Beam Instrumentation and Diagnostics

Hidehiko Arima
Kyushu University

2018/09/08
FFA'18 School
KURNS, OSAKA

References, Resources

Books

P. Strehl; *Beam Instrumentation and Diagnostics*, Springer 2006.

M.G. Minty; *Measurement and Control of Charged Particle Beams*, Spriger 2003.

A. Chao; *Handbook of Accelerator Physics and Engineering*, World Scientific 2013.

Lectures on Particle Acceletors

CERN Accelerator School (CAS)
http://cas.web.cern.ch

Joint Universities Accelerator School (JUAS)
https://indico.cern.ch/category/3833/

US Particle Accelerator School (USPAS)
http://uspas.fnal.gov/index.shtml

KEK Accelerator Seminar (OHO)
http://accwww2.kek.jp/oho/index.html

Typical beam parameters and instruments (1/2)

Beam parameters		Instuments	
		LINAC & transfer line	Synchrotron
Current I	*General* *Special*	Transformer, dc & ac Faraday Cup Particle Detectors	Transformer, dc & ac Pick-up Signal (relative)
Profile x_{width}	*General* *Special*	Screens, SEM-Grids Wire Scanners, OTR Screen MWPC, Fluorescence Light	Residual Gas Monitor Wire Scanner, Synchrotron Light Monitor
Position x_{cm}	*General* *Special*	Pick-up Using position measurement	Pick-up
Transverse Emittance ε_{trans}	*General* *Special*	Slit-grid Quadrupole Variation Pepper-Pot	Residual Gas Monitor Wire Scanner Transverse Schottky

P. Forck, CAS2013

Typical beam parameters and Instruments (2/2)

Beam parameters		**Instruments**	
		LINAC & transfer line	**Synchrotron**
Bunch Length $\Delta\phi$	*General* *Special*	Pick-up Secondary electrons	Pick-up Wall Current Monitor Streak Camera Electro-optical laser mod.
Momentum p **and Momentum Spread** $\Delta p/p$	*General* *Special*	Pick-up (Time-of-Flight) Magnetic Spectrometer	Pick-up (e.g. tomography) Schottky Noise Spectrum
Longitudinal Emittance ε_{long}	*General* *Special*	Buncher variation Magnetic Spectrometer	 Pick-up & tomography
Tune and Chromaticity Q, ξ	*General* *Special*	--- ---	Exciter + Pick-up Transverse Schottky Spectrum
Beam Loss r_{loss}	*General*	Particle Detectors (Ionization chambers, PIN diodes, Optical fibers)	
Polarization P	*General* *Special*	Particle Detectors Laser Scattering (Compton scattering)	
Luminocity L	*General*	Particle Detectors	

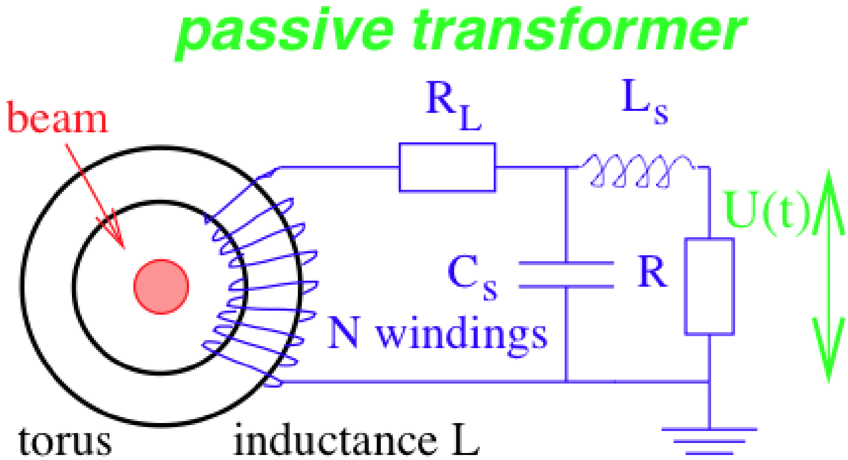
P.Forck CAS2013

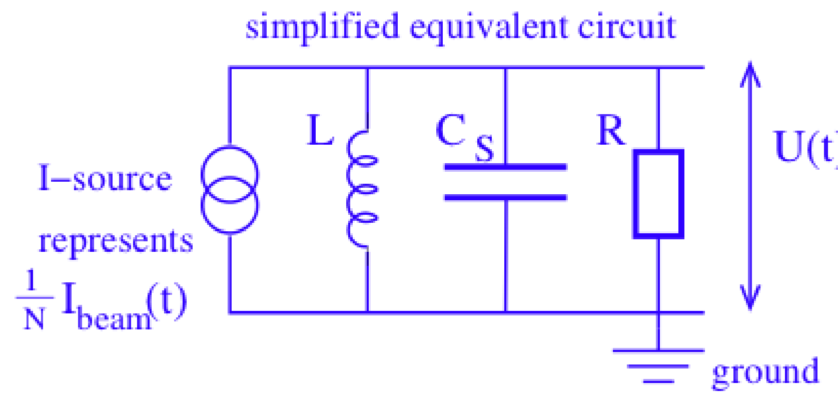
- ***Destructive*** *and* ***non-destructive*** *devices depending on the beam parameters*
- *Different techniques for the same parameters <--> Same techniques for the different parameters*

Beam intensity monitor

Passive Transformer (Fast Current Transformer : FCT)

Simplified electrical circuit of a passively loaded transformer:

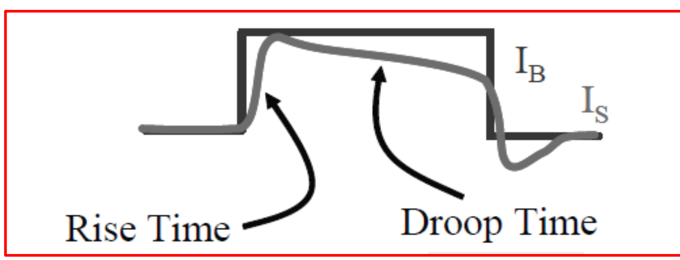




H.Koziol CAS

A voltages is measured: $\boldsymbol{U = R \cdot I_{sec} = R / N \cdot I_{beam} \equiv S \cdot I_{beam}}$

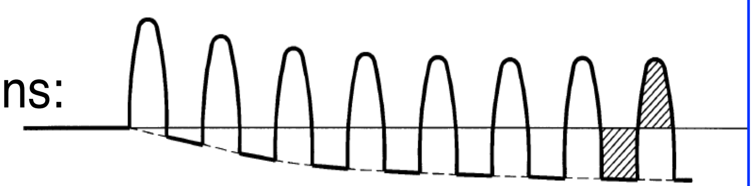
with ***S*** **sensitivity [V/A]**, equivalent to transfer function or transfer impedance ***Z***



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

$$\tau_{droop} = L/(R+R_L)$$

Bunch trains:



- Equal areas
- Baseline shift proportional to intensity

Active Transformer with long droop time

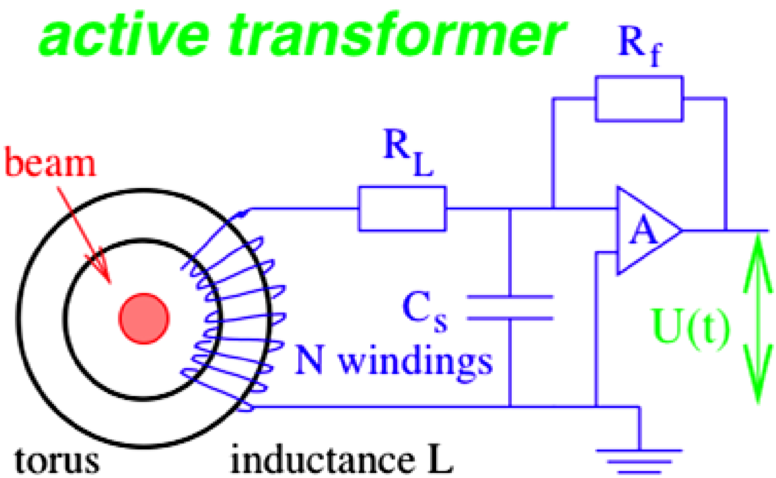
Active Transformer or Alternating Current Transformer ACT:

uses a trans-impedance amplifier (I/U converter) to $\boldsymbol{R \approx 0}\ \Omega$ load impedance i.e. a current sink

+ compensation feedback

$\Rightarrow$ longer droop time $\boldsymbol{\tau_{droop}}$ and rise time τ_{rise}

Application: measurement of longer $\boldsymbol{t} > 10$ µs e.g. at pulsed LINACs



The input resistor is for an op-amp: $\boldsymbol{R_f/A \ll R_L}$

$\Rightarrow \boldsymbol{\tau_{droop} = L/(R_f/A + R_L) \simeq L/R_L}$

Droop time constant can be up to 1 s!

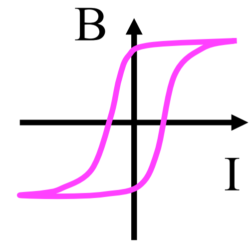
The feedback resistor is also used for range switching.

An additional active feedback loop is used to compensate the droop.

DC beam Current Transformers (DCCT)

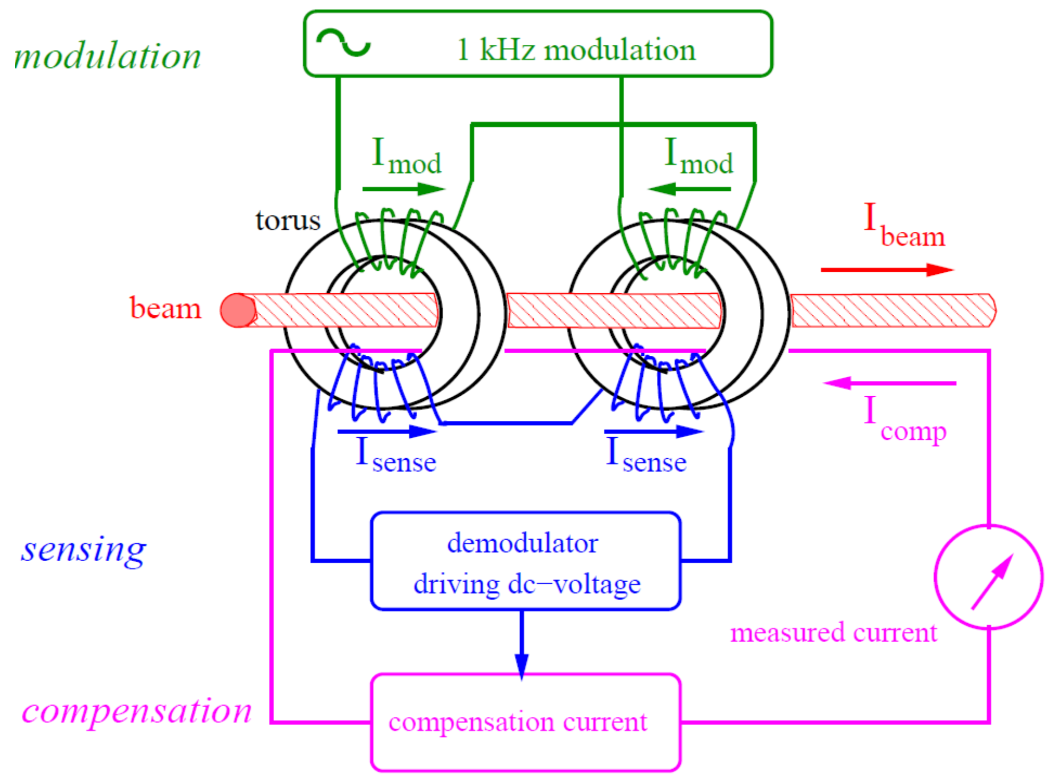
K.Uncer(CERN1969)~

- DC current dB/dt = 0 ⇒ no voltage induced
- Use two **identical** toroids
- Take advantage of non-linear magnetisation curve



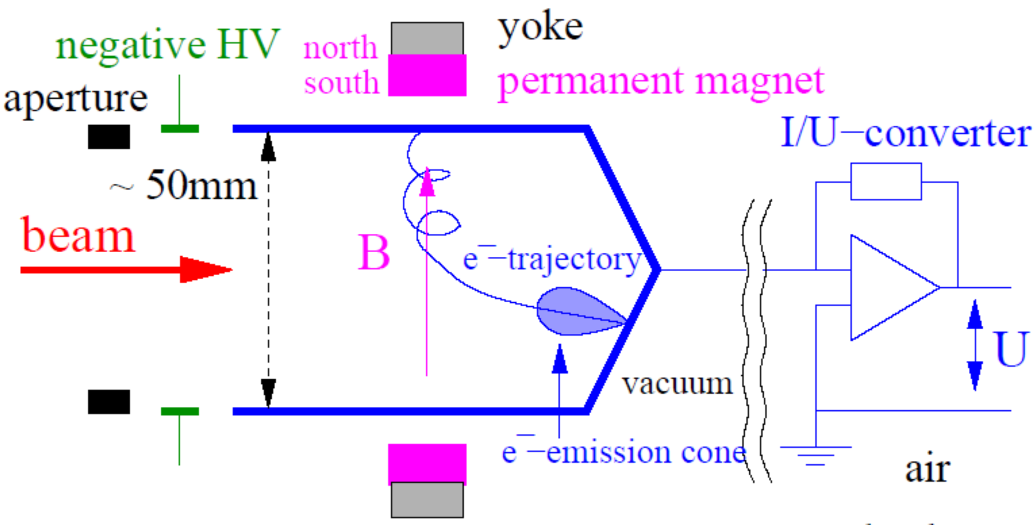
- Modulation of opposite sign drives toroids into saturation
- Sense windings measure the modulation signal
  - Signals from the two toroids cancel each other as long as there is no beam

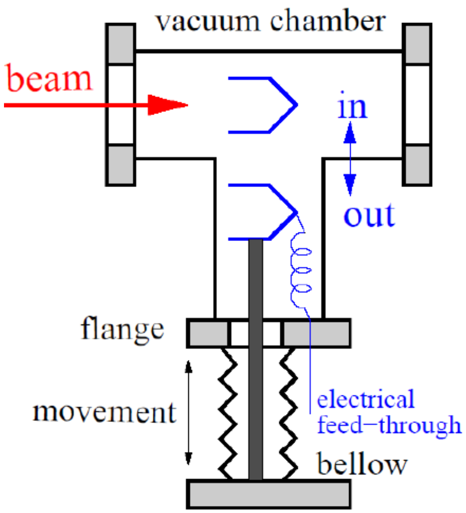
> ➢ But with the I_{beam}, the saturation is shifted and I_{sense} is not zero
>
> ➢ **Compensation current** adjustable until I_{sense} is zero once again



Faraday Cups

The beam particles are collected inside a metal cup
The beam's charge are recorded as a function of time.

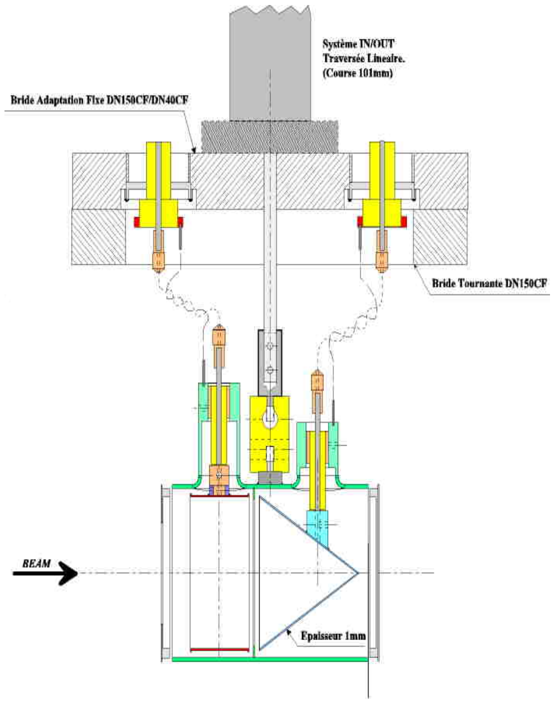


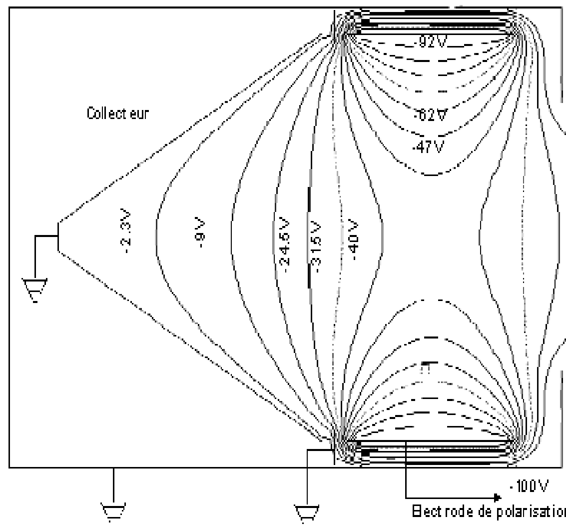


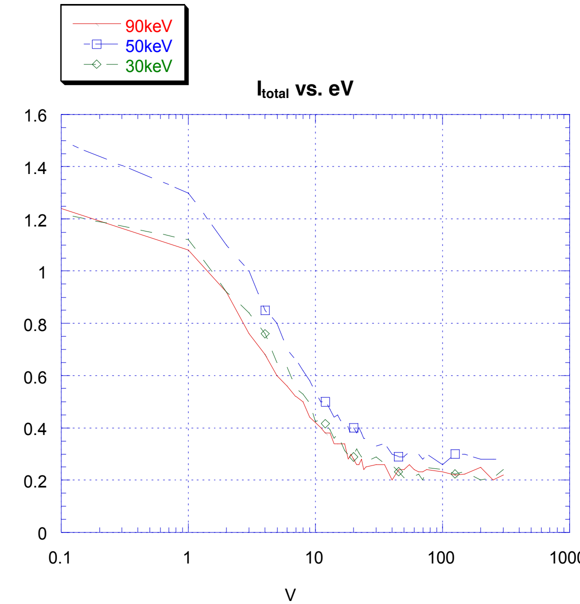
GSI Faraday cup

Currents down to 10 pA with bandwidth of 100 Hz!
To prevent for secondary electrons leaving the cup
Magnetic field and/or Electric field
for potential barrier at the cup entrance

Faraday Cups : repelling voltage







In order to keep secondary electrons with the cup a repelling voltage is applied to the polarization electrode

Since the electrons have energies of less than 20 eV some 100V repelling voltage is sufficient

With increasing repelling voltage the electrons do not escape the Faraday Cup any more and the current measured stays stable.

At 40V and above no decrease in the Cup current is observed any more

Beam position monitor

Electrostatic Position Monitor – The Principle

•Intercept “beam image current” in the vacuum chamber on two isolated (capacitive) pickups.

