U.S. DEPARTMENT OF ENERGY
Office of Science

BERKELEY LAB

ALS-U
ADVANCED LIGHT SOURCE

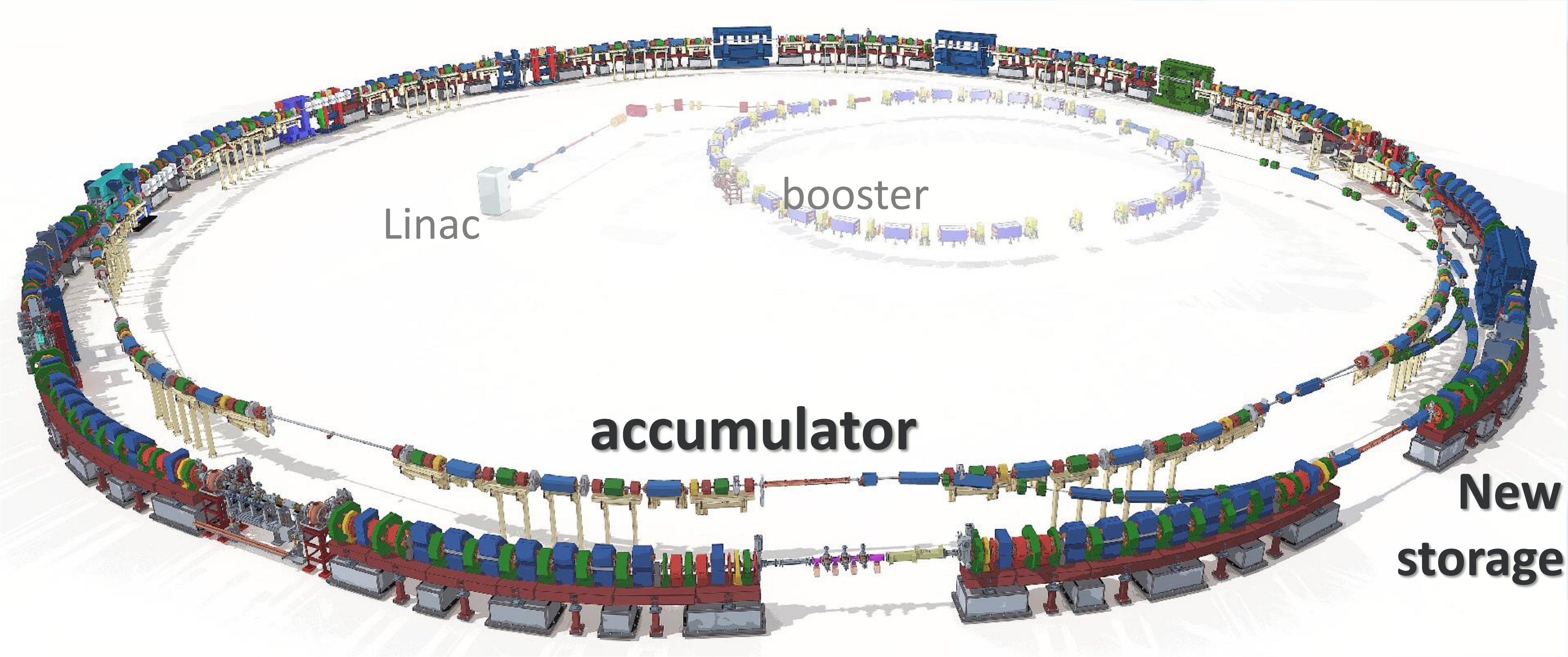
When Landau doesn’t damp

Passive higher-harmonic RF cavities with general settings and longitudinal multi-bunch instabilities in electron storage rings

Marco Venturini, LBNL

ICFA Workshop MCBI, Zermatt, September 23-27, 2019

The Advanced Light Source Upgrade is underway at LBNL

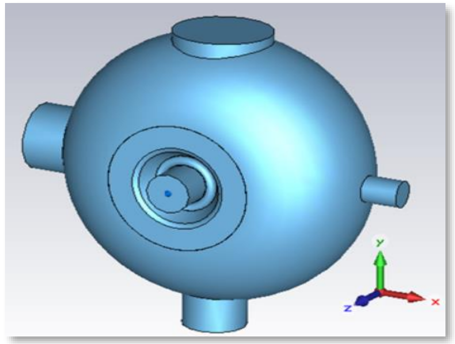


- Replace (**2nm** emittance) **Triple-Bend Achromat** lattice ring with a **100pm** **9BA** ring
- Goal: recycle existing RF system. Two 500MHz main + three 3rd-harmonic passive (normal conductive) cavities

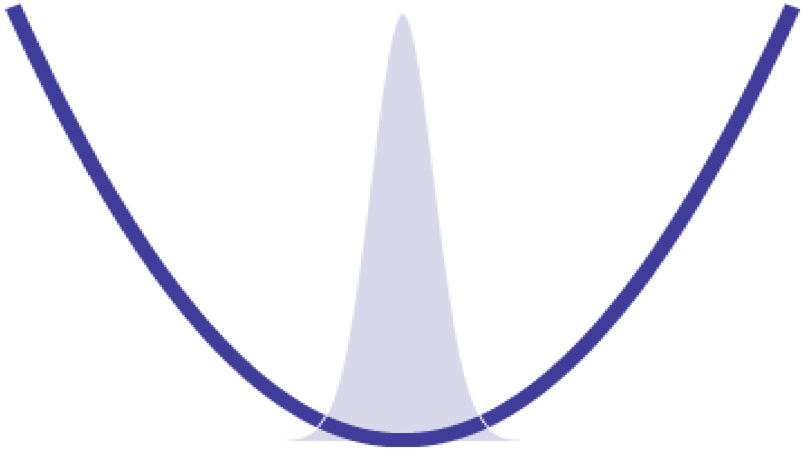
The $1M question:
can ALS-U re-use the existing ALS 3rd-harmonic cavs?

In light sources HCs are for bunch lengthening (better lifetime)

Main RF cavity only

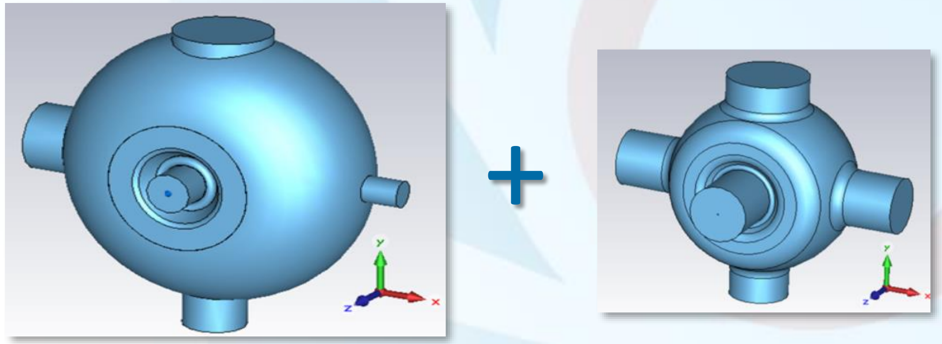


$U(z)$



Quadratic RF potential well

Main + 3rd Harmonic Cavity



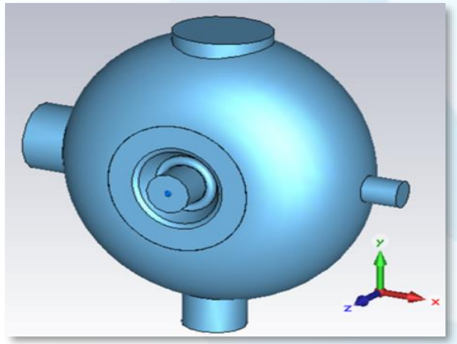
Non-quadratic RF potential well

Longer bunch

With “optimum” HC settings the bunch core is flat

- Vanishing derivatives of RF potential: U', U'', U'''
- $U \sim$ quartic ($\sim z^4$)

Main + 3rd Harmonic Cavity



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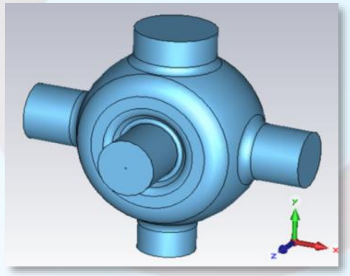


