LHC Optics Measurements with AC Dipoles

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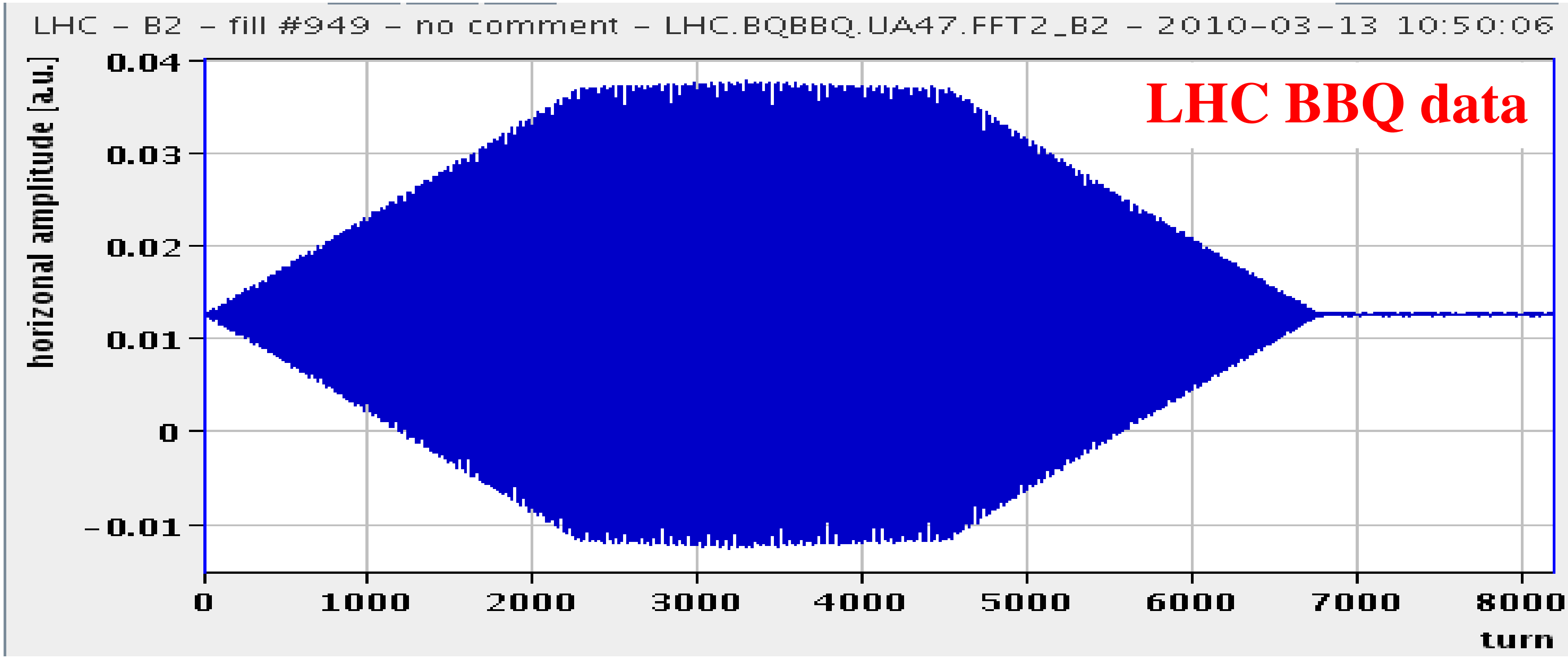
Thanks to R. Calaga, R. Tomas, G. Vanbavinckhove

Outline

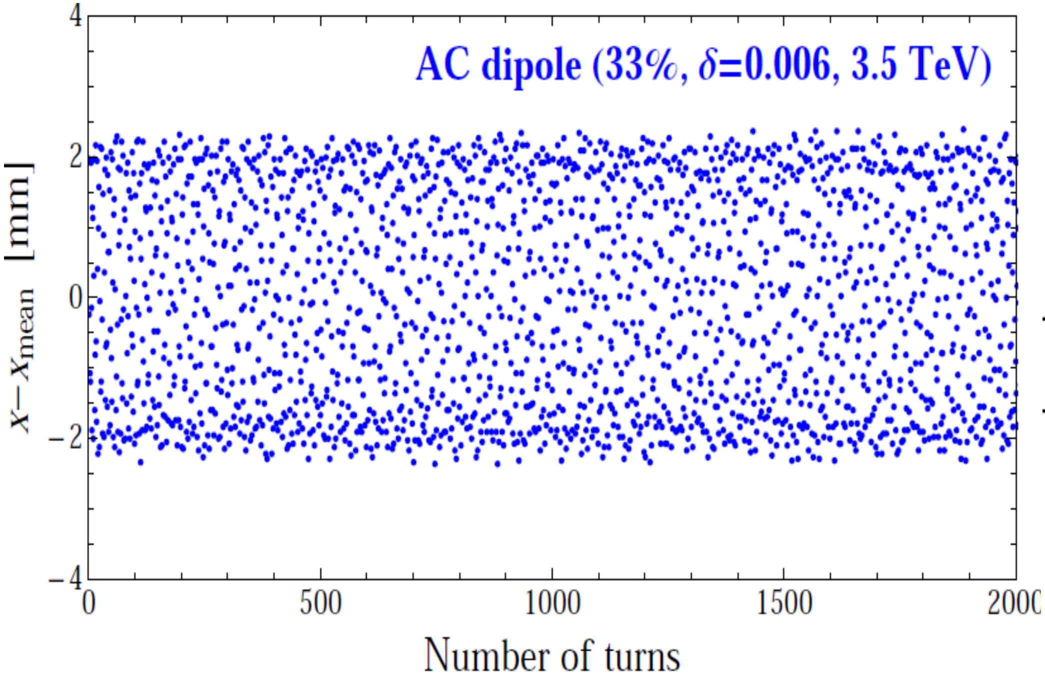
- Introduction to the AC dipole
- AC dipole operation
- Optics measurements with AC dipoles
- Precision of AC dipole measurements
- Summary and outlook

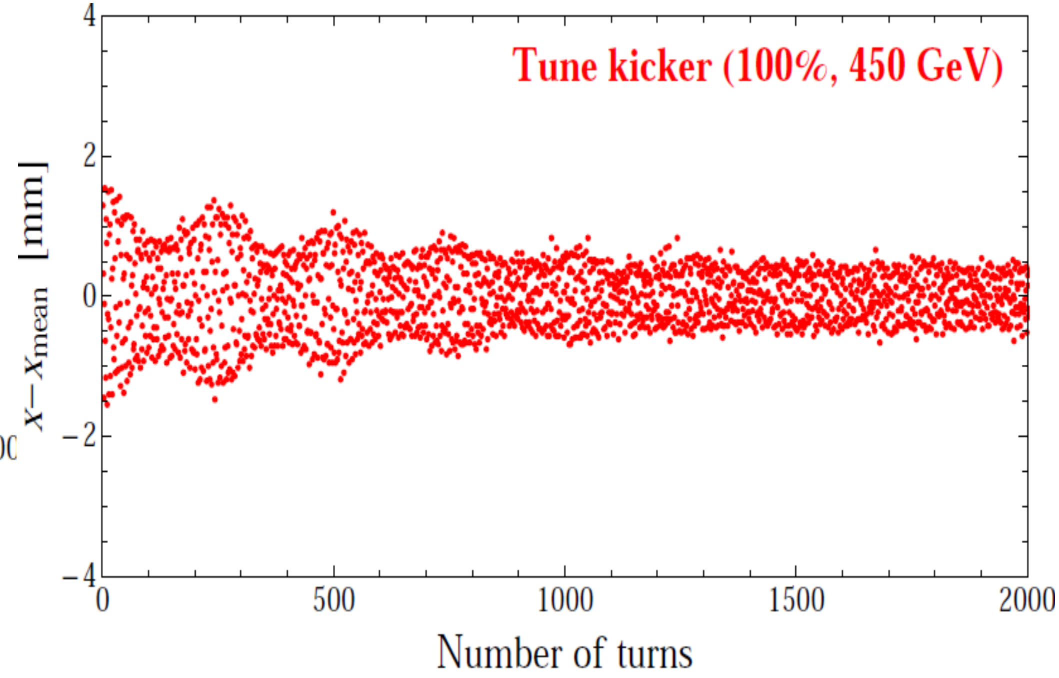
Introduction to an AC dipole

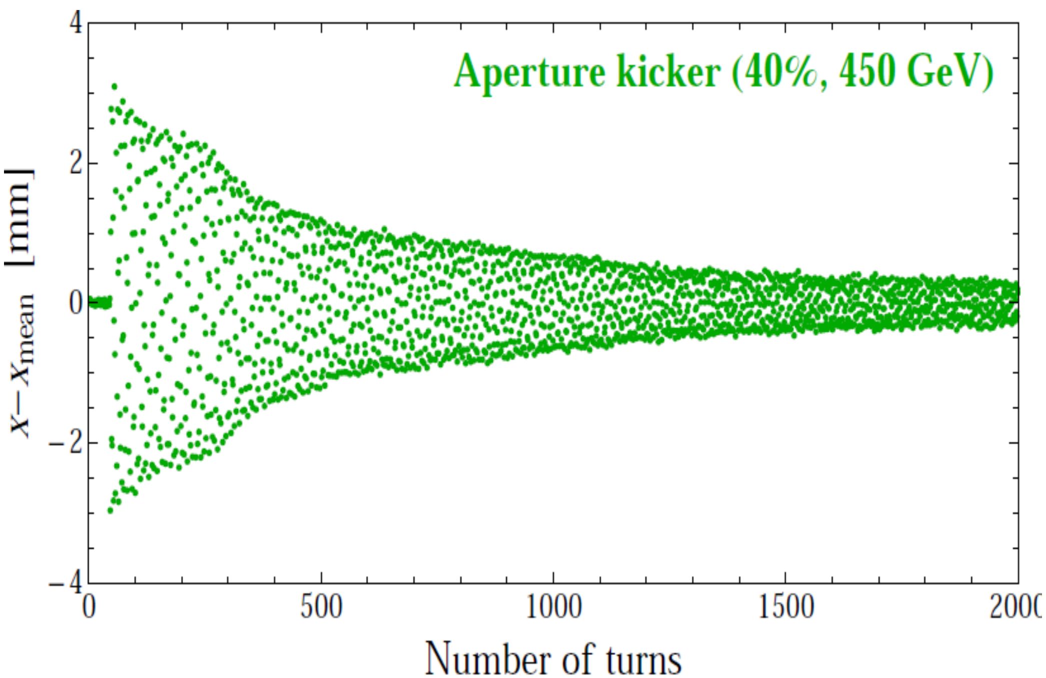


- An AC dipole produces a sinusoidally oscillating dipole field with frequency close to betatron frequency ($\delta = Qd\text{-}Q = 0.005\text{-}0.012$) and excites sustained coherent oscillations of beam particles.
- Slow ramp allows no decoherence and very small emittance growth → multiple measurements with a single beam, good for slow machines.
- LHC has 4 AC dipoles (HV for 2 beams) in IR4.
- The technique first tried and proved in AGS, and then successfully applied to SPS, RHIC, Tevatron, and LHC.

