Harmonic RF System Technology for Electron Storage Rings

Lawrence Berkeley National Laboratory

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- ALS Physics Group

Motivation for Harmonic RF

- Old: emittance is small enough that beam density gives lifetime dominated by large-angle intrabeam (Touschek) scattering. Most low-energy 3GLS have implemented or considered 3HCs.

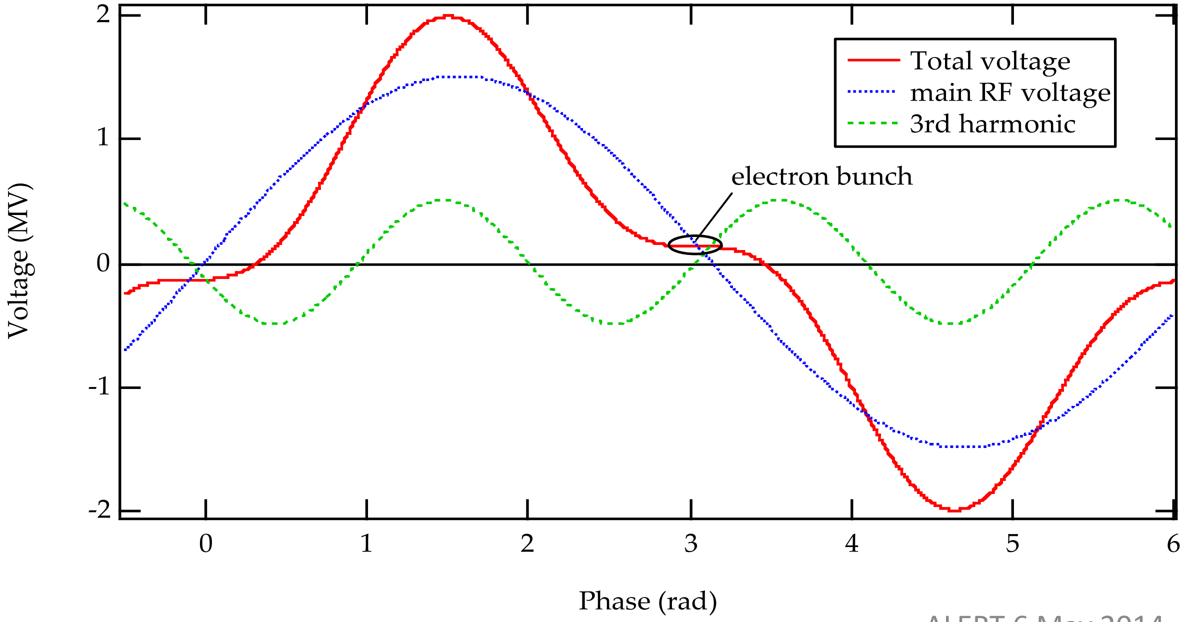
- New: Modern lattice designs reduce horizontal emittance by ~2 orders of magnitude, bunch charge densities are high enough that the equilibrium 3-d emittance increases from small-angle intrabeam scattering.

- 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.

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



Focusing is cancelled at the bunch center

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

$$\sin(n\phi_{h,\mathrm{opt}}) = \frac{-U_0}{V_{h,\mathrm{opt}}(n^2-1)}.$$

For large overvoltage, k_{opt}~1/n and optimum phase is close to 90 deg.

Harmonic RF systems (cont.)

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

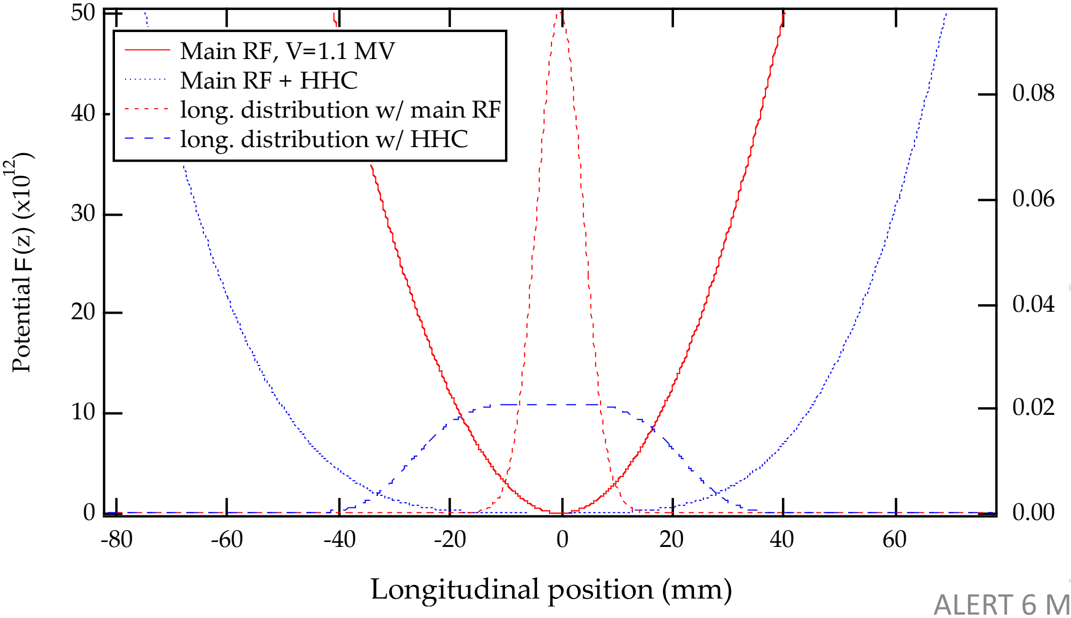
In the bunch lengthening case, the single particle motion is highly nonlinear and a large tune spread is introduced.

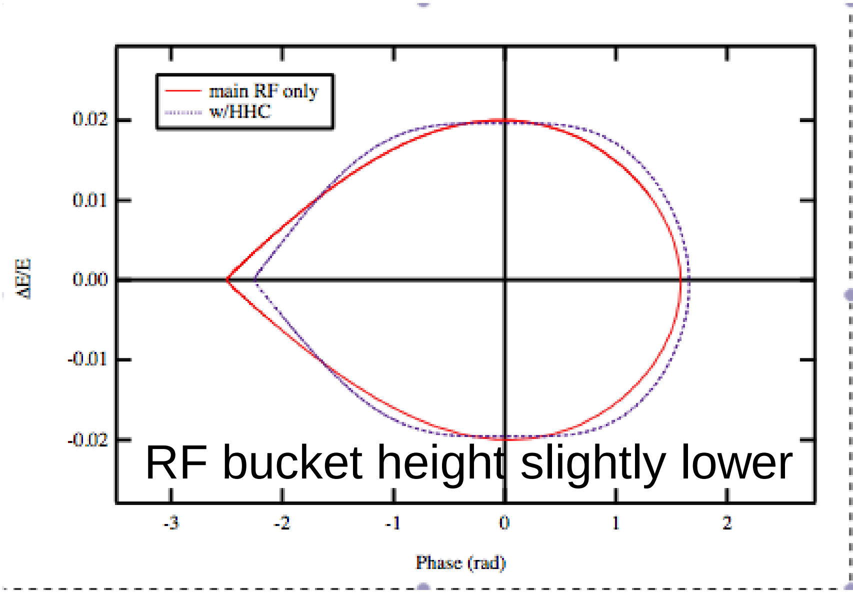
$$\rho(z) = \bar{\rho}\, e^{-\frac{\Phi(z)}{\alpha^2 \sigma_e^2}}$$