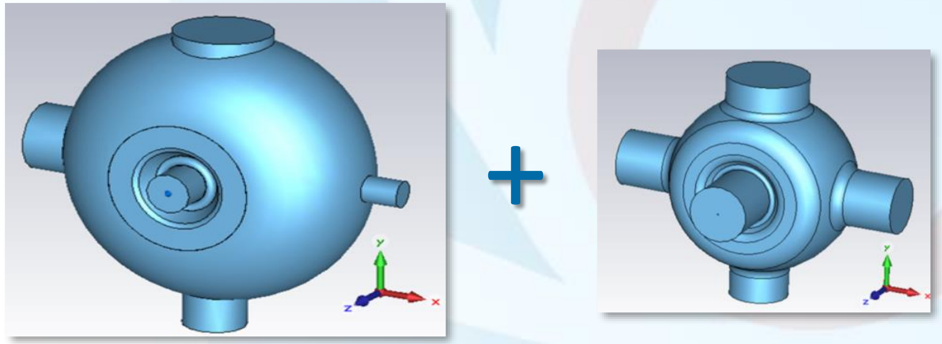
Quartic RF potential well

The beam-HC interaction is well described by a narrow-band resonator-model impedance

shunt impedance

$$Z(\omega) = \frac{R_s}{1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)} \equiv R_s \cos\psi_\omega e^{-i\psi_\omega},$$

Main + 3rd Harmonic Cavity



ψ **(detuning angle)** measures proximity of HC resonance to 3rd harmonic of RF

HHC resonance frequency

RF generator frequency (500 MHz)

$$\tan\psi \simeq 2Q\frac{\omega_r - 3\omega_{\mathrm{rf}}}{\omega_r}$$

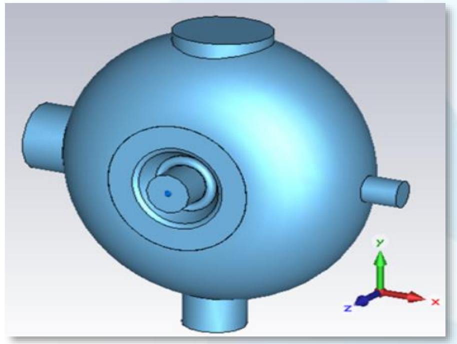
Quality factor Q~20,000 (NC)

Choosing R_s for optimum

Only if R_s has been chosen appropriately can the HCs be tuned to yield a flat beam (optimum setting)

- *optimum R_s depends on beam current, main cav.'s V*

Main + 3rd Harmonic Cavity



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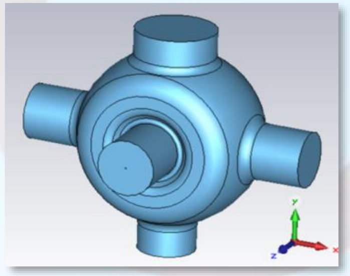
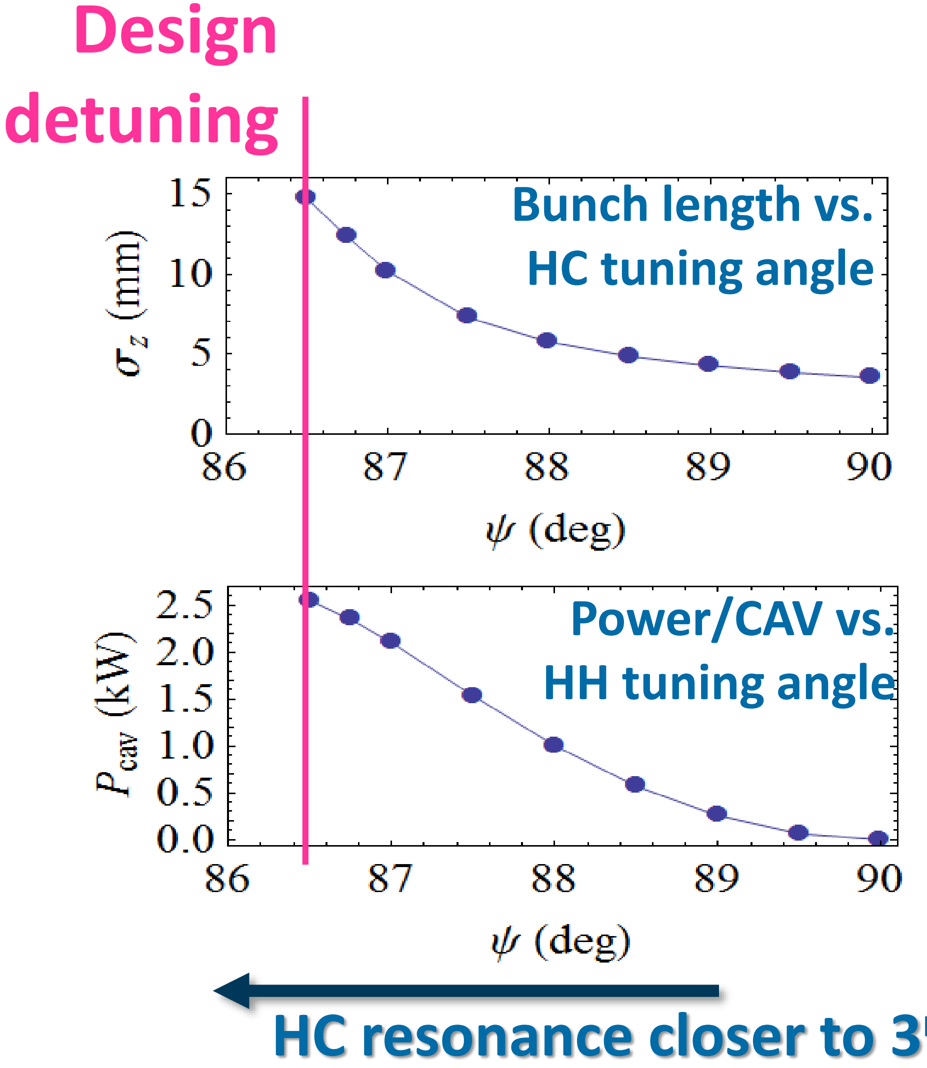
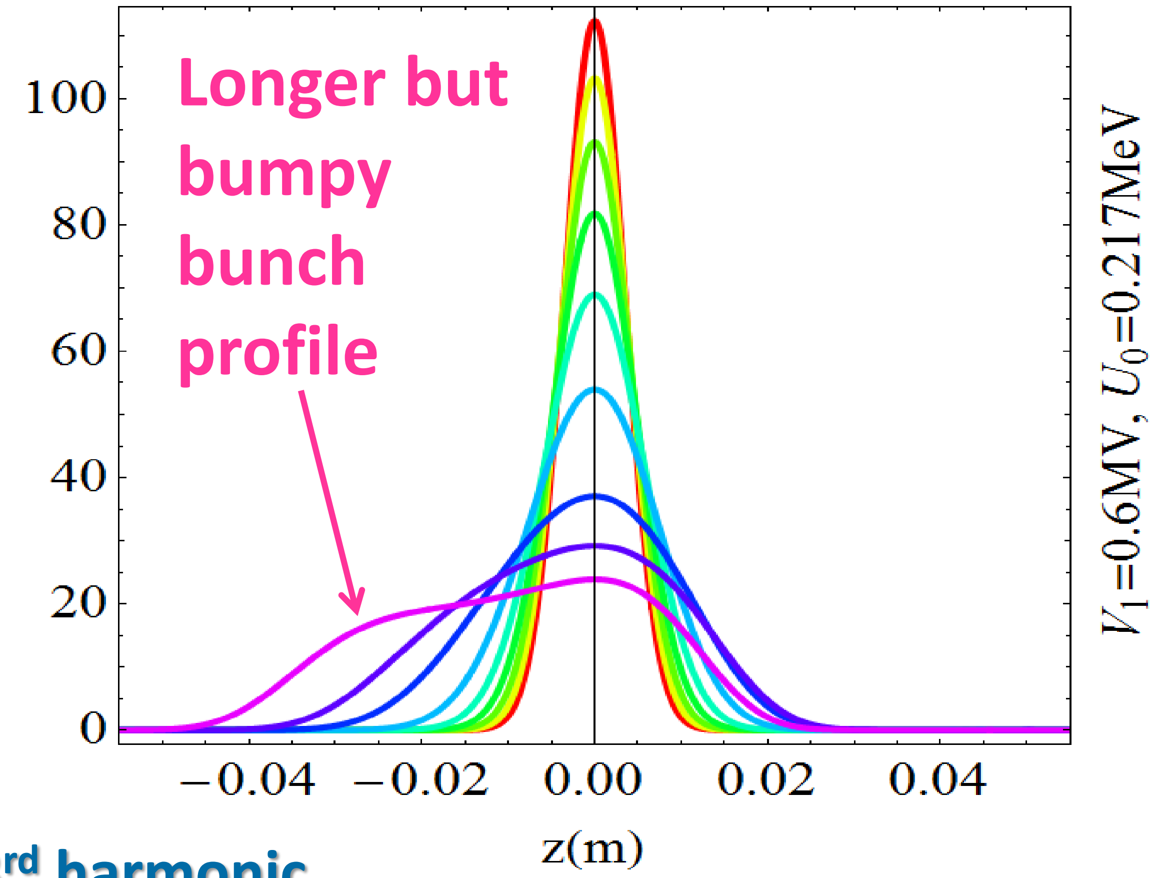


