
CERN

# CERN, from a beam instrumentation perspective
# A deeper view on some traditional instruments

D. Alves on behalf of the CERN SY-BI-IQ section

# Material providers


## Acknowledgements

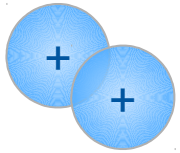
- R. Jones (CERN)
- T. Lefèvre (CERN)
- M. Gasior (CERN)
- O. Marqversen (CERN)
- S. Thoulet (CERN)
- R. Ruffieux (CERN)
- R. Hernandez (IFIC)
- P. Forck (GSI)
- R. Steinhagen (GSI)
- M. Krupa (CERN)

CERN SY-BI-IQ section

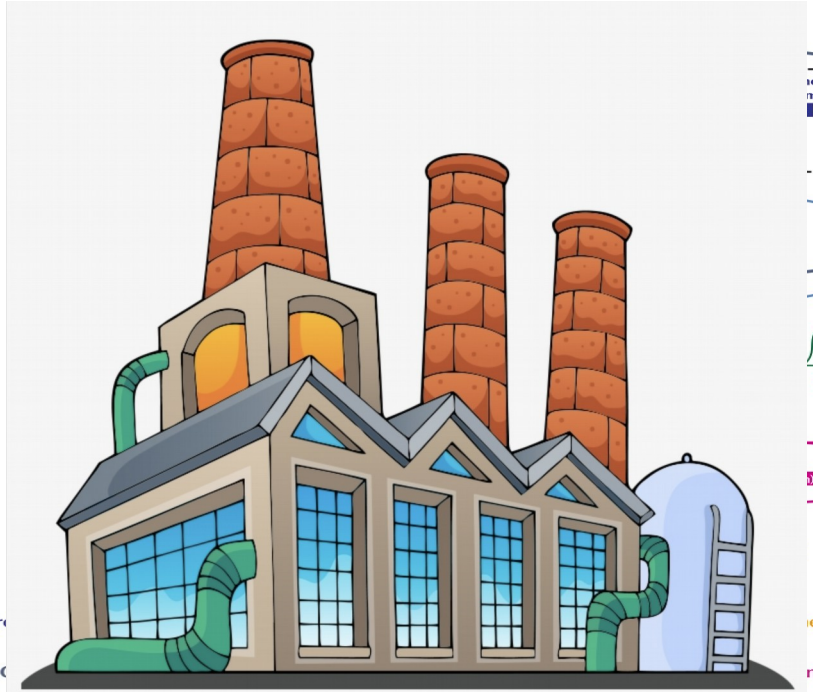
# Outline

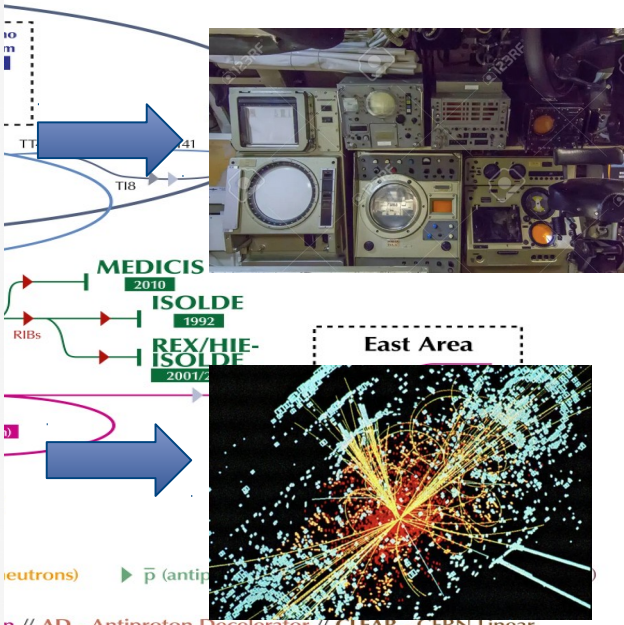
- CERN & Beam instrumentation
- Instruments in SY-BI-IQ
  - Fast beam current transformers
  - Beam position monitors
  - Tune monitors
  - *Potpourri* of other instruments

# CERN




Coffee

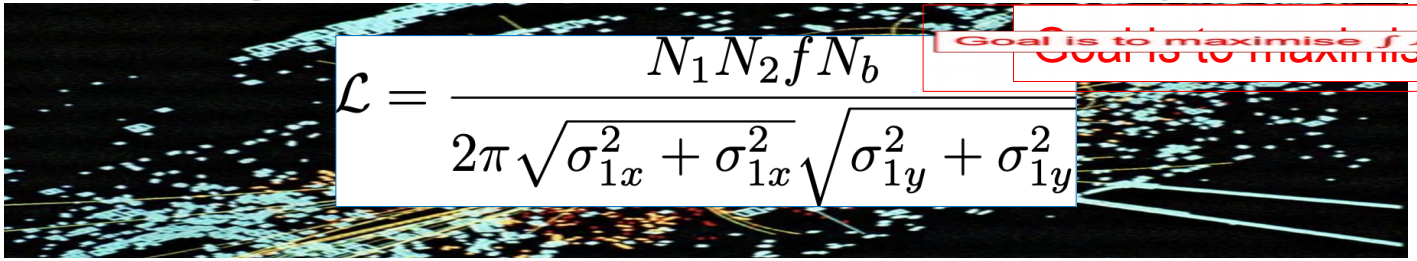



The CERN accelerator complex
Complexe des accélérateurs du CERN
TI8
MEDICIS
2010
ISOLDE
1992
RIBs
REX/HIE-
East Area
Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive
EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator //
n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

# Beam instrumentation

- What do we mean by beam instrumentation?
  - The “eyes” of the machine operators
    - The instruments that observe beam behaviour
    - Enable beam optimization (steering, stability, lifetime, luminosity, …)
- 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

# Colliding beams luminosity



$$\mathcal{L} = \frac{N_1 N_2 f N_b}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{1x}^2}\sqrt{\sigma_{1y}^2 + \sigma_{1y}^2}}$$

Goal is to maximise $\int \mathcal{L}(t)dt$!!!

**LHC**: $N_{1,2}\sim10^{11}, f\sim11kHz, N_b$ **LHC**: $\sim2800, \sigma\sim10\mu m \Rightarrow \mathcal{L}\sim10^{34}cm^{-2}s^{-1}$

Collisions: $\sim6\times10^{8}s^{-1}$ ~20 per bunch crossing

Collisions: , per bunch crossing

- Minimise beam losses (i.e. keep $N_{1,2}$ as large as possible)
- Maximise beam stability
- Minimise beam-beam separation
- Minimise transverse beam sizes
- Luminosity can also be measured directly

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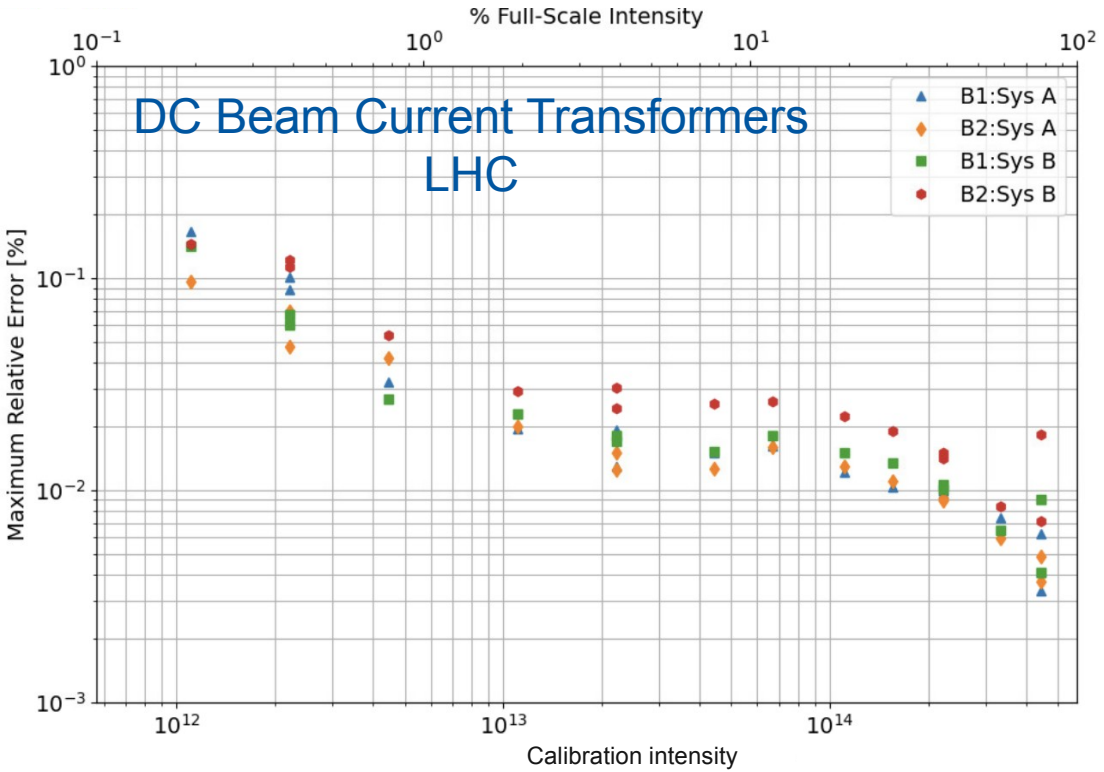
**Beam instrumentation**

# Beam intensity measurement

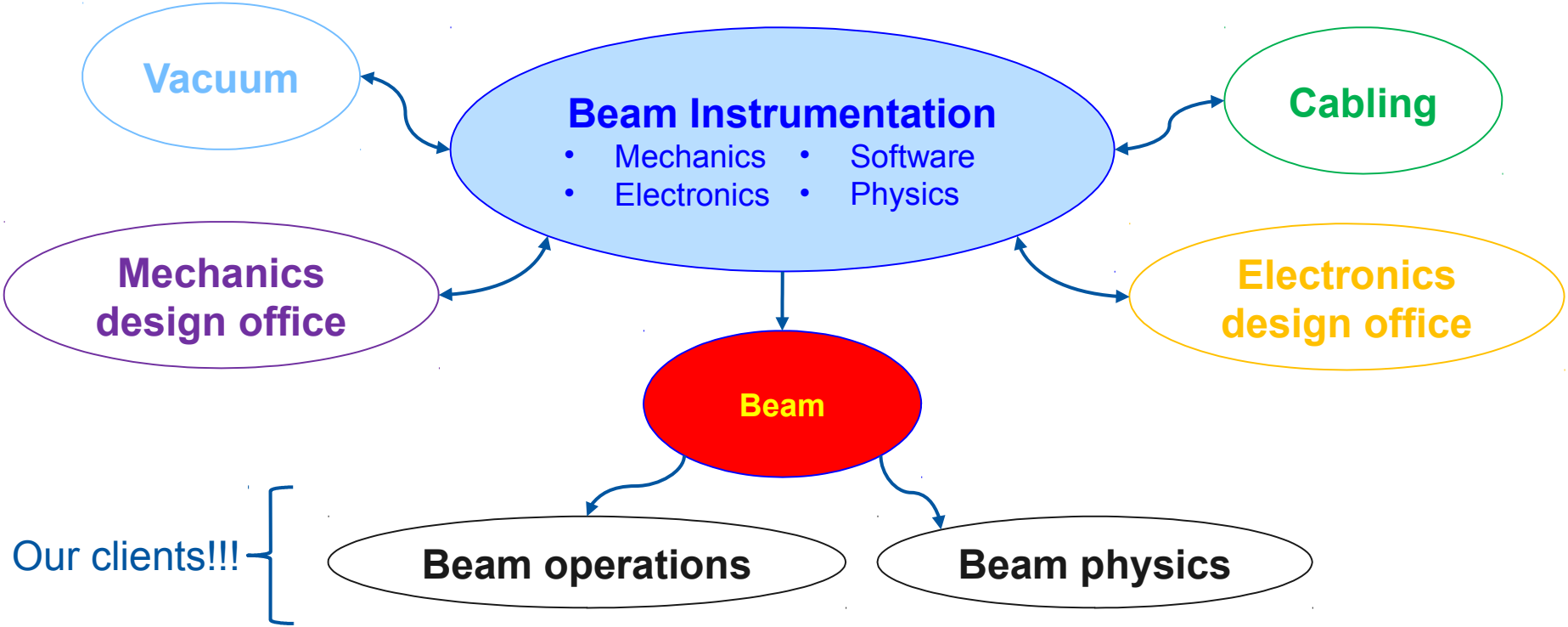



- Need to cover ~ 5 orders of magnitude
- > 1% of full-scale, relative error < 0.03%

# Beam instrumentation – who are we?

- Technicians, Engineers, Physicists
  - Mechanics
  - Electronics (analog + digital)
  - Software
  - Instrumentation physics
  - Beam physics

# Beam instrumentation – where are we?



# Beam instrumentation group structure at CERN

| BP section<br>Position Measurement | IQ section<br>Intensity Measurements | XEI section<br>Experimental Areas, e-Beam, Ion, Monitors |
|---|---|---|
| Position Measurements<br>Pick-up design | Intensity Measurements<br>Schottky Measurements<br>Tune, chromaticity, instability<br>DOROS | N,W,E,EA beam-instrumentation<br>AD/ELENA user beam line<br>e-cooling |

| PM section<br>Profile Measurements | BL section<br>Beam Loss |
|---|---|
| BI optics support<br>TV Syst. SEM monit.<br>Sync. Light Monitors<br>ISOLDE Inst. Fast<br>Cameras - Wire Scanners.<br>LHC Longit. Profile & Lumi | Beam Loss Monitoring<br>Motorisation.<br>Monitoring<br>SPS Spill control |

Work across instruments

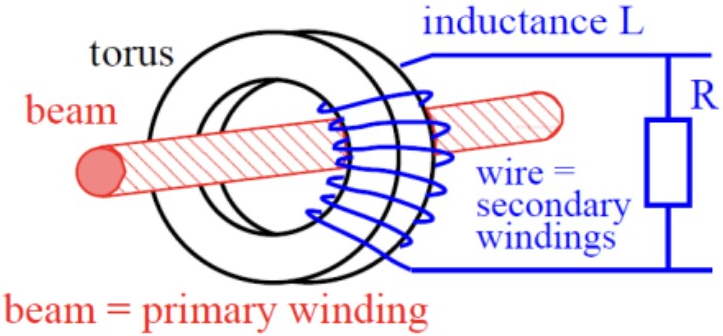
| SW section<br>Software Support | ML section<br>Mechanics & Logistics |
|---|---|
| Software for instruments & expert diagnostic tools | Group support on:<br>Mechanics<br>AT/VAC interface<br>Installations<br>Shutdown planning |

