Beam Current Measurements

The State of Art

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PART I

What is the beam current/charge
What is its origin

- Movement of electrically charged particles generates a current
- Beam = charged particles which move around the accelerator
  - **Beam intensity / Beam charge:**
    - either an equivalent DC current
    - or number of charged particles in a 'region of interest'
  - **Region of interest (ROI):**
    specific time interval corresponding to a measured structure

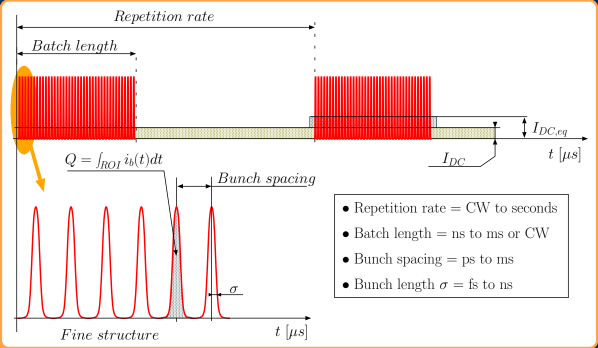
    → next slide
  - The number of charges:

$$NP = \frac{Q}{e} = \frac{\int_{ROI} i_{beam}(t)dt}{e} \approx \frac{I \cdot t}{e} \quad (1)$$

Q is a measured charge, $e = 1.602 \times 10^{-19}$ C.

i_{beam} is the beam current intercepted by measurement device

Region of interest

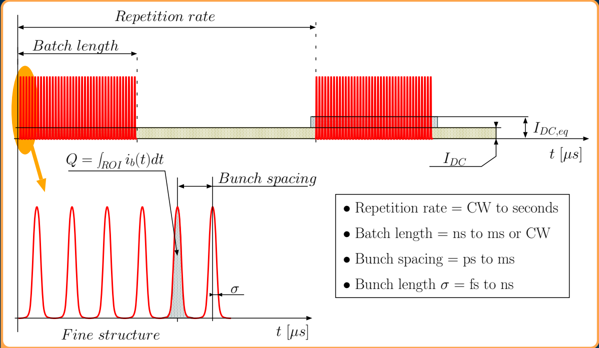


Bunch pattern example

- LINACs: equivalent DC current in a batch
- electron machines/fine structure: bunch charge
- circulating beam: bunch charge / DC beam current
- other, e.g. total charge over a revolution period

Additional information, e.g. amount of debunched beam

Region of interest



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PART II

What measurement methods are available?

What can give precise information about the charge?

- a measurement instrument:
  - provide deterministic absolute measurement value
  - must be calibrated
    - direct calibration - not many devices available
    - indirect calibration - uses directly calibrated devices
  - uncertainty of the measurement and calibration standards
  - dynamic range and noise levels are of utmost importance
- Can provide: instant current, average current, bunch charge, turn charge etc.
- used for machine protection (e.g. Reeg, H. et al., EPAC2006)

- non-intercepting - inductive/capacitive coupling to the beam
  - → insignificant impact on the beam
  - → couple to EM ⇝ image current 'treatment'
  - inductive: FBCTs, DCCTs, WCMs, striplines (EM coupling)
  - capacitive: BPMs, all sorts of button-style pick-ups
  - magnetic sensors: SQUIDs, Magneto-resistive sensors, CCCs, nDCCT

Charge measurement devices

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  → absorption of significant part of the energy
  - Faraday cups (beam stoppers), SEM grids, screens, Ionisation chambers
  - even Wire scanners can provide intensity

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A) Non-DC beam current measurements

What is needed to get the beam signal?
How to process the beam signal?
Calibration?

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A) Non-DC beam current measurements

What is needed to get the beam signal?
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Calibration?

B) DC beam current measurements

DCCT and its calibration
MR sensors

A) Non-DC beam current measurements

We might use these to get the beam signal:

Faraday cups
BPMs and capacitive pick-ups
WCMs
FBCTs

Note:

Faraday cups measure down to DC as well, but ...

A) Non-DC beam current measurements

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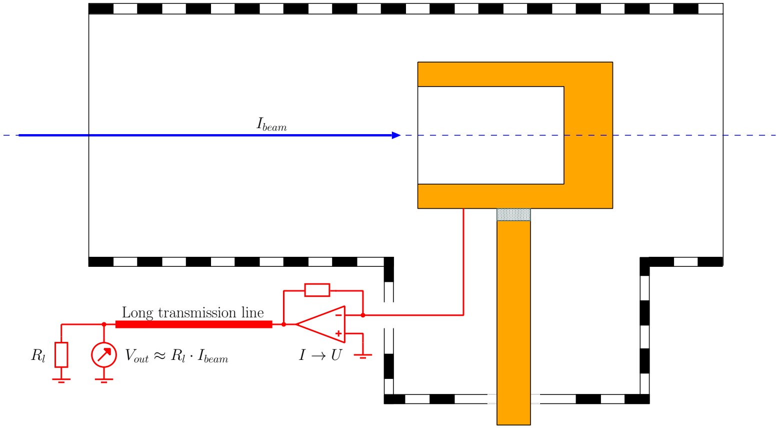
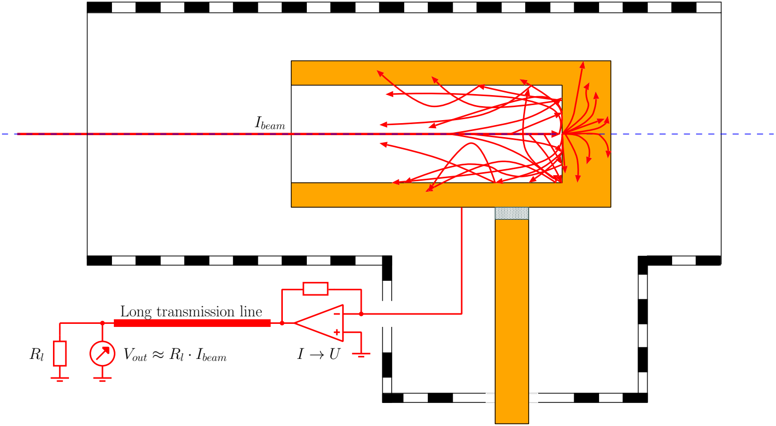
Measurement of low to mA currents



