Longitudinal Stability with Landau Cavities at MAX IV

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Outline

- MAX IV facility and double-RF systems
- Longitudinal collective effects in the two rings
  - Robinson (cavity fundamental modes)
  - Coupled-bunch mode (cavity higher-order modes)
- Robinson mode coupling
- Nonuniform fill:
  - Static phase transient
  - Coupled-bunch modes (tune spread)
- Bunch-by-bunch feedback
- Cavity parking

The MAX IV Facility

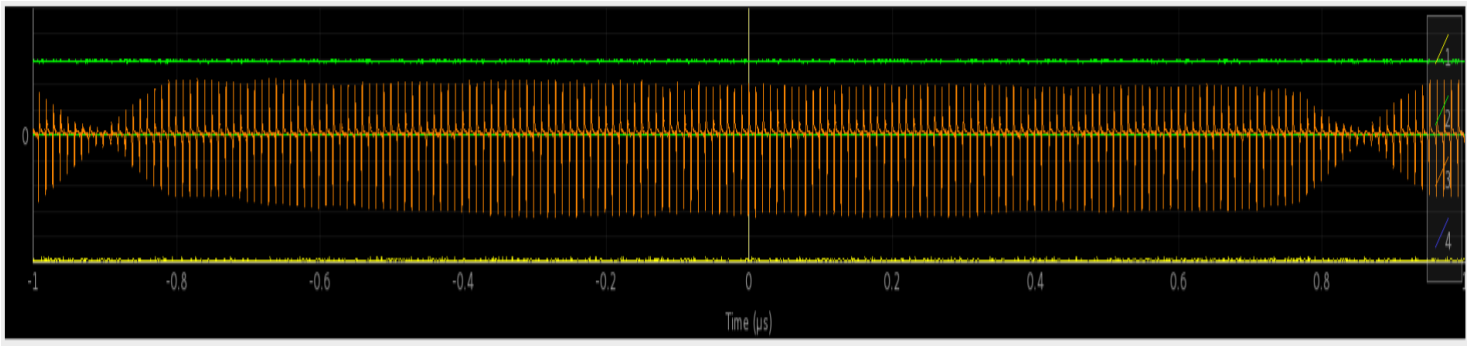
Parameter	3 GeV ring	1.5 GeV ring
RF frequency/MHz	100	
Landau-cavity harmonic	3	
Design current/mA	500	
Natural bunch length/ps	40	49
Bunch length with Landau-cavity lengthening/ps	196	195
Harmonic number	176	32
Number of main (Landau) cavities	5(3)	2(2)

1.5 GeV Ring

- 130 mA-500 mA (design) possible to stable with LCs only
  - Robinson stable
  - No change in main RF voltage with current
  - Around 80 kV per Landau cavity
- Delivery currently at 400 mA
- Uniform fill
- Minimal temperature-tuning required
- Possible to 'park' one LC or tune differently to maintain flat potential (demonstrated up to 240 mA)

3 GeV Ring

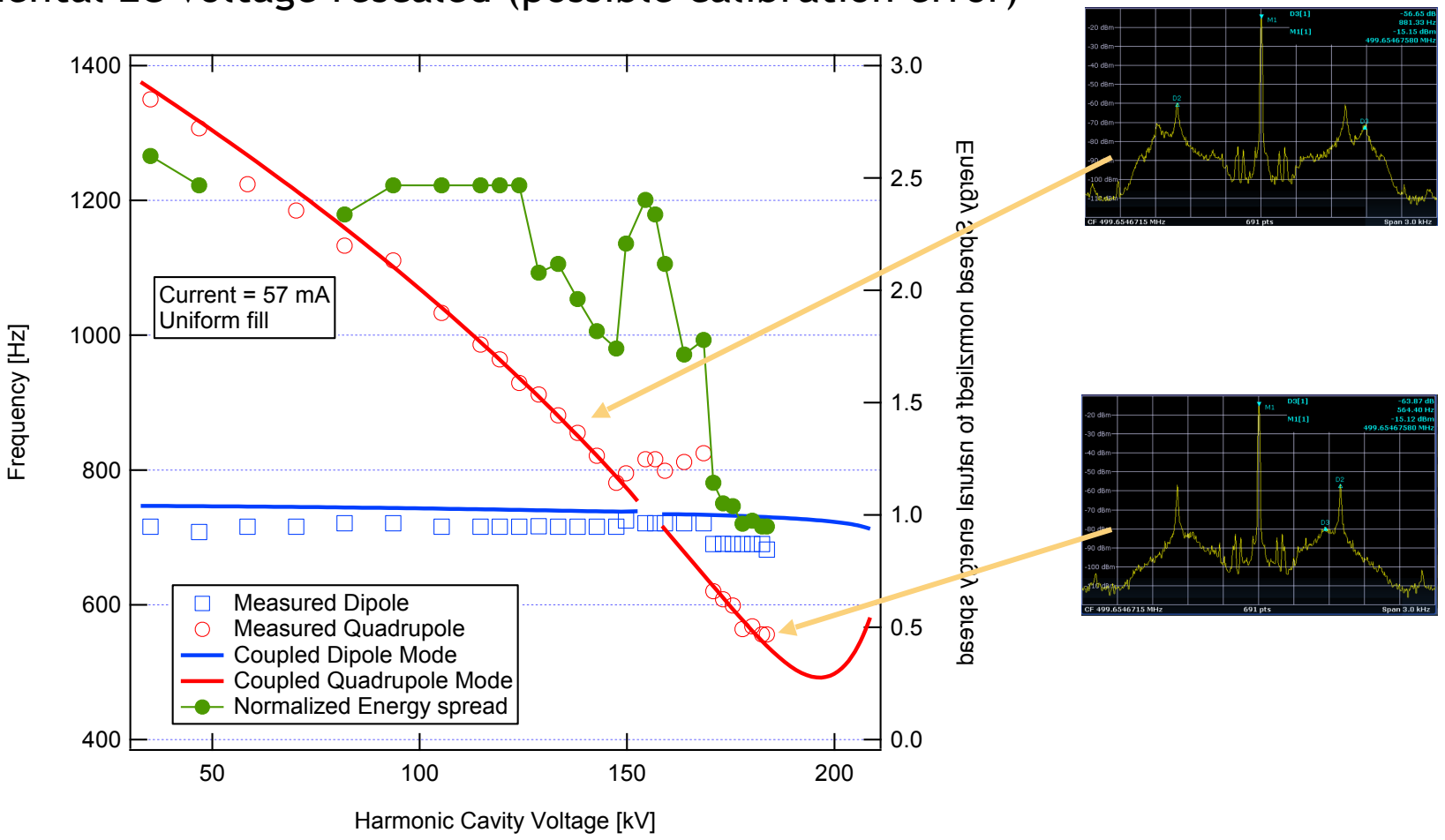
- Extensive temperature-tuning required
- Transition to delivery with LC-lengthened bunches November 2018
- Delivery now at 250 mA (RF power limitation)
  - Mode-0 damper (D. McGinnis)
  - Nonuniform fill (~5 bunch gap)
- Running with 5 of 6 main cavities (one recently reinstalled)



