Ion-Clearing-Gap-Induced Bunch Profiles, Response Functions and RF Noise, and Coupled-Bunch Modes in NSLS-II

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- Longitudinal bunch profiles and bunch lengths due to the ion-clearing gap(s)
- RF-system noise transfer to the machine: response functions computed by Vlasov simulations
- Coupled bunch growth rates of stretched bunches computed by Vlasov simulations.

Machine parameters

Parameter	symbol	value	unit
Synchronous energy	E_0	$= 3$	GeV
Circumference	cT_0	$= 780.3$	m
Revolution frequency	$\omega_0/2\pi$	$= 0.384$	MHz
Momentum compaction	α	$= 3.68 \times 10^{-4}$	
Fractional energy spread	σ_ϵ	$= 9.8 \times 10^{-4}$	
Average beam current	I_{av}	$= 0.5$	A
RF acceptance	$\Delta p/p$	$= 3$	%
HHC impedance per cell	R_0/Q_0	$= 44$	Ω
HHC quality factor	Q_{HHC}	$= 5 \times 10^8$ (est)	
RF frequency	f_{rf}	$= 499.5$	MHz
Bucket harmonic	h	$= 1300$	
Impedance per cavity	R_0/Q_0	$= 45$	Ω
Quality factor	Q_0	$= 5 \times 10^5$ (est)	k
Coupling	Q_{ext}	$= 90$	k
RF feedback	Q_{fb}	$= 180$	k
Loaded Q	Q_{L}	$= 60$	k

Commissioning phase		baseline	phase-four	
Parameter	symbol			unit
Incoherent loss per turn	U_0	0.816	2.16	MeV
Main-cavity field	V_1	3.3	4.9	MV
Synchronous phase	Ψ_V	75.6°	63.8°	
HHCs/cells		1/2	2/4	
Number of main cavities		2	4	
RF field per cavity		1.65	1.225	MV
RF power per amplifier	$\|a_0\|^2/2$	217	280	kW
Reflected power per amplifier	$\|b_0\|^2/2$	12.9	9.7	kW
Main-cavity detuning	$\Delta\omega/2\pi$	-6.6	-8.2	kHz
Coupling for match	Q_{ext}	148	61.7	k
Short-bunch HHC detuning	$\Delta\omega_{\text{HHC}}/2\pi$	62	90	kHz

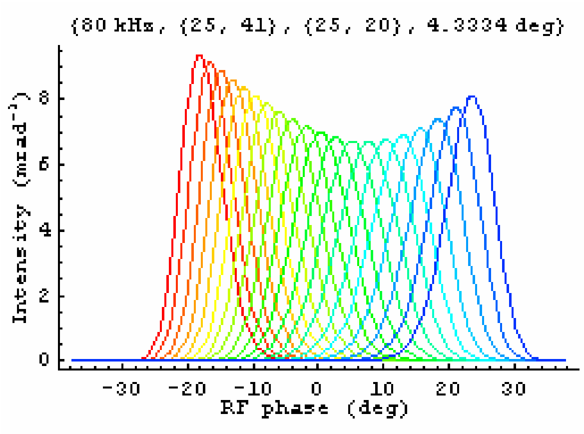
Longitudinal bunch profiles

- The gap in the fill needed for ion clearing introduces a ‘periodic transient’ in the fields in the rf cavities. This perturbs the potential wells across the bunch train and alters the profiles, especially of stretched bunches and especially at the ends of the train. So there is a need to determine the intensity of the effect and its impact on lifetime.
- Profiles and rf fields in the cavities were self-consistently calculated: profiles in the time domain, and rf fields in the frequency domain. The code was checked with published ELETTRA measurements, and against a time-domain code.

