# The Magnetic Quadrupole Pick-Ups in the CERN PS

A. Jansson (CERN)

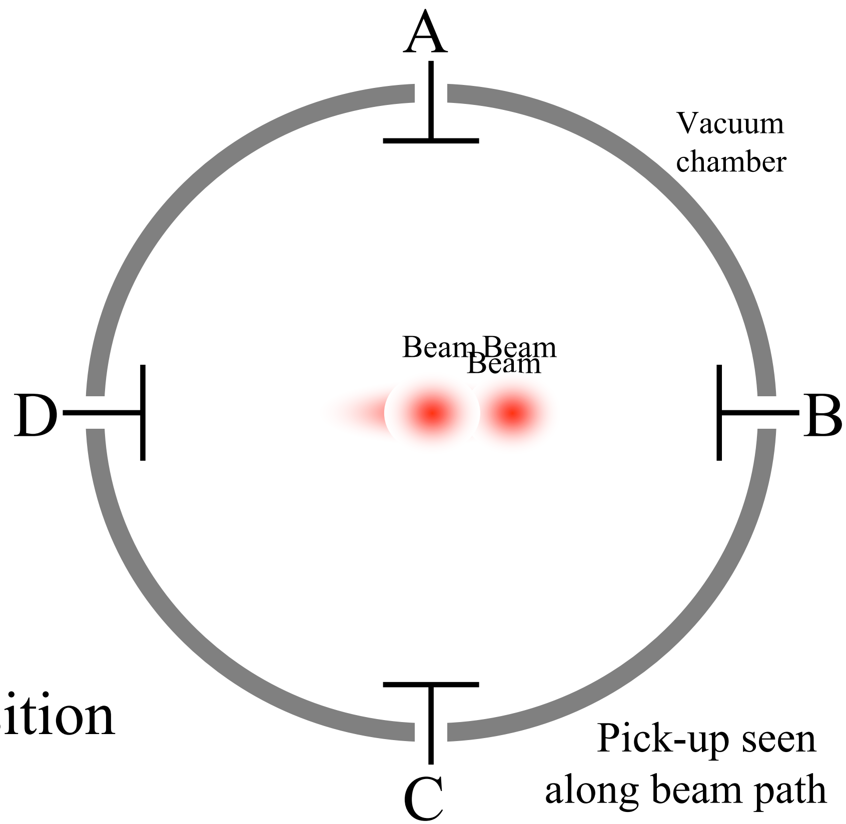
with special thanks to
**David Williams** and **Lars Søby**

# Outline

- Background and introduction
- Pick-up hardware design
- Data acquisition and analysis
- Measurement results (including comparative)
- Applications in other machines

# What is a quadrupole pick-up?

- A pick-up sensitive to the r.m.s. beam size.
- Uses the non-linear terms in electrode response to particle position (very small) to measure quadrupole moment.
- Quadrupole moment is a measure of ellipticity.




$$\frac{B - D}{A + B + C + D} \propto x = \text{horizontal position}$$

$$\frac{(B + D) - (A + C)}{A + B + C + D} \propto \sigma_x^2 - \sigma_y^2 + x^2 - y^2 = \text{quadrupole moment}$$

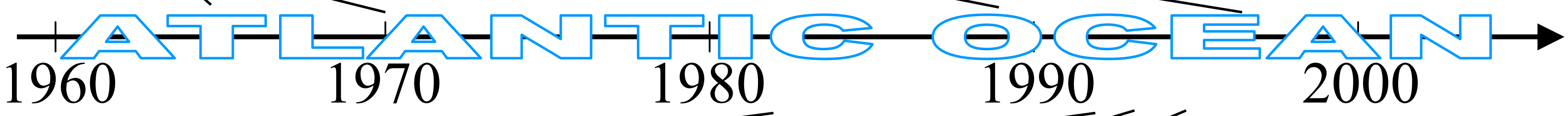
# History

## L.L. Gol'din
"Investigation of a beam of charged particles by means of pick-up electrodes"

## G. Nassibian (CERN)
"The measurement of the multipole coefficients of a cylindrical charge distribution"

## V. Carron et al (CERN)
"Observation of transverse quadrupole mode instabilities in intense cooled antiproton beam in the AA"

## M. Chanel (CERN)
"Study of beam envelope oscillation by measuring the beam transfer function with a quadrupolar pick-up and kicker"




## Y. Yin et al (LANL)
"A multistrip beam profile high order moment monitor"

## R. Miller et al (SLAC)
"Non-interceptive emittance monitor"

## F. Bieniosek et al (FNAL)
"Measurement and reduction of quadrupole injection oscillations in the Fermilab Antiproton Accumulator"

## S. Russell et al (LANL)
"Measuring emittance using beam position monitors"

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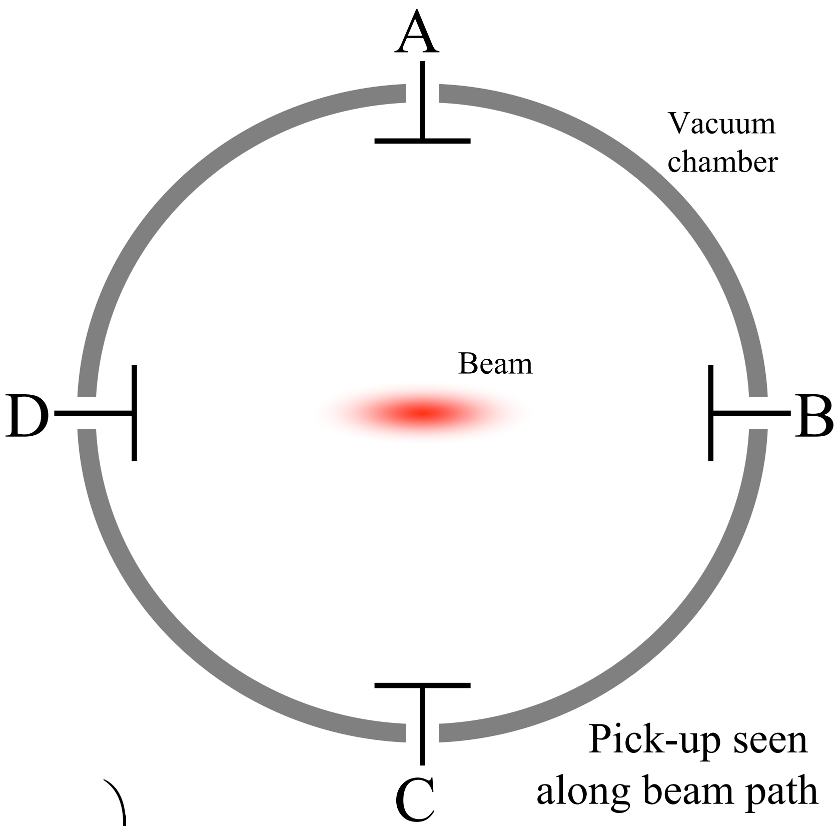
# Problems

- Very large difference in signal strength between dominating and desired signal components.
- Position dependence of the quadrupole signal.

