Review of Linear Optics Measurements and Corrections in Accelerators

May 9, 2016, BEXCO, Busan Korea

R. Tomás, M. Aiba,
A. Franchi and U. Iriso

E.D. Courant and H.S. Snyder 1957

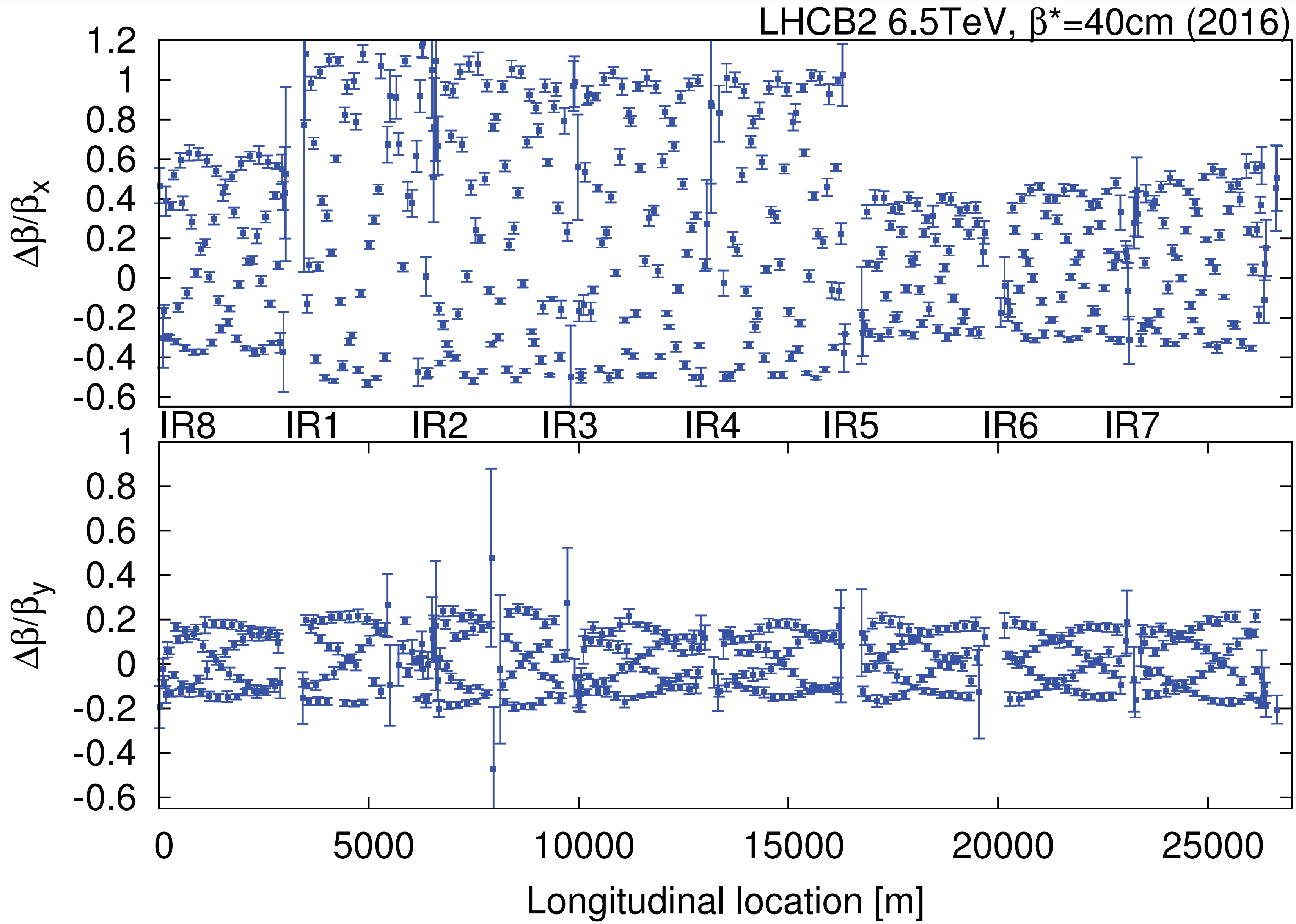
Theory of the Alternating-Gradient Synchrotron:

$$\left(\frac{\Delta\beta}{\beta}\right)_{\rm max} = 4.0\left(\frac{\Delta k}{k}\right)_{\rm rms}$$

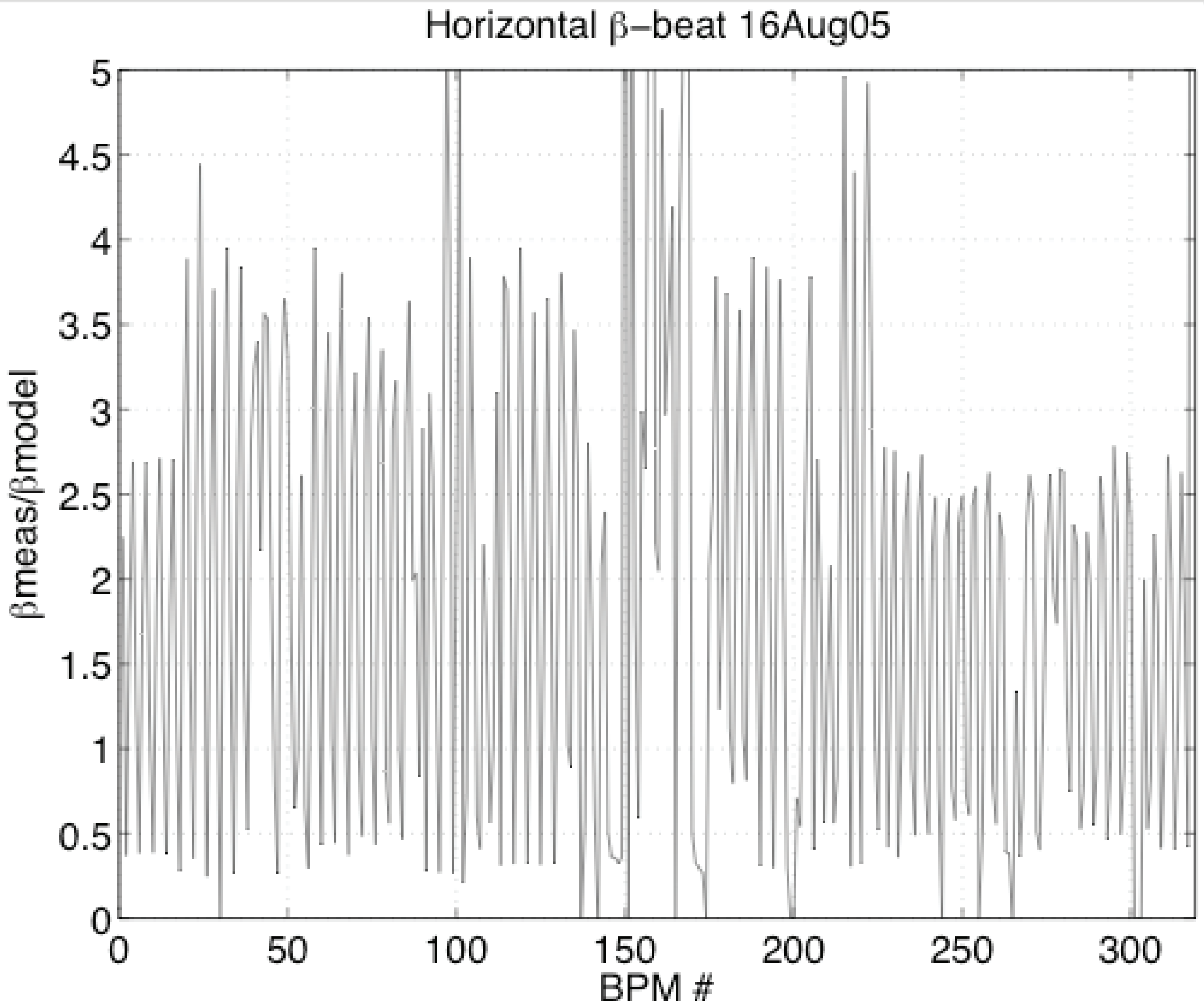
“Thus if the variation in k from magnet to magnet were 1% (...) we would have a β-**beating of 4%**. Any particular machine (...) would be unlikely to be worse by more than factor of 2.”

$\rightarrow$ Expected β-beating below 8% for *any machine*

120% in LHC, commissioning 2016



$\approx$400% in PEP-II, commissioning 2005



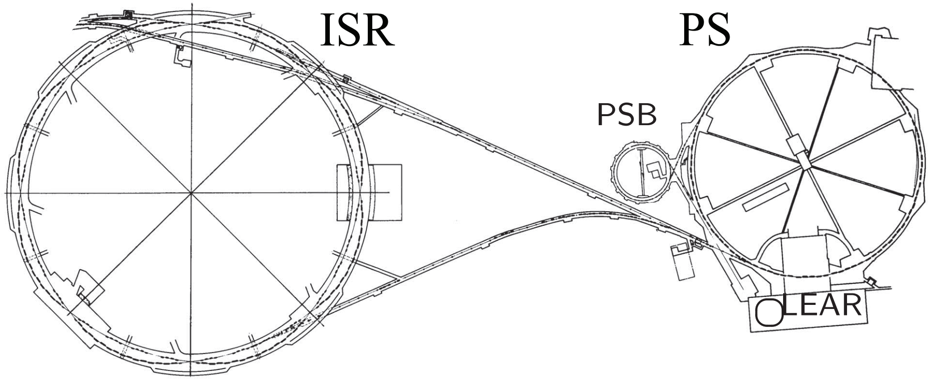
G. Yocky,
SLAC-PUB-12523

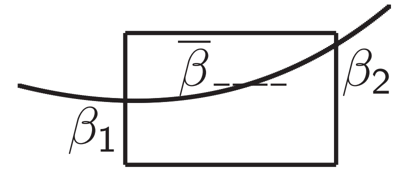
Even $\Delta\beta/\beta \approx 700\%$ was reached when LER tune was pushed closer to the half integer

Techniques for optics measurement & correction

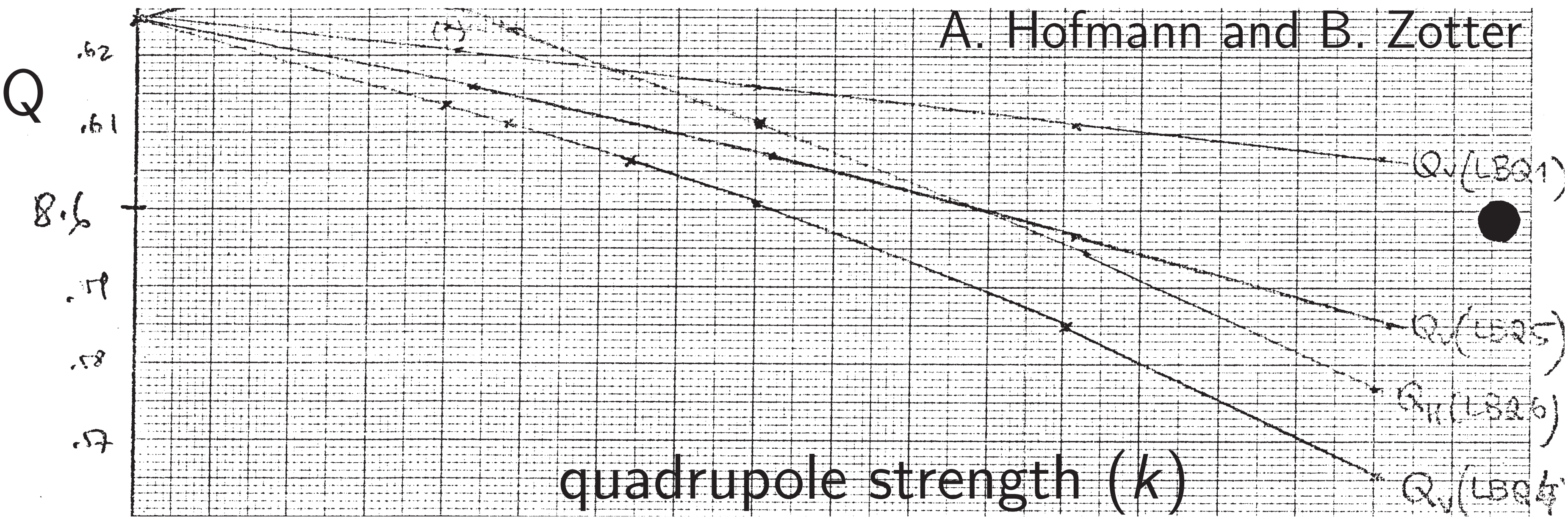
- **K-modulation**
- Turn-by-turn
- Closed orbit (ORM)
- Passive corrections

ISR 1975: K-modulation





quadrupole (k, L)



$$\overline{\beta} \approx \frac{1}{3}\left(\beta_1 + \beta_2 + \sqrt{\beta_1\beta_2 - L^2}\right) \approx \pm\frac{4\pi}{L}\frac{\Delta Q}{\Delta k}$$

