Investigating the transverse mode-coupling instability at the MAX IV 3 GeV storage ring

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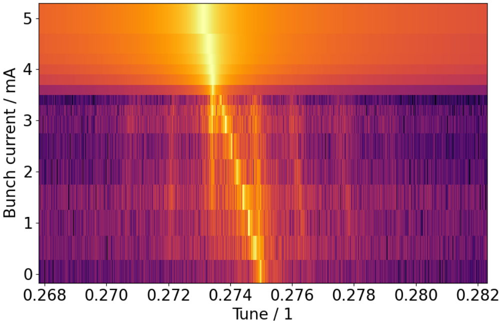
Transverse Mode-Coupling Instability - TMCI

- Current-dependent tune shift couples mode 0 with mode -1 ($-\nu_s$)
- Can be avoided with positive chromaticity (with positive momentum compaction)
- Above threshold abrupt increase in growth-rate
- Presented measurements focused on vertical plane $\rightarrow$ vert. chromaticity reduced, hor. remained > 1



Parameter	Value
Beam energy / GeV	3.0
RF voltage / kV	864
Synchrotron freq. / Hz	830
Synchrotron tune	0.00146
Vertical tune	16.275
Horizontal tune	42.2

- mbtrack2: particle tracking
- Vertical broadband resonator impedance of 200 kOhm/m at 11.5 GHz with Q=1
  G. Skripka et al., NIM-A (2016), doi:10.1016/j.nima.2015.10.029
- Longitudinal broadband resonator of 732 Ohm at 6 GHz with Q = 1
  G. Skripka et al., NAPAC'16, doi:10.18429/JACoW- NAPAC2016-WEA3CO04.

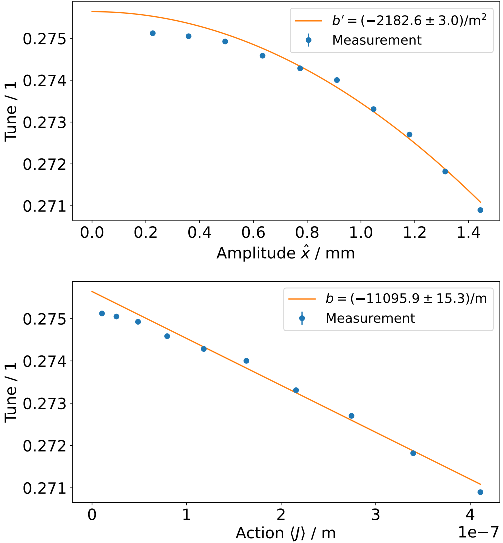
Amplitude-dependent tune shift - ADTS

- Tune shift from non-linear optics contributions
- Octupole magnets allow adjustment
- Measured with kicks of varying amplitude and corresponding shift in tune

$$\nu(\hat{x}) = b' \cdot \hat{x}^2 + \nu(0) \rightarrow b' = \frac{\Delta\nu}{\hat{x}^2}$$

$$\nu(J) = b \cdot J + \nu(0) \rightarrow b = \frac{\Delta\nu}{J}$$

$$J = \frac{\hat{x}_\mathrm{s}^2}{\beta_\mathrm{s}}, \quad [b'] = \frac{1}{\mathrm{m}^2}, \quad [b] = \frac{1}{\mathrm{m}}$$

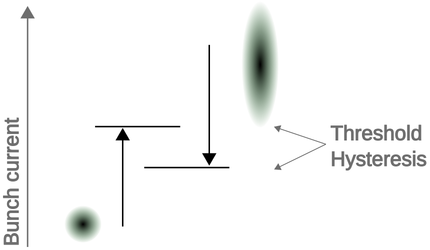


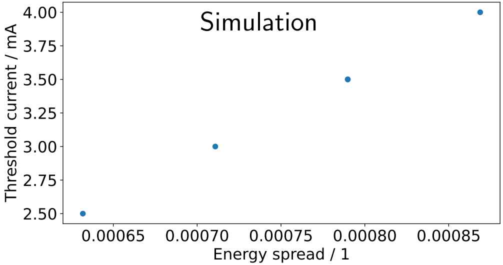
Hysteresis in TMCI threshold current

Hysteresis observed in threshold current depending if charge is increased or decreased