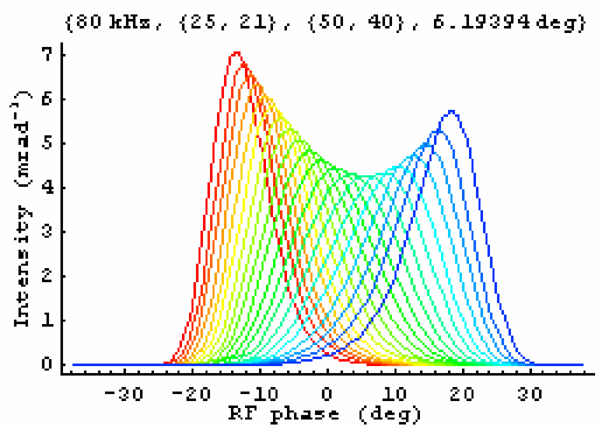
Bunch lengths and phase offsets along train

Illustrative bunch profiles

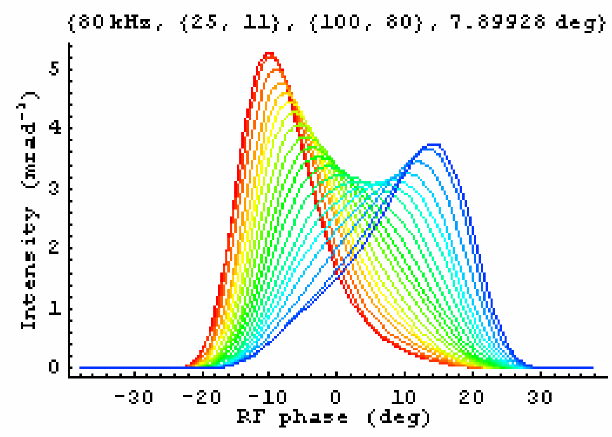
One Gap



Two Gaps



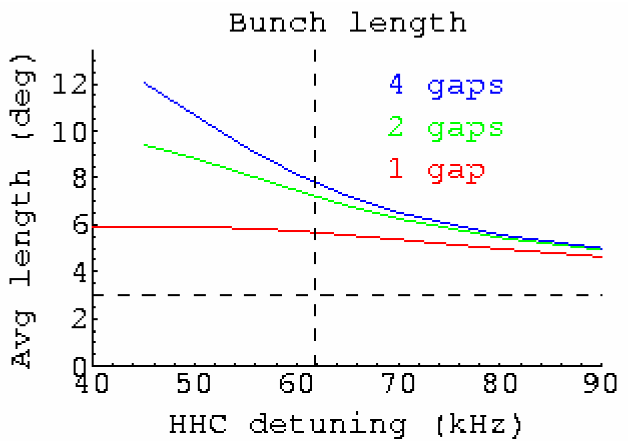
Four Gaps

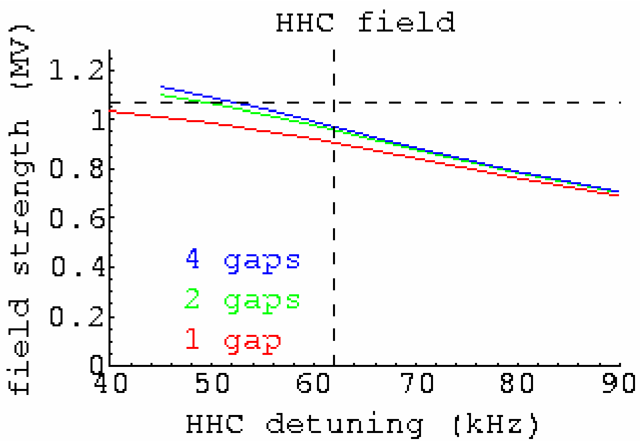


Breaking up the gap lessens the transient due to both shorter gaps and shorter intervals between gaps, keeping the fill fraction constant. Both the ions and the cavities see a smaller ring.

