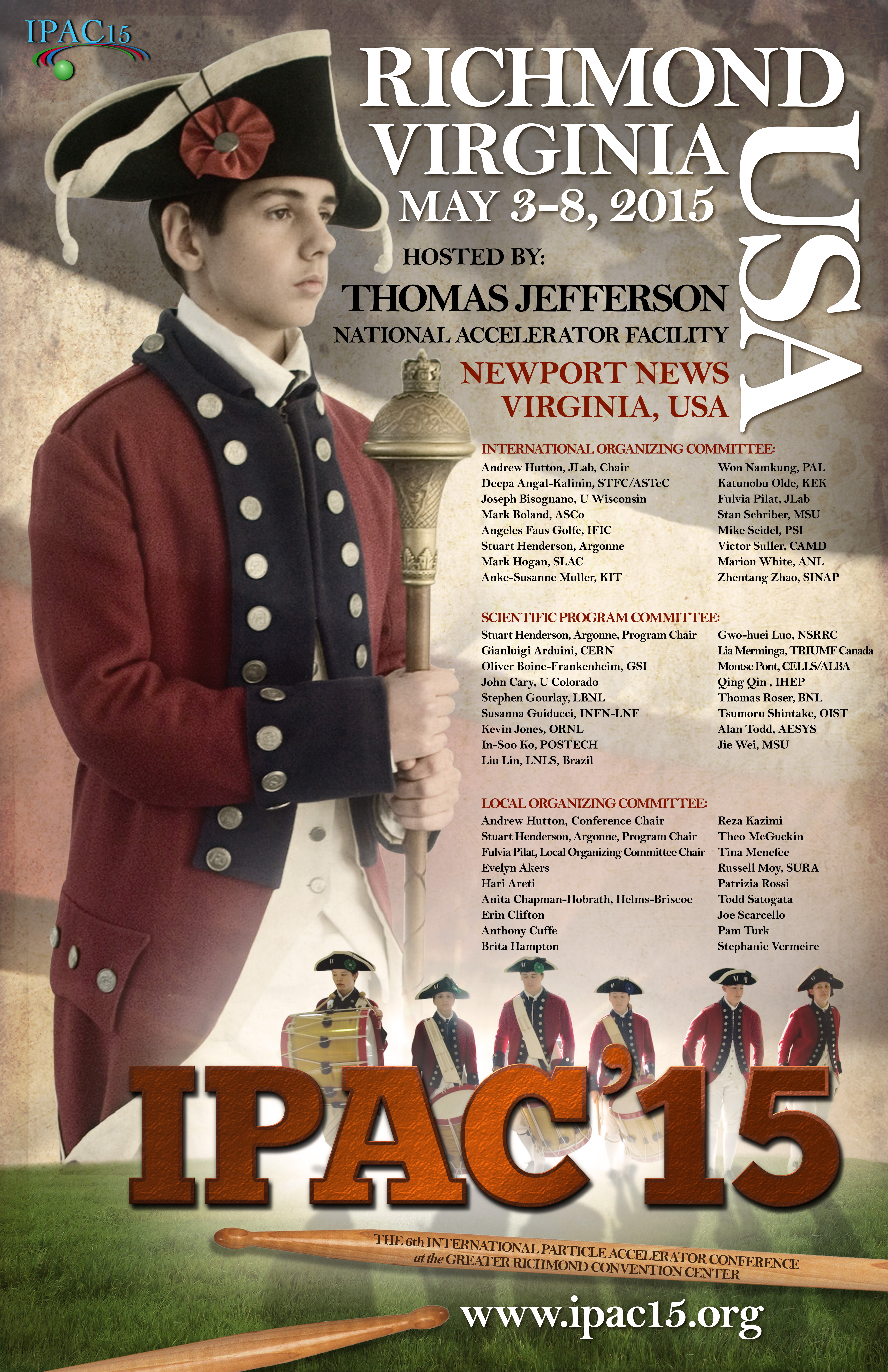

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RF FEEDBACK AND DETUNING STUDIES FOR THE BESSY VARIABLE PULSE LENGTH STORAGE RING HIGHER HARMONIC SC CAVITIES*

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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 superconducting cavities have to be detuned within tight margins to ensure stable operation and low power consumption at a loaded Q of 5×10^7. 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 shots are being simulated.

