Harmonic RF System Technology for Electron Storage Rings

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Motivation for Harmonic RF

- **Old Motivation:**
  - Transverse beam 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. Not needed for high-energy 3GLS.

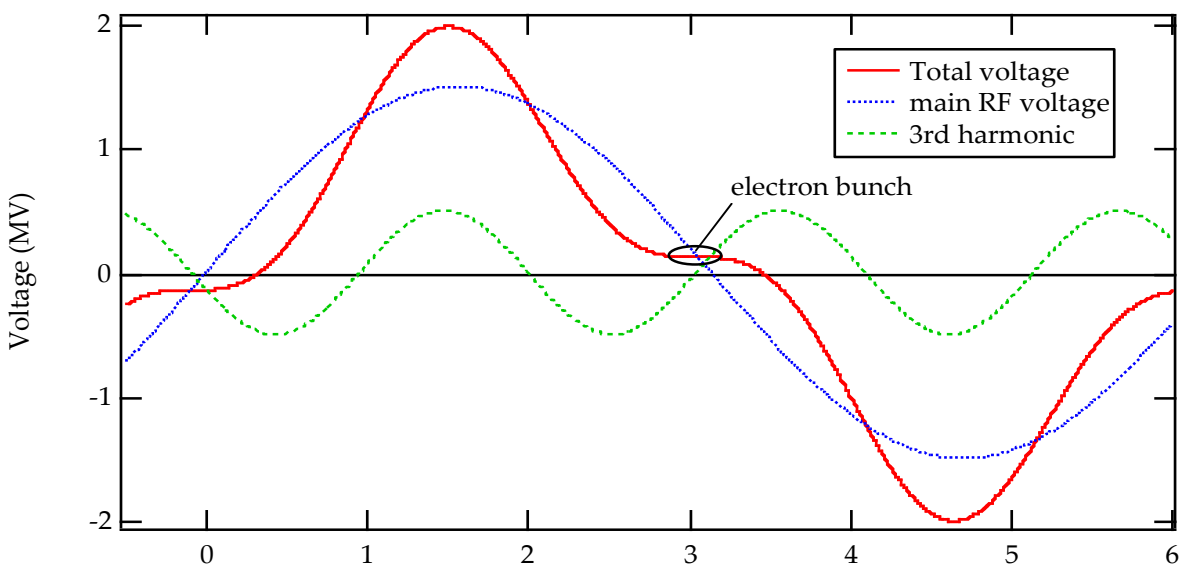
- **New Motivation:**
  - Modern lattice designs reduce horizontal emittance by ~2 orders of magnitude, bunch charge densities are high enough that the equilibrium 3-d emittance increases from small-angle intrabeam scattering in low-energy 3GLS. Lifetime in high-energy 3GLS is dominated by Touschek scattering.

- **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.

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



Focusing is cancelled at the bunch center

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

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

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

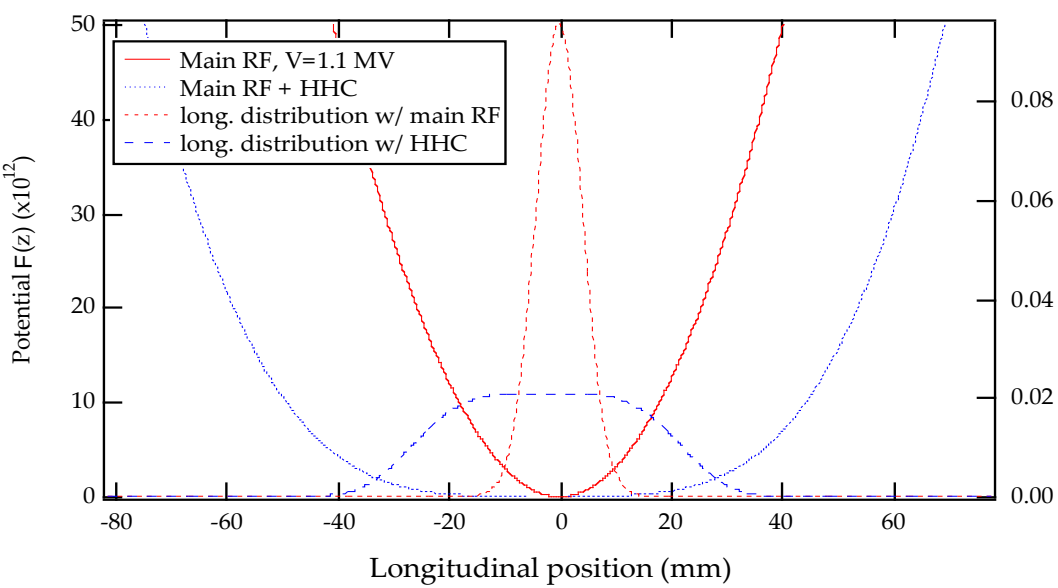
Harmonic RF systems (cont.)

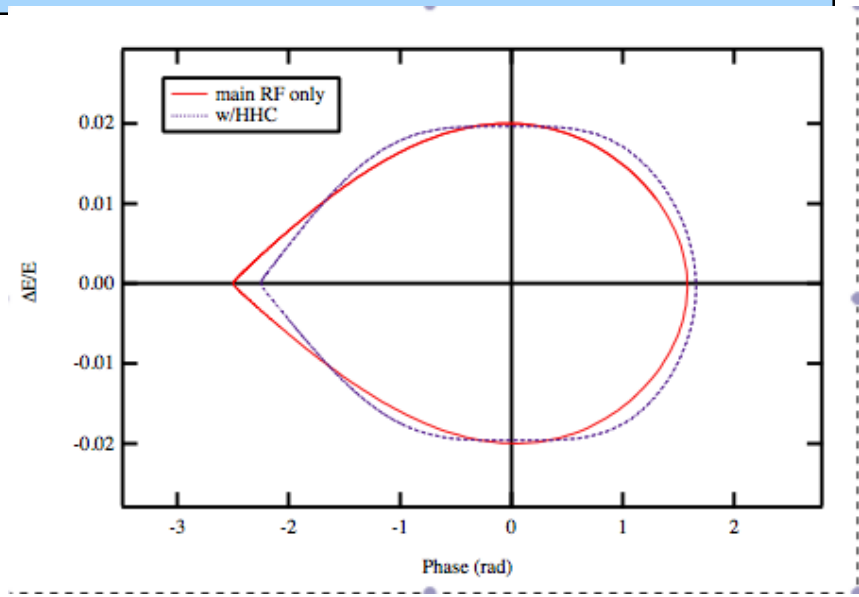
- The bunch shape can be calculated from the resulting distortion of the potential well.
- Single particle motion is highly nonlinear and a large tune spread is introduced.

$$\rho(z) = \bar{\rho}\, e^{-\frac{F(z)}{a^2 s_e^2}}$$ bunch distribution

$$\Phi(z) = \frac{\alpha}{EC}\frac{cV_{rf}}{\omega_{rf}}$$ potential

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





A brief detour: What is the right RF frequency for an electron storage ring?

- The main RF frequency for a ring is often determined by other factors than optimum design of the ring:
  - Existing RF cavities or cavity designs, especially for HOM-damped cavities.
  - Compatibility with existing injector systems.
  - **Exisitng or available RF power sources in the range of ~100-1000 kW.**
- For 4GLS, there is an opportunity to reconsider the "optimum" RF frequency choice, especially for "green-field" machines.
  - Touschek lifetime and Intrabeam Scattering effects scale with bunch peak current.
  - Let's consider two cases....

A brief detour: What is the right RF frequency for an electron storage ring?

- Touschek lifetime and Intrabeam Scattering effects scale with bunch peak current.
- For a fixed RF voltage, peak bunch current scales as
  - $(\text{RF Frequency})^{-1/2}$
  - $(\text{Total Beam Current})^{1}$
  - $(\text{Number of bunches})^{-1}$
- Case 1: Every RF bucket is filled with beam
  - Number of bunches is proportional to RF Frequency
  - Touschek and IBS improve with $(\text{RF Frequency})^{1/2}$. Higher frequency is better.
- Case 2: Number of bunches independent of number of RF buckets (common in large rings).
  - Peak current only scales with $(\text{RF Frequency})^{-1/2}$. Lower frequency is better.

A brief detour: What is the right RF frequency for an electron storage ring? Practical considerations…

- Scientific:
  - Ultrafast science has largely moved to fsec FEL sources. Storage rings still have a limited but dedicated application to ~psec sources. Primary scientific application for 4GLS is in average brightness.
- Beam dynamics:
  - Longer bunches have lower bandwidth frequency content and ”probably” less single bunch instabilities
  - High frequency RF raises synchrotron frequency above potential low frequency noise sources.
- Machine Design:
  - Several important issues addressed in the next slide