AC dipole vs kicker in LHC

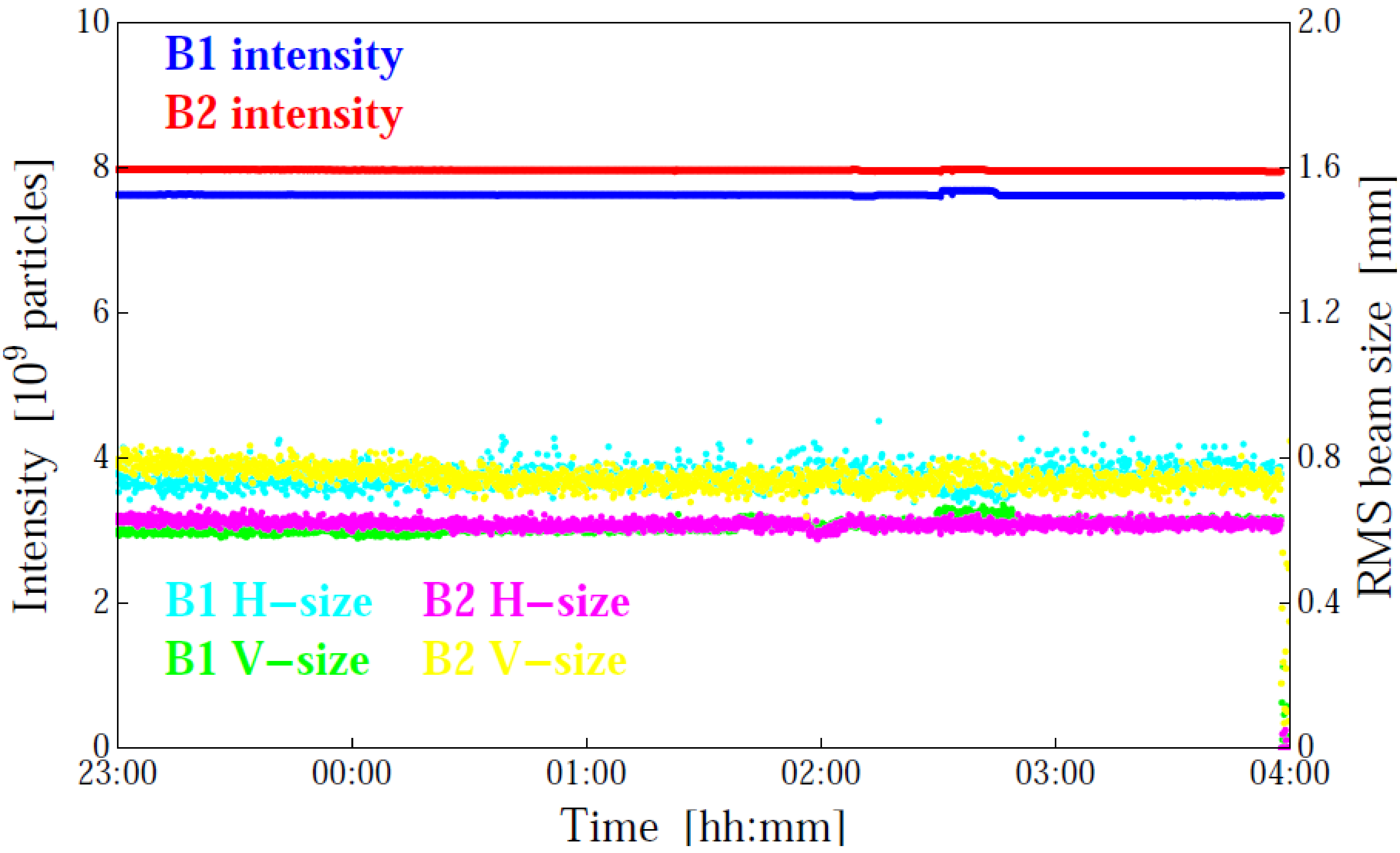






- **LHC AC dipole spec:**
  6σ for |δ|=0.01 at 7 TeV
- **BPM RMS noise ≲ 100 μm**

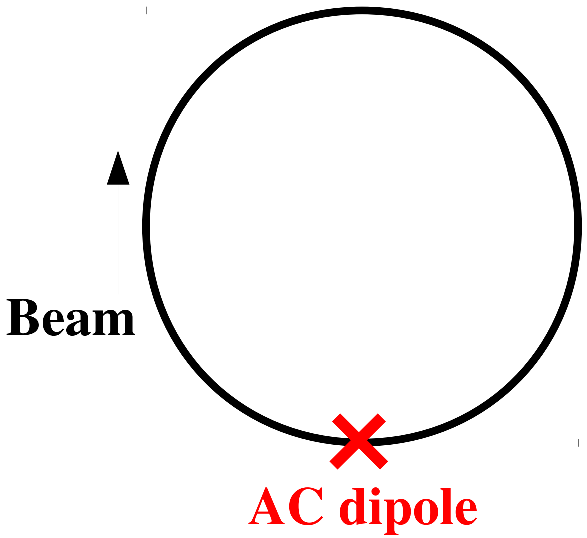
An example of a smooth set of measurements



Each beam is excited ~30 times (squeeze recommissioning on Feb 25)

Modes excited with an AC dipole

Modes exited with an AC dipole can be calculated by accumulating kicks of the AC dipole. (cf.:
S. Peggs and C. Tang, BNL RHIC/AP/Note 159.
S. Fartoukh, CERN-SL_2002-059 AP.
R. Tomas, PRST-AB **8** 024401.)



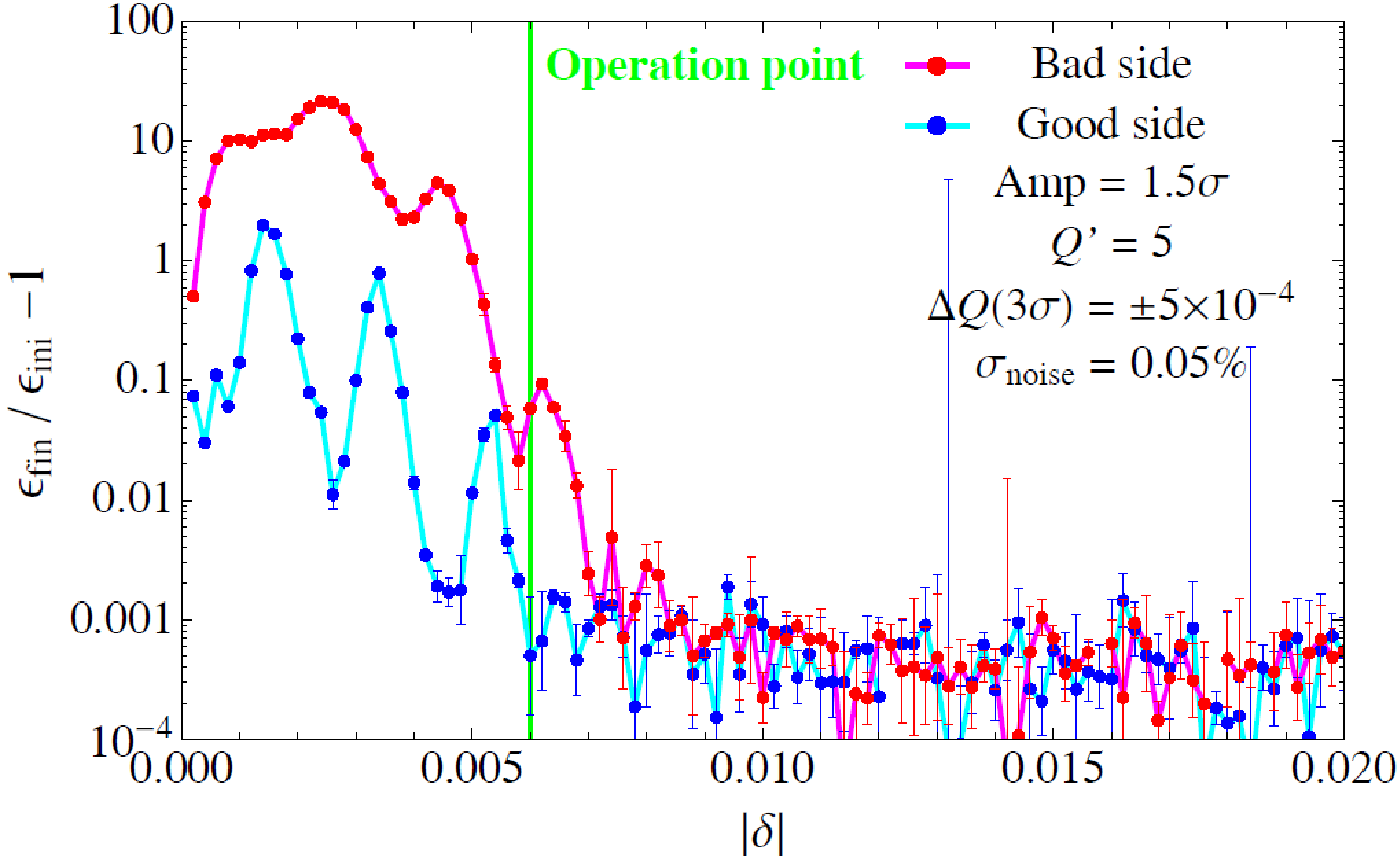
$$x(nC+s)$$
$$= \frac{(B\ell)_{\rm ac}\sqrt{\beta(s_{\rm ac})\beta(s)}}{4(B\rho)\sin[\pi(\nu_d-\nu)]}\cos[2\pi\nu_d n+\psi(s,s_{\rm ac})+\pi(\nu_d-\nu)+\chi_{\rm ac}]$$ **Difference (dominant)**

$$-\frac{(B\ell)_{\rm ac}\sqrt{\beta(s_{\rm ac})\beta(s)}}{4(B\rho)\sin[\pi(\nu_d+\nu)]}\cos[2\pi\nu_d n-\psi(s,s_{\rm ac})+\pi(\nu_d+\nu)+\chi_{\rm ac}]$$ **Sum (small)**

$$-\frac{(B\ell)_{\rm ac}\sqrt{\beta(s_{\rm ac})\beta(s)}\sin[\pi(\nu_d-\nu)N_r]}{4N_r(B\rho)\sin^2[\pi(\nu_d-\nu)]}\cos[2\pi\nu n+\psi(s,s_{\rm ac})+\pi(\nu_d-\nu)N_r+\chi_{\rm ac}]$$
$$+\frac{(B\ell)_{\rm ac}\sqrt{\beta(s_{\rm ac})\beta(s)}\sin[\pi(\nu_d+\nu)N_r]}{4N_r(B\rho)\sin^2[\pi(\nu_d+\nu)]}\cos[2\pi\nu n+\psi(s,s_{\rm ac})-\pi(\nu_d+\nu)N_r-\chi_{\rm ac}]$$

