Diagnosing collective effects in the MAX IV storage rings

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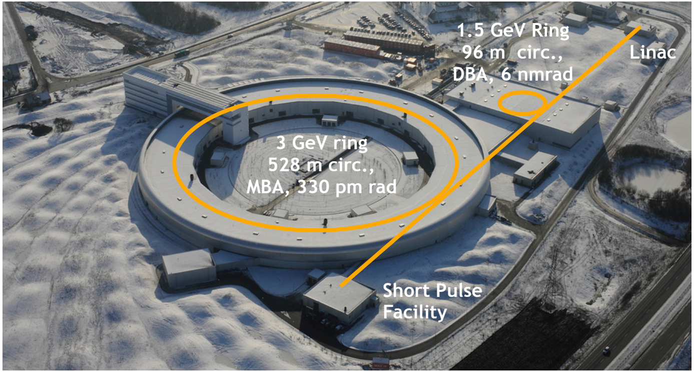
MAX IV

- Linear accelerator:
  - Full energy injector
  - Driver for short pulse facility
  - beam lines 1
- 1.5 GeV Ring:
  - Emittance (6 nm rad)
  - Double-bend achromat
  - Beam lines 5
- 3 GeV Ring:
  - Ultra-low emittance (330 pm rad)
  - Multi-bend achromat
  - Commissioning started in August 2015
  - Delivery to users started in April 2017
  - Beam lines 9 (+2 under commissioning)



P. Tavares et al., 2018, doi:10.1107/S1600577518008111

Examples of diagnostic tools for collective effects

- DCCT for beam current
- BPMs for center of mass position
  - Mode monitor
  - BBB feedback system for measuring of tunes / modes
- Transverse beam size monitors giving emittance and energy spread
  $\Rightarrow$ Talk by Åke Andersson
- Pinger/Kicker for excitation
- Bunch length monitor (optical sampling scope)
  $\Rightarrow$ now also streak camera(s)

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Example 2

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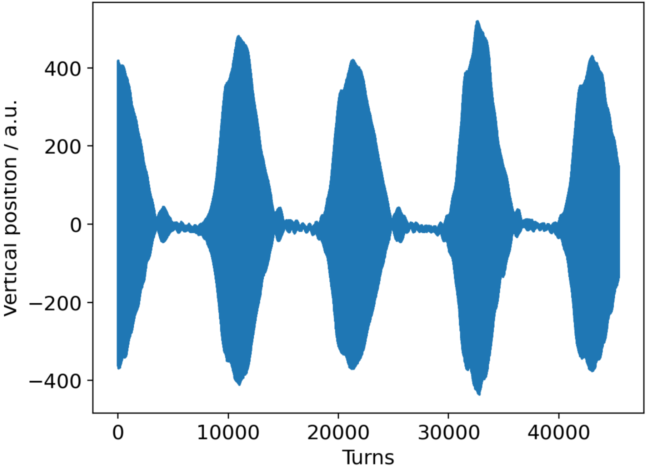
Example 3

Example 1: Transverse mode coupling instability

- Vertical single-bunch instability visible at low vert. chromaticity
- Saw-tooth pattern
- Clear current threshold, found when slowly injecting into single bunch
  - Threshold 3.5 $\pm$ 0.2mA
  - Tunes (h./v.) 0.199 / 0.279
  - Chromaticity (h./v.) 1.08 / 0.18
- No sudden beam loss, but reduced life time
- Easily controlled by BBB feedback



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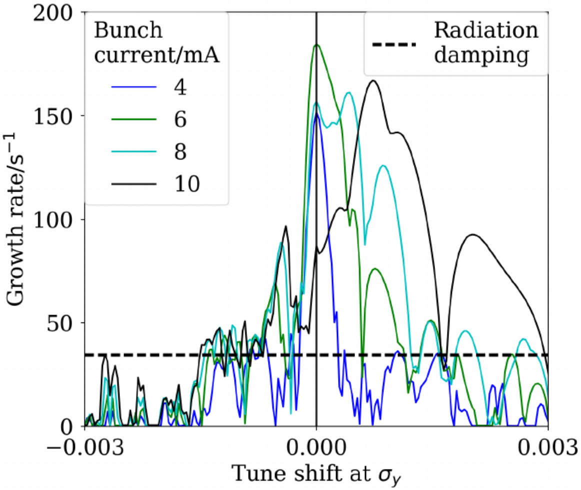
- Easily controlled by BBB feedback
- Simulations suggest influence of sign of amplitude dependent tune shift