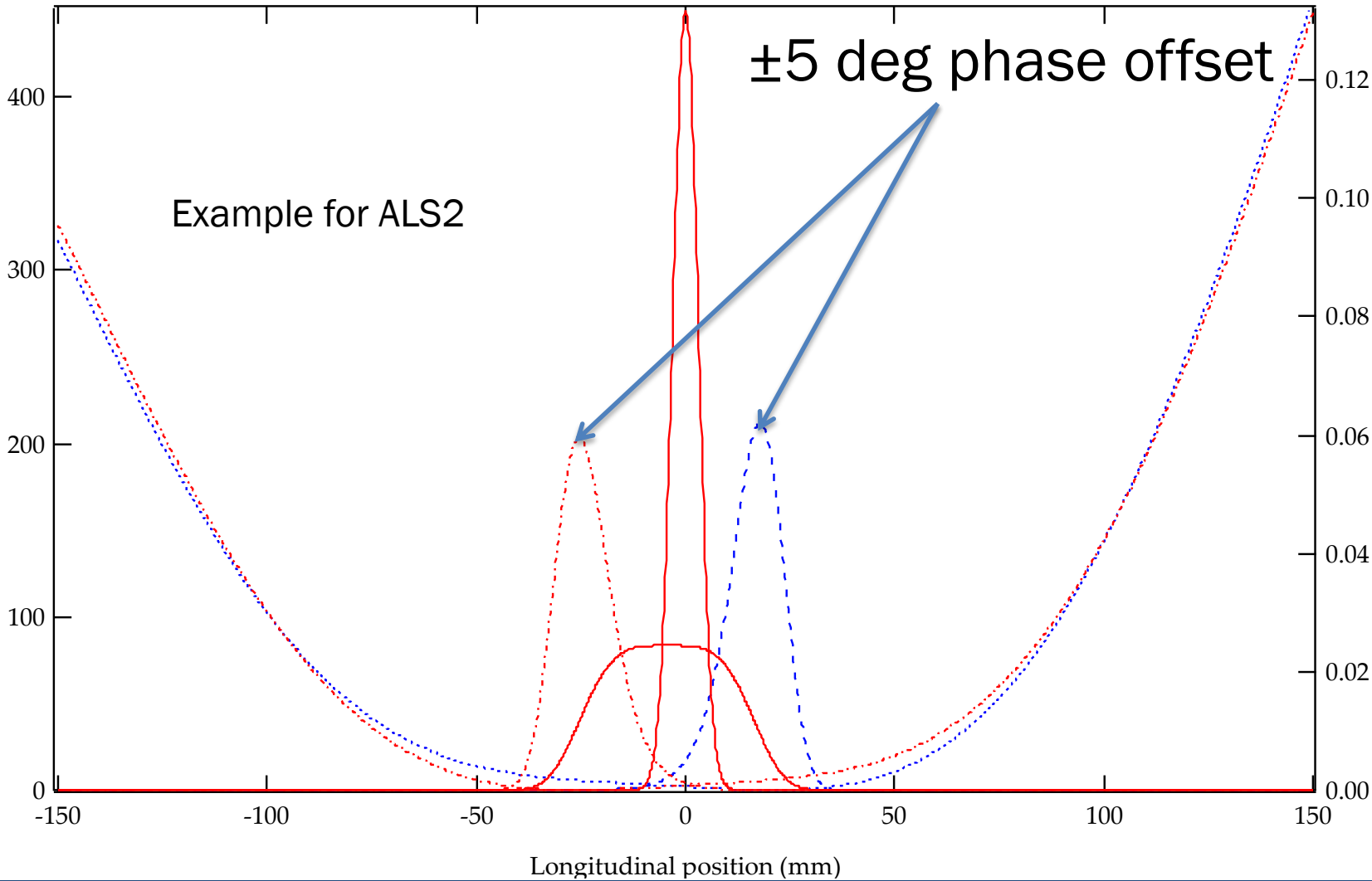
A brief detour: What is the right RF frequency for an electron storage ring? Practical considerations…

- High Frequency RF Systems (>1.5 GHz):
  - Experience with 1.5 GHz storage ring RF systems is limited. (MIT Bates had a 3 GHz cavity).
  - Existing study of 1.5 GHz system for CLIC with demonstration envisioned at ALBA.
  - Production of 10 kW class CW SSPA sources for superconducting electron linacs. Higher power CW sources?
  - Many RF cavity designs (normal and superconducting). However, none demonstrated at the ~100 kW power level. Power density scales with $(\text{frequency})^2$ so more cavities will be needed. Issues with power couplers, etc.
- Low Frequency RF Systems
  - Significant storage ring experience with 50-100 MHz RF systems.
  - A wide variety of sources available. SSPA is now the preferred option at this frequency range with low cost and availability.
  - Designs of HOM-damped cavities exist but there is room for improvement.

RF engineering for accelerators, particularly reliability, remains somewhat a dark art, especially in smaller regional laboratories. Every small improvement requires significant testing to allow >95% machine availability.

Collaboration between labs and industry is essential!!!

Lack of RF focussing increases sensitivity to phase errors

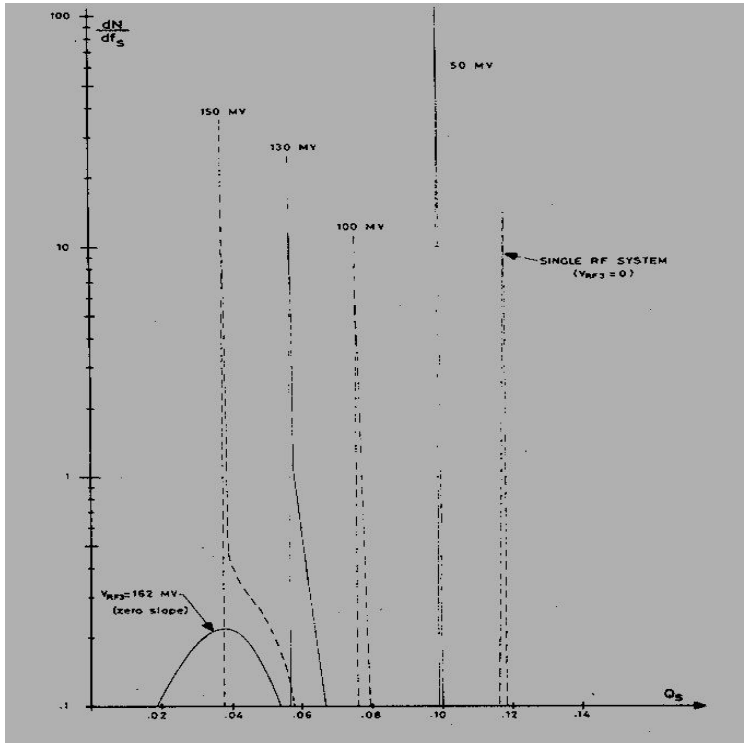


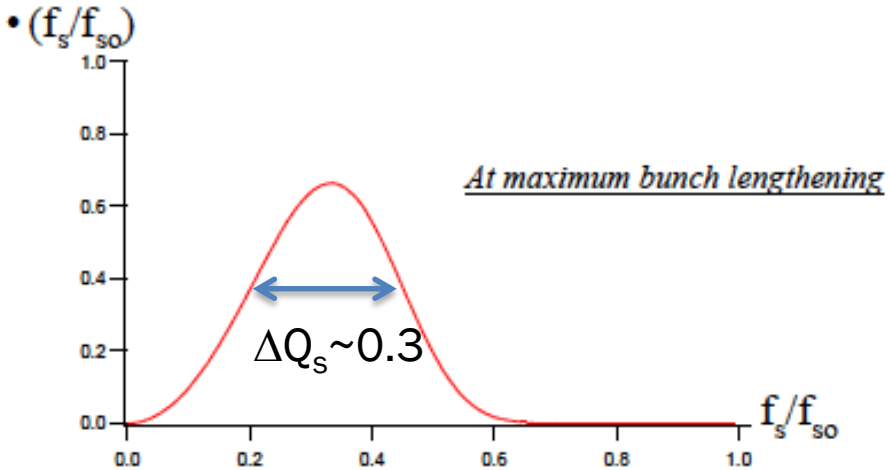
Harmonic caviites are also Landau Cavities

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

Harmonic cavities and the control of coupled bunch instabilities are complicated

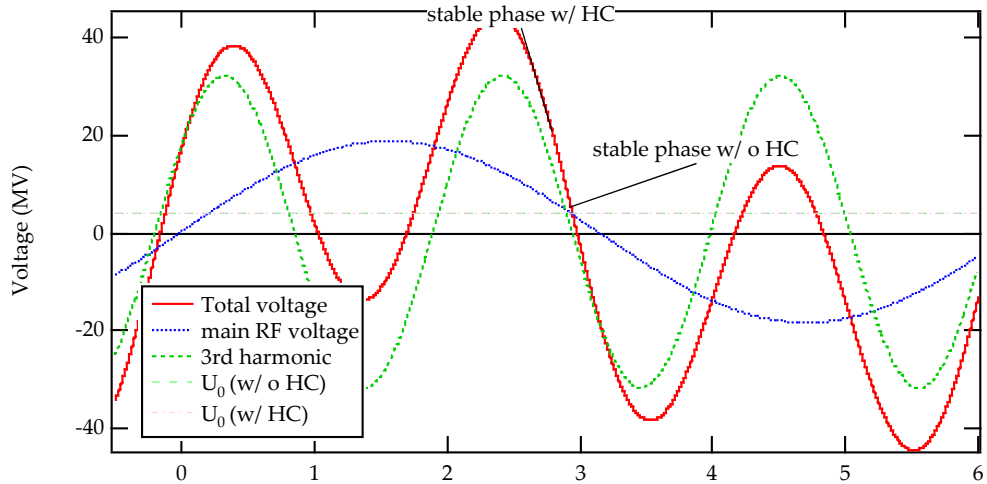
- Control of longitudinal longitudinal coupled bunch instabilities (LCBI) driven by cavity HOMs is essential for 4GLS.
- Longitudinal feedback (LFB) systems exist to completely control LCBI in 3GLS without HCs.
- New complications:
  - HCs introduce large tune spread that LFB cannot control.
  - As the tune spread increases, less LFB is needed (in theory)
  - As the longitudinal focussing decreases, growth rates increase.
- Fantasy Scenario: Harmonic cavities are tuned in and all LCBIs dissappear. Sleep soundly!
- Nightmare Scenario: Neither LFB or HCs cure LCBI and you constantly get phone calls at 3 AM.

