

Characterizing the Coupled-Bunch Driving Terms in a Storage Ring



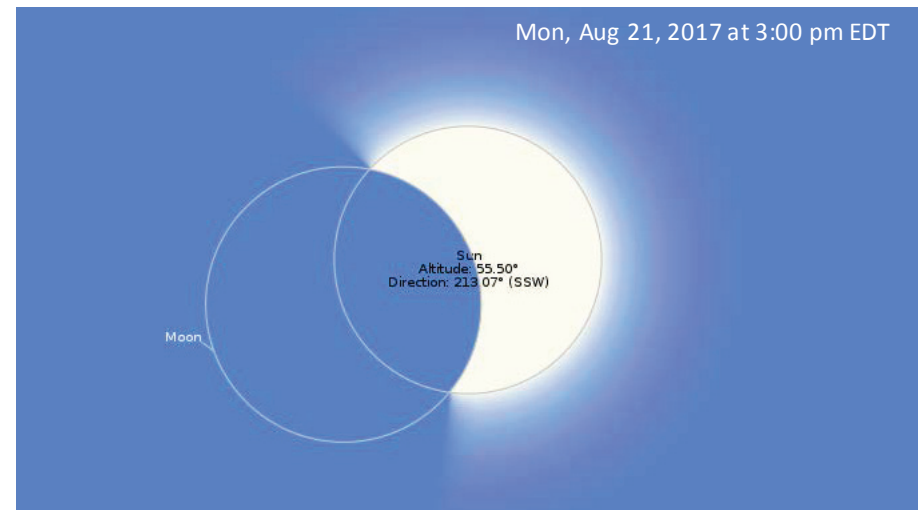
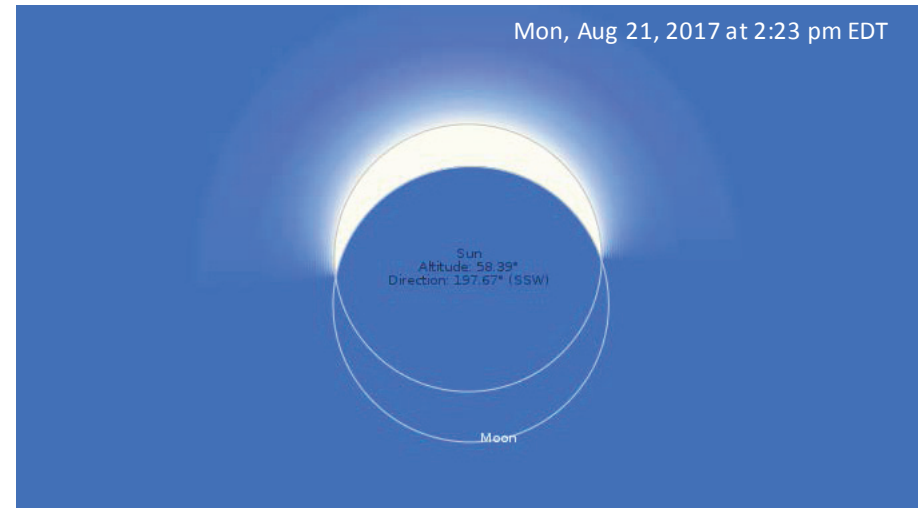
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Outline

- Introduction and motivation
- Measurement technique
- Application
 - MAX-IV
 - Australian synchrotron
 - Advanced Photon Source
- Summary



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Coupled-bunch instabilities (CBIs)

- Narrowband resonance impedances (a.k.a. long-range wakefields) can drive longitudinal or transverse coupled-bunch instabilities.
- Mode number, n , is related to the bunch-to-bunch phase advance. There are a total of $M/2$ possible modes, where M =number of bunches.
- The longitudinal mode frequencies are (in real space):

$$f = (pM \pm n)f_{rev} \pm f_s$$

where p is an integer and f_s is the synchrotron frequency.

- In electron rings, driving the beam at $+f_s$ is unstable (growth) and at $-f_s$ is stable (damping).
- In the transverse plane, the mode frequencies involve the betatron sidebands $\pm f_\beta$. Here, driving at $-f_\beta$ is unstable and $+f_\beta$ is stable.

Motivation

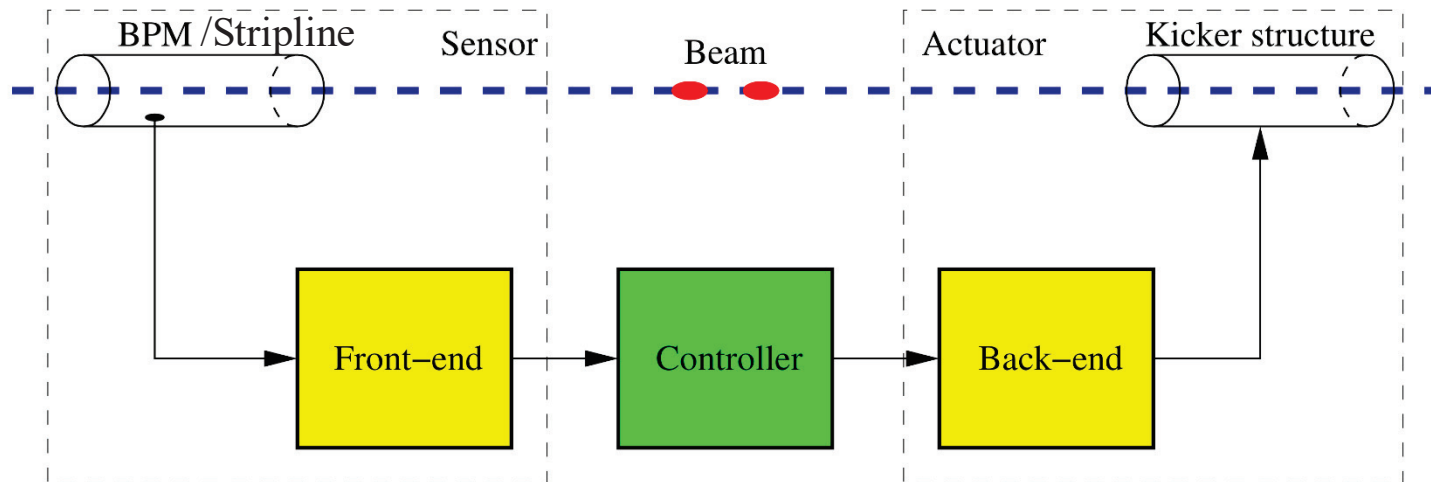
- Resonant modes are generally found in rf cavities (higher-order modes, or HOMs) – damping and longitudinal feedback not always effective.
- Resonant modes are also found in other structures: in-vacuum undulators (IVUs), injection kickers, etc.
- Tools for identifying narrowband resonant impedances are critical for
 - Locating and redesigning driving structures
 - Optimizing operational conditions (temperatures, geometries, etc.) to achieve stability
 - Upgrade planning
- Unique characteristics of 4th generation storage ring light sources are making the beam more sensitive to long-range wakefields.

Brief history of instability characterization

- Digital bunch-by-bunch feedback (FB) systems (1990s) introduced a new tool: transient diagnostics.
- Grow/damp technique
 - Above instability threshold, turn FB off/on while recording beam motion.
 - Characterizes unstable modes; limited to fastest growing modes.
- Drive/damp technique (1996)
 - Use sinusoidal excitation to drive one eigenmode.
 - Turn off excitation and FB, record beam motion (damping or growth)
- Advanced drive/damp technique
 - Scan over multiple modes.
 - Repeat measurement while scanning a parameter, like cavity temperature.

Typical drive/damp measurement

- Back-end drives amplifier at $pf_{rev} + f_s$ pulsed sine waveform, up-converted to an appropriate frequency.
- Controller includes ADC, DAC, and DSP processor. Motion of every bunch acquired turn by turn.
- Analog front-end processes BPM or stripline signals in transverse plane (differential mode) or longitudinal plane (common mode).



Comparative work

HOM-driven longitudinal modes at Diamond using the drive/damp method (Gunther Rehm, IBIC16).