Transient free oscillation modes (quasi-linear case) → emittance growth

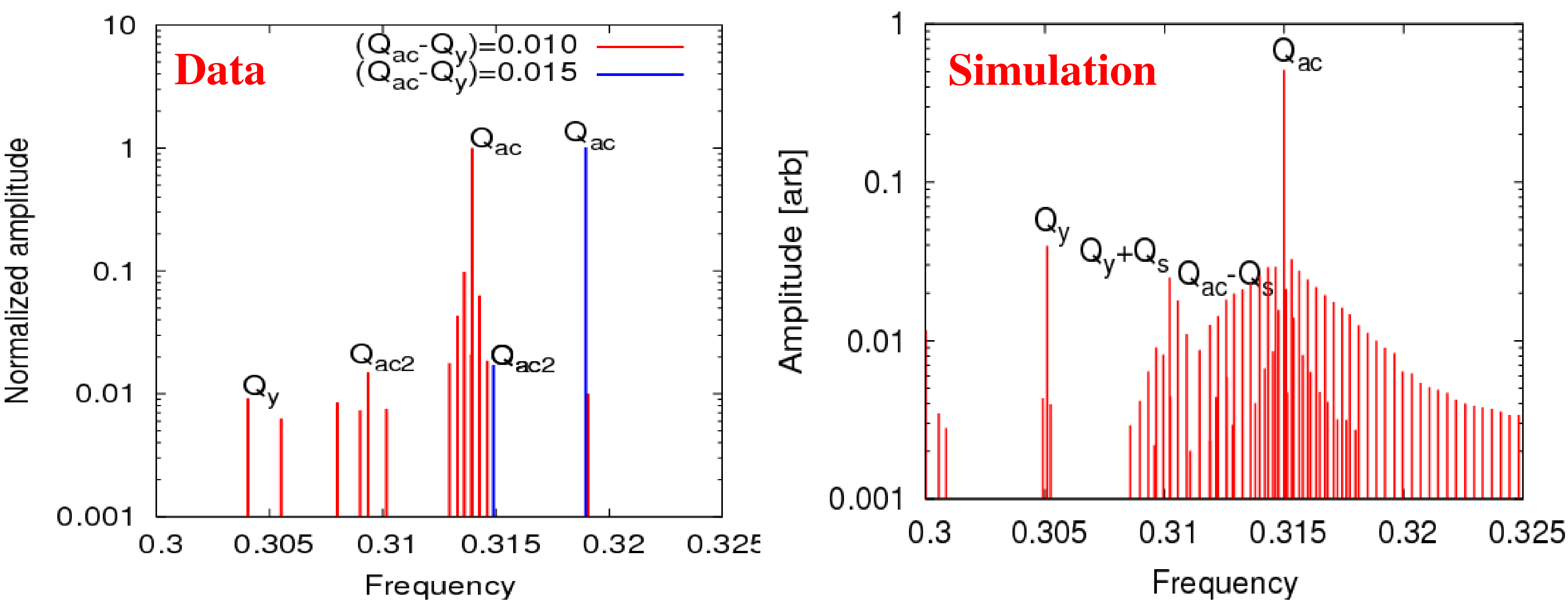
Emittance growth simulation (3.5 TeV)



- A simple (single turn + AC dipole) simulation.
- Direction of detuning ("good" or "bad" side) makes a large difference.
- Ideal to avoid synchrotron sidebands but hard to know where they are with detuning.
- Hard to make an analytical prediction of the "critical" point.

B2 vertical AC dipole mystery

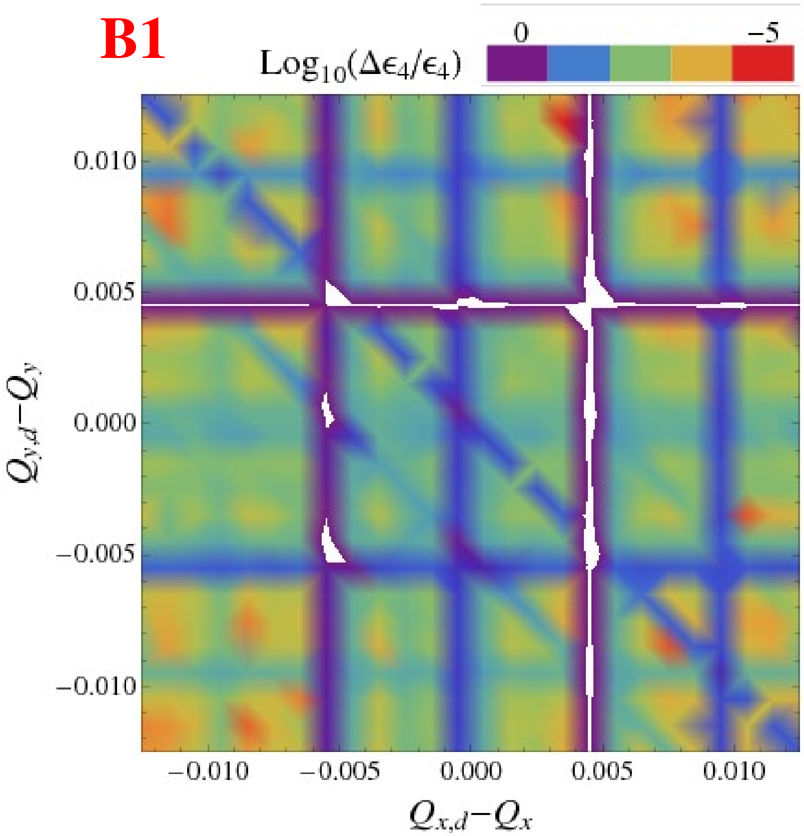
- This year, emittance growths have been observed for B2 mostly V-plane with $Qx,d-Qx$ = -0.006 and $Qy,d-Qy$ = +0.006 (and even with $Qx,d-Qx$ = -0.01 and $Qy,d-Qy$ = +0.01) whereas the same has no problem for B1.
- Looked like a hardware problem (sideband?) but verified not.
- Qs changed to 0.0049 (inj) and 0.0025 (3.5 TeV) this year.
- $Qx,d-Qx$ = -0.01, $Qy,d-Qy$ = +0.012 tried for inj and 3.5 TeV and had no problem (large asymmetry in inputs)
- The asymmetry swapped when tested at 1.38 TeV → detuning?
- $Qx,d-Qx$ = -0.009, $Qy,d-Qy$ = +0.009 tried for 3.5 TeV (1 m) in August and had

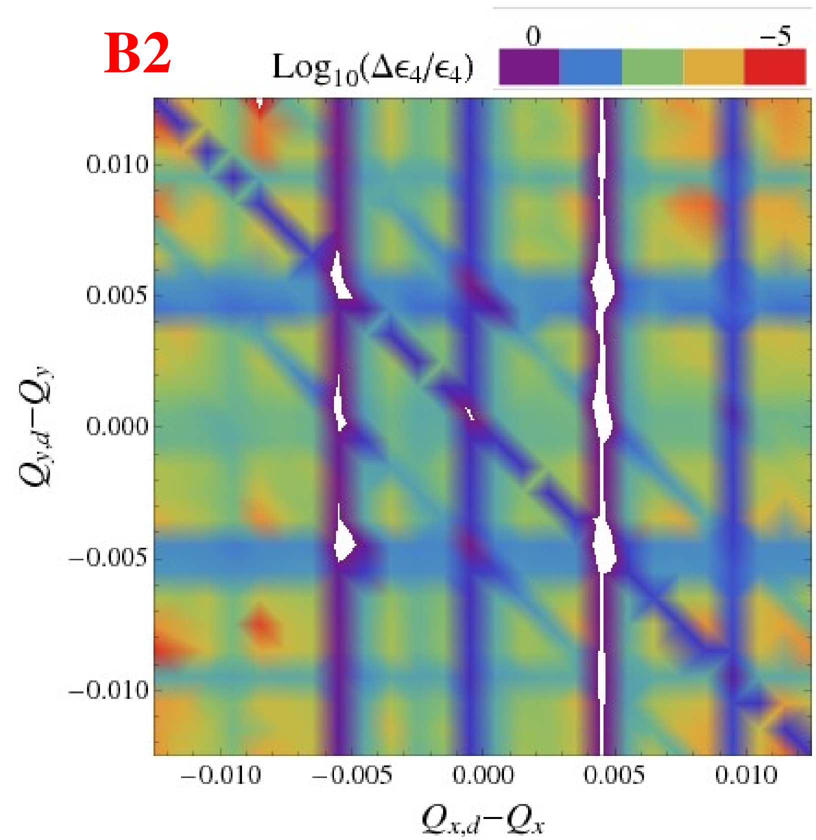


4D simulation based on measured detuning

	dQx/2Jx [μm^{-1}]	dQx,y/2Jy,x [μm^{-1}]	dQy/2Jy [μm^{-1}]
B1 (inj)	-0.0110	0.0070	-0.0060
B2 (inj)	-0.0120	0.0089	-0.0025