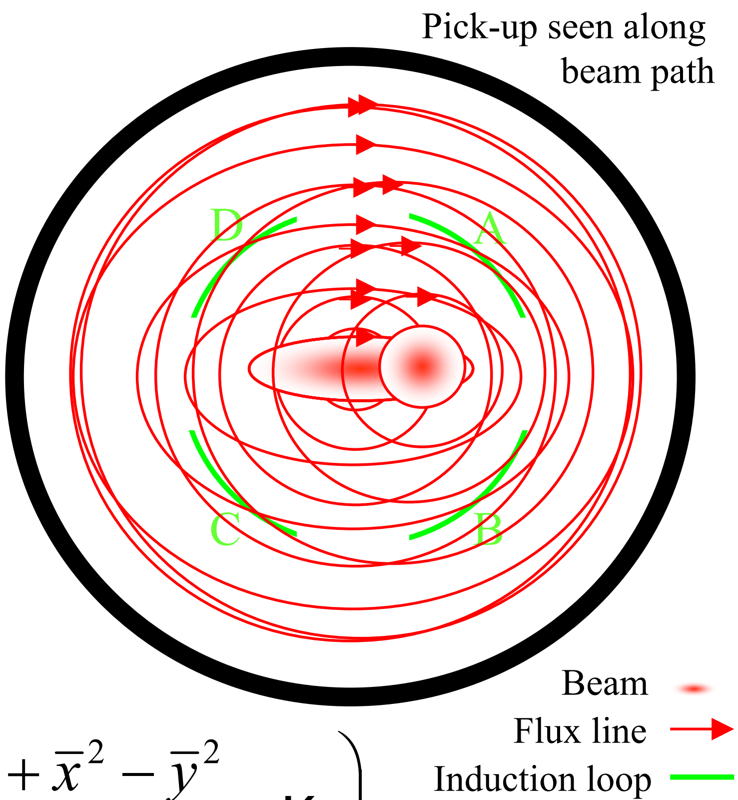



Signal on electrode:

$$A \propto \frac{i_b}{r}\left(1 + 2\frac{\bar{y}}{r} - 2\frac{\sigma_x^2 - \sigma_y^2 + \bar{x}^2 - \bar{y}^2}{r^2} + \ldots\right)$$

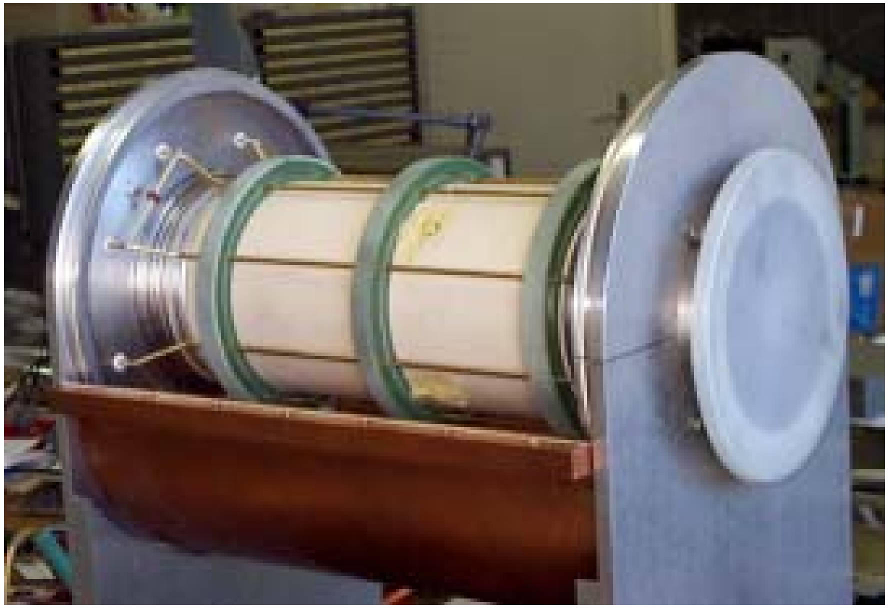
# PS pick-up design

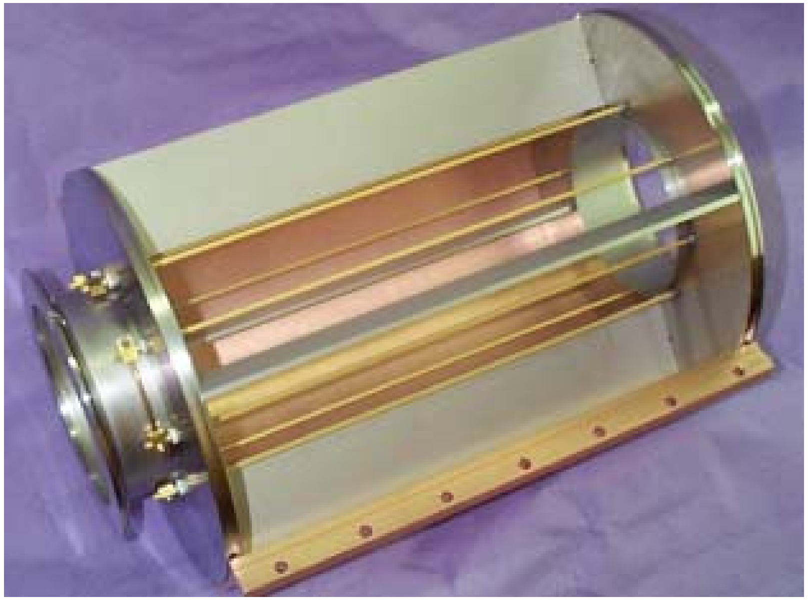
- Magnetic coupling.
- Suppresses the dominating intensity signal by coupling to the radial magnetic field component.
- Position contribution can not be avoided, but can be measured and subtracted.




$$A \propto i_b \left( 0 + 0.41\left(\frac{\bar{x}}{r} - \frac{\bar{y}}{r}\right) + 1.23\frac{\sigma_x^2 - \sigma_y^2 + \bar{x}^2 - \bar{y}^2}{r^2} + \mathrm{K} \right)$$

# Proof-of-principle prototypes

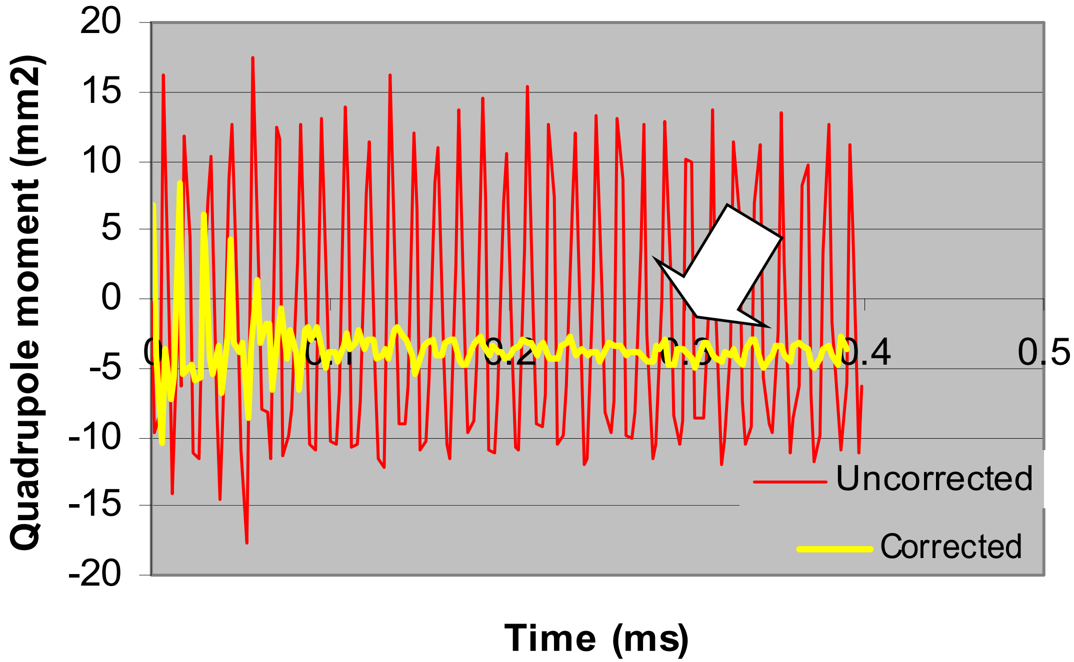




- Proof-of-principle device, built from spare parts.
- Installed and tested with beam in the PS (1999).

- Lab model for testing different design details.