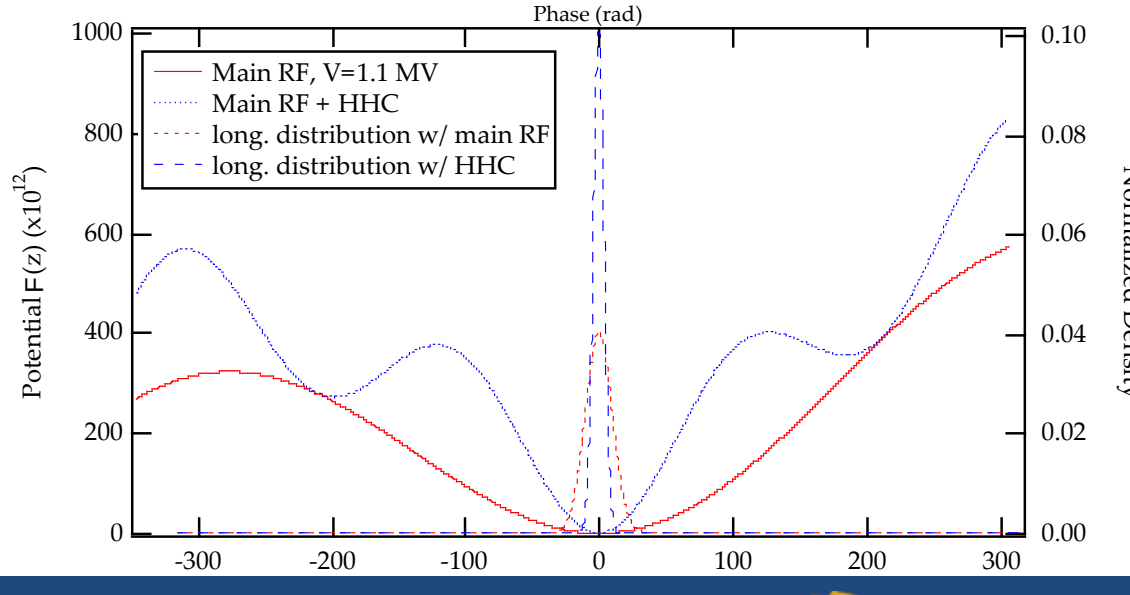
Bunch shortening using HCs

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.

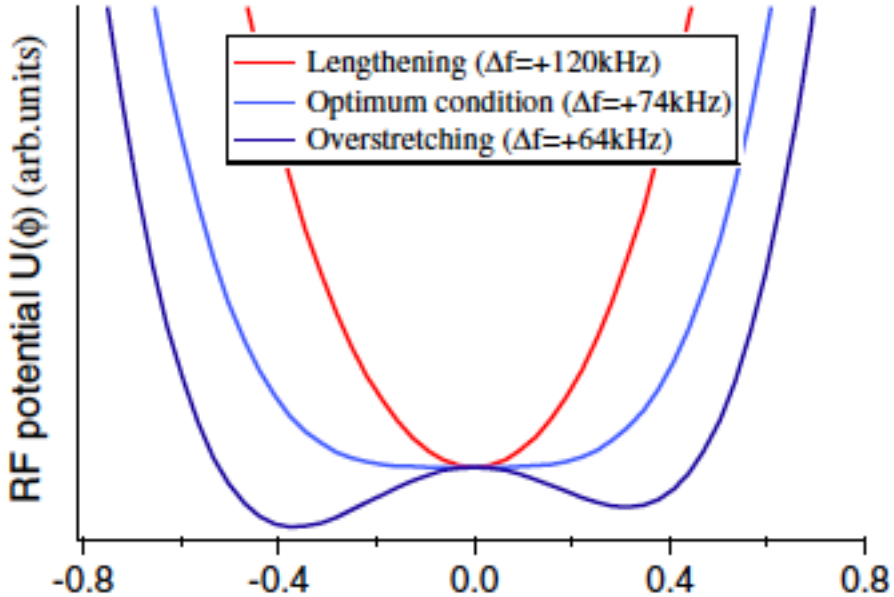
Very economical method for reaching short bunches.
Increased focusing gives higher SB and MB instability threshold.

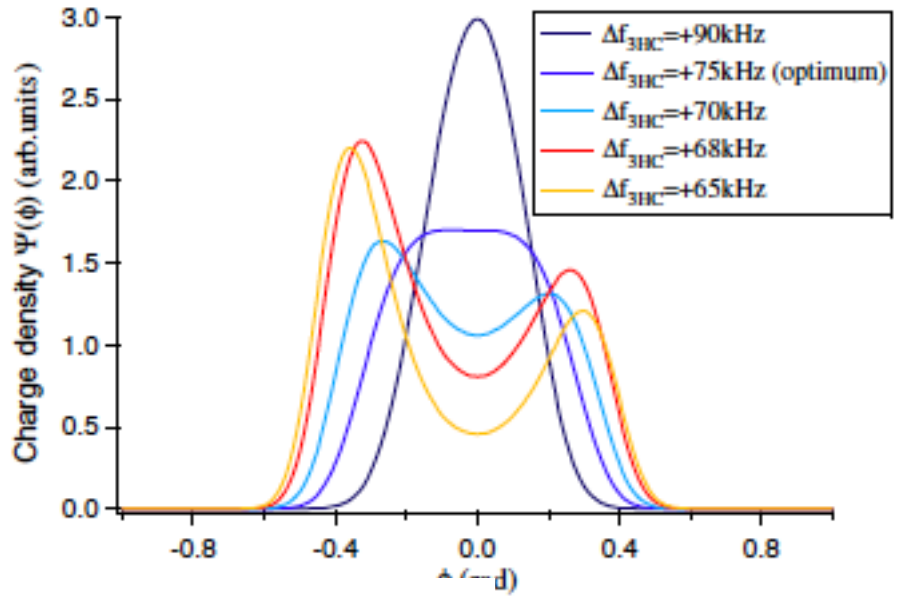




Overstretching

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





Penco and Svandrlik PRSTAB 9, 044401 (2006)

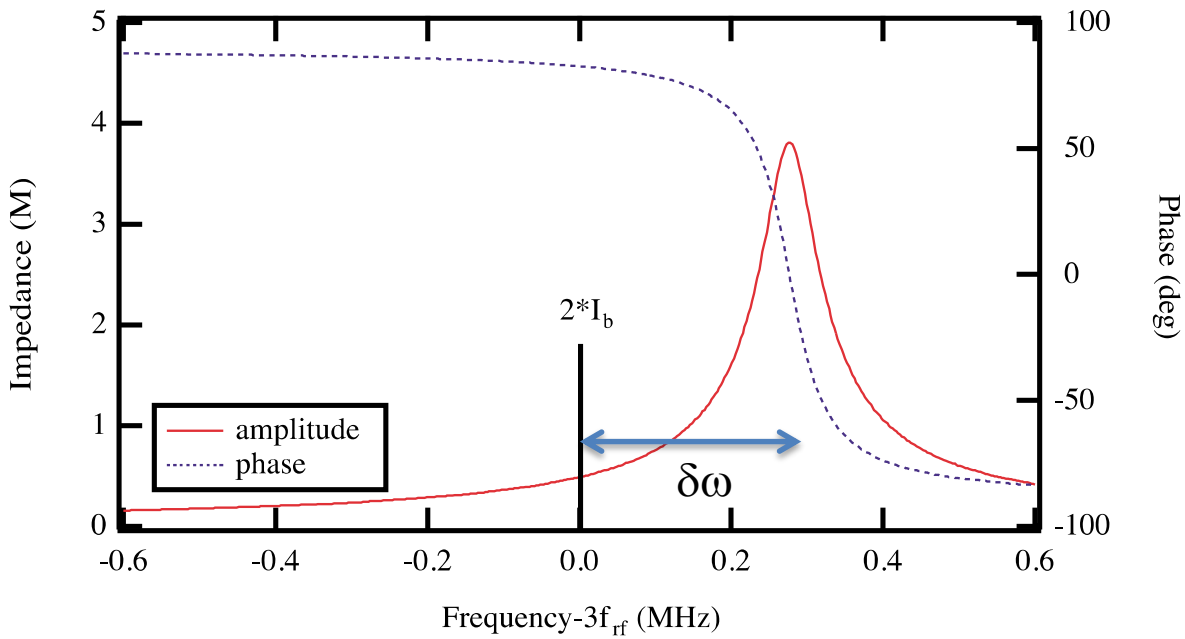
FIG. 14. (Color) Potential well distortion in lengthening mode, at optimum condition (flattened) and in overstretching regime, calculated for $I_{beam} = 315$ mA by using formula (5).

