MD2733 Beam size measurements using quadrupolar BPMs

LSWG

17.01.2019

Outline

- QPU at LHC using collimator BPMs

- Main Goals of this MD

- Results and perspectives

What is a Quadrupolar Pick-Up (PU)?

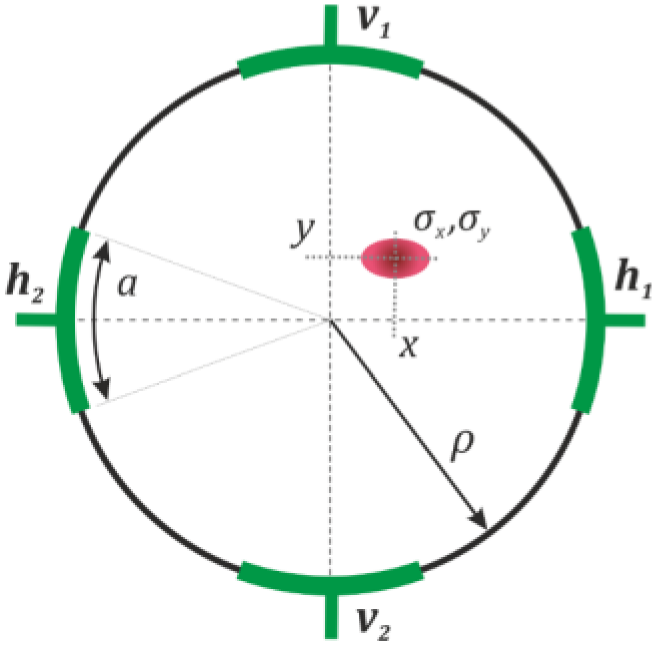
- an **electromagnetic Pick-Up**, *e.g. a BPM*
- measures the 2nd order term (**quadrupolar moment**) of the electrode signals.

$$\frac{U_{h1}}{i_b} \propto \overset{c_0}{\boxed{\frac{a}{2\pi}}} + \overset{c_1}{\boxed{\frac{1}{\rho}\frac{2sin(a/2)}{\pi}}}x + \underset{c_2}{\boxed{\frac{1}{\rho^2}\frac{sin(a)}{\pi}}}\underbrace{\left(\boxed{\sigma_x^2-\sigma_y^2}+\boxed{x^2-y^2}\right)}_{\textbf{Quadrupolar Term}} + \cdots$$

position information

beam size information

(more) position information



Cancel Dipolar moments

$$\Sigma_{hor} = 2i_b c_0 + 2i_b c_2 \boldsymbol{Q}$$

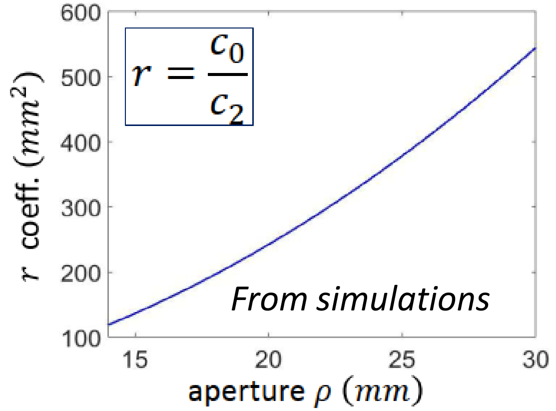
$$\Sigma_{ver} = 2i_b c_0 - 2i_b c_2 \boldsymbol{Q}$$

Cancel Monopole moment

$$\Sigma_{hor} - \Sigma_{ver} = 4i_b c_2 \boldsymbol{Q}$$

Normalize by intensity

$$R_q = \frac{\Sigma_{hor} - \Sigma_{ver}}{\Sigma_{hor} + \Sigma_{ver}} = \frac{c_2}{c_0}\boldsymbol{Q}$$



Main Limitations

1. Low sensitivity : typically $\boxed{\frac{c_2}{c_0} \approx 10^{-3}}$

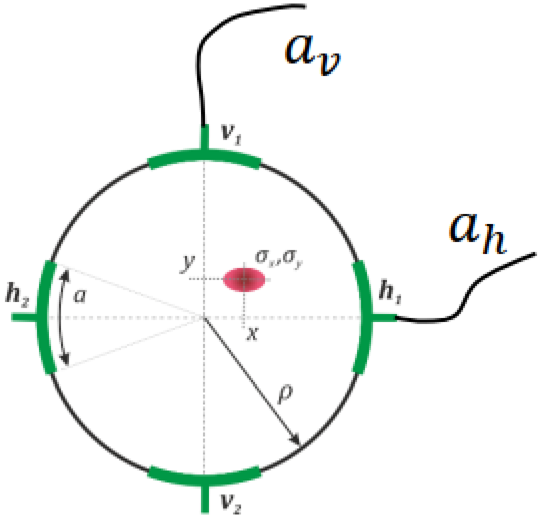
2. Position contribution to quadrupolar moment

$$Q = \underbrace{\sigma_x^2 - \sigma_y^2}_{Q_\sigma} + \underbrace{x^2 - y^2}_{Q_p}$$

beam size signal
to be measured

position signal
parasitic

3. Channel asymmetries



realistic case

small asymmetry

$$\Sigma_{hor} = 2a_h i_b c_0 + 2a_h i_b c_2 Q$$

$$\Sigma_{ver} = 2a_v i_b c_0 - 2a_v i_b c_2 Q$$

$$\downarrow$$

$$Q_m = \frac{c_0}{c_2}\frac{\Sigma_{hor} - \Sigma_{ver}}{\Sigma_{hor} + \Sigma_{ver}} \approx Q + \overbrace{\frac{c_0}{c_2}\frac{a_h - a_v}{a_h + a_v}}^{\text{offset}}$$

Main Limitations

1. Low sensitivity : typically $\boxed{\frac{c_2}{c_0} \approx 10^{-3}}$

2. Position contribution to quad

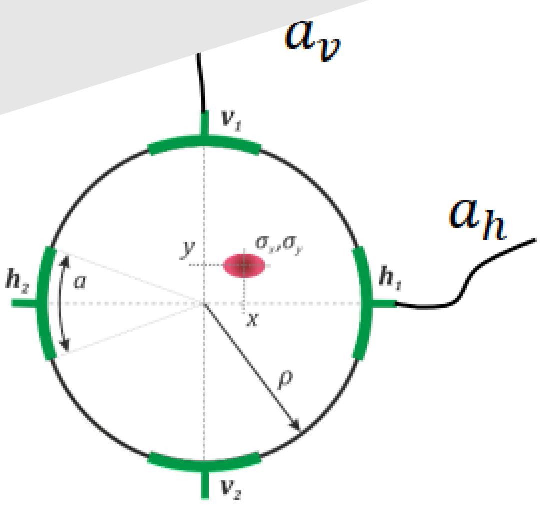
BPMs embedded in collimators help for 1, 2 and 3

asured

position signal

parasitic

3. Char ties



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$$\Sigma_{hor} = 2a_h i_b c_0 + 2a_h i_b c_2 Q$$

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↓

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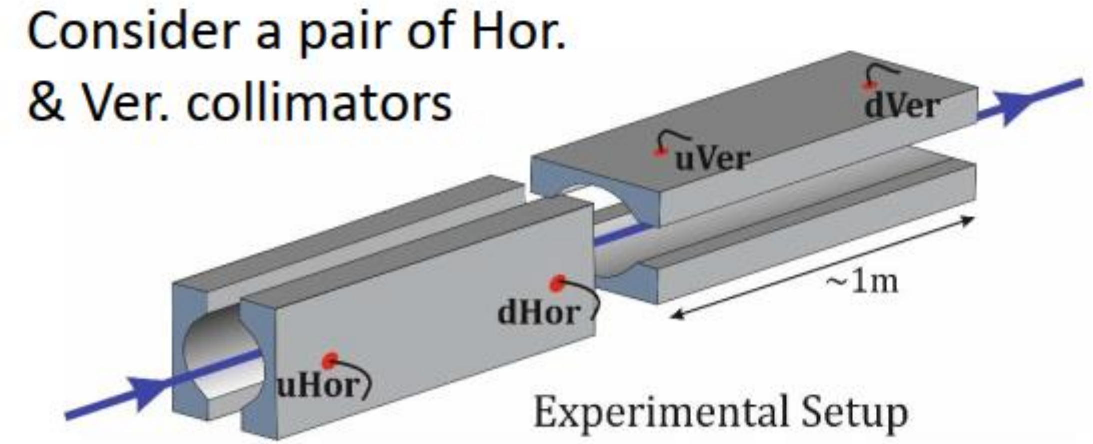
MD set-up

- **Using TCTPH.4L5.B1**, **TCTPV.4L5.B1** and **TCTPH.4R5.B2**, **TCTPV.4R5.B2**



- The standard BPM cabling to the DOROS electronics allows a minimization of the systematic errors for position measurements.
- The second DOROS boxes allows instead a minimization of the electronics errors for quadrupolar measurements (U_h vs U_V and D_h vs D_V)

Can we get better measurements using this new compensation of H/V electronic gain error?

$$\sum_H = (a+b)IC_{0h} + (a-b)IC_{1h}x + (a+b)IC_{2h}Q$$

$$\sum_V = (a+b)IC_{0v} + (a-b)IC_{1v}y - (a+b)IC_{2v}Q$$

$$\sum_H - \sum_V = (a+b)I(C_{0h} - C_{0v}) + (a-b)I(C_{1h}x - C_{1v}y) + (a+b)I(C_{2h} + C_{2v})Q$$

$$\sum_H + \sum_V = (a+b)I(C_{0h} + C_{0v}) + (a-b)I(C_{1h}x + C_{1v}y) + (a+b)I(C_{2h} - C_{2v})Q \approx (a+b)I(C_{0h} + C_{0v})$$

$$R = \frac{\sum_H - \sum_V}{\sum_H + \sum_V} \approx \frac{C_{0h} - C_{0v} + \frac{a-b}{a+b}(C_{1h}x - C_{1v}y) + (C_{2h} + C_{2v})Q}{C_{0h} + C_{0v}}$$

'Standard method'

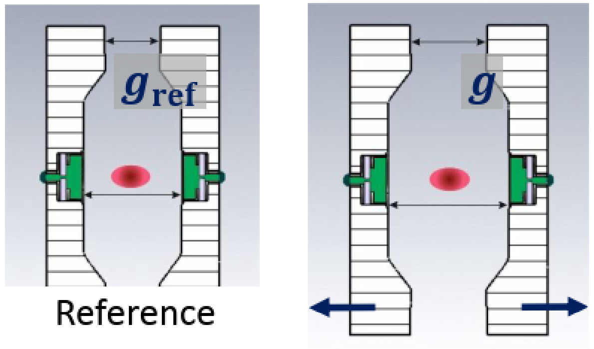
$$Q \approx \frac{(C_{0h} + C_{0v})R + (C_{0v} - C_{0h}) - \frac{a-b}{a+b}(C_{1h}x - C_{1v}y)}{C_{2h} + C_{2v}}$$

$$\varepsilon_Q = \sqrt{\sum_{n=0}^{2}\left(\frac{\partial Q}{\partial C_{nh}}\right)^2 \varepsilon_{C_{nh}}^2 + \sum_{n=0}^{2}\left(\frac{\partial Q}{\partial C_{nv}}\right)^2 \varepsilon_{C_{nv}}^2 + \left(\frac{\partial Q}{\partial x}\right)^2 \varepsilon_x^2 + \left(\frac{\partial Q}{\partial y}\right)^2 \varepsilon_y^2 + \left(\frac{\partial Q}{\partial\left(\frac{a-b}{a+b}\right)}\right)^2 \left(\frac{a-b}{a+b}\right)^2}$$

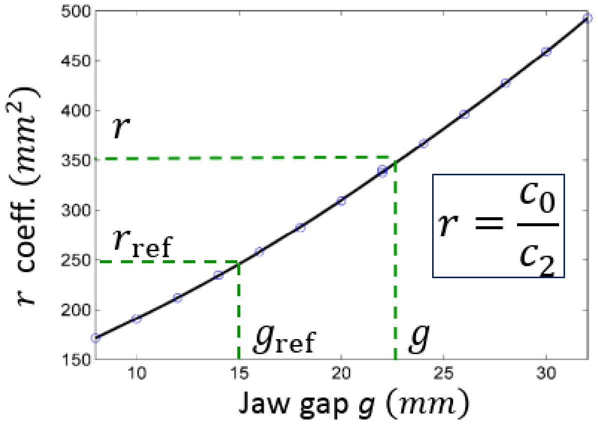
Can we use collimator aperture scans to cancel asymmetric gain errors ?

