Many thanks to all instability team!

INSTABILITIES IN CERN MACHINES

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- Introduction
- Current challenges
- 4 questions raised and discussed here
- Conclusion and next steps
INTRODUCTION

PSB (with LINAC4) 50 (160) MeV => 1.4 (2) GeV
PS (with LINAC4) 1.4 (2) GeV => 25 GeV
SPS 25 GeV => 450 GeV
LHC 450 GeV => 7 (6.5) TeV
INTRODUCTION

LIU = LHC Injectors Upgrade
HL-LHC = High-Luminosity LHC

At SPS extraction:

<table>
<thead>
<tr>
<th></th>
<th>$N$ (x $10^{11}$ p/b)</th>
<th>$\varepsilon$ ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIU/HL-LHC</td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

At SPS Injection:

<table>
<thead>
<tr>
<th></th>
<th>$N$ (x $10^{11}$ p/b)</th>
<th>$\varepsilon$ ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>2.0</td>
<td>~2.0</td>
</tr>
<tr>
<td>LIU/HL-LHC</td>
<td>2.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

G. Rumolo (Chamonix2018)

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INTRODUCTION
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PROTON PHYSICS: STABLE BEAMS

Energy: 6499 GeV  \( I(B1): \) 2.11e+14  \( I(B2): \) 2.40e+14

Inst. Lumi \([(ub.s)^{-1}]\)
IP1: 12353.43  IP2: 1.70  IP5: 11932.32  IP8: 410.48

FBCT Intensity and Beam Energy

Instantaneous Luminosity

Comments (05–May–2018 00:49:10)
physics fill with 2460b
Contining Xing angle leveling ON
XRP's in

BIS status and SMP fields

~ \(2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) with ~ 1.2 \(10^{11} \text{ p/b}\) within ~ 2.5 \(\mu\text{m}\)
CURRENT CHALLENGES

◆ For LIU

- PSB instability during ramp (close to future injection energy) without damper => Could this be a problem in the future?
- PS longitudinal instabilities => New Landau cavity under discussion
- SPS longitudinal instabilities => RF power upgrade + longitudinal impedance reduction
- New SPS horizontal instability observed with higher than nominal bunch intensity => Could this be a problem in the future?
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◆ For HL-LHC
- At LHC injection, high chromaticities, high Landau octupoles current and high damper gain are needed => What will happen for HL-LHC?
- Why do we need more Landau octupoles current than predicted at high energy in the LHC?
- Will we have enough Landau damping for HL-LHC (with new equipment: Crab Cavities, low-impedance collimators, etc.)?
4 QUESTIONS RAISED AND DISCUSSED HERE

- Only transverse instabilities will be discussed
4 QUESTIONS RAISED AND DISCUSSED HERE

◆ Only transverse instabilities will be discussed

◆ 4 questions

1) What is the effect of direct space charge on (coherent) instabilities in CERN machines (PSB, PS, SPS and LHC)?
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◆ 4 questions

1) What is the effect of direct space charge on (coherent) instabilities in CERN machines (PSB, PS, SPS and LHC)?

2) LHC instabilities at injection: we need high chromaticities, high Landau octupoles current and high damper gain => Why and what will happen for HL-LHC?
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3) What is the “16L2 instability” observed in the LHC in 2017 (and 2018)?
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3) What is the “16L2 instability” observed in the LHC in 2017 (and 2018)?

4) Why do we need more Landau octupoles current than predicted at high energy in the LHC (potential worry for HL-LHC)? => Subject I will mostly discuss, with 2 destabilising effects currently studied
1) EFFECT OF DIRECT SPACE CHARGE ON CERN INSTABILITIES?
At CERN, it seems that only the LHC (highest energy machine) sees the (beneficial) effect of space charge...
=> At CERN, it seems that only the LHC (highest energy machine) sees the (beneficial) effect of space charge...