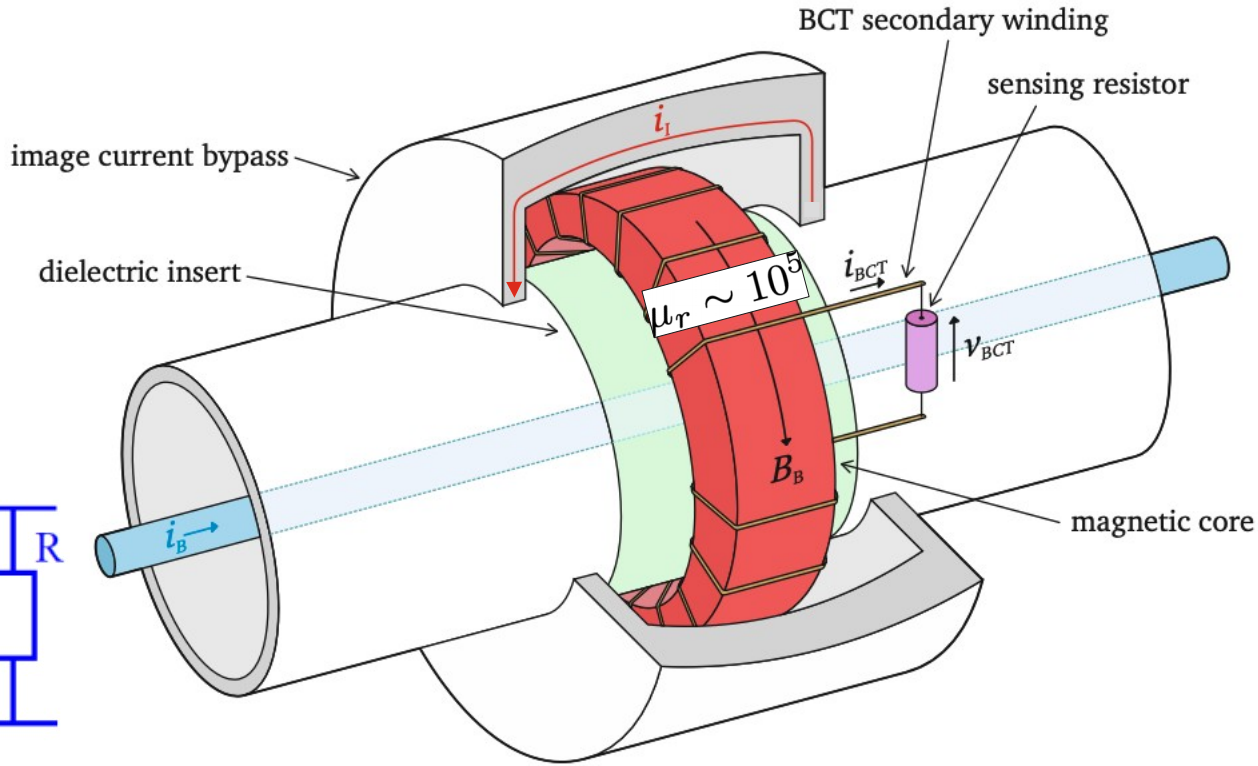
# (Some) instruments in the IQ section

| Instrument | Where? | What do we measure? |
|---|---|---|
| Fast Beam Current Transformers | • All transfer lines<br>• Most circular machines | Beam intensity, bunch intensity |
| DC Beam Current Transformers | • Most circular machines | Beam intensity |
| Tune measurement systems | • All circular machines | Tune (resonant beam oscillations) |
| Beam position monitoring | • AD, ELENA and LEIR<br>• SPS and LHC (DOROS) | Beam position |
| Schottky monitors | • ELENA, LEIR and LHC | Momentum distribution, synchrotron tune, betatron tune, chromaticity, … |
| Head-tail + Instability monitoring | • SPS and LHC | Intra-bunch oscillations |
| LHC beam-based feedbacks | • LHC | Orbit feedback, tune feedback |

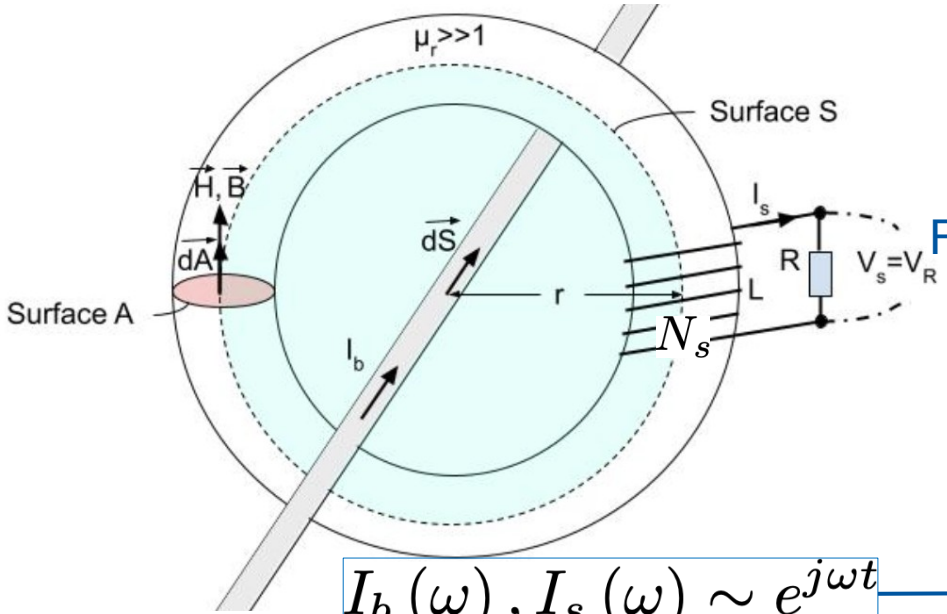
# Fast Beam Current Transformers

# Fast Beam Current Transformers



# Fast Beam Current Transformers




Ampere's law: $$\int_S \left(\vec{\nabla} \times \vec{H}\right) \cdot \vec{dS} = I_b + N_s I_s$$

$$B = \mu_0 \mu_r H = \frac{\mu_0 \mu_r}{2\pi r} \left(I_b + N_s I_s\right)$$

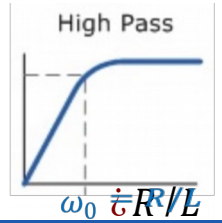
Faraday's law: $$V_s = -N_s \frac{\partial \phi_B}{\partial t} = -N_s \frac{\partial}{\partial t} \int \vec{B} \cdot \vec{dA}$$

$$\frac{L}{N_s}$$

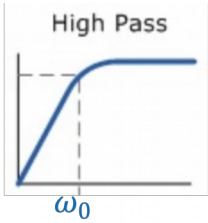
$$RI_s = \frac{\mu_0 \mu_r A N_s}{2\pi r} \frac{\partial}{\partial t} \left(I_b + N_s I_s\right)$$

$$I_b(\omega), I_s(\omega) \sim e^{j\omega t}$$

$$\frac{I_s(\omega)}{I_b(\omega)} = -\frac{1}{N_s} \frac{\frac{\omega^2 L^2}{R^2} + \frac{j\omega L}{R}}{1 + \frac{\omega^2 L^2}{R^2}}$$



# Fast Beam Current Transformers




$$\frac{I_s(\omega)}{I_b(\omega)} = -\frac{1}{N_s}\frac{\frac{\omega^2 L^2}{R^2} + \frac{j\omega L}{R}}{1 + \frac{\omega^2 L^2}{R^2}}$$

$\omega \ll R/L$ derivative

intermediate

$\omega \gg R/L$ proportional

$\frac{I_s(\omega)}{I_b(\omega)}$

$-\frac{1}{N_s}$

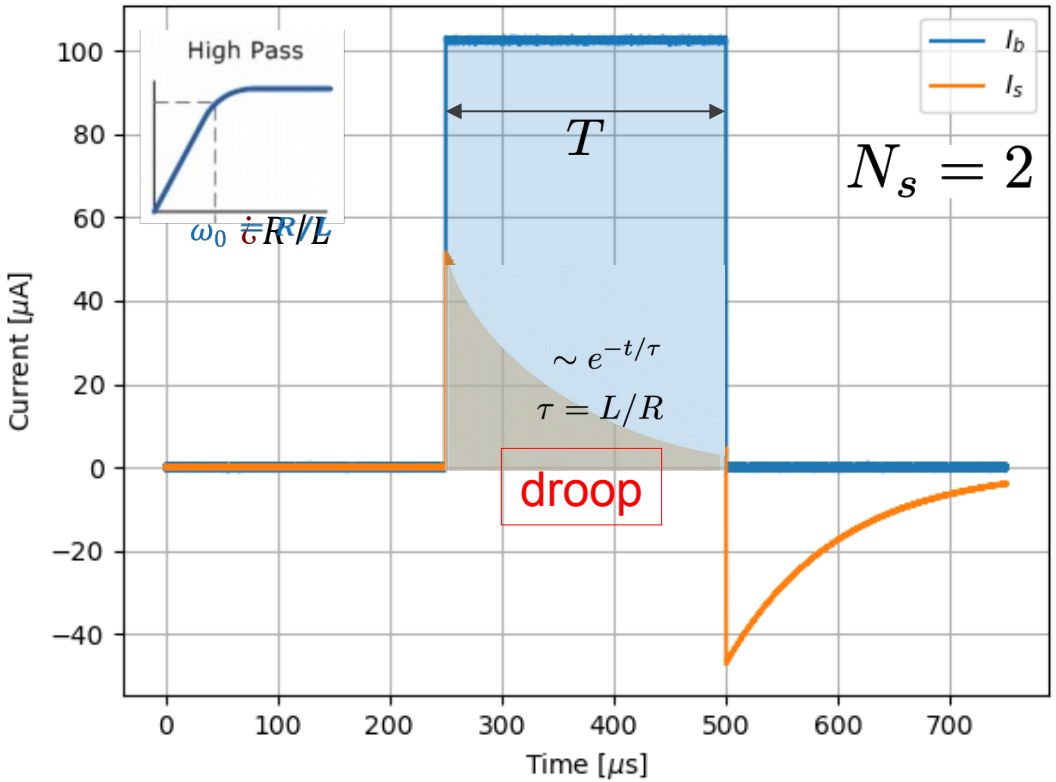
$-I_{beam}$

$I_s$

$10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$

Frequency [Hz]

# Fast Beam Current Transformers – transfer line




$$Q = \int_0^T I(t)dt$$

How to fix it? – Easy, make $\tau \gg T$

- Increase $L$ by increasing $N_s$

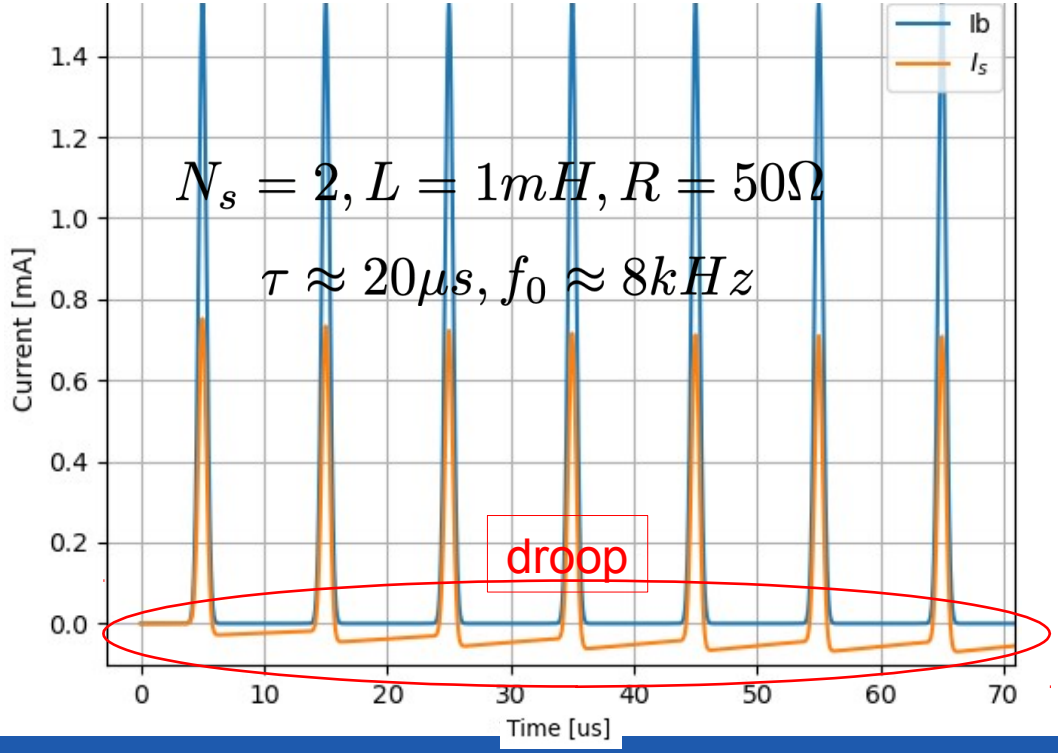
$$L = \frac{\mu_0 \mu_r A N_s^2}{2\pi r}$$ BUT $$V_s \propto -\frac{R}{N_s} I_b$$