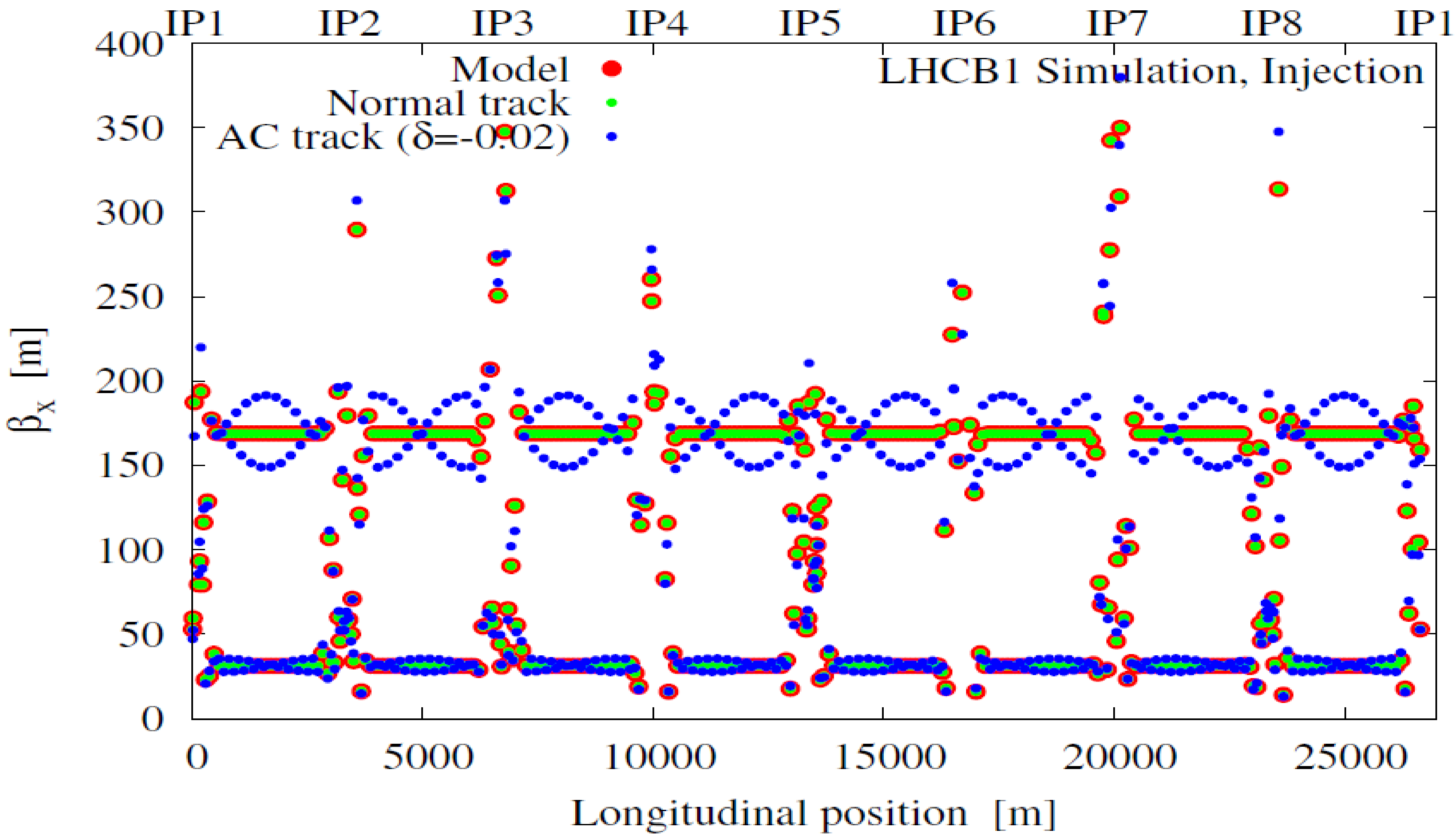
(0.01 ⇔ ~7E-4 at 3σ. specified tolerance: 5E-4)





- No clear difference between B1 and B2 ??
- Strange diagonal line ??
- Cross term makes the emittance really worse.
- A simple model not good enough ??

Sum resonance produces artificial β-beating



- Magnitude is linear with δ: $|\delta| = 0.01 \rightarrow$ 6-7% artificial β-beating
- The effect is equivalent to have an additional thin 2D quad.
- Some remedies:
  1. Simply ignore if β-beating is much larger than this effect.
  2. Two modes can be separated if the phase of the AC dipole is known. (Future option?)
  3. Frequency scan. (Used for the Tevatron)

Optics parameters for the AC dipole motion

Going through a "high school math problem", difference and sum resonance terms are combined to

$$x(nC+s) = A_d\sqrt{\beta_d(s)}\cos[2\pi\nu_d n + \psi_d(s,s_{\rm ac}) + \chi_{\rm ac}]$$

$$A_d = \frac{(Bl)_{\rm ac}\sqrt{\beta(s_{\rm ac})(1-\lambda^2)}}{4(B\rho)\sin[\pi(\nu_d-\nu)]} \qquad \lambda = \frac{\sin[\pi(\nu_d-\nu)]}{\sin[\pi(\nu_d+\nu)]}$$

$$\beta_d(s) = \frac{1+\lambda^2-2\lambda\cos[2\psi(s,s_{\rm ac})-2\pi\nu]}{1-\lambda^2}\beta(s)$$

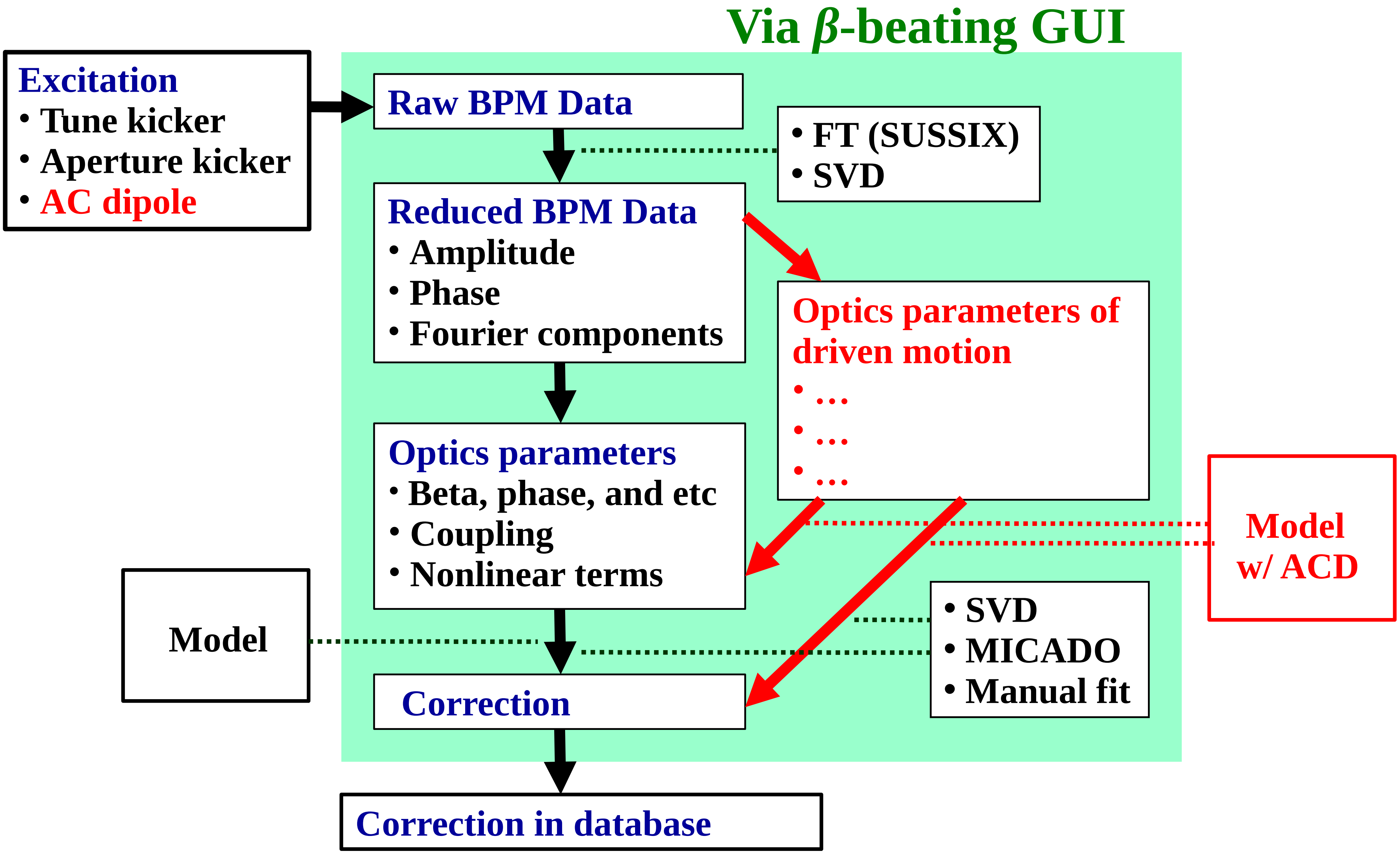
$$\psi_d(s,s_{\rm ac}) = \arctan\left\{\frac{1+\lambda}{1-\lambda}\tan[\psi(s,s_{\rm ac})-\pi\nu]\right\} + \pi\nu_d$$

The effect is equivalent to insert a "2D" thin quad at the AC dipole with

$$q_{\rm ac} = 2\frac{\cos(2\pi\nu_d)-\cos(2\pi\nu)}{\beta(s_{\rm ac})\sin(2\pi\nu)} \simeq -\frac{4\pi\delta}{\beta(s_{\rm ac})}$$

