Forced DA in the LHC using AC Dipoles

ICFA Mini Workshop on Dynamic Aperture

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Direct DA measurements at top-energy are challenging

Two methods have been used for DA measurements in the LHC.

Measurements with beam heating (**Injection & top-energy**):

- Equally challenging at both energies
- Measure beam losses over time
- Used successfully at top-energy in the LHC

Single kick DA measurements (**injection ONLY**):

- Measure beam losses vs. kick amplitude
- Kicked bunches decohere, thus requiring many machine cicles
- Aperture kicker in the LHC **not allowed at top-energy**, for machine protection

  Can we use another approach similar to single kicks?

Forced dynamic aperture has been proposed as an alternative observable

Beam can instead be coherently excited in transverse plane using AC dipoles.

Procedure very similar to single kick DA measurements:

- Use AC dipoles to excite bunch transversely
- Measure beam intensity losses
- Characterise losses over kick actions

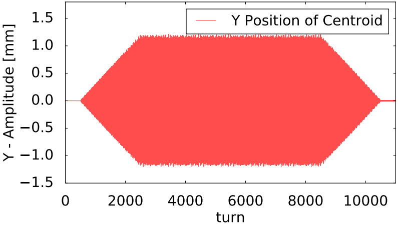
Measure DA under forced oscillations using AC dipoles:

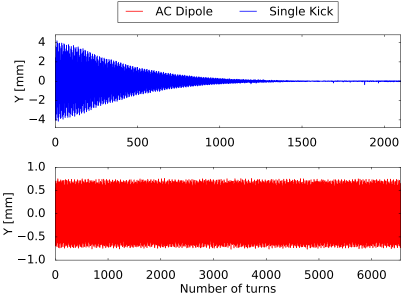
Forced Dynamic Aperture

Provides alternative observable (DA_{forced}) compared to free oscillation DA (DA_{free})

AC dipole vs. Single kick excitations

- AC dipole excitations considered **safe at top-energy** because of slow amplitude ramp-up
- No decoherence, so no recycling needed after excitations → **very fast!**



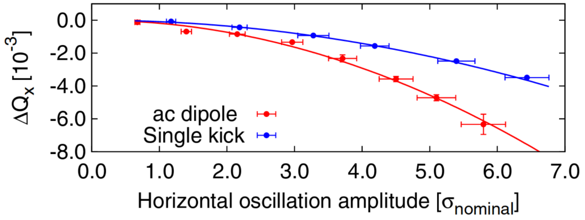


- LHC has two AC dipoles per beam, one for each plane
- **Allows to cover full range of amplitudes and angles**

Direct amplitude detuning with AC dipole is altered

- Amplitude detuning is larger in plane of motion under forced motion

$$
\begin{aligned}
\Delta Q_x &= \frac{q}{p}\frac{3B_4}{8\pi} \cdot (\beta_x^2 J_x^{\text{free}} + 2\beta_x\beta_x' J_x^{\text{forced}}) \\
\Delta Q_y &= -\frac{q}{p}\frac{3B_4}{8\pi} \cdot (2\beta_x'\beta_y J_x^{\text{forced}} + 2\beta_x\beta_y J_x^{\text{free}})
\end{aligned} \tag{1}
$$



S. White, E. Maclean, R. Tomas, PRSTAB 16, 071002 2013

Resonance conditions for forced oscillations are changed

Resonance condition in free motion is given by:

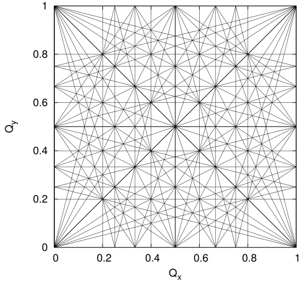
$$(j-k)Q_x + (l-m)Q_y = p \qquad (2)$$

Resonance conditions for forced motion are changed to:

$$(k_1 - j_1)\cdot Q_x + (k_2 - k_3 + j_2 - j_3)\cdot Q_x^{\mathrm{AC}} + (m_1 - l_1)\cdot Q_y + (m_2 - m_3 + l_2 - l_3)\cdot Q_y^{\mathrm{AC}} = p$$

(R. Tomas, PRSTAB, 5, 054001, 2002)

- Larger number of resonances for forced motion
- Free motion resonances still present



(Courtesy, E. Maclean)

Due to extra resonances and larger detuning with amplitude:

$$DA_{forced} \lesssim DA_{free}$$

Forced dynamic aperture is of great interest

Important to improve understanding of motion under forced oscillations:

- Important for HL-LHC where forced DA might not be large enough for linear optics commissioning
- Forced motion arising from other harmonic sources, faulty power supplies, crab cavities, etc..