‘Double normalization technique’

Consider a movable PU, able to change the aperture



Reference measurement



Consider some asymmetry between the Hor. & Ver. channels

$$\Sigma_h = a_h i_b (c_0 + c_2 Q)$$

$$\Sigma_v = a_v i_b (c_0 - c_2 Q)$$

Perform 2 measurements with different apertures

1st normalization ↓ cancel the asymmetric gains a_h, a_v

$$\boxed{S_h = \frac{\Sigma_h}{\Sigma_{h,ref}} = \frac{i_b(r+Q)}{i_{b,\text{ref}}(r_{\text{ref}}+Q)}} \quad \boxed{S_v = \frac{\Sigma_v}{\Sigma_{v,ref}} = \frac{i_b(r-Q)}{i_{b,\text{ref}}(r_{\text{ref}}-Q)}}$$

2nd normalization ↓ normalize intensity

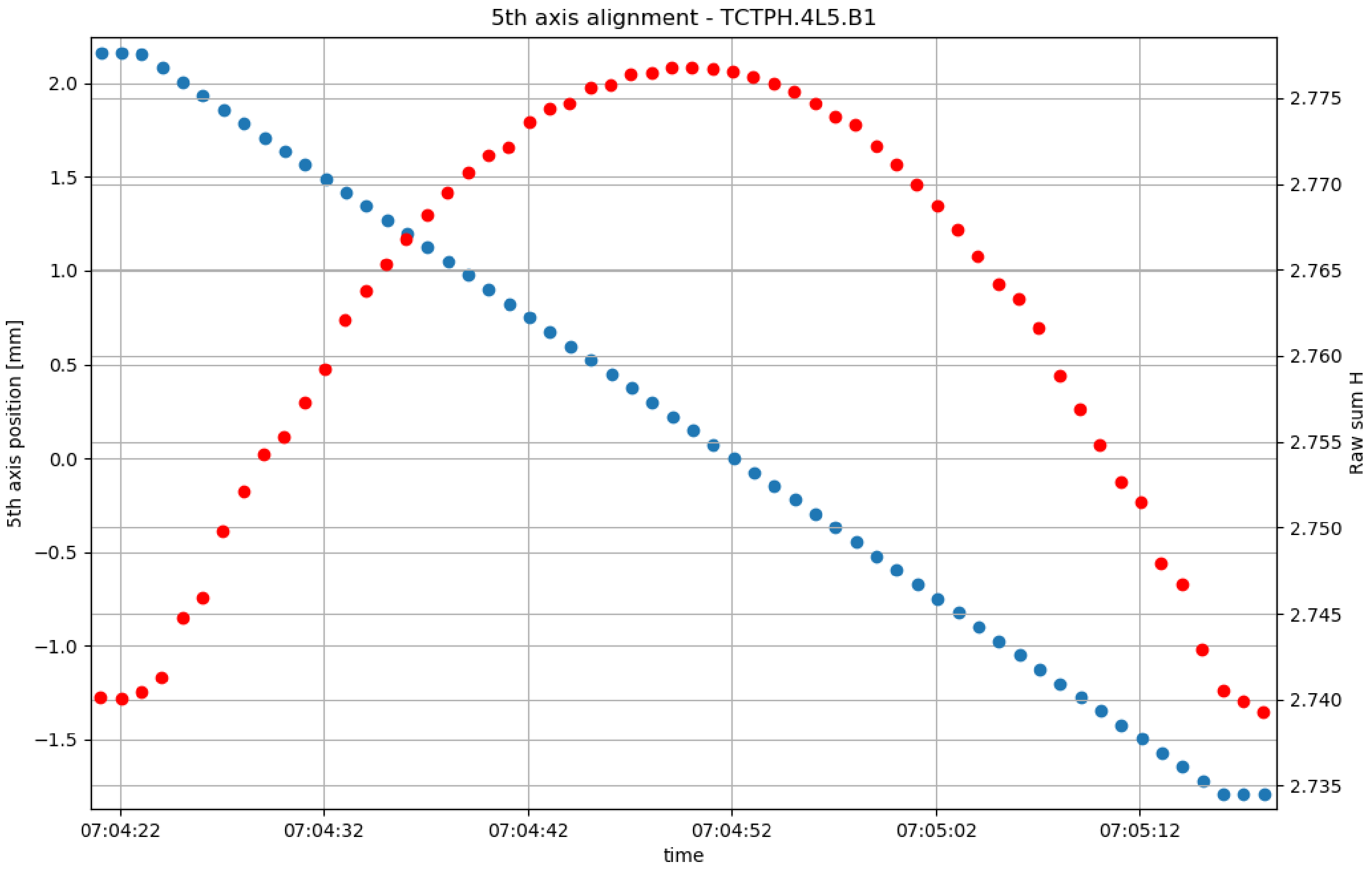
$$\mathrm{R} = \frac{S_h}{S_v} = \frac{r+Q}{r-Q}\,\frac{r_{\text{ref}}-Q}{r_{\text{ref}}+Q}$$

Q obtained by **double-normalization** (*d-Norm*)

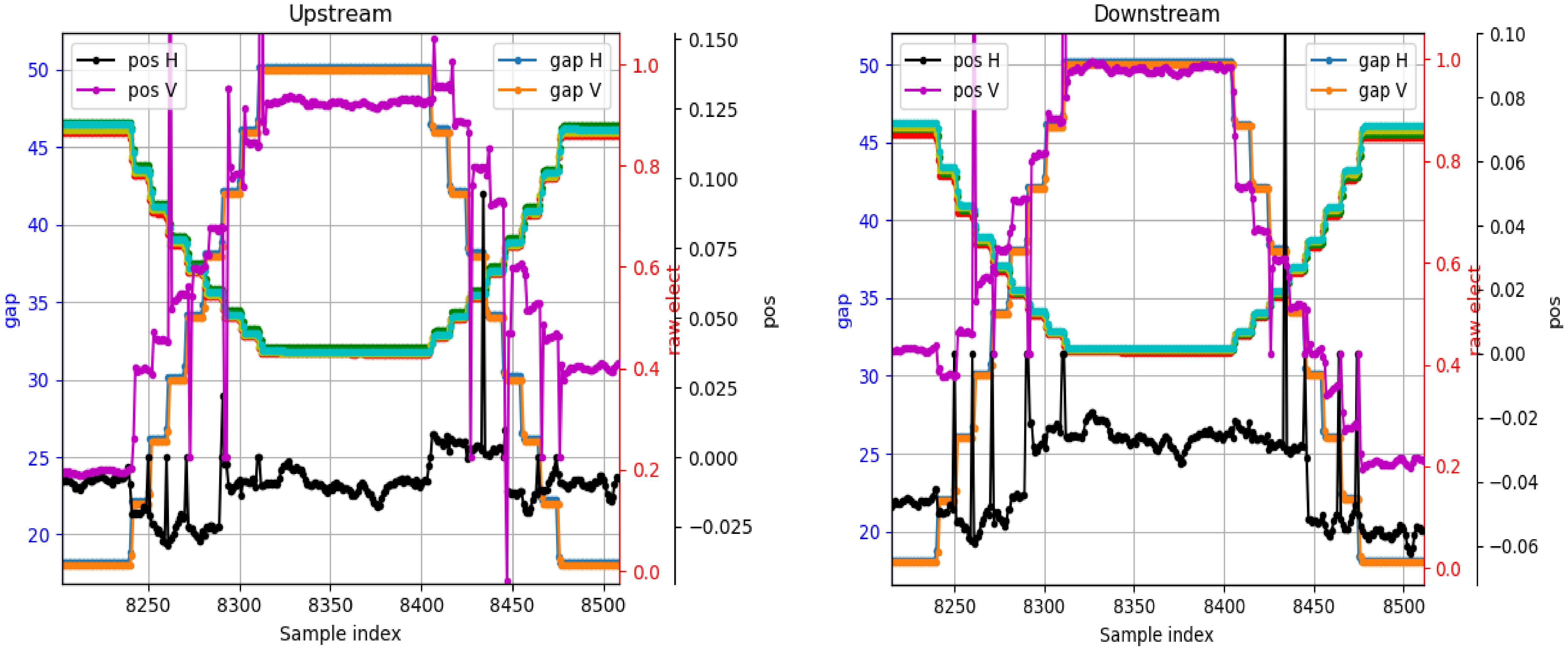
$$\boxed{Q \approx \frac{r r_{ref}}{r - r_{v,ref}}\,\frac{1-R}{1+R}}$$

1.5% error in C0h or C0v means a 200% error in Q

Maximizing signal to get best possible sensitivity



Aperture scan



Small position offsets (around 100um) in V plane observed during the scan

- It may affect the calculation of the C0v

Estimation of BPM non-linearities

Position calculation - crossed cables

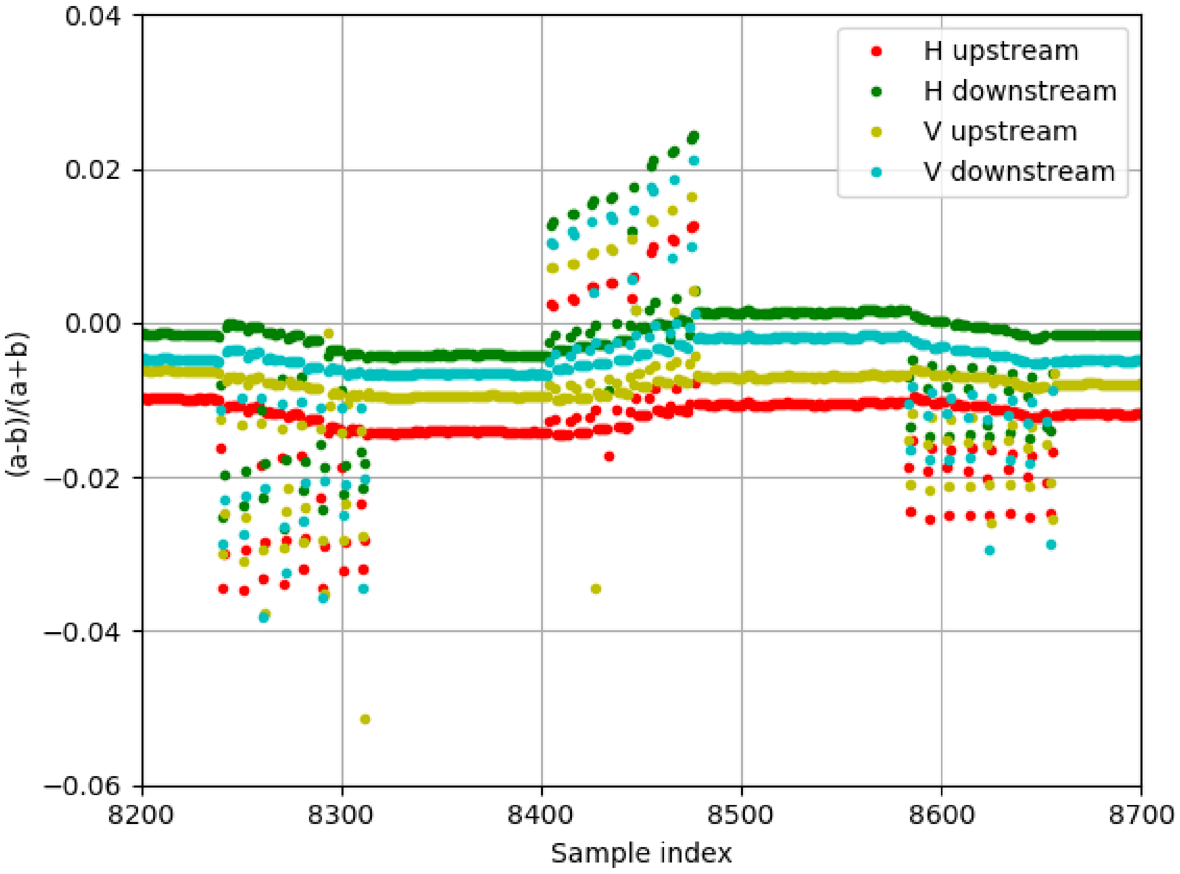
$$\frac{\Delta_H^C}{\Sigma_H^C} \approx \frac{(a-b)IC_{0h}+(a+b)IC_{1h}x+(a-b)IC_{2h}Q}{(a+b)IC_{0h}} \approx \frac{a-b}{a+b} + \frac{C_{1h}}{C_{0h}}x$$