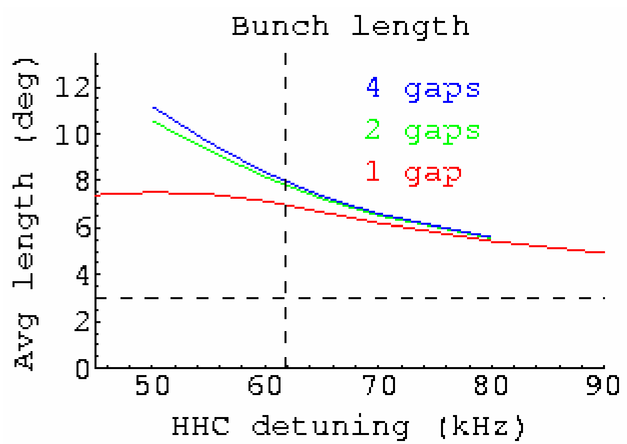
Bunch lengths in the baseline phase

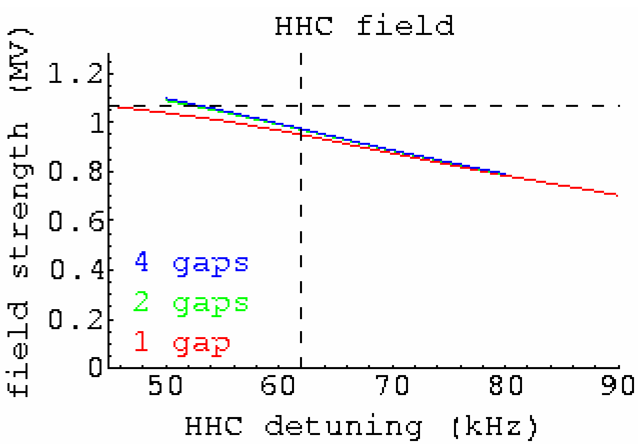
80% fill fraction





90% fill fraction

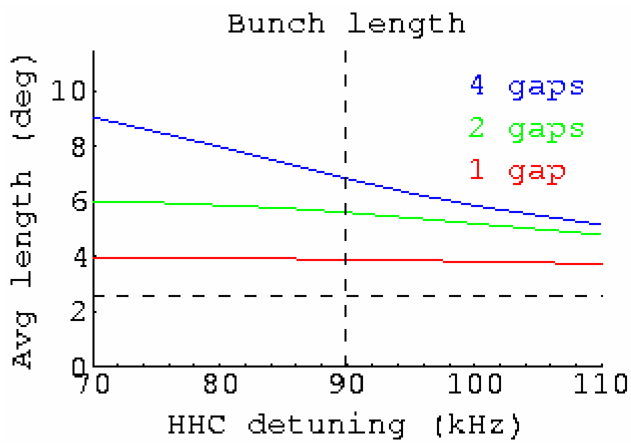


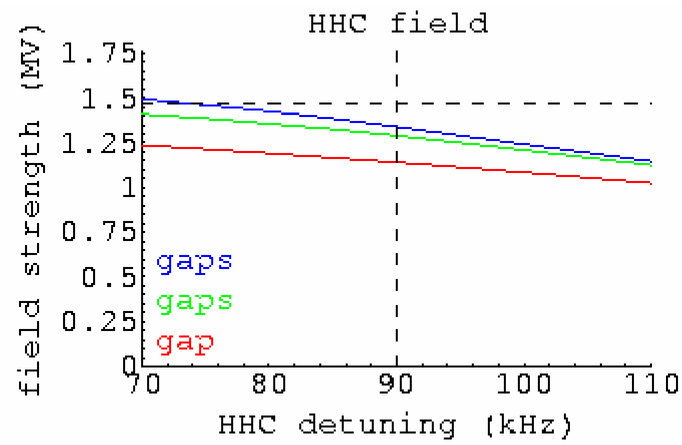


- Vertical dashed lines are the HHC detunings that generate the nominal field when driven by short bunches.
- Horizontal dashed line are the unstretched bunch length (left), and nominal HHC field for stretching (right).