Faraday cup

Provides pA resolution with excellent absolute accuracy

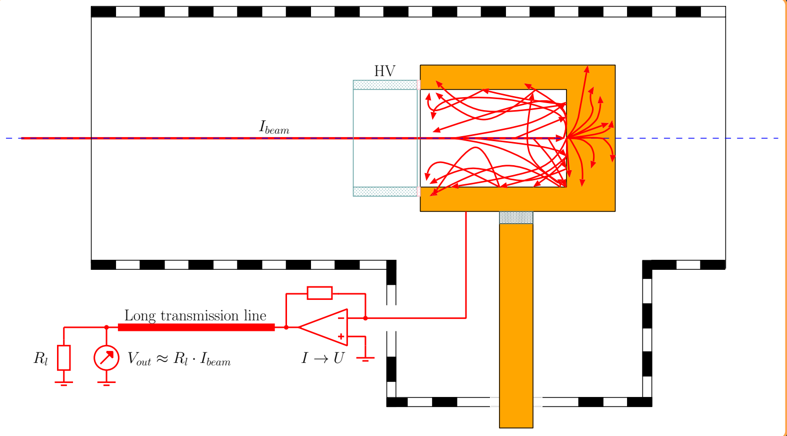
Generated secondary particles can escape the cup



Faraday cup

Install longer cup, or ...

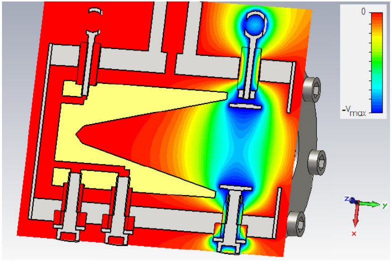
Generated secondary particles can escape the cup

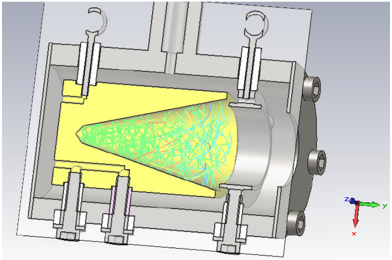


Electrostatic deflector

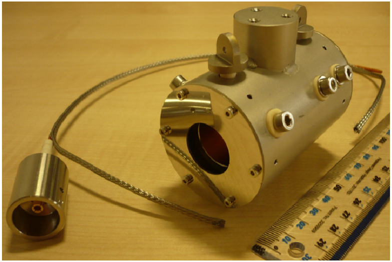
deflect them back using HV higher than mean SE energy

Implementations





SE deflection using electrostatic shielding



SE deflection using electrostatic shielding

- USR/FLAIR anti-proton storage
- mainly for proton beams
- p^- measurements limited due to 100 MeV+ p-p^- annihilation
- 1 μA down to fA, res. < 5 fA

Harasimowicz, J. et al., BIW2010

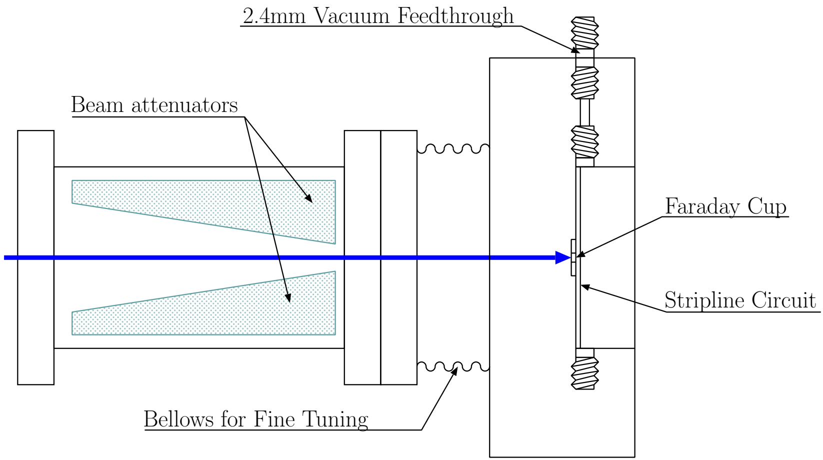
Extremely accurate measurements down to pA levels, used as absolute calibration standard