Position calculation - normal cabling

$$\frac{\Delta_H^N}{\Sigma_H^N} \approx \frac{aIC_{1h}}{aIC_{0h}}x \approx \frac{C_{1h}}{C_{0h}}x$$

Estimation of circuit gain asymetry

$$\frac{\Delta_H^C}{\Sigma_H^C} - \frac{\Delta_H^N}{\Sigma_H^N} \approx \frac{a-b}{a+b}$$



Larger errors during aperture scans : possibly due to non-linearities in the electronic chain

- Similar effects as adding an uncertainty of the knowledge of the BPM aperture

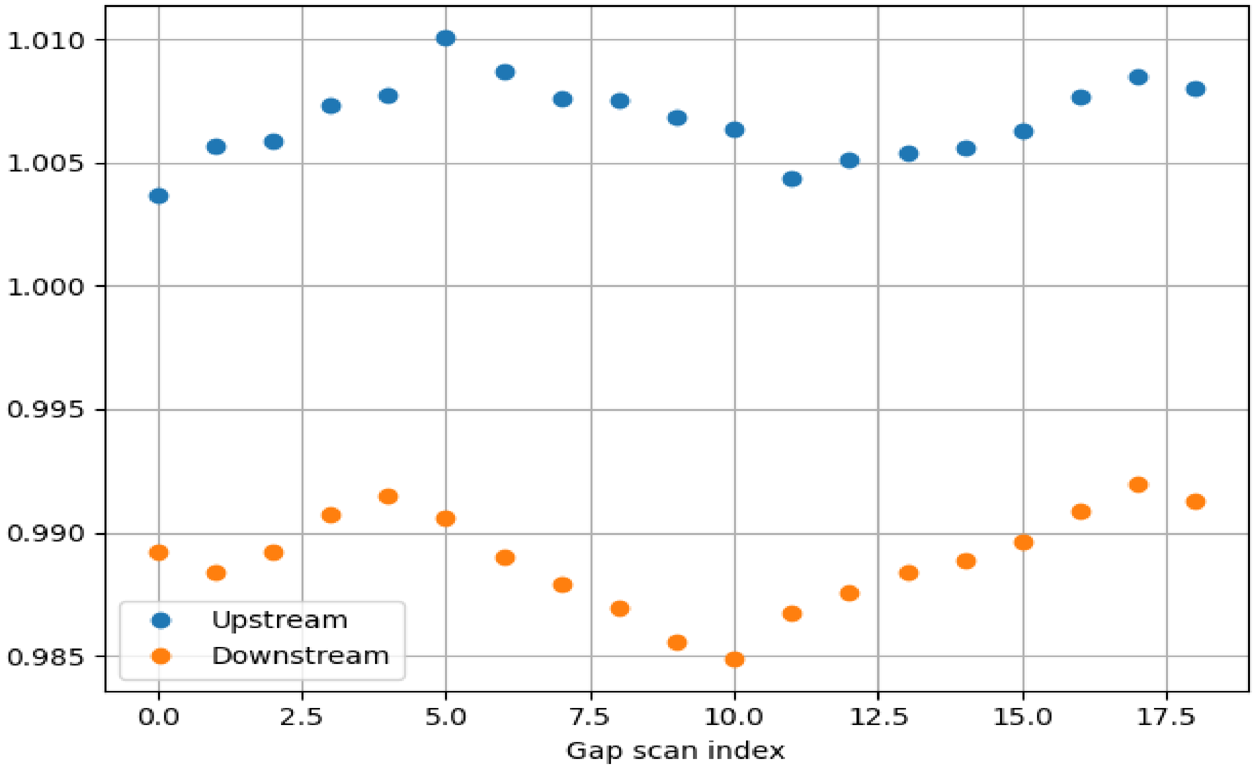
Cross-check between Upstream-Downstream BPM

The intensity seen by $\sum_H$ and $\sum_V$ should be the same, i.e.:

$$I = I_H \approx \frac{\sum_H}{(a+b)C_{0h}} \text{ and } I = I_V \approx \frac{\sum_V}{(a+b)C_{0v}}$$

$$1 = \frac{I_H}{I_V} \approx \frac{\sum_H C_{0v}}{\sum_V C_{0h}}$$

as seen in the plot below, $0.985 \lesssim C_{0v}/C_{0h} \lesssim 1.01$

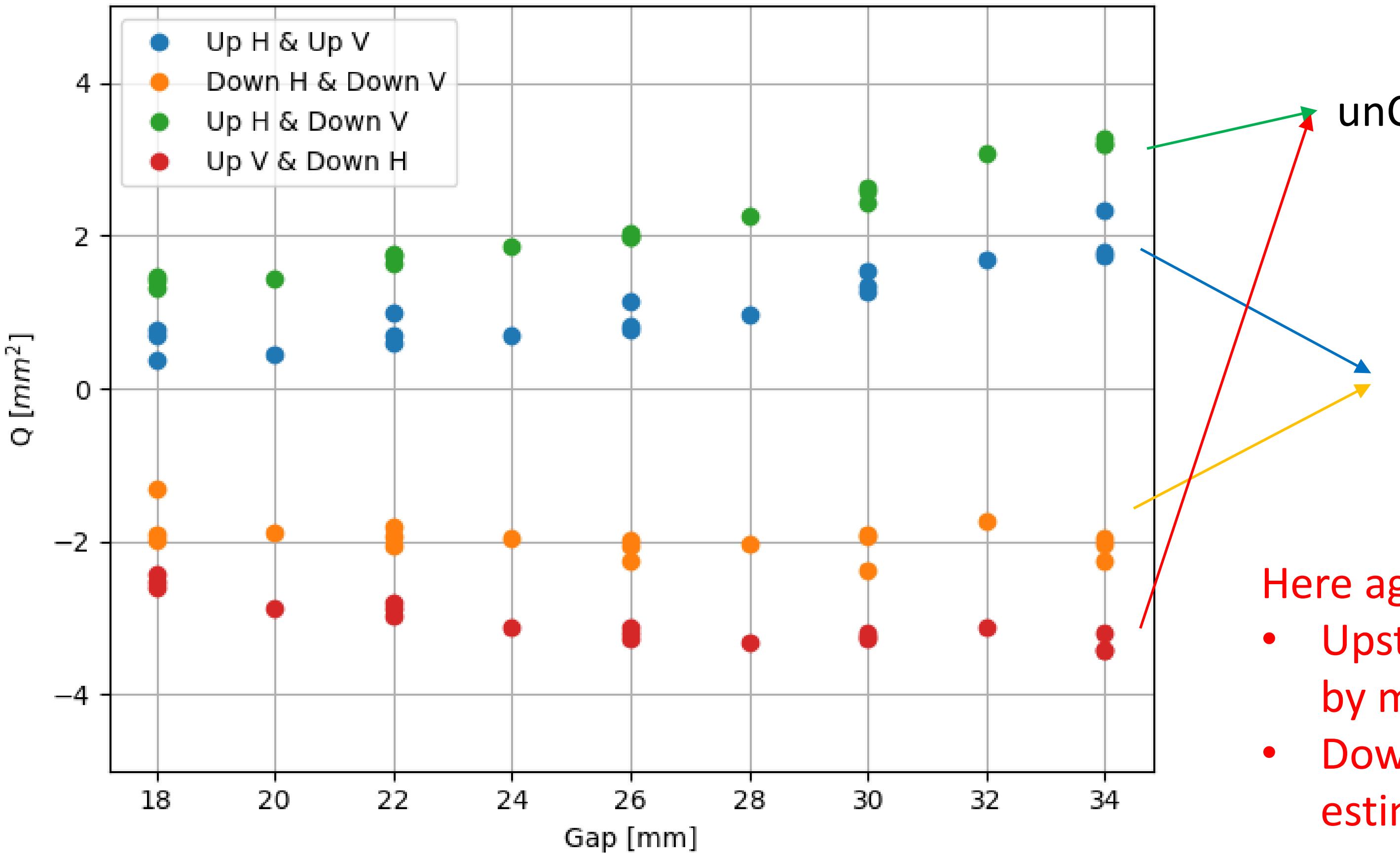


Not measuring 1 implies an aperture different than the one estimated by motor controller

- Upstream : UH larger aperture than estimated
- Downstream : DH smaller aperture than estimated

Quadrupolar measurements

'Standard method'



unCompensated electronic chains leads to larger QPU

Compensated electronic chain

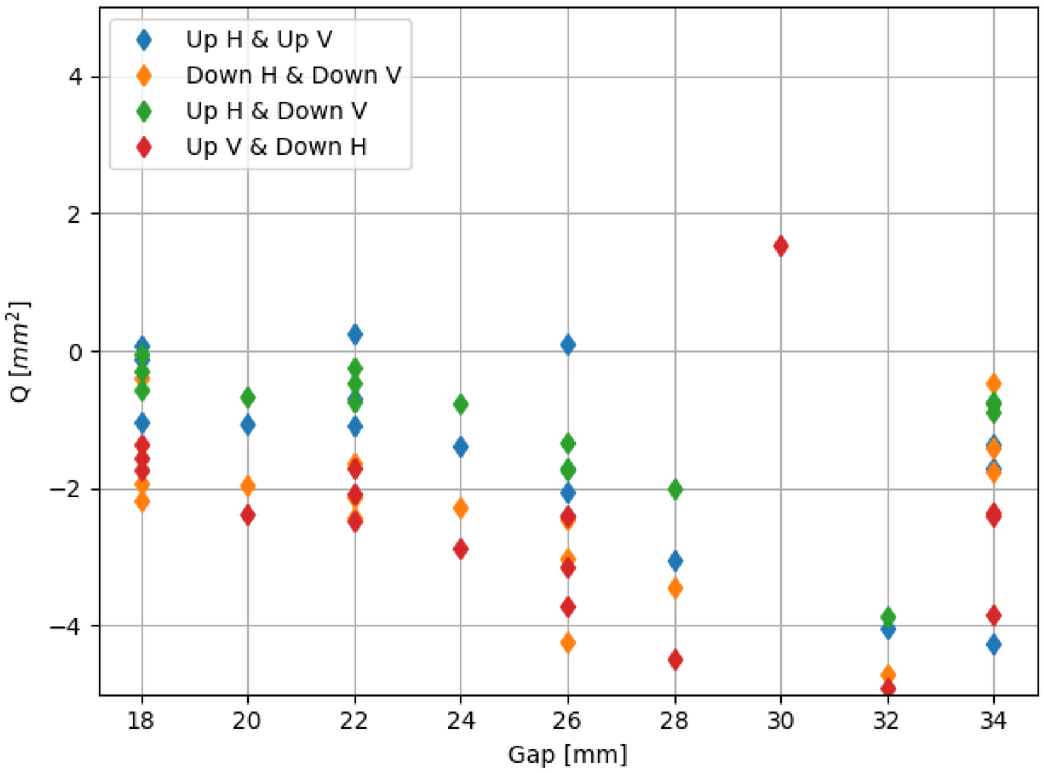
Here again signature of wrong aperture estimation :

- Upstream H has smaller aperture (C0h) than estimated by motor controller
- Downstream H has larger aperture (C0h) than estimated by motor controller

