Modelling and Simulation of the RF system for SOLEIL Synchrotron

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ABSTRACT

An analysis of beam stability in the SOLEIL synchrotron with two different basic systems (direct and amplitude/phase feedback) was carried out during the preliminary design phase in 1999. Since then, on the one hand, the beam energy was pushed from 2.5 GeV to 2.75 GeV, which led to a change of several other machine parameters such as the harmonic number, accelerating voltage, relative beam loading factor and external coupling factor; on the other hand, an analog LLRF system combining one fast direct feedback and slow amplitude/phase loops was approved for the machine commissioning. Therefore, a new simulation for the optimisation of the LLRF system parameters appeared necessary. It additionally takes into account different features (loop delays, bandwidth limitation, extra power budget, possible implementation of a comb-filter, etc.), which were ignored in the preliminary analysis. A comparison with a fast digital I/Q LLRF system, currently under development, is also presented with a Matlab and Simulink based simulation tool, which is more versatile than the formerly used Fortran based code.

INTRODUCTION

In the SOLEIL storage ring, two cryomodules (CM), each containing a pair of 352 MHz cavities, will provide the maximum power of 600 kW, required at the nominal energy of 2.75 GeV and full beam current of 500 mA. Each of the four cavities is powered by a solid state amplifier, which can deliver up to 190 kW.

The Low Level RF system that will be used in a first phase consists in "slow" amplitude/phase and frequency loops, complemented by a fast direct RF feedback in order to cope with the heavy beam loading conditions (Figure 1). A fast digital FPGA-based I/Q feedback is presently under development, that should be implemented, later on (Figure 2).

Stability studies are being performed for both applications, using a Matlab – Simulink based simulation tool. From the modelling point of view, a single resonator represents all cavities, providing the total accelerating voltage.