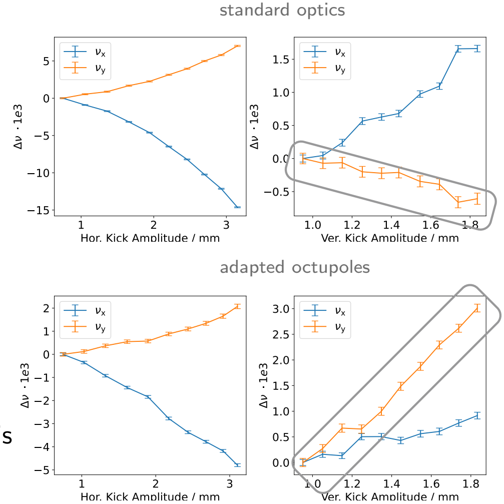
Calculations by F. Cullinan

P. Tavares et al., 2018, doi:10.1107/S1600577518008111
F. Cullinan et al., ARIES 7th Low Emittance Rings Workshop, Jan. 2018, CERN

Example 1: Positive and negative ADTS - preliminary results

- Amplitude dependent tune shift (ADTS)
  - Measured by kicking the beam transversely
  - Detecting center of mass oscillation over turns
  - Extracting oscillation frequency dependent on displacement amplitude
- Vertical kicks in standard optics
  - ⇒ Negative, vertical ADTS
  - ⇒ Observed vertical saw-tooth instability above threshold current
- Vertical kicks in optics with adapted octupoles
  - ⇒ Positive, vertical ADTS
  - ⇒ Instant, partial beam loss at threshold current

⇒ Preliminary, experimental results support hypophysis that a negative vertical ADTS reduces growth-rate of observed instability

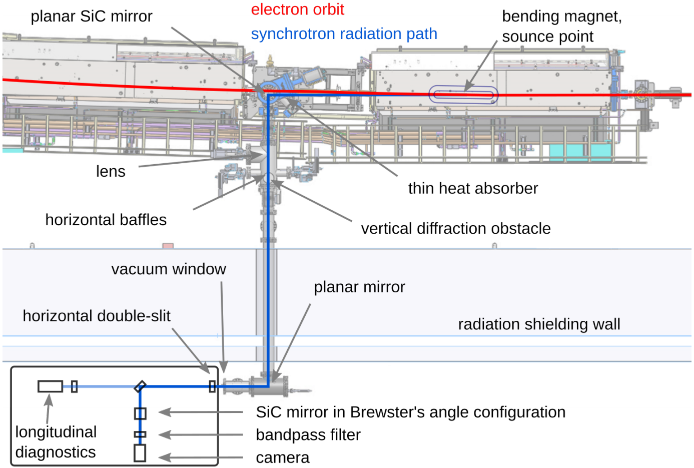


Similar effects were observed for multi-bunch instabilities at ELETTRA
L. Tosi et al., 2003, doi: 10.1103/PhysRevSTAB.6.054401

Data courtesy David K. Olsson

Streak camera at diagnostic beamline - R3

- Synchrotron radiation from bending magnet
- Visible wavelength
- Parallel measurement of transverse and longitudinal beam sizes
- One beamline in dispersive and one in non-dispersive section
  $\Rightarrow$ Talk by Åke Andersson
- NEW streak camera at non-dispersive beamline



