Harmonic RF Systems in Electron Storage Rings

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Topical Workshop on Instabilities, Impedances and Collective Effects

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- Michele Svandrlik
- ALS Physics Group

Caveat: I have not been active in light sources for a decade. I'm sorry if I haven't included the latest results.

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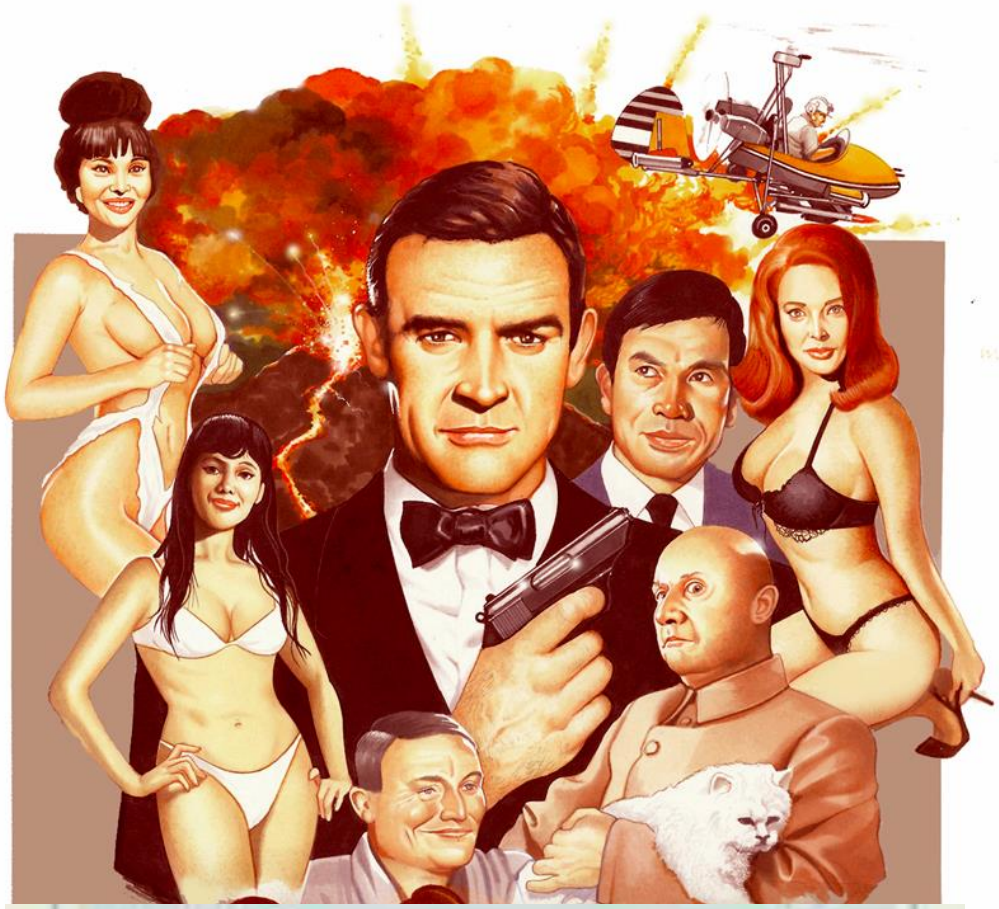

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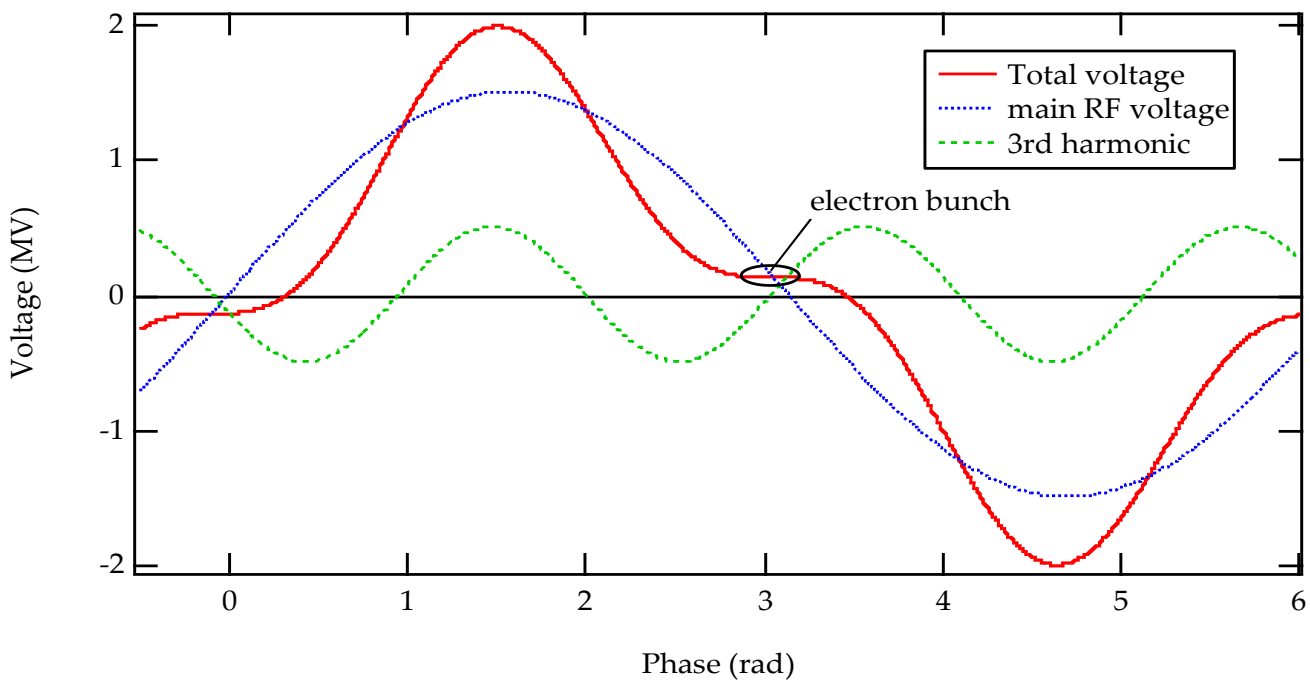
Motivation for Harmonic RF

- As electron rings reach smaller emittances, bunch charge densities are high enough that the equilibrium 3-d emittance increases from the nominal values.
- How to address this problem with the RF system?
  - High RF frequency with many small bunches?
  - Low RF frequency with few large long bunches?
  - Multiple RF systems with variable length bunches?

Physics of harmonic RF systems

- Typical storage ring RF systems typically provide beam power and enough longitudinal focussing to give desired bunch length.
- By adding harmonic voltage(s), we can shape the bunch longitudinally, useful for a variety of applications.

$$V(z) = V_{rf}\left[\sin\left(\frac{\omega_{rf}}{c}z + \phi_s\right) + \sum_{n=1}^{\infty} k_n \sin\left(n\frac{\omega_{rf}}{c}z + n\phi_{hn}\right)\right]$$



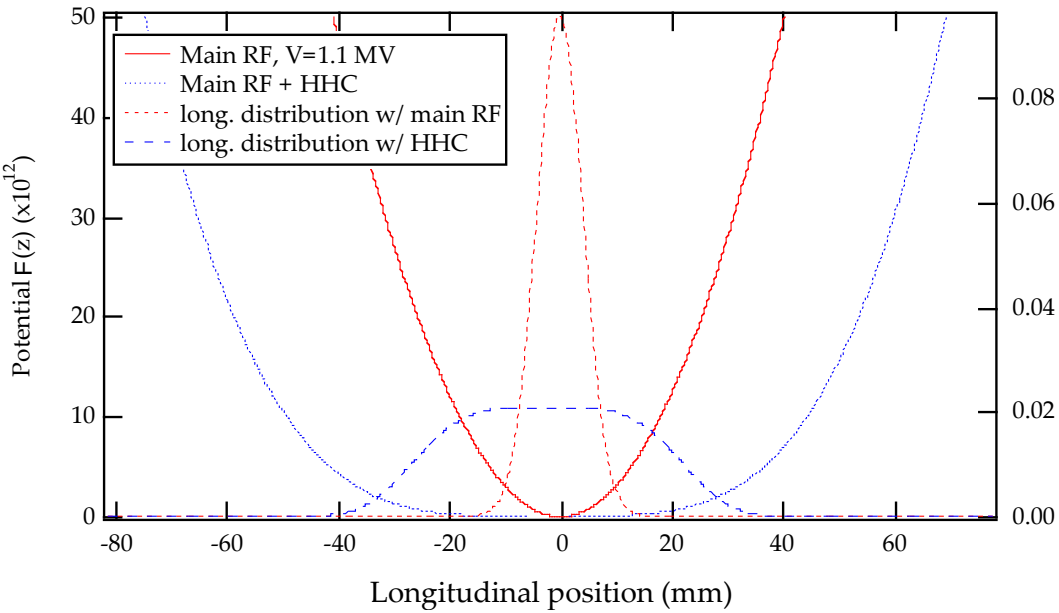
Harmonic RF systems (cont.)

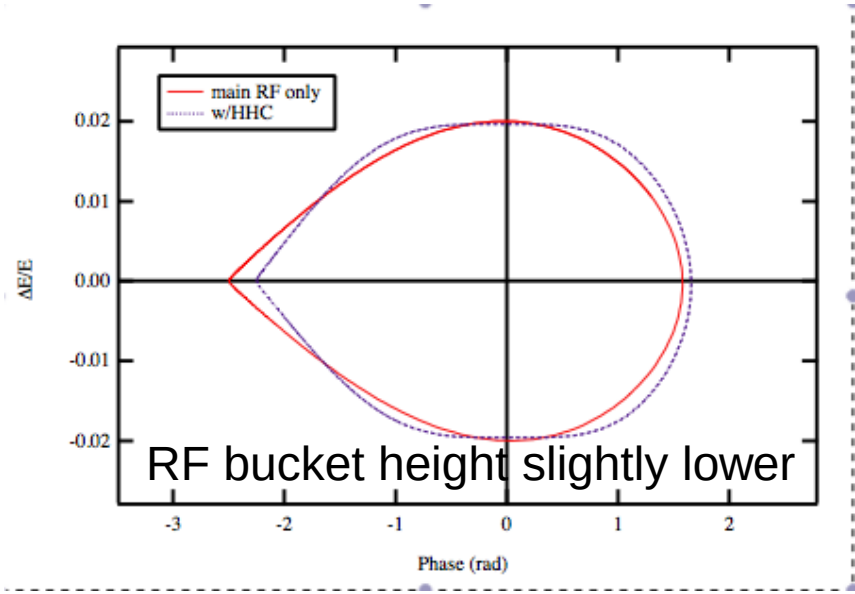
The bunch shape can be calculated from the resulting distortion of the potential well.