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

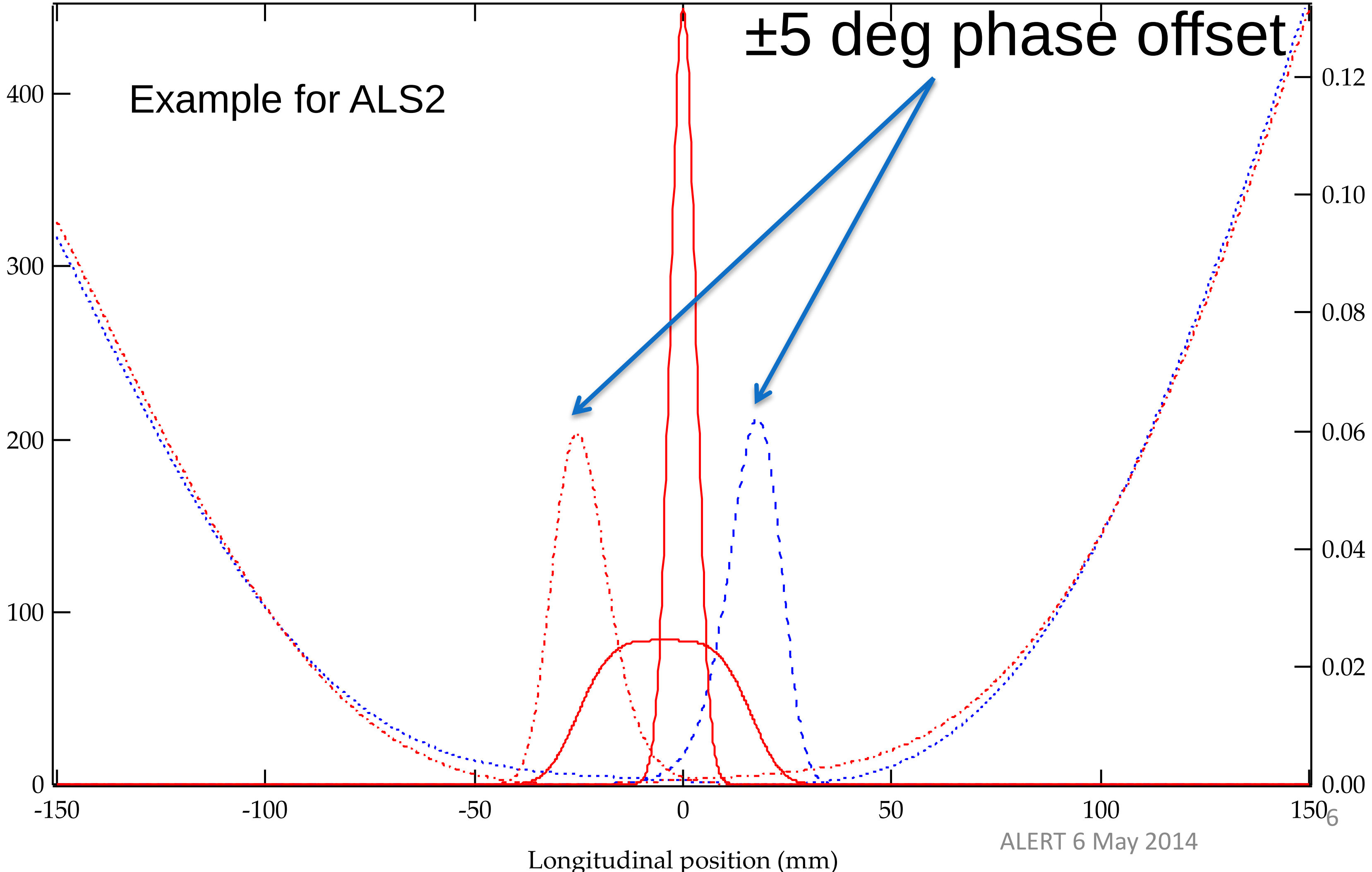




RF bucket height slightly lower

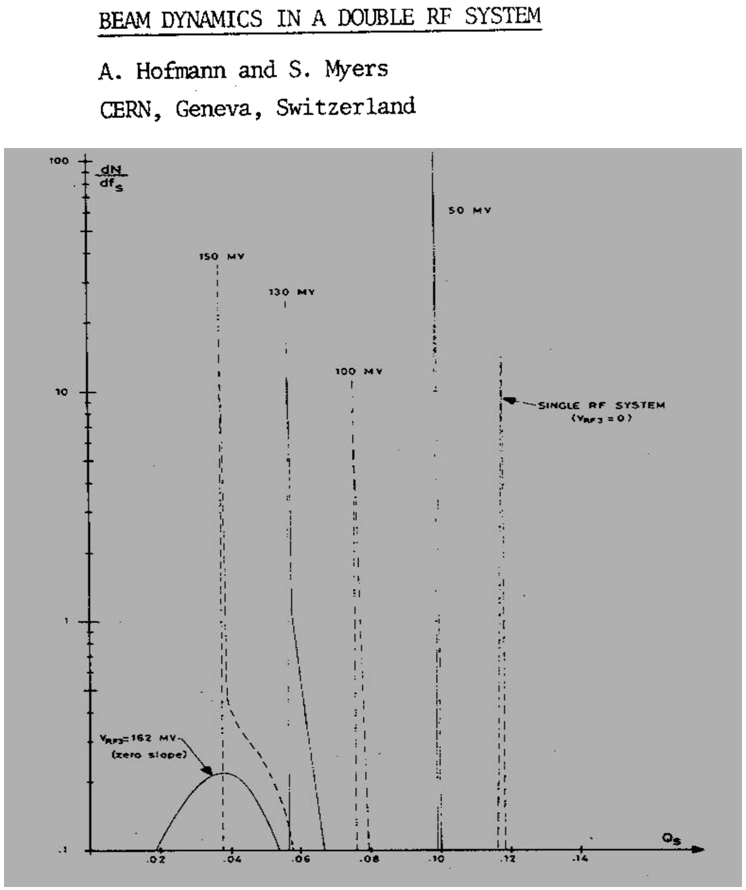
Harmonic RF systems (cont.)

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



Harmonic RF systems (cont.)

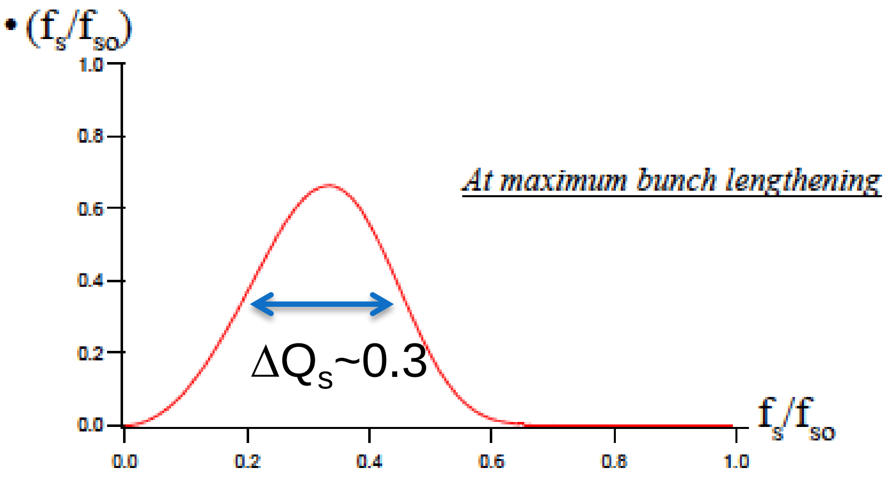
- Flattening of potential well induces large synchrotron frequency spread, providing large Landau damping.



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.

Landau Damping Theory

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

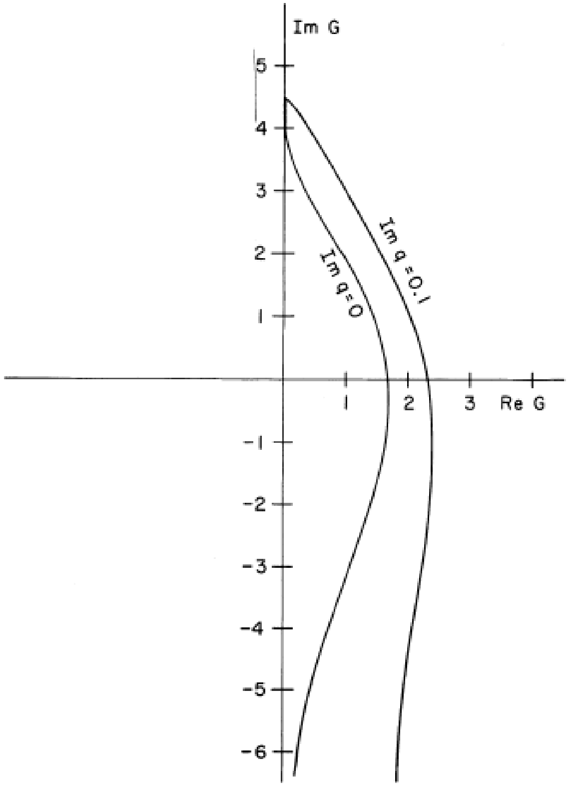


FIGURE 3 Stability boundaries.

