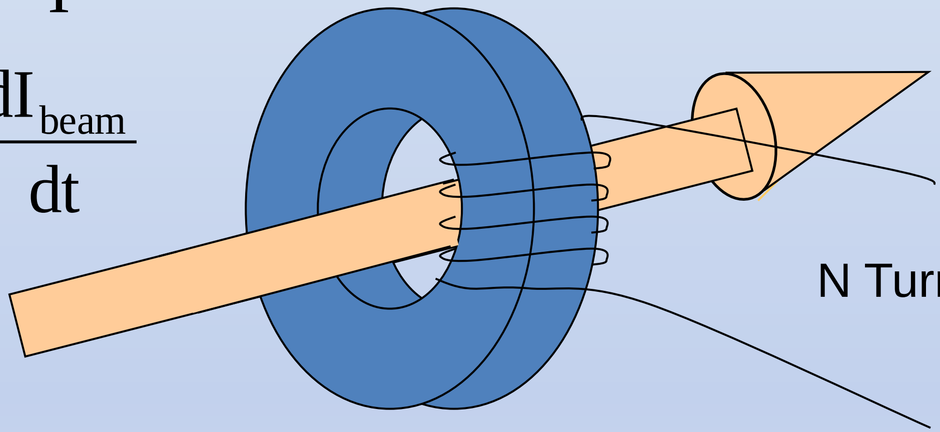
The ideal transformer

$$L = \frac{N^2 \mu_r \mu_0 A}{l}$$

$$U = L \frac{dI_{beam}}{dt}$$

Fields are very low

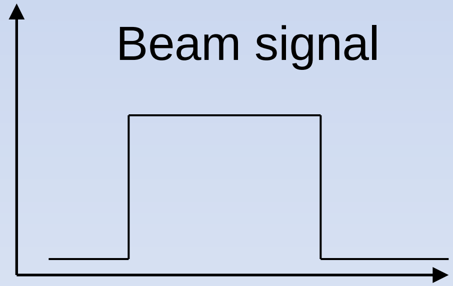
Capture magnetic field lines with cores of high relative permeability