In the bunch lengthening case, the single particle motion is highly nonlinear and a large tune spread is introduced.

$$\rho(z) = \rho_0 e^{-\frac{F(z)}{\alpha^2 \sigma_e^2}}$$ bunch distribution

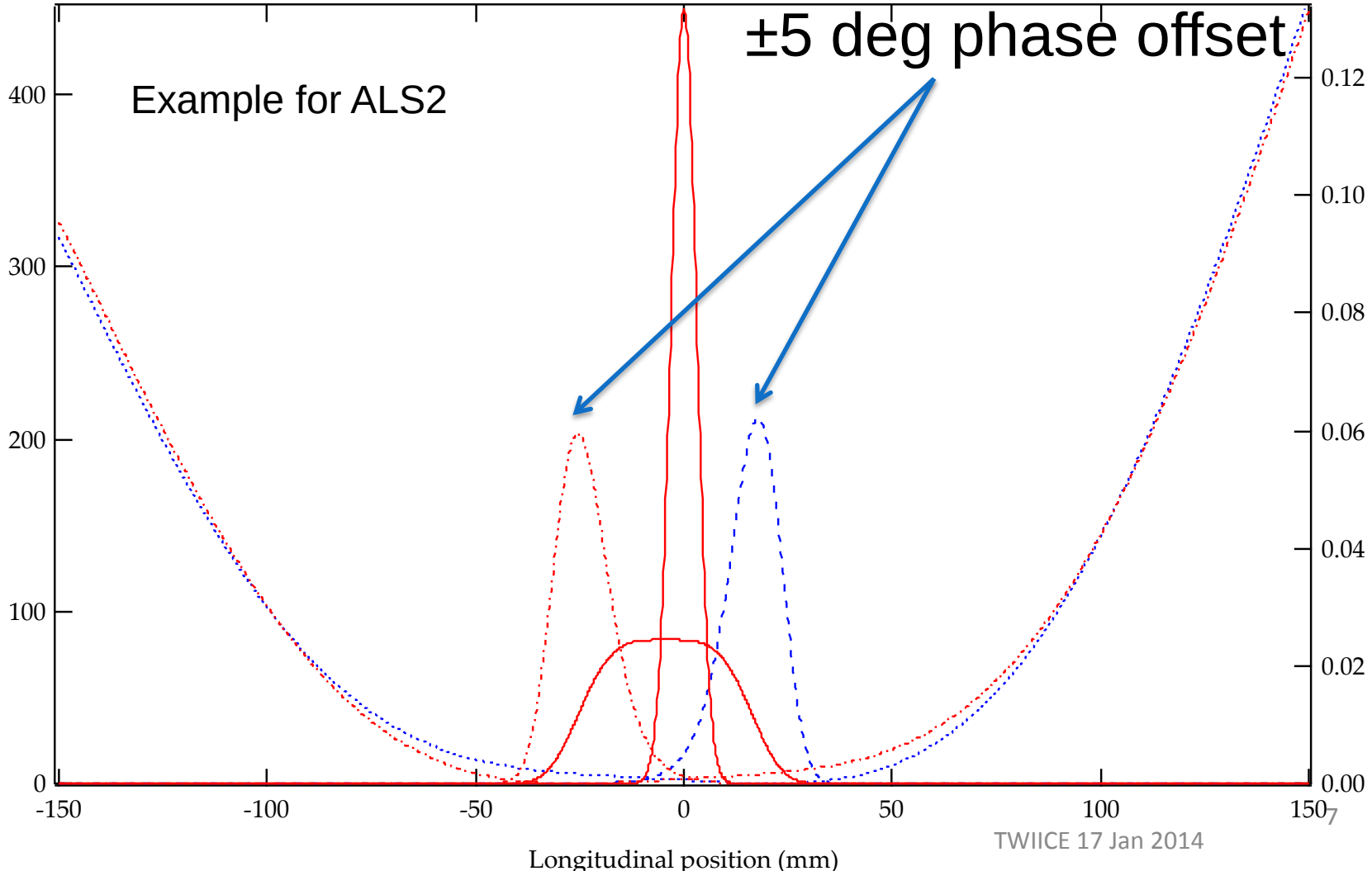
$$\Phi(z) = \frac{\alpha}{EC}\frac{cV_{rf}}{\omega_{rf}}\left[\cos\phi_s - \cos\left(\frac{\omega_{rf}}{c}z + \phi_s\right) + \sum_{n=2}^{\infty}\frac{k_n}{n}\left(\cos n\phi_{hn} - \cos\left(n\frac{\omega_{rf}}{c}z + n\phi_{hn}\right)\right)\right]$$ potential





Harmonic RF systems (cont.)

- Bunch lengthening effects very sensitive to phase of HC when focusing is gone.

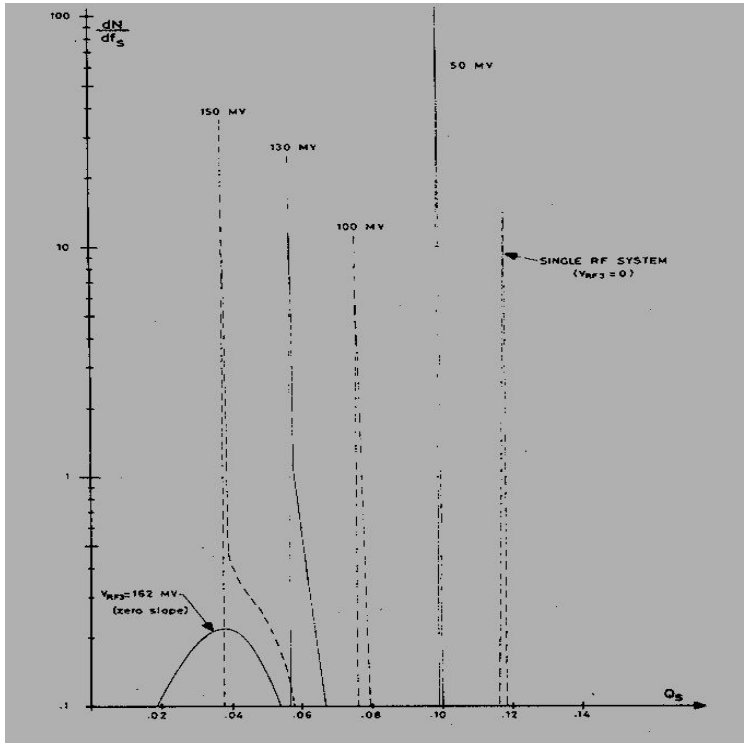


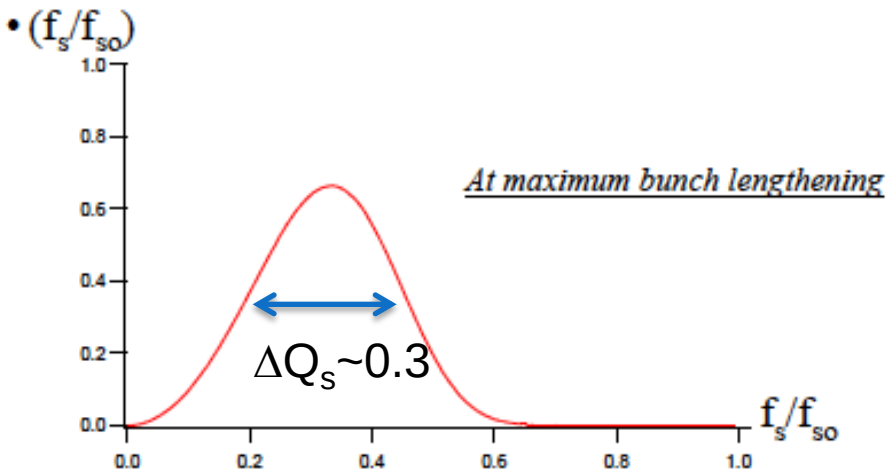
Harmonic RF systems (cont.)

- Flattening of potential well induces large synchrotron frequency spread, providing large Landau damping.

BEAM DYNAMICS IN A DOUBLE RF SYSTEM

A. Hofmann and S. Myers
CERN, Geneva, Switzerland





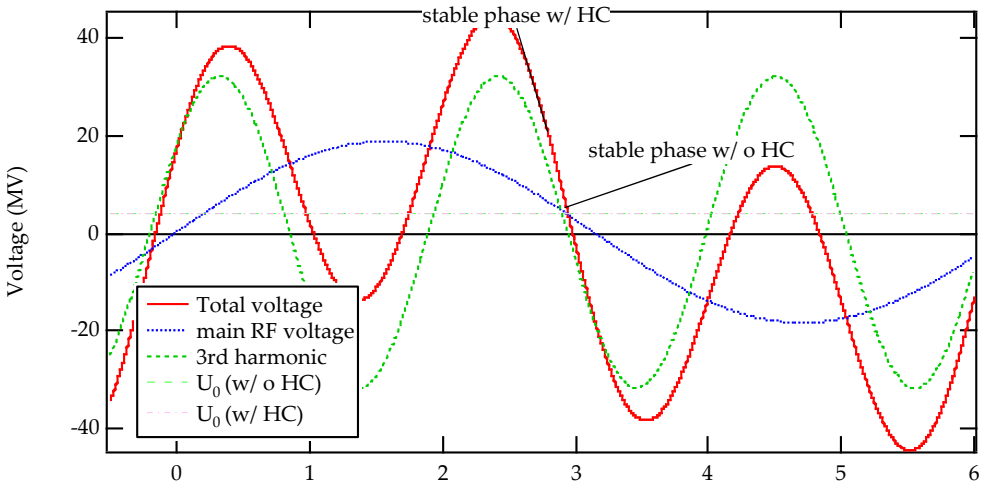
Tune spread ranges from 0.01 (no HC) to 0.3 at optimal bunch lengthening. This should be strong enough to damp all HOM driven instabilities.