CHALLENGES FOR VSR SRF CW CAVITY OPERATION

To simultaneously create RF buckets for long and short pulses two higher harmonic RF systems have to be operated in zero-crossing at 1.5 and 1.75 GHz respectively [1, 2]. With respect to both bucket types the 1.5 GHz cavities will work in the focusing regime, whereas the 1.75 GHz cavities will be defocusing for the long buckets where the latter carry the majority of the average beam current. Table 1 shows the required RF parameters for an continuous fill pattern of the storage ring. In order to achieve the desired bunch shortening the average accelerating field will be E_{acc} 20 MV/m. This scheme implies several challenges for the stable operation of the higher harmonic system. The required power for a given cavity voltage V_{cav}, normalized shunt impedance $R/Q = V_{cav}^2/(\omega U)$, average beam current I_{b0} and accelerating phase ϕ_{acc} is [3]:

Table 1: RF system parameters for an even beam pattern without clearance gaps in the storage ring and two 5 cell cavities per higher harmonic.

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}-$\pi(\Omega)$	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	

$$P_f \approx \frac{V_{cav}^2}{\frac{R}{Q} Q_L} \frac{1}{4} \times \tag{1}$$

$$\left\{ \underbrace{\left(1 + \frac{\frac{R}{Q} Q_L I_{b0}}{V_{cav}} \cos\phi_{acc}\right)^2}_{\text{resistive}} + \underbrace{\left(\frac{\Delta f}{f_{1/2}} + \frac{\frac{R}{Q} Q_L I_{b0}}{V_{cav}} \sin\phi_{acc}\right)^2}_{\text{reactive}} \right\},$$

where $\Delta f / f_{1/2}$ is the ratio of expected peak detuning to cavity half-bandwidth $f_{1/2} = f_{rf}/(2Q_L)$. Assuming the reactive beam loading can be compensated and controlled as

$$\Delta f = -\frac{R}{Q} \frac{f_{rf} I_{b0}}{2V_{cav}} \sin\phi_{acc}, \tag{2}$$

the cavity can be treated as a zero-beam CW SRF cavity operated at potentially high loaded Q to allow for low average forward power level at the coupler. This would reduce the problem to control any unwanted detuning by microphonics and coupled Lorentz-force detuning. Operation at comparable cavity voltages of a TESLA cavity at loaded Q up to 2×10^8 with low residual phase errors below 0.02 deg has been already demonstrated [4]. The optimum Q_L is then given by $\frac{1}{2} f_{rf}/\Delta f$, here about 5×10^7.

Tuning and Ramping the Cavities

In order to inject from the current booster synchrotron into the short bunches, the higher harmonic cavities (HHC) need to be ramped down to about ≤ 0.1MV [5]. As shown in Figure 1 that would require hundreds of kHz, only achievable by slow coarse tuners and such lead to a too long dark time for short pulse users. Also by the shorter lifetime of the short buckets that tuning would be performed with a high duty cycle posing the danger of mechanical stress, tuner failure or even vacuum leakage. For fast piezo tuners the typical range is far below the one needed for the field ramp. Thus an upgrade of the injection is currently discussed at HZB. At the VSR working point a power of about one kW is required to maintain the cavity voltage. The RF power overhead up to a level of 13 kW will allow one effect of the following at a time:

- A factor of three of the expected peak detuning of 20 Hz, thus $4 \times f_{1/2}$
- A not well synchronized top-up injection with a current jump of 1.5 mA

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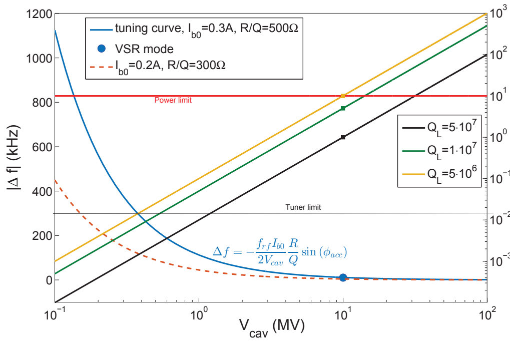

Figure 1: Optimum tuning curve for reactive beam-loading for the VSR (blue curve) and a lower R/Q-reduced intensity scenario (brown curve) as well as the required power with optimum detuning for different Q_L. Limits of the tuner and power source are given by the horizontal lines.