Techniques for optics measurement & correction

- K-modulation
- **Turn-by-turn**
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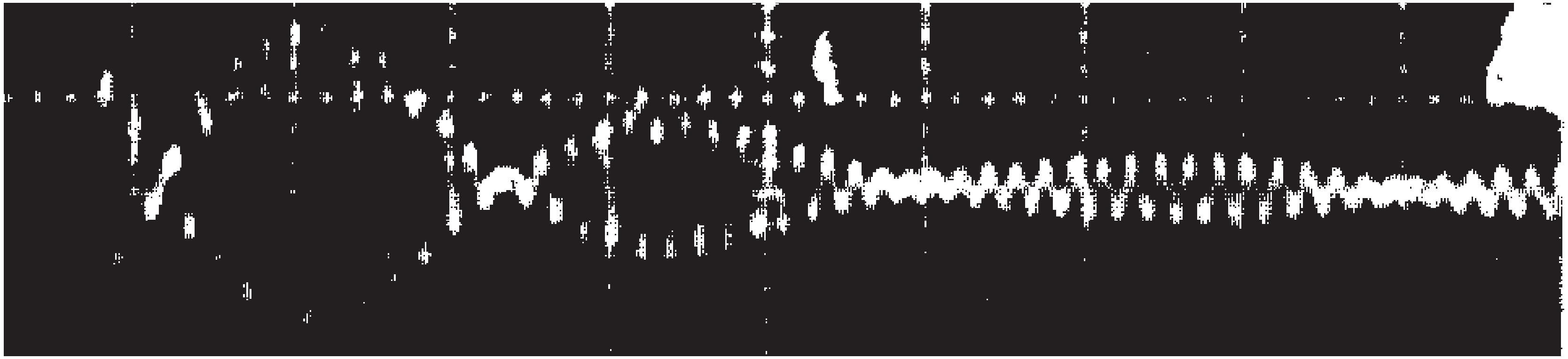
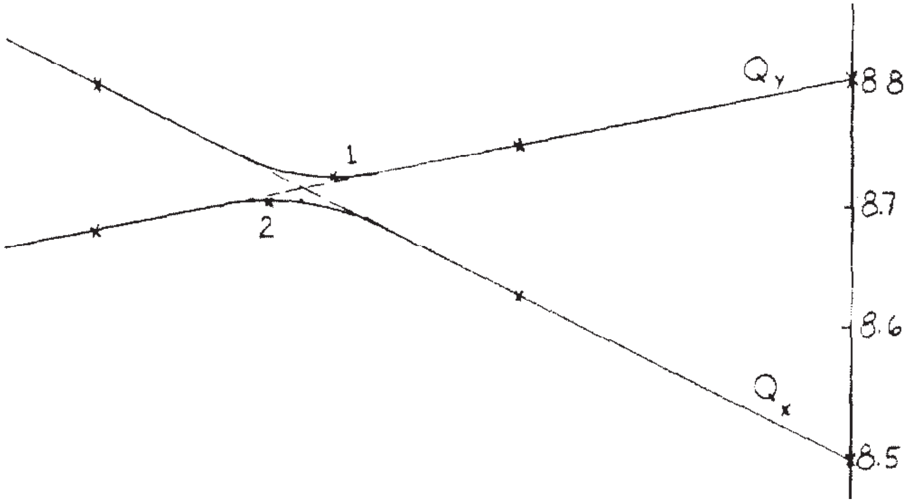
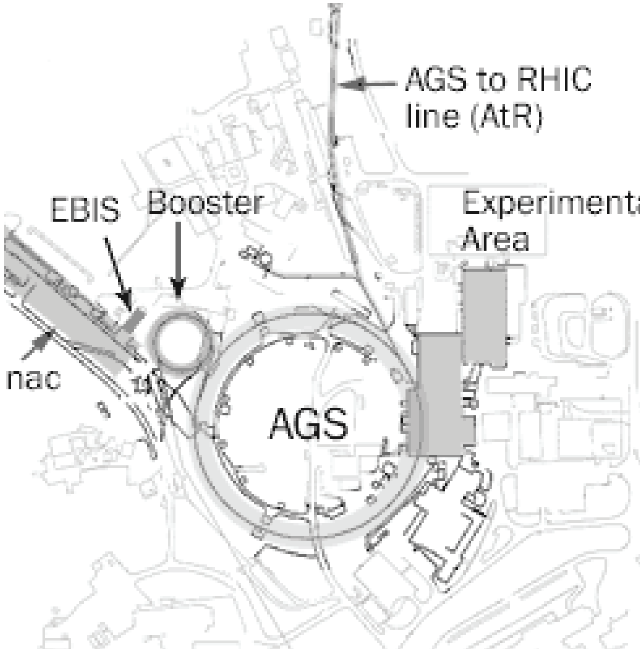
AGS 1975: Coupling correction

E.C. Raka, PAC 1975: turn-by-turn at a single location



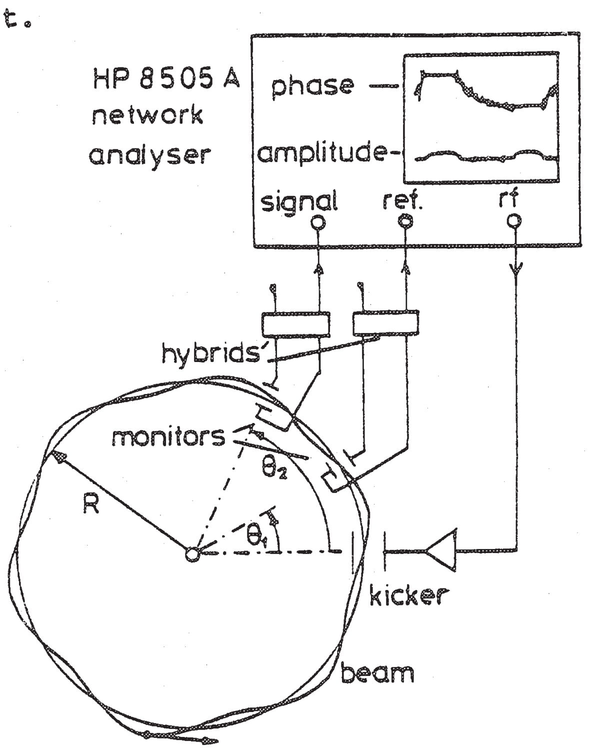
Closest tune approach:





ISR 1983: β and ϕ from turn-by-turn data

$$x(N) = \sqrt{\beta\epsilon}\cos(2\pi QN + \phi)$$



Set-up for phase and amplitude m

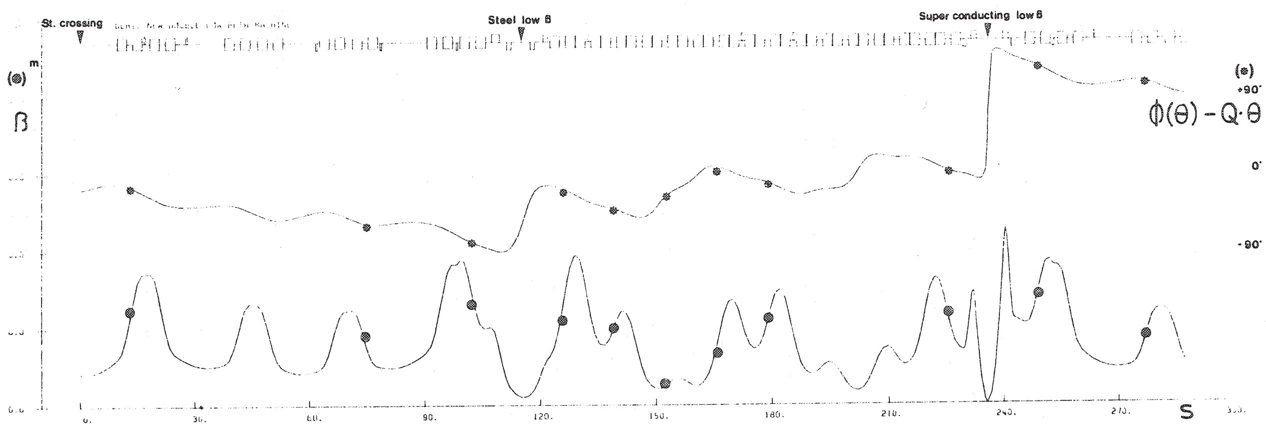


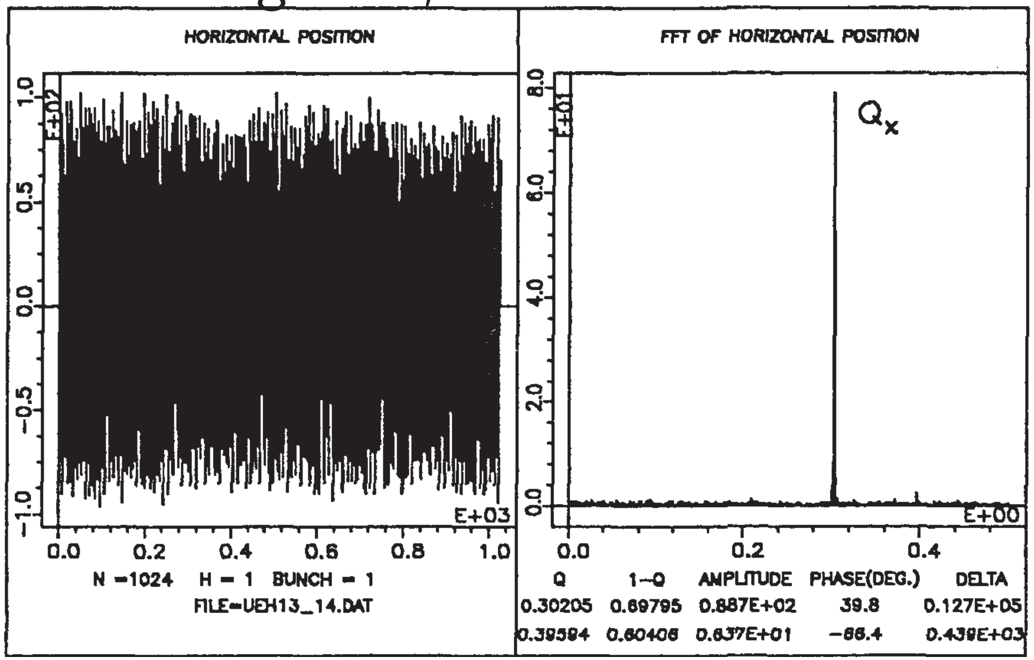
Fig. 3 Vertical betatron phase advance $\phi(\theta)$ relative to $Q\theta$ and beta function $\beta(\theta)$ of approximately one quadrant of the ISR. The lines give the AGS calculations and the points are the measurements.

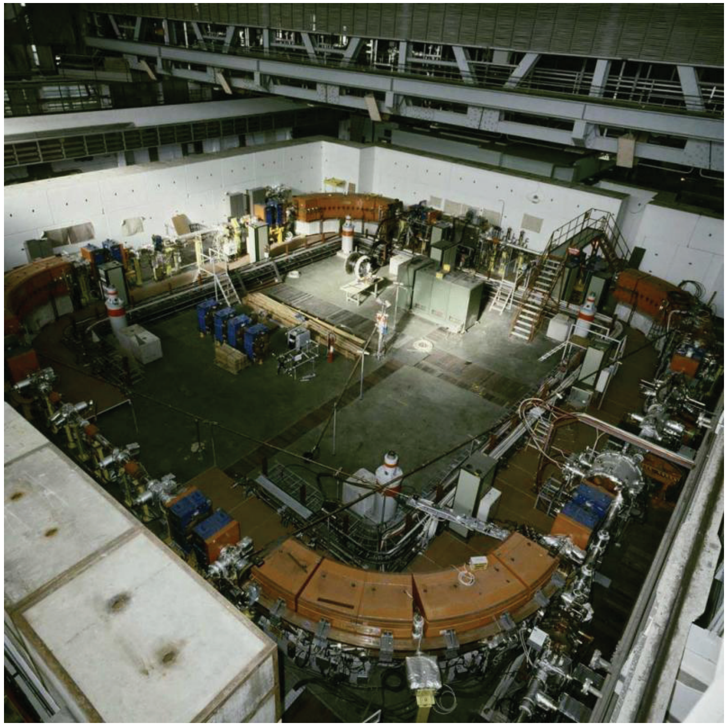
β computed from oscillation amplitude

J. Borer, A. Hofmann, J-P. Koutchouck et al
CERN/LEP/ISR/83-12

LEAR 1988: ϕ from turn-by-turn data

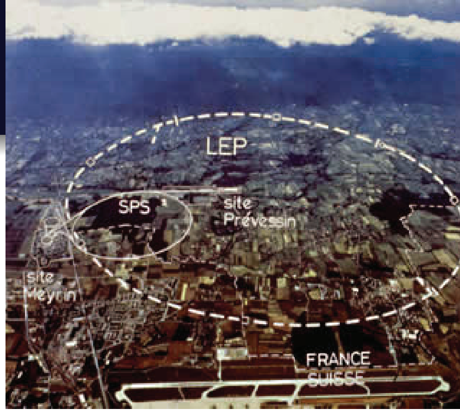
J. Bengtsson, CERN 88-05

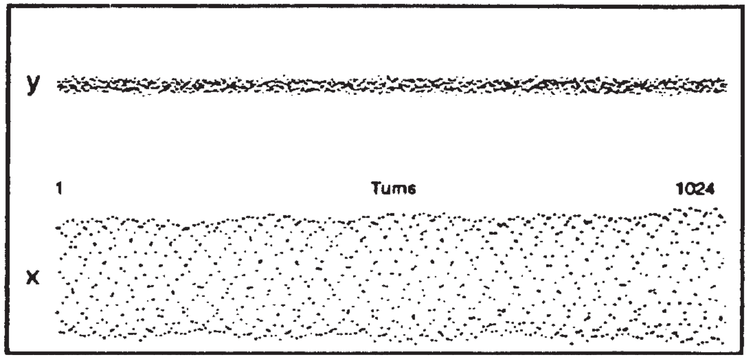




Pick-ups	Measured phase advance (degrees)	Calculated by COMFORT (degrees)
UEH13 – UEH14	15.4	16.0
UEH14 – UEH23	192.1	191.2
UEH21 – UEH22	120.7	118.3
UEH22 – UEH23	34.1	36.3