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? 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.**



The optimum harmonic voltage and phase are given by

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

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

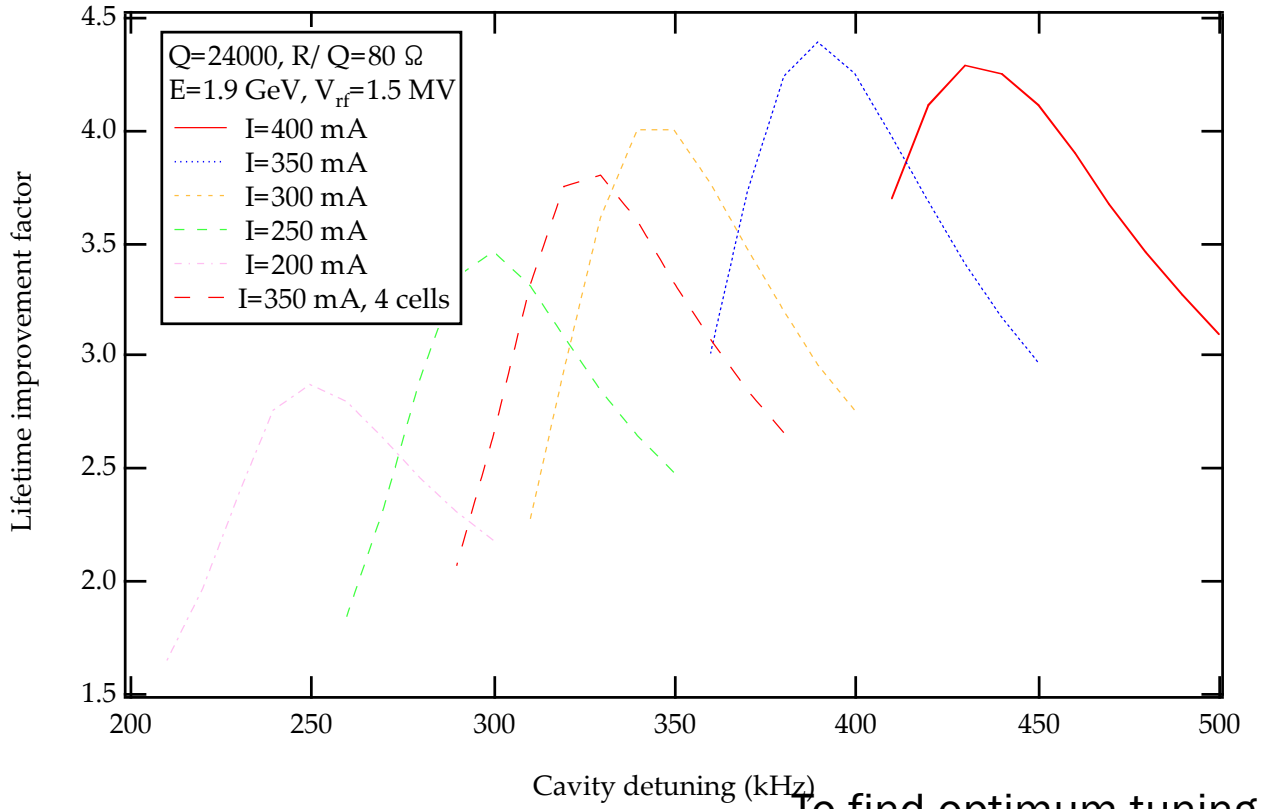
For a fixed cavity Q, it is possible to achieve the optimum lengthening for one current.

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

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

Passive Cavity with Variable Current

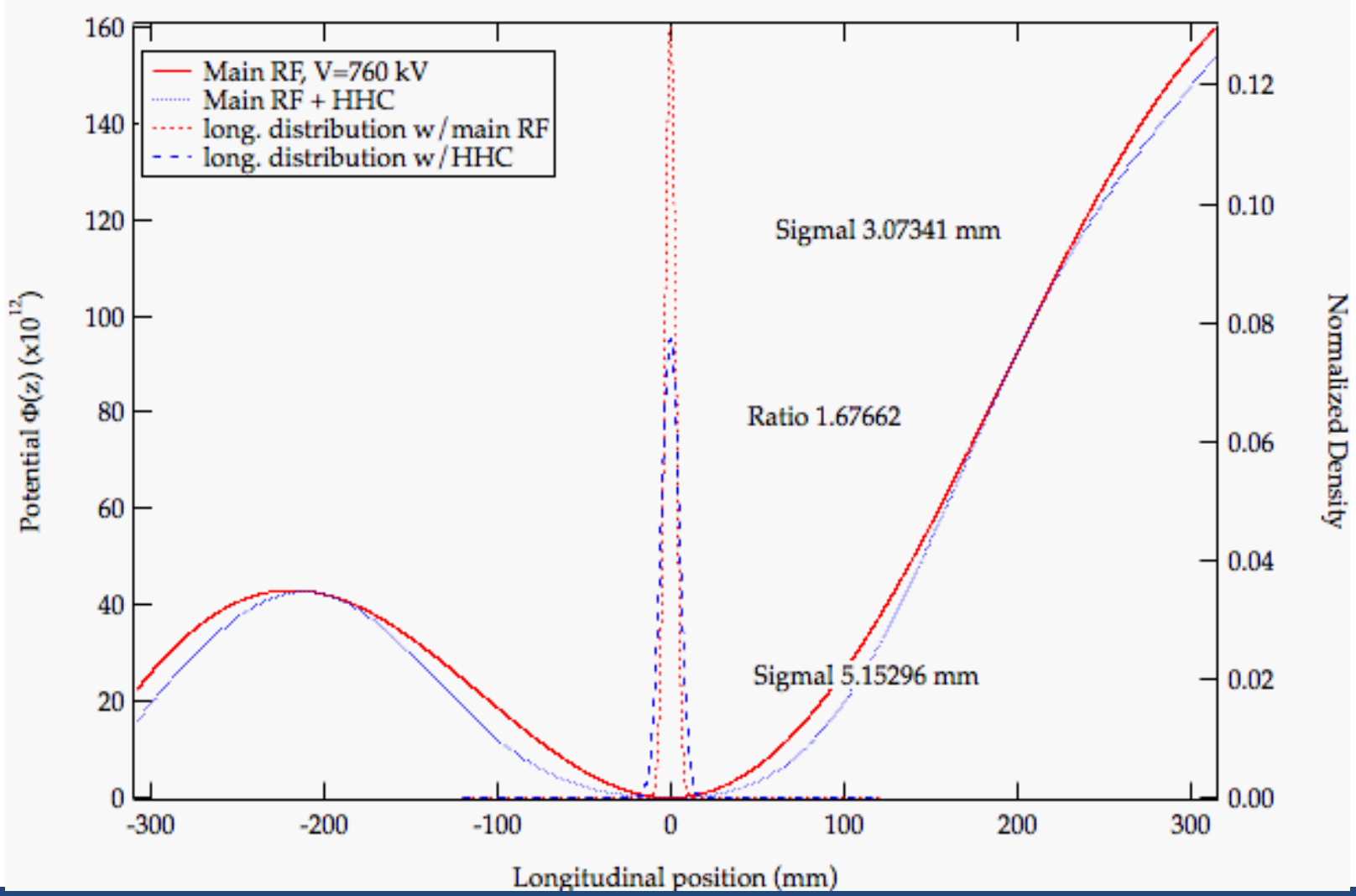
- **If the beam current varies with time (sans topoff), the bunch lengthening varies with current.**



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

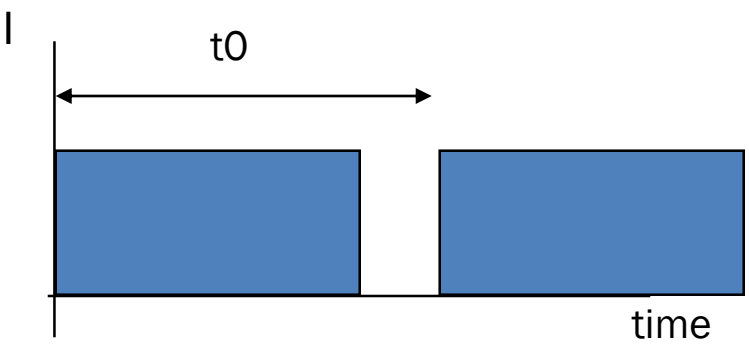
Byrd and Georgsson, PRSTAB 4, 030701 (2001).

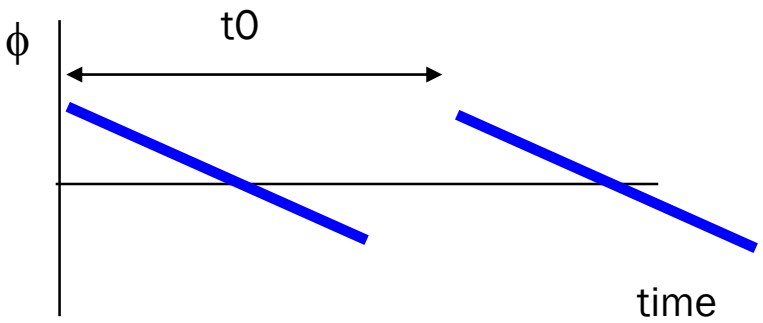
Passive bunch shape vs current



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.)





