Beam Instrumentation – Part I

Ralph J. Steinhagen, CERN

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

Science: High-Energy-Physics
Understand the World in its most fundamental form ...

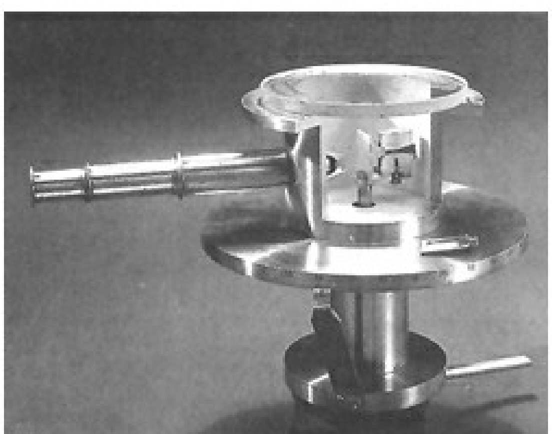
Refined Periodic Table of Elements – 2500 years later

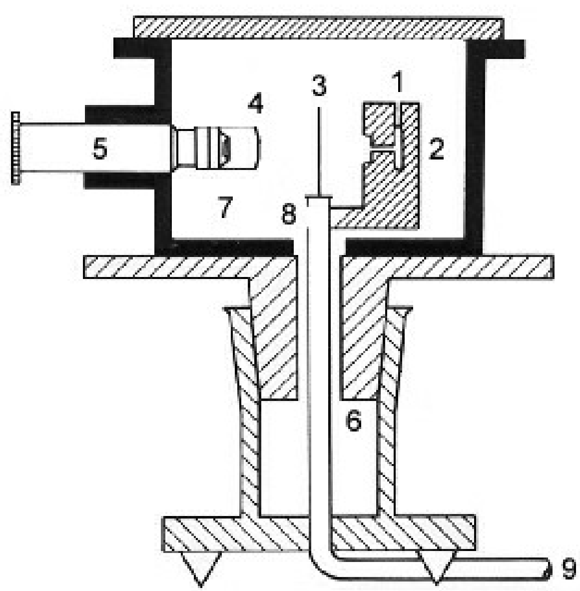
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 –71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 –103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

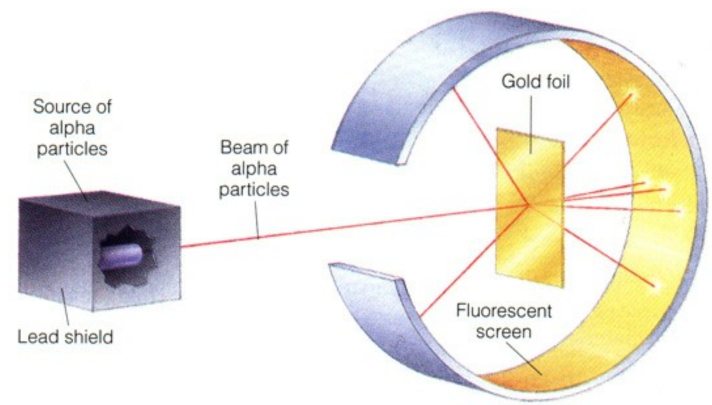
- Known in antiquity
- also known when (akw) Lavoisier published his list of elements (1789)
- akw Mendeleev published his periodic table (1869)
- akw Deming published his periodic table (1923)
- akw Seaborg published his periodic table (1945)
- also known (ak) up to 2000
- ak to 2012

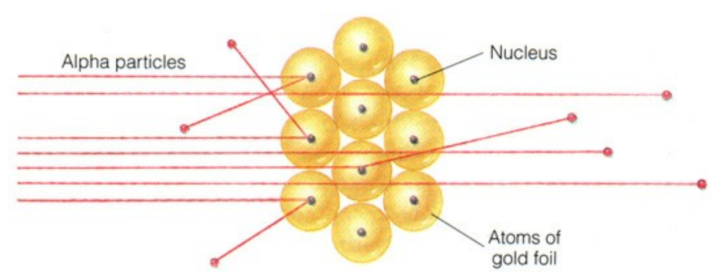
First Particle Physics Experiment: 'Atoms' are not fundamental Particles

1911
Rutherford-Geiger–Marsden experiment: found nuclei in the atom by firing alpha particles at gold foil and observing that most pass and few bounce back

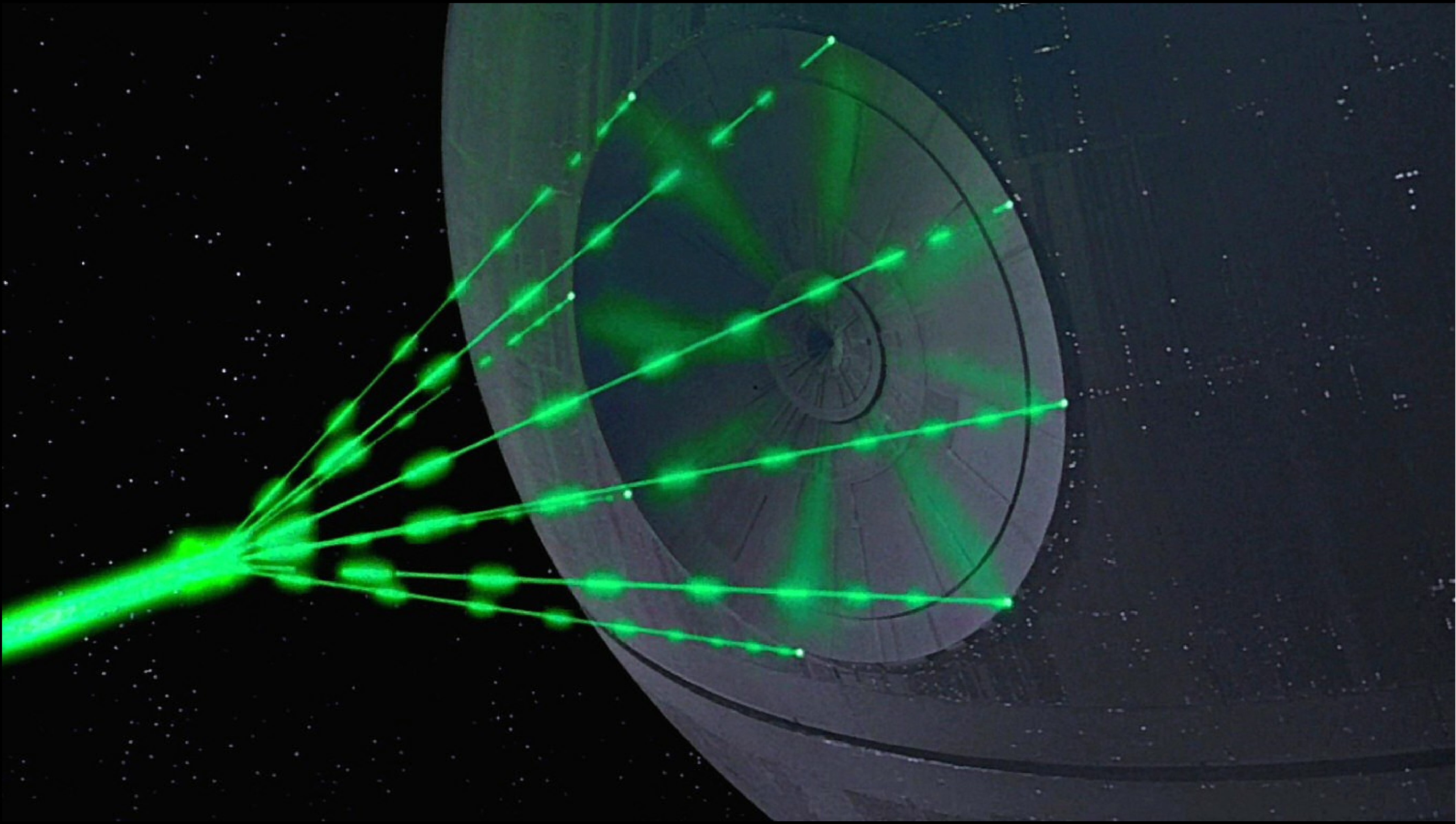






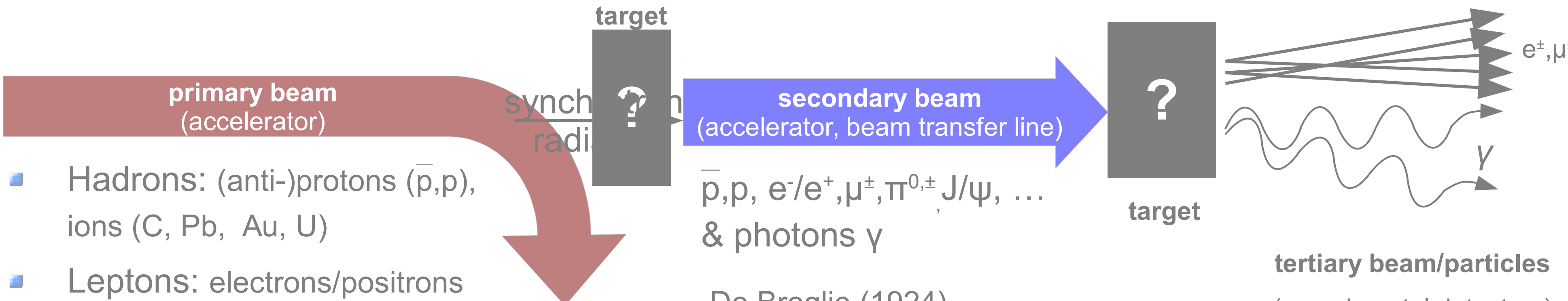


What are Particle Beams?



What is a Particle Beam?

- Wikipedia: "… is a stream of charged or neutral particles in many cases moving at near the speed of light"
- Three different beam categories:



- Hadrons: (anti-)protons ($\bar{p}$,p), ions (C, Pb, Au, U)
- Leptons: electrons/positrons e^-/e^+, muons $\mu^\pm$ (R&D)

$\bar{p}$,p, e^-/e^+,$\mu^\pm$,$\pi^{0,\pm}$, J/ψ, … & photons γ

tertiary beam/particles
(experimental detectors)

- final state: γ,$e^\pm$,$\mu^\pm$,p/$\bar{p}$ (ie. what can be directly detected)

→ high particle intensities, finite transverse and longitudinal beam structure

De Broglie (1924)

$$\lambda = \frac{h}{p}$$

h: Planck's constant
p: momentum of particle
→ accelerators
λ: equivalent wavelength

Input: Intensity, Energy, Momentum, beam parameter → **Physics under study** → Out: Intensity, Energy, Momentum (ie. scattering angle)

Overview

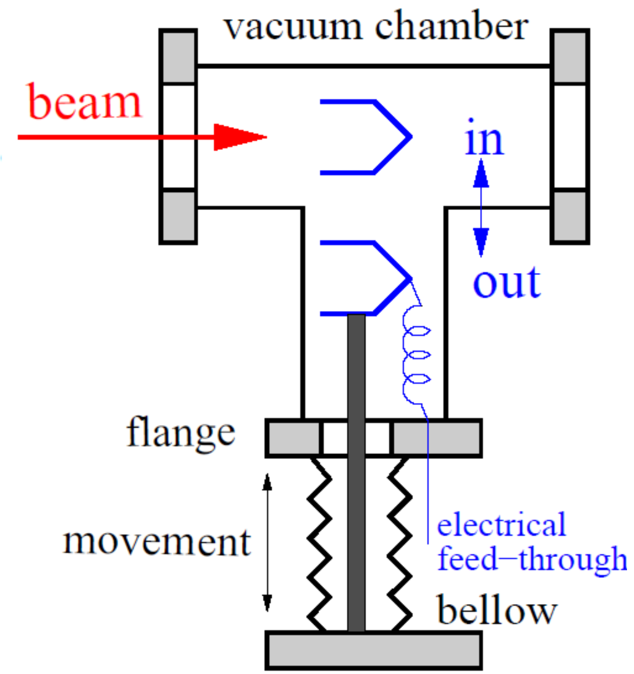
- Beam instrumentation are the 'eyes and ears' of accelerators.
- Part I: electro-magnetic pick-ups
  - Beam intensities: Faraday-Cup, Fast-BCT, DC-BCT, WCM
  - Beam position: position and long. profile: Button-, Strip-line-, and Cavities
- Part II: beam loss and transverse beam profile → tomorrow
  - 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.

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
  - ionisation chambers or pin diodes
- Machine Tune, Chromaticity and Luminosity $\rightarrow$ diagnostics tutorial

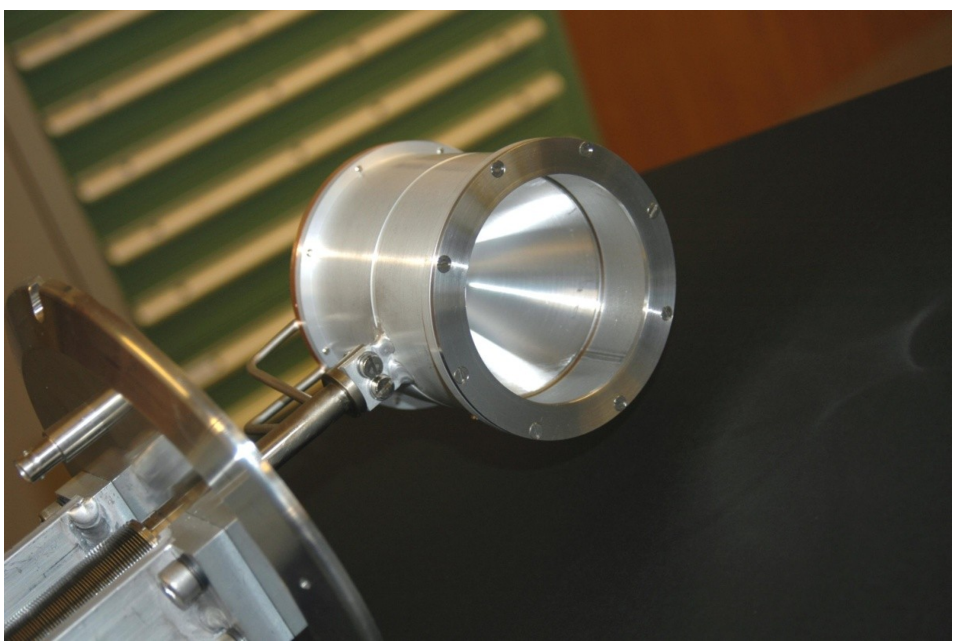
Intensity Measurement – Faraday Cup I/II

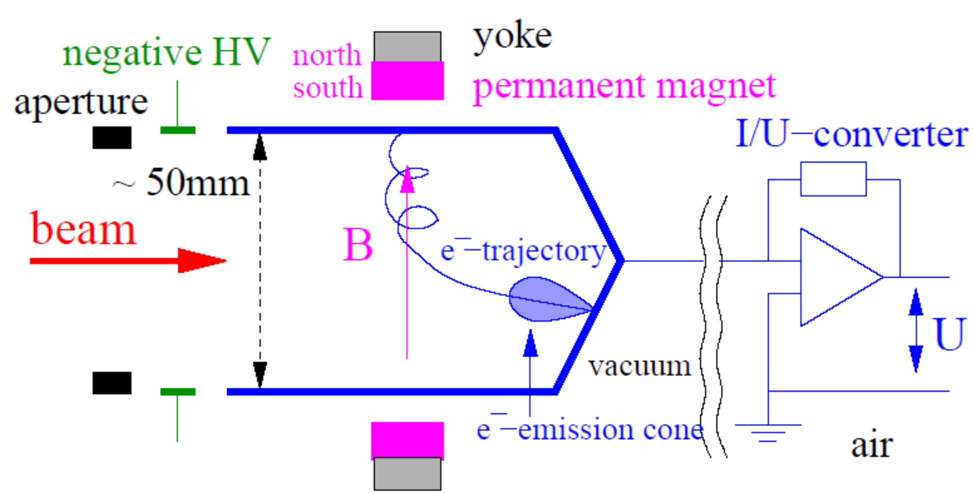
- Intercepts the full beam and measures it's charge
  → acceptable in linacs and at the source
- Can measure very low intensities (≈1 pA)
- Independent on transverse or longitudinal beam structure
- Only for low energy particles



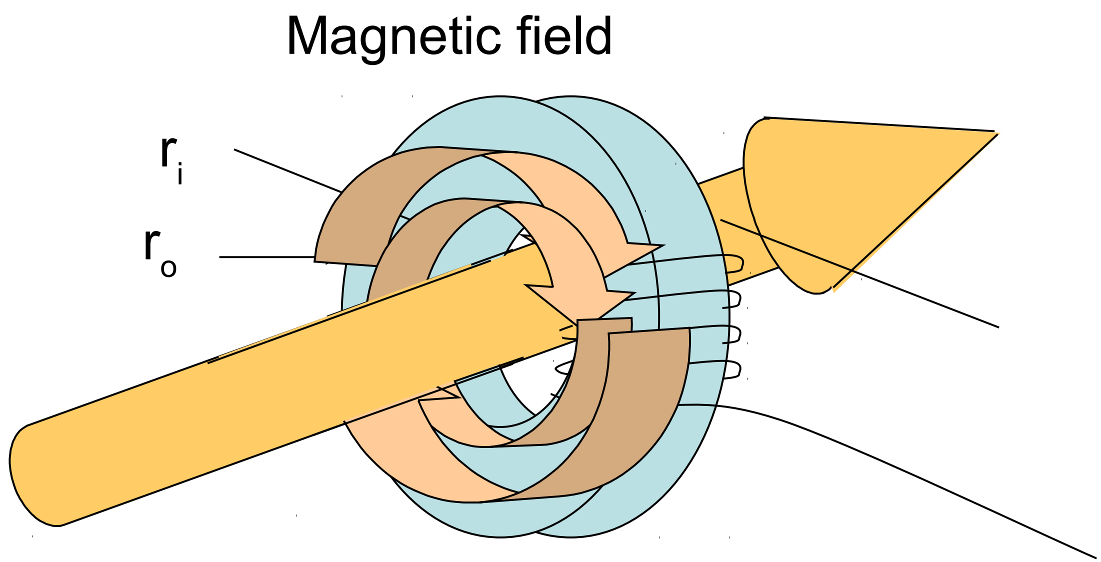
Intensity Measurement – Faraday Cup II/II