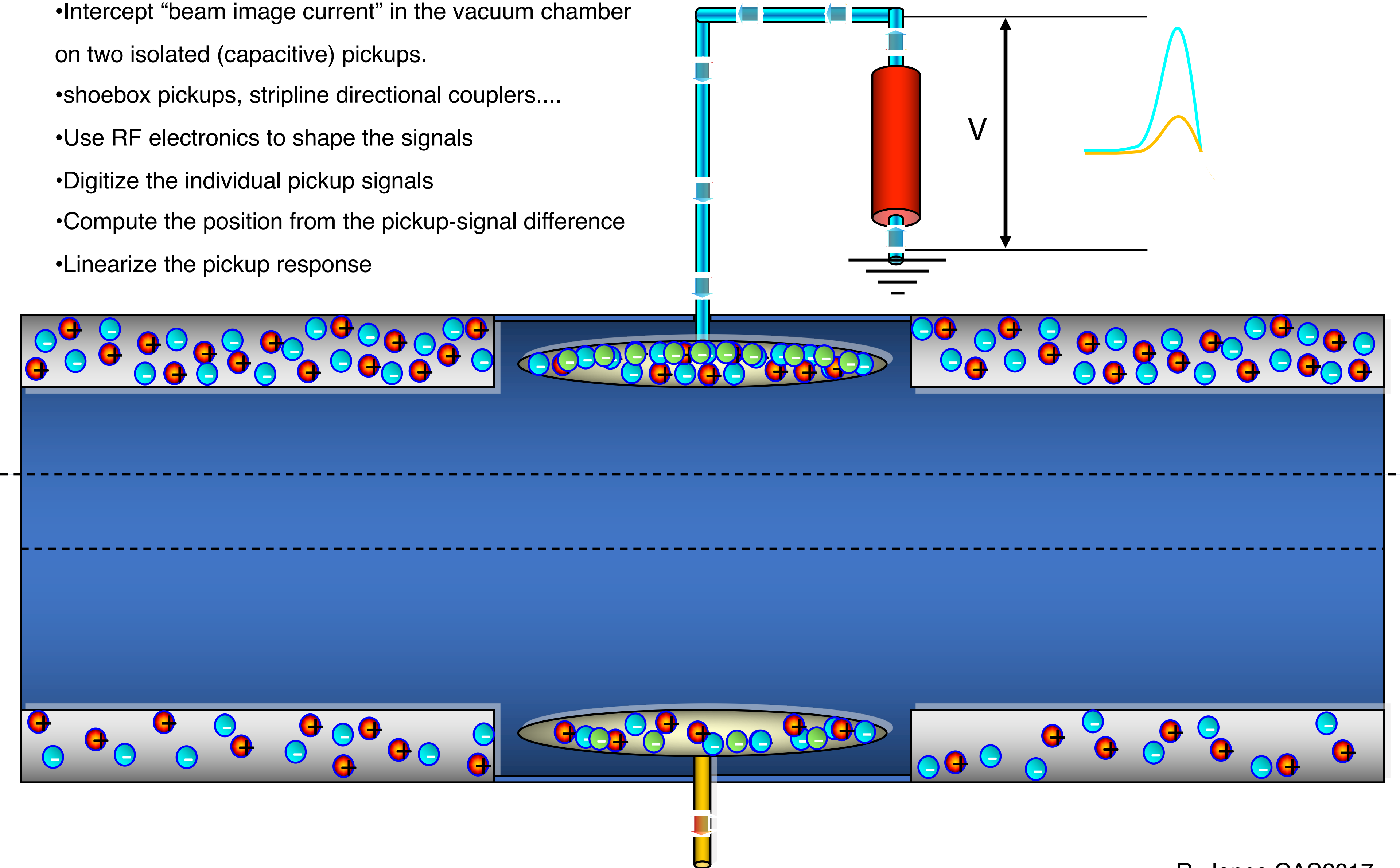
•shoebox pickups, stripline directional couplers....

•Use RF electronics to shape the signals

•Digitize the individual pickup signals

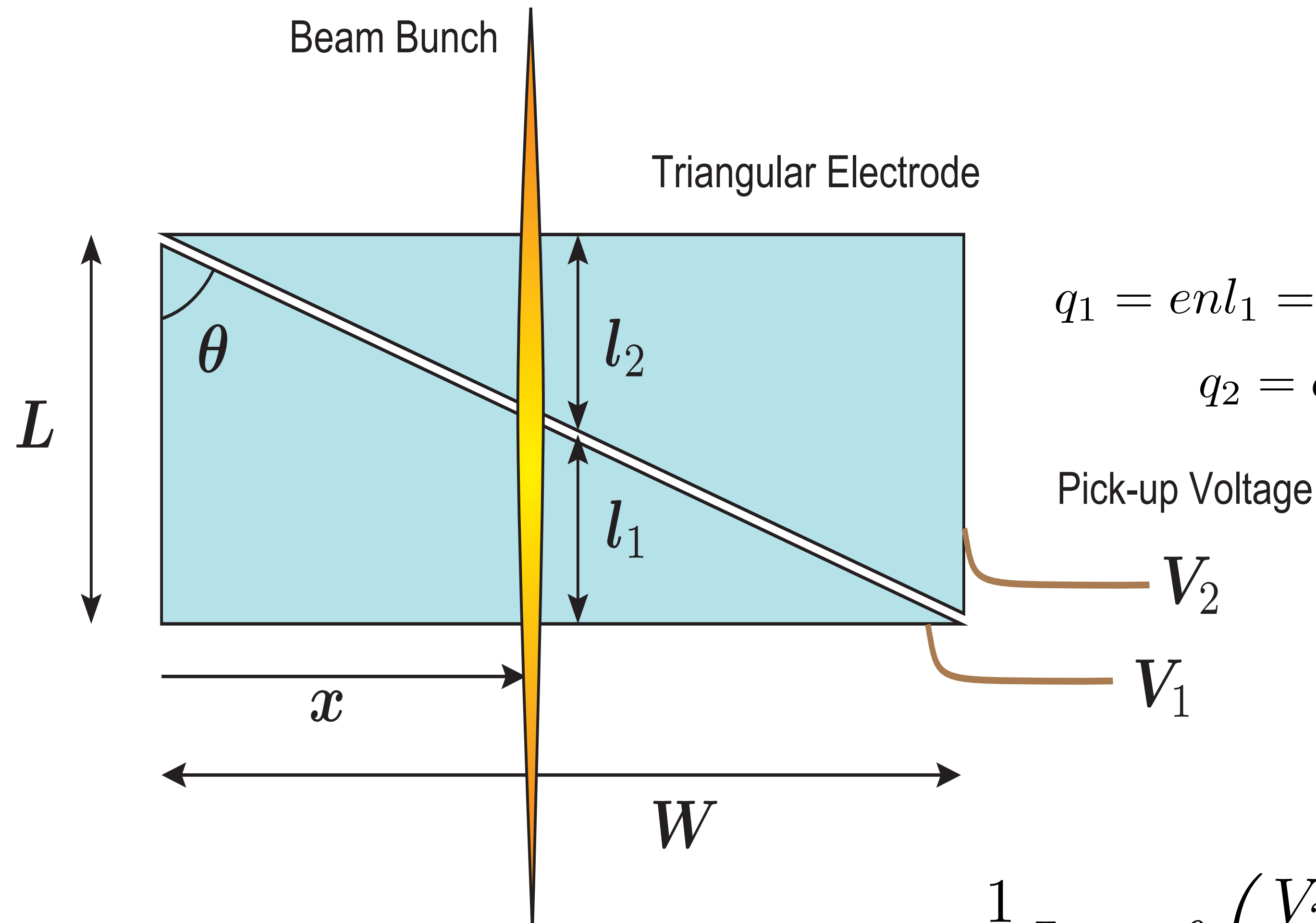
•Compute the position from the pickup-signal difference

•Linearize the pickup response



R. Jones CAS2017

Pick-up position monitor with triangular electrodes

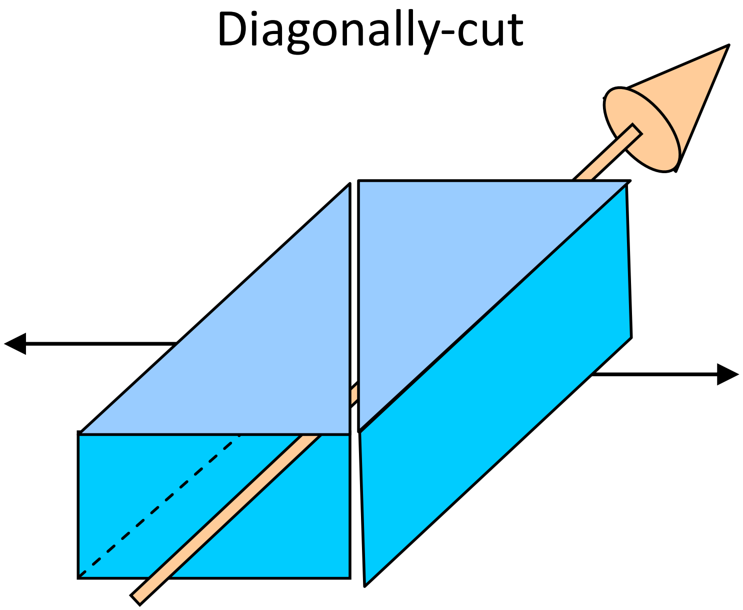


$$q_1 = enl_1 = en(L - x\tan\theta)$$

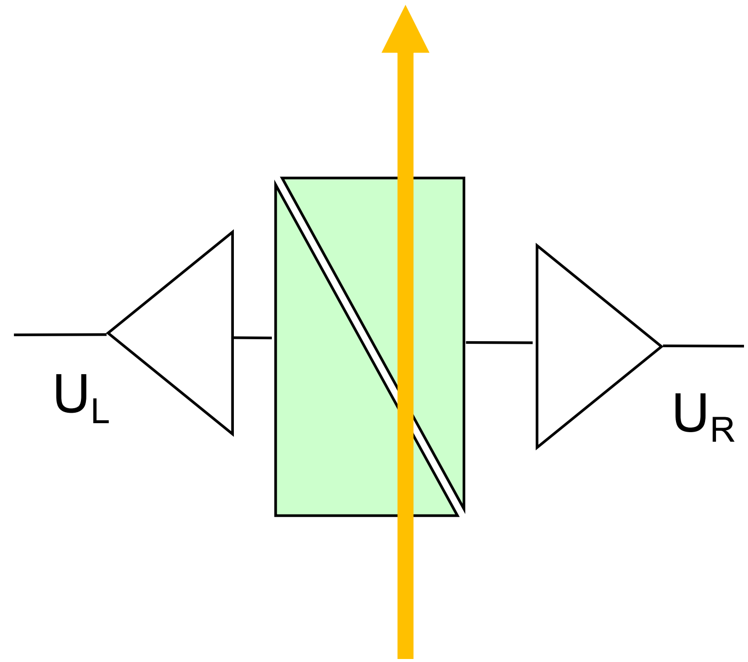
$$q_2 = enl_2 = enx\tan\theta$$

$$x = \frac{1}{2}L\tan\theta\left(\frac{V_2 - V_1}{V_2 + V_1} + 1\right)$$

"Shoebox" pick-up monitor



Linear cut through a shoebox



$$x \propto \frac{U_L - U_R}{U_L + U_R} = \frac{\Delta U}{\Sigma U}$$

Advantage: Very linear, low frequency dependence
i.e. position sensitivity ***S*** is constant

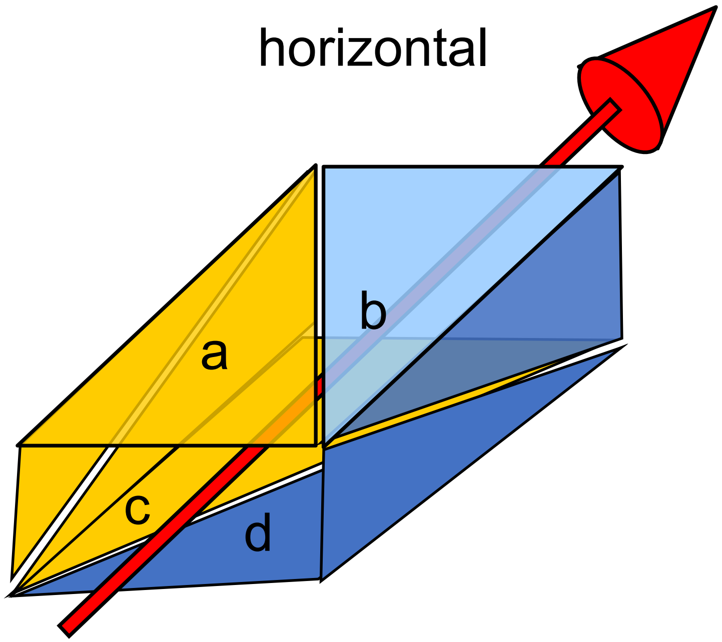
Disadvantage: Large size, complex mechanics

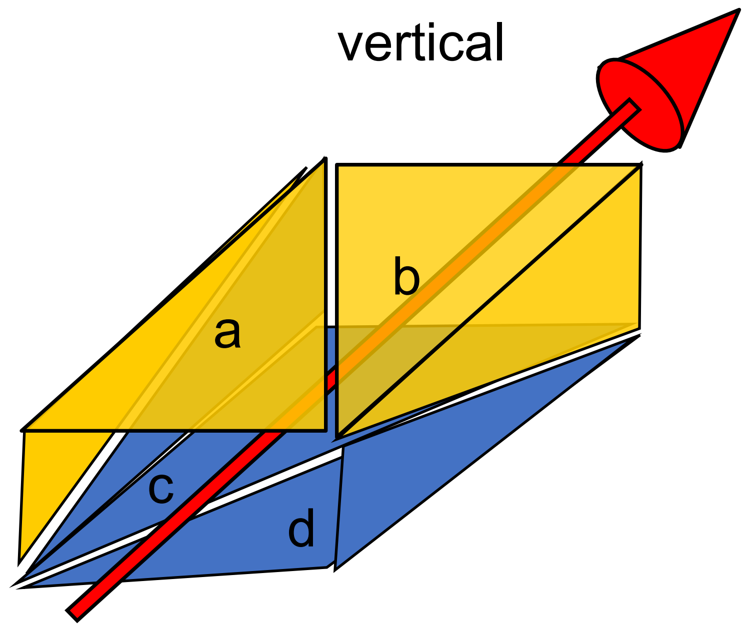
Usage: proton synchrotron
frf < 10MHz

Calibration is required before installing.

Simulatenous horizontal and vertical measurement

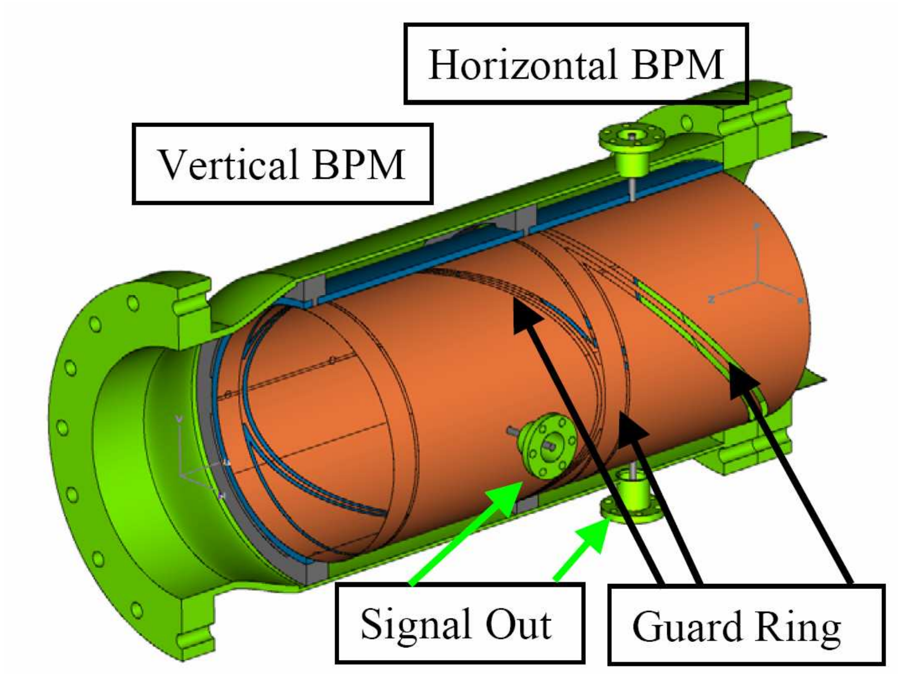
- Horizontal and vertical position at once
- 4 electrodes