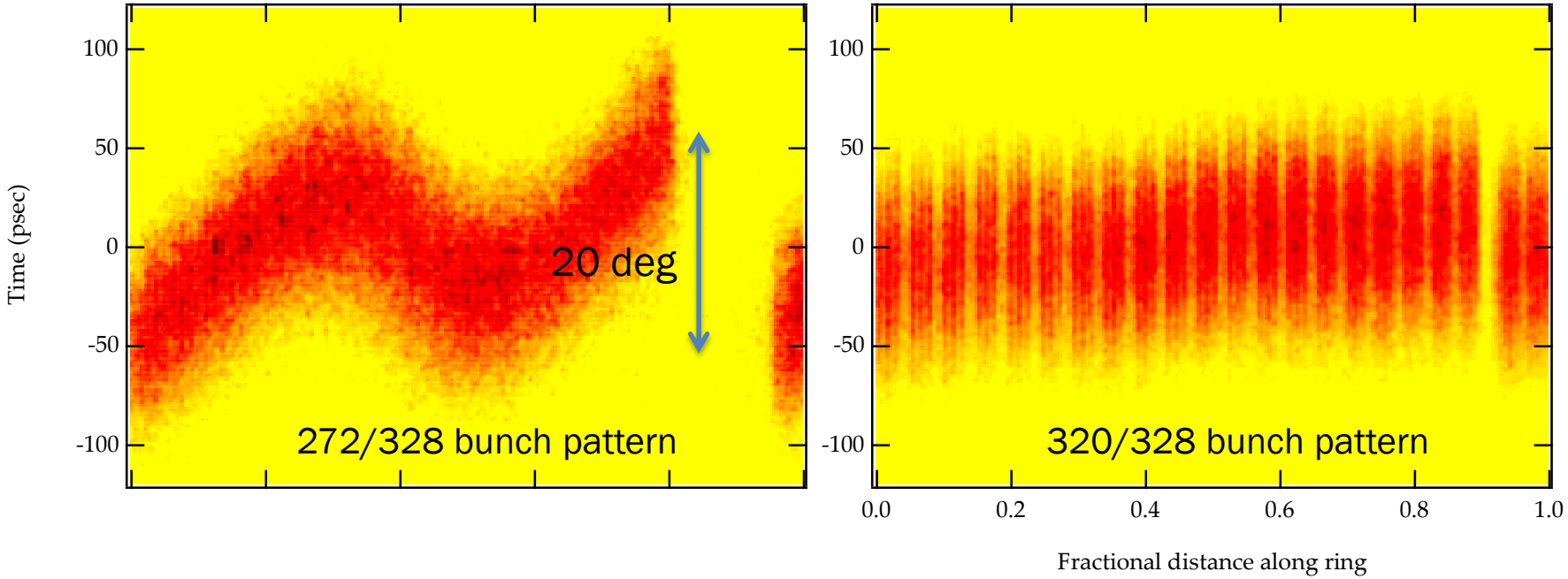
For the main RF only, this effect is small (few degrees). With the HCs, the effect is much larger. This affects both the lifetime improvement and operation of the multibunch feedback systems.

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

Observation of Large Phase Transients from gaps in the beam filling pattern

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

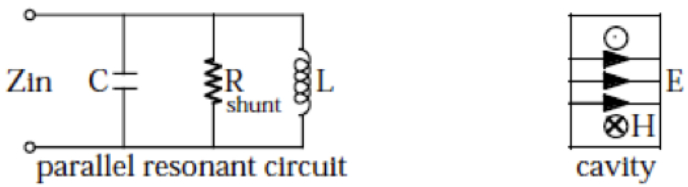
3 cavities in Landau mode
2 parked at ±2.5*f0



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.

Inductive-like cavity leads to phase transients

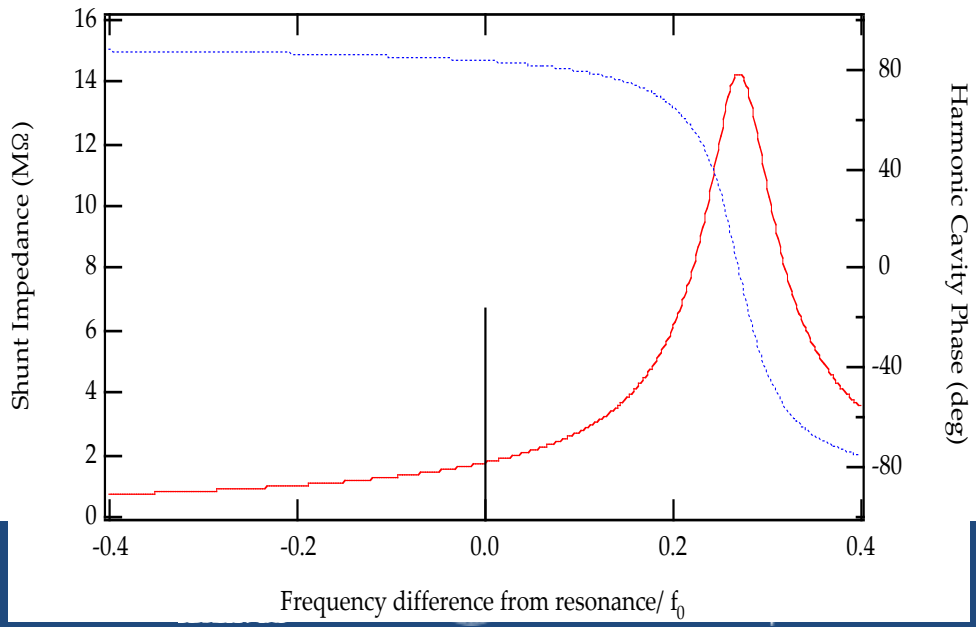


- The input impedance of the equivalent circuit can be expressed as:

$$_{in} = \left(\frac{1}{R} + \frac{1}{j\omega L} + j\omega C\right)^{-1}$$

where $\omega_o = \frac{1}{\sqrt{LC}}$ and $Q = \omega_o RC$ (or $Q = \frac{R}{\omega_o L}$).

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



- 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.

Phase Transients also observed for High Q SC Hamonic Cavities

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

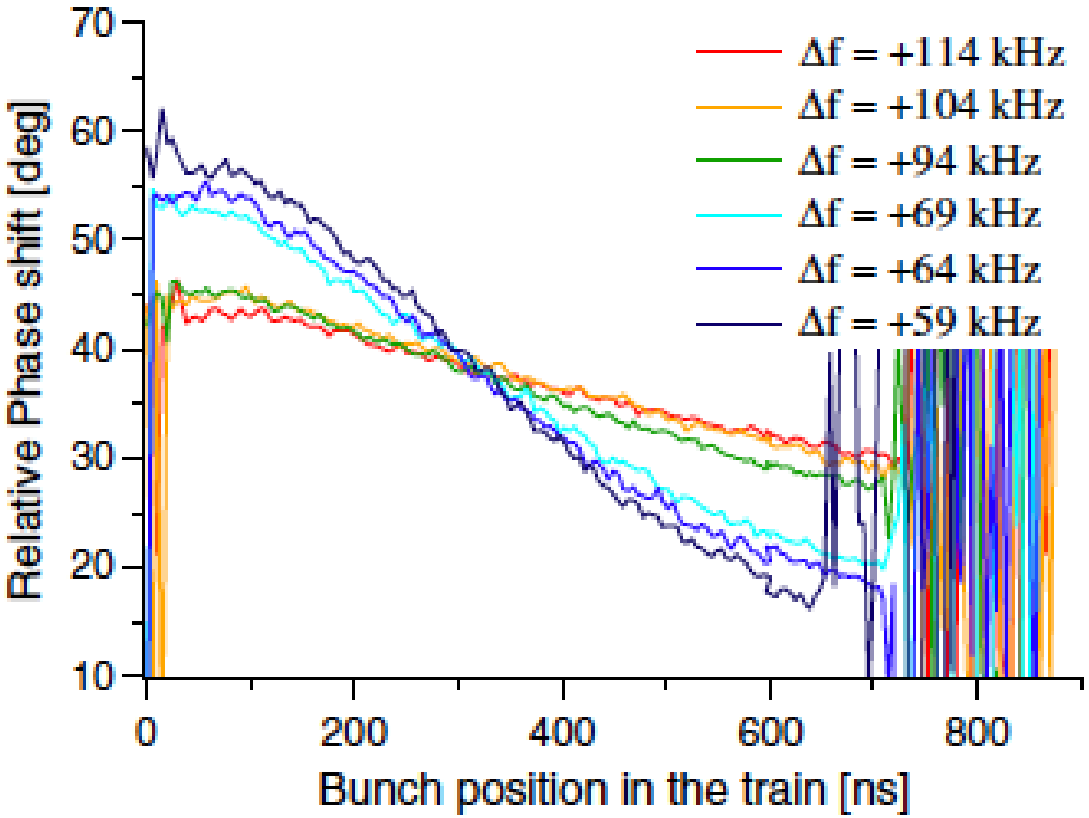


FIG. 6. (Color) Relative stable phase along the bunch train vs the 3HC detuning, for a 80% filling; $I_{beam} = 315$ mA, $E = 2.0$ GeV.

The phase transient is a reactive transfer of energy from beam-cavity with dependence on R/Q (not Q!).
Strong effect from beam gap. **4GLS must have symmetric fill patterns with passive HCs.**

Penco and Svandrlik
PRSTAB 9, 044401 (2006)

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 $2*f_{rev}$
- Damping or control of HOMs