Quartic RF potential well

With non-optimum setting, HCs still lengthen the bunch, but the bunch profile will be bumpy. OK for lifetime.





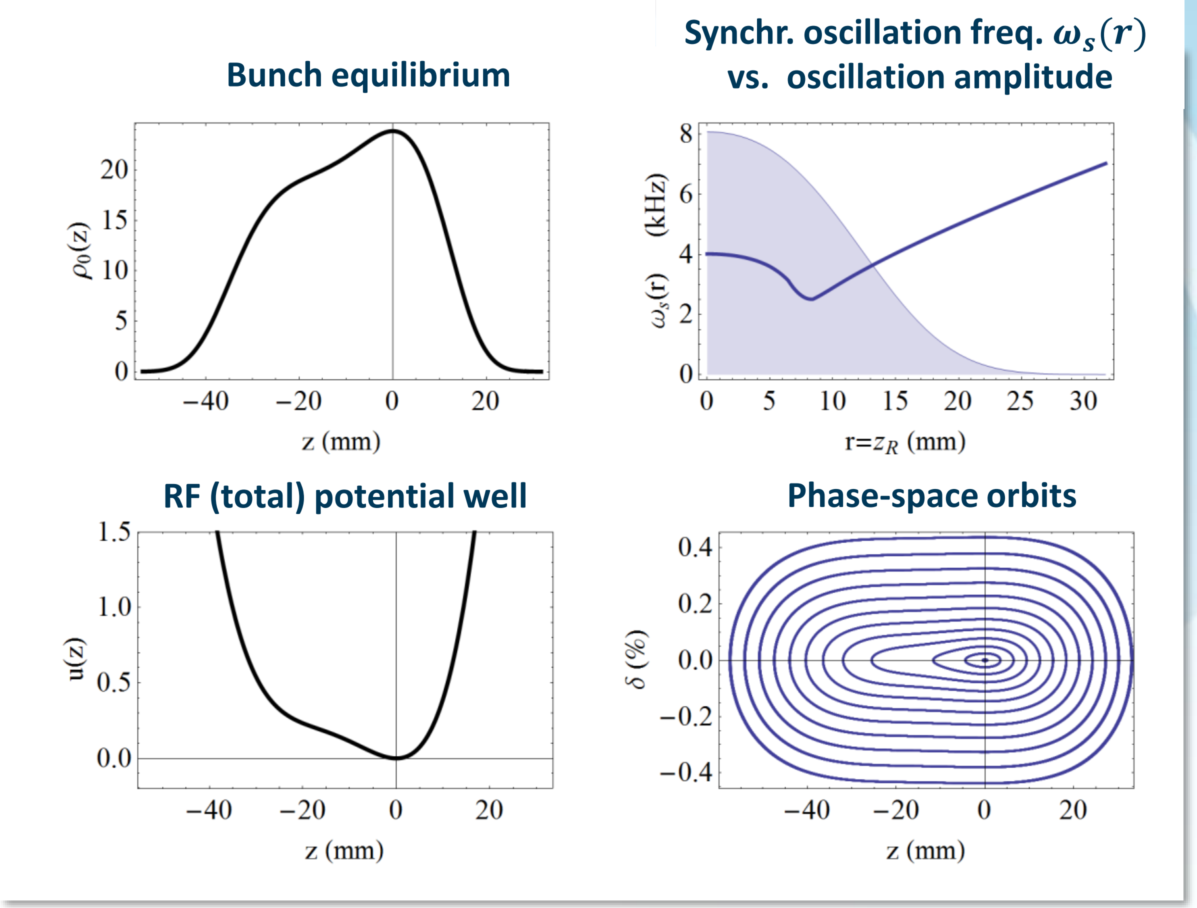
Two options on the table for reusing the ALS HCs

- Optimum ALS-U 3rd-HC shunt impedance: $\boldsymbol{R_s = 1.4\ M\Omega}$
- One ALS 3rd-HC: $\boldsymbol{R_s = 1.7\ M\Omega}$

- **Possible solutions:**
  1. **Use a single ALS HC**
     - shunt impedance fairly close to optimum ☺
     - power dissipated on single HC is too high ☹☹
  2. **Use two ALS HCs**
     - power problem solved ☺;
     - shunt impedance far from optimum. Bumpy profile OK but is it otherwise an issue? Instabilities? Robinson?

Stripped-down semi-analytical model to study multi-bunch instabilities

- **Uniform beam fill, nominal ALS/ALS-U average current (500mA)**
  - No transients, etc.
- **Main cavities as static objects (no beam-loading effects)**
  - Expect main cavity fundamental mode to counter Robinson instability from HC
- **Perturbation theory based on exact (numerical) single-particle motion in RF bucket**
  - Is it important to capture exact single-particle dynamics?
- **Compare**
  1. **Two ALS-like cavities**
  2. **Optimum cavities**



Aside: Longitudinal Coupled-Bunch Instability (CBI) modes (uniform beam fill with M bunches)

There are $\boldsymbol{M}$ CBI modes, characterized by integer $\ell = 0,1,2, \ldots, M-1$

CBI mode $\ell = 0$

(All bunches move in phase, Robinson instability)

Mode ℓ corresponds to $\frac{2\pi\ell}{M}$ bunch-to-bunch phase difference

Will be interested in $\ell = 0$ and $\ell = 1$

The truth is in the dispersion-relation (dipole approx.)

effective impedance:

$$\boldsymbol{\omega_{p,\ell} = ph\omega_0 + \ell\omega_0 = p\omega_1 + \ell\omega_0}$$

$$Z_{\text{eff}}(\Omega) = \sum_{p=\pm 3} \frac{\omega_{p,\ell}}{\omega_1} Z(\omega_{p,\ell} + \Omega)$$

This is ω_{rf}

CBI mode no.

Z is peaked at 3rd harmonic, only relevant terms are $p = \pm 3$

Z of HC fundamental mode

$$\boxed{1 + 4\pi i \frac{e I_{\text{avg}} c Z_{\text{eff}}(\Omega)}{9 E_0 T_0 \omega_1} \int_0^\infty dJ \frac{\partial \Psi_0(J)}{\partial J} \frac{|H_{1,3}(J)|^2 \omega_s(J)}{\Omega^2 - \omega_s(J)^2} = 0.}$$

$$H_{m,p}(J) = \frac{1}{2\pi} \int_0^{2\pi} e^{im\varphi + i\omega_p \zeta(J,\varphi)/c} d\varphi,$$

Single-particle synchr. oscillation frequency

Canonical transformation (unperturbed single-particle motion)

- Equation valid for $Im\, \Omega > 0$
- ℓ-dependence is through Z_{eff} and $H_{1,3}$