Forced DA has the potential to:

- Give estimate of lower bound on free DA
- Characterize nonlinear content of the machine
- Improve understanding of nonlinear model
- Validate nonlinear corrections

Action calculations in simulations & measurements

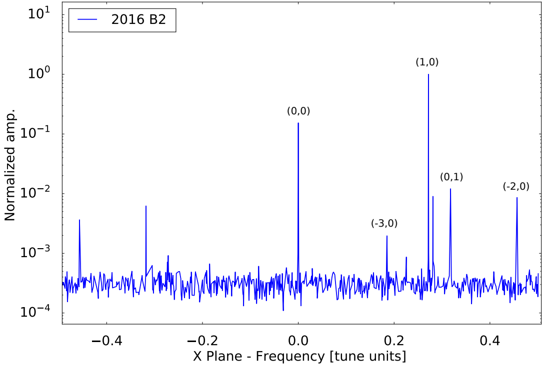
- Actions may not be trivialy described using initial conditions for forced oscillations.
- Actions are calculated from amplitude of main line of spectra from turn-by-turn data (A).
  - Used for all simulations & AC dipole measurements

$$2J_{x,y} = \frac{A^2}{\beta_{x,y}} \,. \tag{3}$$

- This may not be used for single kick measurements due to strong decoherence:
  - Use peak-to-peak amplitude of tbt signal instead $A = P2P/2$

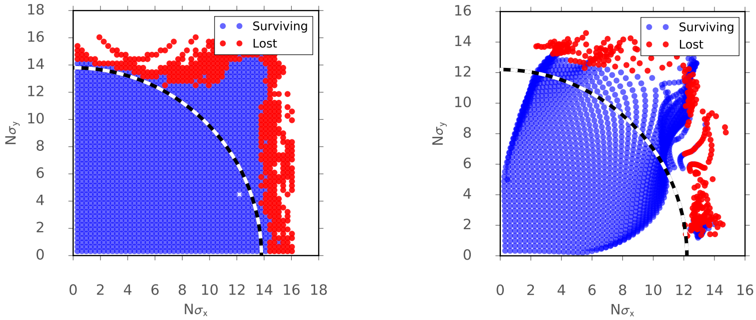
Main line from turn-by-turn data for action calcuation

Main line (1,0) provides actions measurement. In this case AC dipole excitation



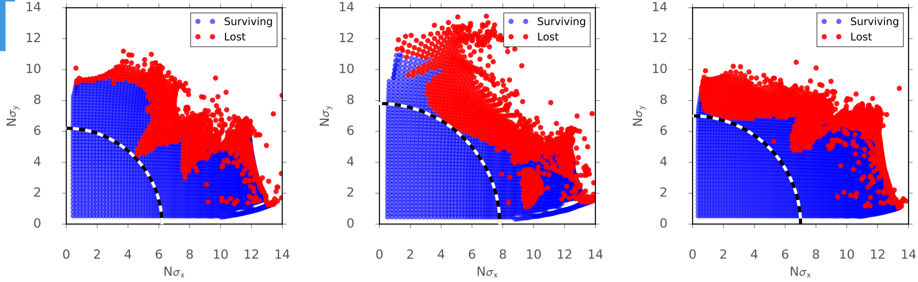
Single particle DA tracking simulations

- Tracking simulations were done for Beam 1 with nominal top energy model of 2016 and magnetic field errors.
- Free DA, with actions from initial conditions (left), from main line (right)



Minimum DA defined as distance to first losses

Simulations of forced DA at top energy at various working points (Q_x^{AC}, Q_y^{AC})



(0.298, 0.332)
$DA_{forced} = 6.2\,\sigma_{nom}$

(0.30, 0.334)
$DA_{forced} = 7.0\,\sigma_{nom}$

(0.295, 0.332)
$DA_{forced} = 7.8\,\sigma_{nom}$

- **Forced DA (6.2 - 7.8 σ_{nom}) smaller than free DA (12.1 σ_{nom})**
- **Forced DA shape and size varies for different working points**