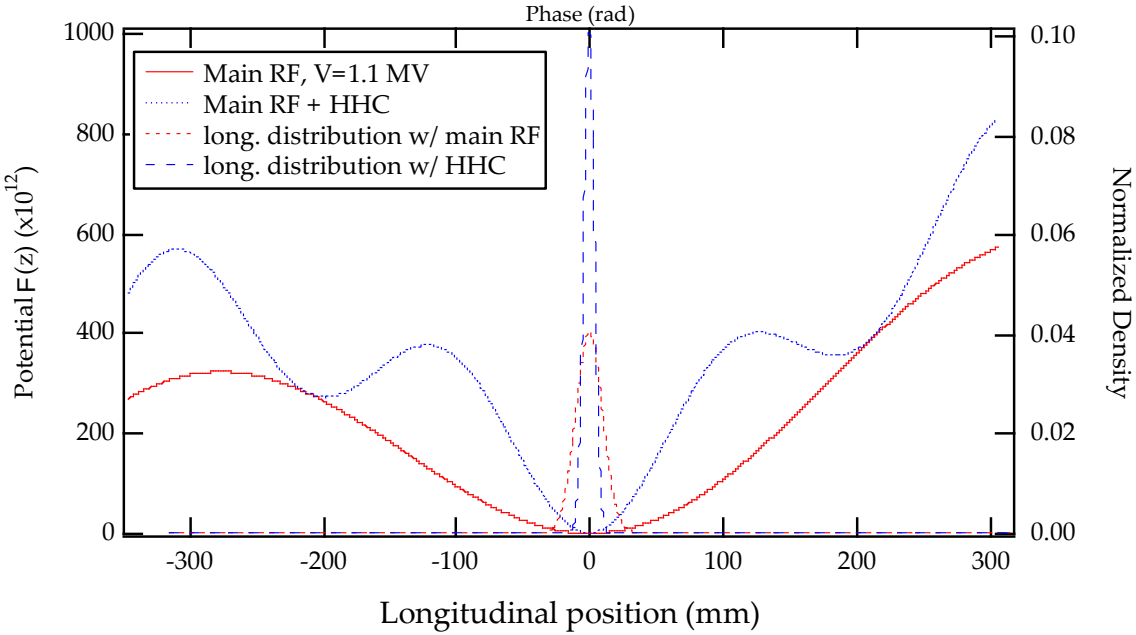
Bunch shortening using HCs

The harmonic voltage can be phased to add the focussing of the main RF.

Since the focussing is reactive, a passive (i.e. idling) cavity can be used to generate the voltage.

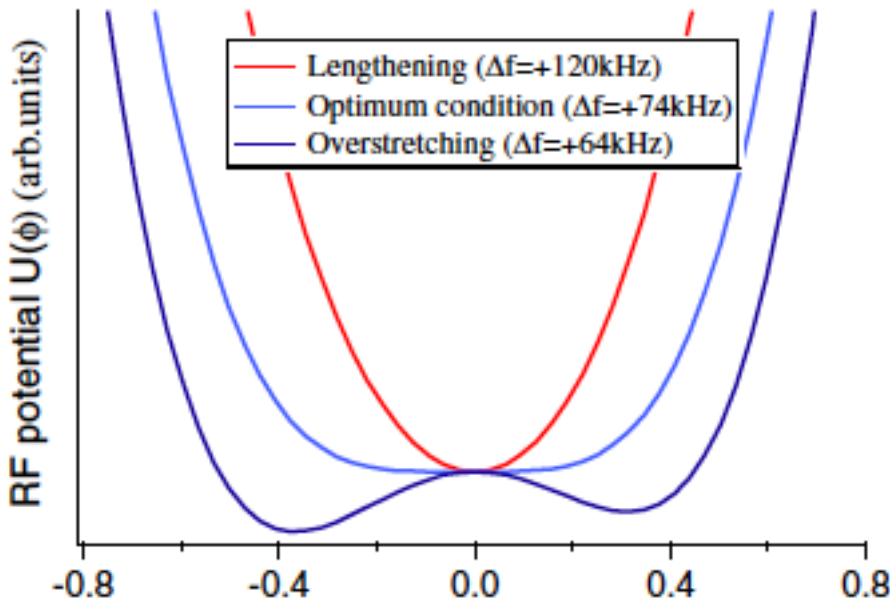
Very economical method for reaching short bunches. Increased focusing gives higher SB and MB instability threshold.

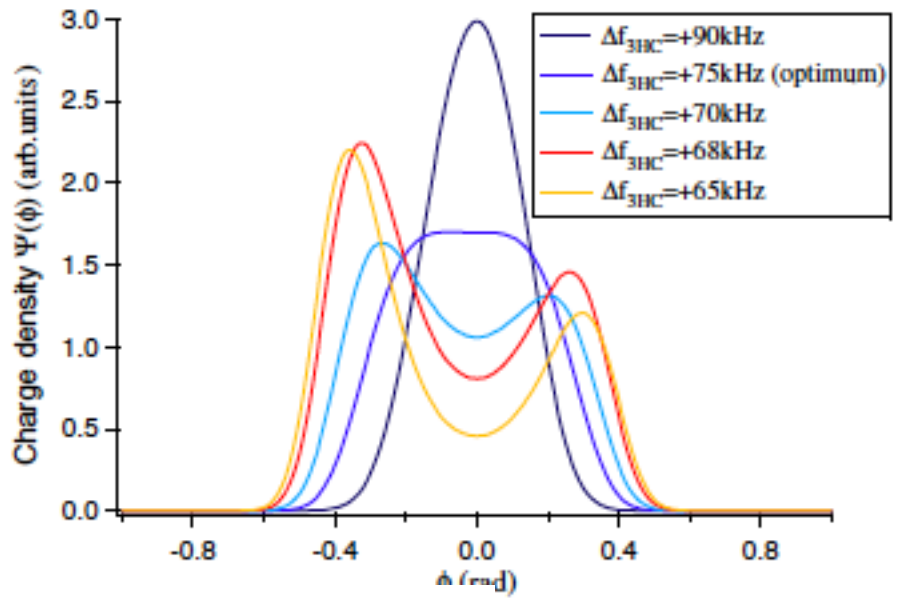




Overstretching

- Increasing the harmonic voltage past a flat potential well creates multiple fixed points in the RF bucket.





Penco and Svandrlik PRSTAB 9, 044401 (2006)

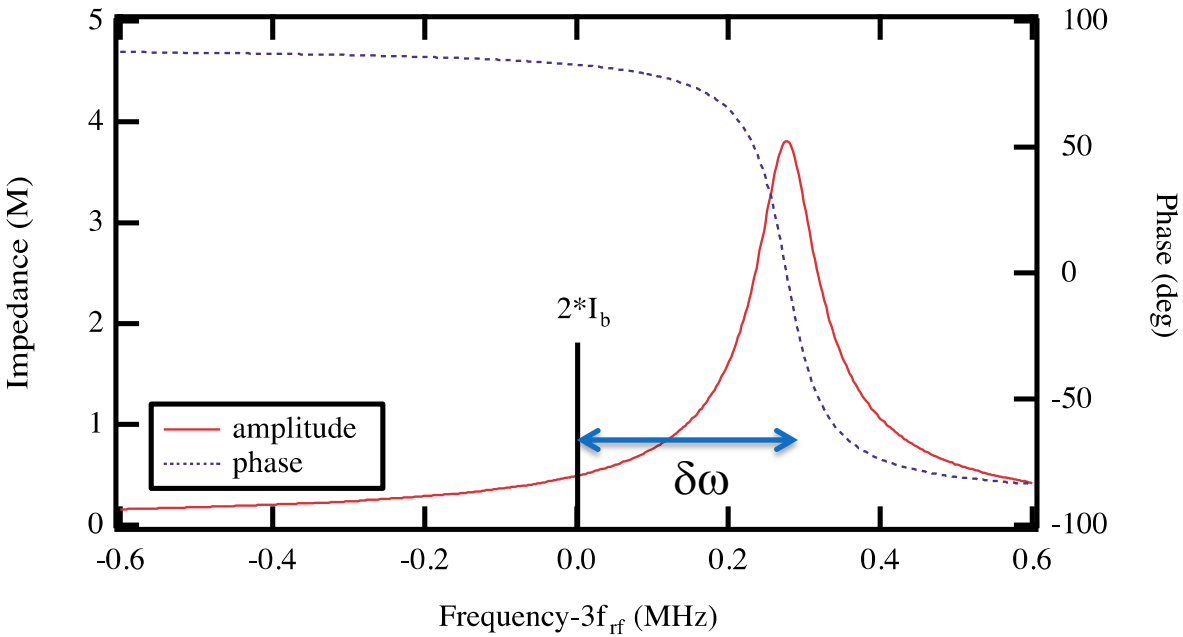
FIG. 14. (Color) Potential well distortion in lengthening mode, at optimum condition (flattened) and in overstretching regime, calculated for $I_{beam} = 315$ mA by using formula (5).

FIG. 15. (Color) Nominal charge density in the bunch in function of the 3HC detuning, calculated in uniform filling and at 315 mA by using formula (9).

- Interesting? Yes. Useful? Small lifetime increase.
- What is the effect on transverse head-tail instabilities?

Passive Cavity Operation

- Because the harmonic voltage is almost completely reactive (90 deg out of phase with beam), we can use the beam to drive the harmonic cavity.