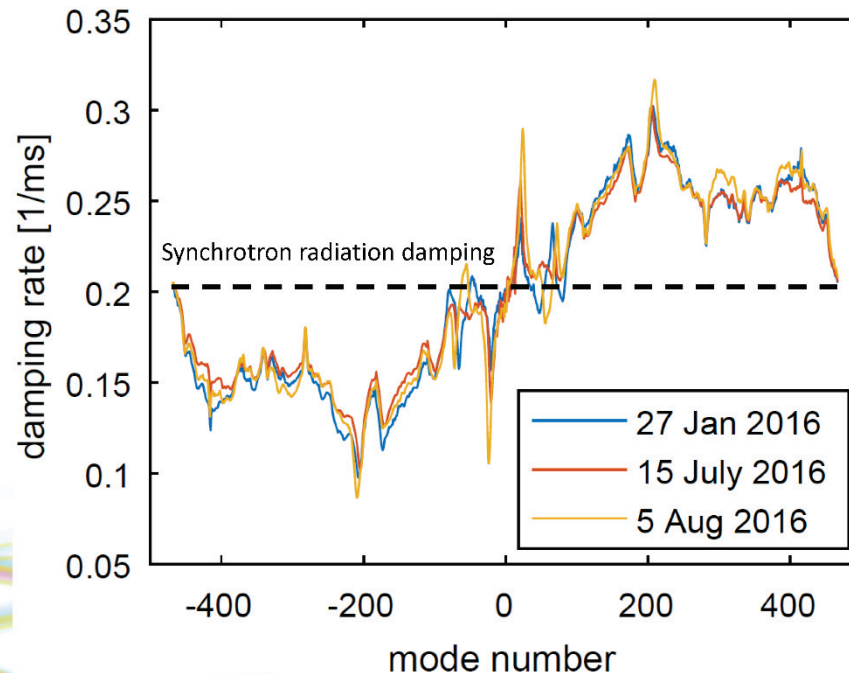


Extracting Damping Rates

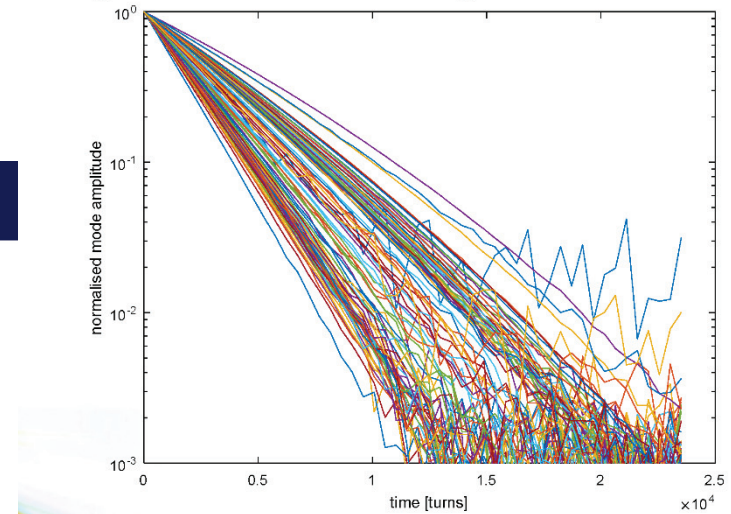
- Extract only times of damping
- Normalise to peak for plotting
- Fit logarithm of magnitude with straight line for damping rate



Longitudinal Damping Rates



Measurements of Longitudinal Coupled Bunch Instabilities and Status of New Feedback System, G. Rehm, IBIC2016



Instabilities and Status of New Feedback System, G. Rehm, IBIC2016

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Features of present work

- Measure modal eigenvalues:
 - Growth/damping rate, giving $\mathcal{R}e(Z_{eff})$, or R_s
 - Frequency shift, giving $\mathcal{I}m(Z_{eff})$
- Characterize Q and tuning sensitivity of HOMs using a parameter scan
 - Joint fitting process of $\pm n$ eigenmodes (at $nf_{rev} \pm f_s$) automatically extracts temperature tuning
- Identify HOMs from mode scan
- Measurements below the instability threshold are easier and cleaner; i.e., longer time to measure damping time.

Application

■ MAX-IV

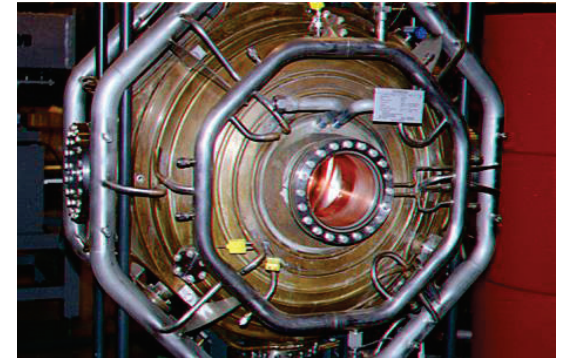
- Longitudinal instabilities driven by the HOMs in main and harmonic rf limited beam current.
- Raised threshold significantly after temperature optimization.

■ Australian Synchrotron

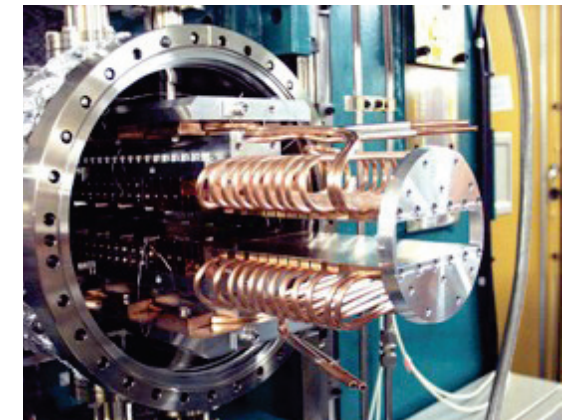
- Observed fast vertical CBI driven by IVUs.
- Investigated gap-dependency and optimization for operations.

■ Advanced Photon Source Upgrade (APS-U)

- Predicted fast longitudinal CBIs driven by rf cavity HOMs.
- Investigated temperature tuning of HOMs to reduce FB requirements.



352-MHz rf cavity, APS (ANL)



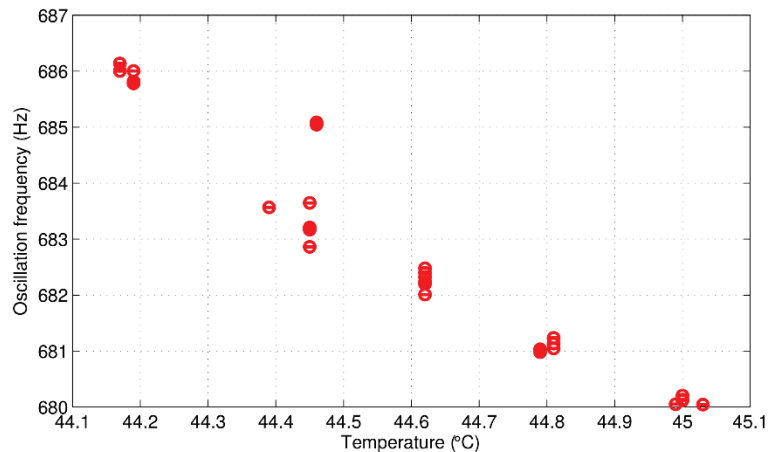
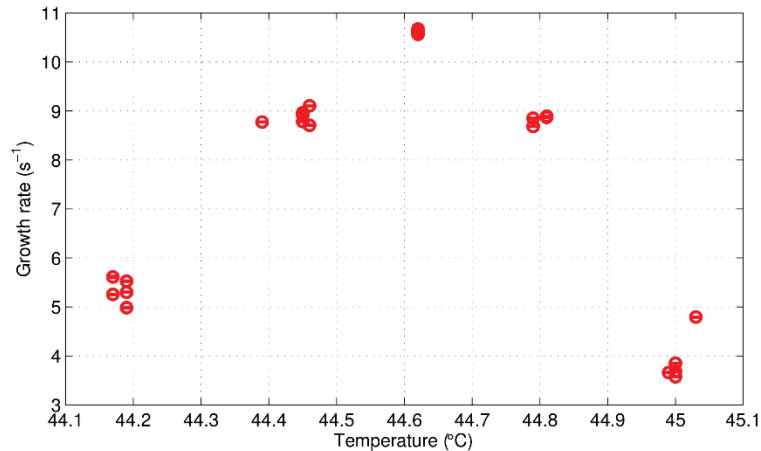
IVU, ALS (LBNL)

MAX-IV

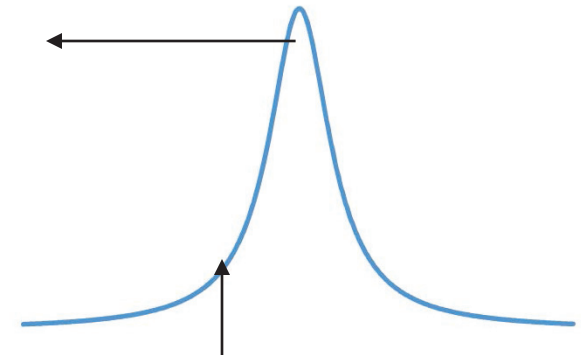
Parameter	Value
Beam energy	3 GeV
Beam current	500 mA
Number of bunches	176
Rf frequency	100 MHz
Harmonic number	176
Synchrotron frequency	680 Hz



