LHC Single Beam DA: measurements vs simulations

Ewen H. Maclean

Studies in collaboration with R.Tomás, M.Giovannozzi, F.Schmidt, T.H.B.Persson & R.Appleby, with many thanks to the LHC optics measurement and correction team

Many thanks to the LHC@home volunteers!

Compensation & understanding of the nonlinear single-particle dynamics has begun to emerge as an operational constraint in LHC Run 2

7th Evian Workshop: Nonlinear optics commissioning in the LHC

Single beam DA is expected to be a significant challenge for the High-Luminosity LHC upgrade

Optics Measurement and Correction Challenges for the HL-LHC, CERN-ACC-2017-0088

→ Since 2011, a program of beam-based measurements has studied NL-dynamics throughout the LHC cycle

DA is a key observable & figure-of-merit for LHC. Examined via 3 methods:

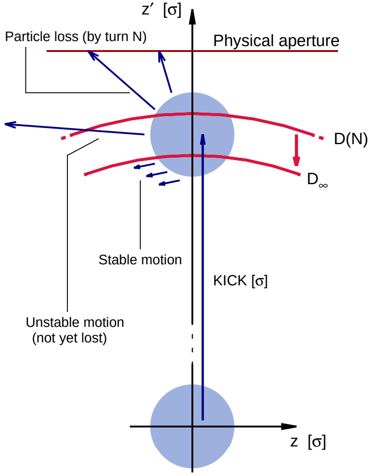
Long-term dynamic aperture (free oscillations):

- Conventional measurement via single kicks
- Measurement of long-term evolution of DA with heated beams

Short-term dynamic aperture:

- Short term DA of driven oscillations
  (seen next talk by F.Carlier)

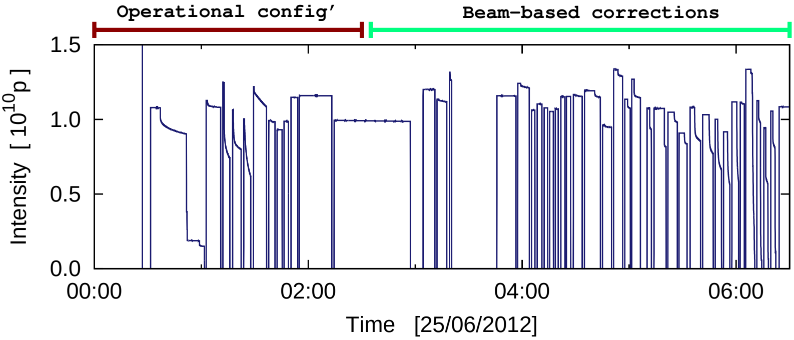
Measurement via single kicks



- **LHC 'aperture kicker' dipole ramps up/down in $\sim 1/2$ turn**
- **Provide large amplitude displacement of pilot bunch ($\sim 10^{10} p$)**
- **Kick action determined from TbT BPM position data**
  $\rightarrow (0.5 \times \mathit{Peak\text{-}to\text{-}Peak})^2/\beta$
- **Beam-loss following kick determines distance between kick and DA(N)**

First detailed measurements performed in 2012 (LHCB2) to study DA and amplitude detuning

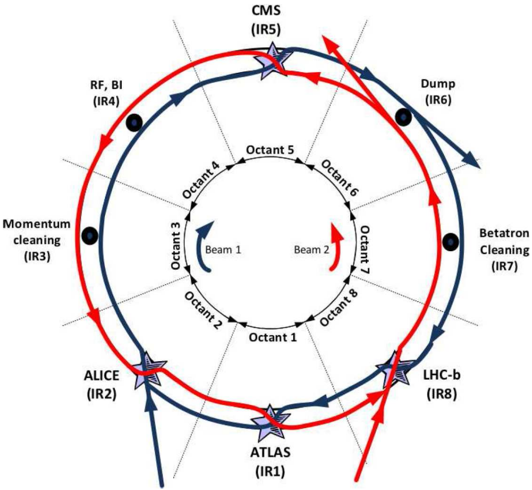
E.H. Maclean, R. Tomás, F. Schmidt, T.H.B. Persson, Phys. Rev. ST Accel. Beams 17 081002 (2014)



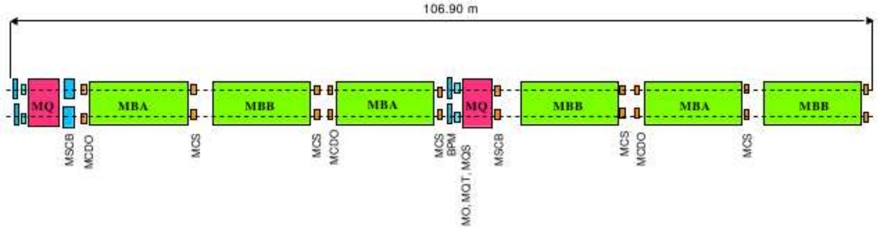
Two configurations examined at injection:

- **Operation configuration:** Landau octupoles (MO) for instability damping
  → Measurements in H & V planes
- **Corrected configuration:** MO off + beam-based correction for b_4 & b_5 errors
  → Measurement in H, V, & diagonal