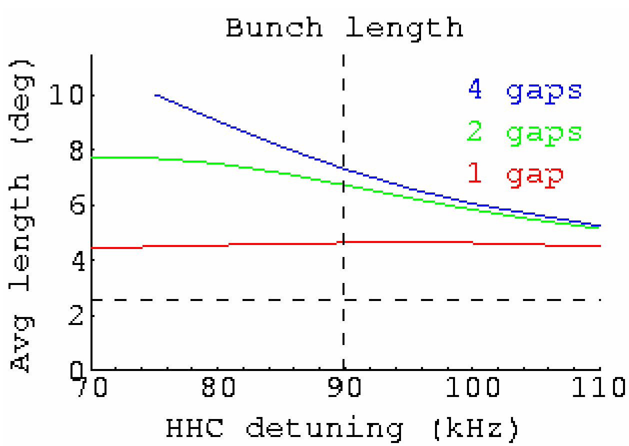
Bunch lengths in phase four

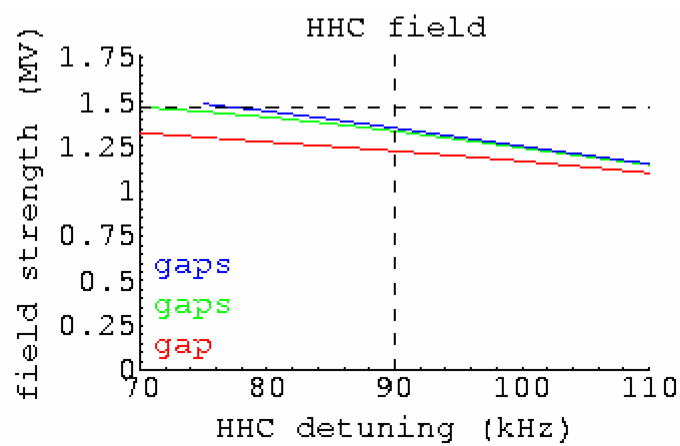
80% fill fraction





90% fill fraction





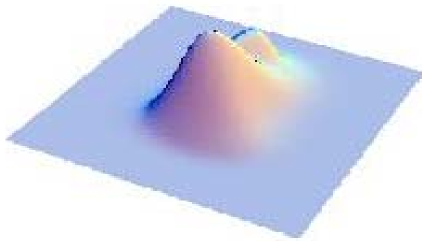
- Vertical dashed lines are the HHC detunings that generate the nominal field when driven by short bunches.
- Horizontal dashed line are the unstretched bunch length (left), and nominal HHC field for stretching (right).

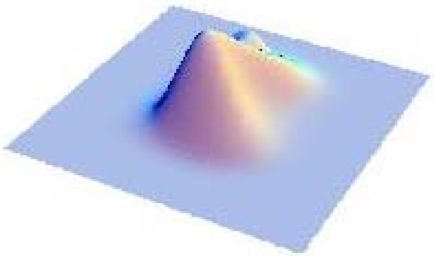
Beam phase noise

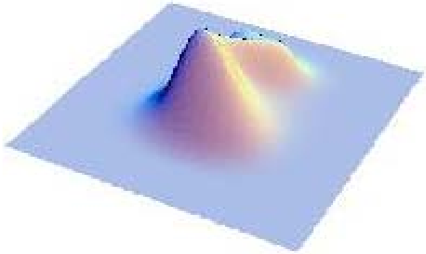
- RF-system noise is transferred to the beam through the RF to the cavity. There is LLRF noise, power-supply ripple, klystron phase and amplitude modulation, synthesizer, etc.
- Some experiments are sensitive to beam phase noise, e.g., timing and FTIR, and a fairly tight tolerance is established for this noise.
- Response functions specify a couple of things.
  - How noise in the waveguide power is transferred to the beam-cavity system. This constrains the spectral dependence of that noise.
  - Structure in the response functions, i.e., poles and zeros, tell us how feedback can be applied to suppress noise from various sources (types of loops, gain, bandwidth, compensation).

Vlasov simulations for response functions

- Vlasov simulations model the longitudinal phase space of a bunch, taking into account the rf fields from main and harmonic cavities, cavity higher-order mode impedances, and short range wakes and their potential well distortion.
- Noise in the rf system perturbs the rf power going to the cavity, and the coupled cavity/beam system responds to this noise in its characteristic way. The rf-to-cavity/beam response function is a measure of this response.