- PSB ($\Delta Q_{sc} / Q_s >> 1$)
  - Instabilities observed during the ramp without damper => Space charge could potentially play a role
  - However: no important change of instability onset along the cycle when changing bunch length (and shape) for constant intensity. Tbc

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  - TMCI between modes - 2 and - 3 at injection (Q’ ~ 0)

- **LHC (ΔQ_{sc} / Q_s ~ 1)**
  - Head-Tail instability with 1 node (Q’ ~ 5) => Stabilized by space charge below a certain energy
  - Predicted threshold for TMCI (modes - 1 and 0) at injection (Q’ ~ 0) increased by space charge

G. Rumolo
**SPS case: HEADTAIL simulations from 2014 (H. Bartosik) for different optics WITHOUT space charge**

![Graph showing vertical growth rate vs. N (p/b) for different Q values. Q26, Q22, and Q20 are compared. The plots illustrate the threshold for HL-LHC and measured thresholds for different Q values.](image)
SPS case: HEADTAIL simulations from 2014 (H. Bartosik) for different optics WITHOUT space charge

![Graph showing vertical growth rate vs. N (p/b)](image)

- Q22 measured in 2017
- Q26 measured threshold
- Required for HL-LHC
SPS case: HEADTAIL simulations from 2014 (H. Bartosik) for different optics WITHOUT space charge

- Intensity thresholds also well predicted with simple formula (which is the same as coasting-beam with peak values => Space charge is predicted to have no effect…)
- Our simulations predict only little effect of space charge on threshold

\[ N_{b,th}^y \propto |\eta| Q_y \varepsilon_L \]
SPS case: HEADTAIL simulations from 2014 (H. Bartosik) for different optics WITHOUT space charge

- Intensity thresholds also well predicted with simple formula (which is the same as coasting-beam with peak values => Space charge is predicted to have no effect...)
- Our simulations predict only little effect of space charge on threshold

=> Question for theories with space charge: can they explain these 3 thresholds by changing the optics?
2) LHC INSTABILITIES AT INJECTION
E-clould in dipoles (~ 65% of the machine) is not expected to drive instabilities both at injection and top energy

- Becomes better with higher intensity => No issue expected for HL-LHC
- Becomes worse for lower intensity => Some observations already made
◆ E-cloud in dipoles (~ 65% of the machine) is not expected to drive instabilities both at injection and top energy
  ▪ Becomes better with higher intensity => No issue expected for HL-LHC
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◆ E-cloud in quadrupoles (~ 7% of the machine) alone is a key driver of instabilities at LHC injection energy
  ▪ Explains high chroma (~ 15-20 units) + high Landau octupoles current (~ 20-40 A) + high damper gain (~ 10-20 turns) in both transverse planes
    => Favorable scaling with intensity expected
  ▪ Instability suppressed when increasing beam energy up to 6.5 TeV due to increased beam rigidity

A. Romano (finalising PHD)
3) “16L2 INSTABILITY”
16L2: cryogenic beam vacuum at half-cell 16 left of LHC-IP2

See 2 IPAC18 papers by B. Salvant et al.
16L2: cryogenic beam vacuum at half-cell 16 left of LHC-IP2

- 67 beam dumps in 2017 due to fast beam losses in 16L2, which led to transverse coherent instabilities with rise-times of few 10s of turns (i.e. 1-2 orders of magnitude faster than instabilities from e-cloud or impedance)

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Interaction of LHC proton beam with flakes of these frozen gases detaching from beam screen surface is assumed to be at the origin of the beam losses in 16L2 => Ionization: ions + e-

See 2 IPAC18 papers by B. Salvant et al.
Single-bunch and coupled-bunch instabilities observed

Important > 0 tune shift measured: + ~ 0.01-0.02
Approximated model (as only e- are expected to oscillate within bunch passage)

- Equivalent impedance from an e-cloud (as F. Zimmermann et al.)
  - Measured (>0) tune shift => Deduce e- density => ~ 150 MΩ/m shunt impedance
  - e- frequency => ~ 2.6 GHz
  - Q = 1