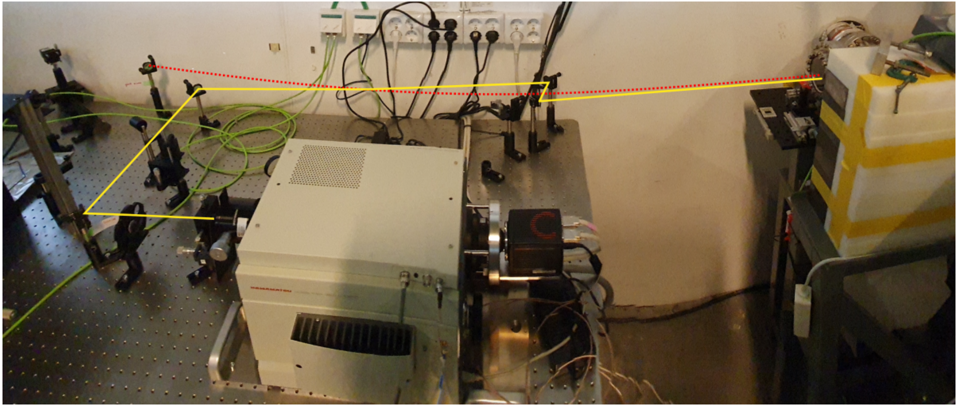
Streak camera

sketch by courtesy of J. Breunlin

J. Breunlin et al., 2016, DOI:10.18429/JACoW-IPAC2016-WEPOW034

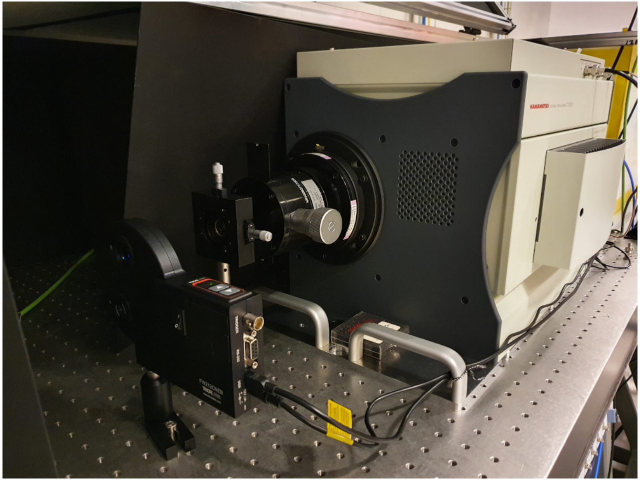
Streak camera at diagnostic beamline - R3

- Light split after last vacuum window
- Added foccussing element to reduce transverse size of light spot on streak camera
- Hamamatsu universal streak camera C10910



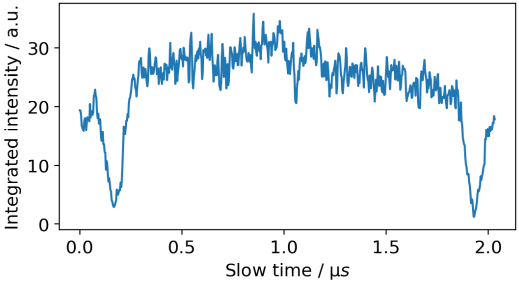
Streak camera at diagnostic beamline - R1

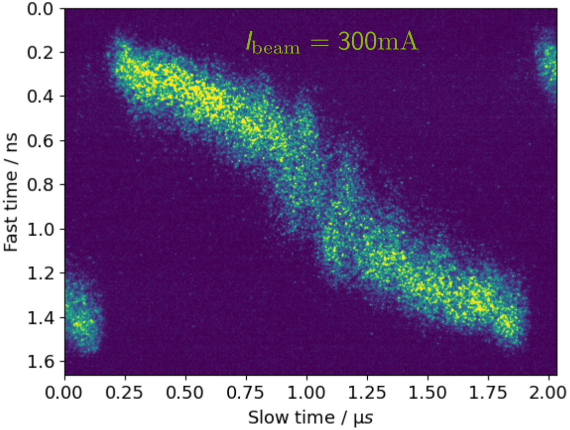
- Similar setup as R3
- Non-dispersive beamline
- Light split for transverse and longitudinal diagnostic
- Automated filterwheel with neutral density filters
  → Integrated in HPDTA software
- Different streak units
  - Synchro scan
  - Slow & Fast single sweep
    → Bunch-picking in multi-bunch possible



Example 2: Multi-bunch

- Beam loading due to passive Landau cavities
- Standard inhomogeneous filling (165/176 bunches)
- Transient in synchronous phase and bunch length visible





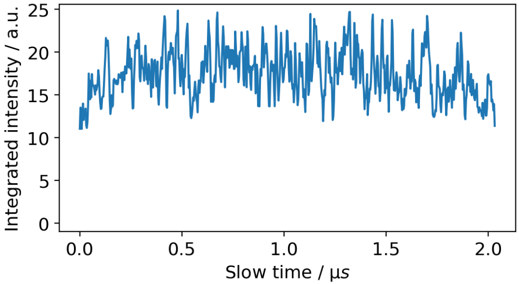
$T_{\mathrm{rev}} \approx 1.76\mu\mathrm{s}$