Cavity temperature scan



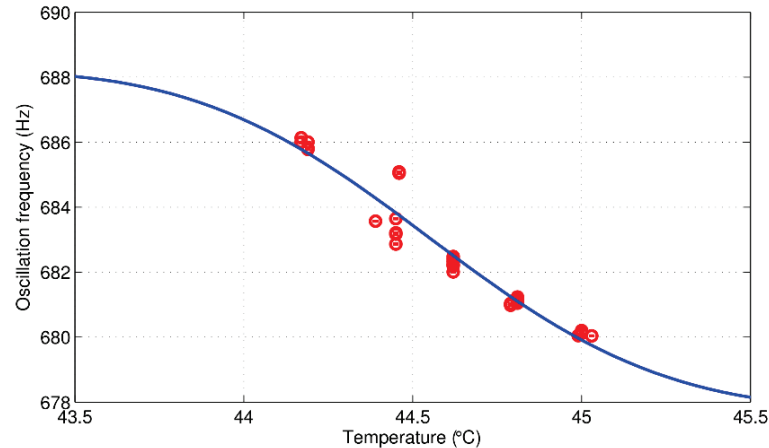
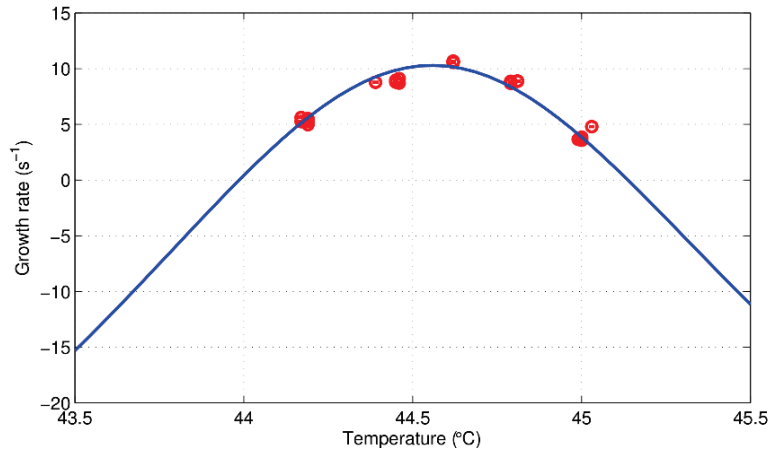
higher temperature,
HOM freq shifts down



Growth rate at mode freq changes

- Moved cavity temperature from nominal 35 °C;
- Growth rate peak seen around 45 °C — mode 167;
- Detailed scan at 0.2 °C steps reveals a clear resonance;

Cavity temperature scan fit



- Fit resonator response:

Parameter	Value
T_{center}	44.56 °C
Bandwidth	2.64 °C
Rad. damping	18.5 ms

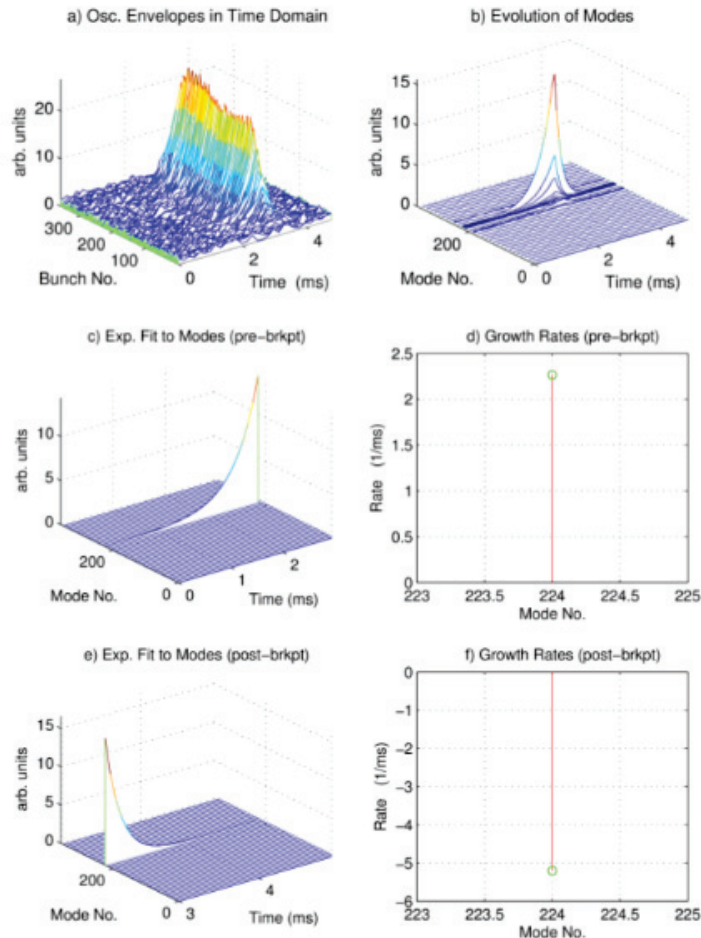
- Cavity temperature adjusted to shift HOMs off synchrotron sideband.
- Repeated for each cavity.
- Instability threshold raised from 3 mA to 17 mA.
- Max current with improvised feedback - from 20 to 100 mA.

Australian synchrotron parameters

Parameter	Value
Beam energy	3 GeV
Beam current	200 mA
Number of bunches	300
Rf frequency	500 MHz
Harmonic number	360
Vertical tune	5.216



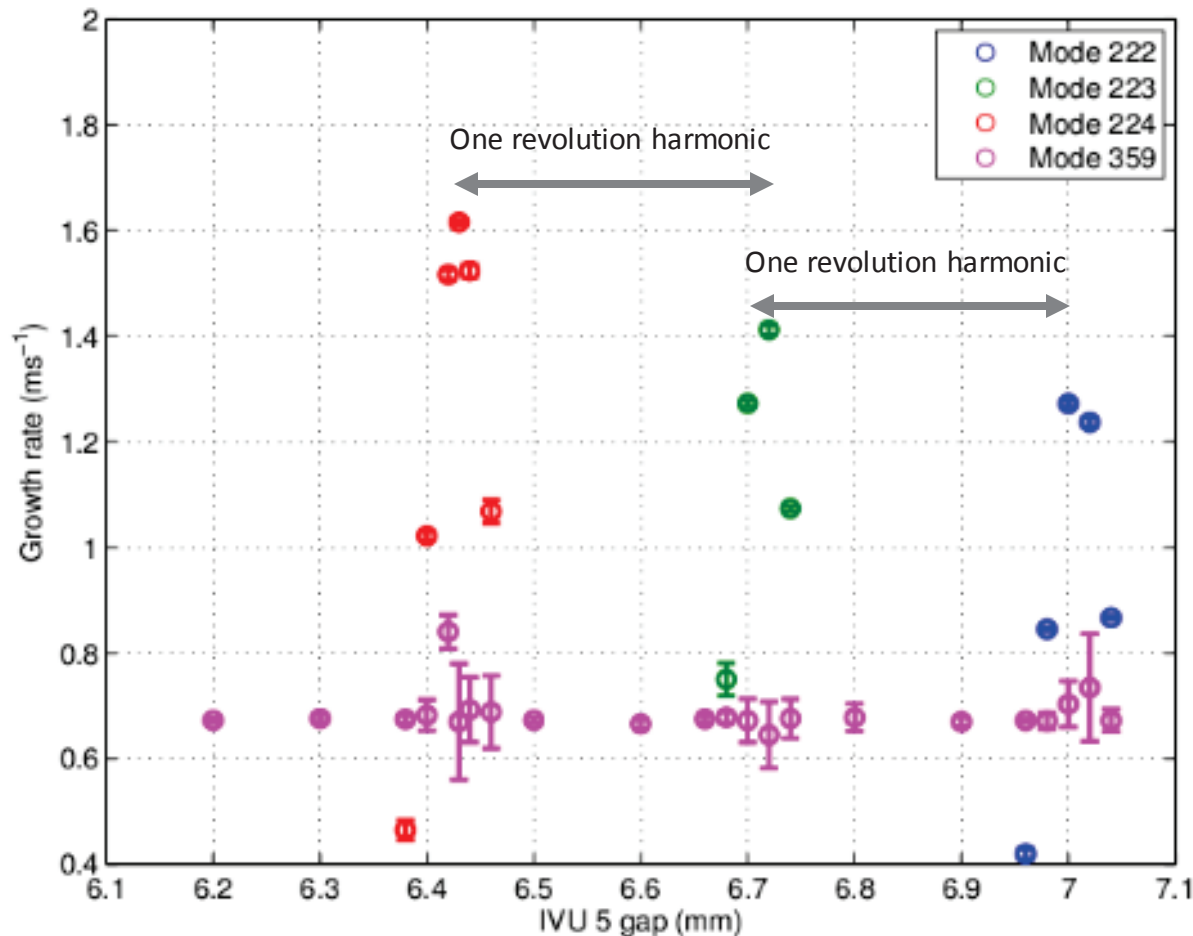
Resistive wall and HOMs



SLSA:sep1715/220556: Io= 195.9256mA, Dsamp= 1, ShiftGain= 5, Nbun= 360,
At Fs: G1= 69.3875, G2= 0, Ph1= -74.4768, Ph2= 0, Brkpt= 4148, Calib= 1.