MAX IV

LCs and Coupled Robinson Instabilities

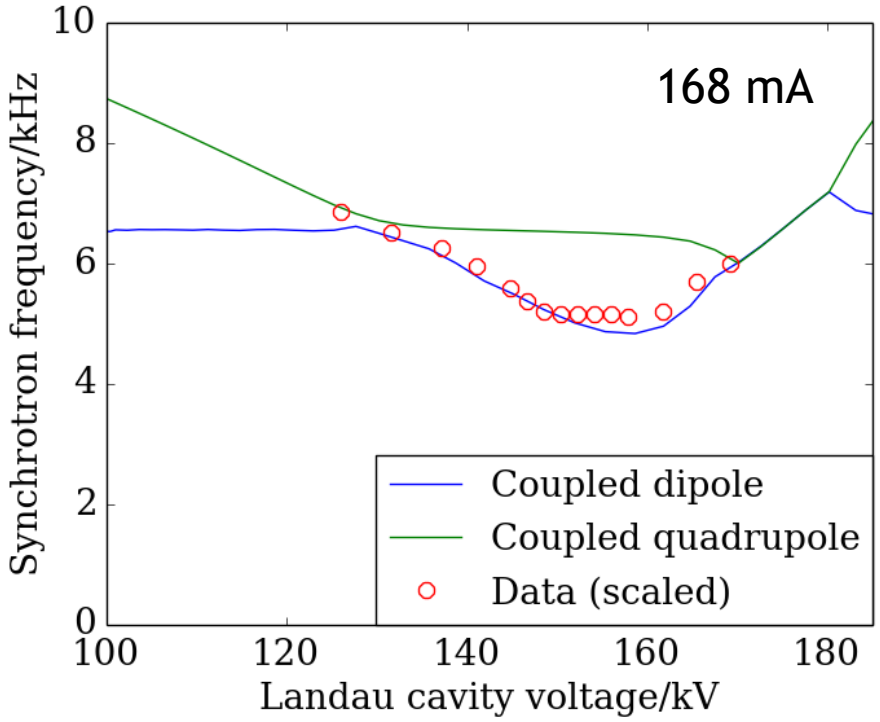
- Theoretical curves: R.A.Bosch et al, PRSTAB Vol. 4 074401, 2001
- Beam response observed on spectrum analyser, excitation by BbB feedback system
- Experimental LC voltage rescaled (possible calibration error)