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

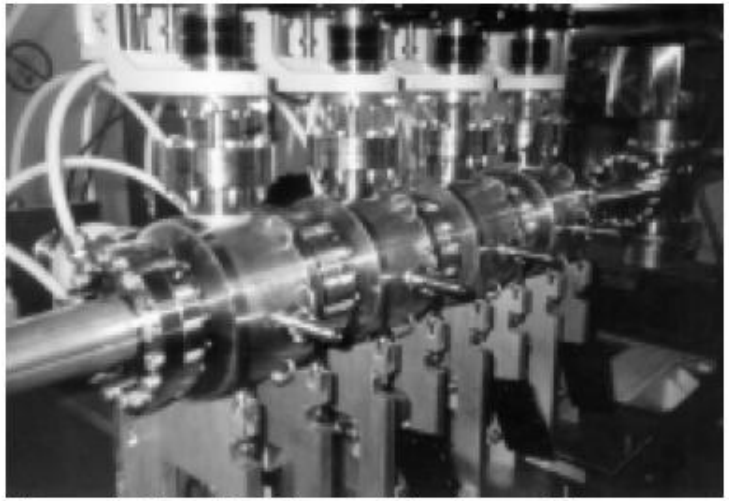
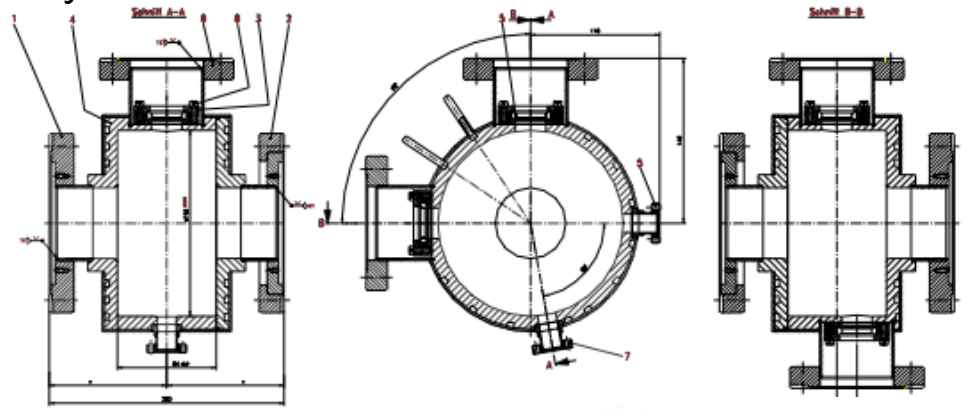
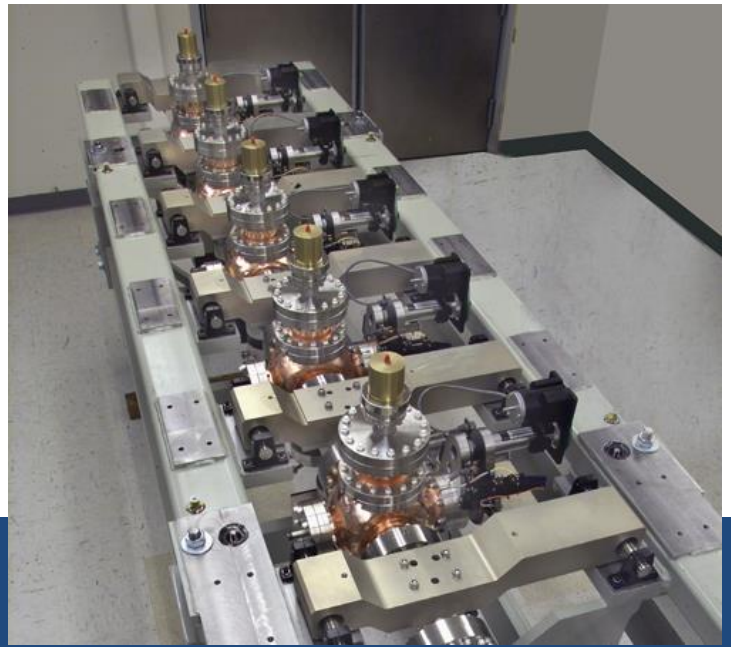


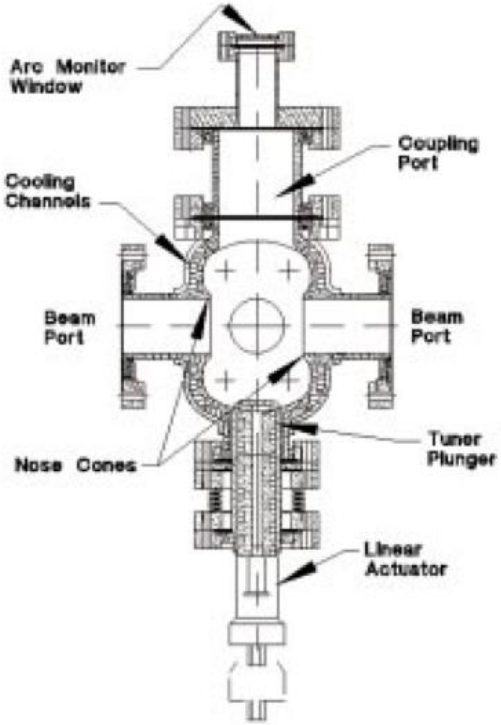
Figure 1. Four Landau cavities inserted into Bessy II.

Bessy-II



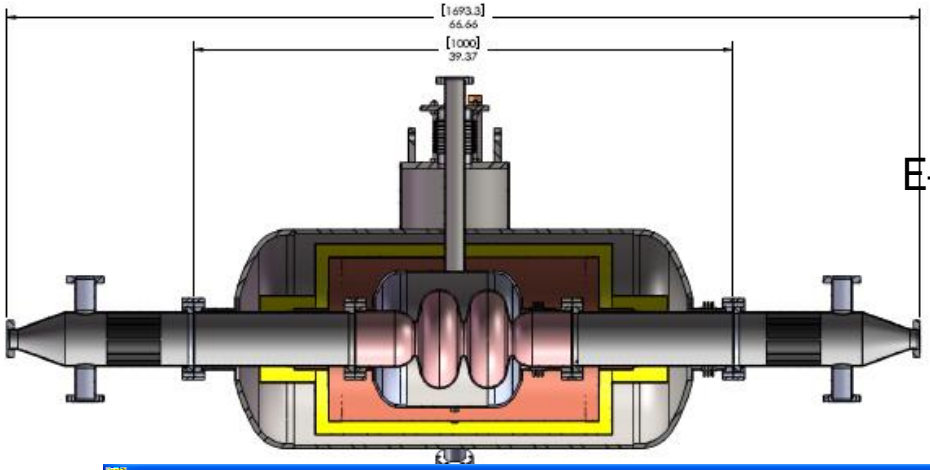


ALS

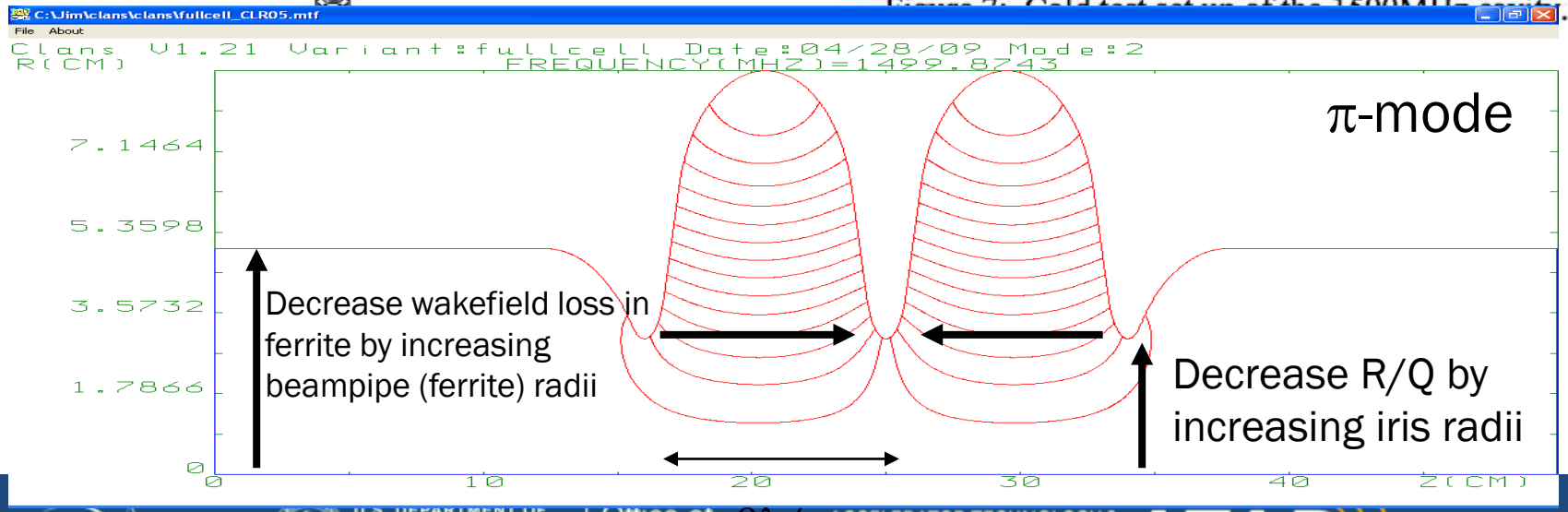


SCRF Harmonic Cavity Examples

- **NSLS-II (Courtesy Jim Rose)**



E-fields



SCRF Harmonic Cavity Examples

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

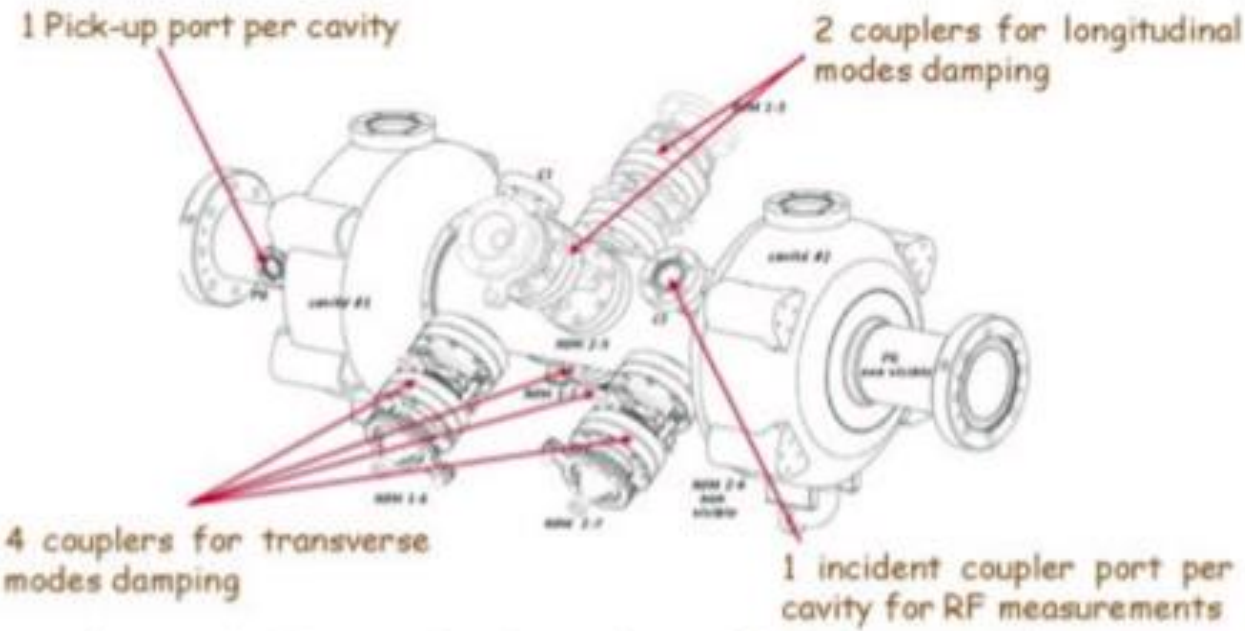


Figure 2: Super-3HC cavity with HOM couplers.