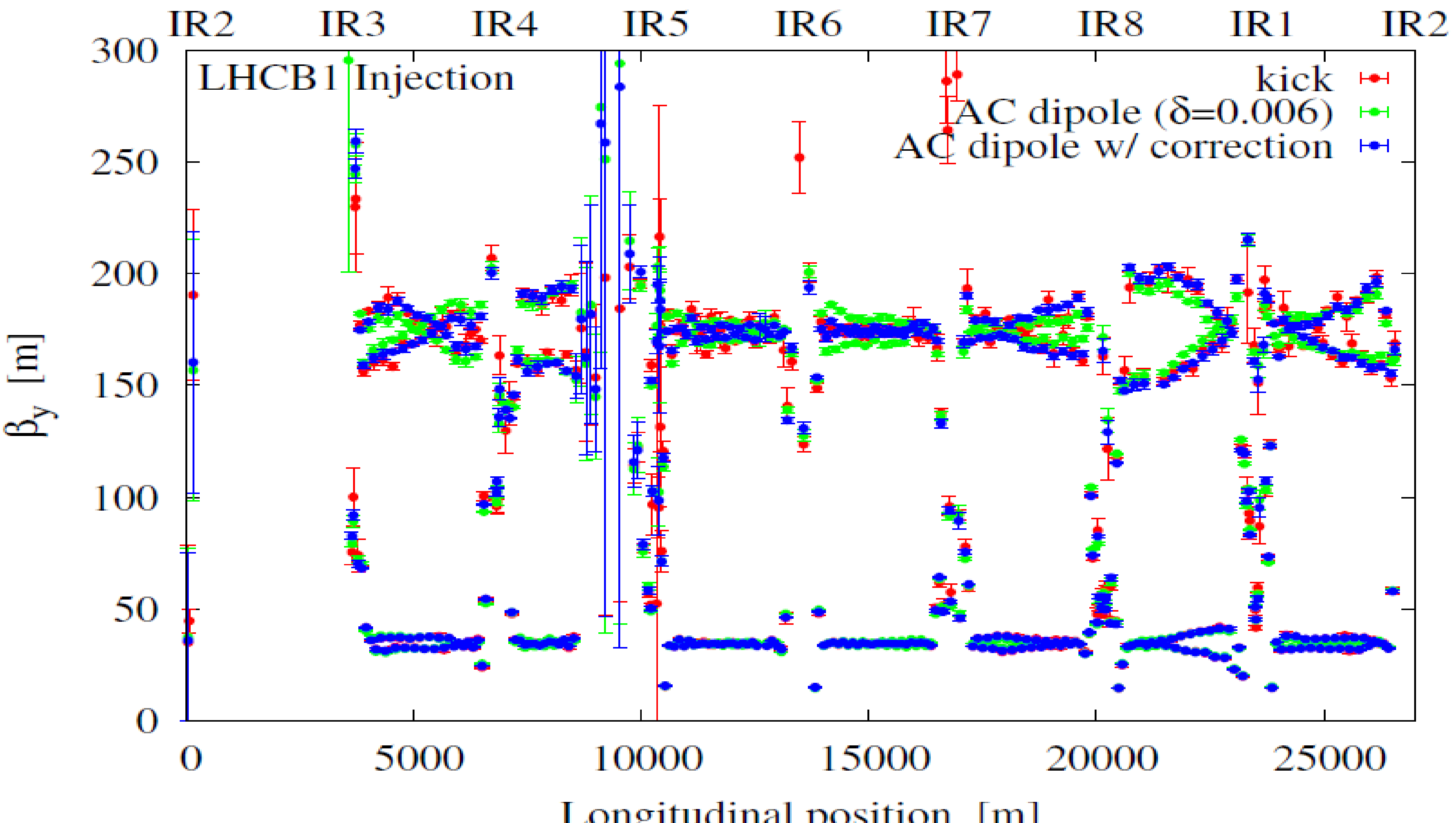
New β and phase, β_d and ψ_d, are direct observables from the TBT data. We can calculate original β and ψ from measured β_d and ψ_d if we have BPMs next to the AC dipoles.

Flow chart of the AC dipole based diagnosis



* Local correction based on SBS technique is immune to this effect.

Application to real data: comparison with a kicker measurement



The systematic error from using the model phase advance from the AC dipole to its closest BPM is only 0.2-0.3% in β when δ=0.01 and β-beating is 100%.

Motion with skew quads + AC dipoles

1st order modes from skew fields:

$$\tilde{x}^{(1)}(n;\bar{s}) = 2iA_y f_-(\bar{s})\sqrt{\beta_x(\bar{s})}e^{-2\pi i\nu_y n - i\psi_y(\bar{s}) - i\phi_y} + 2iA_y f_+(\bar{s})\sqrt{\beta_x(\bar{s})}e^{2\pi i\nu_y n + i\psi_y(\bar{s}) + i\phi_y}$$

$$\tilde{y}^{(1)}(n;\bar{s}) = 2iA_x f_-^*(\bar{s})\sqrt{\beta_y(\bar{s})}e^{-2\pi i\nu_x n - i\psi_x(\bar{s}) - i\phi_x} + 2iA_x f_+(\bar{s})\sqrt{\beta_y(\bar{s})}e^{2\pi i\nu_x n + i\psi_x(\bar{s}) + i\phi_x}$$

Characterized by resonance driving terms:

$$f_\mp(\bar{s}) = \frac{1}{8i\sin[\pi(\nu_x \mp \nu_y)]}\sum_{j=1}^{N}\kappa_j\sqrt{\beta_x(\bar{s}_j)\beta_y(\bar{s}_j)}e^{-i[\Psi_x(\bar{s},\bar{s}_j)\mp\Psi_y(\bar{s},\bar{s}_j)]}$$

Sum and difference of the AC dipole double number of modes and introduce terms summing skew fields between the AC dipole and the observation point (cf: S. Fartoukh, CERN-SL_2002-059 AP)

$$\begin{aligned}\tilde{x}^{(1)}(n;\bar{s}) = \quad & 2iA_{y,v}\frac{\sin[\pi(\nu_x-\nu_y)]}{\sin[\pi(\nu_x-\nu_{y,v})]}\left[f_-(\bar{s}) - 2\pi i\delta_v f_-(\bar{s};\bar{s},\bar{s}_v)\right]\sqrt{\beta_x(\bar{s})}e^{-2\pi i\nu_{y,v}n - i\psi_y(\bar{s},\bar{s}_v) - i\phi_v} \\ & + 2iA_{y,v}\frac{\sin[\pi(\nu_x+\nu_y)]}{\sin[\pi(\nu_x+\nu_{y,v})]}\left[f_+(\bar{s}) + 2\pi i\delta_v f_+(\bar{s};\bar{s},\bar{s}_v)\right]\sqrt{\beta_x(\bar{s})}e^{2\pi i\nu_{y,v}n + i\psi_y(\bar{s},\bar{s}_v) + i\phi_v} \\ & - 2iA_{y,v}\frac{\sin[\pi(\nu_x+\nu_y)]}{\sin[\pi(\nu_x-\nu_{y,v})]}\left[\lambda_v f_+(\bar{s}) - 2\pi i\delta_v e^{-2\pi i\nu_y \mathrm{sgn}(\bar{s}-\bar{s}_v)} f_+(\bar{s};\bar{s},\bar{s}_v)\right]\sqrt{\beta_x(\bar{s})}e^{-2\pi i\nu_{y,v}n + i\psi_y(\bar{s},\bar{s}_v) - i\phi_v} \\ & - 2iA_{y,v}\frac{\sin[\pi(\nu_x-\nu_y)]}{\sin[\pi(\nu_x+\nu_{y,v})]}\left[\lambda_v f_-(\bar{s}) + 2\pi i\delta_v e^{2\pi i\nu_y \mathrm{sgn}(\bar{s}-\bar{s}_v)} f_-(\bar{s};\bar{s},\bar{s}_v)\right]\sqrt{\beta_x(\bar{s})}e^{2\pi i\nu_{y,v}n - i\psi_y(\bar{s},\bar{s}_v) + i\phi_v}\end{aligned}$$

Similar to β, having BPMs next to the AC dipole allow to calculate the real $f_\mp$ from the effective $f_\mp$. (BNL CAD-AP-Note 410).

Explicit expressions

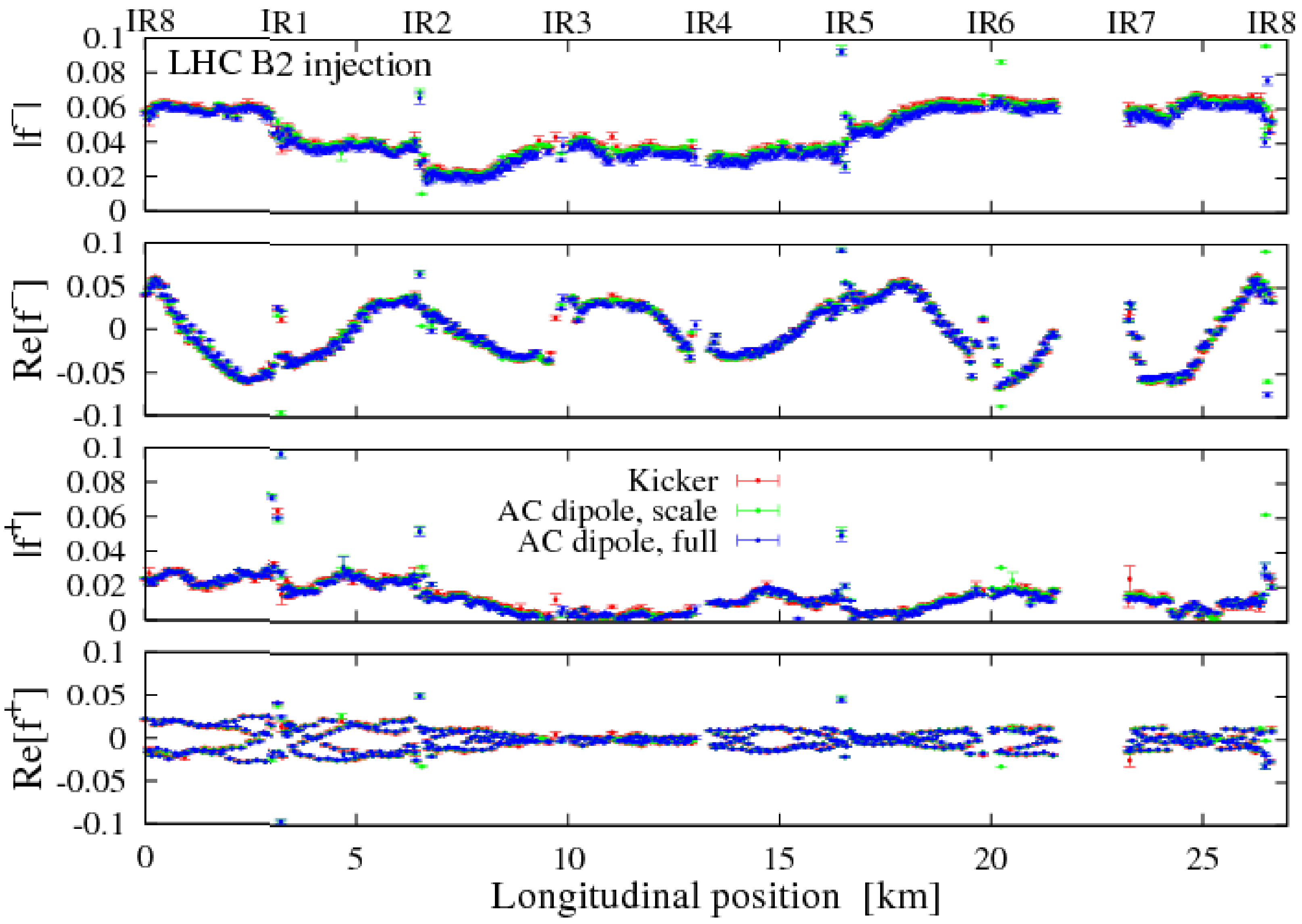
$$\tilde{x}^1_{s,n} = 2iA^v f_s^{-,v,h}\sqrt{\beta_s^h}e^{-2\pi i\nu^v n - i\psi^v_{s,s_v} - i\chi^v} + 2iA^v f_s^{+,v,h}\sqrt{\beta_s^h}e^{2\pi i\nu^v n + i\psi^v_{s,s_v} + i\chi^v}$$

$$\tilde{y}^1_{s,n} = 2iA^h (f_s^{-,h,v})^*\sqrt{\beta_s^v}e^{-2\pi i\nu^h n - i\psi^h_{s,s_h} - i\chi^h} + 2iA^h f_s^{+,h,v}\sqrt{\beta_s^v}e^{2\pi i\nu^h n + i\psi^h_{s,s_h} + i\chi^h}$$

