LLRF2017 Low Level Radio Frequency Workshop

BARCELONA 16-19 October 2017

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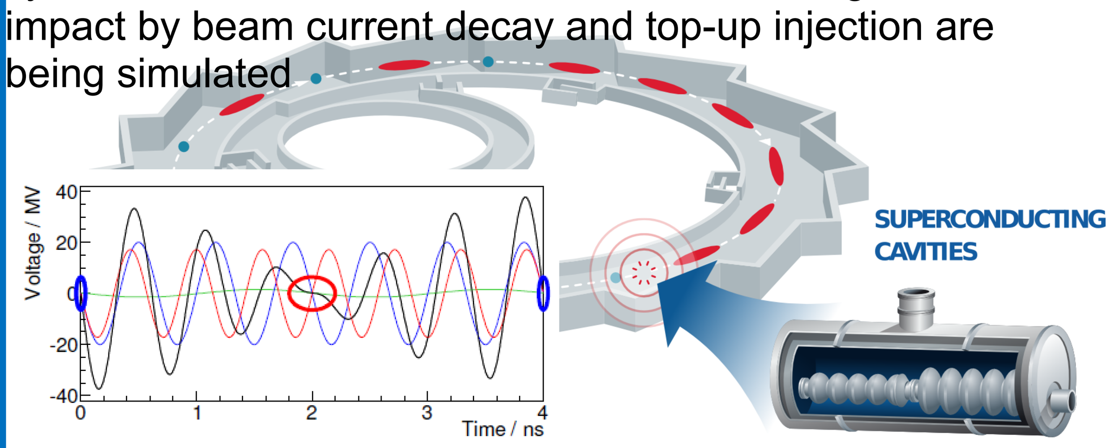
HZB Helmholtz Zentrum Berlin BESSY VSR

Detuning, RF stability and transient beam-loading studies of RF control for the BESSY VSR higher harmonic SC Cavities

Abstract

For the feasibility of the BESSY VSR upgrade project of BESSY II two higher harmonic systems at a factor of 3 and 3.5 of the ring's RF fundamental of 500 MHz will be installed in the ring. Operating in continuous wave at high average accelerating field of 20 MV/m and phased at zero-crossing, the SC cavities have to be detuned within tight margins to ensure stable operation and low power consumption at a loaded Q of $5 \cdot 10^7$. This is especially of importance as the three cavity system is operating in Robinson stable regime whereas the higher frequency harmonic system is intrinsically unstable, requiring the RF feedback systems to damp any rise of instability by exact field control.
The field variation of the cavities is mainly driven by the repetitive transient beam-loading of the envisaged complex bunch fill pattern in the ring. Within this work combined LLRF-cavity and longitudinal beam dynamics simulation will demonstrate the limits for stable operation, especially the coupling between synchrotron oscillation and RF feedback settings. Further impact by beam current decay and top-up injection are being simulated



Add four higher harmonic SC 4-cell cavities, 2 x 1.5 GHz, 2 x 1.75 GHz

Parameter per cavity	1.5 GHz	1.75 GHz
Voltage (MV)	10	8.7
E_{acc} (MV/m)	20.0	20.0
Q_L	5×10^7	4.3×10^7
R/Q TM$_{010}$-π (Ω)	500	500
ϕ_{acc} (degree)	90	-90
Δf for beam-loading (kHz)	-11.25	15.3
Average $P_f(kW)$	1.49	1.0
Voltage 0.5 GHz	1.5 MV	