- Decrease $R$

Again, the price to pay is $$V_s \propto -\frac{R}{N_s} I_b$$

# Fast Beam Current Transformers – circular machine

1 bunch with $f_{rev} = 100kHz$



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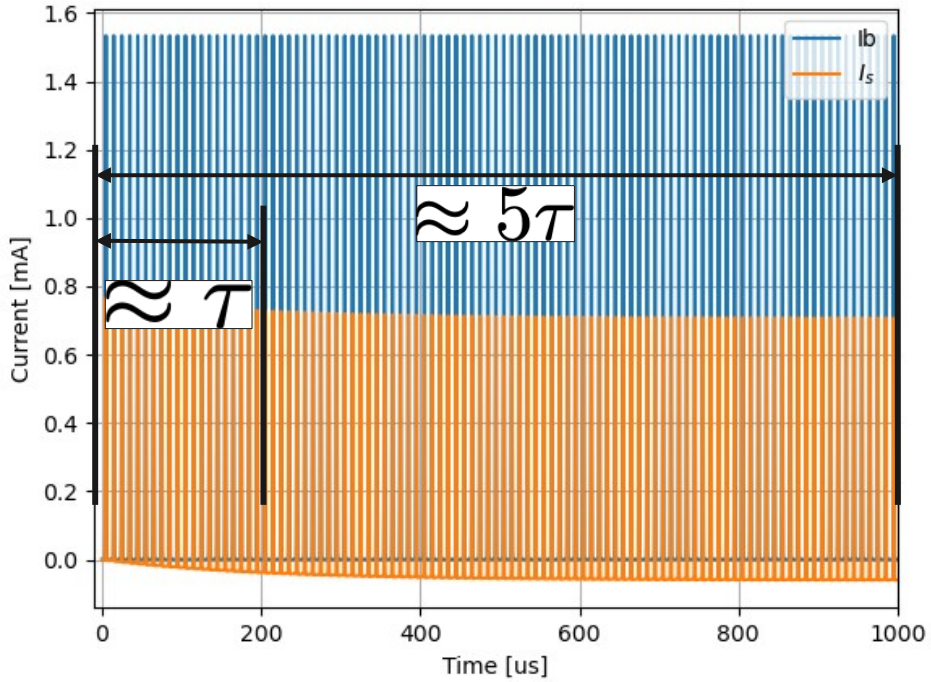
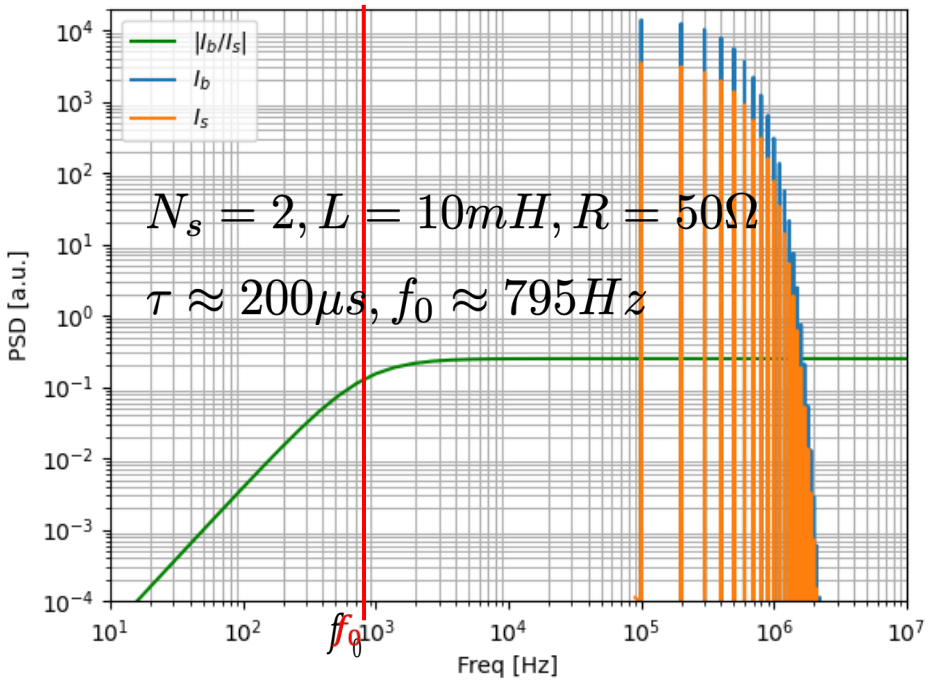
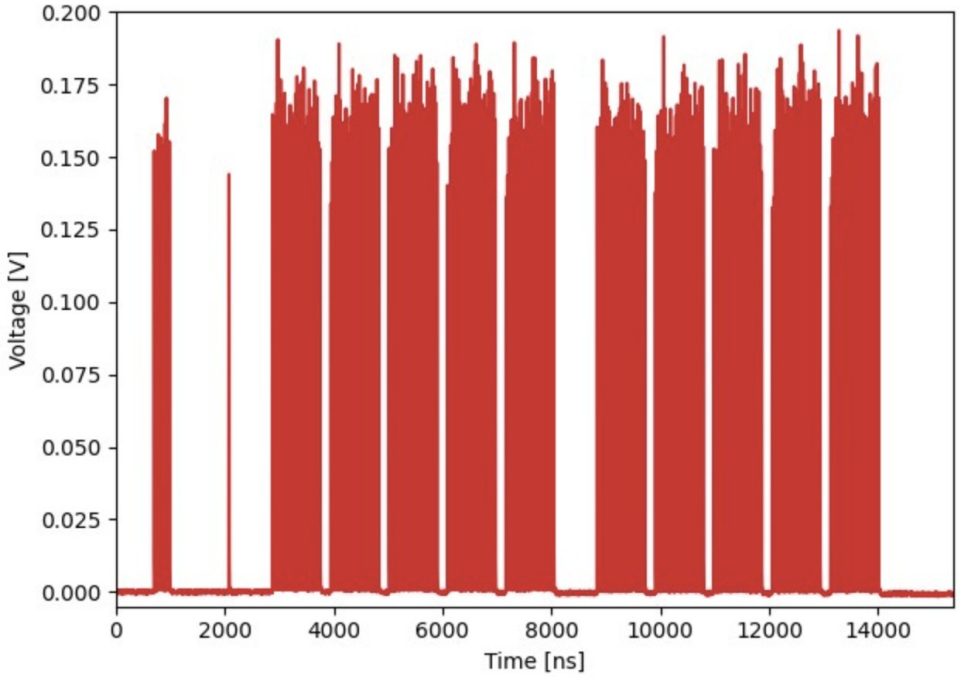
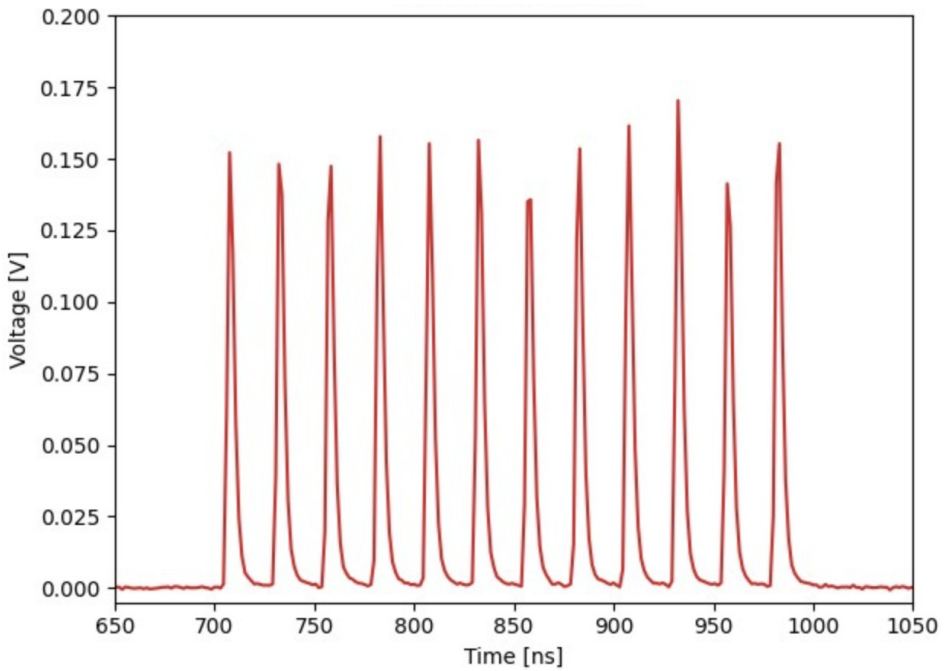


# Fast Beam Current Transformers – live measurements

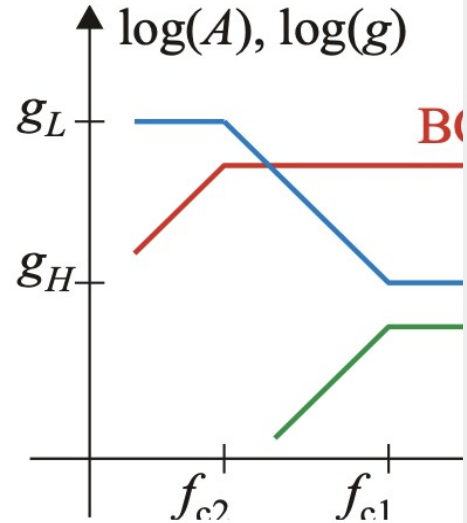


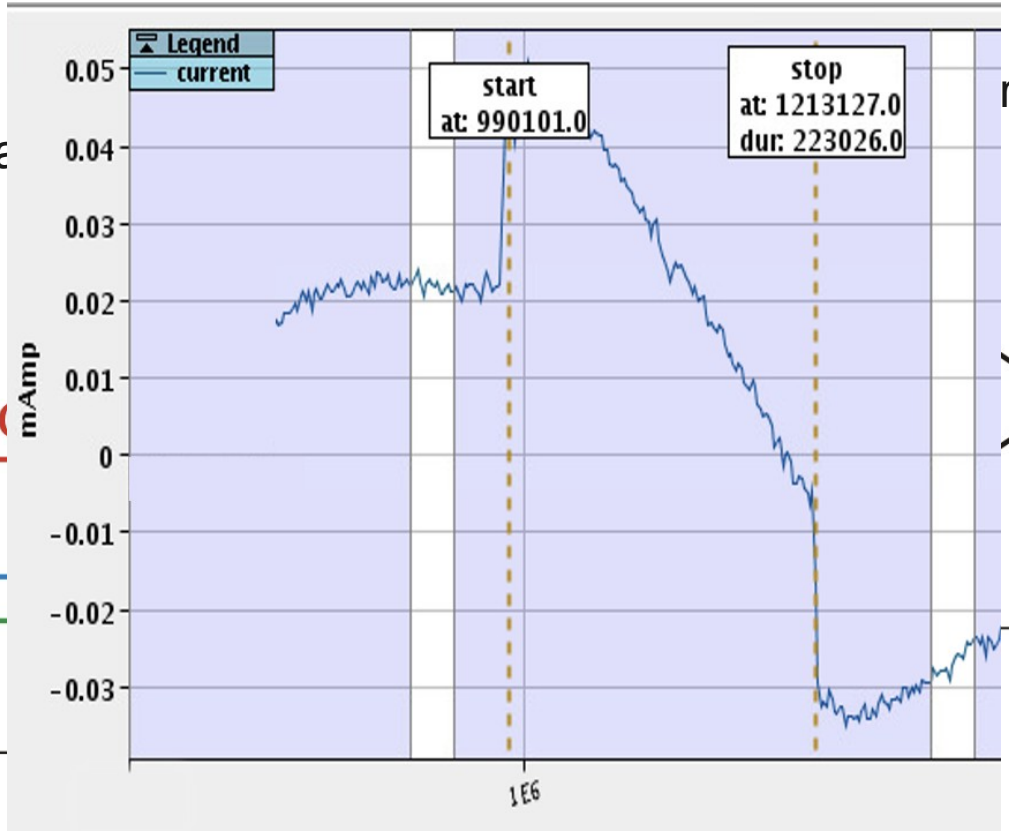



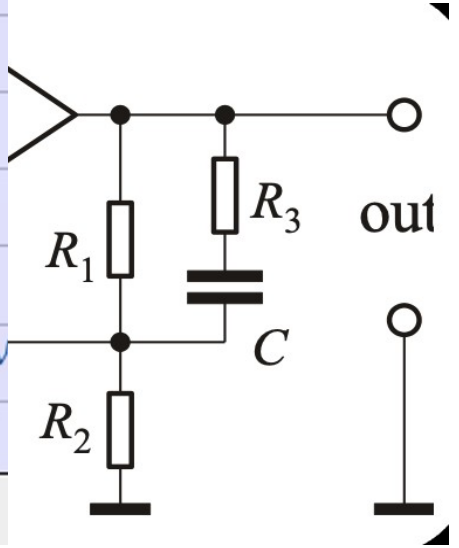
# Fast Beam Current Transformers – droop mitigation

- Compensation
- General accura

roop time)