LEP, β from ϕ, 1993



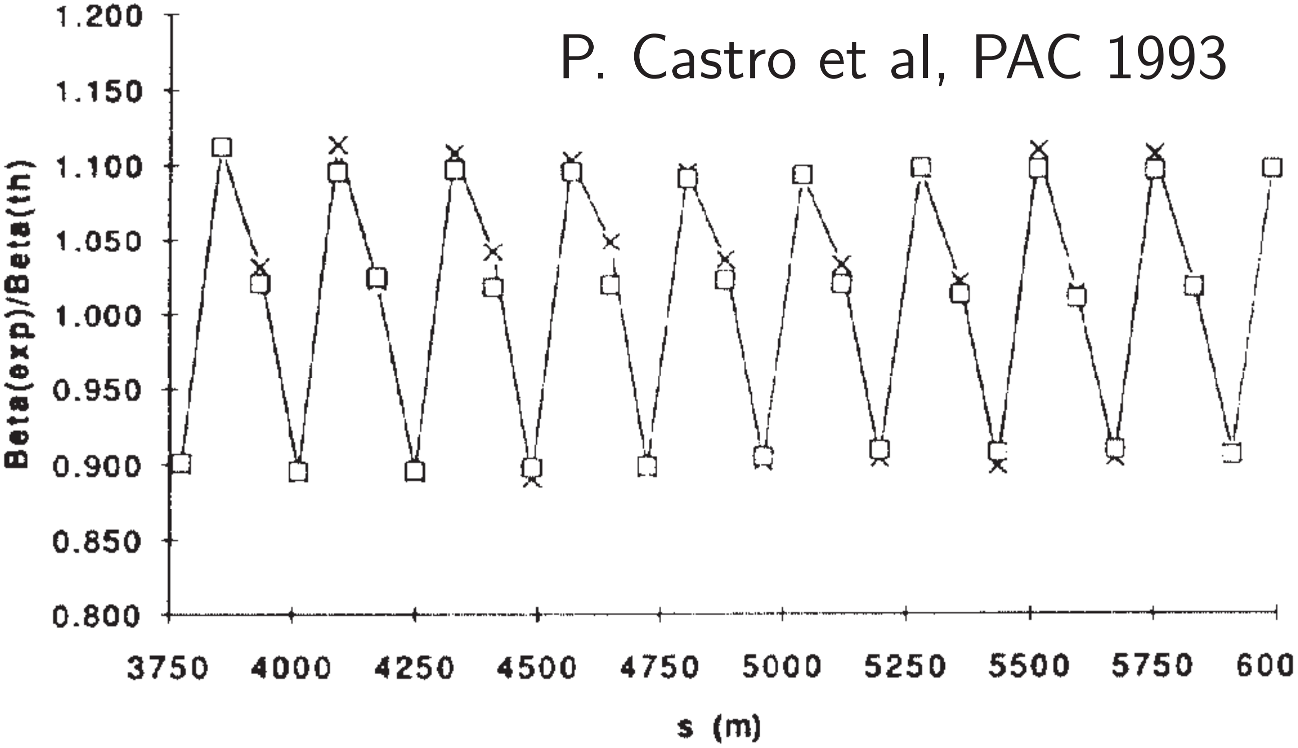


$$\beta_{1(exp)} = \beta_{1(theo)} \frac{\cot \Psi_{12(exp)} - \cot \Psi_{13(exp)}}{\cot \Psi_{12(theo)} - \cot \Psi_{13(theo)}} \quad (10)$$

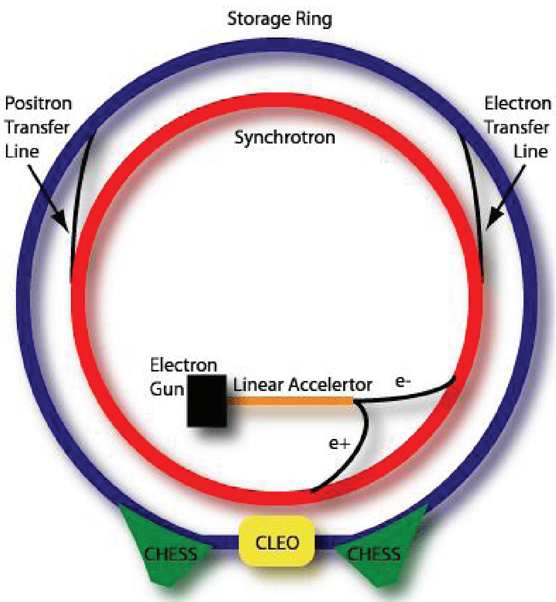
β from ϕ, 3-BPM method, model dep.

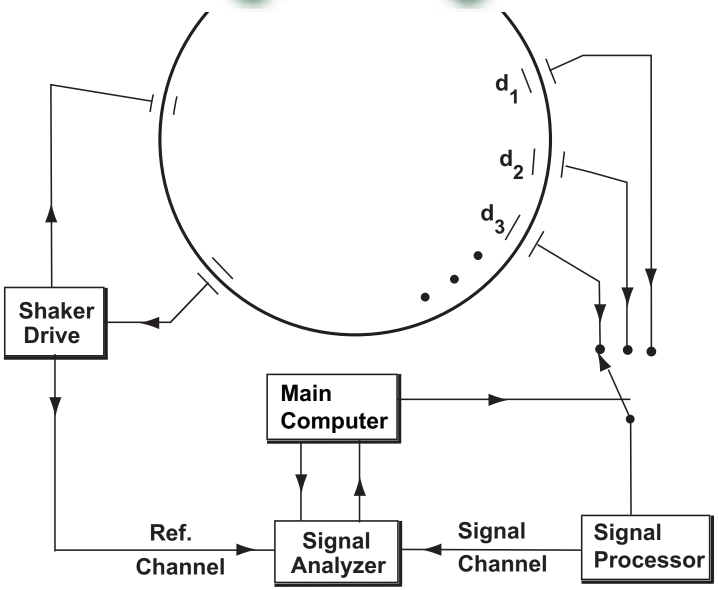
P. Castro et al, PAC 1993

$\frac{\Delta\beta}{\beta}$=10%



Cornell e^+/e^- Storage Ring (CESR) 2000





D. Sagan et al, PRSTAB **3** 092801.

Using LEP method for β functions.

Best optics correction in lepton colliders

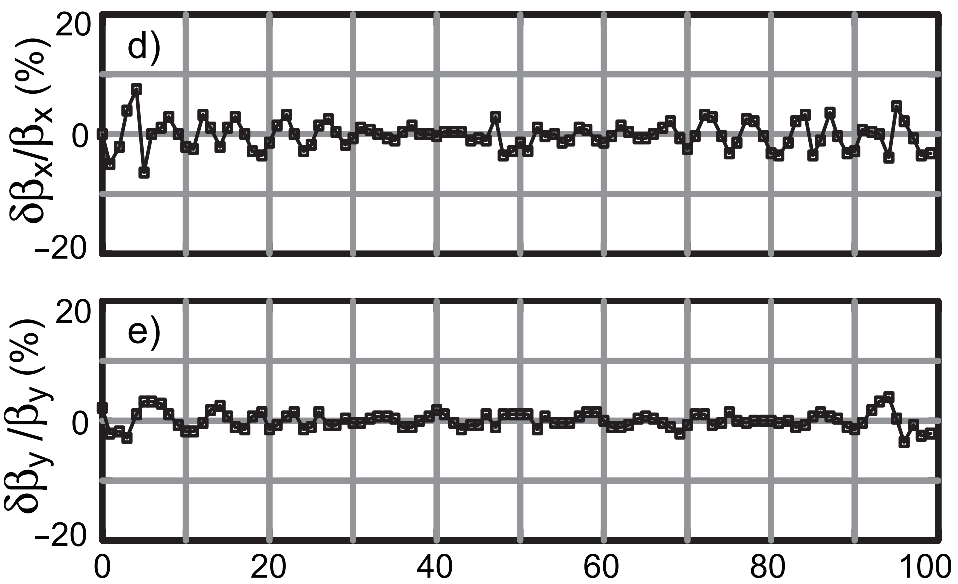
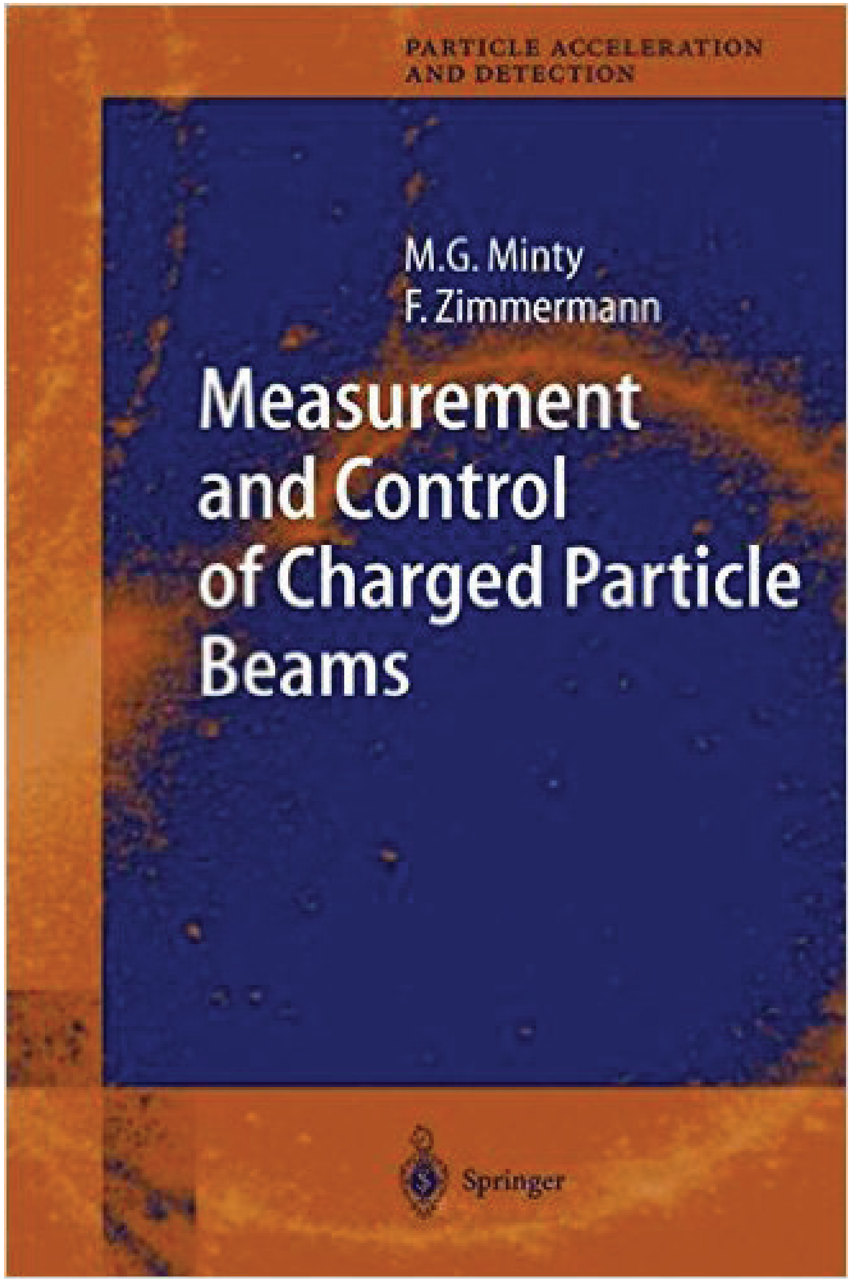


FIG. 6. Measurement after correcting the phase and coupling

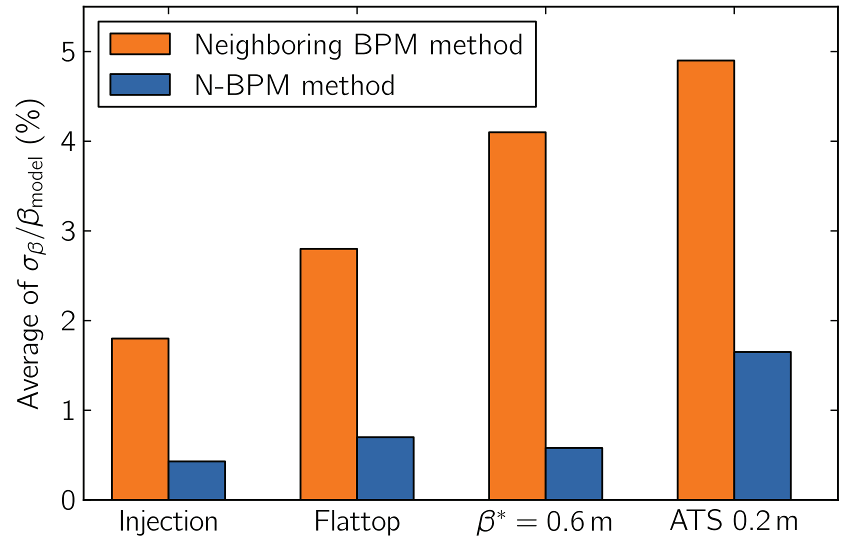
Consolidation of the new discipline (2003)



N-BPM method, LHC 2015

TABLE III. Systematic error of the measured β-function at arc BPMs for using different BPM combinations. The phase advance between consecutive BPMs is approximately $\pi/4$.

BPM combination	Systematic error (%)
(blue triangle): probed, (red triangle): used, (gray triangle): unused	
unused used probed used unused	0.3
used used probed unused unused	0.4
used unused probed used unused	1.0
used unused probed unused used	7.1
used unused used probed unused unused unused	1.1
used unused unused probed unused unused used	1.4
used used unused probed unused unused unused	1.7
unused used unused probed unused unused used	1.8
used unused unused probed used unused unused	7.9
used used unused unused unused probed unused unused unused unused unused	22.3
used unused used unused unused probed unused unused unused unused unused	1.3
used unused unused used unused probed unused unused unused unused unused	1.9
used unused unused unused used probed unused unused unused unused unused	6.1
used unused unused unused unused probed used unused unused unused unused	1.0
used unused unused unused unused probed unused used unused unused unused	3.0
used unused unused unused unused probed unused unused used unused unused	4.5
used unused unused unused unused probed unused unused unused used unused	5.2
used unused unused unused unused probed unused unused unused unused used	1.6



Extension of the LEP 3-BPM method to any number of BPMs. **Great improvement on β measurement** (from ϕ). Good knowledge of lattice errors fundamental.