Over-estimation of C0v visible from the evolution of Q for larger aperture

Quadrupolar measurements

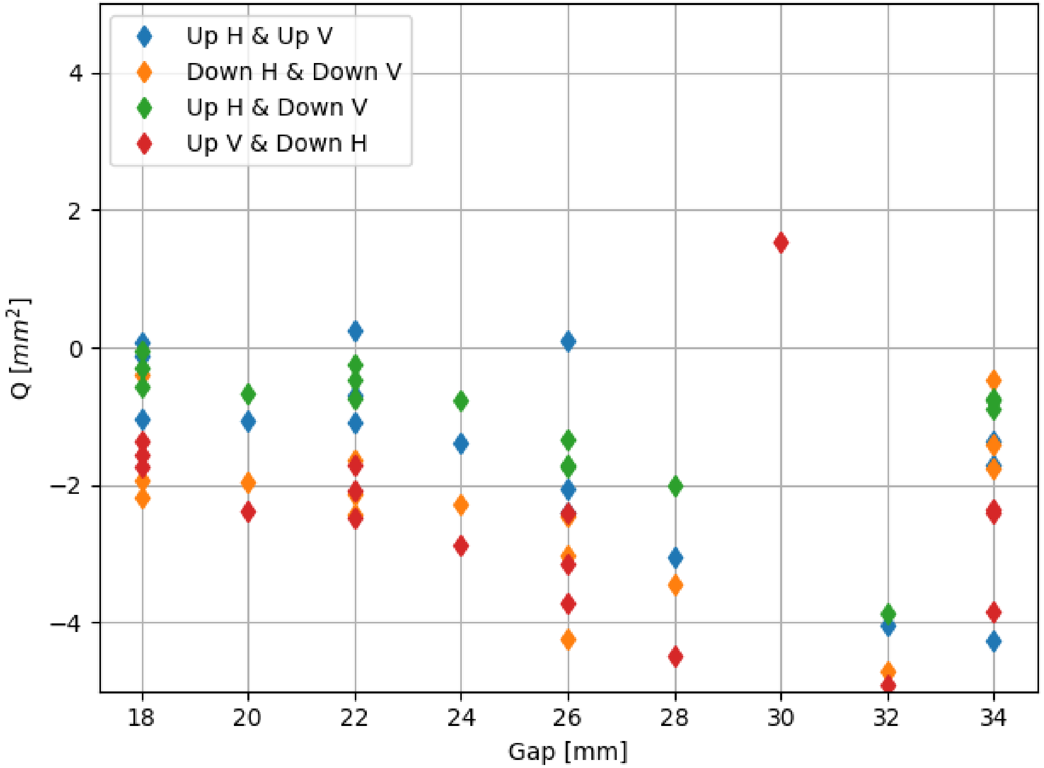
‘Double normalization technique’

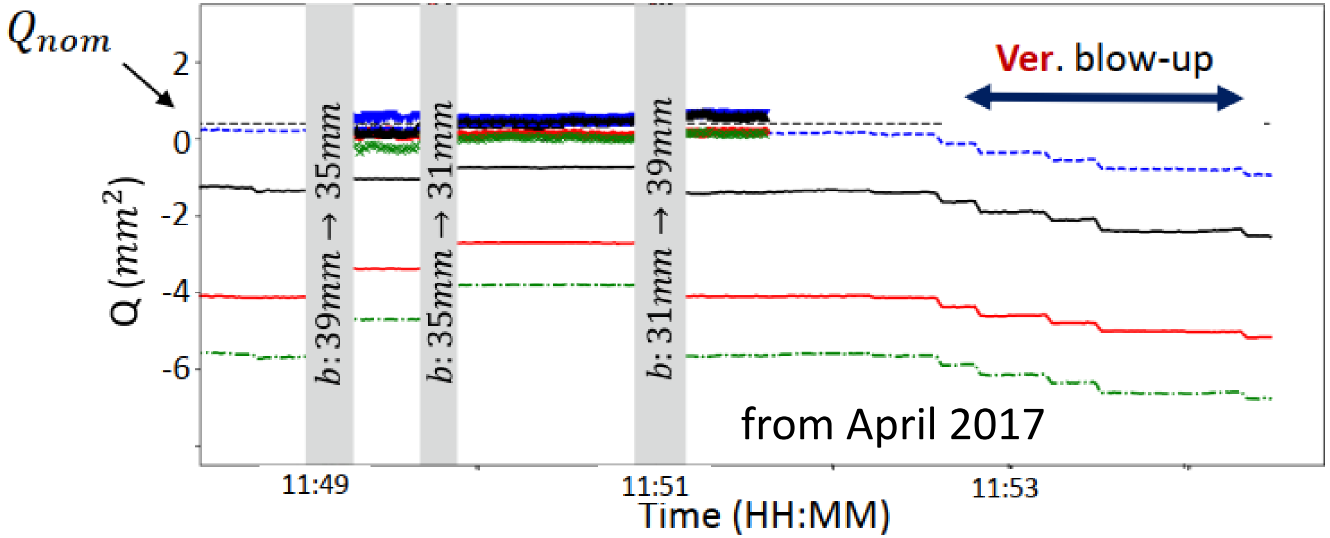


- Measurement quite noisy – errors not improving compared to standard methods
- Help removing the issue of UpstreamH - Dowstream H aperture
- Over-estimation of C0v visible from the evolution of Q for larger aperture

Quadrupolar measurements

‘Double normalization technique’





from April 2017

- Measurement quite noisy – errors not improving compared to standard methods
- Help removing the issue of UpstreamH - Dowstream H aperture
- Over-estimation of C0v visible from the evolution of Q for larger aperture

Conclusions

- Absolute Quadrupolar Measurements are simple by concept but very challenging in reality

- Movable BPMs offer a great opportunity to cancel/remove uncertainty
  - But having to rely on 2 consecutives collimators adds some complexity and uncertainties

  - Analysis still on going to see if we can provide more reliable numbers

- Differential measurements would nonetheless provide useful information (e.g. during the ramp)

Thank you for your attention

CERN

Parasitic Position Signal

$$Q = \underset{Q_\sigma}{\underline{\sigma_x^2 - \sigma_y^2}} + \underset{Q_p}{\underline{x^2 - y^2}}$$

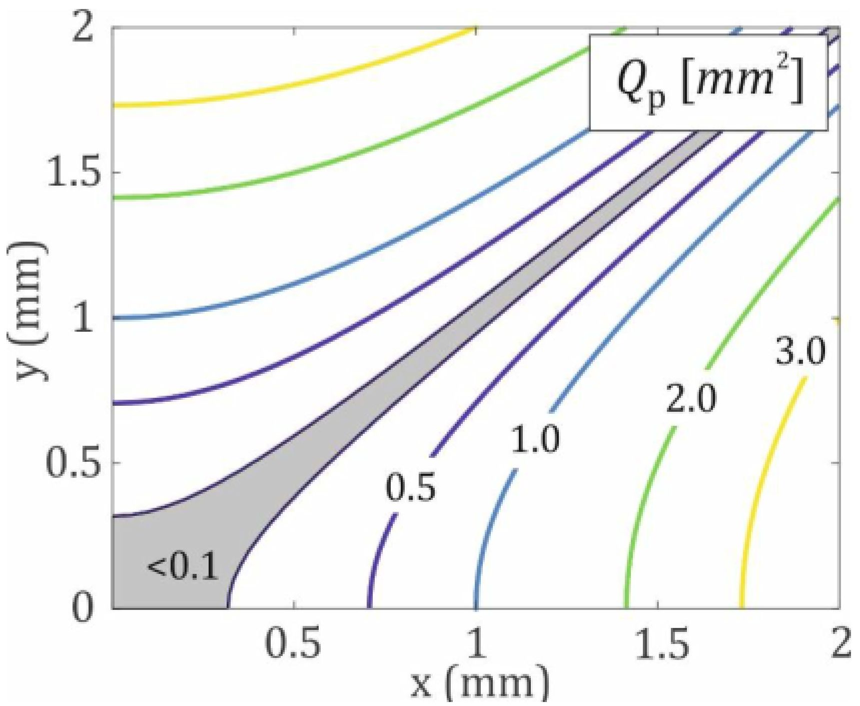
beam size signal
to be measured

position signal
parasitic

Typical values in LHC PUs

$[450\ GeV]$	→	$Q_\sigma \backsim 0.30 - 1.50\ mm^2$
$[6.5\ TeV]$	→	$Q_\sigma \backsim 0.05 - 0.30\ mm^2$

Even small beam displacements may result in large parasitic signal Q_p

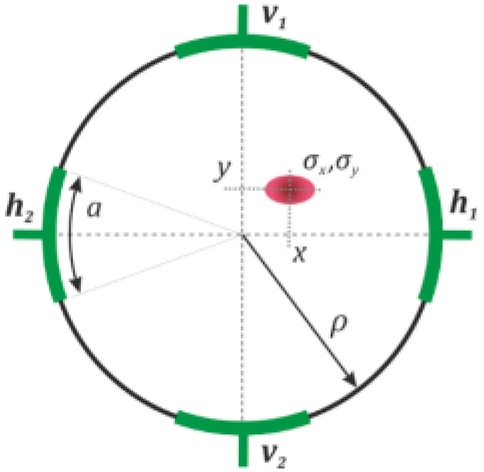


Fundamental Limitations	*Unfavourable Conditions*		Destructive Measurement Effects
Low quadrupolar sensitivity $U_{h1} \propto c_0 + c_1 D_x + c_2 Q + \cdots$ $\boxed{c_2 Q \ll c_0}$	*asymmetries (electronics, cabling, geometrical)*	→	Beam size information lost in **large offsets**
	noise (electronics)	→	**Low resolution**[**]
Parasitic Position Signal $Q = \sigma_x^2 - \sigma_y^2 + \boxed{x^2 - y^2}$	*off-centered beam*	→	Beam size signal lost in **parasitic position signal**

[**] **Noise** from electronics may significantly affect the quadrupolar measurements. However, existing BPM acquisition systems typically achieve sufficient resolution.

Example: $\sim 1\mu m$ position resolution → $\sim 0.01 - 0.02mm^2$ quadrupolar resolution

Direct subtraction (Fixed PU)

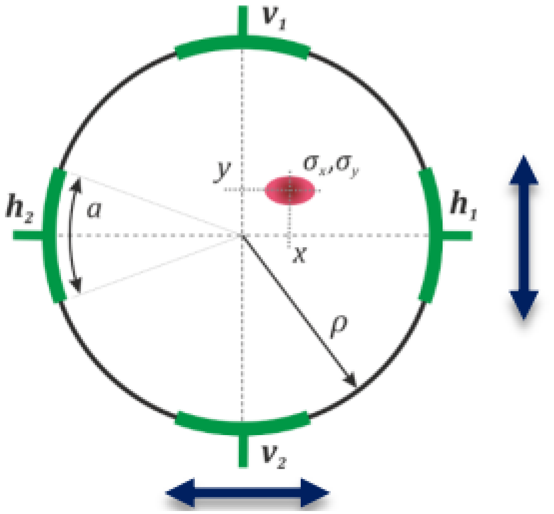


Measure & subtract beam position

Remaining Error:

$$Q_{x,rem} \approx 2x\Delta x$$

Subtraction by Alignment (Movable PU)