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

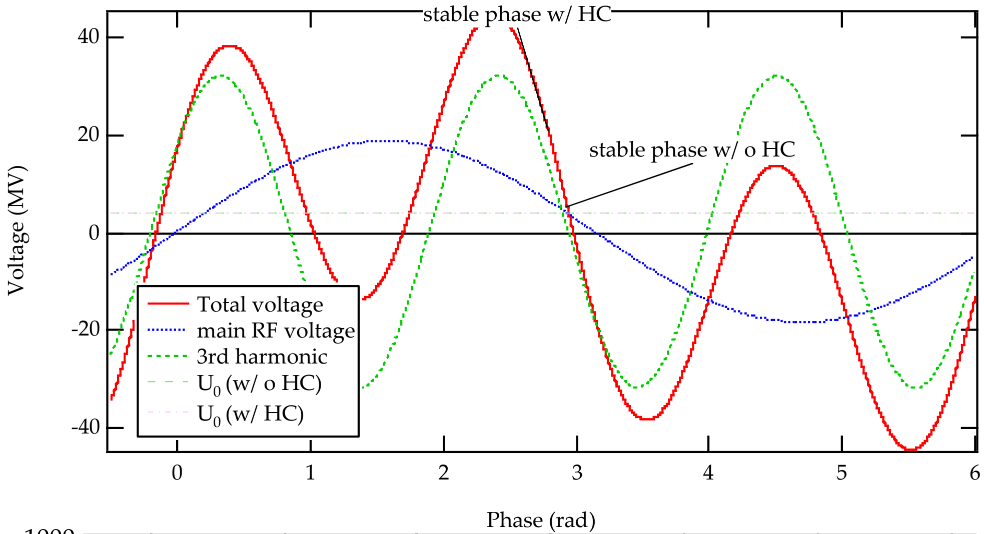
Landau damping rate is approximately half of (angular) frequency spread.

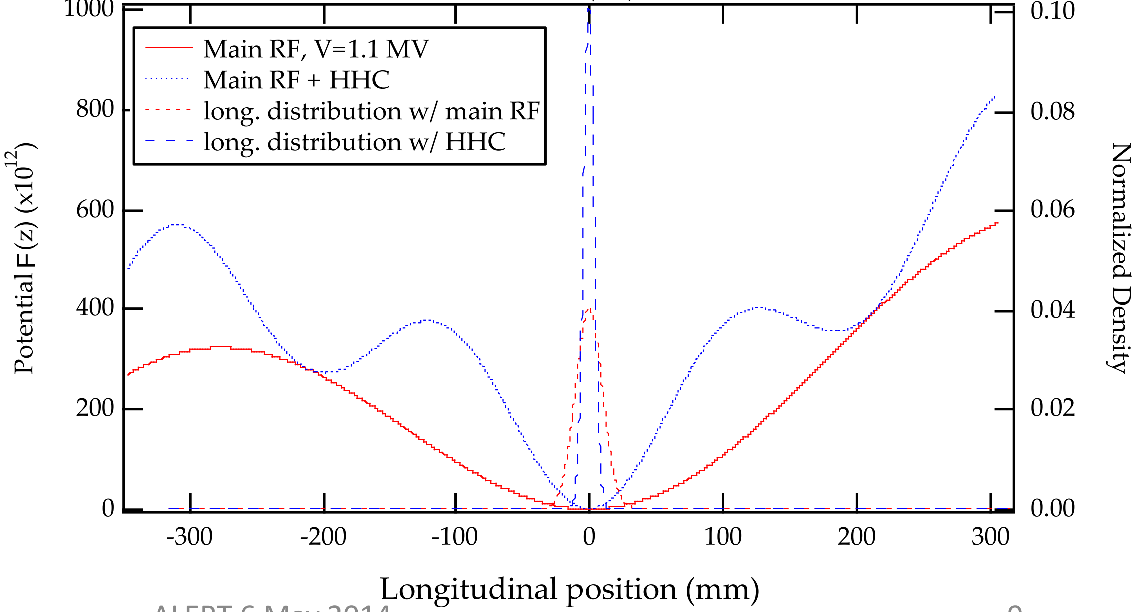
Bunch shortening using HCs

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.

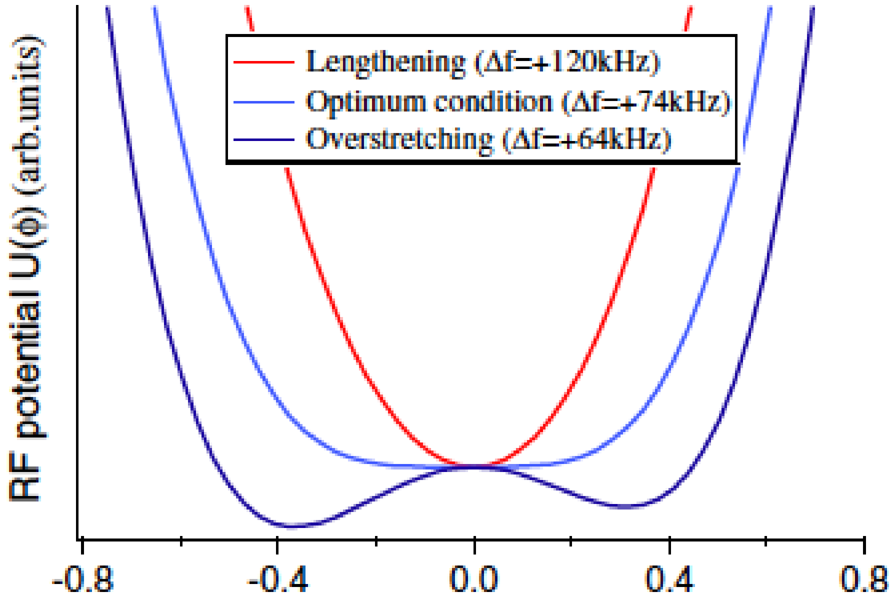
Very economical method for reaching short bunches. Increased focusing gives higher SB and MB instability threshold.

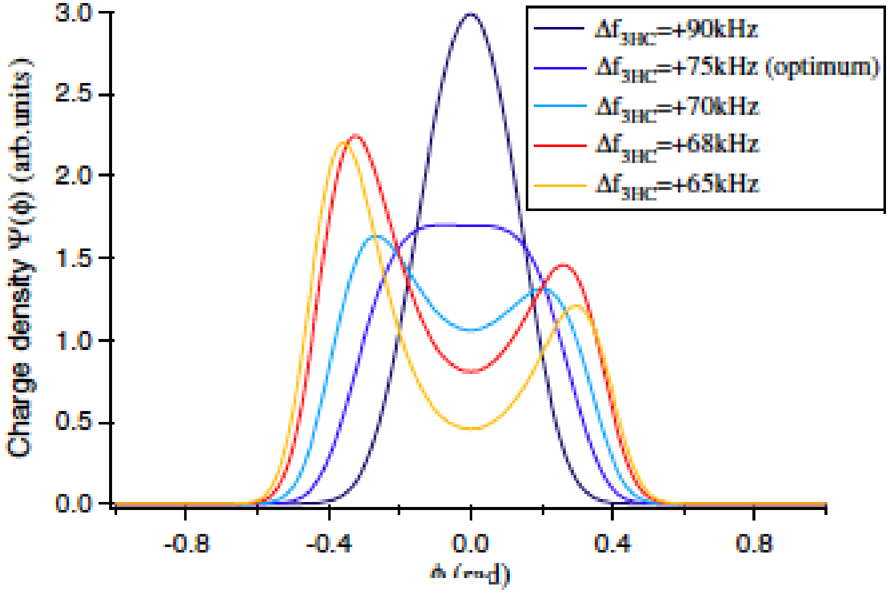




Overstretching

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





Penco and Svandrlik PRSTAB 9, 044401 (2006)

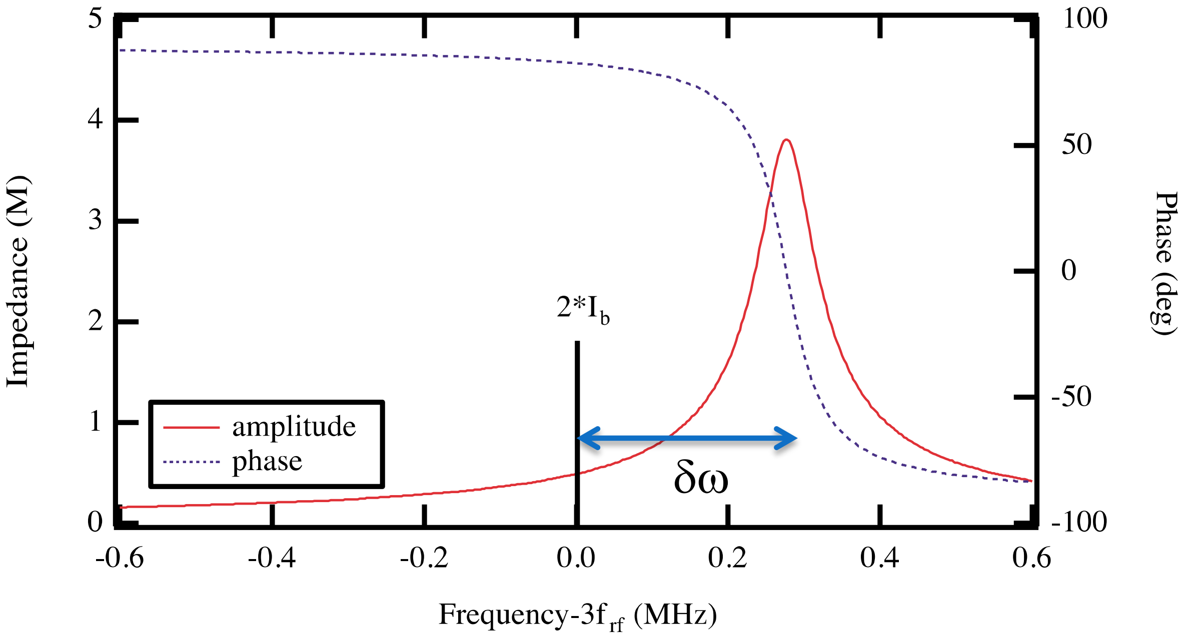
FIG. 14. (Color) Potential well distortion in lengthening mode, at optimum condition (flattened) and in overstretching regime, calculated for $I_{\text{beam}} = 315$ mA by using formula (5).