Setup details for measurements at injection

Proof of principle showed at injection

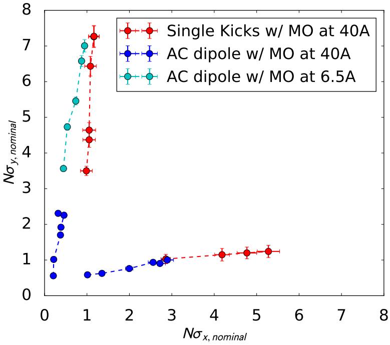
- Single beam (Beam 1) with single pilot bunch ($9 \cdot 10^9$ protons)
- Landau octupoles (MO) powered at 2 different strengths:
  - 40 A (18 m^{-4}) $\rightarrow$ 2016 operational strengths
  - 6.5 A (3 m^{-4}) $\rightarrow$ 2012 operational strengths
- Transverse excitations in H & V planes with:
  - Single kicks using aperture kicker (MKA in LHC)
  - AC dipole

Measure beam intensity losses with BCT as function of excitation amplitude

Summary of excitations at injection

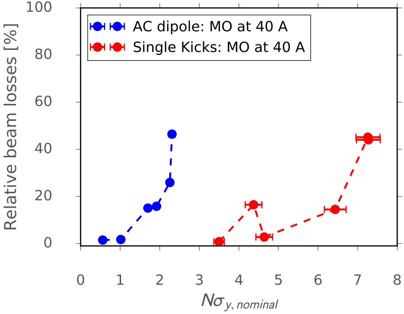
Main tunes and AC dipole working points used for measurements

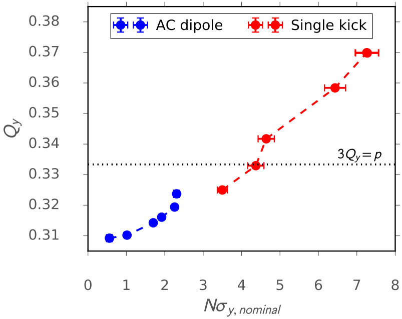
- $Q_x, Q_y = 0.28, 0.31$
- $Q_x^{\mathrm{AC}}, Q_y^{\mathrm{AC}} = 0.262, 0.296$



Vertical free & forced DA measurements

Landau octupoles at 40A (operational settings 2016)

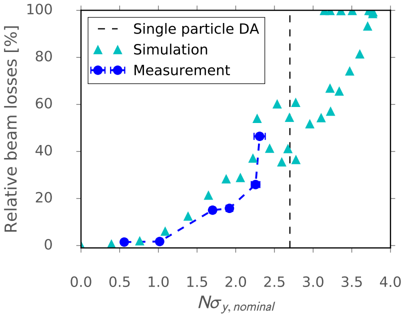




- $DA_{forced} \sim 2.4\sigma_{nom}$ and $DA_{free} \sim 4.3\sigma_{nom}$

Limited by skew sextupolar $3Q_y = p$ resonance

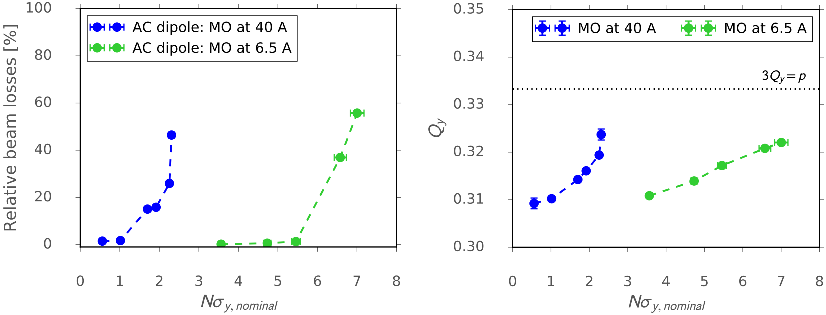
Forced DA measurement compared to multiparticle tracking simulations



- Geometrical rotational errors of multipoles needed to reproduce sources for $3Q_y$ resonance
- Improved understanding of nonlinear model