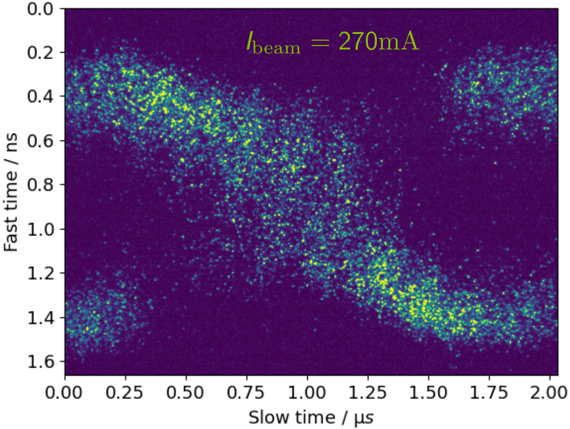
MAX IV

Example 2: Multi-bunch Instability

- Mode 1 instability
- Homogeneous filling
- Transient not stationary with respect to main RF

⇒ Talk by F. Cullinan





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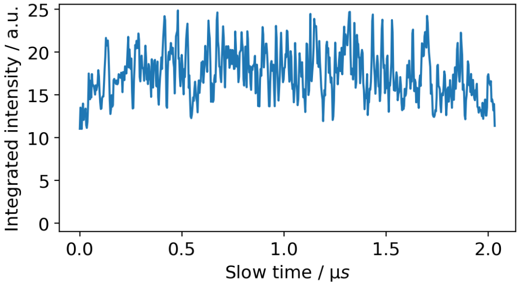

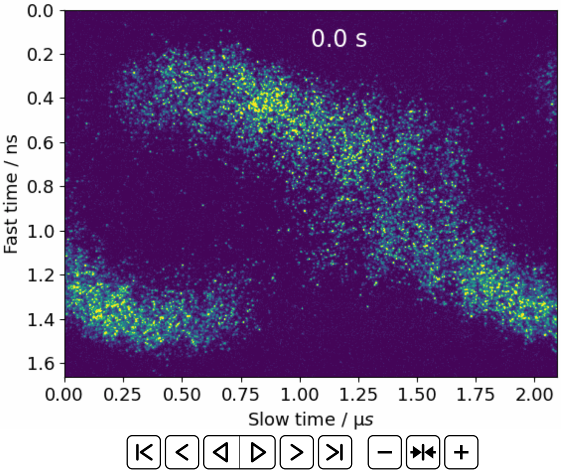

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Example 2: Multi-bunch Instability

- Mode 1 instability
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- “Strength” of pattern depends on LC strength

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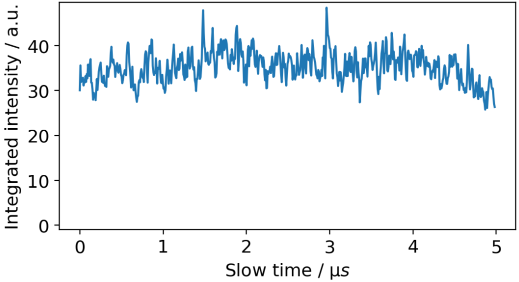
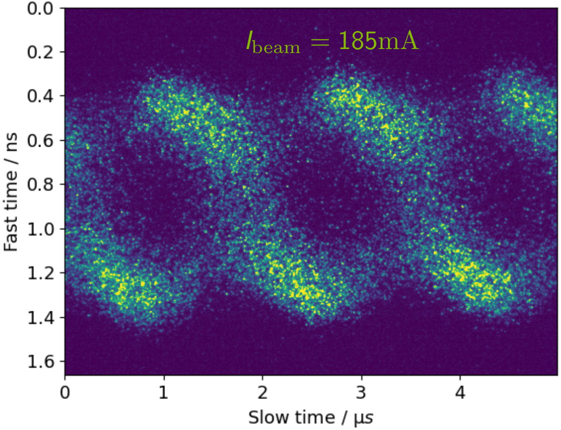