NL-dynamics at injection dominated by sources in LHC arcs



NL-dynamics at injection dominated by sources in LHC arcs



MQT: trim quadrupole

MQS: skew trim quadrupole

MO: lattice octupole

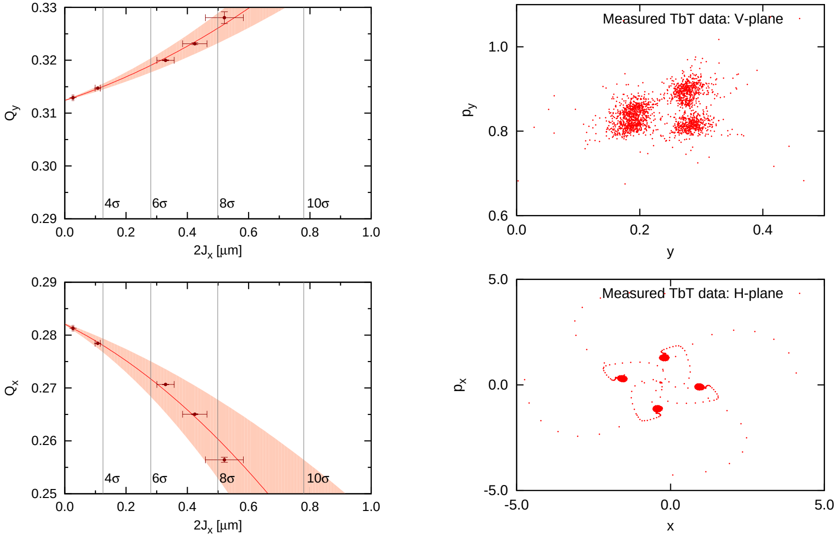
MSCB: sextupole (skew sextupole) + orbit corrector

MCS: spool piece sextupole

MCDO: spool piece octupole + decapole

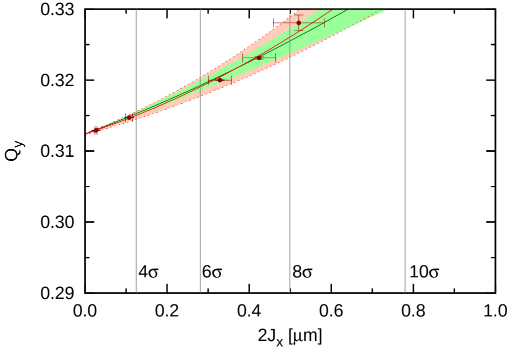
Operational config', H-plane:

- **Observe large first and second order detuning-with-amplitude**



- **Simultaneously reach 3rd and 4th order resonances**

- **Compare measured detuning to best-knowledge model:**
  measured errors, measured alignments, octupole hysteresis

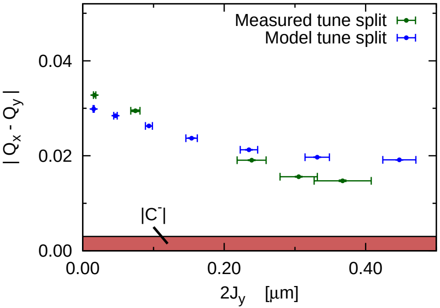


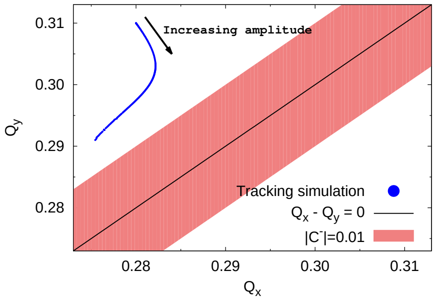
	[unit]	Meas'	± err	Model	± err
$\frac{\partial Q_x}{\partial \epsilon_x}$	$[10^3 m^{-1}]$	−29	7	−27	1
$\frac{\partial Q_y}{\partial \epsilon_x}$		19	3	21	2
$\frac{\partial Q_x}{\partial \epsilon_y}$		24	4	21	2
$\frac{\partial Q_y}{\partial \epsilon_y}$		−33	1	−31	1
$\frac{\partial^2 Q_x}{\partial \epsilon_x^2}$	$[10^9 m^{-2}]$	−60	30	−14	4
$\frac{\partial^2 Q_y}{\partial \epsilon_x^2}$		34	10	18	9

- Single biggest source of uncertainty in NL-model is linear coupling (see **IPAC'17 WEPIK092** and reserve slides)

Operational configuration, V-plane:

Main feature observed is **Amplitude dependent closest tune approach**
→ **Action dependent analogue of ΔQ_{min} from $|C^-|$** (PRSTAB 17 081002, IPAC'15 TUPTY042)

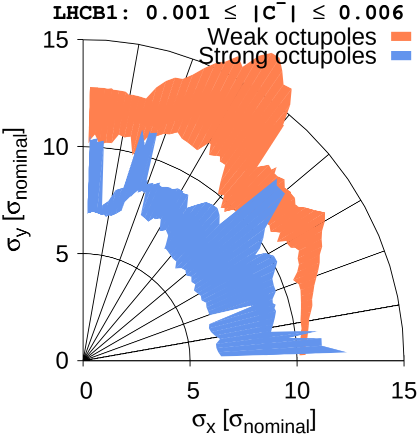




- **Major source at $450\,\mathrm{GeV}$ is linear coupling + h_{1111} (cross-term detuning)**
- Mechanism has been proposed: **R.Tomás,T.Persson,E.Maclean, PRSTAB, 19, 071003 (2016)**
- Predictions validated during 2016 LHC MD (to be published)

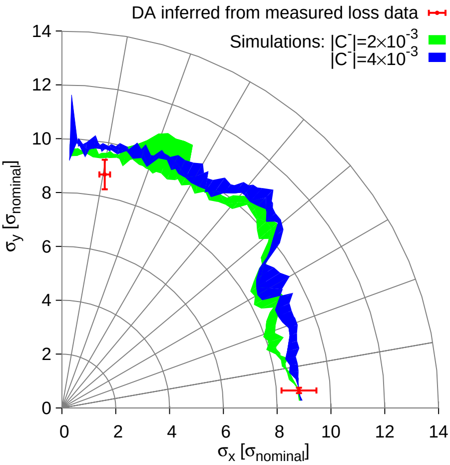
We believe we have a good understanding of the dynamics in H & V planes

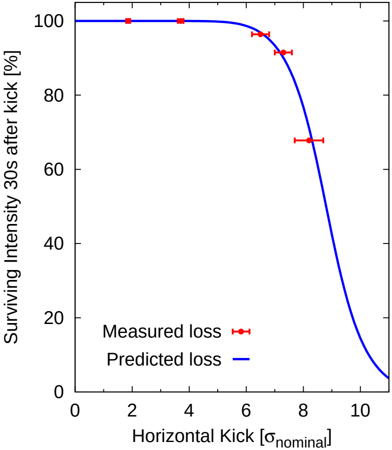
- **Linear coupling has a major influence on the observed behaviour**
- **This also translates into a large influence on dynamic aperture**