Measure beam position
& align PU

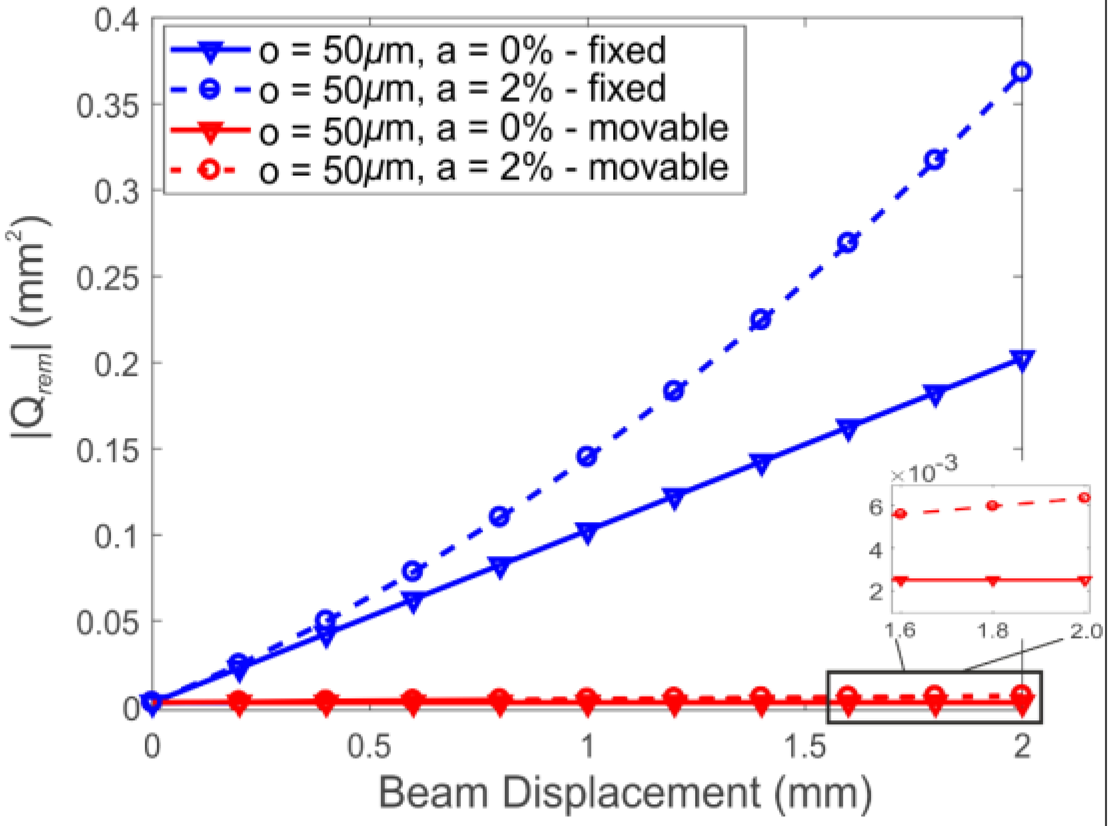
Remaining Error:

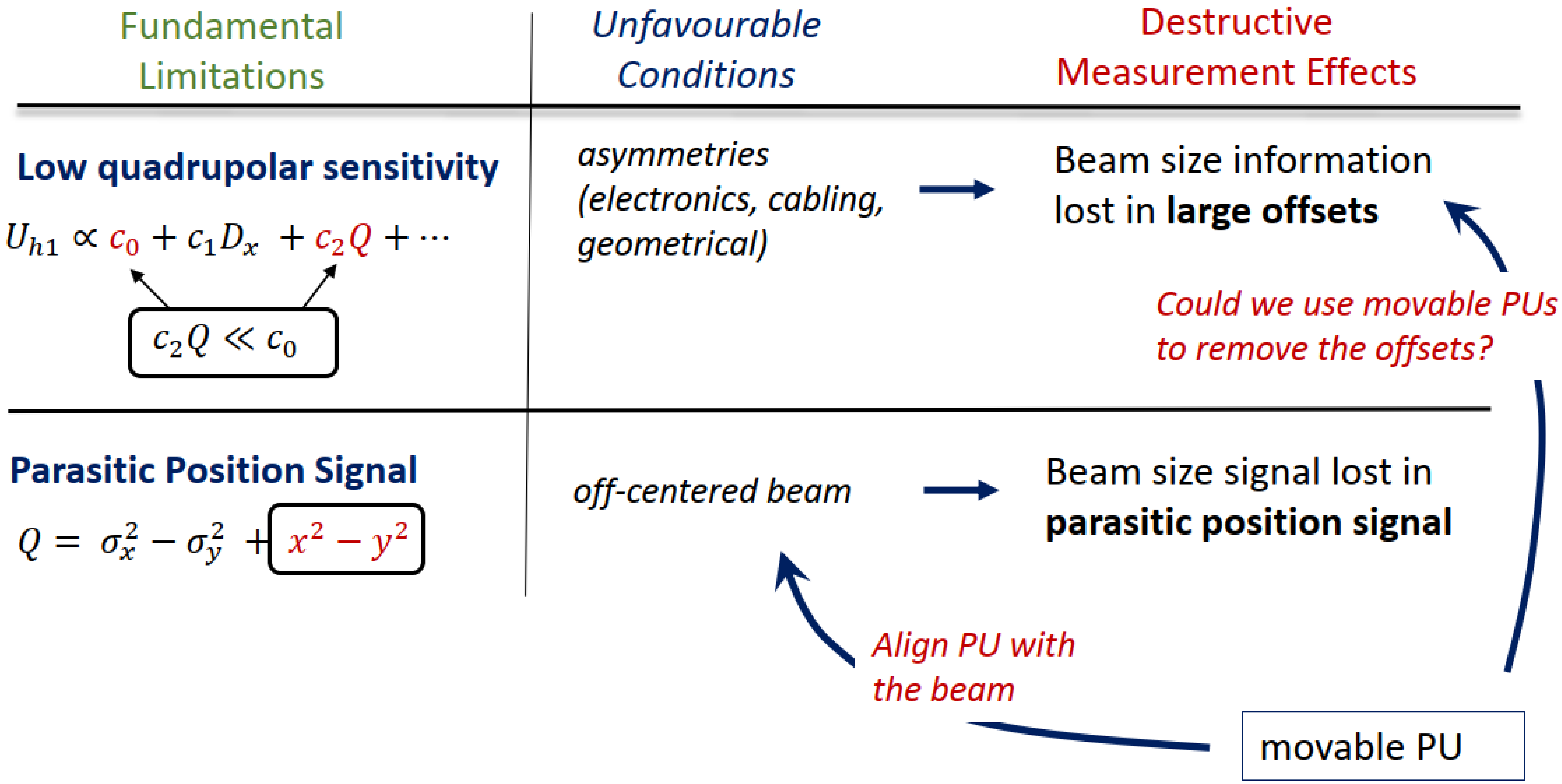
$$Q_{x,rem} \approx \Delta x^2$$

Example

Remaining parasitic signal considering offset, *o*, & scaling, *a*, errors in position measurement:

$$\Delta x = o + ax$$





Fundamental Limitations	*Unfavourable Conditions*		Destructive Measurement Effects
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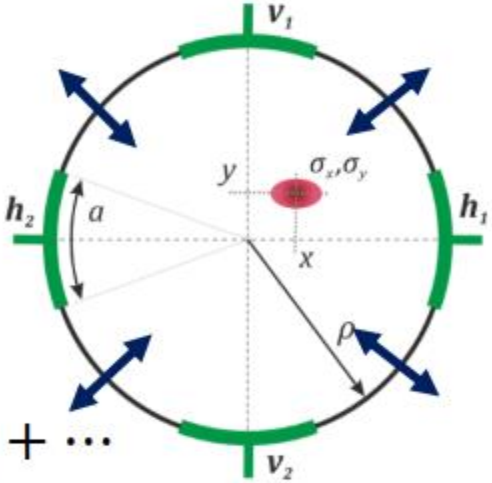
Parasitic Position Signal $Q = \sigma_x^2 - \sigma_y^2 + \boxed{x^2 - y^2}$	*off-centered beam*	→	Beam size signal lost in **parasitic position signal**

Could we use movable PUs to remove the offsets?

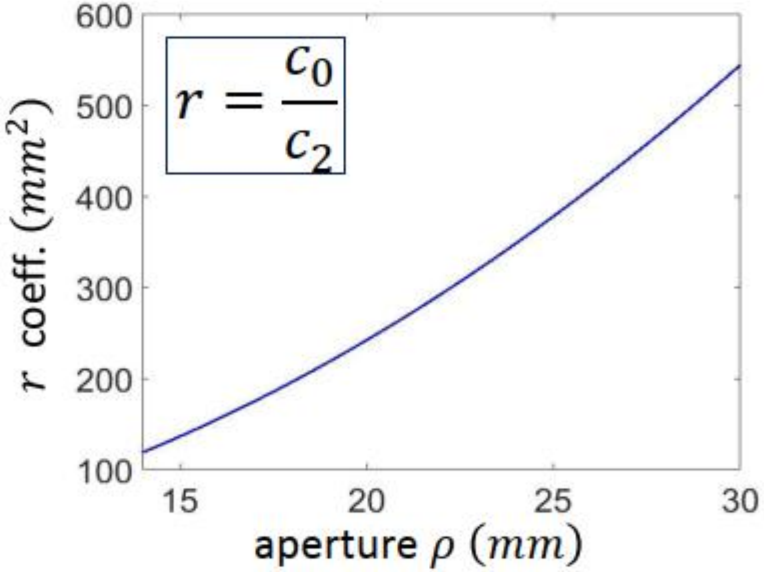
Align PU with the beam

movable PU

Consider a (*theoretical*) circular PU able to change its aperture ρ



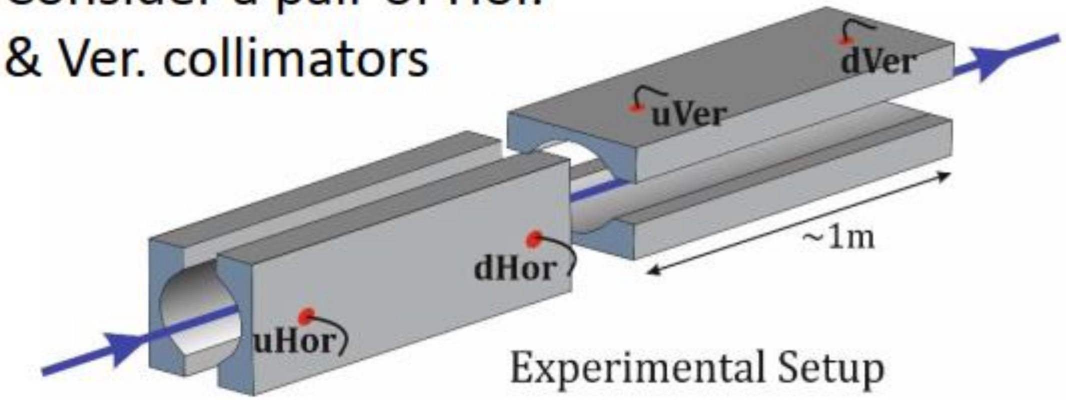
$$\Sigma_{hor} \propto \underbrace{\frac{a}{2\pi}}_{c_0} + \underbrace{\frac{1}{\rho^2}\frac{sin(a)}{\pi}}_{c_2} Q + \cdots$$



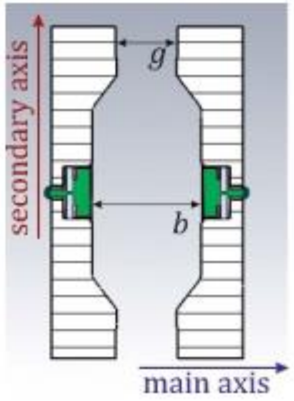
A more realistic example?

