BPM Technologies for Quadrupolar Moment Measurements

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Outline

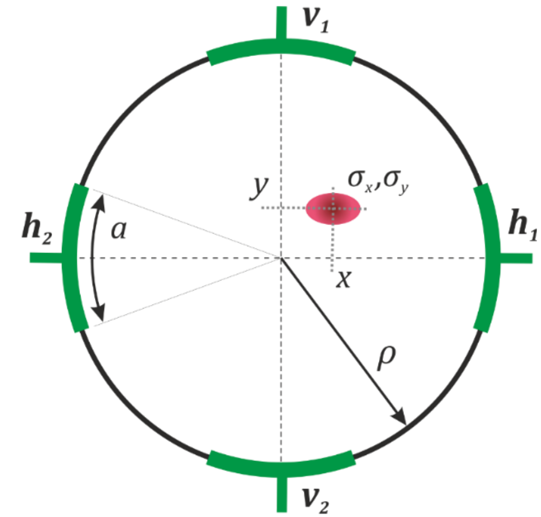
- Introduction
- Problem Overview - Fundamental Limitations
- New Approach based on Movable BPMs
- Preliminary Tests
- Differential Measurements
- Conclusion

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.

$$U_{h1} \propto \frac{a}{2\pi} + \frac{1}{\rho}\frac{2sin(a/2)}{\pi}x + \frac{1}{\rho^2}\frac{sin(a)}{\pi}\underbrace{\left(\sigma_x^2 - \sigma_y^2 + x^2 - y^2\right)}_{\text{Quadrupolar Term}} + \cdots$$

Quadrupolar Term



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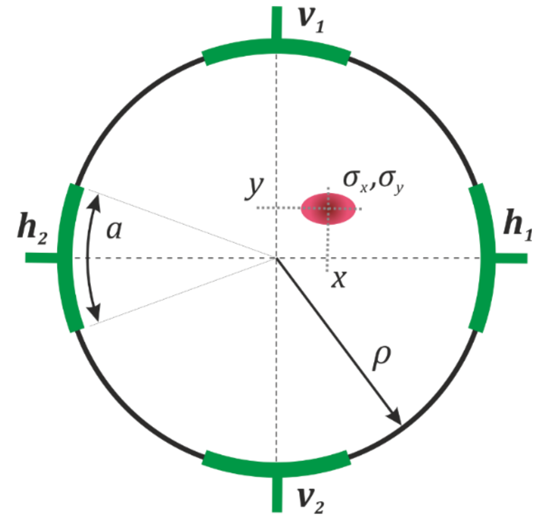


Motivation

Support Beam Size / Emittance measurements

- Non-intercepting
- Existing PU technology (BPMs)
- Energy independent

Wire Scanners (WS)
- Partially distractive
- Limited by Intensity

Synchrotron Light Monitors (BSRT)
- Limitations during energy ramp
- Need WS for calibration

Standard Measurement Technique

PU signals as a multipole expansion

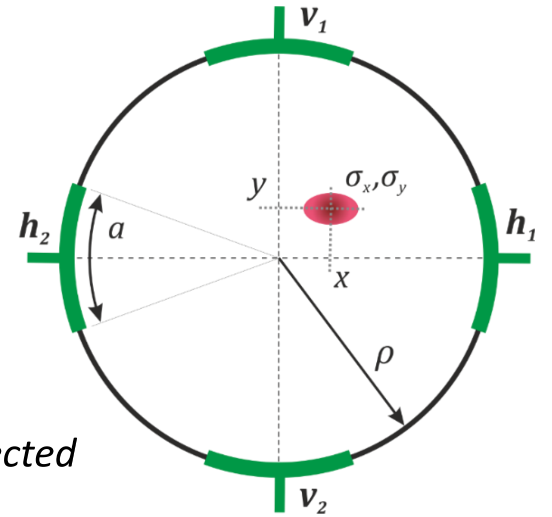
$$U_{h1} = i_b[c_0 + c_1 D_x + c_2 \boldsymbol{Q} + \cdots]$$

$$U_{h2} = i_b[c_0 - c_1 D_x + c_2 \boldsymbol{Q} + \cdots]$$

$$U_{v1} = i_b[c_0 + c_1 D_y - c_2 \boldsymbol{Q} + \cdots]$$

$$U_{v2} = i_b[c_0 - c_1 D_y - c_2 \boldsymbol{Q} + \cdots]$$

High order terms can be fairly neglected



Quadrupolar Term

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

Standard Measurement Technique

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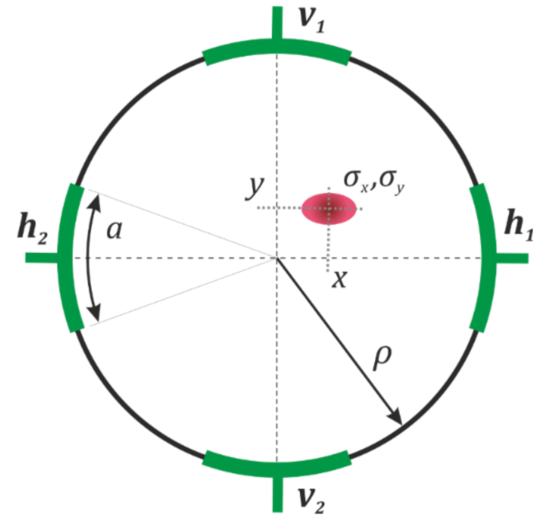

Cancel Dipolar moments

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

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

Cancel Monopole moment

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

Normalize by intensity

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

Standard Measurement Technique

PU signals as a multipole expansion

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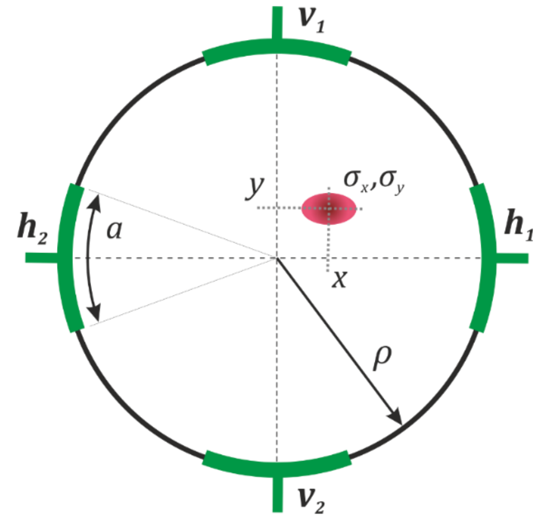

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Pretty straightforward…
but very challenging!

Challenges (1)

Low Quadrupolar Sensitivity

Analytical 2D Case

$$U_{h1} \propto \frac{a}{2\pi} + \frac{1}{\rho}\frac{2sin(a/2)}{\pi}x + \frac{1}{\rho^2}\frac{sin(a)}{\pi}\left(\sigma_x^2 - \sigma_y^2 + x^2 - y^2\right) + \cdots$$

General Case

$$U_{h1} \propto c_0 + c_1 D_x + c_2 Q + \cdots$$

$$\frac{c_2}{c_0} Q \propto (\sigma_{\text{eff}}/\rho)^2 \ll 1$$

Quadrupolar moment constitutes only a *very small part* of the total BPM signal

Typical values: *few per milles*

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channel **asymmetries** —low sensitivity→ large **offsets**

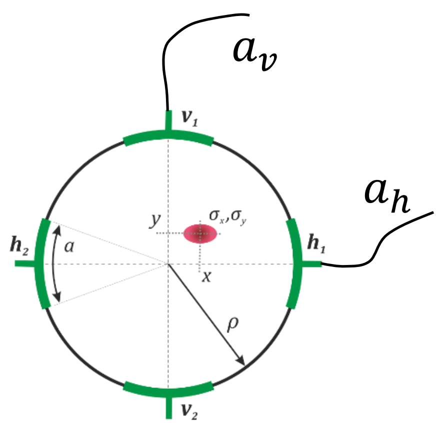
ideal world

symmetric channels

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

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

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



realistic case

small asymmetry

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

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

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

Challenges (1)

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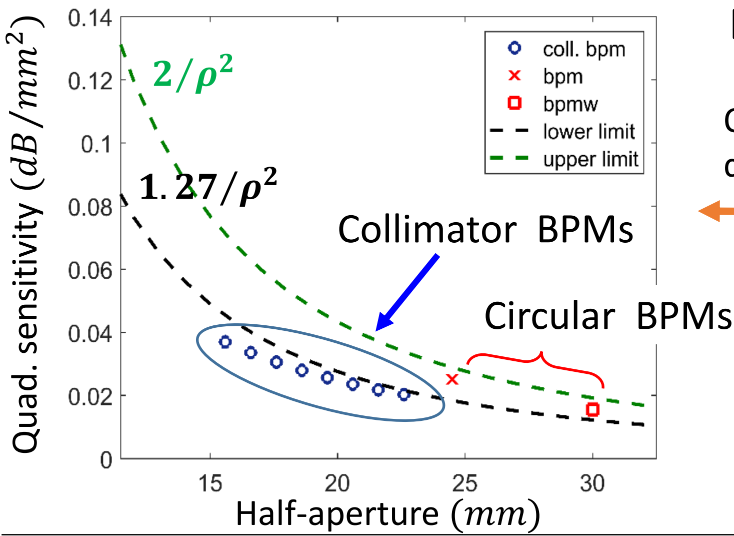
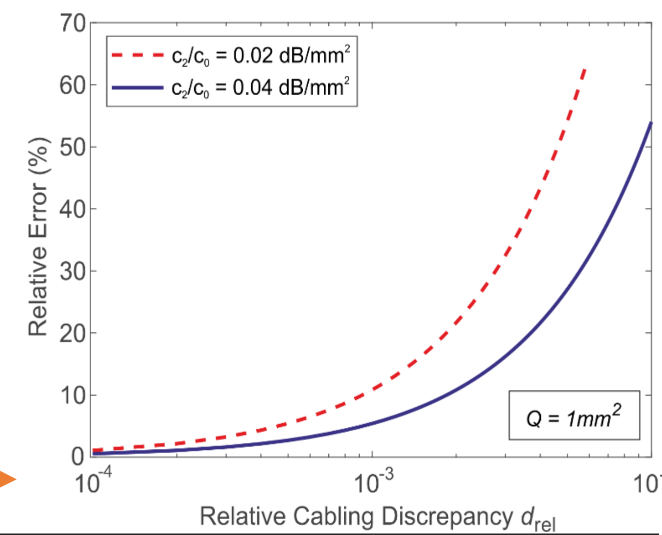


Example: LHC BPMs

Quad. sensitivity (c_2/c_0) for different types of LHC BPMs

Error considering a cabling discrepancy in one channel



Challenges (2)

Parasitic Position Signal

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

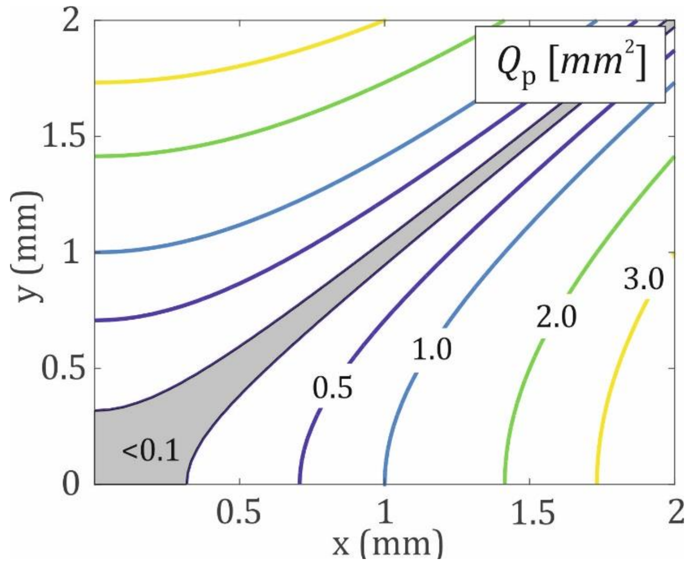
beam size signal
to be measured

position signal
parasitic

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



Problem – Overview

Fundamental Limitations	*Unfavourable Conditions*		Destructive Measurement Effects
Low quadrupolar sensitivity $U_{h1} \propto c_0 + c_1 D_x + c_2 Q + \cdots$ $c_2 Q \ll c_0$	*asymmetries (electronics, cabling, geometrical)*	→	Beam size information lost in **large offsets**
	noise (electronics)	→	**Low resolution****
Parasitic Position Signal $Q = \sigma_x^2 - \sigma_y^2 + x^2 - y^2$	*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 → $\sim 0.01 mm^2$ quadrupolar resolution

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

Subtract Position Signal

Direct subtraction

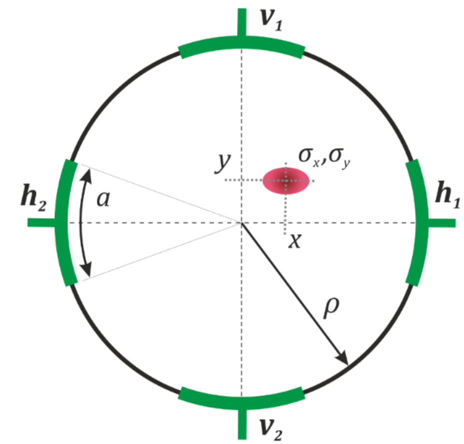
Manipulate PU as a beam position monitor (BPM)

1. Measure the beam position

$$x_m = P\left(\frac{U_{h1} - U_{h2}}{U_{h1} + U_{h2}}\right) \qquad y_m = P\left(\frac{U_{v1} - U_{v2}}{U_{v1} + U_{v2}}\right)$$

2. Subtract the parasitic signal

$$Q_{\sigma,m} = Q - x_m^2 + y_m^2$$



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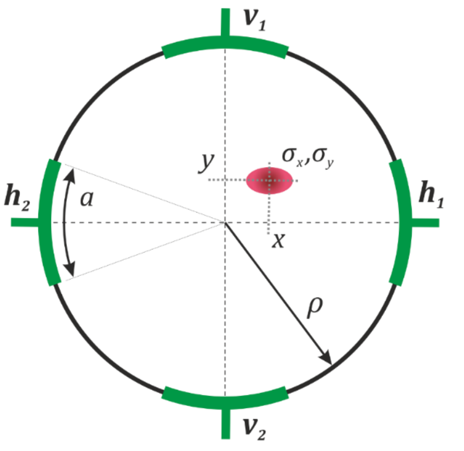
Is this subtraction sufficient to cancel the position signal?



Subtract Position Signal

Direct subtraction

Manipulate PU as a beam position monitor (BPM)

1. Measure the beam position, **with certain accuracy**

$$x_m = P\left(\frac{U_{h1} - U_{h2}}{U_{h1} + U_{h2}}\right) \qquad y_m = P\left(\frac{U_{v1} - U_{v2}}{U_{v1} + U_{v2}}\right)$$

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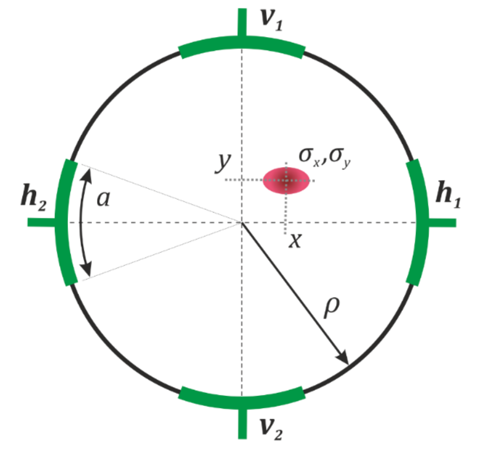

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Subtract Position Signal

Direct subtraction

Manipulate PU as a beam position monitor (BPM)

1. Measure the beam position, **with certain accuracy**

$$x_m = x + \Delta x \qquad y_m = y + \Delta y$$

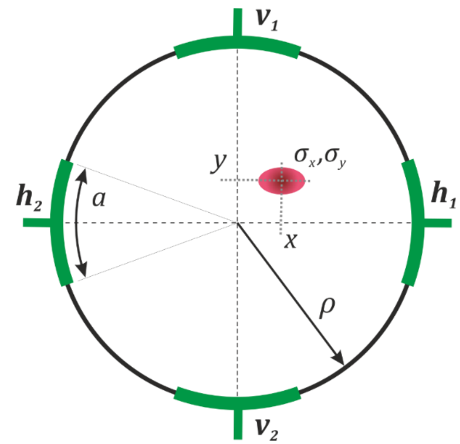
2. Subtract the parasitic signal

$$Q_{\sigma,m} = Q - x_m^2 + y_m^2$$

Remaining Error:

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

Significant for large offsets



Towards a Movable PU..

Direct subtraction

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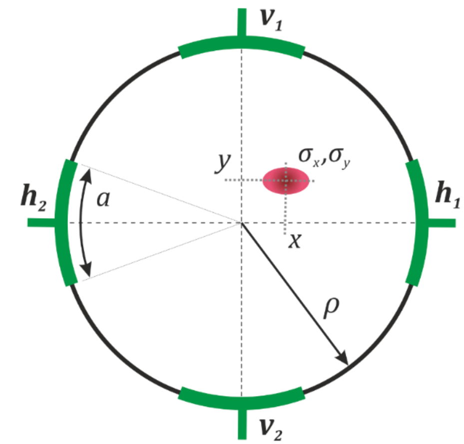


Subtraction by Alignment (Movable PU)

1. Measure the beam position, **with certain accuracy**

$$x_m = x + \Delta x \qquad y_m = y + \Delta y$$

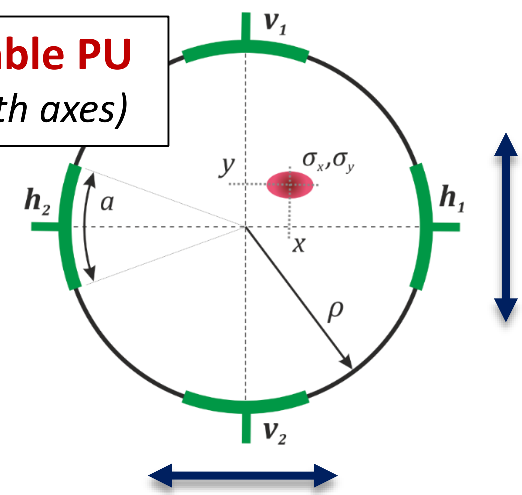
2. Align PU according to (x_m, y_m)

$$x' \approx \Delta x \qquad y' \approx \Delta y$$

Remaining Error:

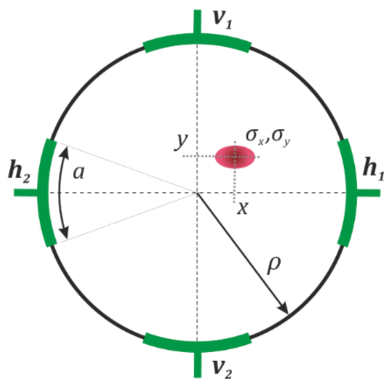
$$Q_{x,rem} \approx \Delta x^2$$

Movable PU
(in both axes)



Towards a Movable PU..