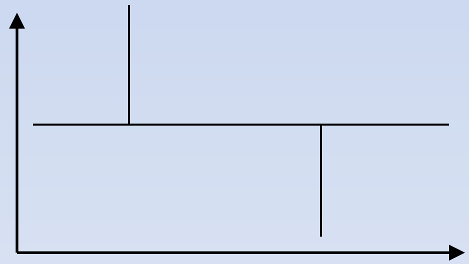
N Turn winding

Inductance L of the winding

Beam signal



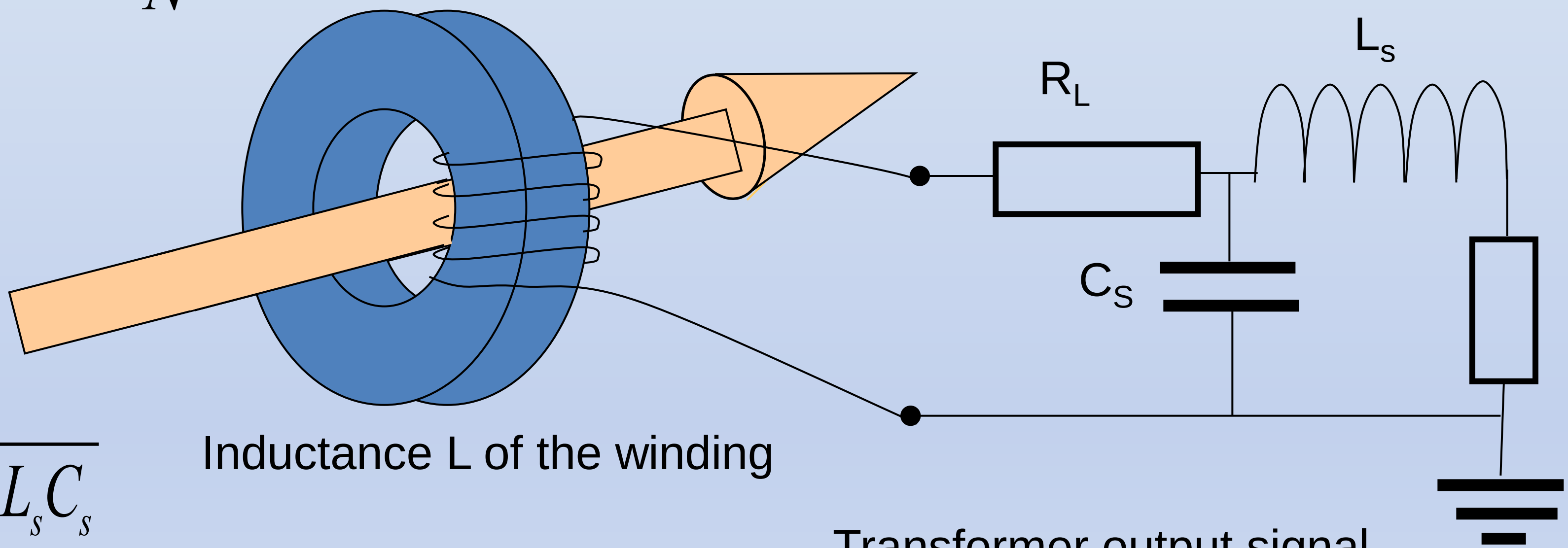
Transformer output signal



The AC transformer

$$U(t) = I_{beam}(t)\frac{R}{N}e^{-\frac{t}{t_{droop}}}$$

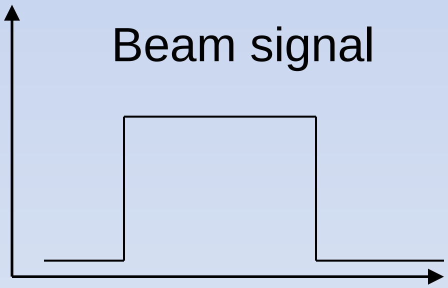
Winding of N turns and Inductance L



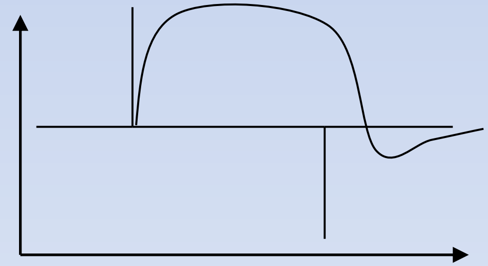
Inductance L of the winding

$$t_{rise} = \sqrt{L_s C_s}$$

$$t_{droop} = \frac{L}{R + R_L}$$



Transformer output signal



Beam Profile Monitoring using Screens

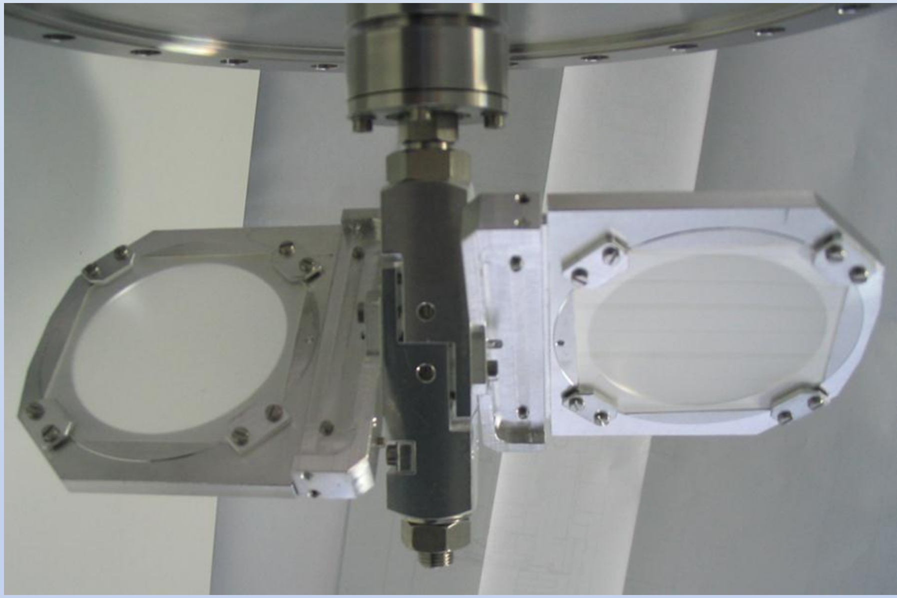
- Screen Types
  - Luminescence Screens
    - destructive (thick) but work during setting-up with low intensities
  - Optical Transition Radiation (OTR) screens
    - much less destructive (thin) but require higher intensity