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? Better 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

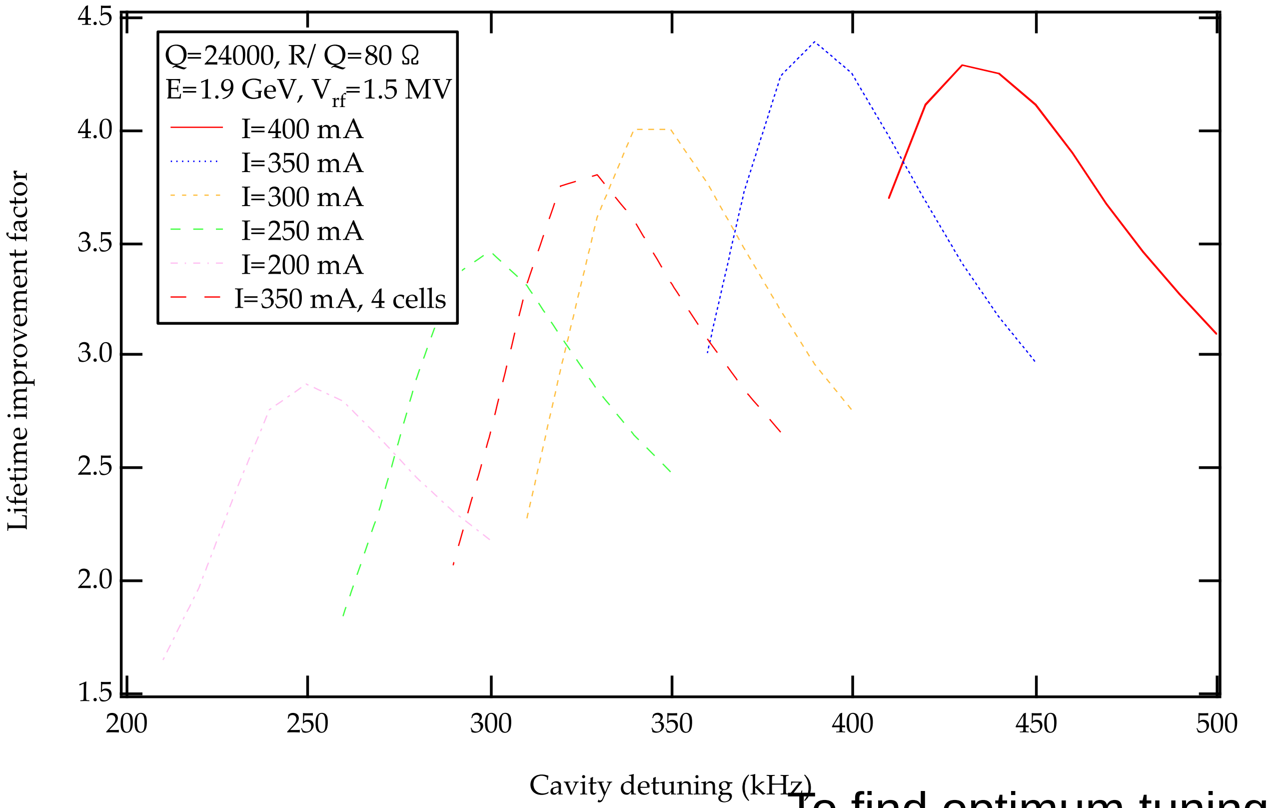
$$k_{\rm opt} = \frac{V_{h,\rm opt}}{V_{\rm rf}} = \sqrt{\frac{1}{n^2} - \frac{(U_0/V_{\rm rf})^2}{n^2-1}},$$ ~1/n

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

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

Passive Cavity with Variable Current

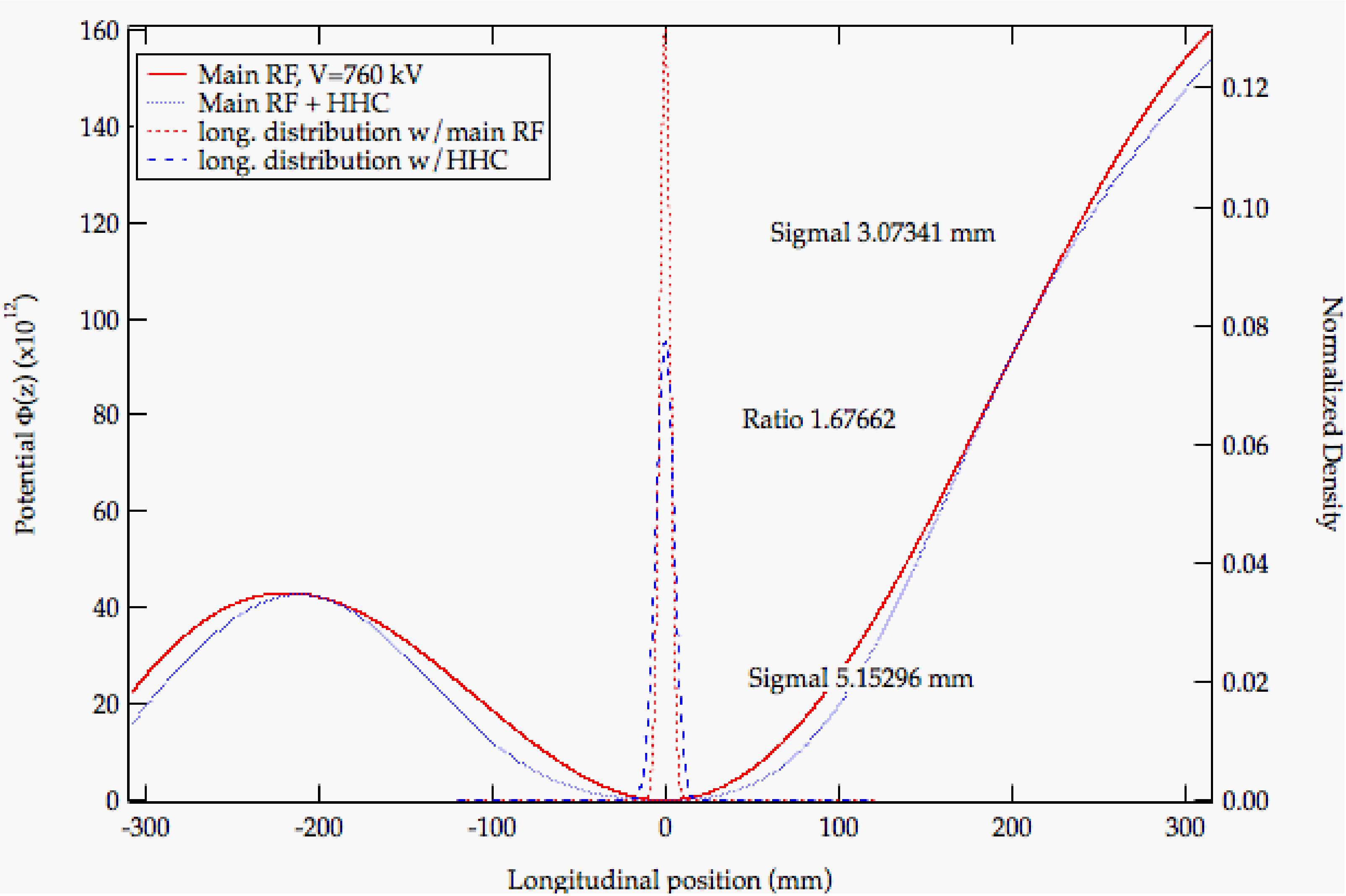
- If the beam current varies with time (sans topoff), the bunch lengthening varies with current.