For high Q cavity, the beam induced voltage is given by

$$V \sim I_b \cdot R/Q \cdot \frac{\omega_r}{\delta\omega},$$

The optimum harmonic voltage and phase are given by

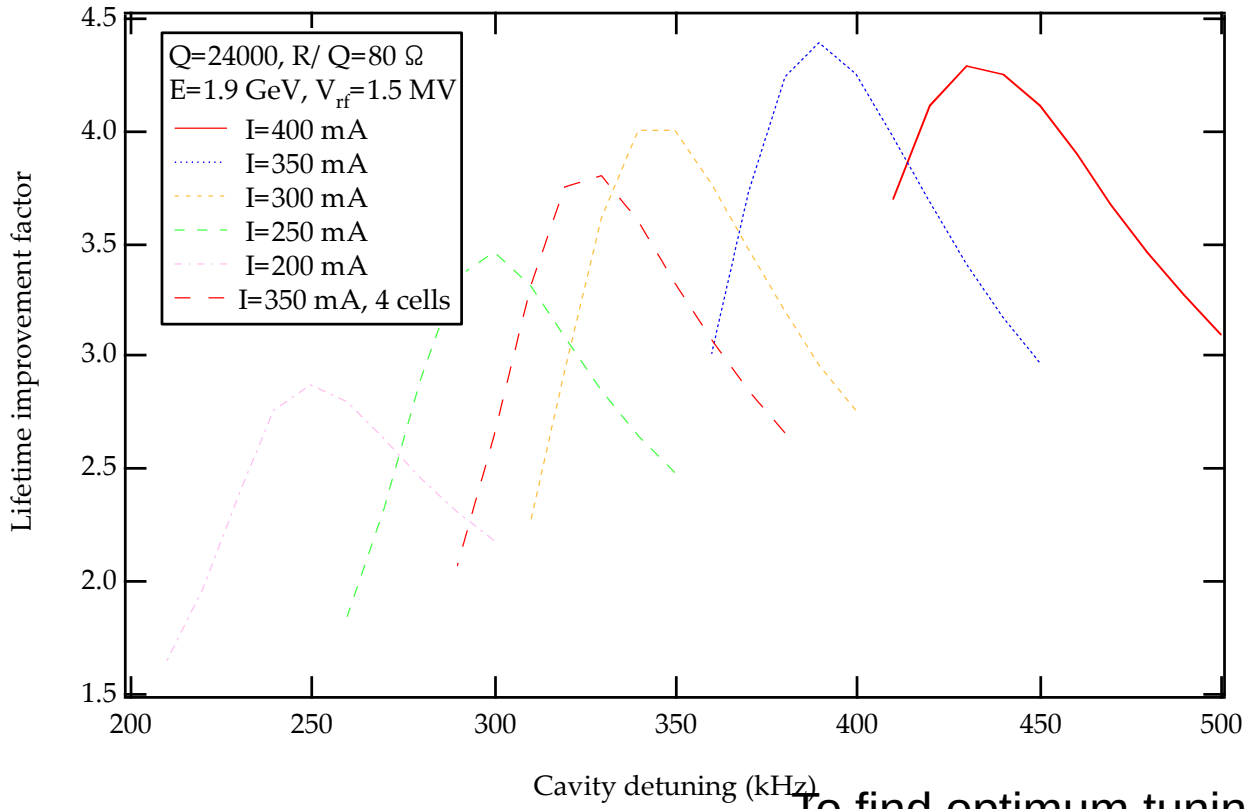
$$k_{\rm opt} = \frac{V_{h,\rm opt}}{V_{\rm rf}} = \sqrt{\frac{1}{n^2} - \frac{(U_0/V_{\rm rf})^2}{n^2-1}},$$ ~1/n

$$\sin(n\phi_{h,\rm opt}) = \frac{-U_0}{V_{h,\rm opt}(n^2-1)}.$$ ~0 (90 deg)

For a fixed cavity Q, it is possible to achieve the optimum lengthening for one current.

Passive Cavity with Variable Current

- If the beam current varies with time (sans topoff), the bunch lengthening varies with current.

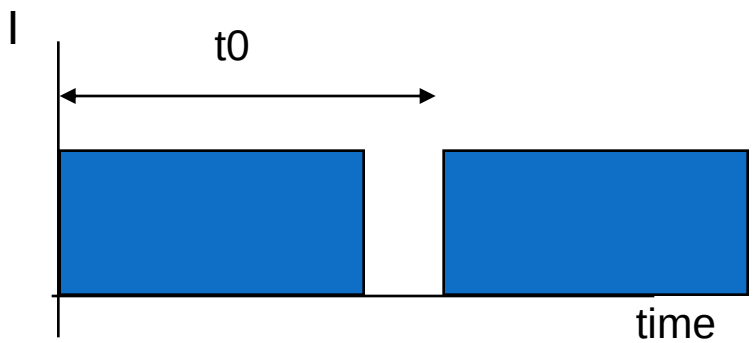


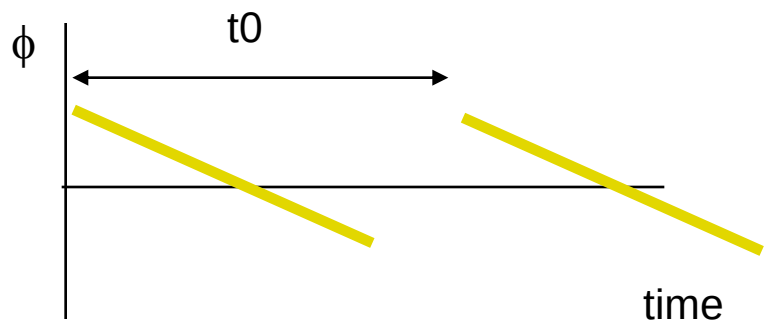
To find optimum tuning position, plot lifetime improvement vs. resonant frequency for several beam currents for a fixed beam-induced voltage.

Byrd and Georgsson, PRSTAB 4, 030701 (2001).

Transients beam loading effects

The unequal filling of the ring (i.e. gaps) create a transient loading of the main and harmonic RF systems, causing bunches to be at different RF phases (i.e. different arrival times.)



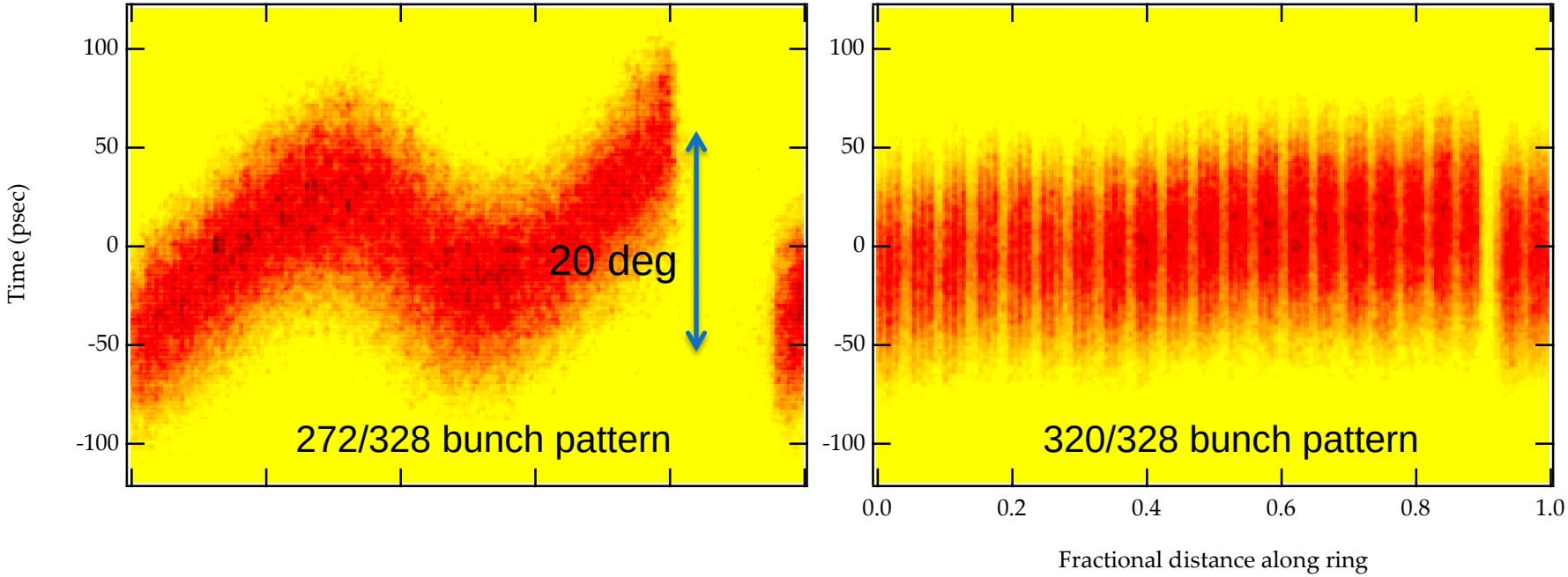


For the main RF only, this effect is small (few degrees). With the HCs, the effect is much larger. This affects both the lifetime improvement and operation of the multibunch feedback systems.

Observation of Large Phase Transients

2 cavities in Landau mode
3 parked at ±1.5*f0

3 cavities in Landau mode
2 parked at ±2.5*f0



Unequal fill or gap of 20-25% (users' demand) aggravates this problem.

This result was NOT expected and not reported in prior literature. We began an investigation to understand the effect.