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	*$2\ 10^7$*

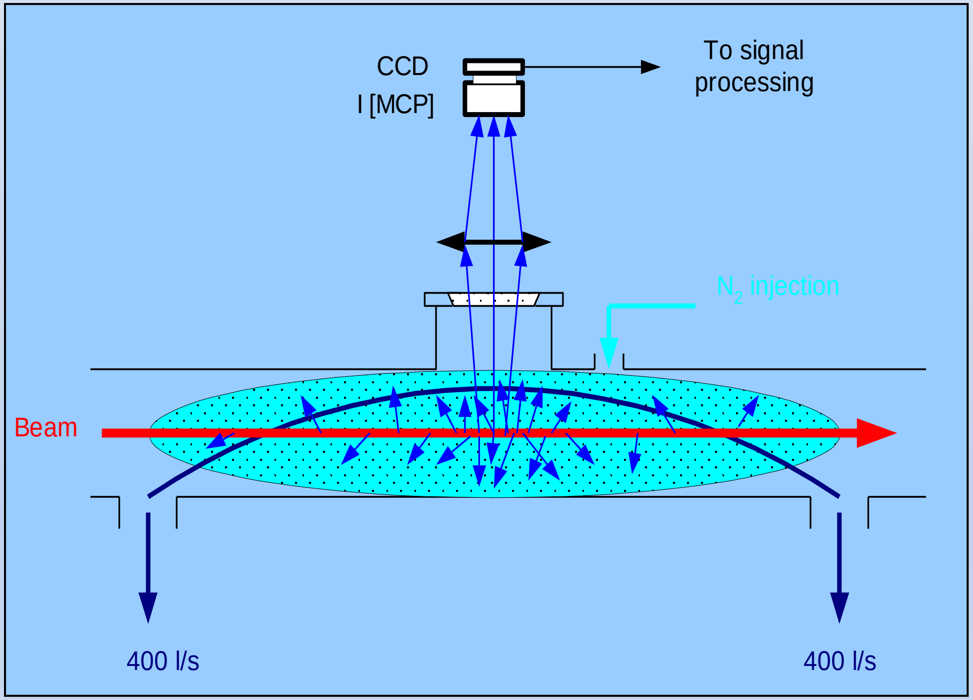
Beam Profile Monitoring using Screens

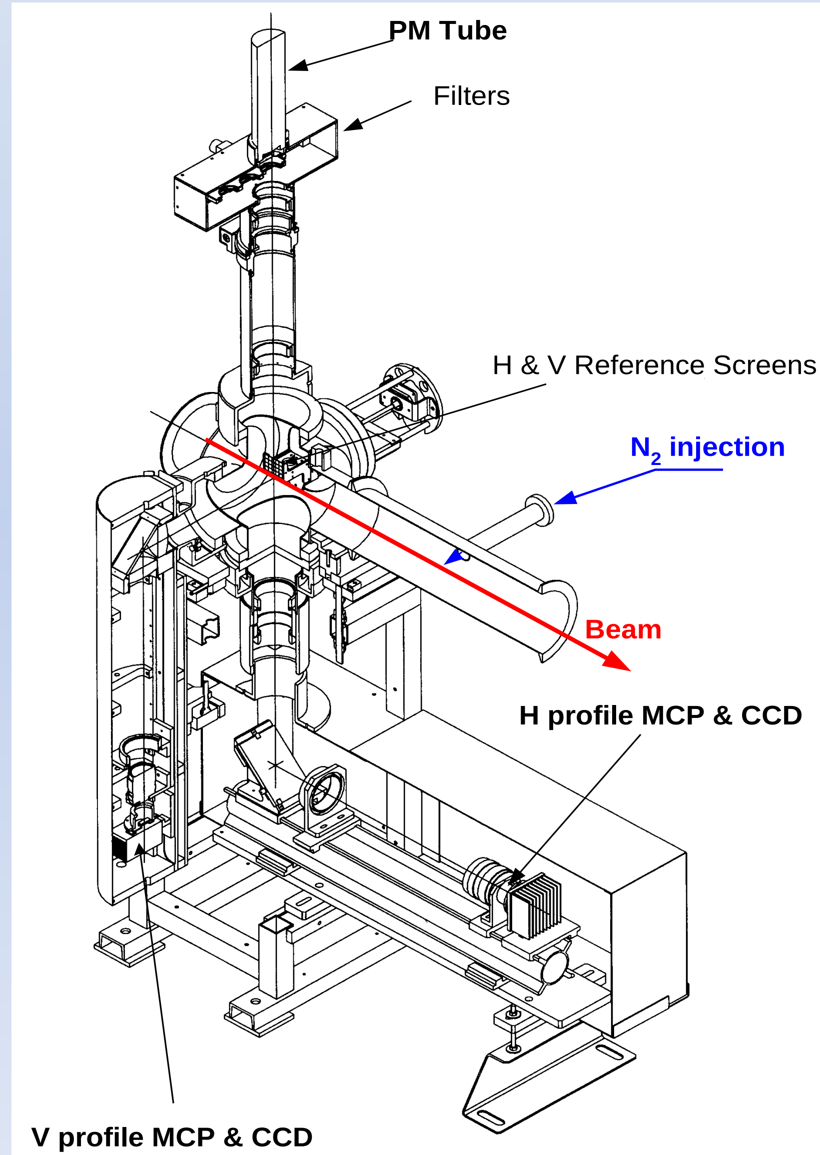
- Usual configuration
  - Combine several screens in one housing e.g.
    - Al_2O_3 luminescent screen for setting-up with low intensity
    - Thin (~10um) Ti OTR screen for high intensity measurements
    - Carbon OTR screen for very high intensity operation