A. Langner & R. Tomas PRSTAB **18**, 031002 (2015)

Further developments (2016)

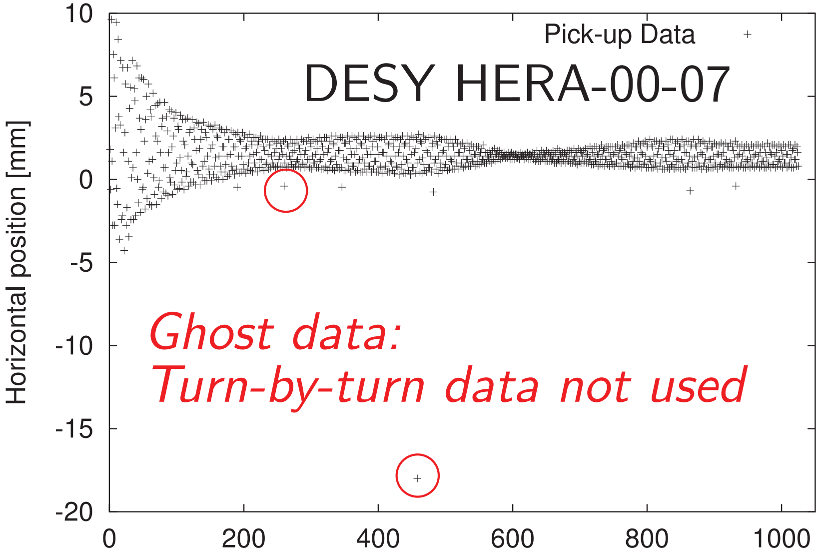
A. Franchi, arXiv:1603.00281v2:

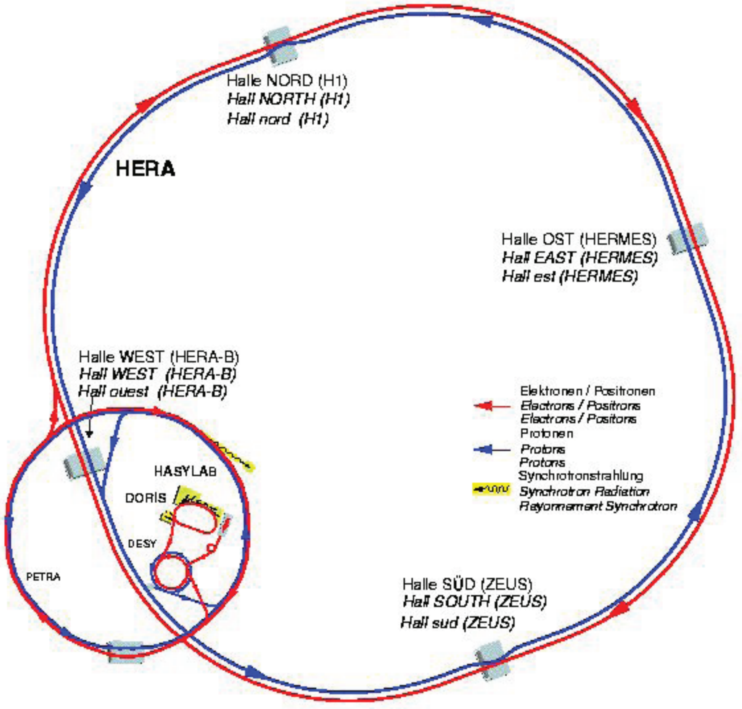
- ★ β from ϕ, extended 3-BPM equation :

$$\beta_1^{(meas)} = \beta_1^{(mod)} \frac{\cot \Delta\phi_{12}^{(meas)} - \cot \Delta\phi_{13}^{(meas)}}{\cot \Delta\phi_{12}^{(mod)} - \cot \Delta\phi_{13}^{(mod)} + (\bar{h}_{12} - \bar{h}_{13})}$$

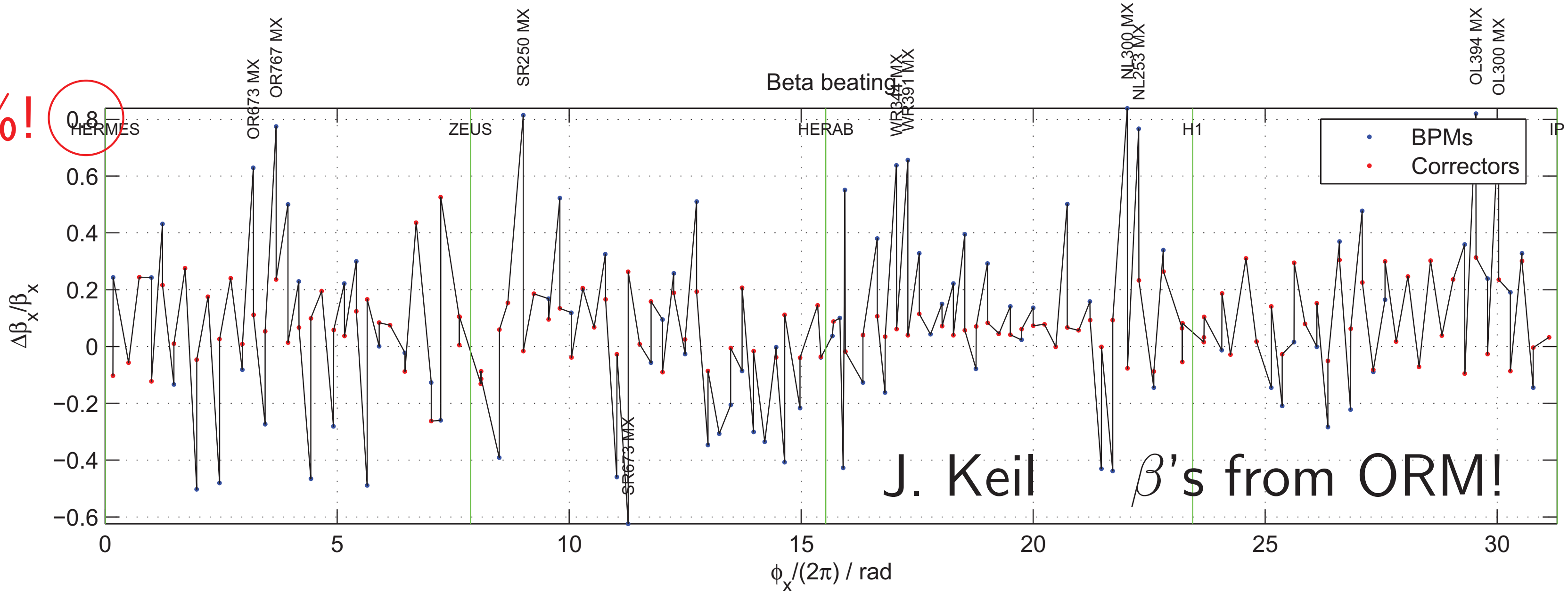
- ★ Effects of non-linearities on the β, ϕ and coupling measurements

HERA-p



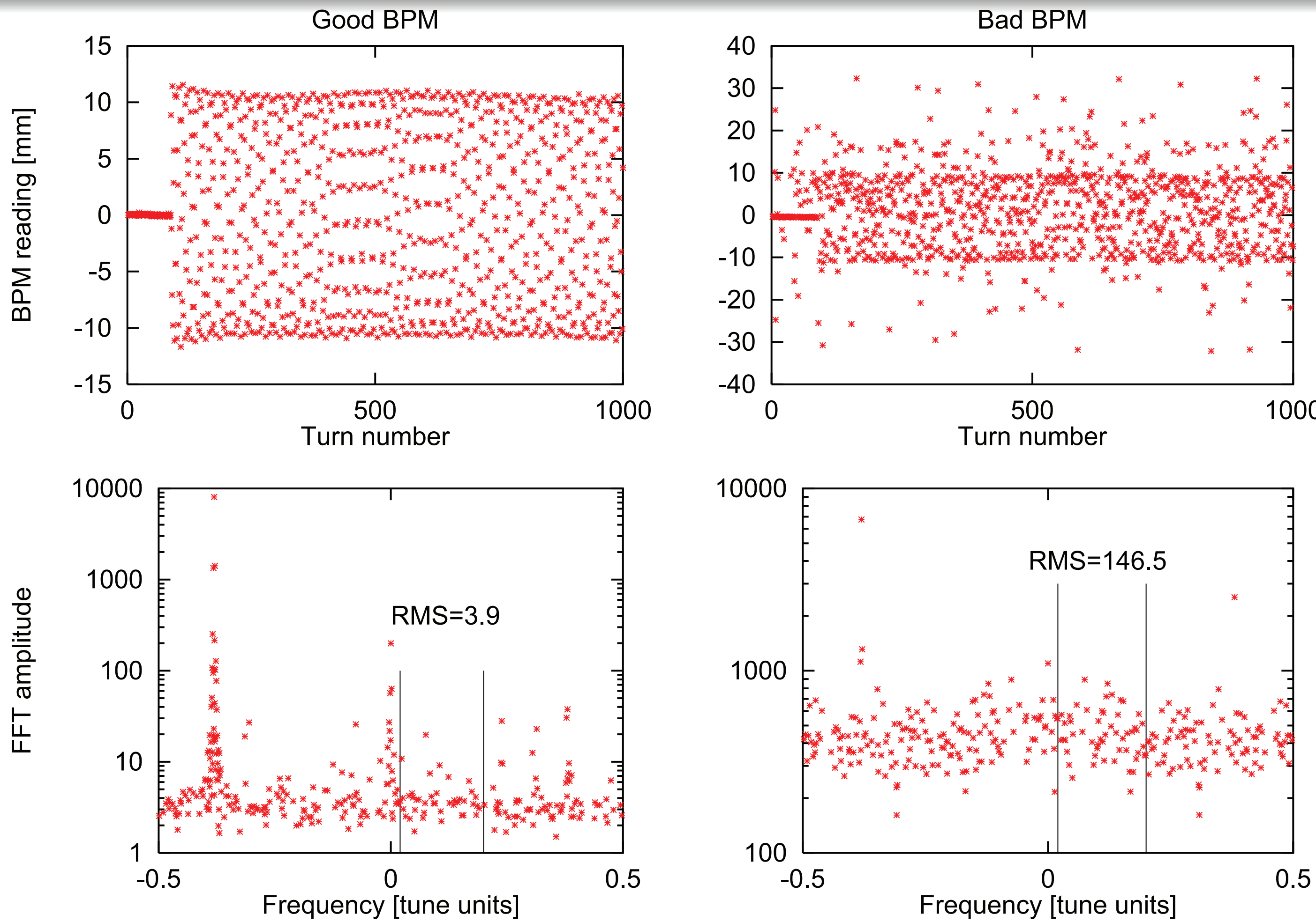


80%!



J. Keil β's from ORM!

SPS BPM signals in 2000

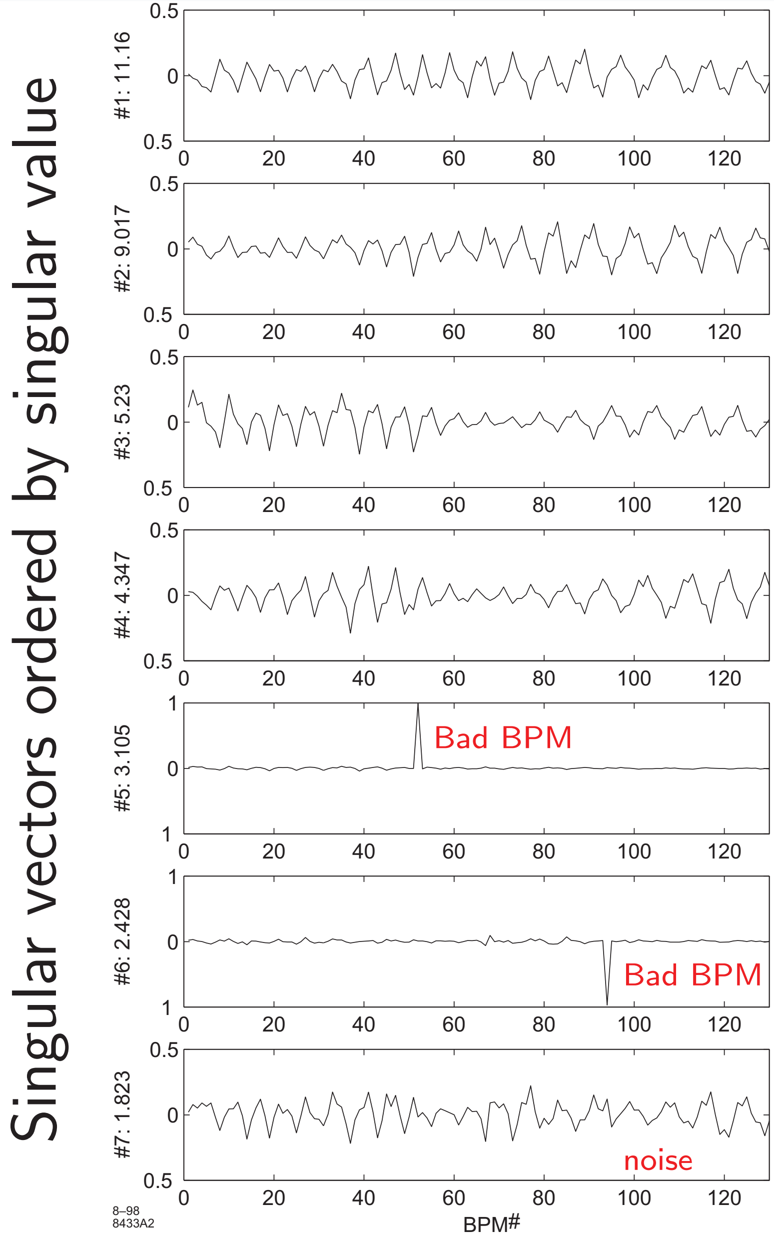


R. Tomas, CERN-THESIS-2003-010

BPM issues required bad BPM detection techniques.

The **RMS** in a FFT window is a good indicator.

SLC: Cleaning with SVD, 1999



$$B_{t-b-t} = USV^T$$

bpm matrix

Bad BPMs easily identified as uncorrelated signals.