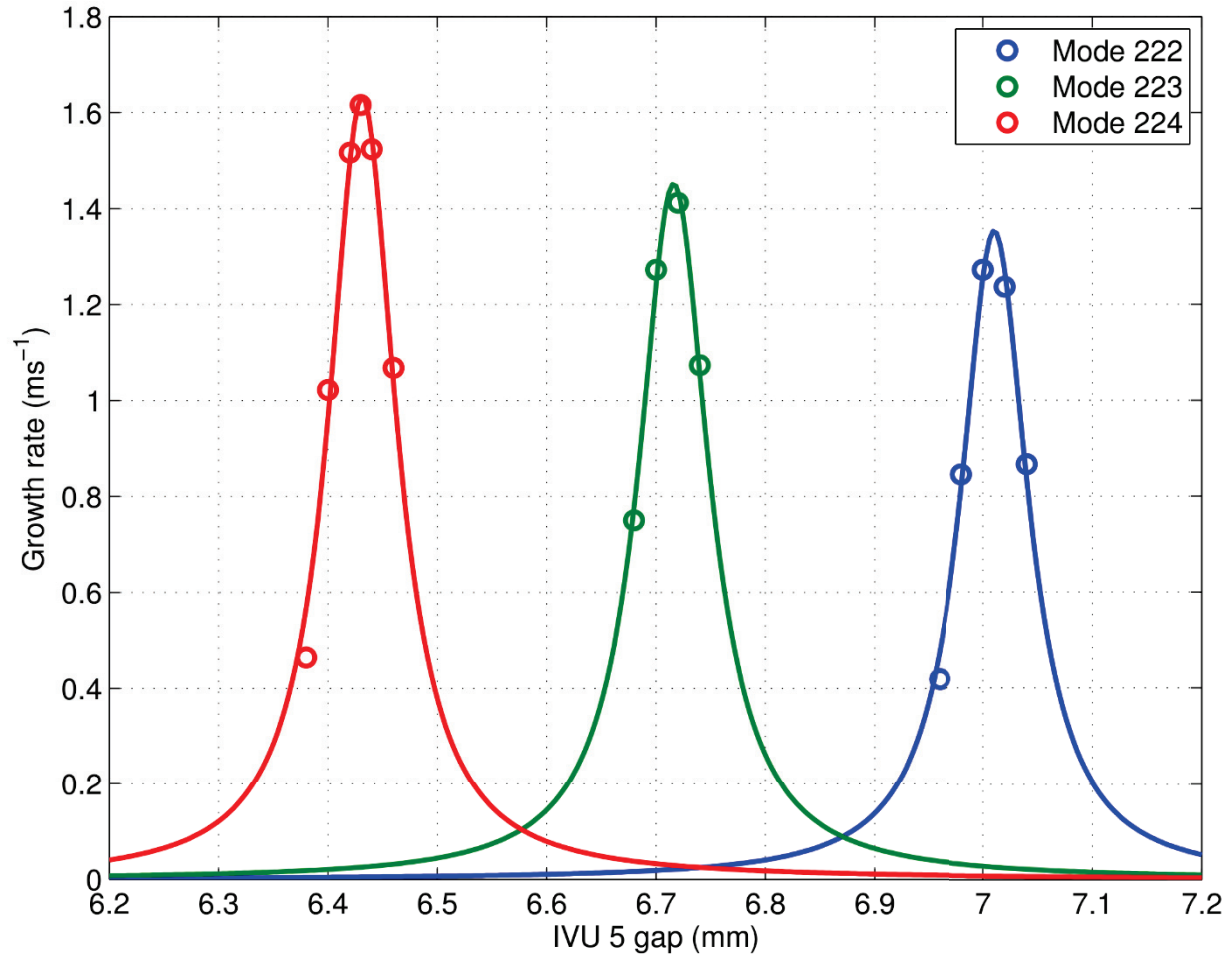
- Australian Synchrotron has 3 in vacuum undulators (IVUs);
- With IVU gaps open vertical instabilities are dominated by resistive wall;
- When the gaps are closed, much faster HOMs appear;
- The goal of this study is to pinpoint the source of these HOMs.

In-Vacuum Undulator gap scan



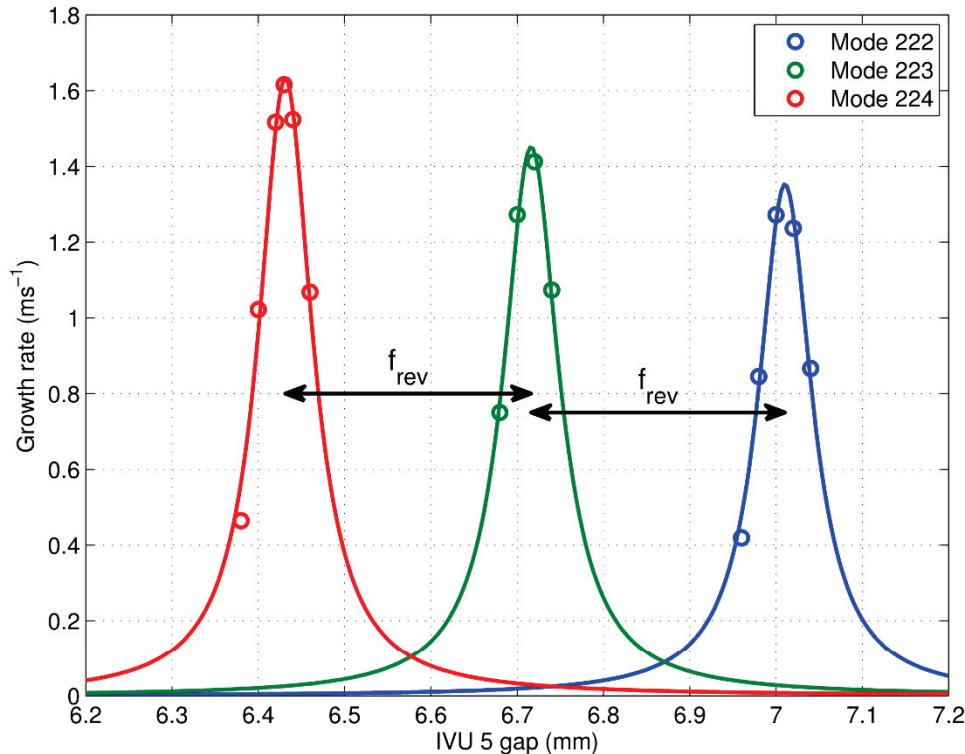
- Moved the HOM in the IVU over 3 revolution harmonics allowing a resonant frequency/gap calibration.
- Resistive wall mode is practically constant.

Fit to resonances



- Fit resonances to each mode.
- Consistent results: bandwidth 75-78 μm .
- Impedance seems to increase as we get closer to the beam (small gap).