- cup heat-load with intense beams require active cooling
- emission of secondary particles
- may have problems with attraction of particles flying around (e.g. electron showers)

Signal transmission bandwidth in hundreds of MHz. For electron machines/fine beam structures appropriate HIBW connection to the current meter must be provided to tens of GHz

→ Fast Faraday Cups (FFC), e.g. ELETTRA

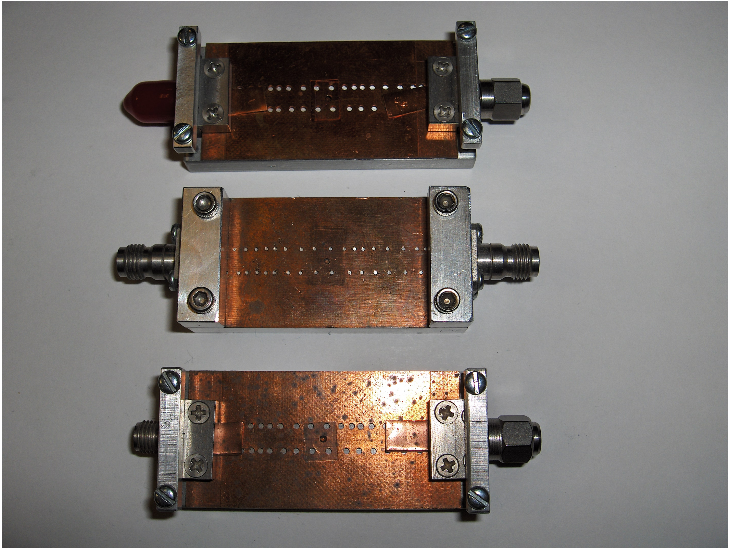
FFC principle of operation



C. Deibele, Fast Faraday Cup, SNS

Ferianis., M. et al. DIPAC 2003
Up to 40 GHz transmission bandwidth

Implementations



C. Deibele, Fast Faraday Cup, SNS

Non-DC: What is needed to get the beam signal

We might use these to get the beam signal:

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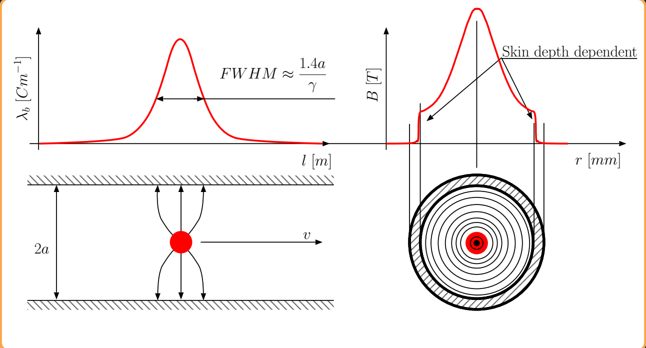
Wall image current

Any moving charged particle is accompanied with EM field:



Distribution of the mirror charge and flux lines

E field looks as a pillbox for relativistic speeds and causes a charge deposit on the inner wall of the vacuum chamber. Deposited charge moves with particle and generates current = Wall Image Current (WIC). **B field** gets attenuated

As beam signal is "the source" of the information about the beam charge, we need to intercept it

- couple to EM field produced by the beam current
  - diverge the wall image current
  - install the detector in the vacuum chamber

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- Why?

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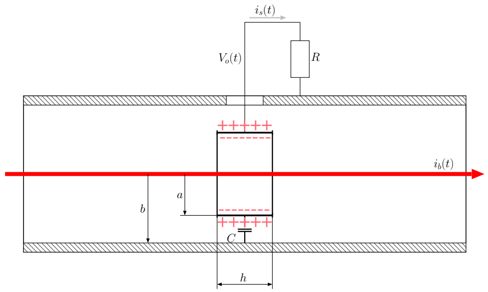
- couple to EM field produced by the beam current
  - diverge the wall image current
  - install the detector in the vacuum chamber
- Why?
  - Electric field: cancelled
  - Magnetic field: Attenuation by $\approx 8.7\ dB$ by one skin-depth length: non-magnetic conductor$\rightarrow \delta = \frac{\sqrt{10}\cdot 10^3}{2\pi}\sqrt{\frac{\rho}{f}}$:

	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz
Copper [mm]	2.1	0.66	0.21	0.066	0.021

  - 3mm copper tube: A≈50 dB @ 10MHz
  - radio with ≈30dB dynamic range to intercept weakest beam signal attenuated by 50 dB?