$V_{\mathrm{LC}} = 424\mathrm{kV}$



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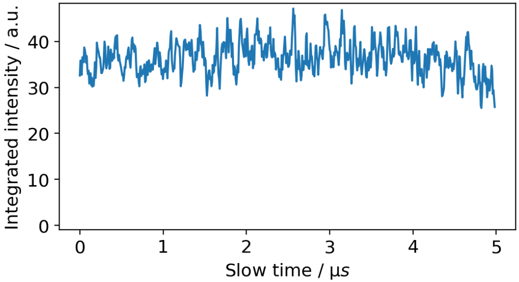
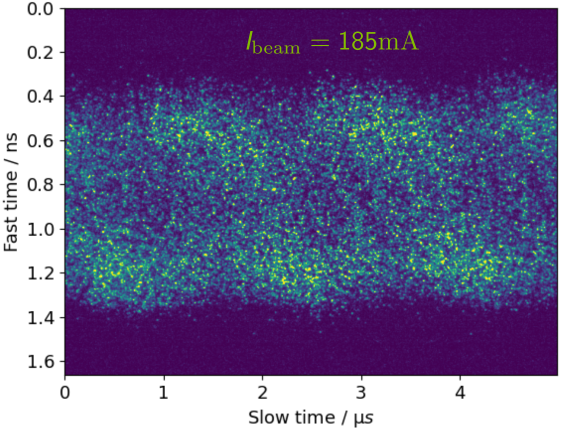


$V_{\mathrm{LC}} = 416\mathrm{kV}$



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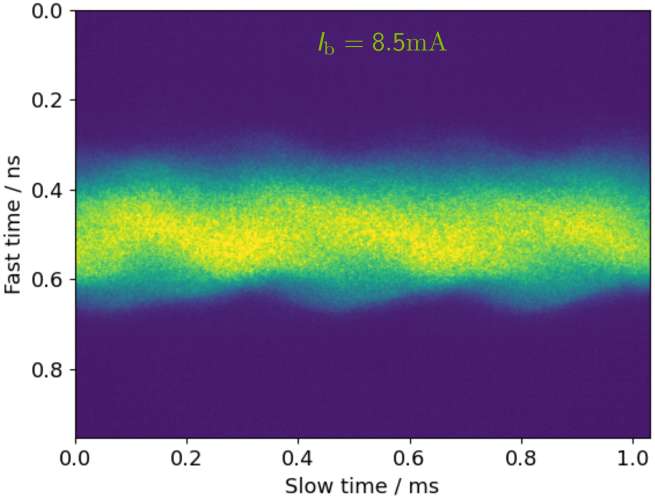
Example 3: Single bunch instability

- Longitudinal instability
- Single bunch operation
- Dynamic bunch profile deformations above threshold in bunch current
- Repetition rate approx. $2.7 \times f_s$



$T_s = 0.95\text{ms}$ $f_s = 1.05\text{kHz}$

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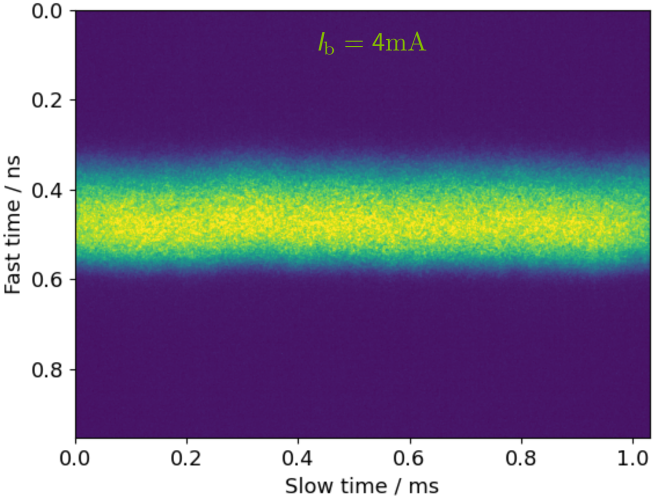

