Operational Experience of Beam Stability Control

Rende Steerenberg – CERN BE/OP

Collective Instability or Stability.. ?
Contents

• The CERN Accelerator Complex & Beams
• Operational Instability Observation & Mitigation
• Experience in CERN Machines
• Some Feedback From Other Labs
• Conclusions
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The CERN Accelerator Complex
Before Long Shutdown 2

Rende Steerenberg, CERN BE-OP
The Most Challenging Beams (1/2)

- **ISOLDE high intensity from PSB**

<table>
<thead>
<tr>
<th>(N_b \times 10^{11} \text{ p/b})</th>
<th>#bunches</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>~85  (\times 10^{11} \text{ p/b})</td>
<td>4 per extr.</td>
<td>RF H1+H2</td>
</tr>
</tbody>
</table>

- **nToF single bunch high intensity from PS**

<table>
<thead>
<tr>
<th>(N_b \times 10^{11} \text{ p/b})</th>
<th>#bunches</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 90  (\times 10^{11} \text{ p/b})</td>
<td>1</td>
<td>Bunch rotation at extraction to &lt; 20 ns</td>
</tr>
</tbody>
</table>
The Most Challenging Beams (2/2)

- LHC high brightness bunch trains from SPS
  - Standard beam
    
    | $N_b$ [$\times 10^{11}$ p/b] | $\epsilon_{x,y}$ [mm mrad] | bunch spacing | Beam             |
    |-----------------------------|-----------------------------|---------------|------------------|
    | ~ 1.15                      | 2.5                         | 25 ns         | 1 - 4 x 72 = 288 bunches |

- BCMS beam

<table>
<thead>
<tr>
<th>$N_b$ [$\times 10^{11}$ p/b]</th>
<th>$\epsilon_{x,y}$ [mm mrad]</th>
<th>bunch spacing</th>
<th>Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>1.4</td>
<td>25 ns</td>
<td>1 – 4 x 48 = 192 bunches</td>
</tr>
</tbody>
</table>
Filling of the LHC with Protons

Energy & Trains
Time Structure
Beam Brightness

- Field in main magnets
- Proton beam intensity (current)
- Beam transfer

To LHC clock-wise or counter clock-wise

450 GeV
26 GeV
1.4 GeV
1.2 seconds

SPS
PS
PSB

Time
**PS: LHC 50 & 25 ns Standard Beam Production**

- Double batch injection
- Triple splitting at 2.5 GeV
  - Lower space charge, Larger bucket
- Two times splitting at 26 GeV/c
- Non-adiabatic bunch rotation before extraction ➔ 4ns bunch length (4σ)
- For 25 ns PSB bunch intensity divided by a factor 12
  - $I_{LHC} = 1.2 \times 10^{11}$ ppb ➔ $I_{PSB} = 14.4 \times 10^{11}$ ppb
- Transverse emittance determined by PSB
- The multi-turn proton injection is now being replaced by multi-turn H<sup>+</sup> injection

### 25 ns:
- Each PSB bunch divided by: 12 ➔ $6 \times 3 \times 2 \times 2 = 72$

### 50 ns:
- Each PSB bunch divided by: 6 ➔ $6 \times 3 \times 2 = 36$
PS: LHC 50 & 25 ns BCMS Beam Production

- BCMS = Batch Compression, Merging & Splitting
- Same cycle with BCMS at 2.5 GeV
- For same LHC bunch intensity PSB bunch intensity and transverse emittance is ~50% of standard scheme
- For 25 ns the intensity of 2 PSB bunches are divided by a factor 6 each
  - $I_{LHC} = 1.2 \times 10^{11}$ ppb $\rightarrow I_{PSB} = 7.2 \times 10^{11}$ ppb

For 25 ns the intensity of 2 PSB bunches are divided by a factor 6 each:
- $I_{LHC} = 1.2 \times 10^{11}$ ppb $\rightarrow I_{PSB} = 7.2 \times 10^{11}$ ppb

For 25 ns the intensity of 2 PSB bunches are divided by a factor 6 each:
- $I_{LHC} = 1.2 \times 10^{11}$ ppb $\rightarrow I_{PSB} = 7.2 \times 10^{11}$ ppb

50 ns: PSB bunches ‘divided’ by: 3 $\rightarrow 8/2 \times 3 \times 2 = 24$
Why Operational Beam Stability Control?