Parameters for storage ring beam pattern without clearance gaps

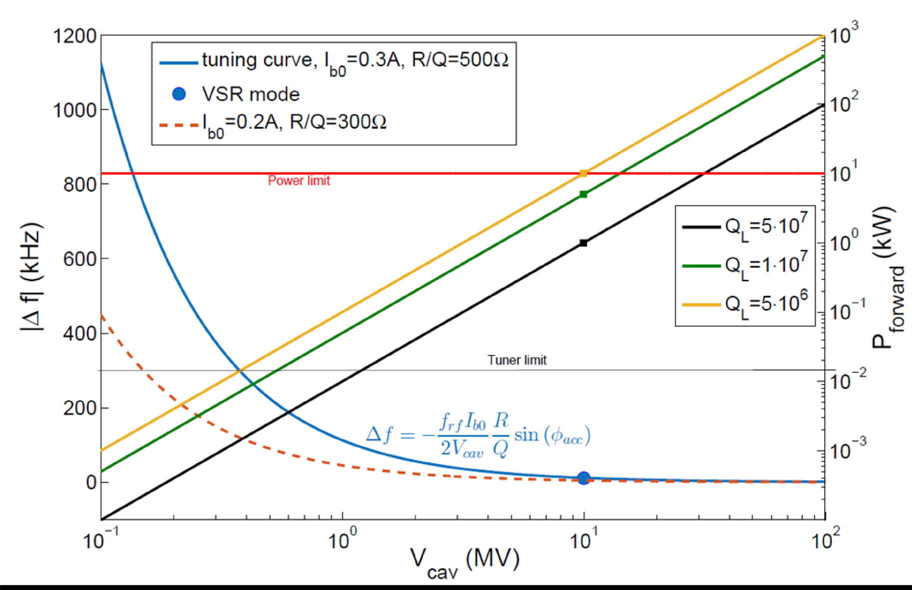
Power requirements, tuning, limitations

For the feasibility of the BESSY VSR upgrade project of BESSY II two higher harmonic systems at a factor of 3 and 3.5 of the ring's RF fundamental of 500 MHz will be installed: Continuous wave operation at 20 MV/m at zero-crossing → Reactive beam-loading dominates required power, compensate by proper tuning

$$P_f \approx \frac{V_{cav}^2}{\frac{R}{Q}Q_L}\frac{1}{4}\left\{\underbrace{\left(\overbrace{1+\frac{\frac{R}{Q}Q_L I_{b0}}{V_{cav}}\cos\phi_{acc}}^{\simeq 1}\right)^2}_{\text{resistive}}+\underbrace{\left(\overbrace{\frac{\Delta f}{f_{1/2}}+\frac{\frac{R}{Q}Q_L I_{b0}}{V_{cav}}\sin\phi_{acc}}^{\text{At best}=0}\right)^2}_{\text{reactive}}\right\} \Rightarrow \boxed{\Delta f = -\frac{R}{Q}\frac{f_{rf} I_{b0}}{2V_{cav}}\sin\phi_{acc}}$$

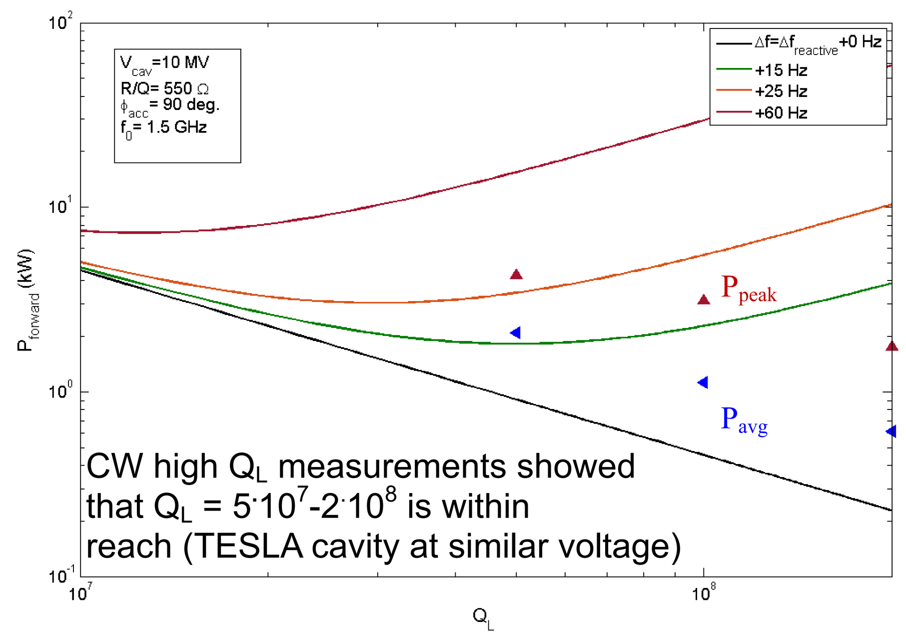
Relax coupler thermal load: Q_L as high as possible

Control $\Delta f(t)$, microphonics, coupled Lorentz force detuning



Tuning needs to be set precisely to avoid large power overhead while ramping the field. Requires slow coarse tuner, ramping for top-up injection in short buckets not an option.