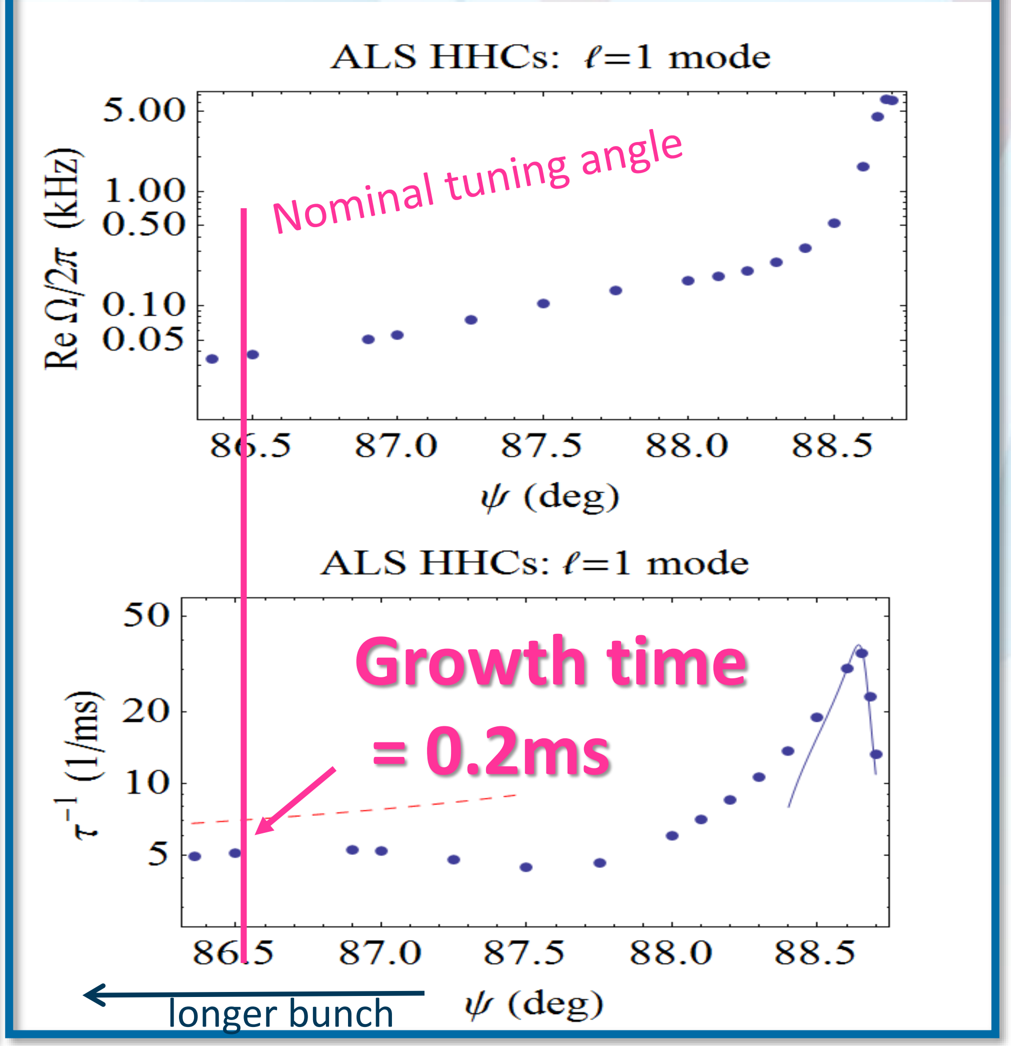
The main result: The CBI-mode $\ell = 1$ is a killer: the two ALS-HC solution won't work

$\ell = 0$ mode (Robinson)

$\ell = 1$ mode

Mode oscillation frequency

Mode growth rate



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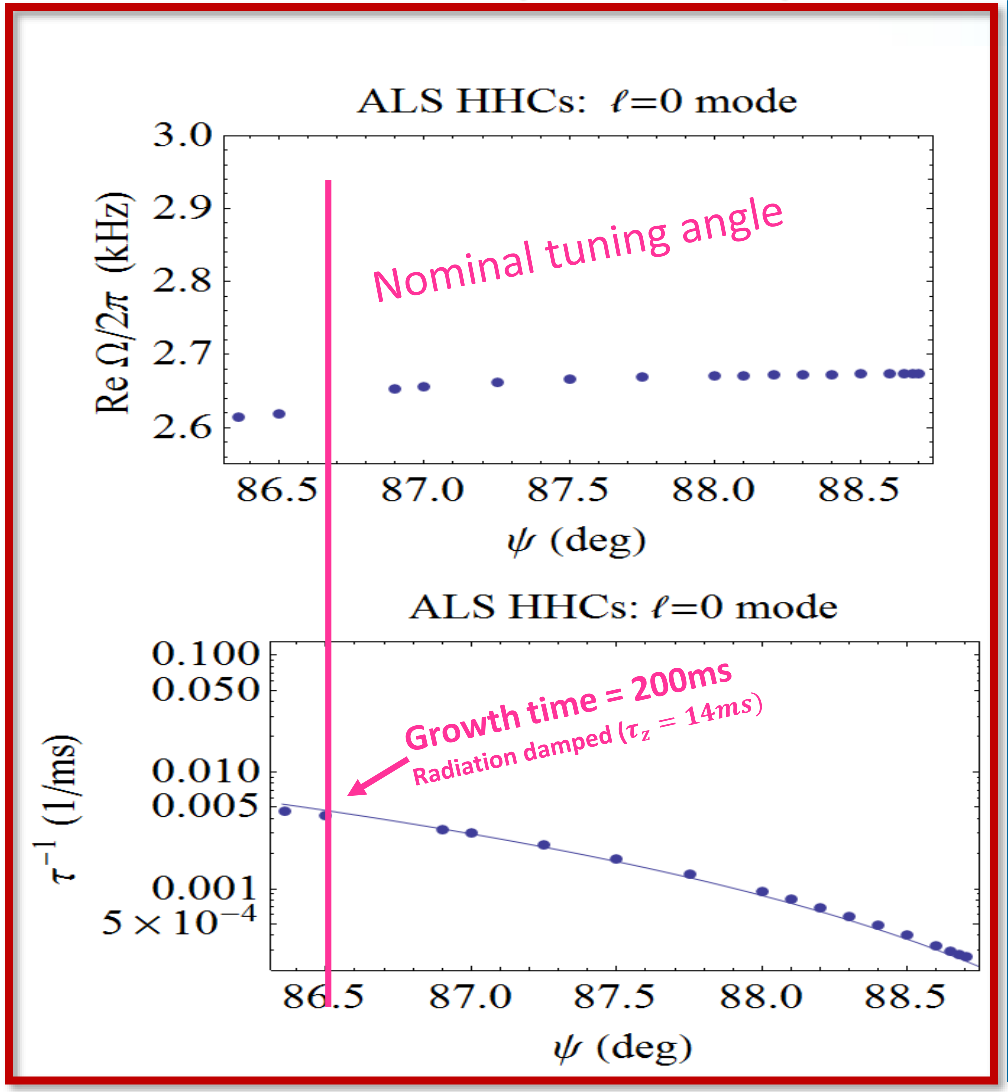
Main result: The CBI-mode $\ell = 1$ is a killer: the two ALS-HC solution won't work