- Simulations with DELPHI Vlasov solver

Note: Self-consistent simulations, taking into account both ions and e-, are on-going (L. Mether)
Comparison with observations

Growth rate:

Radial pattern:

N. Biancacci and D. Amorim

SIMULATIONS

MEASUREMENTS
4) WHY DO WE NEED MORE LANDAU OCTUPOLES CURRENT THAN PREDICTED AT HIGH ENERGY IN THE LHC?
2 main issues => Already observed with 1 bunch

- Factor ~ 2 higher Landau octupoles current in OP conditions (Q’ ~ 15, ~ 50 turns damper) => ~ 400-450 A needed vs. ~ 200-250 A predicted
- Even more critical for Q’ ~ 0
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2 destabilising mechanisms under study

1) “Perfect” damper (for Q’ ~ 0)
2) External source of noise (e.g. damper)
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- Even more critical for Q' ~ 0

2 destabilising mechanisms under study

1) “Perfect” damper (for Q' ~ 0)
2) External source of noise (e.g. damper)

In addition to other 3 already discussed in the past:

1) Interplay octupoles & beam-beam
2) Linear coupling
3) Lattice non-linearities
4.1) DESTABILISING EFFECT OF “PERFECT” DAMPER

Needed for TCBI
(Transverse Coupled-Bunch Instabilities)
MOTIVATION

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

$L.R. \ Carver \ et \ al.$
MOTIVATION

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

Predictions
MOTIVATION

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

Predictions

Measurements

L.R. Carver et al.
MOTIVATION

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

Predictions

Measurements

=> 2 questions:

1) What is the (exact) predicted instability mechanism?

2) Is Landau damping well computed (stability diagram => 1-mode approach)?
NEW VLASOV SOLVER: GALACTIC
(GA\textit{rn}ier-LA\textit{c}lare Coherent Transverse Instabilities Code)

Note that the same approach can be used also for Longitudinal Instabilities: GALAC\textit{L}IC $\Rightarrow$ Will be discussed at CERN at the next section meeting on 14/05/18 (https://indico.cern.ch/event/725645/)

See IPAC18 paper by E. Métral et al.
NEW VLASOV SOLVER: GALACTIC
(GA­nier­LA­clare Coherent Transverse Instabilities Code)

- Approximated model with $Q' = 0$
  (no damper, no Landau damping)

\[
\begin{pmatrix}
-1 & -0.23 j x \\
-0.55 j x & -0.92 x
\end{pmatrix}
\]

$\alpha$ bunch intensity
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$\alpha$ bunch intensity

TMCI
(Transverse Mode-Coupling Instability)
NEW VLASOV SOLVER: GALACTIC
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◆ Approximated model with $Q' = 0$
(with damper: $n_d = d / 2 = 50$ turns)

$$
\begin{pmatrix}
-1 & -0.23 j x \\
-0.55 j x & -0.92 x + 0.48 j
\end{pmatrix}
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IMPACT ON LANDAU DAMPING

![Graph showing the relationship between \( \Delta q \) and \( x \)](image)

- Required tune spread to reach bunch stability.
IMPACT ON LANDAU DAMPING

1-mode approach (usual stability diagram)

2-mode approach

\[ I_{m=-1}^{-1} - 0.23 j x \]
\[ - 0.55 j x \quad I_{m=0}^{-1} + 0.92 x - 0.48 j \]
\[ = 0 \]

Required tune spread to reach bunch stability
IMPACT ON LANDAU DAMPING

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Required tune spread to reach bunch stability

\( \Delta q \)

\( x \)

~ threshold for TMCI (without damper)
CONCLUSION for 4.1)

- 1\textsuperscript{st} step: new (single-bunch) instability mechanism => Confirmed and finalised (still to be confirmed by measurements)
CONCLUSION for 4.1)

- **1st step**: new (single-bunch) instability mechanism => Confirmed and finalised (still to be confirmed by measurements)

- **2nd step**: Landau damping => To be confirmed and finalised
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- Below $\sim$ TMCI intensity threshold (without damper), 1-mode approach (usual stability diagram) seems fine
CONCLUSION for 4.1)