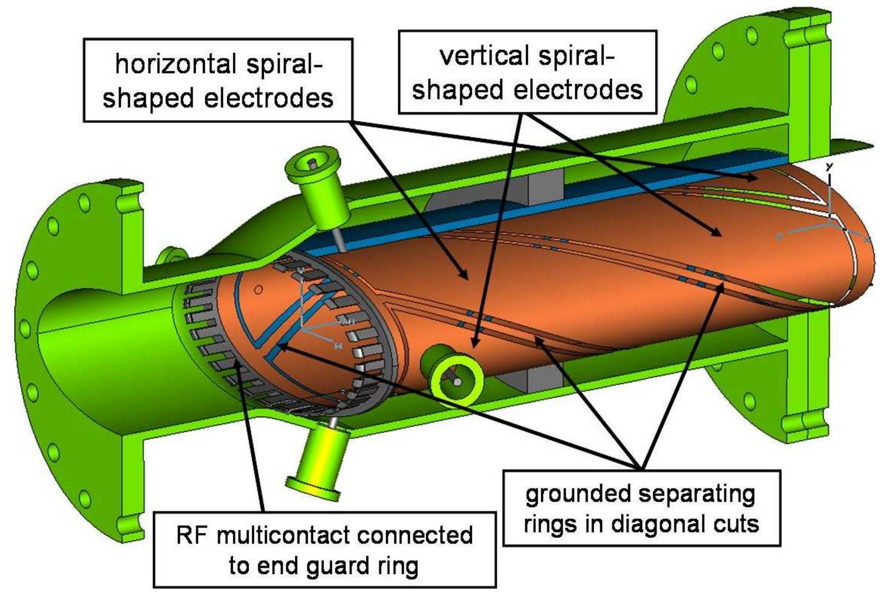


$$X = \frac{(U_a + U_c) - (U_b + U_d)}{\Sigma U}$$

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

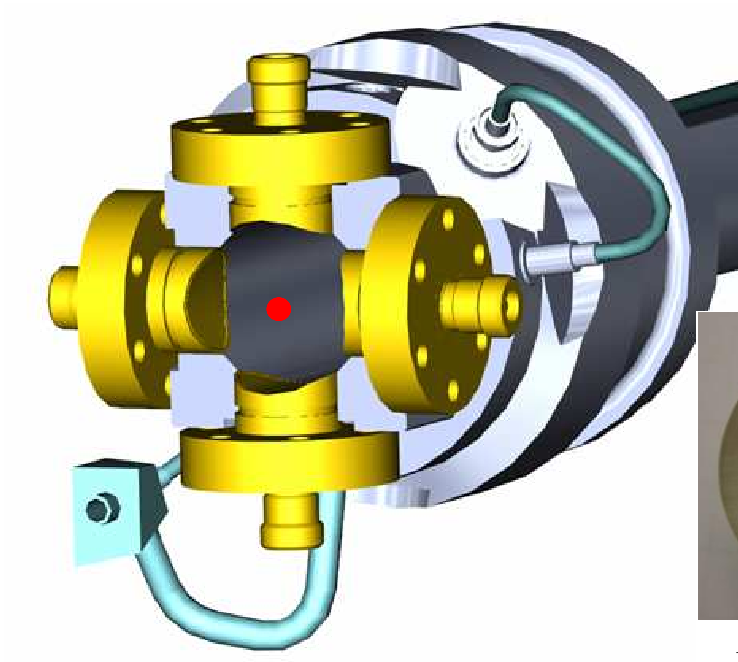


Linear-cut BPM in cylindrical geometry

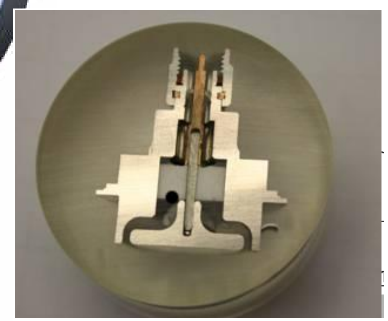


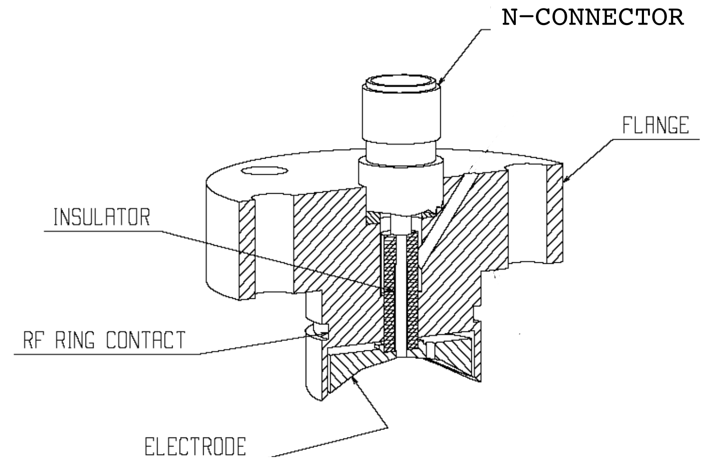
Wounded strip geometry

Button pick-up BPM

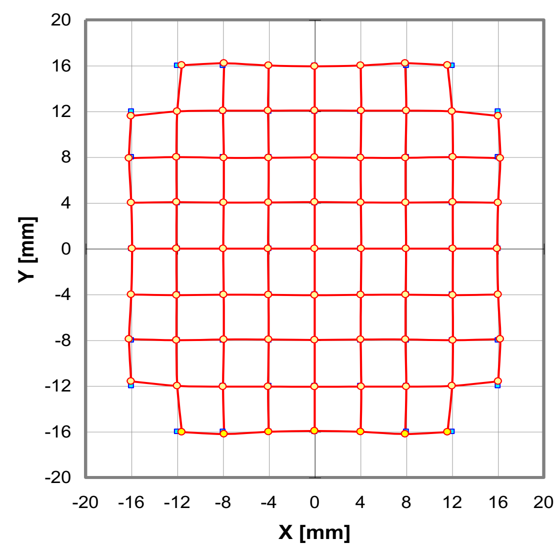


The installation of the curved Ø 24 mm button BPMs at the LHC beam pipe of Ø 50 mm.





BPM used at LHC

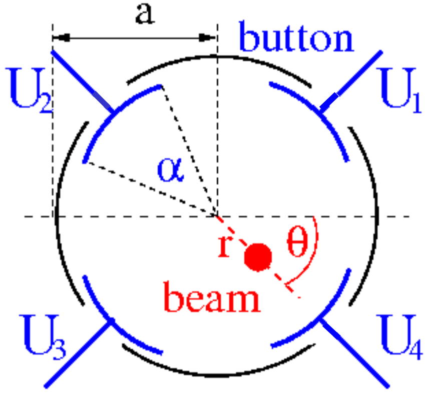


calibration map after correction

Button BPM – example for synchrotron light sources

The button BPM can be rotated by 45^0 to avoid exposure by synchrotron light:

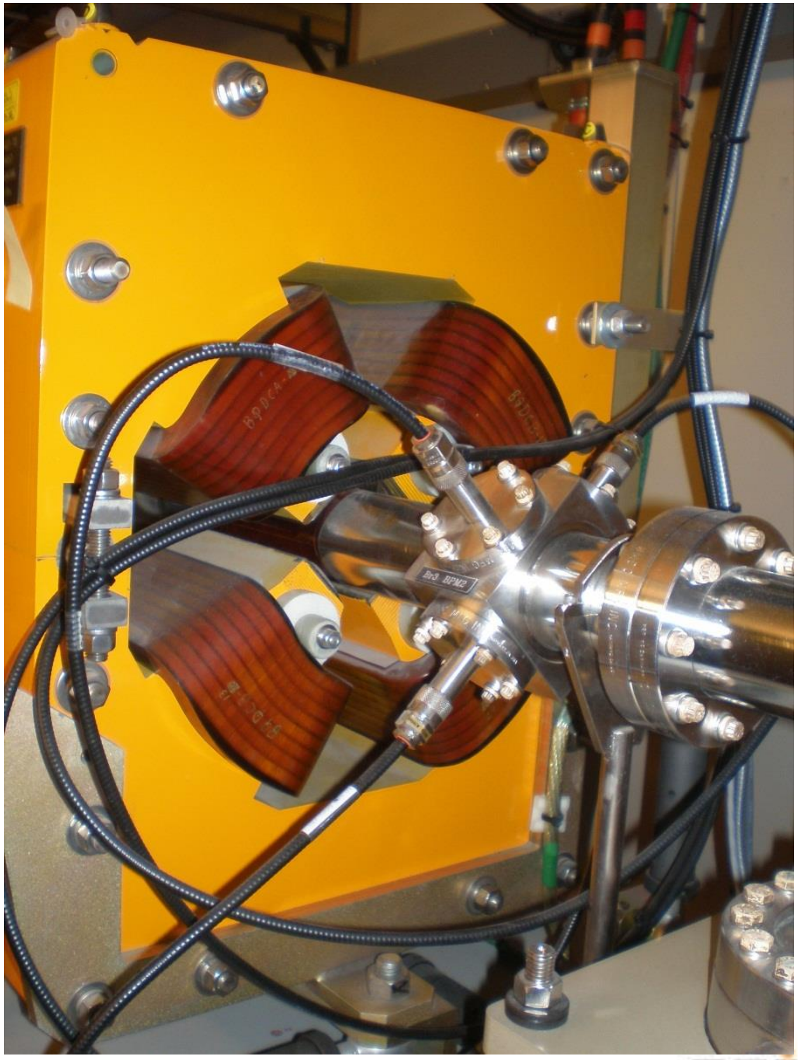
Frequently used at boosters for light sources



$$\text{horizontal}: x = \frac{1}{S} \cdot \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

$$\text{vertical}: \quad y = \frac{1}{S} \cdot \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4}$$

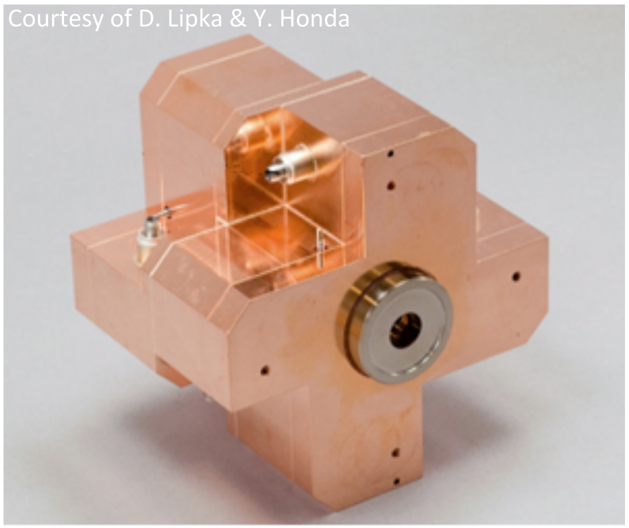
Example: Booster of ALS, Berkeley

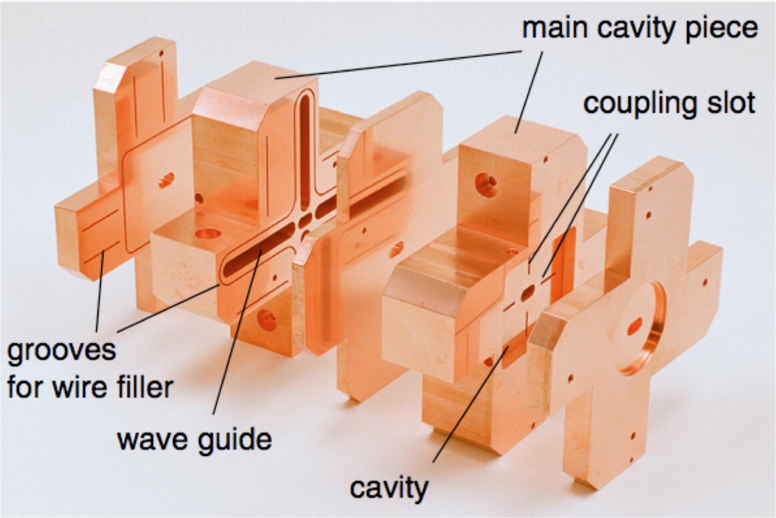


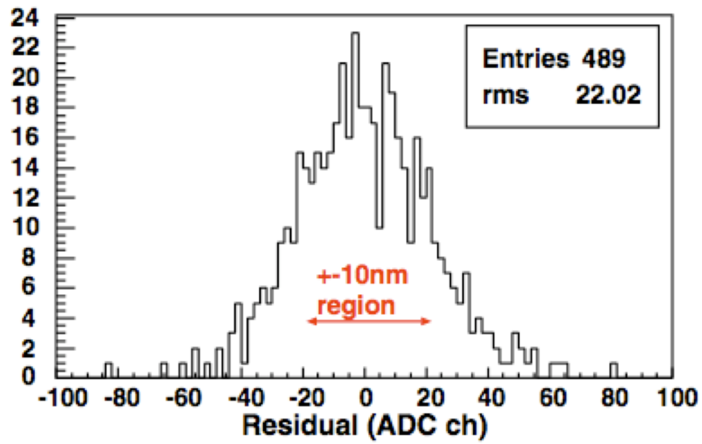
Today's State of the Art BPMs

Prototype BPM for ILC Final Focus

- Required resolution of 2nm (nano!) in a 6×12mm diameter beam pipe
- Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)



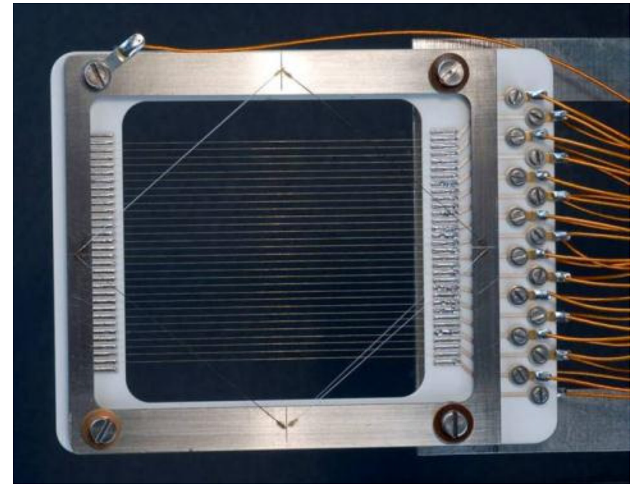


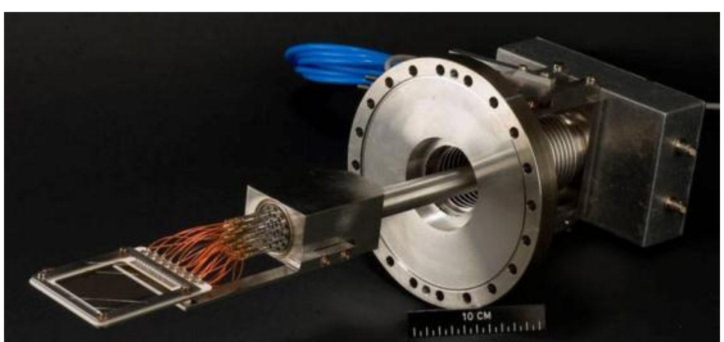


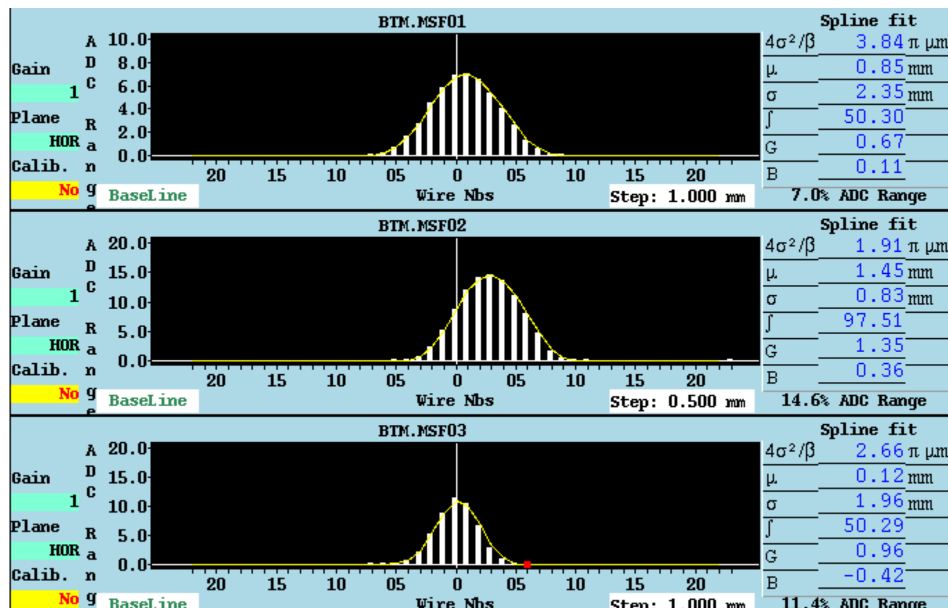
Beam profile monitor

Secondary Electron eMission (SEM) Grids

- When the beam passes through, secondary electrons are emitted from a wire, proportional to beam intensity
- The current flowing back onto the wires is measured using one amplifier/ADC chain for each wire
- Very high sensitivity, semi-transparent
- Good absolute measurement
- Spatial resolution limited by wire spacing to <≈ 0.25mm
- Dynamic range: ≈ 10^6





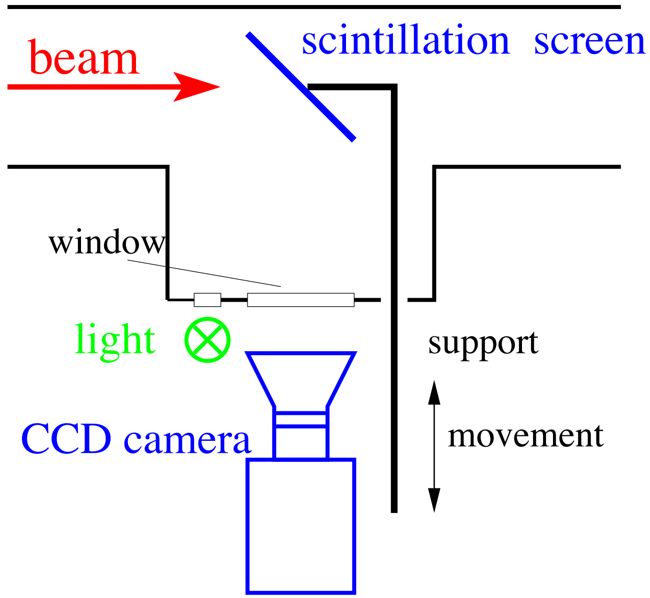


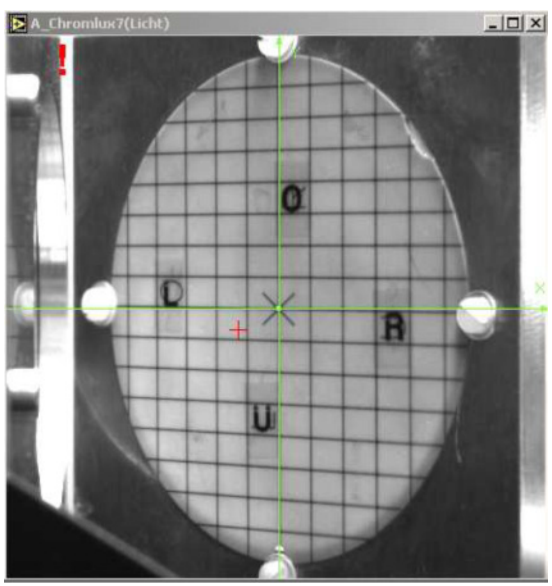
E. Holzer CAS2012

Scintillation screens

• Typically for setting-up with low intensities, screen thickness (mm)