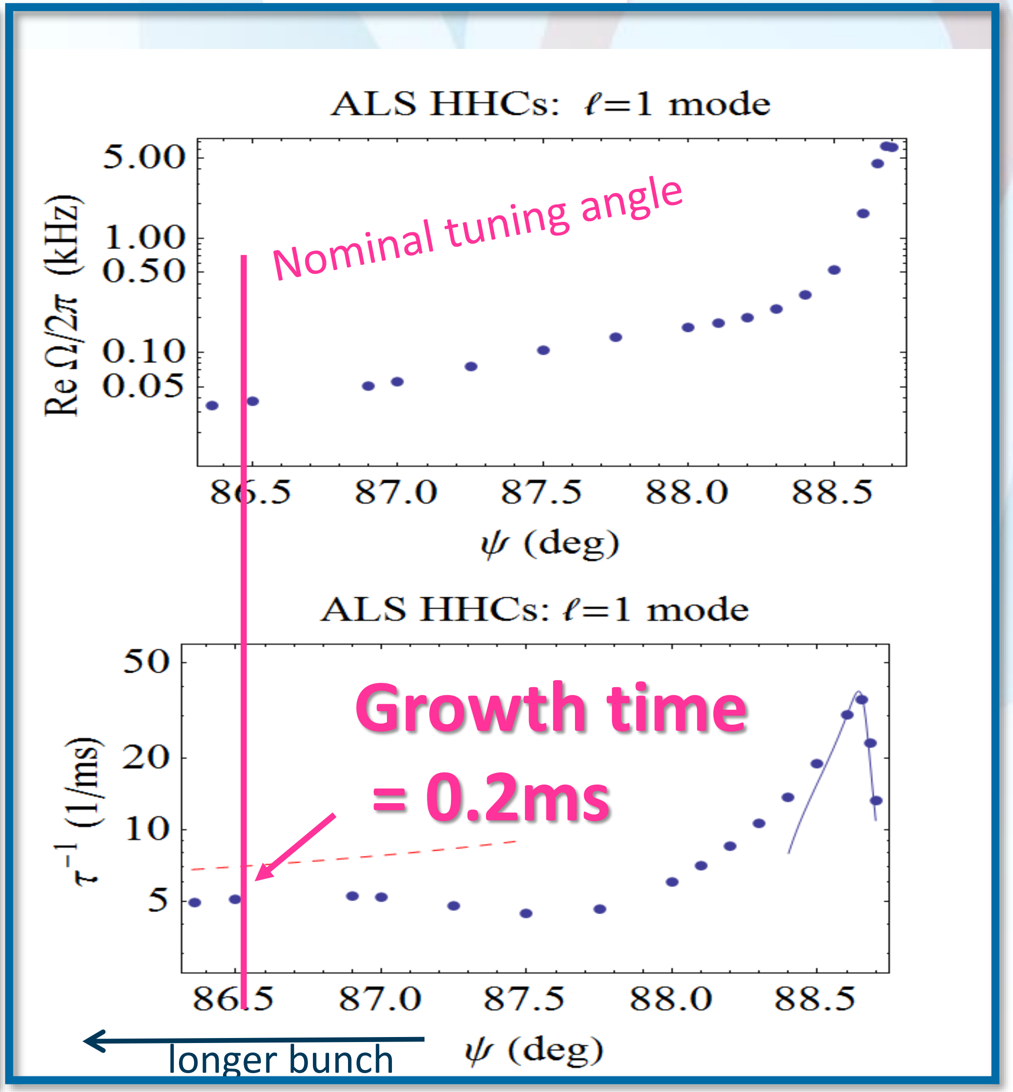
$\ell = 0$ mode (Robinson)

$\ell = 1$ mode

Mode oscillation frequency

Mode growth rate





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Lesson learned no. 1: there is no Landau damping of the Robinson instability associated with HCs

- For optimum HCs, it can be analytically demonstrated that the oscillation frequency of the Robinson mode is always a bit larger than the single-particle synchr. oscillation frequency
  - For ALS-U: $\Omega_r \equiv Re\,\Omega\,/2\pi \simeq 2.5\,kHz$ vs. $\langle\omega_s\rangle/2\pi \simeq 500Hz$

$$1 + 4\pi i \frac{eI_{\rm avg}cZ_{\rm eff}(\Omega)}{9E_0T_0\omega_1}\int_0^\infty dJ \frac{\partial\Psi_0(J)}{\partial J}\frac{|H_{1,3}(J)|^2\omega_s(J)}{\Omega^2-\omega_s(J)^2} = 0.$$

Ω can be pulled out from under the integral; Eq. simplifies

Growth rate: $\Omega_i \simeq \dfrac{3\hat{I}}{2\Omega_r} Re[\,Z(3\omega_{\rm rf}+\Omega_r) - Z(3\omega_{\rm rf}-\Omega_r)]$

Essentially independent of Ω_r since $\Omega_r \ll \omega_{rf}$

Much ado about nothing?

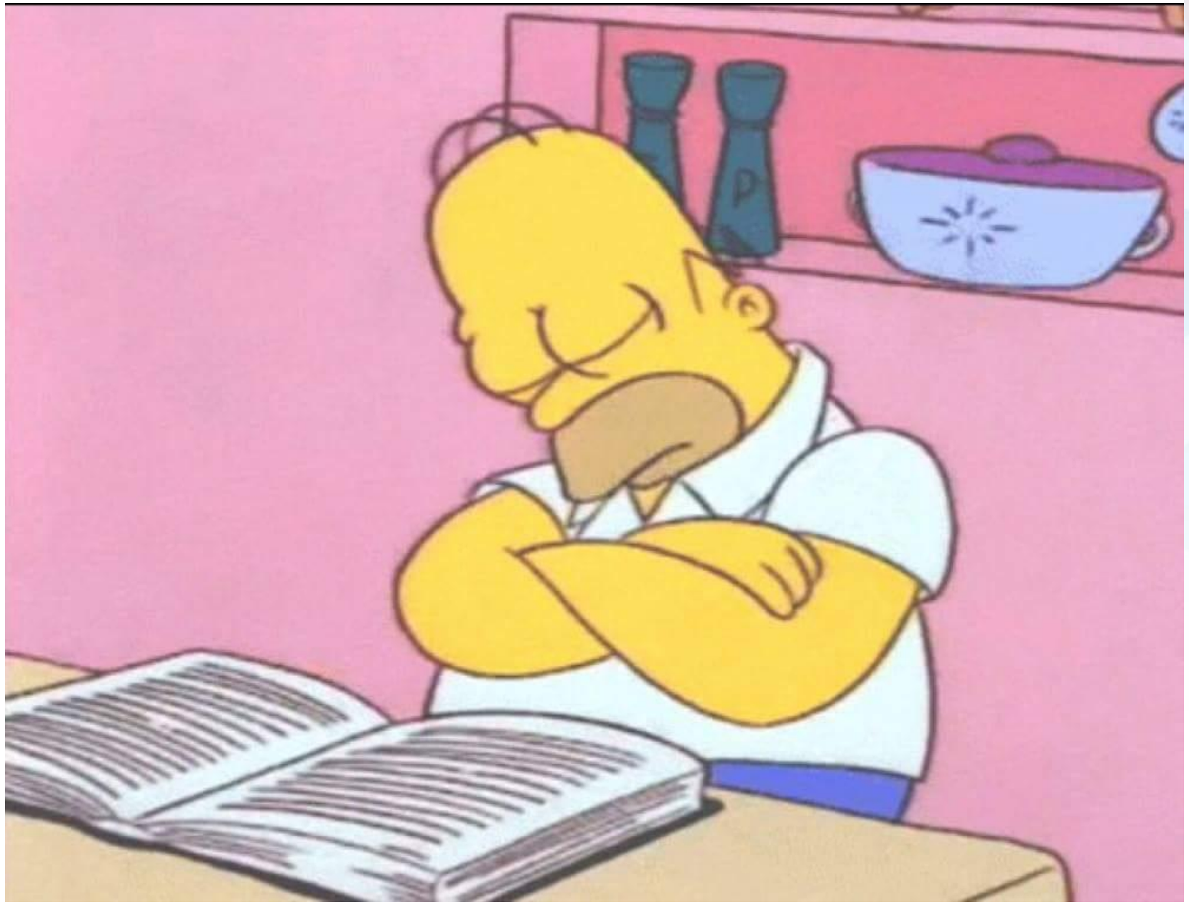
- Formally, same result as formula for case where particle-motion in RF bucket is linear (all particles have same synchrotron oscillation frequency)

- A popular "hand waving" derivation assumes "for simplicity" that one can simply ignore the effect of the HC on single-particle dynamics
  - Result is accurate within 10% (ALS-U)

- Problem is, occasionally a "hand waver" may feel that important physics is left out if HC nonlinearities are simply ignored (next slide)

Lesson learned no. 2: *"Quandoquidem bonus dormitat Homerus"*

(Sometimes even good ol' Homer falls asleep)



Lesson learned no. 2: *"Quandoquidem bonus dormitat Homerus"*

(Sometimes even good ol' Homer falls asleep)

$$\frac{1}{\tau} = \mathcal{I}m\,\Omega \approx \frac{\eta e I_0 \omega_{\rm rf}}{2E_0 T_0 \bar{\omega}_s}\Big\{\Big[\mathcal{R}e\,Z_0^{\parallel}(\omega_{\rm rf}+\bar{\omega}_s) - \mathcal{R}e\,Z_0^{\parallel}(\omega_{\rm rf}-\bar{\omega}_s)\Big] + m\Big[\mathcal{R}e\,Z_0^{\parallel}(m\omega_{\rm rf}+\bar{\omega}_s) - \mathcal{R}e\,Z_0^{\parallel}(m\omega_{\rm rf}-\bar{\omega}_s)\Big]\Big\}, \quad (8.110)$$

$(\ell = 0)$

Main Cavs

Harmonic Cavs

very large. As a result, Eq. (8.110) can only be viewed as an estimate.