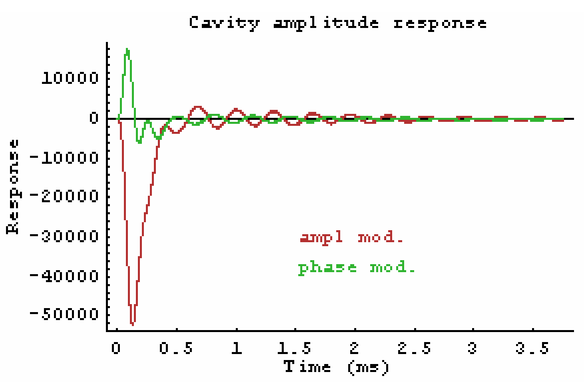


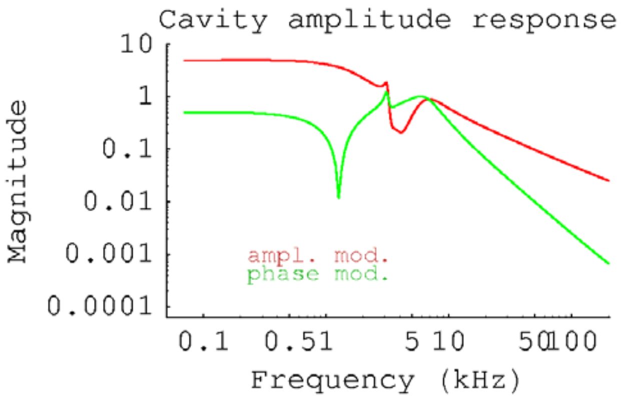




Response function types

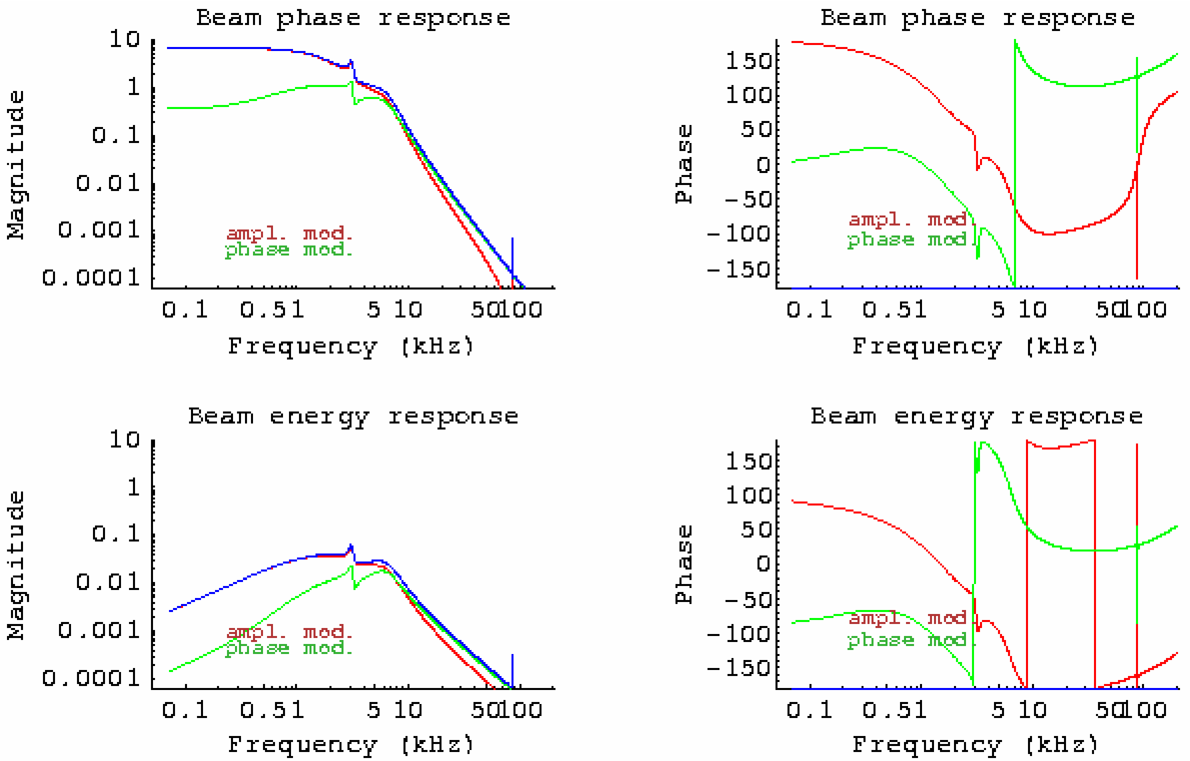
- There are amplitude and phase modulation of the rf, each can carry noise, and they can be correlated.
- The cavity/beam system responds with beam phase modulation, beam energy modulation, cavity phase modulation, and cavity amplitude modulation.
- So there are eight response functions relating to the performance of the machine, each has magnitude and phase components.
- Frequency domain response functions are calculated from corresponding impulse response functions.