Tracking Model

- Use macroparticle tracking to follow longitudinal motion of each bunch and fields in fundamental and harmonic cavity modes.

$$\varepsilon_{i+1} = (1 - 2\lambda_{rad})\varepsilon_i + \frac{1}{E}(eV_g(\phi_i) + eV_{bi}(\phi_i) - U_{s,i})$$

$$\phi_{i+1} = \phi_i + 2\pi . T_0 . \alpha . h . \varepsilon_i$$

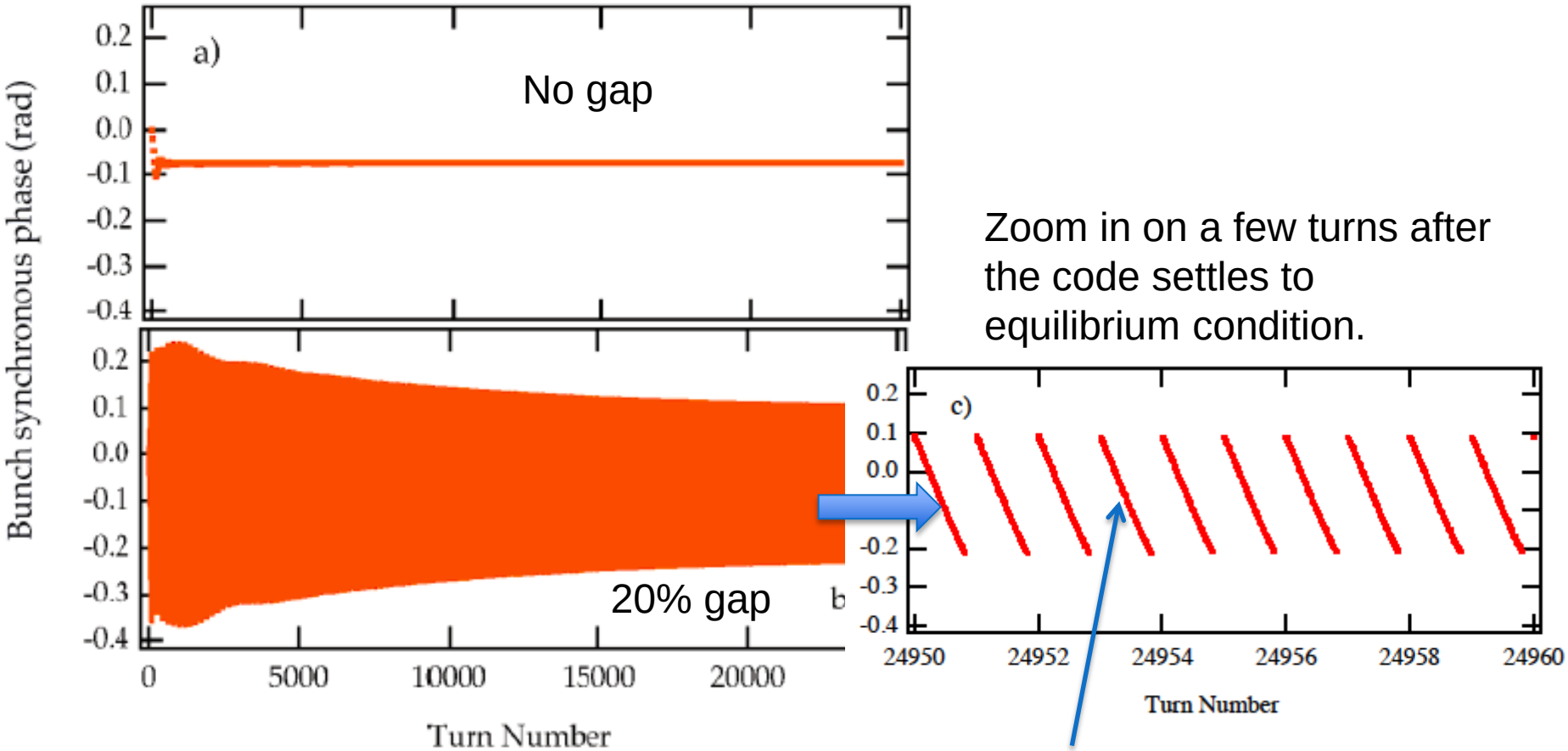
$$\tilde{V}_{b,i+1} = \tilde{V}_{b,i} \exp((j\omega_r + \frac{\omega_r}{2Q})\Delta t) - kq$$

$$\Delta t = \frac{\phi_{i,n} - \phi_{i,n-1}}{\omega_{rf}} + T_b$$

- A few points:
  - Fund and Harmonic cavity fields are initialized to steady-state values assuming uniform filling and ideal beam-loading compensation.
  - Assumes harmonic voltages are always below overstretching condition.
  - Does not include Landau damping because bunches are point particles.

Transient Results

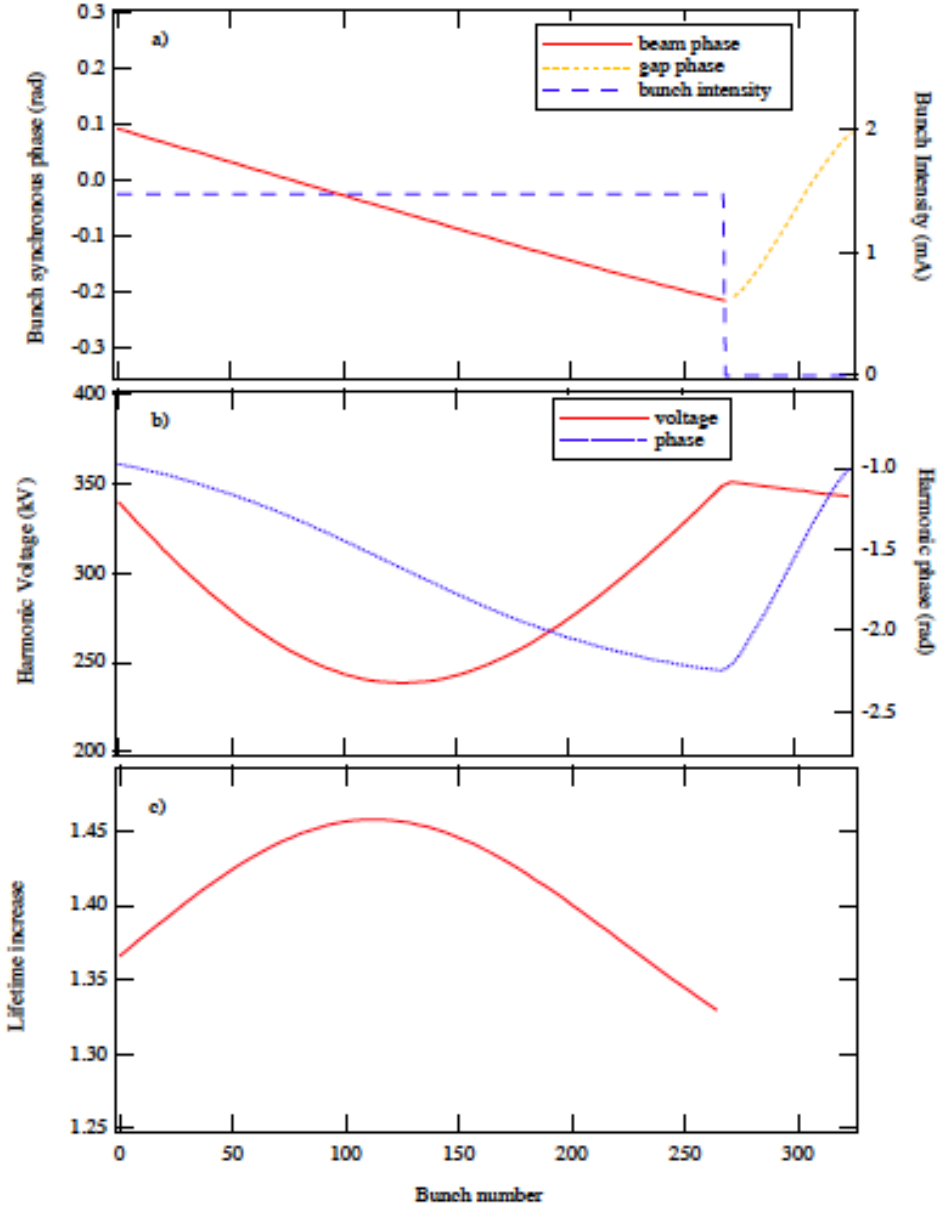
- Run code for ALS parameters.



Zoom in on a few turns after the code settles to equilibrium condition.

Large phase transient observed.

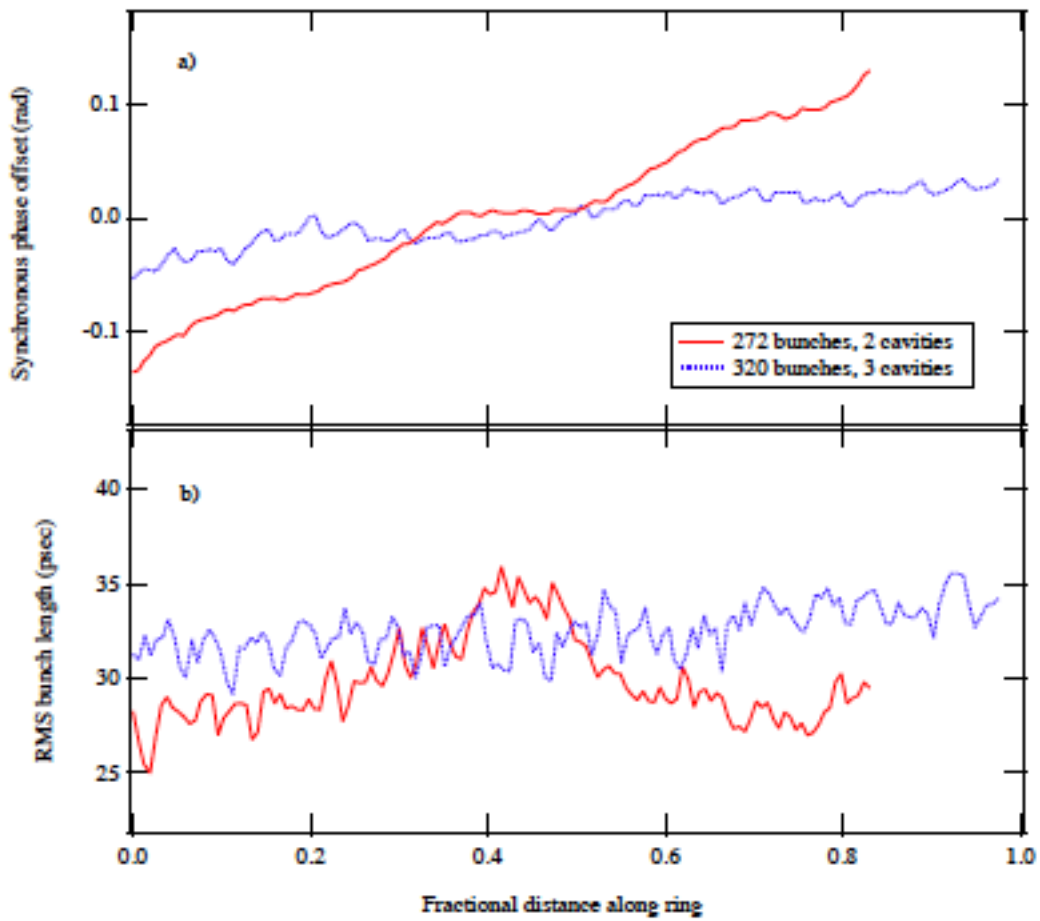
Transient Results



- Linear synchronous phase shift along bunch train
- Harmonic cavity voltage and phase transient along bunch train.
- Calculated bunch length along bunch train.