# Prototype results with beam



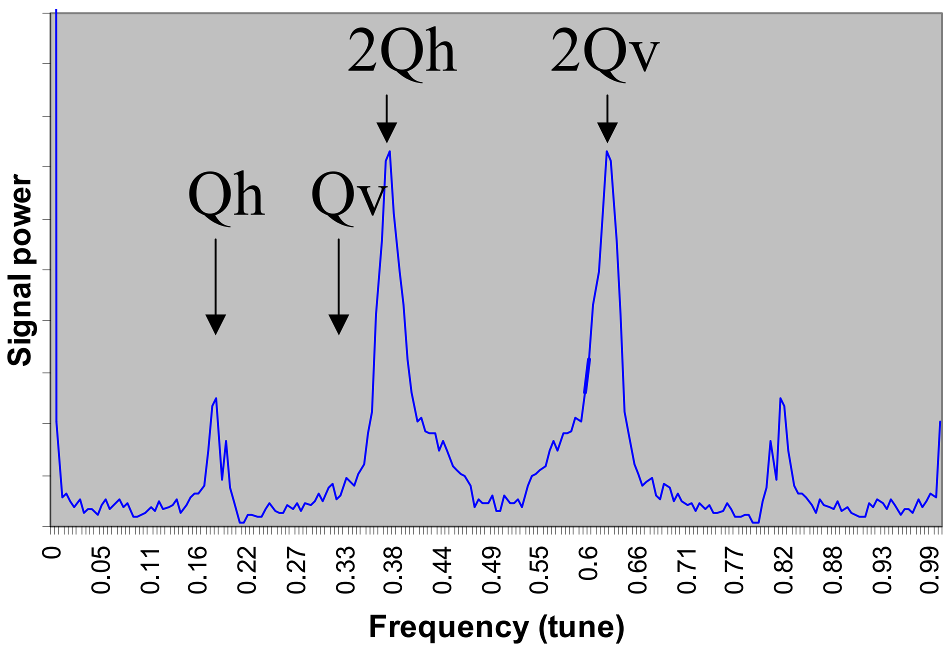

$$\kappa = \sigma_x^2 - \sigma_y^2 + x^2 - y^2$$

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

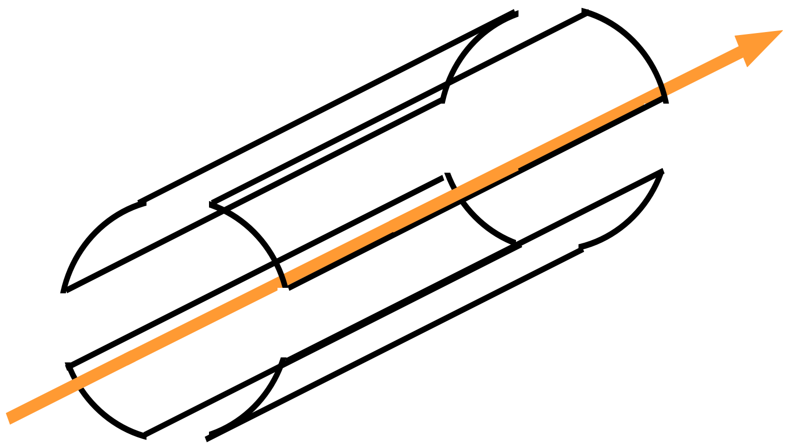
- **The 'signal pollution' from beam position can be subtracted using the measured position, to within a few percent.**
- **Correction efficiency can be verified on data taken after beam-size filamentation.**

# Lessons from beam measurements

- Working point in PS machine often such that peaks are close or overlapping.
- Fourier analysis not very useful due to fast decoherence (caused by space charge tune spread).
- Need two pick-ups to separate signal components!
- Use fit instead of Fourier transform.

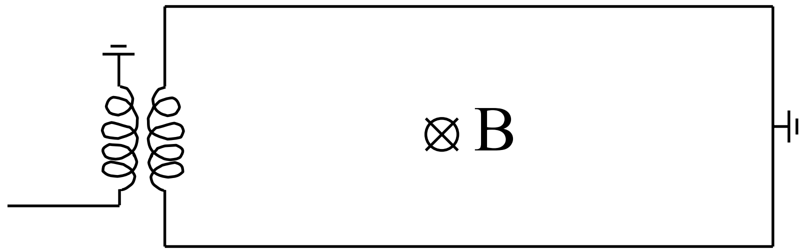


# Lessons from lab measurements



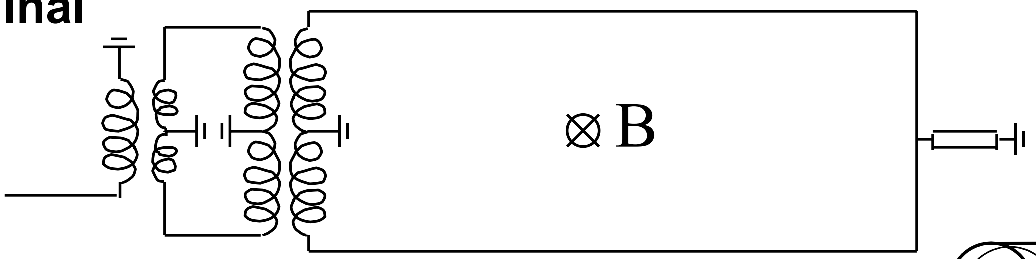
- Initial design of induction loop had problem with resonances.

Initial design:



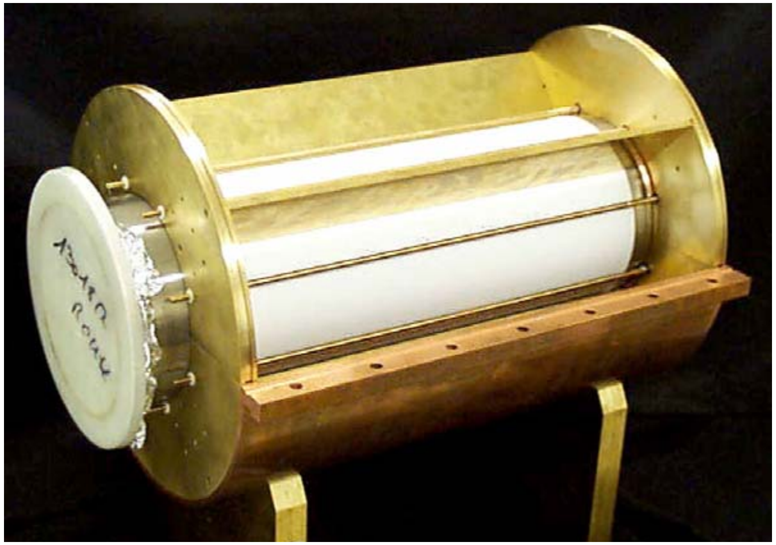

- After some iterations, a design with good common-mode rejection and low longitudinal impedance, was found.

Final design:



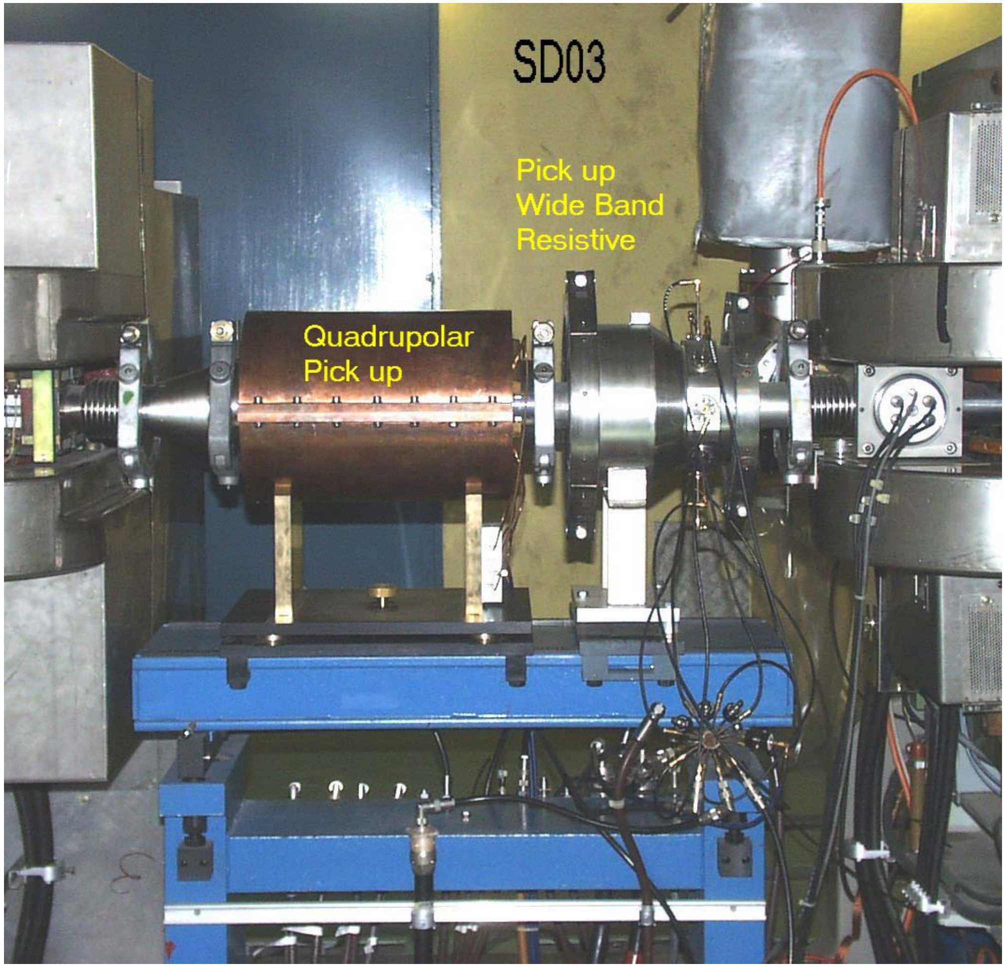
# *Final pickup parameters*

- **Transfer impedance**
  - Sum: 0 Ω
  - Dipole: 1.4 mΩ/mm
  - Quadrupole: 34 μΩ/mm$^2$
- **Bandwidth**
  - ~70 kHz - 25 MHz (limited by hybrid and amplifier)
- **Longitudinal impedance**
  - Z/n < 70 mΩ
- **Dimensions:**
  - Length: 50 cm
  - Aperture: 14.5 cm



Pick-up partly assembled

# Installation in the PS machine

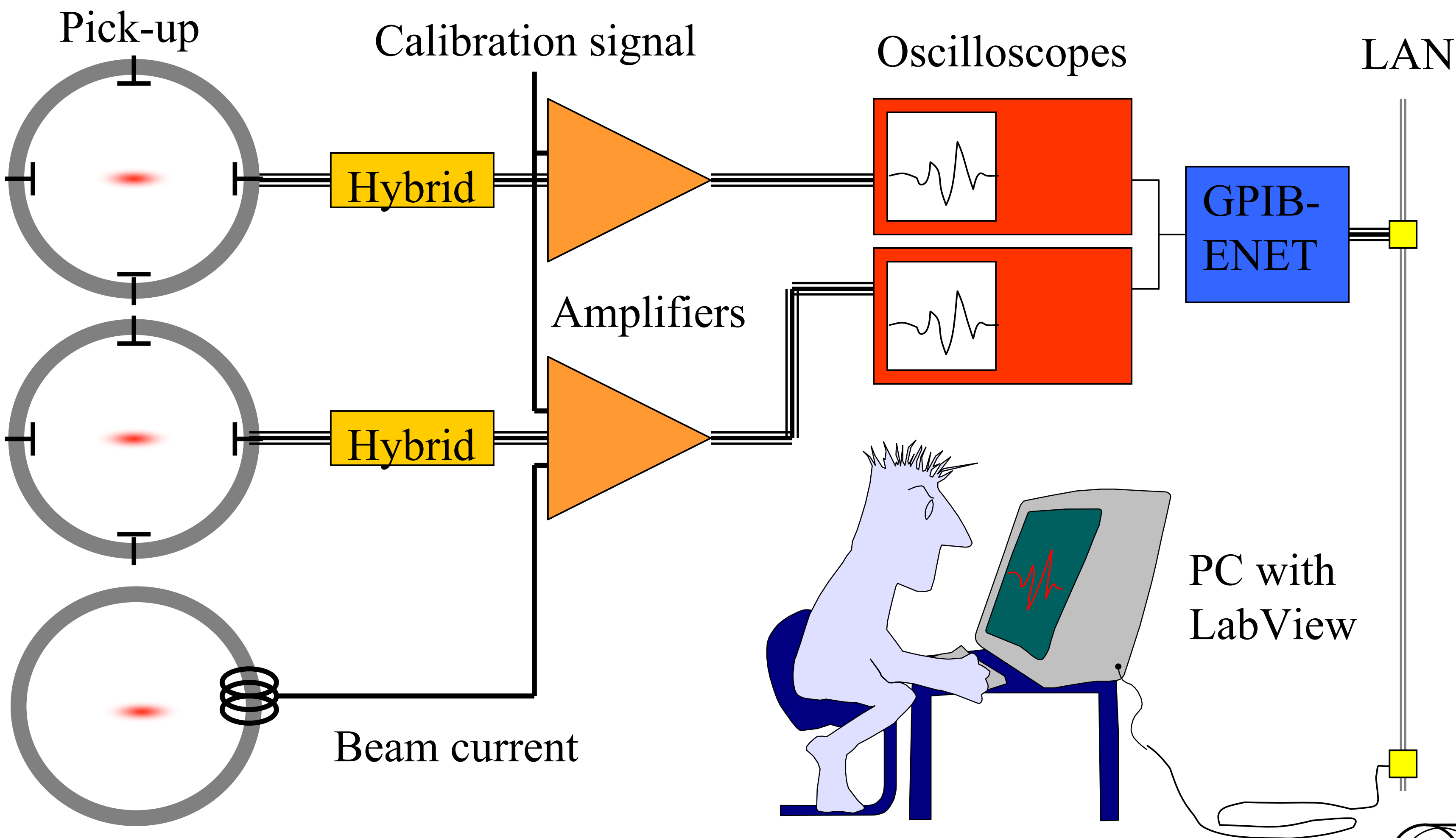



- Two pick-ups in consecutive sections
- "One pick-up per plane"

| | $\beta_h$ | $\beta_v$ | $D_h$ |
|---|---|---|---|
| SS 03 | **22 m** | **12 m** | **3.2 m** |
| SS 04 | **12 m** | **22 m** | **2.3 m** |

- Phase advance between pick-ups independent of machine tune

# Data acquisition



# Intensity normalization

- Usually done by peak search or pulse integration.
- Requires correction for baseline offset and drift.

- If there is no variation in position or beam size along the bunch, the pulse shape is identical on all outputs (in an ideal pick-up).
- Use simple least squares fit.

