56 MHz SRF Cavity for RHIC and Longitudinal Coupled-Bunch Instabilities

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MAC meeting

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Outline

- Summary of the computer codes
- Longitudinal coupled-bunch (CB) instabilities:
  - Absolute thresholds at transition energy
  - Emittance growth across transition: 168-MHz HOM and minimum damping
  - Thresholds at storage energy
- Ramping up the SRF-cavity field
- Conclusions

Machine parameters (gold)

Parameter	symbol	value	unit
Circumference	cT_0	= 3833.845	m
Gold ions per bunch		$= 10^9$	
Transition	γ_t	= 22.3	
RF buckets	h	= 360	
Buckets potentially filled	B	$= h/3$	
Bunches in fill		= 105	every third bucket
Average beam current	I_{av}	= 104	mA
Broad-band impedance	$\lvert Z_n\rvert/n$	= 3.5	Ω
	ω_{BBI}	$= 2\pi \times 1.7$	GHz
Main cavity voltage	V_1	= 100	kV (transition)
		= 300	kV (storage)
SC HHC voltage	V_2	= 0	(transition)
		= 2.5	MV (storage)
Momentum compaction	η	$= 0.9 \times 10^{-4}$	(transition)
		$= 2.0 \times 10^{-3}$	(storage)
Nonlinear α	α_1	= -1.15	(Blaskiewicz et al. (2001))
Bunch length	σ_t	= 1.7	ns (transition)
		= 1.0	ns (storage)
Longitudinal emittance		= 0.5	eV-s (95%) (transition)
		$= \sim 0.7$	eV-s (95%) (storage)

Parameter	symbol	value	unit
Main cavity			
impedance	R_0/Q_0	= 63.64	Ω
count	n_{cav}	= 2	per ring
frequency	f_{rf}	= 28	MHz
harmonic	h	= 360	
Normal-conducting HHC			
impedance per cell	R_0/Q_0	= 162	Ω
count	n_{cav}	= 3	per ring
		+ 4	in common
frequency	f_{rf}	= 197	MHz
harmonic	nh	= 2520	
Super-conducting HHC			
impedance per cell	R_0/Q_0	= 46.1	Ω
count	n_{cav}	= 1	per ring
frequency	f_{rf}	= 56	MHz
harmonic	nh	= 720	

RHIC

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Vlasov and tracking codes

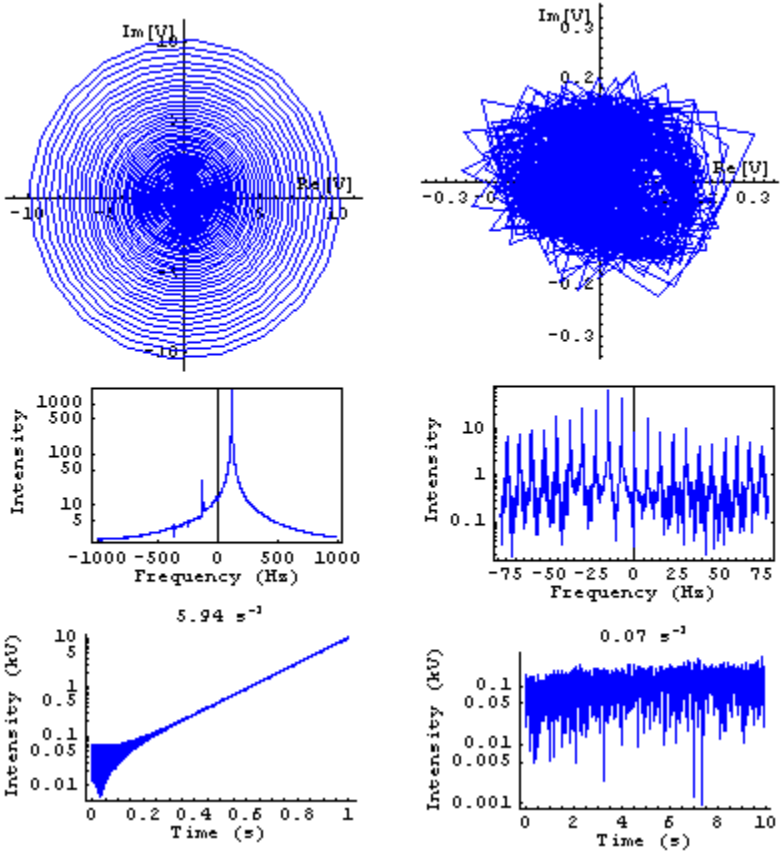
- A few data points came from a longitudinal Vlasov solver (N. Towne, Phys. Rev. ST-AB **4** 114401 (2001)), used in a number of other studies for NSLS and NSLS-II. But it is written in Mathematica and is quite slow -- much too slow to be practical when the HOM frequency is high and growth rates are low.
- Results in this study came primarily from a tracking code written in Visual Basic.net.
- RF modes are assumed to have long-range wakes. Each bunch kicks each rf mode, and each mode rings during the intervals between bunches. Similarly, each rf mode kicks each bunch and each bunch drifts (filaments) in longitudinal phase space during its orbit around the ring.
- Broad-band impedance is not handled.