Direct subtraction (Fixed PU)

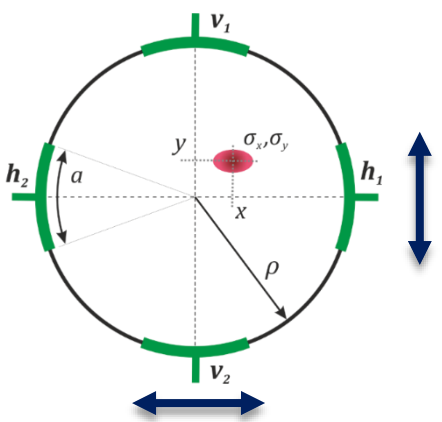


Measure & subtract beam position

Remaining Error:

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

Subtraction by Alignment (Movable PU)



Measure beam position & align PU

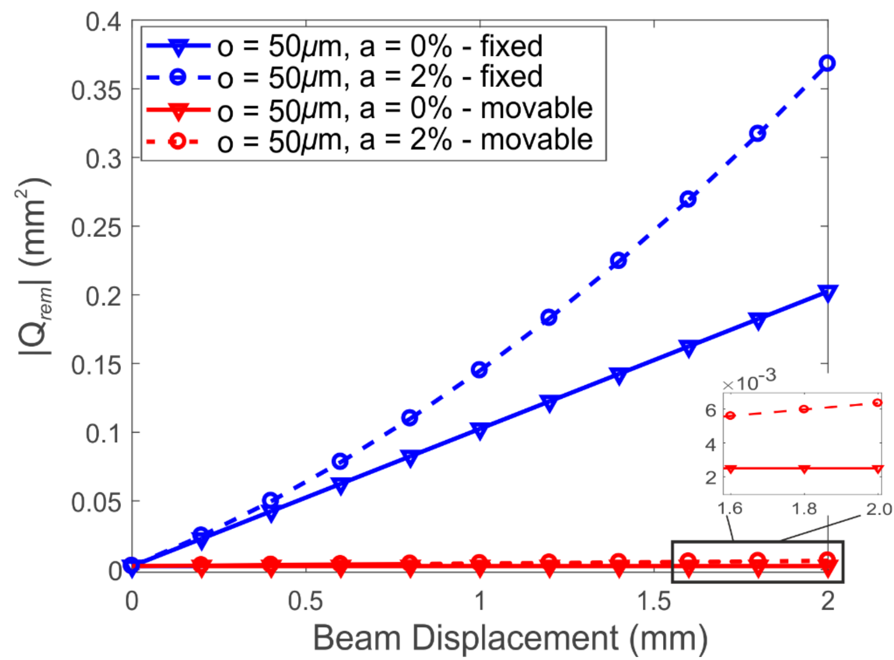
Remaining Error:

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

Example

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

$$\Delta x = o + ax$$



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Align PU with the beam ← movable PU

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

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	noise (electronics) →	*Could we use movable PUs to remove the offsets?*
Parasitic Position Signal $Q = \sigma_x^2 - \sigma_y^2 + x^2 - y^2$	*off-centered beam* →	Beam size signal lost in **parasitic position signal**

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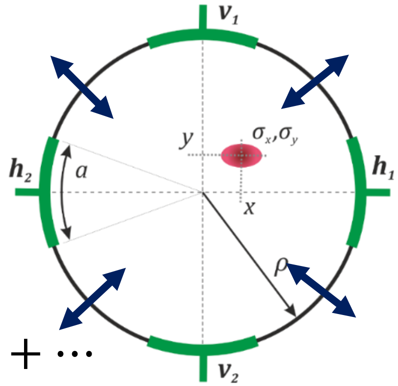
Aperture Scans

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



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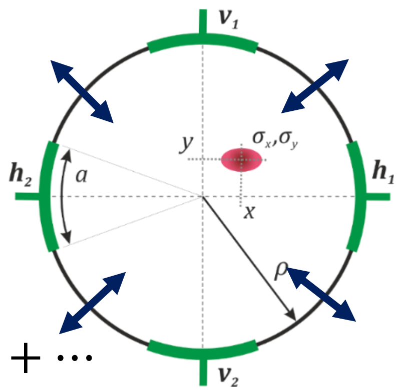

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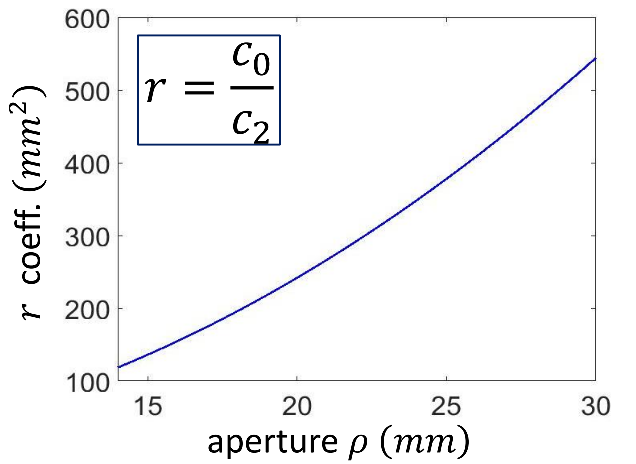

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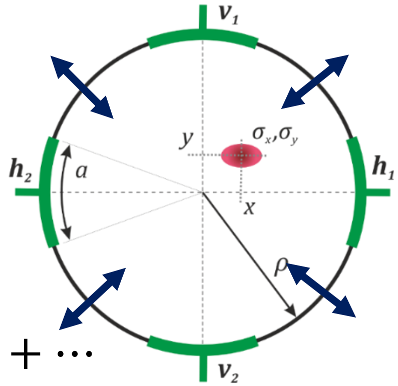

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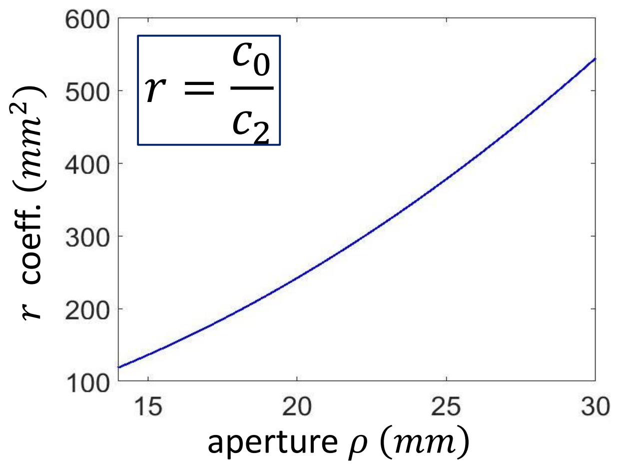

Monopole & Quadrupolar moments **change differently** w.r.t. to the aperture change → stable beam → Calibrate PU system (e.g. electronics/ cabling)

reference point

Aperture Scans

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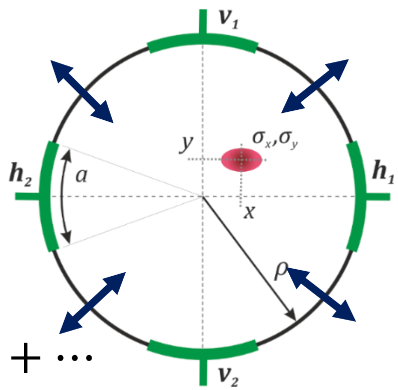

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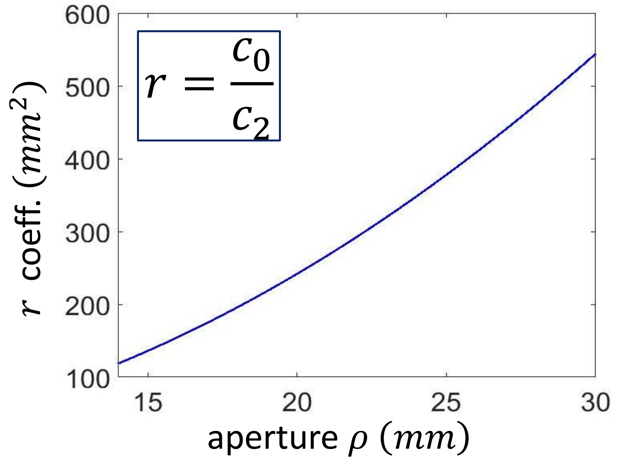

A more realistic example?

Monopole & Quadrupolar moments **change differently** w.r.t. to the aperture change → stable beam → Calibrate PU system (e.g. electronics/ cabling)

Aperture Scans

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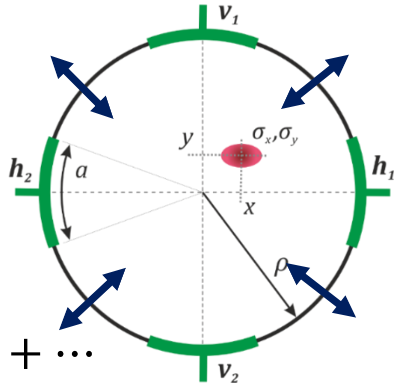

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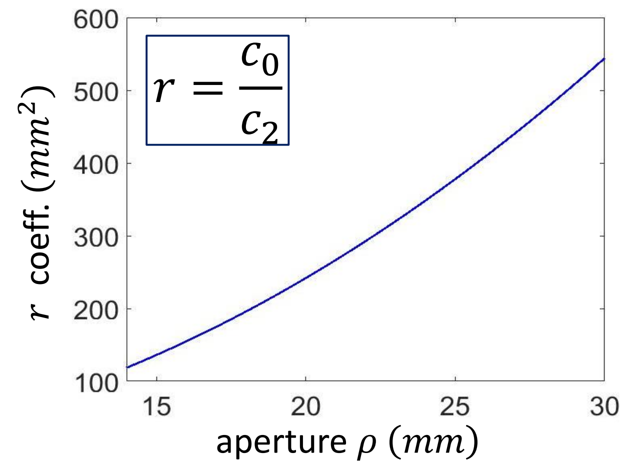
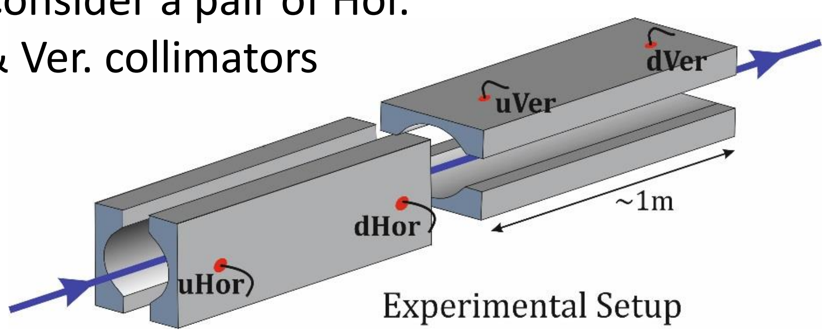


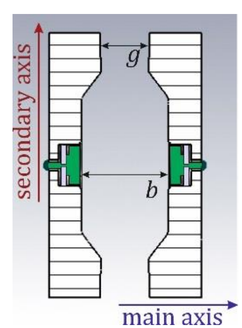
Monopole & Quadrupolar moments **change differently** w.r.t. to the aperture change

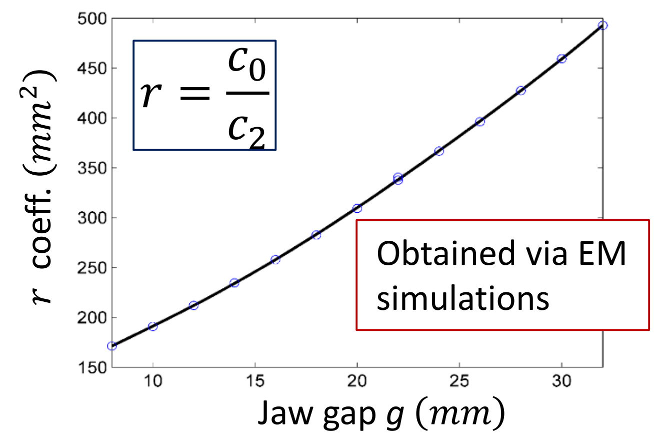
stable beam → Calibrate PU system (e.g. electronics/ cabling)

A more realistic example?

Consider a pair of Hor. & Ver. collimators

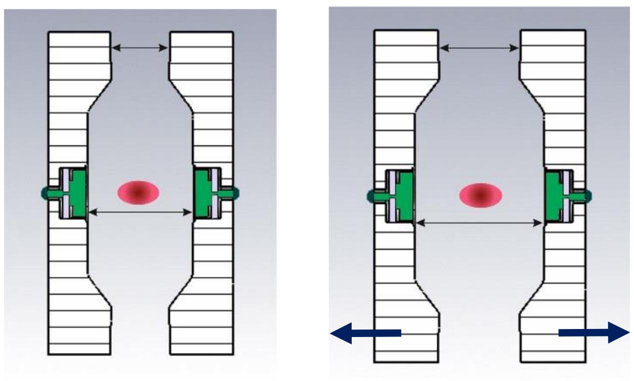






A New Approach: The d-Norm Method

Consider a movable PU, able to change the aperture



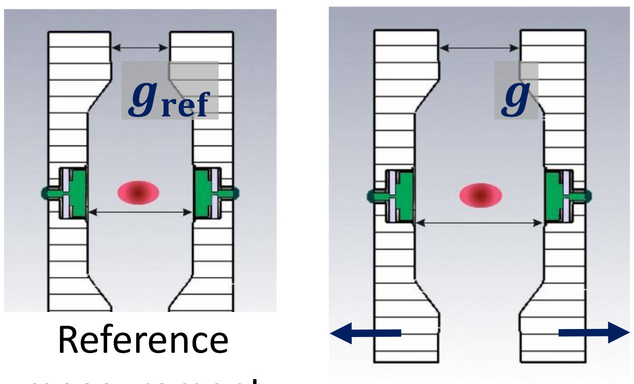
Consider some asymmetry between the Hor. & Ver. channels

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

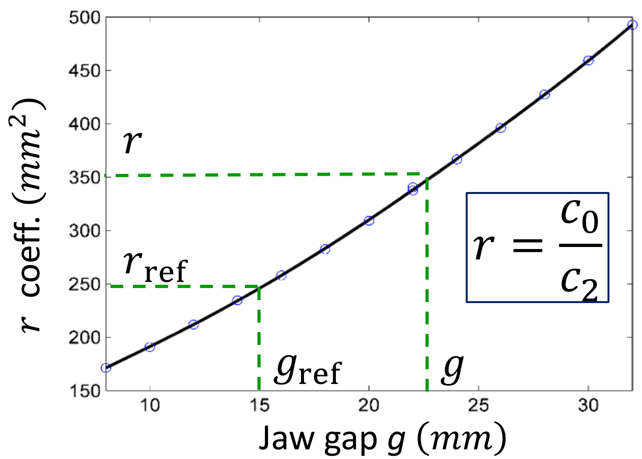
$$\Sigma_v = a_v i_b (c_0 - c_2 Q)$$

A New Approach: The d-Norm Method

Consider a movable PU, able to change the aperture



Reference measurement



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Perform 2 measurements with different apertures

A New Approach: The d-Norm Method

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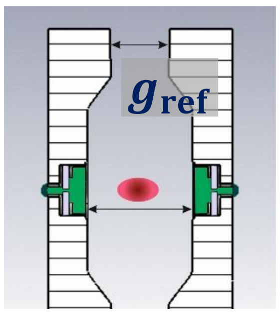

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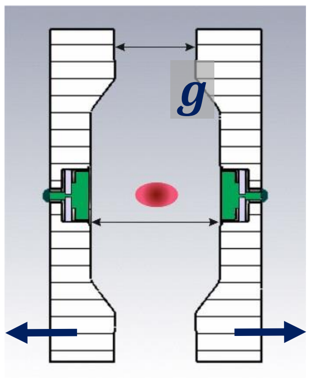

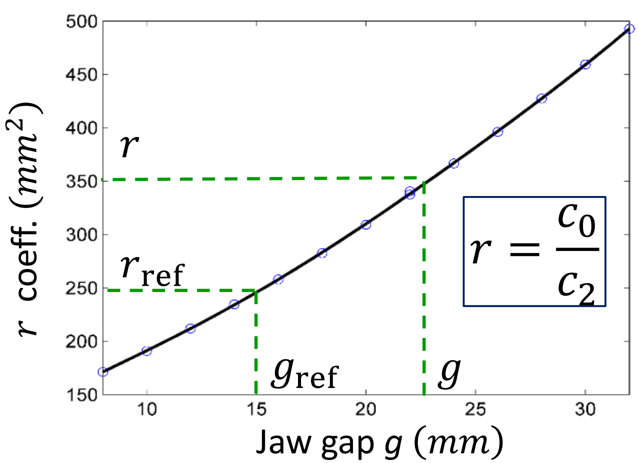

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Perform 2 measurements with different apertures

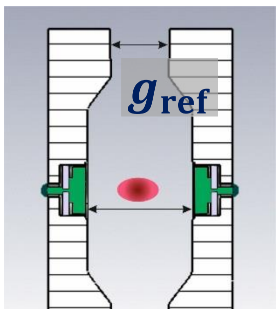
1st normalization — cancel the asymmetric gains a_h, a_v

$$S_h = \frac{\Sigma_h}{\Sigma_{h,ref}} = \frac{i_b (r + Q)}{i_{b,\mathrm{ref}} (r_{\mathrm{ref}} + Q)}$$

$$S_v = \frac{\Sigma_v}{\Sigma_{v,ref}} = \frac{i_b (r - Q)}{i_{b,\mathrm{ref}} (r_{\mathrm{ref}} - Q)}$$