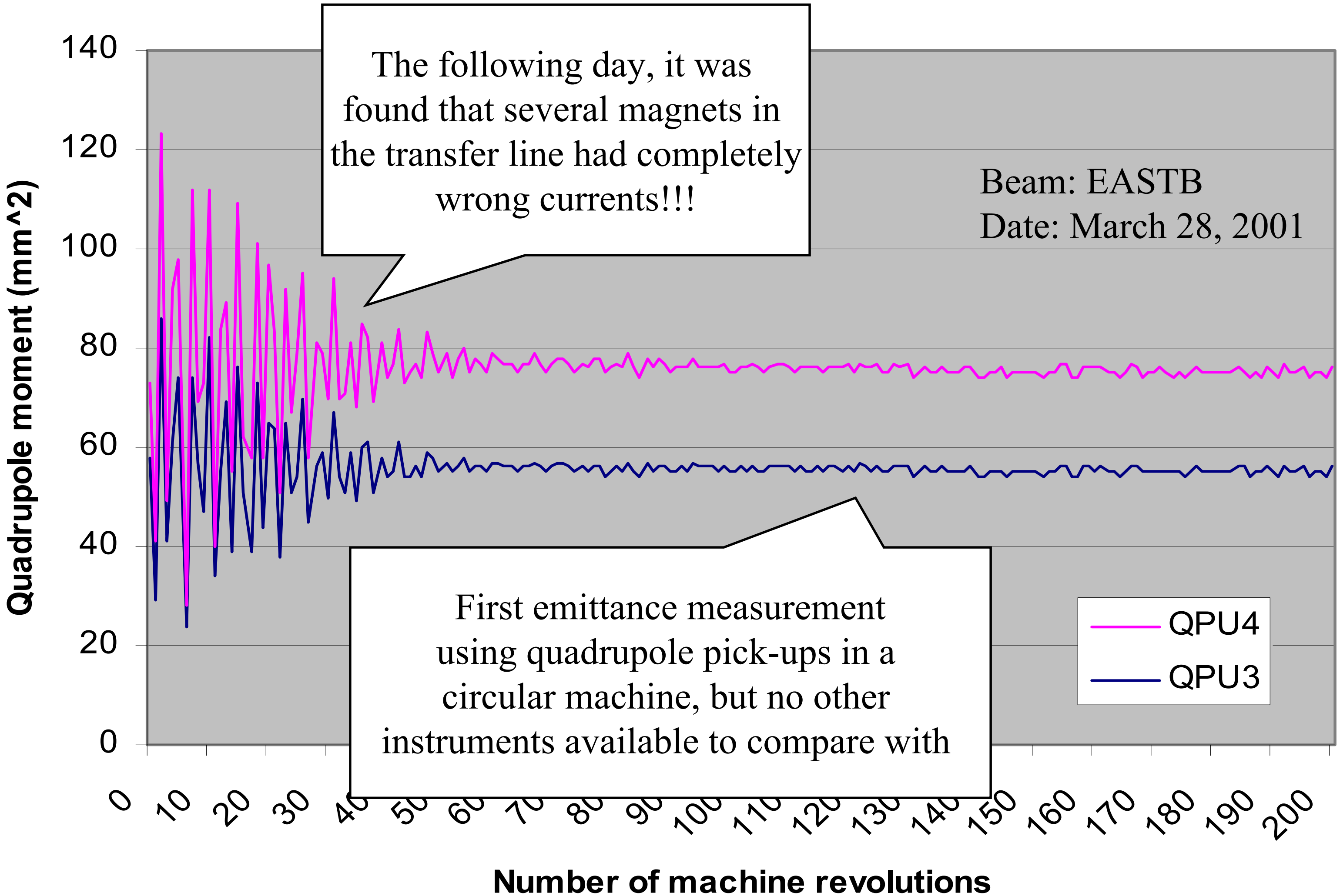
$$s = \text{sum signal}$$

$$q = \text{quadrupole signal}$$

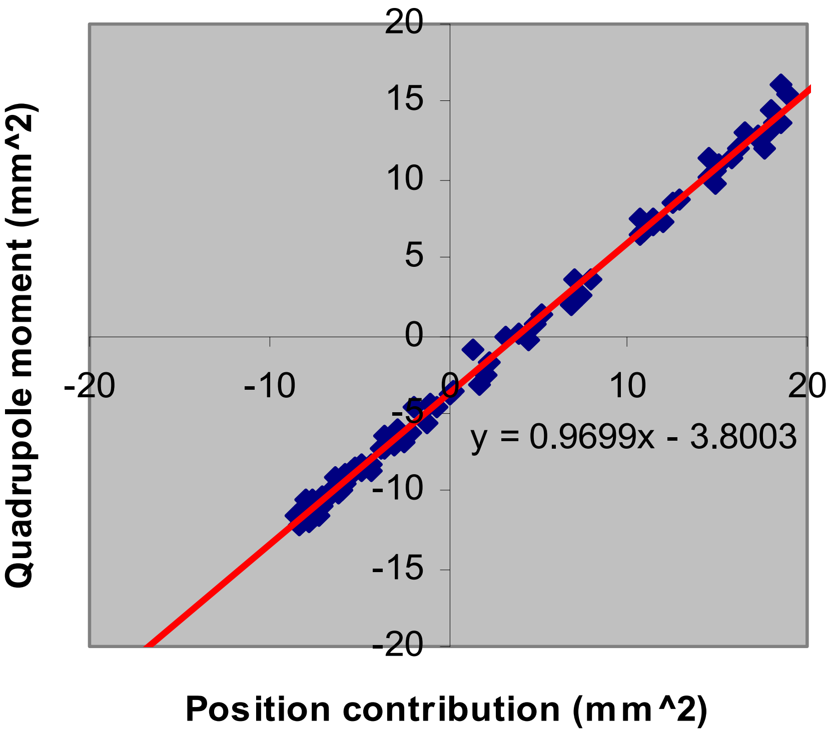
$$\begin{pmatrix} s_1 & 1 \\ s_2 & 1 \\ \vdots & \vdots \\ s_n & 1 \end{pmatrix} \begin{pmatrix} k \\ l \end{pmatrix} = \begin{pmatrix} q_1 \\ q_2 \\ \vdots \\ q_n \end{pmatrix}$$

$$\kappa = \frac{Z_s}{Z_q} k$$

# First signals



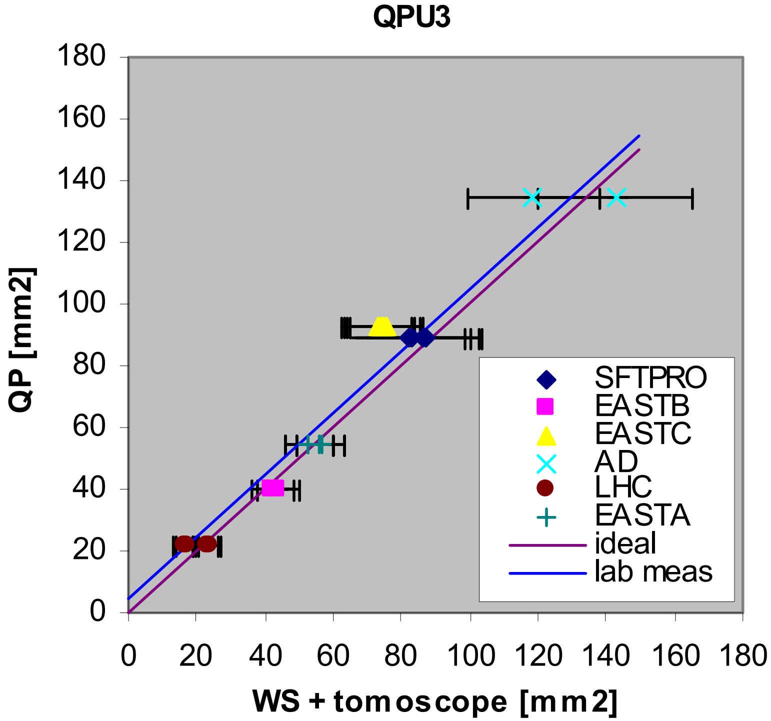
# Beam based calibration - position

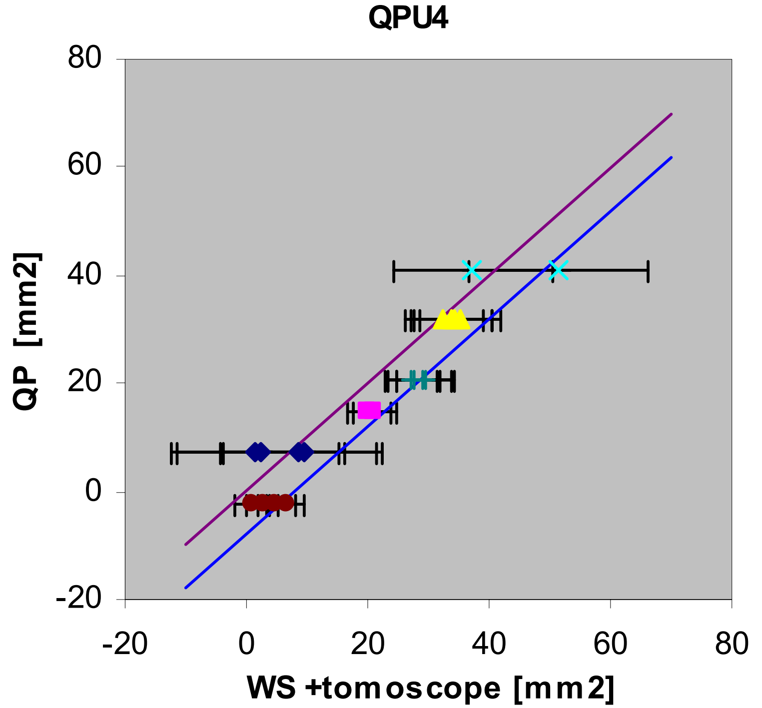



- Take data after filamentation.
- No beam size oscillations.