Bracketing of thresholds

- Initially, stability was evaluated using runs at fixed energy.
- At low HOM frequencies and short bunches, very precise growth rates can be determined.
- But cavity and beam spectra are intrinsically noisy, and at higher HOM frequency, saturation occurs early and an exponential-growth regime often cannot be seen. So it is typically not clear when the beam is stable. Emittance growth provides some information.
- The longitudinal dipole mode has the lowest threshold and has very low growth rate.

Unstable
f = 56 MHz

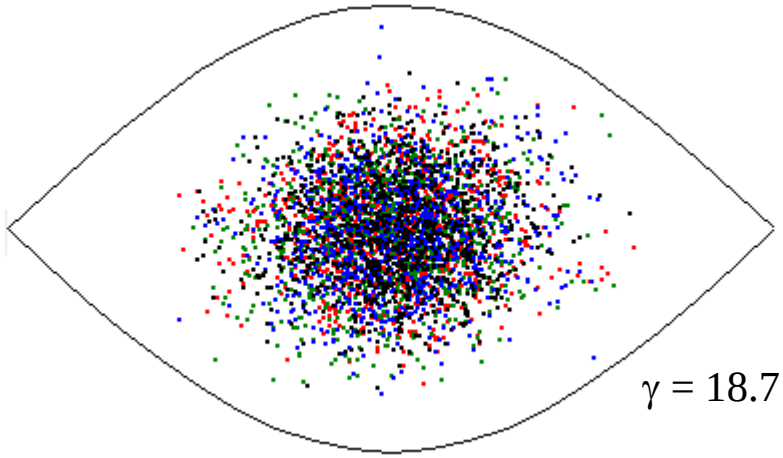
Unstable?
f = 560 MHz



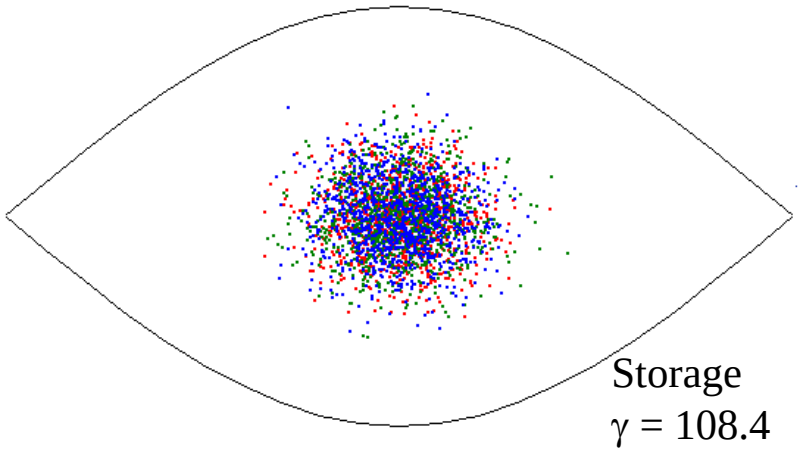
Storage

Transition

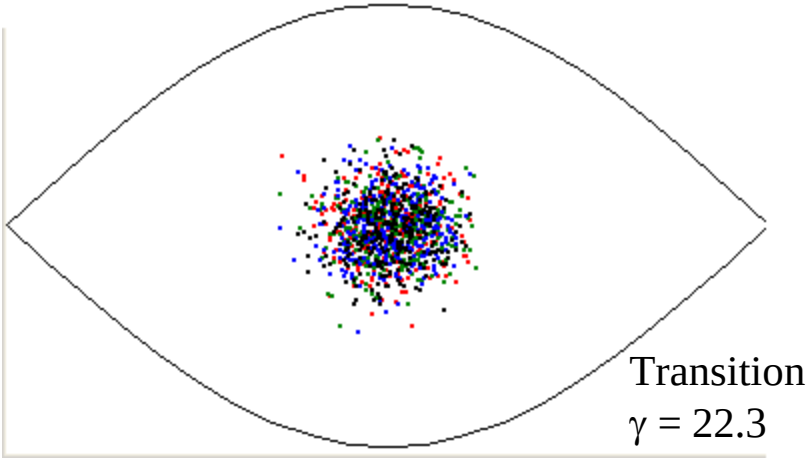
RF buckets



ε = 0.5 eV-s (95%)



ε = 0.7 eV-s (95%)

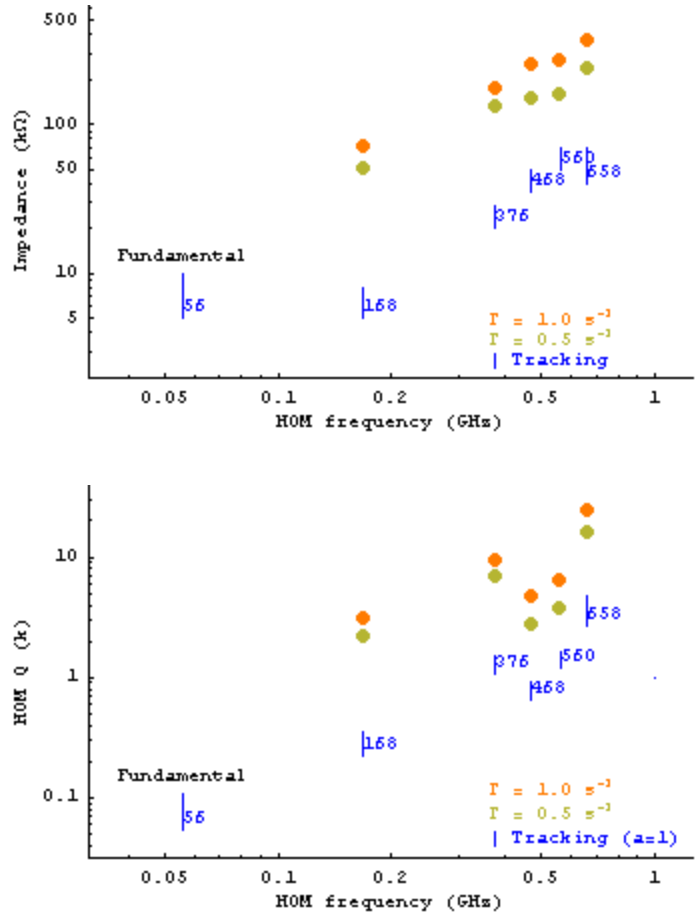


- Transition shows the largest bucket area compared to bunch emittance. Little synchrotron frequency spread.
- Without rebucketing, longitudinal emittance at the end of the ramp is not so large and thresholds are rather smaller that thresholds with rebucketing.