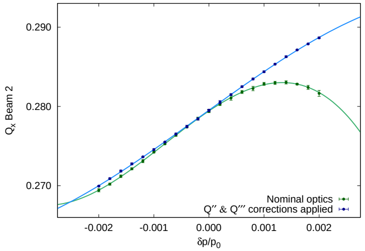
- **Match coupling in DA simulations measured values, with spread reflecting coupling measurement quality**

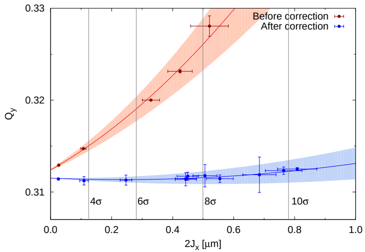
Compare DA 30s after kick to best-knowledge model in SIXTRACK

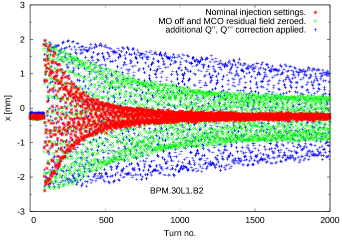


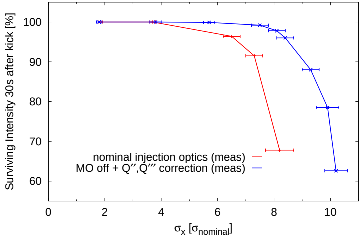


Corrected configuration, with beam-based minimization of Q'' & Q'''





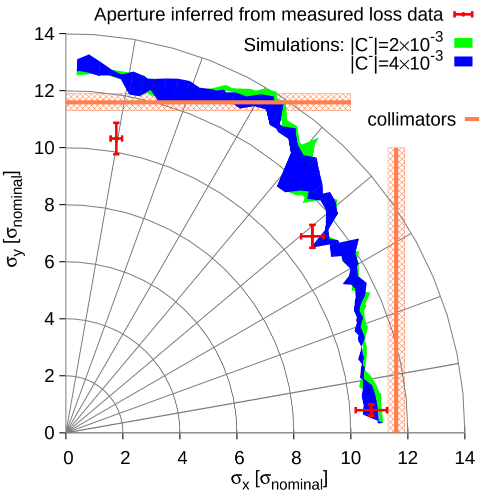


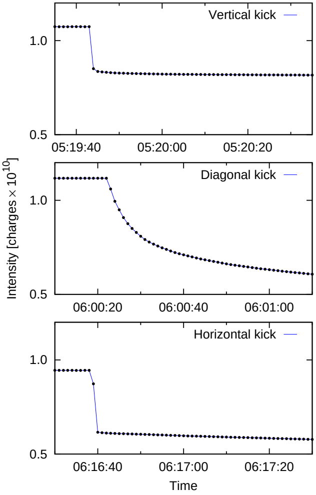


- **Improved decoherence, detuning, & DA**
- **Beam-based correction operational at injection since 2015**

Compare DA 30s after kick to model in SIXTRACK

→ residual NL-chroma matched in NL-model





- **Losses in H & V consistent with physical aperture**

DA measured via single-kicks shows excellent agreement to model predictions at injection (within 10 %)

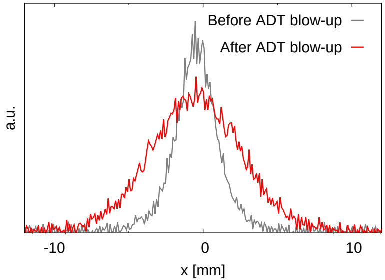
But single-kick method suffers from some limitations:

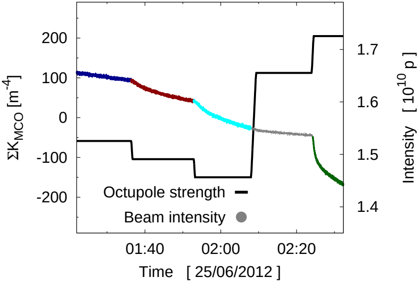
- Time consuming to measure full parameter space in σ_x/σ_y angles
- Only possible to measure at injection:

  → machine protection concerns
  (large, rapid losses upon kick risk quench, or even damage!)

  → require fresh injection after every kick

Measurement of DA evolution using transverse damper





- **LHC transverse damper (ADT) used to blow-up bunch to large emittance**
  - → viable method @ 6.5 TeV
  - → slow heating limits quench risk
  - → blow-up in H+V so sample DA over entire parameter space
- **Examine intensity evolution upon changes in powering of NL-elements**
- **Change to fractional intensity related to an average DA after *N* turns**

$$\frac{I(N)}{I(1)} = 1 - \iint_{D(N)}^{\infty} \rho \, \mathrm{dA} = 1 - e^{\frac{D^2(N)}{2}}$$

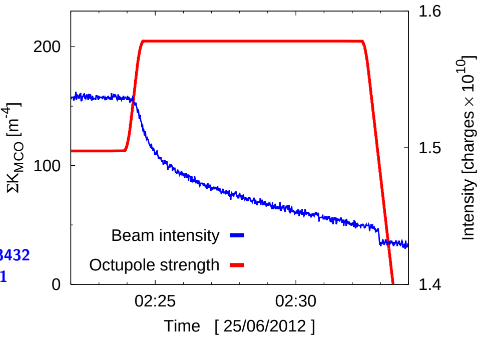
- **Normalize to standard DA units using synchrotron telescope profile data**