• **Beam Quality:**
  • Delivery of a large variety of beams to various experiments.
  • **Beam intensity** (e.g. ISOLDE, nToF, SPS North area, ..)
  • **Beam brightness** (e.g. LHC)

• **Beam Losses:**
  • **Reduce activation** of machine components to allow for hands-on maintenance or repair with a minimum amount of cool-down time.
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The Operational Knobs to Control Stability

- **Transverse**
  - Octupoles
  - Chromaticity
  - Tune & Linear Coupling
  - Transverse Feedback
  - Controlled Transverse Blow-up

- **Longitudinal**
  - RF Voltage
  - Controlled longitudinal Blow-up
  - Higher order cavity
  - Longitudinal feedback
Main Observation/Diagnostics Means

- OASIS signals (all machines, but mainly injector):
  - Wide band longitudinal and transverse pick-ups
  - Converters, many feedback loop signals etc..
  - Water fall views, mountain range views

- Dedicated analysis systems such as BSM, TomoScope, BQM

- ADT-ObsBox (LHC)
  - Very advanced tool, mainly for offline analysis, thanks to triggers and logging

- Logging
  - Logging of machine and beam parameters allows for post-mortem analysis

- Spectrum Analysers
  - Still some available, but we lost the advantages of the real spectrum analysers
  - Offline analysis in the frequency domain can still be done using OASIS signals or logged data
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Some General Comments

• We only have leptons in CLEAR at CERN, otherwise only protons, antiprotons and ions, which do not give really useable synchrotron damping in any of the machines.
• We apply electron and stochastic beam cooling in the low energy AD, ELENA and LEIR machines, but not for any high energy, high intensity and/or high brightness proton beams.
• The LHC Injector Upgrade is being installed during Long Shutdown 2. Therefore no operational experience yet available.
  • Some systems or principles were deployed during the last run, but mainly used for study purposes
  • Many promising beam performance studies and tests have been made successfully
PS Booster

**Main phenomena:**
- Coupled bunch instability - cured by changing harmonics from H1+H5 to H1+H2 (design)
- Space charge tune spread - Resonance compensation scheme (single particle effect)
- Potential Horizontal instability in presence of high space charge dq ~ 0.5 (ref. Erini talk)
  - Good working transverse damper made the instability invisible for OP
  - Cause found – See talk of E. Koukovini Platia on Wednesday

**Main means of correction:**
- Transverse damper
- Tune (single particle effect)
- Various multipoles for resonance compensation (single particle effect)
- Controlled longitudinal blow up (mainly for PS preparation)
- No chromaticity correction sextupoles
- No Landau octupoles
PS – In General

- **Main phenomena:**
  - Space charge (single particle)
  - Head-tail (in presence of high space charge $dQv \sim 0.3$)
  - Beam break up at transition in the presence of space charge (or Transverse Microwave Convective Instability, A. Burov)
  - Longitudinal coupled bunch instabilities
  - Transverse coupled bunch instability

- **Main means of correction:**
  - Transverse damper (not much used until recently, but now....)
  - Tune & Coupling (for coherent instability)
  - Chromaticity – Flip sign of chromaticity at gamma transition jump
  - Landau octupoles (rarely used and only available for below transition)
  - RF voltage (reduced after transition to maximise Landau damping)
  - Controlled longitudinal blow up through 200 MHz cavities
  - Longitudinal damper (recent)
PS – nToF Beam

- **Issue:**
  - Beam Break Up Instability at transition

- **Cure applied:**
  - Controlled longitudinal blow up prior to transition, but limited by extraction losses due to dispersion after bunch rotation
  - Special setting of longitudinal blow up parameters to blow up most efficiently the core and not the tails

- **Experience:**
  - To solve problems operators tended to increase longitudinal blow up
  - Expert study – know-how transferred to OP and now operators optimise further
  - Operators play important role in fine tuning of beam performance for nTOF
  - Nowadays more an more optimisation is being done in more automated way (ML)