CB thresholds at transition energy

- Simulated threshold impedances (upper plot) and quality factors (lower) with fixed energy are shown. Bars indicate bracketing of thresholds. Orange and yellow points indicate 1.0- and 0.5-s^{-1} growth rates, respectively.
- Transition has very low momentum compaction (0.9×10^{-4}), leading to low thresholds. Absolute stability at transition imposes the tightest constraints on HOM impedances.
- The fundamental can potentially excite nearby CB modes, but the main rf system has sufficient bandwidth that damping of those modes can be accomplished using that bandwidth.
- Based on these results, absolute thresholds at fixed energy give minimum mode damping too low to be realized in some cases. Need to another way.

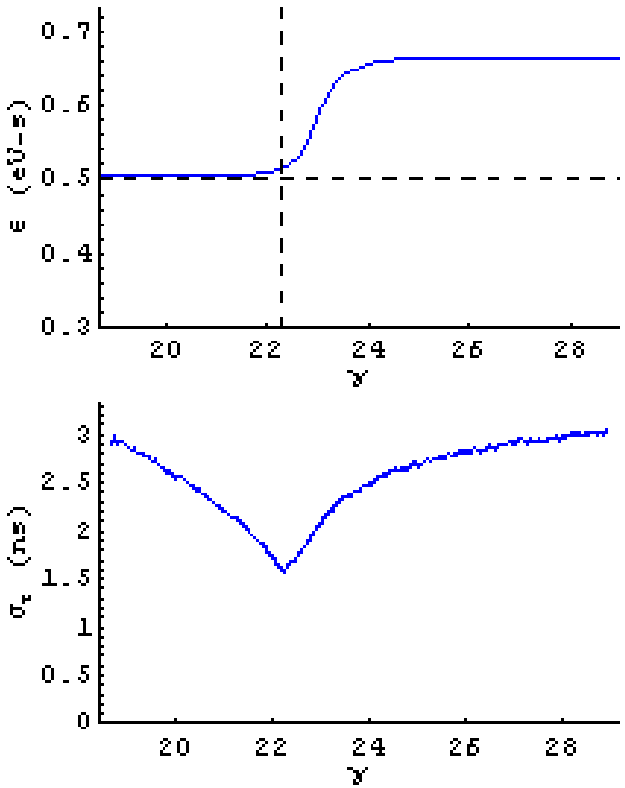
Thresholds



Two SC HHCs

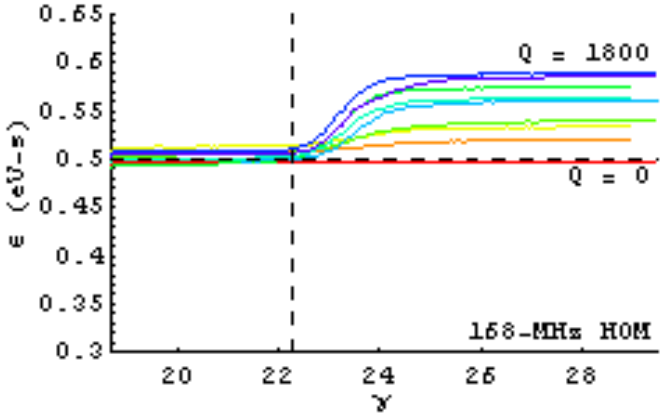
Simulating the ramp

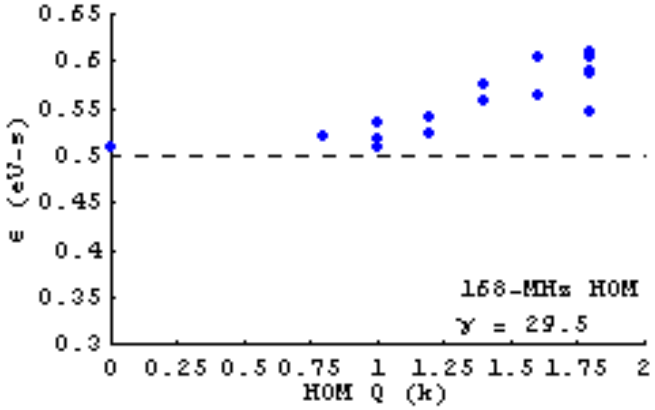
- Modes that are unstable at transition energy are often stable not far away from transition. The question is whether the ramp can push through unstable energies with acceptable emittance growth, and at what rf-mode damping.
- Simulations with a variety of fills of about 90%, starting at γ = 16 to 21 and ending at γ = 25 to 30.
- Transition is modeled by an instantaneous γ_t jump with continuous $|\eta_0|$.