Capacitive pick-up

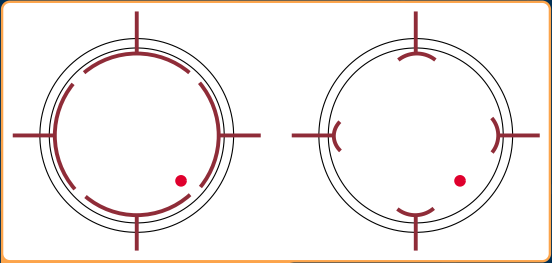


Principle of capacitive pick-up

- conductive electrode subjected to charge deposit → charge flows through R
- RC filter limits the BW (C includes cables if electrode impedance not matched!)
- split the electrodes and you get capacitive BPM

Capacitive pick-up

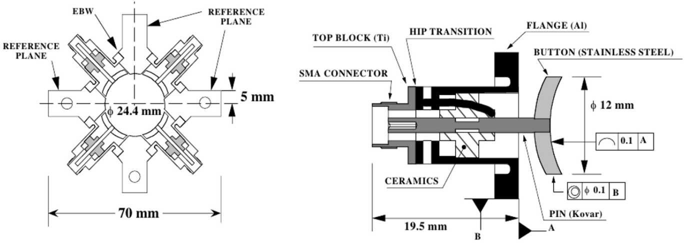
- sensitivity ≈ 10 nV/nA, resolution down to 20 pA/e
- Intensity measurement using sum signal: $\int v(t)dt = Q \cdot \frac{Z}{2} \cdot \frac{\Phi}{2\pi}$
  - sum suppresses first order position dependence
  - using math third and fifth order can be eliminated as well, but:



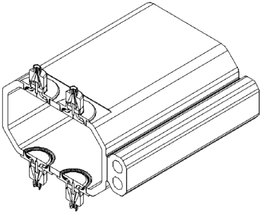
Pick-up electrode size matters

- Pickups/BPMs are many. Averaging over a ring increases resolution (e.g. ESFR storage ring 224 BPMs $\rightsquigarrow$ factor of 15, Scheidt, MOPD64)

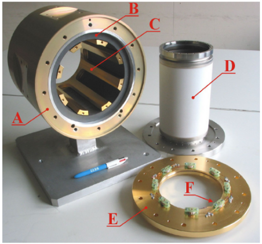
Button pick-up



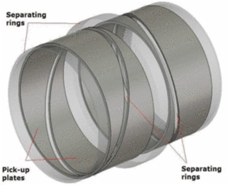
KEK ATF damping ring BPM (Hinode F. el al, PAC95)



SLAC PEP-II button pickup
(Kurita, N. et al., PAC95)



Inductive PU, CERN
(Gasior, M., DIPAC 2003)



Google knows

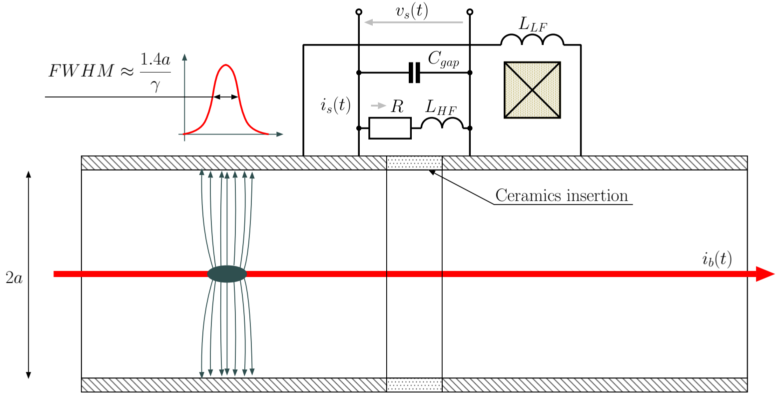
Possible realisations

Non-DC: What is needed to get the beam signal

We might use these to get the beam signal:

Faraday cups
BPMs and capacitive pick-ups
WCMs
FBCTs

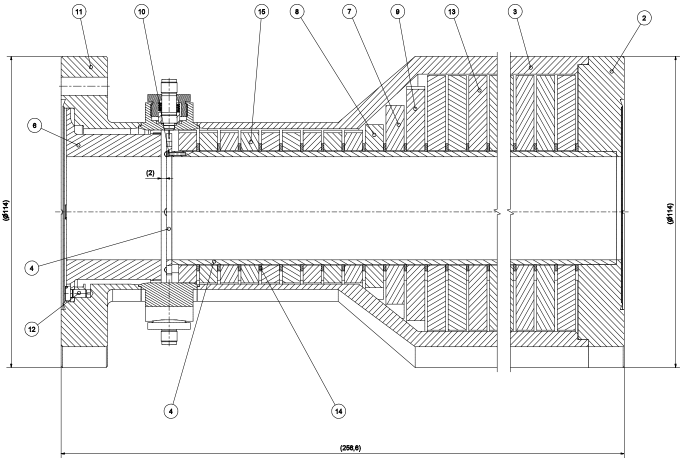
To measure intensity using WCMs



Wall Current Monitor

- Direct measurement of a wall current
- Bandwidth from few kHz to tens GHz range (e.g. RHIC 3 kHz to 6 GHz, Cameron, PAC99)

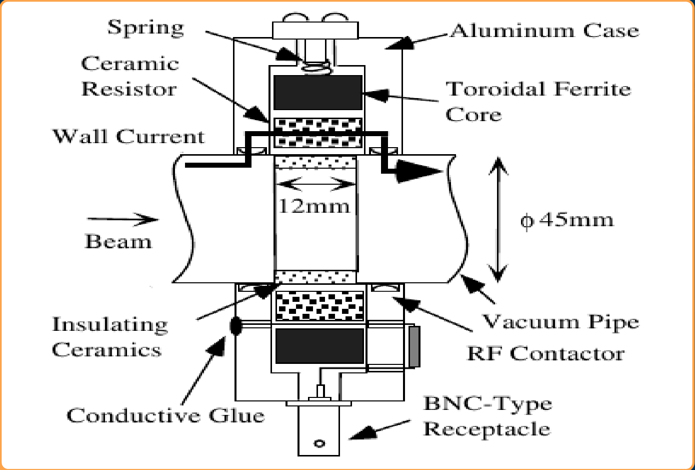
Practical implementation ...