Now let us estimate how large a Landau damping we obtain from the passive Landau cavity coming from the spread of the synchrotron frequency. The stability criterion is roughly

$$\boxed{\frac{1}{\tau} \lesssim 4\sigma_{\omega_s},} \quad (8.116)$$

where th[illegible]nchrotron angular frequency spread is given by E[illegible]09), and we have taken appro[illegible]ely $4\sigma_{\omega_s} = 29.4$ kHz as the total [illegible]ead. In other words, the higher-harmonic cavit[illegible] to damp an in[illegible]ity that has a growth time longer than 0.034 ms, an improveme[illegible]ut 160 folds better than when the higher-harmonic cavity is absent[illegible]us, theo[illegible]lly, this Landau damping is large enough to alleviate [illegible]obinson's antidamping o[illegible]er-harmonic cavity as well. We can [illegible] rewrite the growth rate of Eq. (8.115) [illegible]s of the

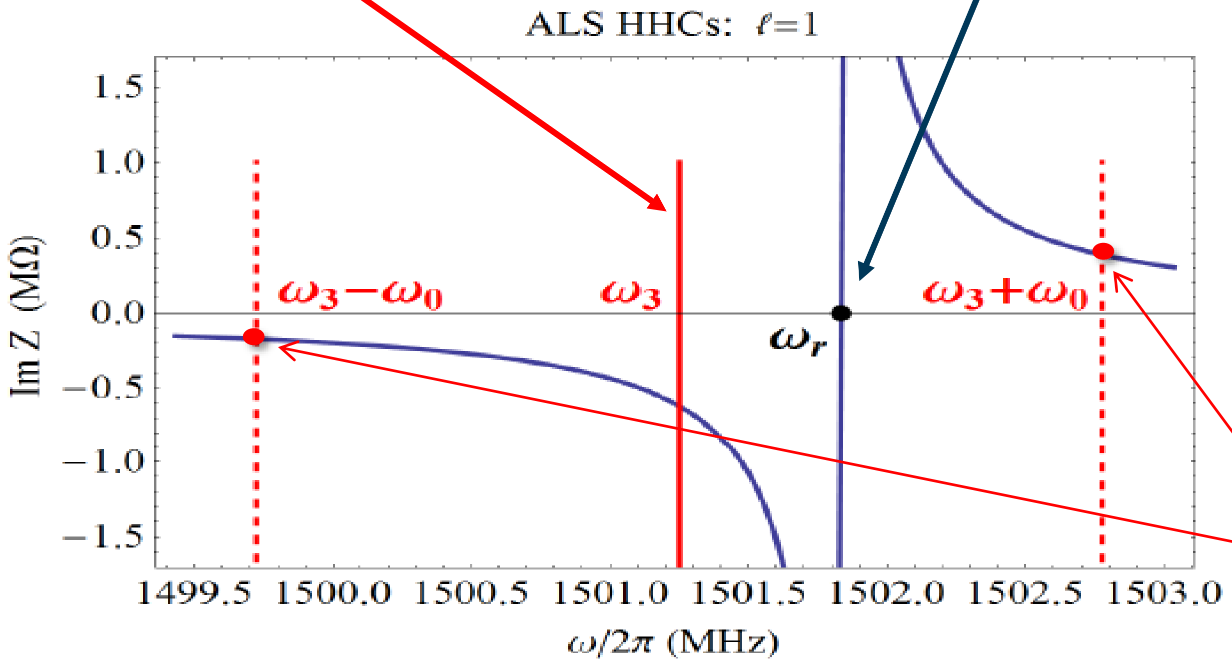
Lesson learned no. 3: the CBI mode $\ell = 1$ instability is associated with $Im\mathbf{Z}$ rather than $Re\mathbf{Z}$

$$\Omega_i \simeq \sqrt{3\hat{I}\, Im[\, Z(3\omega_{\mathrm{rf}} + \omega_0) + Z(3\omega_{\mathrm{rf}} - \omega_0)\,]}$$

- Relevant frequencies are the satellite beam harmonics at $\omega_3 \pm \omega_0$
- Formula valid if growth rate is large

3rd harmonic of RF

HC resonance frequency



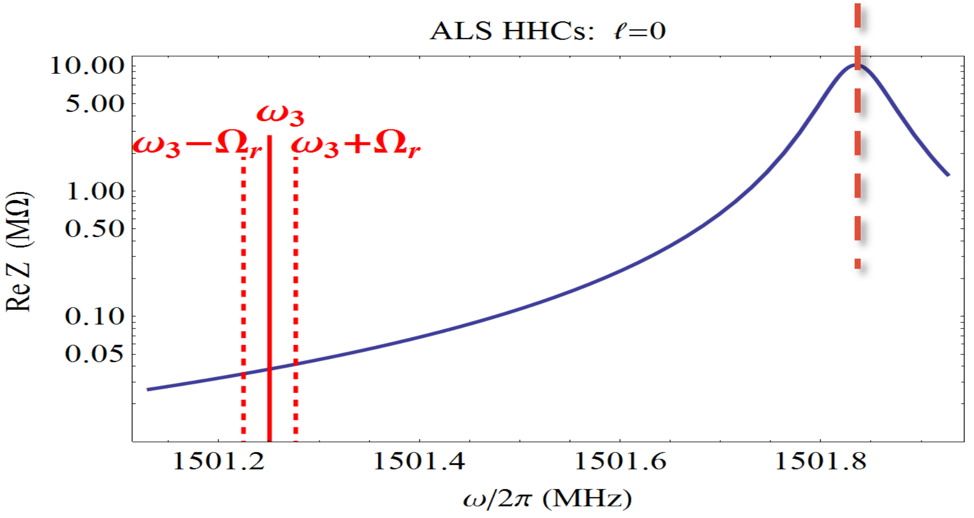
Growth rate proportional to √ of algebraic sum of Im Z at two harmonics: sum>0 ➔ instability

Optimal HCs are $\ell = 1$ stable (R_s is smaller; HCs have to be detuned less)

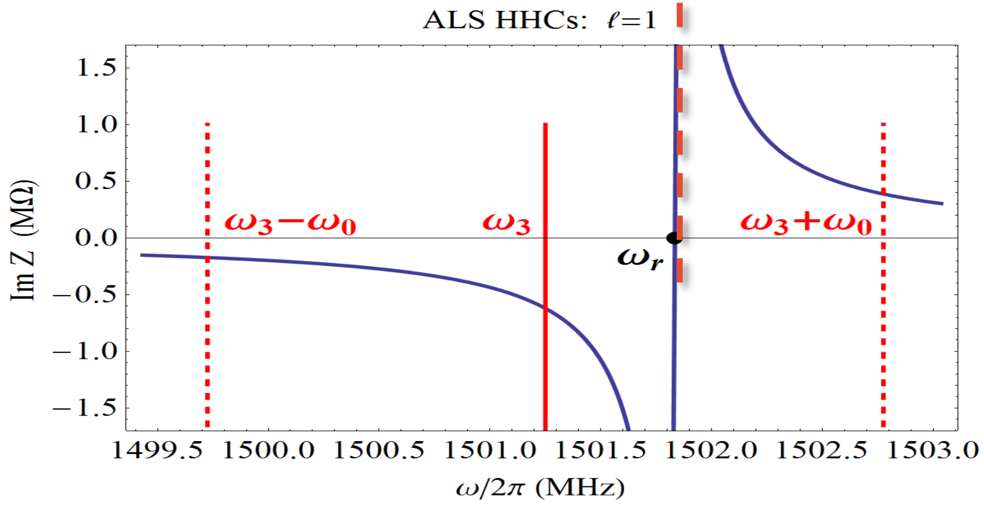
Optimal 3^{rd}HCs

Two ALS 3^{rd} HCs

$\ell = 0$ (Robinson)