A New Approach: The d-Norm Method

Consider a movable PU, able to change the aperture



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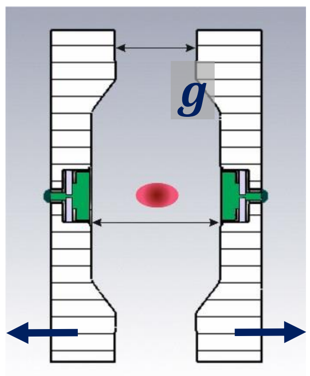

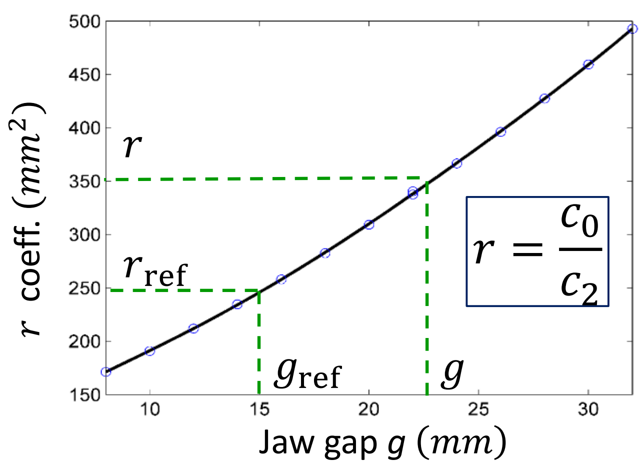

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Perform 2 measurements with different apertures

1st normalization — cancel the asymmetric gains a_h, a_v

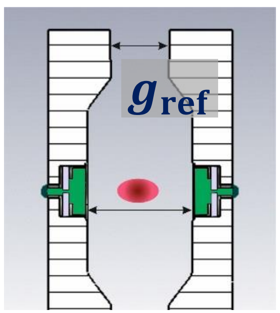
$$S_h = \frac{\Sigma_h}{\Sigma_{h,ref}} = \frac{i_b(r+Q)}{i_{b,\text{ref}}(r_{\text{ref}}+Q)} \qquad S_v = \frac{\Sigma_v}{\Sigma_{v,ref}} = \frac{i_b(r-Q)}{i_{b,\text{ref}}(r_{\text{ref}}-Q)}$$

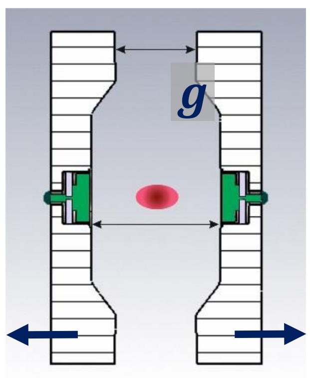
2nd normalization — normalize intensity

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

A New Approach: The d-Norm Method

Consider a movable PU, able to change the aperture





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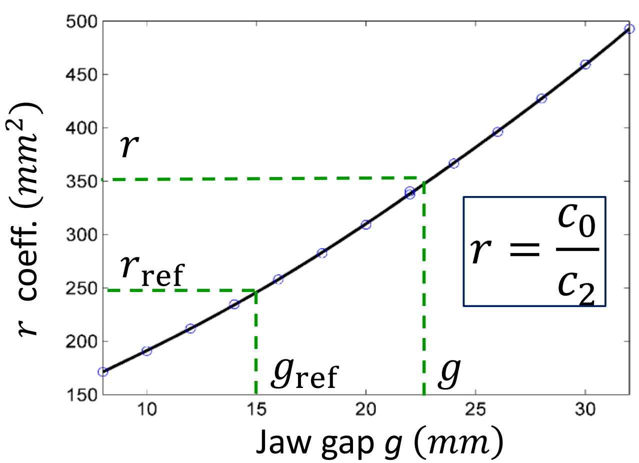

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Perform 2 measurements with different apertures

1st normalization — cancel the asymmetric gains a_h, a_v

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2nd normalization — normalize intensity

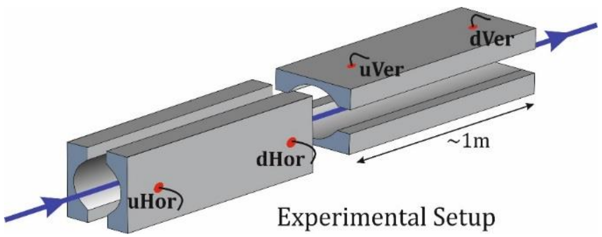
$$\mathrm{R} = \frac{S_h}{S_v} = \frac{r+Q}{r-Q}\,\frac{r_{\text{ref}}-Q}{r_{\text{ref}}+Q}$$

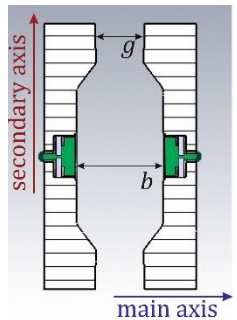
Q obtained by **double-normalization** (*d-Norm*)

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

First Observations

Experimental Setup: Collimator BPMs

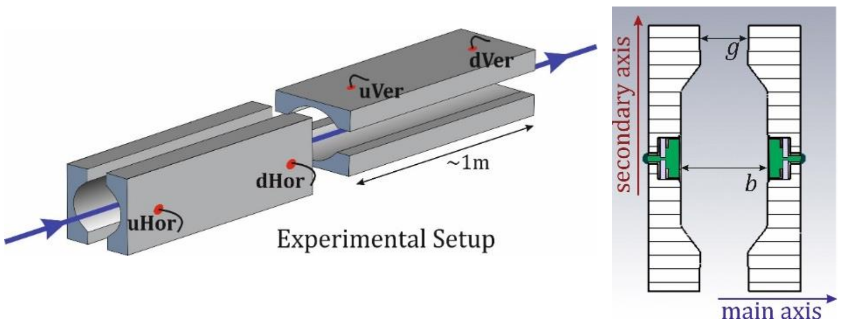




- Dioded-based electronics (DOROS) – **high resolution** (better than $1um$ for position measurements)
- BPM signals are **processed separately**
- Select a pair of Hor. –Ver. Collimators to form **4-electrodes PUs**
- **4 PUs in total** by combining upstream/downstream collimator BPMs

First Observations

1st phase: PU alignment



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

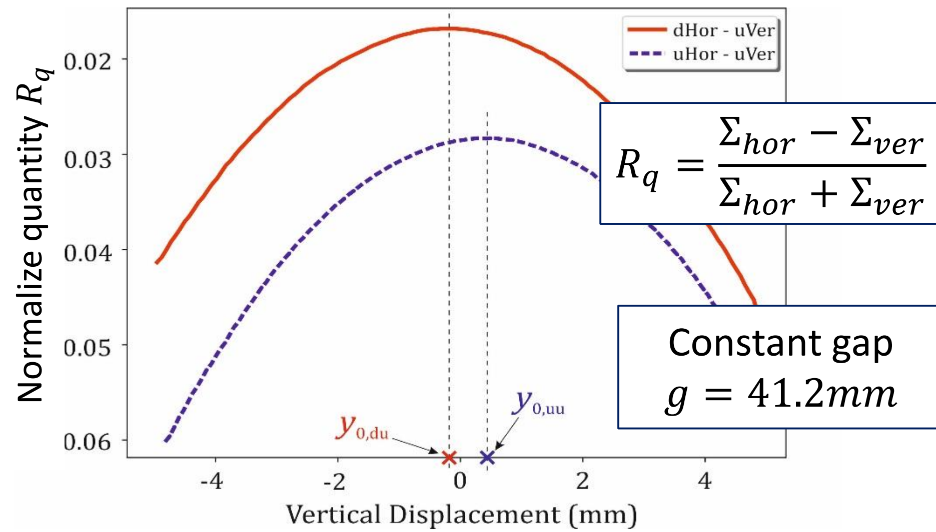
$$Q = \sigma_x^2 - \sigma_y^2 + x^2 - y^2$$

↓ During scans on the secondary axis

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

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

Alignment process on the secondary axis



First Observations

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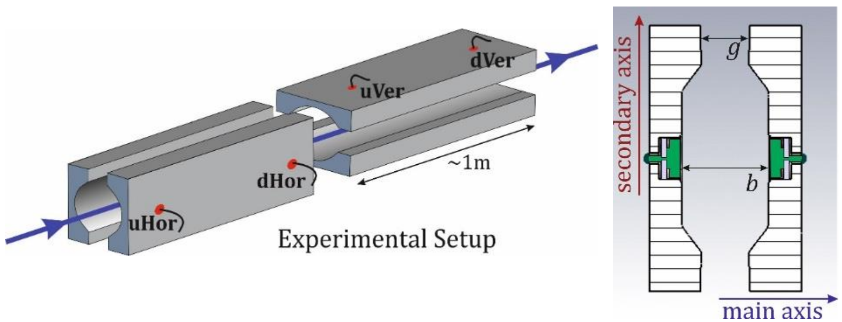

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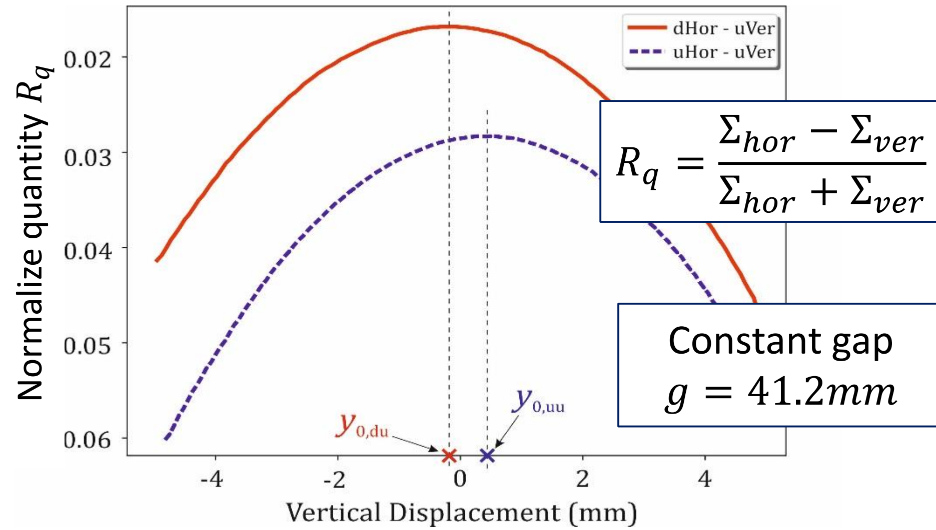
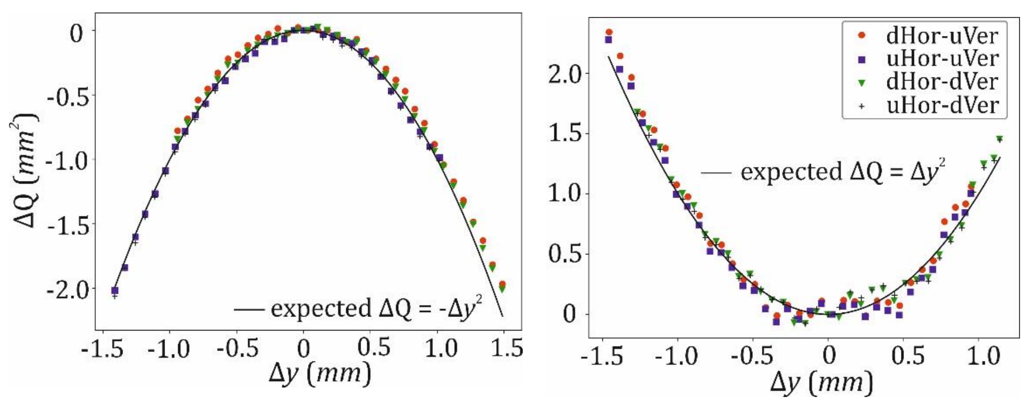
Alignment process on the secondary axis



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

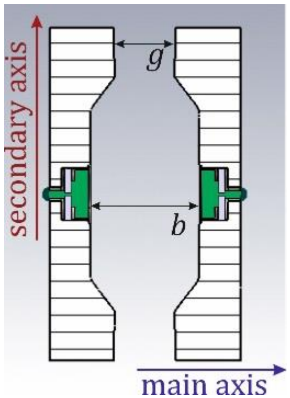
Constant gap
$g = 41.2mm$

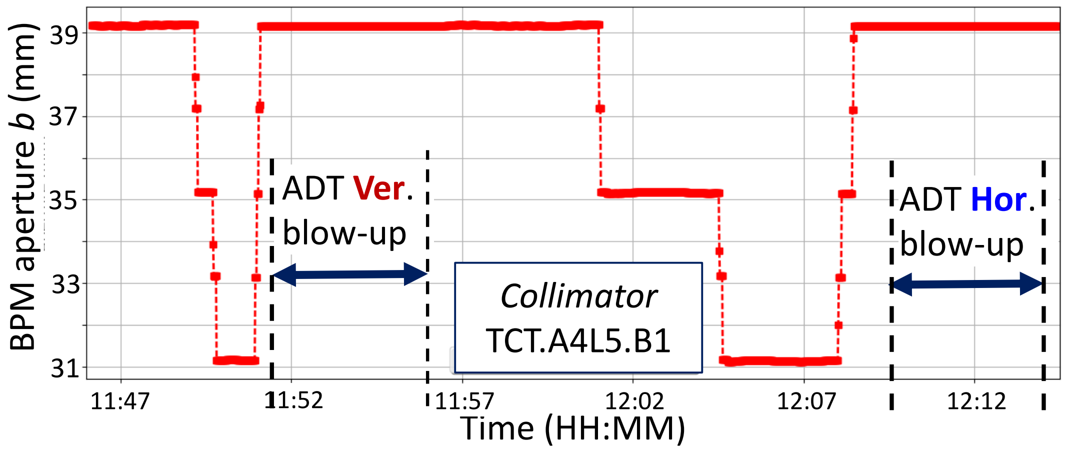
Scan around beam center after alignment



First Observations

2nd phase: aperture scans + emittance blow-up





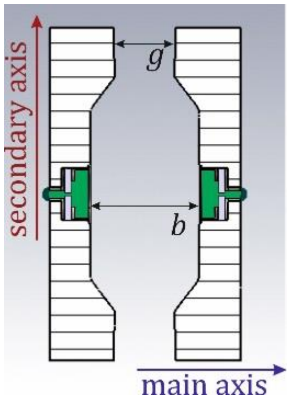
Injection energy ($450\ GeV$)

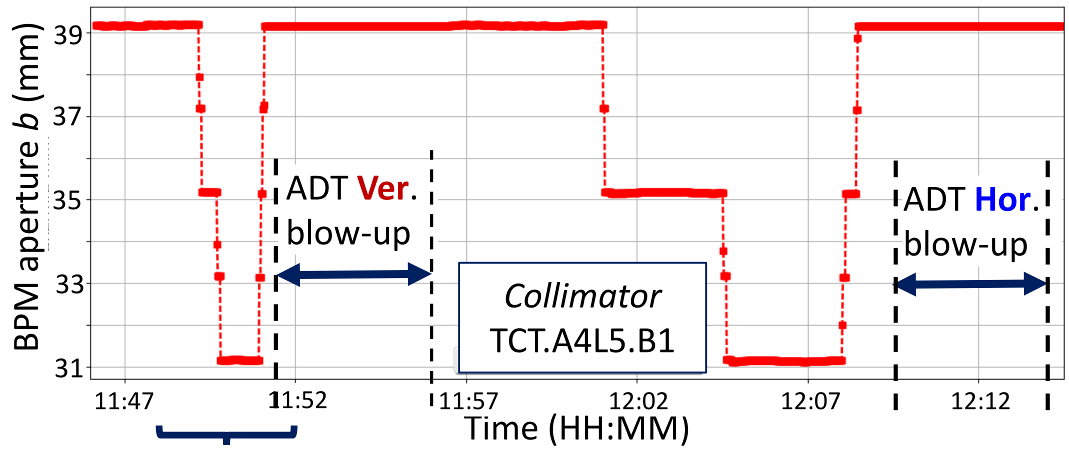
Nominal values:

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

First Observations

2nd phase: aperture scans + emittance blow-up





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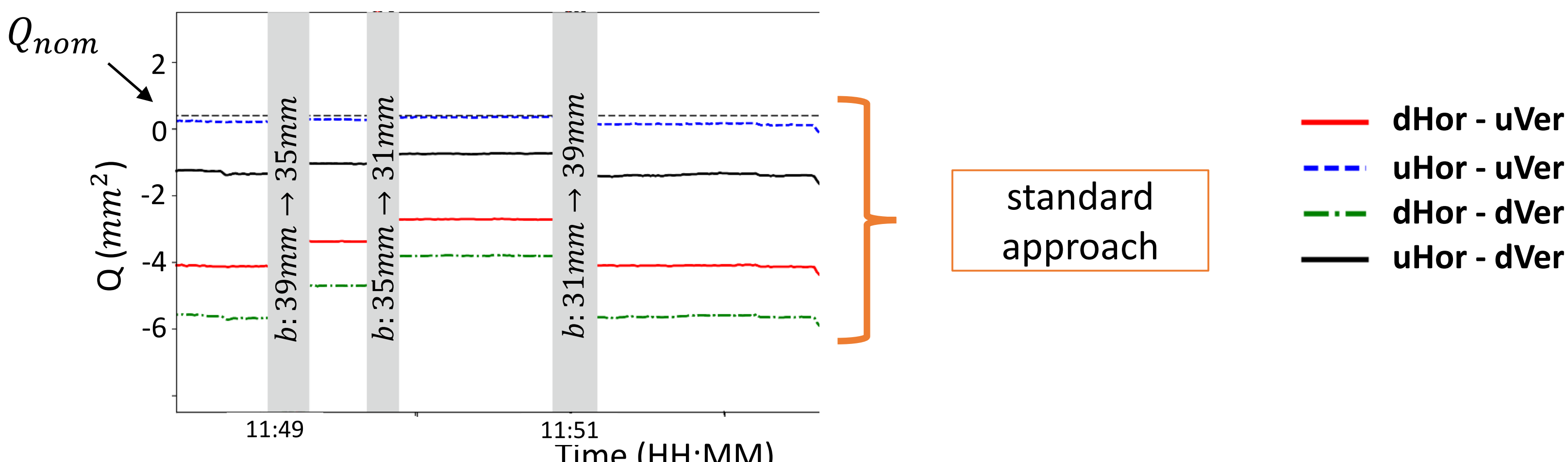
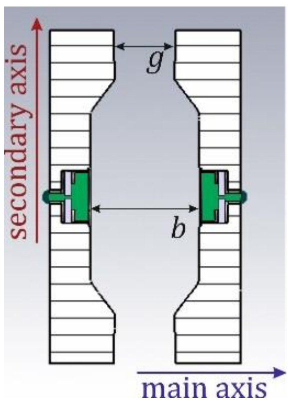
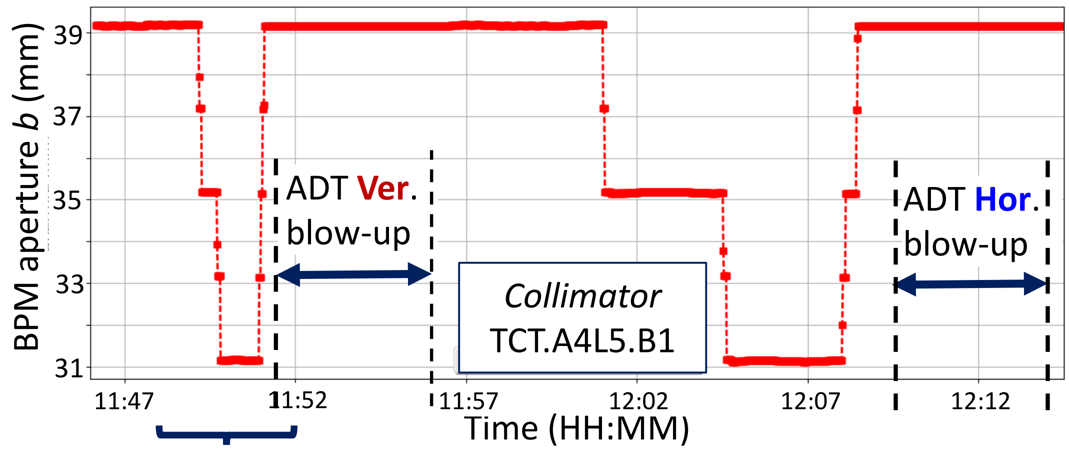


First Observations

2^{nd} phase: aperture scans + emittance blow-up





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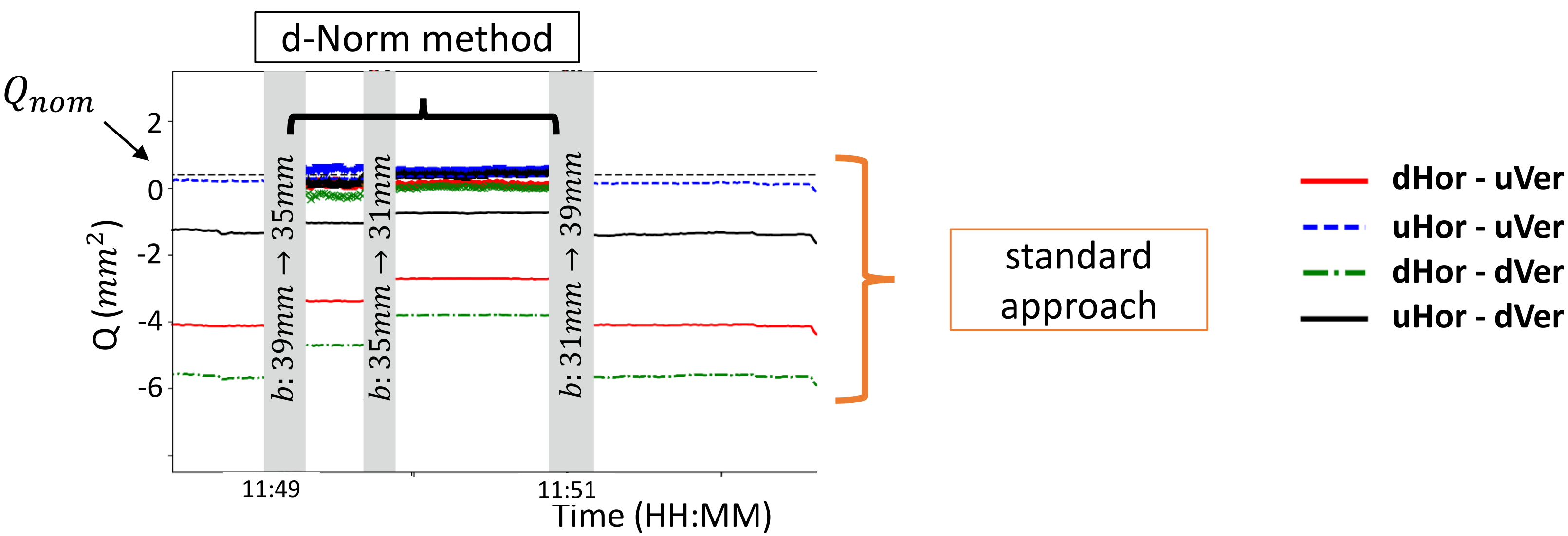

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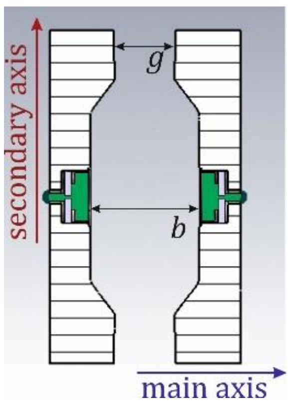

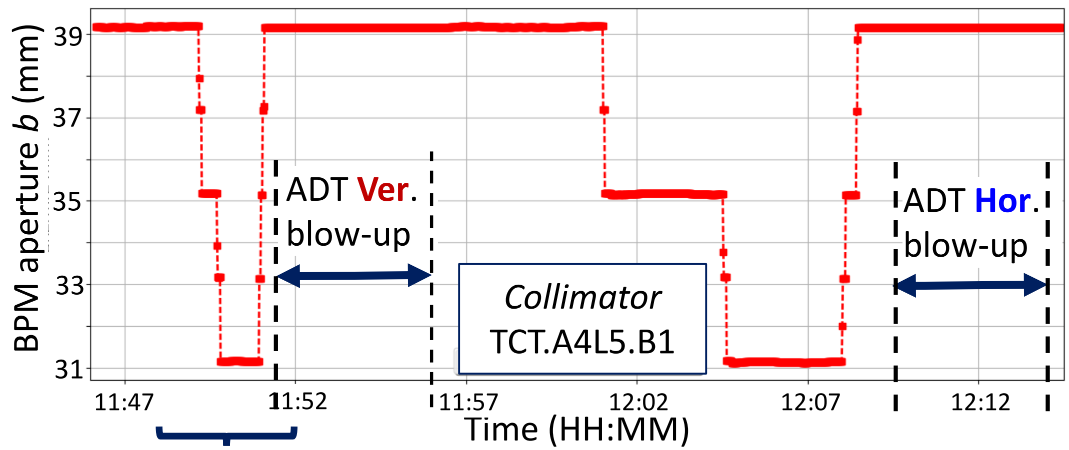

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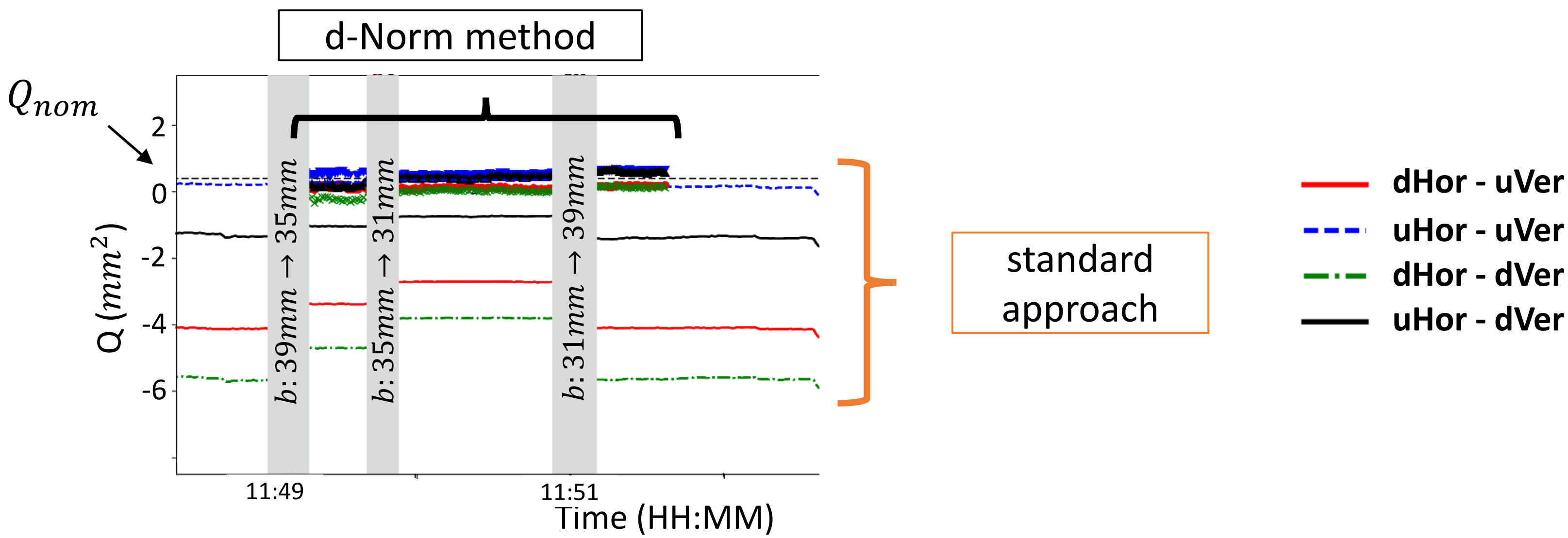

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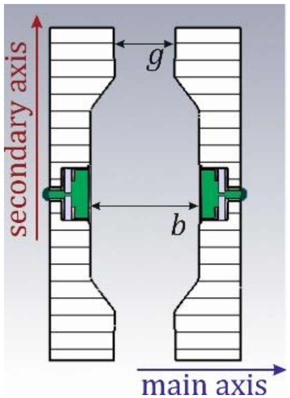

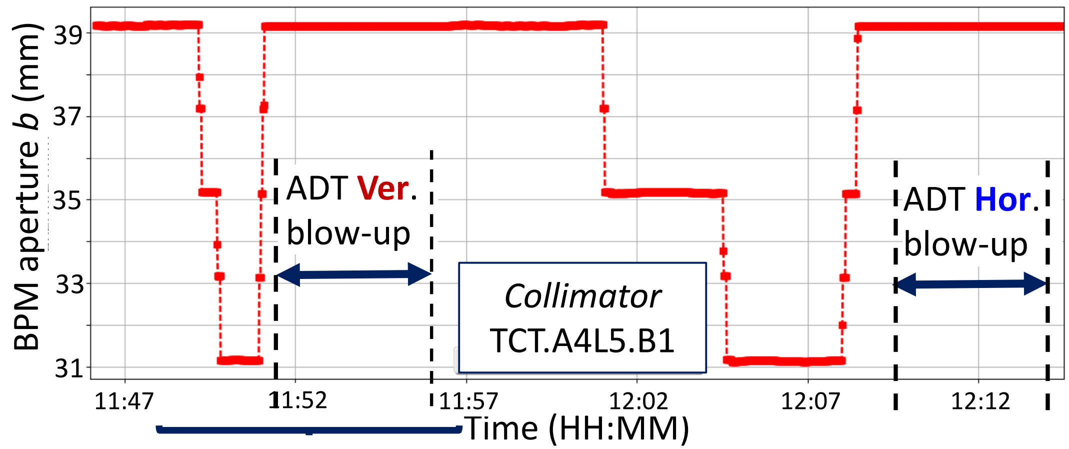

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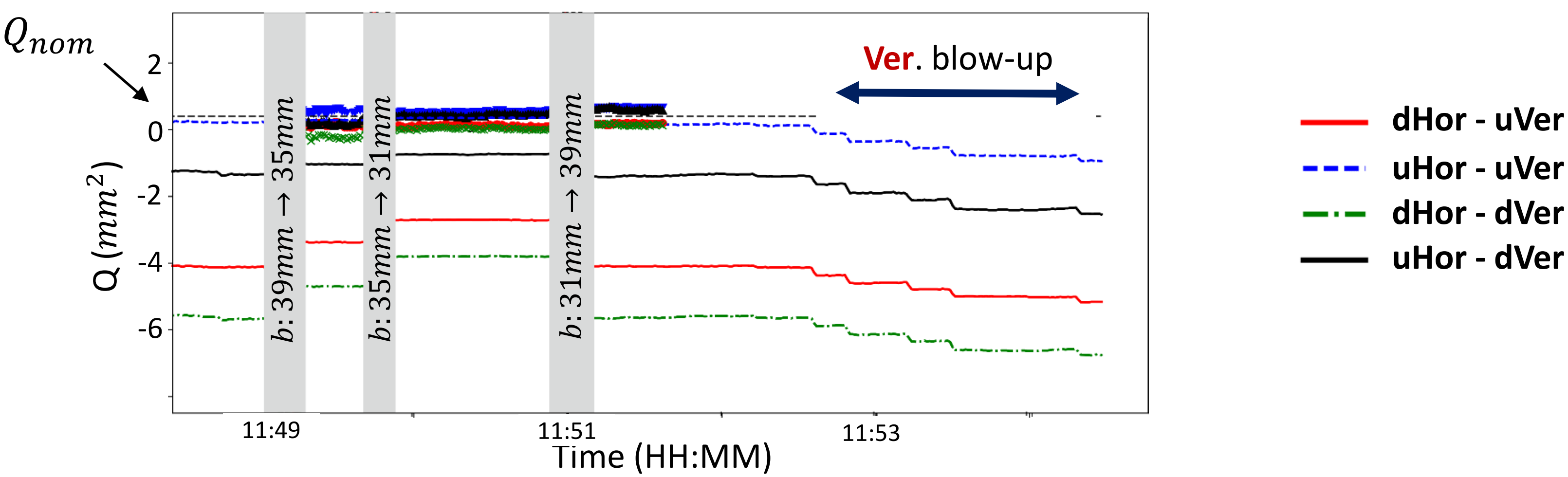

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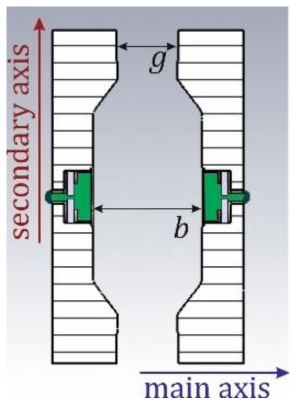

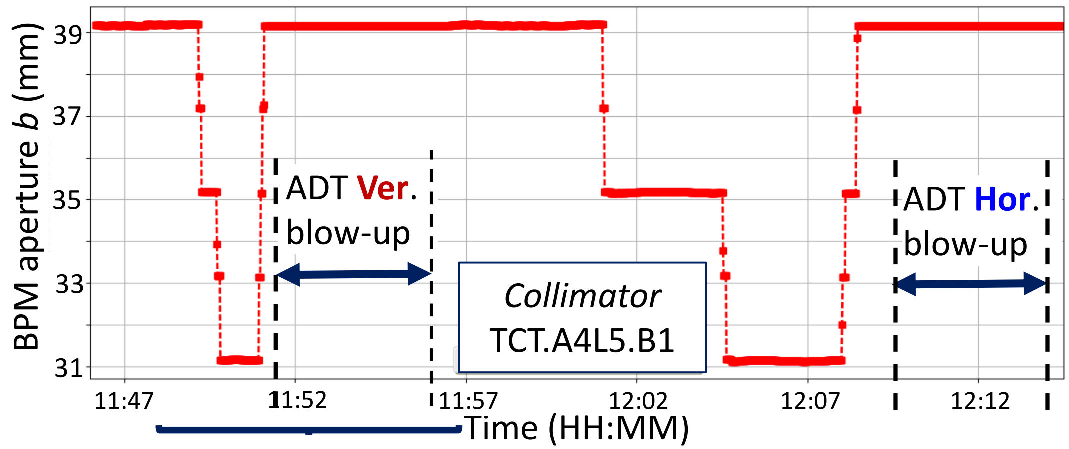

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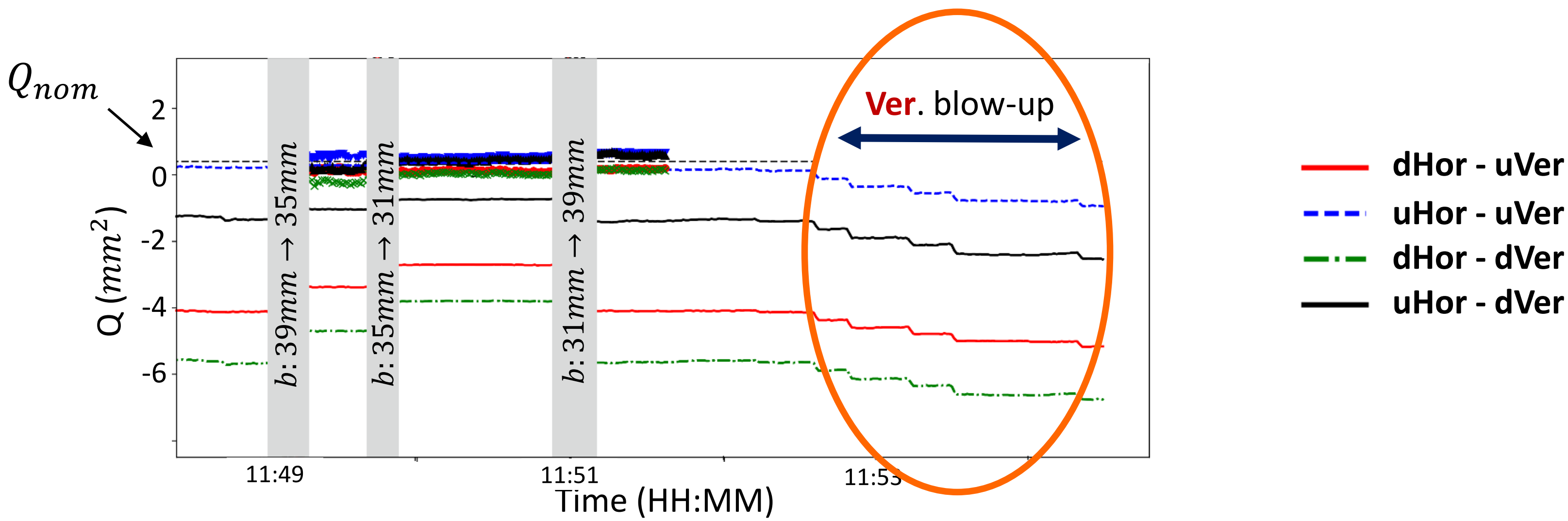

