β-beating

Focusing on techniques using turn-by-turn BPM data

R. Tomás

Thanks to M. Aiba, M. Carlá, A. Franchi, A. Garcia, U. Iriso, A. Langner, E. Maclean, L. Malina, T. Persson and P. Skowronski

Beam dynamics meets diagnostics 2015

November 4, 2015

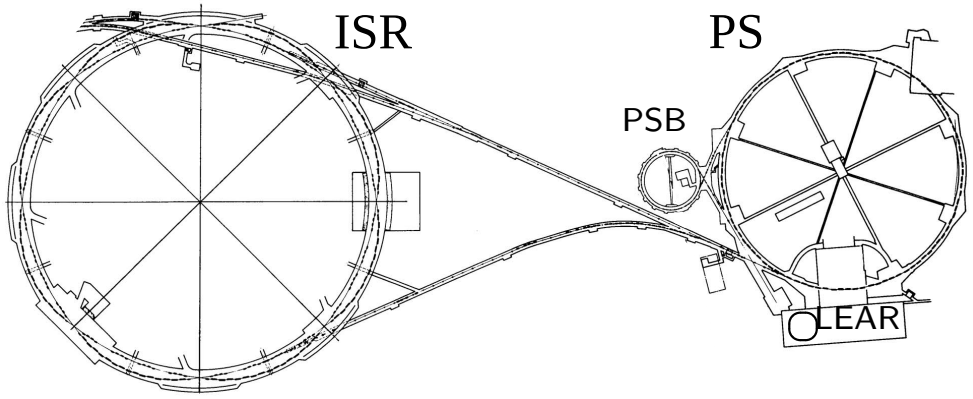
Contents

- ★ Techniques and historical overview
- ★ Hadron accelerators and colliders
- ★ HL-LHC challenge
- ★ Light sources

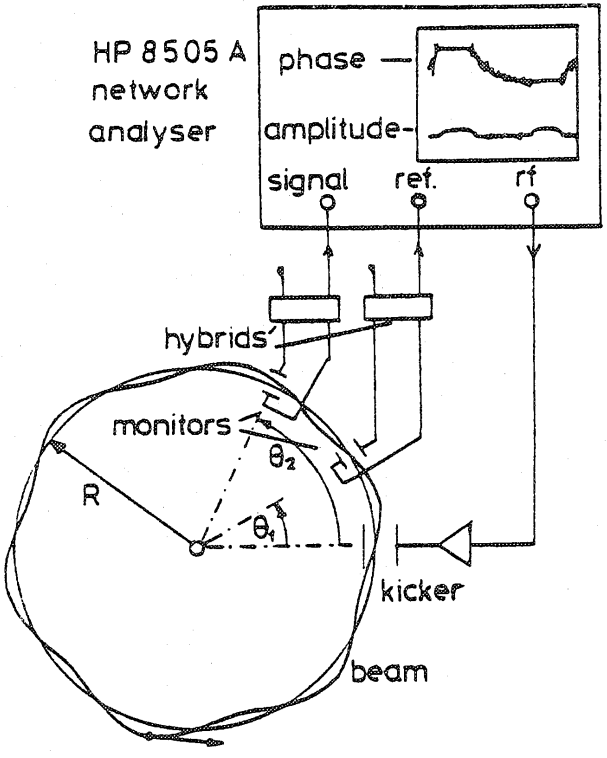
Overview of optics measurements

		Observable	Analysis	Parameter	Depends on
Excitation	Betatron oscillation, free or forced + RF freq + RF phase	centroid position T-b-T	Fit, FT, SVD	ϕ	-
				β from ϕ	M
				β from ampl.	C & M
				Action	C & M
				Coupling	C
				$D_x/\sqrt{\beta_x}$	M
				Chrom. coupling	-
				Q'	-
	Orbit correctors	Orbit	ϕ, β fit	ϕ, β	C
			Model fit	any parameter	C & M
			Fit	Arc Action	C & M
	Quadrupole gradient	Tune	Fit	$\langle\beta\rangle$	C
				$\Delta Q_{\min}$	-
Passive		Beam size	Optimizers	Coupling	-
		Loss rate			-
		Luminosity		Int. luminosity	-
		Lifetime		IP beam size	-
		Schottky noise		Q, Q'	

ISR 1983



t.



Set-up for phase and amplitude m

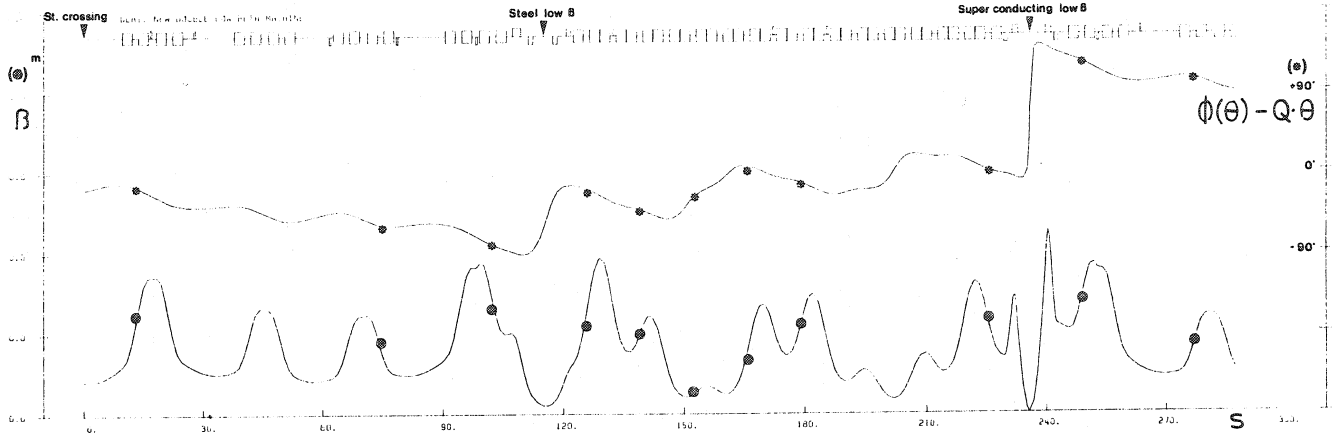


Fig. 3 Vertical betatron phase advance $\phi(\theta)$ relative to $Q\theta$ and beta function $\beta(\theta)$ of approximately one quadrant of the ISR. The lines give the AGS calculations and the points are the measurements.