Data by F. Cullinan, Å. Andersson, R.A.Bosch & P. F. Tavares

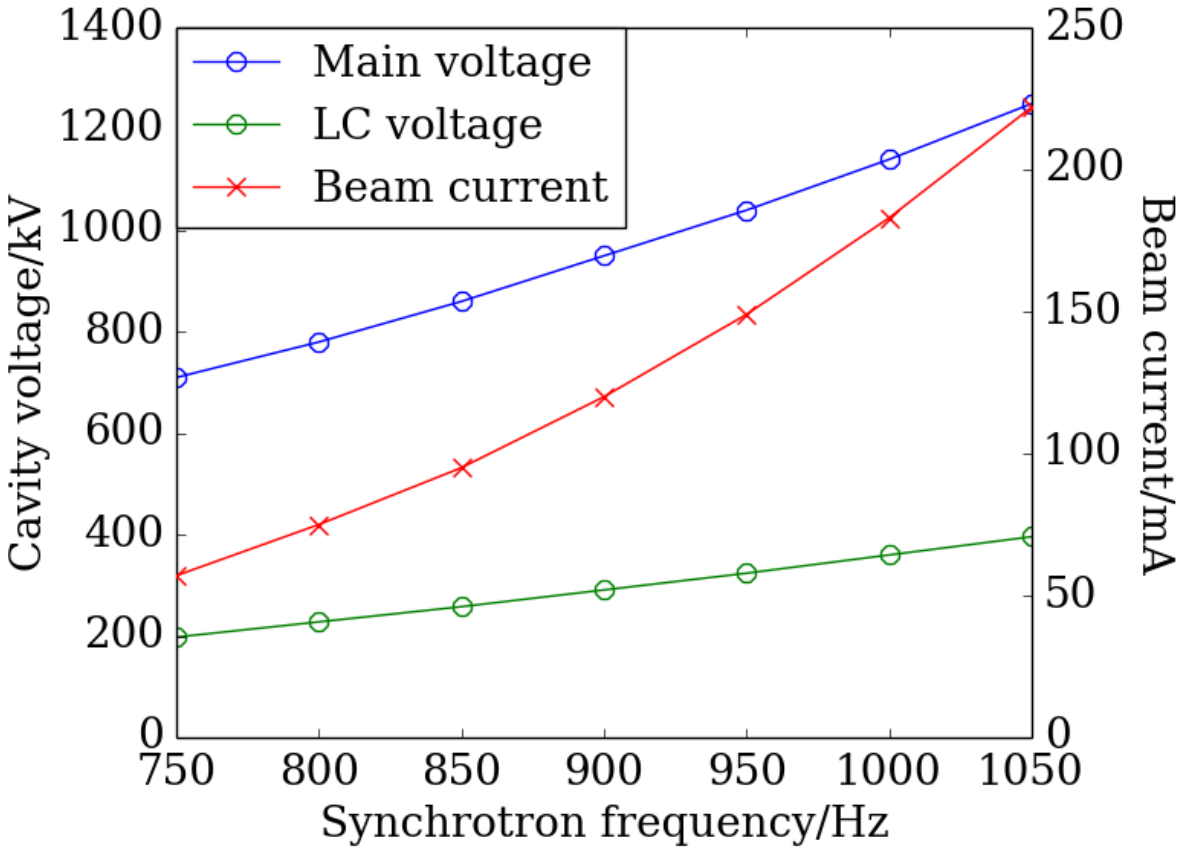
Robinson Mode Coupling - 1.5 GeV

- Same phenomenon observed in 1.5 GeV ring
- Robinson damping factor of 100 stronger because of main-cavity detuning