- **Beam Breakup Instability in the CERN PS near transition** – R. Cappi, E. Métral, G.Métral
- **Ghost bunches and blow-up losses with high intensity beams** – S. Hancock & E. Métral
PS – LHC Beam: Double Batch Injection

• Issue:
  • Beam blow up and losses due to horizontal instability during 1,2 second flat bottom
  • Intrinsically unstable in the horizontal plane with nominal ($\xi_{x,y} \approx -1$, below transition)

• Cure applied:
  • Both tunes close to coupling resonance and adding linear coupling through skew quadrupoles
  • Lately changed to small negative chromaticity and use of transverse damper
    • Reduced further losses and increase of final beam quality
    • Faster rise time and lower head-tail modes
    • Reliable performance of Transverse Feedback required and demonstrated

• Experience:
  • Many machine development studies were done and operators were involved in them.
  • Following knowledge transfer, the operations teams regularly and successfully adjusted tune and coupling when intensities were changed
  • Procedures with references were documented in web-based beam documentation
PS – LHC Beam: e-cloud Instability

• Issue:
  • Electron cloud build-up is observed on BPMs in TT2 transfer line since 1999
  • When during final splitting process bunched are too short (<12 ns) for too long time the electron cloud runs the beam instable
  • Being verified and simulated (impedance and e-cloud) in anticipation for future

• Cure applied:
  • RF cavity voltage was higher that set in the control room to a calibration error

• Experience:
  • Operational observation leading to ABP, RF and OP team work
  • Cause: RF voltage calibration error in 2006
  • Lesson: avoid short bunches for too long time
  • Further tests have been made since then (by G. Sterbini): If longer time is needed with short bunches then the transverse damper can be used to delay the instability
PS – LHC Beam: Coupled Bunch Instabilities

• Issue:
  • Dipolar (and quadrupolar) coupled bunch instabilities during the ramp limit the bunch intensity

• Cure applied:
  • Partly efficient damping system using 10 MHz cavities
  • Partial mitigation through controlled longitudinal blow up in PSB and PS at injection, but limited by maximum longitudinal emittance at extraction of 0.35 eVs

• Non-operational measures being addressed:
  • Dedicated longitudinal damper (Finemet® cavities) was installed and tested recently
  • Impedance reduction of the 10 MHz cavity system through upgrade of the amplifiers
  • Enhanced understanding on the source of the coupled bunch instabilities – further studies during LS2

• Experience:
  • This additional feedback systems on the 10 MHz cavities caused regular trips of cavities concerned
  • Bunch splitting timings and blow up voltages regularly adjusted by operators to optimise beam quality
  • Good measurement and control tools available
SPS – In General

• **Main phenomena**
  - Fast vertical single bunch instability
  - Horizontal coupled bunch instability at flat bottom since 2015 for $1.8 \times 10^{11}$ ppb on the LHC beam
  - Electron Cloud
  - Longitudinal coupled bunch instability - limited by RF power - RF cavity beam loading

• **Main means of correction:**
  - Transverse damper
  - Landau Octupoles
  - Chromaticity
  - Lower gamma transition (through studied optics change)
  - Prototype intra bunch damper for *studies only* in vertical place (limited power)
  - 800 MHz cavities were used *in the past* for controlled longitudinal blow up, but no as Landau cavity
  - RF voltage (no or little margins)
SPS - Fast vertical single bunch instability

• Issue:
  • TMCI-like / Transverse Microwave Convective Instability

• Cure applied:
  • Run with increased chromaticity
  • Lower gamma transition and use Q20 instead of Q26 (cycle design feature)
    • The aim is to have a higher $f_s$ - further away from transition
  • Drawback is that Q20 imposes higher RF voltage, which is limited already
    • Therefore Q22 is being studied as alternative

• Experience:
  • Used in day-to-day LHC beam production - proven to work well in practice
  • Expert driven change through very good collaboration with OP
SPS - Horizontal Coupled Bunch Instability

- Issue:
  - A horizontal coupled bunch instability is present at flat bottom for LHC bunch intensities of $1.8 \times 10^{11}$ ppb