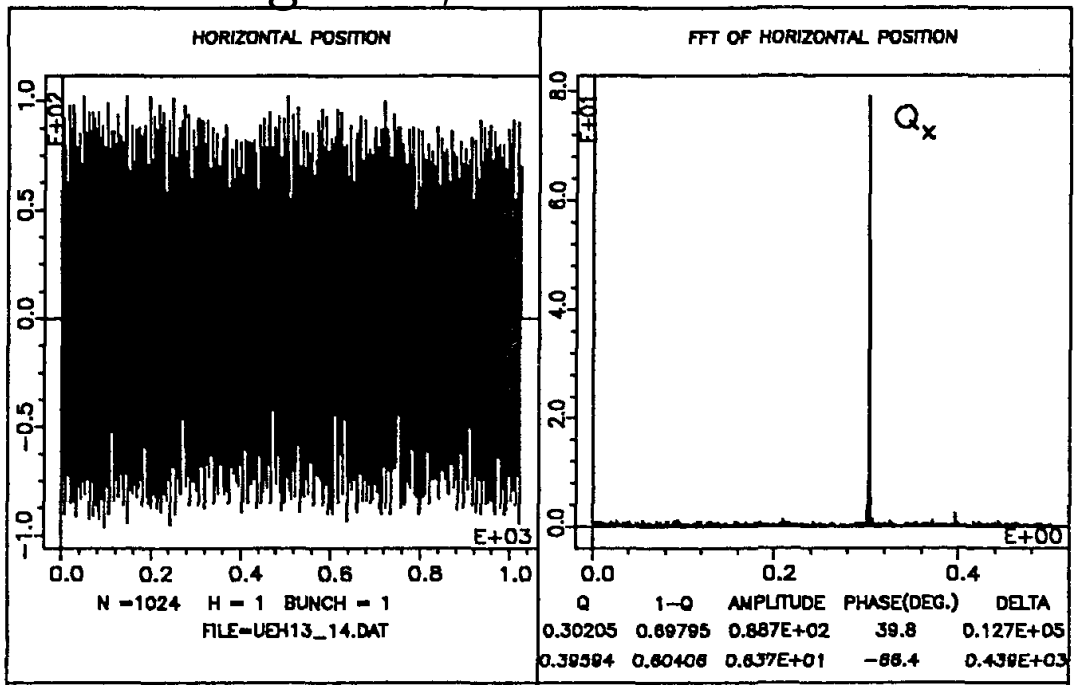
β computed from oscillation amplitude

J. Borer, A. Hofmann, J-P. Koutchouck et al

CERN/LEP/ISR/83-12

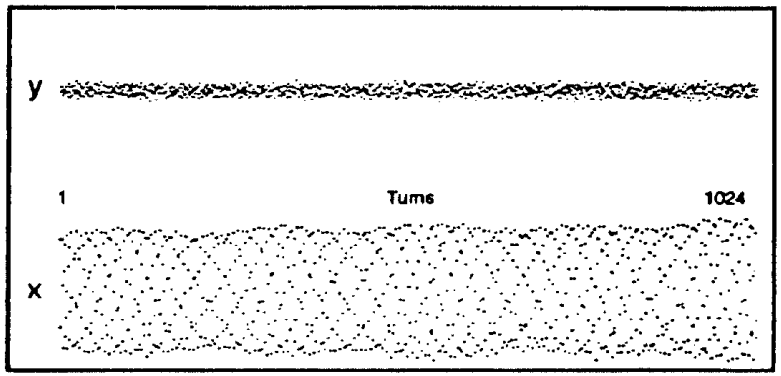
LEAR 1988

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

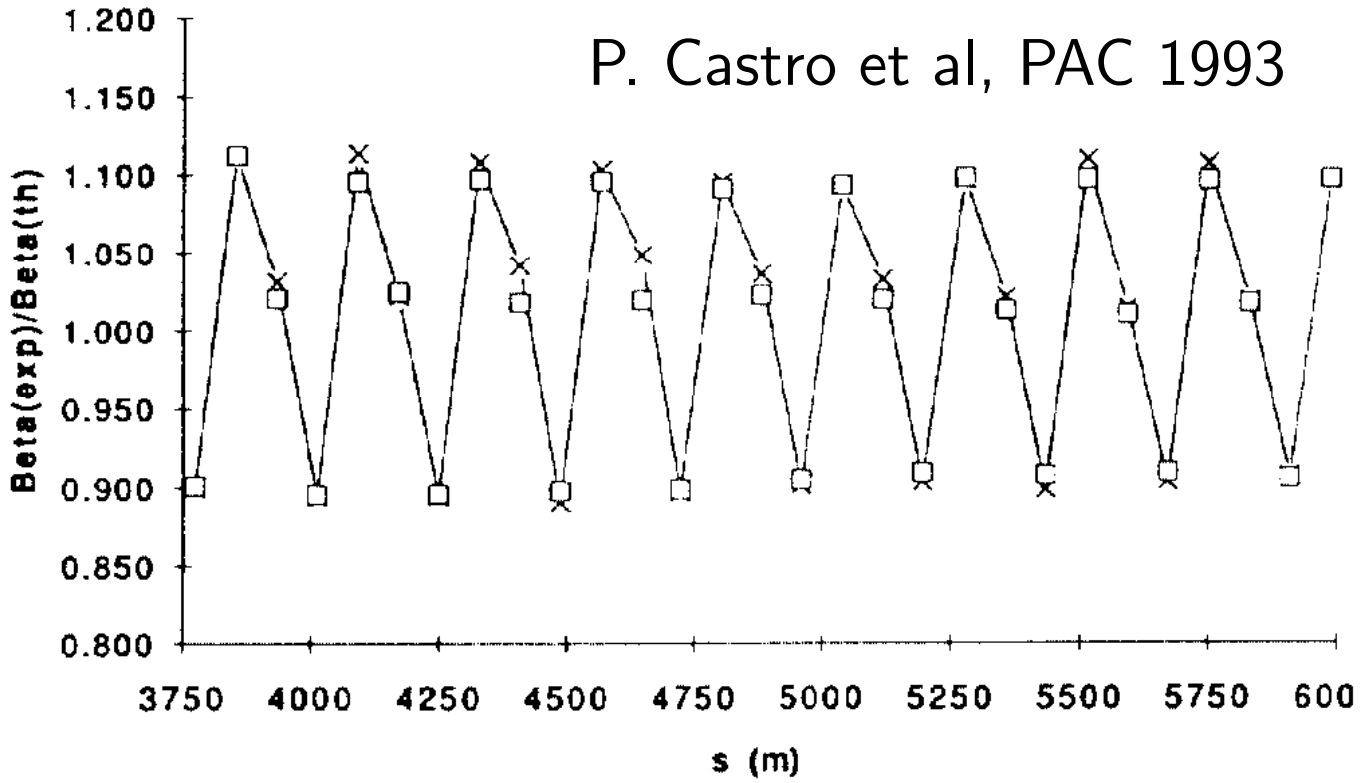


$$\beta_{1(exp)} = \beta_{1(theo)} \frac{\cot \Psi_{12(exp)} - \cot \Psi_{13(exp)}}{\cot \Psi_{12(theo)} - \cot \Psi_{13(theo)}} \quad (10)$$

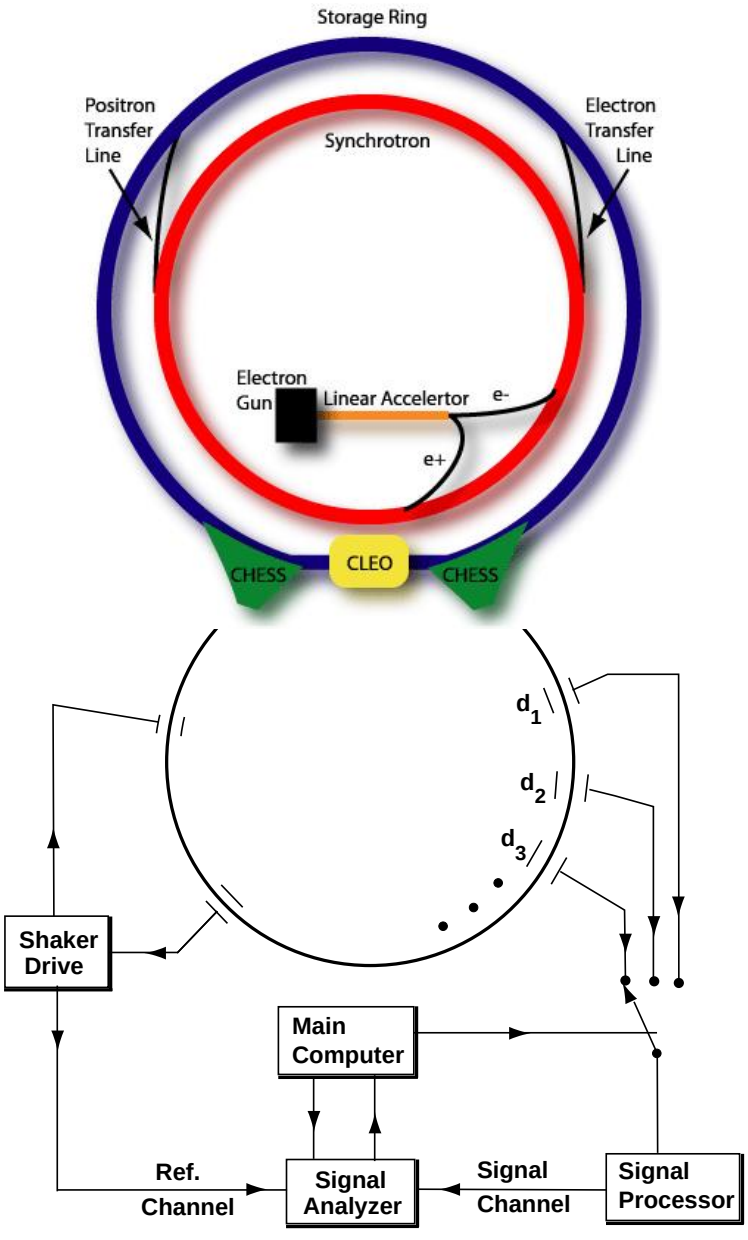
β from ϕ, 3-BPM method, model dep.

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

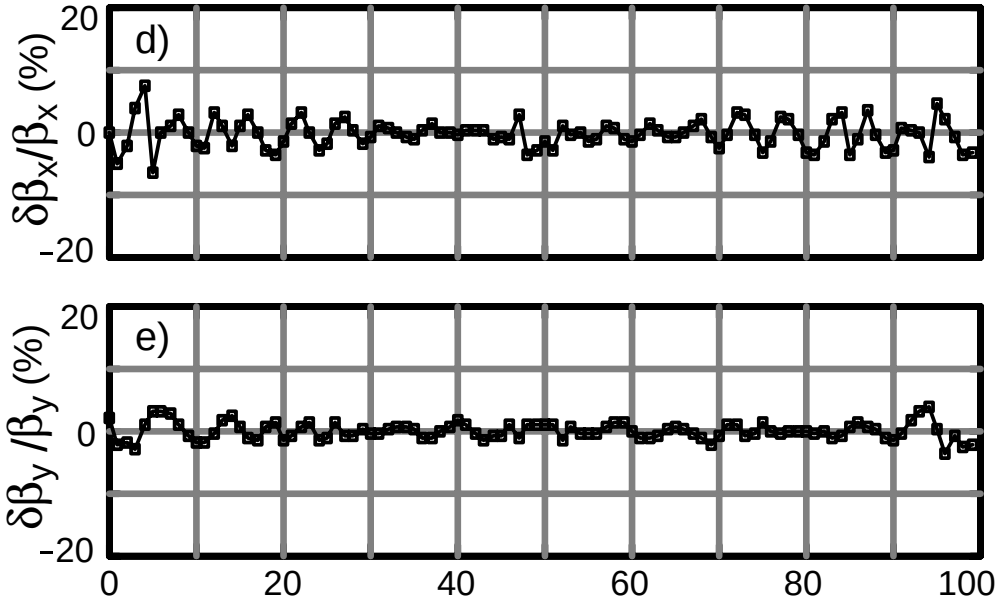
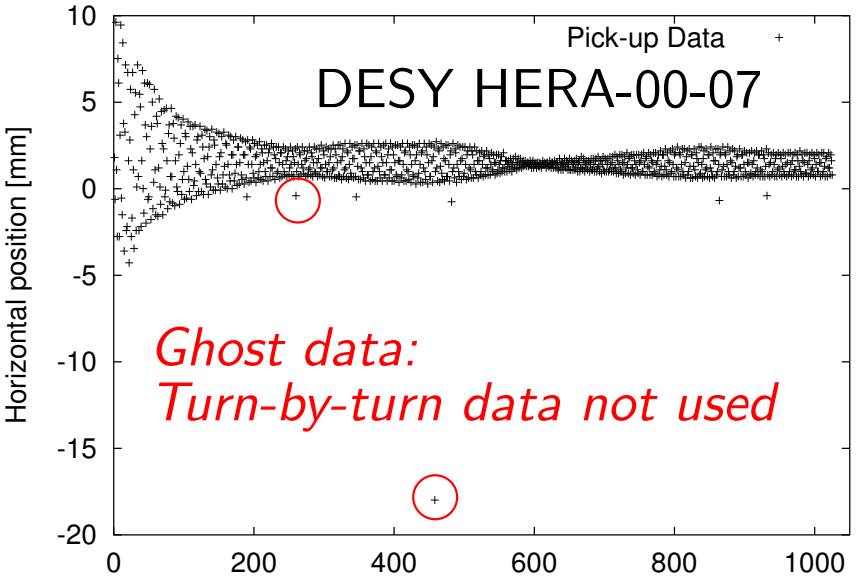
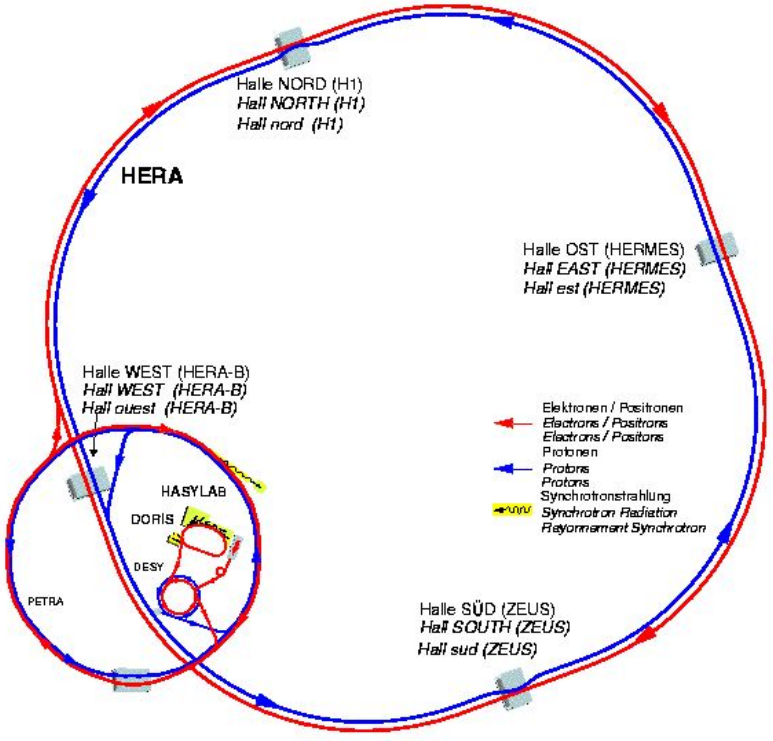