- Plot quadrupole moment versus its expected position contribution.
- Should be straight line with unit slope.

# Beam based calibration – quad moment

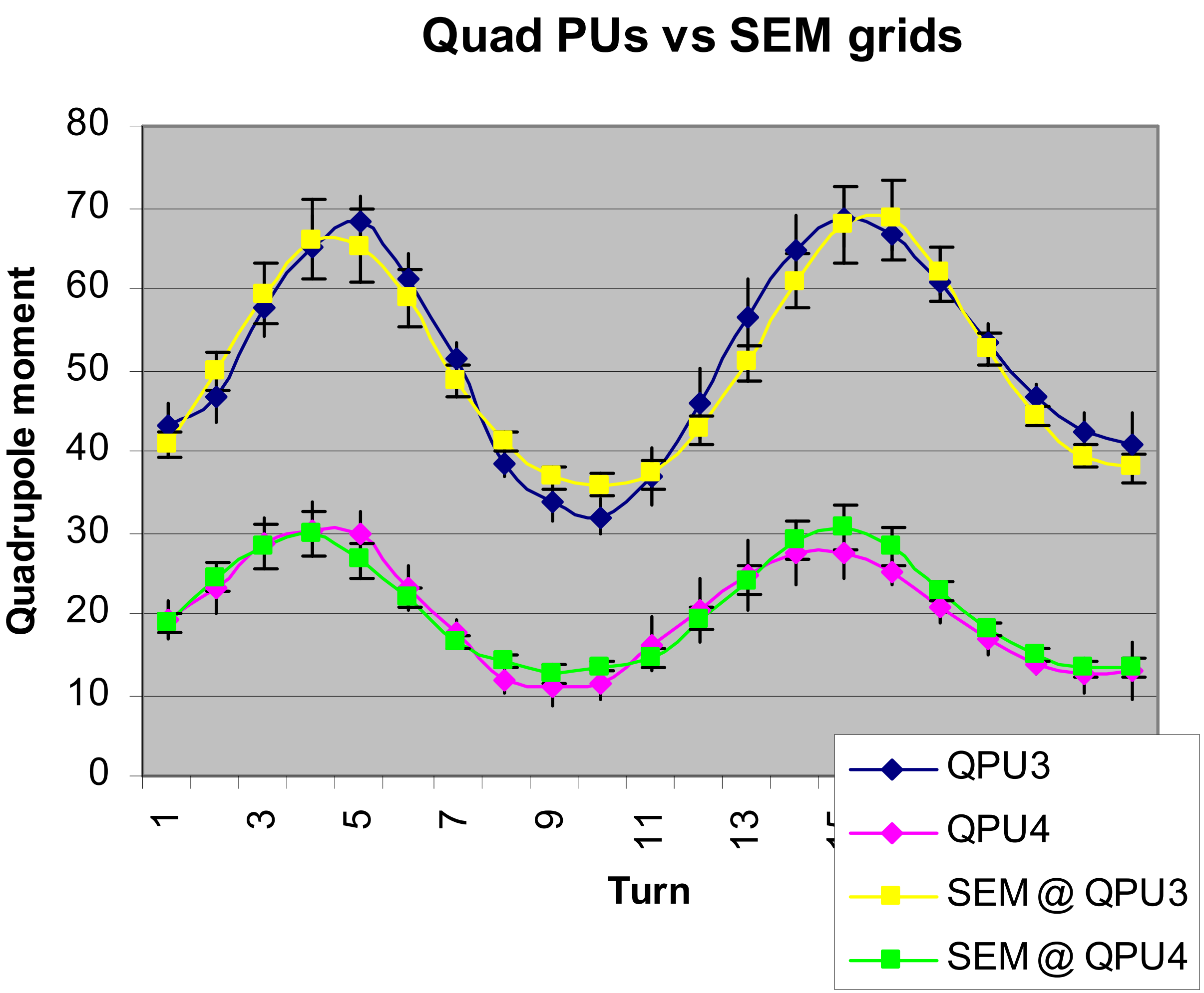



- **Comparison Quad PU vs. Wire-scanner on stable beam.**
- **Several different beam types.**

- **Systematic error bar from:**
  - Beta function ~10%
  - Dispersion ~10%
  - Mom. spread ~3%

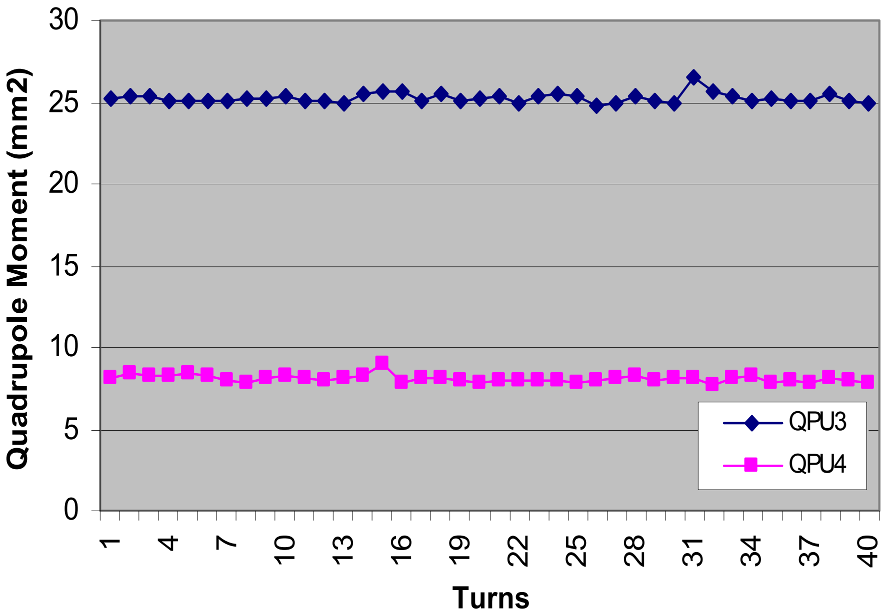
# Comparative matching measurement




- Quad moment measured by pick-ups versus quad moment reconstructed from turn-by-turn SEM grid data.
- Oscillation is mainly due to dispersion mismatch

# Pick-up sensitivity

- Estimated from measurement on stable beam.
- Fluctuation lower than 0.5 $mm^2$ r.m.s. ($4\ 10^{11}$ p/bunch ).
- This corresponds to a 1-2% beta beating at PS injection (negligible emittance blow-up).
- Improvement may still be possible.