•Sensitivities of different materials vary by orders of magnitudes



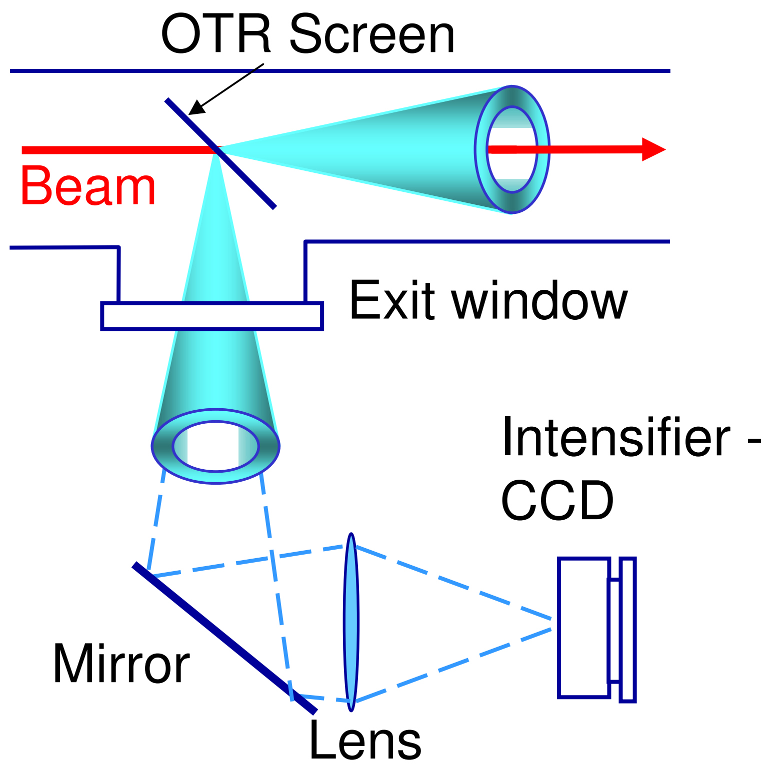


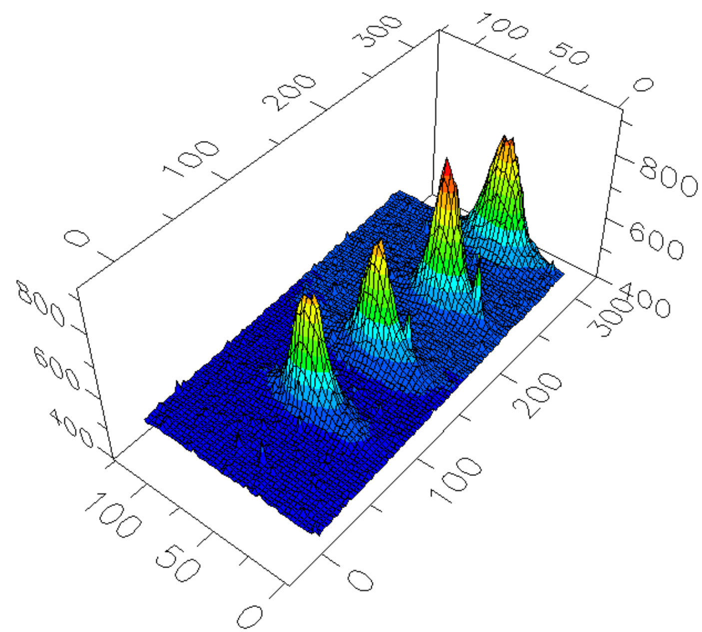
Properties of inorganic scintillators

Abbreviation	Material	Activator	max. emission	decay time
Quartz	SiO_2	none	470 nm	< 10 ns
	CsI	Tl	550 nm	1 μs
Chromolux	Al_2O_3	Cr	700 nm	100 ms
YAG	$Y_3Al_5O_{12}$	Ce	550 nm	0.2 μs
	Li glass	Ce	400 nm	0.1 μs
P11	ZnS	Ag	450 nm	3 ms
P43	Gd_2O_2S	Tb	545 nm	1 ms
P46	$Y_3Al_5O_{12}$	Ce	530 nm	0.3 μs
P47	$Y_2Si_5O_5$	Ce&Tb	400 nm	100 ns

Optical Transmission Radiation (OTR) screens

- Radiation emitted when a charged particle beam goes through the interface of two media with different dielectric constants
- Surface phenomenon allows the use of very thin screens (~10µm)
- much less intercepting, but requires higher intensity





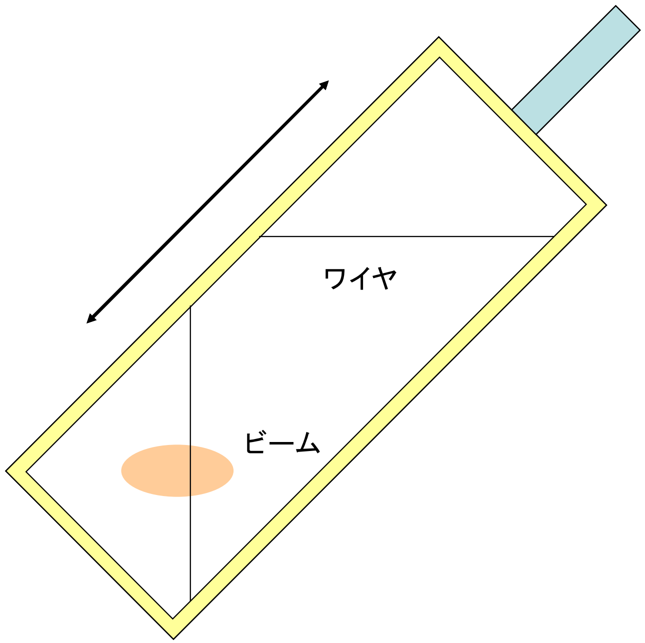
CERN SPS at injection

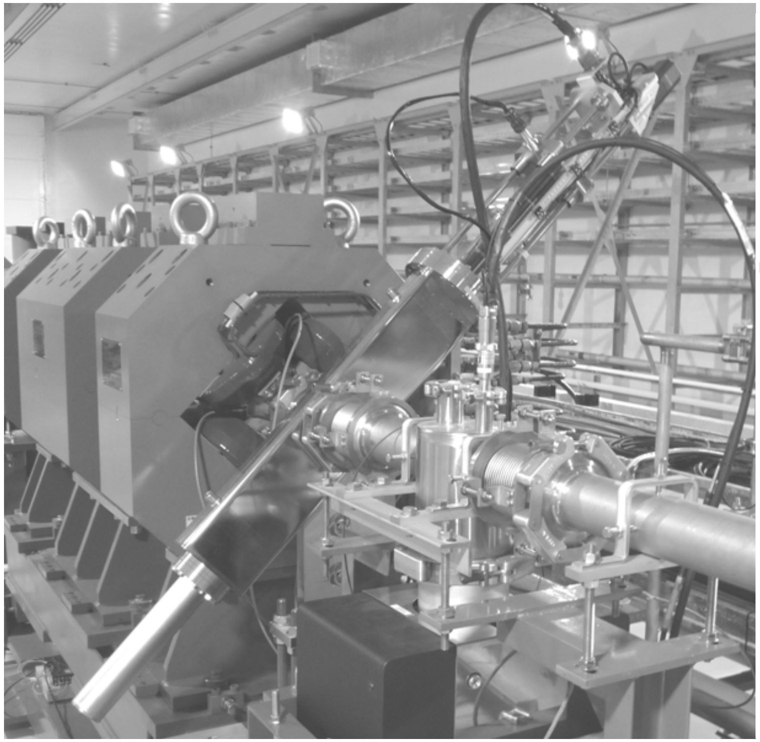
for electron accelerators

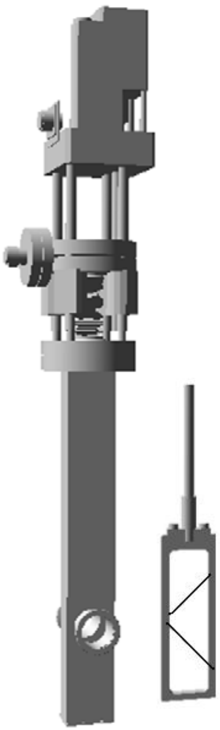
E. Holzer CAS2012

Wire scanners

WSM (J-Parc LINAC)



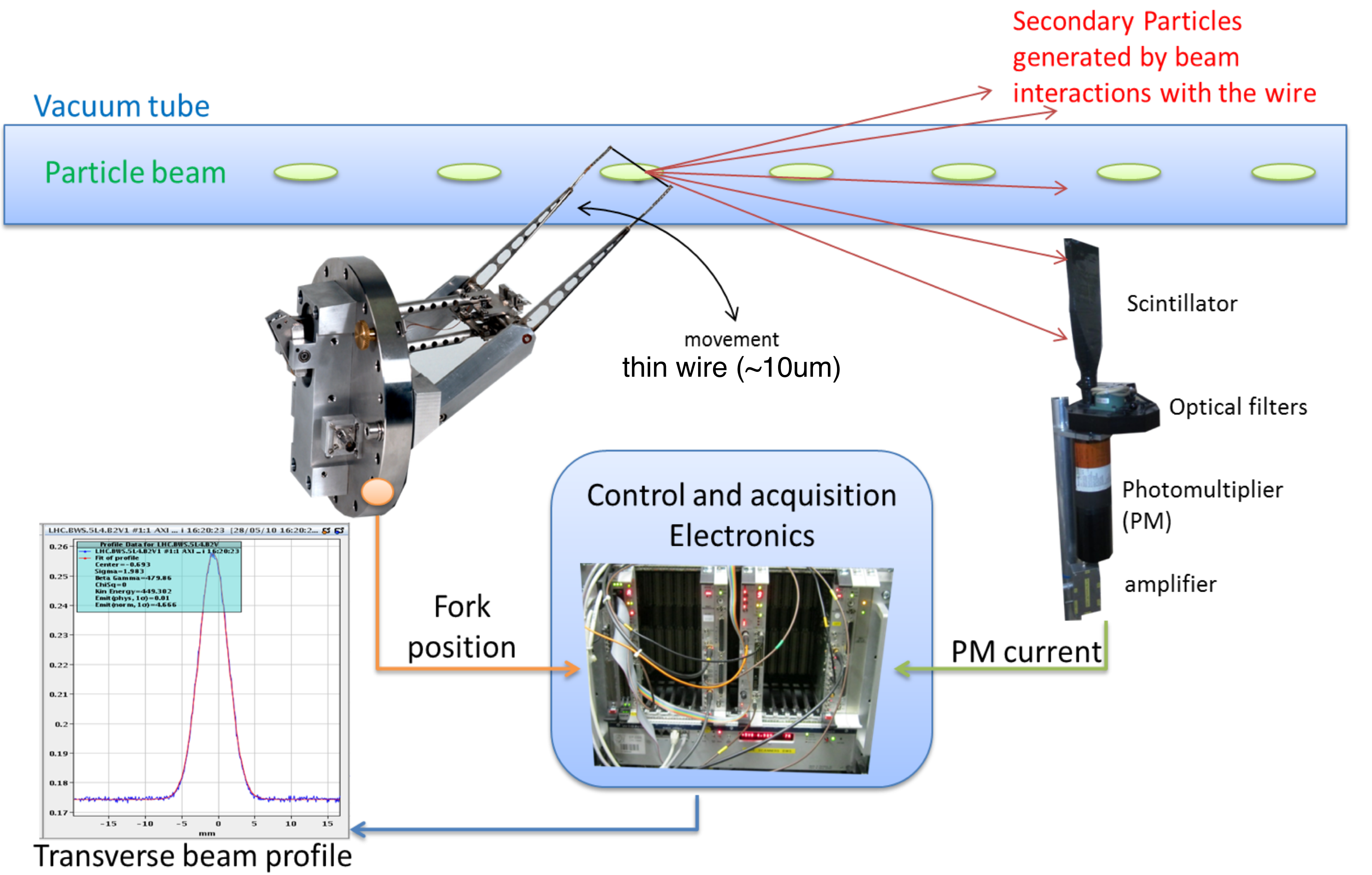




The wires are connected on a frame with 45deg, if the frame is installed with 45deg against the horizontal axis, both horizontal and vertical profiles can be measured in a stroke.

Miura IPAC2010, Sato OHO2010

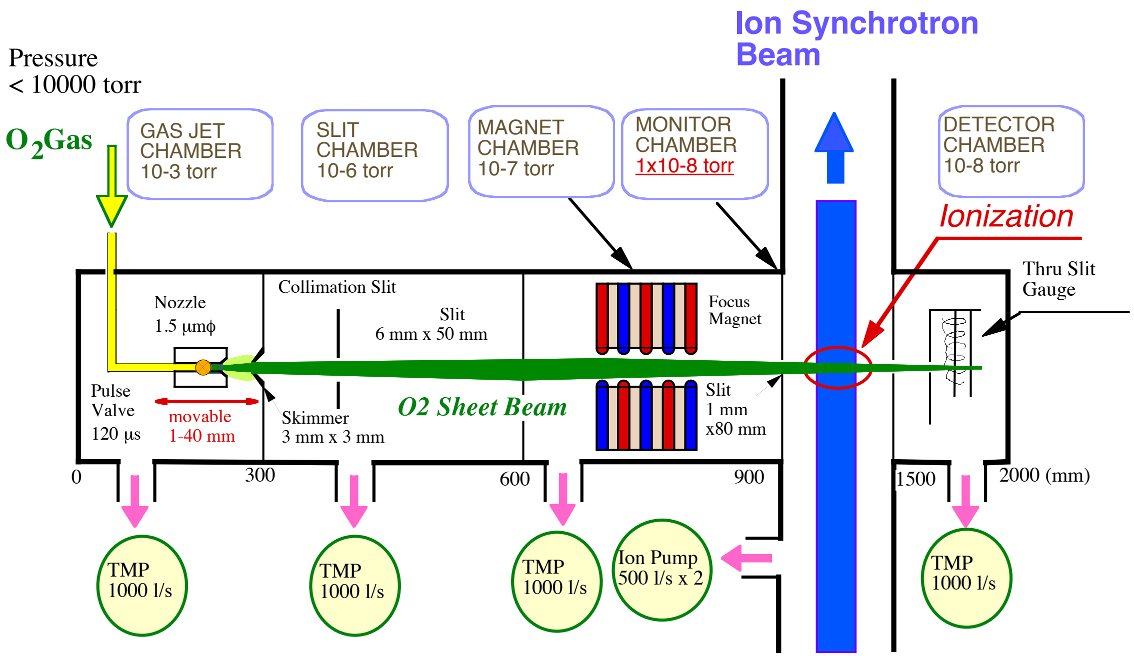
Wire scanners

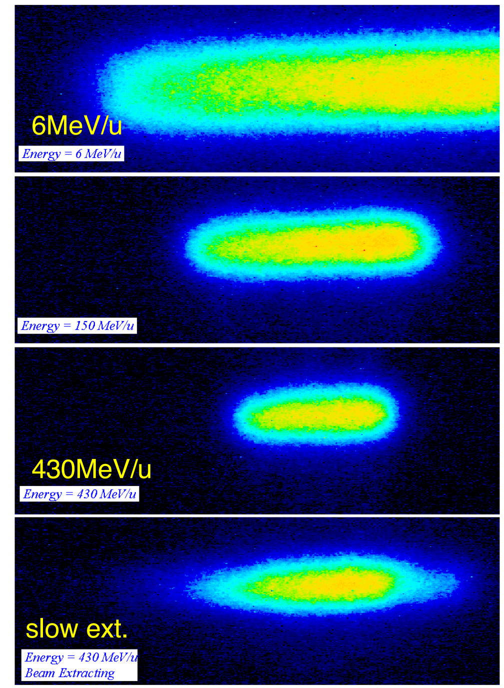


R. Jones CAS2015

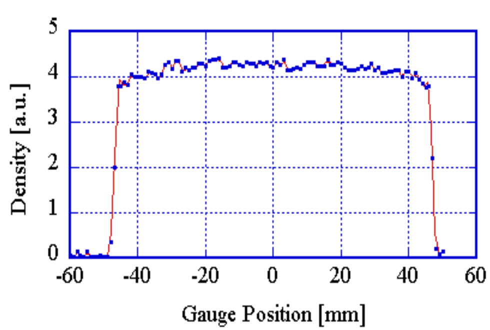
Gas sheet BPM

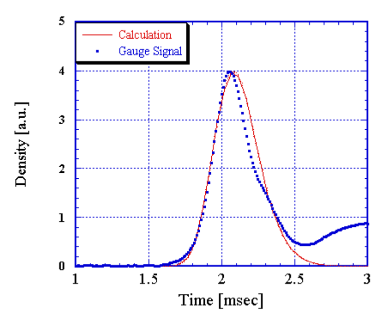
- non-destructive





Thickness of O_2 sheet beam : ~1mm

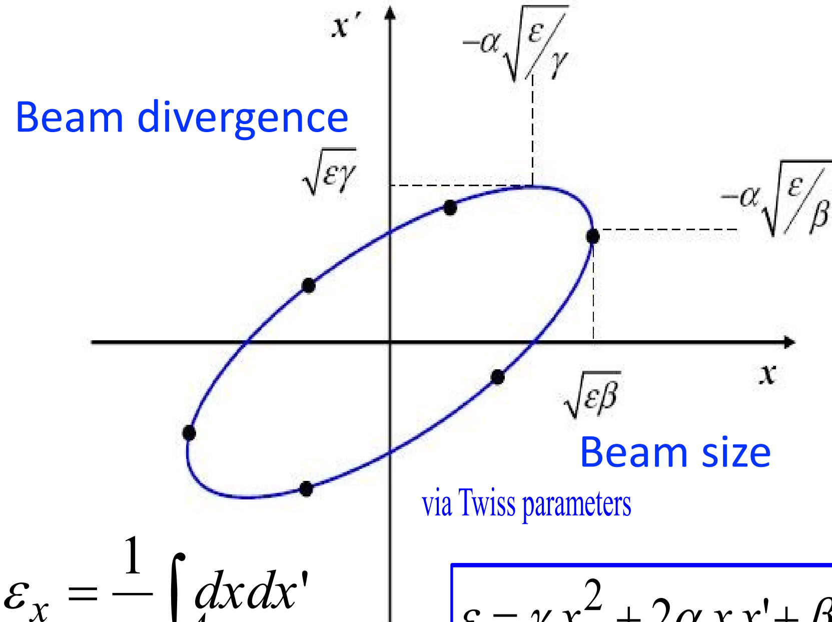




Profile images of HIMAC C^{6+} beam

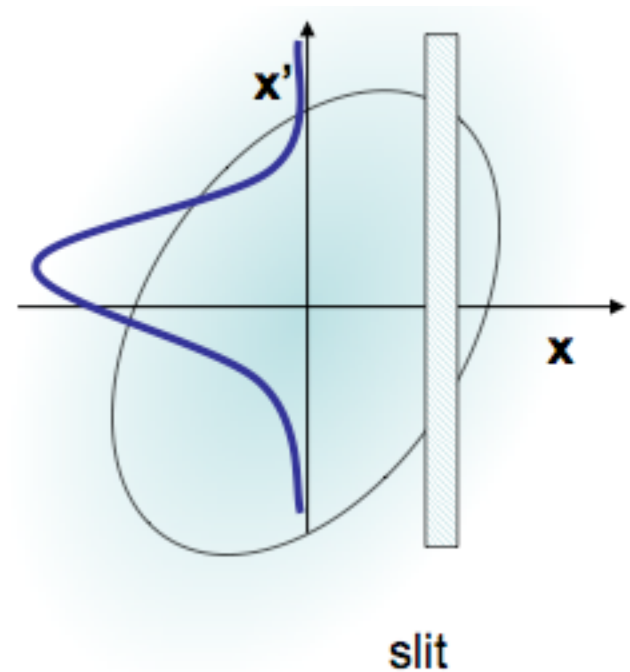
S.Hiramatsu OHO2011etc.