- Creation of secondary electrons of low energy (below 20 eV) → repelling electrode (≈100 V)
- Water cooling needed for higher beam Intensities





Intensity Measurement – Current Transformers



Fields are very low

Capture magnetic field lines with cores of high relative permeability

(CoFe based amorphous alloy Vitrvac: μ_r= 105)

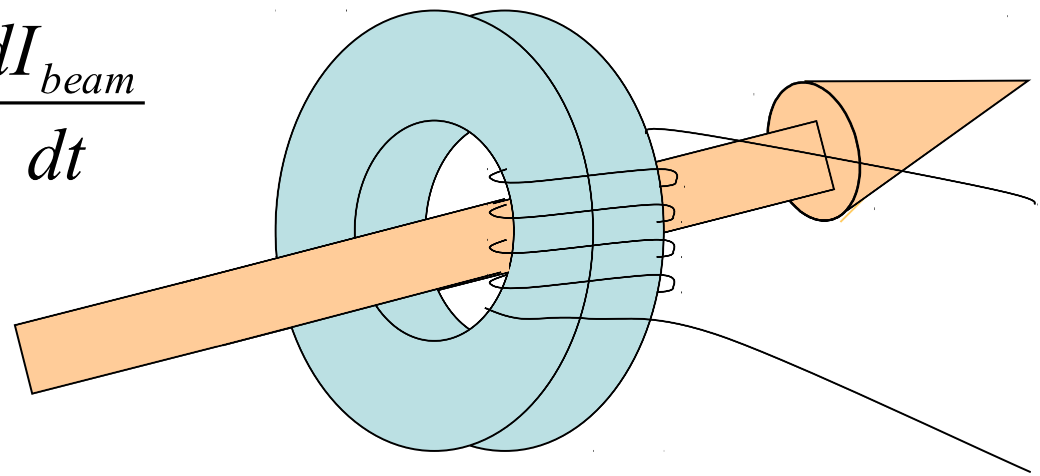
Beam current

$$I_{beam} = \frac{qeN}{t} = \frac{qeN\beta c}{l}$$

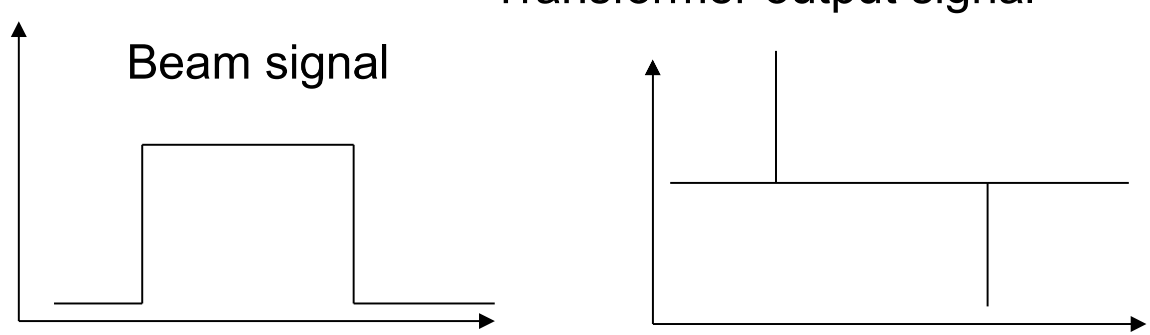
$$L = \frac{\mu_0 \mu_r}{2\pi} l N^2 \ln \frac{r_0}{r_i}$$