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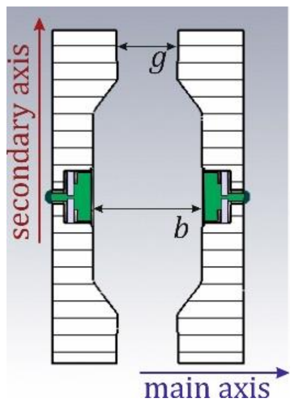

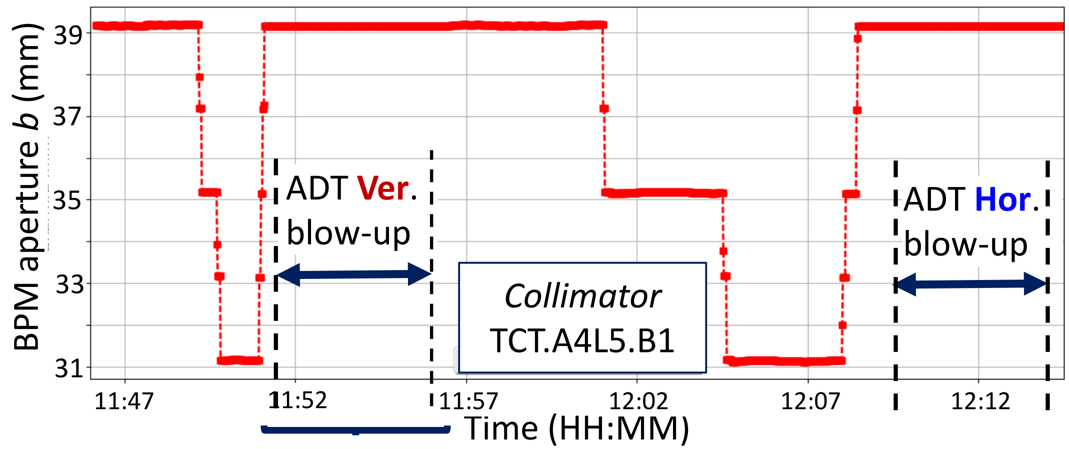

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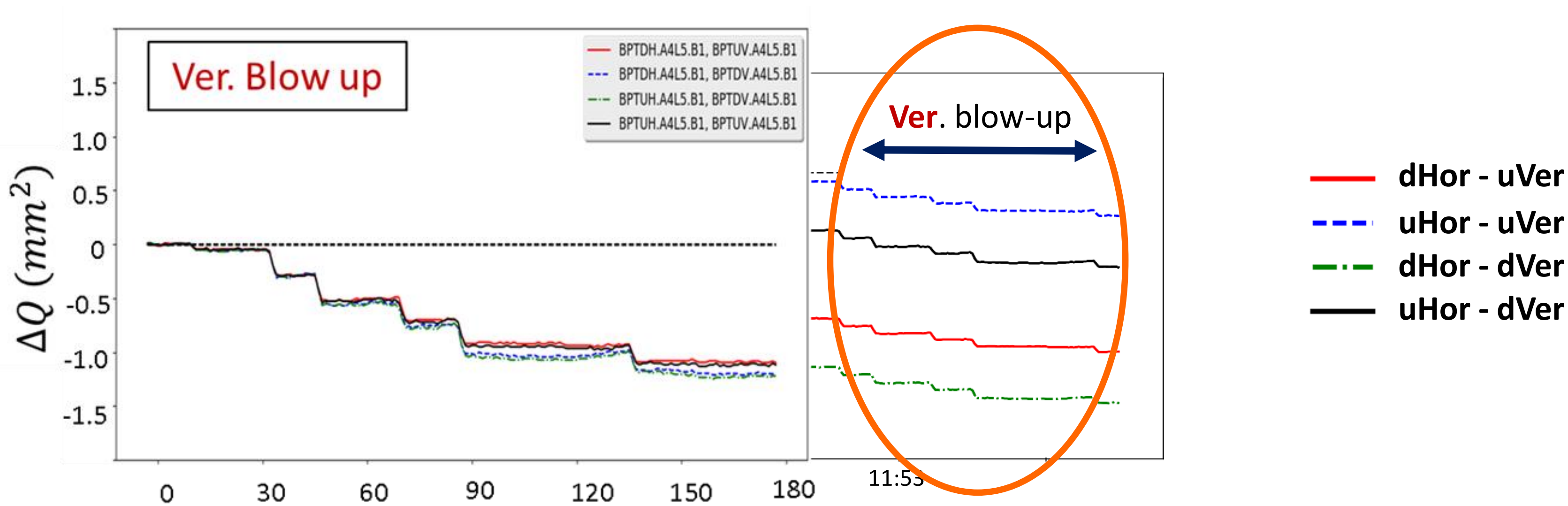

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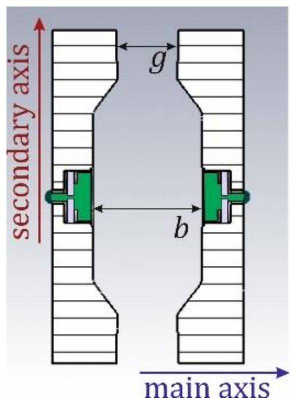

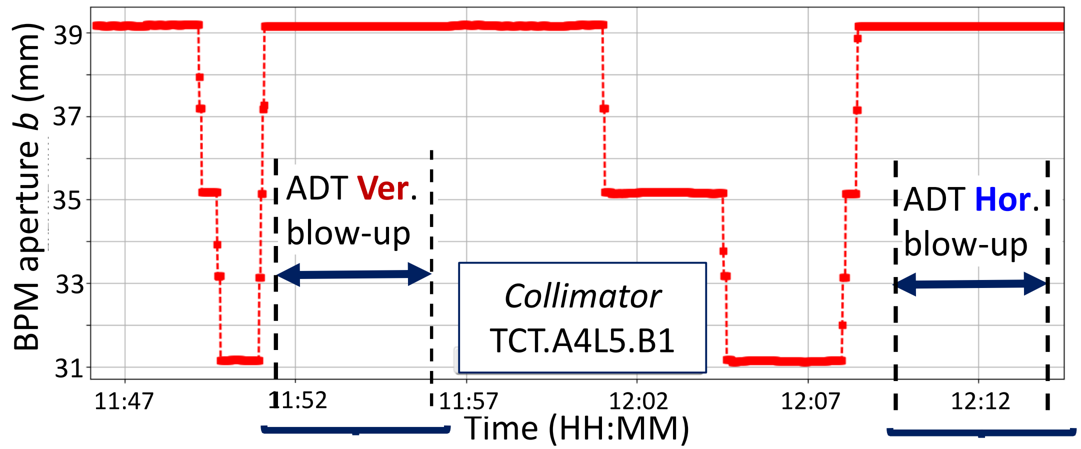

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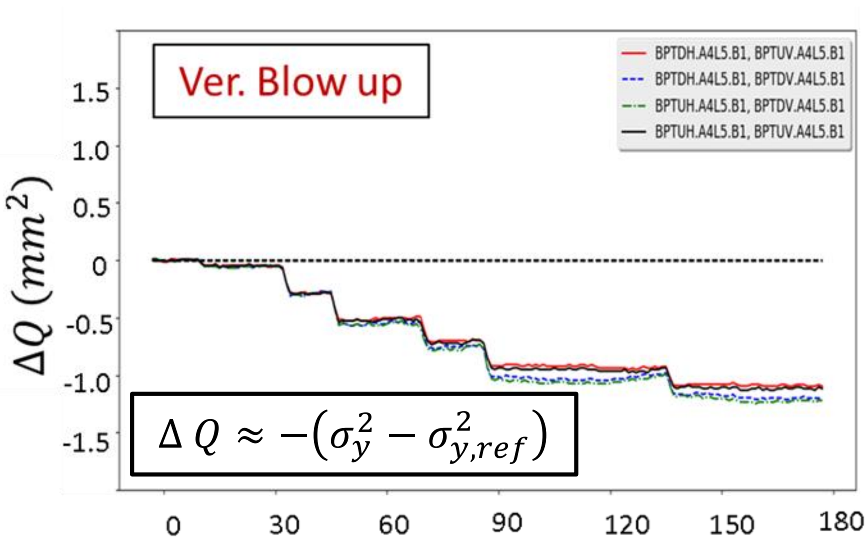
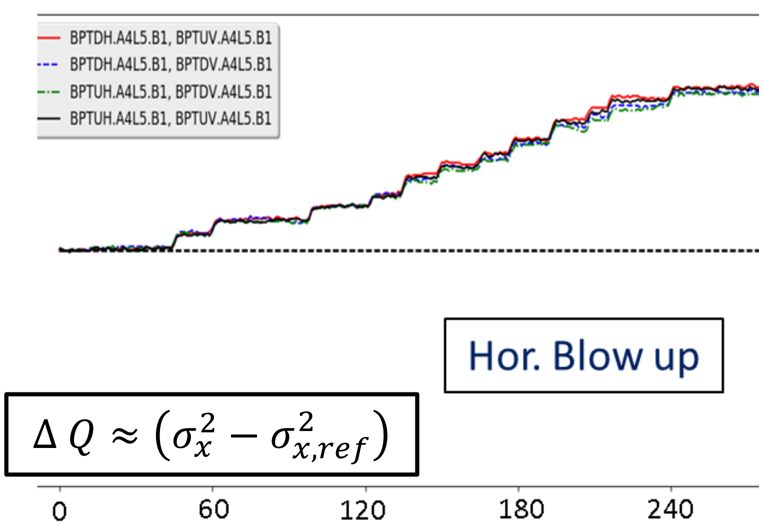


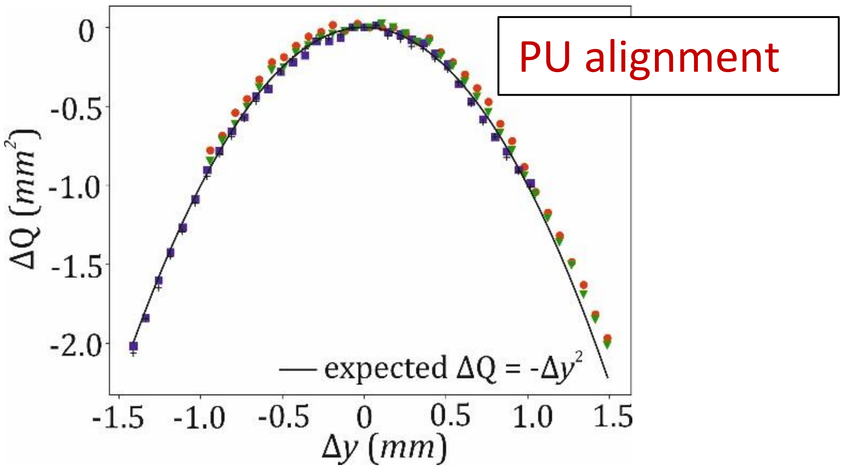
$\Delta Q \approx -(\sigma_y^2 - \sigma_{y,ref}^2)$

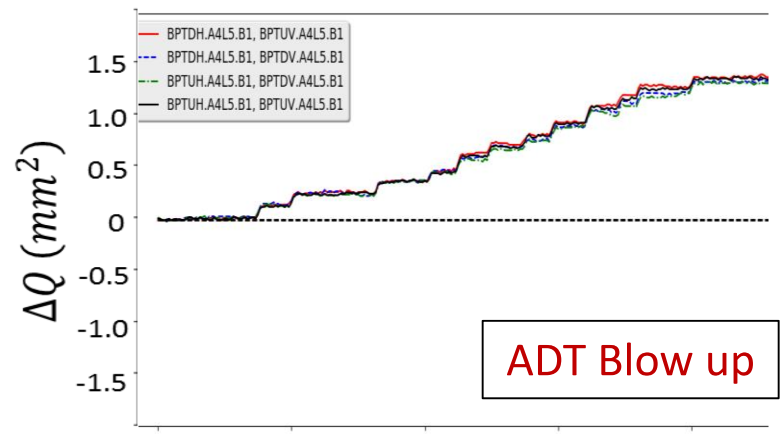


$\Delta Q \approx (\sigma_x^2 - \sigma_{x,ref}^2)$

Last Point: Differential measurements

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





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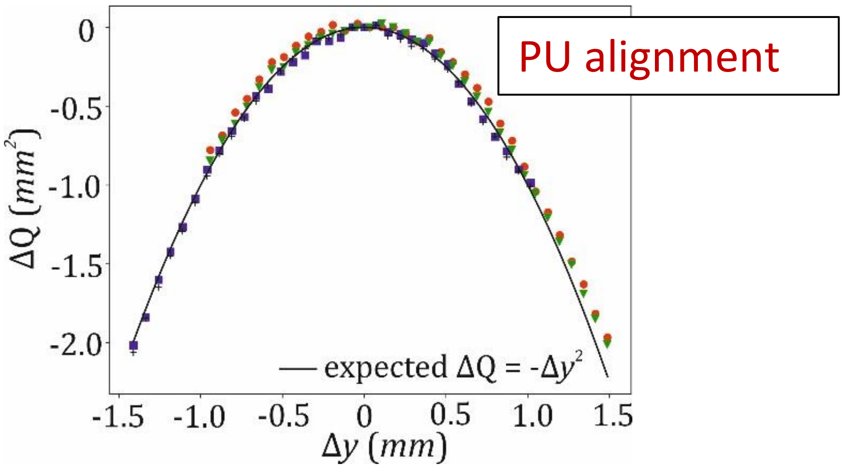
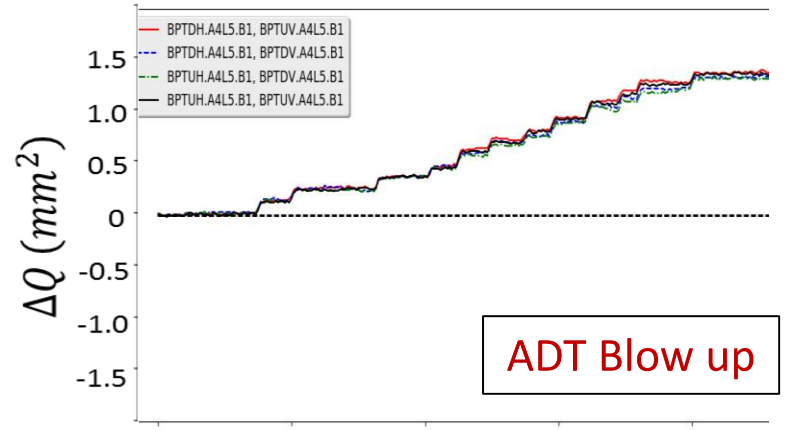
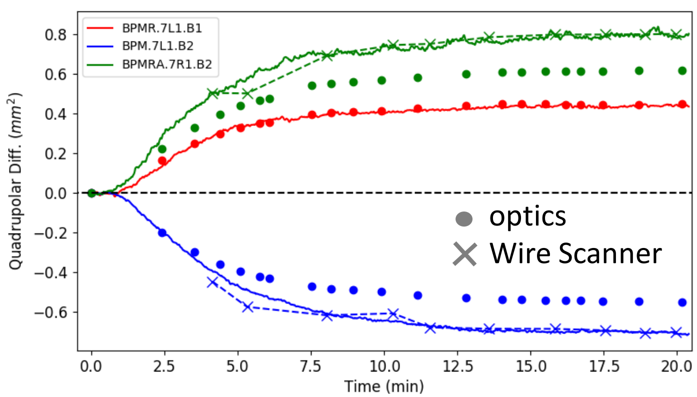
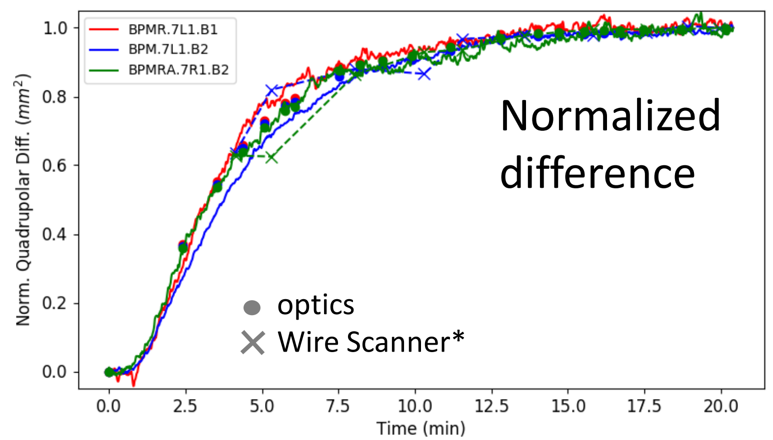