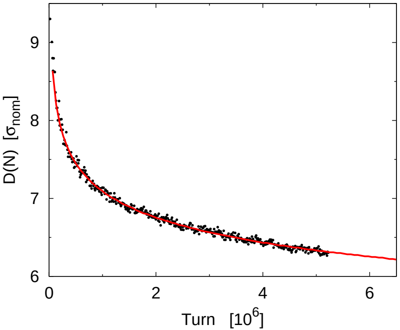
Aim not only to measure DA at given time, but also as function of turns

- Apply scaling law to measured/ simulated DA:

$$D(N) = D_\infty + \frac{b}{(\log N)^\kappa}$$

M.Giovannozzi, W.Scandale, E.Todesco, Phys. Rev. E 57 3432
M.Giovannozzi, Phys. Rev. ST Accel. Beams 15, 024001



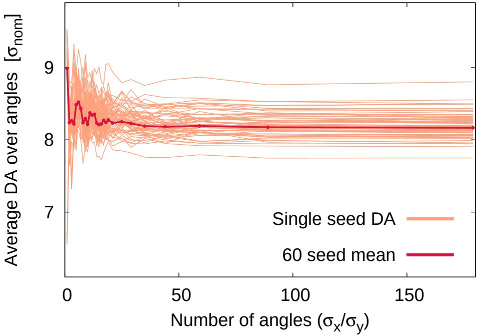


- **Allows extrapolation of DA to operational timescales**
  - → 2.5 hours ≡ 10^8 turns
  - → typical LHC simulation is 10^5 - 10^6 turns
- **Provides more robust test for comparison of measurement to simulation**

Basic model for comparison very similar to study with kicked beams on Beam 2:

- Measured normal/skew errors from 2-pole to 15-pole → 60 instances ('seeds') to account for measurement uncertainties
- Measured alignment errors
- Applied settings of octupole/decapole/skew-sextupole correctors
- Match $Q_{x,y}$ & $Q'_{x,y}$ with quadrupole/sextupole correctors
- Some beam-based input: octupole hysteresis, decapole feed-down

Ensure limits on model/measurement comparison come from machine knowledge rather than simulation parameters



Study DA saturation with simulation granularity

- e.g. Number of angles → use 60
- **Large number of tracking simulations per configuration (∼2e6)!**
- **Volunteer computing essential to success**

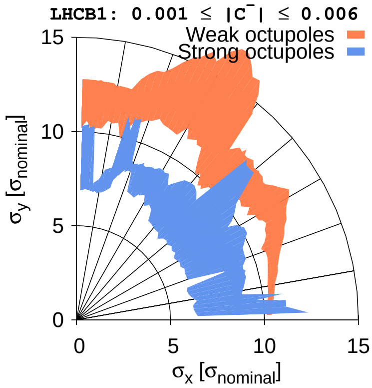
LHC@home

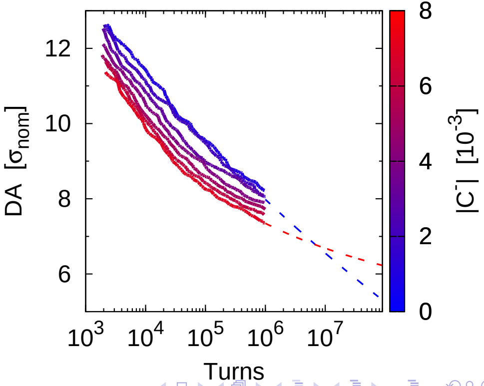
N.Hoimyr et.al J.Phys.Conf.Ser. 396 032057

Closed orbit / beta-beat checked to have small impact on predicted DA evolution (see reserve slides)

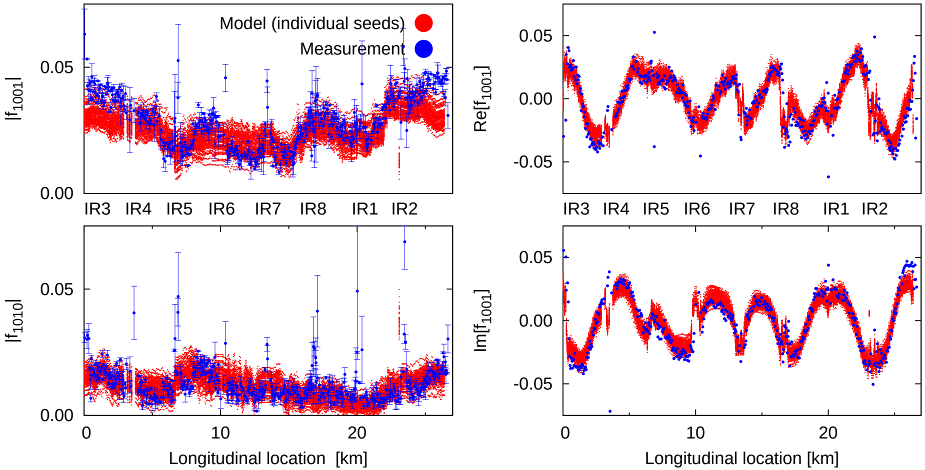
Linear coupling can have a very large impact on LHC DA (IPAC'17 WEPIK092)

- Typical operational range of $|C^-|$ has larger effect than uncertainty on magnetic measurements
- Accurate coupling model is a priority for comparison to measurements





- **Match amplitude/phase of linear couling resonance driving terms to earlier studies with AC-dipole, & injection oscillations during DA measurements**

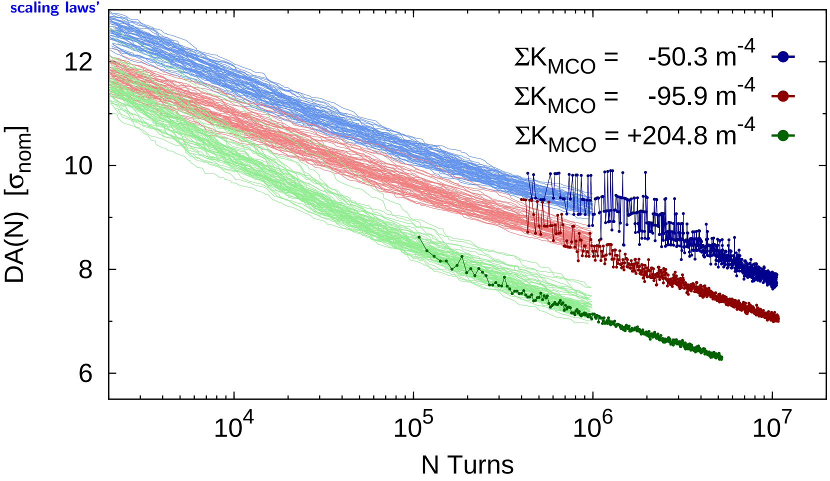


- **For new measurements ensure coupling is well corrected & include witness bunch to monitor linear coupling RDTs**