The ideal transformer

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

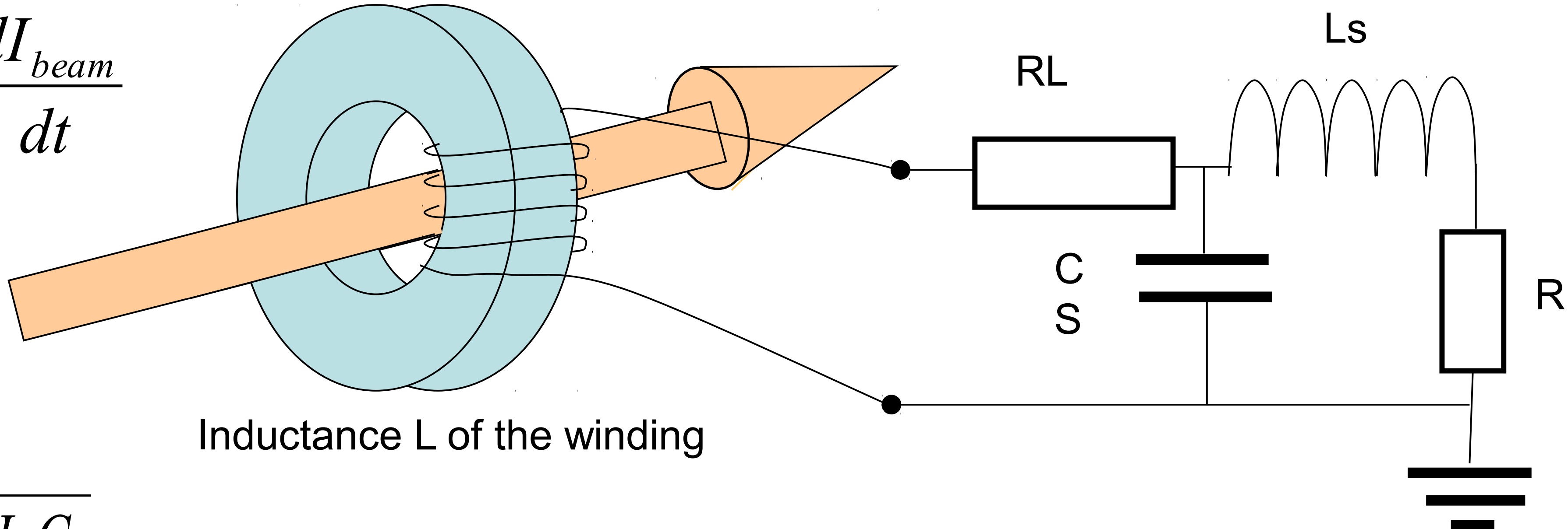


Inductance L of the winding



The AC Transformer

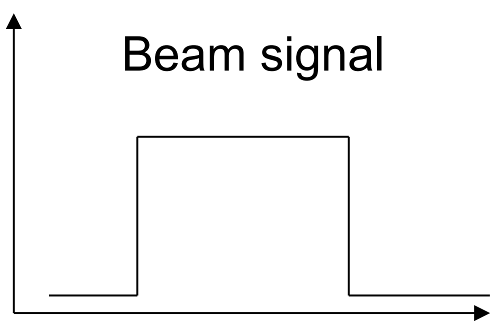
$$U = L\frac{dI_{beam}}{dt}$$



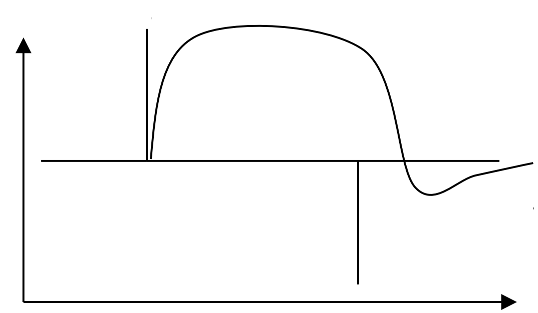
Inductance L of the winding

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

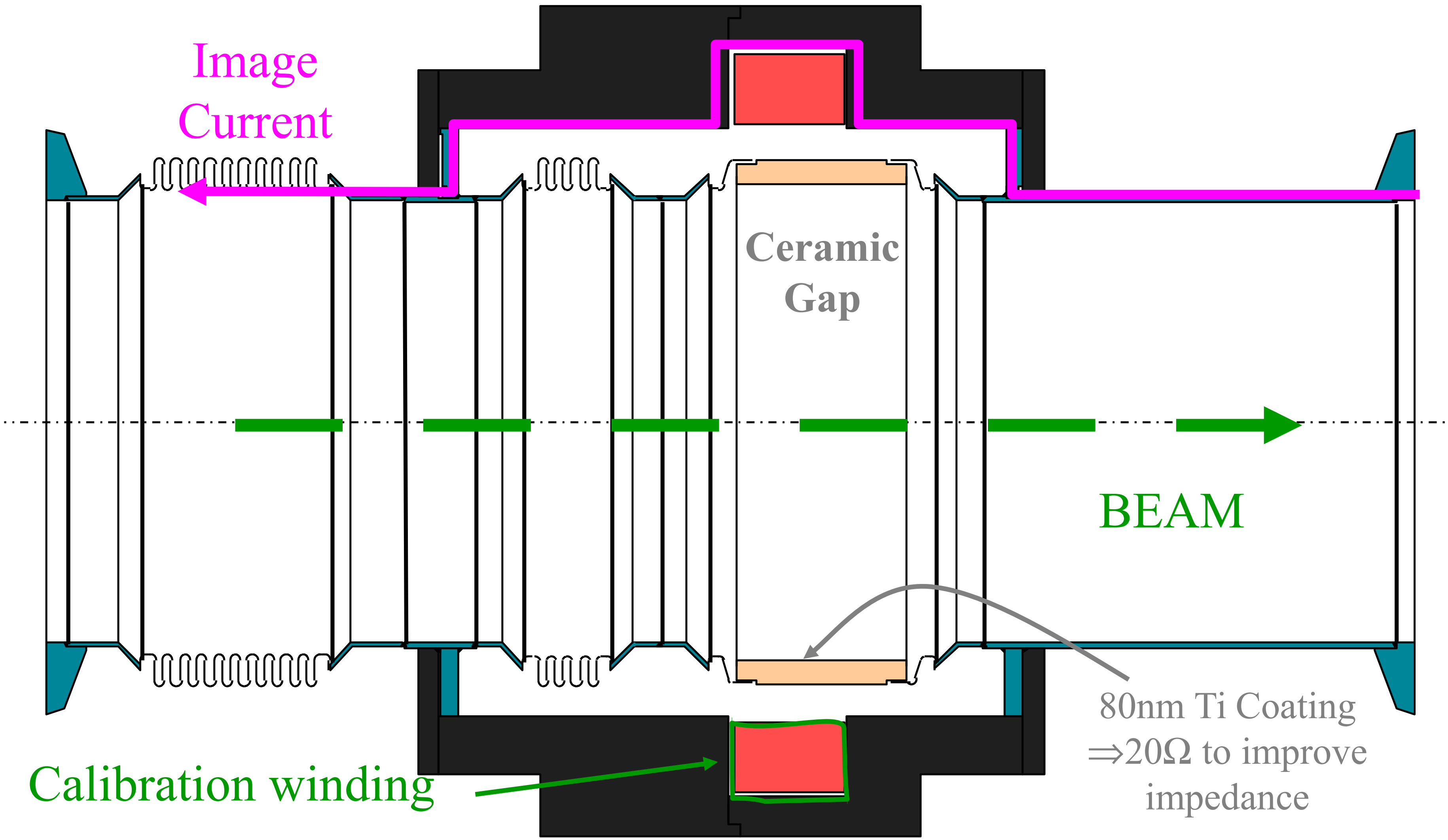
Beam signal



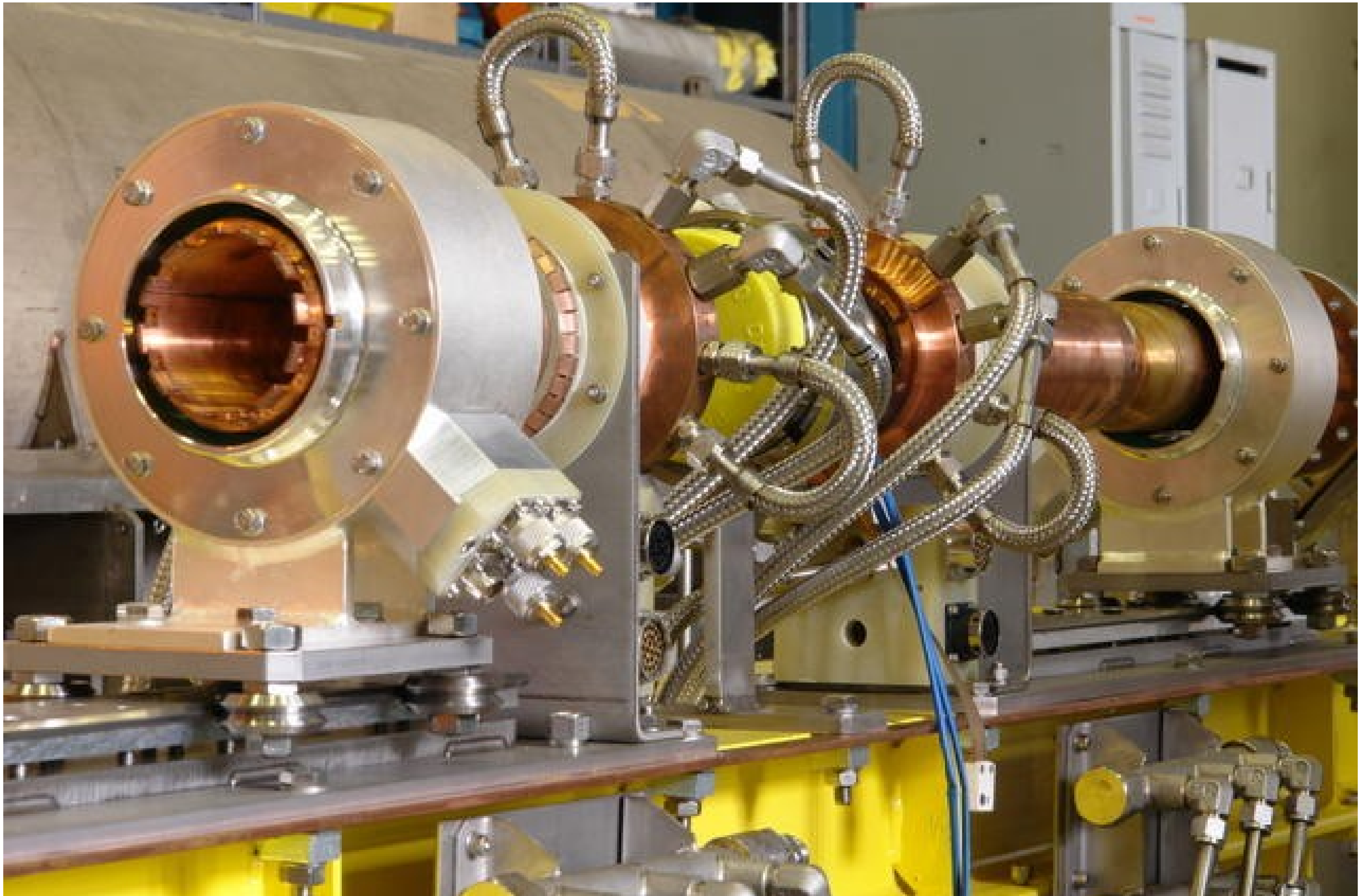
Transformer output signal



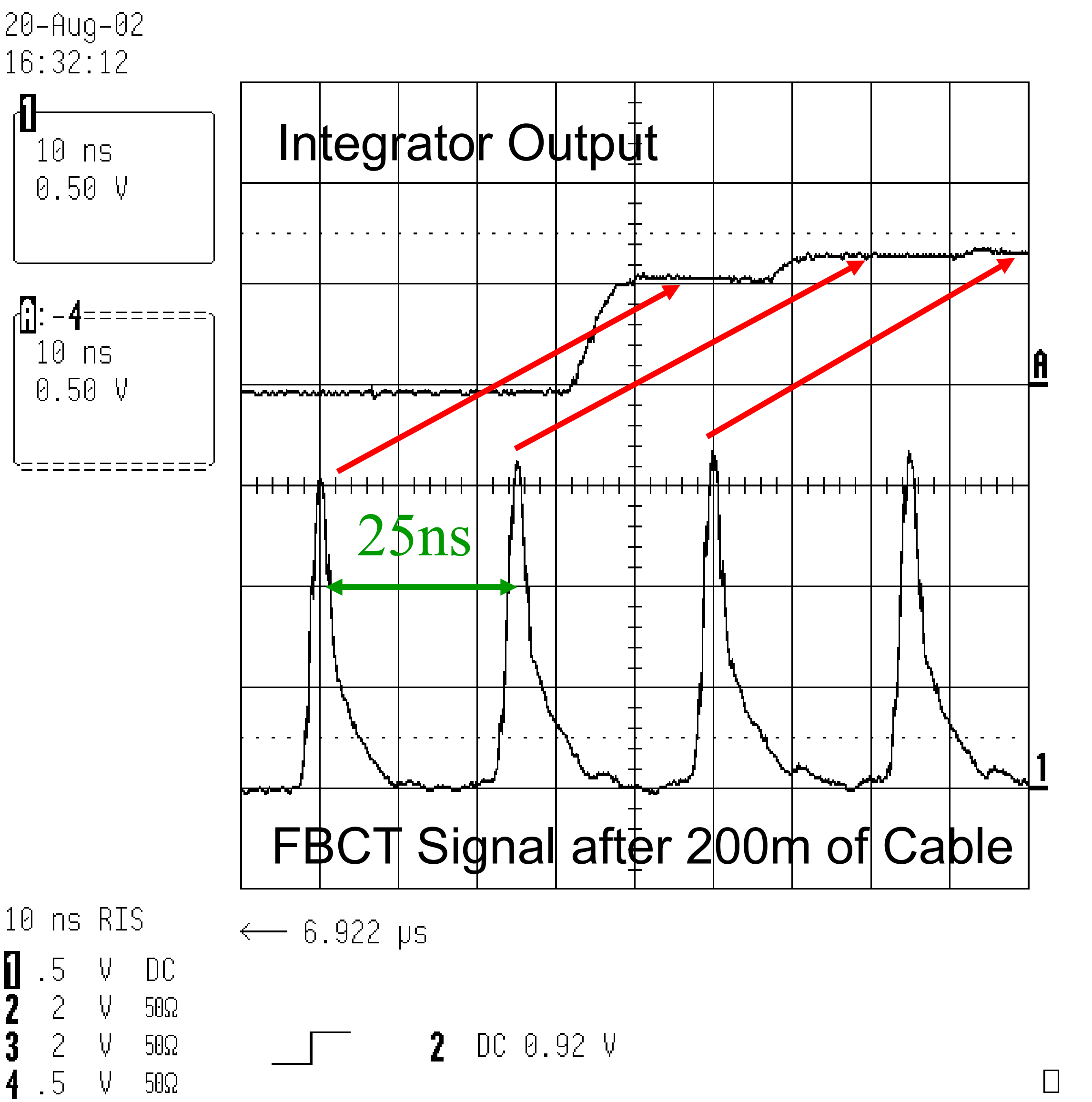
Fast Current Transformer Principle



LHC Fast Current Transformers

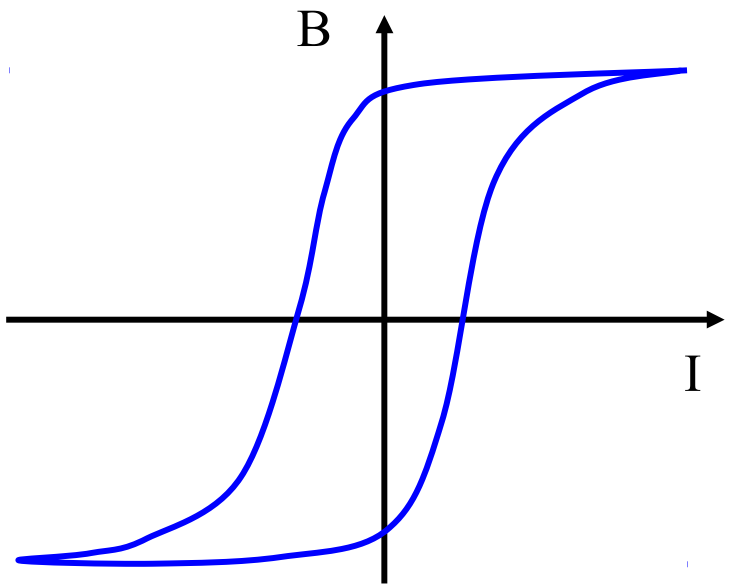


Acquisition Electronics



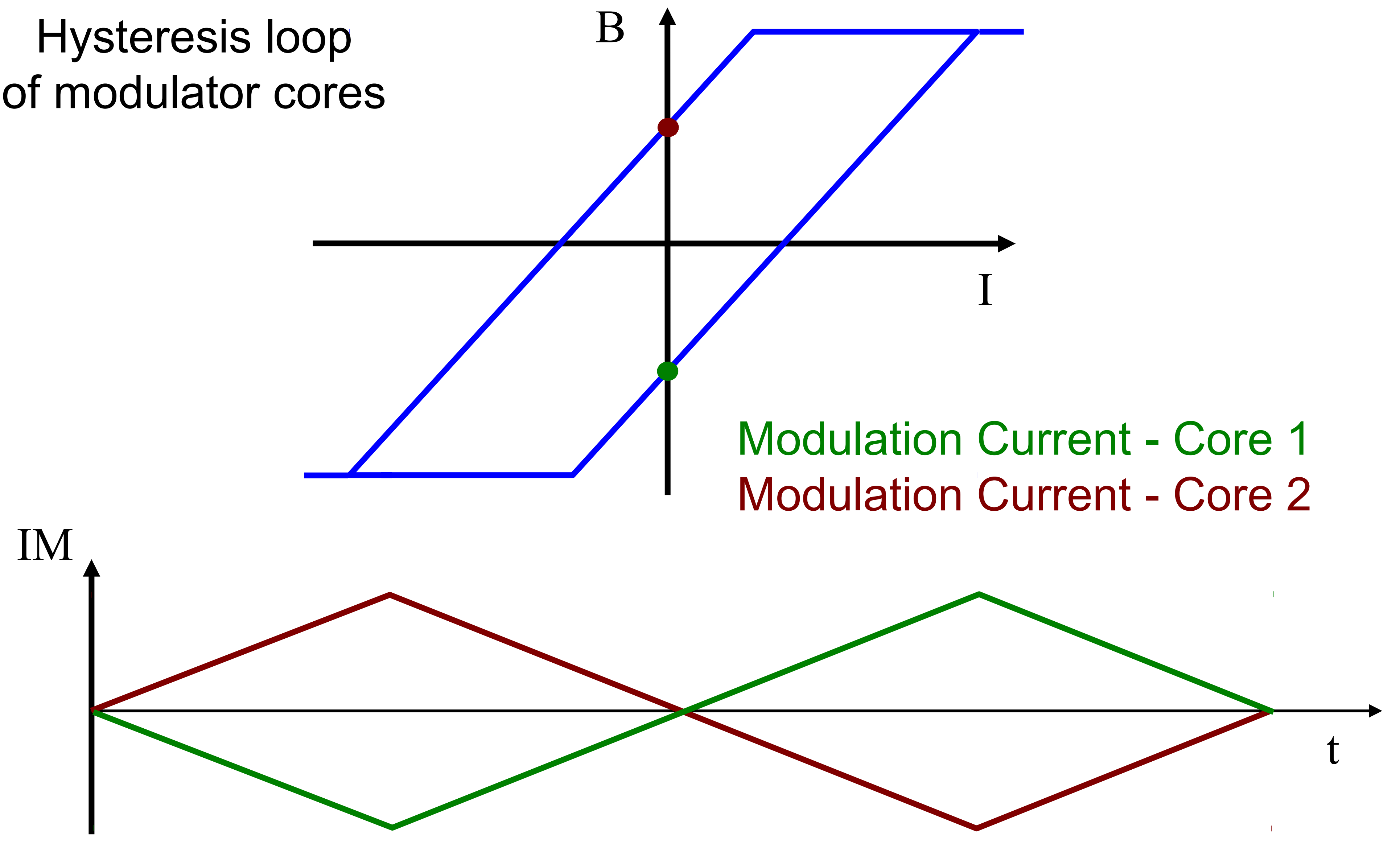
The DC transformer

- AC transformers can be extended to very low frequency but not to DC (no dI/dt!)
  - DC measurement is required in storage rings to assess un-captured beam intensities (mostly hadrons) and bunches in non-nominal buckets (all)
- DC operation principle:
  - take advantage of non-linear magnetisation curve
  - use two identical cores modulated with opposite polarities



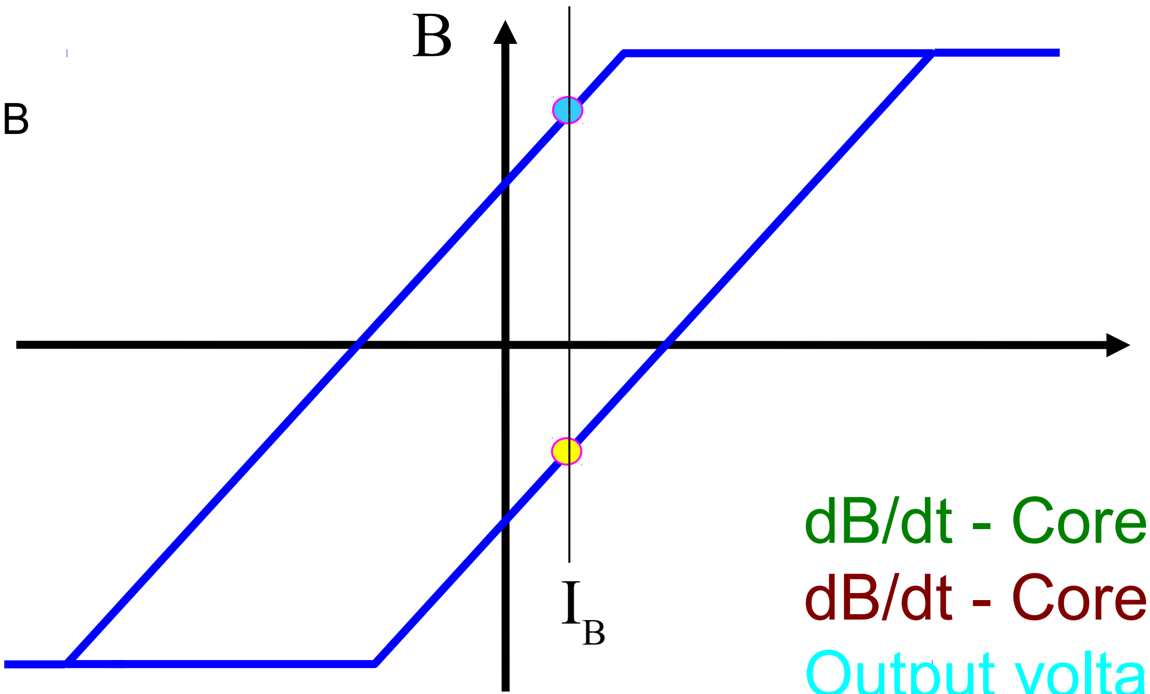
DCCT Principle – Case 1: no beam

Hysteresis loop
of modulator cores



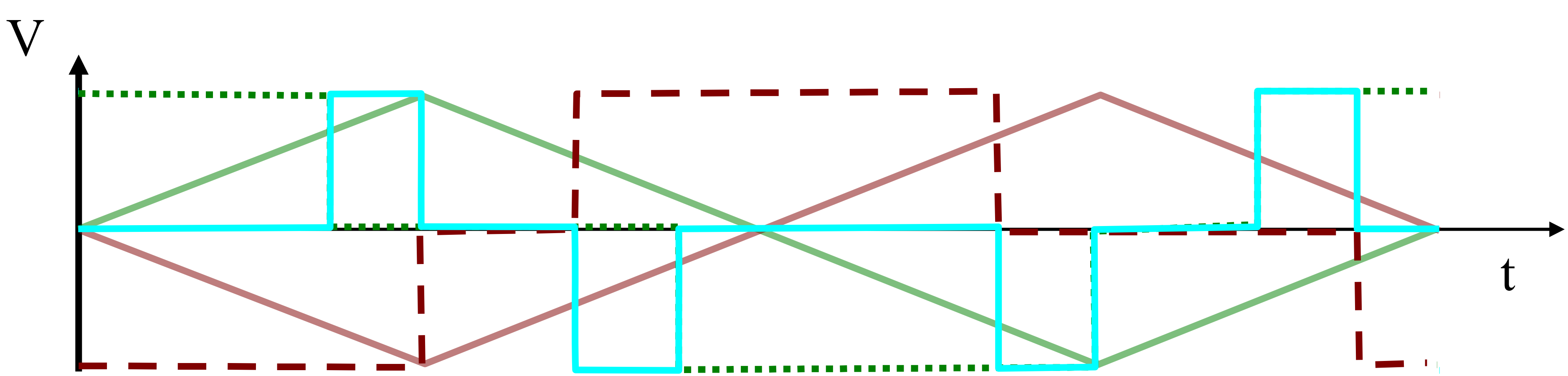
DCCT Principle – Case 2: with beam

Beam Current I_B

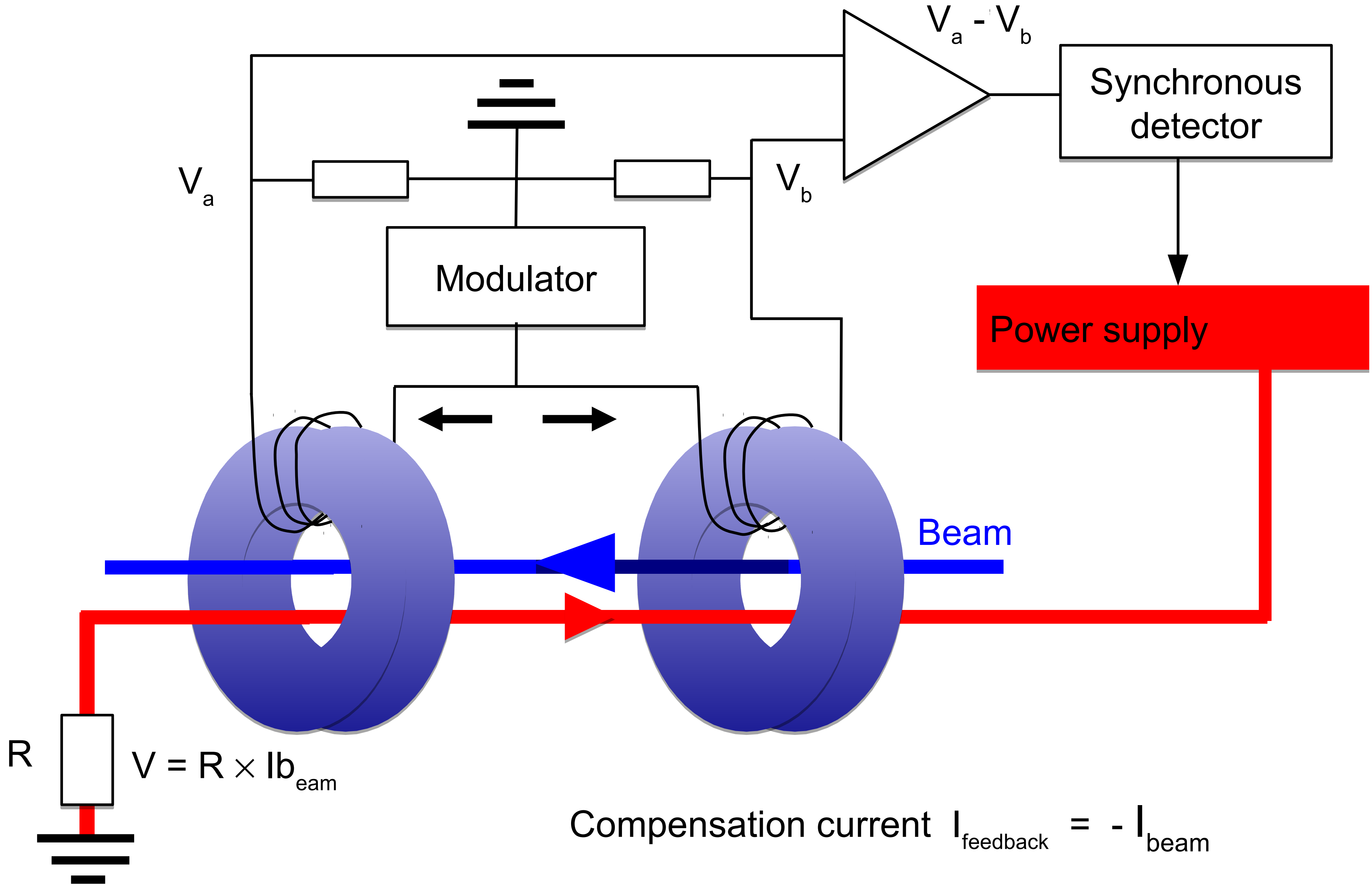


Output signal is at TWICE the modulation frequency

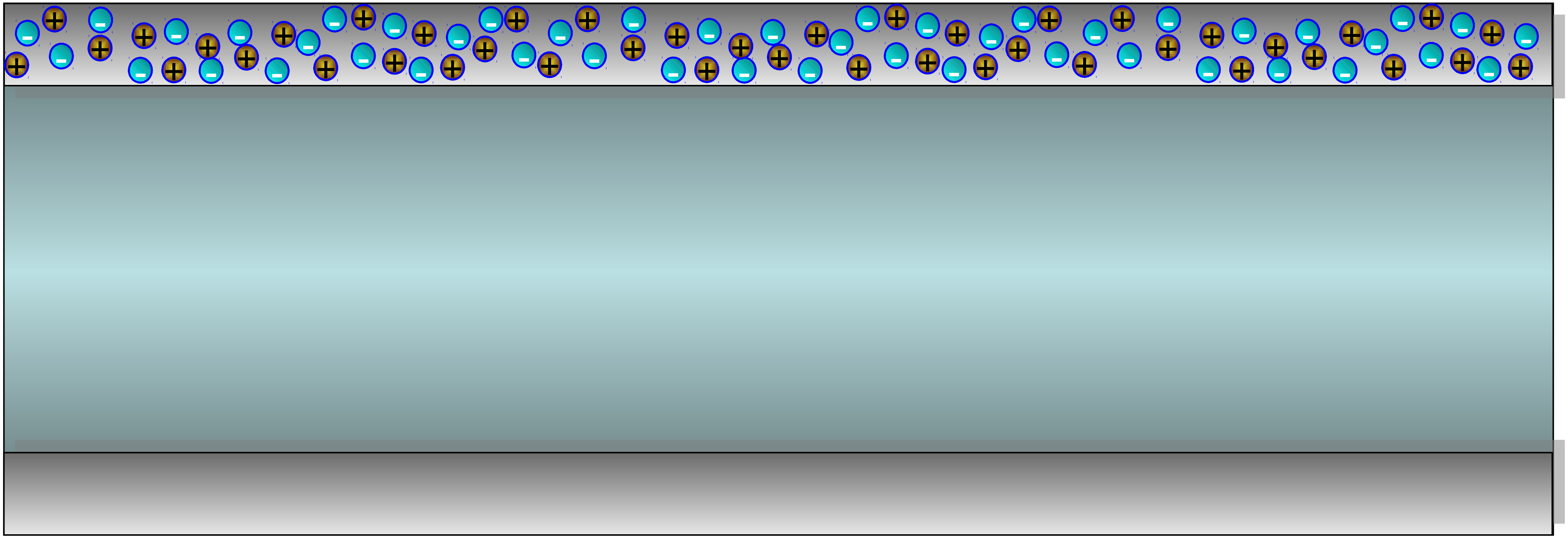
dB/dt - Core 1 (V1)
dB/dt - Core 2 (V2)
Output voltage = V1 – V2