Comparison with Measurements

- ALS with 20% and 2% gap



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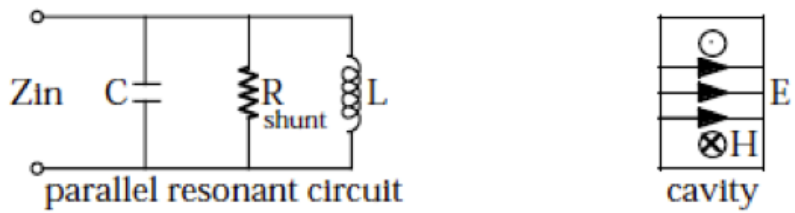
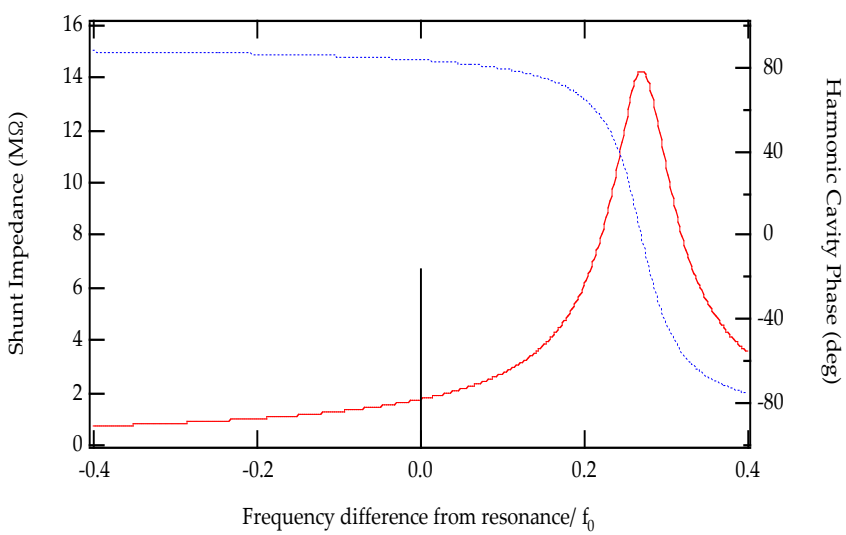
Cavity mode as parallel LRC resonator



- The input impedance of the equivalent circuit can be expressed as:

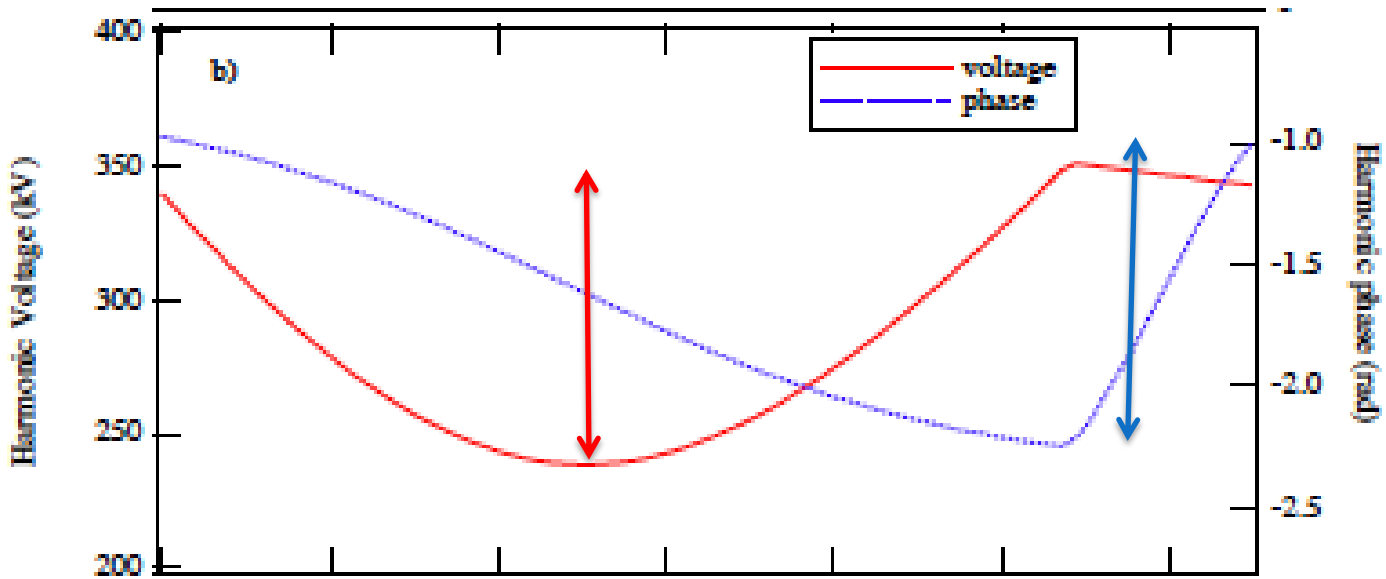
$$_{in} = \left(\frac{1}{R} + \frac{1}{j\omega L} + j\omega C\right)^{-1} \qquad \text{where } \omega_o = \frac{1}{\sqrt{LC}} \text{ and } Q = \omega_o RC \text{ (or } Q = \frac{R}{\omega_o L}\text{).}$$

$$= \frac{R}{1 + jQ\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right)} \approx \frac{R}{1 + jQ2\left(\frac{\delta\omega}{\omega_o}\right)}$$



- Cavity excited well below bandwidth looks like inductor with $R/Q = \omega_r L$
- The transient effect can be roughly described as the transient effect in an inductor.
- See pubs for detailed analysis.

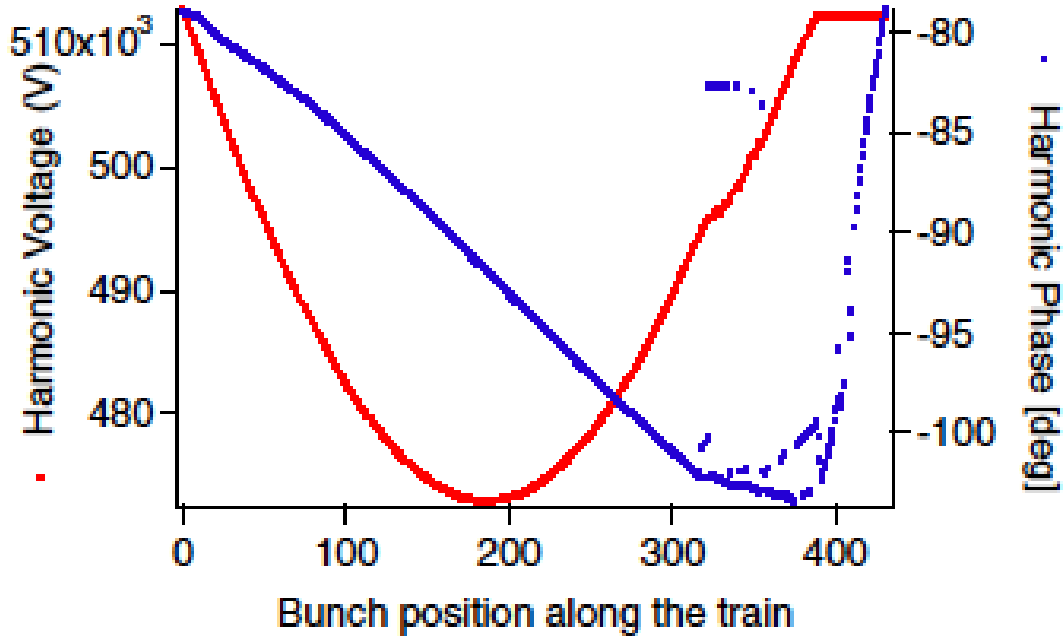
More transient details



- HC phase varies greatly over bunch train (almost 70 degrees in this example)
- HC phase is correct at middle of bunch train.
- HC voltage is largest at ends of bunch train, where phase is not correct.
- Depth of HC voltage modulation proportional to total R/Q, beam current, and detuning.

Transient effects for SC HC

- The transient effect is dependent on total R/Q, **not Q**. Therefore. SC HC should see similar effect.

