Beam instabilities measurements and analysis in MAX IV 3 GeV ring

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MAX IV Laboratory

- Currently under commissioning in Lund
- 3 GeV ring based on multibend achromat lattice:
  - Ultralow emittance
  - High beam intensity
- Technical parameters:
  - Strong compact quadrupoles
  - Small vacuum chambers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal emittance (pm)</td>
<td>328 (200 with IDs)</td>
</tr>
<tr>
<td>Design/reched current (mA)</td>
<td>500 / 198</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>99.931</td>
</tr>
<tr>
<td>Bunch length (ps)</td>
<td>40 (196 with HCs)</td>
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</tbody>
</table>

Increased resistive wall and geometric impedances

*Mitigation of instabilities by harmonic cavities (HC)*

Low Emittance Rings 2016, 26-28 September, SOLEIL, France
Outline

● Impedance model
● Measurements of collective effects

  – Single bunch instabilities
    • Bunch lengthening
    • Tune shift and TMCI

  – Multibunch instabilities
    • Resistive wall
    • Ions
    • Longitudinal coupled bunch motion
Impedance model (I)

- Geometric impedance (GdfidL) for 23 machine components:
  - 4 mm bunch length
  - Longitudinal: sum of all the components considering the repetitions
  - Transverse: sum of all the 'weighted' components

\[
W_i = \sum_i \beta_i l_i
\]

- Post processing of numerical impedance
Impedance model (II)

- GdfidL calculated wake potential
- Tracking code uses wake function

Some post processing required
  - Reduce bunch length → increase CPU time
  - Impedance processing

Electromagnetic field solver (GdfidL, ECHO, etc.)

Wake potential of a Gaussian bunch \( \rightarrow \) FT Numerical impedance \( \rightarrow \) Decomposition to known impedance functions (BBR, inductive, resistive, etc.)

Wake function (wake of a point charge)
Impedance model (II)

● Geometric impedance budget is fitted with:
  – Longitudinal: resonators, resistive and inductive components
  – Transverse: resonators

● Tracking
  – Short range effect of the geometric wake can be simulated
  – Resistive wall impedance included
Longitudinal single-bunch

- Diagnostics beamline taking synchrotron radiation from a dipole bending magnet:
  - Bunch length
  - Transverse beam sizes

- Second diagnostic beamline for $\sigma_\delta$ will be installed in 2017

- Bunch lengthening assuming only potential well distortion:
  - Fitted with a single resonator (blue)
  - Numerical effective impedance about 2 times smaller than estimated from measurements
Single-Bunch Transverse – Tune Shift

- Close to zero chromaticity
- Vertical tune shift with bunch current measured using turn-by-turn BPM data
  - Detuning: \(-0.481 \pm 0.002 \text{ A}^{-1}\)
- Detuning about a factor of 1.8 larger than predicted in simulation
  - Similar discrepancy to longitudinal plane
- Detuning is larger than one synchrotron tune
Single-Bunch Transverse – Mode Coupling

- Increase chromaticity to make head-tail modes visible to BPM
- Modes appear to merge in frequency and couple
- Use single resonator and resistive wall to reproduce detuning
- Bunch lengthening included
- No TMCI such as hard limit on injection or sudden beam loss
  - Simulation predicts threshold of 5.5 mA

\[ \xi = 0.70 \]

\[ \xi = 1.15 \]
Single Bunch Transverse – Growth Rates

- Using imaginary tune-shift from mode-coupling theory
- Growth rates remain within the same order of magnitude as radiation damping time
- Decoherence due to amplitude dependent tune shift could be limiting saturation of instability
Transverse Multibunch – Ion Instability

- Different filling patterns
- Ion instabilities seen in multibunch filling patterns as low as 40 mA:
  - Gaps of 10 empty buckets
- Vacuum still in conditioning phase

Shorter bunch trains suppress instability: 25f-10e and 11f-3e-11f-10e fills

Marek Grabski, ALERT workshop 2016
Transverse Multibunch – Modes

- Decompose motion of multiple bunches into coupled-bunch modes

- Filling pattern of 5 trains of 25 bunches, each with gap of 3 in center of each
  - Ion peak is suppressed

- Coupled-bunch mode -1 dominates suggesting resistive wall
  - Other peaks are due to uneven fill

![Graph showing mode number vs amplitude/μm]
Transverse Multibunch – Resistive Wall

- Slightly positive chromaticity
- Grow-damp measurement with ion-free filling pattern
  - Bunch-by-bunch feedback turned off for 100 ms
- Small amplitude growth
  - Measured growth time: 31.6 ms
- Assuming
  - Growth rate proportional to current
  - 29 ms radiation damping time

<table>
<thead>
<tr>
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<th>RW threshold/mA</th>
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<tr>
<td>Experiment</td>
<td>27.4</td>
</tr>
<tr>
<td>Frequency domain</td>
<td>21.6</td>
</tr>
<tr>
<td>Macroparticle tracking</td>
<td>21.9</td>
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Longitudinal Multibunch

- **HOMs in cavities**
  - Beam unstable at 3 mA in even fill
  - With feedback (stripline) stable up to 90 mA

- **Temperature tuning**
  - Possible to tune HOMs away from a synchrotron sideband
  - Bad control and long temperature stabilization time

- **Stabilization with HCs**
  - 100 mA beam, not loaded enough to reach flat potential condition
  - 140 mA beam, fields corresponding to flat potential condition
  - At 125 mA a single mode left (mode119)

- **Longitudinal feedback (cavity kicker)**
  - Designed
Conclusion

- Single bunch collective effects have been measured
  - Similar discrepancy between experiment and simulation in vertical (tune shift) and longitudinal (bunch lengthening) planes

- No TMCI up to 8.5 mA
  - Decoherence due to amplitude-dependent tune shift is a possible explanation

- Multibunch instabilities investigated
  - Ion-driven instability dominates for uniform filling patterns
  - First estimate for threshold current of resistive-wall instability
  - Longitudinal coupled bunch motion can be suppressed by temperature tuning and HCs

- Mitigation
  - Bunch-by-bunch feedback in 3 planes
  - Harmonic cavities

- Injection beam of 198 mA achieved with no feedback but longitudinally unstable beam

More measurements will be done before 2017
**Acknowledgements**

We thank the MAX IV commissioning team for their support during the experiments and Dmitry Teytelman for instability-related discussions and for tuition in the use of the Dimtel bunch-by-bunch feedback system.
Thank you