WCM for CERN CTF3, Odier, P. DIPAC2003, D'Elia, EPAC08

- BW≈100kHz-20GHz
- Ferrite to diverge LF via external bypass
- signal from 8 feedthroughs combined using resistive combiners

Practical implementation ...



Suwada, T., KEK

- 2.5Ω ceramics resistance (Alumina+carbon powder)
- 4 pick-up electrodes + combiner
- up to 2.5GHz BW

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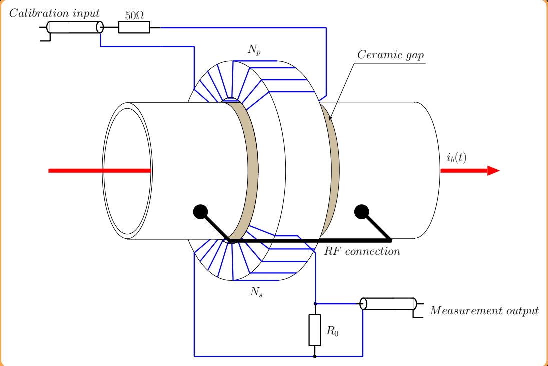
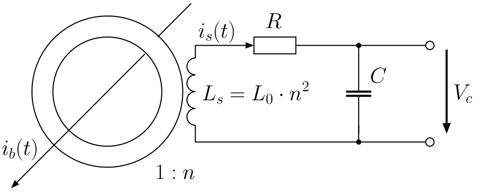


Fast Beam Current Transformer

- Bandwidth from few Hz to GHz range
- typ. resolution 2-5 pC, but sub pC optimisations ongoing (< 1 pC see Werner, MOPD65)
- measurement winding optimised to match cable on HF
- Not always High-μ material (ex. Reeg, H., GSI, FCT using Ferroxcube 3E25, $\tau \approx 1$ μs)

To measure intensity using FBCTs



$$I(t) = c_1 e^{-\lambda_1 t} + c_2 e^{-\lambda_2 t}, \lambda_{1,2} = \frac{R}{2L_s} \pm \sqrt{\frac{R^2}{4L_s^2} - \frac{1}{L_s C}}$$

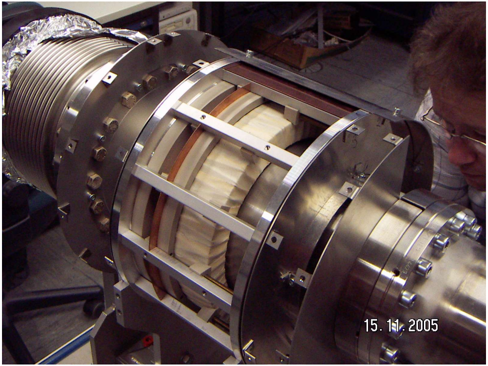
FBCT equivalent lumped circuit

Works as RLC circuit, can be used in two measurement modes:

- $\frac{R^2}{4L_s^2} - \frac{1}{L_s C} > 0$: time constant $\tau = L_s/R$, $I_s = I_b/n$ →integrated signal related to charge
- $\frac{R^2}{4L_s^2} - \frac{1}{L_s C} < 0$: C charged during pulse, then resonant discharge→ discharge amplitude proportional to # of charges (e.g. Clarke-Gayther, EPAC96)

Practical implementation ...

Resonant-mode FBCT:



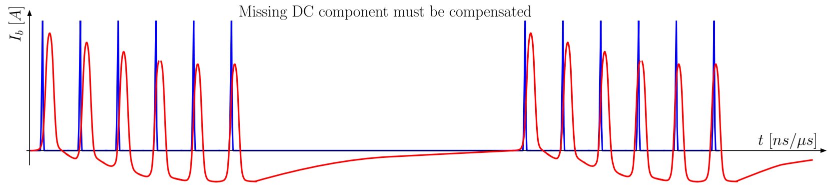
Reeg, H., Resonant mode BCT for GSI HEBT lines

- peak detector to detect the voltage over capacitor
- 4 dynamic ranges down to 10 pC resolution
  - offset/zero value fluctuations due to noise rectification of the peak detector circuit
  - precision of calibration due to uncertain coupling efficiency of single turn cal. winding

We have used one of these to get the beam signal:

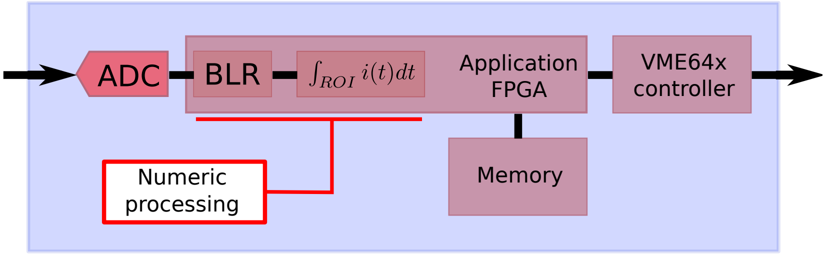
Faraday cups
BPMs and capacitive pick-ups
WCMs
FBCTs

and we get this ...