Comparison of modelled and measured DA

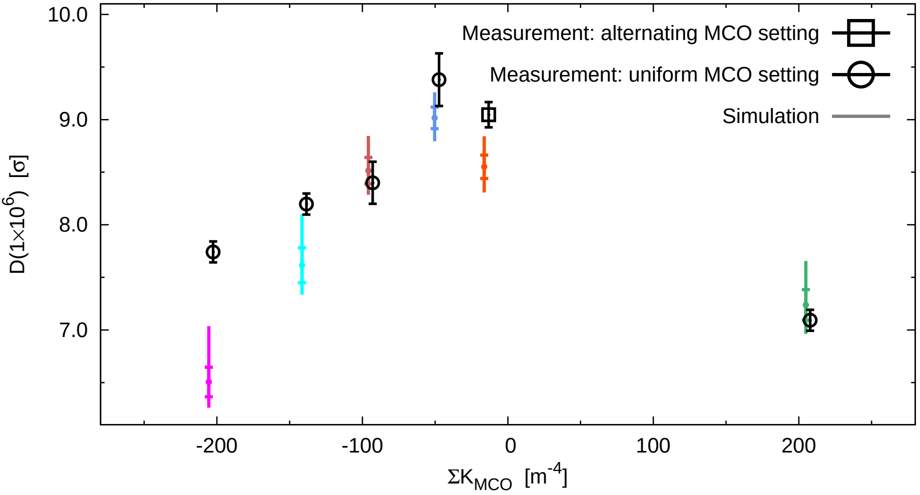
In preparation: E.H.Maclean, M.Giovannozzi & R.Appleby

'Novel method to measure the extent of the stable phase space region of proton synchrotrons using Nekoroshev-like scaling laws'

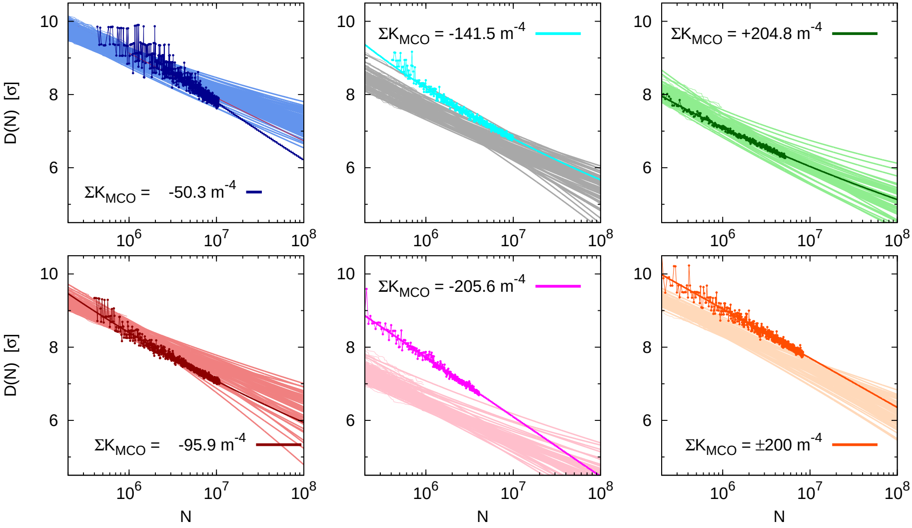


- **Successful measurement of DA vs octupole strength via blow-up with transverse damper**

Comparison of modelled and measured DA at 10^6 turns, for full range of octupole corrector strength



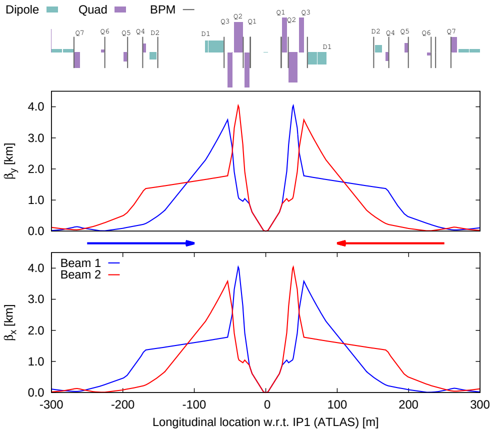
Extrapolation of measured & simulated DA via scaling law



- Measured and simulated dynamic aperture agree within 10 %, over wide range of octupole strength

Correction of NL-errors in low-β^* IRs is a major motivation for DA studies in LHC

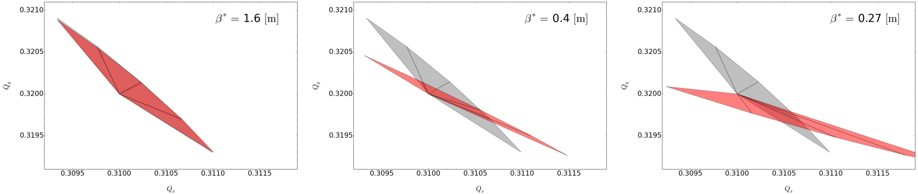
- Significant impact due to large $\beta_{x,y}$ in triplets and separation dipoles, e.g. IP1@$0.6\,\mathrm{m}$



- High-Luminosity (HL)-LHC upgrade planned for 2025
  $\rightarrow$ increase β^* reach to $\sim 0.15\,\mathrm{cm}$