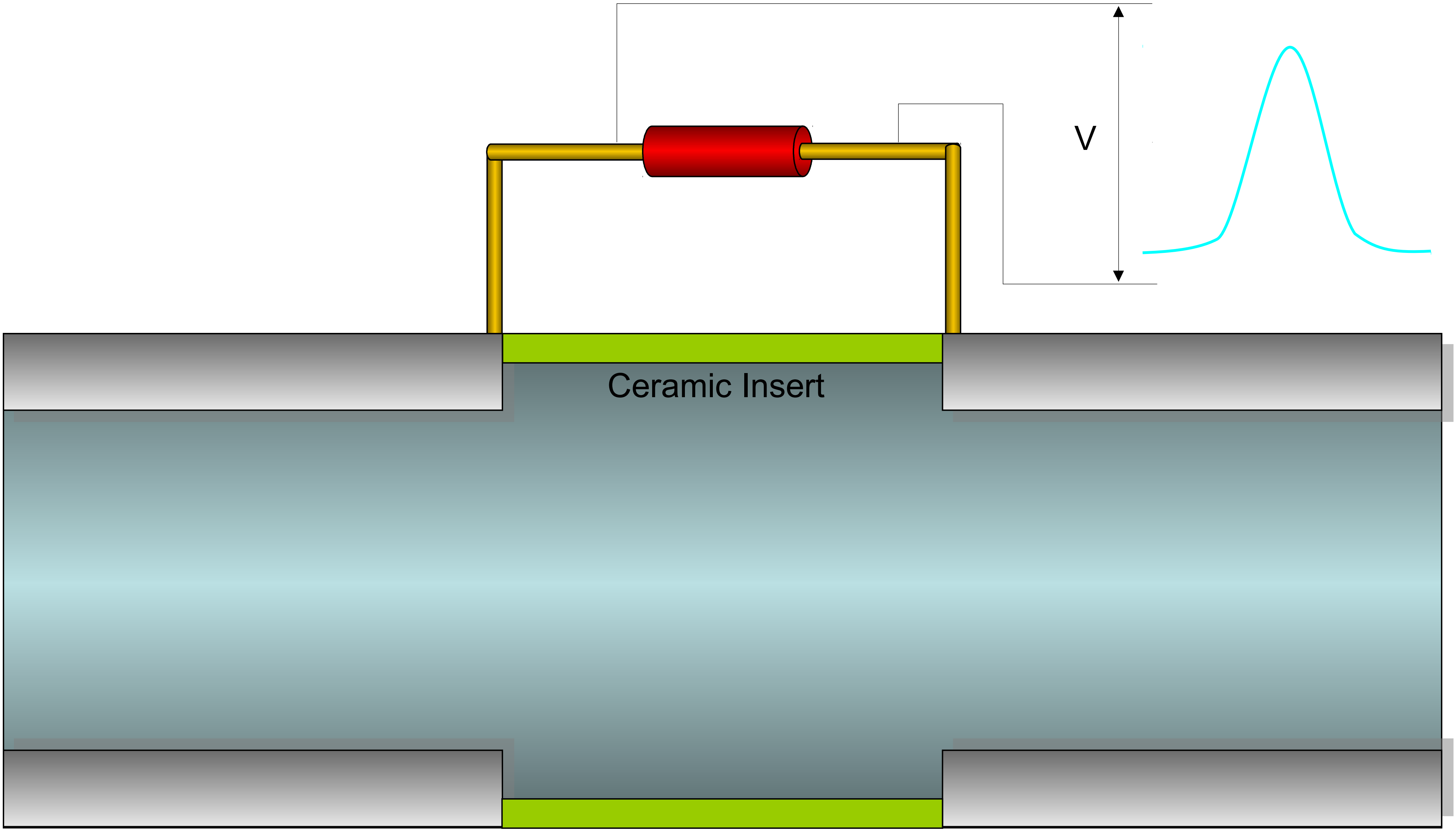
Zero Flux DCCT Schematic



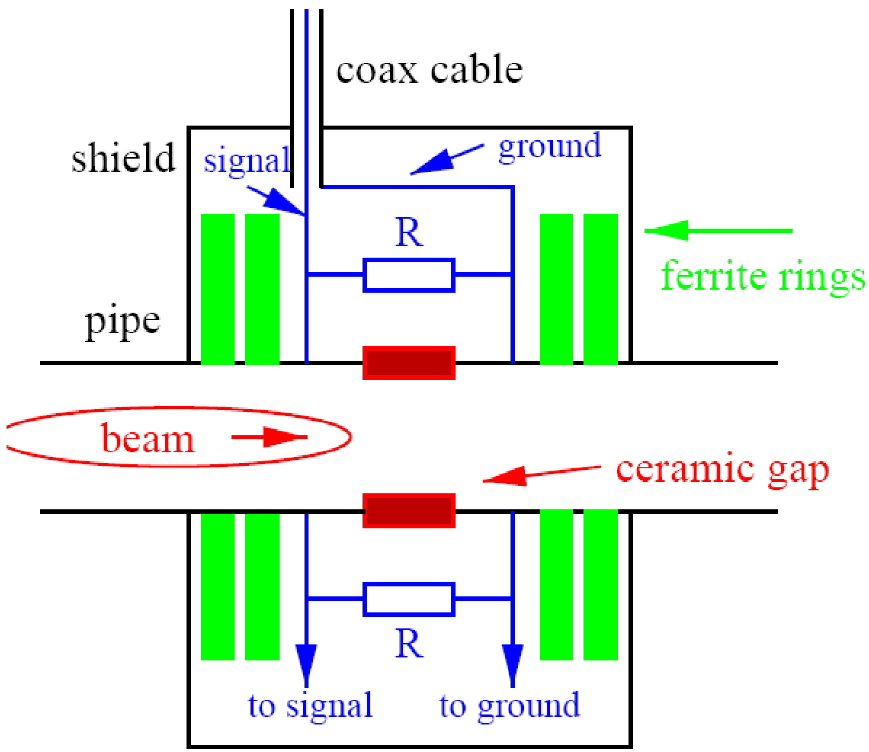
Measuring Beam Position – The Principle

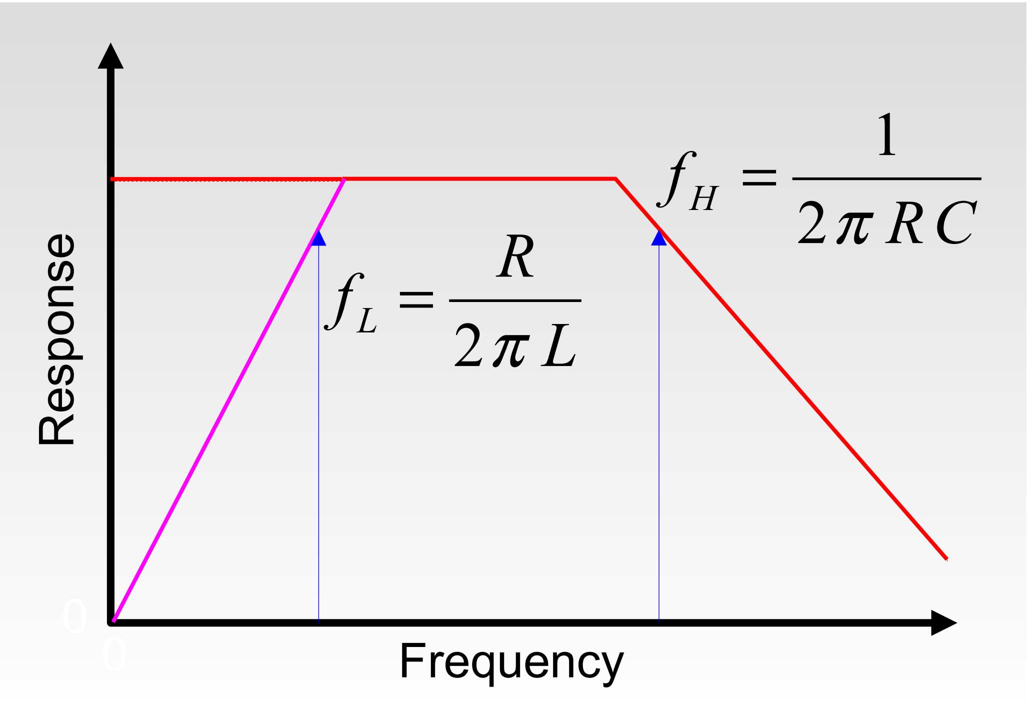


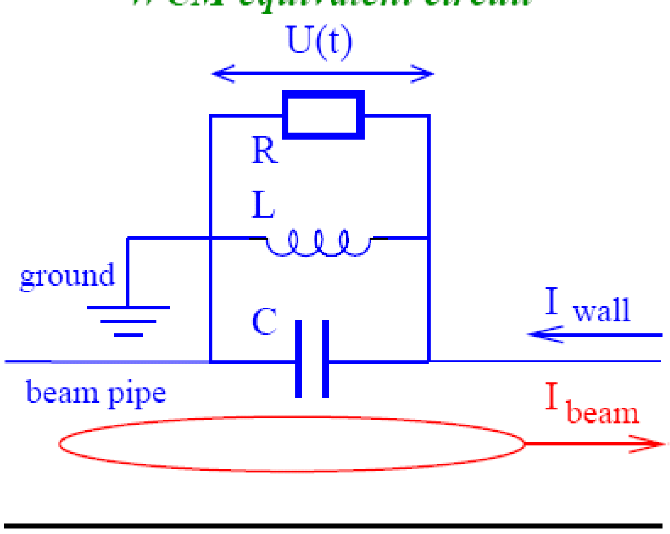
Wall Current Monitor – The Principle



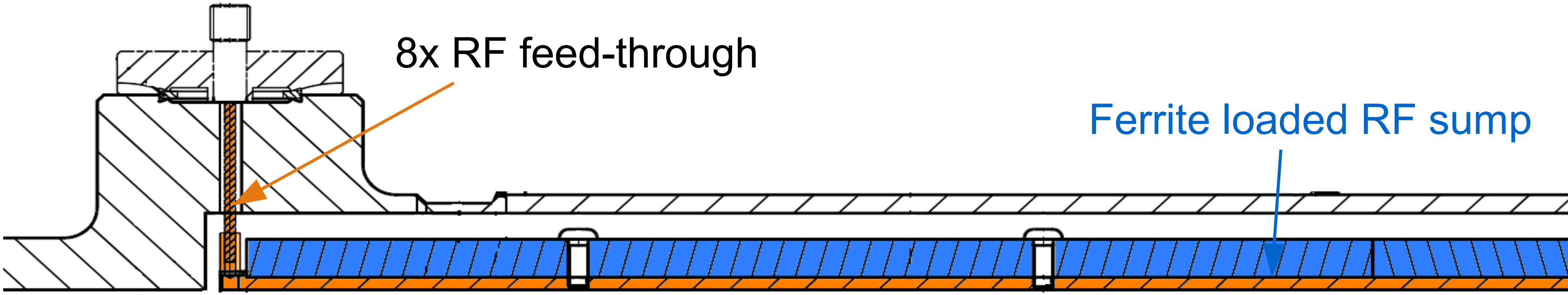
Wall Current Monitor – Beam Response

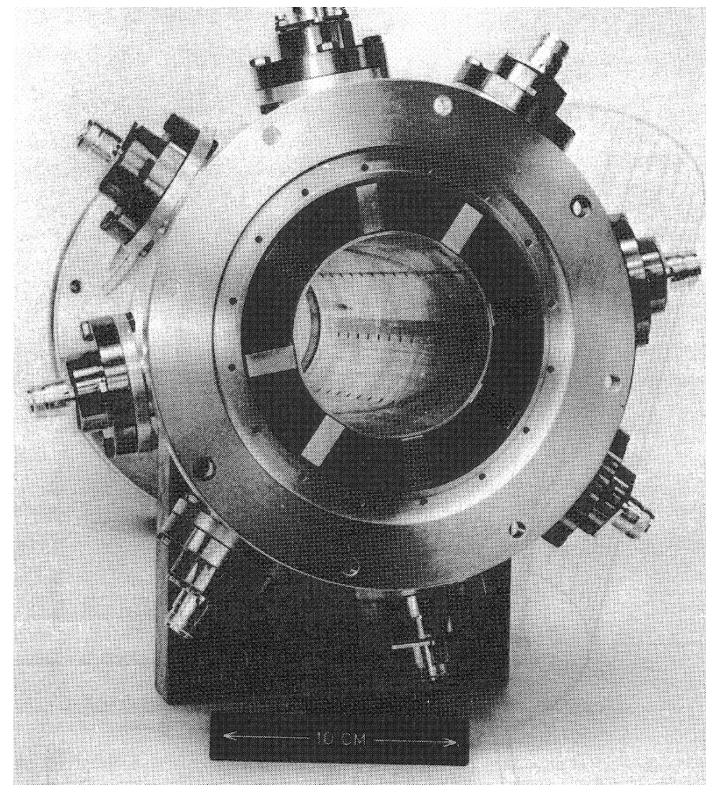






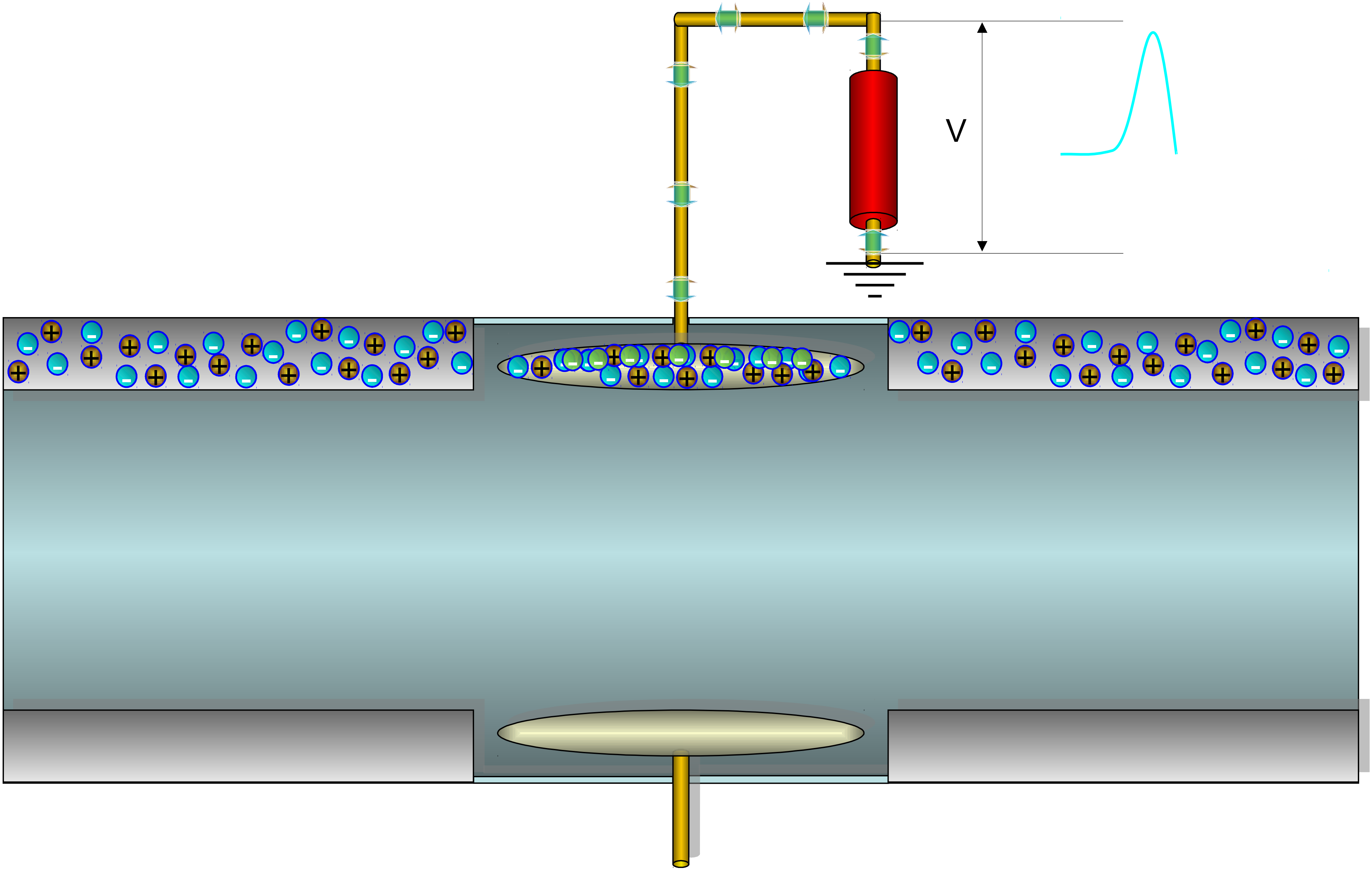
SPS/LHC Wall Current Monitor





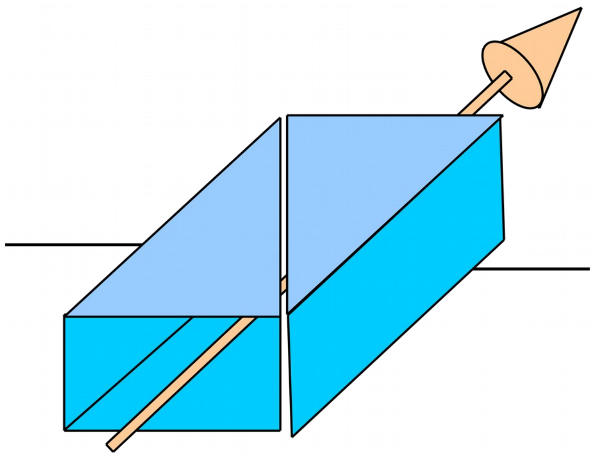
[1]T. Linnecar, “The high frequency longitudinal and transverse pick-ups used in the SPS”, CERN-SPS/ARF/78-17, 1978
[2]Th. Bohl, “The APWL Wideband Wall Current Monitor”, CERN-BE-2009-006, 2009
[3]R. Cappi et al., “Single-Shot Longitudinal Shape Measurements [..]”, CERN-PS-87-31-PSR, PAC 1987, 1987