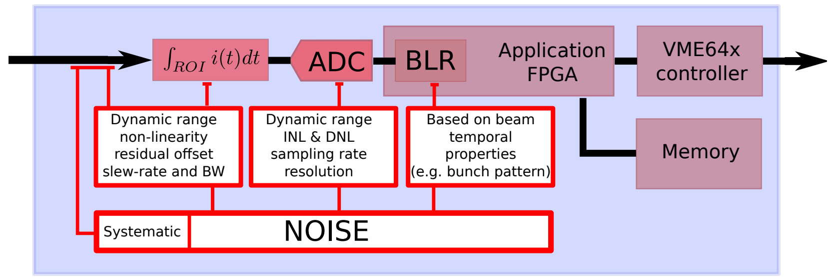
Beam signal provided by above devices, τ short wrt beam repetition

and then we have to process it by the electronics ...



Signal processing

Note: BLR = Base Line Restorer
This method work only if sampling rate is appropriate.

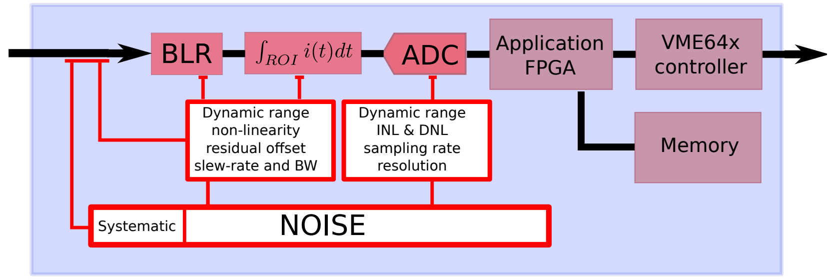


Signal processing

Base line restorer must be based on temporal properties of the beam: one must know, where the beam cannot be. However, working with integrated value makes restoration more difficult → maybe doing that before integration is a good idea ...

BTW: this is the LHC FBCT system

Non-DC: processing electronics

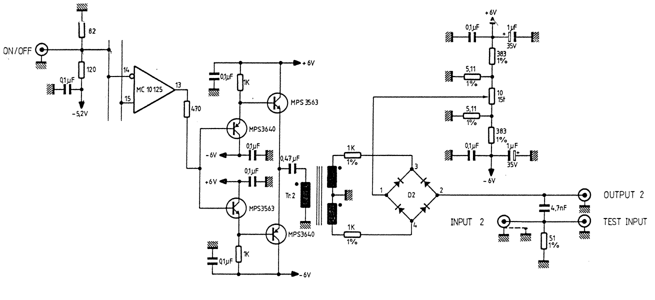


Signal processing

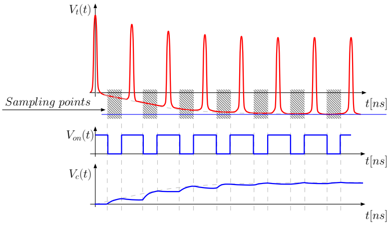
BLR & integrator are analogue processing blocks, difficult to tune

...

Non-DC: analogue BLR example

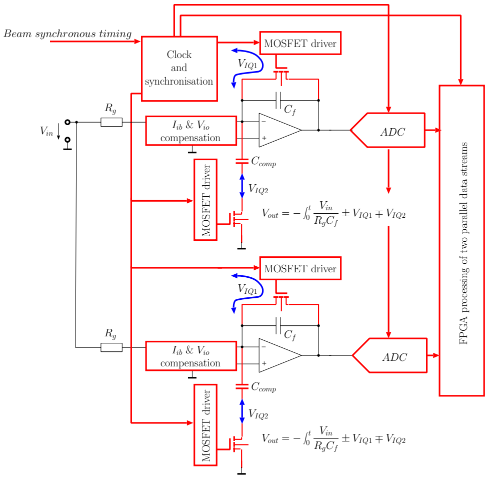


Schottky diode based analogue BLR



BLR signals

Non-DC: analogue integrator example



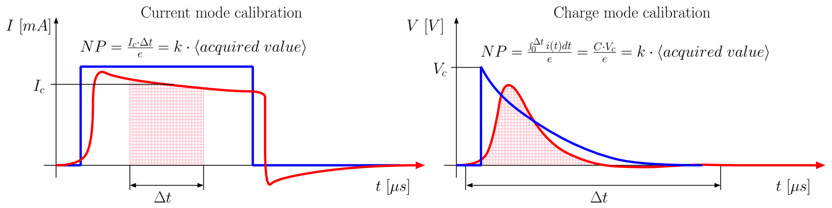
Streaming data integration

Well, very complex for such small thing as integrator

Faraday cups	electronics chain calibration by DC current
Pickups	compared to DCCTs or FBCTs, or to Faraday cup
WCMs	compared to DCCTs or FBCTs, or to Faraday cup
FBCTs	absolute calibration using current or charge source

Matching the measurement result with known current/charge permits to calculate gain.