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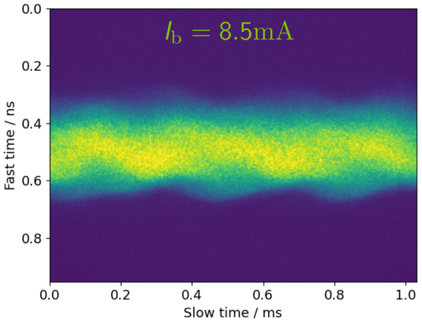
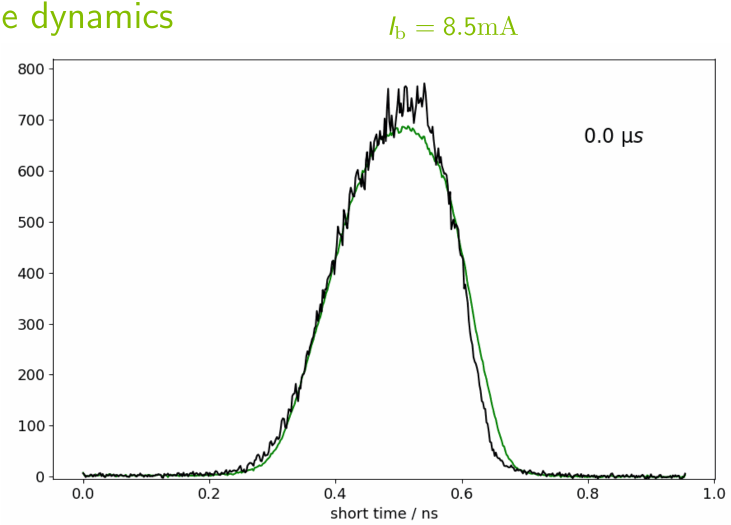
Example 3: Bunch profile dynamics

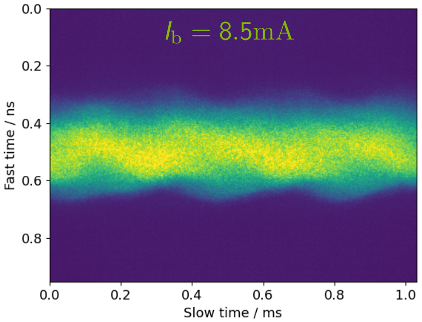
- Temporal development of bunch profile
- Average profile in green
- Clear deformations visible

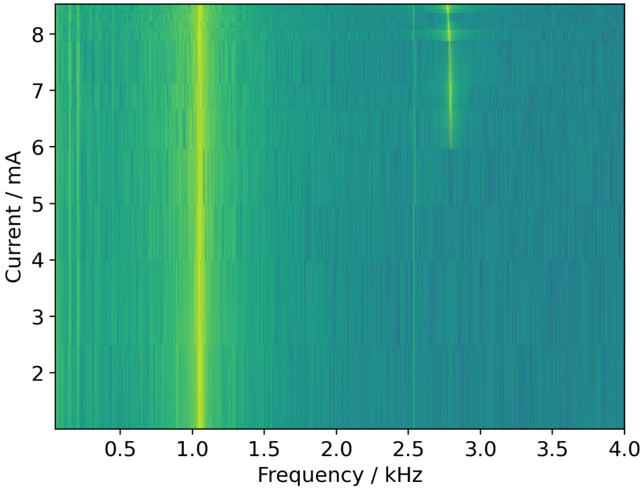




Example 3: Longitudinal beam spectrum

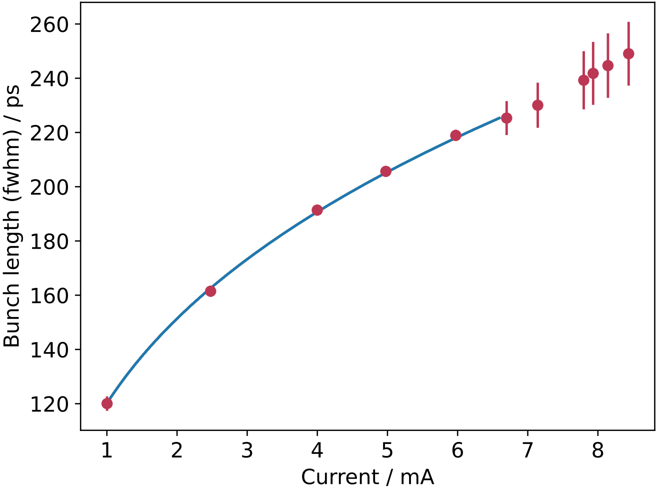
- Visible in long. beam spectrum measured on BBB system
- Additional line at $\approx 2.7 \times f_s$ $\rightarrow$ corresponds to repetition rate
- Small frequency shift with bunch current visible