Working theory: change in energy spread due to IBS

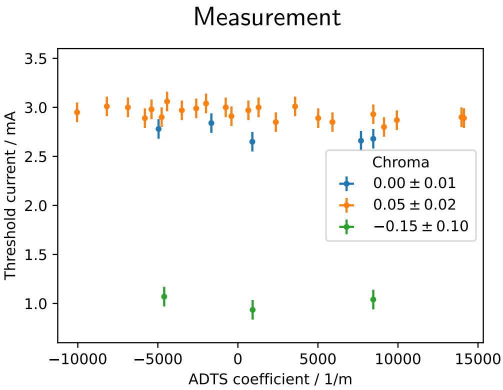
- **Stable beam** means vertical bunch size is small
  → small vertical size means stronger IBS
  → IBS increases the energy spread
  → **higher TMCI threshold**
- **Unstable beam** means vertical bunch size is blown up
  → IBS decreases and energy spread goes down
  → **lower TMCI threshold**
- IBS not included in simulation
- Energy spread dependence manually simulated shows threshold dependence as expected

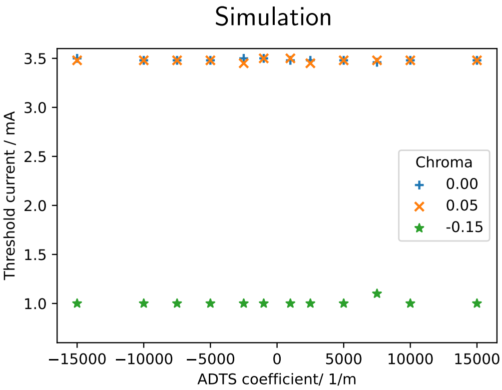




Threshold current and ADTS

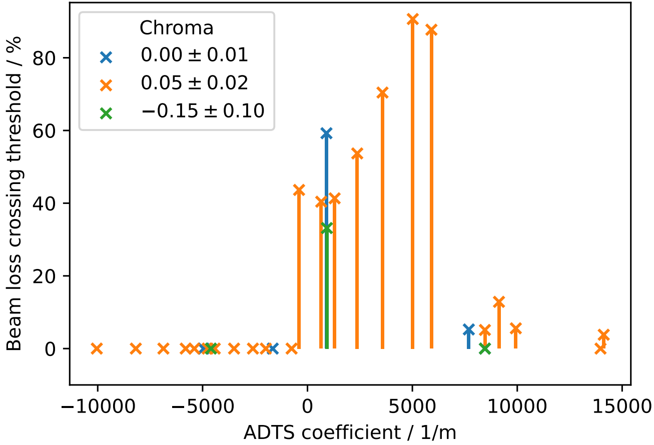
Measurements of the vertical TMCI threshold during injection at low vertical chromaticity.

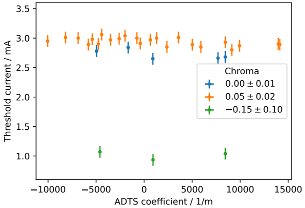




→ No significant influence of ADTS coefficient on threshold current observed

Beam loss at threshold





Previously reported in:

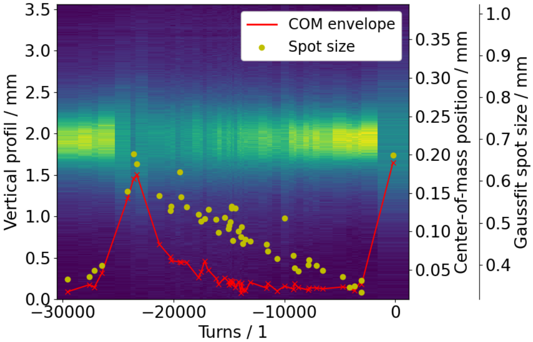
P. F. Tavares et al., Commissioning and first-year operational results of the MAXIV 3GeV ring, Journal of Synchrotron Radiation 25, 1291 (2018).

