Requirements for LHC Tune, Chromaticity & Coupling Measurements

Tune Feedback Workshop

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Outline

- Introduction
- Commissioning & Early Physics
  - → Summary of requirements
  - → Expected Instrumentation
- Normal Operation
  - → Summary of requirements
  - → Additional Instrumentation
- Summary

Introduction

- Requirements specified in:
  - → LHC-B-ES-0009 (Q, Q' and coupling)
- Main area of concern is during ~30 seconds of snap-back
  - → Q change of up to ~ 6×10^{-2}
  - → Q' change of up to ~ 80 units
  - → Changes during injection plateau, ramp & β-squeeze 10-1000 times slower
- Will assume that 80% of these changes can be corrected using knowledge of the LHC magnetic systems

Commissioning - Summary of Requirements

- First Beam
  - → Individual pilot bunches of ~5×10^{9} ppb
  - → Q and Q' constraints relaxed
- First Physics Run (end of commissioning)
  - → 43 on 43 bunches of $3\text{-}4\times10^{10}$ ppb

Commissioning (first physics)	**Drift Rate (snap-back)** (Unit per sec for ~30sec)		**Tolerance**	**Requested Accuracy**	**Correction Rate** (Hz)
	Max	80% Pred	Inj / ramp	±	80% Pred
Orbit (mm)					**<1**
Tune (´ 10^{-3})	2.8	0.6	~10	3	**0.1**
Chromaticity (Qx)	3.8	0.8	5	2.5	**0.3**

Tune Measurement – Day 1 systems

Single Kick excitation - Observed using:

→ BPM System

- 500 button monitors per ring measuring in both transverse planes
- Use a single monitor or sum FFTs from all BPMs
- BUT, 1 bit ~ 20 μm ⇒ will need ~mm kicks (⇒ ε blowup)

→ Q-measurement system

- Dedicated BPMs located in higher beta regions of IP4
- Equipped with special electronics for micron level oscillations

Tune Measurement – Early beam systems:

→ Chirp/Noise

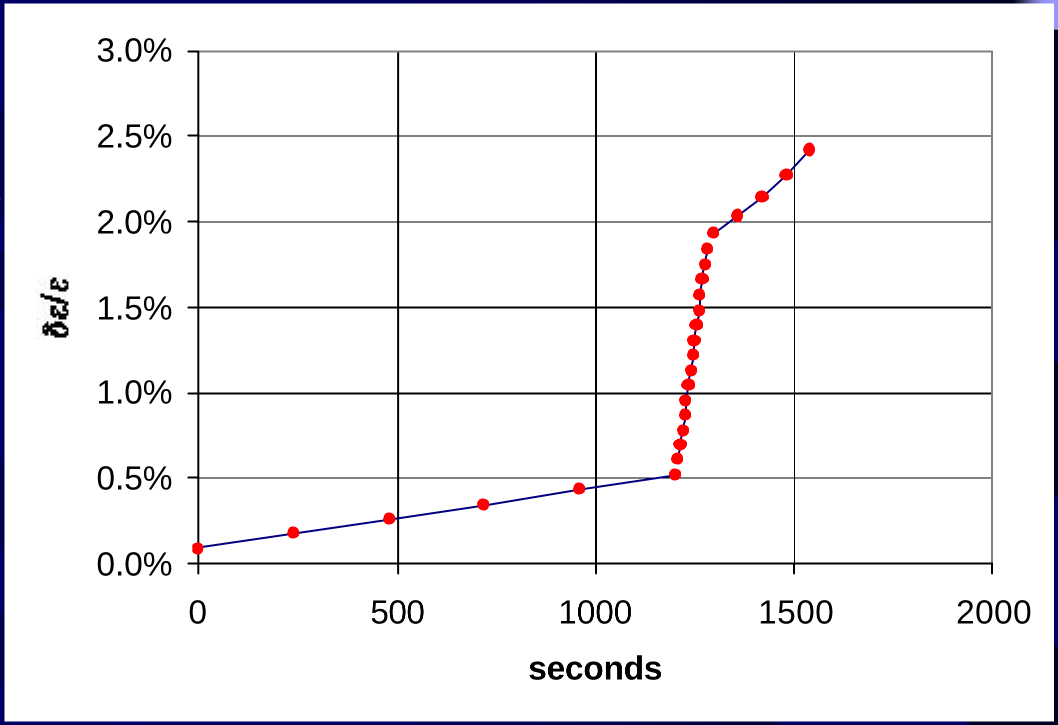
- Signal Injected into transverse damper electronics.
- Chirp excitation allows a full beam transfer function measurement.

All these methods will result in emittance blow-up when used continuously during injection, ramp and squeeze

Tune Measurement & Emittance Blow-up

- 1999 simulation of series of single-kick Q meas. assuming:
  - → 400μm initial kick
  - → 50-turn damping time
  - → 128-turn FFT + interpolation
    - error $\delta Q < 3.10^{-3}$
  - → 20 μm PU noise level
  - → using 4 of 12 batches

Measure every 5 sec during snap-back & every 4 min during injection



- Conclusion:
  - → After some 25 of such measurements the 2% BDI emittance budget will have been exceeded, in this case before the ramp has even started!

Chromaticity Measurement

Classical method:

- Measure tune for different beam momenta by changing f_{RF}
  - → For commissioning $\delta p/p$ limited to 2.5×10^{-3}
  - → Performed using kicked or chirped excitation
  - → Limited to < 1Hz by applied RF modulation & kicker rep rate (2Hz max)
    - Interference with orbit feedback loop?