168-MHz HOM

- Longitudinal simulations of the ring with the 168-MHz HOM at different Qs show the continuum of variation of emittance growth. The growth of emittance starts at transition and persists for a time after.
- Emittance growth due to the 168-MHz HOM is modest at Q = 1000 and two cavities, even though well above threshold.
- With one cavity, Q between 2000 and 2500 has modest emittance growth.





Two SC HHCs

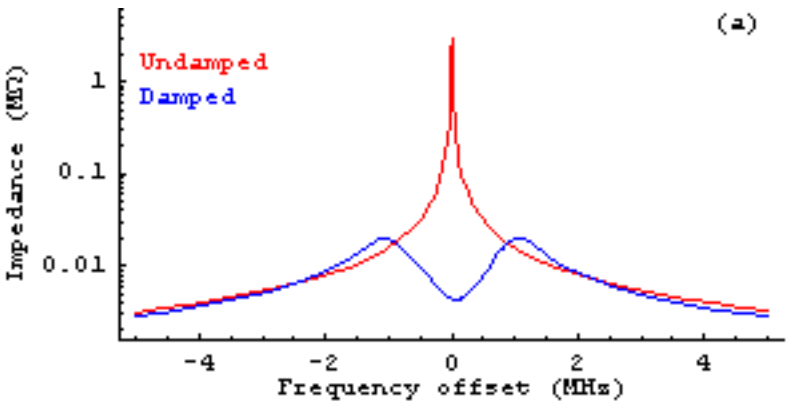
SRF-cavity minimum damping estimates

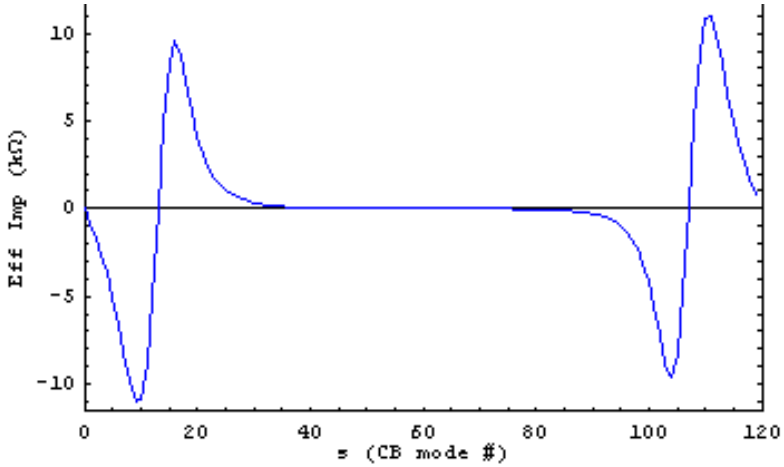
		Transition		Storage	
f_{HOM} (MHz)	R/Q (Ω)	R_{max} (kΩ)	Q_{max} (k)	R_{th} (kΩ)	Q_{th} (k)
168	11.5	23	2	90	8
376	9.4	140	15	160	17
468	27.1	140	5	320	12
560	21.1				
658	7.5				
762	1.5				
1107	29.4				
		(ε = 0.5 eV-s)		(ε = 0.7 eV-s)	

- $Q_{max} = R_{max}/(R/Q)$ and $Q_{th} = R_{th}/(R/Q)$.
- R_{max} and R_{th} are functions of frequency not tied directly to HOM.