F. J. Cullinan, Collective effects in MAX IV (Presented at the 7th Low Emittance Rings Workshop, 2018).

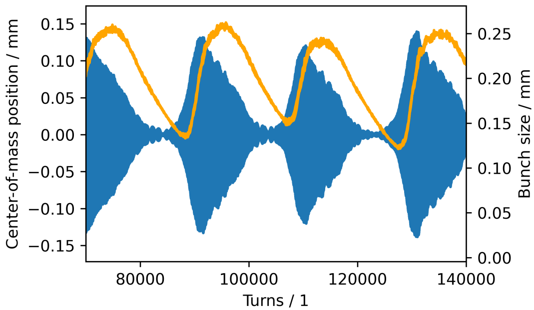
→ Beam loss asymmetrically around zero ADTS, ranging further to positive coefficients

Dynamic above threshold at negative ADTS

Measurement



Simulation

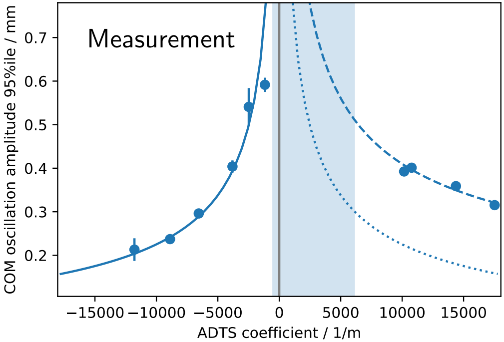


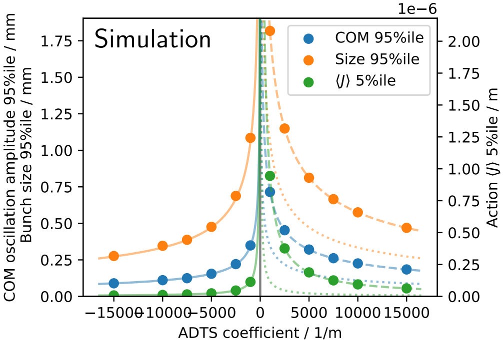
→ Self-containing instability possibly caused by Landau damping, which only sets in when bunch is "blown-up" and ADTS results in bigger tune shift/spread

→ Upper "turning point" when damping becomes predominant

→ Lower "turning point" when bunch size so low that ADTS not enough to Landau damp any longer

Magnitude at threshold

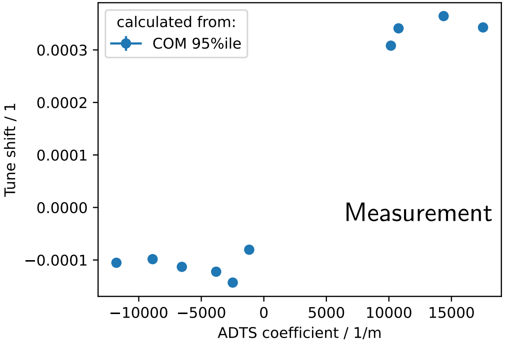


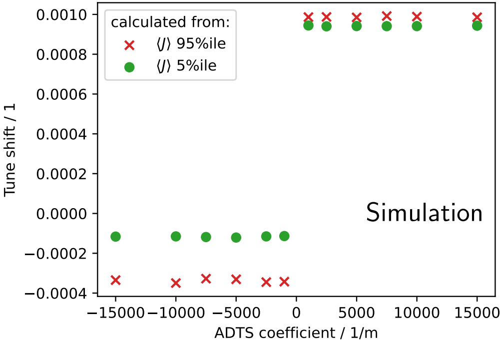


- Asymmetry between positive and negative ADTS coefficient b
- $1/\sqrt{b}$ dependence of maximal COM oscillation amplitude and bunch size (95%ile)
- $1/b$ dependence minimal $\langle J \rangle$ (average action of particle ensemble) (5%ile)