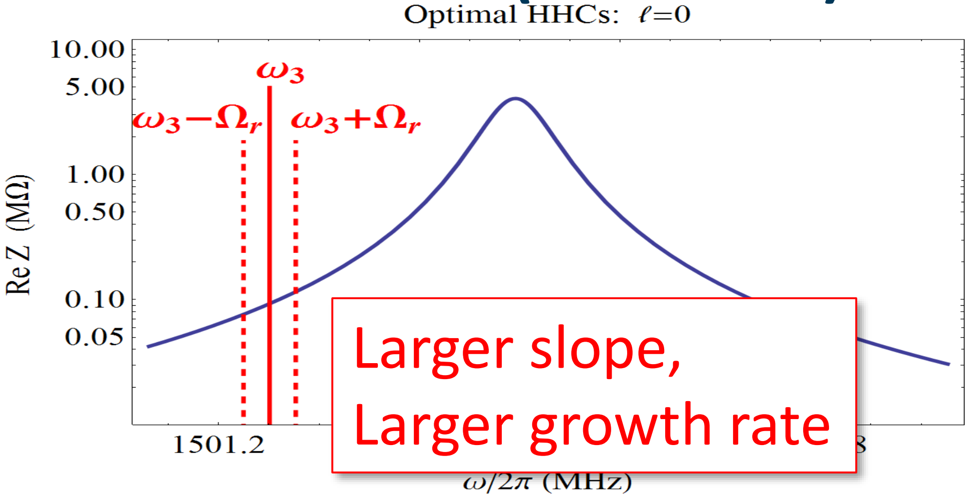
$\ell = 1$



Optimal HCs are $\ell = 1$ stable (mostly) because they have to be detuned less, having smaller R_s

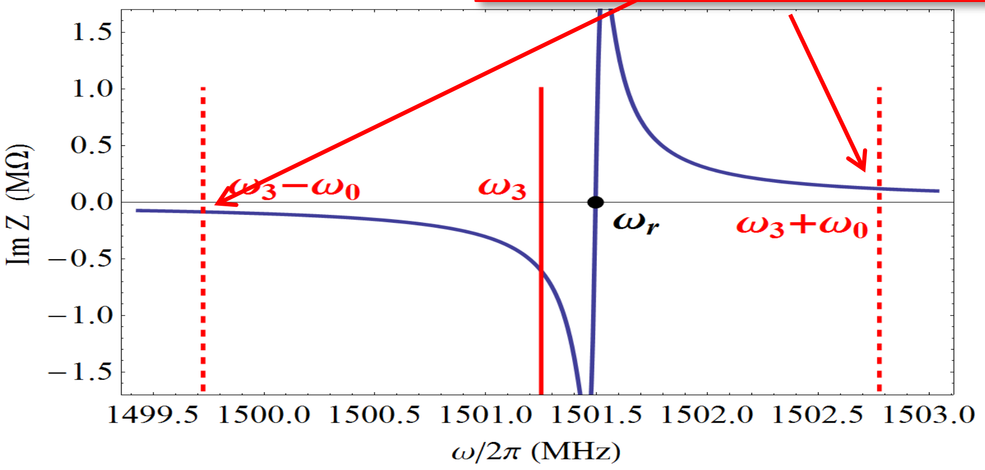
$\ell = 0$ (Robinson)

Optimal 3^{rd}HCs

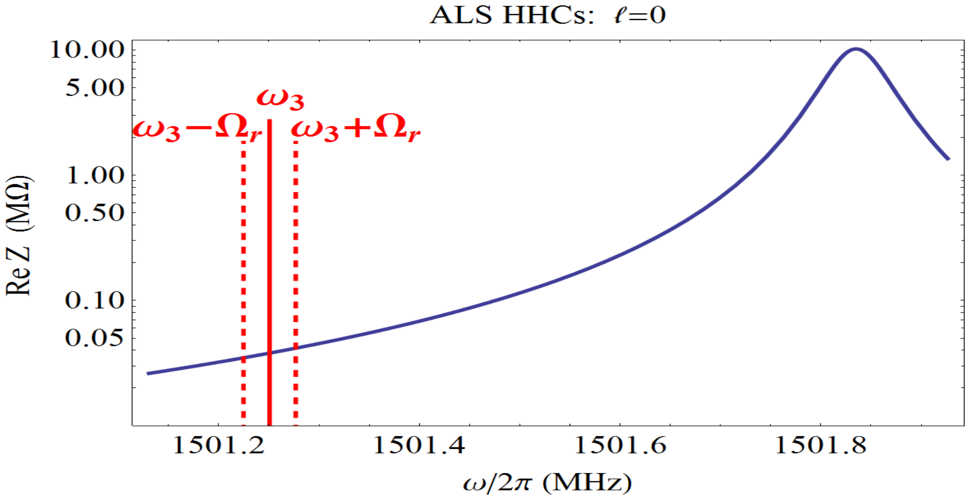


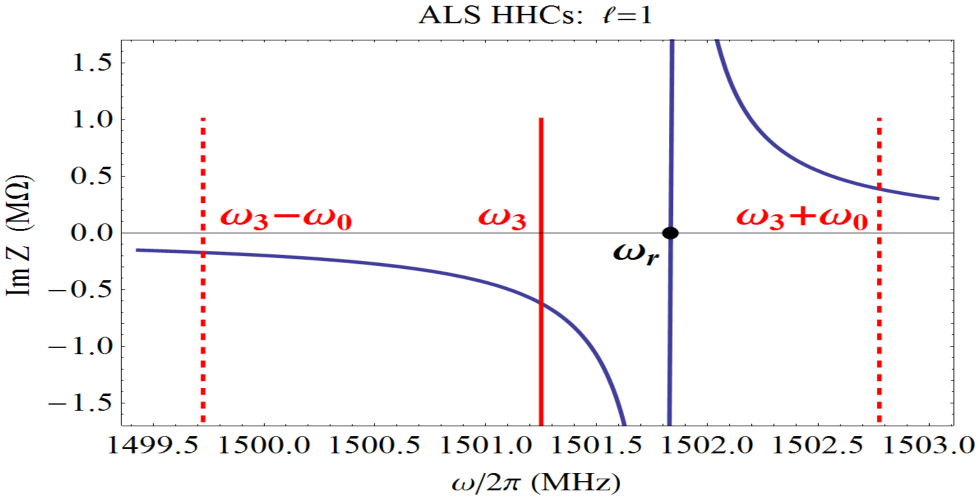
Larger slope,
Larger growth rate

smaller growth rate



Two ALS 3^{rd} HCs



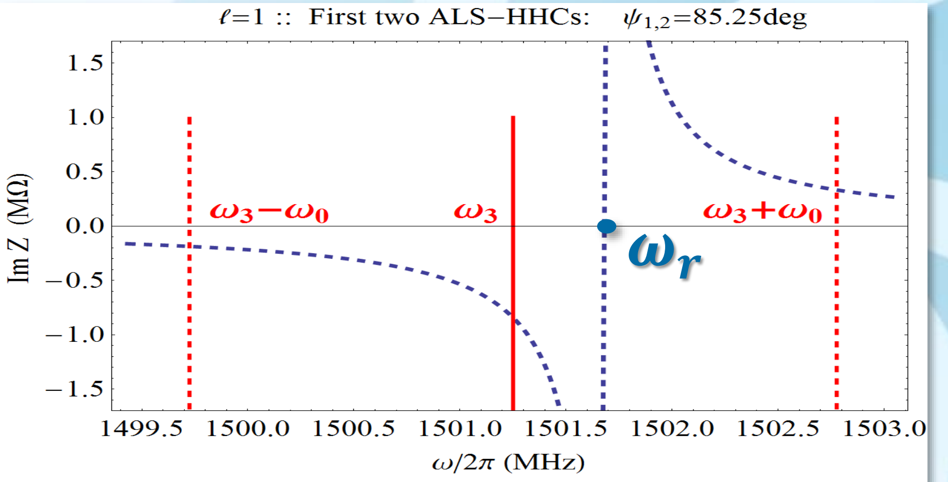


Lesson learned no. 4: Using the third ALS HC in bunch shortening mode would stabilize the system

Two HCs with

$\omega_r > 3\omega_{\mathrm{rf}}$

(bunch lengthening)