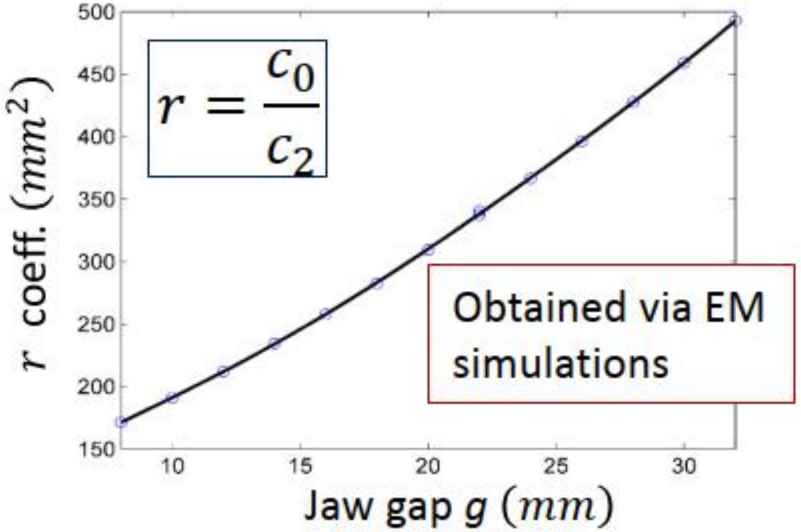
BPMs with DOROS electronics installed in LHC collimators

Consider a pair of Hor. & Ver. collimators



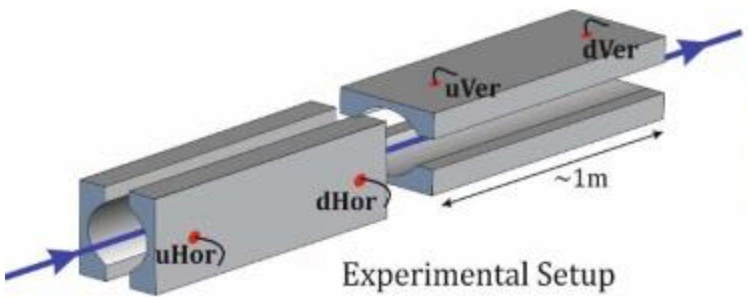
Experimental Setup

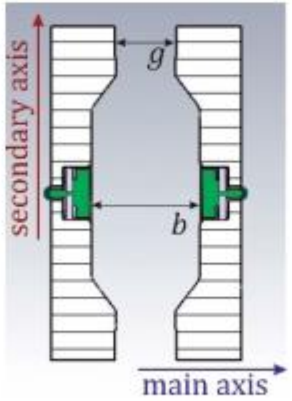




Obtained via EM simulations

1st phase: PU alignment





- **Main Axis**: direct alignment using position readings
- **Secondary Axis**: quadrupolar measurements

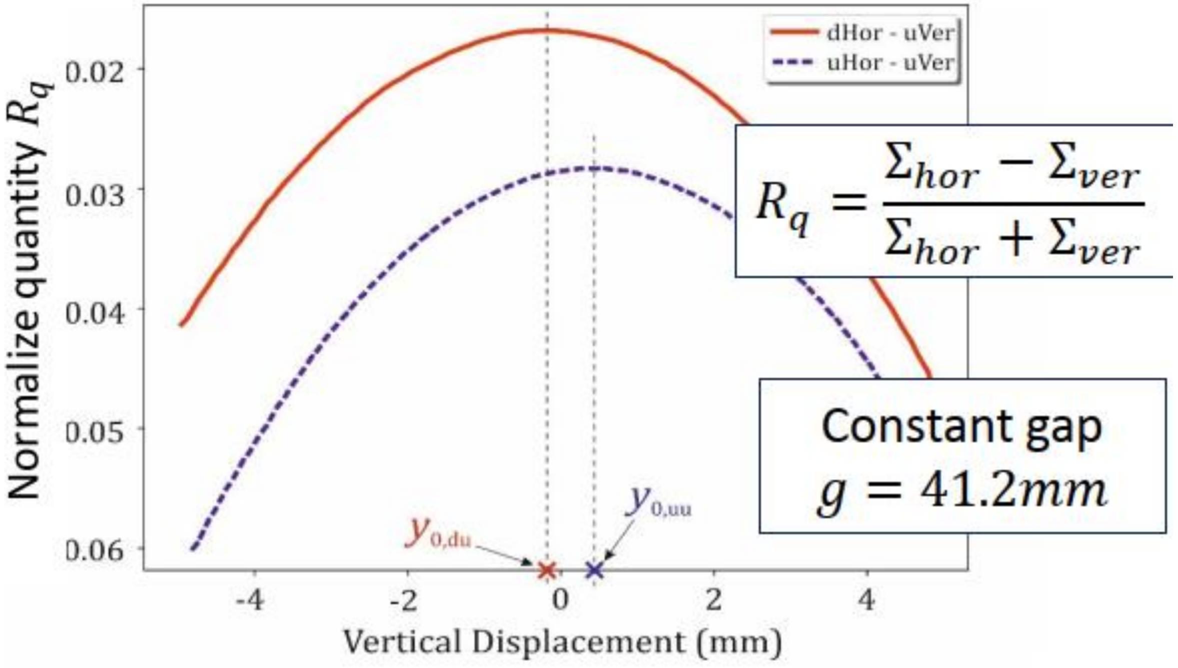
$$Q = \sigma_x^2 - \sigma_y^2 + x^2 - y^2$$

$\downarrow$ During scans on the secondary axis

$$Q_h = Q_{h,0} - y^2 \quad \text{Hor. collimator}$$

$$Q_v = Q_{v,0} + x^2 \quad \text{Ver. collimator}$$

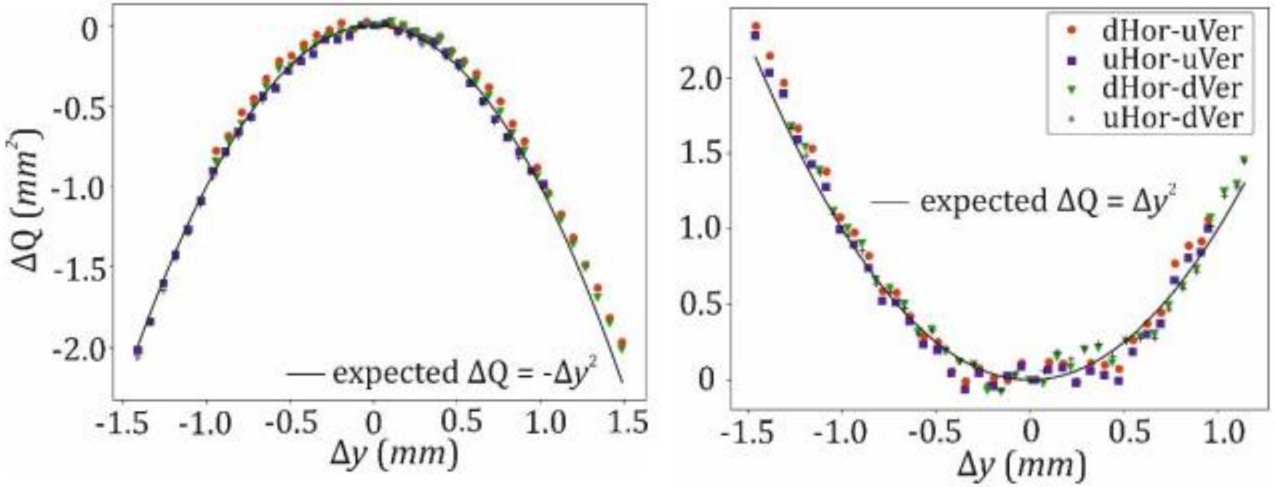
Alignment process on the secondary axis



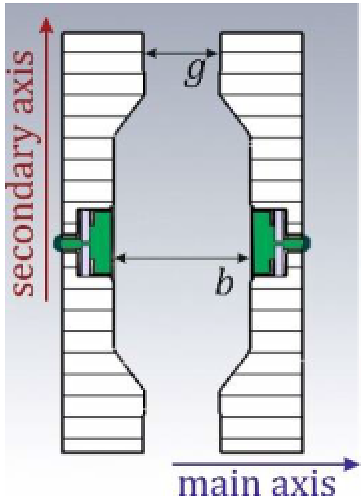
$$R_q = \frac{\Sigma_{hor} - \Sigma_{ver}}{\Sigma_{hor} + \Sigma_{ver}}$$

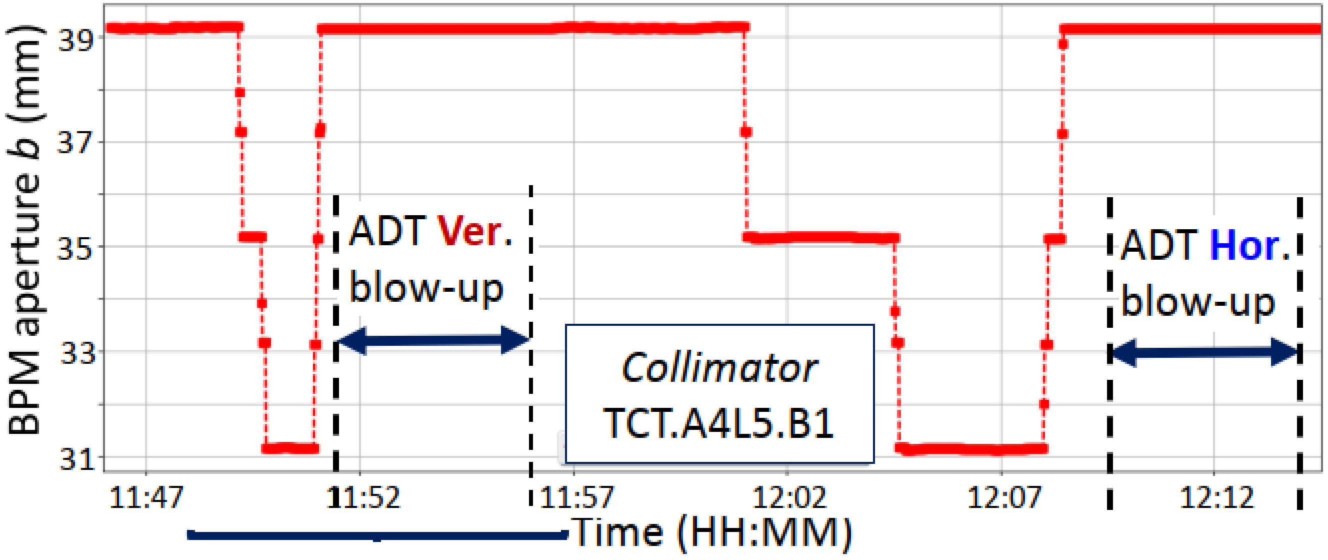
Constant gap
$g = 41.2mm$

Scan around beam center after alignment



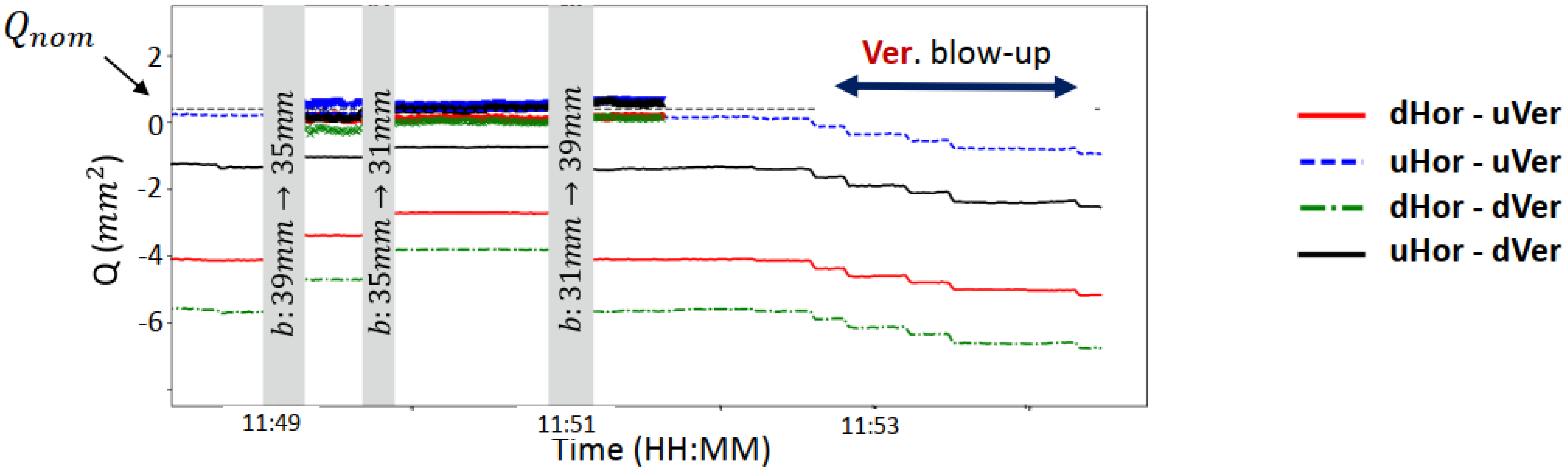
2nd phase: aperture scans + emittance blow-up