Optimum tuning case:



- Transient beam-loading by bunch pattern leads to phase shift along bunch train as

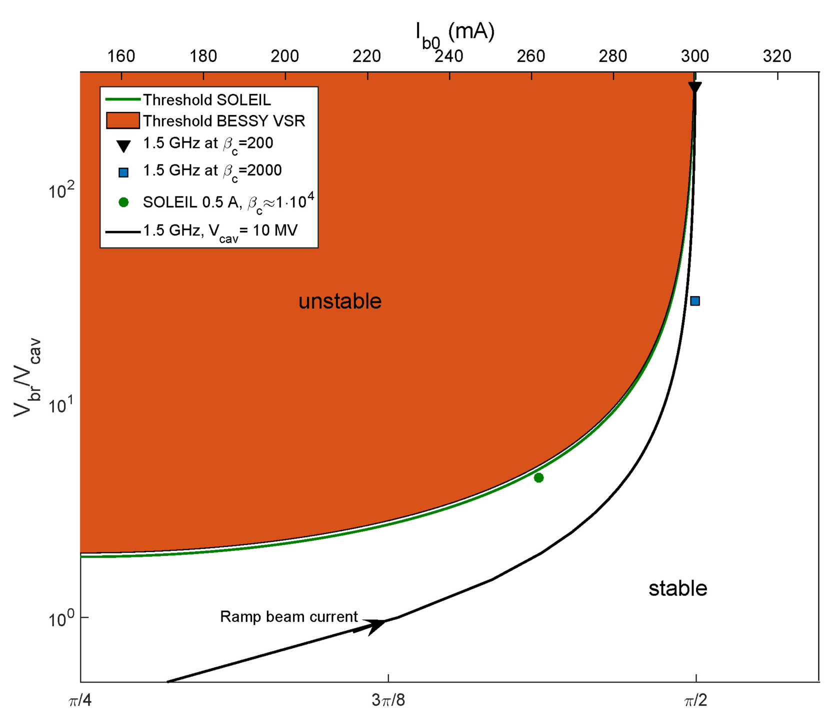
$$\Delta\phi_{max} = \frac{1}{2}\frac{R}{Q}\frac{\omega_{RF}}{V_{cav}} I_{b,0}\,(T - t_0) \Rightarrow$$

Variation of focussing voltage, transient in synchronous phase, time varying RF bucket along bunch train

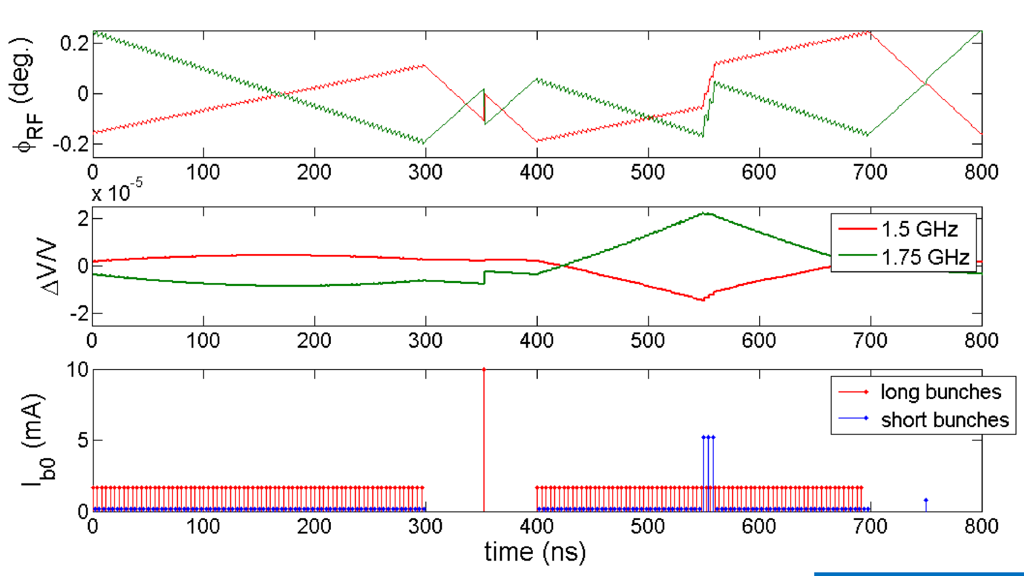
- 1.5 GHz system operated close to DC Robinson limit, 1.75 GHz system intrinsically unstable for DC and AC Robinson w.r.t. long buckets