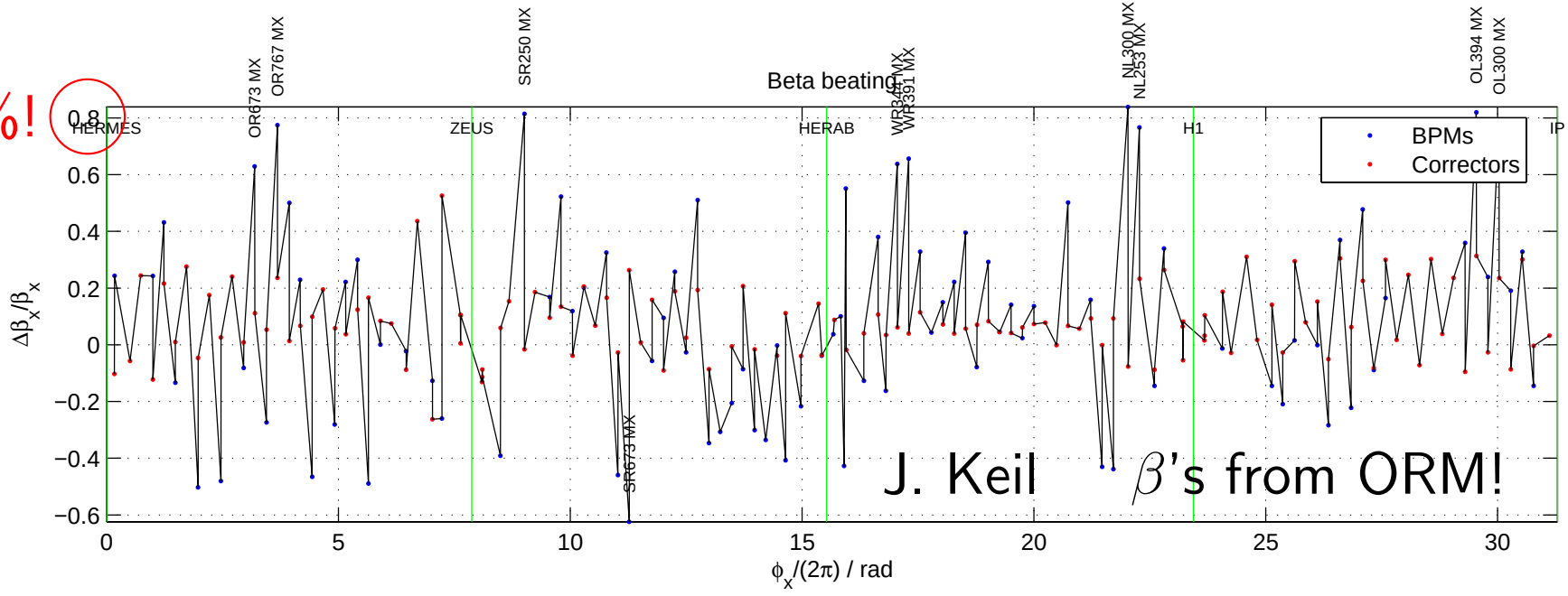
FIG. 6. Measurement after correcting the phase and coupling

HERA-p

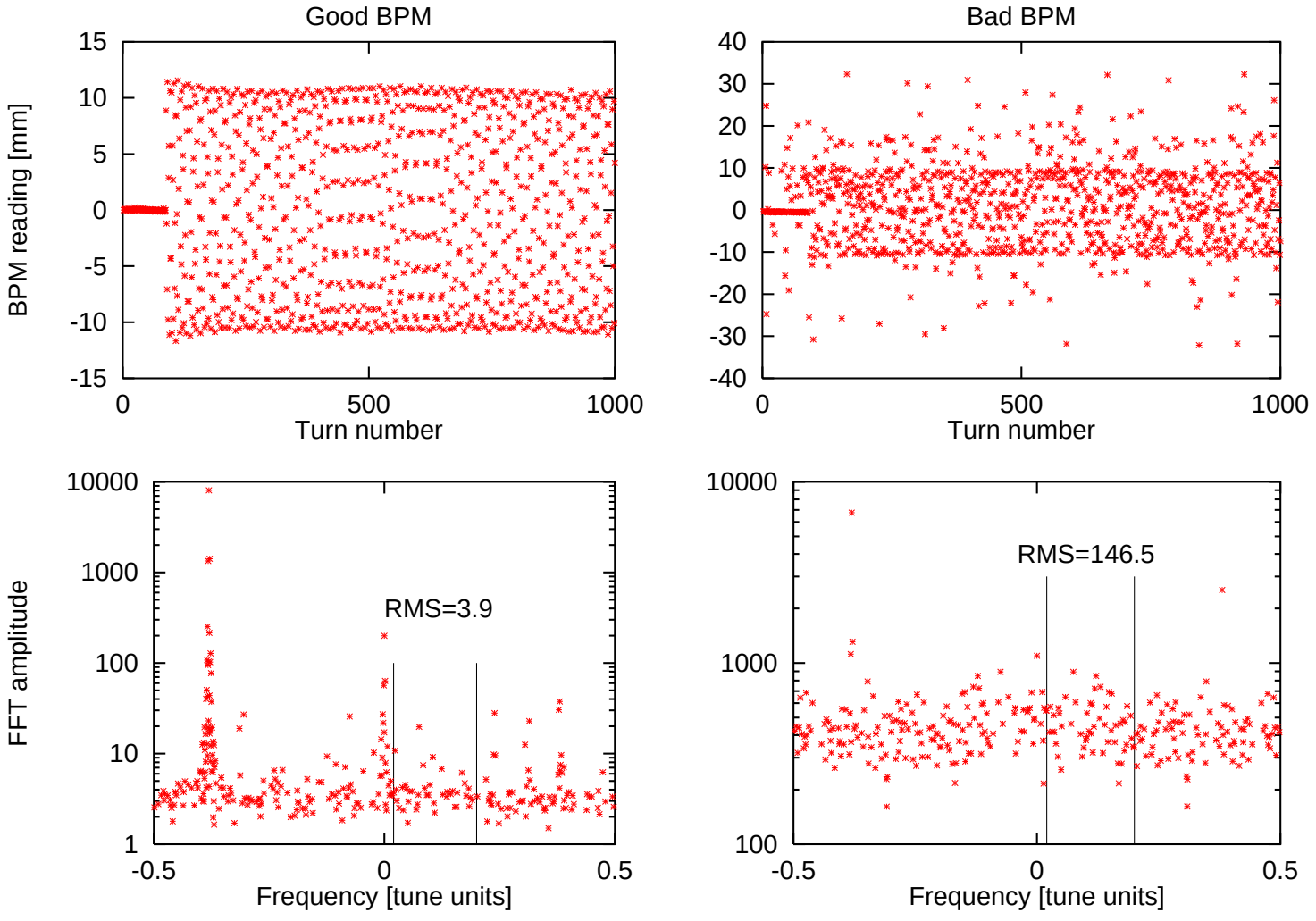

Pick-up Data
DESY HERA-00-07
Horizontal position [mm]
Ghost data:
Turn-by-turn data not used


Halle NORD (H1)
Hall NORTH (H1)
Hall nord (H1)
HERA
Halle OST (HERMES)
Hall EAST (HERMES)
Hall est (HERMES)
Halle WEST (HERA-B)
Hall WEST (HERA-B)
Hall ouest (HERA-B)
HASYLAB
DORIS
DESY
PETRA
Halle SÜD (ZEUS)
Hall SOUTH (ZEUS)
Hall sud (ZEUS)
Elektronen / Positronen
Electrons / Positrons
Electrons / Positrons
Protonen
Protons
Protons
Synchrotronstrahlung
Synchrotron Radiation
Rayonnement Synchrotron

80%!


Beta beating
HERMES
ZEUS
HERAB
H1
IP
OR673 MX
OR767 MX
SR250 MX
SR673 MX
WR347 MX
WR391 MX
NL300 MX
NL253 MX
OL394 MX
OL300 MX
BPMs
Correctors
$\Delta\beta_x/\beta_x$
$\phi_x/(2\pi)$ / rad
J. Keil
β's from ORM!

SPS BPM signals in 2000

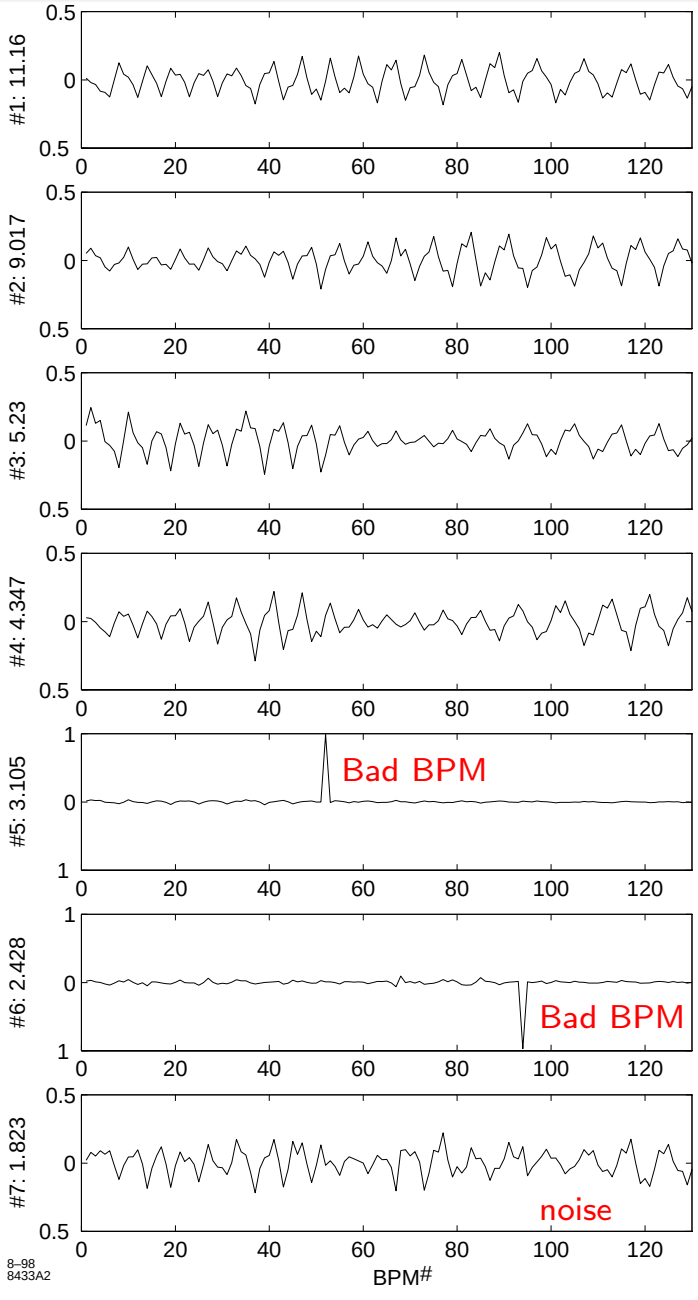


R. Tomas, CERN-THESIS-2003-010

BPM synchronization issues required bad BPM detection.

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

Cleaning with SVD, 1999



$$B_{\substack{t-b-t \\ bpm \\ matrix}} = USV^T$$

Bad BPMs easily identified as uncorrelated signals.