Transverse emittance measurement



$$\varepsilon_x = \frac{1}{\pi}\int_A dx\,dx'$$

$$\varepsilon = \gamma\, x^2 + 2\alpha\, x\, x' + \beta\, x'^2$$



beam matrix

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} = \varepsilon \cdot \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \text{ with } \vec{x} = \begin{pmatrix} x \\ x' \end{pmatrix}$$

$$x_\sigma = \sqrt{\sigma_{11}} = \sqrt{\varepsilon\beta} \quad \text{and}$$

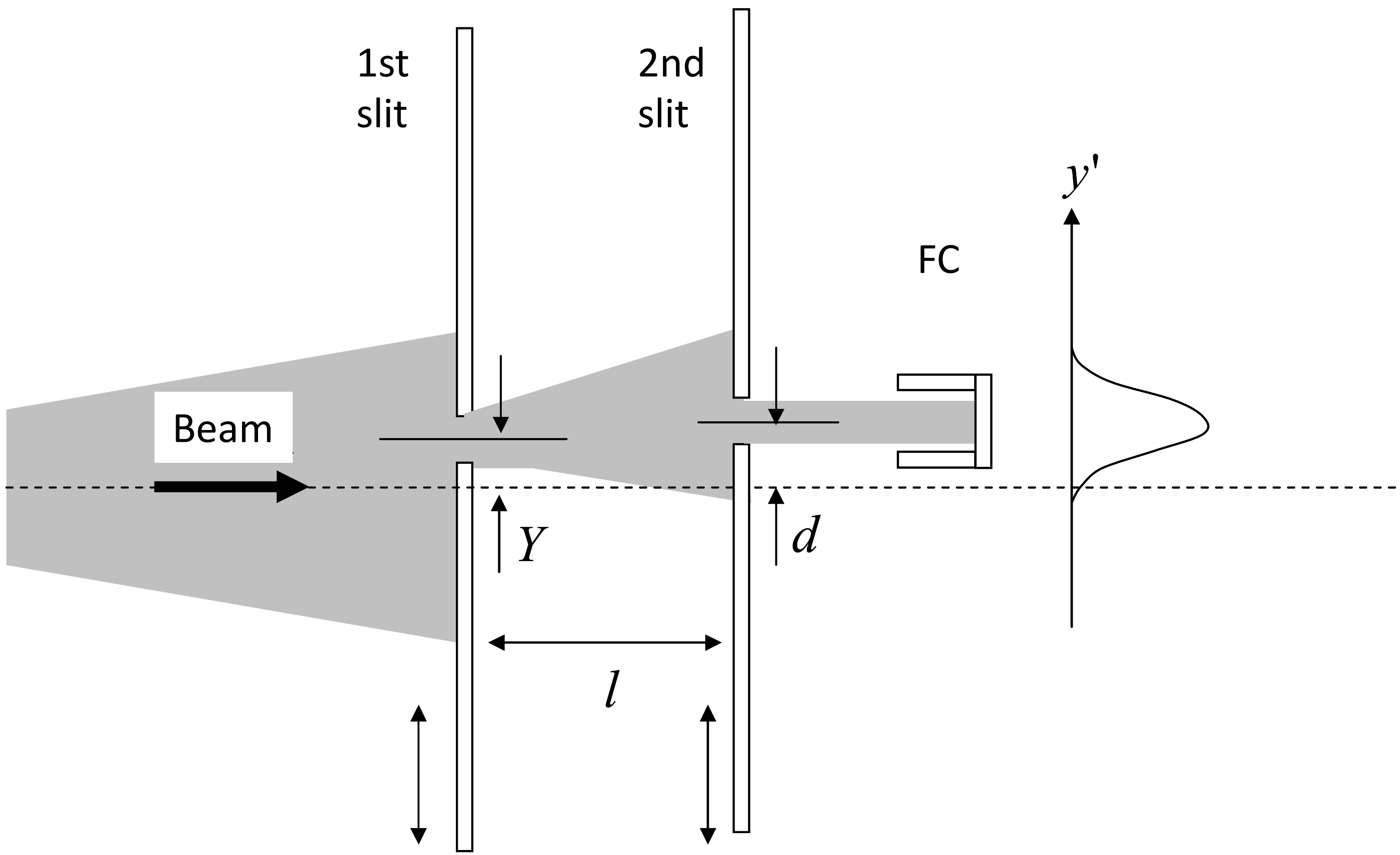
$$x'_\sigma = \sqrt{\sigma_{22}} = \sqrt{\varepsilon\gamma}$$

- If for each beam particle we plot its position and its transverse angle we get a particle distribution who's boundary is an usually ellipse.
- The projection onto the x axis is the beam size.

- If we place a slit into the beam we cut out a small vertical slice of phase space.

- Converting the angles into position through a drift space allows to reconstruct the angular distribution at the position defined by the slit.

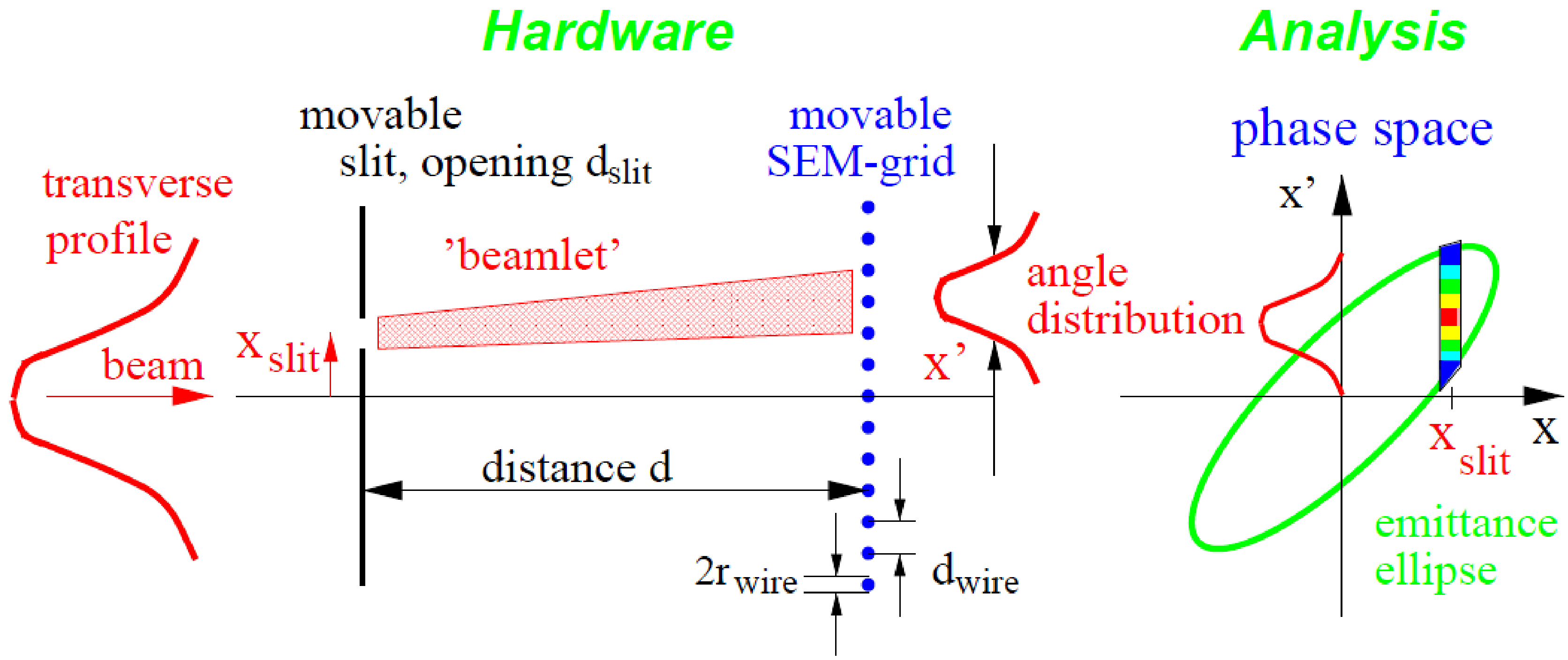
Double-Slit emittance measurement



Slit-Grid emittance measurement

Slit-Grid: Direct determination of position and angle distribution.

Used for protons/heavy ions with $E_{kin} < 100$ MeV/u ⇔ range $R < 1$ cm.



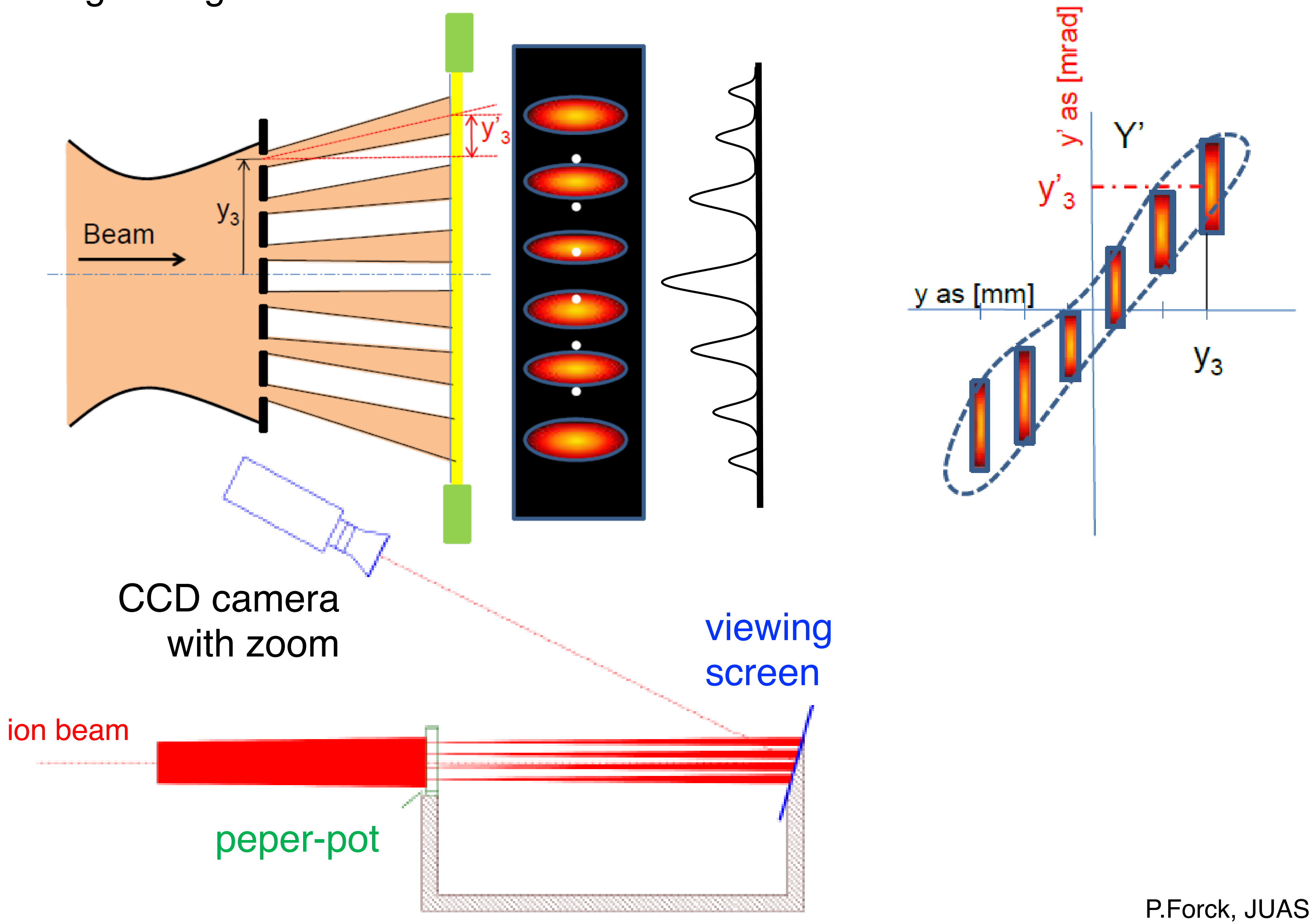
Slit: position ***P(x)*** with typical width: 0.1 to 0.5 mm

Distance: 10 cm to 1 m (depending on beam velocity)

SEM-Grid: angle distribution ***P(x')***

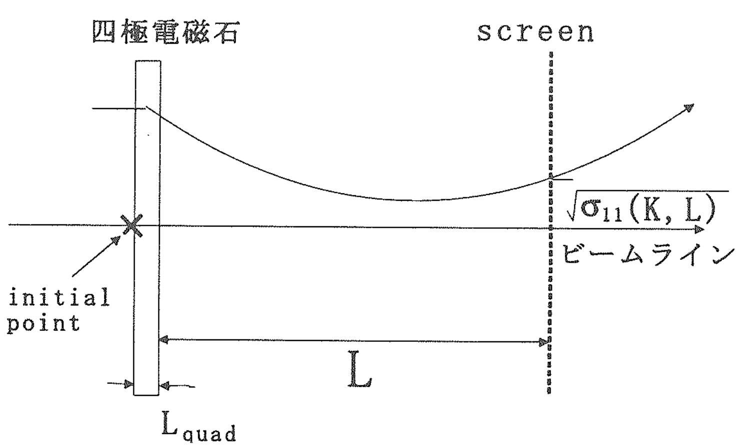
Pepper-pot emittance measurement

Advantage: Single-shot measurement



P.Forck, JUAS 2017

Emittance measurement : Quadrupole scan technique (Q-scan)



Transfer matrix of the drift space

$$\mathbf{R}_{\mathbf{drift}} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

Transfer matrix of the quadrupole

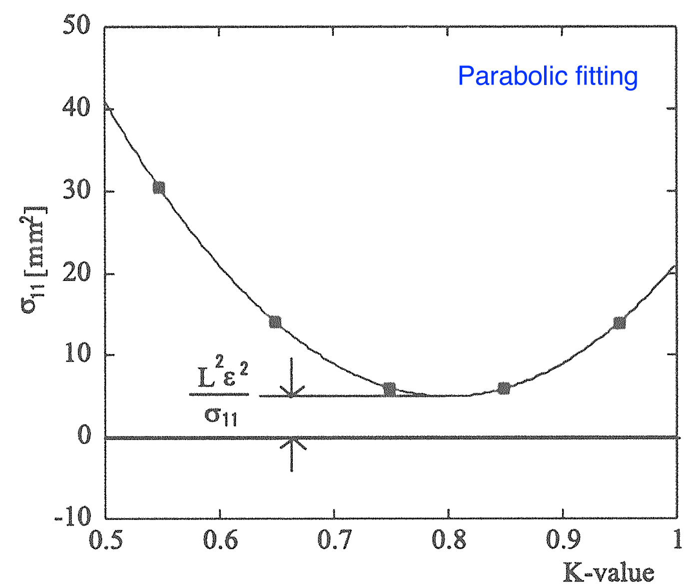
$$\mathbf{R}_{\mathbf{quad}} = \begin{pmatrix} 1 & 0 \\ -K & 1 \end{pmatrix} \qquad K = \frac{\partial B_y}{\partial x}\frac{L_{quad}}{(B\rho)}$$

$$\mathbf{R}(\mathbf{K},\mathbf{L}) = \mathbf{R}_{\mathbf{drift}}\mathbf{R}_{\mathbf{quad}} = \begin{pmatrix} 1-KL & L \\ -K & 1 \end{pmatrix}$$

$$\begin{aligned}\sigma(\mathbf{K},\mathbf{L}) &= \mathbf{R}(\mathbf{K},\mathbf{L})\sigma_0\mathbf{R}^t(\mathbf{K},\mathbf{L}) \\ &= \begin{pmatrix} 1-KL & L \\ -K & 1 \end{pmatrix}\begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} \\ &\quad \times \begin{pmatrix} 1-KL & -K \\ L & 1 \end{pmatrix}\end{aligned}$$

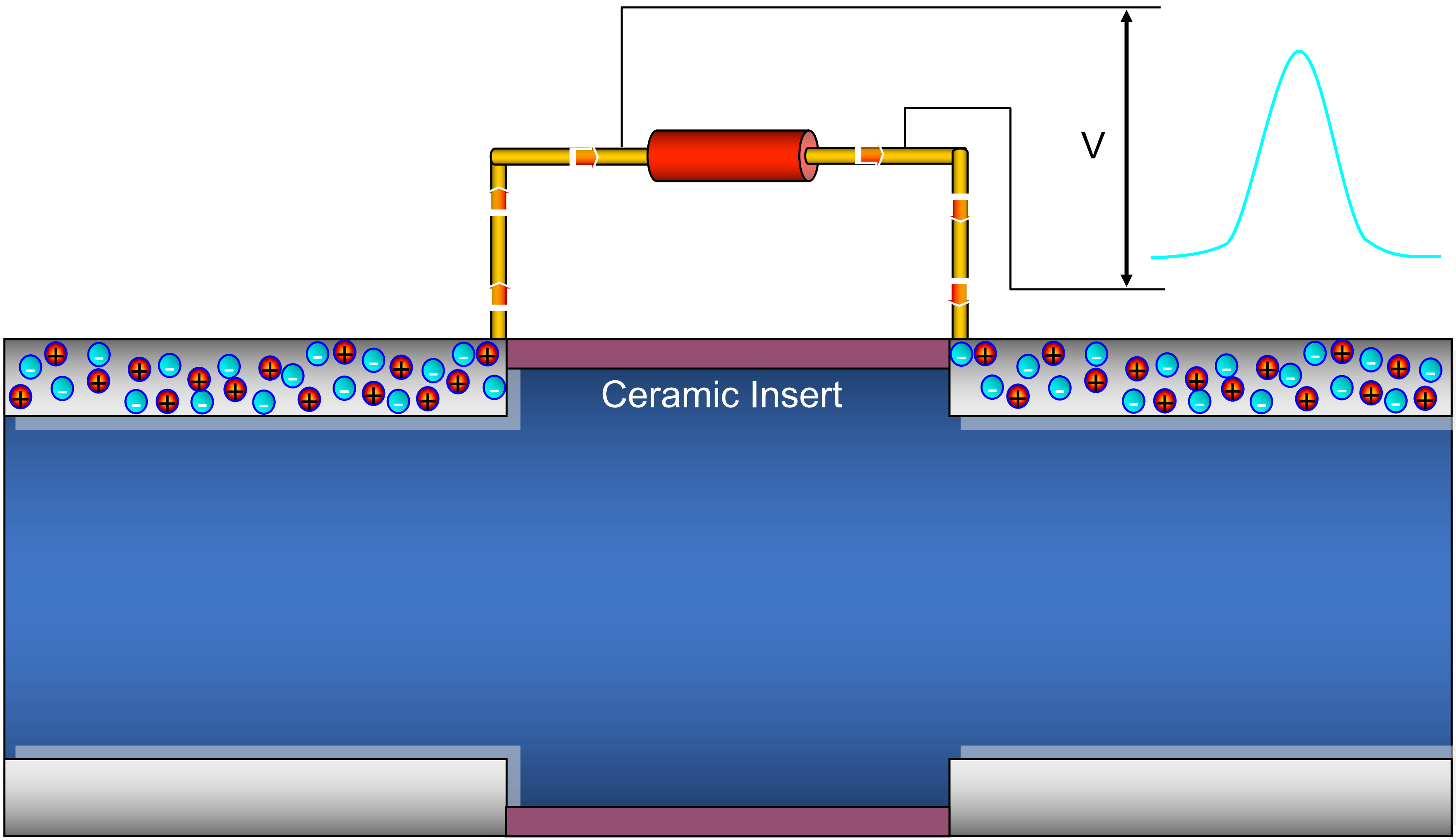
$$\begin{aligned}\sigma_{11}(K,L) &= (1-KL)^2\sigma_{11} \\ &\quad + 2L(1-KL)\sigma_{12} + L^2\sigma_{22}\end{aligned}$$