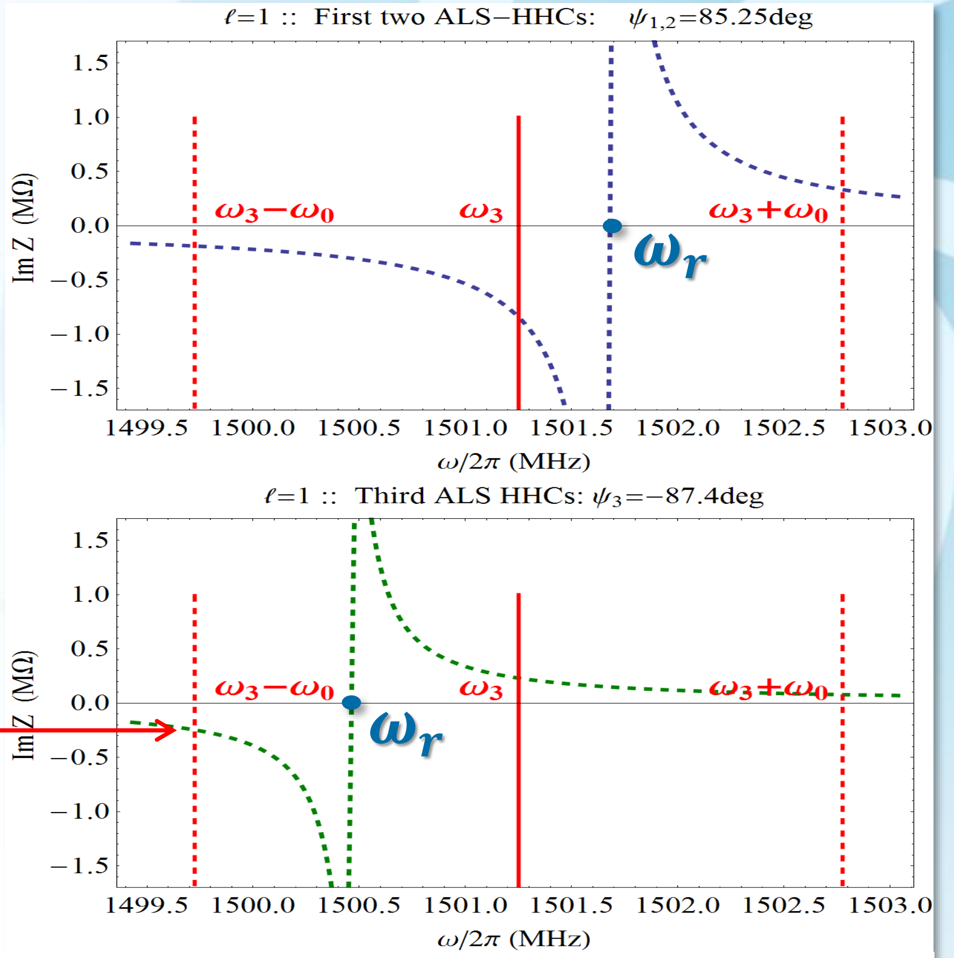


Lesson learned no. 4: Using the third ALS HC in bunch shortening mode would stabilize the system

Two HCs with
$\omega_r > 3\omega_{rf}$
(bunch lengthening)

This large negative Im Z contribution is stabilizing

One HC with
$\omega_r < 3\omega_{rf}$
(bunch shortening)



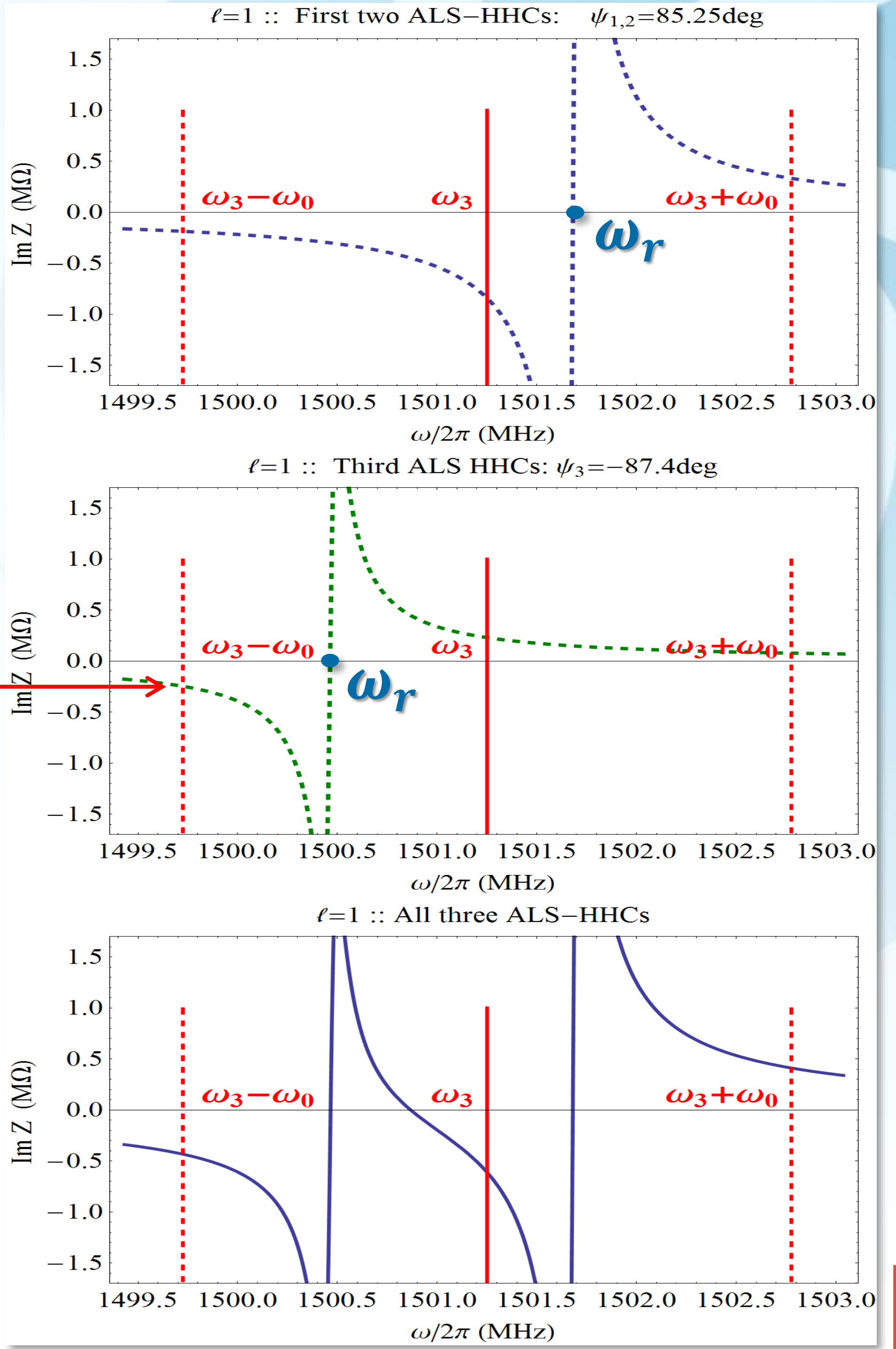
Lesson learned no. 4: Using the third ALS HC in bunch shortening mode would stabilize the system

Two HCs with
$\omega_r > 3\omega_{rf}$
(bunch lengthening)

This large negative Im Z contribution is stabilizing

One HC with
$\omega_r < 3\omega_{rf}$
(bunch shortening)

One + two HCs:
overall bunch shortening & stability



Lesson learned no. 5: In accelerator design, as in life, money is not everything …

Project has opted for brand new 3rd HCs

Conclusions

- **Studied perturbation-theory to multi-bunch instabilities driven by the fundamental mode of HHC**
  - Based on exact, numerical single-particle motion in RF bucket
  - Theory predict strong CBI $\ell = 1$ mode instability

- **Instability confirmed by independent macroparticle simulations**
  - Courtesy of G. Bassi (BNL)
  - Growth-rate estimate ~20% larger than theory's

- **For the details see** https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.21.114404

- **Landau does not damp Robinson !**

Bonus finding: simple formula for beam power dissipated to HC (optimum settings)

No explicit dependence (!) on shunt impedance, detuning angle, etc.

$$\boxed{P_{\mathrm{cav}} = \frac{F}{8} P_{\mathrm{rad}} \simeq 10\% \times P_{\mathrm{rad}}}$$

3rd HCs

Form factor: $F \simeq 1 - (3\omega_{\mathrm{rf}}\sigma_t)^2/2 \simeq 0.9$