→ The three frequency system forms a stable RF potential, but how stable is that system?

Robinson stability

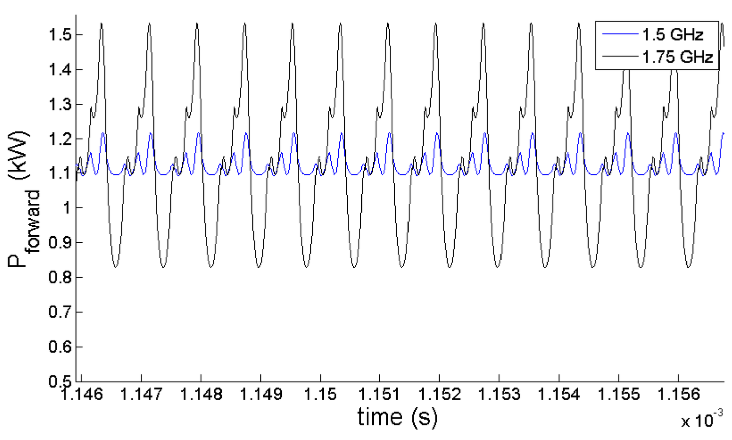


Coupled RF Cavity-LLRF-long. beam dynamics Simulations



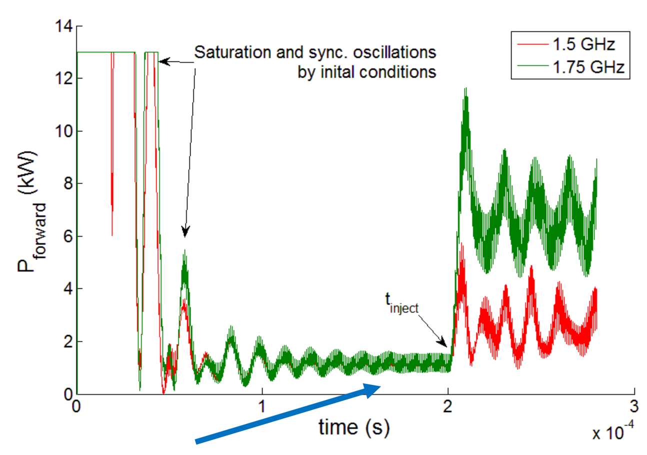
Beam dynamics and RF settings	
Beam Energy	1.7 GeV
Momentum compaction α	7.1×10^{-4}
Effective beam current I_{b0} at 1.5 GHz	300.3 mA
I_{b0} at 1.75 GHz	257.5 mA
Harmonics number 1.5 GHz	1199.991
and at 1.75 GHz	1400.008
Revolution period	800 ns
Radiation damping time	8 ms
with feedback	0.75 ms
LLRF and Cavity settings	
DC Feedback gain K_P	3500
Loop filter cutoff	50 kHz
Loop latency	800 ns
Q_L	5×10^7
$P_{forward}$	13 kW

- Based on LCR model [11]
- Tracks bunches as macro particles
- Includes long. dynamics