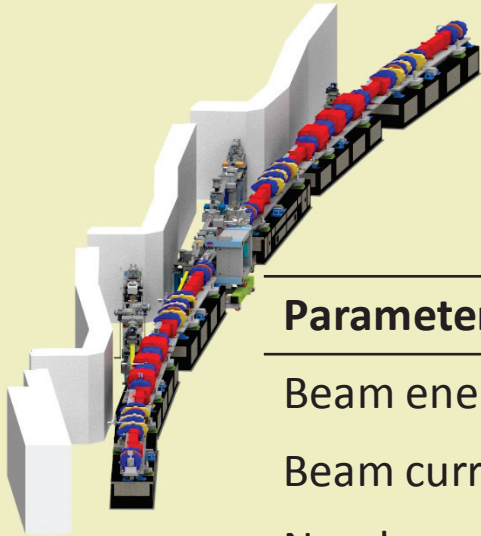
IVU impedance conclusions



$$f_{rev} = 1.38 \text{ MHz}$$

- HOM frequency seems to change linearly with the gap position:
 - Two revolution harmonic distances are within 3%;
- Tuning sensitivity 4.8 MHz/mm;
- Bandwidth of 76 μm translates to 365 kHz;
- Consistent with HFSS HOM modeling: 4.6 MHz/mm, bandwidth >240 kHz (194 MHz).

APS/APS-U parameters



Parameter	APS now	APS-U
Beam energy	7 GeV	6 GeV
Beam current	100 mA	200 mA
Number of bunches	24, 57, 324	48, 324
Momentum compaction	2.82×10^{-4}	3.96×10^{-5}
Rf frequency	352 MHz	352 MHz
Harmonic number	1296	1296
Synchrotron frequency, f_s	2.2 kHz	0.56 kHz ^a
Radiation damping time	4.82 ms	20.13 ms
Horizontal emittance	3100 pm-rad	42 pm-rad

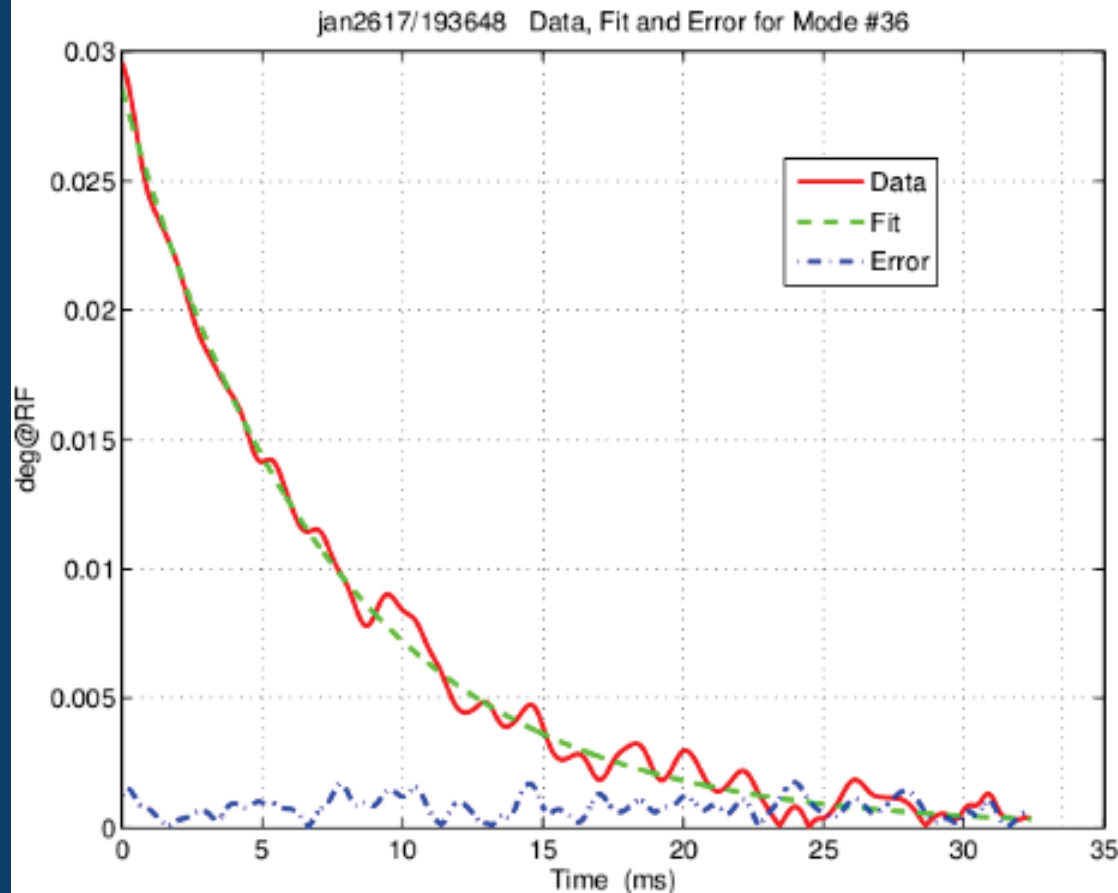
^a Higher harmonic cavity (HHC) off. With HHC on, f_s is centered at 0.1 kHz.

APS-U instability issue

- APS is currently stable up to 250 mA after installing HOM dampers on 4 of 16 rf cavities and tuning the temperatures. Typical beam current is 100 mA.
- No LFB system is installed; driving HOMs identified and characterized only when CBI observed.
- APS-U will use 12 of the 16 APS cavities.
- Predicted longitudinal CBI growth rates are much higher for APS-U due to lower beam energy and very low synchrotron tune. Also, the radiation damping time is 4× longer.
- LFB becomes impossible when growth time faster than synchrotron period.
- Detailed HOM characterization was desired in order to investigate whether temperature tuning can be used to reduce the CBI growth rate.

This will be common issue for many of the 4th generation MBA-based storage ring light sources

Multibunch drive/damp experiment

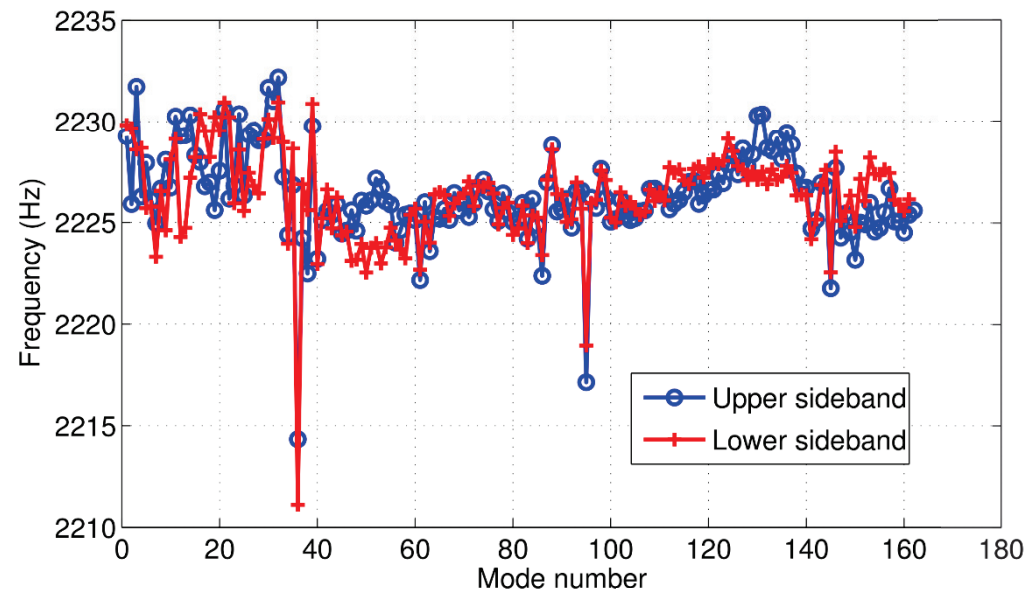
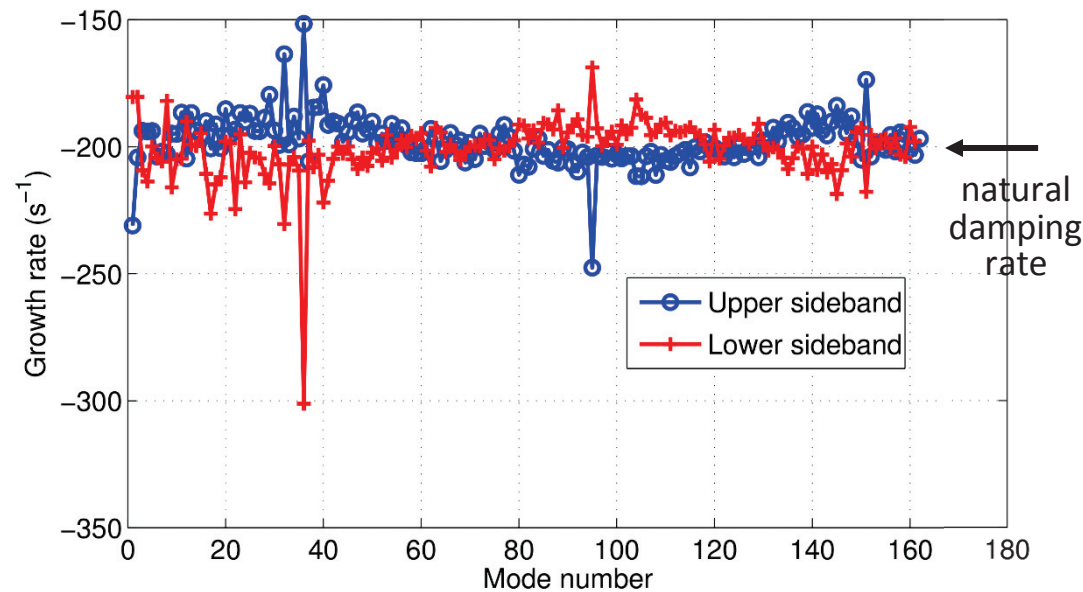