Example 3: Bunch length over current

- Bunch length increases with bunch current
- Fit:
  $\frac{\sigma_z}{a} - \left(\frac{\sigma_z}{a}\right)^3 = I_\mathrm{b} \cdot \frac{b}{a^3}$
- Bunch length fluctuations become visible between 6 and 7 mA
  $\rightarrow$ indicating instability threshold

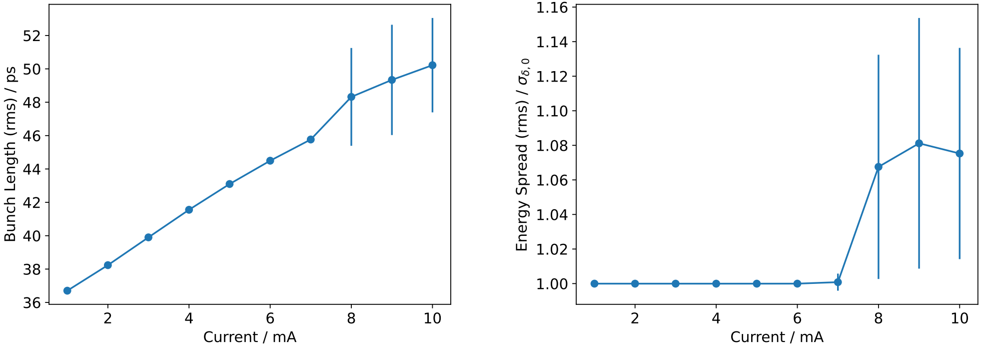


Example 3: Single bunch instability - Simulation

https://github.com/Inovesa

- Simulations with Vlasov-Fokker-Planck solver Inovesa
- Temporal development of longitudinal phase space density
- Simplified 6 GHz broad band resonator impedance [1]

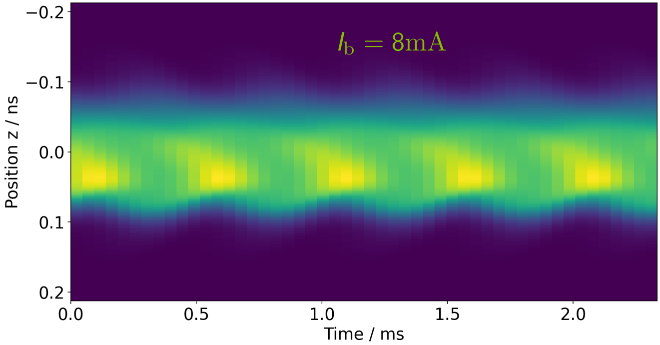
⇒ Clear onset of instability visible between 7 and 8 mA



mbtrack simulations with more complex impedance models can be found here:
NIM A 806 (2016) 221–230, doi:10.1016/j.nima.2015.10.0
[1] F. Cullinan et al., http://dx.doi.org/10.18429/JACoW-NAPAC2016-WEA3CO04

Example 3: Single bunch instability - Simulation

- Temporal development of bunch profile
- Similar overall deformations
- Difference in repetition rate approx. $1.9 \times f_s$ instead of $2.7 \times f_s$ (measured)
- Also difference in threshold 7-8 mA vs 6-7mA (measured)

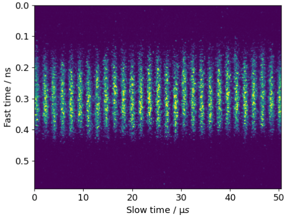


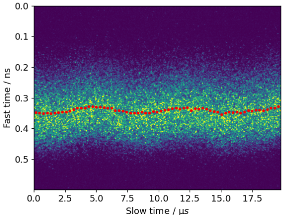
Next steps:

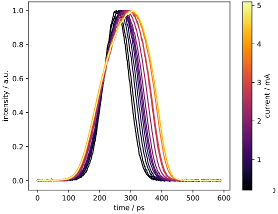
- Update Inovesa model of 3 GeV ring
- Determine more accurate impedance model from measurements
- Discuss addition of further effects, e.g. resistive wall impedance/NEG impedance, Landau Cavities, ...