- Cure applied:
  - Transverse damper
  - Landau Octupoles
    - Was not used often in the past. Was used for controlled transverse emittance blow up through Octupoles and Transverse damper was used for the LHC beam
    - With 4 batches and LIU coupled bunch instability in horizontal will enhance
    - Landau octupole circuit was reconfigured in 2018 to make them more efficient for Q20

- Experience:
  - Expert driven study with good collaboration with OP for planning the change and tests
SPS – e-cloud driven instability

• Issue:
  • Beam instability observed in presence of electron cloud

• Cures applied:
  • Run with increased chromaticity
  • Apply scrubbing runs
    • Effective but can be time consuming depending on shutdown work
    • Kicker heating due to impedance observed and slowed down scrubbing (being cured by change to serigraphy)
  • Ac coating is being deployed

• Experience:
  • Scrubbing runs done together by experts and operations team
  • Chromaticity can be adjusted by operators but not often done
  • Ac coating is part of the LIU project
LHC – In General

• **Main phenomena:**
  • Instability driven by e-cloud at injection
  • Instability at high energy driven by impedance from closing collimators
  • Very fast instability as a result of a non-conformity (16L2)
  • Longitudinal Beam instability after Injection

• **Main means of correction:**
  • Transverse feedback (ADT) both planes close to max (50 – 100 turns)
  • Tune
  • Chromaticity (Large chromaticity is imposed during the whole cycle)
  • Landau Octupoles
  • RF voltage
  • Controlled longitudinal blow up
LHC – e-cloud

• Issue: e-cloud at injection

• Cure applied:
  • Large value of chromaticity ~15 units in both planes
  • Large value of Landau Octupoles (40 A instead of a few Amp if there would be no e-cloud)
    • This imposed reviewing the working point to avoid resonances
  • Linear coupling at injection has to be well-corrected
    • Coupling effect increases due to approaching tunes induced by additional batches
    • Laslett tune shift correction was implemented by OP to have constant tune while injecting batches

• Experience:
  • Operations team regularly measures and if necessary corrects chromaticity
  • Following expert findings on coupling OP developed coupling measurement and correction application, which is used regularly by operators.
LHC – Impedance Induced Instability

• Issue:
  • Impedance induced instabilities at high energy (Closure of collimators)

• Cure applied:
  • High positive chromaticity in both planes (~15 units)
  • Interplay of octupole settings and coupling (See talk by L. Carver on Tuesday)
    • Landau Octupoles (close to max of 550 A both signs have been used)
    • More recently studies also are directed to noise (ADT and power converters), beam-beam

• Experience:
  • Topic seen as very complex by most operator, but involved in monitoring
  • OP physicist involved in setting up of cures and monitoring tools
LHC – 16L2 Non-Conformity

• Issue:
  • Fastest LHC instability by one or two order of magnitude higher than for impedance or e-cloud driven instabilities
  • Driven by the 16L2 (non-conformity) see talk by L. Mether talk

• Cure applied
  • Conditioning - trial and error
  • One knob added Arduini-Solenoid

• Experience:
  • In these cases avoid pushing performance and take a (small) step back
  • Empirically recovery scheme was found
LHC - Longitudinal

• Issue:
  • Longitudinal beam instability after Injection.

• Cure Applied
  • Voltage reduced in steps from 6 MV to 4 MV.
    “The optimum voltage is a compromise between acceptable losses (at injection and flat bottom) and sufficient damping of injection oscillations.”

• Experience:
  • Good collaboration between RF and OP with a gradual approach ensuring that every step was evaluated and that no operational problems were encountered.
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j-PARC – RCS

- Transverse instabilities
  - Cures applied:
    - Controlled transverse emittance blow up
    - Larger negative chromaticity than design for low emittance beam to the Main ring

- Longitudinal.
  - Higher harmonic RF system in bunch flattening mode

- Experience:
  - Iterative tuning of most or all parameters mentioned above for each increase in beam power
  - This is done by experts and not the operators