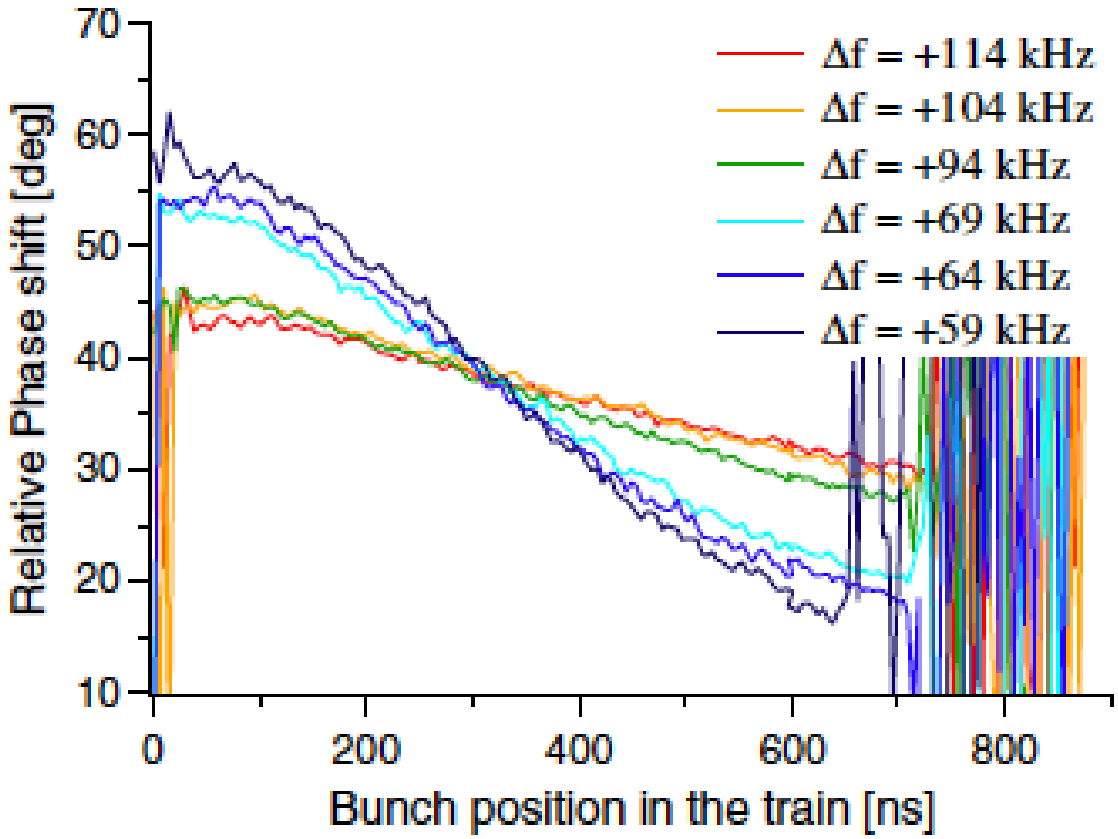


Penco and Svandrlik
PRSTAB 9, 044401 (2006)

FIG. 9. (Color) ESRF code results of the harmonic voltage (red) and phase (blue) modulation along the bunch train after the transient beam loading, obtained for a beam current of 315 mA, a 90% filling and a 3HC detuning of +81 kHz.

Transient Measurements for SC HC

- ST/SLS SuperHC (2 cell cavity R/Q=88 Ohm)



Penco and Svandrlik
PRSTAB 9, 044401 (2006)

FIG. 6. (Color) Relative stable phase along the bunch train vs the 3HC detuning, for a 80% filling; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

Transient Measurements for SC HC

- ST/SLS SuperHC (2 cell cavity R/Q=88 Ohm)

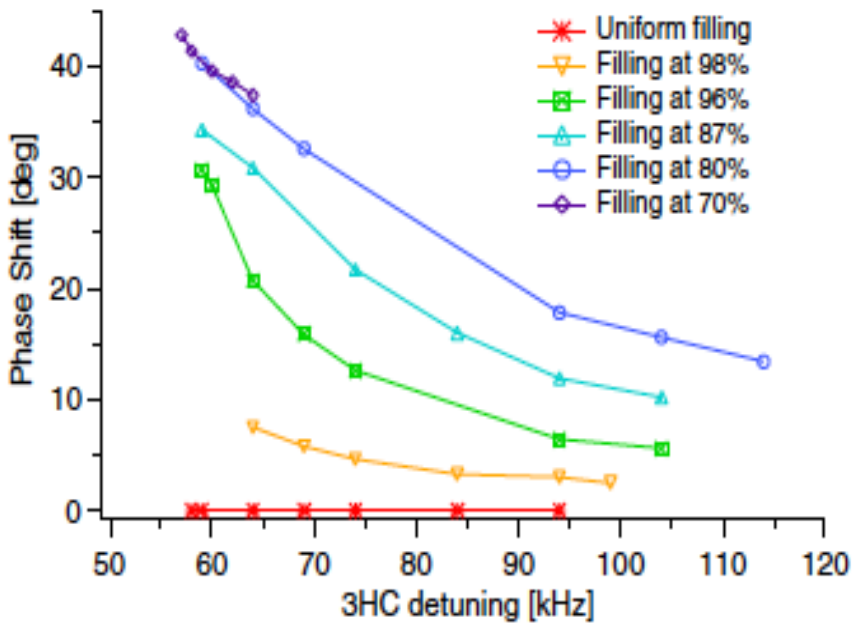


FIG. 7. (Color) Phase difference between the head and the tail of the bunch train vs the 3HC detuning, for several fractional fillings; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

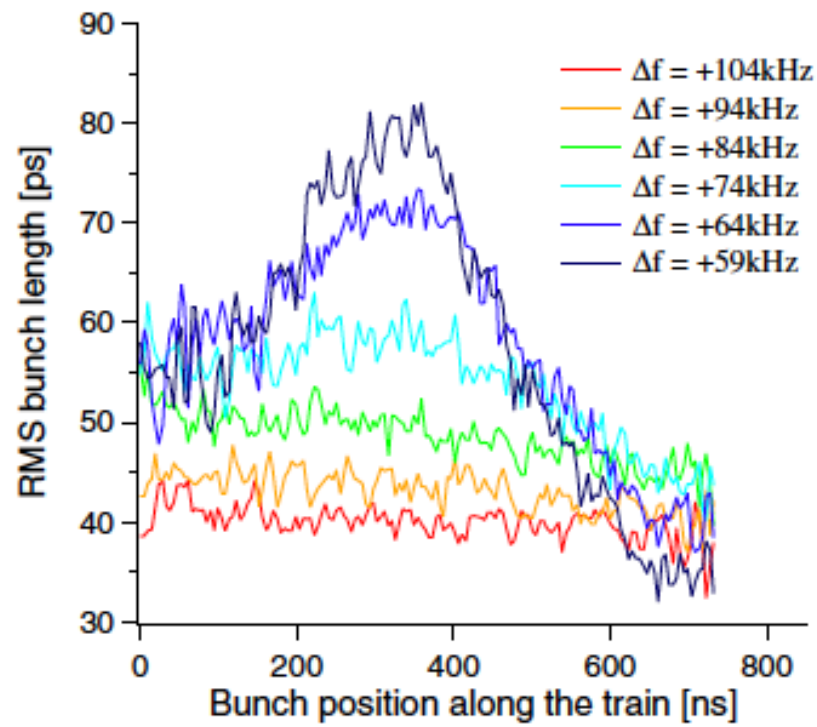


FIG. 10. (Color) rms bunch length along the bunch train for several 3HC tuning for a filling of 90%; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

Penco and Svandrlik
PRSTAB 9, 044401 (2006)

HC Options

- NC cavity
  - R/Q=80-100 Ohm
- SC cavity
  - R/Q=40 Ohm/cell
- ARES NC cavity
  - R/Q=15 Ohm

For ALS-II SC HC is the baseline. It would be "uncool" to find an ARES option.