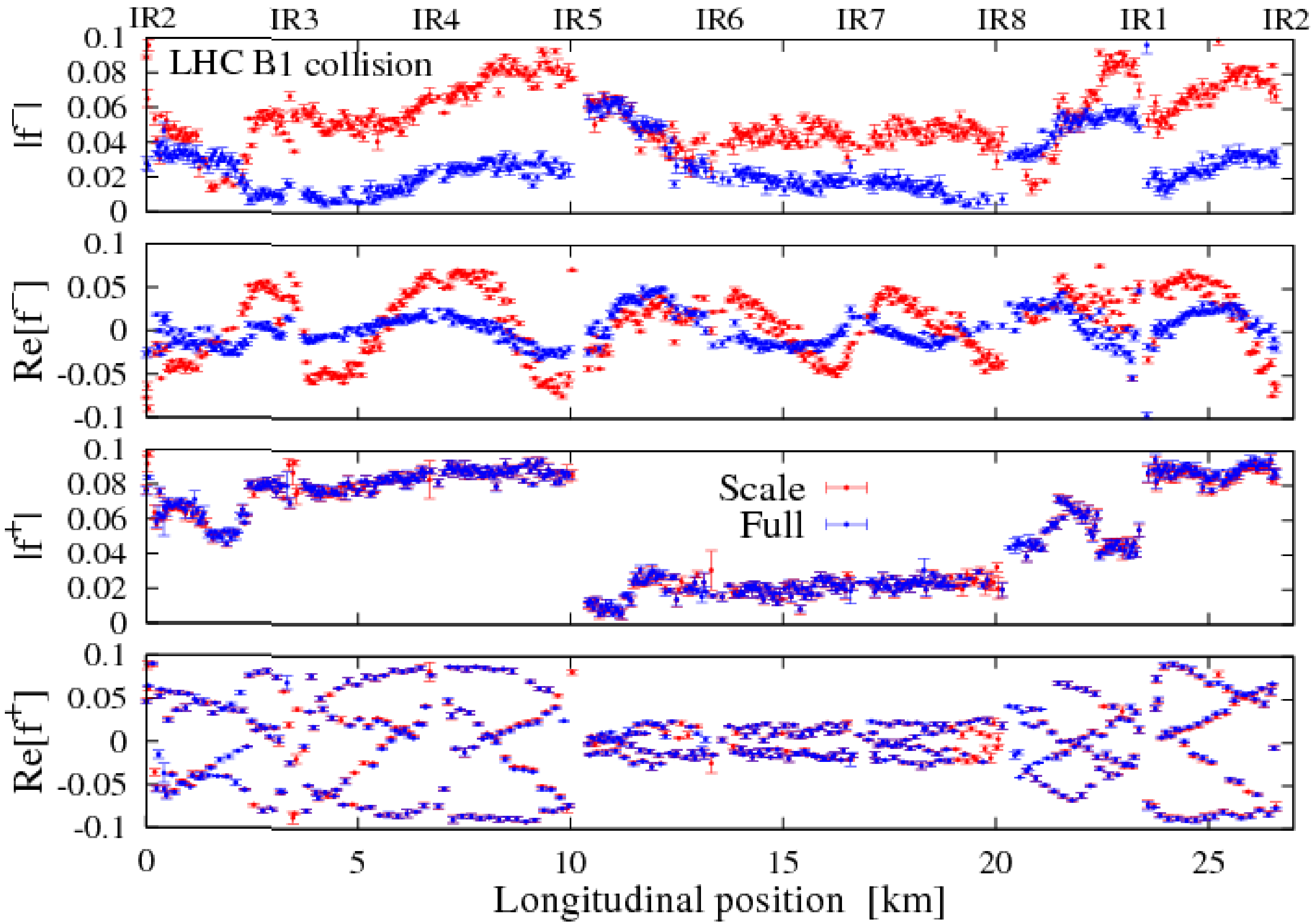
$$f_s^{\mp} = \frac{1}{\sqrt{1-(\lambda^h)^2}}\frac{\sin[\pi(\nu^h \mp \nu^y)]}{\sin[\pi(\nu^x \mp \nu^y)]}\Big[e^{i(\psi^h_{s,s_h} - \psi^x_{s,s_h})} f_s^{\mp,h} - \lambda^h e^{-i(\psi^h_{s,s_h} + \psi^x_{s,s_h})}(\lambda^{c,h})^{\mp 1}(f_s^{\pm,h})^* - 2\pi i\delta^h e^{i(\Psi^h_{s,s_h} - \Psi^x_{s,s_h})}\hat{f}^{\mp,h}_{s,s_h} - 2\pi i\delta^h e^{-i(\Psi^h_{s,s_h} + \Psi^x_{s,s_h})}(\lambda^{c,h})^{\mp 1}(\hat{f}^{\pm,h}_{s,s_h})^*\Big], \quad (12)$$

$$f_s^{\mp,h} = \frac{1}{\sqrt{1-(\lambda^h)^2}}\Big[e^{\mp i(\Psi^v_{s,s_v} - \Psi^y_{s,s_v})} f_s^{\mp,h,v} + \lambda^v e^{\pm i(\Psi^v_{s,s_v} + \Psi^y_{s,s_v})} f_s^{\pm,h,v}\Big],$$