→ Asymmetry in level at which instability contained

Magnitude at threshold





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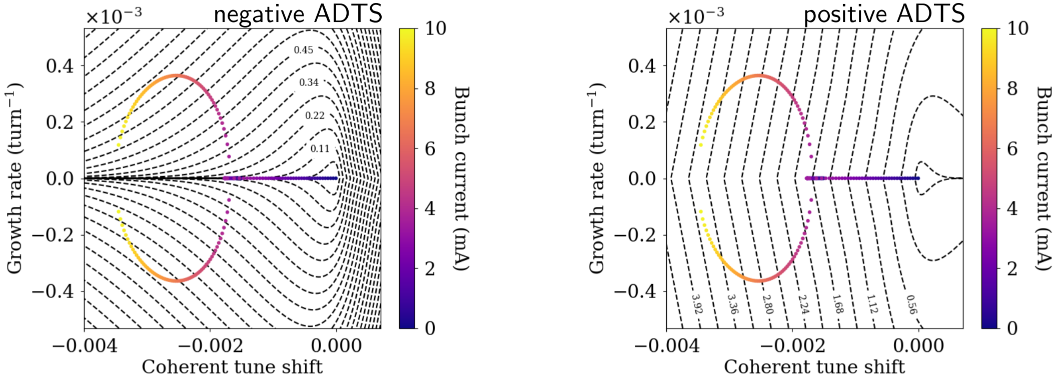
- $1/\sqrt{b}$ dependence of maximal COM oscillation amplitude and bunch size (95%ile)
- $1/b$ dependence minimal $\langle J \rangle$ (average action of particle ensemble) (5%ile)

→ Asymmetry in level at which instability contained

→ Constant but different levels of tune shift for each sign of the ADTS

Stability considerations for Landau damping



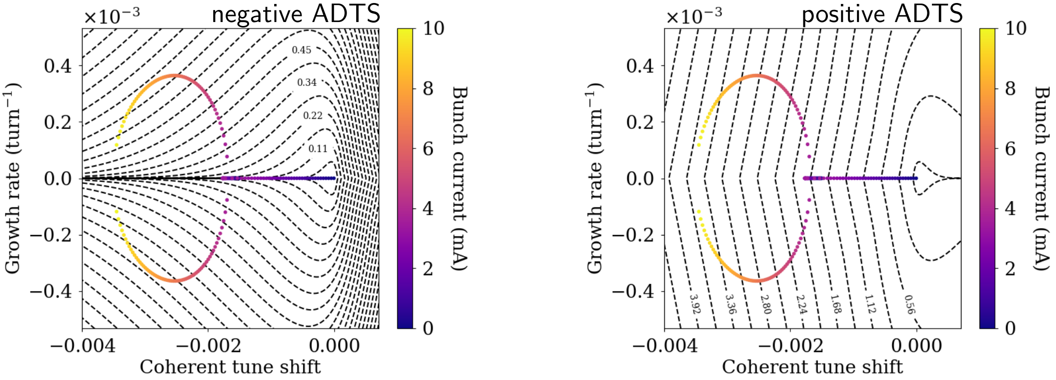
$$I_m = -2\pi \int_0^\infty \frac{J}{V - m\nu_s - \nu_\beta - \Delta\nu(J)} \left(\frac{df}{dJ}\right) dJ$$

$$\det(I_m^{-1}\delta_{ml}\delta_{nk} - \nu_s \mathbf{M}_{nl}^{mk}) = 0$$

Y. H. Chin, Hamiltonian Formulation for Transverse Bunched Beam Instabilities in the presence of Betatron Tune Spread, CERN SPS/85-9 (1985).