- Head-tail Measurement:
  - → Observe evolution of head & tail of a single bunch after applying a single kick
    - The phase shift between head and tail is proportional to the chromaticity
    - Advantage: one kick immediately gives Q'
  - → Tested in SPS but yet to be fully verified for day-to-day operation

Commissioning – Summary (1/2)

- Tune
  - → Measure & Correct at 0.1Hz
    - ⇒ 3 kicks (400μm) during snap-back
    - ⇒ OK for emittance blow-up
- Chromaticity
  - → Measure and correct at 0.3Hz with head-tail
    - ⇒ 10 kicks during snap-back
    - ⇒ OK for emittance blow-up
  - → Measure tune at 1Hz + RF modulation for correction at ~0.3Hz
    - ⇒ requires 30 kicks during snap-back
    - ⇒ at the limit for BDI emittance budget

Commissioning – Summary (2/2)

Problems Envisaged

- With 80% predictability on b2 & b3 from fill-to-fill feedforward will not be sufficient for snap-back control of Q and Q’ for first physics

- Require an accurate, automatic measurement & correction of Q and Q’
  - → Either operator joystick control for correction (HERA) or rely on software algorithms
  - → Accuracy in turn will depend on how well chromaticity & coupling are controlled!

Normal Operation - Summary of Requirements

Normal Operation	Drift Rate (snap-back) (Unit per sec for ~30sec)		Tolerance	Requested Accuracy	Correction Rate (Hz)
	Max	80% Pred	Inj / ramp		80% Pred
Orbit (mm)					**<1**
Tune (´ 10^{-3})	2.8	0.6	3	0.75	**0.3**
Chromaticity (Qx)	3.8	0.8	1	0.5	**1**

- Tolerance on Chromaticity reduced by a factor of 5
- Requested accuracy better than 1 unit
- Correction rate of 1Hz required during snap-back
  - → Implies a measurement rate >1Hz

Normal Operation – Additional Instrumentation

PLL Tune Measurement System

Collaboration with BNL as part of the US-LARP programme

- Advantages
  - → Provides a continuous tune measurement & can be used for feedback
  - → Precision a function of bandwidth (~10^{-5} for 1-10Hz)
  - → Necessary for continuous coupling and chromaticity measurements
- Problems
  - → Requires constant excitation
    - For proton & heavy ion machines this implies small amplitudes.
  - → PLL functioning strongly linked to Chromaticity & Coupling
    - Synchrotron sidebands can interfere with the main tune peak
    - Large chromaticity can widen the main tune peak ⇒ PLL can lose lock
    - Large coupling can cause PLL to jump from H to V tune peaks

Schottky Systems

- → For measuring beam parameters without beam perturbation
- → Foreseen for use mainly during coast
  - at RHIC was also used extensively during commissioning phase

Normal Operation – Additional Instrumentation

Feedback using the PLL tune system

- Tune feedback
  - → Not trivial to go from tune measurement to feedback
  - → Requires a stable PLL tune measurement system
  - → Experience from RHIC
    - Although feedback was available from an early stage there has been considerable difficulty in making it reliable under varying machine conditions.
    - After 3 years feedback is still not used routinely during operation.
    - Main problem is the stability of the PLL tune measurement when crossing transition with heavy ion beams. More stable with proton beams where there is no transition crossing.
  - → Can expect similar difficulties during LHC snap-back when all machine parameters change simultaneously
- Chromaticity feedback
  - → Not yet attempted on other high energy hadron machines
    - Tests at RHIC ?
  - → Two options for creating dp/p variations:
    - Standard RF frequency modulation – too slow?
    - Fast RF phase modulation – can PLL track the tune with this bandwidth?

Summary of Requirements (1/3)

Dynamic Ranges

Parameter	Minimum		Nominal operation		Maximum	
	450 GeV	7 TeV	450 GeV	7 TeV	450 GeV	7 TeV
Q	.09 (.005*)		.28 → .32		.41 (.495*)	
Q′	-50		+2		50	
|c|	-.1	.-0.05	0		.1	0.05

Summary of Requirements (2/3)

Maximum Momentum Deviations

energy	Scenario	Maximum dc momentum offset	Maximum ac momentum offset
450 GeV (injection optics)	nominal	$\pm$ 0.5 10^{-3}	$\pm$ 0.1 10^{-3}
	Pilot, momentum collimators withdrawn	$\pm$ 2.5 10^{-3}	
7TeV (squeezed optics)	Pilot and nominal	$\pm$ 0.15 10^{-3}	
	Pilot, crossing angle suppressed, collimator setting scheme relaxed accordingly	$\pm$ 10^{-3}	

Summary of Requirements (3/3)

	Resolution		scenario
	on observable	on tunes	
Q	~ ± 3. 10^{-3}		Commissioning
			Tune measurement and/or feedback in operation (injection,ramp, flat top during squeeze)
			Nominal (pre-collision and collision)
			Bunch by bunch
			Low-β non-linearities
			Pilots, bunch by bunch (detunings)
Q′	±2.5	± 3. 10^{-3}	Commissioning
			Nominal, 450 GeV to 7 TeV (measurement and/or feed-back)
$\vert c \vert$	±3 10^{-3}		Commissioning
			Nominal beam at Injection, ramp and squeeze
			Nominal beam in collision

Summary

- Even for the early physics beams simple feedforward from ramp to ramp will not be enough to control Q & Q' during snap-back
- We should envisage running without continuous Q & Q' feedbacks during the first year of operation
  - → Will have to rely on measure & correct techniques either via direct operator intervention or simple software algorithms
- Will aim to get PLL Q measurement on-line as soon as possible
  - → Experience from other machines show that stable operation requires a fairly good control of chromaticity and coupling in particular
    - exactly the things that are not well controlled during commissioning!
- Q' measurement without emittance blow-up is difficult
  - → Best candidate is still slow RF modulation & PLL tune-tracking
  - → Requires the PLL to be operational
  - → Measurement rates will be at the limit of what is required