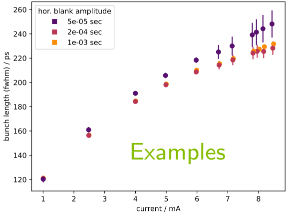
Analysis

- Small python module
  - Reads saved image data
  - Provides a class to access data and metadata like axis scaling
- Further analysis functions
  - Background substraction
  - Center of mass correction
  - Profile calculation
  - Bunch length calculation
    - FWHM or rms
    - User definable slice width (pixel to whole image/sequence)
  - Synchronous phase
  - Filling pattern









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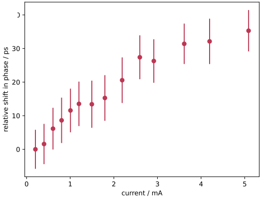

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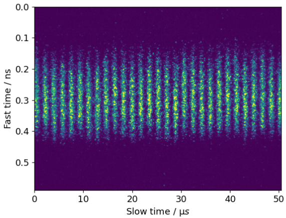
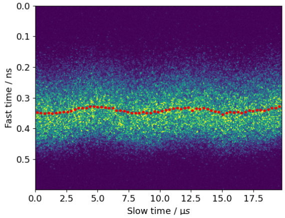
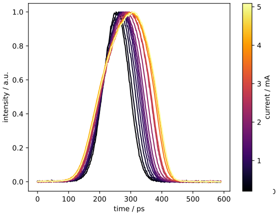
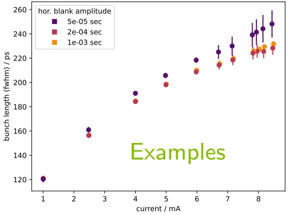
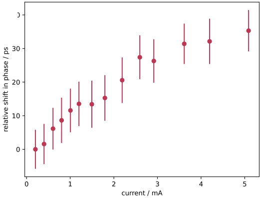
  - Bunch length calculation
  - Synchronous phase
  - Filling pattern
- Discussion points
  - FWHM vs STD bunch length calculation
  - Handling of different slow sweep durations with respect to signal to noise and center of mass motion
  - Influence of MCP Gain











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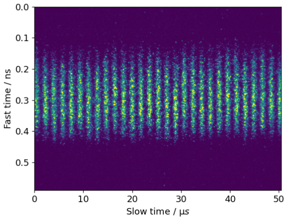
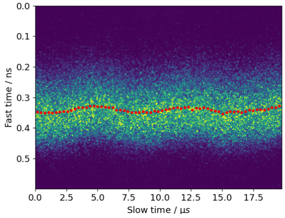
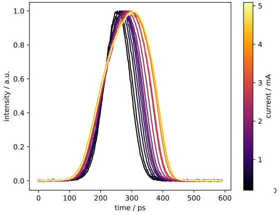
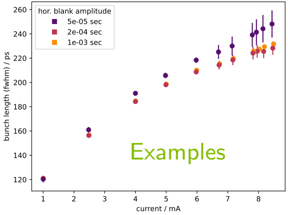
  - Synchronous phase
  - Filling pattern
- Next steps
  - Employ existing TCP/IP interface
  - Remote control
  - Automated (standard) measurements
  - Fast, direct analysis

⇒ “live” diagnostic of the bunch length, longitudinal profile and dynamics









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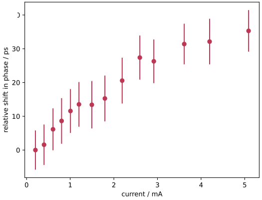
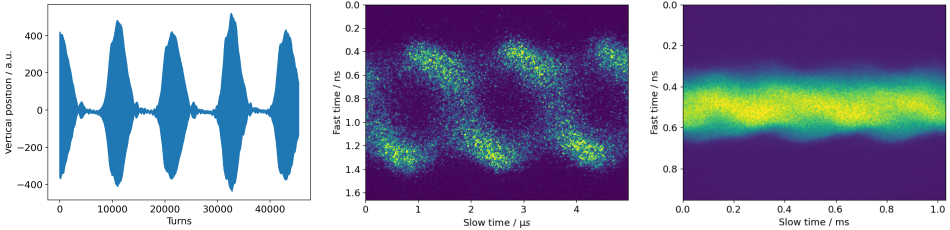


Summary

- Diagnostic for collective effects vital for studies at MAX IV
  - Example 1: Understanding transverse instability without beam loss
  - Example 2: Mode 1 instability during homogeneous filling
  - Example 3: Longitudinal microwave instability during single-bunch
- Streak cameras widen the diagnostic possibilities for collective effects
- Installed at non-dispersive, optical diagnostic beam lines in R1 and R3
- Python module towards fast analysis of streak camera data
- Next steps: Remote control and automated analysis



MAX IV