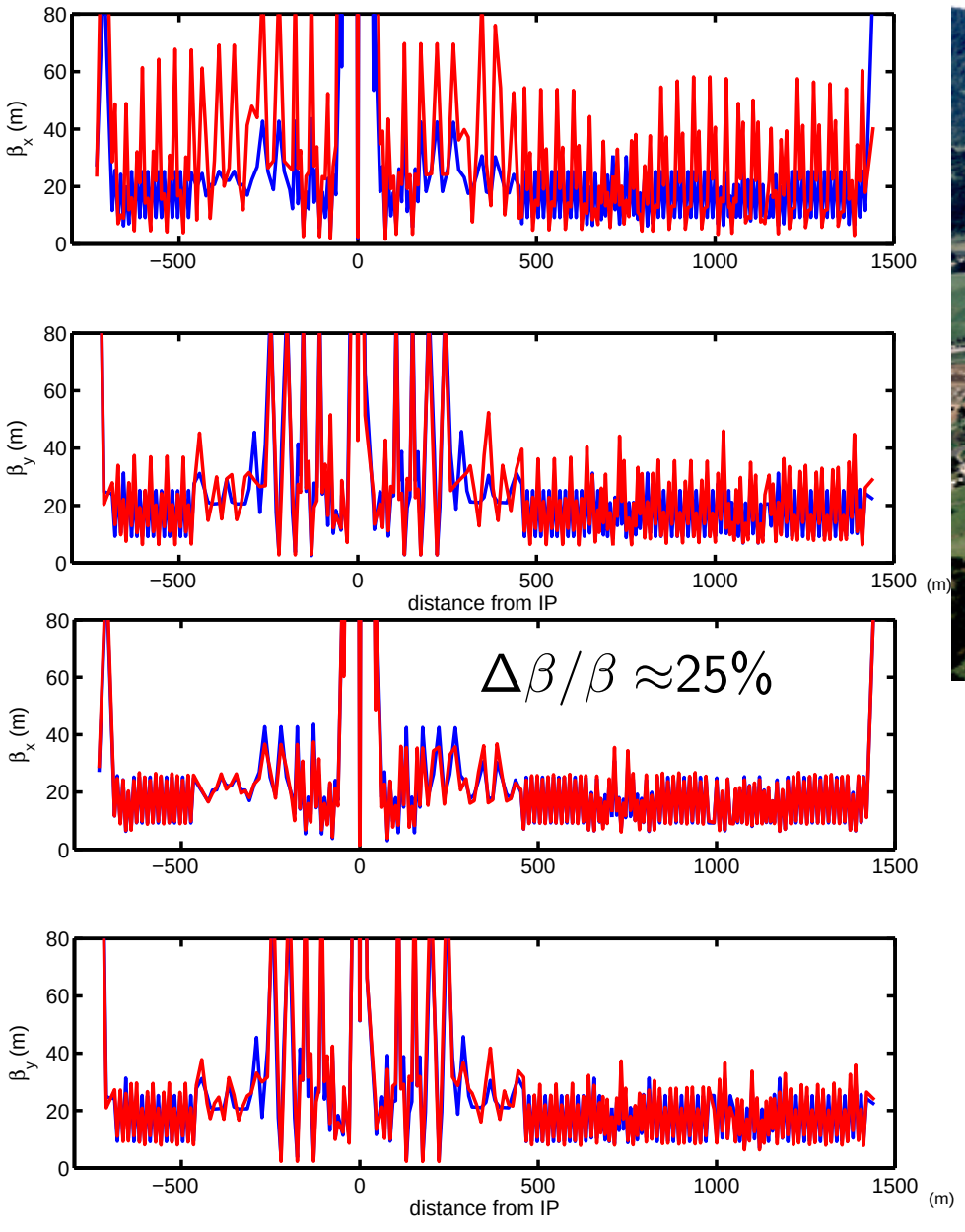
Noise removed by cutting low singular values

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

PEP-II, from ϕ to virtual model to β

before corrections

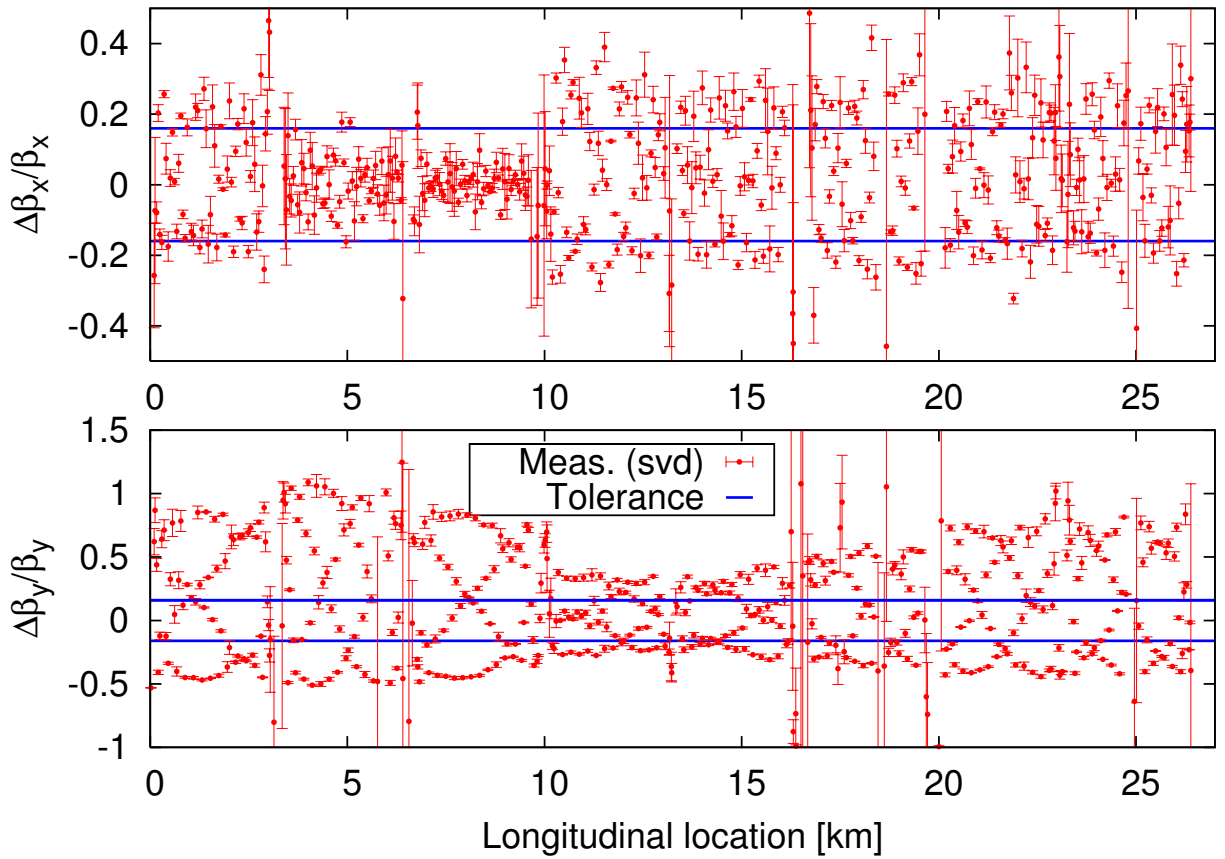
after corrections



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

LHC 1st measurement (inj, 90 turns), 2008

M. Aiba et al, PRSTAB 12, 081002 (2009)



β from ϕ, 3-BPM method

100% β-beating!!

Single error identified with segment-by-segment technique

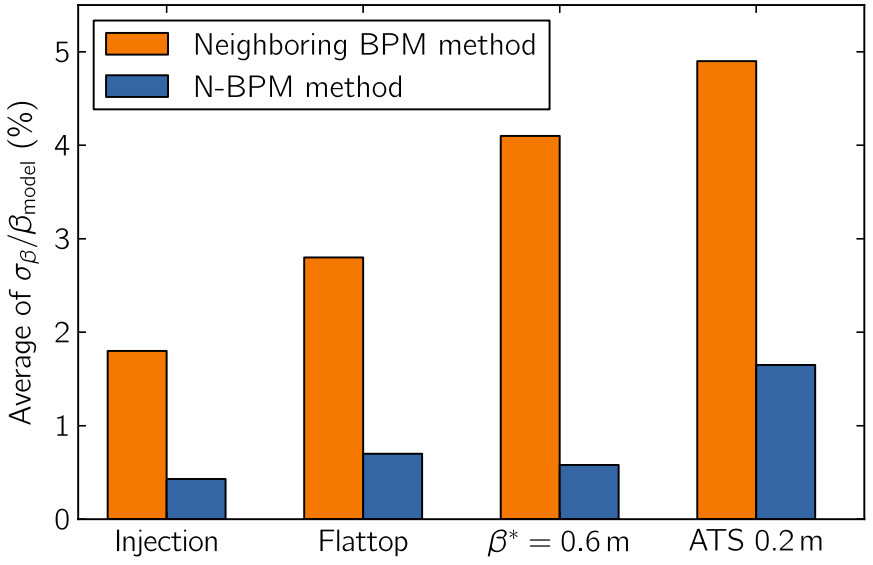
AC dipole

- 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

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 $\pi/4$.

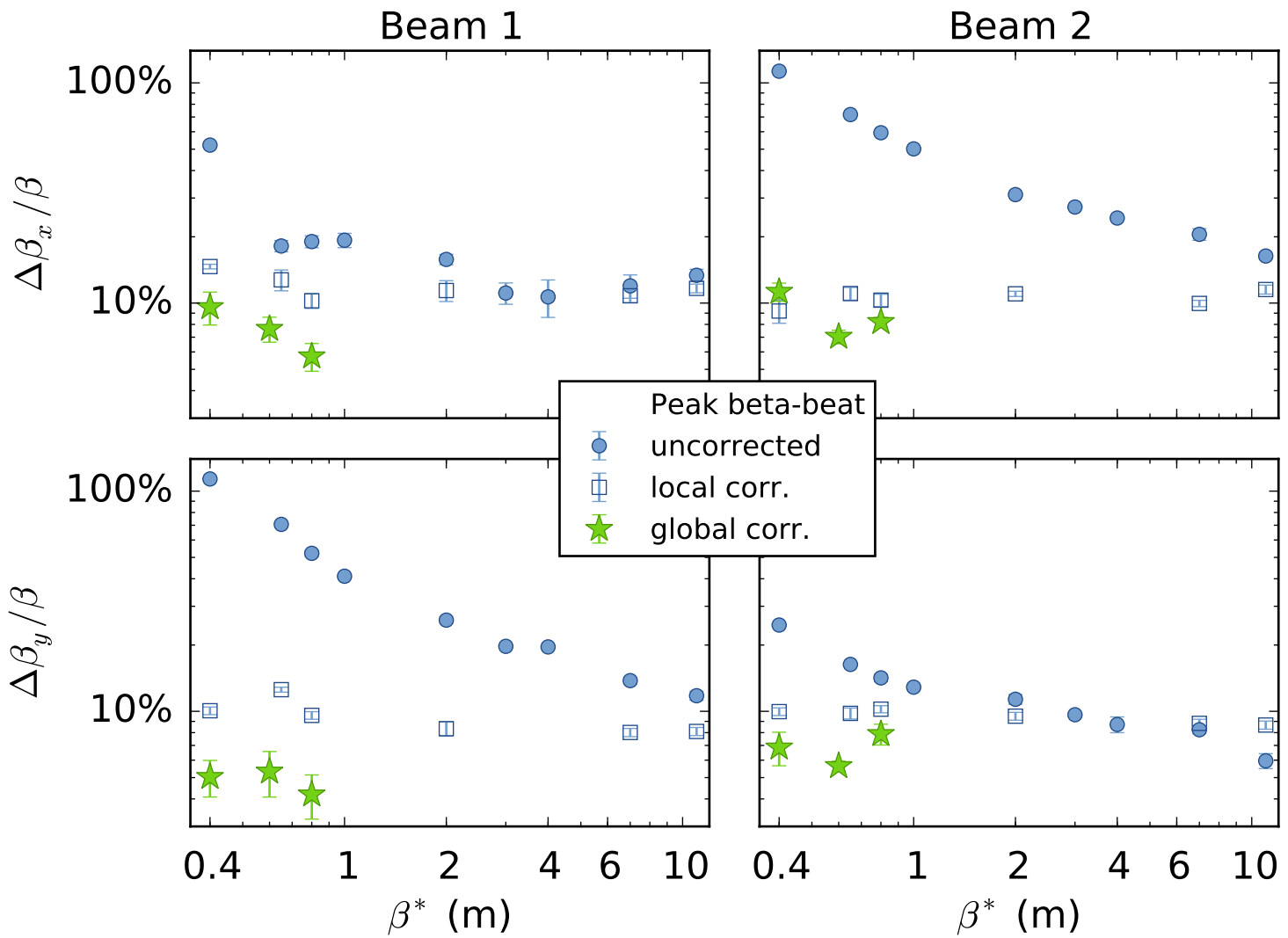
BPM combination	Systematic error (%)
▲: probed, ▲: used, ▲: unused	
▲▲▲▲▲	0.3
▲▲▲▲▲	0.4
▲▲▲▲▲	1.0
▲▲▲▲▲	7.1
▲▲▲▲▲▲▲	1.1
▲▲▲▲▲▲▲	1.4
▲▲▲▲▲▲▲	1.7
▲▲▲▲▲▲▲	1.8
▲▲▲▲▲▲▲	7.9
▲▲▲▲▲▲▲▲▲▲	22.3
▲▲▲▲▲▲▲▲▲▲	1.3
▲▲▲▲▲▲▲▲▲▲	1.9
▲▲▲▲▲▲▲▲▲▲	6.1
▲▲▲▲▲▲▲▲▲▲	1.0
▲▲▲▲▲▲▲▲▲▲	3.0
▲▲▲▲▲▲▲▲▲▲	4.5
▲▲▲▲▲▲▲▲▲▲	5.2
▲▲▲▲▲▲▲▲▲▲	1.6