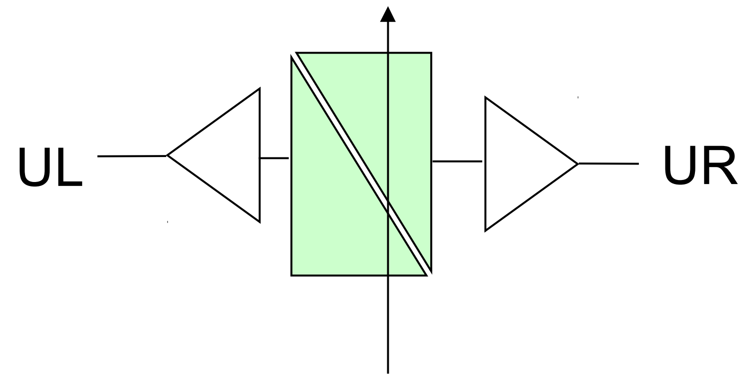
Electrostatic Monitor – The Principle



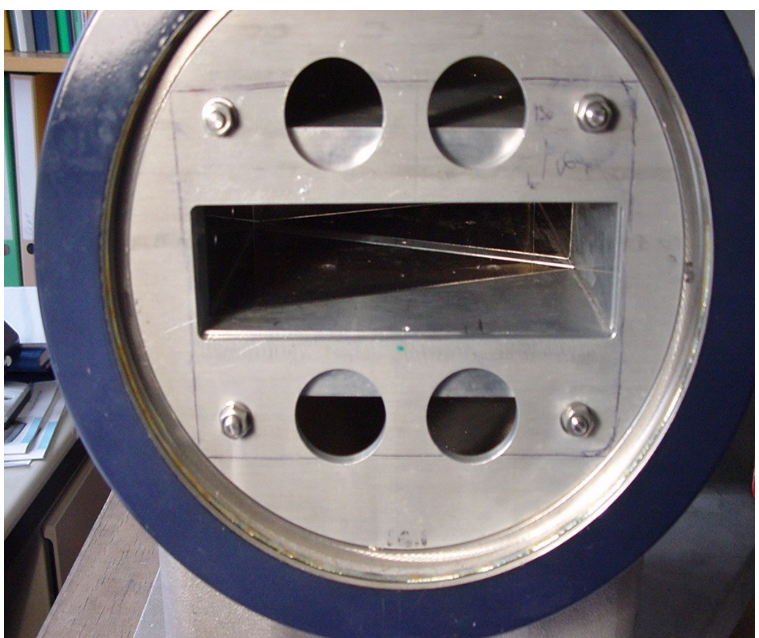
Shoebox Pick-Up I/II

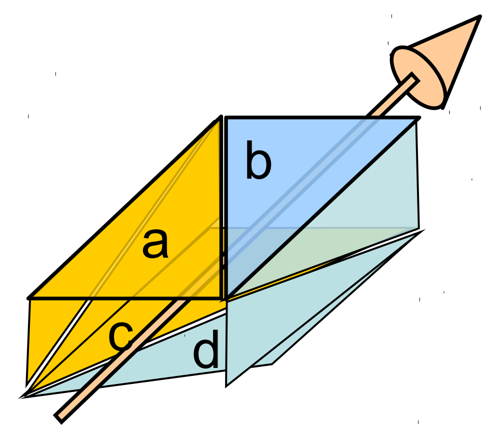
Linear cut through a shoebox





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

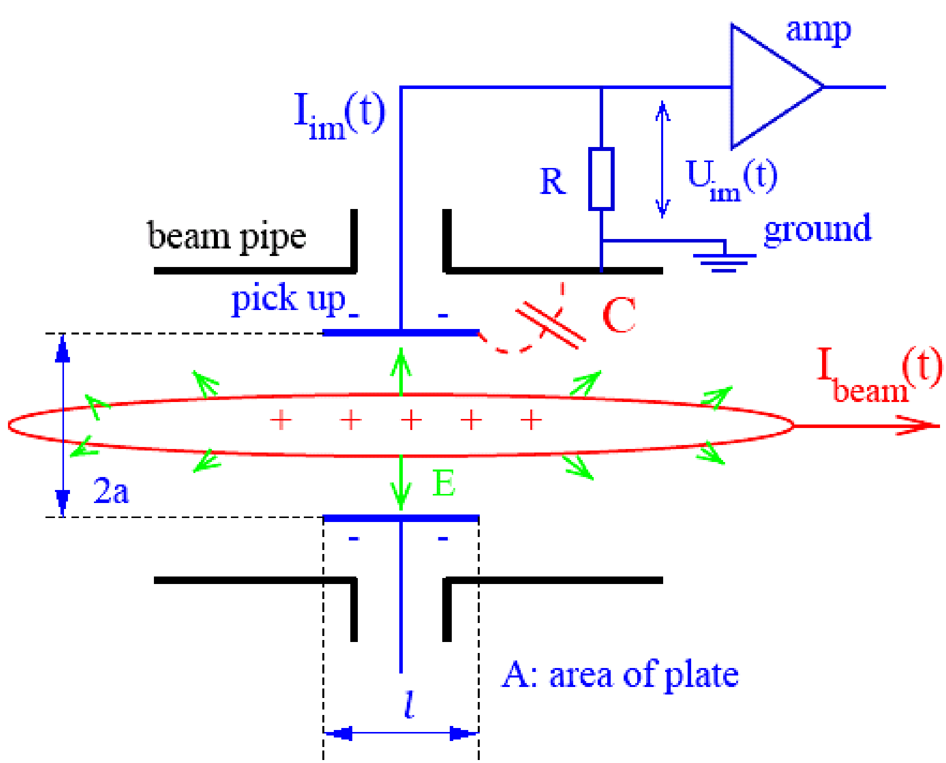


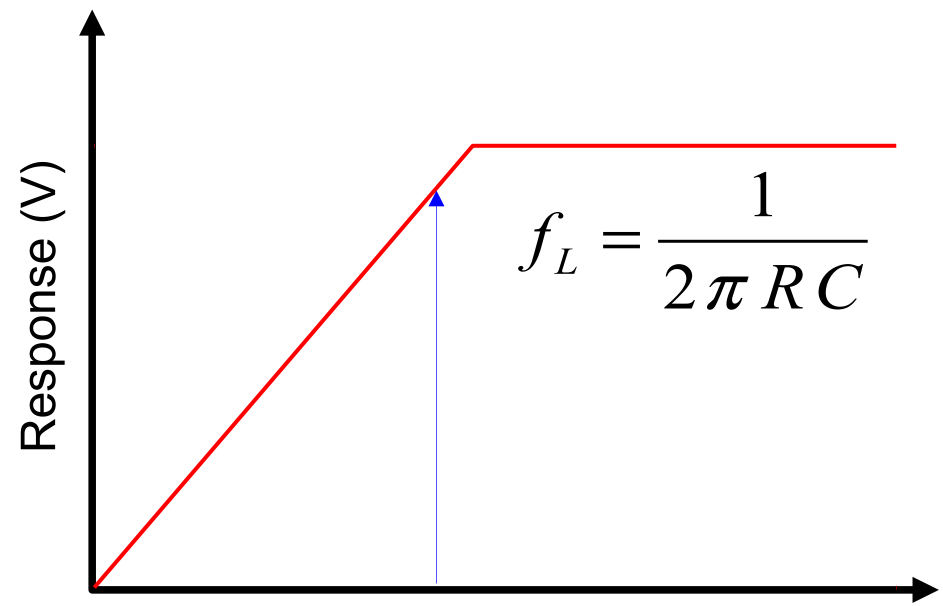


$$X = \frac{(U_a + U_c) - (U_b + U_d)}{\Sigma U}$$

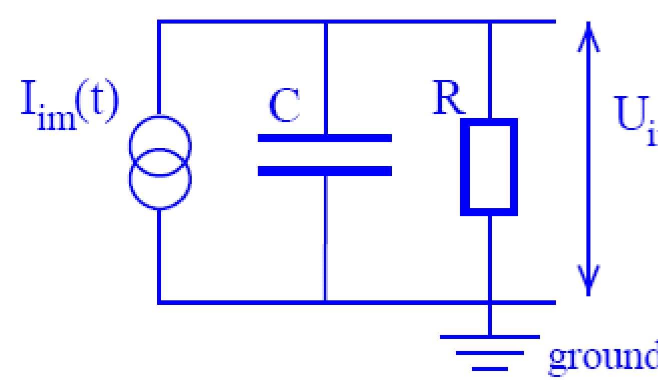
$$Y = \frac{(U_a + U_b) - (U_c + U_d)}{\Sigma U}$$

Electrostatic Beam Monitor – Response



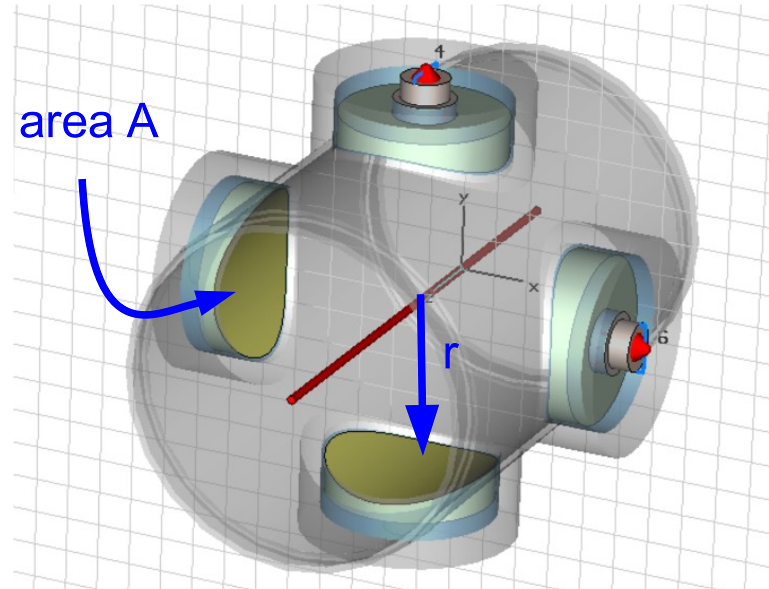


equivalent circuit



Electrostatic Pick-up – Button

- ✓ Low cost ⇒ most popular
- × Non-linear



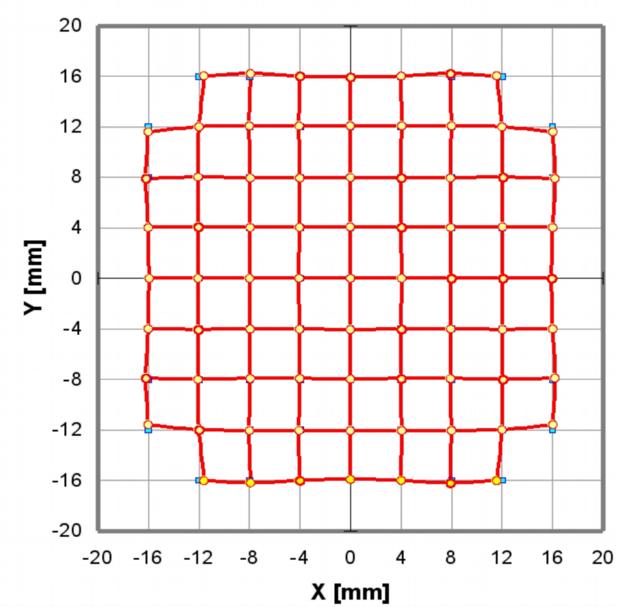
For Button with Capacitance C_e & Characteristic Impedance R_0

Transfer Impedance:

$$Z_{T(f>>f_c)} = \frac{A}{(2\pi r)\times c\times C_e}$$

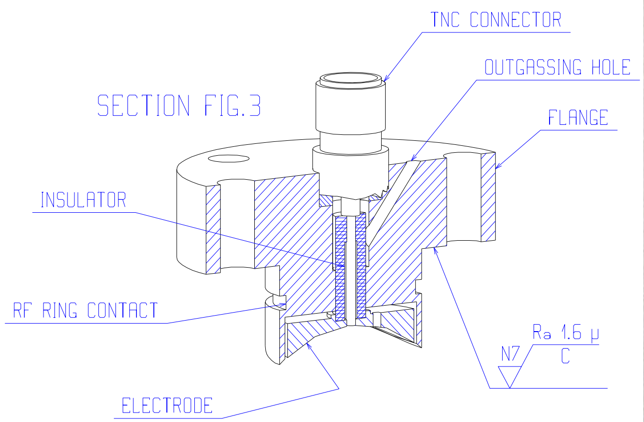
Lower Corner Frequency:

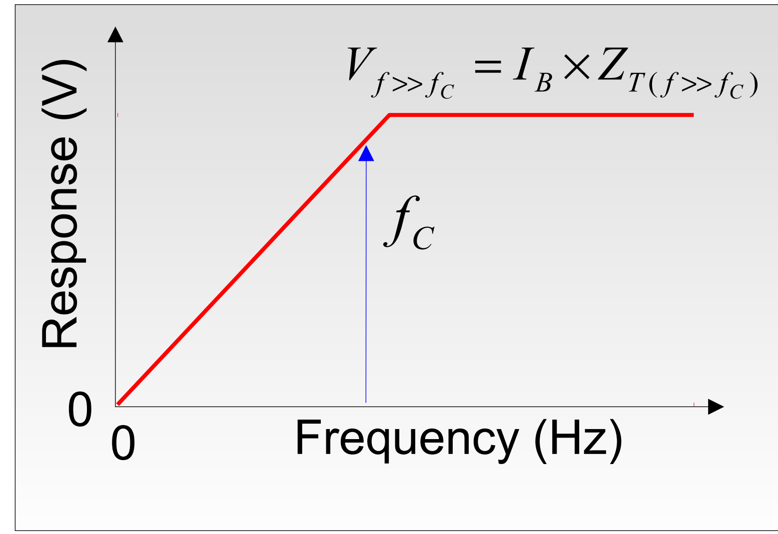
$$f_L = \frac{1}{2\pi R_0 C_e}$$



$$X = 2.30\cdot 10^{-5} X_1^5 + 3.70\cdot 10^{-5} X_1^3 + 1.035 X_1 + 7.53\cdot 10^{-6} X_1^3 Y_1^2 + 1.53\cdot 10^{-5} X_1 Y_1^4$$

Real-World Example: The LHC Button





$$f_L = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 50\Omega \times 8pF} = 400MHz$$

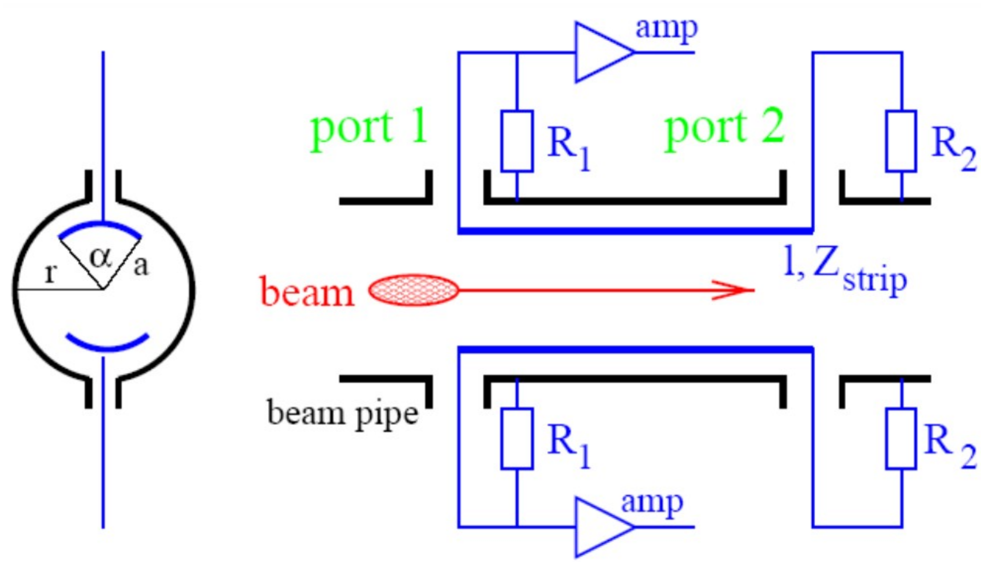
$$Z_{T\infty} = \frac{A}{(2\pi r)\times c \times C_e} = \frac{\pi \times (12mm)^2}{(2\pi \times 24.5mm)\times c \times (8pF)} = 1.2\Omega$$

$$I_B = \frac{N_{pilot}e}{t} = \frac{5\times10^9 \times 1.6\times10^{-19}}{1\times10^{-9}} = 0.8A_{peak} \Rightarrow V_{f=\infty} = 0.8\times1.2 = 1V_{peak}$$

$$= \frac{N_{nom}e}{t} = \frac{1\times10^{11} \times 1.6\times10^{-19}}{1\times10^{-9}} = 16A_{peak} \Rightarrow V_{f=\infty} = 16\times1.2 = 20V_{peak}$$