Measured beam size as a function of the quadrupole field strength



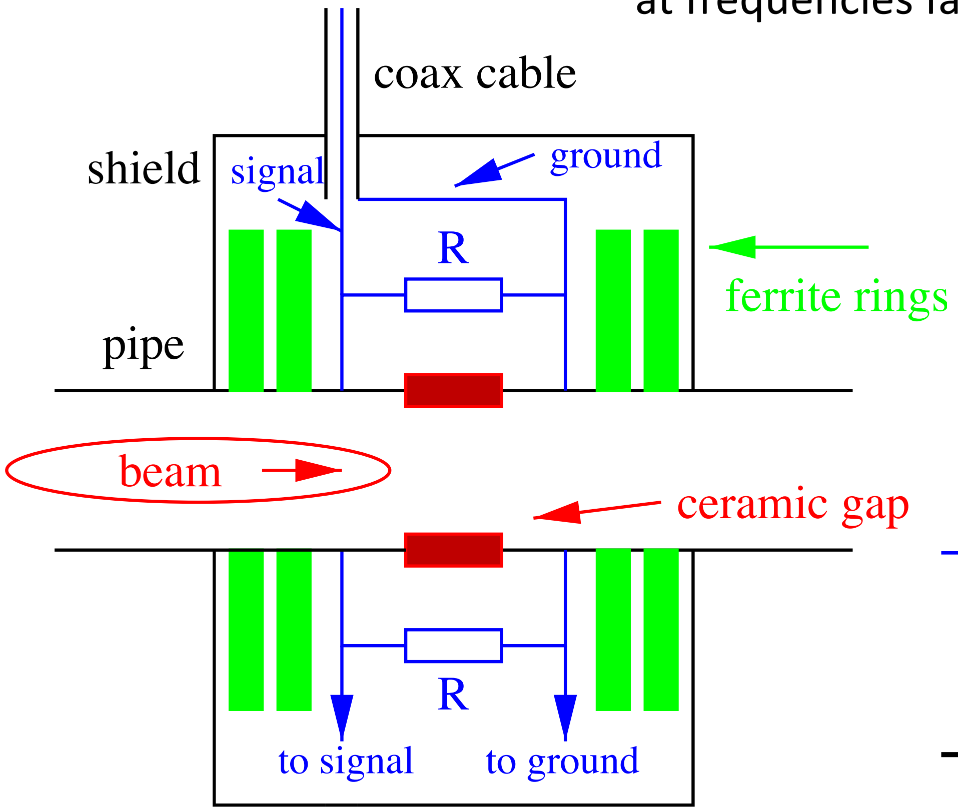
H.Sakai OHO2002

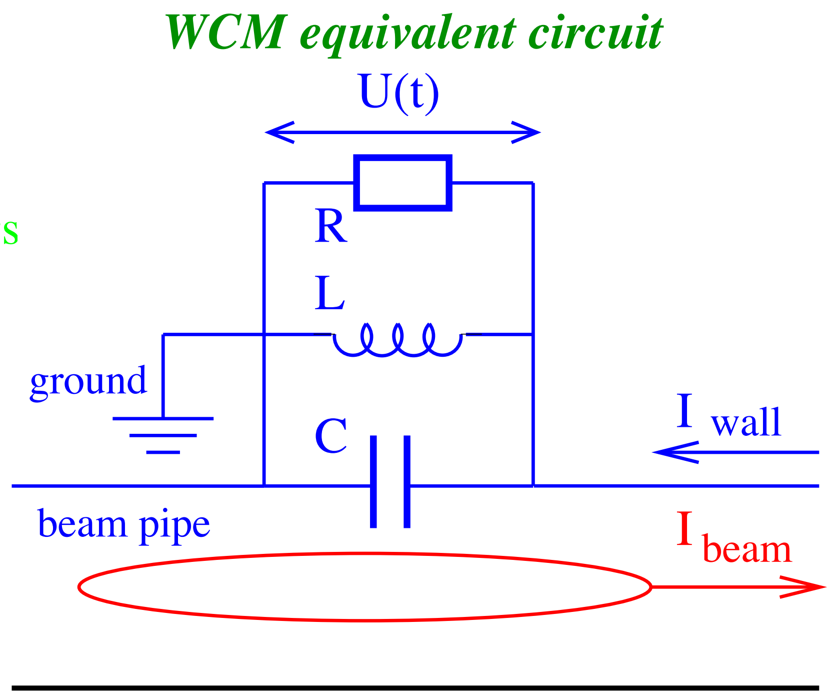
Wall Current Monitor – The Principle



Wall current monitors

WCM can observe the short bunch shape of electrons at frequencies far beyond the few 100 MHz.



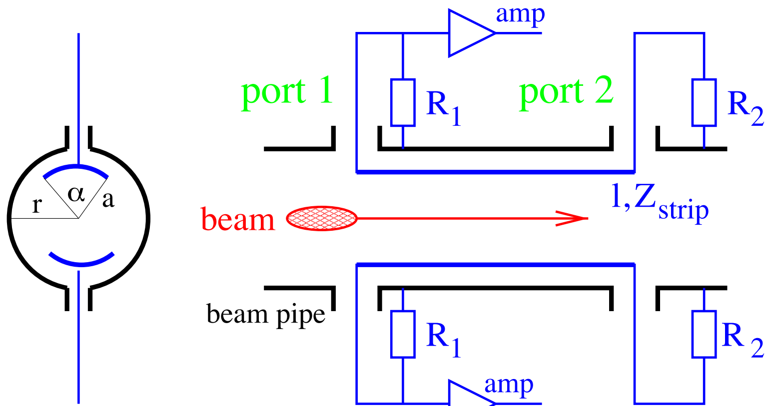


When the beam is not at the centre of the vacuum chamber, the wall-current will be unequally distributed around the circumference of the chamber.

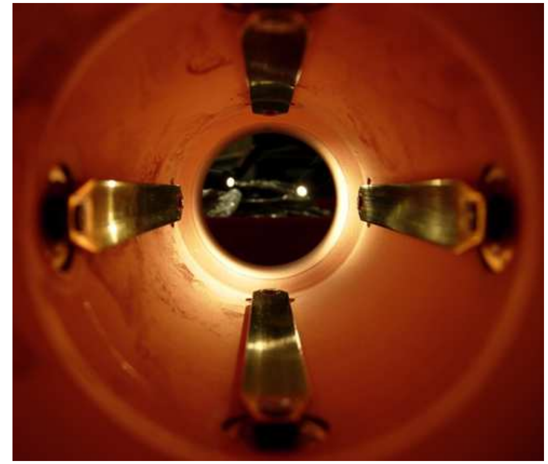
The signals are picked-up separatedly → Beam position monitoring

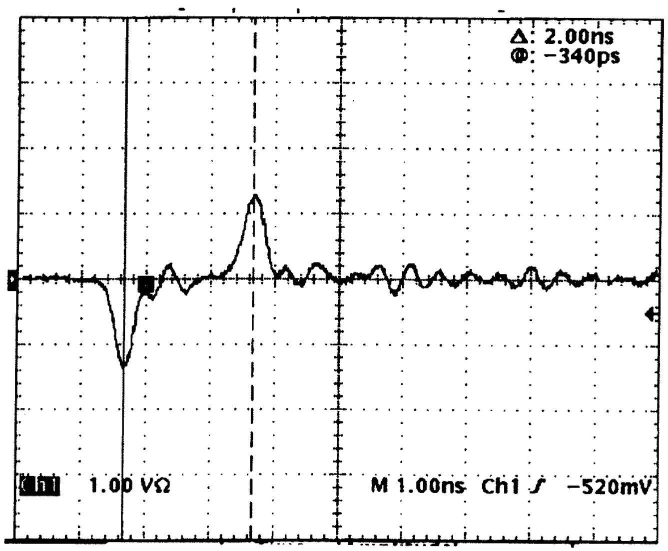
P. Forck, CAS2011

Stripline pick-ups ~ bunch monitor



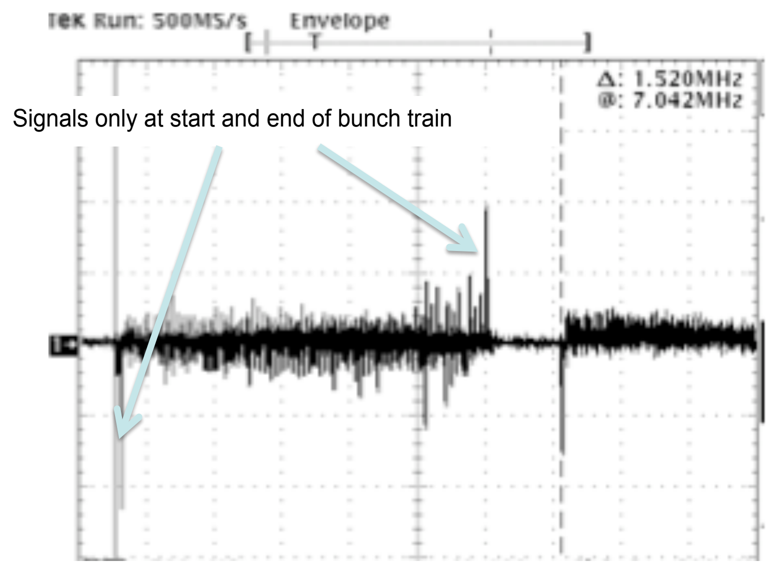
Scheme of a stripline pick-up





Single shot signal
from a 30 cm stripline pick-up

(t=2L/c)



Multibunch signal
L=30cm, bunch spacing 60cm (2ns)

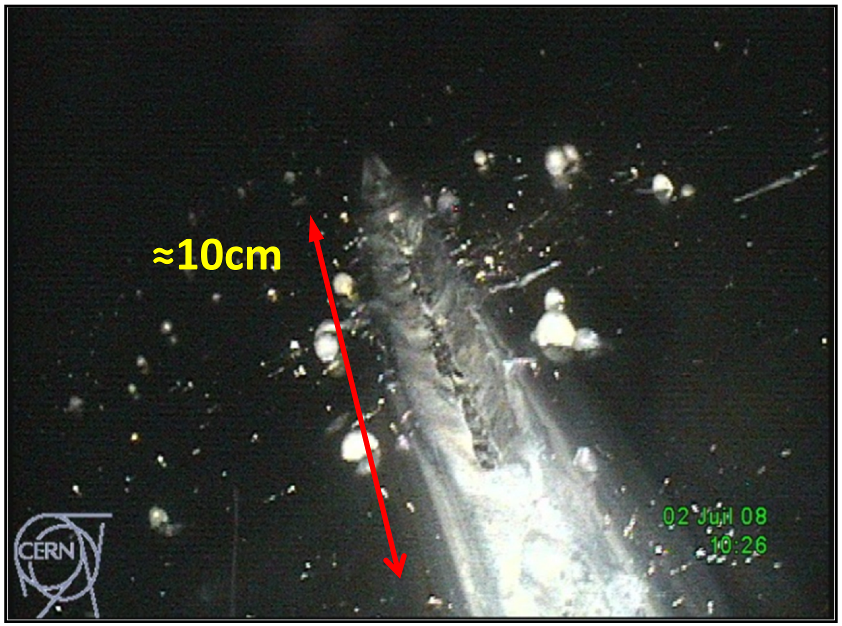
Beam loss monitors

Beam Loss

secondary products from electromagnetic or hadronic shower

Role of beam loss monitor :

- Protect the machine from damage and activation
- Dump the beam to avoid magnet quenches (for superconducting magnets)
- Diagnostic tool to improve the performance of the accelerator



SPS incident

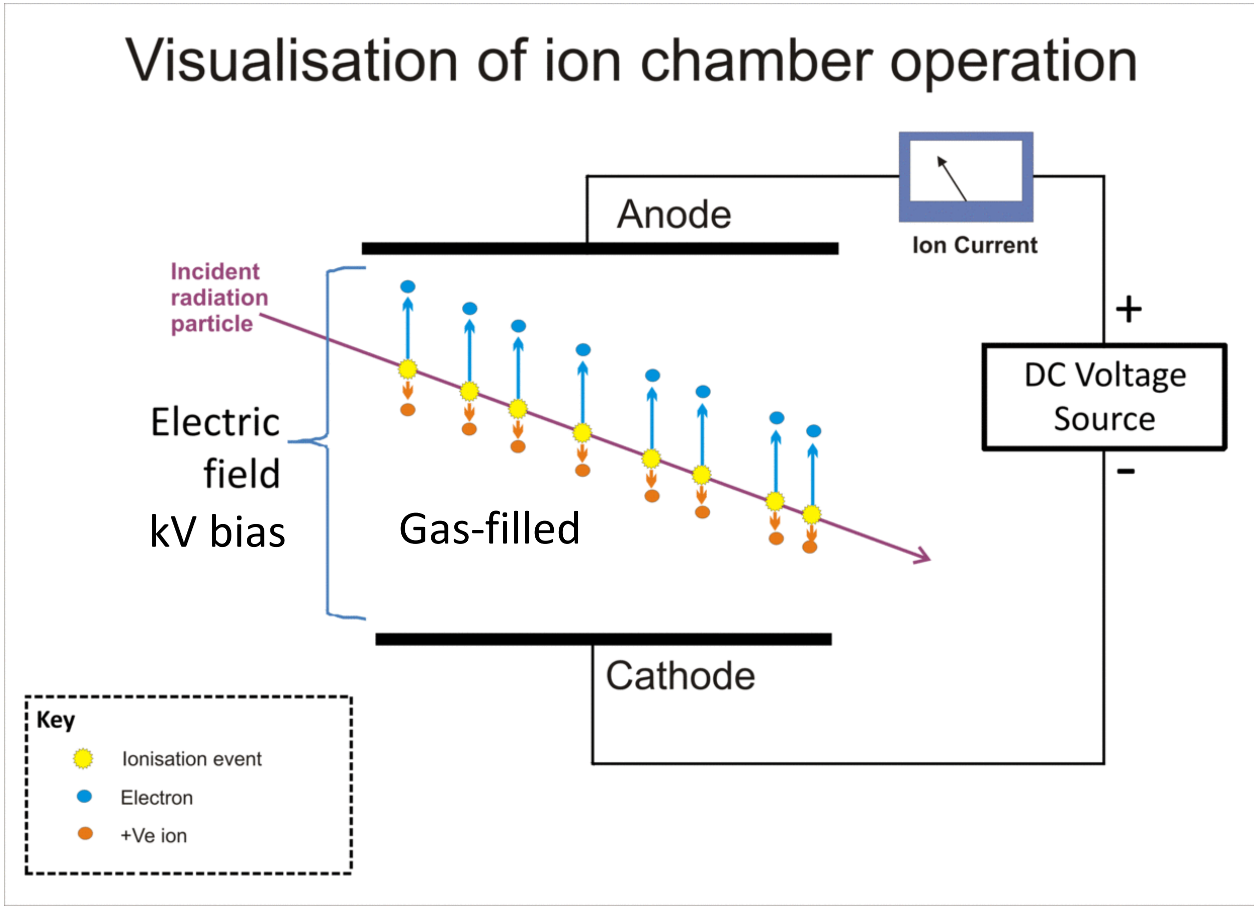
- June 2008
- 2MJ beam lost at 400MeV

R. Jones, CAS2017

Beam Loss Monitors (BLM) - Ionization chambers

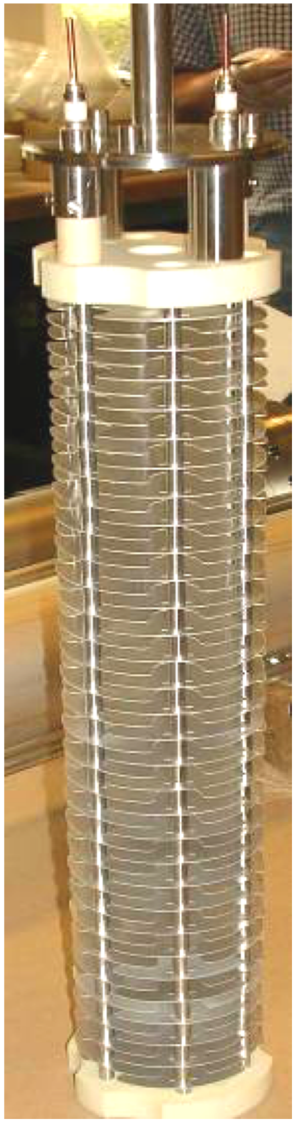
Ionization chambers (charge detection)

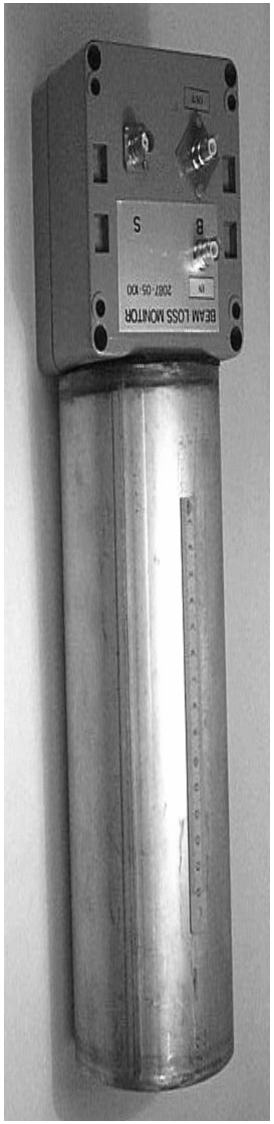
- Dynamic range of < 10^8
- Slow response (μs) due to ion drift time