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)

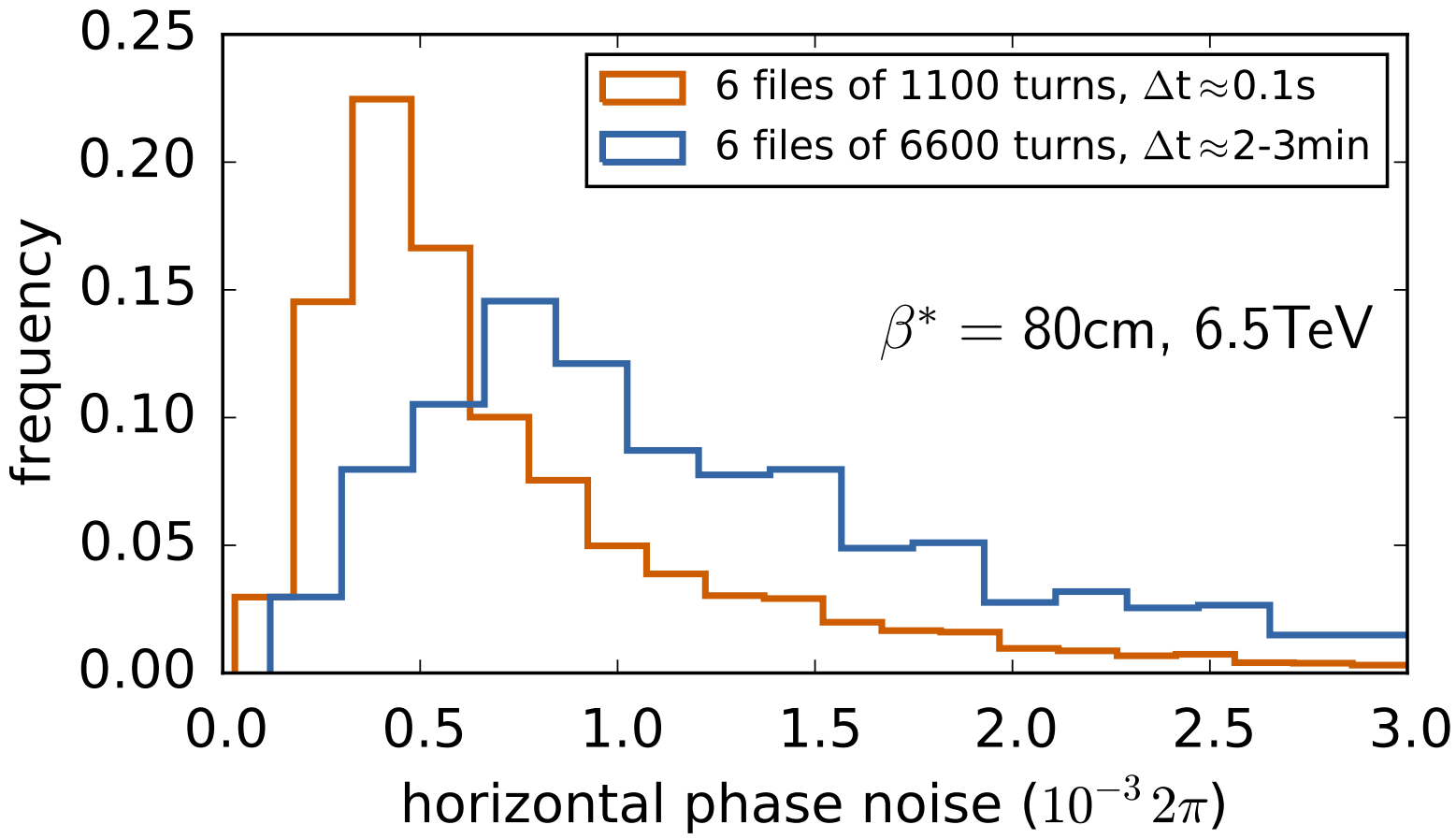
2015 LHC Optics commissioning



Beam 2 corrections not optimal for time constraints

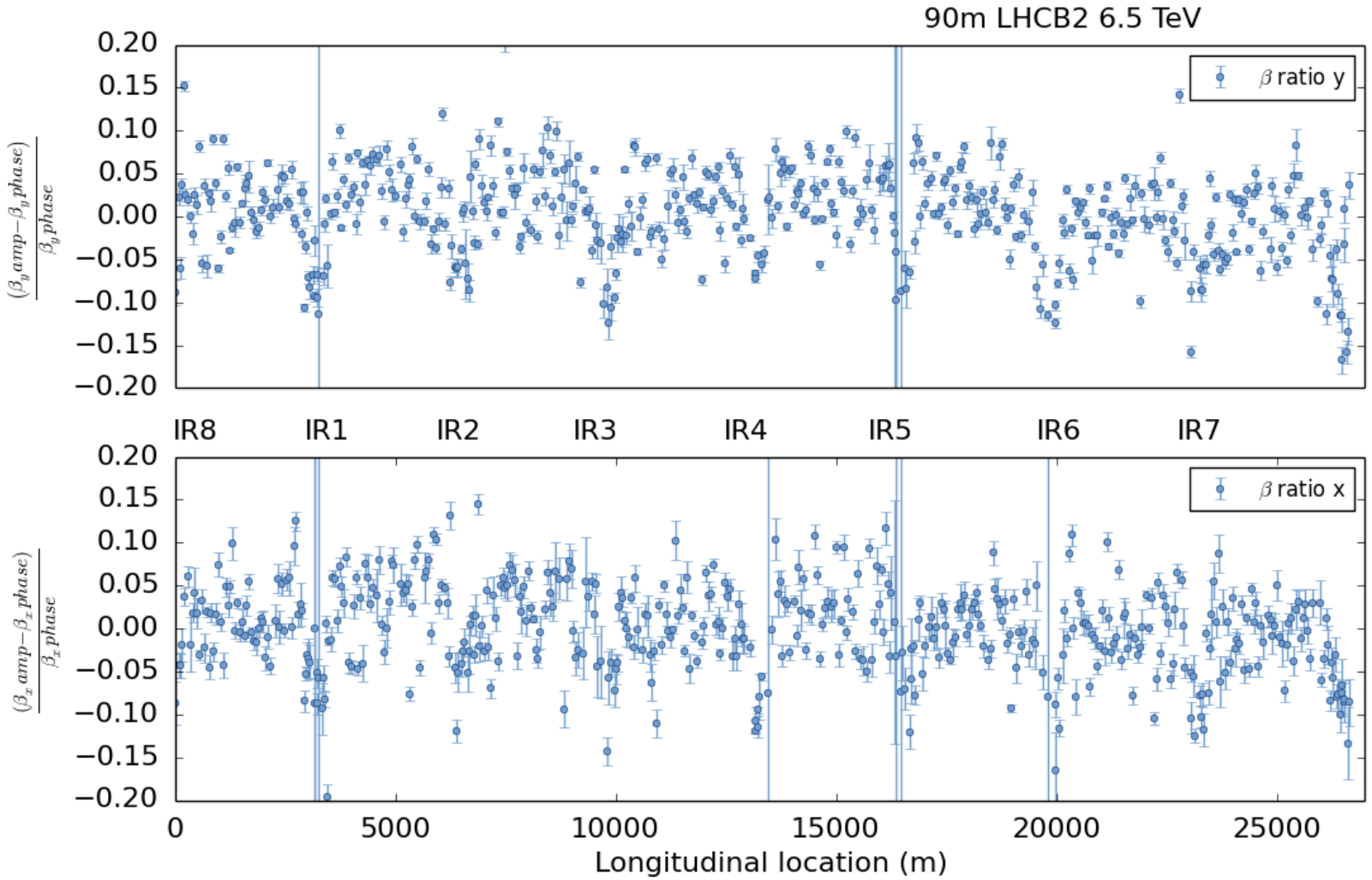
100% peak β-beating again at β^* =40 cm.
After corr rms β-beating 2-3%

LHC changing in time scale of minutes



BPM phase advance seems to jitter in the $\approx 3 \times 10^{-4} 2\pi$ ($\Delta\beta/\beta_{jitter} \approx 0.3\%$) level in minutes $\rightarrow$ 4 times larger in HL-LHC?