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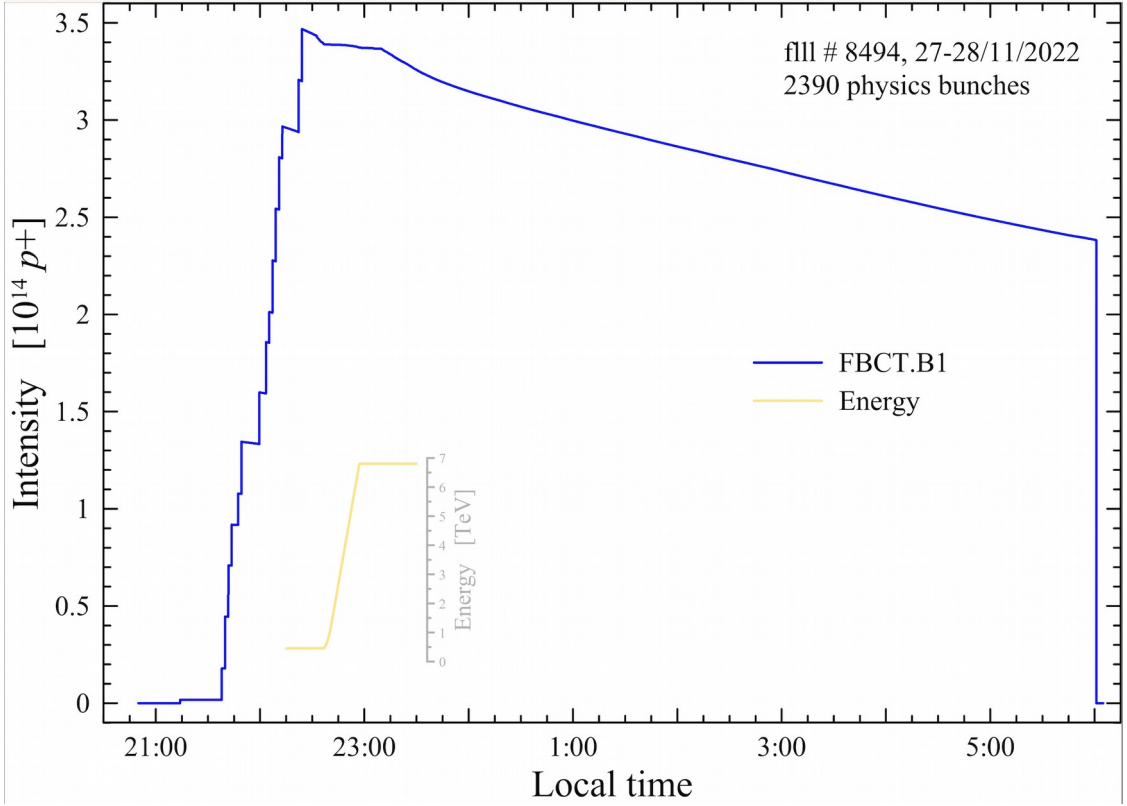
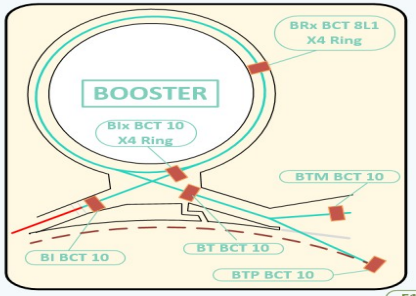
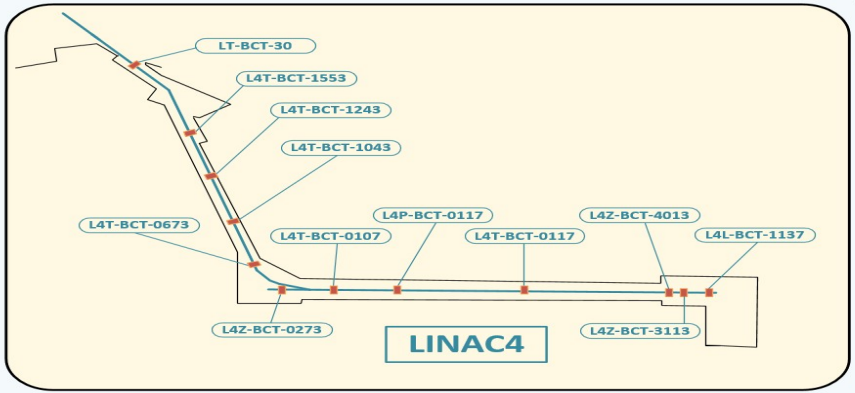
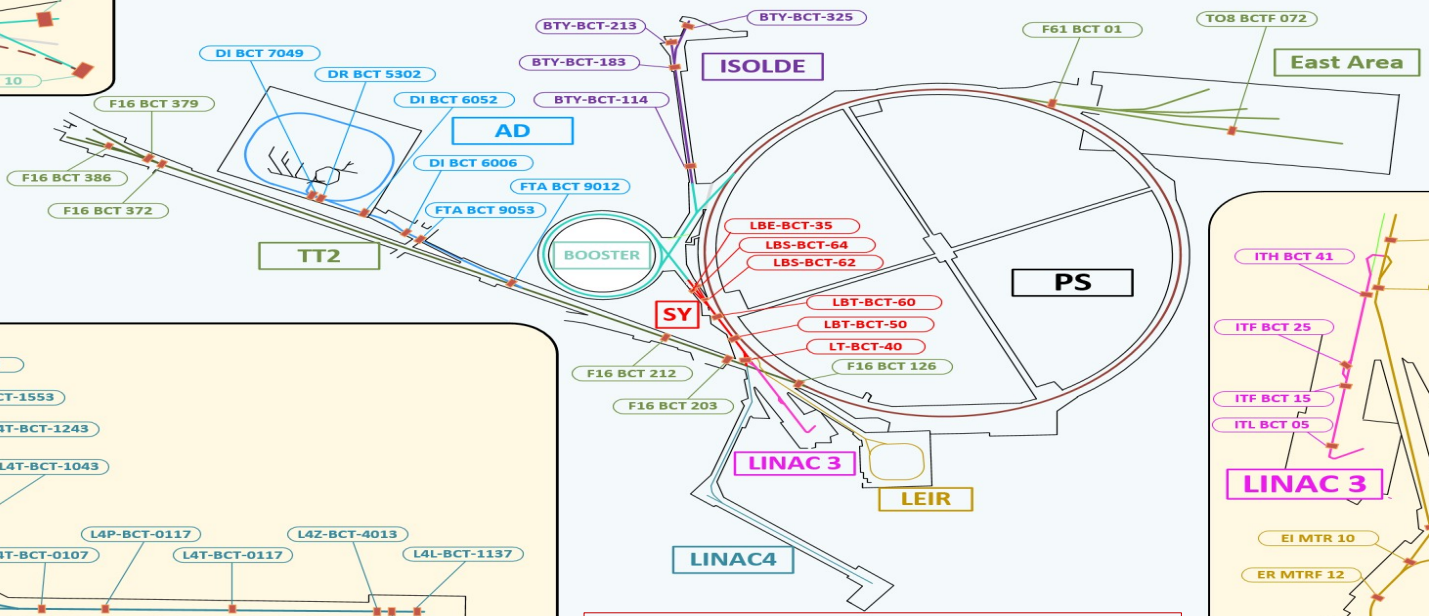
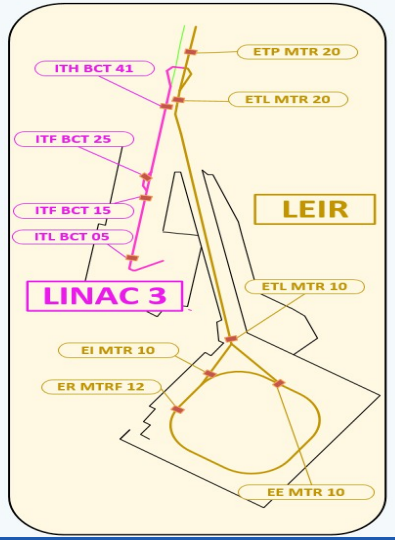


# Fast BCT PS Complex



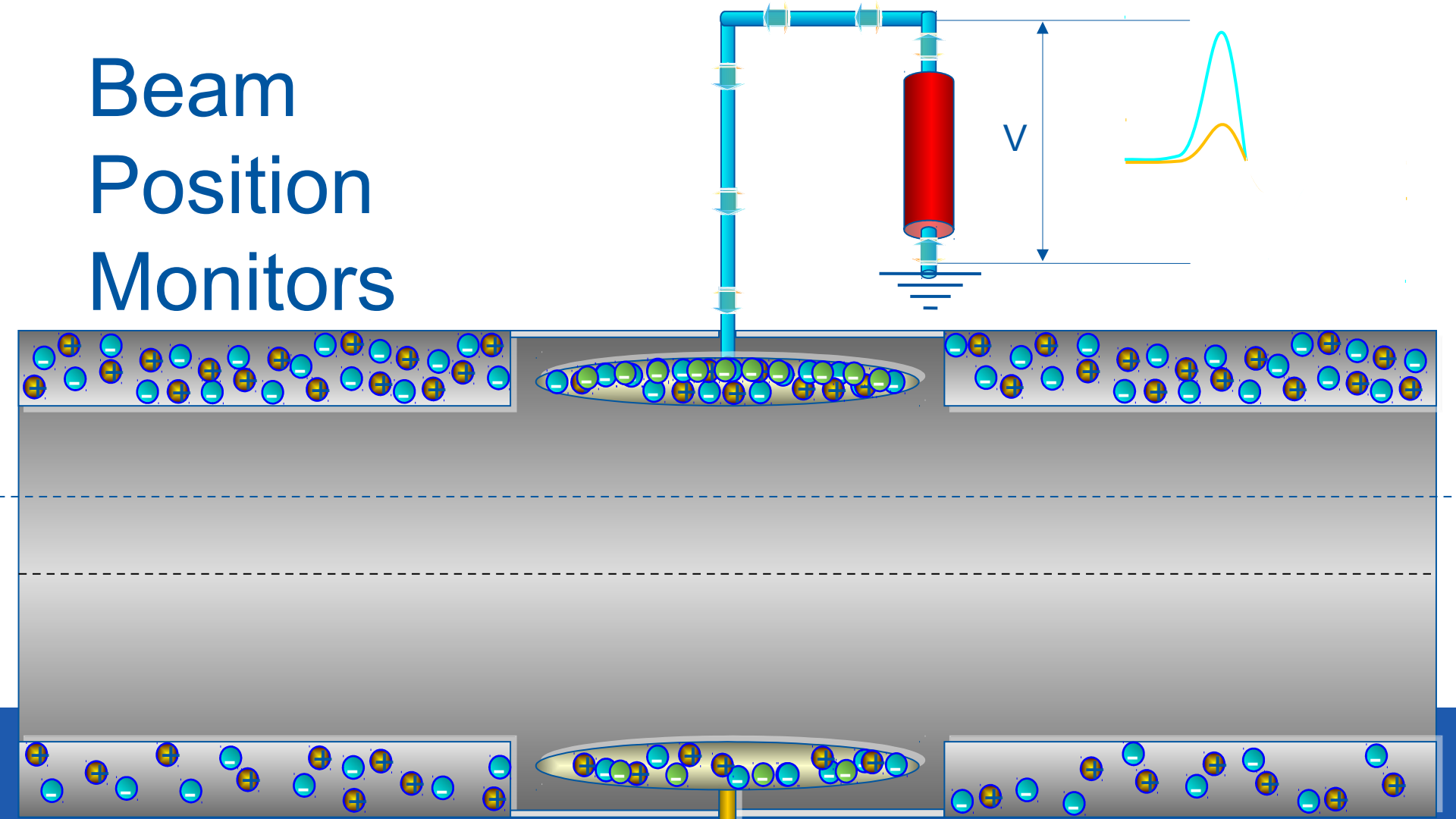




~ 70 installations

# Beam Position Monitors

# Beam Position Monitors



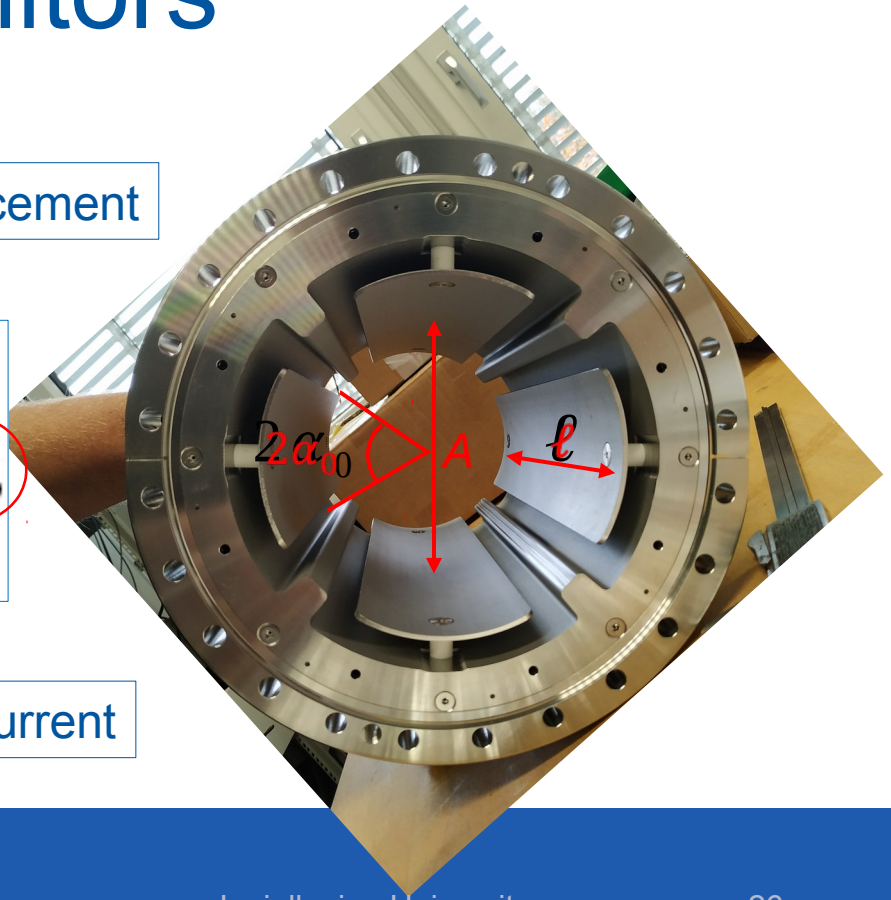
# Beam Position Monitors

Electrode charge

Beam displacement

$$Q \approx \frac{\alpha_0 l A/2}{\pi \beta c (A/2 + \Delta d)} I_b$$

Beam current



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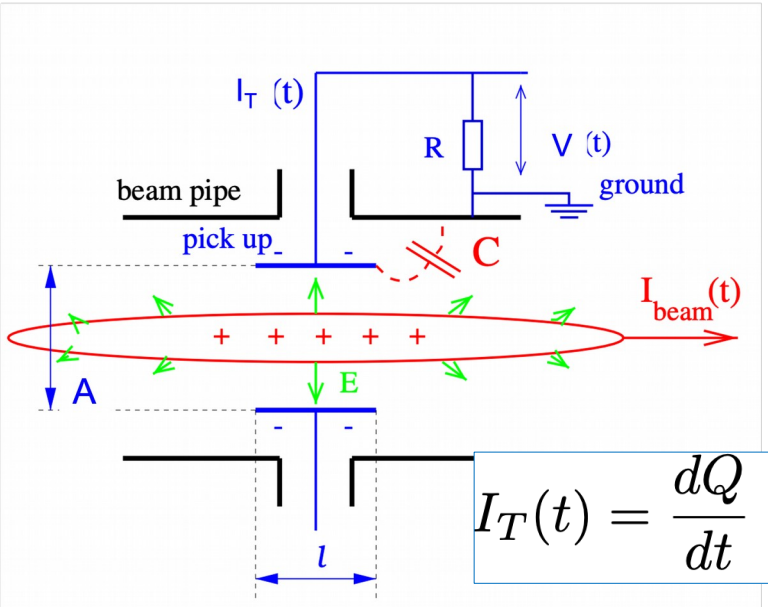
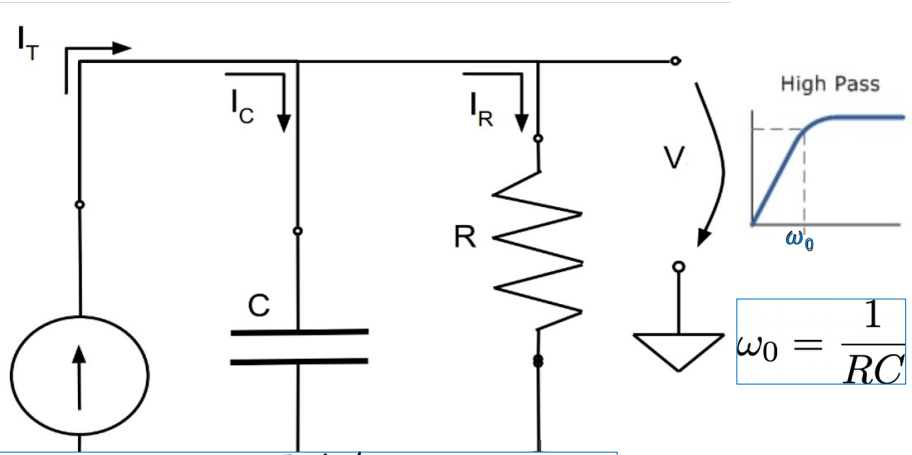
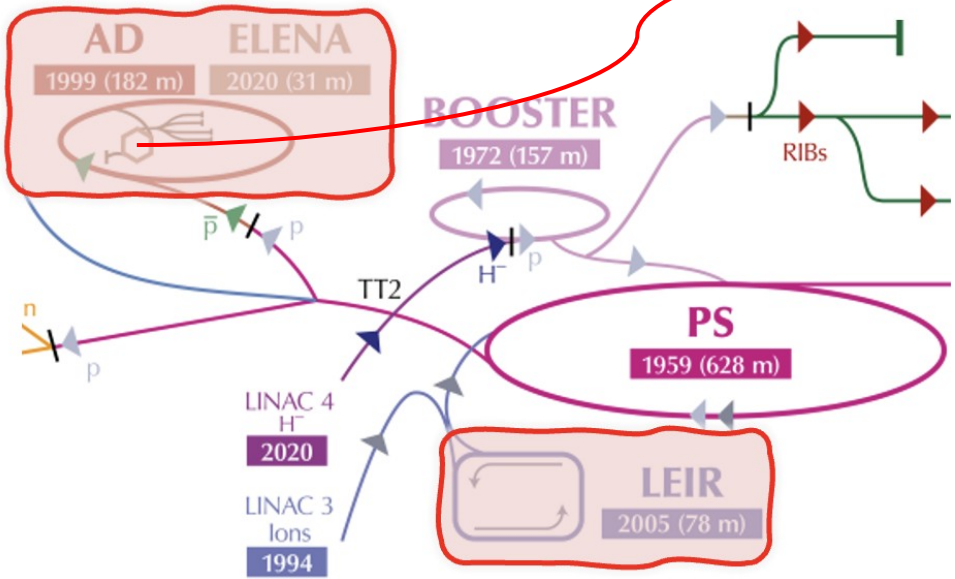