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  - Below ~ TMCI intensity threshold (without damper), 1-mode approach (usual stability diagram) seems fine
    - LHC currently operated below TMCI (without damper)
    - In agreement with recent tracking results (X. Buffat) and past analytical computations below TMCI (A. Burov)
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   ▪ Above ~ TMCI intensity threshold (without damper), 2-mode approach needed => More tune spread required

◆ Seems that destabilising effect of LHC (resistive) transverse damper (alone) cannot explain LHC observations with \( Q' \sim 0 \)

=> Another mechanism needs to be identified / added...
4.2) DESTABILISING EFFECT OF EXTERNAL SOURCE OF NOISE
MOTIVATION

1st studies with white noise in 2012 (X. Buffat) but other mechanisms (with larger effects) had to be mitigated first
MOTIVATION

1\textsuperscript{st} studies with white noise in 2012 (X. Buffat) but other mechanisms (with larger effects) had to be mitigated first

- Latency time of several minutes for noise amplitude of $\sim 10^{-4}$ (in unit of beam size)
- Compatible with emittance growth measured in collision and dedicated MDs with high-brightness bunches
- Noise amplitude compatible with $\sim \mu m$ resolution of damper pick-up
- Noise attributed mainly to damper-induced noise and power converter ripple
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- Several instabilities observed with long latency time in 2017 (up to $\sim 40$ min at flat-top)

- Observation in 2017 (and confirmation by simulations) of an instability triggered by a harmonic excitation during BTF (Beam Transfer Function) measurements without damper (C. Tambasco et al.)
LONG LATENCY

Observations

Fill 5664
1b
Flat top
Coll. Tunes

$I_{\text{oct}} = 301$ A

40 min
LONG LATENCY

Observations

Simulations (COMBI)

Fill 5664
1b
Flat top
Coll. Tunes

\[ I_{\text{oct}} = 301 \text{ A} \]

External source of noise (in unit of beam size)

\[ \text{Simulations (COMBI)} \]

\[ \times 10^{-7} \]

\[ 0.0001 \]

\[ 0.0002 \]

\[ 0.0005 \]

\[ 0.0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1.0 \]

\[ 1.2 \]

\[ 1.4 \]

\[ 1.6 \]

\[ 1.8 \]

\[ 0 \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

\[ 4 \]

\[ 5 \]

\[ 6 \]

\[ 7 \]

\[ 8 \]

\[ 9 \]

\[ \times 10^6 \]

\[ \text{Turn} \]

\[ \text{Oscillation amplitude} \]

\[ \text{External source of noise (in unit of beam size)} \]

\[ \approx 13 \text{ min} \]
CONCLUSION for 4.2)

- External source of (dipolar) noise (e.g. damper) is a potential explanation for missing factor ~ 2 in octupoles
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  => Proposal (MDs): Test long-term stability model by introducing noise in a controlled way with damper on different bunches and measure latency time
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CONCLUSION AND NEXT STEPS

Answers to 4 questions raised

1) What is the effect of direct space charge on (coherent) instabilities in CERN machines (PSB, PS, SPS and LHC)?

=> Seems that only the LHC (highest energy machine) sees the (beneficial) effect of space charge! Tbc…
CONCLUSION AND NEXT STEPS

- **Answers to 4 questions raised**

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  2) **LHC instabilities at injection: we need high chromaticities, high Landau octupoles current and high damper gain**

     => Why and what will happen for HL-LHC?

     => Due to e-cloud in quadrupoles (~ 7% of the machine)

     => Favorable scaling with intensity expected
CONCLUSION AND NEXT STEPS

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   => Instability due to non-conformity: accidental air inlet into the LHC beam vacuum with beam screen at 20 K

4) Why do we need more Landau octupoles current than predicted at high energy in the LHC?
   => Destabilising effect of damper (for Q’ ~ 0): not enough
   => External source of noise (e.g. damper) could explain remaining missing factor ~ 2 and long latency time. Tbc…