- Filled 100 mA in 324 bunches;
- Apply excitation to the beam at $36f_{\text{rev}} + f_s$;
- Upon software trigger turn off excitation and feedback, record 35 ms of bunch-by-bunch data;
- Need to zoom in to see the mode we are trying to measure;
- Mode 36 initial amplitude is 0.03° vs. 0.13° average for mode 0;
- Mode 36 has very quiet noise floor

- The damping rate will be a combination of natural damping and interaction with impedance.
- The frequency shift for each mode can also be extracted from the data.
- This can be automated and applied to all modes across the spectrum.

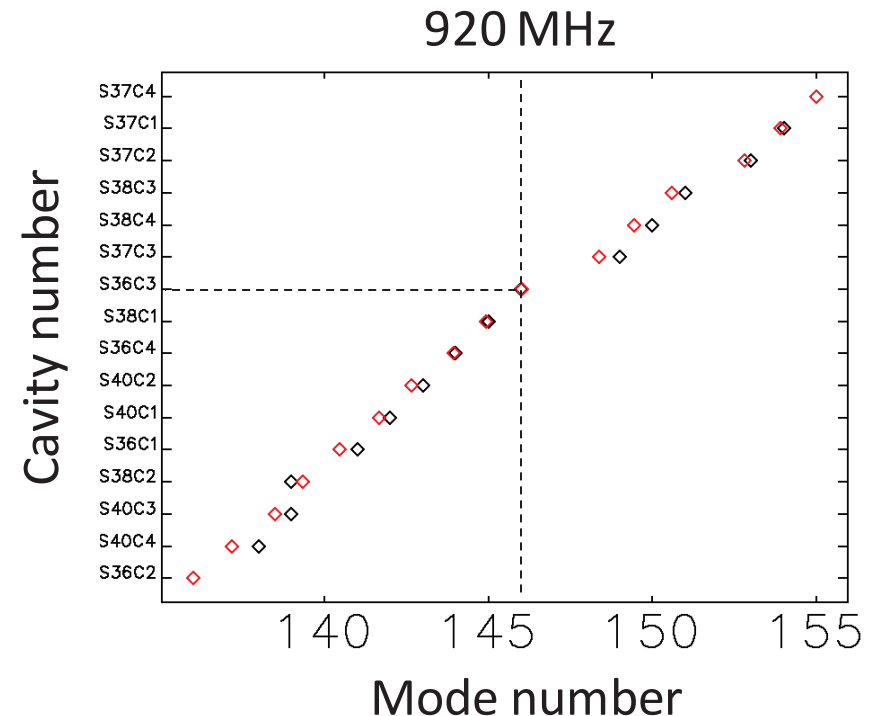
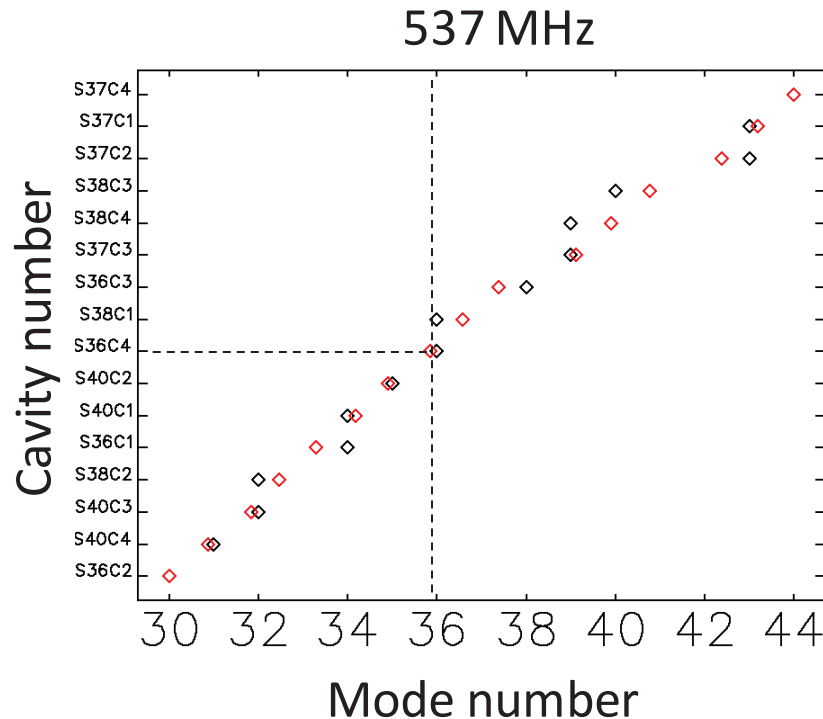
Single all-mode scan

- Growth rates (top) and freq shifts (bottom) for M=324 bunches, 76 mA.
- Modes $M-n$ (red) shown overlapped with modes n (blue), showing expected antisymmetry (top) and symmetry (bottom).
- Modes 32, 36, 40, -95, 191 are clearly driven by high-Q resonances.
- Next step: vary parameter (cavity temperatures in Sector 36) and analyze modes with detailed scans.



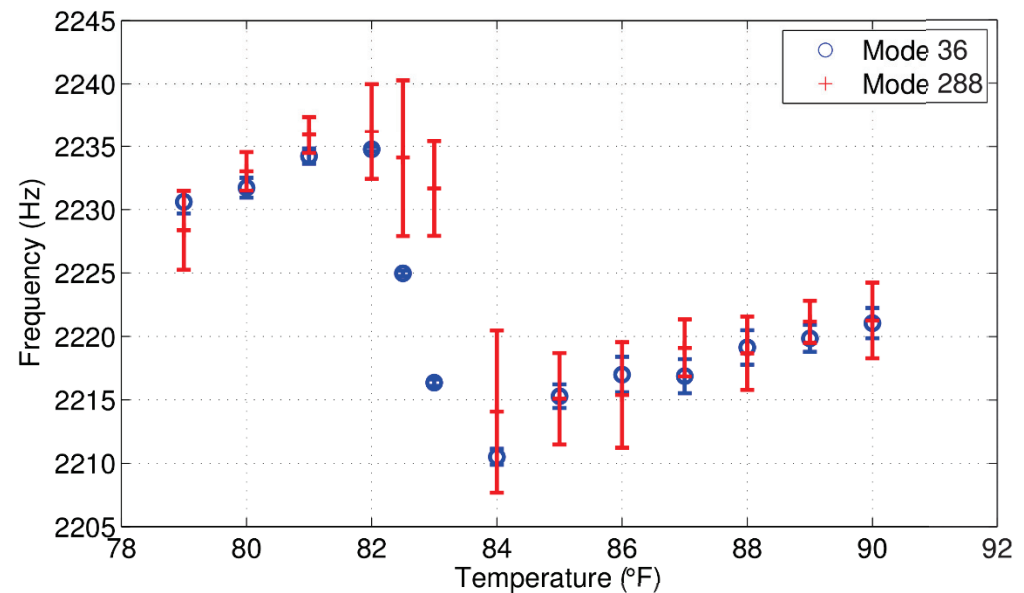
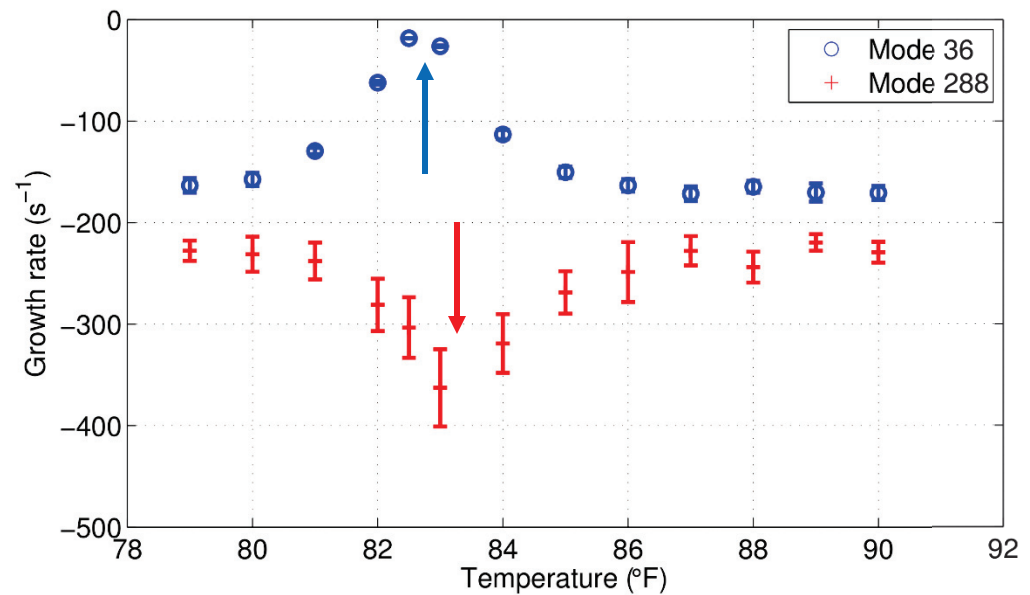
Modes vs HOM identification