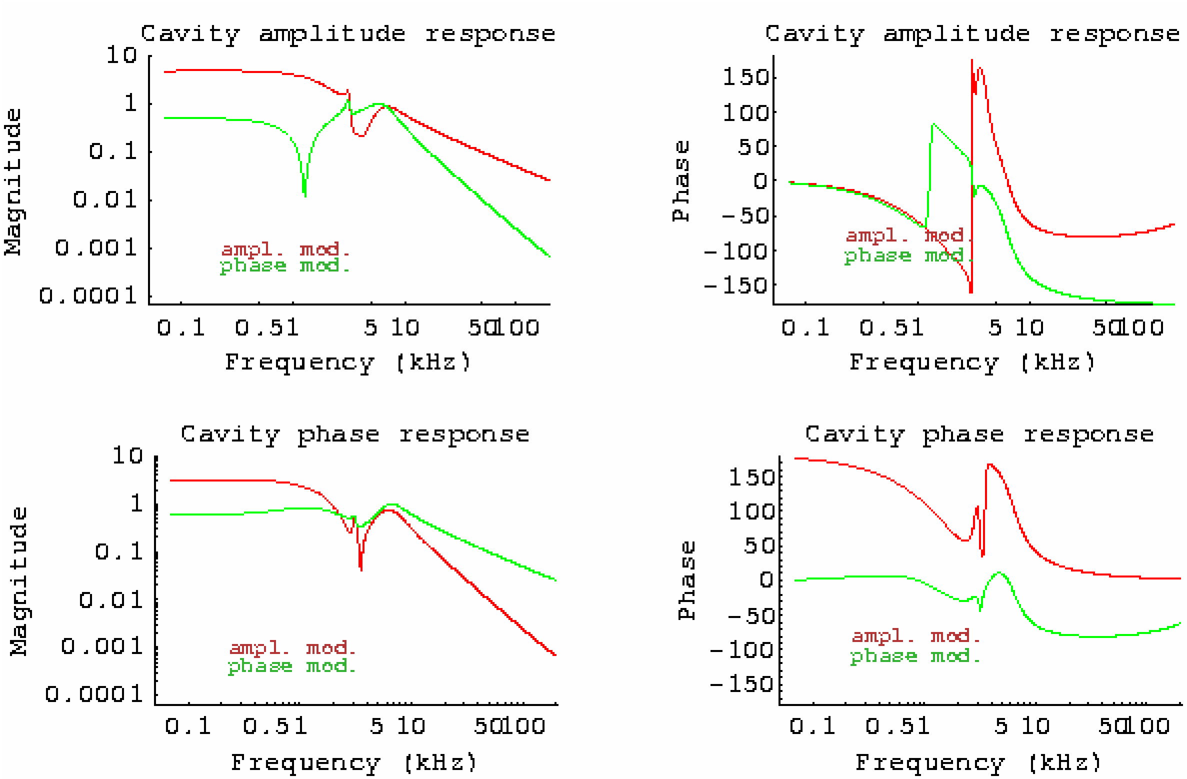
Phase-Four beam response functions

- Upper pair are beam phase responses, lower are beam energy responses.
- Left column are the magnitudes of the responses, right column are the phases.
- Red traces are driven by amplitude modulation, green by phase modulation.