Normal-conducting HHC

- The normal-conducting (NC) cavities are also damped during acceleration. They are reasonably accurately modeled by two resonators of 18.75 kΩ impedance, separated by 2-MHz frequency, and having Qs of 250 and 300, respectively. With seven cavities, this is a rather large impedance.
- At transition energy, the rf line is 190 kHz below the resonant frequency of the cavities. The effective impedance is calculated for the dipole mode for each CB mode, 0 to 119 for a uniform fill. The impedance peaks above threshold, but only very mildly so. Positive impedance excites CB modes.
- In the following slide, spectra of voltage in each of the two rf modes simulated at fixed energy is shown. It shows the unstable CB modes and that they qualitatively match the positive impedance in the lower plot to the right.

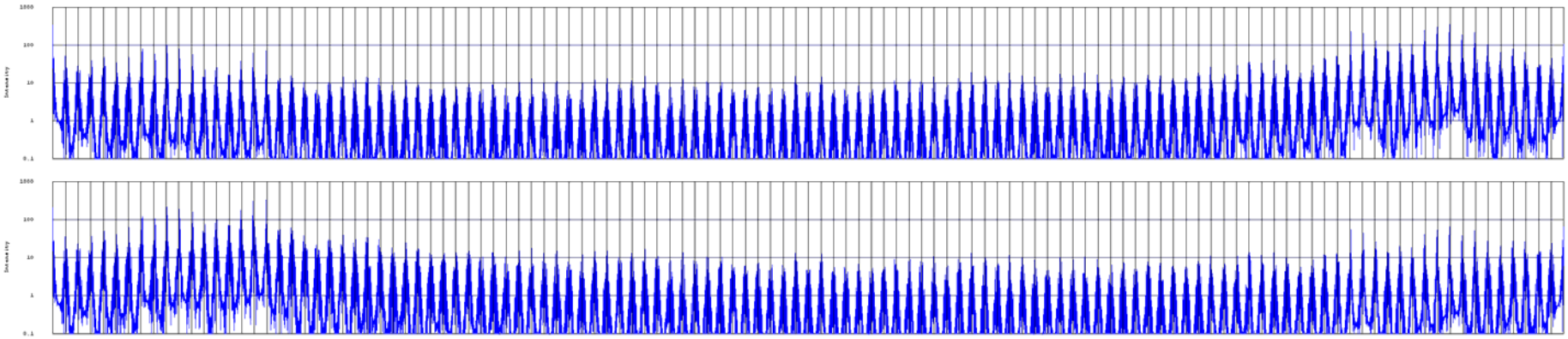




NC HHC spectra with abort gap

- Below are 120-line rf-mode spectra from a 2.5-s, 105-bunch simulation with the energy fixed at transition energy with abort gap. The beam is unstable with ~0.6 s^{-1} growth rate.
- In these spectra, frequency is compressed through special sampling of the rf-mode phasers.