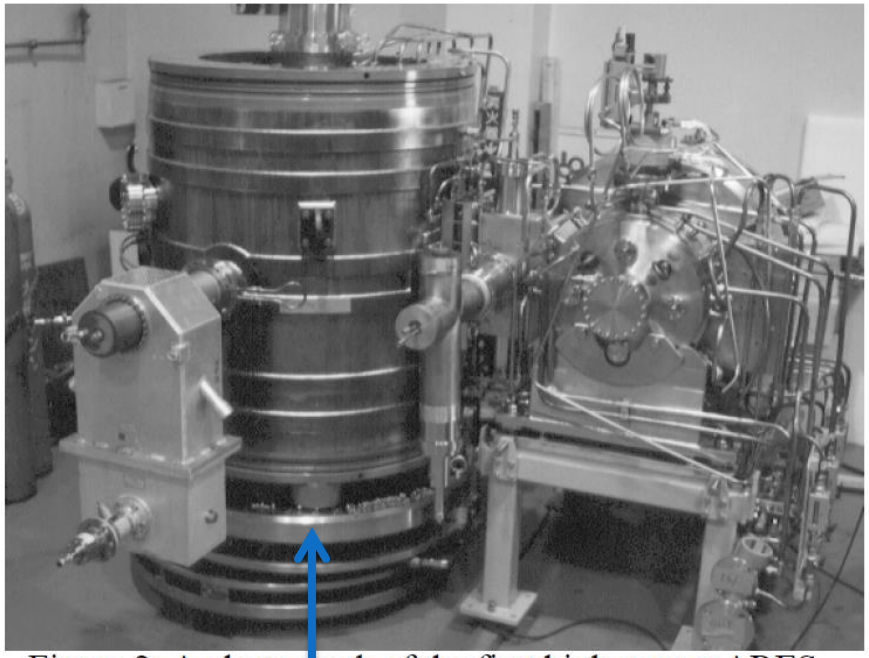


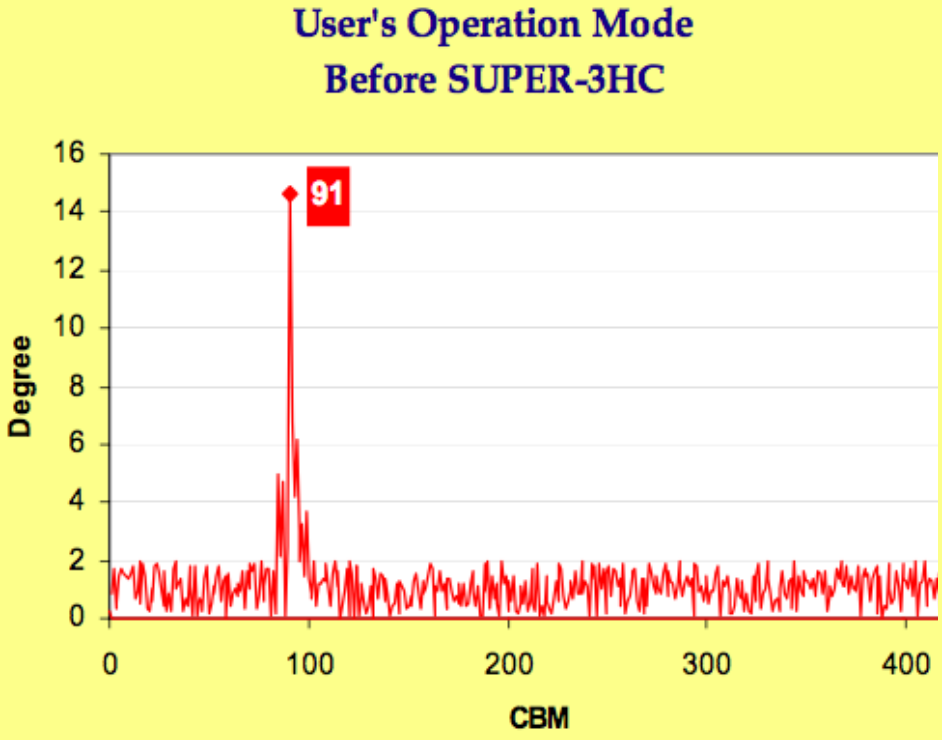
Figure 2: A photograph of the first high-power ARES cavity.

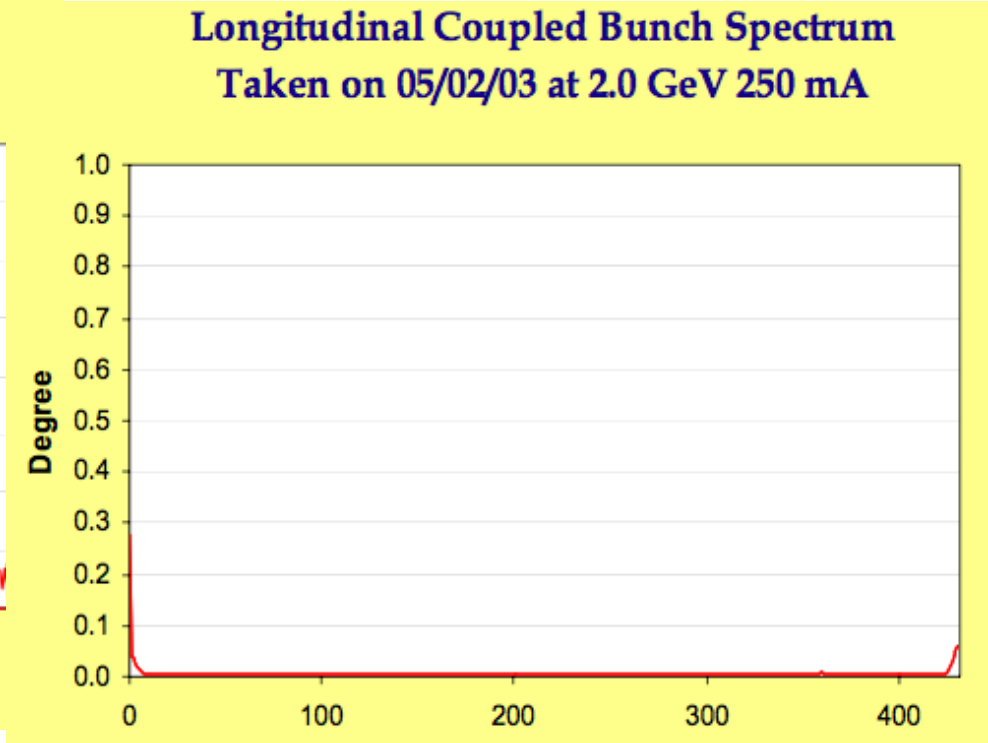
d=1070 mm, l=1190 mm

"The ARES Cavity for the KEK B-Factory", T Kageyama et al, EPAC 1996, WEP054

Landau Damping of MBI

- With nearly uniform fill pattern, bunch lengthening is more effective, and a large frequency spread is induced. This provides Landau damping for all instabilities.





- Same effect seen at ALS. Other rings? To my knowledge the Landau damping has never been quantitatively characterized.

Characterization of Landau Damping of MBI

- To characterize Landau damping, we should perform grow/damp measurements with and w/o HCs. Has anyone done this? Elettra has measured level of disappearance of MB sidebands.

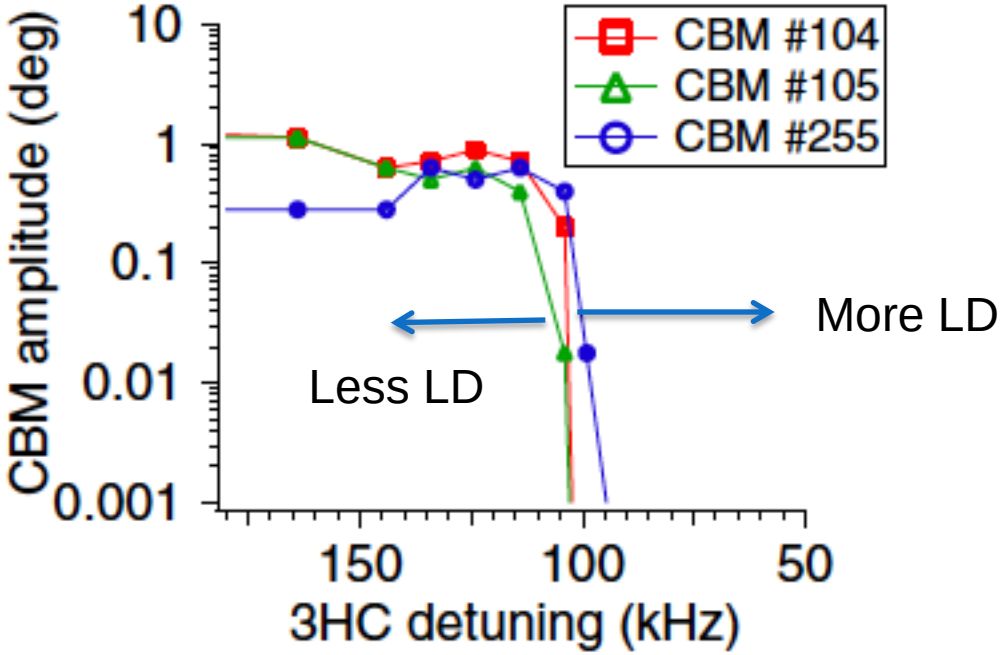


FIG. 2. (Color) CBMs amplitude versus 3HC tuning for a 80% filling of the ring; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

- Same effect seen at ALS. Other rings? To my knowledge the Landau damping has never been quantitatively characterized for HC.

Landau Damping Theory

- Much work done in 1980's. Example Krinsky and Wang, Particle Accelerators 17 (1985).

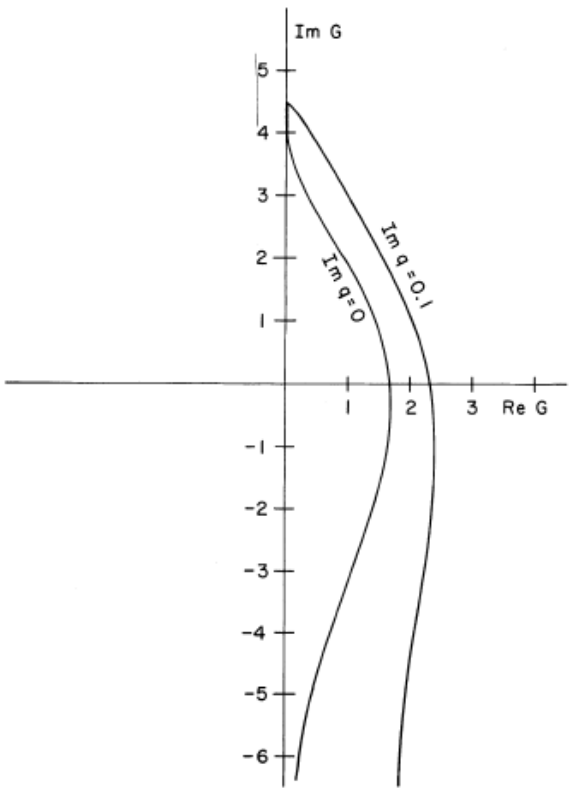


FIGURE 3 Stability boundaries.

$$|\delta\Omega_0| \leq 0.6\ \Delta\omega_s.$$

Landau damping rate is approximately half of (angular) frequency spread. This gives a naïve damping rate of <1 turn! Clearly not correct but actual rate is very fast.

Current study for ALS-II

- ALS-II is an initiative towards an ultralow (50 pm) upgrade of the ALS and incorporates several “new” features: on-axis injection, beam swap-out.
- ALS-II requires bunch lengthening to avoid emittance blowup from IBS.
- We are performing a study to characterize HC requirements and beam dynamics effects for ALS-II. We welcome collaborators in this process.

Summary

- Harmonic cavities are a useful tool for controlling bunch shapes in light sources.
- The reduction of longitudinal focusing makes the bunch shape very sensitive to variations in the harmonic cavity phase.
  - Hybrid modes will be tricky if harmonic cavities are required.
  - Scale of transient effects is proportional to R/Q of harmonic cavity.
- Harmonic cavities provide huge increase in longitudinal Landau damping. All rings see damping of LCBI in uniform fill patterns (negligible transient effects.)
- Outstanding questions:
  - Effect on single bunch instabilities?
  - Effect of Landau damping on HT instabilities?
  - Effect of overstretching (multiple longitudinal fixed points)?