Phase-Four cavity response functions

- Upper pair are cavity amplitude responses, lower are cavity phase responses.
- Left column are the magnitudes of the responses, right column are the phases.
- Red traces are driven by amplitude modulation, green by phase modulation.



Noise calcs and phase information

- The calculation of phase noise in the cavity or beam requires not only knowledge of the response functions, but also the rf modulation, both AM and PM, and their correlations. For practical reasons, phases and correlations of modulation signals are not normally recorded. But even without this information, cavity and beam noise may be bounded given the spectrum of rf noise. For example cavity-field noise may be bounded:

$$\left\langle \left(\frac{\delta V}{V} \right)^2 \right\rangle \le \int d\omega \left| G(\omega) \right|^2 \left| \frac{\delta a}{a}(\omega) \right|^2$$

$$\left| G(\omega) \right|^2 = \left| G_{AM} \right|^2 + \left| G_{PM} \right|^2$$

$$\left| \frac{\delta a}{a} \right|^2 = \left| AM \right|^2 + \left| PM \right|^2$$

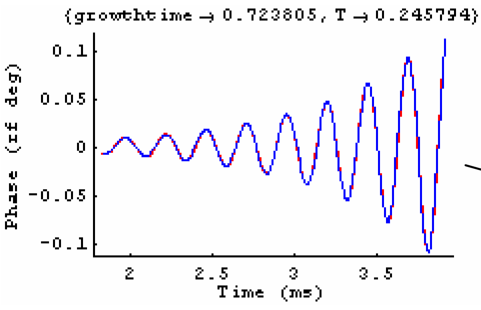
Noise summary

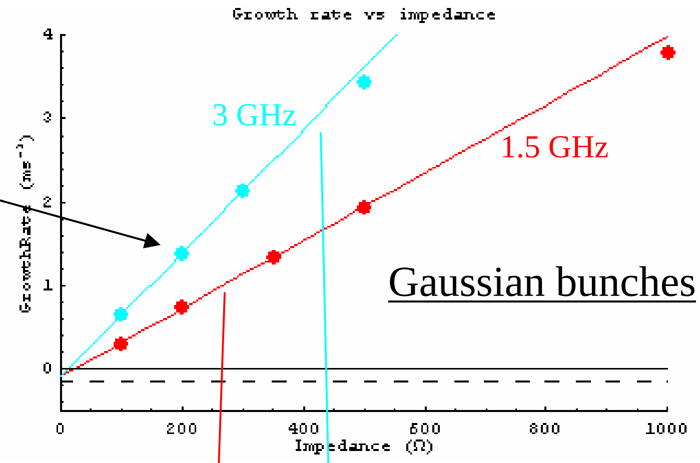
- Amplitude modulation has greater transfer to the beam and to the cavity. Phase modulation transfer is smaller, although it still constrains system-oscillator phase noise.
- The structure in the response functions make it difficult to extend feedback loops to very large bandwidth--perhaps less that a kHz. Cavity loops may have little effect on switching transients at higher 60-Hz harmonics. Beam feedback still has the potential to suppress noise [Bosch et al. (2007)].
- Klystron gain and phase ripple are tightly constrained by the noise specification. Due to the sensitivity of klystron gain and phase shift to power supply ripple, gain and phase loops around the klystron are essential. Klystron group delays seem to be low enough that lots of bandwidth is available.