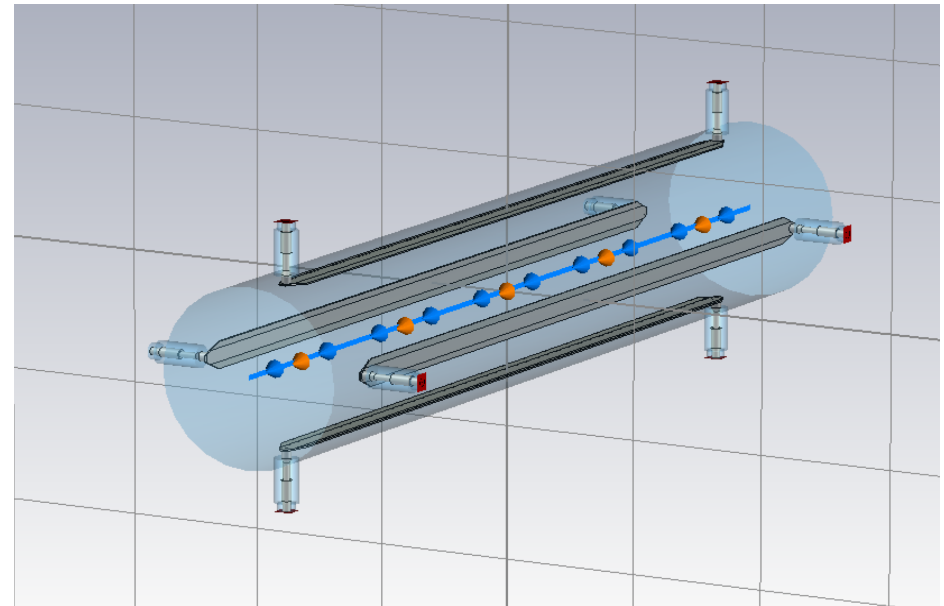
Strip-Line Pick-Up

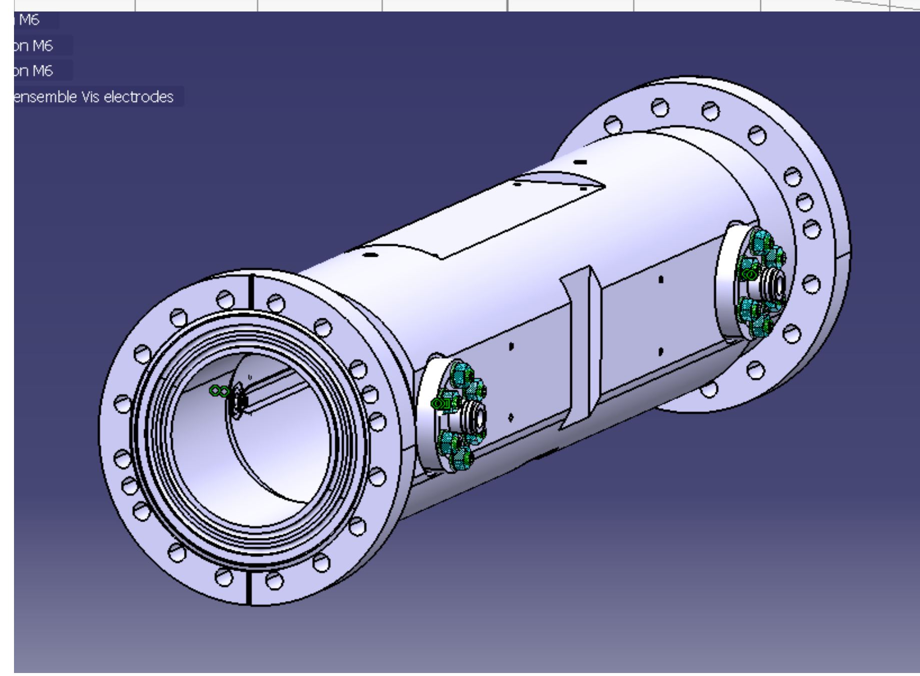
- piece of transmission-line parallel to the beam
  ↔ broad-band antenna



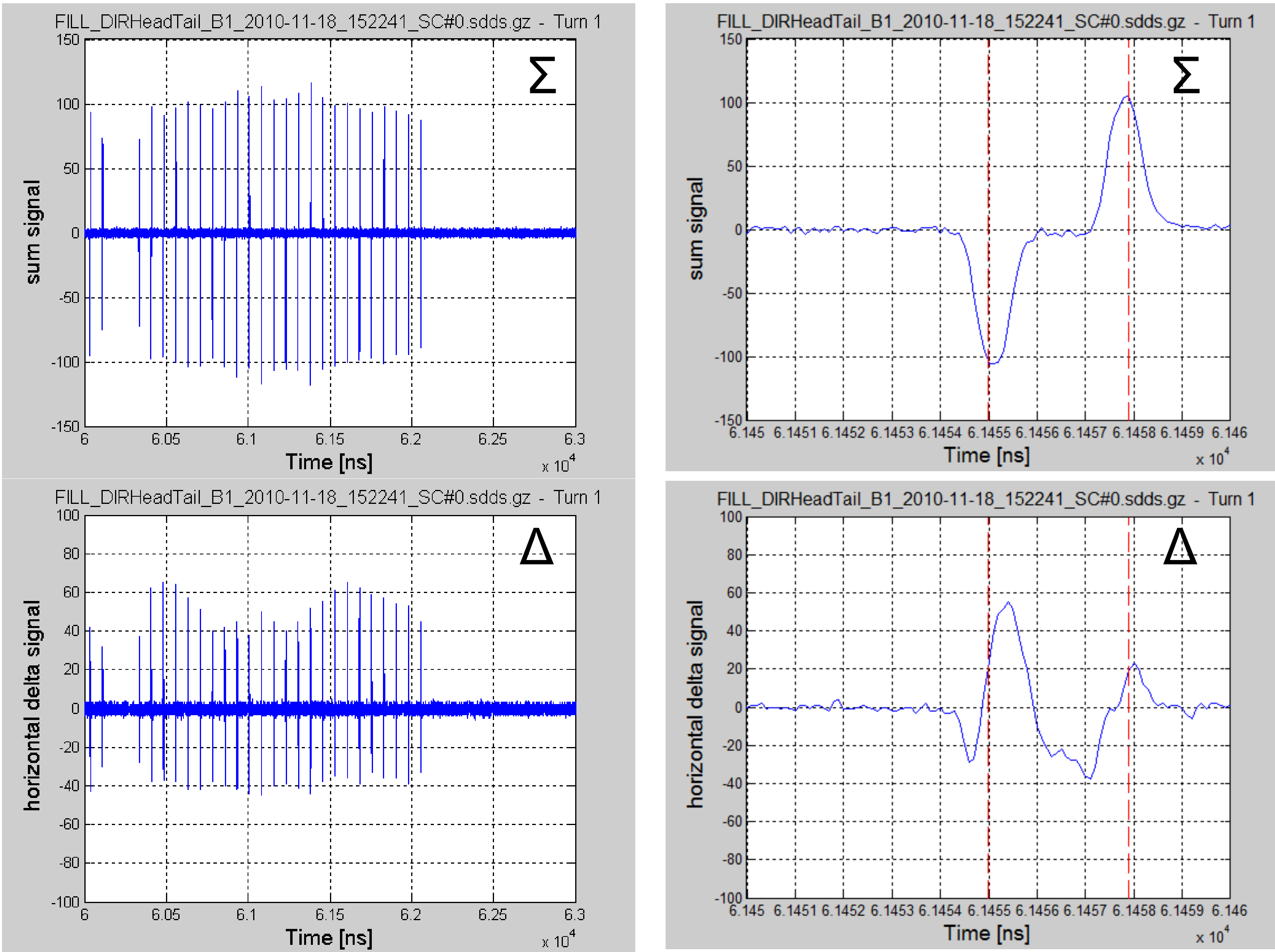
  - transverse impedance Z_t depends on bunch length σ_t

$$Z_t(\omega) = \frac{Z_{strip}\, a}{2\pi} \cdot e^{\frac{-(\omega\,\sigma_t)^2}{2}} \cdot \sin\left(\frac{\omega\, l}{c}\right) \cdot e^{j\left(\frac{\pi}{2} - \frac{\omega\, l}{c}\right)}$$



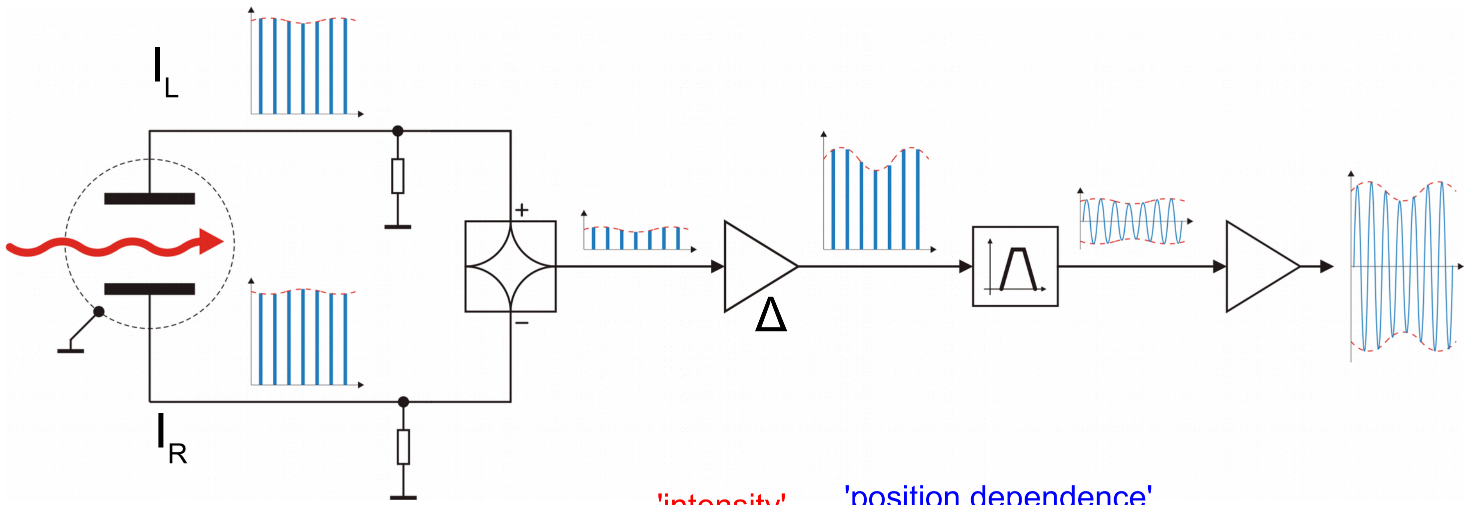


Strip-Line Pick-Up – Example SPS



animation courtesy B Salvant (2010)

“Classic” Detection Scheme



$$I_{L/R}(t)=\frac{I_\omega(t)}{2\pi}\left[2\psi \mp 2\frac{x}{R}\sin(\psi)+\frac{x^2-y^2}{R^2}\sin(2\psi)+h.o.\right]$$

'intensity' (2ψ), 'position dependence' ($\frac{x}{R}$), 'beam size dependence' ($\frac{x^2-y^2}{R^2}$)

- Classic detection approach: Σ-Δ hybrid

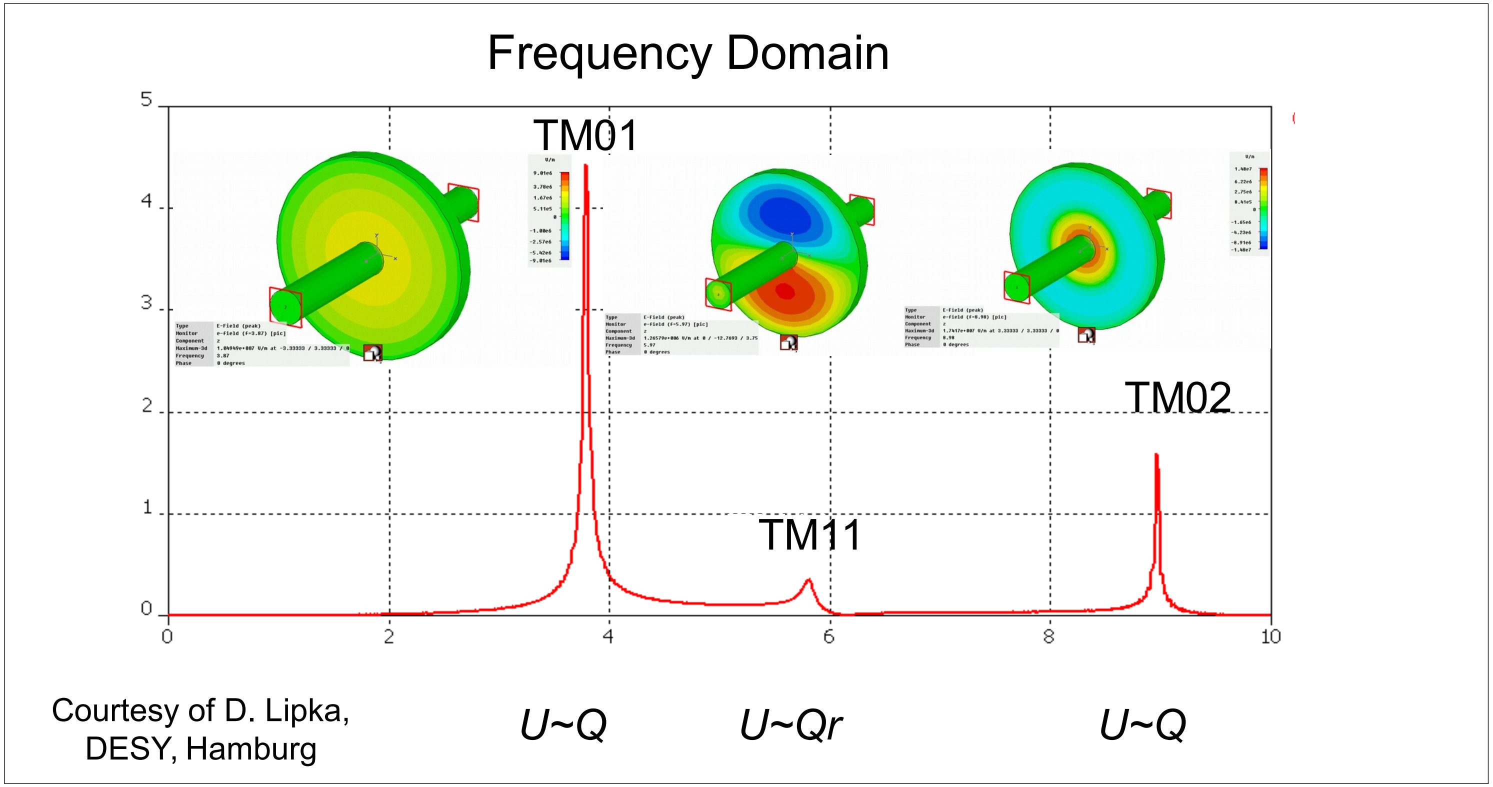
$$\rightarrow \boxed{\frac{x}{R} \approx \frac{\Delta}{\Sigma} = \frac{I_L - I_R}{I_L + I_R}}$$

R: pickup half-aperture

- Eliminates most 'common mode' signal (e.g. intensity),
  - However ADC needs still to accommodate 'common mode' signals due to:
  - Closed orbit offset
  - 2nd order: intensity bleed-trough intrinsic to any Σ-Δ hybrid

Improving the Precision for Next Generation Accelerators

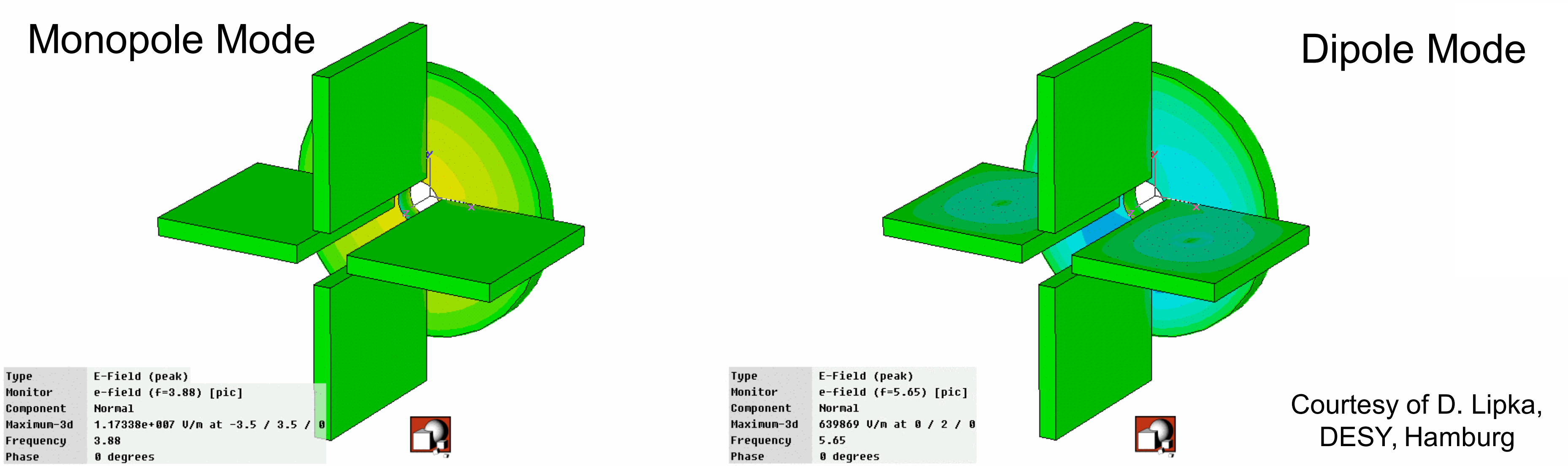
- Standard BPMs give intensity signals which need to be subtracted to obtain a difference which is then proportional to position
  - Difficult to do electronically without some of the intensity information leaking through
  - When looking for small differences this leakage can dominate the measurement
  - Typically 40-80dB (100 to 10000 in V) rejection ⏶ tens micron resolution for typical apertures
- Solution – cavity BPMs allowing sub micron resolution
  - Design the detector to collect only the difference signal
  - Dipole Mode TM11 proportional to position & shifted in frequency with respect to monopole mode



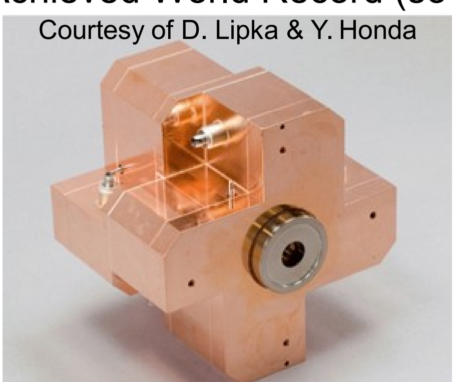
Courtesy of D. Lipka, DESY, Hamburg

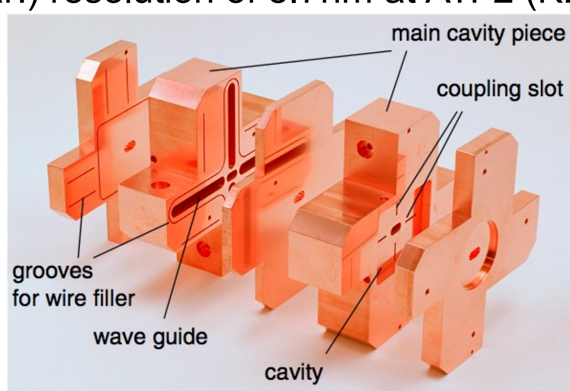
Today's State of the Art BPMs

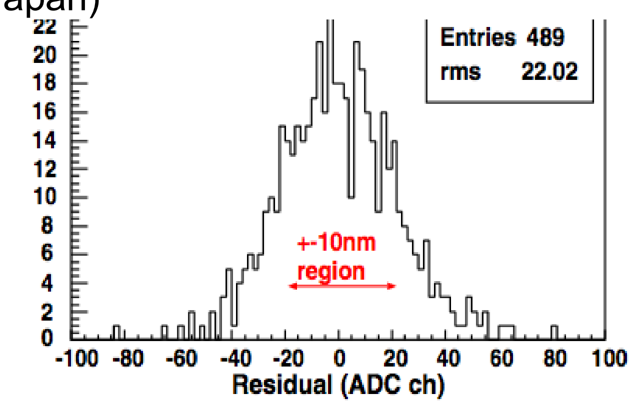
- Obtain signal using waveguides that only couple to dipole mode
  - Further suppression of monopole mode