NL-errors in low-β^* IRs have potential to affect many key properties

- **Lifetime reduction** → single-beam DA is a serious concern for HL-LHC upgrade
- **Normal octupole errors distort Q-footprint during β^*-squeeze**
  → affects Landau damping of instabilities

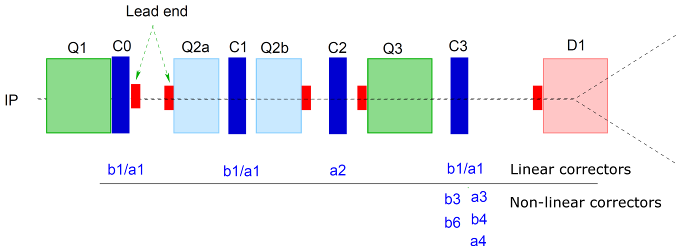


MO footprint, **MO+IR-b_4 footprint**

- **Observe/predict large feed-down to linear coupling from X'ing & sep bumps**
  → can distort footprint causing loss of Landau damping
- **Feed-down in IR also generates beta-beating**
  → detrimental to ATLAS/CMS luminosity imbalance
  → potential > 20 % beta-beating due to sextupole feed-down in HL-LHC
  → Not just problem of machine optimization: machine protection!

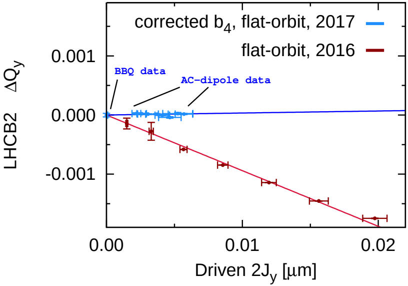
Dedicated nonlinear correctors for sextupole→dodecapole, located left/right of all experimental IRs

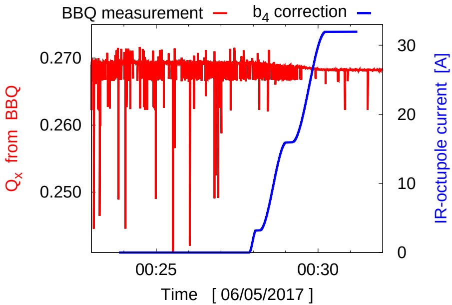
- **LHC:** b_3, a_3, b_4, a_4, b_6
- **HL-LHC:** b_3, a_3, b_4, a_4, b_5, a_a5, b_6, a_6



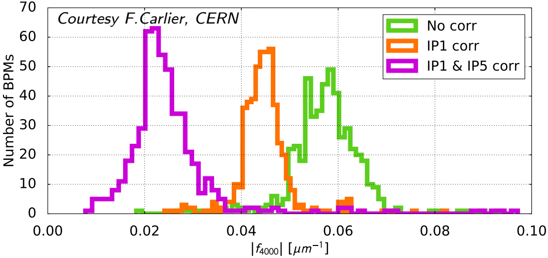
First commissioning of NL-corrections in LHC experimental IRs implemented in 2017

Normal octupole corrections determined to locally compensate amplitude-detuning generated in IR1 & IR5 at $\beta^* = 0.4\,\mathrm{m}$

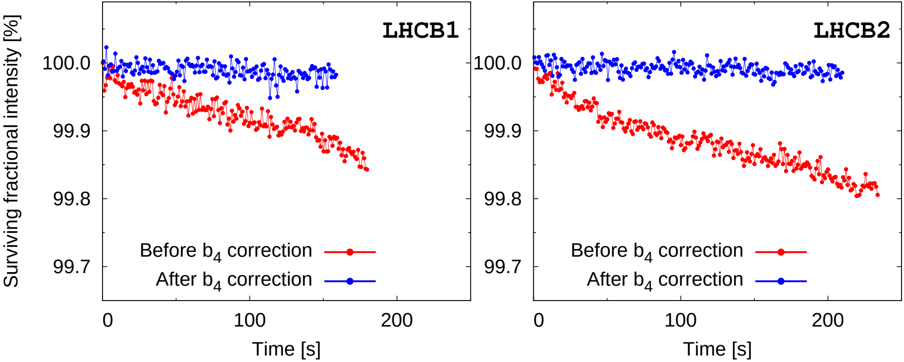




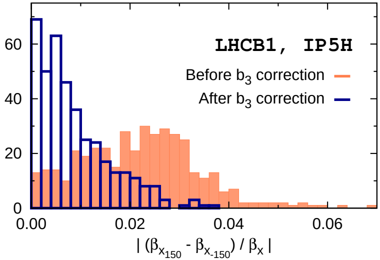
- **Improved online tune & coupling measurement**
- **reduced strength of $4Q_x$ resonance**



Normal octupole correction improved lifetime at $\beta^* = 0.14\,\mathrm{m}$
(machine development test to probe β^* reach of collider)

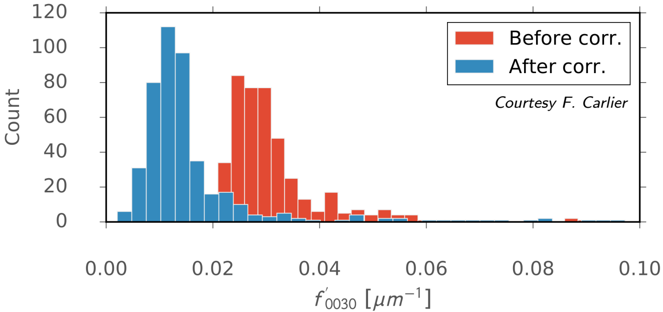


Normal/skew sextupole in IR5 & IR1 corrected by minimizing linear shift of tune with crossing angle



- **Improved stability of linear optics with crossing-angle**
- **Reduced strength of $3Q_y$**
- **Skew octupole correction applied to minimize feed-down to coupling RDTs**

(see reserve slides)