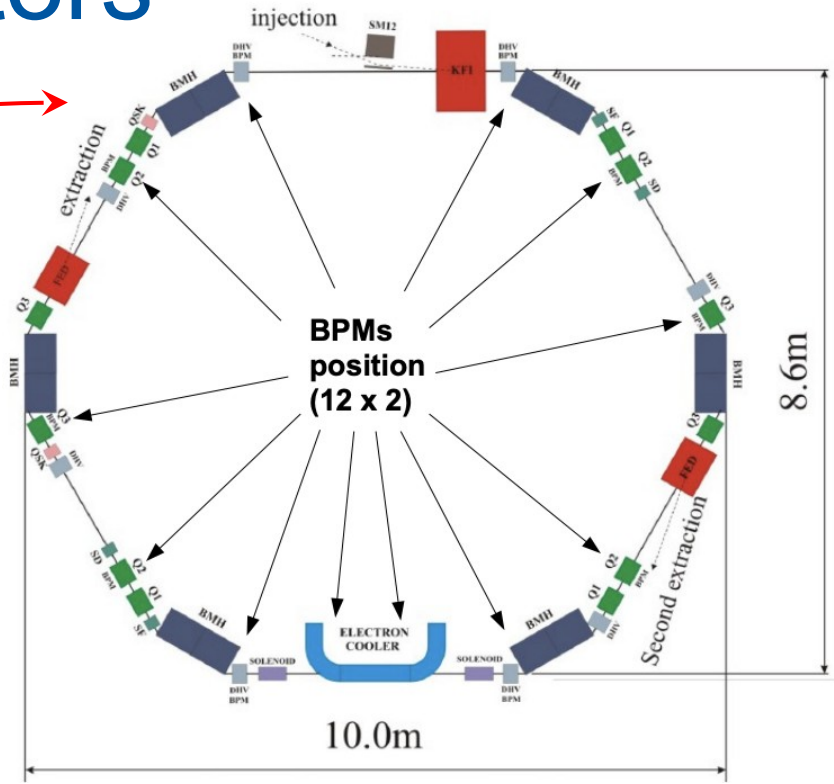




$$I_T(t) = \frac{dQ}{dt} \Rightarrow I_T(\omega) \approx j\omega \frac{\alpha_0 l A/2}{\pi\beta c(A/2 + \Delta d)} I_b(\omega)$$

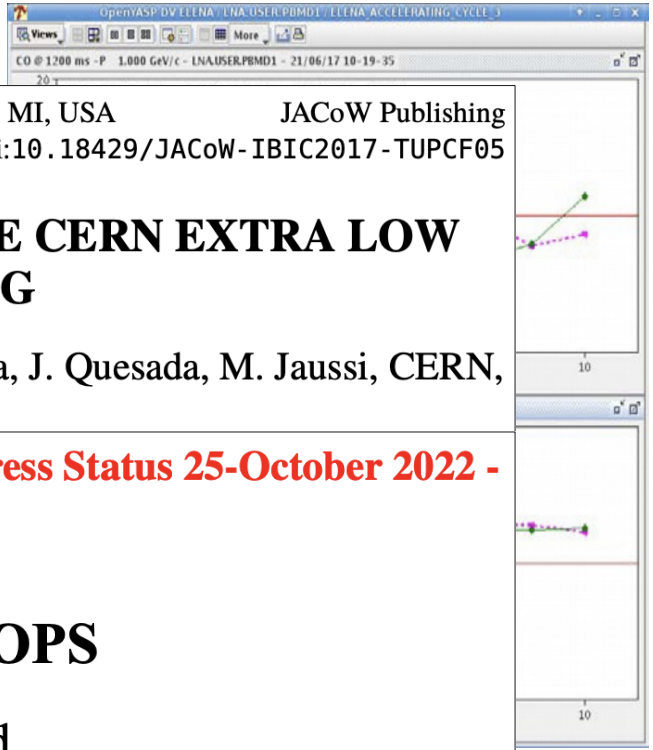
$$V(\omega) \approx \frac{1}{C} \frac{\omega^2 R^2 C^2 + j\omega RC}{1 + \omega^2 R^2 C^2} \frac{\alpha_0 l A/2}{\pi\beta c(A/2 + \Delta d)} I_b(\omega)$$

# Beam Position Monitors



# Beam Position Monitors - ELENA


6th International Beam Instrumentation Conference IBIC2017, Grand Rapids, MI, USA JACoW Publishing
ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TUPCF05

Momentum [MeV/c]

work, publisher, and DOI.

## THE ORBIT MEASUREMENT SYSTEM FOR THE CERN EXTRA LOW ENERGY ANTIPROTON RING

O. Marqversen†, R. Ruffieux, L. Søby, J. Molendijk, M.E. Angoletta, J. Quesada, M. Jaussi, CERN, Geneva, Switzerland

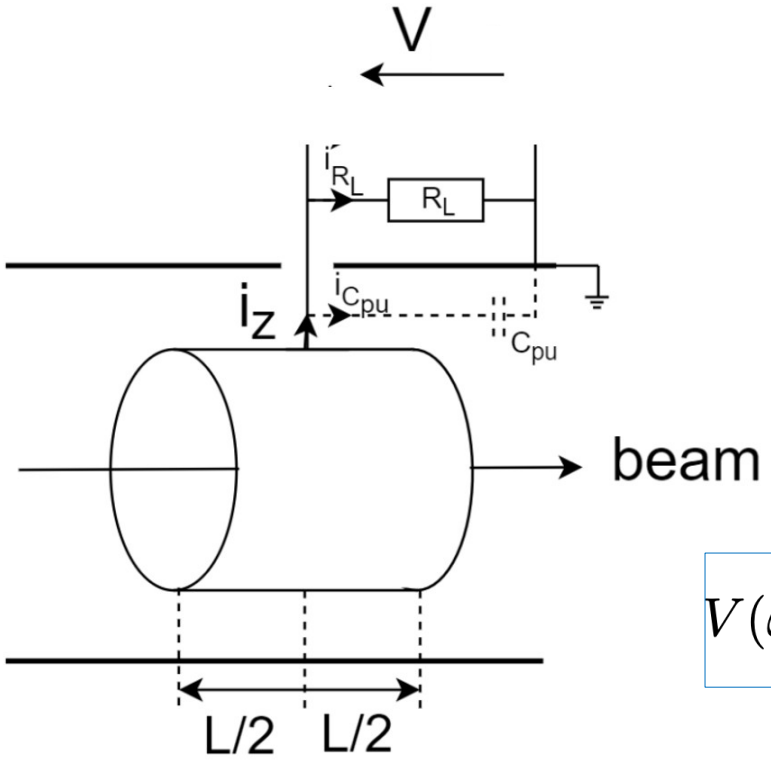
Proceedings of IBIC2022, Kraków, Poland - Pre-Press Status 25-October 2022 -

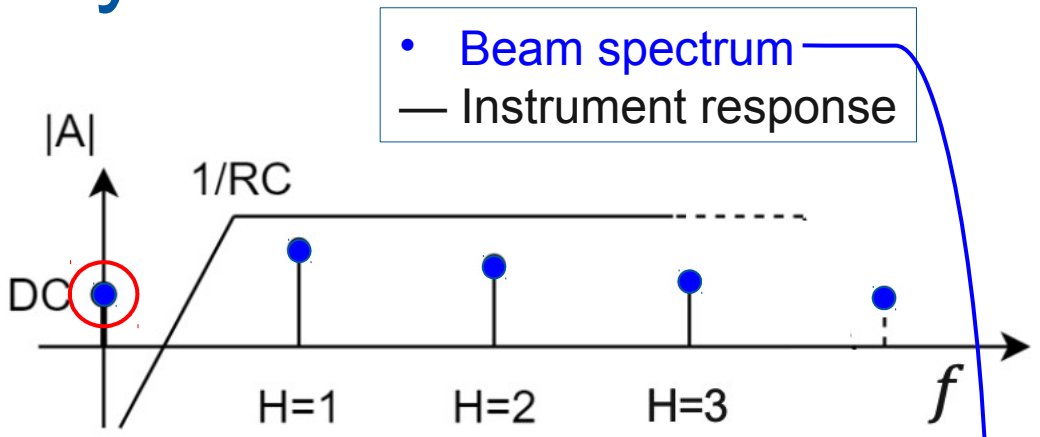
## AN LHC PROTECTION SYSTEM BASED ON FAST BEAM INTENSITY DROPS

M. Gasior, T. Levens, CERN, Geneva, Switzerland

$\Delta d \approx$

# BPM-based intensity

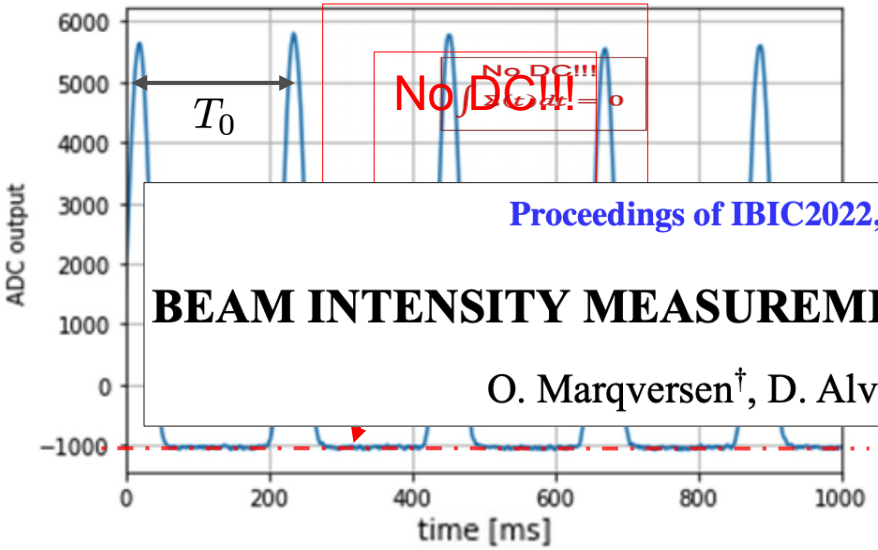


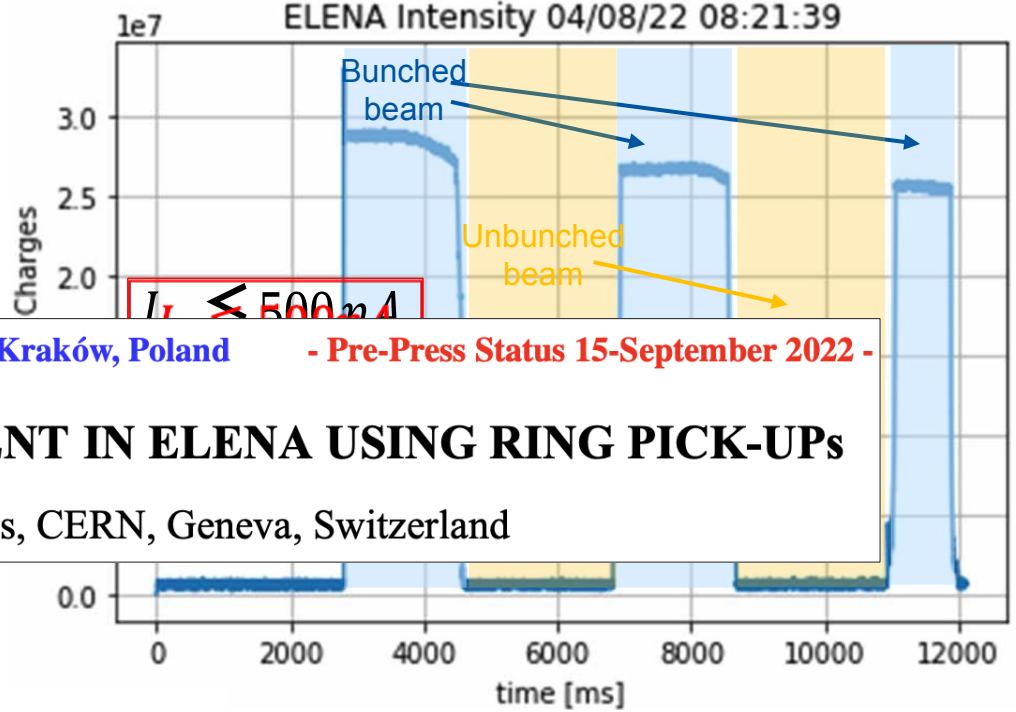




$$\omega \gg 1/(RC)$$

$$V(\omega) \approx \frac{1}{C} \underbrace{\frac{\omega^2 R^2 C^2 + j\omega RC}{1 + \omega^2 R^2 C^2}}_{\approx 1} \frac{lA/2}{\beta c(A/2 + \Delta d)} I_b(\omega)$$