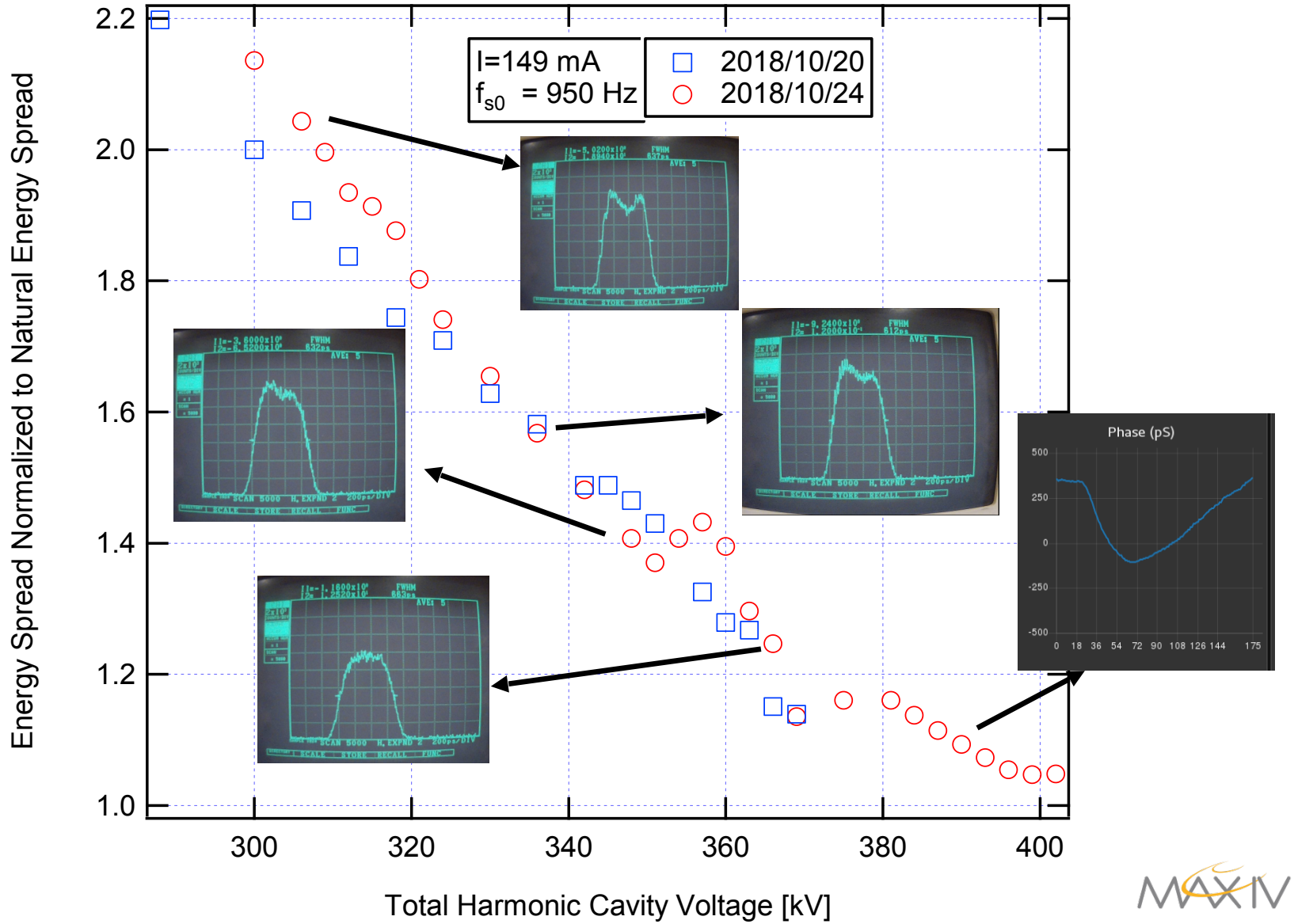
3 GeV Ring

Current ramped while maintaining the flat potential condition:



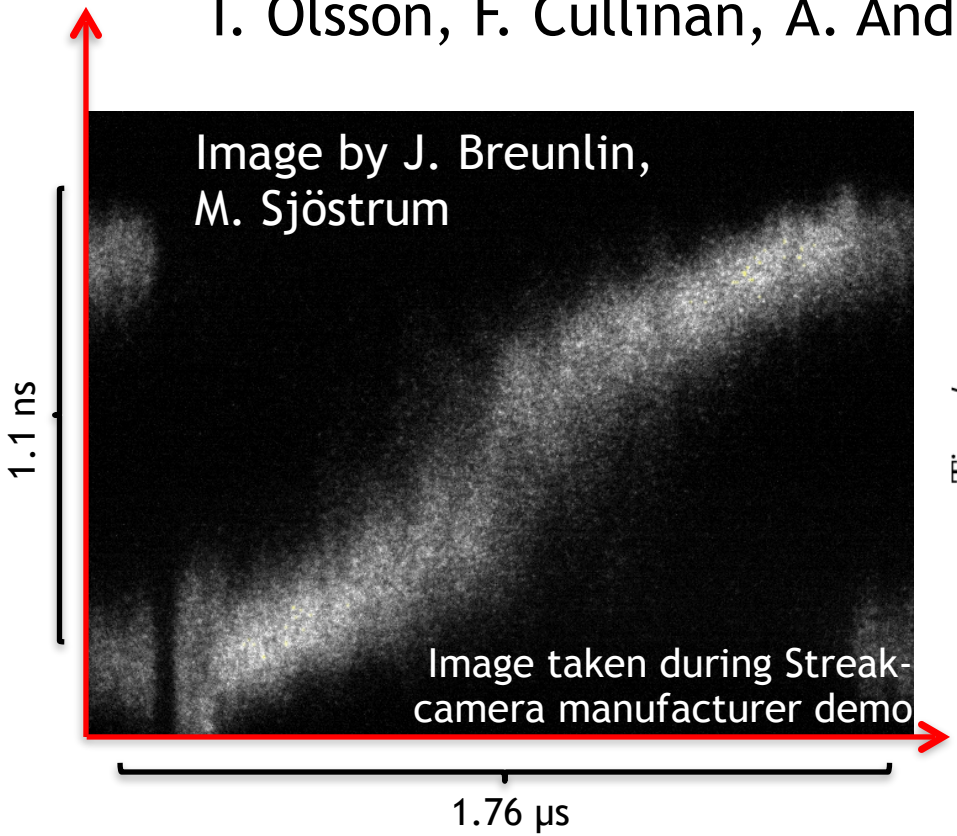
P. F. Tavares

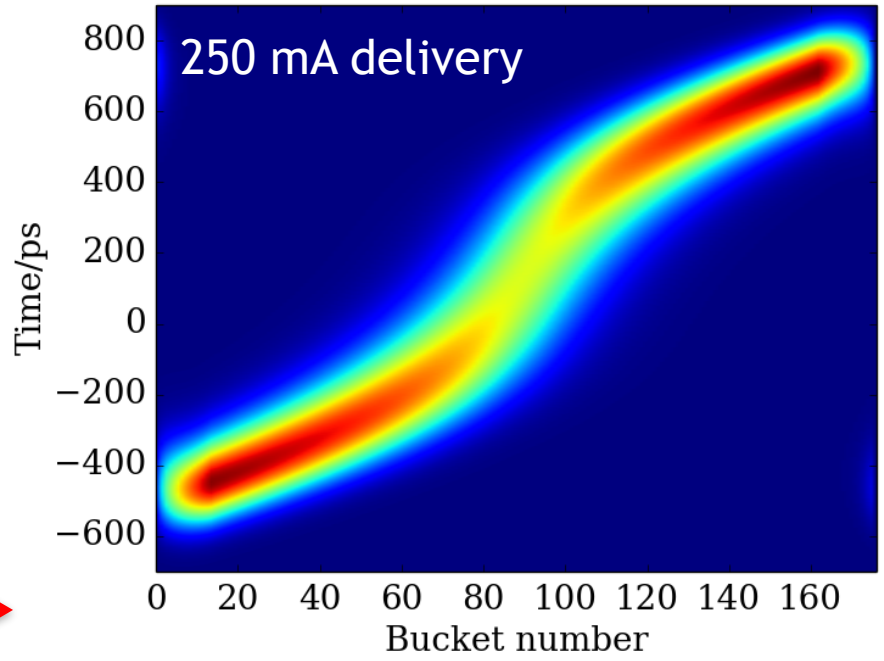
Harmonic Cavities: Suppression of Coupled Bunch Instabilities and Bunch Lengthening