- HOM spectra measured in cavities using single bunch.
- HOMs are staggered because cavity lengths vary.
- Mode 36: Sector 36, Cav 4
- Mode 146: Sector 36, Cav 3



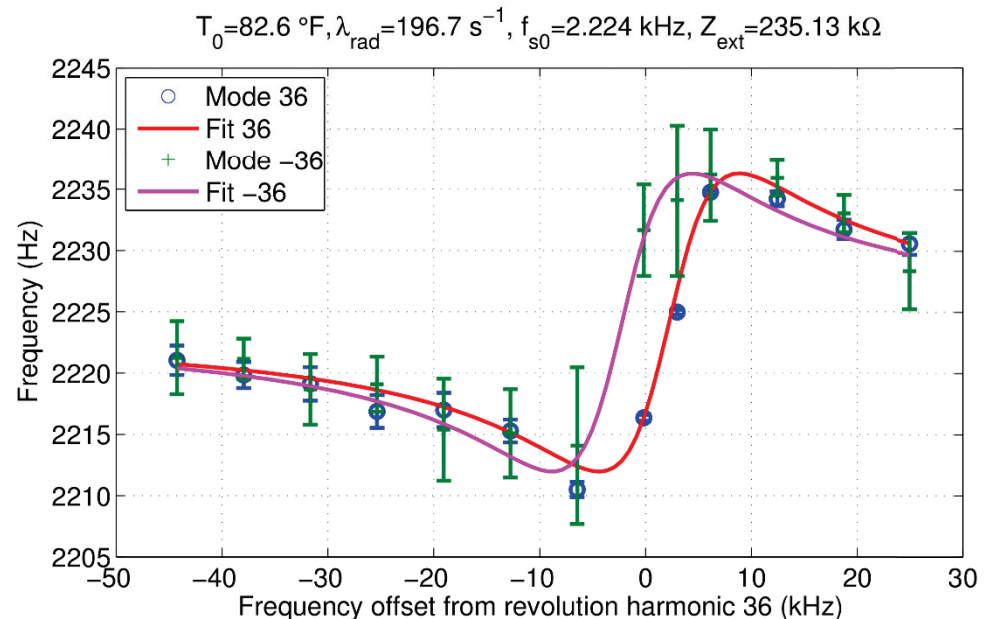
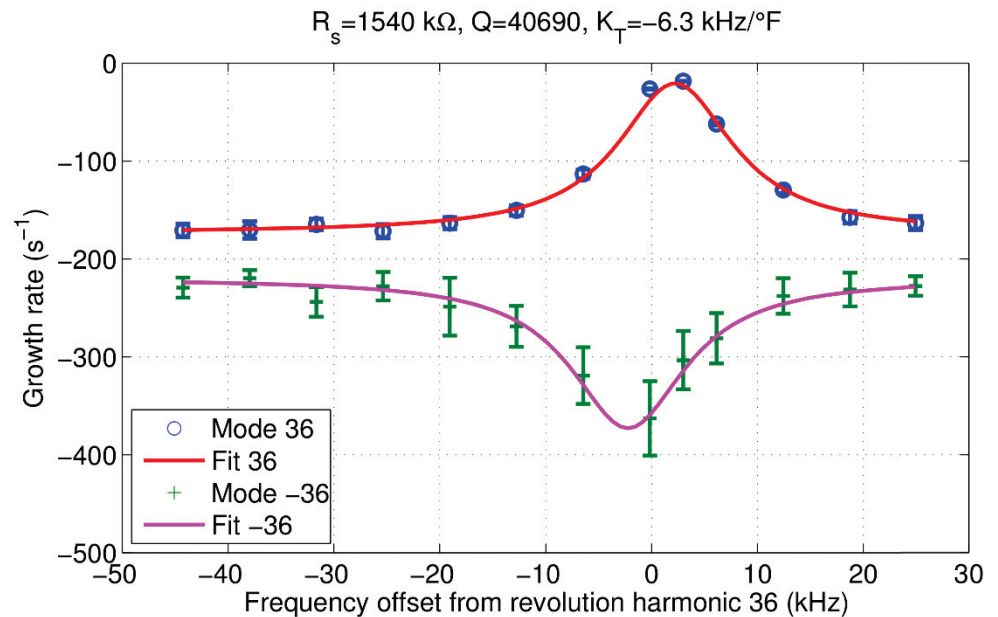
Temperature scan

- Mode 36 (288 = -36) shows growth (damping) rate peak, scanning Sector 36 cavity temperatures.
- Slight shift observed between positive and negative modes.
- Positive mode sampled at $+f_s$ while negative modes sampled at $-f_s$; same HOM.
- Separation of $2f_s$ can be used to extract the HOM temperature tuning, if Q sufficiently high.



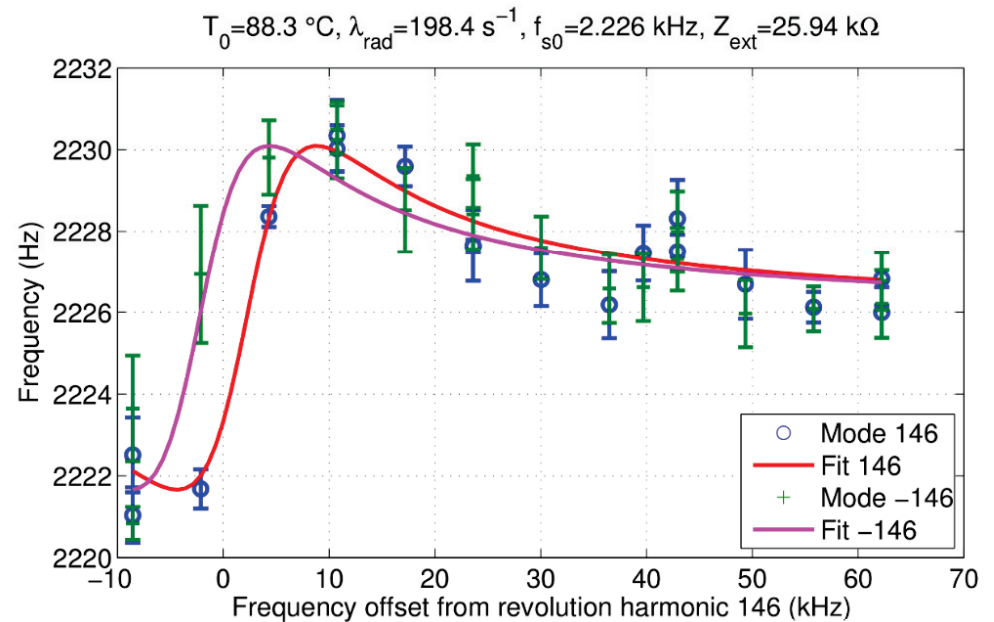
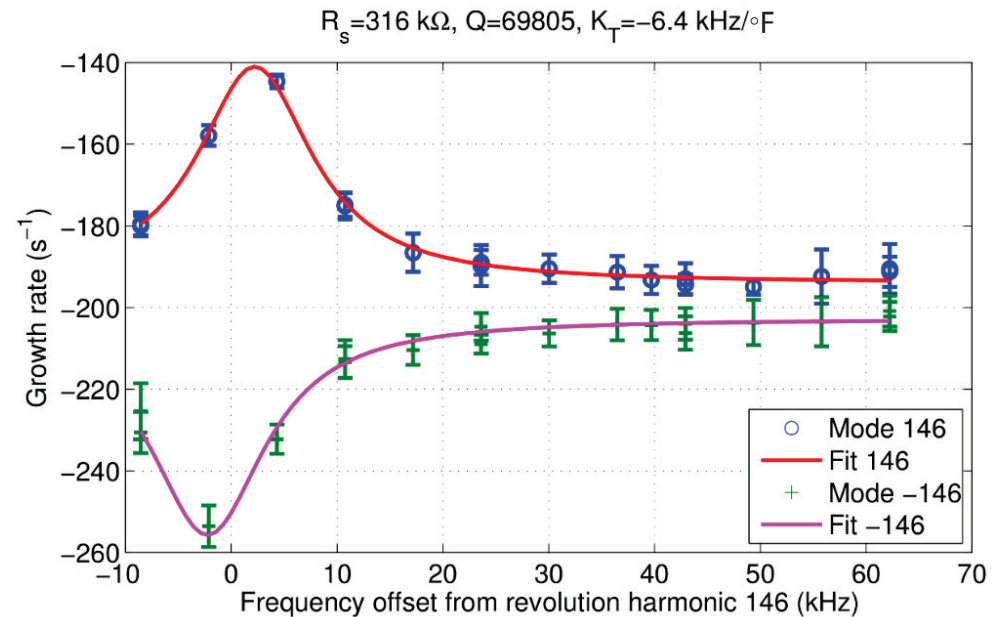
Temp. coefficient