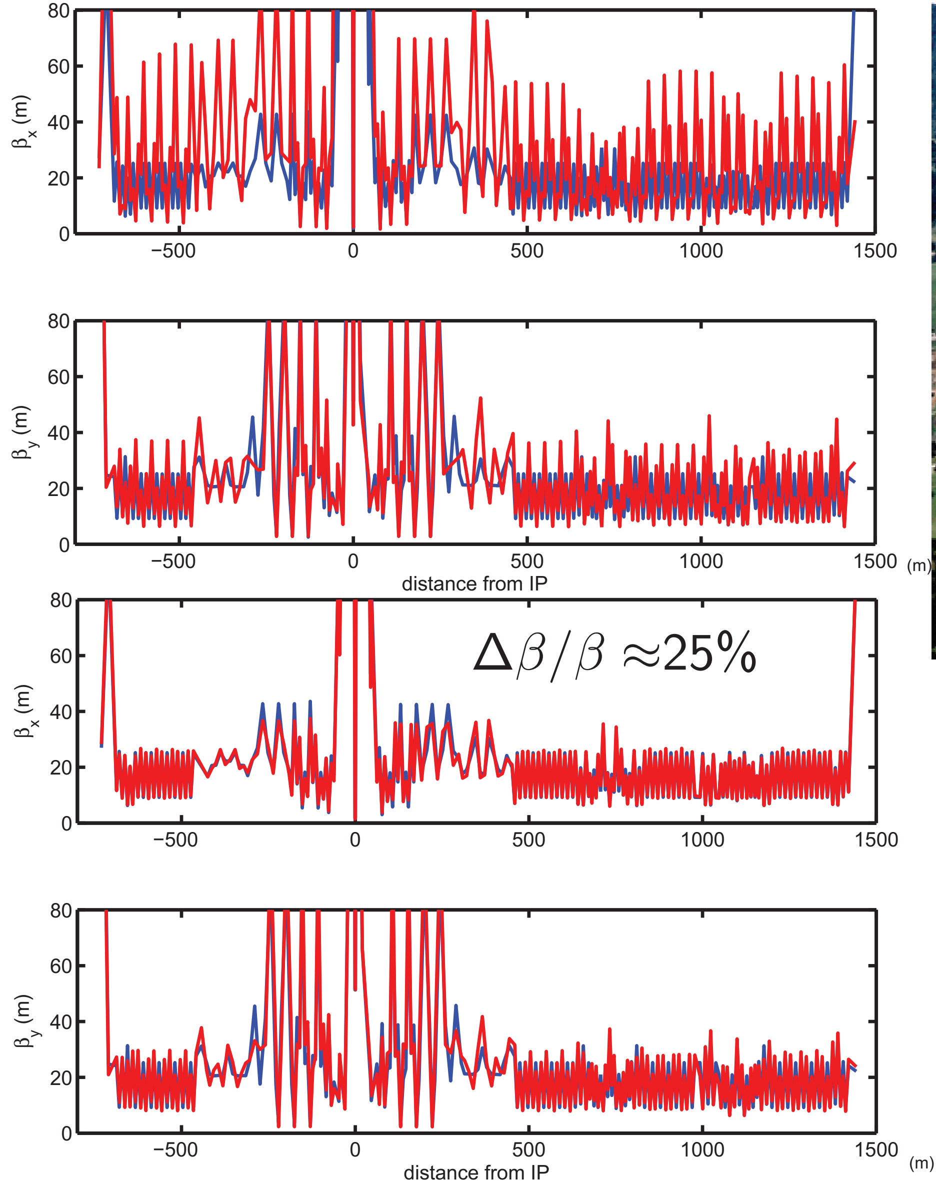
Noise removed by cutting low singular values

J. Irwin et al., Phys. Rev. Letters **82**, 8

PEP-II, from ϕ to virtual model to β

before corrections

after corrections



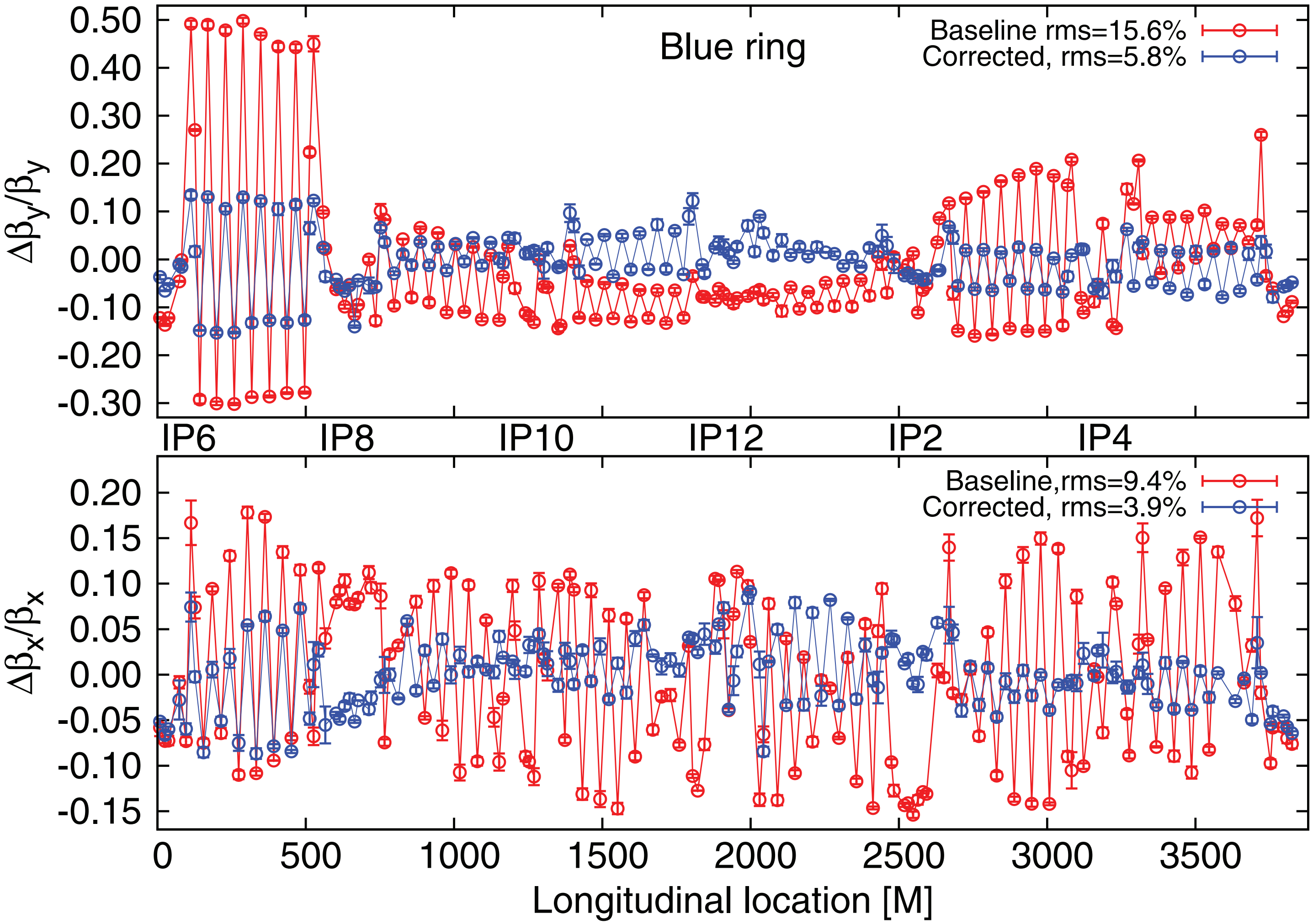
Using SVD modes

Y. Yan et al, SLAC-PUB-11925 2006

AC dipole, 1998

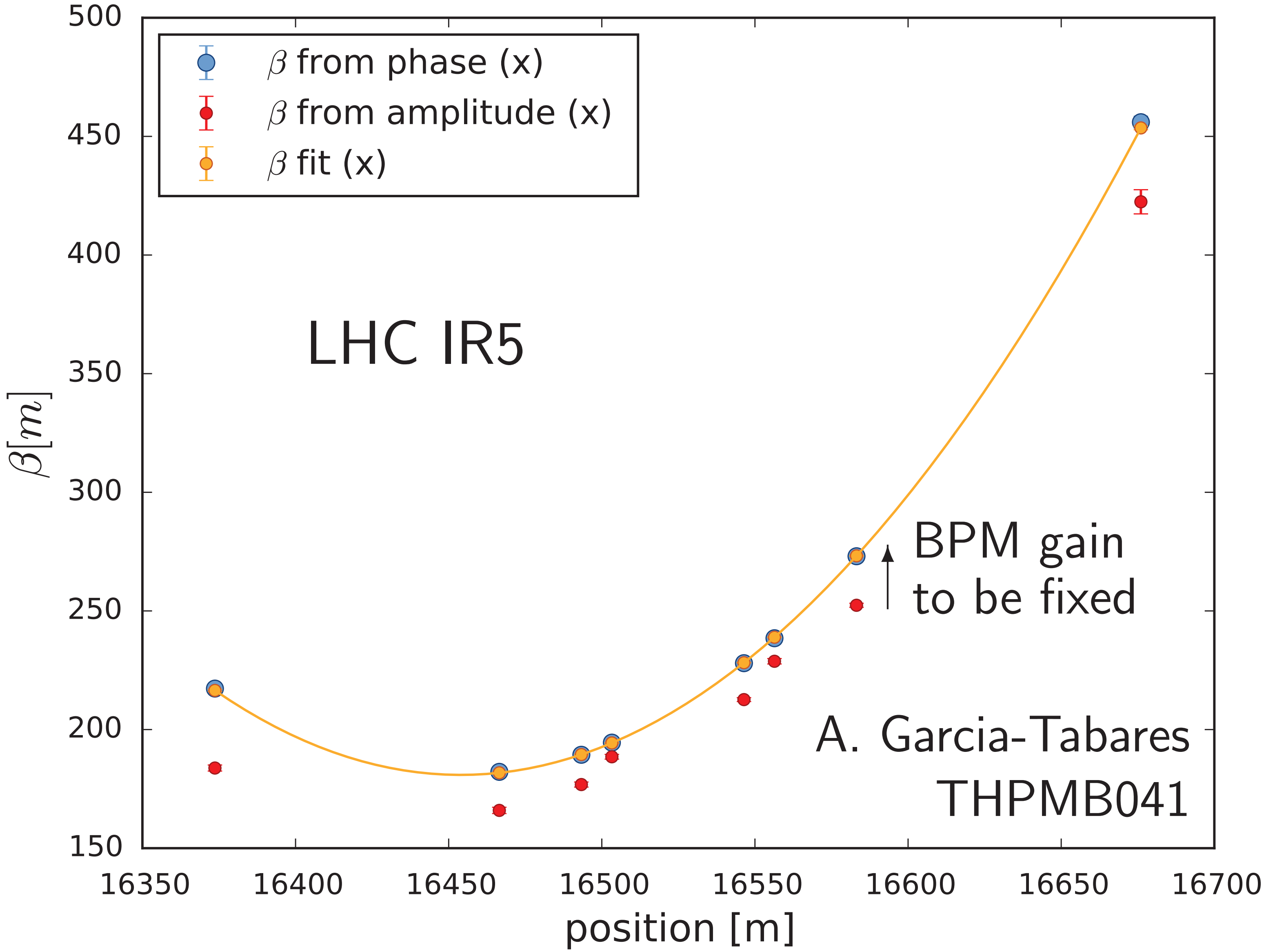
- AC dipoles were proposed to avoid spin resonances and do optics meas: M. Bai et al, Phys. Rev. Lett. **80**, 4673 (1998).
- Major breakthrough for protons: *Excite betatron oscillations (forced) without emittance blow-up*
- Used in AGS, RHIC, SPS, Tevatron & LHC
- LHC has ≈20 optics within the magnetic cycle
- The magnetic cycle takes about 2.5h
- LHC optics commissioned thanks to AC dipole

RHIC: Using amplitude info from BPMs



Successful corrections of β from amplitude using ICA (SVD).
X. Shen et al, PRSTAB **16**, 111001 (2013)

Calibrating BPMs by switching off quads



Techniques for optics measurement & correction

- K-modulation
- Turn-by-turn
- **Closed orbit (ORM)**
- Passive corrections

β and ϕ from closed orbit data (1987)

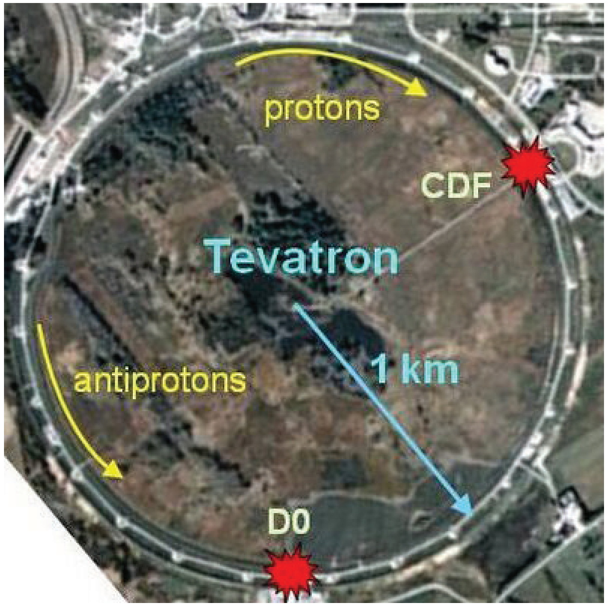
$$x(s) = \sqrt{\beta(s)\beta_0}\frac{\theta}{2\sin(\pi Q)}\cos(|\phi(s)-\phi_0|-\pi Q)$$

GLOBAL BETA MEASUREMENT FROM TWO PERTURBED CLOSED ORBITS

PAC 1987

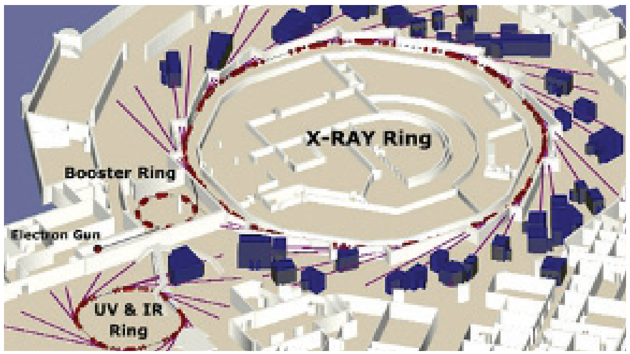
M. Harrison, Fermilab*, Batavia, Illinois
S. Peggs, SSC-CDG*, Berkeley, California

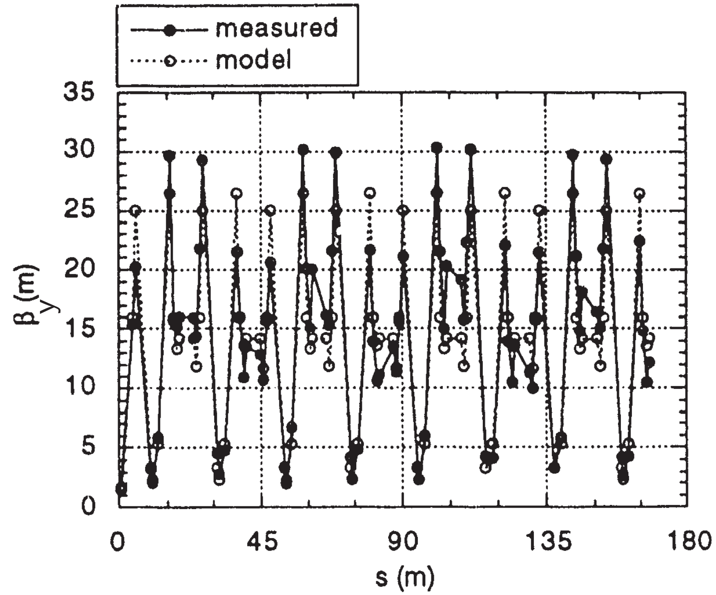
The conventional 'cusp' beta measurement technique assumes that the BPM is close enough to the corrector to declare that their β, ϕ values are identical, leaving only one unknown, β, on the right hand side. Disadvantages of this method are that one closed orbit observation is needed to measure β at only one BPM, and that the BPM may be distant from the corrector. (In the realistic model of the Tevatron used below, each corrector is 2.5 metres away