R. Jones, CAS2017

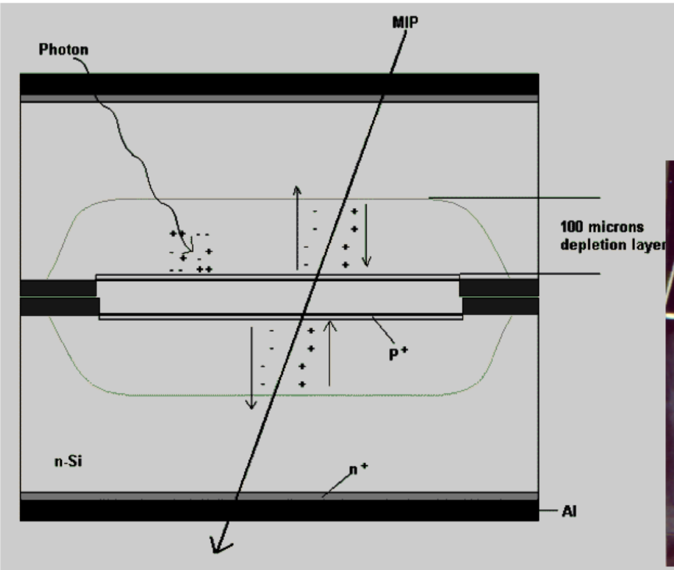
LHC BLM system

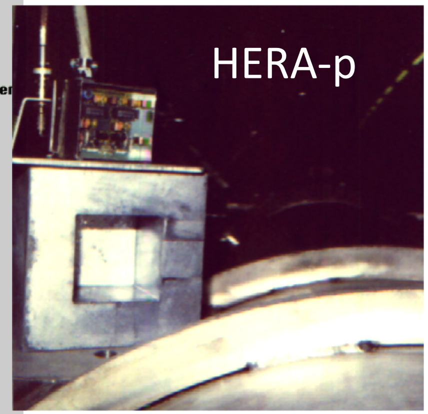


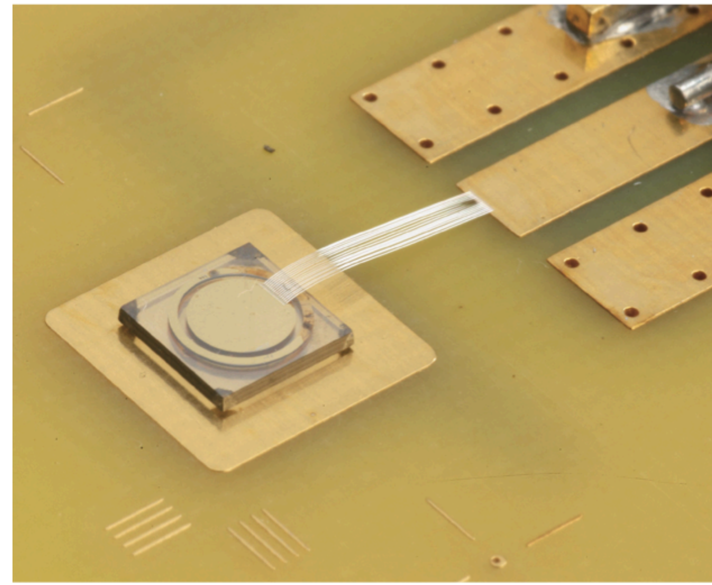


- Main purpose: prevent damage and quench
- 3600 Ionization chambers
- reaction time : ~100μs
- radiation hard : ~ kGy

Beam Loss Monitors







PIN photodiode
(solid state ionisation chamber)

Count detection

Detect coincidence of ionising particle crossing photodiodes
Insensitive to photons from synchrotorn radiation
Count rate proportional to beam loss with speed limited by integration time
Can distinguish between photon & ionising particles
Dynamic range of up to 10^9

Diamond Detectors

- Fast & sensitive
- Used in LHC to distinguish bunch by bunch losses
- Work **in** cryogenic conditions

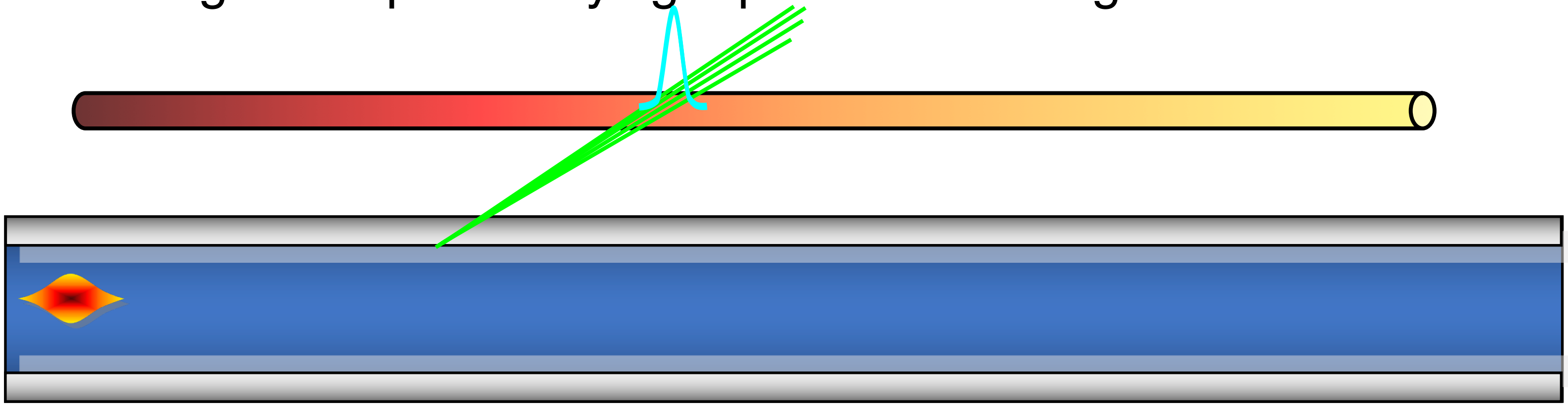
Beam Loss Monitors

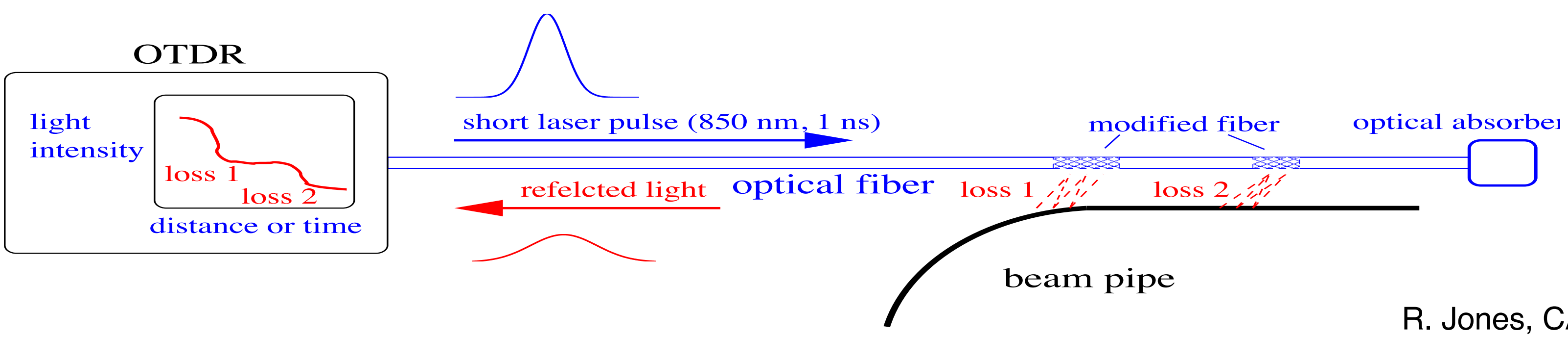
Long ionization chamber (charge detection)

- Up to several km of gas filled hollow coaxial cables
- Position sensitivity achieved by comparing direct & reflected pulse
- SLAC – 8m position resolution (30ns) over 3.5km cable length

Fiber optic monitors

- Electrical signals replaced by light produced through Cerenkov effect





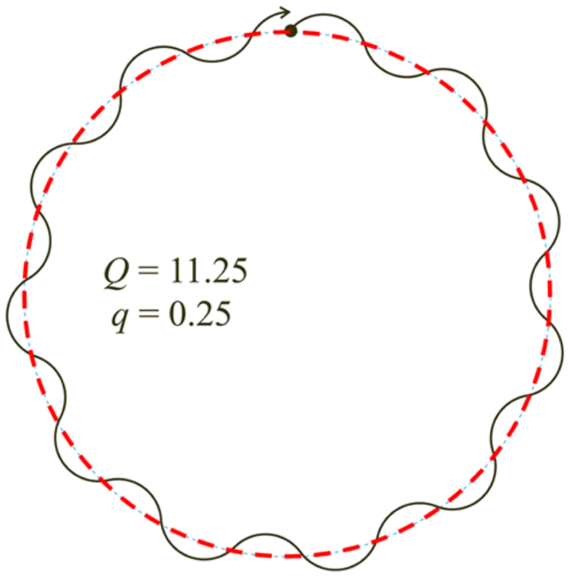
R. Jones, CAS2017

Tune, Chromaticity, Momentum

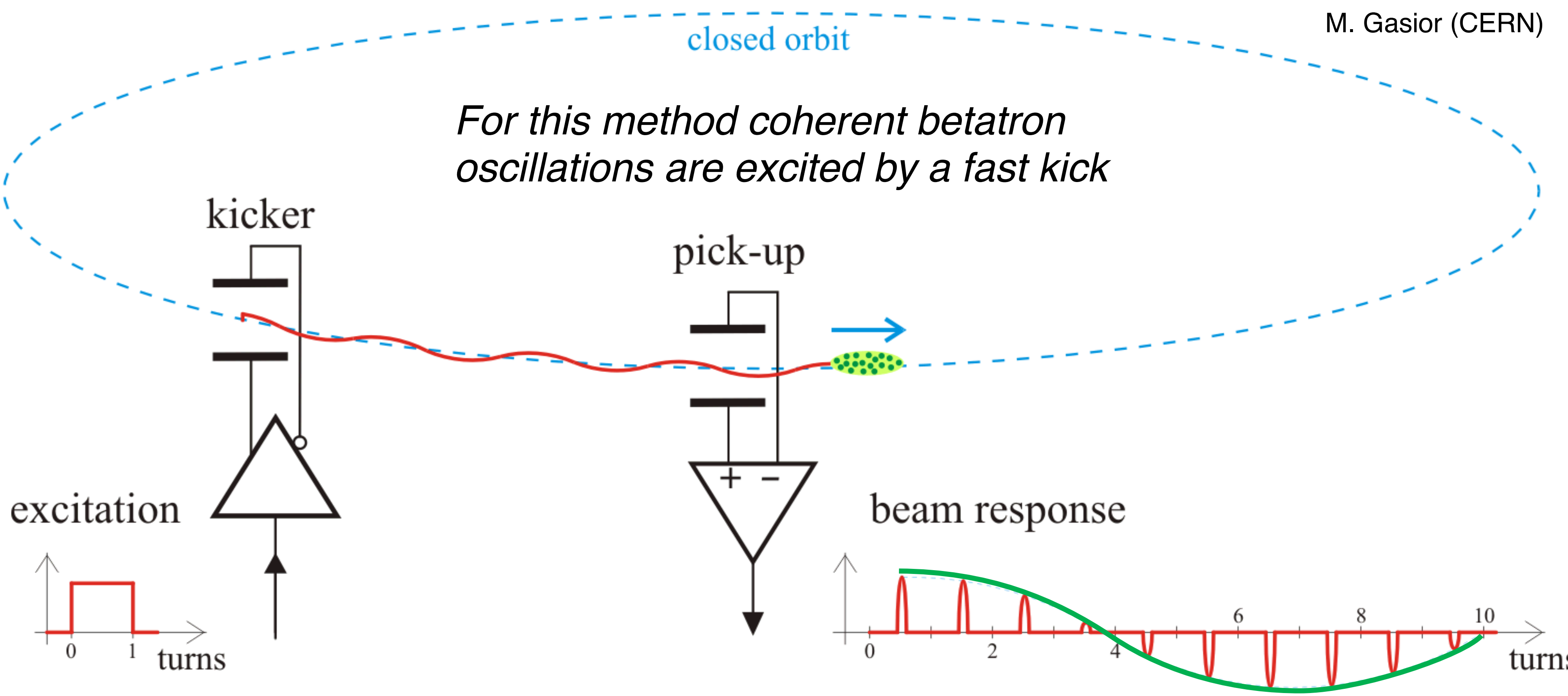
Tune

Characteristic Frequency of the Magnetic Lattice
Given by the strength of the Quadrupole magnets

- Parameters
  - Q : Full betatron tune
  - n : Integer tune
  - q : Fractional tune (Q=n+q)
  - horizontal, vertical



Tune measurement – principle

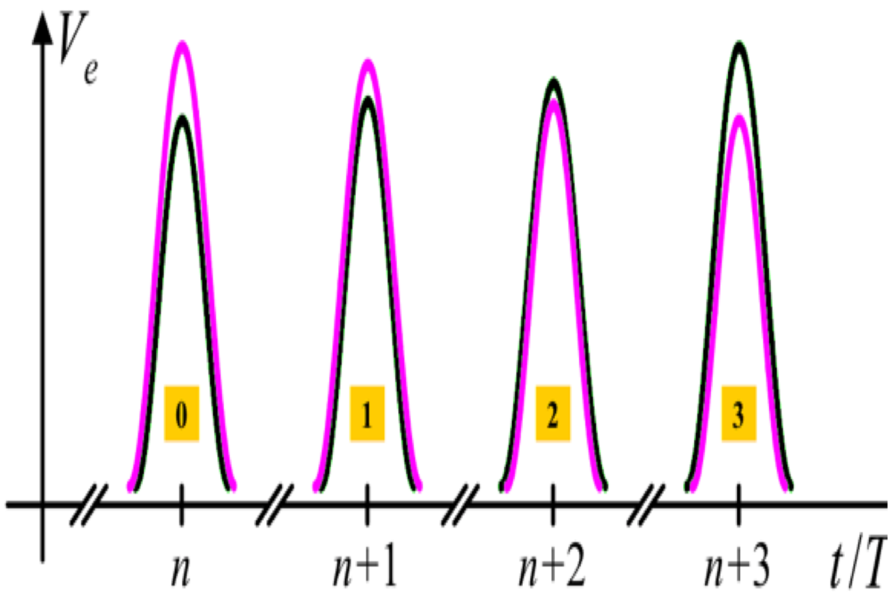


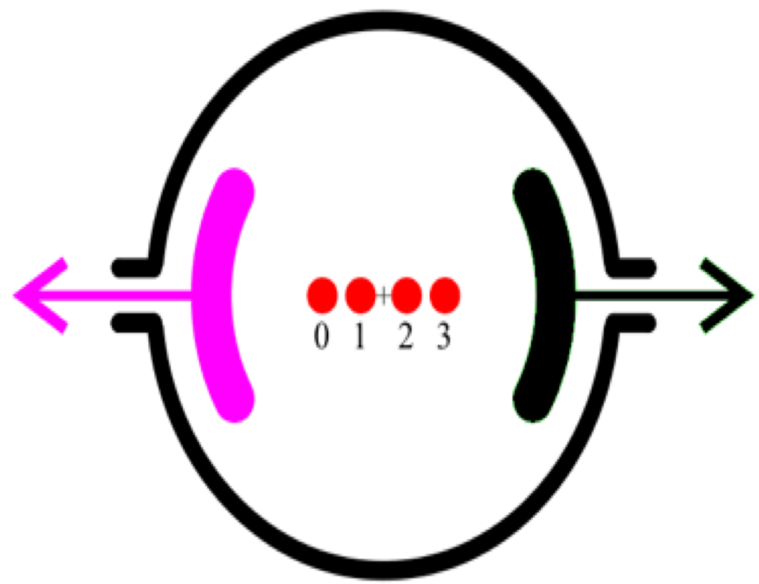
A **stimulus** is needed to globally excite the beam.

- Resulting betatron oscillations observed on a position pick-up
- Time domain signals usually converted to frequency domain
  - Displays which frequencies are present in the oscillations

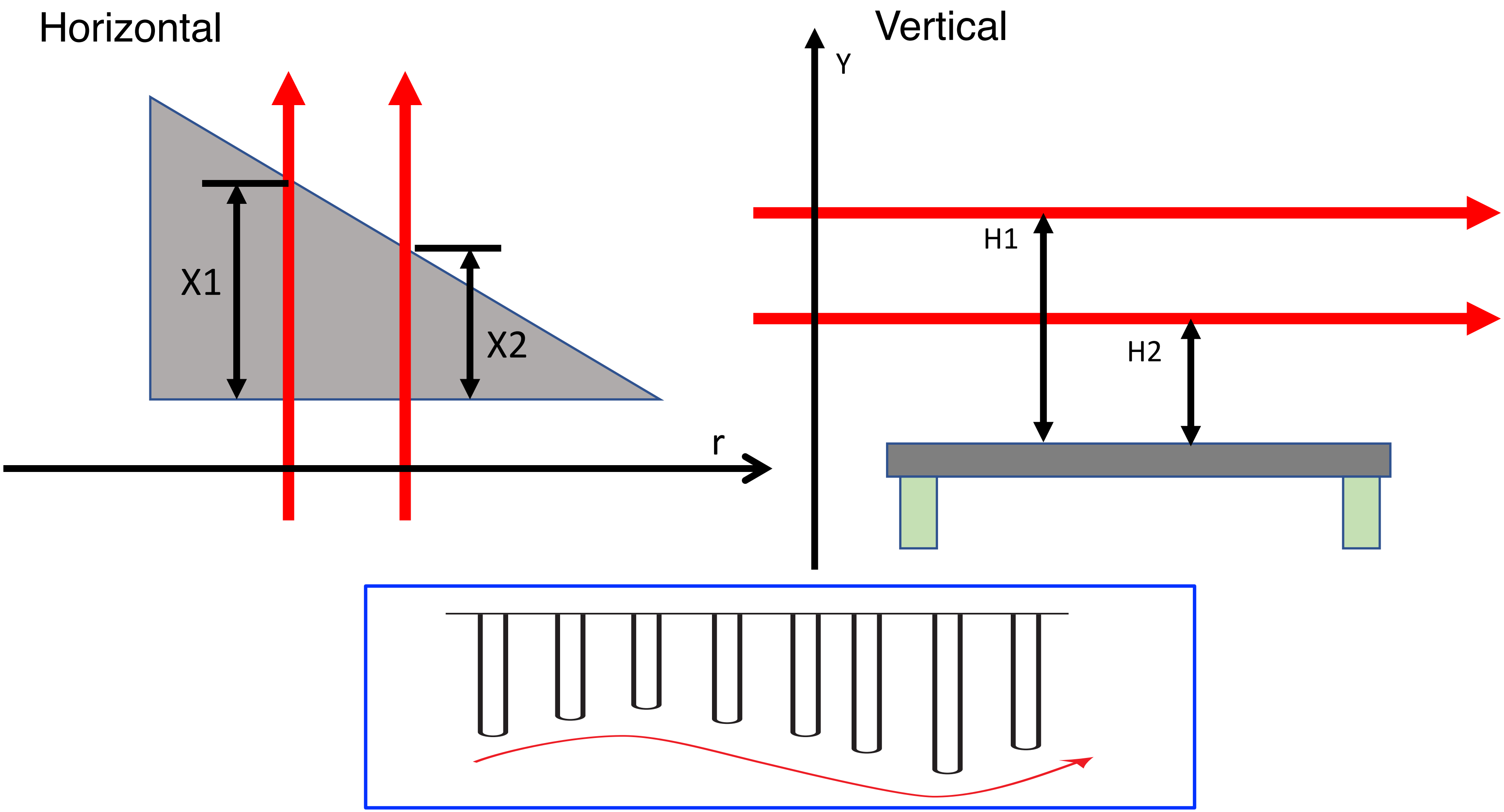
Tune measurement – principle

- Observable is typically turn-by-turn position from a BPM
- BPM electrode signal has temporal shape related to the temporal structure (intensity profile) of the passing beam





Tune measurement



Induced voltage (pulse height) each turn depends on **path length of electrode** by the betatron oscillations.