Nonuniform Fill - Static Transient

- Nonuniform fill leads to phase transients and interbunch tune spread
- Reproduced using matrix method:
  T. Olsson, F. Cullinan, Å. Andersson, PRAB **21** 120701, (2018).



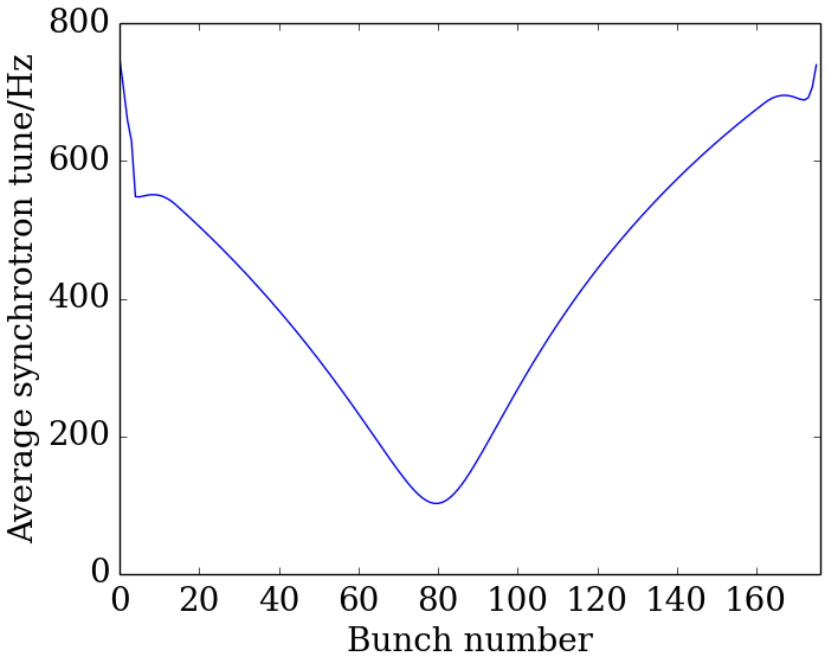


Nonuniform fill - Coupled-bunch modes

- Add up the forces on a single bunch as system of coupled resonators

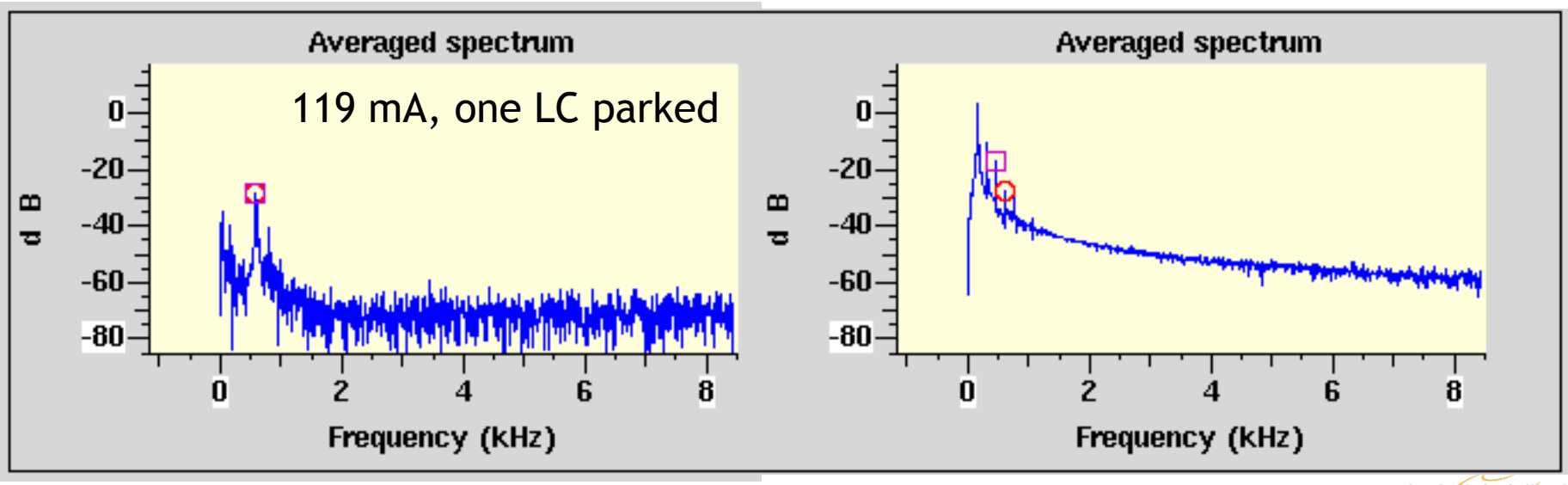
$$\tau_l'' - i\frac{2}{\mathcal{T}_0}\tau_l' + \omega_{s,l}^2\tau_l = \frac{\alpha_c}{E_0 T_0}\sum_{j=0}^{h-1}\sum_{n=0}^{\infty}\tau_j(nT_0)\mathrm{Re}\left[F_l^* F_j q_j \frac{dW}{dt}(nT_0 + \Delta t(\tau_l, \tau_j))\right]$$