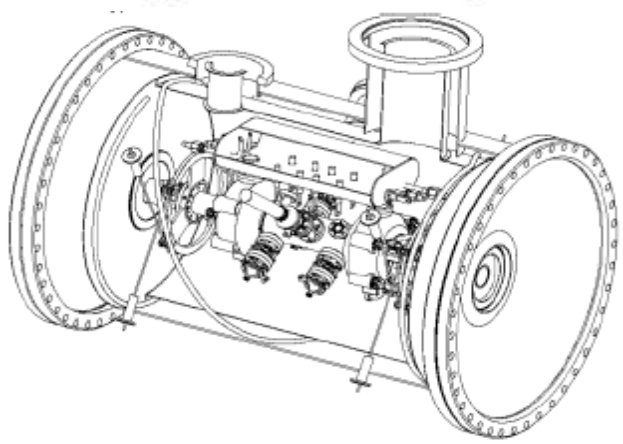


Figure 10: the cryomodule on SLS storage ring.

SCRF Harmonic Cavity Examples

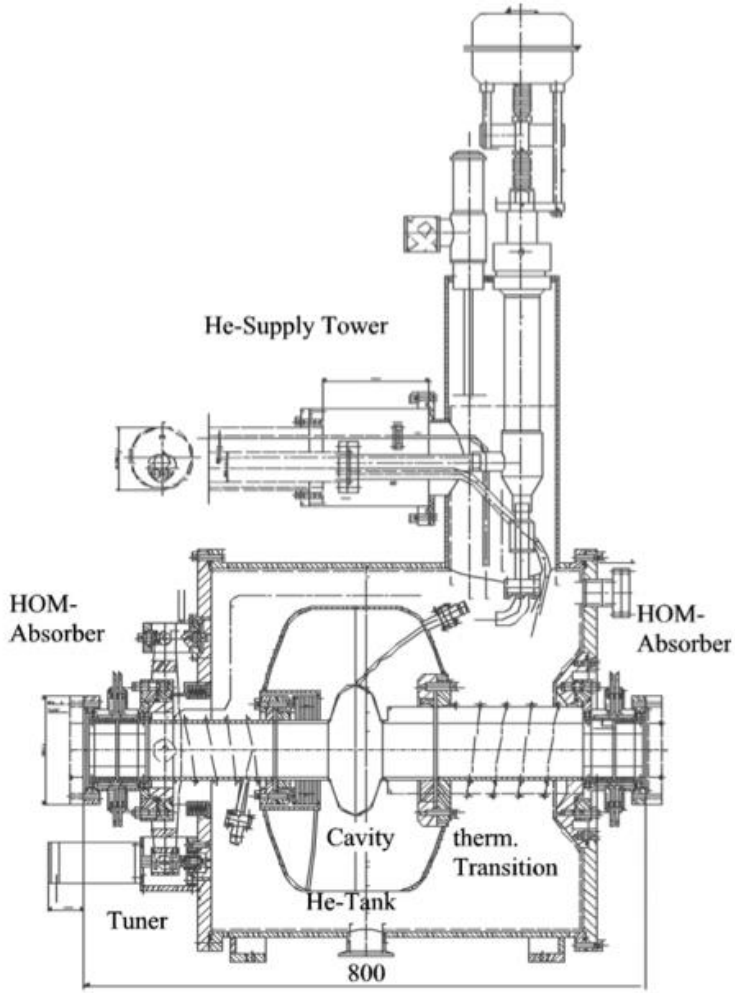


Figure 9: Layout of the Landau Module


Figure 8: Landau Cavity in handling frame

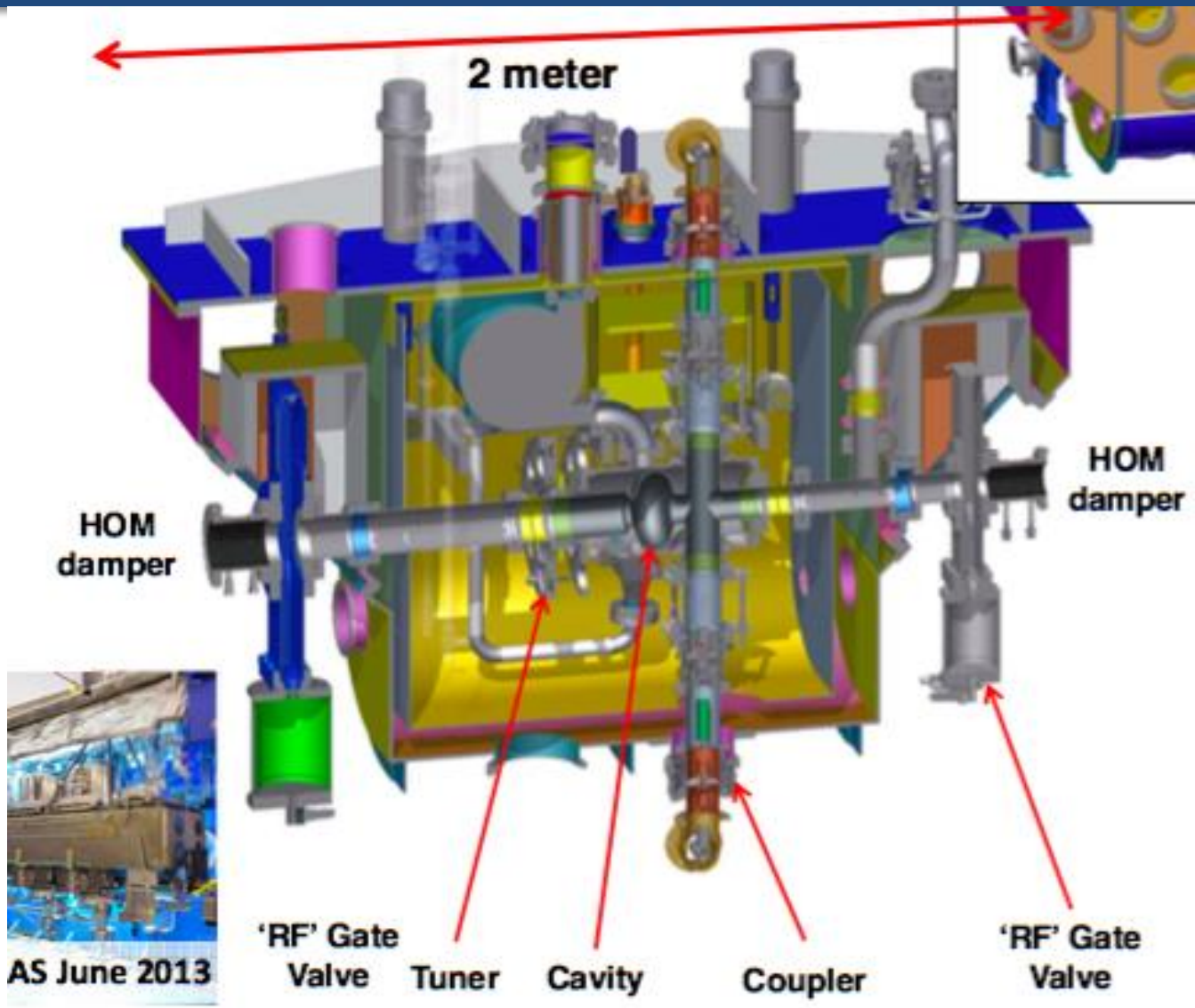
APSU SC HC Study

- The APSU is an upgrade of the APS. The are considering an 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 degree detuning angle, fundamental-mode couplers are necessary to reduce cavity Q and allow ideal phase detuning. The power couplers are specified for 50 kW and could eventually be modified for active operation of the cavities.

Courtesy Sanghoon Kim, Mike Kelly, and Peter Ostroumov

APS-U 1.4 GHz SC 4th Harmonic Cavity Design

- F_r=1408 MHz
- HOM damping on beam pipe
- Control of cavity phase by variable coupling to fundamental
- Design is well advanced with prototype cavity built and cryo under assembly.



ALS-U Considering Two RF Options

500 MHz NC Main RF/1500 MHz passive HC with two cavities

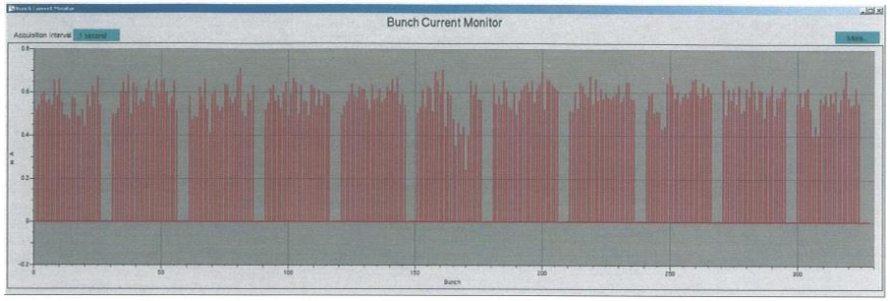
- Well understood system uses existing fundamental and passive RF system. Reduced RF power needs with MBA lattice helps.
- Requires filling pattern of bunch trains with >10 nsec gaps depending on performance of fast injection kickers.
- R&D issue: Do the small gaps cause phase transients and reduced effectiveness of HCs?