# BPM-based intensity

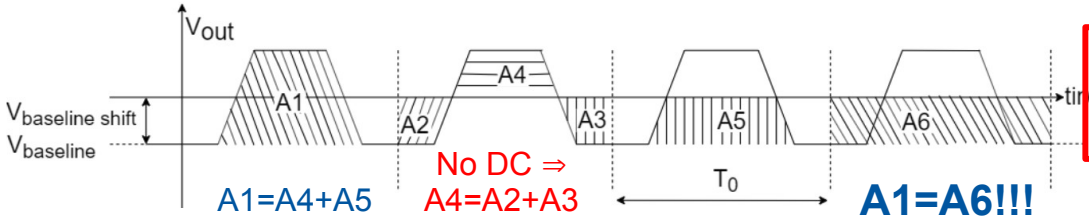



Proceedings of IBIC2022, Kraków, Poland - Pre-Press Status 15-September 2022 -

**BEAM INTENSITY MEASUREMENT IN ELENA USING RING PICK-UPs**

O. Marqversen†, D. Alves, CERN, Geneva, Switzerland

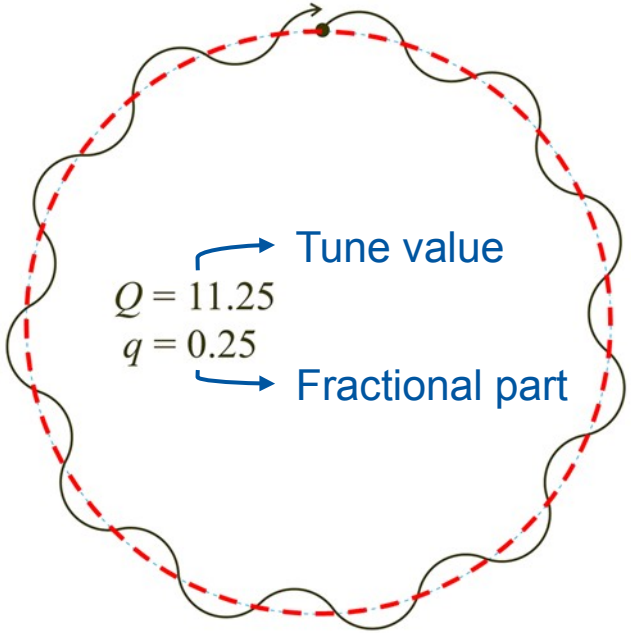


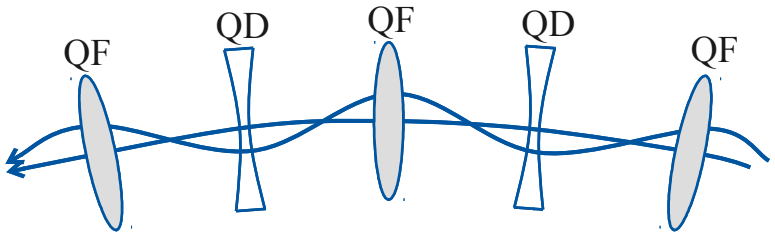

$$Q \approx C\frac{\beta c}{l}\int_0^{T_0}\Sigma(t)dt \approx CV_{baseline}\frac{L_{ring}}{l}$$

**Beam intensity, $\beta$ independent!!!**

# Tune monitors

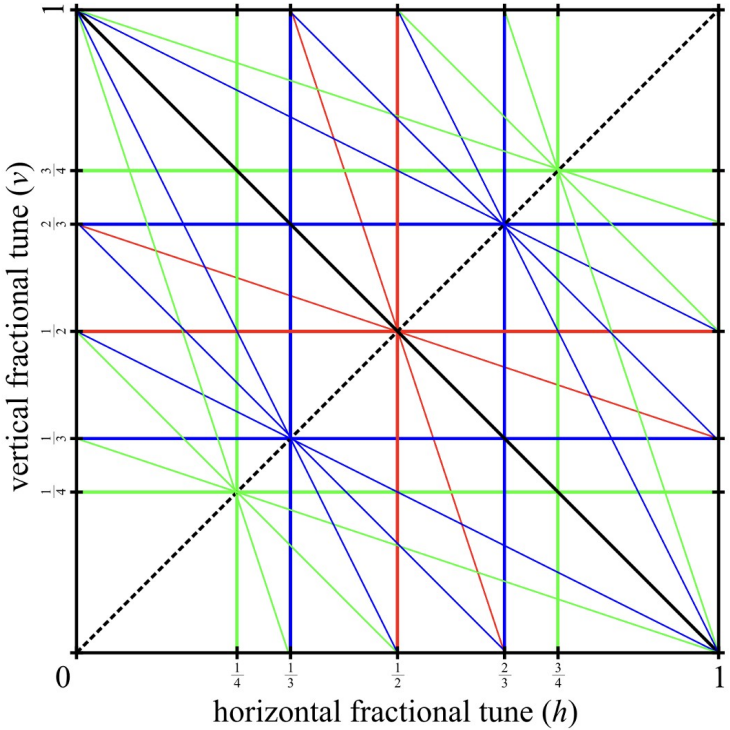
# Tune – what is it?




- Characteristic frequency of the magnetic lattice
- Given by the strength of the quadrupole magnets
- Defined as the number of transverse oscillations in a single turn
- Controlling the fractional part is crucial for beam stability

# Tune - beam stability




Resonance condition:

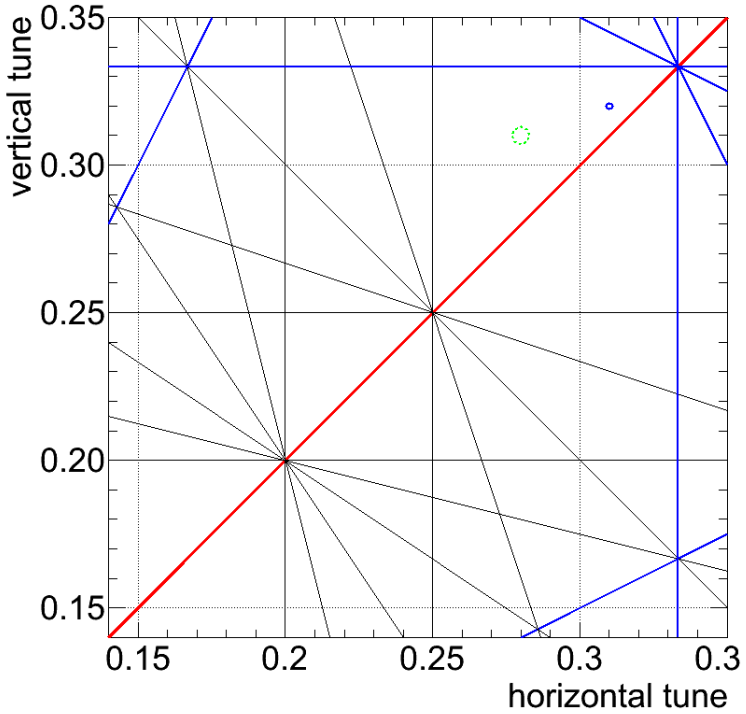
$$m\,h + n\,v = p$$

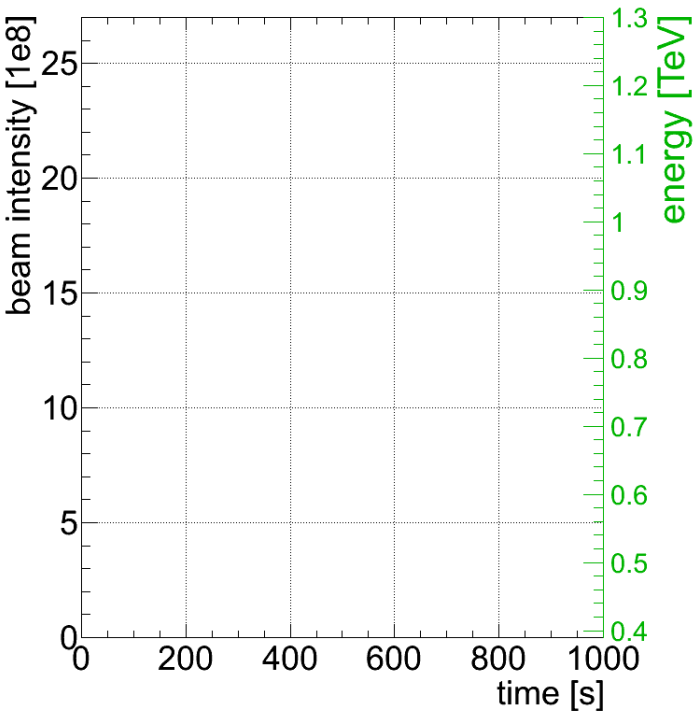
$h$, $v$ - horizontal and vertical tunes