Coupled-bunch modes for stretched bunches

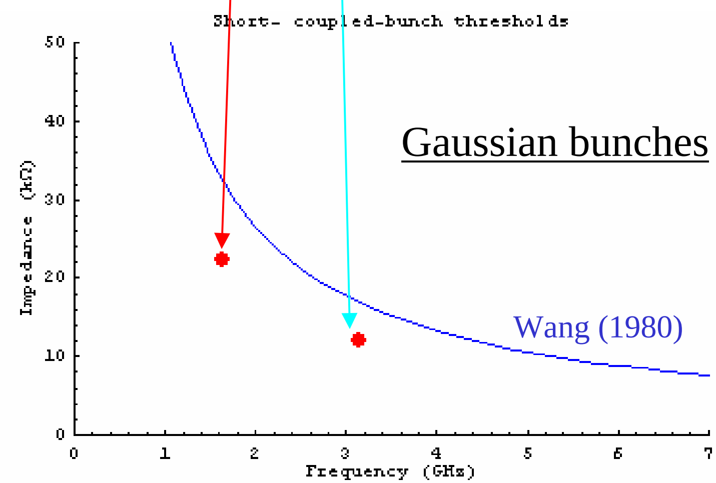
- A simple and accurate formula for stability boundary of coupled-bunch (CB) multipole modes for gaussian bunches exists. But for stretched bunches where a non-harmonic potential and Landau damping are present, no such formula is available. Alternatives are numerical codes.
- As a means to calculate CB thresholds for stretched bunches, I modified my Vlasov integration code to track multiple bunches and used it to track CB modes under the influence of single HOMs at several frequencies from 1 to over 6 GHz in a symmetric fill. Four bunches were simulated.
- The modifications were tested with gaussian bunches, verifying thresholds and the influence of upper vs lower sidebands.

Vlasov simulations of CB modes



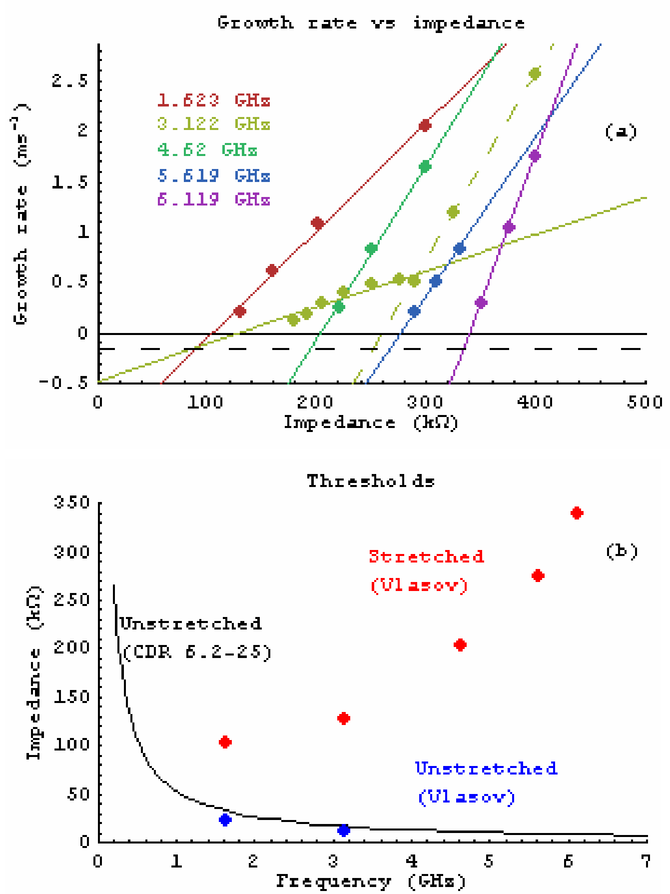


- At a given HOM frequency and impedance, the motion of the bunch centroid is fit to exponentially growing oscillation, and growth rate and frequency are extracted.
- Growth rates extracted from runs at different impedances but the same frequency are fit to a line, and the fit extrapolated to the zero-growth impedance.



CB modes in stretched bunches: results

- Unstable bunch mode switches from a 1.5-kHz mode at lower frequencies, to a 2.5-kHz mode at higher frequencies. The two modes compete at 3 GHz, possibly a collision nearby.
- Thresholds increase quickly with increasing HOM frequency.



CB-modes summary

- Stretched CB modes are not likely to be unstable at high frequencies.