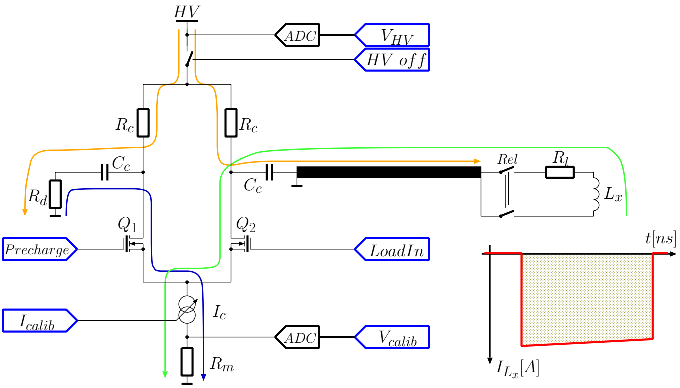
DC current sources of no-use for FBCTs → require pulsed source, calibration signal discharged into calibration turn.



Two pulse-mode calibration methods

Absolute accuracy of 1 to 5 % of the measurement full scale.

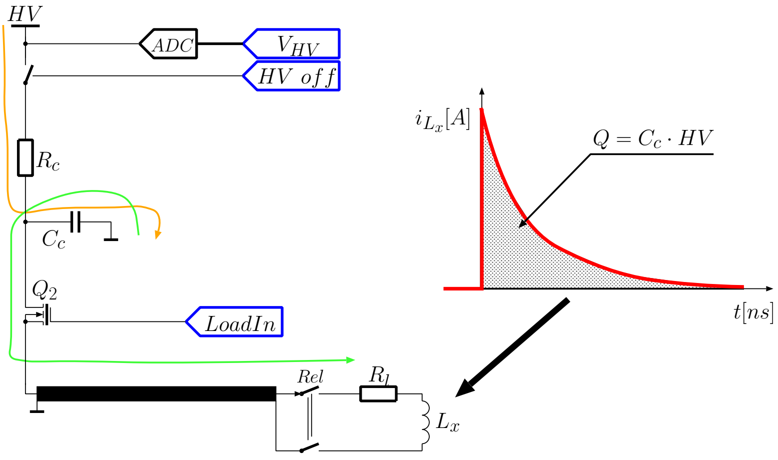
for those interested, e.g.:



Pulsed current sink

Calibration by charge

for those interested:



Charge-type calibrator

There are of course other methods how to obtain the charge information from the beam signal acquired by discussed devices, e.g.:

- observation of initial amplitude of resonant-mode transformer
- observation of specific harmonic frequency of the beam
- integrating current transformer (e.g. Vos., SL/94-18, CERN)
- dark current monitor (see today's talk of D. Lipka, WEOC03)

See the references section at the end of this presentation ...

PART II

What measurement methods are available?

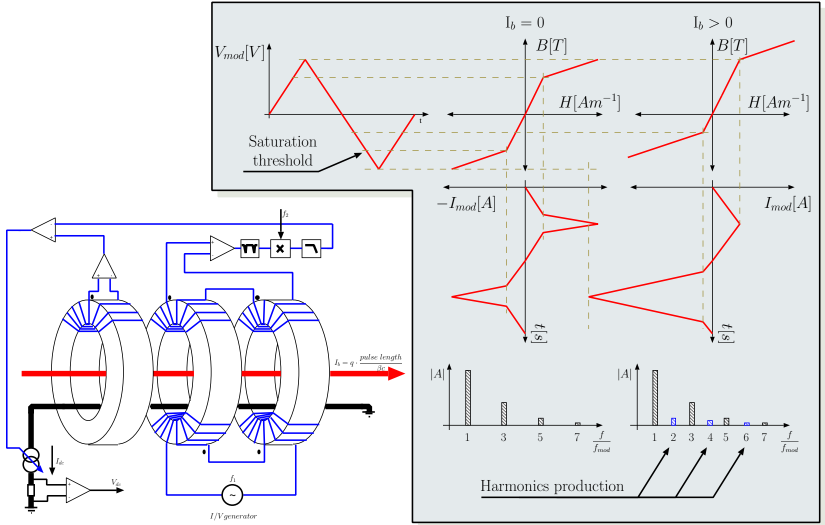
A) Non-DC beam current measurements

What is needed to get the beam signal?
How to process the beam signal?