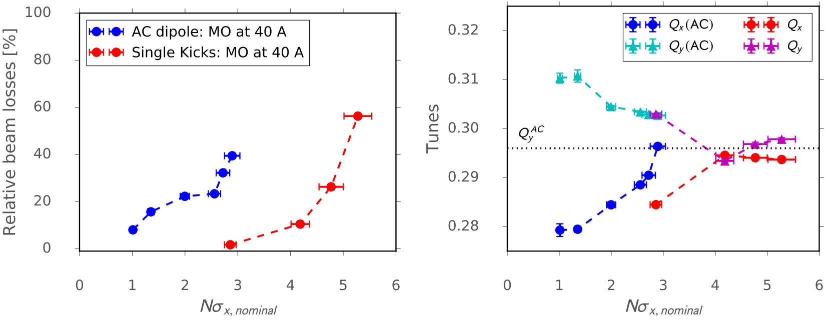
Forced DA with reduced Landau octupole strengths

Landau octupoles at 6.5 A (comparable to 2012 settings)



- Measured increase of forced DA to $\sim 6.7\sigma_{nom}$
- Still limited by $3Q_y = p$ resonance

Horizontal measurement of free & forced DA



- Forced DA at $\sim 2.6\sigma_{nom}$ while free DA at $\sim 5.2\sigma_{nom}$
- The approaching tunes drive multiple coupling resonances: free motion:

Measurement setup at top-energy

First forced DA measurements at top-energy in the LHC

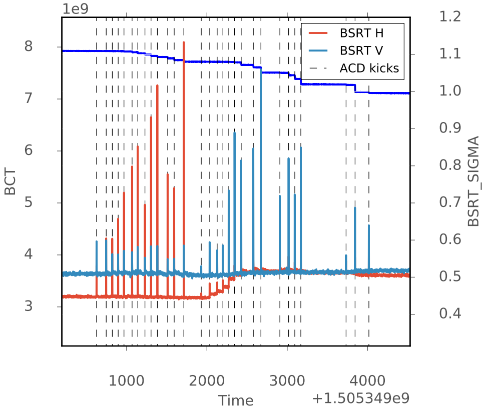
- Single beam: Beam 1
- Single pilot bunch with $9 \cdot 10^9$ protons

Three different measurement settings:

1. Landau octupoles at: 340 A ($10.8\ \mathrm{m}^{-4}$)
2. Landau octupoles at: 450 A ($14.3\ \mathrm{m}^{-4}$)
3. Landau octupoles at: 450 A ($14.3\ \mathrm{m}^{-4}$)
   $+$ Dodecapoles at: 76 A , ($38000\ \mathrm{m}^{-6}$)

Overview of measurements in Beam 1

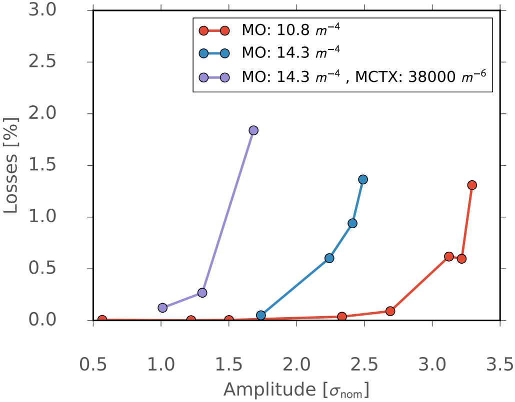
- Losses observed in the BCT data at each AC dipole kick (dashed lines)
- Only minimal blowup in Beam 1 H for vertical kicks in the BSRT data



Observed losses smaller than for injection measurements
$\rightarrow$ machine protection

First measurements of forced DA at top energy

- Small losses observed for the different octupole and dodecapole settings
- Forced DA reduces for increasing octupoles and dodecapoles
- As yet, no forced DA can be quantified → first analyse WS and BSRT



Forced DA decrease observed for increased nonlinear sources

Concluding remarks

- **First demonstration of forced DA measurements at injection and top-energy**
- **Changes in corrector magnet strengths have measurable impact on forced DA**
- **Nonlinear model understanding at injection improved with forced DA measurements**
- **Lower bound estimate on free DA given using forced DA measurements**