- Points: eigenvalues of coupling matrix for modes 0 and -1 without Landau damping
- Contours: inverse dispersion integral for different ADTS coefficients

Stability considerations for Landau damping



- Low synchrotron tune results in small tune shift before mode-coupling
  → low ADTS coefficients required to achieve sufficient tune spread for Landau damping
- Contours form teardrop shape around zero tune shift
- For positive ADTS opposed to tune shift from impedance → higher ADTS coefficient required

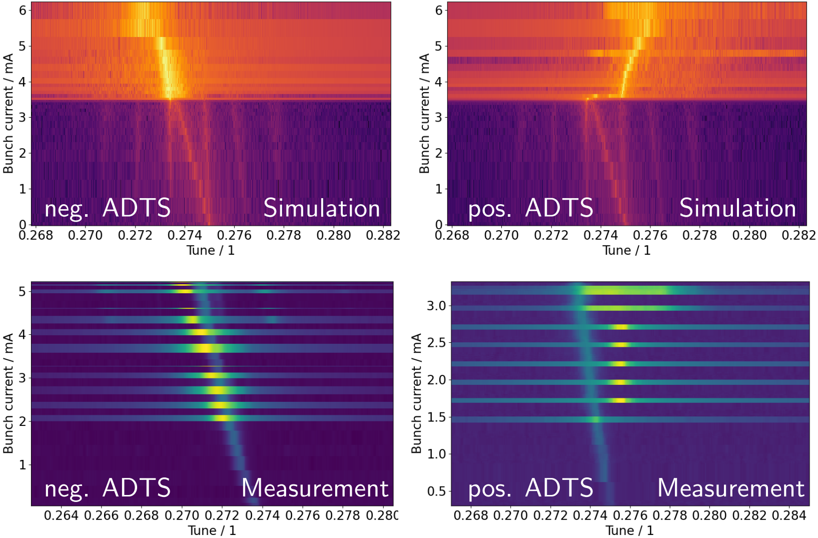
Coherent betatron tune shift with current

Simulation

- Negative ADTS: shift to lower values
- Positive ADTS: jump to mode 0 and then shift to higher values

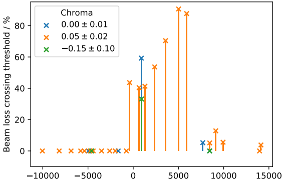
Measurement

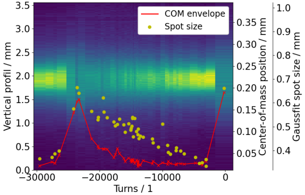
- Same as simulation
- Alternative stabilized / destabilized beam (possible due to observed threshold hysteresis)

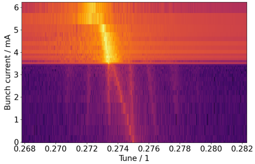


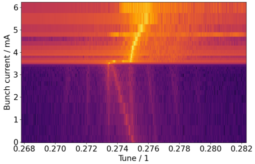
Summary

- Investigated vertical TMCI at close to zero chromaticity
- Threshold hysteresis observed, attributed to IBS
- No significant ADTS dependence of threshold
- Different level of tune spread/ADTS required to contain the instability depending on sign of ADTS → Landau damping
- Low synchrotron tune at 4th generation light-sources
  - Contained instability for negative and high positive ADTS: mode 0 to mode -1 tune shift in range of Landau damping (due to ADTS) before beam loss
  - Beam loss for close to zero ADTS and low positive ADTS
- Good qualitative agreement with tracking simulation and stability calculations
- Difference in current-dependent coherent tune shift above instability threshold









Thank you!

Necessity of cleaning

- Residual bunches with low current
- Below threshold therefore stable
- Interference pattern overshadows stretched bunch profile of the unstable main bunch