- Separation ($2f_s$) of peaks gives temperature coefficient of $-6.3 \text{ kHz}/^\circ\text{F}$.
- Figures show simultaneous fitting of both modes 36 and -36, on frequency axis.
- R_s and Q consistent with modeled values for 537 MHz HOM: $1.67 \text{ M}\Omega$ and 41,000.



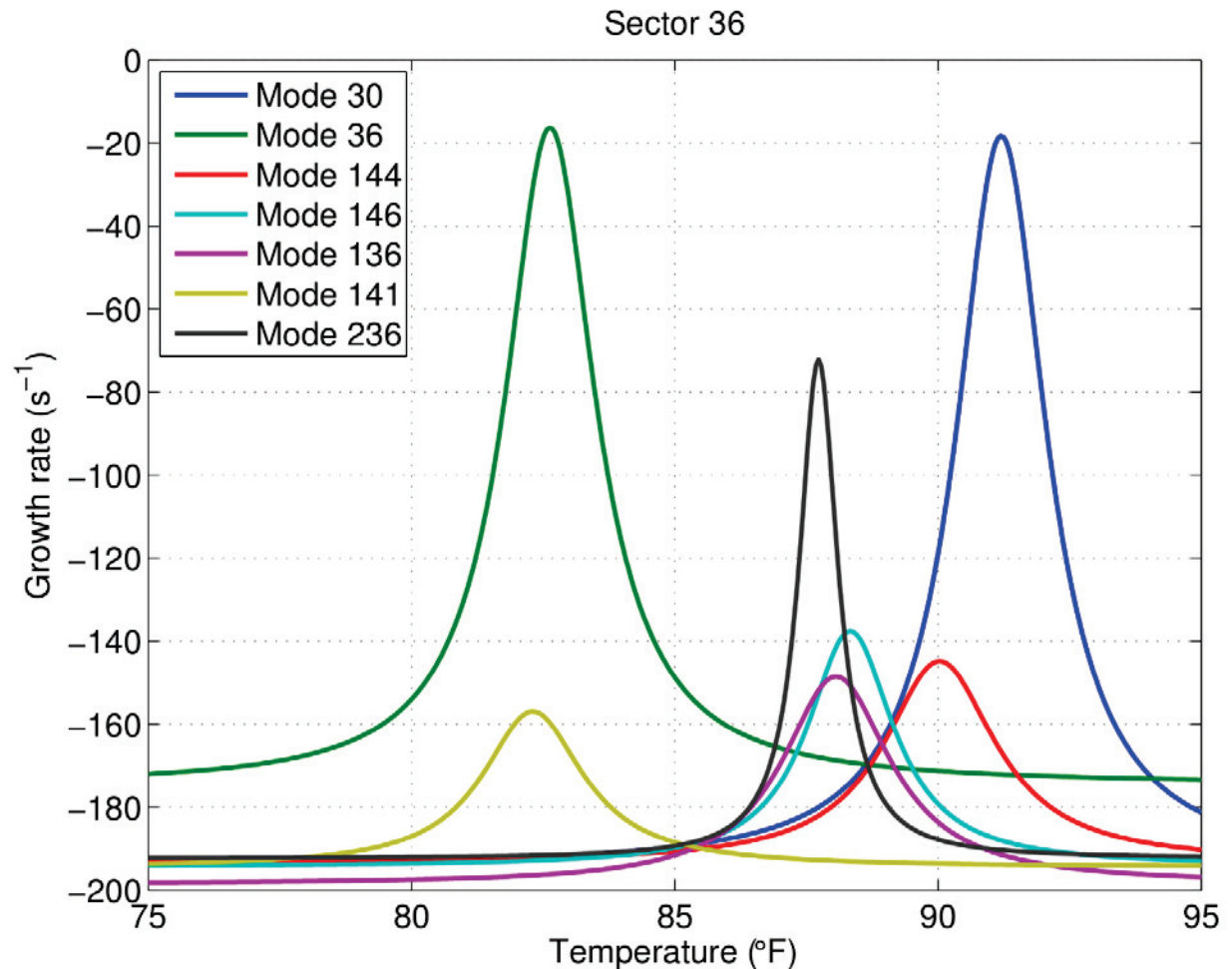
Another mode

- Analysis of another mode (e.g. 146 and -146) shows similar results: $-6.4 \text{ kHz}/^\circ\text{F}$.



Temperature optimization

- Plot shows fits to all the HOMs observed in Sector 36 cavities during temperature scans.
- Minimum growth rate at 86-87°F.
- Need measurements of cavities in all the other rf sectors for full optimization.



Summary

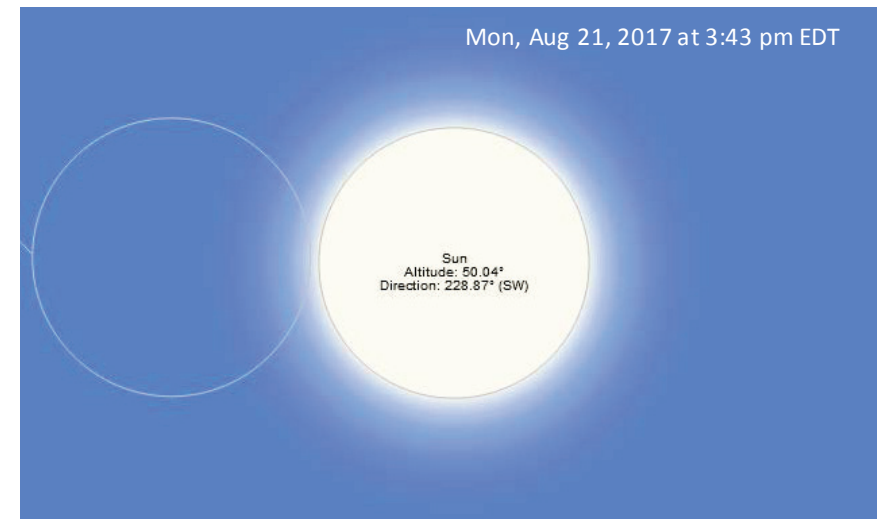
- Multibunch feedback systems have been in operation for electron storage rings for over two decades...there is still more to learn!
- The next generation of storage ring light sources are presenting several new challenges.
 - Low synchrotron tunes with harmonic cavities push growth rates up by factors of 3-4.
 - Soda-straw vacuum chambers push resistive wall growth rates up by an order of magnitude.
 - New In-vacuum insertion devices present resonant impedances.
 - Ultra-low emittance makes small beam more sensitive to residual dipole motion.
- Analog and digital signal processing techniques are demonstrating new methods to characterize resonant impedances with the beam with extremely good accuracy.

Acknowledgements

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