Orbit Response Matrix (ORM), PAC 1993

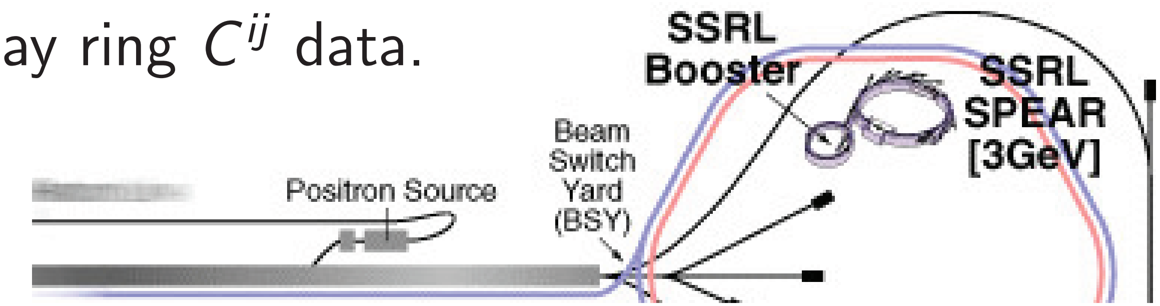
$$C^{ij} = \frac{\Delta x \text{ at BPM i}}{\theta \text{ at corrector j}}$$





$$\frac{\Delta \beta}{\beta} \approx 20\%$$

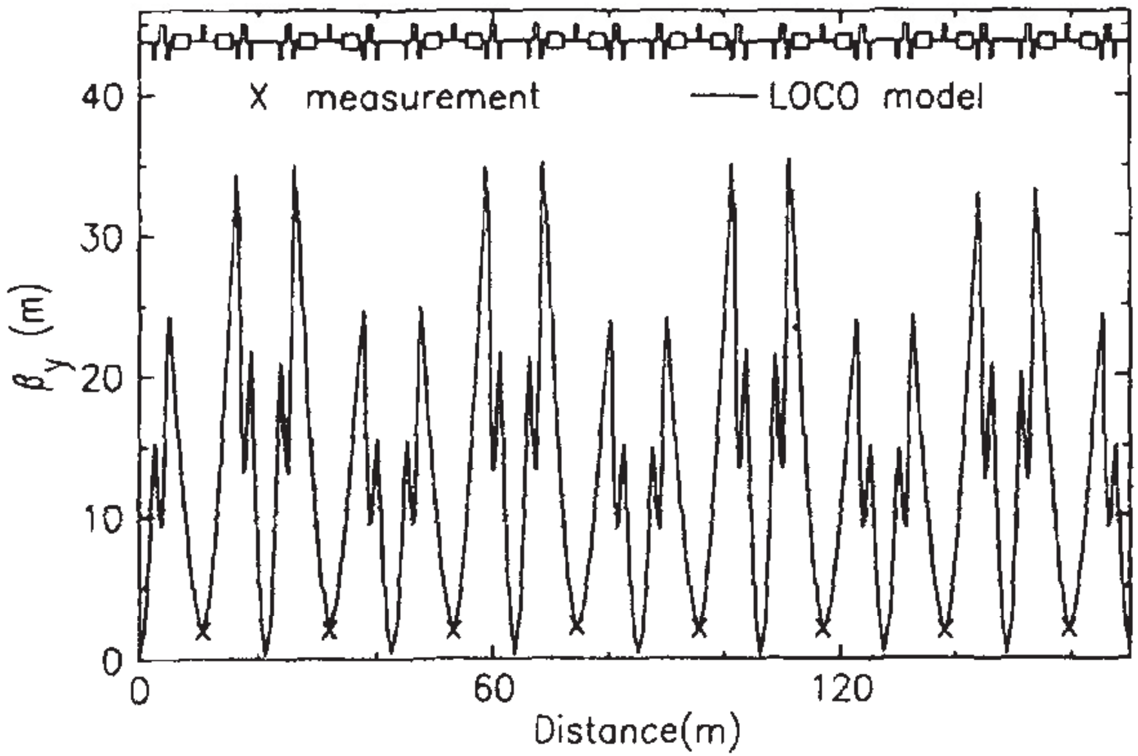
Y. Chung, G. Decker and K. Evans **extract** β and ϕ from NSLS X-Ray ring C^{ij} data.



W.J. Corbett, M.J. Lee and V. Ziemann **fit** a model to reproduce the measured C^{ij} in SPEAR, obtaning: $<1\%$ quad errors and $<10\%$ orbit corrector errors.

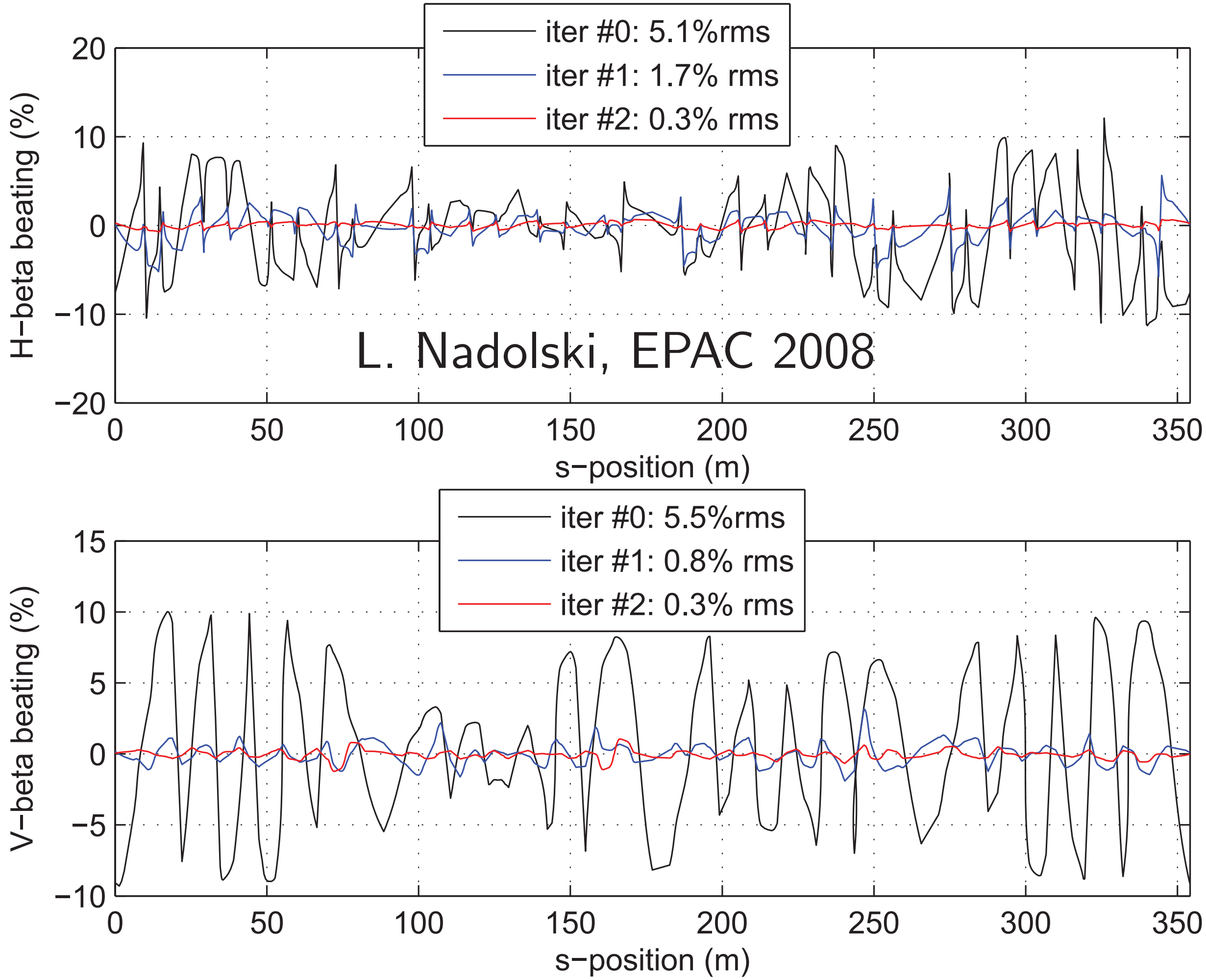
NSLS X-Ray ring, 1996: LOCO

J. Safranek, NIM-A **388**:



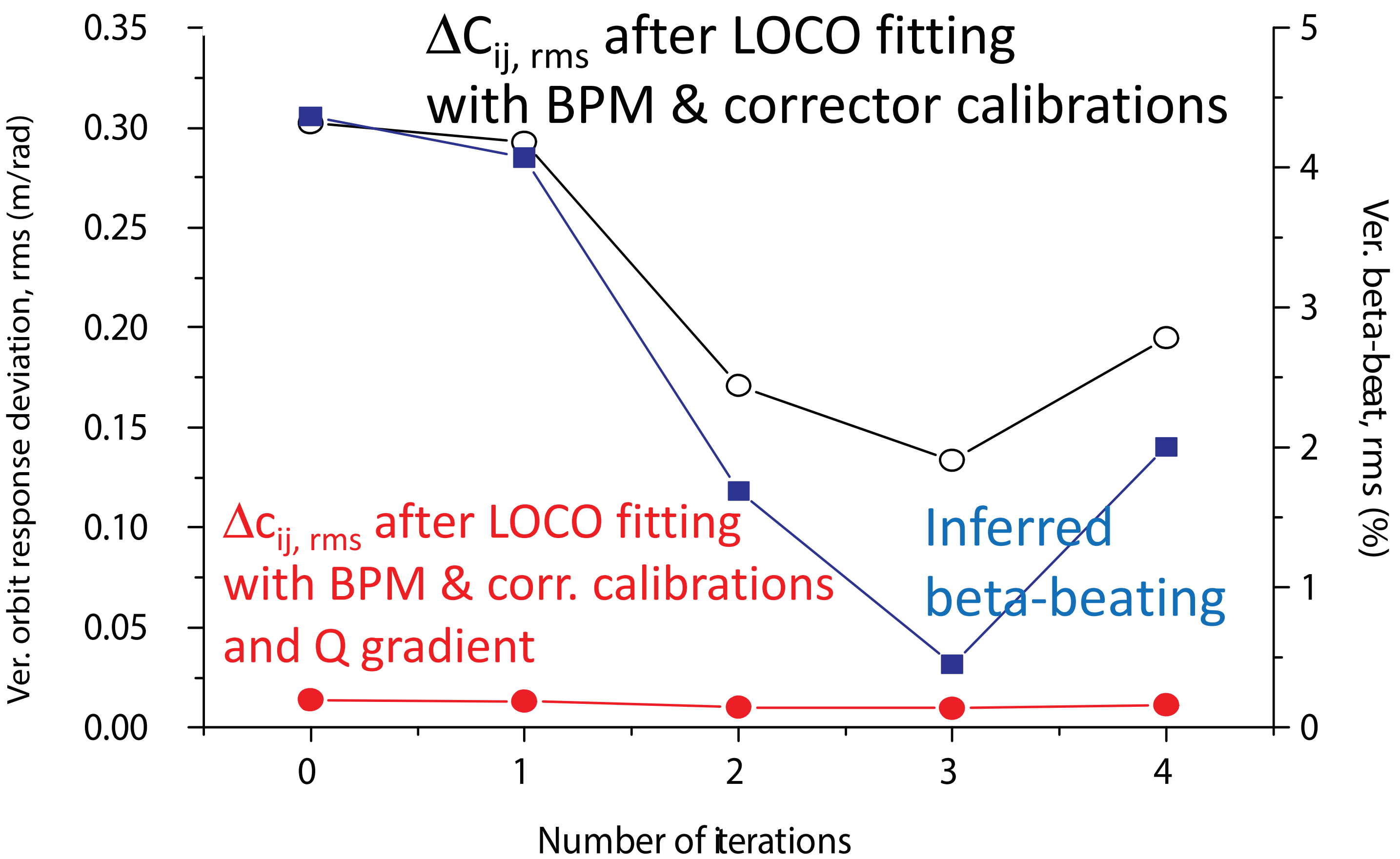
K-modulation measurements in agreement with the model fitted to reproduce C^{ij} using the code LOCO.

SOLEIL, LOCO, 2008



rms $\Delta\beta/\beta_{loco}$=0.3% after 3 iterations

Iterating LOCO in SLS, 2013

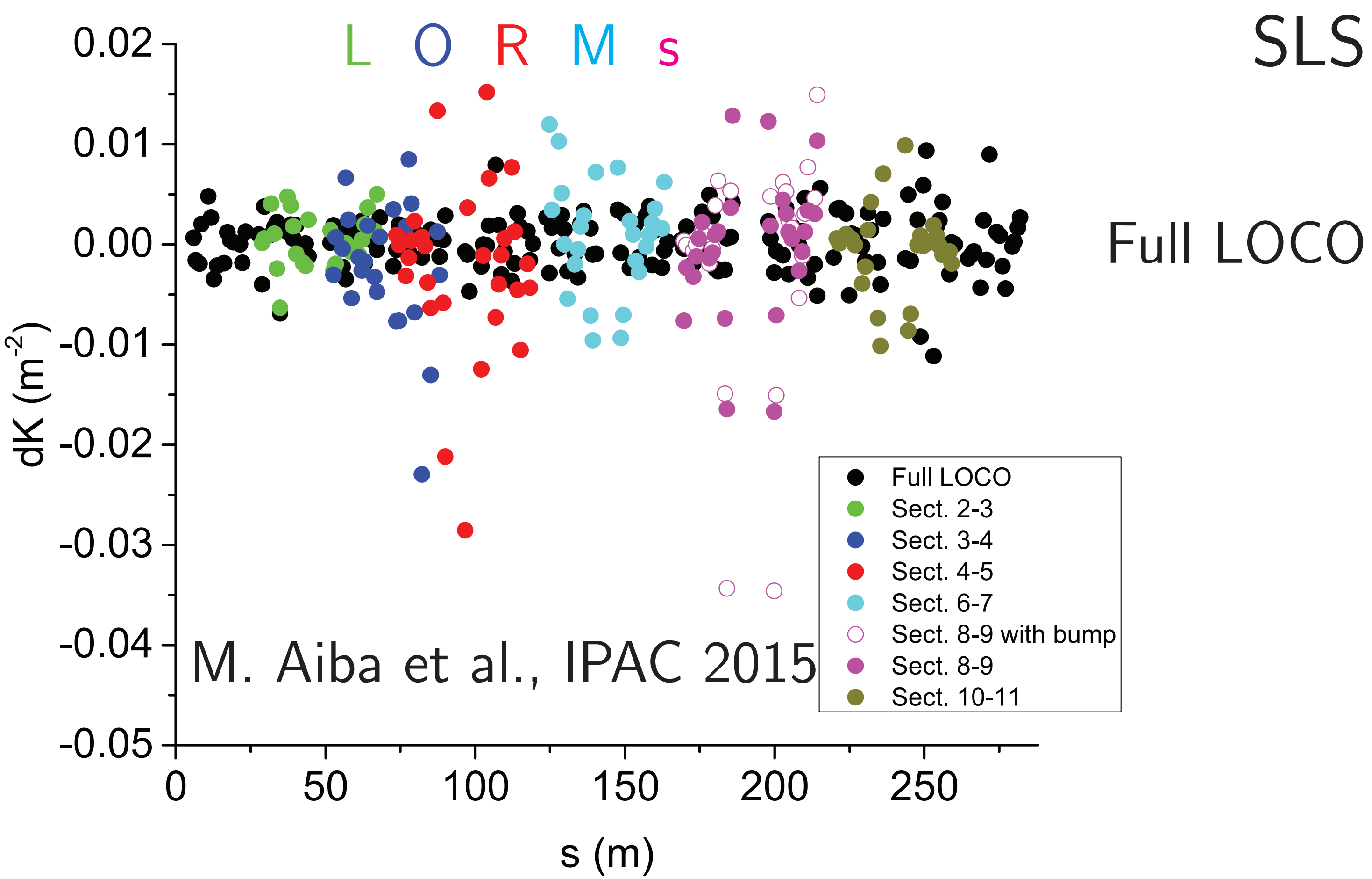


LOCO fitting was successful (ΔC_{ij} ~ Measurement noise)