$m$, $n$, $p$ - small integers

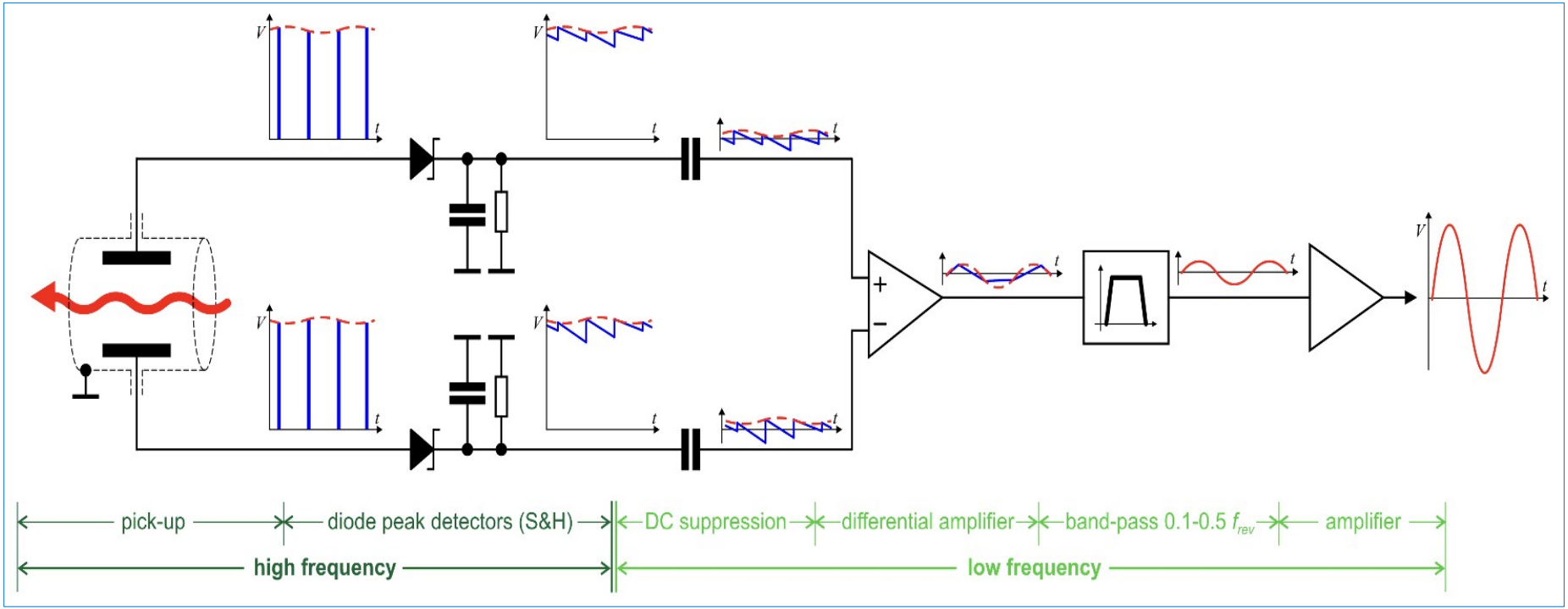
$|m| + |n|$ is the resonance order

# Tune – early energy ramps in the LHC

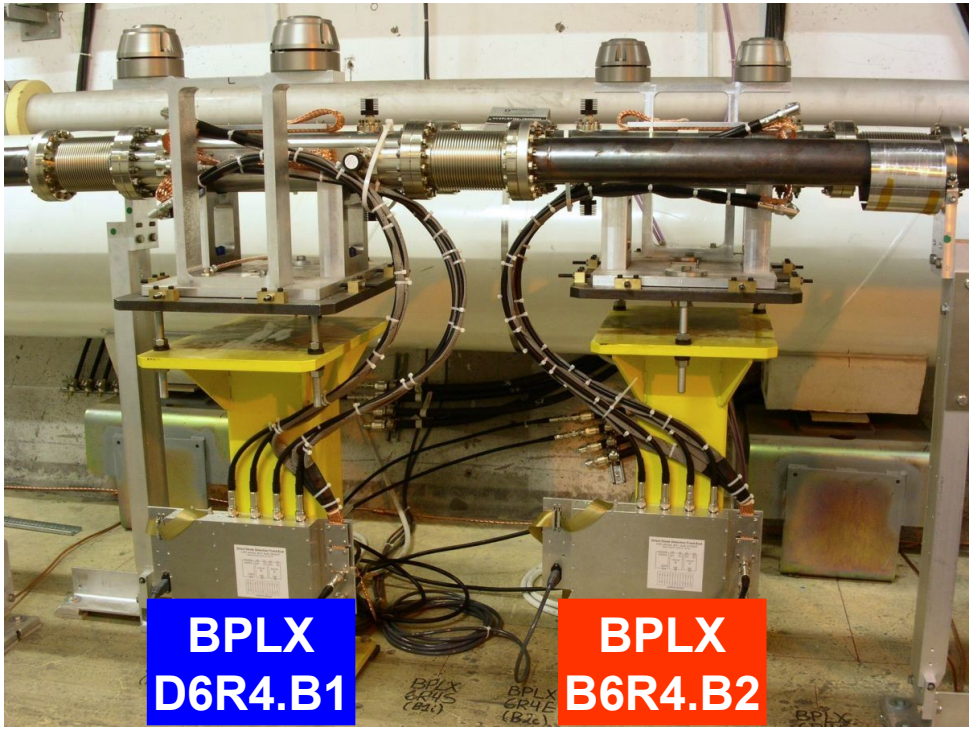


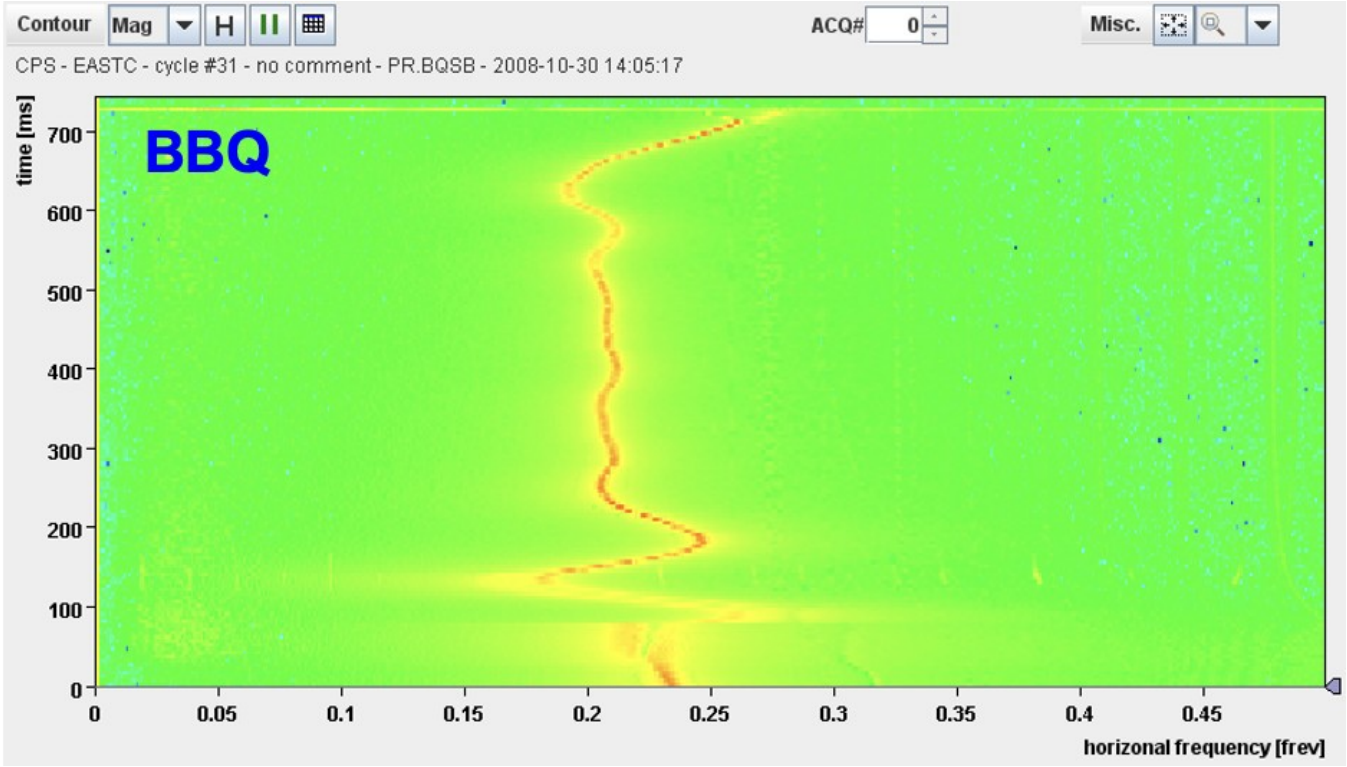
# Tune – a beam position monitor with special electronics



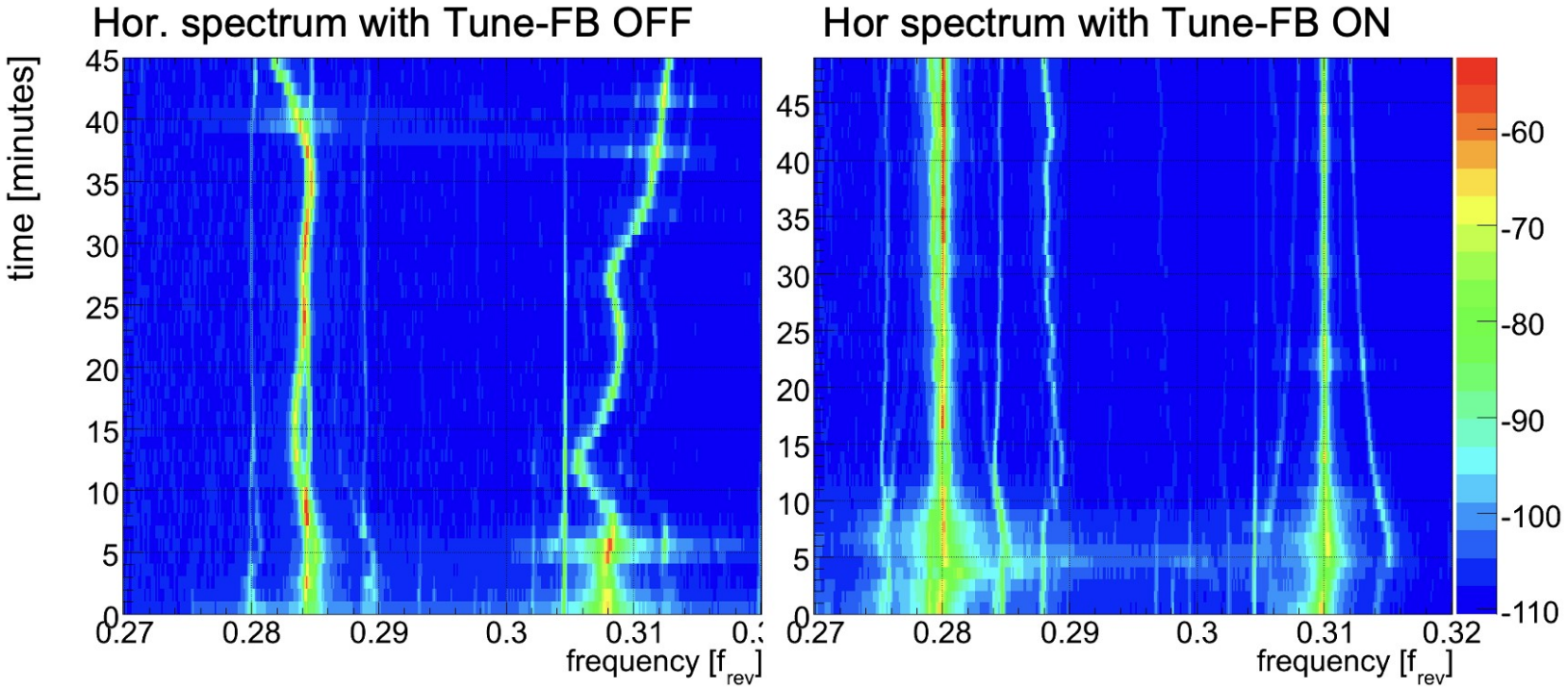
# Tune – a beam position monitor with special electronics




# Tune measurement in the PS ring

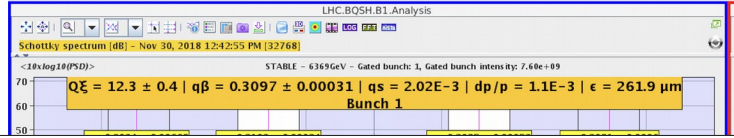


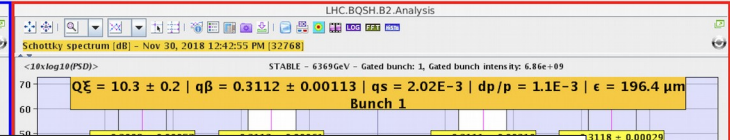
# Tune feedback in the LHC



# *Potpourri* of other instruments

# Schottky



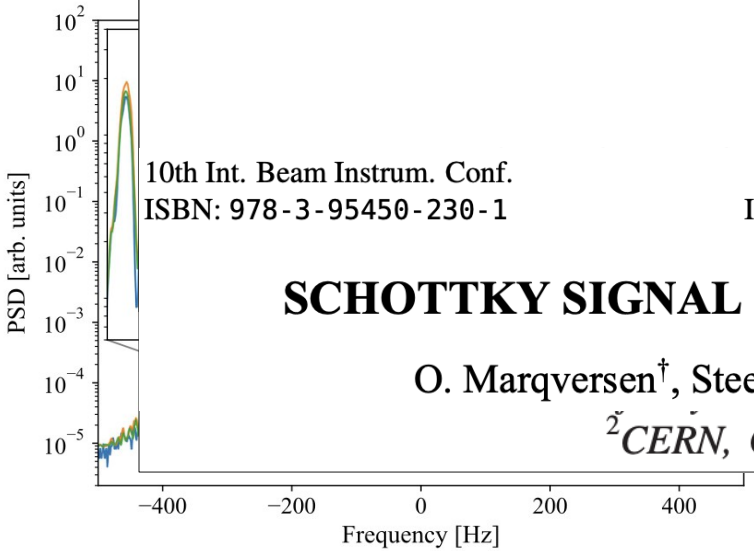

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 062803 (2020)

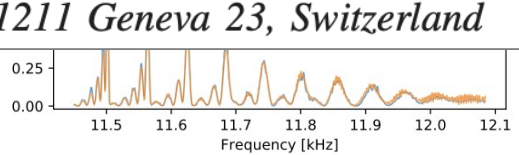
PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 062801 (2022)

10th Int. Beam Instrum. Conf. IBIC2021, Pohang, Rep. of Korea JACoW Publishing
ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-WEPP04

**SCHOTTKY SIGNAL FROM DISTRIBUTED ORBIT PICK-UPs**

O. Marqversen†, Steen Jensen, CERN-SY-BI, Geneve, Switzerland
[2]*CERN, CH-1211 Geneva 23, Switzerland*

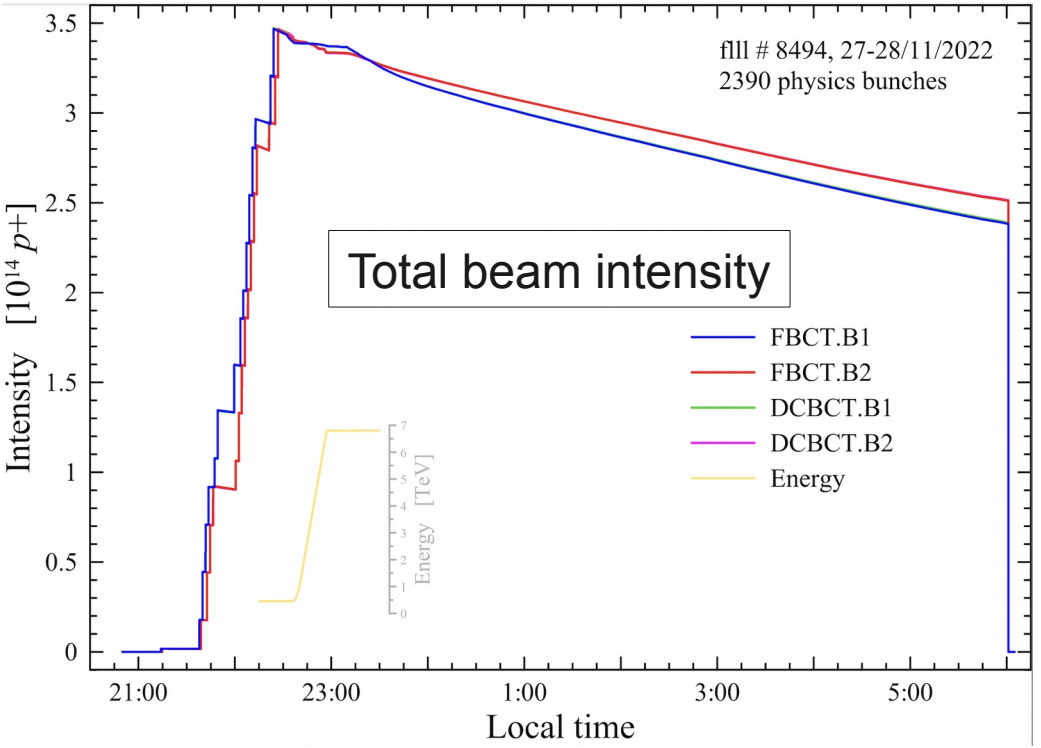


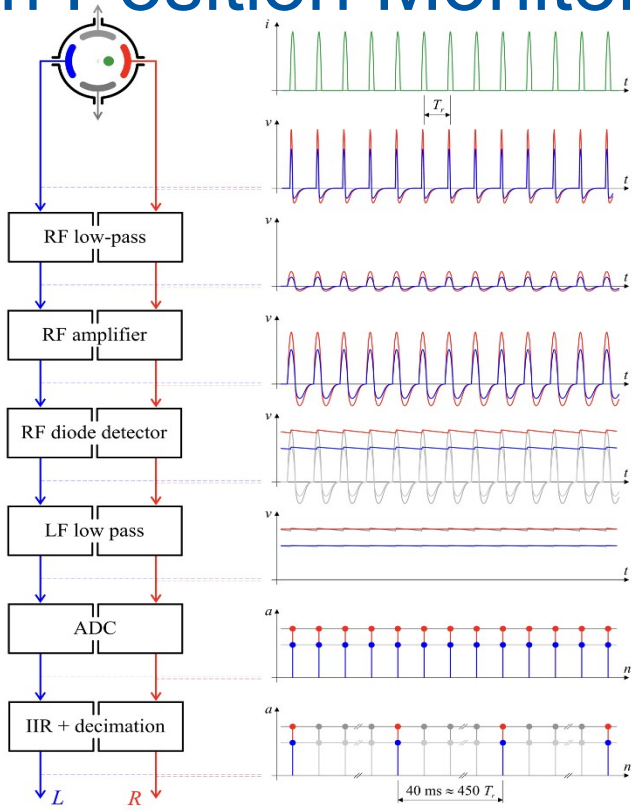

ne

- Chromaticity
- Bunch shape

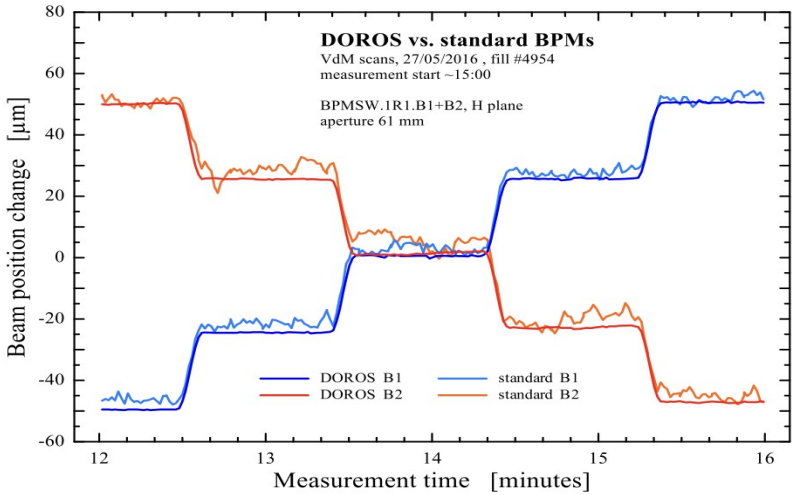
# DC Beam Current Transformers



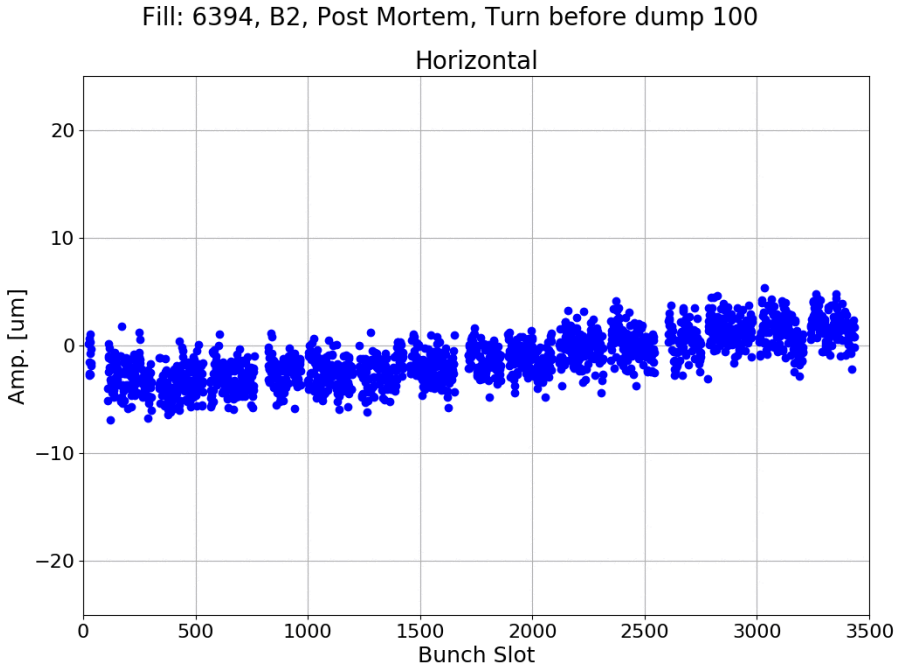
# Beam Position Monitors with DOROS electronics