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

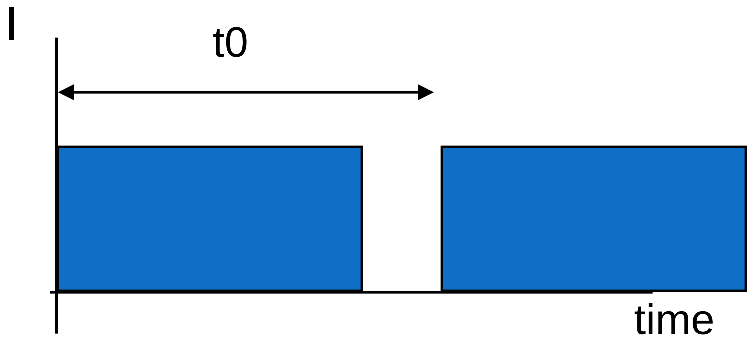
Byrd and Georgsson, PRSTAB 4, 030701 (2001).

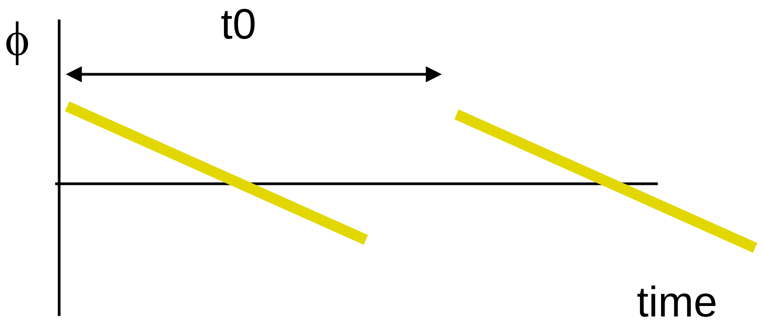
Passive bunch shape vs current



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.)





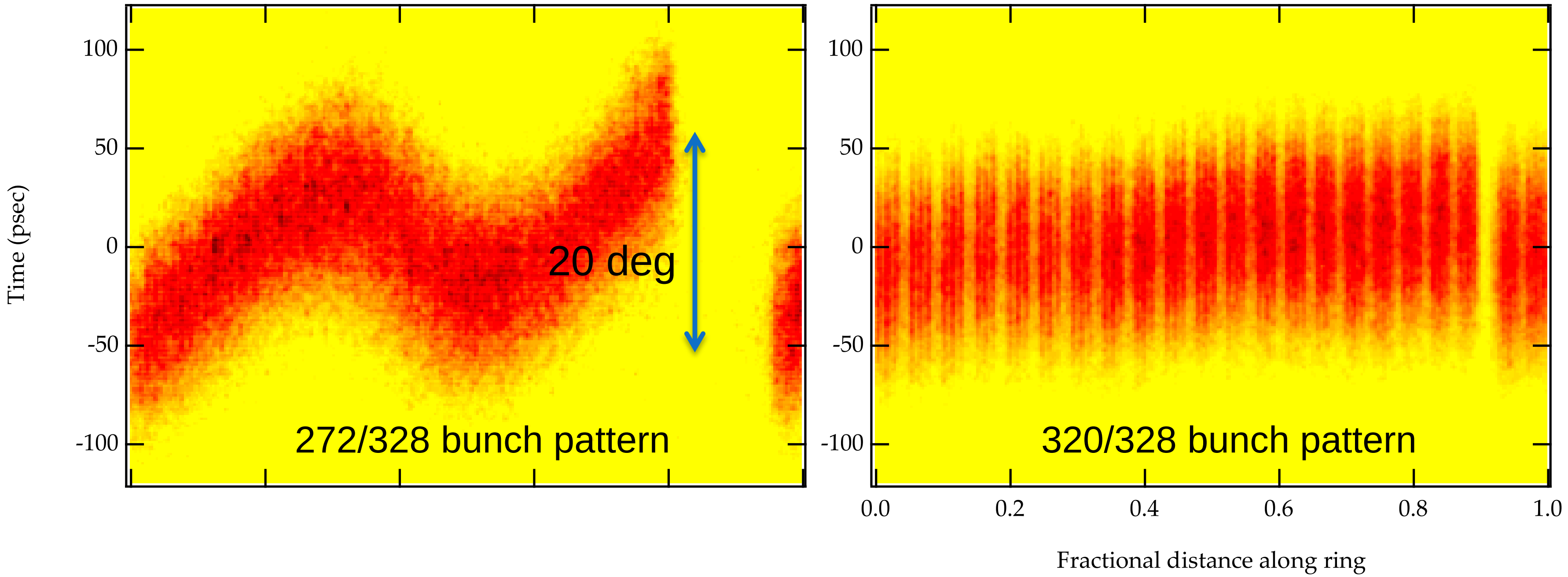
For the main RF only, this effect is small (few degrees). With the HCs, the effect is much larger. This affects both the lifetime improvement and operation of the multibunch feedback systems.

$$\Delta\phi = \frac{\Delta V}{V_{\mathrm{rf}}\cos\phi_1} = \frac{h\alpha\Delta V}{2\pi E Q_s^2},$$

Observation of Large Phase Transients

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

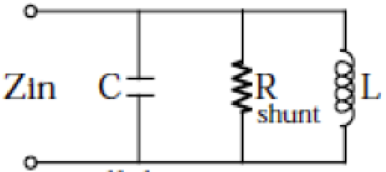
3 cavities in Landau mode
2 parked at ±2.5*f0



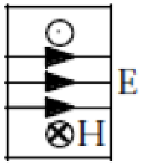
Unequal fill or gap of 20-25% (users' demand) aggravates this problem.

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

Cavity mode as parallel LRC resonator



parallel resonant circuit

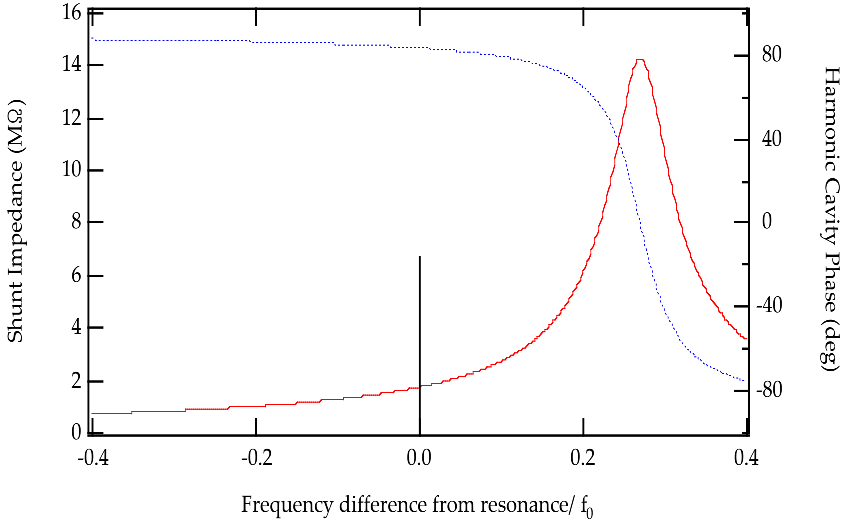


cavity

- 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.