# Measurement of filamented emittance

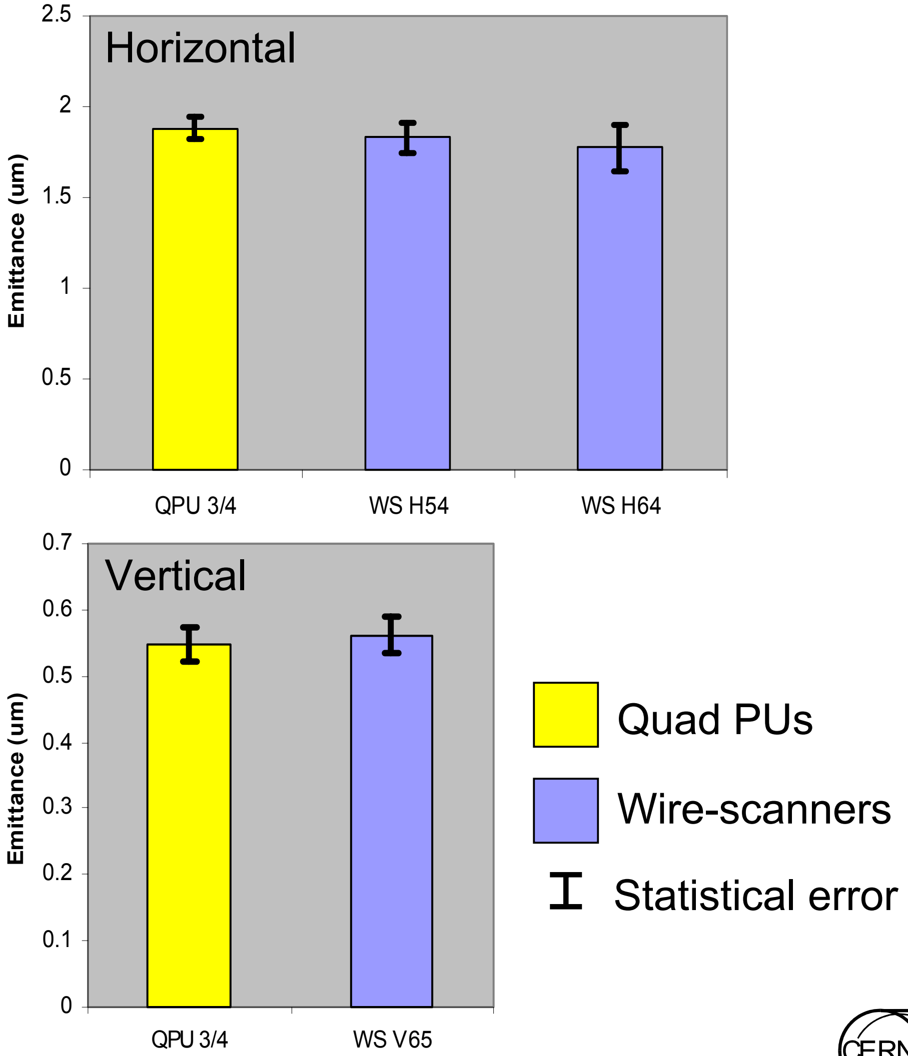
- For a stable beam, the emittance can be calculated from only two pick-up readings.

$$\kappa = \sigma_x^2 - \sigma_y^2$$

$$\kappa_1 = \varepsilon_x \beta_{x1} - \varepsilon_y \beta_{y1} + \sigma_p^2 D_{x1}^2$$

$$\kappa_2 = \varepsilon_x \beta_{x2} - \varepsilon_y \beta_{y2} + \sigma_p^2 D_{x2}^2$$

- Different horizontal/vertical beta function ratios at the two pick-ups are required.
- Signal noise can be reduced by averaging over many turns.

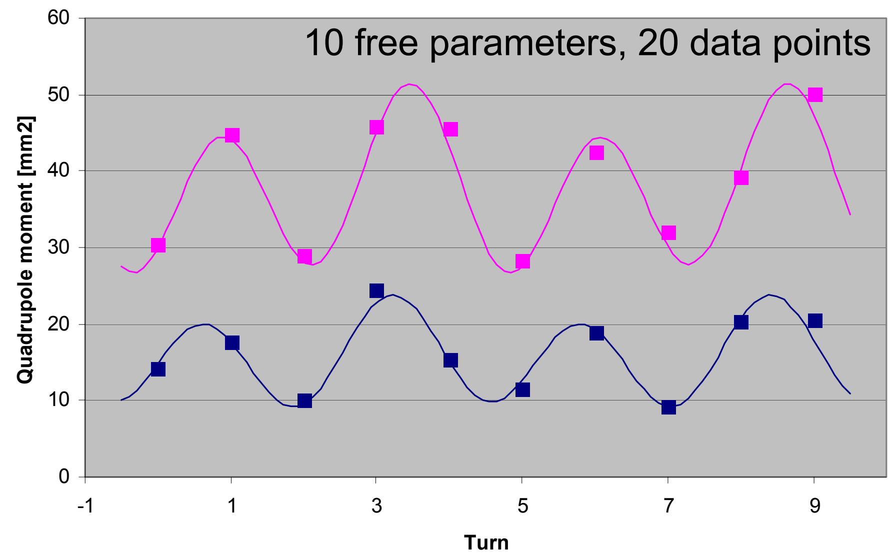


# Measurement of matching

$$\kappa \propto \sigma_x^2 - \sigma_y^2 =$$

$$\varepsilon_x(\beta_x + \underbrace{\Delta\beta_x}_{2q_x}) - \varepsilon_y(\beta_y + \underbrace{\Delta\beta_y}_{2q_y}) +$$

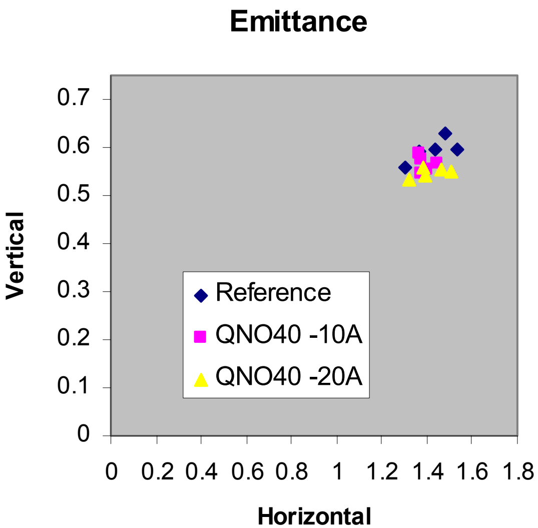
$$+\sigma_p^2(D_x^2 + \underbrace{D_x \Delta D_x}_{q_x} + \underbrace{\Delta D_x^2}_{2q_x} - \underbrace{\Delta D_y^2}_{2q_y})$$

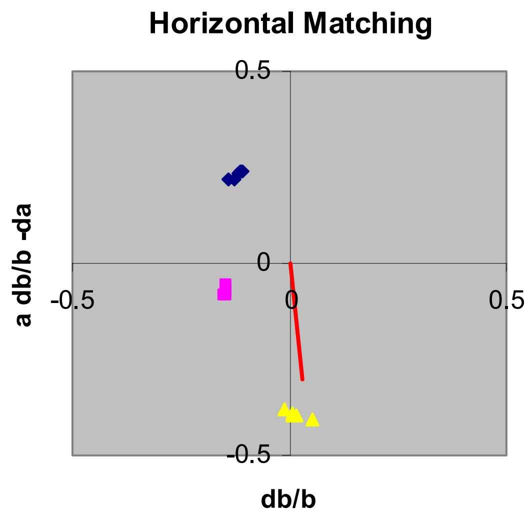


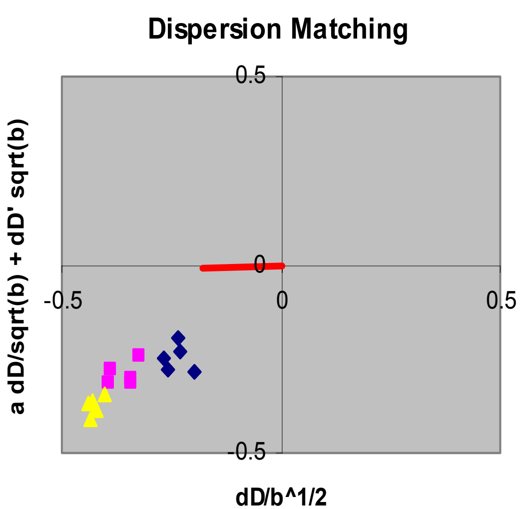

- **Simultaneous fit to the two pick-up signals gives:**
  - Injected emittances.
  - Betatron mismatches.
  - Horizontal dispersion mismatch.