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



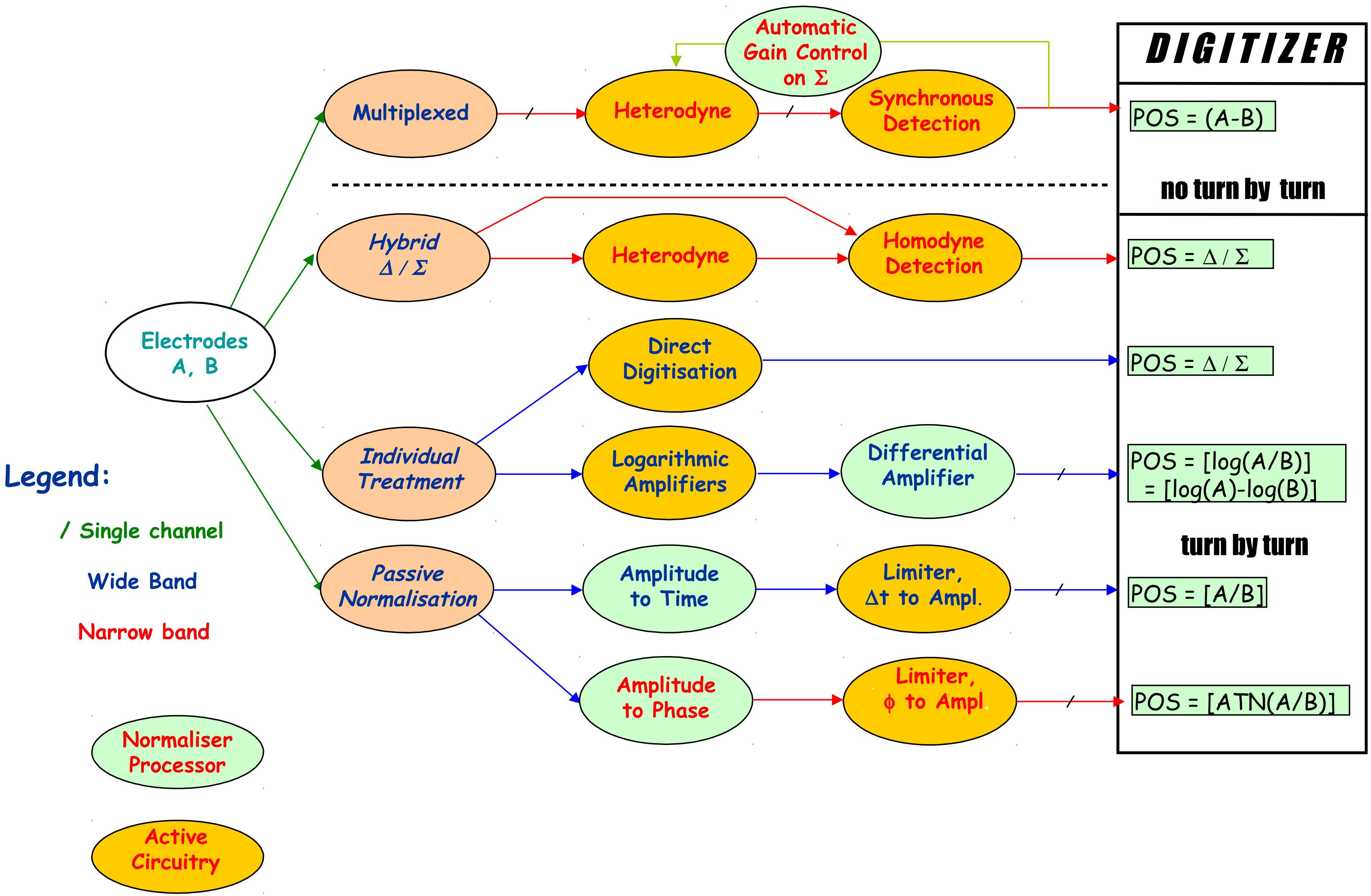




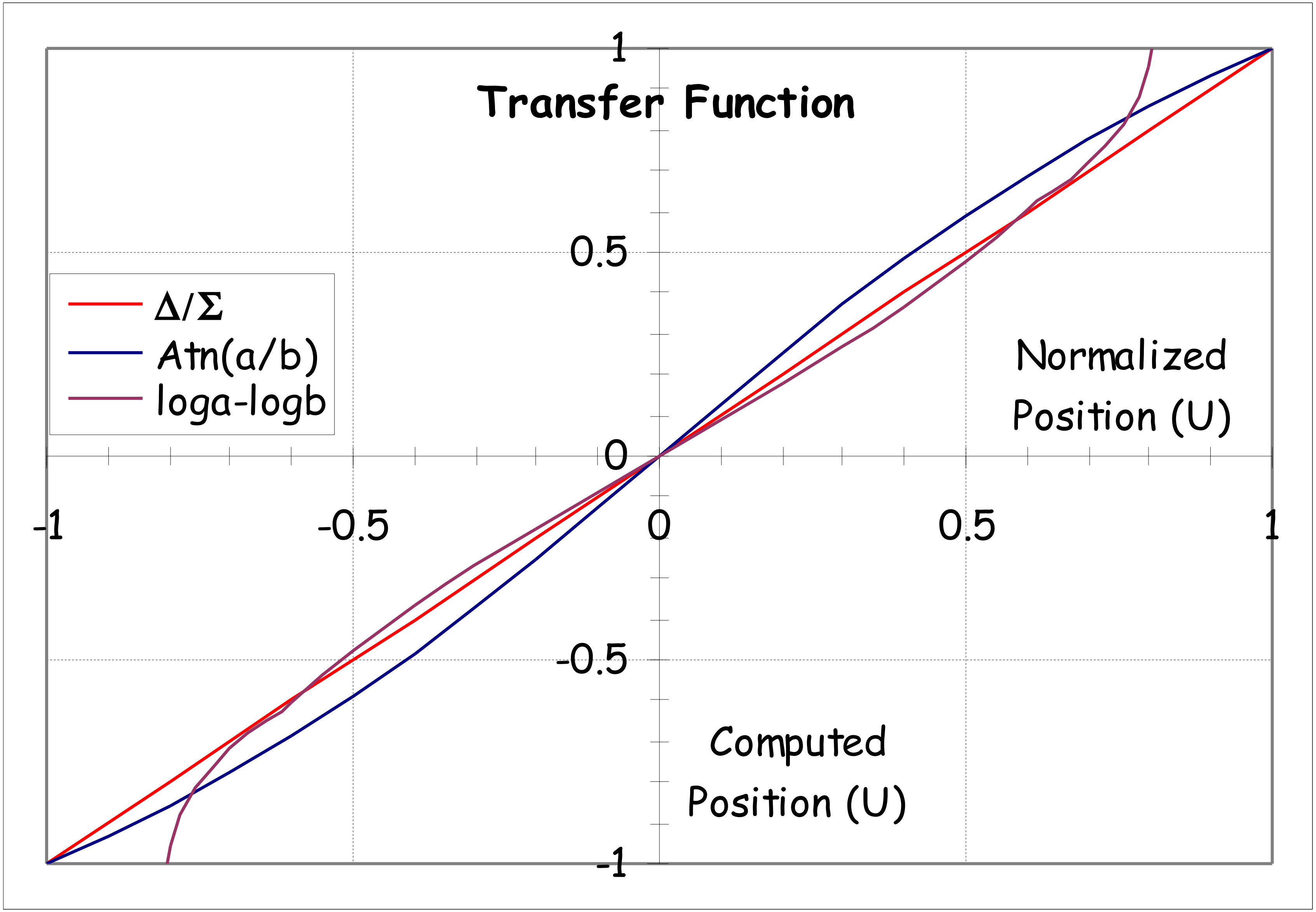
Analog Front-End Electronics Criteria

- Accuracy
  - mechanical and electromagnetic errors
  - electronic components
- Resolution
- Stability over time
- Sensitivity and Dynamic Range
- Acquisition Time
  - measurement time
  - repetition time
- Linearity
  - aperture & intensity
- Radiation tolerance

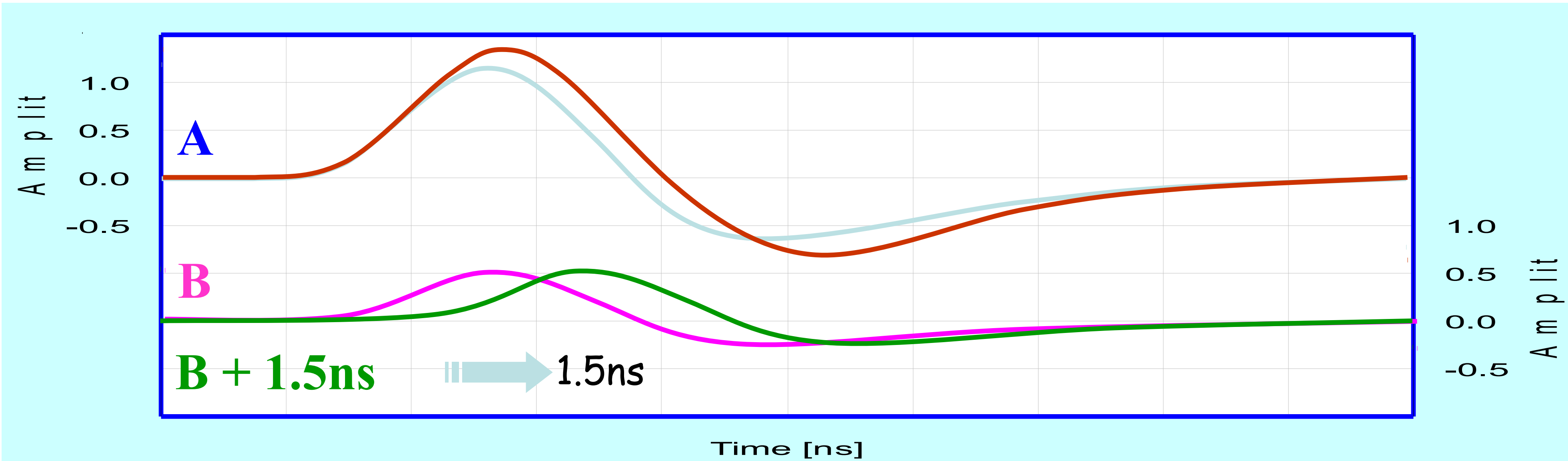
Analog Front-End Electronics Processing Families

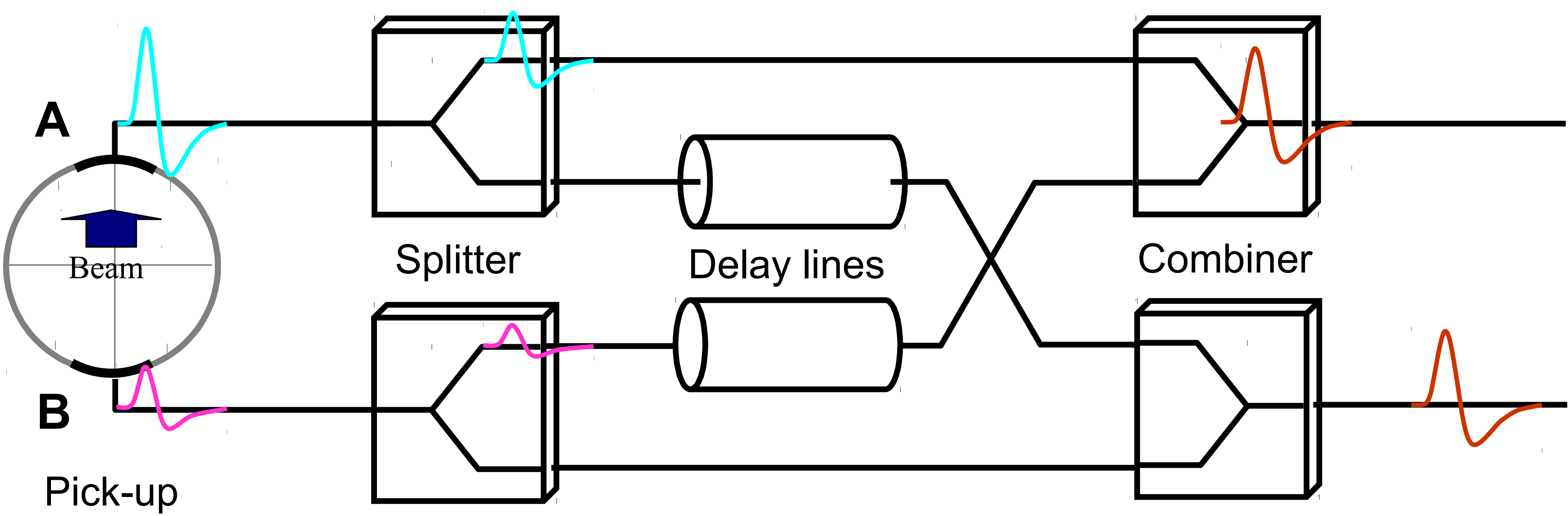


Linearity Comparison



Amplitude to Time Normalisation





BPM Acquisition Electronics
Amplitude to Time Normaliser

Advantages

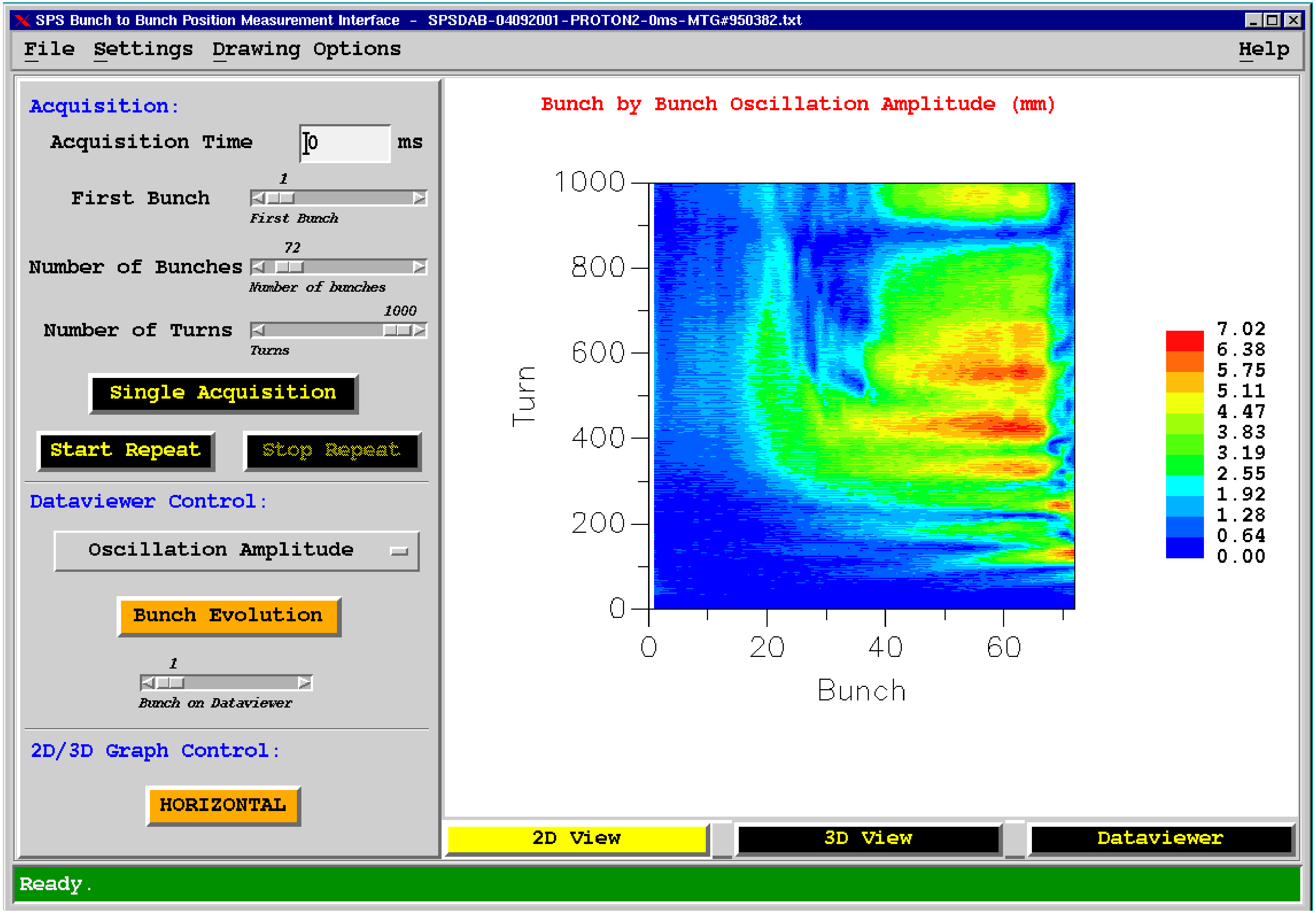
- Fast normalisation (< 25ns)
  - bunch to bunch measurement
- Signal dynamic independent of the number of bunches
  - Input dynamic range ~45 dB
  - No need for gain selection
- Reduced number of channels
  - normalisation at the front-end
- ~10 dB compression of the position dynamic due to the recombination of signals
- Independent of external timing
- Time encoding allows fibre optic transmission to be used

Limitations

- Currently reserved for beams with empty RF buckets between bunches e.g.
- LHC 400MHz RF but 25ns spacing
  - 1 bunch every 10 buckets filled
  - tight time adjustment required
- No Intensity information
- Propagation delay stability and switching time uncertainty are the limiting performance factors