Transient Measurements for SC HC

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

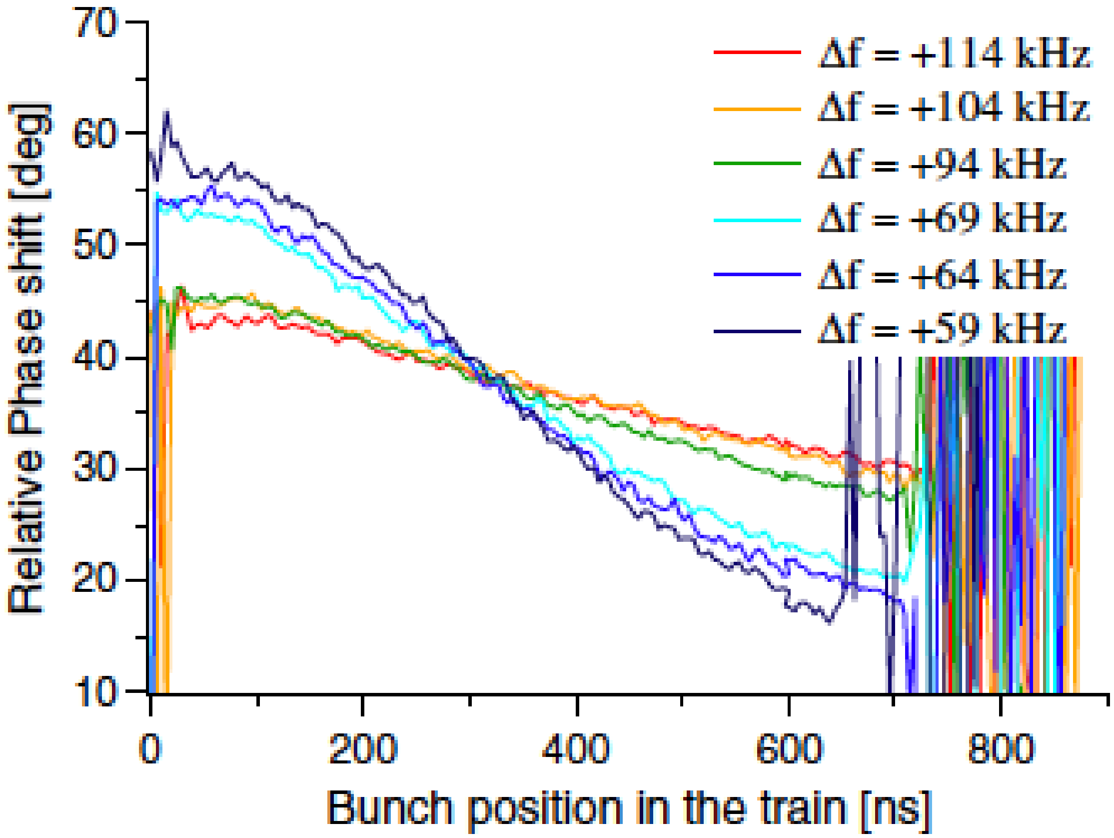


FIG. 6. (Color) Relative stable phase along the bunch train vs the 3HC detuning, for a 80% filling; $I_{\text{beam}} = 315$ mA, $E = 2.0$ GeV.

Penco and Svandrlik
PRSTAB 9, 044401 (2006)

Main and Harmonic Cavity Options

- First, consider 3 different main RF frequencies: 100, 352, 500 MHz.
  - Well developed RF power amplifiers exist for all 3 frequencies. SS PA are better developed at lower frequencies.
  - Bunch length ~$f^{-1/2}$. Short bunches are harder to achieve at lower frequency.
  - For equal beam current, bunch charge is ~f^{-1} and peak current ~$f^{-1/2}$. Therefore IBS effects are worse at lower frequency.
- Second, consider both passive and active systems at 3rd, 4th, and 5th harmonics. Cavity can be either NCRF or SCRF.

Passive or Active HC?

	Active	Passive
NCRF	• Requires input coupler • Requires RF source and controller • Can reach optimum BL at any current • Multiple cavities	• Lower cost • Only “optimum” bunch lengthening at most at a single high current (maybe nowhere) • Higher total R/Q for transients • Multiple cavities
SCRF	• Requires SC infrastructure • Requires input coupler • Requires RF source and controller • Can reach optimum BL at any current • Lower R/Q for transients • One or two cells	• Requires SC infrastructure • Never reaches optimum BL (always 90 deg phase) • Lower R/Q for transients • One or two cells

HC design considerations

- Total voltage of V_{rf}/n. Usually between 0.3-2 MV.
- Number of cells determined by $V \sim I_b \cdot R/Q \cdot \frac{\omega_r}{\delta\omega}$, and R/Q/cell and voltage/cell limit
- Wide tuning range
  - In operation at least $0.5 * f_{rev}$
  - Parking: at least $2 * f_{rev}$

NCRF

- R/Q~80 Ohm limited by large beam pipe
- Two tuners (TM010 and TM110)
- Gradient/voltage limited by surface power density. Harder at higher frequency.

SCRF

- R/Q~40 Ohm/cell
- Strong HOM damping
- One tuner
- Voltage easily reached with 1 or 2 cell design.

NCRF Harmonic cavity examples

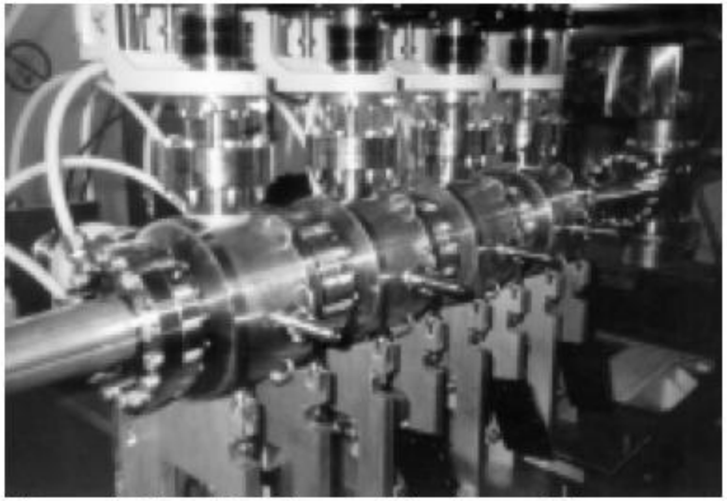
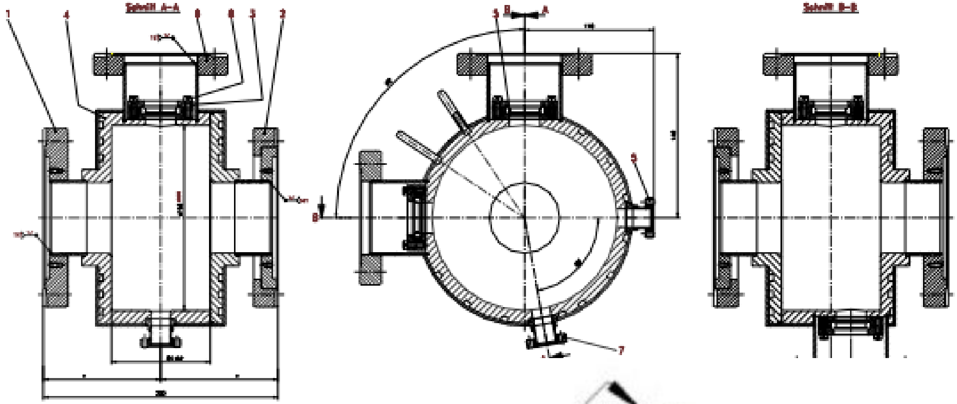
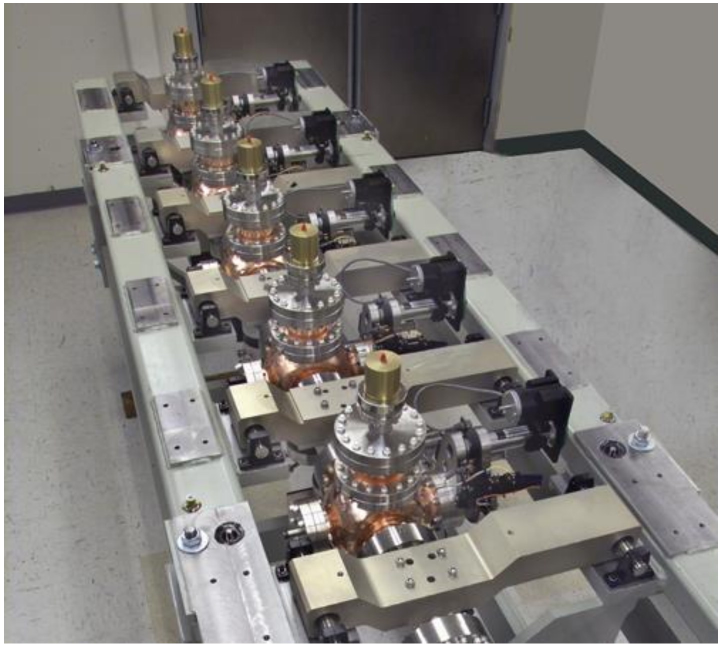


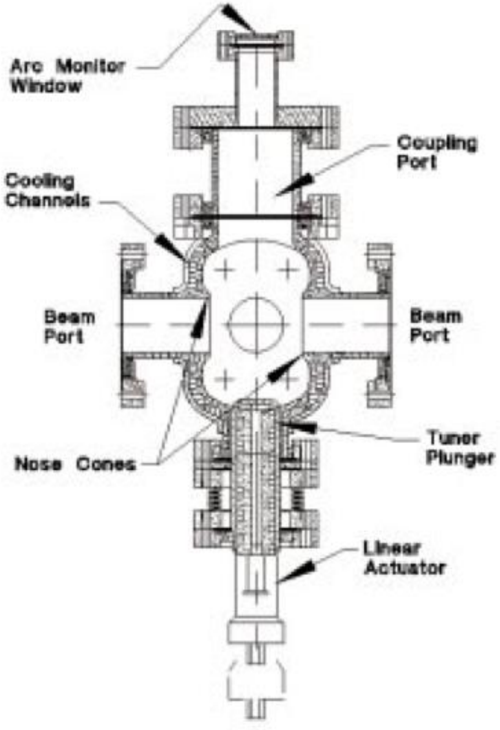
Figure 1. Four Landau cavities inserted into Bessy II.