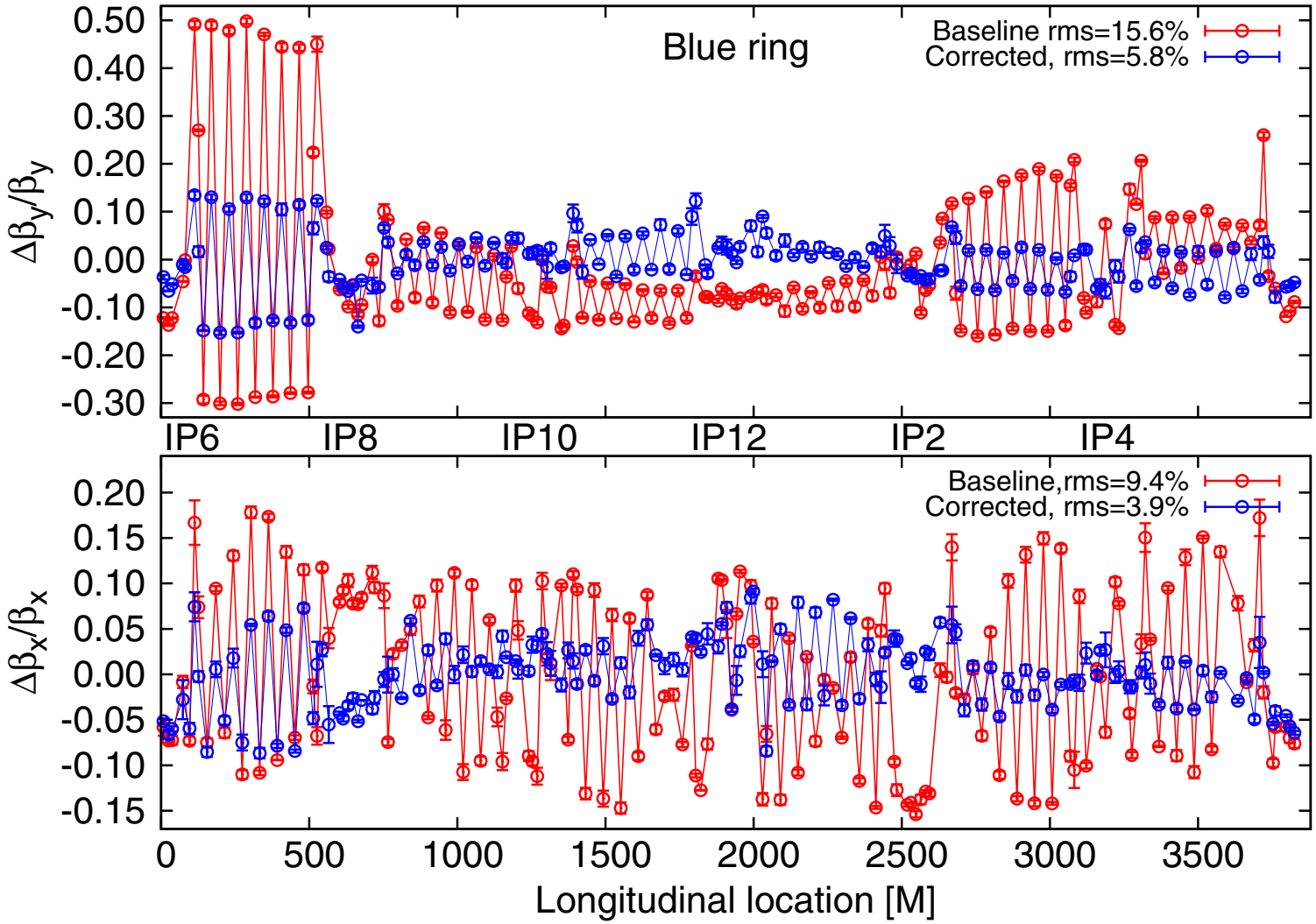
LHC: Using amplitude info from BPMs



Currently up to 20% error in β from amp. due to BPM cal.

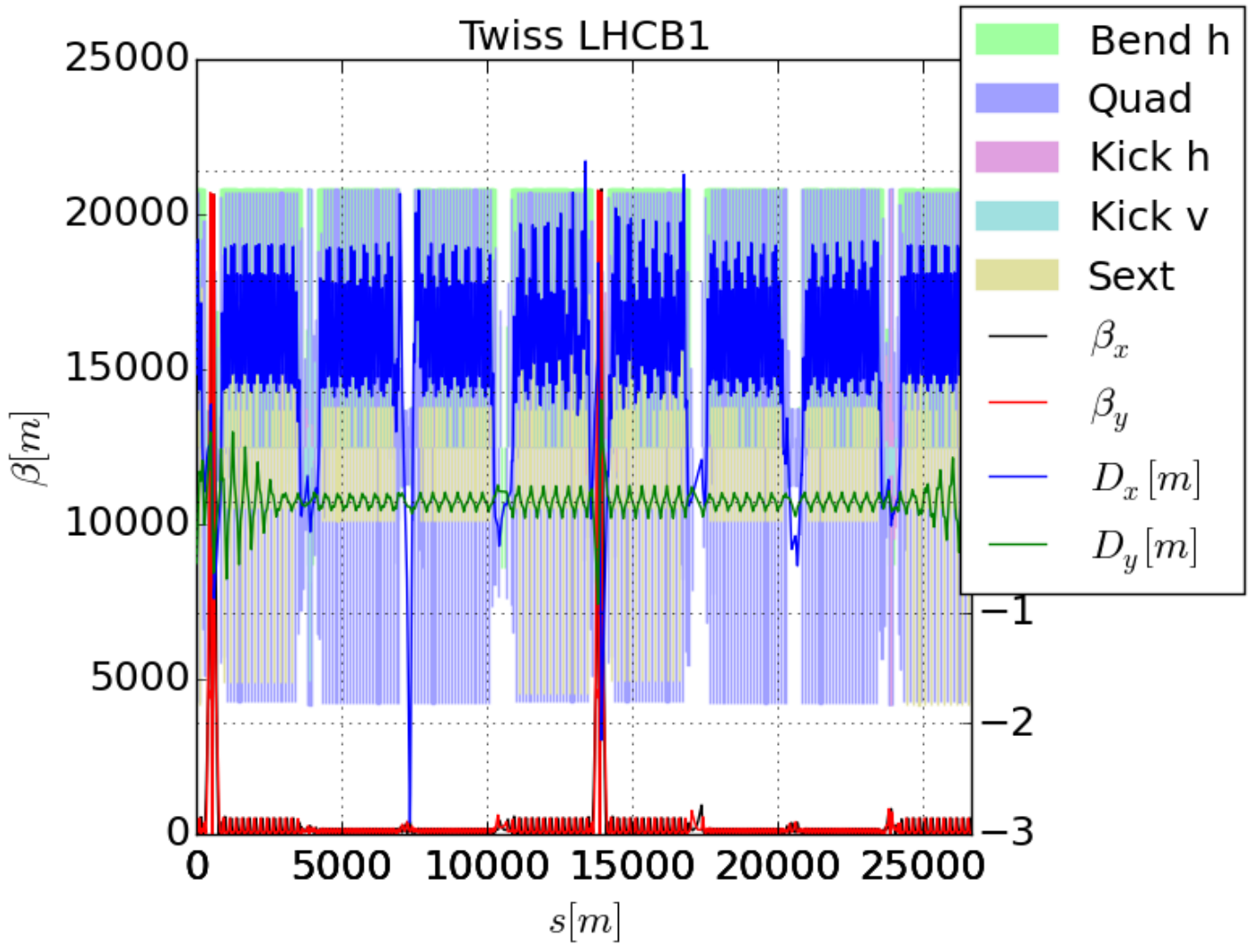
Could we do a beam-based calibration?

RHIC: Using amplitude info from BPMs



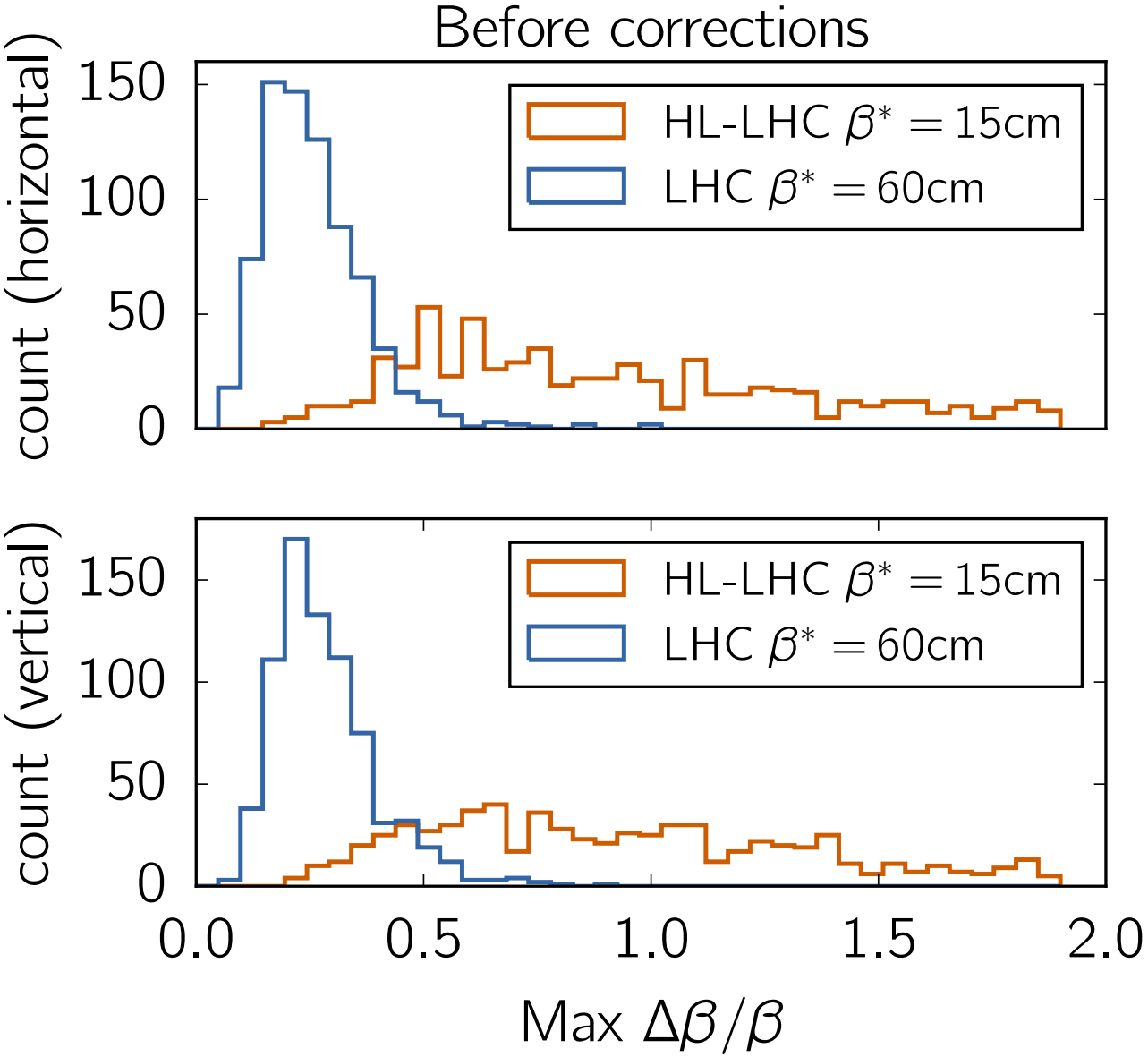
Successful corrections of β from amplitude using ICA (SVD).
X. Shen et al, PRSTAB **16**, 111001 (2013)

The LHC High Luminosity upgrade



Peak β of 20 km! Larger β in the arcs...