- An one mbar pressure change of the under-pressure 16 mbar helium system

Thus, a Q_L =5 × 10^7 and 13 kW operation is within reach allowing to use existing L-band RF coupler designs. Besides microphonics and Lorentz-force detuning compensation [6] a dedicated tuning loop including beam current measurement and cavity voltage monitoring is mandatory.

Transient Beam-Loading and Robinson Instability

However, there are two major drivers of longitudinally instabilities which need to be considered. For VSR a rather complicated bunch pattern is foreseen to serve the different needs of the high flux long pulse users and the time resolved experiments relying on single short bunches. Figure 2 shows the more complex pattern envisaged for VSR operation. Two 100 ns gaps induce a variation of the beam induced voltage along the bunch train leading to transient beam-loading at revolution frequencies of 1.25 MHz and 2.5 MHz.

By the mainly reactive beam-loading and high impedance a linear gap induced phase transient in the cavity RF can be calculated as [3, 7, 8]:

$$\Delta\phi_{\max} = \frac{1}{2}\frac{R}{Q}\frac{\omega_{\mathrm{RF}}}{V_{\mathrm{cav}}} I_{\mathrm{b},0}\,(T - t_0)\,. \quad (3)$$

Here, ω_{RF} is the RF frequency and $(T - t_0)$ the gap length. For VSR a peak phase transient of ≈0.4 degrees can be expected. Because of the different phasing, the phase transient of the 1.75 GHz cavity will have opposite sign than the 1.5 GHz cavity transient.

Another limitation is given by the high intensity beam-loading limit often referred to as DC Robinson stability [9]. The 3$^{\mathrm{rd}}$ harmonic cavity would be close to the edge of the DC stability limit for tuning of the reactive beam-loading given the coupling of β_c ≈200 to account for 15-20 Hz peak detuning. With respect to the AC stability the tuning shifts the beam coupling impedance to the stable side of the resonance. Figure 3 shows the fraction of beam induced to cavity voltage maintained by the RF system including

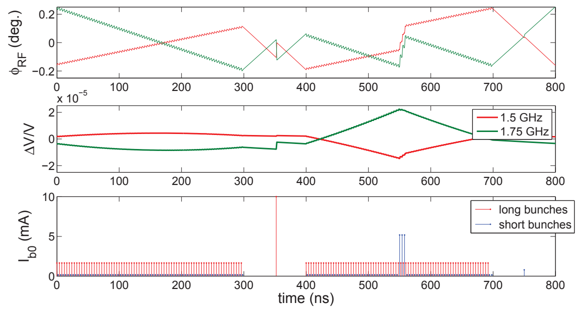

Figure 2: Transient in RF phase and relative cavity voltage due to the beam-loading of the bunch pattern shown below.

the ramping of the beam current at full cavity voltage and optimum detuning for the 1.5 GHz cavity.

The 1.75 GHz cavity is always within the unstable regime given by the defocusing of the long buckets with respect to the DC Robinson case and also for the reactive beam-loading compensation, thus giving rise to growing synchrotron oscillations.

Further, the tuning for reactive beam-loading for both systems is within the range of the varied synchrotron frequency along the train, also being a cause of the transient beam-loading, see [10]. In theory, the combination of all three voltages form a restoring potential compensating the beam induced voltage deviation. The key questions are, if this is a stable potential or a labile system perturbed by any small change of any given parameter? Further, is there an unwanted net power transfer between the different cavity systems? It is well known, that reducing the cavity impedance seen by the beam by increasing the coupling and adding an anyway required high gain LLRF feedback loop helps mitigating any rise of unstable oscillation or decay in the longitudinal phase space [8]. The first option will be only used within some limitations (Q_L ≥1 × 10^7). Given the complex bunch structure and the different tuning and RF

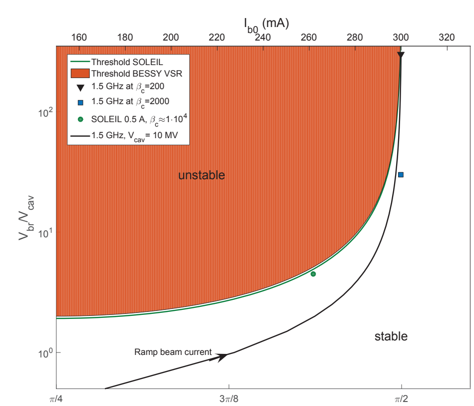

Figure 3: DC Robinson stability plot for BESSY-VSR including ramping of the beam current (black line) and a comparison to the SOLEIL fundamental system.

feedback loops stabilizing both systems, these questions are best addressed by means of simulations.