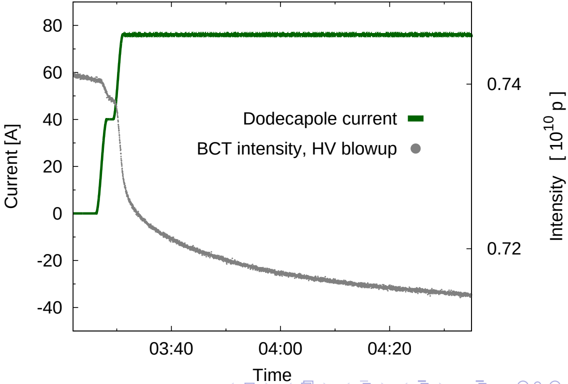
Very high-order errors are hard to measure:

→ **direct DA compensation may be best method**

→ **First detailed measuremens at** $6.5\,\mathrm{TeV}$ **several weeks ago (**$\beta^* = 0.4\mathrm{m}$**)**

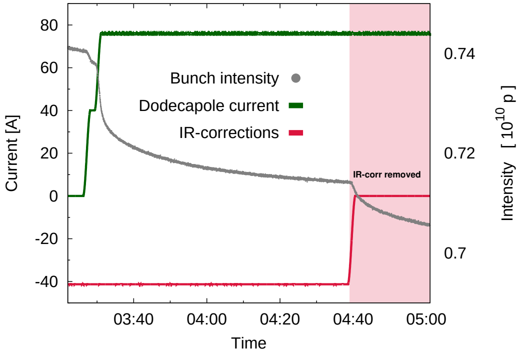
- **Biggest challenge was finding the DA!**
- No losses observed for operational powering of Landau octupoles
- Only saw significant losses with dodecapole correctors in experimental IRs powered to maximum strength

- **DA** $> 10\,\sigma_{\mathrm{nom}}$ **for operational configuration of octupoles**
- **Max dodecapole powering reduced DA to** $\sim 8\,\sigma_{\mathrm{nom}}$
- dodecapole effects scale rapidly with $(\beta^*)^{-3}$



In 2017 LHC operated with local corrections for normal/skew sextupoles & normal/skew octupoles in low-β^* IRs

- **Clear practical benefits to operation:**
  $\rightarrow$ instrumentation & understanding/damping of instabilities
- **Does optimization of indirect observables (e.g. feed-down) improve DA?**
- **How important is DA in relation to other parameters influenced by IR-nonlinearities?**

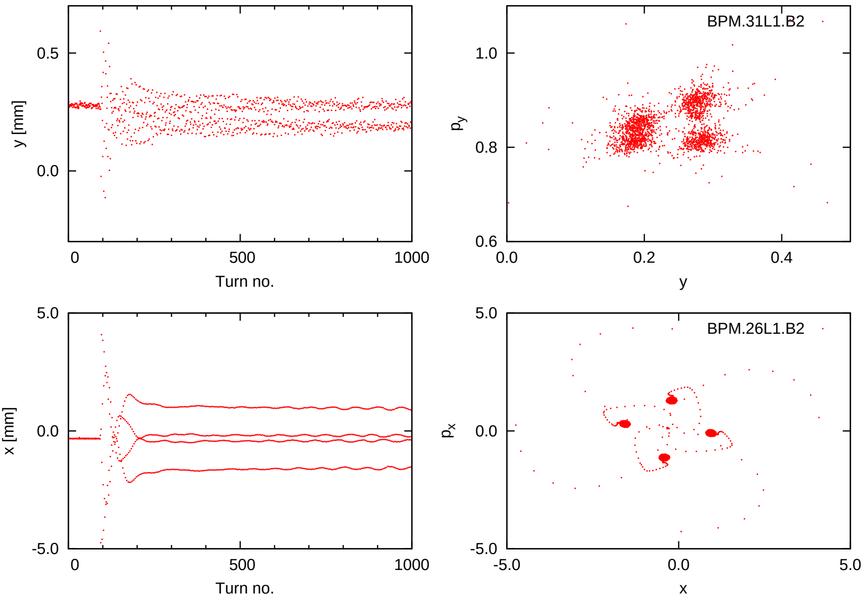


- **Slight improvement to Beam1 DA from to IR-corr**
- **Significant improvement to dynamic aperture of Beam 2**

Conclusions

- **Modelled & simulated DA at LHC injection agree within $10\,\%$ via 2 techniques**
- **Technique based on slow blow-up of bunch with transverse damper validated at injection**
- **First beam-based commissioning for NL-errors at $6.5\,\mathrm{TeV}$ performed in 2017 with promising results**
- **Begun to apply DA measurement at $6.5\,\mathrm{TeV}$ as tool to study high-order NL-errors in experimental insertions**

Reserve Slides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p_y
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Turn no.
BPM.26L1.B2
5.0
0.0
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p_x
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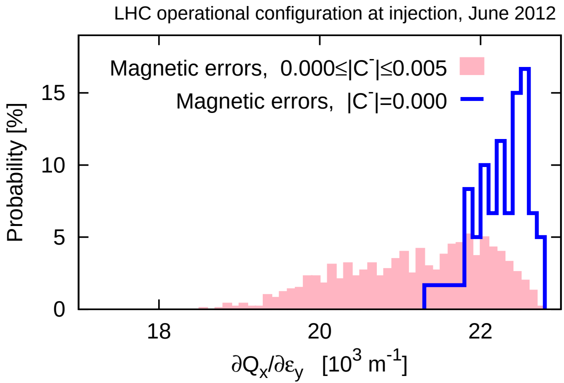
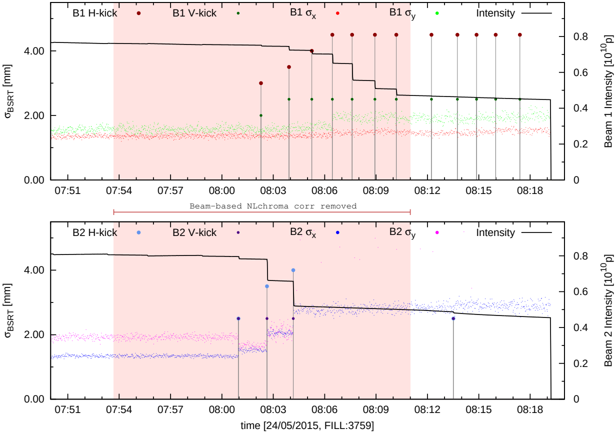
5.0
x