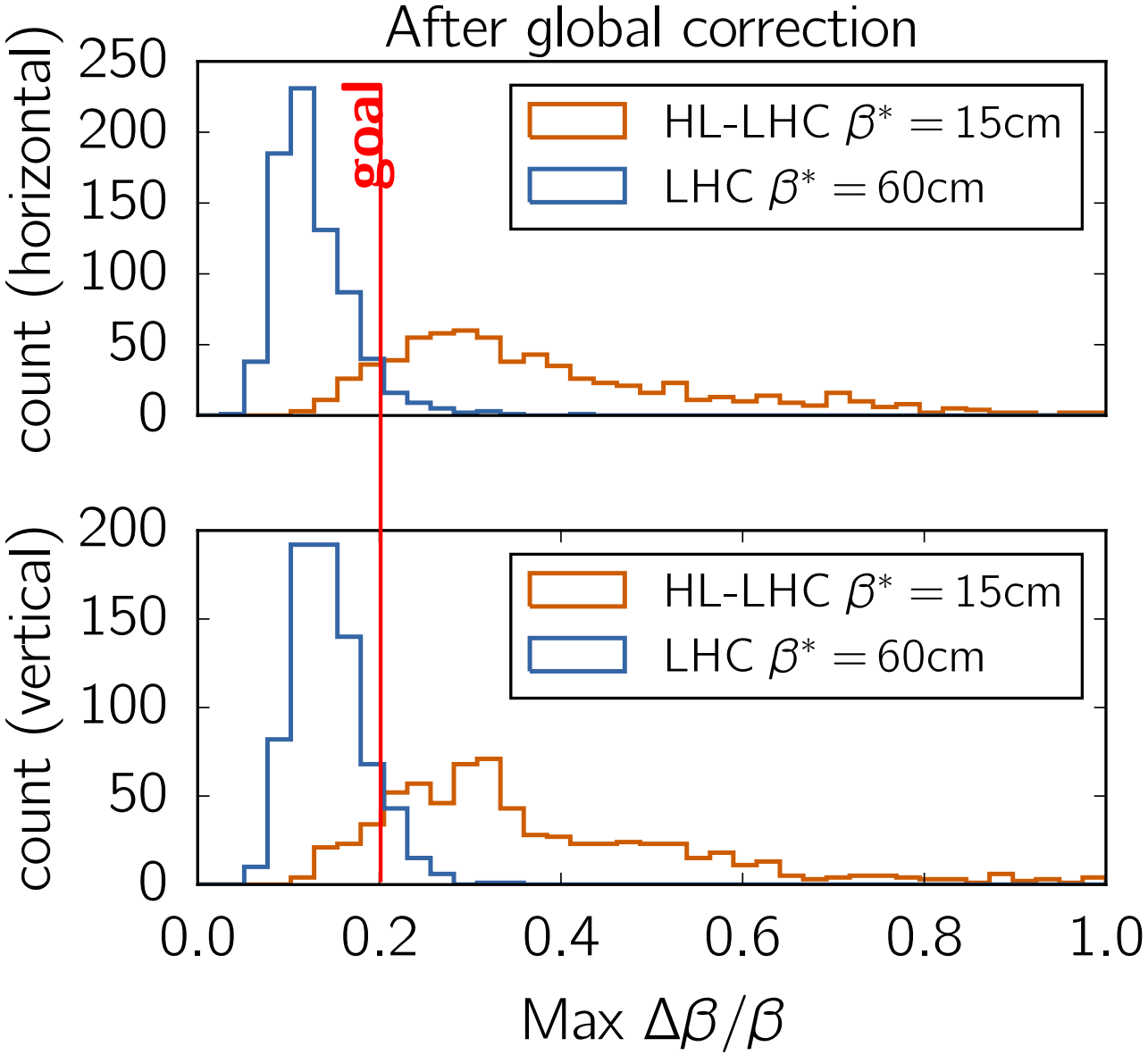
β-beating in HL-LHC before correction



Almost 200% β-beating...

...is it possible?

β-beating in HL-LHC after corrections

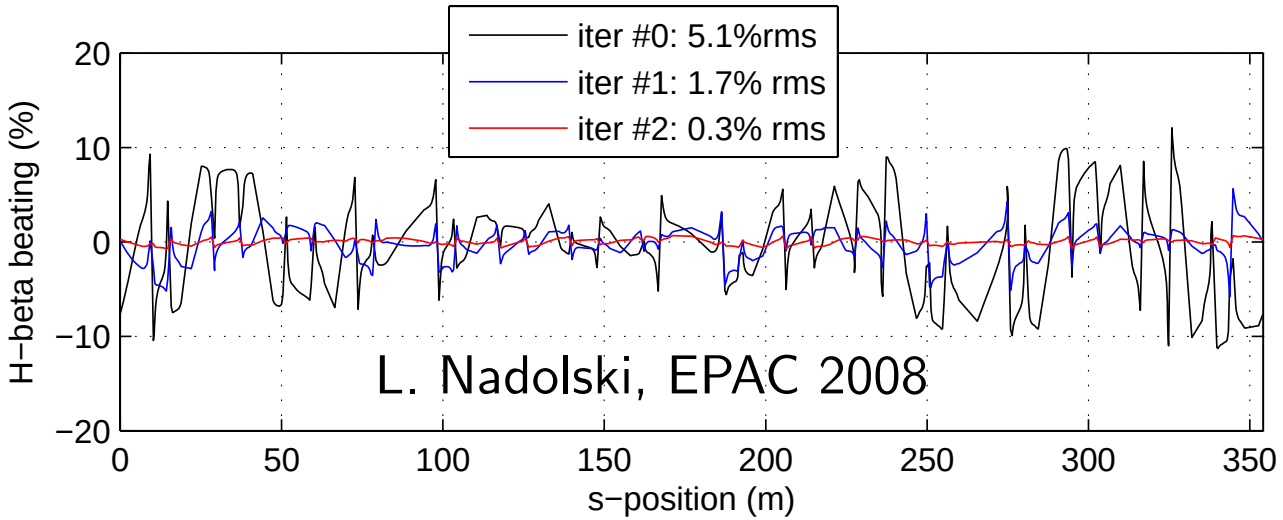


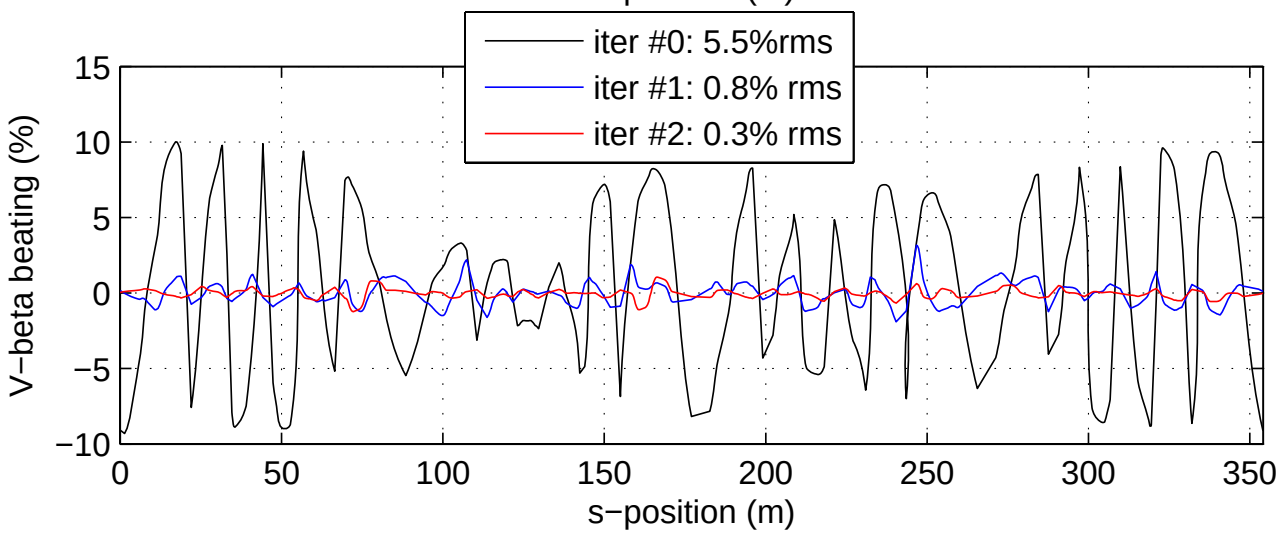
The HL-LHC challenge lies ahead!

Light sources

- ★ Optics measurements dominated by closed orbit techniques: ORM and LOCO (J. Safranek, NIM-A **388**, 1997)
- ★ Recently improved BPM electronics and filters have allowed turn-by-turn techniques with the potential of being faster
- ★ Comparison campaign (various labs) on-going
- ★ Brief overview follows

SOLEIL, LOCO, 2008





$$\Delta\beta/\beta_{loco}=0.3\%$$

DIAMOND reached similar β-beating

SOLEIL, turn-by-turn, 2015

M. Carlá et al, IPAC 2015

Table 1: Beta and phase beat results for Soleil and Alba. The measurements have been acquired after correcting the machine with LOCO to a beta-beat smaller than 1%.

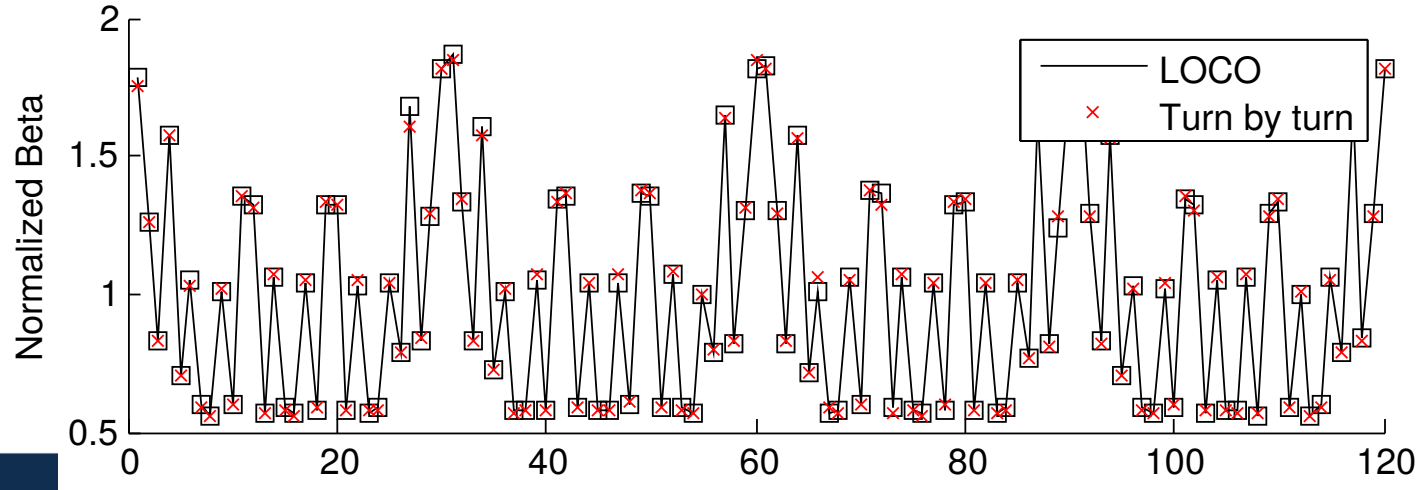
	Soleil	**Alba**
β-beat (H)	1.9×10^{-2}	1.5×10^{-2}
β-beat (V)	1.8×10^{-2}	1.4×10^{-2}
ϕ-beat (H)	8.5×10^{-3}	5.9×10^{-3}
ϕ-beat (V)	1.3×10^{-2}	4.6×10^{-3}

β from amp.