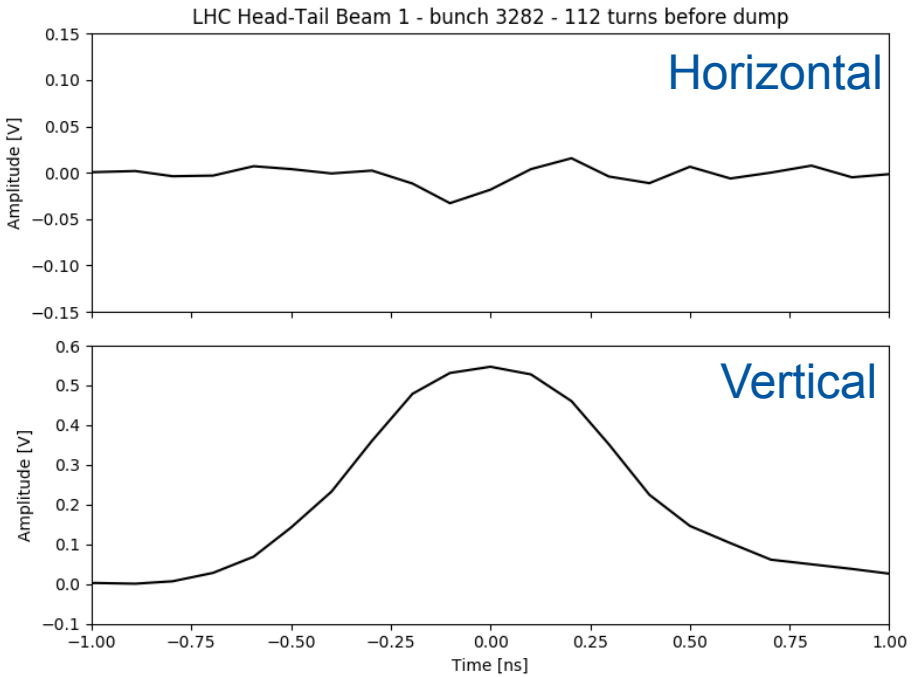



- Heavy analogue and digital filtering to reduce noise
- High resolution and therefore slow acquisition
- Beam resolution ≈ 0.1 μm, accuracy ≈ 10 μm
- Price to pay: 1 Hz measurement rate and one averaged position for all circulating bunches

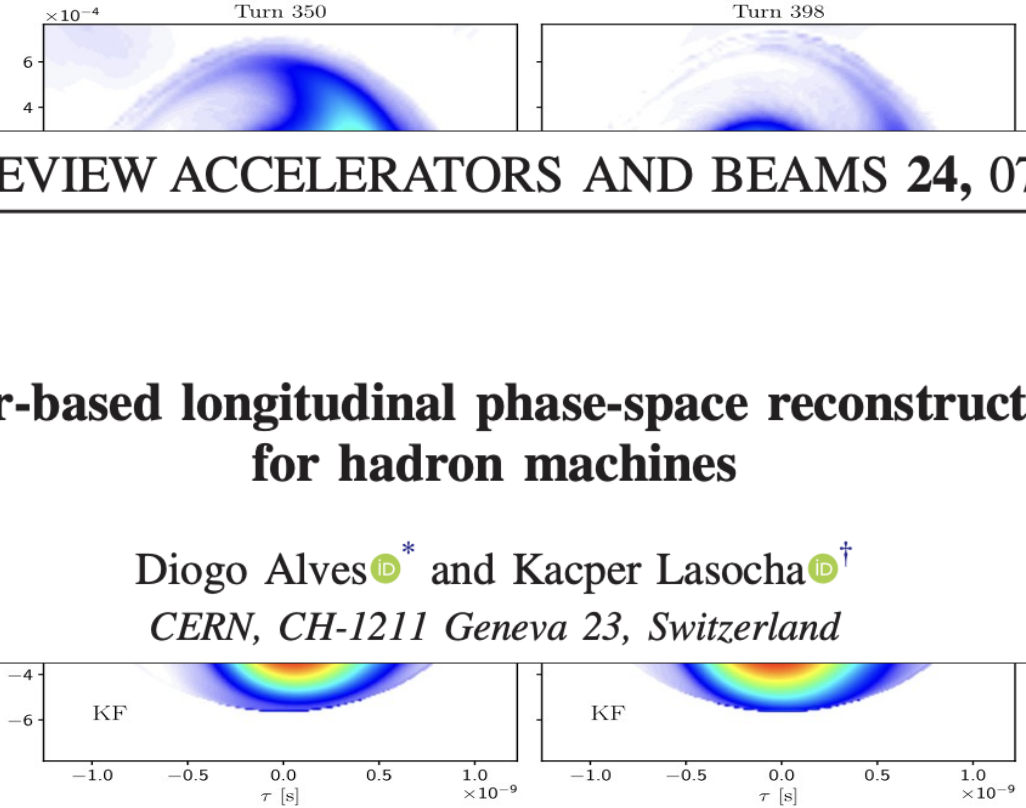


# Head-tail beam position monitors



# Kalman filter – longitudinal phase space reconstruction




PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 072801 (2021)

**Kalman filter-based longitudinal phase-space reconstruction method for hadron machines**

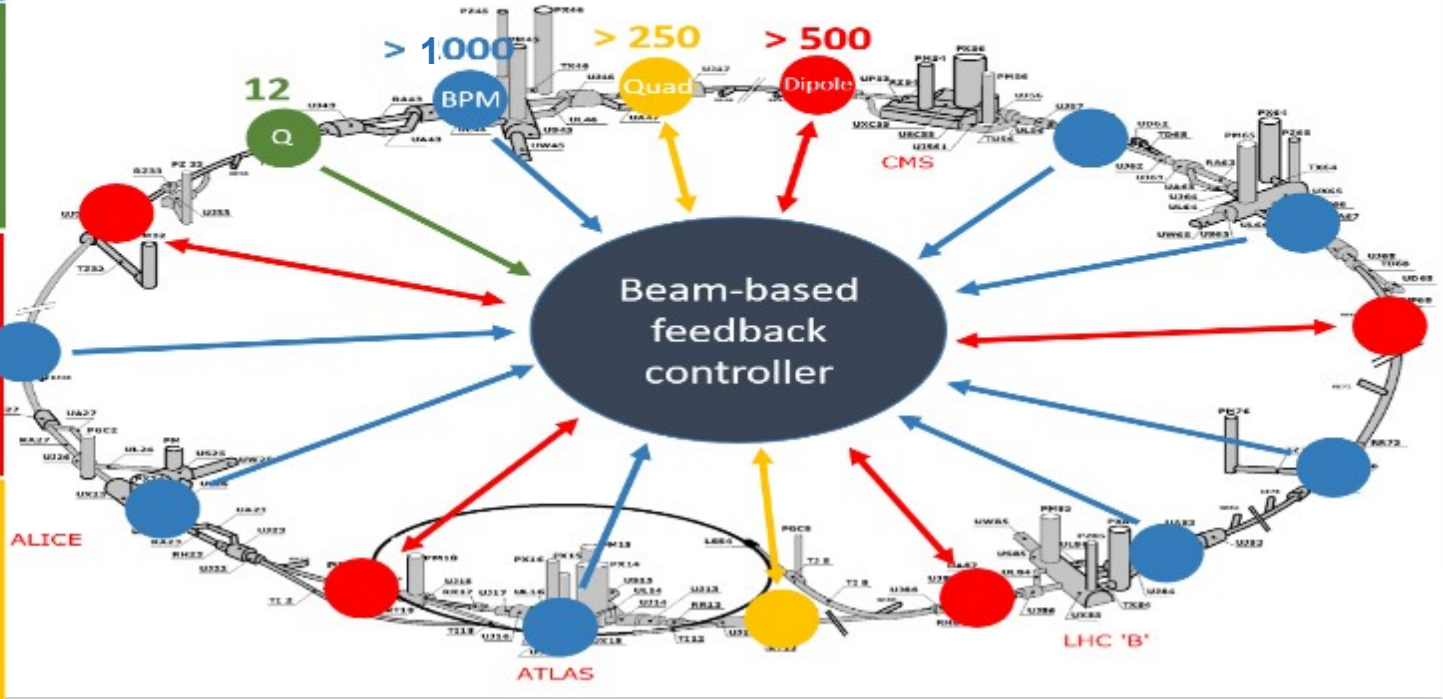
Diogo Alves * and Kacper Lasocha †

*CERN, CH-1211 Geneva 23, Switzerland*

# LHC beam-based feedback system





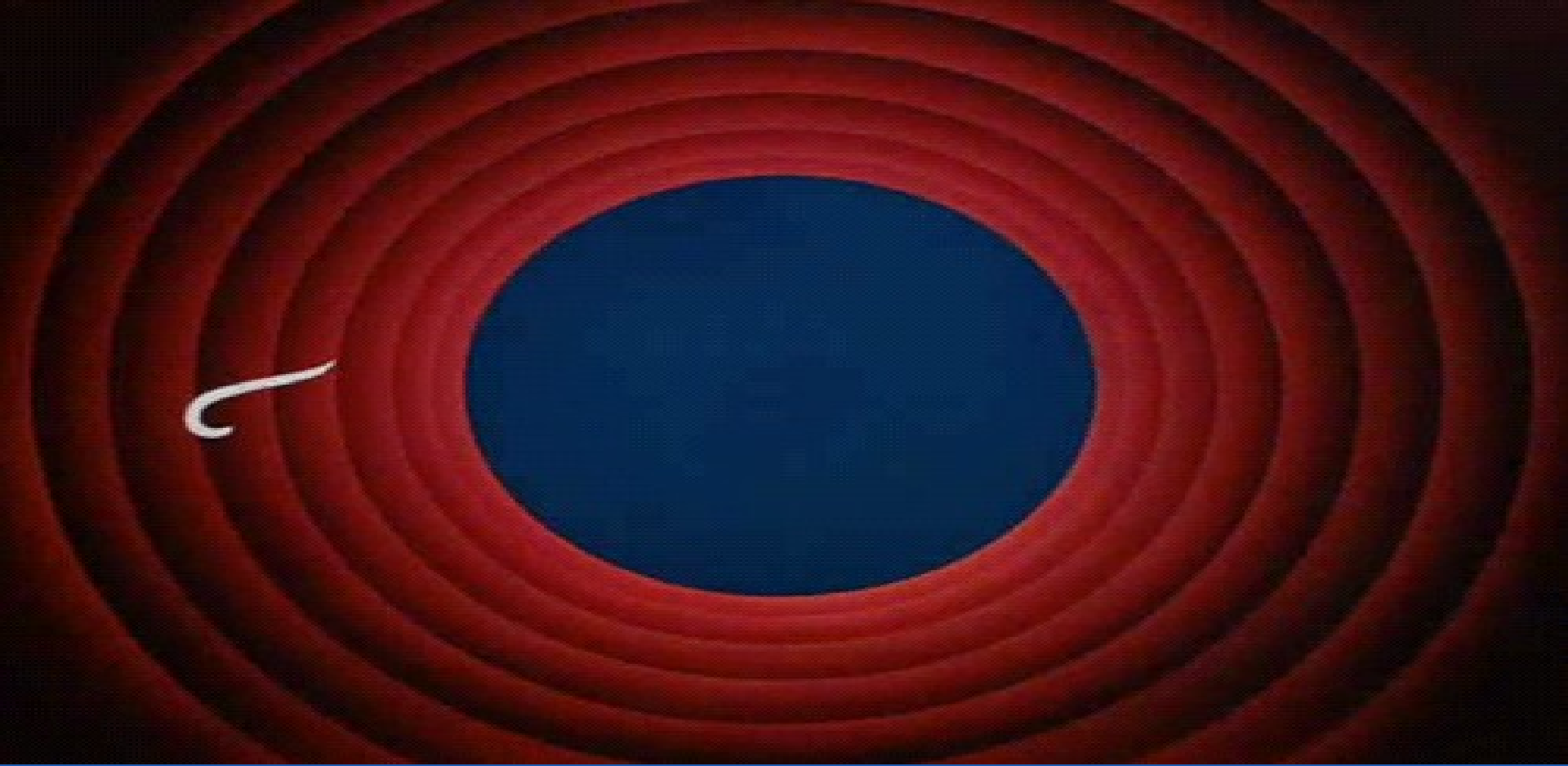


# Material providers


## Acknowledgements

- R. Jones (CERN)
- T. Lefèvre (CERN)
- M. Gasior (CERN)
- O. Marqversen (CERN)
- S. Thoulet (CERN)
- R. Ruffieux (CERN)
- R. Hernandez (IFIC)
- P. Forck (GSI)
- R. Steinhagen (GSI)
- M. Krupa (CERN)

CERN SY-BI-IQ section



# Spare slides

# BPM-based intensity

- Simulation using finite element EM solvers (e.g. CST)
- Measured H pos independent of V offset
- Sum signal independent of beam offset (position)