- Coupled-bunch modes can be evaluated including interbunch Landau damping
- Tune spreads:
  - Uniform fill: 360 Hz intrabunch
  - Nonuniform fill: 180 Hz interbunch
- More detailed analysis needed



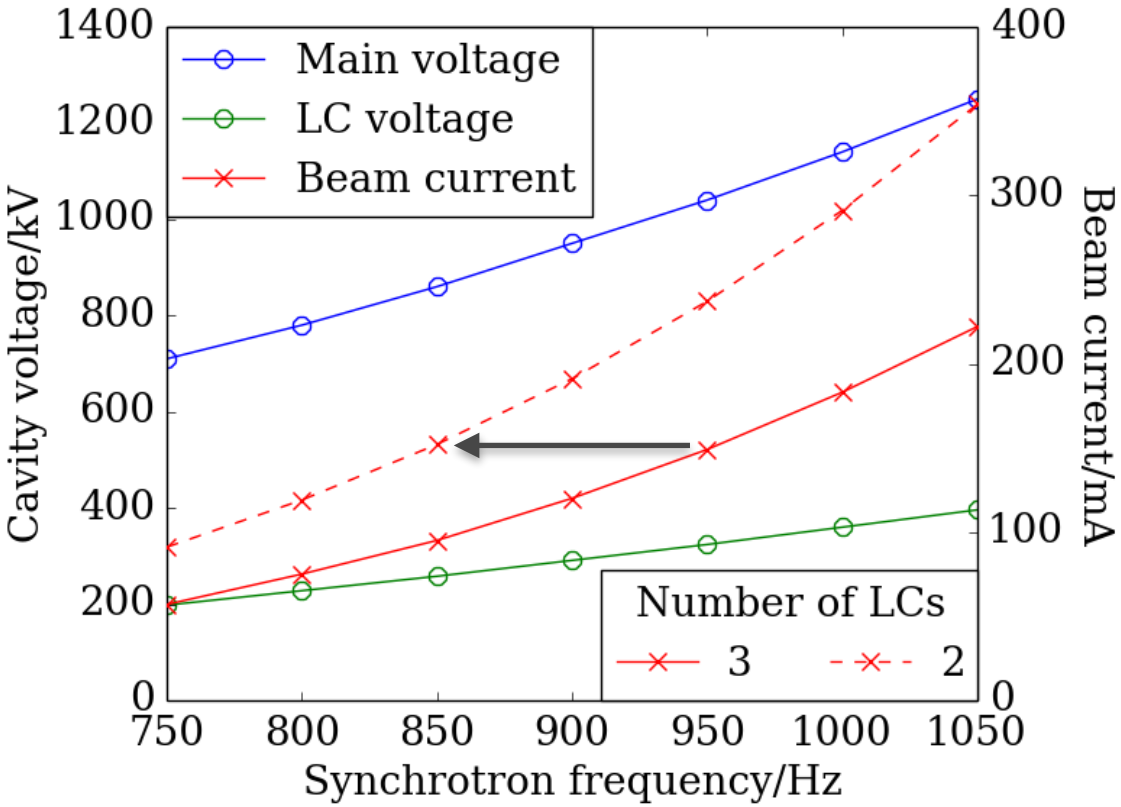
Bunch-by-bunch feedback with Landau Cavities

- Feedback challenging with large tune spread
- Able to capture remnant coupled-bunch modes
- Two-tap differentiator filter with downsampling
- So far, not used in nonuniform fill (Front/Back-end frequencies)



Landau cavity parking

- Lower RF voltage required for flat-potential at same current
- LC power = (Beam power)/(n^2-1)



Main Cavity Parking

- Two main cavities parked
- Overstretching instead of slow coupled-bunch mode
- Limited to 150 mA by transmitter power

Conclusion

- Landau cavities play a crucial role in delivery in both storage rings at MAX IV
- Clear differences seen between two rings. Stable beam easier in 1.5 GeV ring due to:
  - Increased Robinson damping
  - Sparser coupled-bunch modes (factor≈5)
  - Lower impedance (fewer cavities)
- Static transient in nonuniform fill can be evaluated with matrix method
- Tune spread between bunches helps to fight longitudinal instabilities
- Parking one Landau cavity will help with going to higher current, installing more IDs in future