Uncertainty in predicted DA due to typical operational range of $|C^-|$, compared to uncertainty in magnetic measurements



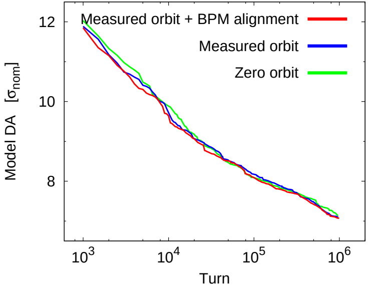
Beam-based correction of Q''/Q''' implemented operationally in 2015

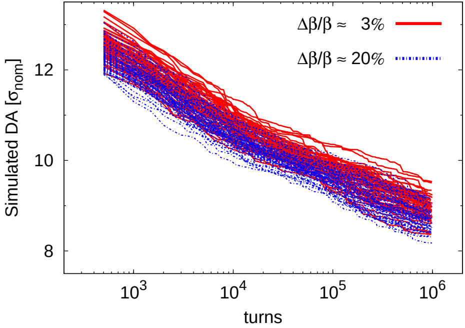
- Significantly improved beam-losses and blow-up upon AC-dipole excitation

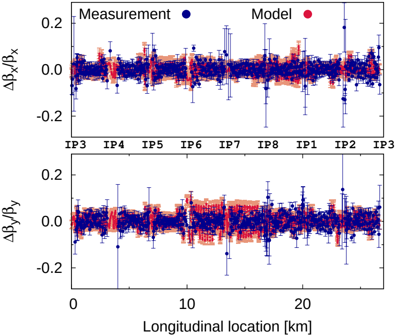


Detailed report found at: **(CERN-ACC-Note-2016-0013)**

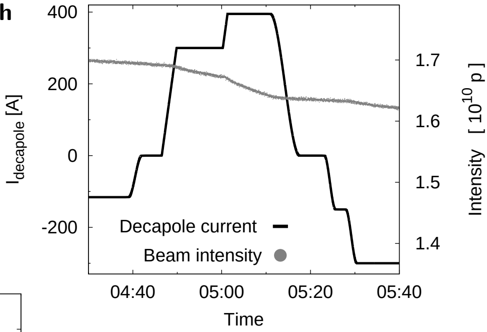
- **Closed orbit and beta-beat have small impact on predicted DA**
  - $\longrightarrow$ replicate operational behaviour to create effective model
  - $\longrightarrow$ avoids large number of virtual correctors, allowing simulations on LHC@home volunteer computing service

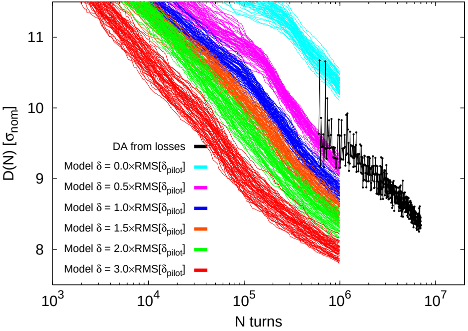






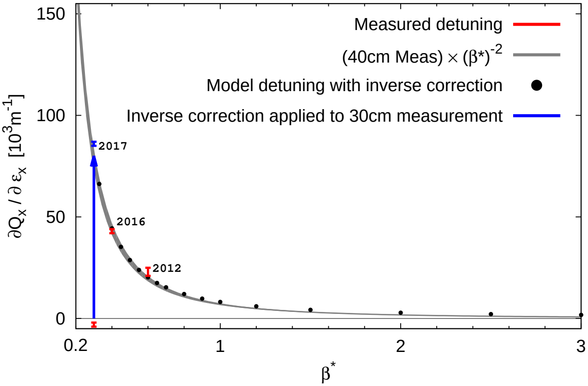
Measurements also performed with varying decapole strength in LHC arcs ($450\,\mathrm{GeV}$)



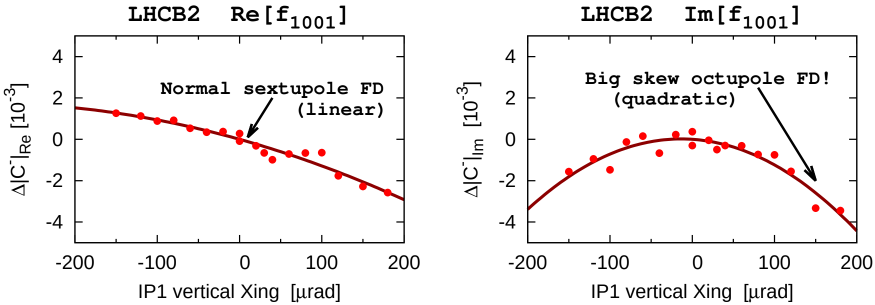


- DA variation with $\delta p/p$ was very small for octupole configurations at $450\,\mathrm{GeV}$
- Strong decapole sources caused large momentum dependent DA in model

- Expect IR-tunespread to scale with $\sim (\beta^*)^{-2}$
- IR-tunespread appears consistent over extended period



Skew octupole compensation at $\beta^* = 0.4\,\mathrm{m}$
→observe large feed-down to linear coupling



Difficult correction → a_4 corrector L1 dead

- **Before correction:** $\Delta|C^-|_{0\to150\mu\mathrm{rad}} = 5 \times 10^{-3}$
- **After correction:** $\Delta|C^-|_{0\to150\mu\mathrm{rad}} = 1.5 \times 10^{-3}$

Important for instabilities during crossing-angle levelling!