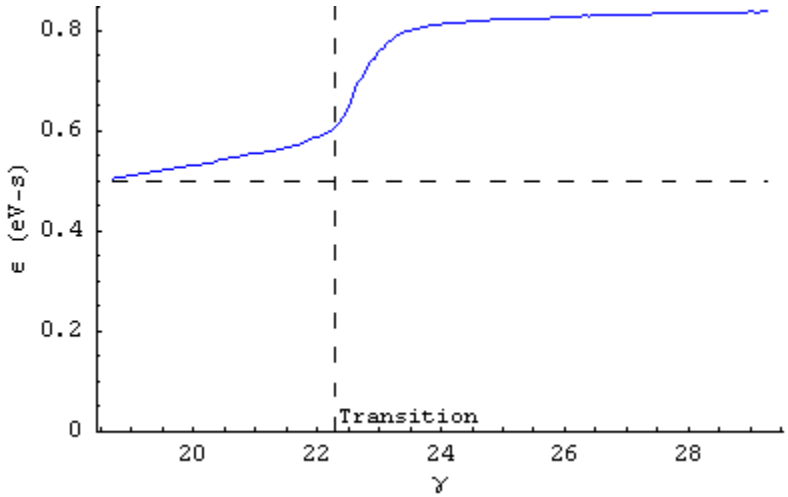
Lower rf mode



Upper rf mode

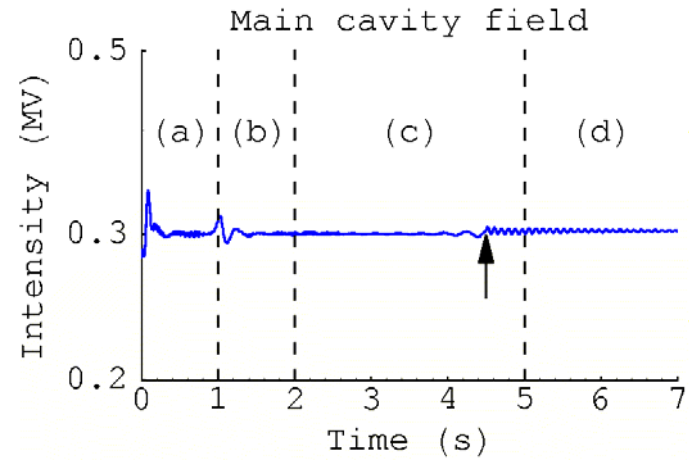
Emittance growth across transition due to the NC HHC

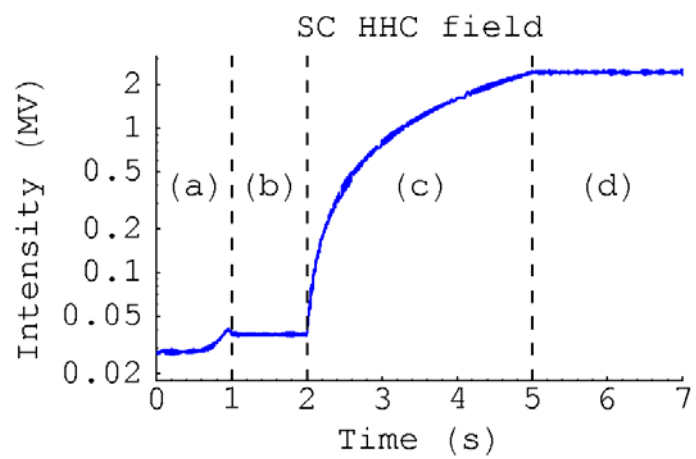
- Simulation across transition shows substantial emittance growth.
- Are the NC HHCs responsible for some of the emittance growth before rebucketing? With SC HHCs and no rebucketing, would removal of some cavities reduce emittance at the top of the ramp?



Ramping the SC HHC to field

- The SC HHC is initially damped and detuned -10 kHz.
  - (a) Cavity damping is reduced to zero.
  - (b) No change.
  - (c) Detuning is reduced to nominal.
  - (d) No change.
- HHC detuning ramps the field linearly.
- For the main cavity, simple field, phase, and tuning servos were implemented in code. The arrow marks where they are switched off due to instability.
- At storage energy, ramping the SC HHC to field seems to pose no particular challenge.





Two SC HHCs assumed

Conclusions

- Stability of CB modes at transition energy is probably not attainable. Instead, it is necessary to manage emittance growth crossing transition with sufficient damping of the SC HHC HOMs.
- Sufficient HOM damping is almost certainly realizable, although not all HOMs are adequately explored. More to do both at transition and at storage energy.
- Tracking using a model of the NC-HHC impedance based on bench measurement shows instability and emittance growth across transition. I speculated that one or more could be removed resulting in less emittance growth during the ramp, and still leave a few to further reduce bunch length.
- Because CB modes near rf harmonics driven by the fundamental can be controlled through the rf systems of the 28-MHz cavities, CB modes have little impact on the damping of the fundamental.
- It is uncertain what the impact of the broad-band impedance on stability is.
- Ramping the SC HHC to field poses no particular challenge.

Acknowledgments

- Thanks to Mike Blaskiewicz and Ilan Ben-Zvi for guidance in this work.