Applications to real data 1

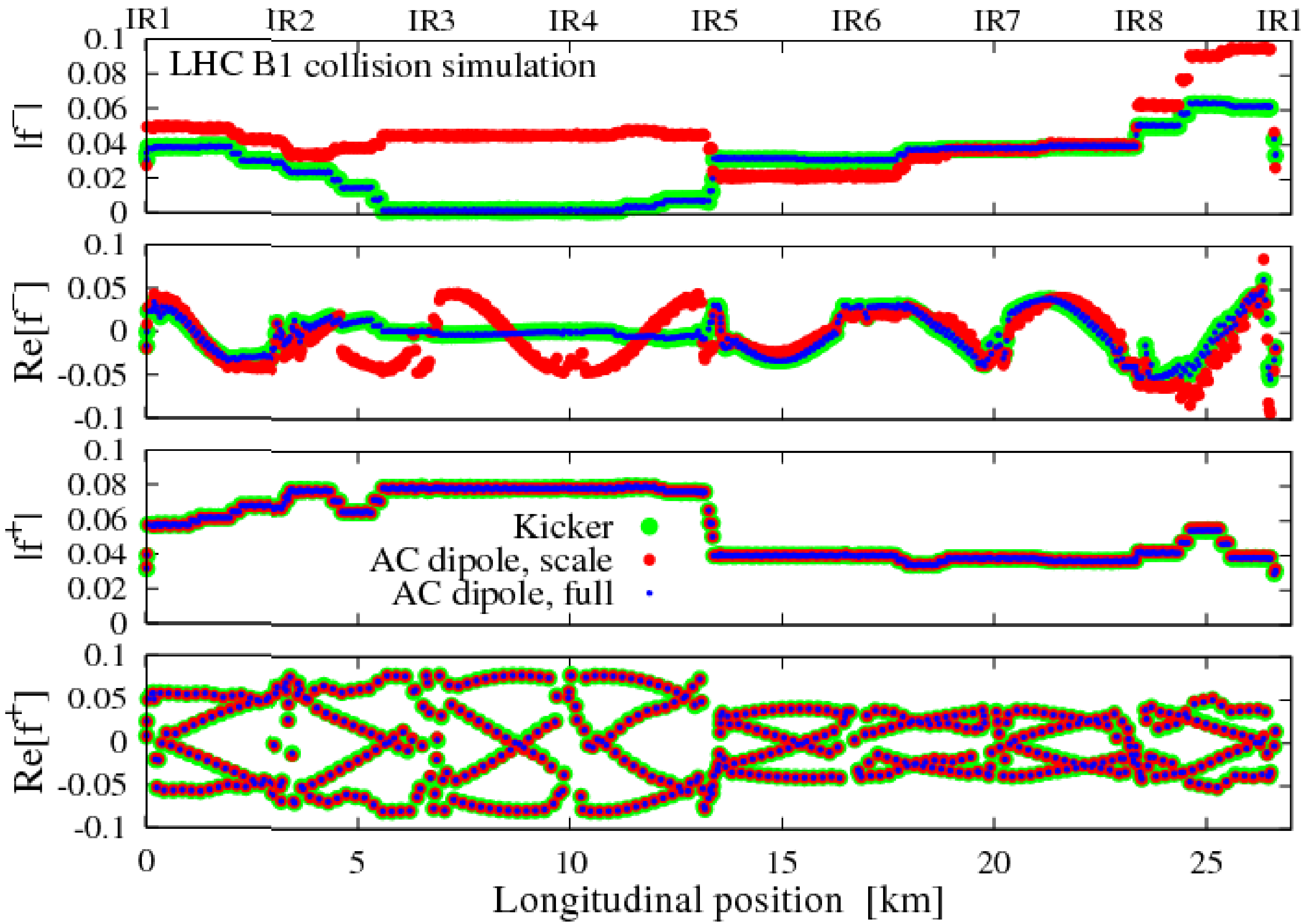


Applications to real data 2



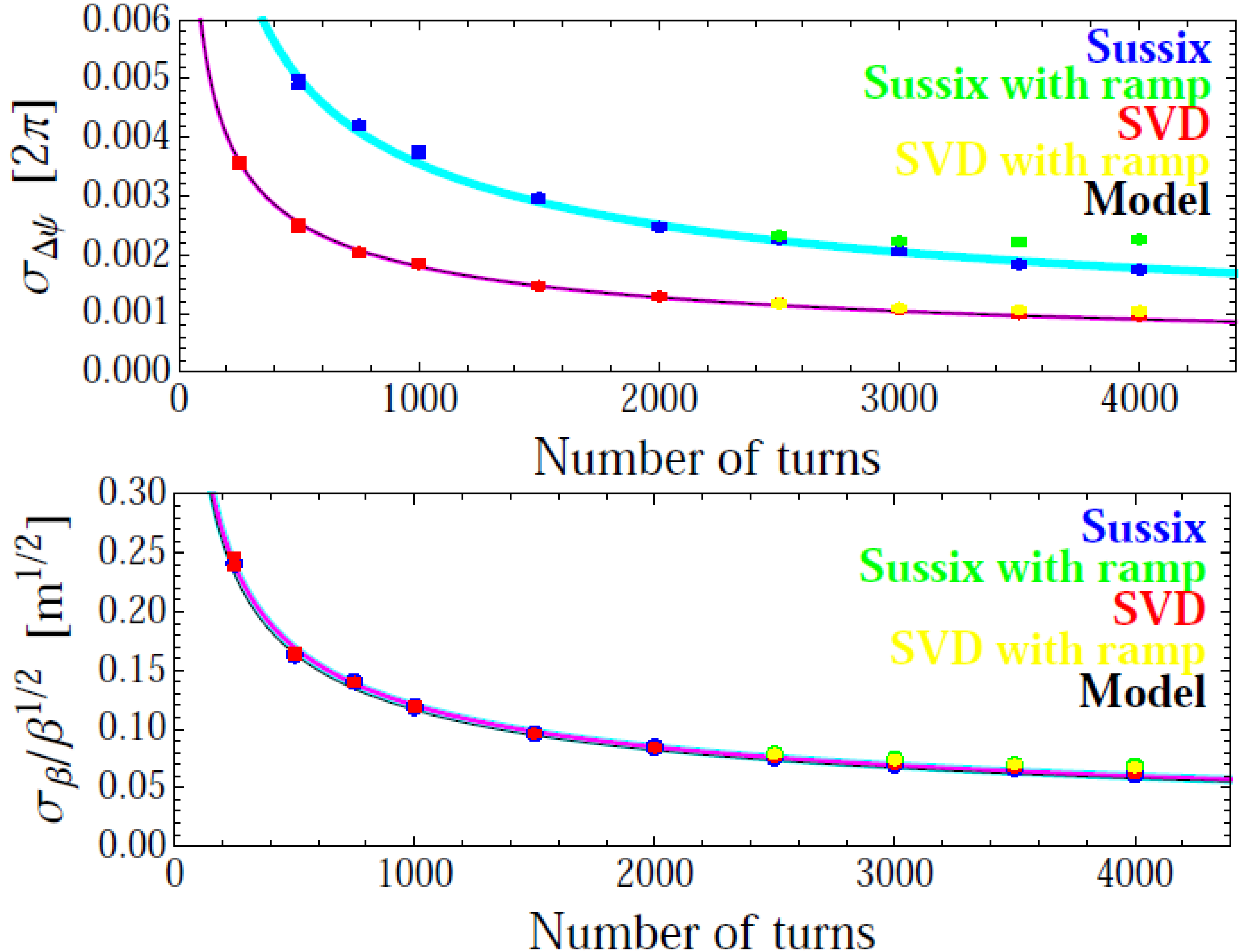
- The simple scaling could be screwed up when the sum (f1010) is not small.
- **No impact on the local correction based on SBS technique.**

Test with a simulation



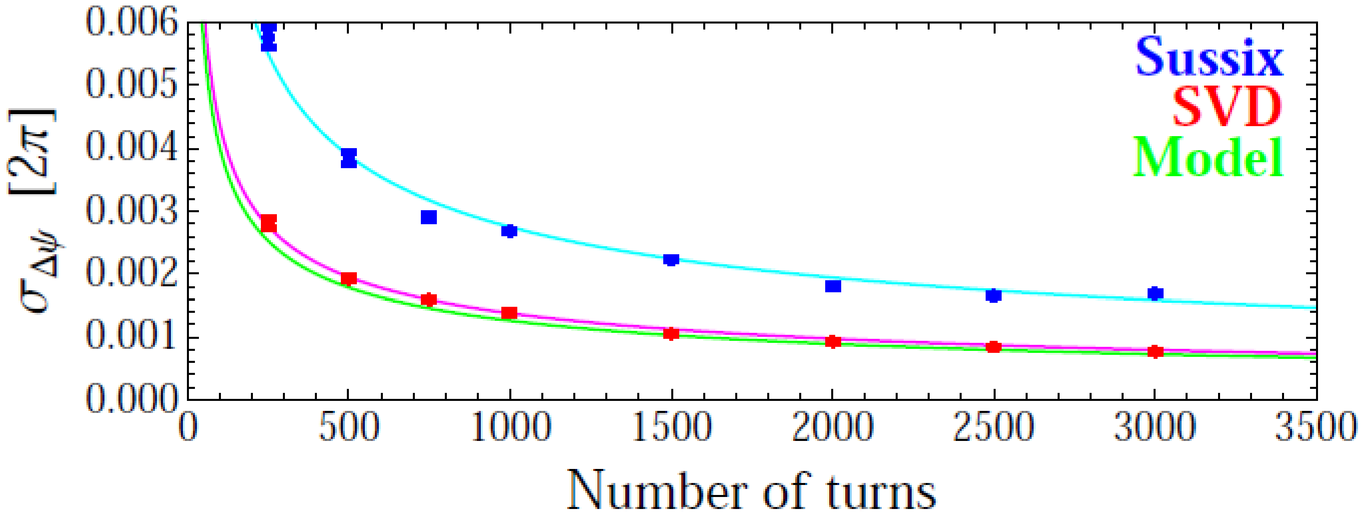
- The model modified based on the measurement.
- The algorithm is verified with the simulation.

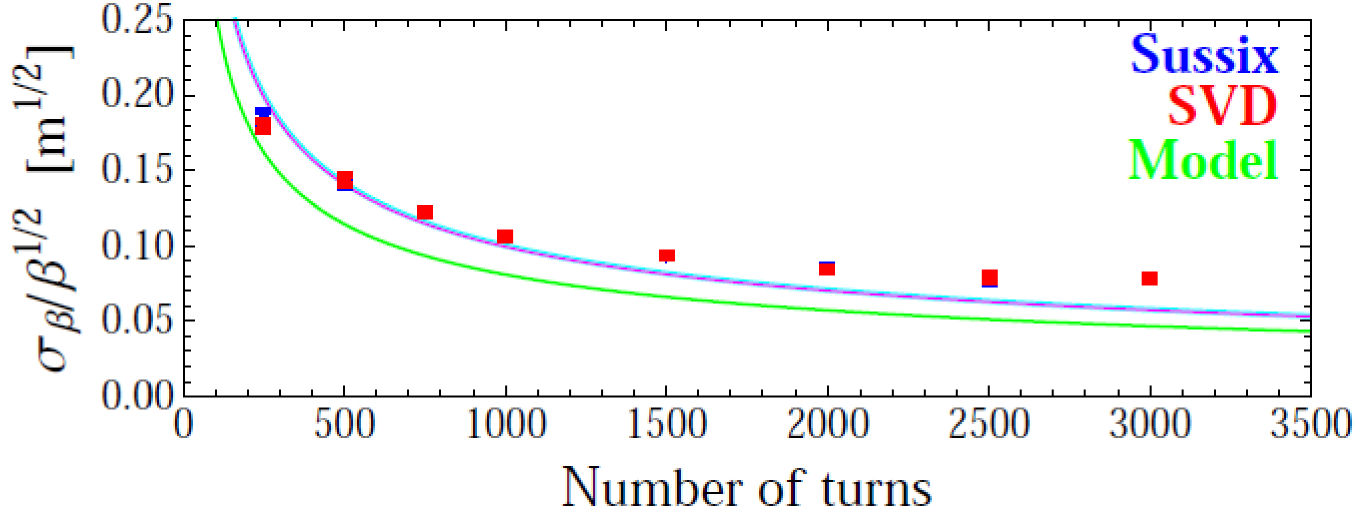
Simulation of the noise effect



- BPM noise (SNL ~ 0.1) is added to simulations.
- The signal from the AC dipole is a pure sine wave and the precision is as predicted from a simple model (except the phase from Sussix) .
- Including the ramp MAY degrade the result.

Measurement of the noise effect





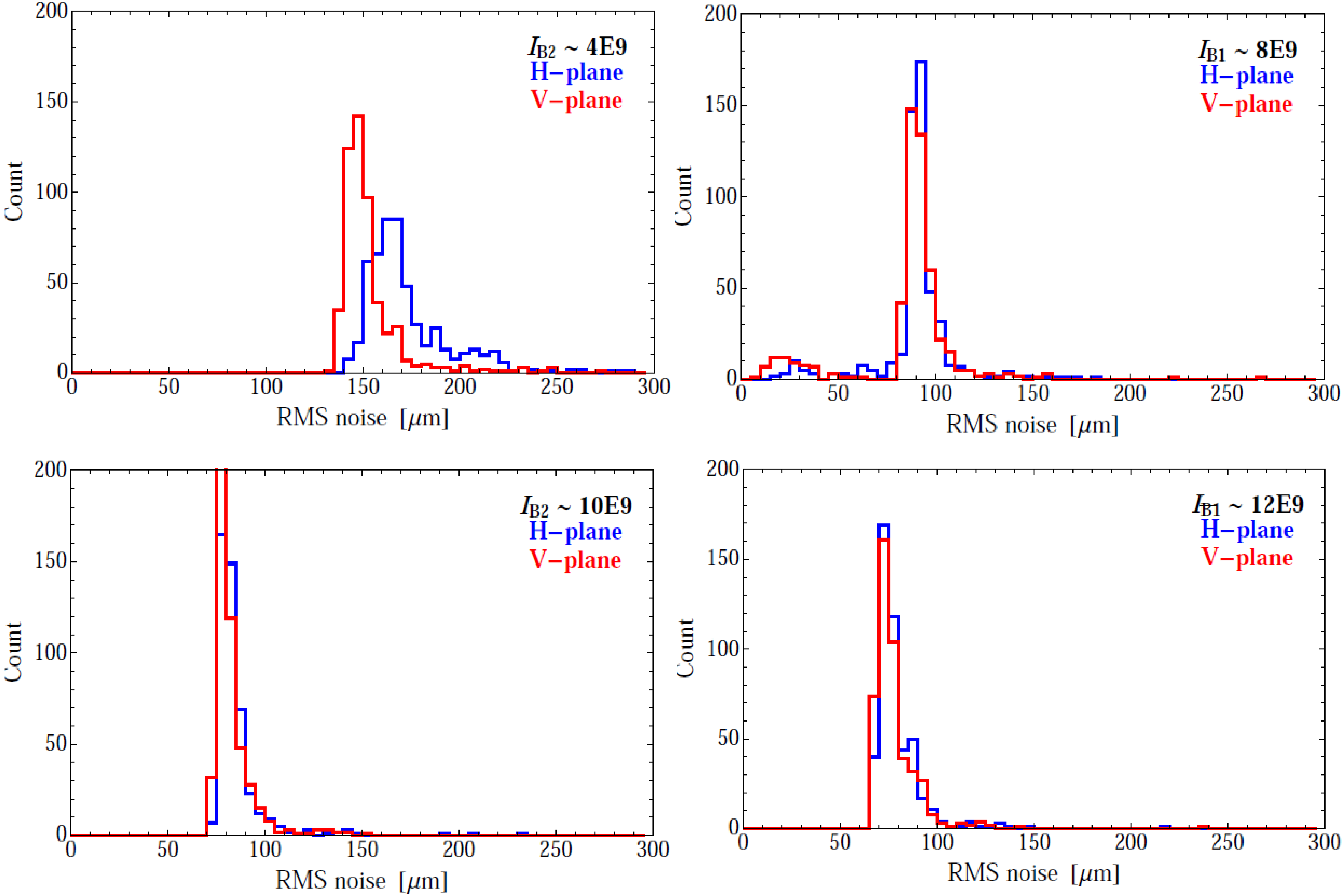
- Behavior of the phase as predicted (SVD as good as the model and Sussix is larger about twice).
- Beta worse that the model unlike the simulation ??
- Intensity was changing for 3 measurements.