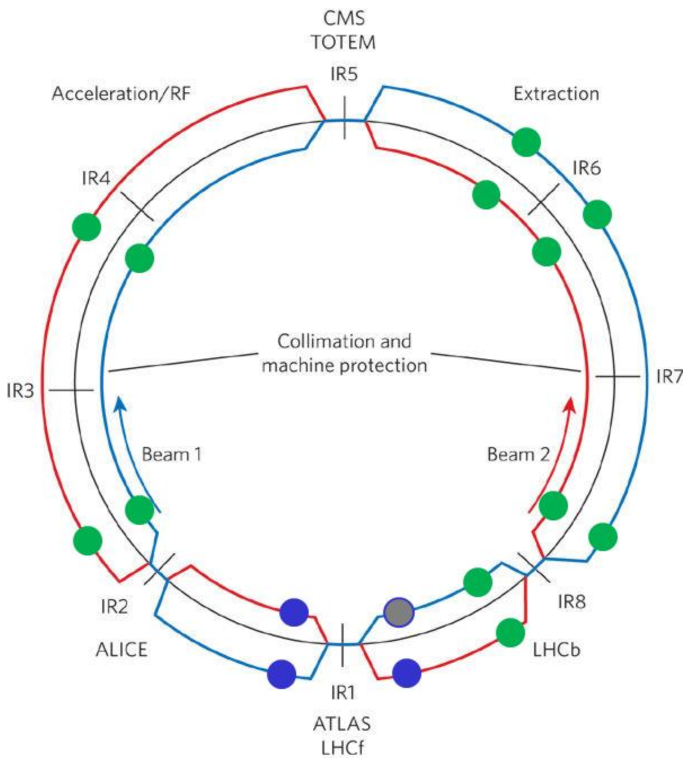
..and during the energy ramp





Emittance Measurements During the Ramp

12 BPMs all around LHC

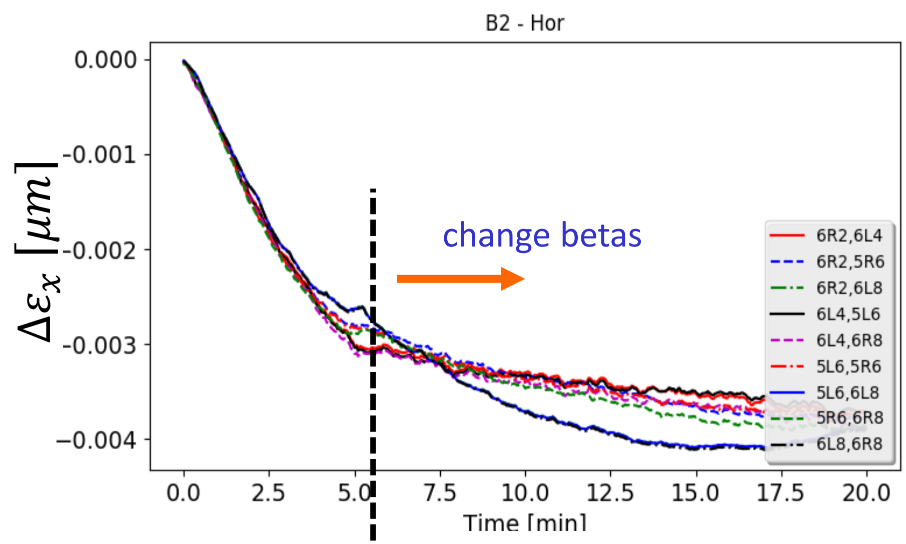


Absolute change on the geometric emittance

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

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

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



start squeezing

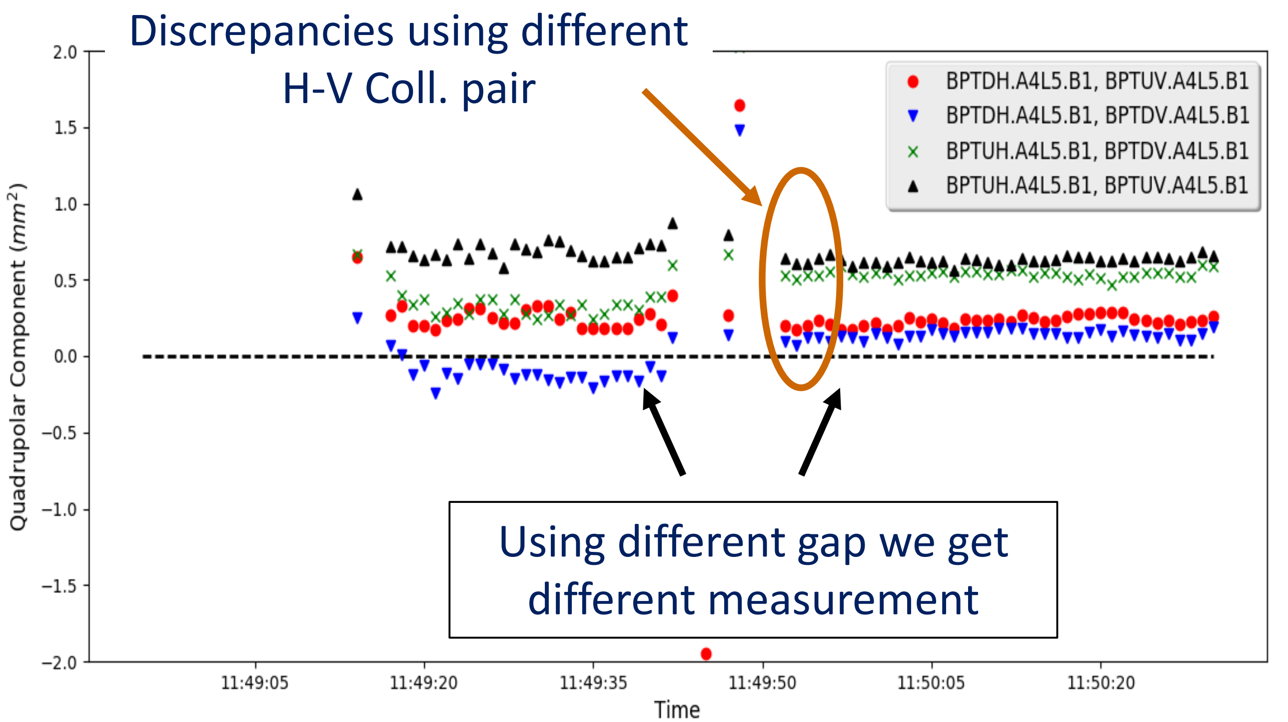
Summary

- **Quadrupolar Measurements**
  - simple concept but very challenging in reality
- **Fundamental Limitations**
  - Low quadrupolar sensitivity → *large offsets*
  - Parasitic Position Signal -> big errors when beam is displaced
- **Movable PUs**
  - Sufficiently cancel position signal (direct subtraction do not work for large beam displacements)
  - Calibrate the measurements system via **aperture scans**
- **Differential Measurements**
  - Use of existing BPM technologies
  - Promising results during the energy ramp

Thank You for your attention!

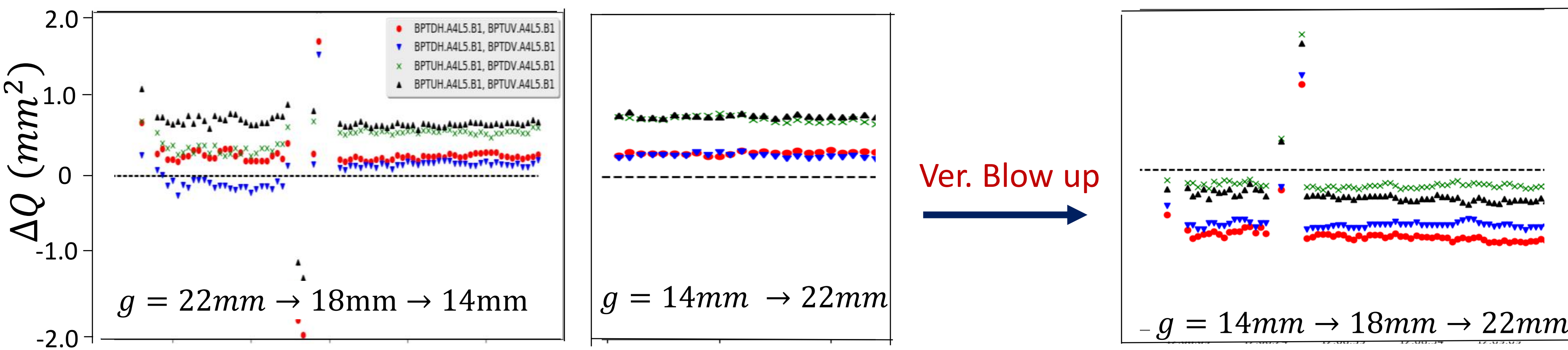
Spare slides

Understand the Uncertainties



First Observations

2nd phase: absolute & differential measurements



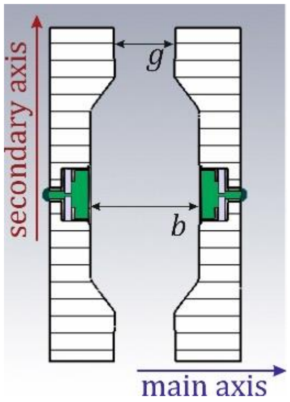
scan #1 scan #2 scan #3

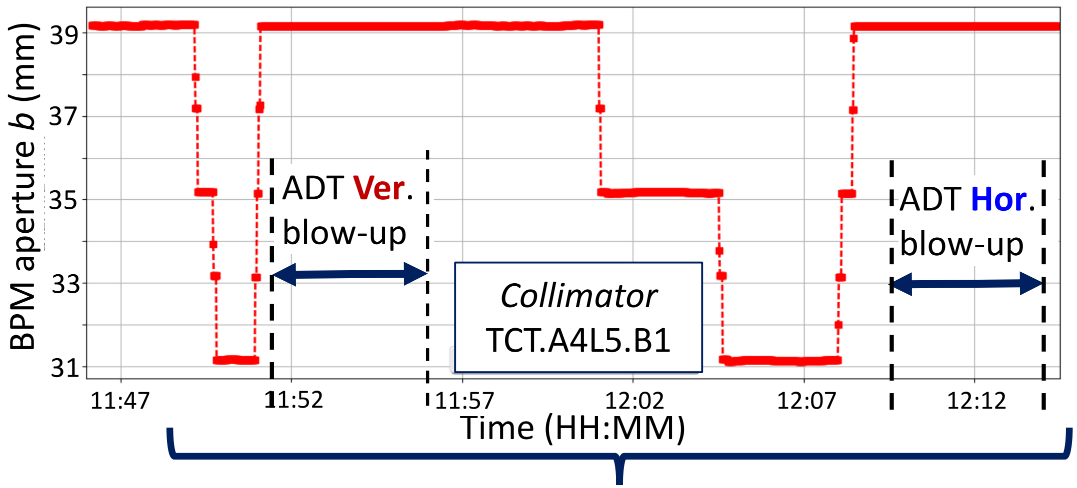
	Qabs1 (mm^2)	Qabs2 (mm^2)	Qdiff1 (mm^2)	Qabs3 (mm^2) Estimation**	Qabs3 (mm^2)	Diff. (mm^2)
DH - UV	0.25	0.29	-1.09	-0.80	-0.87	**0.07**
DH - DV	0.14	0.14	-1.20	-1.07	-0.71	**-0.36**
UH - DV	0.54	0.55	-1.22	-0.68	-0.21	**-0.47**
UH - UV	0.64	0.71	-1.12	-0.41	-0.37	**-0.04**

$$**Q_{3,est} = Q_2 + \Delta Q_1$$

First Observations

2nd phase: aperture scans + emittance blow-up

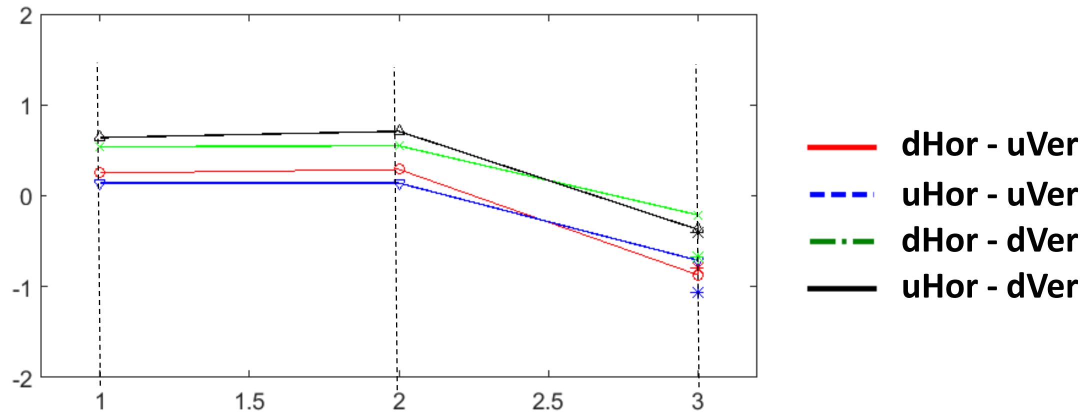




Injection energy ($450\ GeV$)

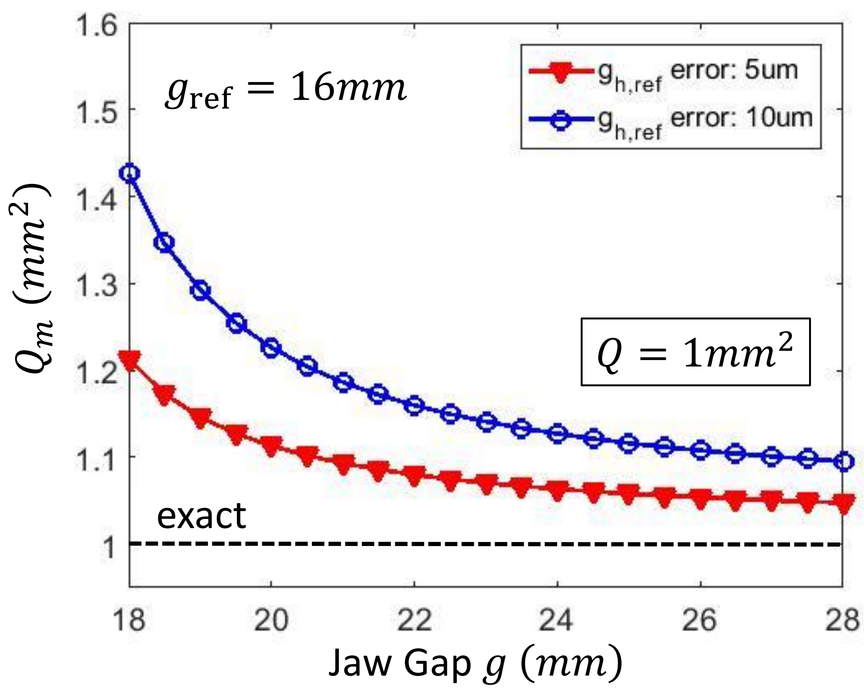
Nominal values:

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



Aperture Measurement – Limitation?

Consider an error in the measurement of the reference gap, g_{ref}



Aperture Measurement – Limitation?

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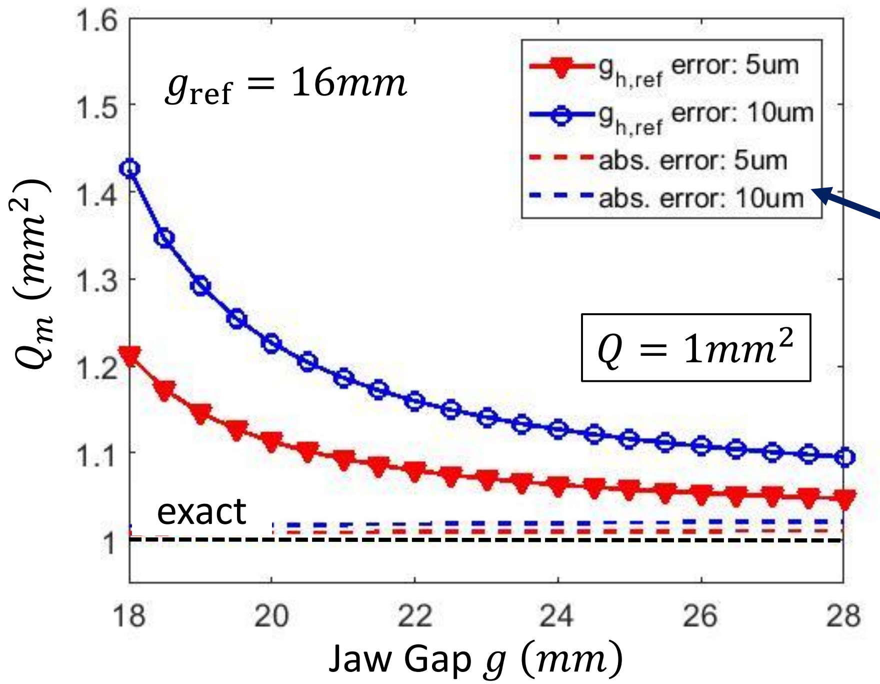
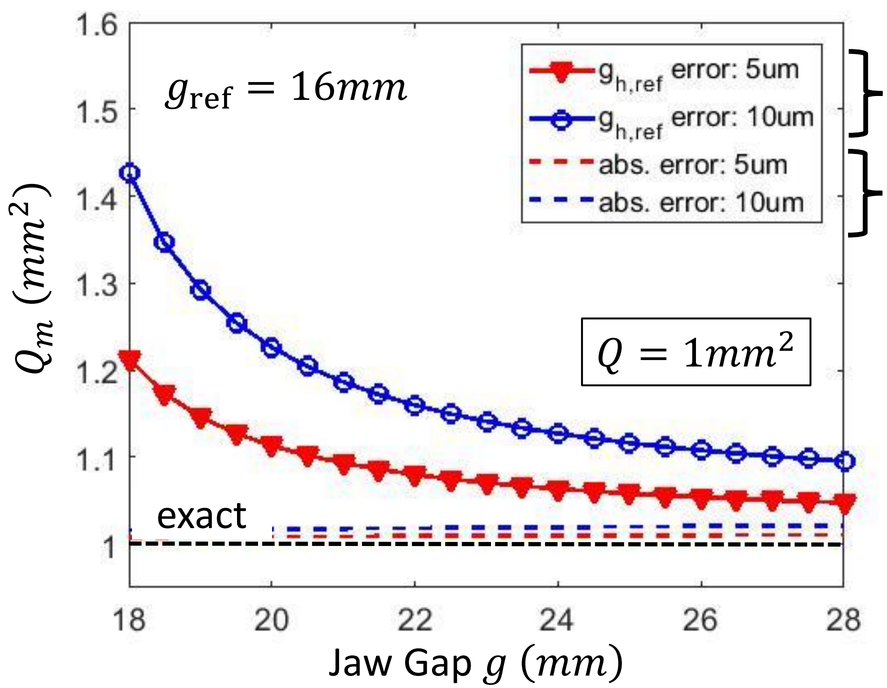


Consider the same error for all gaps g

Aperture Measurement – Limitation?