Lack of convergence (ΔC_{ij} >> ΔC_{ij}), however, indicated existence of systematics

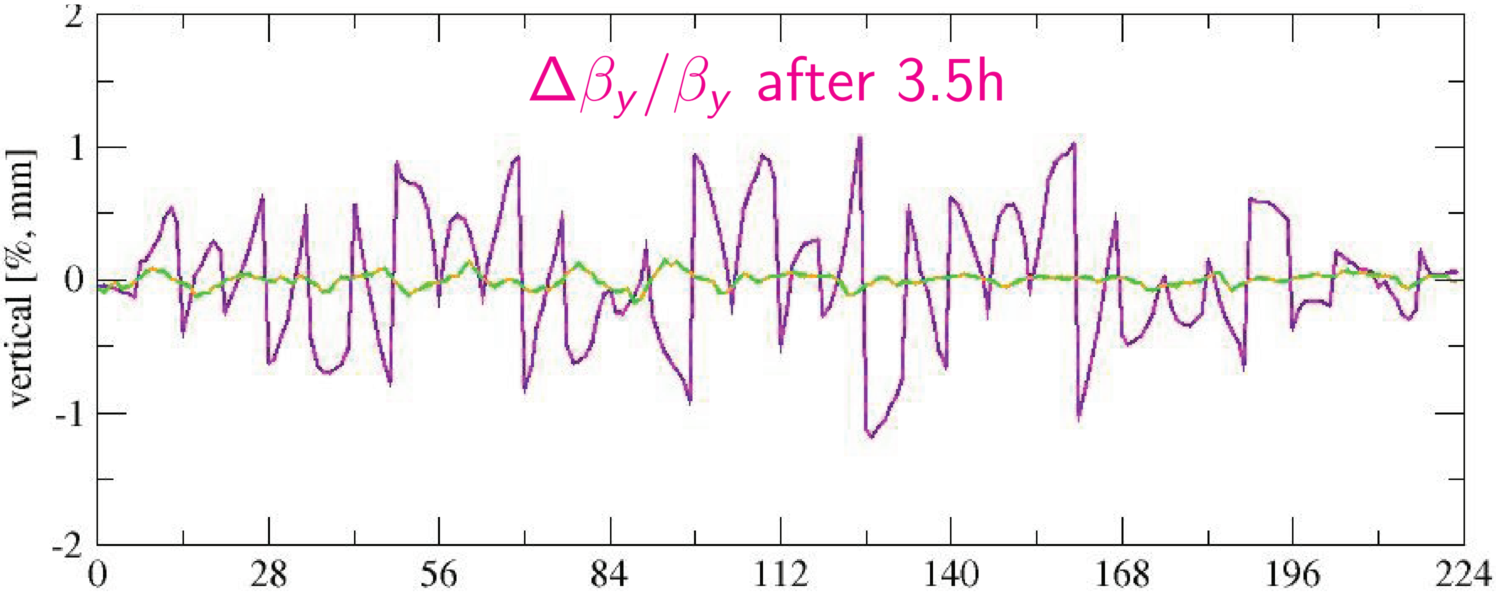
M. Aiba, PRST-AB 2013

Local Orbit Response Matrix (LORM)



LORM is an ORM but keeping orbit unchanged out of selected region → Revealed systematic errors

ESRF optics stability in time (ORM)



1% peak β-beating develops in 3.5h

ALBA: LOCO Vs N-BPM (turn-by-turn)

A. Langner et al, IPAC 2015

Method vs. nominal model	**RMS β-beating (%)**	
	horizontal	vertical
N-BPM (phase)	1.5	2.2
From amplitude	2.0	2.7
LOCO	1.1	1.6

Techniques are consistent at 1% level, but:
is LOCO underestimating $\Delta\beta/\beta$?
is β from amp overestimating it? (due to BPM gain?)

Similar studies in ESRF and NSLS-II:
L. Malina et al., THPMB045
X. Huang et al., IPAC 2015

Techniques for optics measurement & correction

- K-modulation
- Turn-by-turn
- Closed orbit (ORM)
- **Passive corrections**

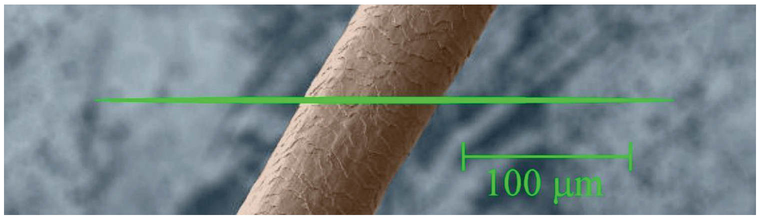
Passive corrections

F. Bulos et al., SLAC-Pub-5488 (1991): "*For future linear colliders (...) with demanding tolerances (...) it becomes increasingly important to use the beam as a diagnostic tool.*"

Few optimization algorithms in operation:

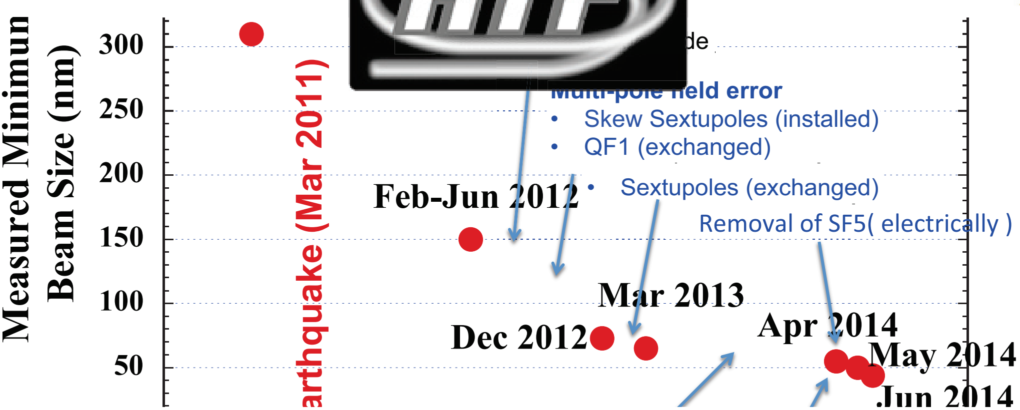
- **Simplex**: KEKB injector linac, KEKB and RHIC luminosities
- **Scan of orthogonal knobs**: SLC, FFTB and ATF2 beam sizes, SPEAR3 and BEPCII lumi
- **Random walk**: SLS emittance