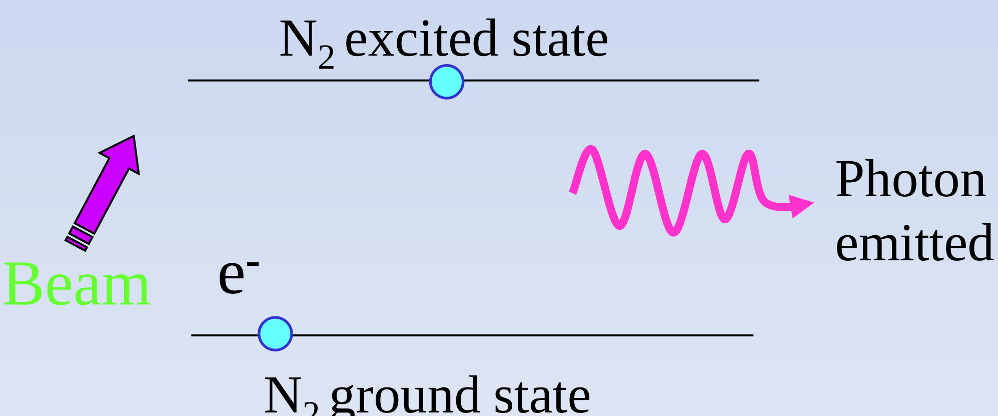


- Advantages compared to SEM grids
  - allows analogue camera or CCD acquisition
  - gives two dimensional information
  - high resolution: ~ 400 x 300 = 120'000 pixels for a standard CCD
  - more economical
    - Simpler mechanics & readout electronics
  - Time resolution depends on choice of image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