Differential vs Absolute Error

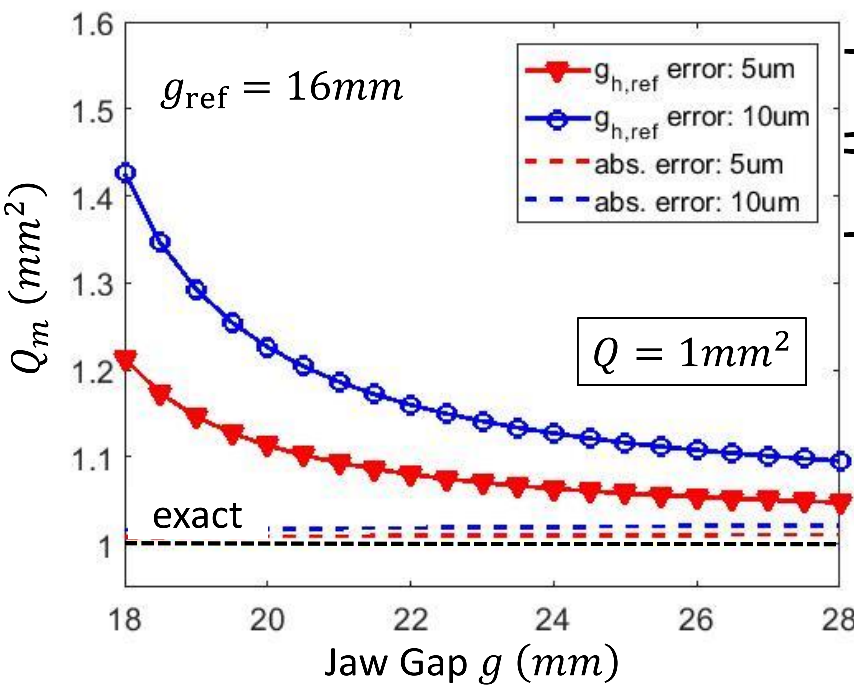


Differential errors are crucial

Absolute errors → acceptable

Aperture Measurement – Limitation?

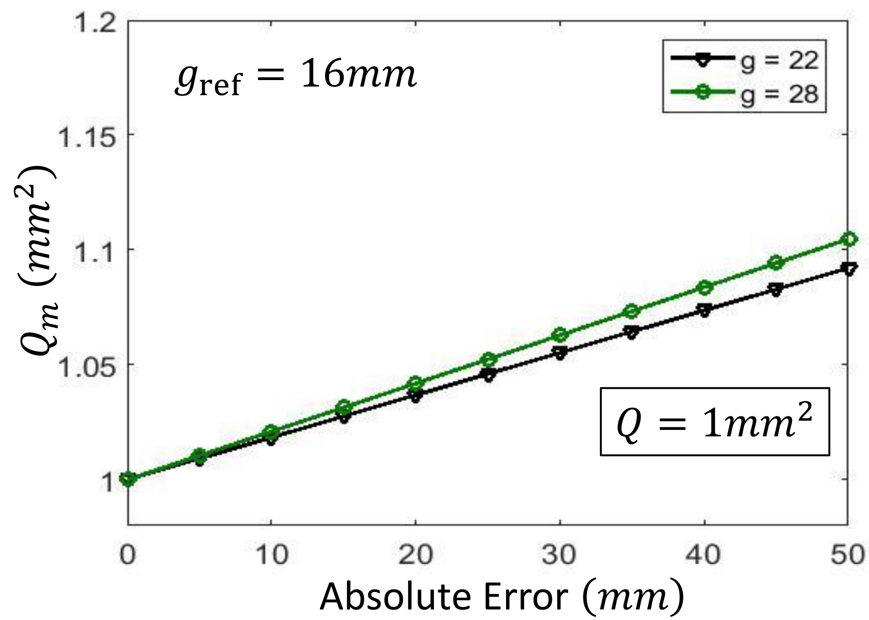
Differential vs Absolute Error



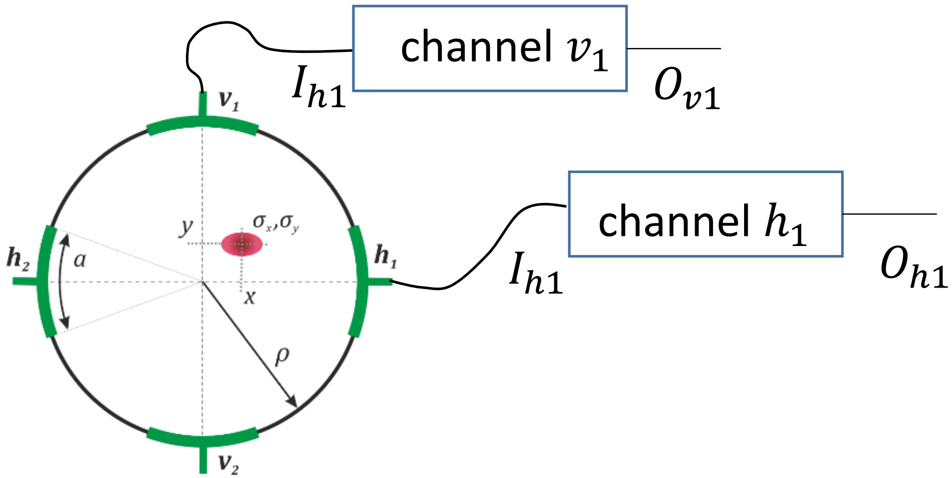
Differential errors are crucial

Absolute errors → acceptable

Less than 10% error for absolutes aperture measurement errors up to $50um$



What about Non-Linearities?

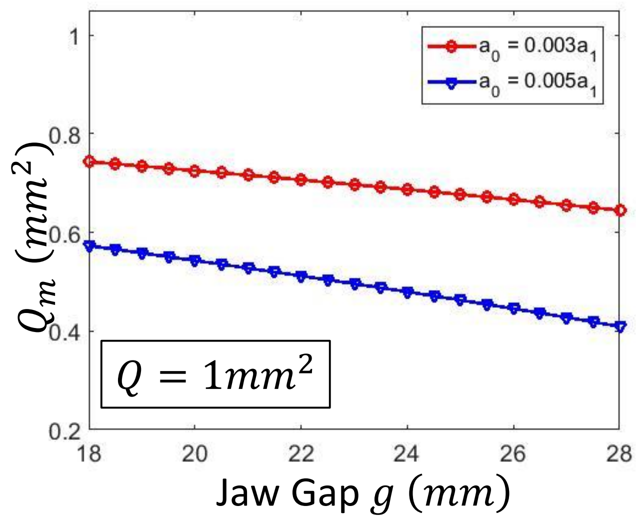


Active components may introduce offsets/ non-linear terms

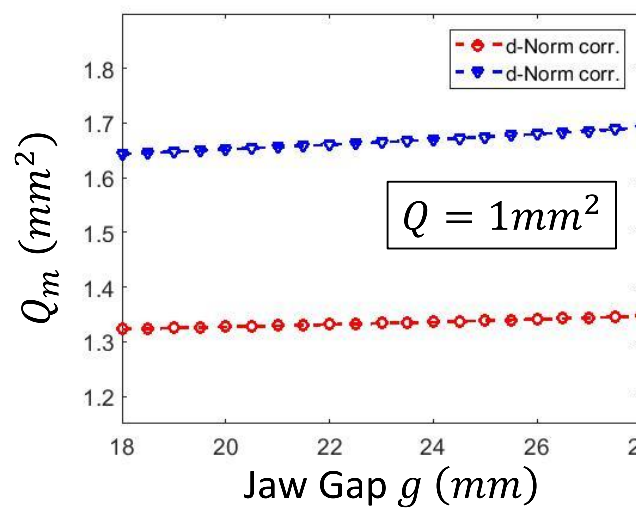
$$O = a_0 + a_1 I + a_2 I^2$$

d-Norm method is optimized to cancel linear asymmetries (in the whole channel)

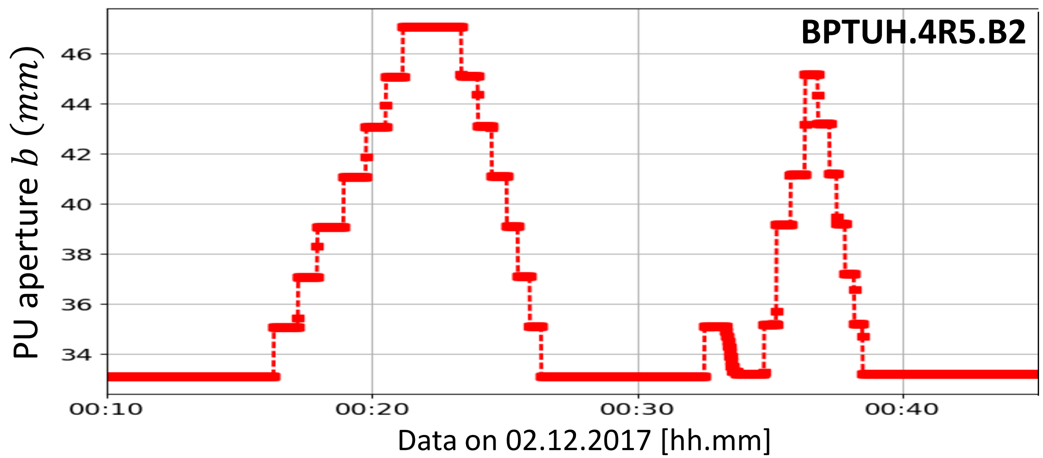
$$O_h = a_{0,h} + a_{1,h} I_h \quad O_v = a_{1,v} I_v$$



$$O_h = a_1 I_h + a_2 {I_h}^2 \quad O_v = a_{1,v} I_v$$

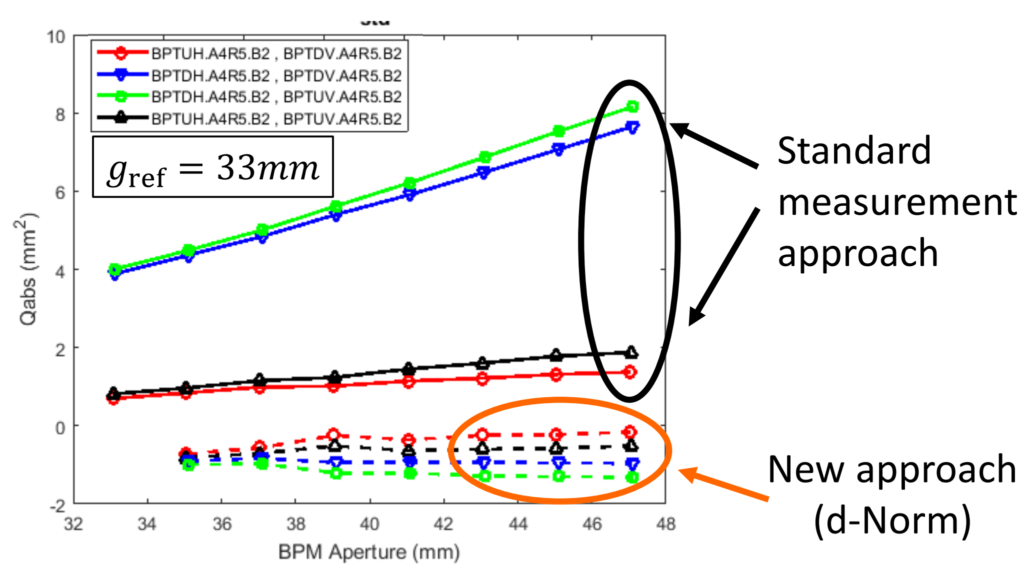


Further Tests

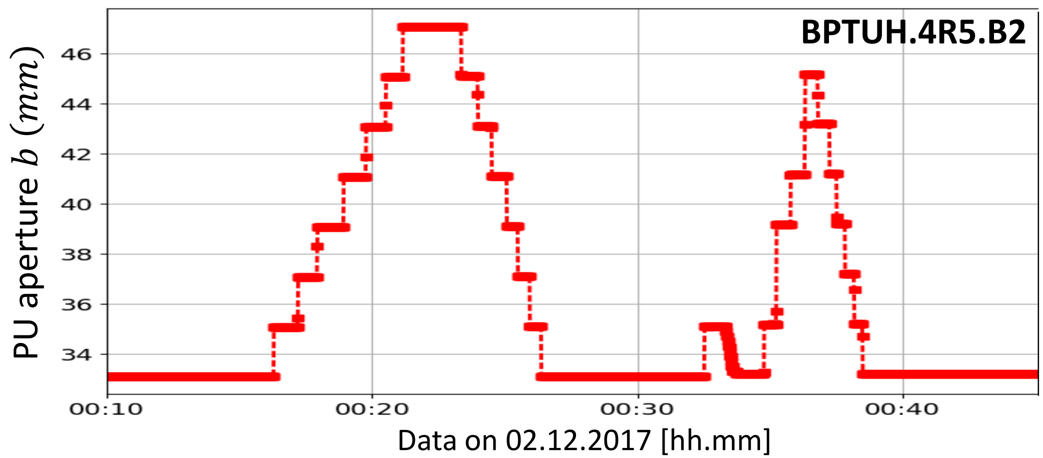


- More samples
- Cover wide aperture range
- Reconstruct uncertainties behaviour

- Error of standard method dominated by linear asymmetry.
- Much smaller deviations using the d-Norm approach
- Further studies to understand the small discrepancies of d-Norm method



d-Norm Method: More Studies



- More samples
- Cover wide aperture range
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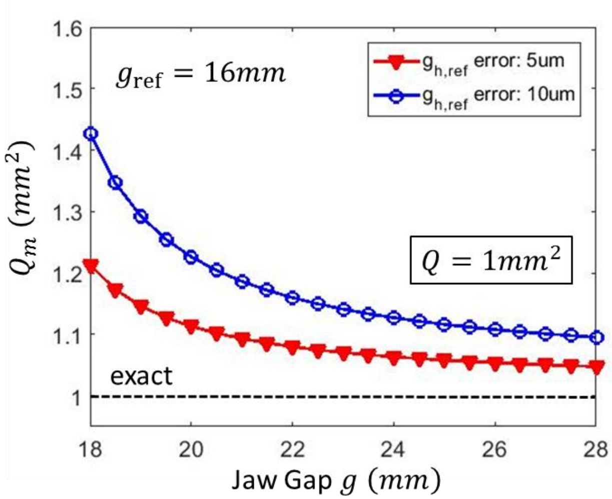
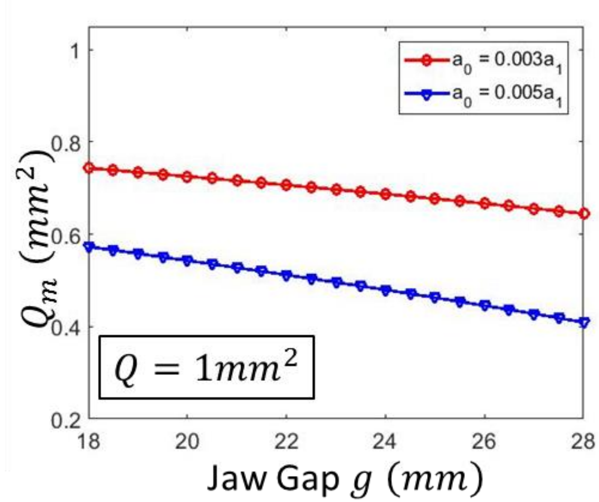
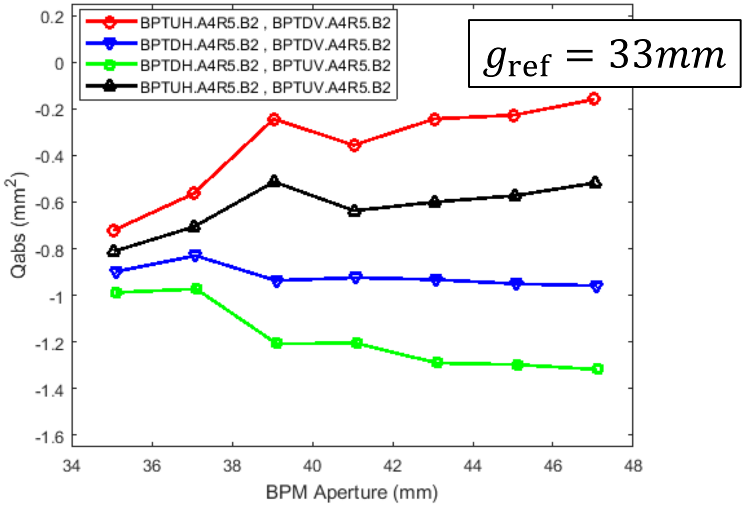