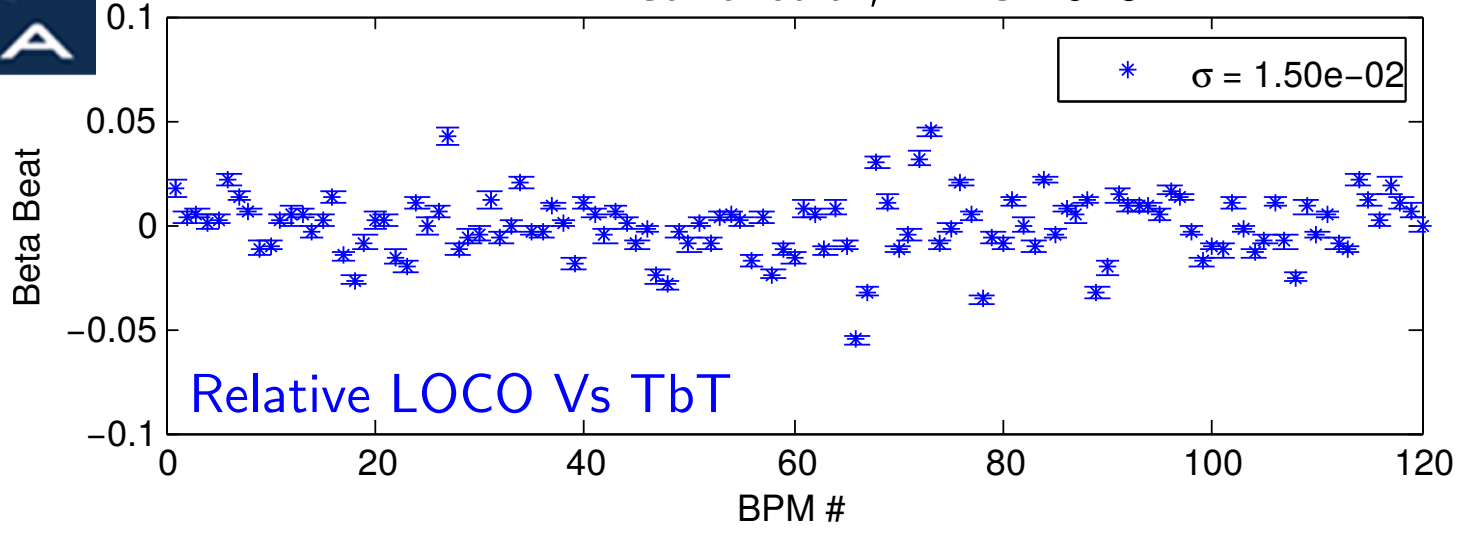
$$\Delta\beta/\beta_{tbt} \approx 2\%$$

What would β from ϕ (N-BPM) say?

ALBA, LOCO Vs β from Amp. (turn-by-turn)



M. Carlá et al, IPAC 2015

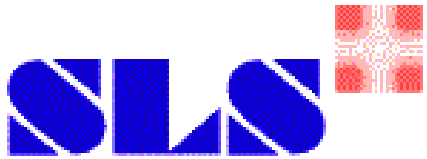


ALBA, LOCO Vs N-BPM (turn-by-turn)

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

Consistent β-beating measurements but:
is LOCO underestimating $\Delta\beta/\beta$?
is β from amp overestimating it? (due to BPM gain)



SLS $\Delta\beta/\beta \approx$2-3%. Turn-by-turn likely inaccurate due to bad BPMs. Interesting comment on LOCO:

M. AIBA *et al.* Phys. Rev. ST Accel. Beams **16,** 012802 (2013)

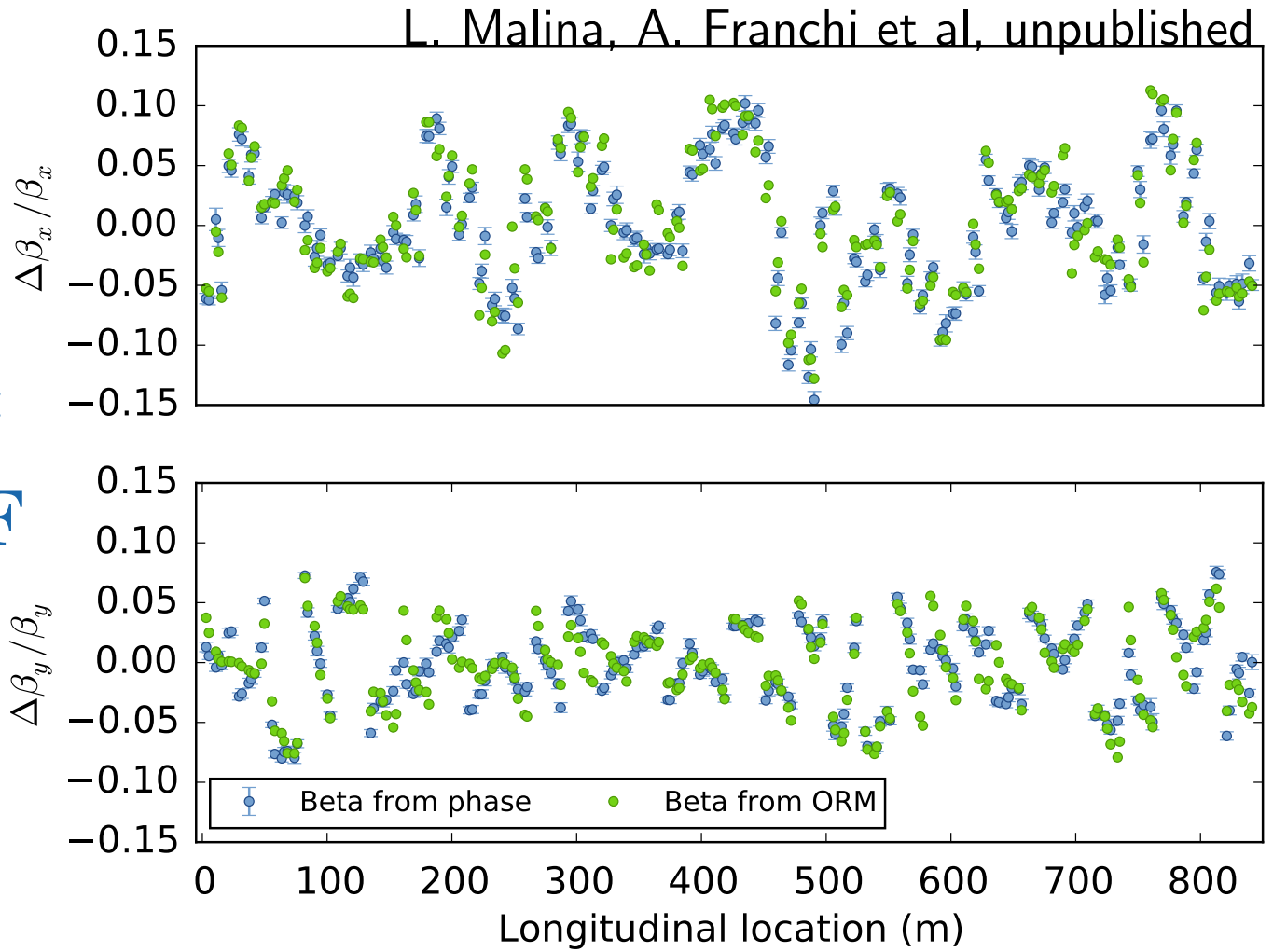
systematic error(s). In the analyses presented, all methods show limitations arising from systematic errors when the beta-beat is corrected down to a few % level. In the case of LOCO, the calibrated model may underestimate the beta-beat, when its minimum value is taken.

[5] P. Castro *et al.*, in *Proceedings of the Particle Accelerator Conference, Washington, DC, 1993* (IEEE, New York, 1993), pp. 2103–2105.

[6] M. Bai, S. Lee, J. Glenn, H. Huang, L. Ratner, T. Roser, M. Syphers, and W. van Asselt, Phys. Rev. E **56**, 6002 (1997).

[7] R. Tomás, Ph.D. thesis, University of Valencia, 2003.

ESRF, ORM Vs N-BPM



rms β-beating of 3-5%. Good agreement between the 2 techniques

ESRF, ORM Vs N-BPM Vs β from amp.

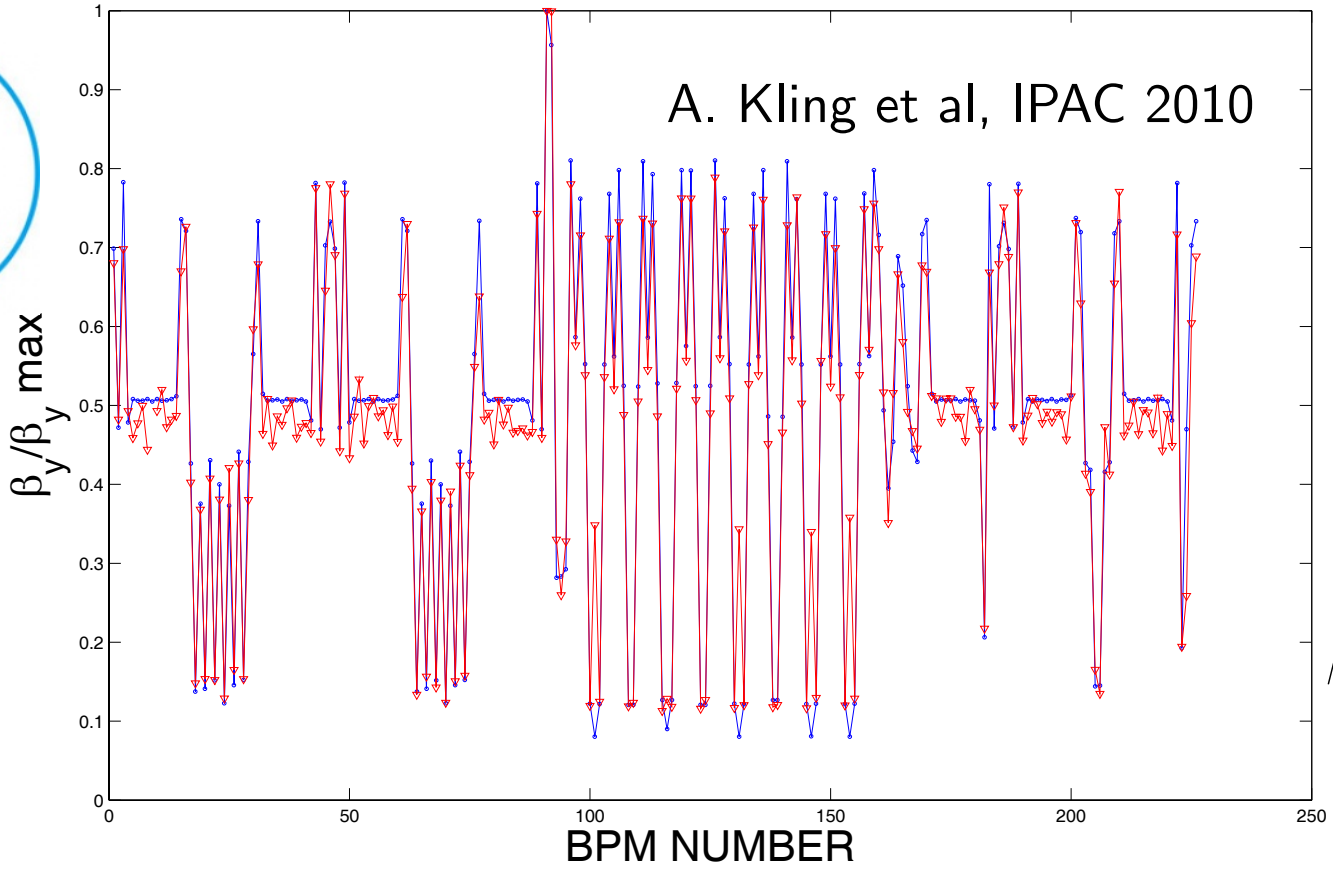
ESRF

L. Malina, A. Franchi et al, unpublished

Beta-beating	Phase [%]	Amp [%]	ORM [%]
betax	5	5	5.2
betay	3.4	3.4	3.4

Good agreement between all techniques

PETRA III, turn-by-turn, 2010



β from amp.

β-beating=4-5%, similar to LOCO measurement.

Summary & Outlook

- ★ LHC has achieved an rms β-beating of 2-3%, comparable to most light sources
- ★ The challenge lies ahead for HL-LHC ($\Delta\beta/\beta$=200% !)
- ★ SOLEIL and DIAMOND have achieved 0.3-0.4% β-beating with LOCO
- ★ Still missing: Observe this 0.3% β-beating with turn-by-turn techniques