RF CAVITY AND LONG. BEAM DYNAMICS STUDIES

The cavity RF field and LLRF feedback model is derived from the LCR circuit model as presented in [11]. It features RF feedback and tuning loops, second order mechanical models of piezo action and Lorentz-force detuning. It was extended with a new beam model and tracks bunches as macro-particles in the storage ring longitudinal phase space. The whole model makes use of the MATLAB-Simulink™ environment. The simulation parameters and LLRF settings

Table 2: RF and Beam Dynamics Simulation Parameters

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

are summarized in Table 2. Although there is a high gain feedback still within stable margin according to Bode plot analysis not shown here, the effective gain at the synchrotron sidebands is about 2-4. This is by a steep cut-off of the loop filter to avoid same passband modes ($\Delta f_{4/5\text{-}\pi}$ ≈0.81 MHz, see [12]) excitation and to suppress high power transient beam-loading compensation at the revolution frequency. Figure 2 depicts the phase and cavity voltage transient by the bunch train pattern. The deviation of about 0.4 deg. is of the expected order. There is significant influence by the single bunches. In steady state the required power is close to the zero-beam case and there is no net energy transfer between the cavity systems. Only on a short time scale across the train there is a back and forth swapping of beam power.

Figure 4 shows the damped synchrotron oscillations of a long bucket bunch and its new stable solution after 1.2 mA beam injection. As there is no tuning adjustment, the power overhead is required for compensation (Figure 5) and the synchronous phase shifts.

Figure 6 shows, that for a factor of 100 lower feedback gain, the total system becomes unstable and a DC Robinson instability can be observed.

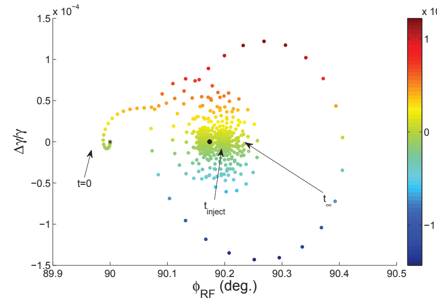

Figure 4: Synchrotron oscillation of a long bucket bunch and new stable solution after injection without tuning adjustment.

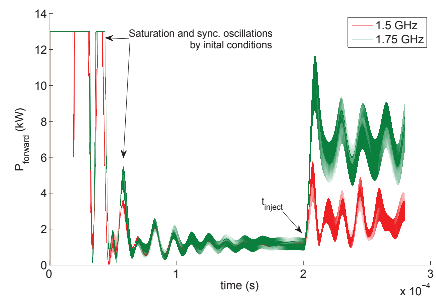

Figure 5: Required RF power due to initial synchrotron oscillations, following steady state and deviation by 1.2 mA beam injection in three long buckets.

CONCLUSIONS AND OUTLOOK

There seems to be no net energy transfer between the cavity systems and given a high gain feedback the total system is stable. The power overhead can compensate for improper tuning of the cavities e.g. during top-up injection or detuning offsets as expected. The 1.75 GHz system is generally more susceptible towards any perturbation hinting at the intrinsic Robinson unstable regime of operation, but is partly stabilized by the other system. Future studies will map this onset of instability using these simulations and study further means to compensate those.

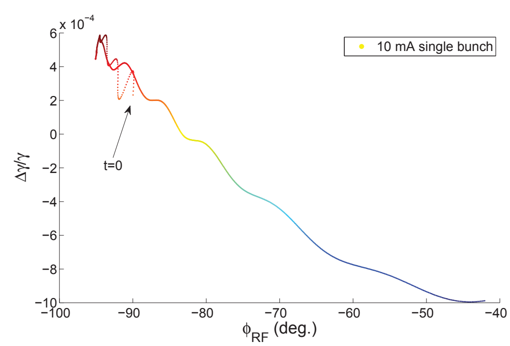

Figure 6: Example of DC Robinson instability caused by a too low feedback gain of K_P=35.

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