B) DC beam current measurements

How DCCTs and Magneto-resistance sensors work

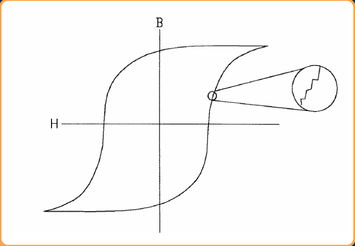
DCCT - principle of operation



DCCT: principle of operation

DCCT design issues

- Modulation current/voltage:
  - what signal: triangular, sine, square
  - high voltage/current amplitude to drive cores into saturation
  - generator signal purity (minimise even components of f_{mod}) when non-linear load
- Choice of modulation frequency limits the modulator BW:
  - crystalline material (NiFe): few hundreds Hz
  - amorphous/nanocrystalline material (Fe, Co-based): few kHz
- Magnetic material used:
  - $\mu_r \geq 50000$
  - low BH curve area
  - low coercive field $H_c \approx 1\ A/m$
  - wound using combination of mg. material + Mylar (typ. 20/5 μ ratio) to minimise eddy current losses
  - low magnetostriction
  - small magnetic domains to minimise Barkhausen noise



B-H granularity ⇝ mg. domains size

To be used for precise DC current measurements

- measures everything: debunched, ghost and satellites, circulating beams
- due to feedback linear over 6 decades
- FS=$\langle 10mA; 100A \rangle$, resolution down to 1 μA, BW$\leq$50 kHz

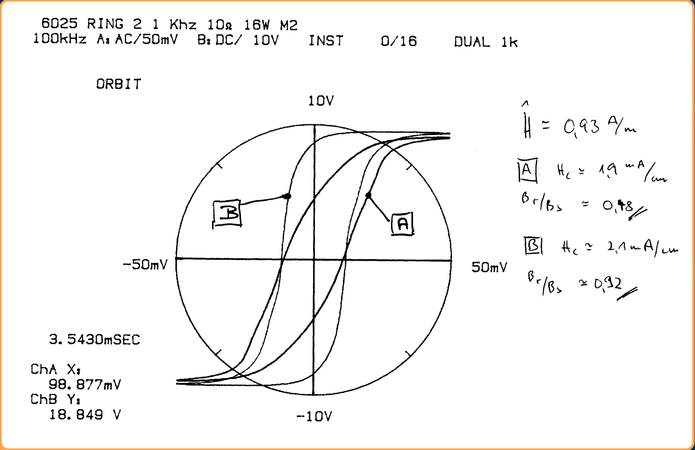
Calibration mostly using commercial DC current sources:

- Yokogawa GS200: accuracy ± 0.03 % of setting + 5 μA
- Keithley 224: accuracy ± 0.05 % of setting + 10 μA on 20 mA

Development heading to resolve:

- offset suppression & temp. dependence ($\approx$ 5 μ A/K)
- material procurement

DCCT - material procurement is fancy stuff

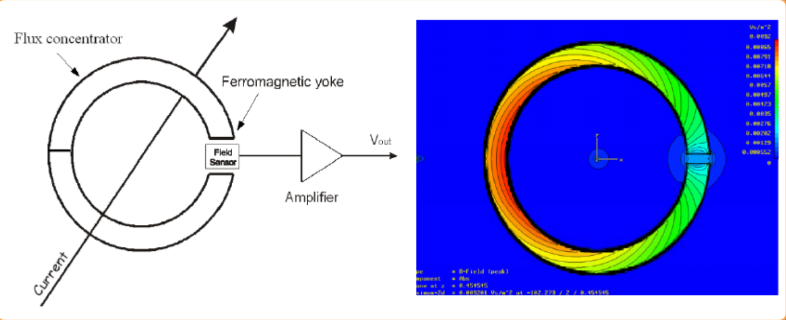


H. Reeg: B-H curve measurements, Vitrovac 6025F

Vitrovac ordered with the same specification at different time.

(VacuumSchmelze production technology didn't change!)

Usage of magneto-resistance (GMR, AMR) and magneto-impedance sensors to get the beam info: GSI novel-DCCT



Häpe, M. et al., DIPAC2005

Beam currents in hundreds-A range, clip-on configuration

Invite you to see next talk by Wolfgang Vodel

Overview on Cryogenic Current Comparators for Beam Diagnostics

THANK YOU FOR YOUR ATTENTION

This presentation would not be possible without kind participation of many people around the world - thanks a lot:

P. Cameron, M. Heron, K. Scheidt, H. Reeg, D. Lipka, P. Forck, M. Wendt, A. Peters, M. A. Ibrahim, M. Wilinski, W. Vodel, P. Odier, S. Smith, M. Ferianis, E. C. Deibele, M. Werner, K. Wittenburg

PART III
References used

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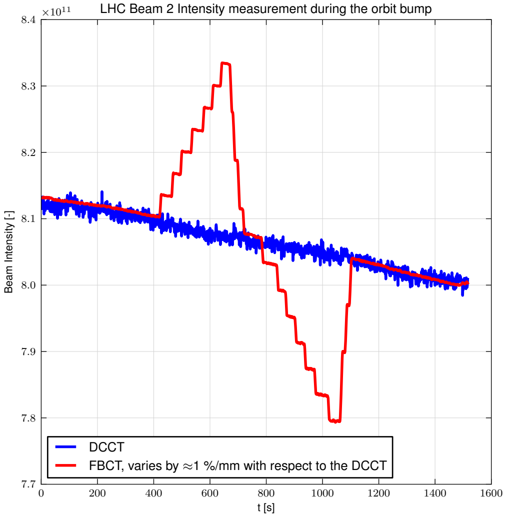
PART IV
Extras

Intensity measurements during LHC orbit bump



≈1 %/mm bunch position dependency of the FBCT toroid