Injection energy
($450\ GeV$)

Nominal values:
- $\beta_x = 165m$
- $\beta_y = 79m$
- $Q_{nom} = 0.47mm^2$



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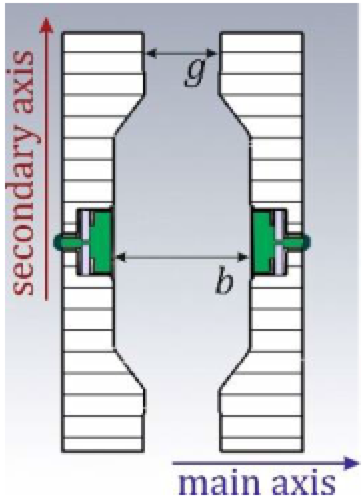

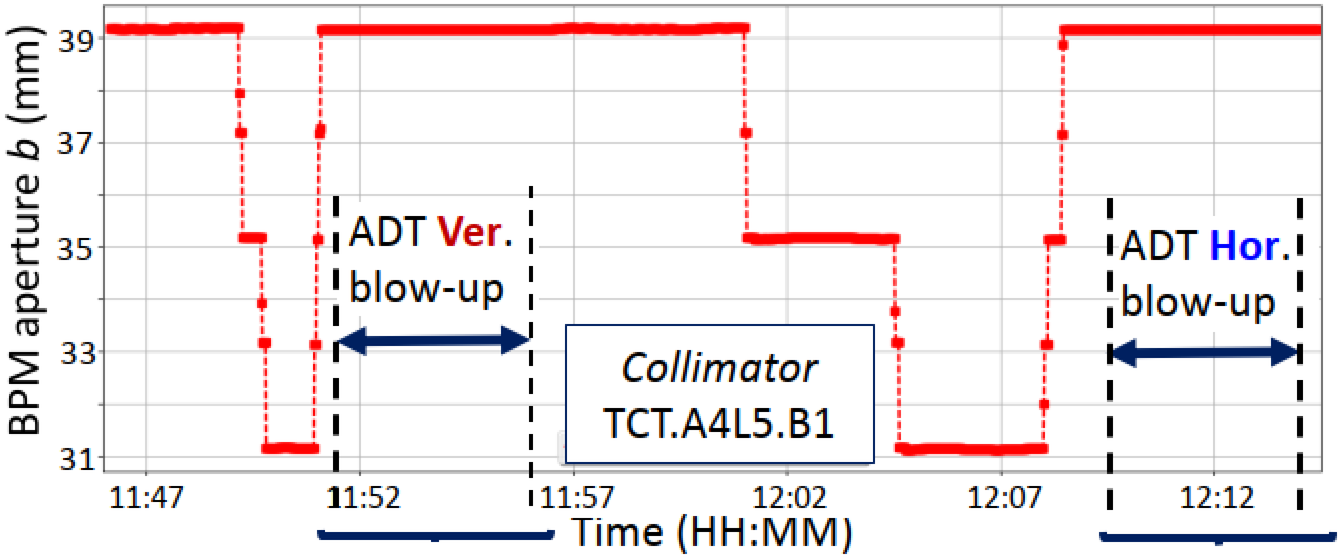

Collimator TCT.A4L5.B1

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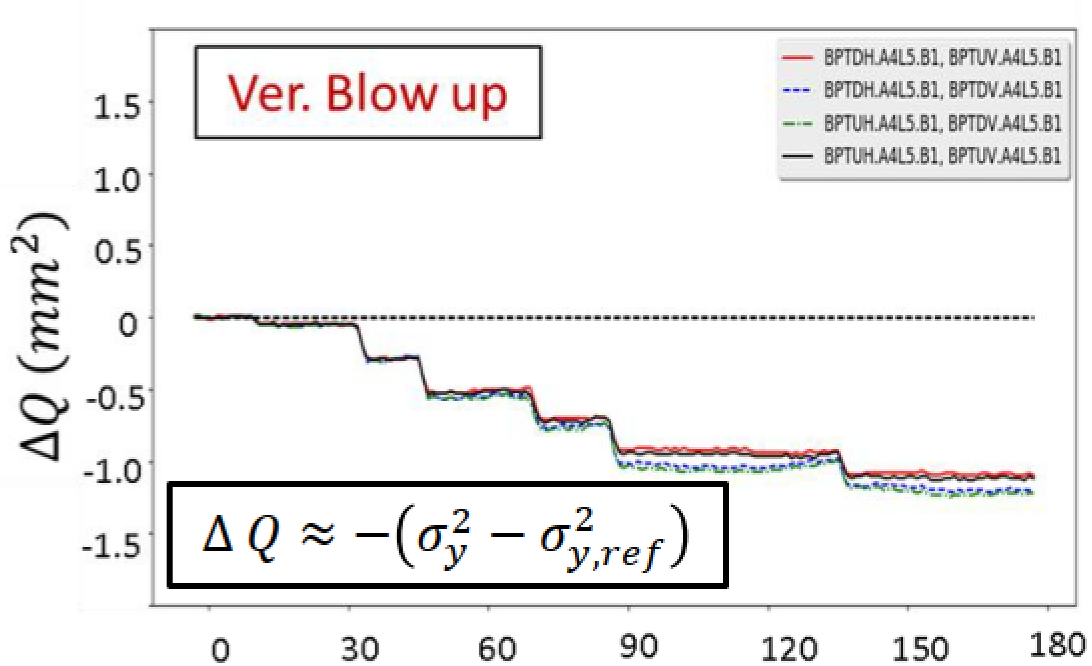
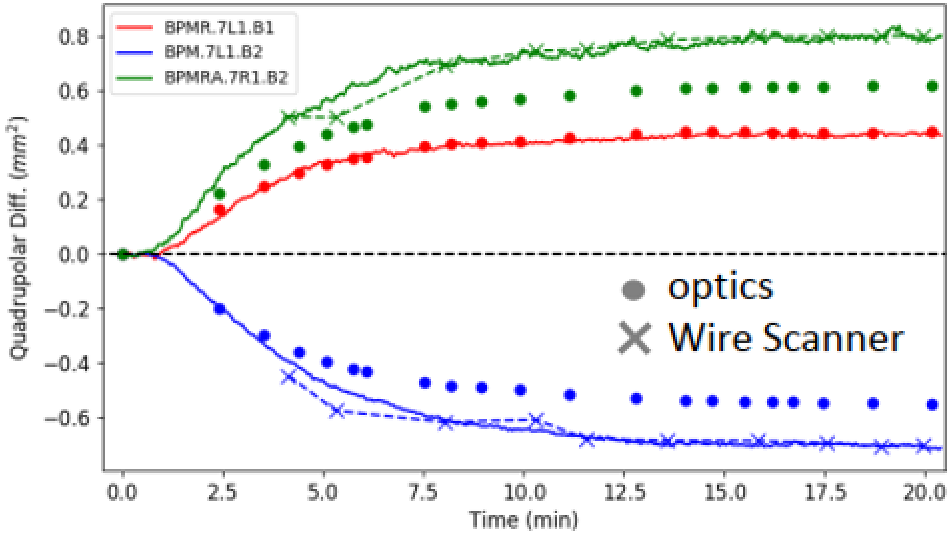
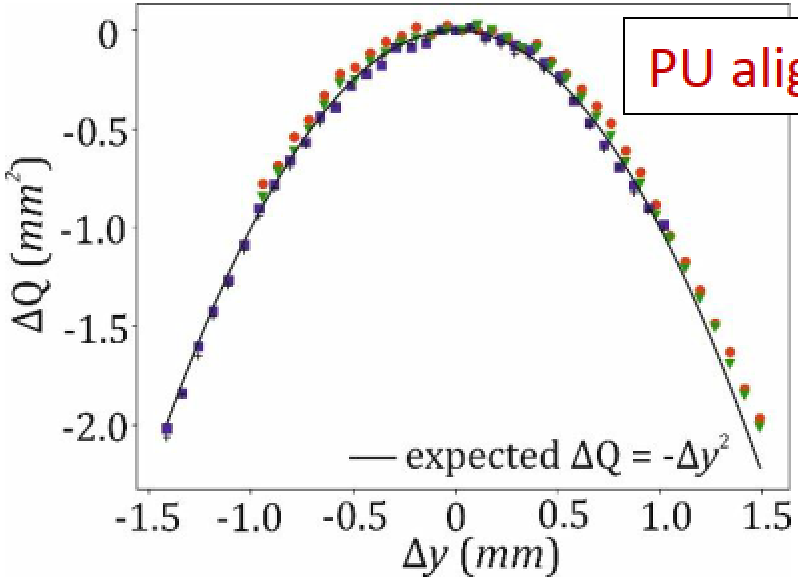


$$\Delta Q \approx -(\sigma_y^2 - \sigma_{y,ref}^2)$$

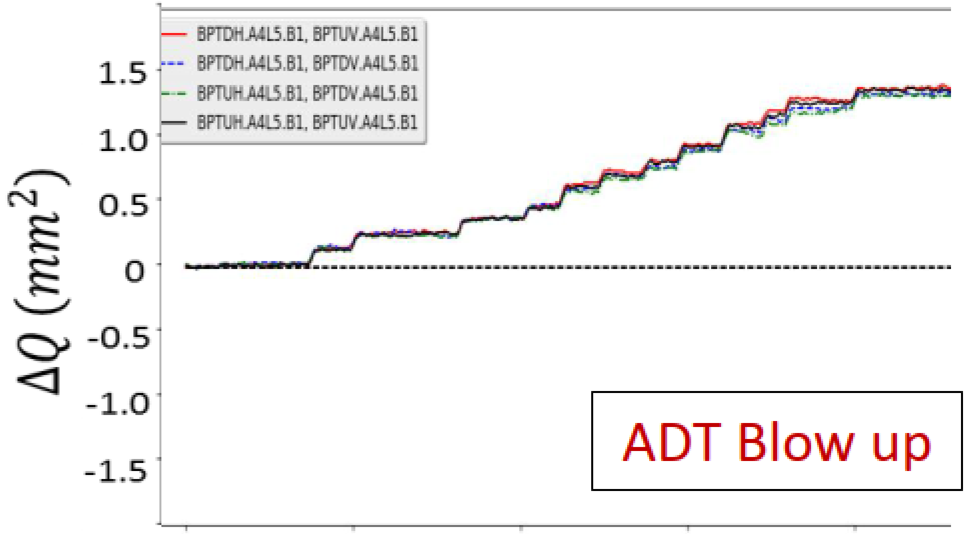
..and during the energy ramp → $\varepsilon \propto (\gamma\beta)^{-1}$