Bessy-II



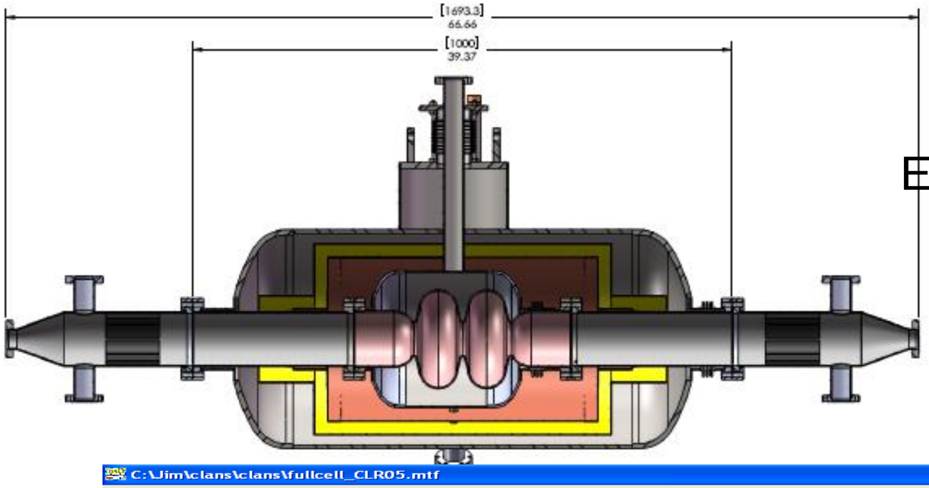


ALS



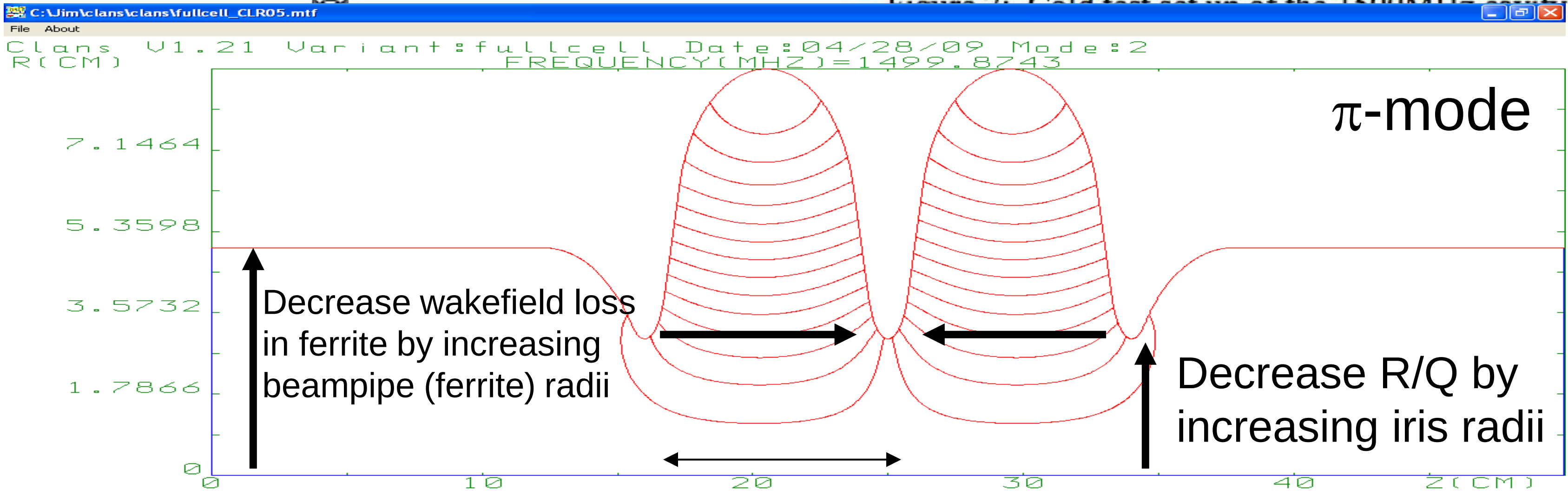
SCRF Harmonic Cavity Examples

- NSLS-II (Courtesy Jim Rose)



E-fields

Figure 7: Cold test set up of the 1500MHz cavity.



```
Clans  V1.21  Variant:fullcell  Date:04/28/09  Mode:2
                       FREQUENCY(MHZ)=1499.8743
```

π-mode

Decrease wakefield loss in ferrite by increasing beampipe (ferrite) radii

Decrease R/Q by increasing iris radii

βλ/2

SCRF Harmonic Cavity Examples

- Elettra/SLS Super 3HC (Courtesy Michele Svandrlik)

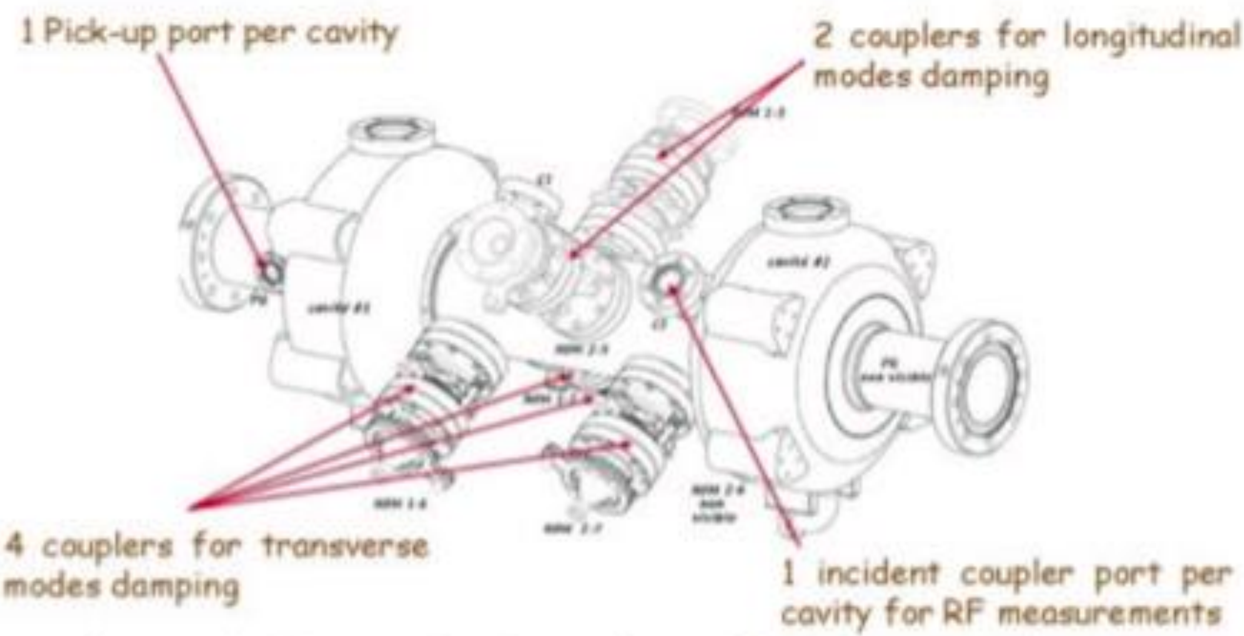


Figure 2: Super-3HC cavity with HOM couplers.

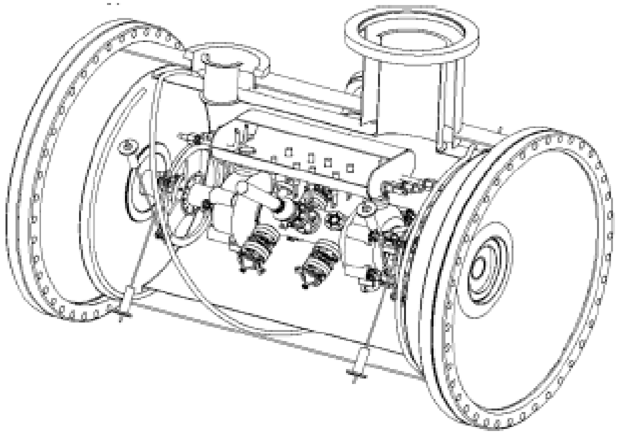


Figure 10: the cryomodule on SLS storage ring.