~125 MHz Main RF/500 MHz NC active HC

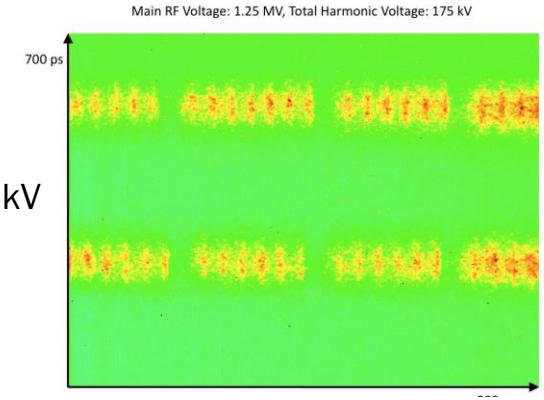
- Uses half of existing 500 MHz active system as harmonic (3rd 4th or 5th depending on fundamental frequency.)
- Requires addition of new ~125 MHz RF system (ala MAXIV)
- Unclear if compatible with existing beam instrumentation (BPMs, etc)
- Bunch spacing ~10 nsec possibly compatible with kicker risetime. No gaps needed.
- Longer bunches better for vacuum system and instabilities.
- Reversion to 500 MHz possible for special user mode.

ALS Measurements of ALS-U bunch t

The ALS can be used to test an ALS-U like fill: same RF and harmonic frequencies, nearly identical harmonic numbers (328 vs. 330). ALS main RF voltage can be lowered to 1.1 MV, which is higher than the ALS-U's 760 kV, but the three HHC installed can be tuned to produce the ideal 378 kV of harmonic voltage, although at a non-ideal phase.

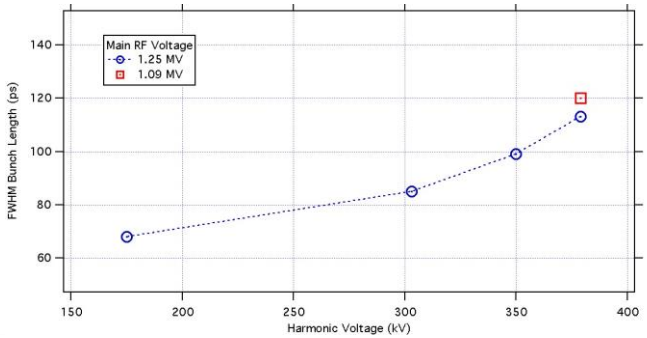


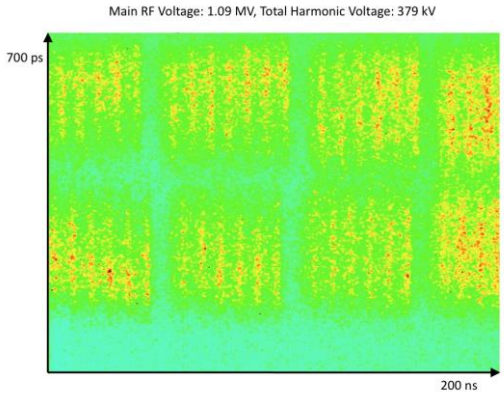
FILL PATTERN



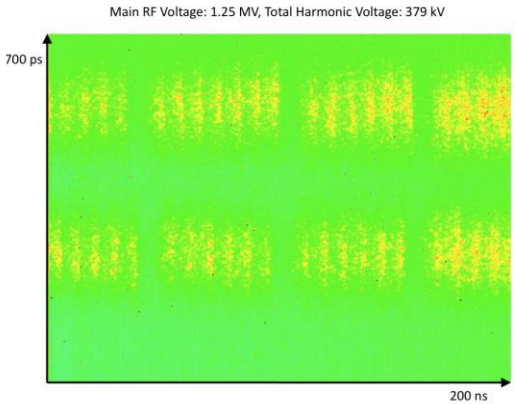
V_h= 175 kV

Stefano De Santis





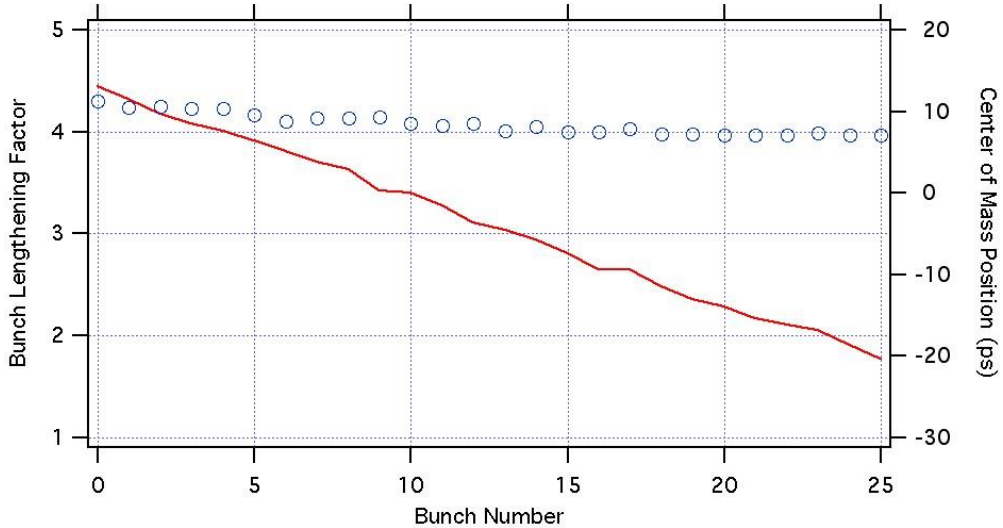
V_h= 379 kV, V_{RF} lowered to 1.1 MV



V_h= 379 kV

mbtrack Simulations

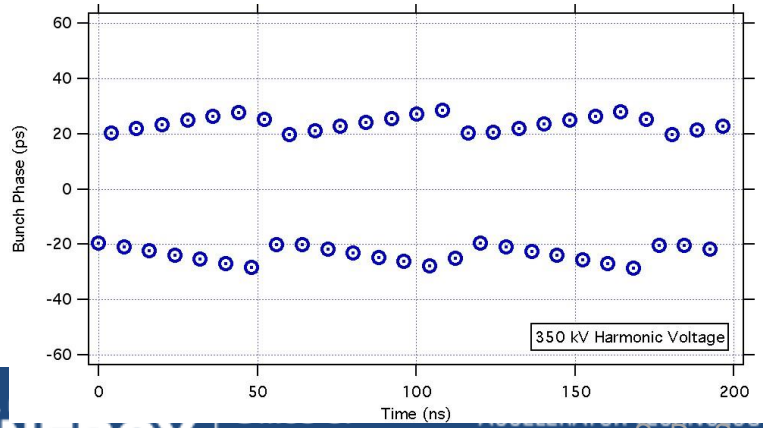
The code, in the version available to us, is able to simulate idealized fills i.e. all bunches have the same charge, or are empty.

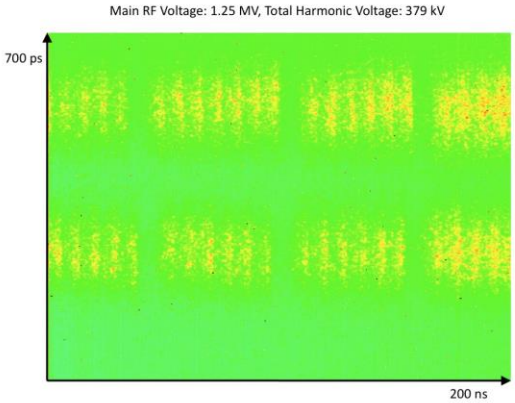


One of the 11 ALS-U trains when the harmonic system is tuned to obtain the optimal harmonic voltage and phase.
Phase transient is limited to 30 ps and a factor 4 increase in bunch length is achieved.

Thanks to Ryutaro Nagaoko and colleagues for mbtrack

Tracking of bunch phases, simulating a streak camera measurement. The ~10 ps transient is practically invisible on the 700 ps vertical scale of the streak camera





Summary of accelerator physics issues

- Harmonic cavities are becoming essential for controlling bunch shapes in all 4GLS to mitigate Touschek lifetime and 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.
  - Unclear if longitudinal feedback is needed or how it can be used with large synchrotron frequency spread.

Summary of technology issues

- RF sources:
  - Low Frequency (50-200 MHz) offers several technology options at the right power range. SSPA favored.
  - High Frequency (>1.5 GHz) available at the 10 kW range in SSPA format. Higher power sources more rare.
- RF cavities:
  - High frequency cavities (>1.5 GHz) exist. NC have large power densities and are limited to ~10 kW/cell. HOM-damped SC cavities exist but typically limited by input power coupler. Is the small beam pipes of 4GLS hinting towards higher frequency cavities?
  - Most HOM-damped designs exist in the 350-500 MHz range. HOM-damping for low frequency cavities can still be optimized. How much HOM damping is needed with Landau cavities in use?
- Almost all of the machine diagnostic/auxiliary systems depend on choice of RF frequency. The practical optimum frequency depends on many factors.