Promising differential measurements during PU alignment, during ADT blow-up

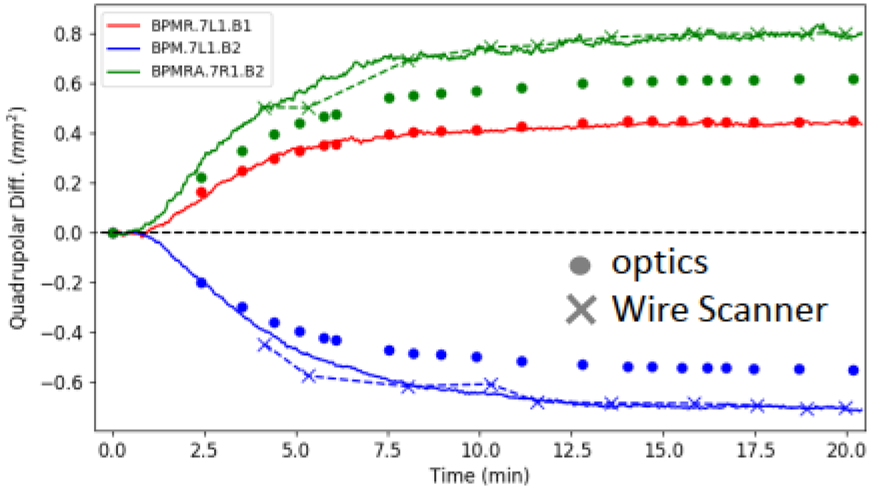


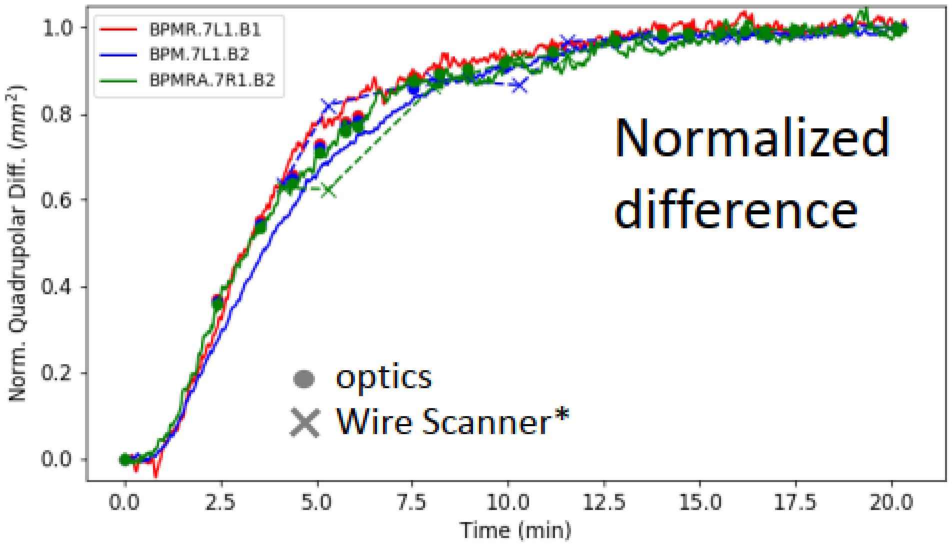
PU alignment



ADT Blow up

..and during the energy ramp

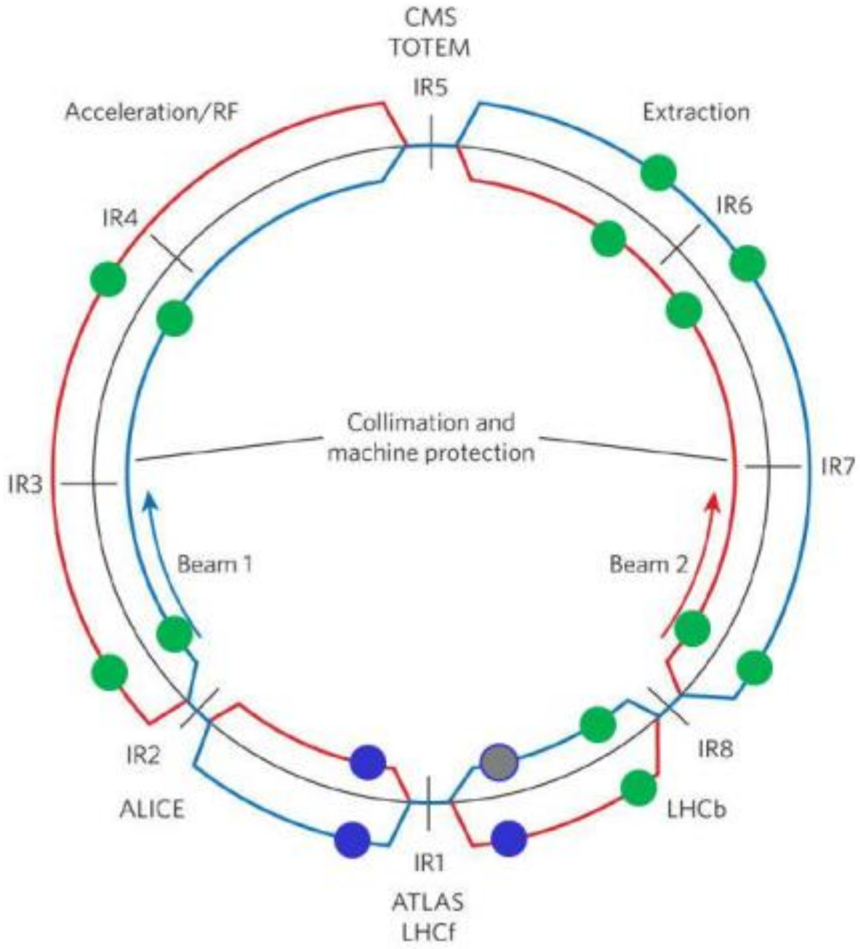




Normalized difference

Estimating change of geometrical emittance during the ramp

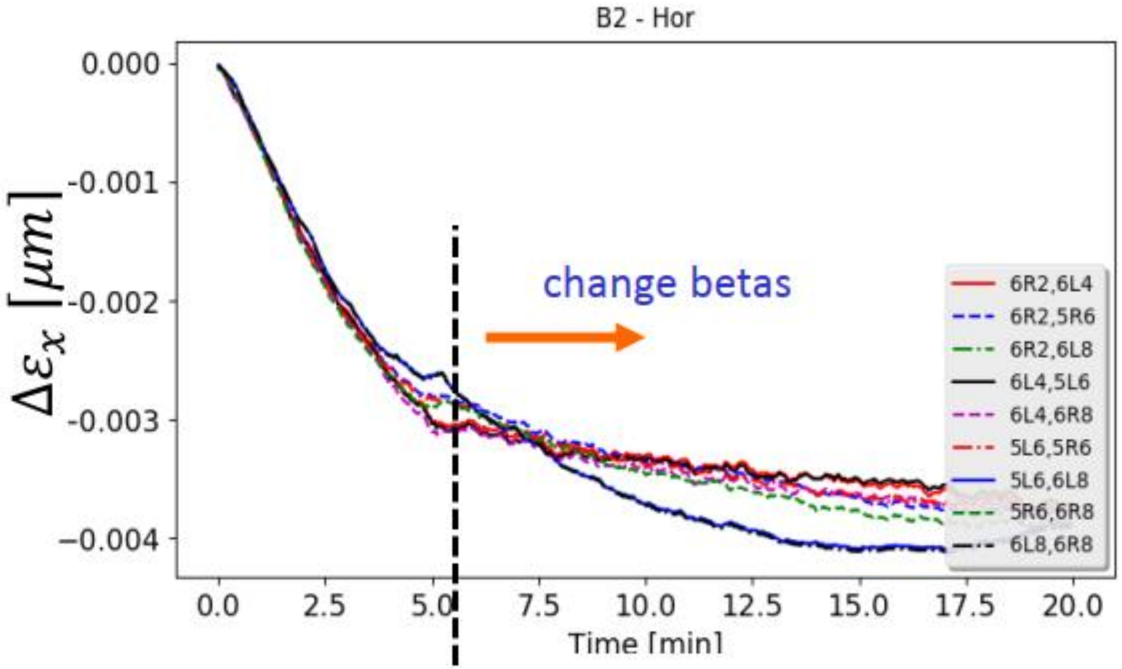
12 BPMs all around LHC



- Combine (at least) 2 BPMs with different beta functions

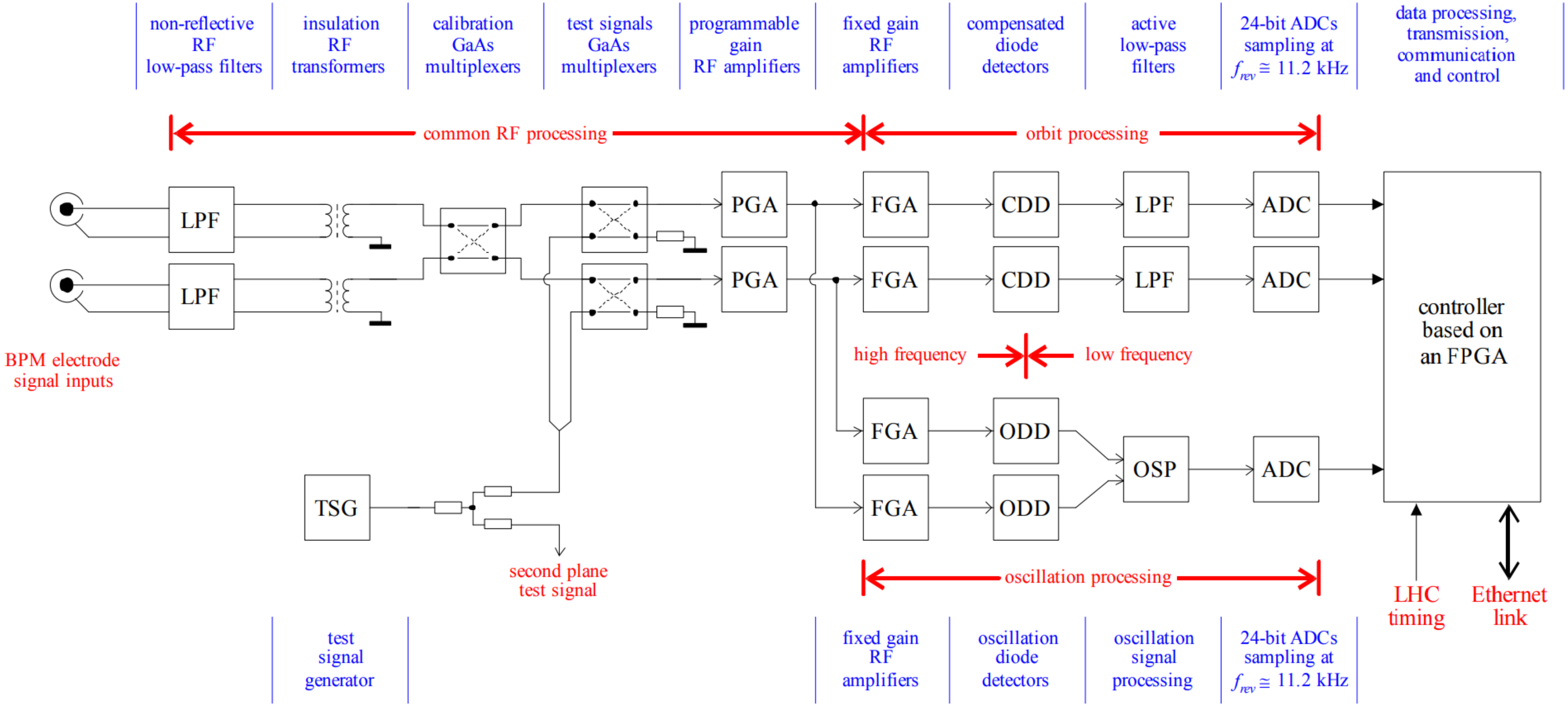
$$\Delta Q^{(1)} = \beta_x^{(1)} \Delta\varepsilon_x - \beta_y^{(1)} \Delta\varepsilon_y$$

$$\Delta Q^{(2)} = \beta_x^{(2)} \Delta\varepsilon_x - \beta_y^{(2)} \Delta\varepsilon_y$$



change betas

start squeezing


non-reflective RF low-pass filters
insulation RF transformers
calibration GaAs multiplexers
test signals GaAs multiplexers
programmable gain RF amplifiers
fixed gain RF amplifiers
compensated diode detectors
active low-pass filters
24-bit ADCs sampling at $f_{rev} \cong 11.2$ kHz
data processing, transmission, communication and control
common RF processing
orbit processing
LPF
LPF
PGA
PGA
FGA
FGA
CDD
CDD
LPF
LPF
ADC
ADC
controller based on an FPGA
BPM electrode signal inputs
high frequency
low frequency
FGA
FGA
ODD
ODD
OSP
ADC
TSG
second plane test signal
oscillation processing
LHC timing
Ethernet link
test signal generator
fixed gain RF amplifiers
oscillation diode detectors
oscillation signal processing
24-bit ADCs sampling at $f_{rev} \cong 11.2$ kHz