What one can do with such a System

Used in the CERN-SPS and LHC for electron cloud & instability studies



Summary

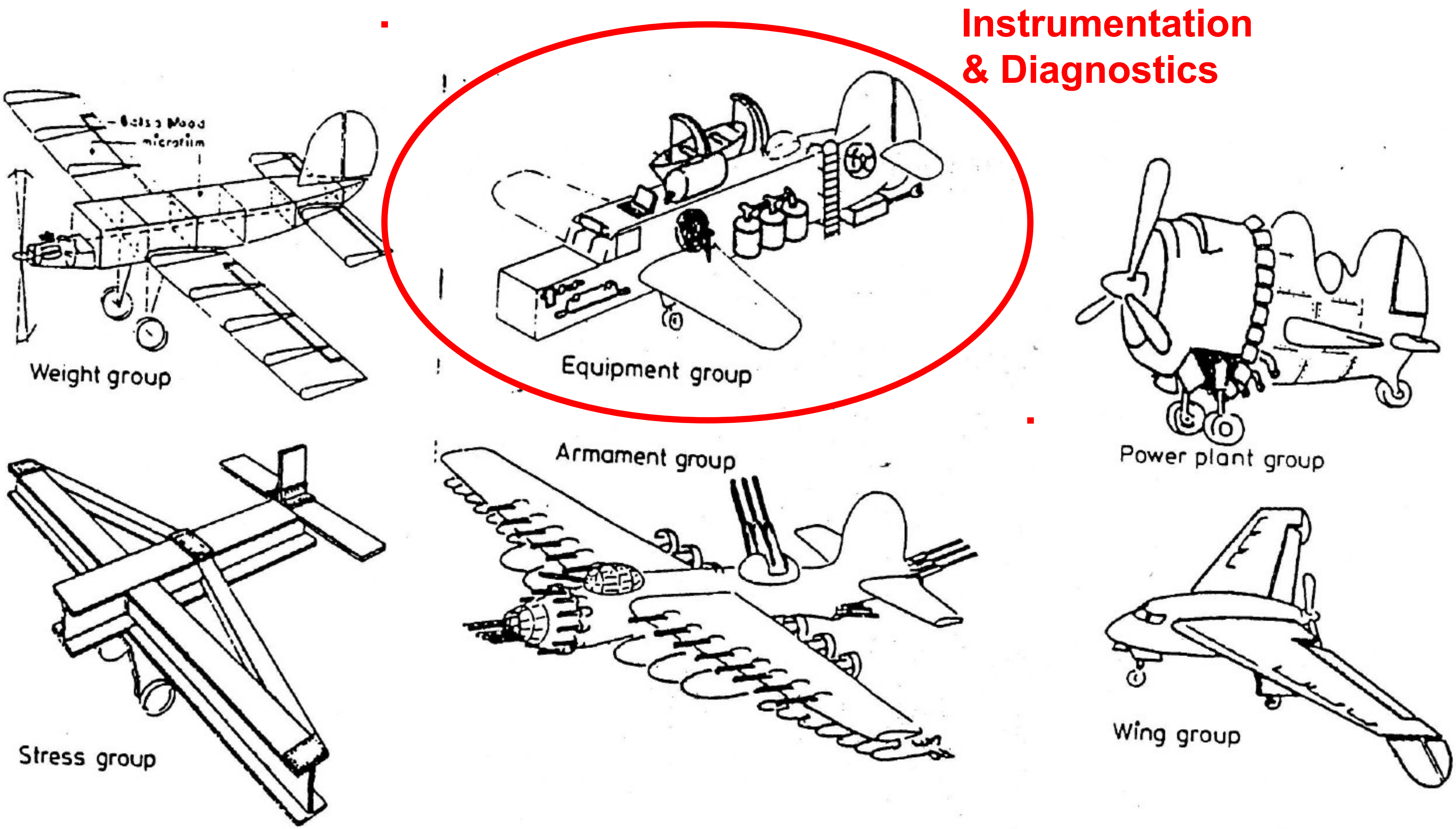
- Beam instrumentation are the 'eyes and ears' of accelerators.

- 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 → tomorrow
  – 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.

Summary



For a successful construction and operation of an accelerator, the understand and right balance of all disciplines is required!

Additional Slides

Beam Position Measurement Principle

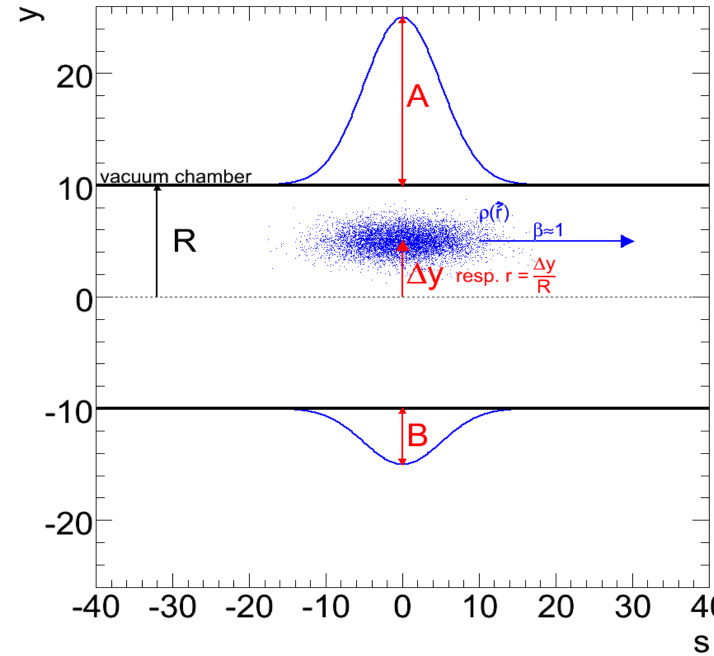
- Several BPM design possibilities:
  - wall-current, shoebox, button, strip-line, resonant Schottky pickups, ...

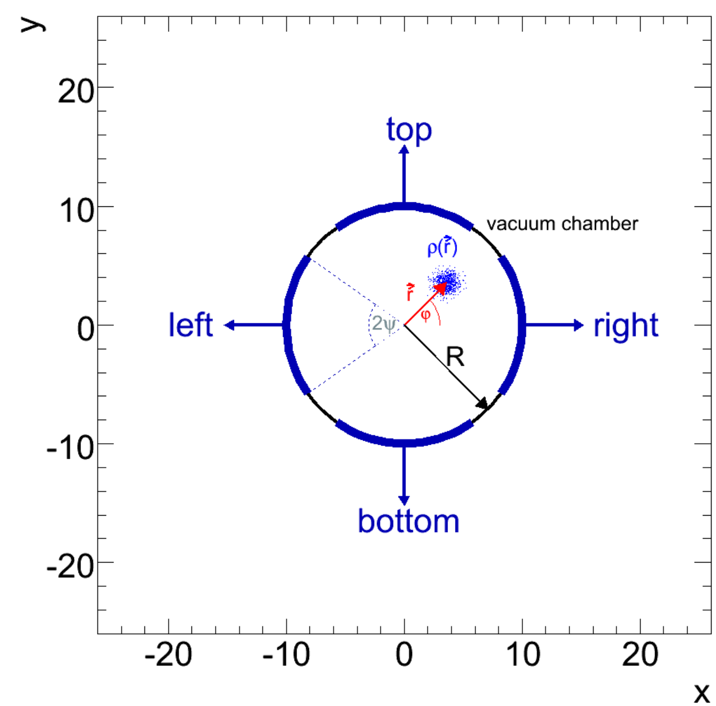
- Pick-up response[1]:

$$I_{L/R}(t)=\frac{I_{\omega}(t)}{2\pi}\left[2\psi\mp 2\frac{x}{R}\sin(\psi)+\frac{x^2-y^2}{R^2}\sin(2\psi)+h.o.\right]$$

longitudinal beam signal — transverse beam signal

- Real-life signal is further convoluted with pickup and acq electronics response[2,3]!
  → good resource: CAS'08 on Beam Diagnostics
  http://cas.web.cern.ch/cas/France-2008/Dourdan-after.html

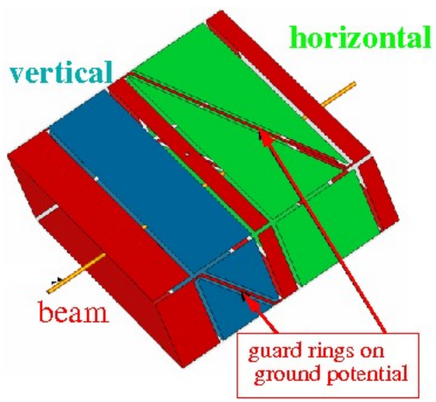


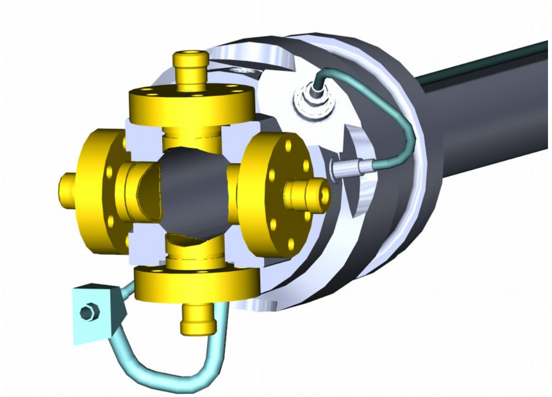


[1]R. Littauer, *"Beam Instrumentation"*, *SLAC Summer School*, 1982. (p.902)
[2]D. McGinnis, *"The Design of Beam Pickup and Kickers"*, BIW'94, 1994
[3]G. Vismara, *"Signal Processing for Beam Position Monitors"*, CERN-SL-2000-056-BI

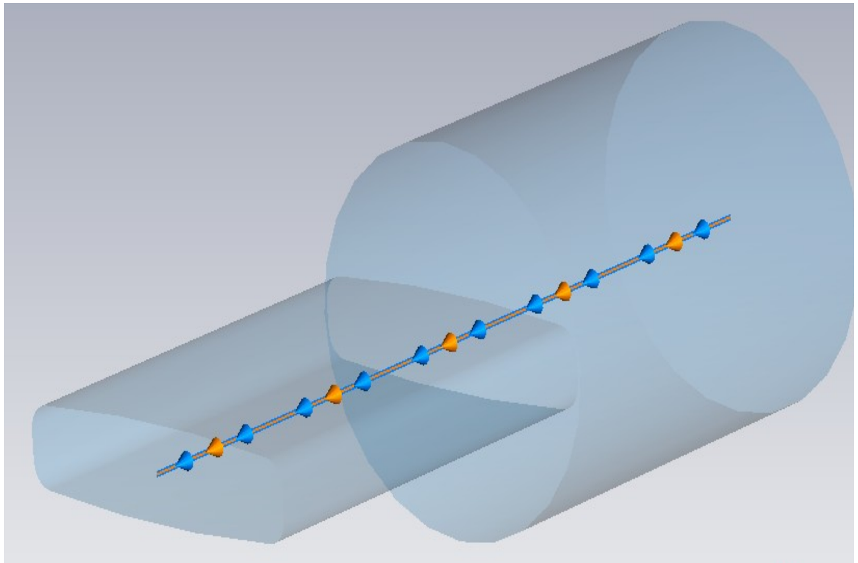
Comparison Shoe-Box and Button BPM

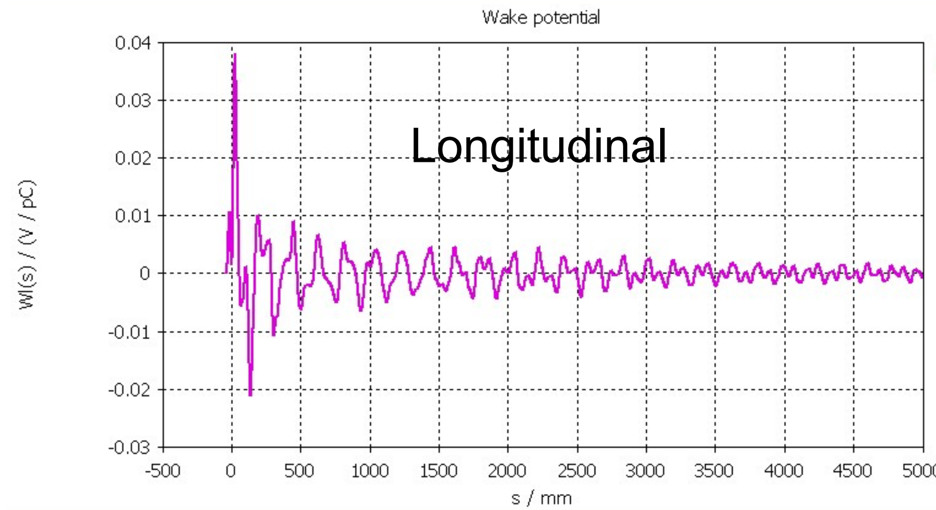
	Shoe-Box BPM	Button BPM
Precaution	Bunches longer than BPM	Bunch length comparable to BPM
BPM length (typical)	10 to 20 cm length per plane	∅1 to 5 cm per button
Shape	Rectangular or cut cylinder	Orthogonal or planar orientation
Bandwidth (typical)	0.1 to 100 MHz	100 MHz to 5 GHz
Coupling	1 MΩ or ≈1 kΩ (transformer)	50 Ω
Cutof ffrequency (typical)	0.01… 10 MHz (C=30…100pF)	0.3… 1 GHz (C=2…10pF)
Linearity	Very good, no x-y coupling	Non-linear, x-y coupling
Sensitivity	Good, care: plate cross talk	Good, care: signal matching
Usage	At proton synchrotrons, f_{rf}< 10 MHz	All electron acc., proton Linacs, f_{rf}> 100 MHz

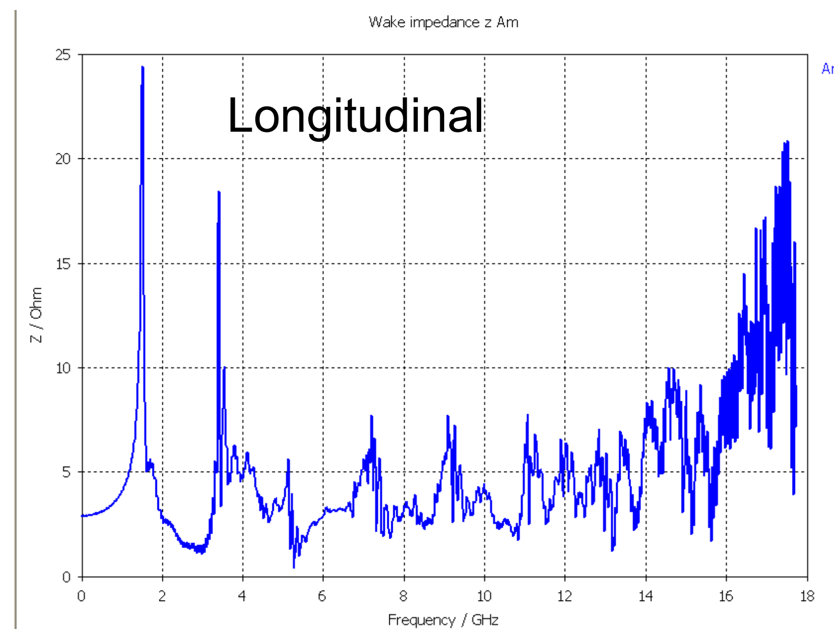




Vacuum Transitions – Simulation







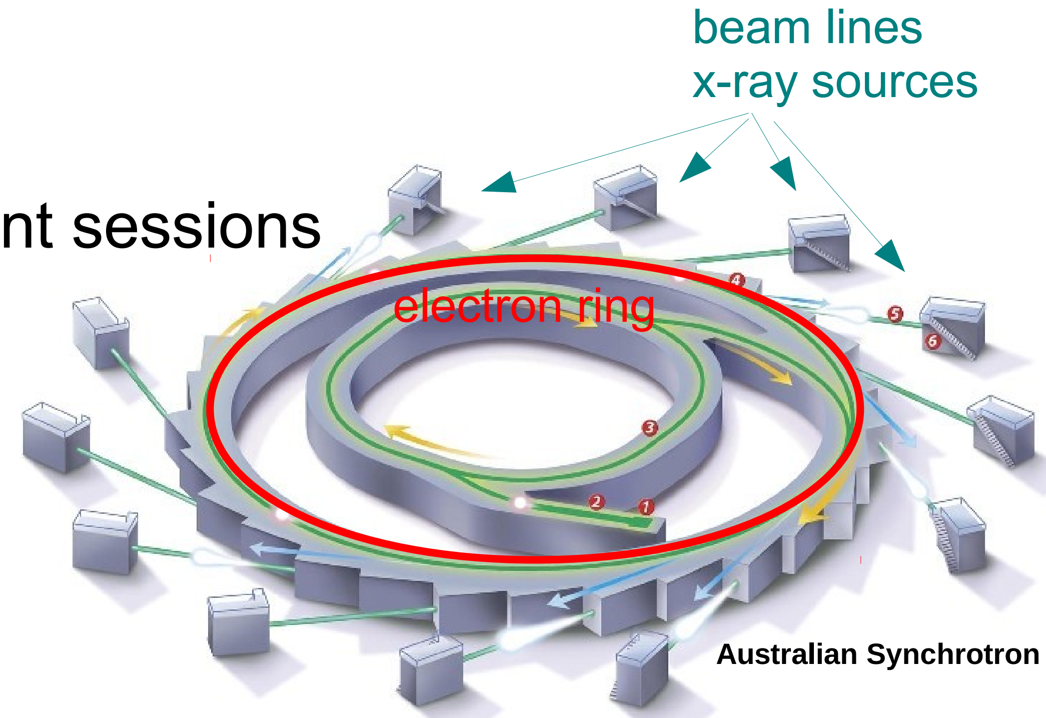
Longitudinal

f	*R*	*Q*	*R/Q*
1.5 GHz	31 MΩ	3200	960 Ω

courtesy B Salvant (2010)

Different uses of Beam Diagnostics

- Regular crude checks of accelerator performance
  - Beam intensity → Faraday cups, current transformers, wall-current monitors
  - Beam losses/radiation levels
- Standard regular measurements
  - Emittance measurement
  - Beam position & trajectories
  - Tune & Chromaticity
- Sophisticated measurements
  e.g. during machine development sessions
  - May require offline evaluation
  - May be less comfortable



Example: Diagnostics Bench for the Commissioning of an RFQ