SCRF Harmonic Cavity Examples

- BESSY-II (not yet installed?)

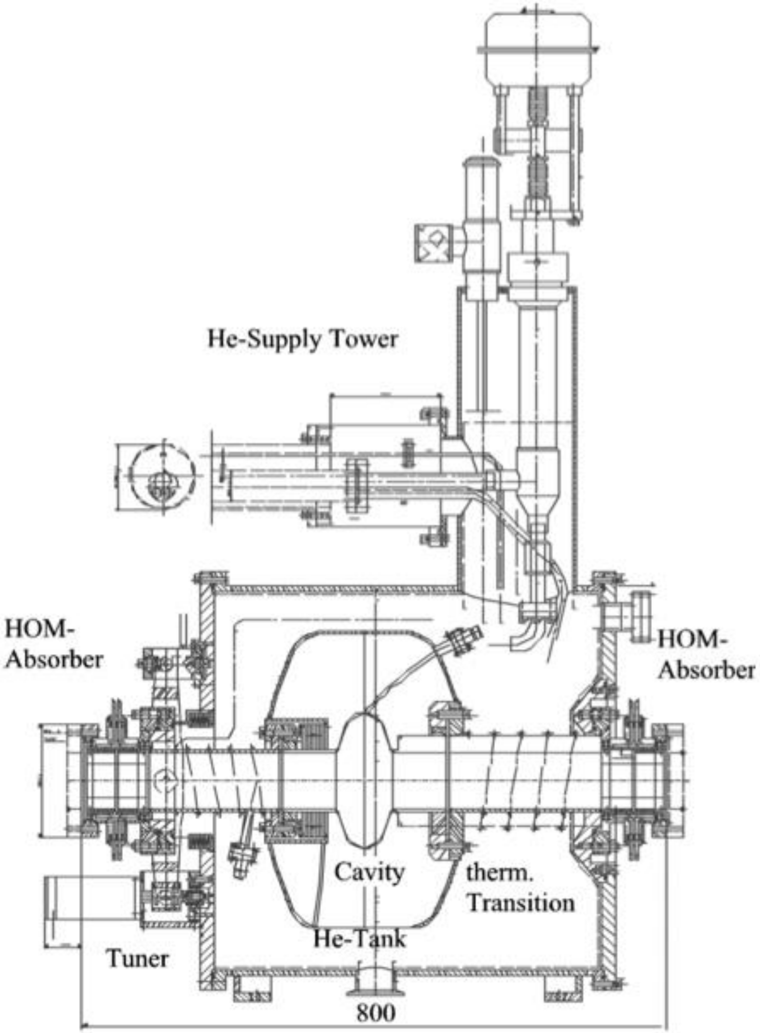


Figure 9: Layout of the Landau Module

Figure 8: Landau Cavity in handling frame

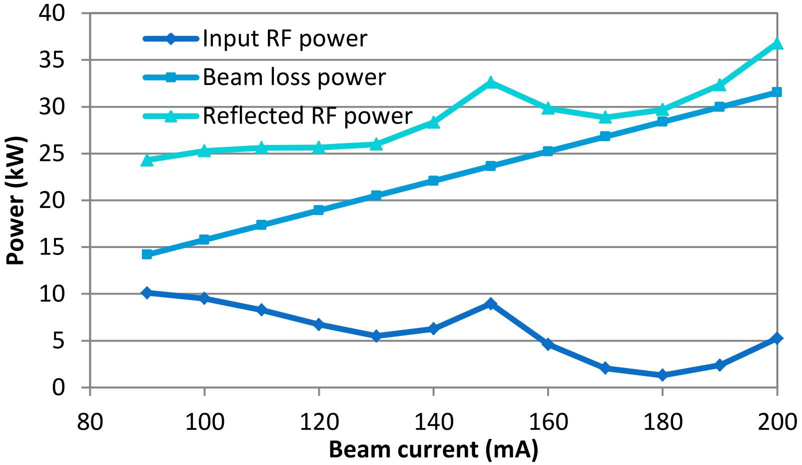
APSU Active SC HC Study

- The APSU is an upgrade of the APS. The are considering an active SCRF harmonic cavity.
  - Energy loss per turn ≈ 2.6 MeV, main RF voltage = 4.5 MV.
  - Harmonic voltage for optimum potential-well flattening is 0.9 MV with 79 degree detuning angle at the 4th harmonic RF (1408 MHz).
  - With this harmonic voltage, 4-fold beam lifetime improvement is expected.
  - To operate at 79⍰ detuning angle, fundamental-mode couplers are necessary. Active-mode operation is chosen for the range of beam currents from 50 mA to 200 mA.

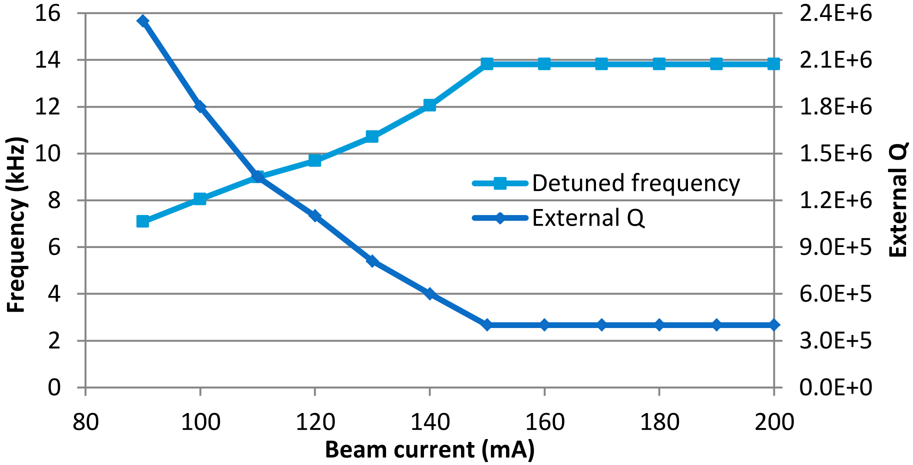
Courtesy Sanghoon Kim, Mike Kelly, and Peter Ostroumov

SC Harmonic Cavity in Active Mode

- SC single cell cavity
  - Modified from the ILC-shape single cell cavity: larger beam tube to extract HOMs from the cavity.
  - Rather low gradient in SC cavity: $E_{peak} \approx 17$ MV/m, $B_{peak} \approx 35$ mT.



- Active-mode operation with various beam currents
  - For the optimum harmonic voltage and suppression of the Robinson instability, frequency tuning, adjustable RF coupler, and external RF power are required.
  - Two 20 kW RF couplers and 10 kW RF source will be required.



S. Kim, M.P. Kelly, S.V. Kutsaev, P.N. Ostroumov, ANL Physics Division

Current study for ALSU

- ALSU is an initiative towards an ultralow (50 pm) upgrade of the ALS and incorporates several “new” features: on-axis injection, beam swap-out. 10 nsec risetime assumed.
- ALSU requires bunch lengthening to avoid emittance blowup from IBS.
- We are performing a study to characterize HC requirements and beam dynamics effects for ALSU. We welcome collaborators in this process.

ALSU RF Options

- ALSU is considering two RF options

500 MHz NC Main RF/1500 MHz SC passive HC

- Well understood system.
- Requires bunch trains with 10 nsec gaps. Transient effects?
- Requires addition of SC RF infrastructure.
- Allows bunch shortening mode.

100 MHz Main RF/500 MHz NC active HC

- Uses half of existing 500 MHz active system as harmonic.
- Requires addition of new 100 MHz RF system (ala MAXIV)
- Unclear if compatible with existing beam instrumentation (BPMs, etc)
- Bunch spacing 10 nsec compatible with kicker risetime. No gaps needed.
- Longer bunches better for vacuum system and instabilities.
- Reversion to 500 MHz possible for short bunch mode.

Summary

- Harmonic cavities are a useful tool for controlling bunch shapes in light sources. Considered to be essential for lower energy MBA lattices to counteract IBS emittance growth.
- The reduction of longitudinal focusing makes the bunch shape very sensitive to variations in the harmonic cavity phase.
  - Hybrid filling modes will be tricky if harmonic cavities are required. Symmetric filling patterns are best.
  - 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.) Unclear how much damping of HOMs is required if Landau damping is always present.
- Harmonic cavity technology well-developed. New developments in active 1.5 GHz RF