Error in **differential aperture measurement**

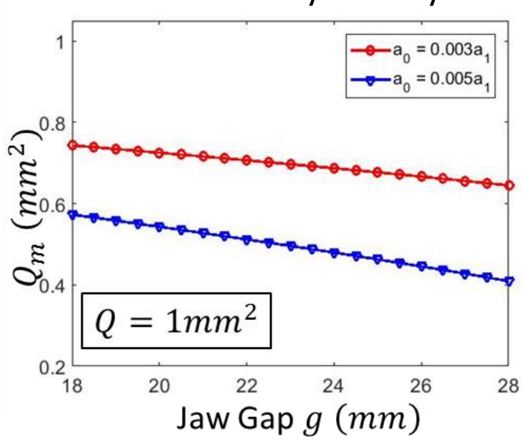
Error due to **offset asymmetries**



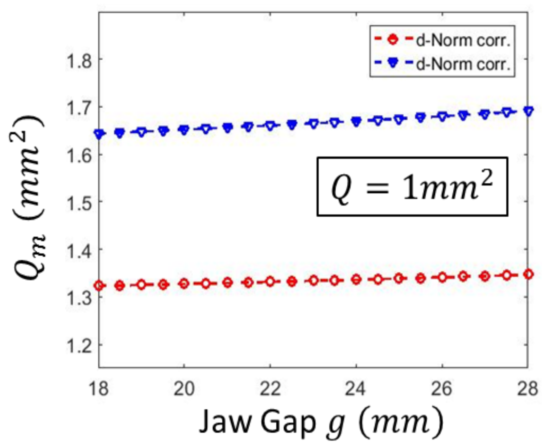
Identifying Uncertainty



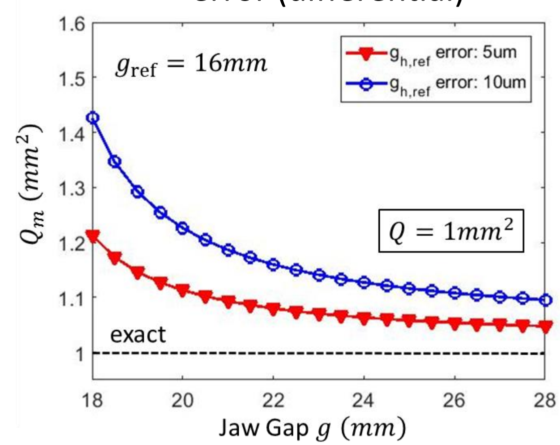
offset asymmetry



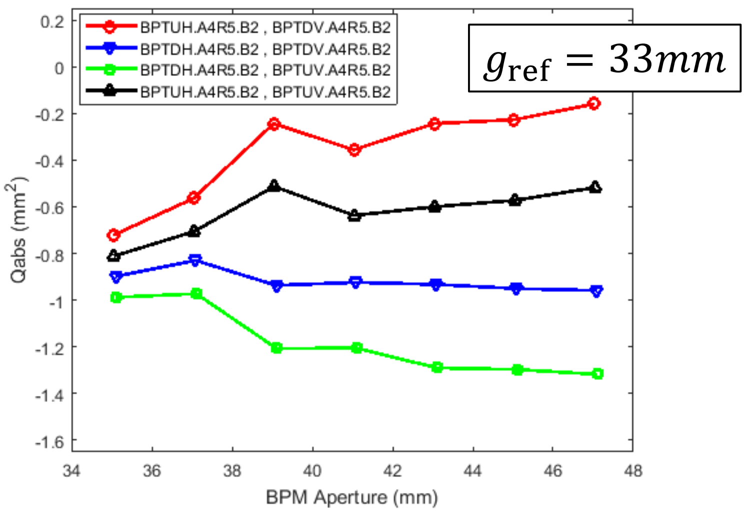
non-linear asymmetry



Aperture measurement error (differential)

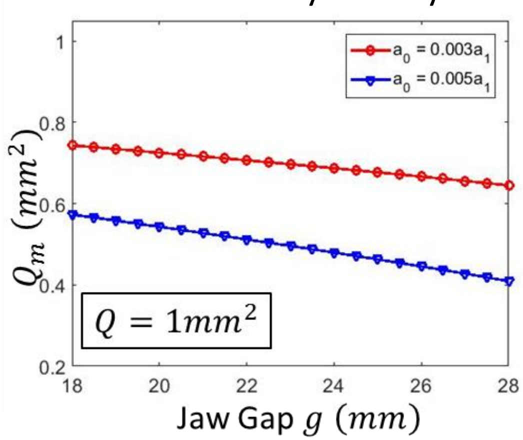


Identifying Uncertainty

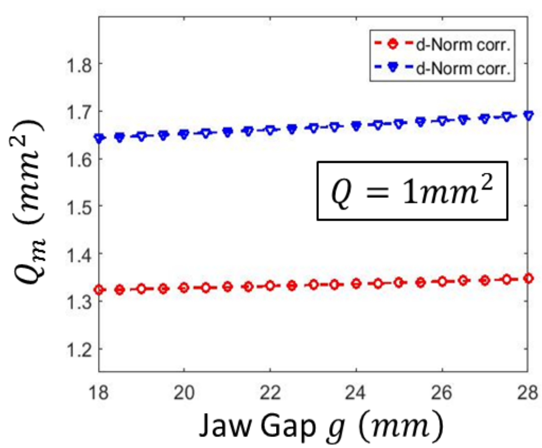


Different behaviour of aperture error - *should expect clear convergence as g increases*

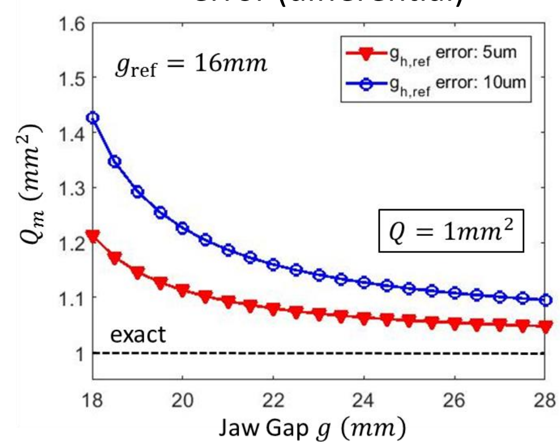
offset asymmetry



non-linear asymmetry

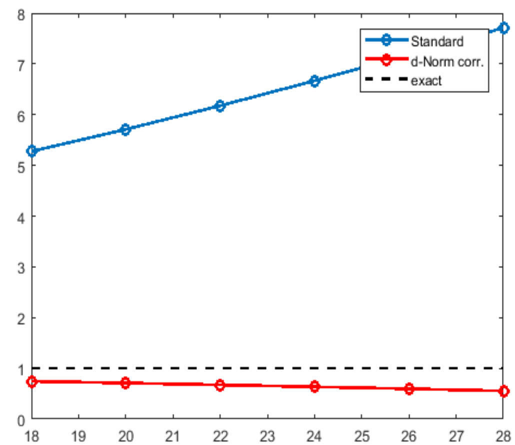


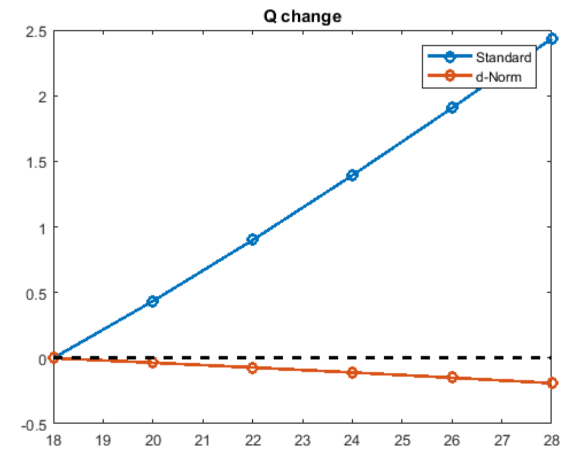
Aperture measurement error (differential)



Identifying Uncertainty

Additional overview via the "standard method"



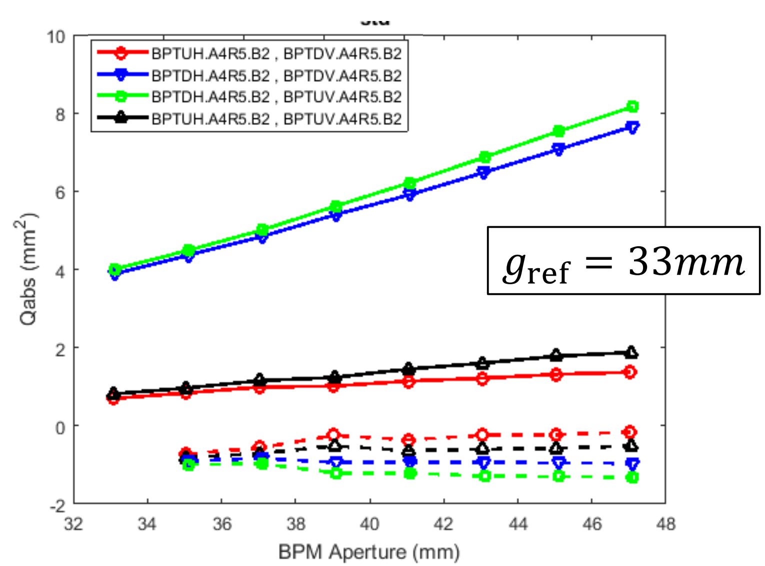


Estimation assuming asymmetries:

- $a_0 = 0.005$
- $a_1 = 0.02$
- $a_2 = 0.005$

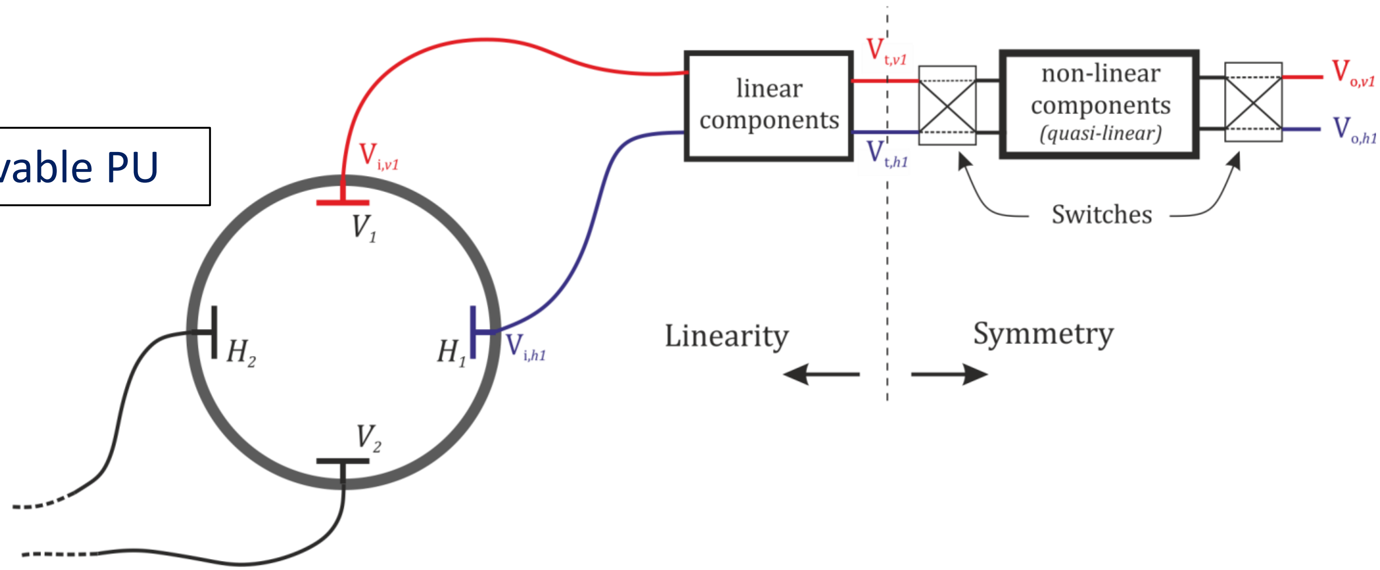
Error of standard method dominated by linear asymmetry.

Much smaller deviations using d-Norm method



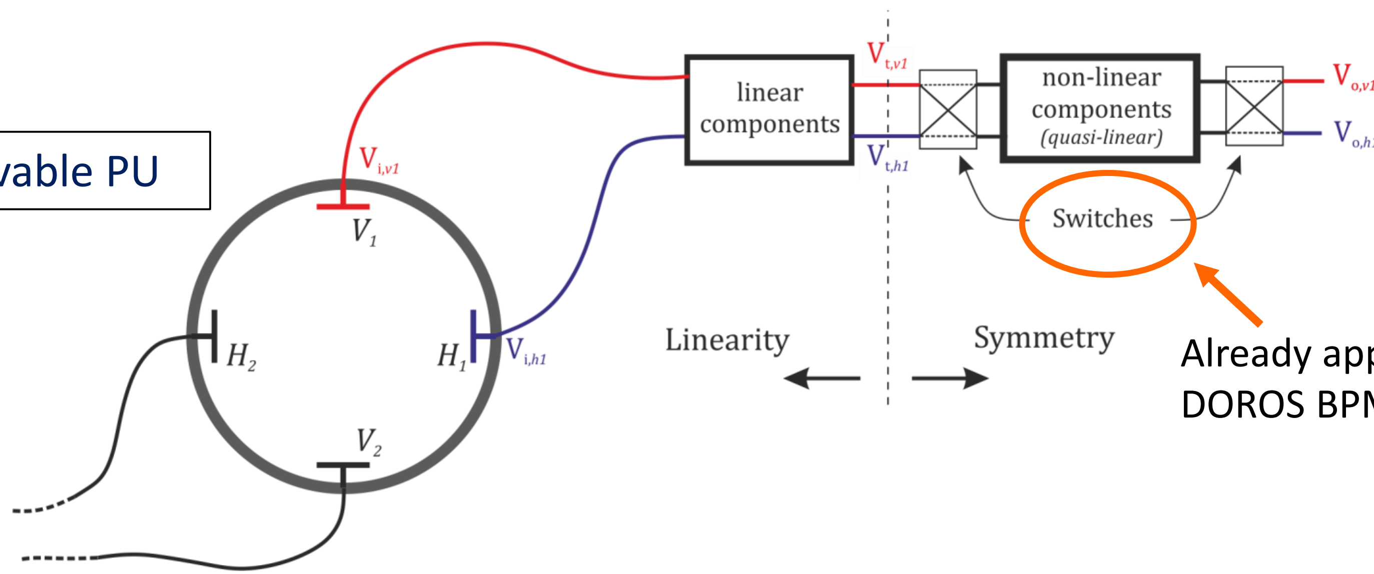
d-Norm Method – Modified

Movable PU



d-Norm Method – Modified

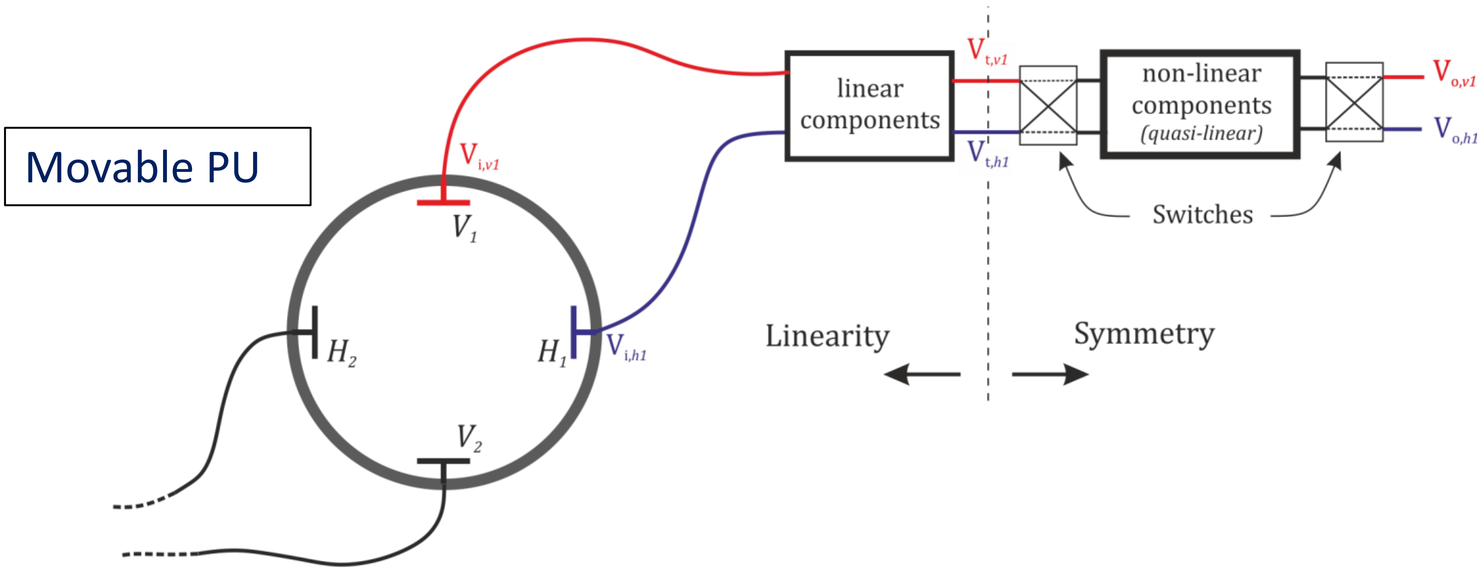
Movable PU

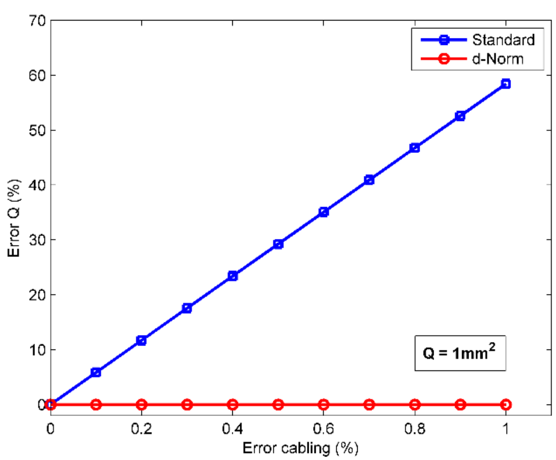


Already applied in LHC DOROS BPM system*

*M. Gasior, "Calibration of a non-linear beam position monitor electronics (…)", Proceedings of IBIC 2013

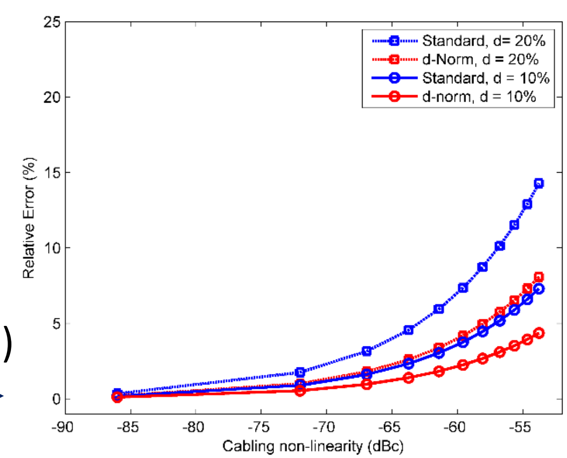
d-Norm Method – Modified





Considering a cabling asymmetry

Considering a 'non-linearity' in the cabling part (including connectors/attenuators/switches)



Emittance Measurement

Consider two PUs at different, low dispersion, locations

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

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

The emittances can be derived by solving the above linear system