Three world records



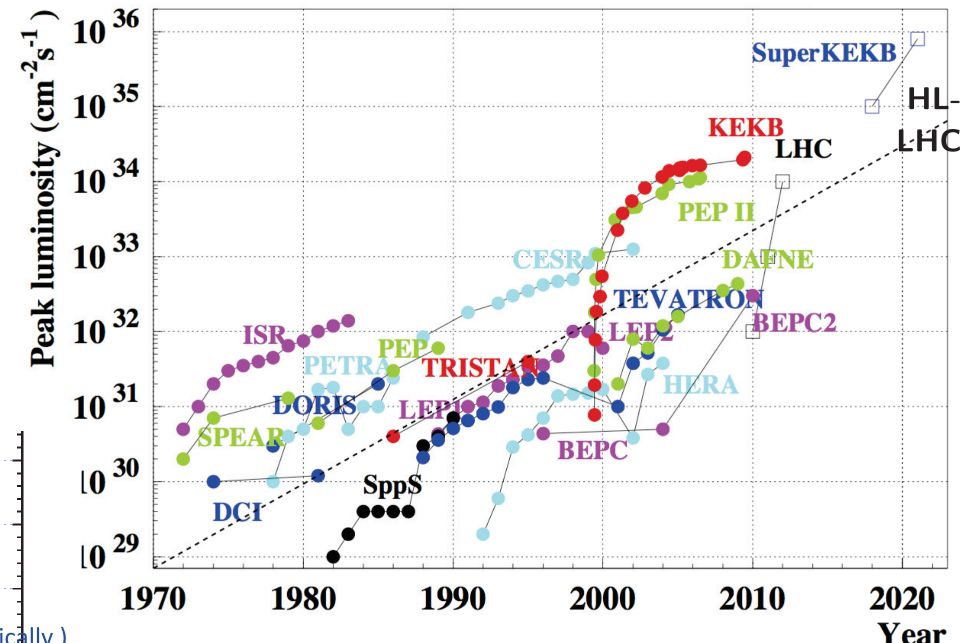
$\epsilon_y = 0.9 \pm 0.4$ pm

via random walk optimization



$\sigma_y = 44 \pm 3$ nm

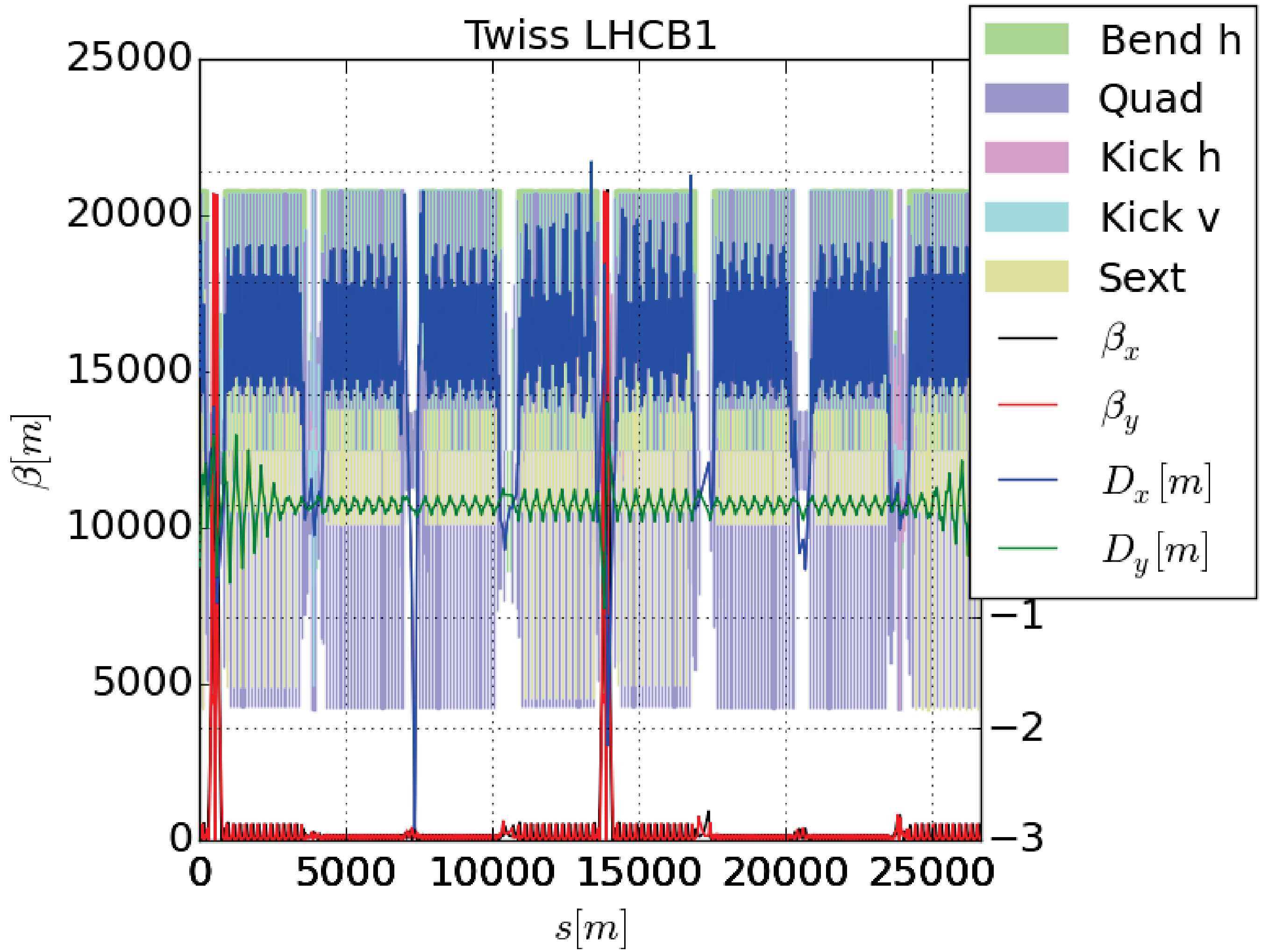
via scanning orthogonal knobs



$L = 2.1 \times 10^{34}$ cm^{-2}s^{-1}

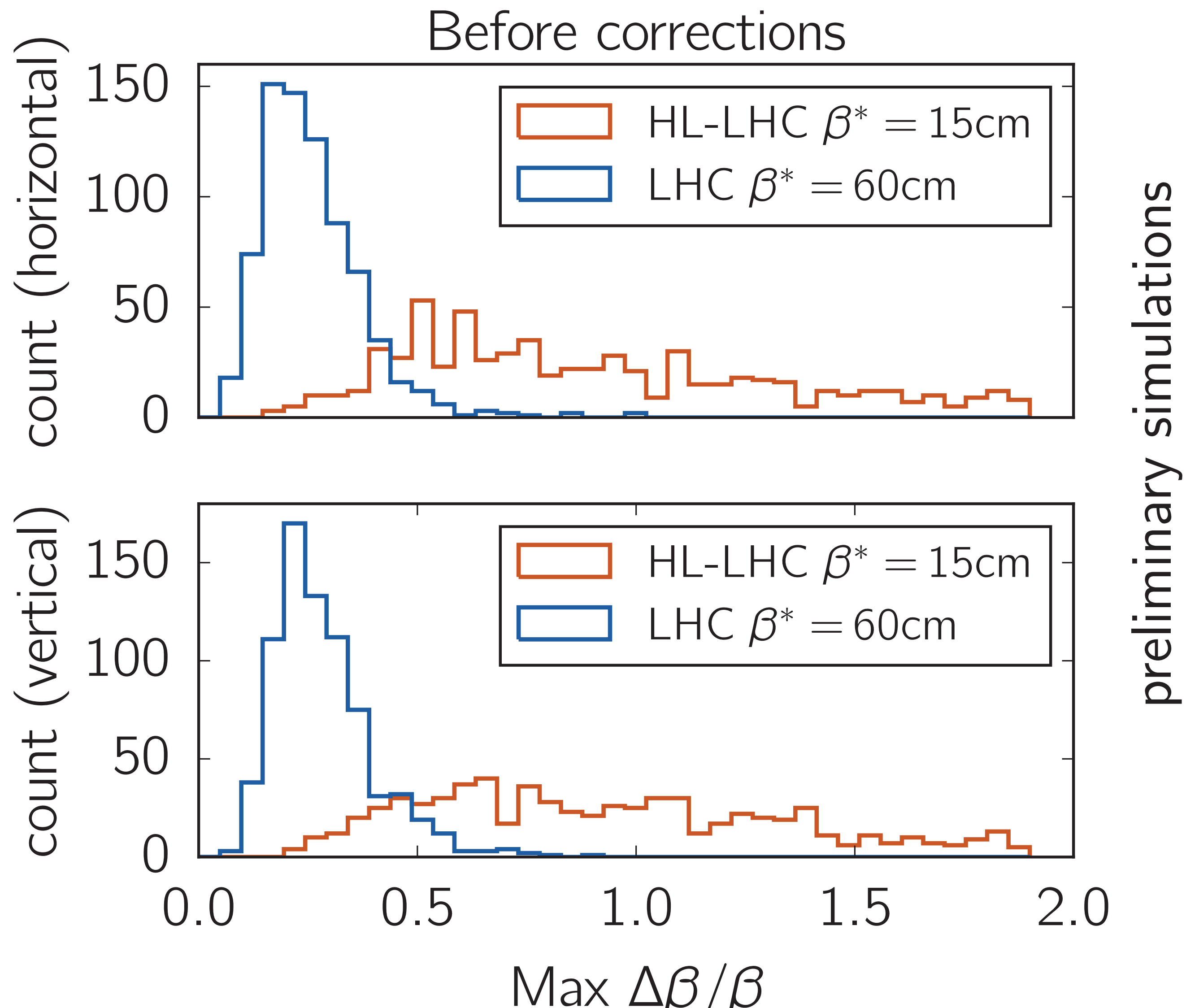
Luminosity optimized via downhill Simplex

The LHC High Luminosity upgrade



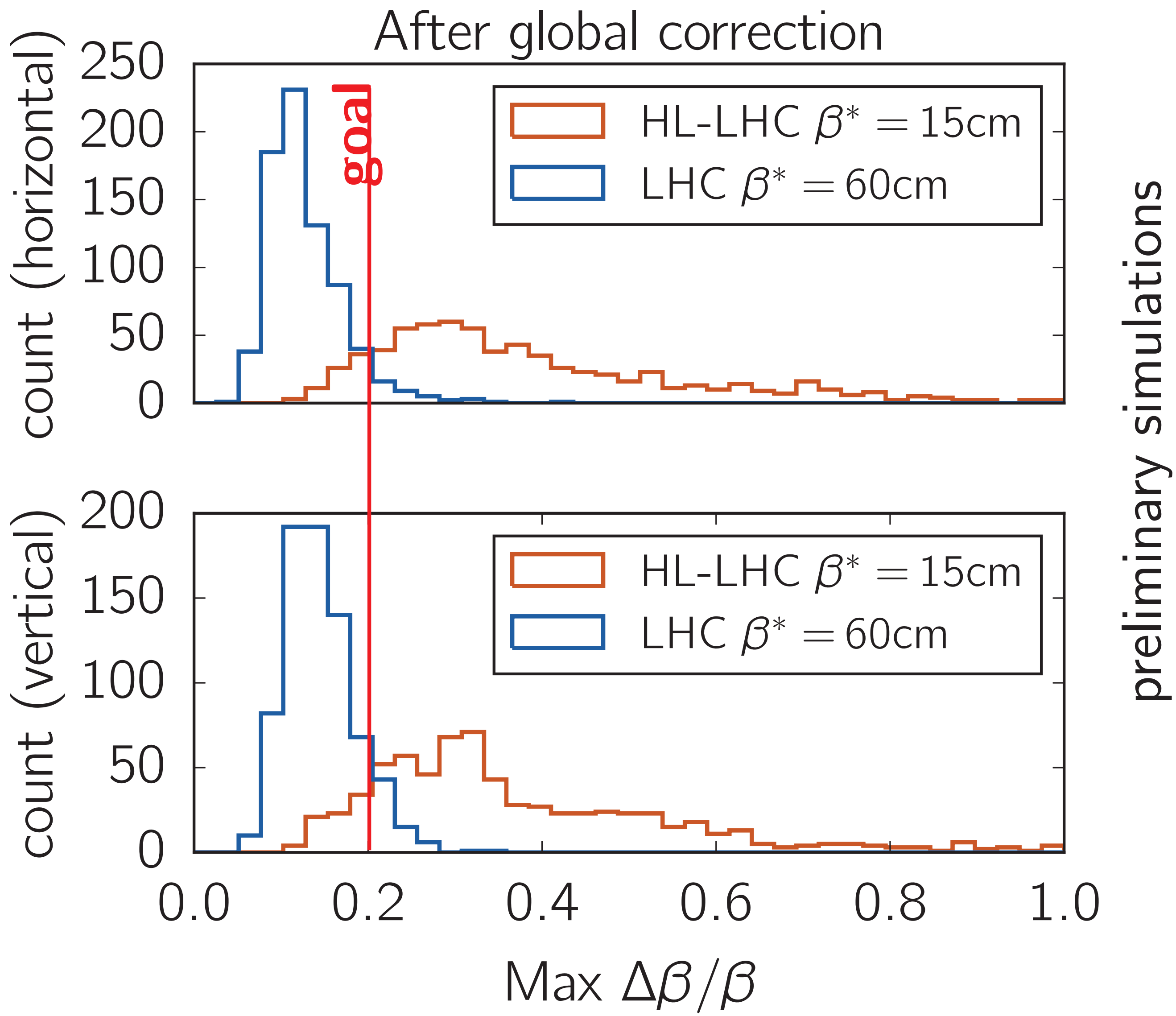
Peak β of 20 km! (today 6 km)

β-beating in HL-LHC before correction



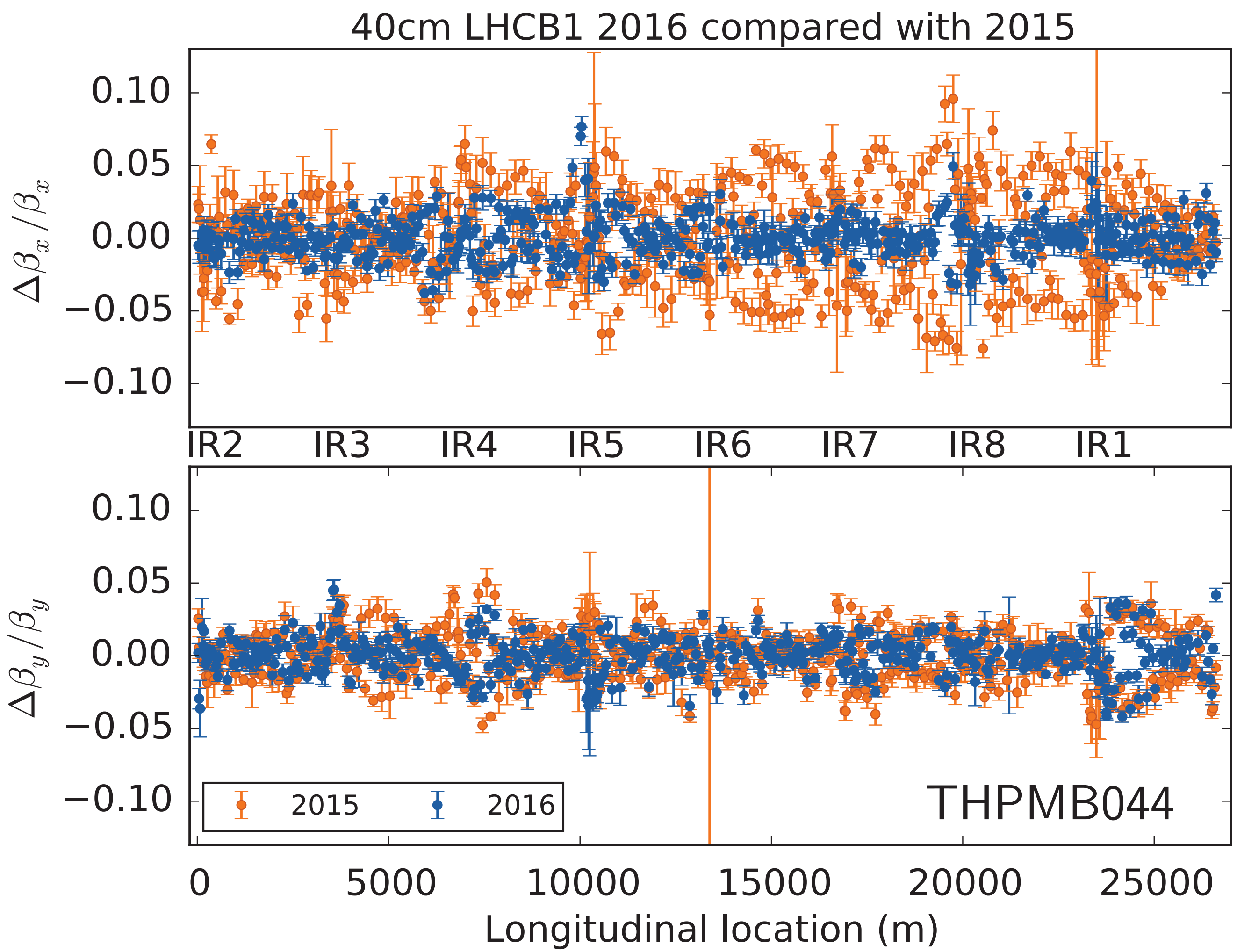
Almost 200% β-beating...

β-beating in HL-LHC after corrections



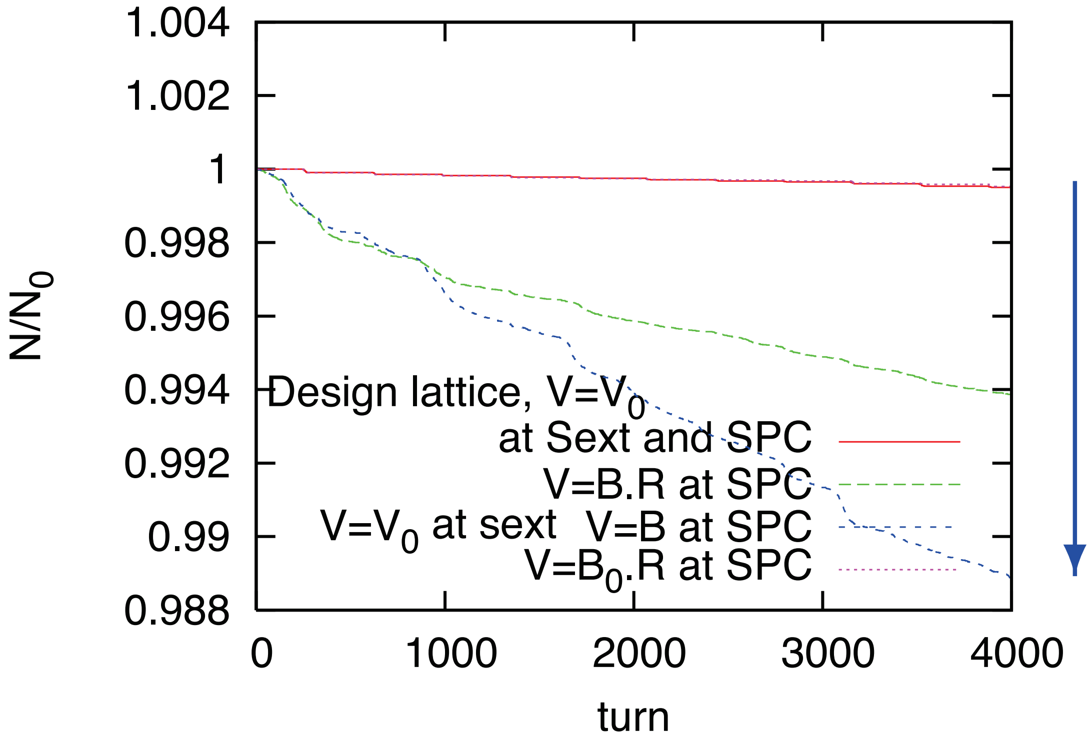
The HL-LHC challenge lies ahead!

LHC few weeks ago



All planes below 2% rms $\Delta\beta/\beta$.

Space charge simulations with measured optics in J-PARC, K. Ohmi et al., IPAC 2013



Beam loss due to introducing measured $\frac{\Delta\beta}{\beta}$=5% in simulations

K. Ohmi et al.: "Estimation of errors of accelerator elements is inevitable to study beam loss."

Summary & Outlook

- The 1-2% β-beating level has been conquered in light sources and large colliders
- Can we measure β functions with an accuracy better than 1%?
- Could optics correction be as fast as orbit correction?
- The challenge lies ahead for HL-LHC, SuperKEKB, MAX IV, ESRF upgrade, etc.
- Should light sources use long and weak AC dipole excitations to avoid decoherence and errors from non-linearities?