With thanks to Tadashi Koseki, Yoichi Sato, Yoshihiro Shobuda
j-PARC – Main Ring

- Transverse instabilities
  - Source: Resistive-wall impedance and kicker impedance
  - Cures applied:
    - Larger negative chromaticity
    - Transverse intra-bunch feedback system
    - Landau octupoles

- Longitudinal Coupled bunch Instabilities during acceleration for beam powers above 480 kW:
  - Source: RF cavity beam loading.
  - Cures applied:
    - New feedback system (tested at low beam power)
    - Mismatch at injection to increase longitudinal emittance

- Experience:
  - Iterative tuning of most or all parameters mentioned above for each increase in beam power
  - This is done by experts and not the operators

With thanks to Tadashi Koseki, Yoichi Sato, Yoshihiro Shobuda
FermiLab (FNAL Booster)

- Transverse instability
  - Source: instability at injection under high space charge regime
  - Cures applied:
    - Large negative chromaticities (~12 units)
    - Plan to build transverse damper and reduce chromaticities

- Longitudinal coupled bunch modes after transition
  - Source: probably RF cavity beam loading
  - Cures applied:
    - Longitudinal emittance blow up after transition by bunch-bucket mismatch
    - Longitudinal dampers, but mode 2 is not yet well-controlled (being worked on)

- Experience:
  - The Booster is tuned daily by experts to minimise losses with all knobs that are available

*With thanks to M. Convery, Cheng-Yang Tan*
BNL – Booster & AGS

• Booster (protons & ions):
  • Running at near natural chromaticity without losses
  • Octupole winding were retired, as they had little or no use
  • Space charge issues prominent at injection; dual harmonic RF system used to control bunching factor

• AGS (polarised protons & ions):
  • In the past when high intensity protons (>8x10^{13} ppp) for slow extraction, many instability issues
  • Cures applied:
    • Transverse damper
    • Higher frequency dilution cavities at injection and after transition (decommissioned for ions)
    • Skew quadrupoles used for empirical linear coupling correction by the operators
    • Higher order multipoles used empirically by operators to improve beam transmission

• Experience:
  • No longer high intensity protons, easier for Booster and AGS
  • Many adjustments done by operators based on experience

With thanks to G. Marr
BNL – RHIC (ions & pol. protons)

- Intra beam scattering and capture losses dominate at injection
- Transition crossing with high intensities more unstable, probably due to e-cloud
  - Cures applied: NEG coating and scrubbing
- Transverse damper to combat injection oscillations adjusted by experts and monitored by operators
- Transverse bunch-by-bunch system was deployed in 2014 but not yet operationally used (tech. issues)
- Chromaticity is measured and controlled by operators
  - Slightly increased for higher intensities to avoid losses (5 units instead of 2 units)
  - In addition Octupoles are used sometimes by operators with some input from accelerator physicist
- Landau damping cavities are necessary for beam stability at high ion intensities during injection acceleration past transition
  - A longitudinal bunch-by-bunch damper is used since 2013 for protons – relaxes Landau cavity voltage
- For low energy physics the LEReC has been commissioned and operators start now participating in the electron beam tuning too.
- Linear coupling and tune are controlled by feedback systems. Setup by experts, monitored by operators

With thanks to G. Marr
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• Instabilities and their mitigation are sometimes seen as “black magic” by member in OP, but this perception changes when basic understanding among operators has been achieved.

• Different approaches are used in various labs
  • Ranging from full expert control to large involvement and autonomy by operators
  • At CERN the much appreciated inter-group collaborative approach is very much used, leaving a large autonomy to operators

• A good collaboration between ABP, RF,.. and OP during MDs and day-to-day operation is vital
  • It is a specialist business but transfer of knowledge and sharing of experience helps operators finding ad-hoc solutions

• Good models an tools are important to measure, predict and correct
  • The presently available system are mostly adequate for operations
  • Enhanced software tools are necessary and mostly available

• Some times take a small step back in performance to have an overall gain.

• With the commissioning and performance ramp up following the LIU deployment we have new challenges and interesting times ahead…..
Knowledge transfer and Collaboration between Experts and Operations are key to ensure that we all move in the same direction to produce stable beams.
THANKS

www.cern.ch