Induced voltage (pulse height) each turn depends on **distance between beam-electrode** by the betatron oscillations.

Tune measurement by FFT analysis

<u>Measured voltage from monitor</u>

$$V_{\mathrm{moni}} = \sum_m A\left\{1 + A_b\cos(2\pi f_b t + \theta)\right\}\cdot\delta\left(t - \frac{m}{f_{\mathrm{rev}}}\right)$$

<u>tune</u> $\nu = \dfrac{f_b}{f_{rev}} = n + c$

$$V_{\mathrm{moni}} = \sum_m A\left\{1 + A_b\cos\left(2\pi(n+c)f_{\mathrm{rev}}t + \theta\right)\right\}\cdot\delta\left(t - \frac{m}{f_{\mathrm{rev}}}\right)$$

$$= \sum_m A\left\{1 + A_b\cos\left(2\pi c f_{\mathrm{rev}}t + \theta\right)\cos(2\pi n f_{\mathrm{rev}}t)\right.$$

$$\left. - A_b\sin\left(2\pi c f_{\mathrm{rev}}t + \theta\right)\sin(2\pi n f_{\mathrm{rev}}t)\right\}\cdot\delta\left(t - \frac{m}{f_{\mathrm{rev}}}\right)$$

$$= \sum_m A\left\{1 + A_b\cos\left(2\pi c f_{\mathrm{rev}}t + \theta\right)\cos(2\pi n f_{\mathrm{rev}}t)\right\}\cdot\delta\left(t - \frac{m}{f_{\mathrm{rev}}}\right)$$

n : integer tune

c : fractional part of tune

f_{rev}: revolution frequency

f_{side}: sideband frequency

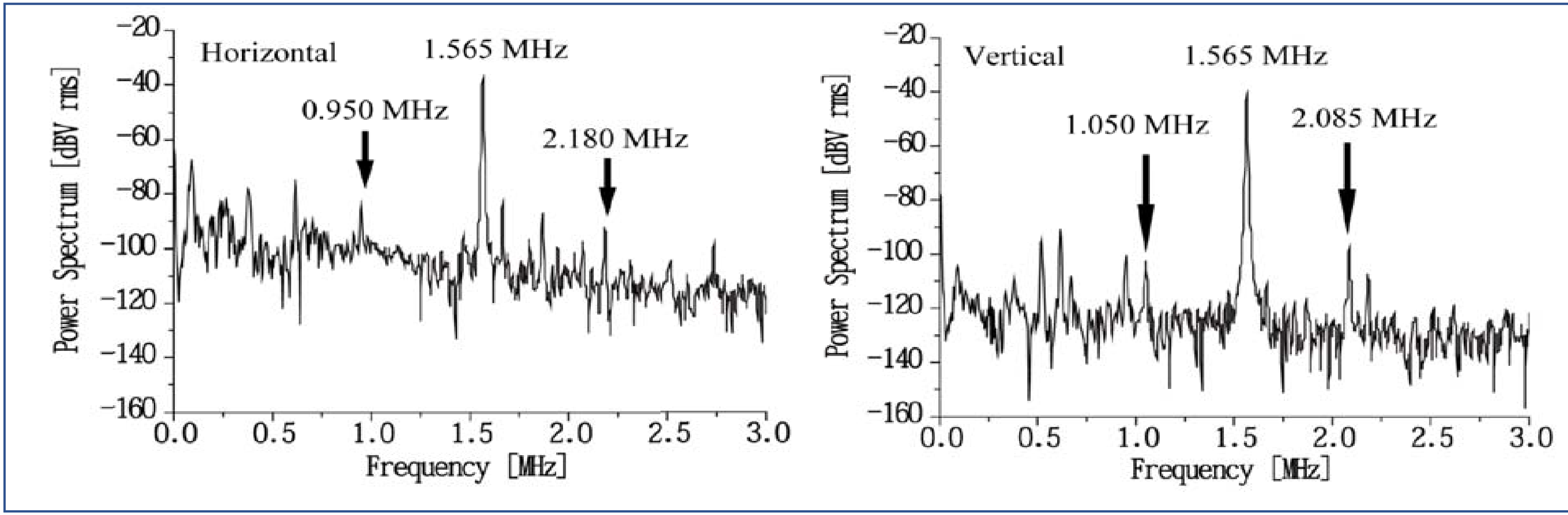
m : order of harmonic

$$V_{\mathrm{moni}} = \sum_m A f_{\mathrm{rev}}\left[\cos(2\pi m f_{\mathrm{rev}}t) + \frac{A_b}{2}\cos\left\{2\pi(m+c)f_{\mathrm{rev}}t + \theta\right\}\right.$$
$$\left. + \frac{A_b}{2}\cos\left\{2\pi(m-c)f_{\mathrm{rev}}t + \theta\right\}\right]$$

$$c = \frac{|f_{side} - m f_{rev}|}{m f_{rev}}$$

Tune measurement by FFT analysis (example)

example: Kyushu FFAG, 10MeV proton beam



$$\nu = \frac{f_b}{f_{rev}} = n + c$$

$$c = \frac{|f_{side} - m f_{rev}|}{m f_{rev}}$$

n : integer tune

c : fractional part of tune

f_{rev}: revolution frequency

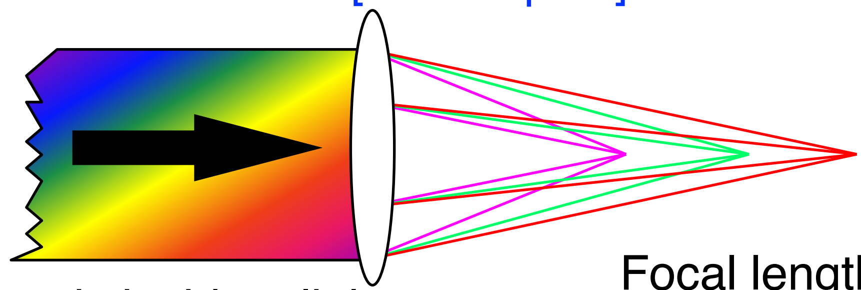
f_{side}: sideband frequency

m : order of harmonic

ν in holiz. & vert. --> “tune diagram”

Chromaticity

Optics Analogy:



Spread in the Machine Tune due to Particle Energy Spread

(Relative increase in tune for an off-momentum particle)

Chromaticity ξ $\quad Q' = \xi Q$

tune change $\Delta Q = Q' \frac{\Delta p}{p}$ $\qquad \xi = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta p}{p}}$ <-- momentum change

- **Measure tune for slightly different beam energies (by varying RF frequency and keeping magnetic field constant and calculate the gradient.**
- Correct with sextupole magnets.
- Chromaticity can be tracked continuously by combining RF modulation with PLL tune measurement.

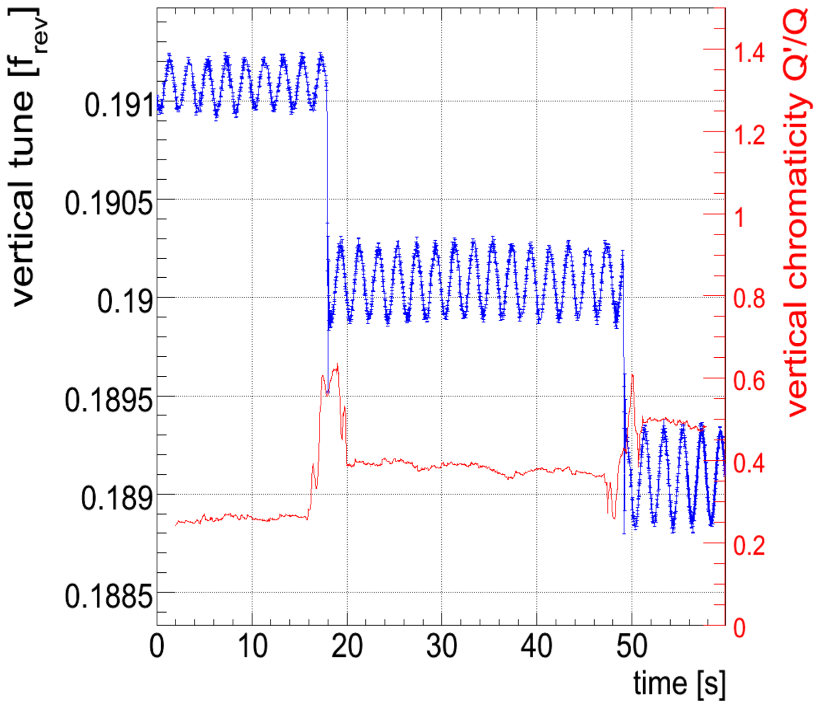
Chromaticity Measurement

Many techniques available to measure chromaticity

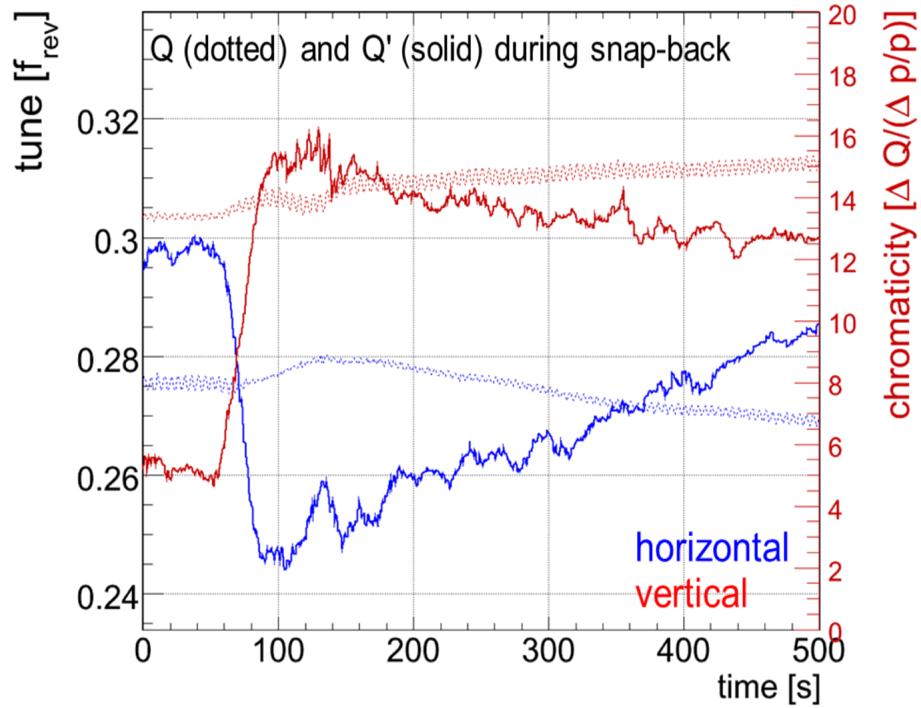
Tune change for different beam momenta	Standard method used on all machines. Can be combined with PLL tune tracking to give on-line measurement
Width of tune peak or damping time	Model dependent, non-linear effects, not compatible with active transverse damping
Amplitude ratio of synchrotron sidebands	Difficult to exploit in hadron machines with low synchrotron tune, Influence of collective effects
Width ratio of Schottky sidebands	Used on many machines & ideally suited to unbunched or ion beams. Measurement is typically very slow
Bunch spectrum variations during betatron oscillations	Difficult to disentangle effects from all other sources – e.g. bunch filling patterns, pick-up & electronics response
Head-tail phase advance	Good results on several machines but requires kick stimulus $\Rightarrow$ emittance growth!

Chromaticity measurement in the LHC (Q' tracker)

Modulates the RF frequency to give Δp/p of 10^{-4} @ 2Hz
Measures the effect on the tune & demodulates the sinusoidal variation
Resolution of 1-2 units achieved with results fed-forward for next ramp



Test showing effect of RF modulation on tune in presence of chromaticity



Real-time tune & chromaticity measurement in the LHC during start of acceleration

$$Q' = \frac{\Delta Q}{\Delta p/p}$$

ΔQ ← measured tune change

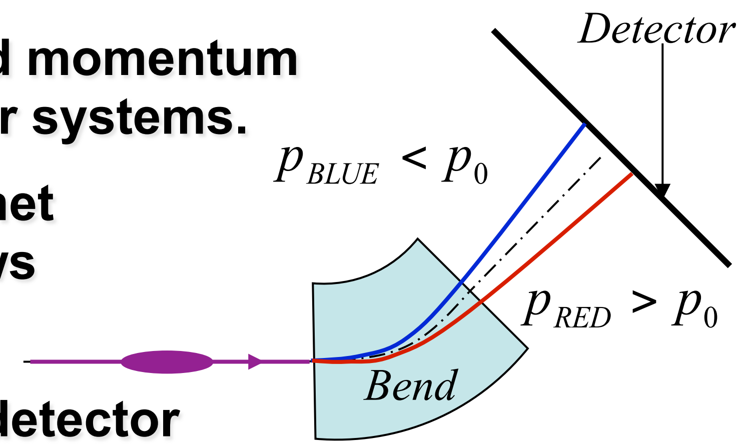
Δp/p ← RF induced momentum change

$$\xi = \frac{Q'}{Q}$$

R. Jones, CAS2014

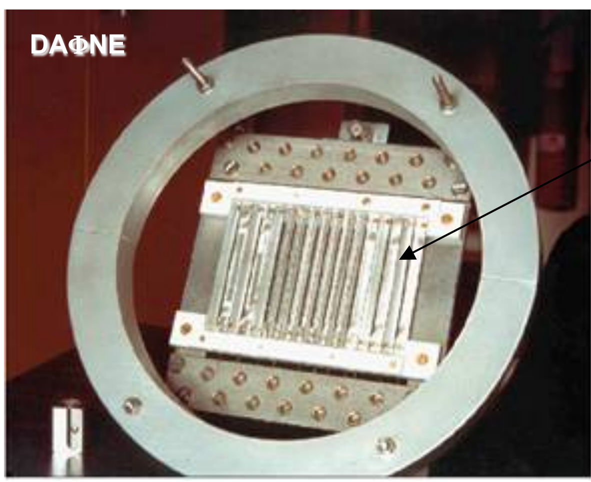
Momentum measurement

- In linacs and transferlines the momentum and momentum spread are mainly measured by spectrometer systems.



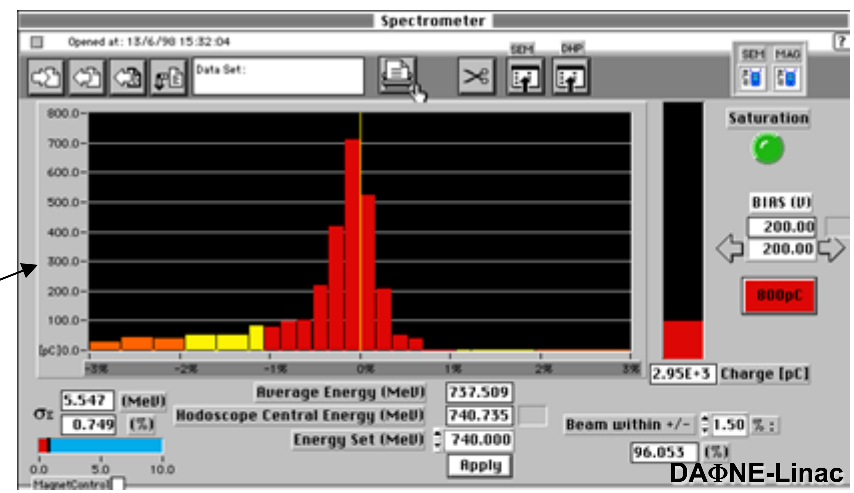
- The beam enters in the field of a dipole magnet where particles with different momenta follows different trajectories.

- The particle position is then measured on a detector downstream the magnet.



Secondary emission hodoscope

Spectrometer control window

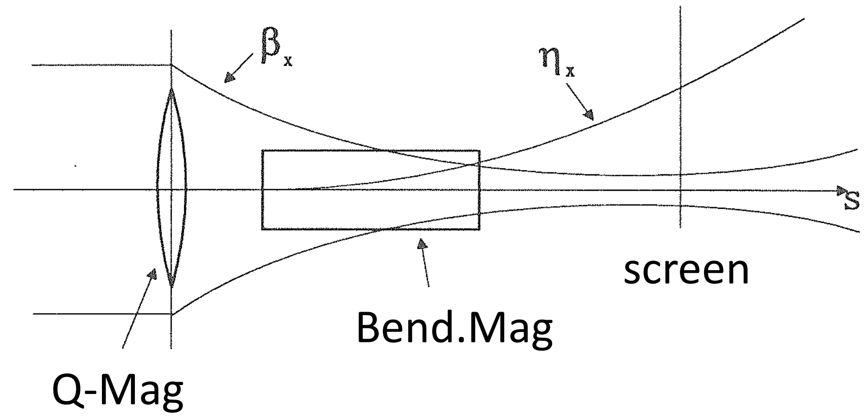


- The spectrometer resolution is limited by the intrinsic beam size at the detector plane and by field non-linearities.

Momentum measurement

<u>Beam Size</u>

$$\sigma_x = \sqrt{\beta_x \varepsilon_x + \left(\eta_x \frac{\sigma_p}{p}\right)^2}$$



β_x is minimized before passing though bending magnet using Q-magnet.
Beam size is measured at point where β_x is minimum.

$$\beta_x \varepsilon_x \ll (\eta_x \sigma_p / p)^2$$

$$\sigma_x \simeq \eta_x \boxed{\frac{\sigma_p}{p}}$$

beam size (σ_x)

dispersion (η_x)

Overview of typical beam parameters and diagnostic instruments

Beam quantity		LINAC, transfer line	Synchrotron
current I	*general* *special*	transformer (dc, pulsed) Faraday cup particle detector (Scint. IC, SEM)	transformer (dc) normalized pick-up signal
position $\overline{x}$	*general* *special*	pick-up using profile measurement	pick-up cavity excitation (e^-)
profile x_{width}	*general* *special*	SEM-grid, wire scanner viewing screen, OTR-screen grid with ampl. (MWPC)	residual gas monitor synch. radiation (e^-) wire scanner
trans. emittance ϵ_{trans}	*general* *special*	slit grid quadrupole scan pepper-pot	residual gas monitor wire scanner transverse Schottky pick-up wire scanner
momentum p and $\Delta p/p$	*general* *special*	pick-up (TOF) magn. spectrometer	pick-up Schottky noise pick-up
bunch width $\Delta\varphi$	*general* *special*	pick-up particle detector secondary electrons	pick-up wall current monitor streak camera (e^-)
long. emittance ϵ_{long}	*general* *special*	magn. spectrometer buncher scan TOF application	 pick-up + tomography
tune, chromaticity Q, ξ	*general* *special*	— —	exciter + pick-up (BTF) transverse Schottky pick-up
beam loss r_{loss}	*general*	particle detector	
polarization P	*general* *special*	particle detector Compton scattering with laser	
luminosity $\mathcal{L}$	*general*	particle detector	

P. Forck 2011