References

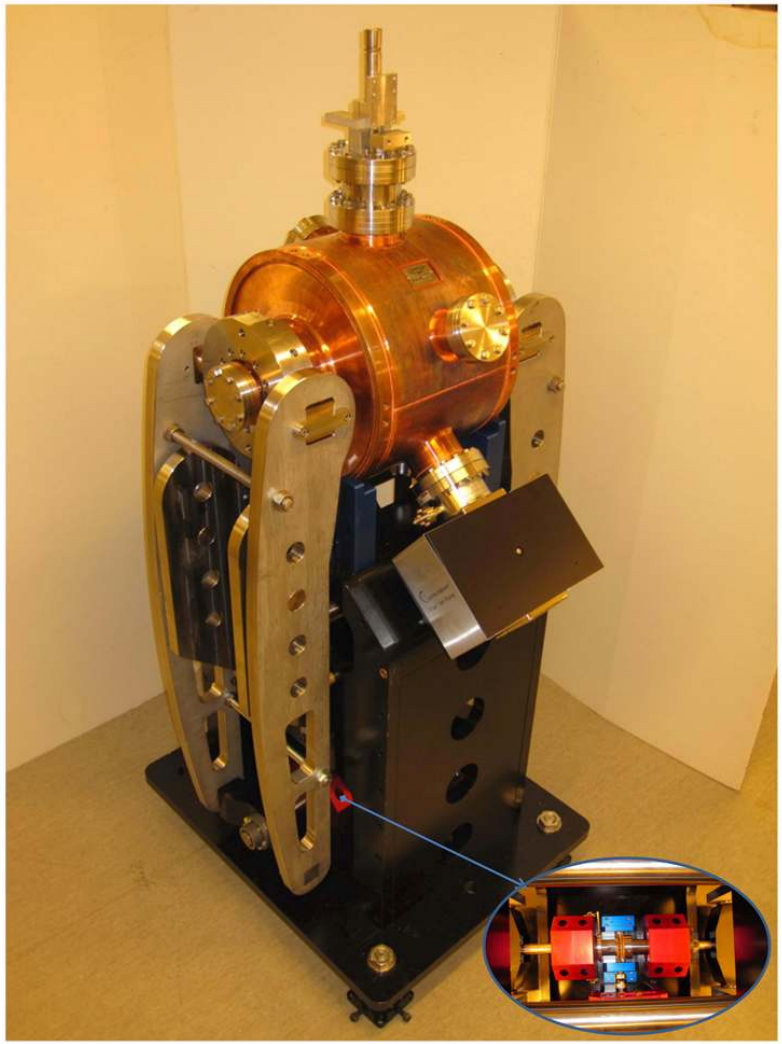
Landau damping with nonuniform fill:

- G. Penco, M. Svandrik, “Experimental studies on transient beam loading effects in the presence of a superconducting third harmonic cavity”, Phys, Rev. ST Accel. Beams **9** 044401, 2006.
- T. Olsson, F. J. Cullinan, Å. Andersson, “Self-consistent calculation of transient beam loading in electron storage rings with passive harmonic cavities”, Phys, Rev. Accel. Beams **21** 120701, 2018.
- G. Bassi, A. Blednych, V. Smaluk, “Self-consistent simulations and analysis of the coupled-bunch instability for arbitrary multibunch configurations”, Phys, Rev. Accel. Beams **19** 024401, 2016.
- K. A. Thompson, R. D. Ruth, “Transverse and longitudinal coupled bunch instabilities in trains of closely spaced bunches”, PAC 1989, SLAC-PUB-4872.
- O. Naumann, J. Jacob, “Fractional filling induced landau damping of longitudinal instabilities at the ESRF”, PAC 1987.
- M. H. Wang, P. J. Chou, “Study of uneven fills to cure the coupled-bunch instability in SRRC”, PAC 2001.

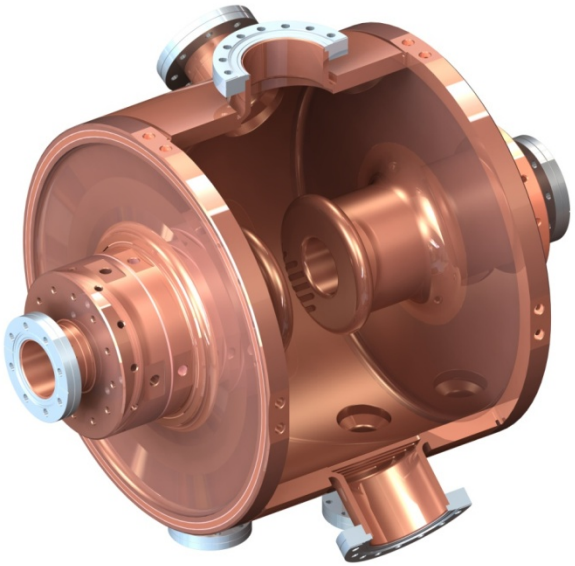
General Landau cavity:

- P. F. Tavares, Å. Andersson, A. Hansson, J. Breunlin, “Equilibrium bunch density distribution with passive harmonic cavities in a storage ring”, Phys, Rev. ST Accel. Beams **17** 064401, 2014.
- R. R. Lindberg, “Theory of coupled-bunch longitudinal instabilities in a storage ring for arbitrary rf potentials”, Phys, Rev. Accel. Beams **21** 124402, 2018.
- M. Venturini, “Passive higher-harmonic rf cavities with general settings and multibunch instabilities in electron storage rings”, Phys, Rev. Accel. Beams **21** 114404, 2018.
- R. A. Bosch, K. J. Kleman, J. J. Bisognano, “Robinson instabilities with a higher-harmonic cavity”, Phys, Rev. ST Accel. Beams **4** 074401, 2001.