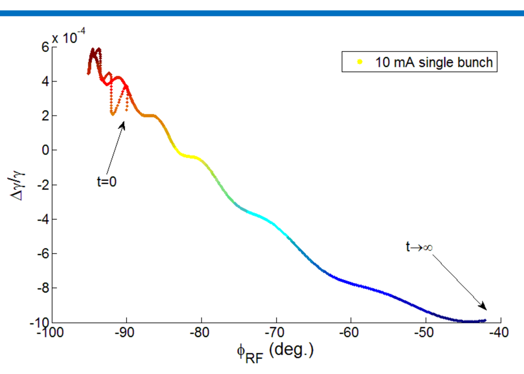
Short term power transfer between systems, net transfer zero on average

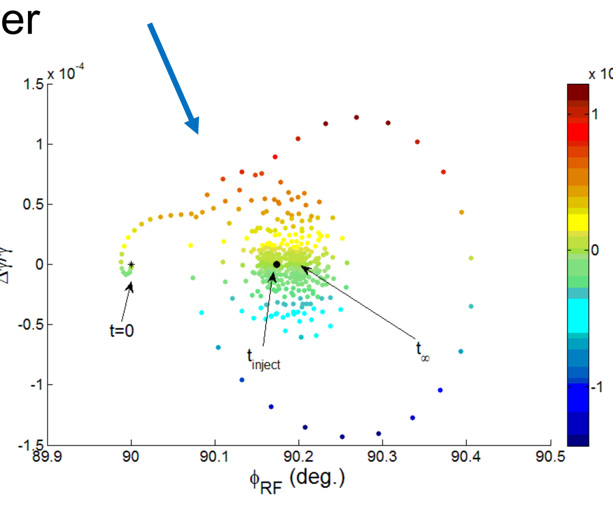
- Given sufficient feedback gain the system is stable, phase transient is of the expected order and deviation with time
- Coupling to voltage by gaps and single bunches
- 1.75 GHz system intrinsically more susceptible towards perturbations



Top-up injection without proper tuning, new stable solution by increased RF power

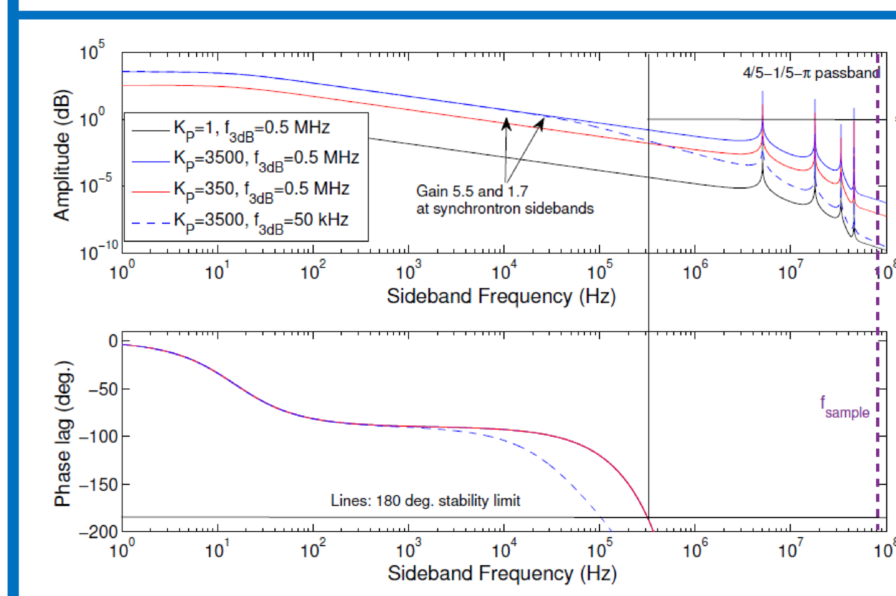
Given a too small LLRF feedback gain, about factor of 100 lowered, gives rise to coupled AC and DC Robinson instability, starting in the 1.75 GHz system →





Conclusions

- The total system is stable, even for a very complex bunch pattern, the tuning working point can be determined by simulation
- A beam current measurement needs to be implemented for stable operation
- Given the power reserve (13 kW), a 60 Hz detuning offset or 1.5 mA beam current shift are still being compensated
- Both SC cavity systems can be operated at low power and high Q_L
- Transient beam-loading dominates cavity field amplitude and phase variations
- Given a low gain, Robinson instability can be observed
- Todo: Frequency domain analysis



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