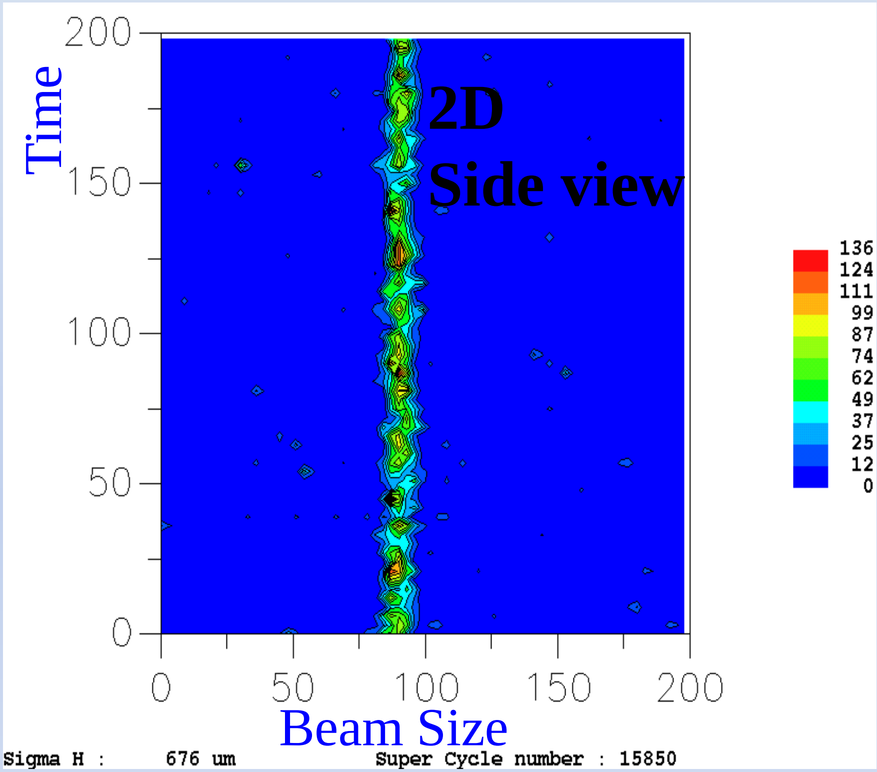
Luminescence Profile Monitor

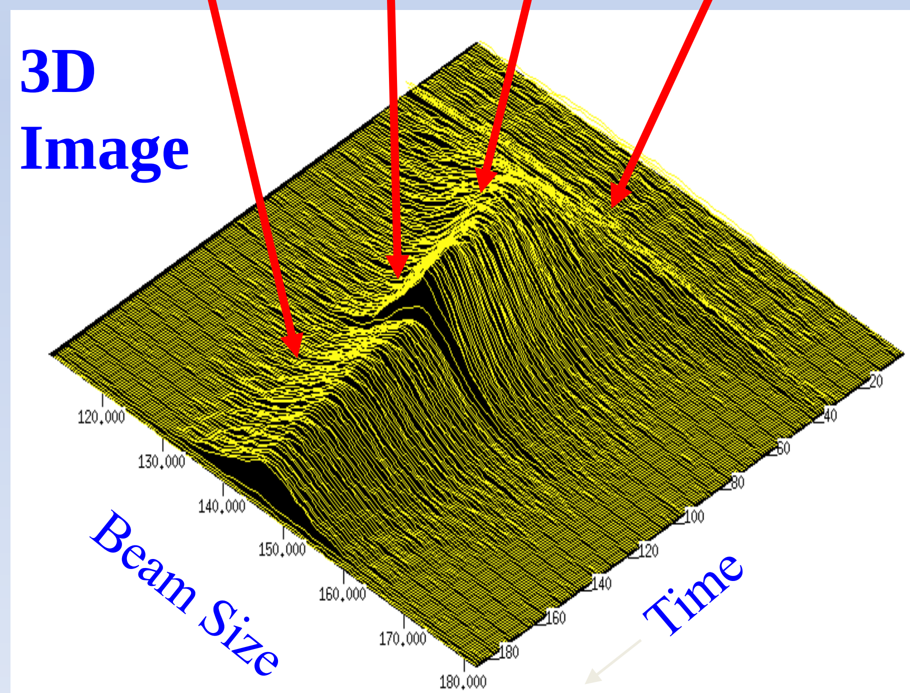






Luminescence Profile Monitor





CERN-SPS Measurements

- Profile Collected every 20ms
- Local Pressure at ~5×10^{-7} Torr