Our 300 MHz 3rd Harmonic Cavities



Mechanical design, Elsayed Elafifi, MAX-lab

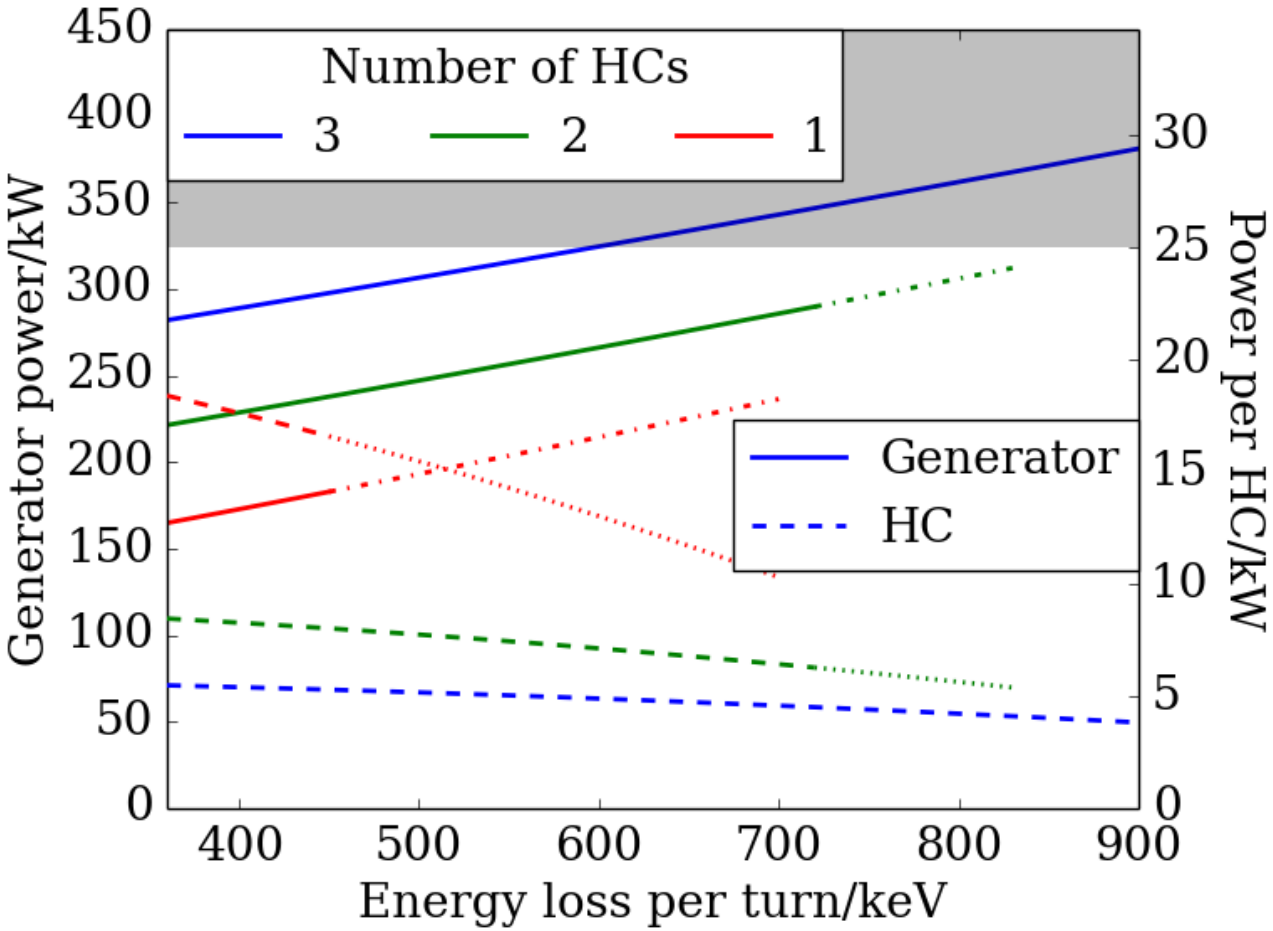


Inner length/diameter: 312mm/ 400mm

Theory R_{sh}/Q: 5.7MΩ/21600
(Definiton: $R_{sh} = V^2/P$)
Measured Q: Around 20900 ➔
R_{sh} = 5.5 MΩ

MAX IV

Power Requirements



Landau cavity parking

Number of Landau cavities	3		2	
RF voltage/MV	Voltage per LC/kV	Current/mA	Voltage per LC/kV	Current/mA
0.71	66	57	99	91
0.78	76	75	114	119
0.86	86	95	129	152
0.95	97	120	145	191
1.04	108	149		237
1.14	120	183	180	291
1.25	132	222	198	354

3 GeV ring

Synchrotron frequency/Hz	RF voltage/MV	LC voltage per cavity/kV	Current/mA
750	0.71	66	57
800	0.78	76	75
850	0.86	86	95
900	0.95	97	120
950	1.04	108	149
1000	1.14	120	183
1050	1.25	132	222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