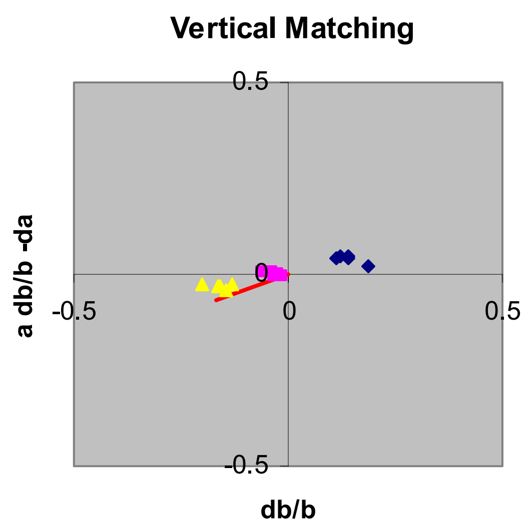
- **"Best fit" tunes gives information on space charge.**
- **Fixed tune give wrong fit results for matching parameters.**

# Injection matching measurement



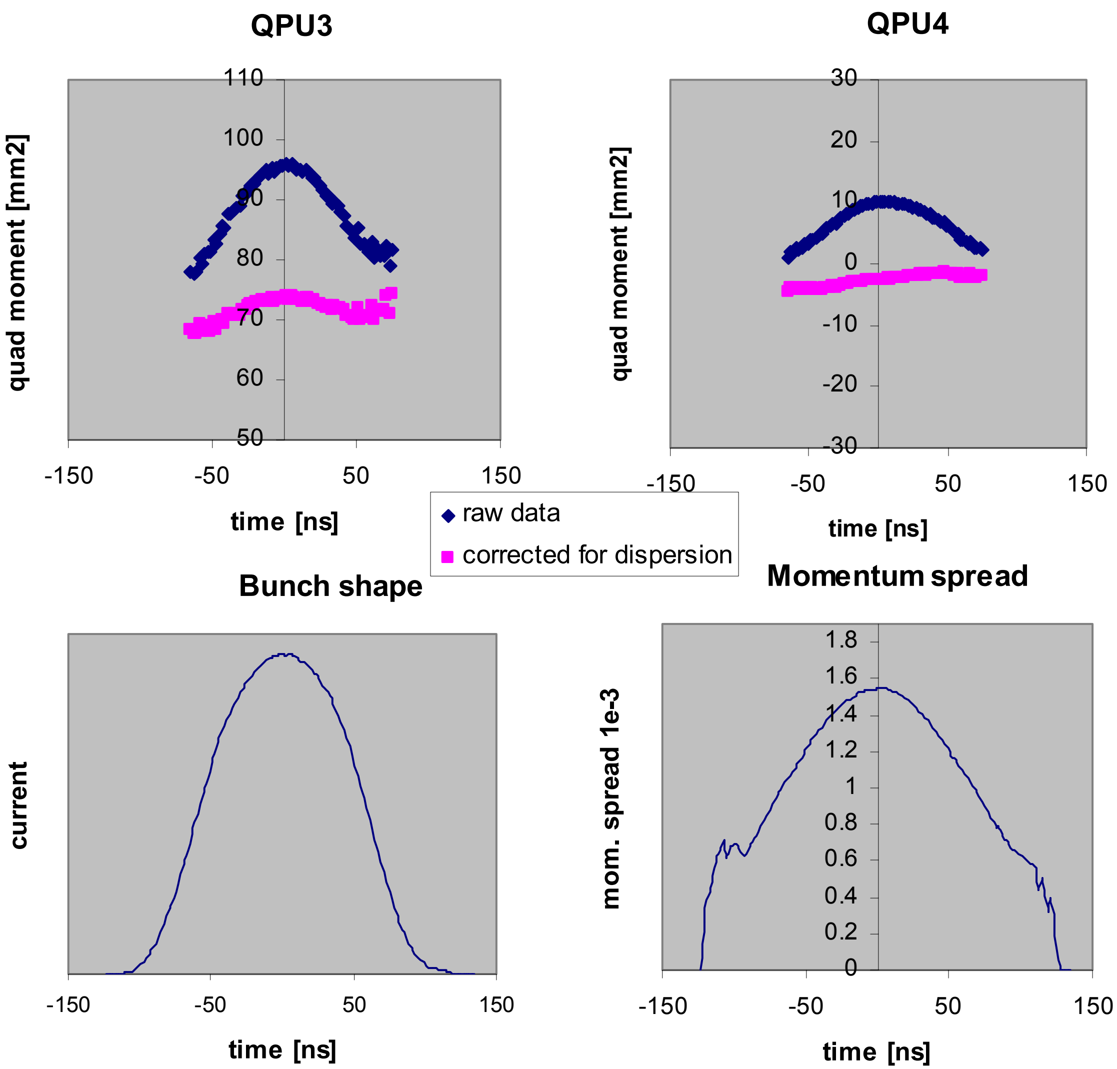

- ➔ **Betatron mismatch**

$$k_\beta = \begin{pmatrix} \dfrac{\Delta\beta}{\beta} \\ \dfrac{\Delta\beta}{\beta}\alpha - \Delta\alpha \end{pmatrix}$$

- ➔ **Dispersion mismatch**

$$k_D = \begin{pmatrix} \dfrac{\Delta D}{\sqrt{\beta}} \\ \dfrac{\Delta D}{\sqrt{\beta}}\alpha + \sqrt{\beta}\Delta D' \end{pmatrix}$$

# Measurements within the bunch




- **Normalized for intensity in each point separately.**
- **Variation in quad moment along bunch mainly due to dispersion and momentum spread.**

# Can the same pick-ups be used elsewhere?

- The pick-ups were optimized for the LHC beam parameters at <u>injection</u> into the PS.
- The most important difference between PS and SPS/LHC is the <u>bandwidth</u> requirement .

| | PS | SPS | LHC |
|---|---|---|---|
| Bunch length | 50 ns | 1 ns | 1 ns |
| Bunch spacing | 300 ns | 25 ns | 25 ns |
| Max beam size | 5 mm | 4 mm | 1.2 mm |
| Chamber radius | 76 mm | 78 mm | 22 mm |

Note that a design that works in the SPS would work in the LHC!

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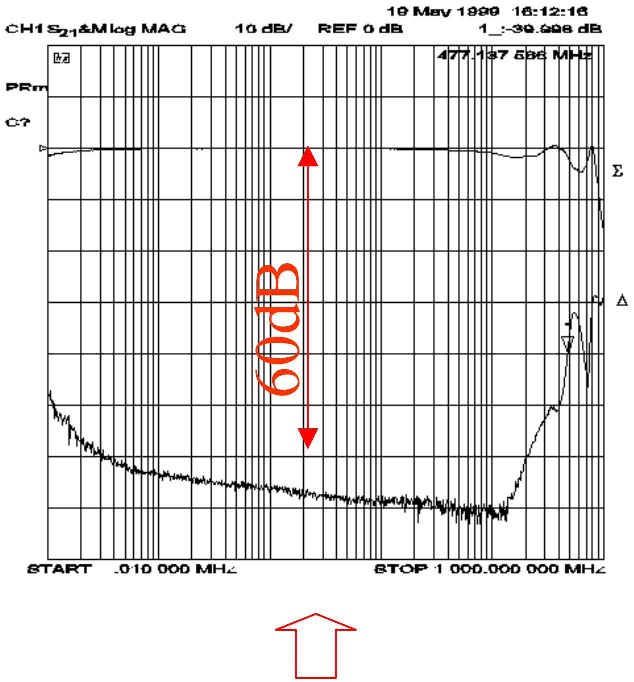
# *A high frequency quadrupole pick-up*

- **At high frequencies, the loops essentially behave like badly matched strip-line couplers.**
- **Use matched 50Ω strip-lines instead?**
- **Requires a good wideband hybrid.**
- **Transfer impedances x10 larger than in PS.**




Four-decade hybrid,
J.M. Belleman,
PS/BD/Note 99-09

# Summary

- Quadrupole pick-ups are not as exotic as one might think.
- The measurement can be checked for ‘internal consistency’.
- They can be used to measure both matching and emittance, continuously on each bunch individually, without perturbing the beam.
- Betatron mismatch of a few percent can be detected (both amplitude and phase).
- The accuracy of the emittance measurement is <u>comparable</u> to the wire-scanners, although the method is less direct and therefore not directly competing with these instruments.