Summary and outlook

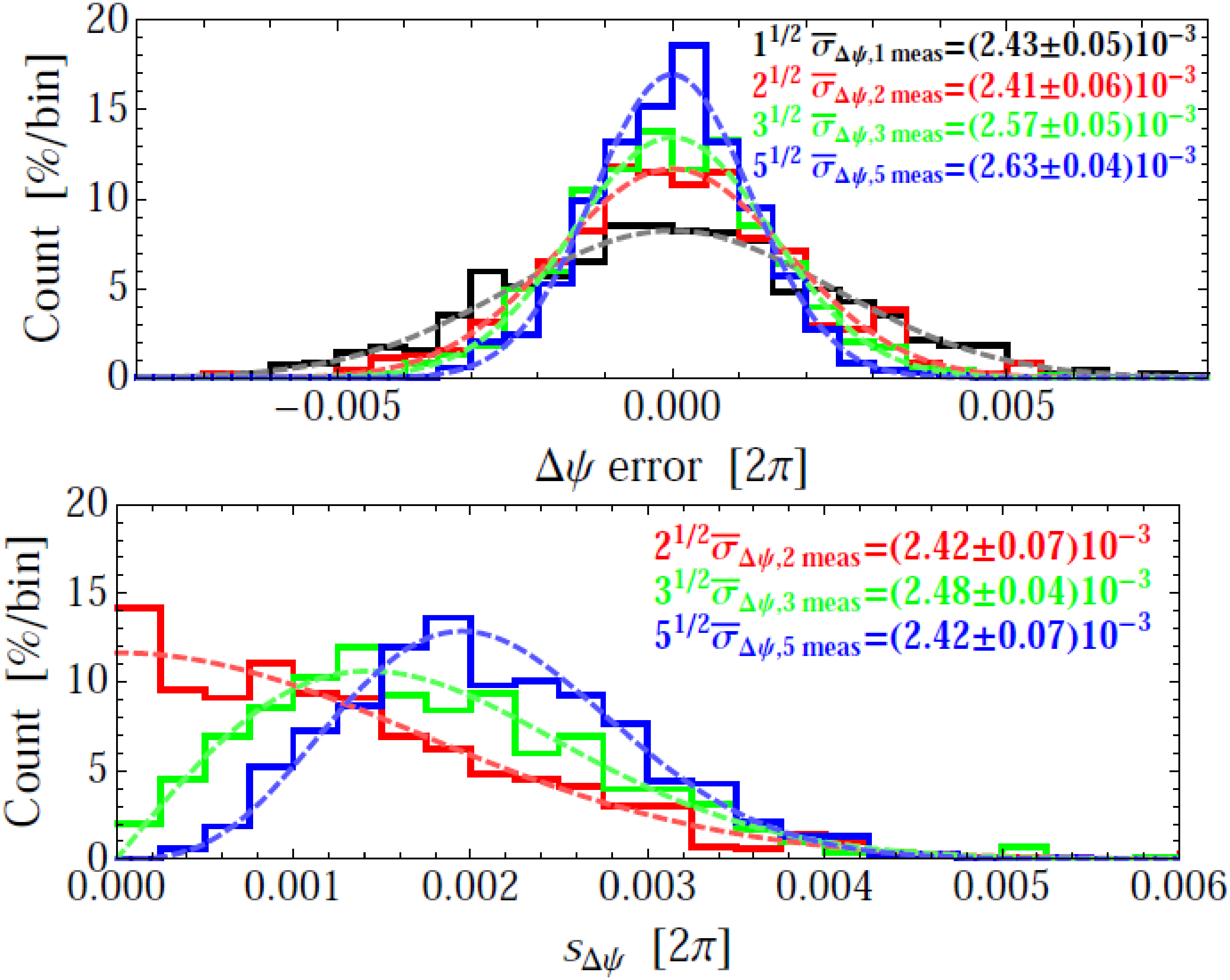
- An AC dipole can produce a sustained transverse oscillation with almost no emittance growth and allows multiple measurements with a single bunch even in a hadron machine. The principle has been tested in various hadron rings and it's been used as the primary excitor in the LHC.
- In 2011, emittance growths have been observed for B2 vertical AC dipole. It may be caused by a synchrotron sideband. A systematic study is ideal for future.
- An algorithm to remove the systematic effect from the AC dipole, based on an introduction of effective optics parameters, have been developed and successfully applied to the LHC.
- The algorithm was extended to the coupling resonance driving terms and tested in simulations and experiments. The extension to other nonlinear resonance driving terms is straightforward
- The signal from an AC dipole is almost a pure sine wave and provide a statistical precision almost as good as predicted from a simple model (except for the phase reconstructed from Sussix).

Backup slides

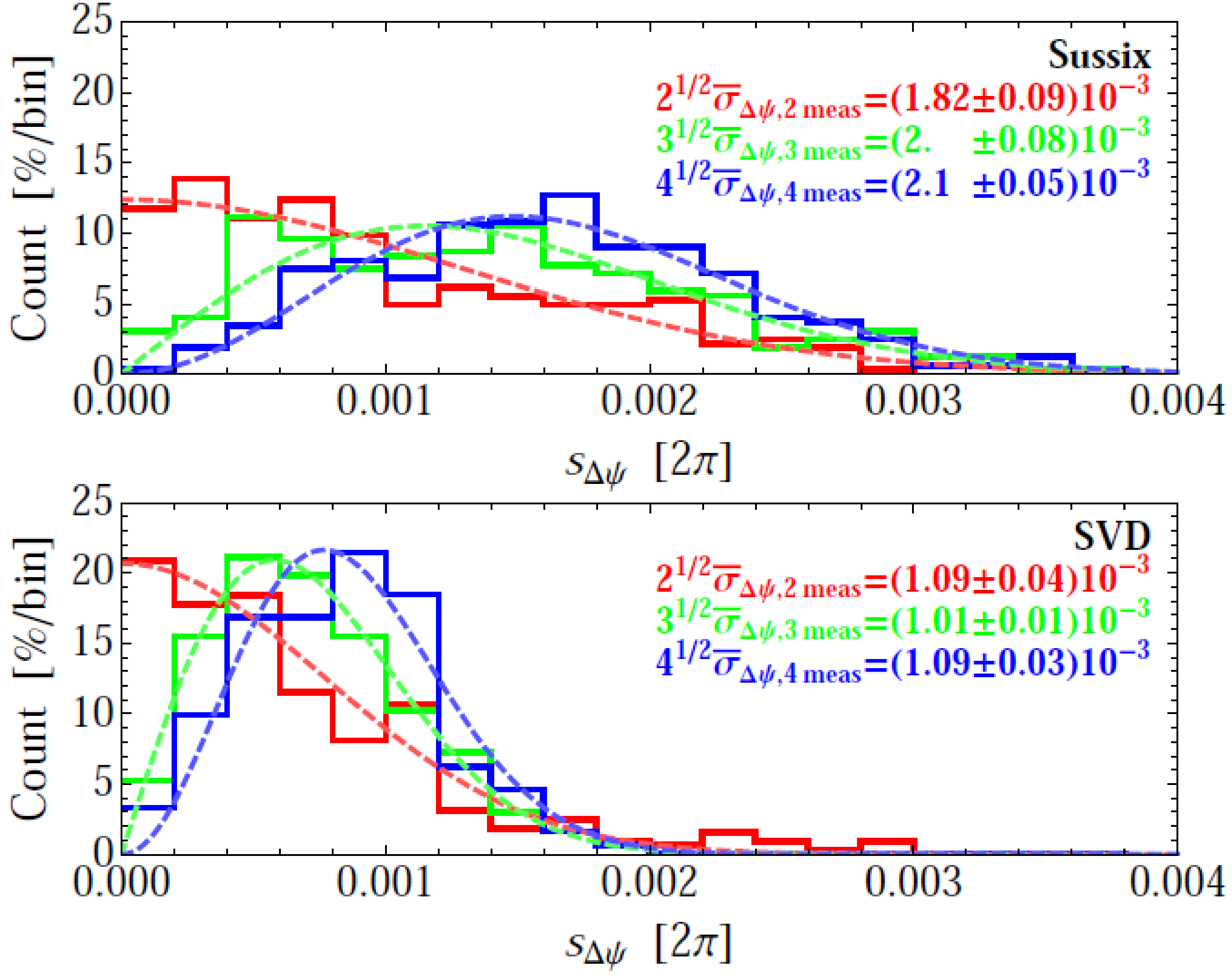
BPM RMS noise



Distribution of the phase error (sim)



Distribution of the phase error (data)



Distribution of beta error (data)