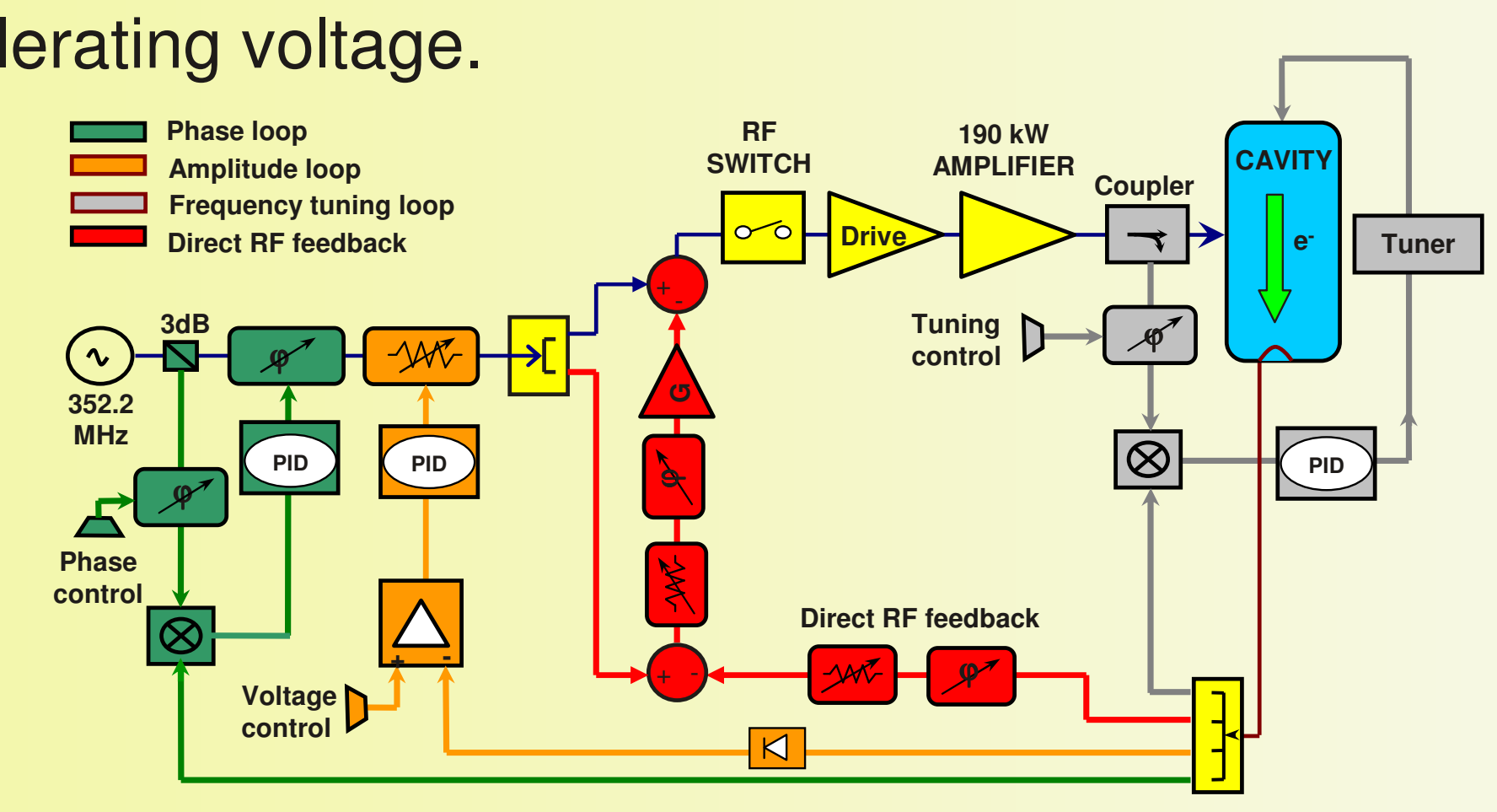


Figure 1 – Analog "slow" loops and RF feedback

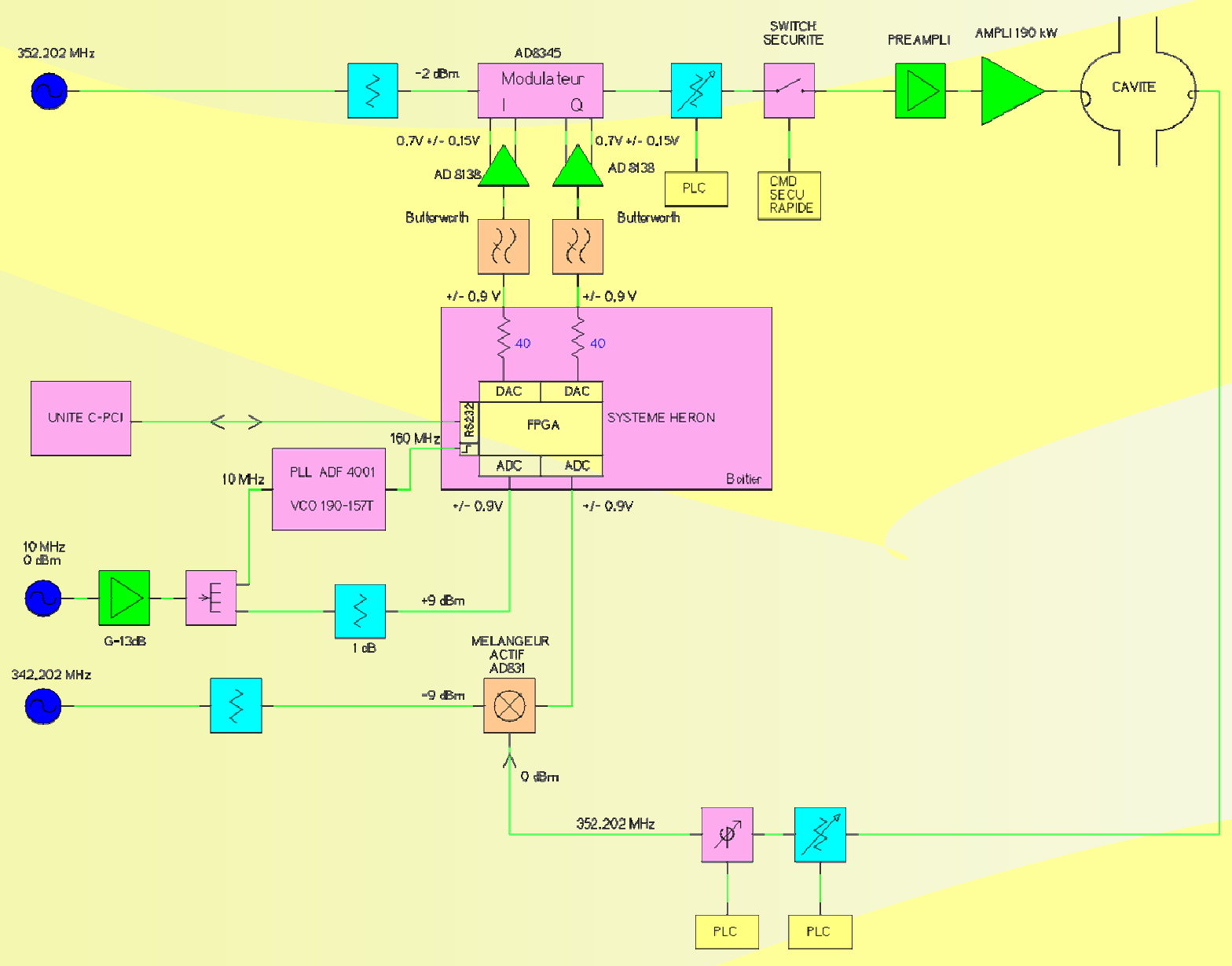
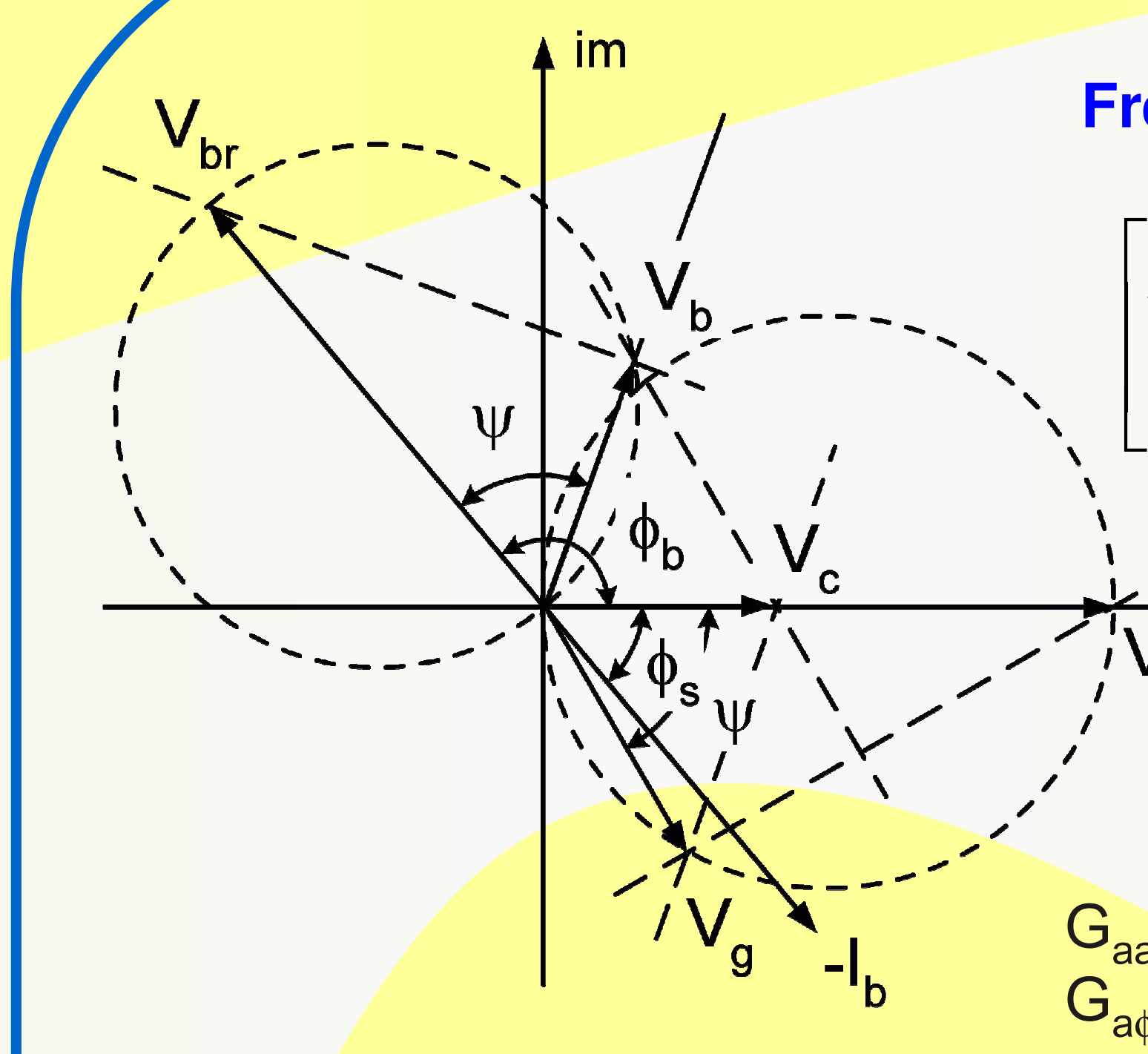


Figure 2 – Digital I/Q Control loop

MODELLING



Phasor diagram

Frequency domain analysis (Pedersen model)

$$\begin{bmatrix}\frac{\delta V_c}{V_c}\\ \delta\phi_c\end{bmatrix}=\begin{bmatrix}G_{aa} & G_{a\phi}\\ G_{\phi a} & G_{\phi\phi}\end{bmatrix}\begin{bmatrix}\frac{\delta V_b}{V_b}\\ \delta\phi_b\end{bmatrix}$$

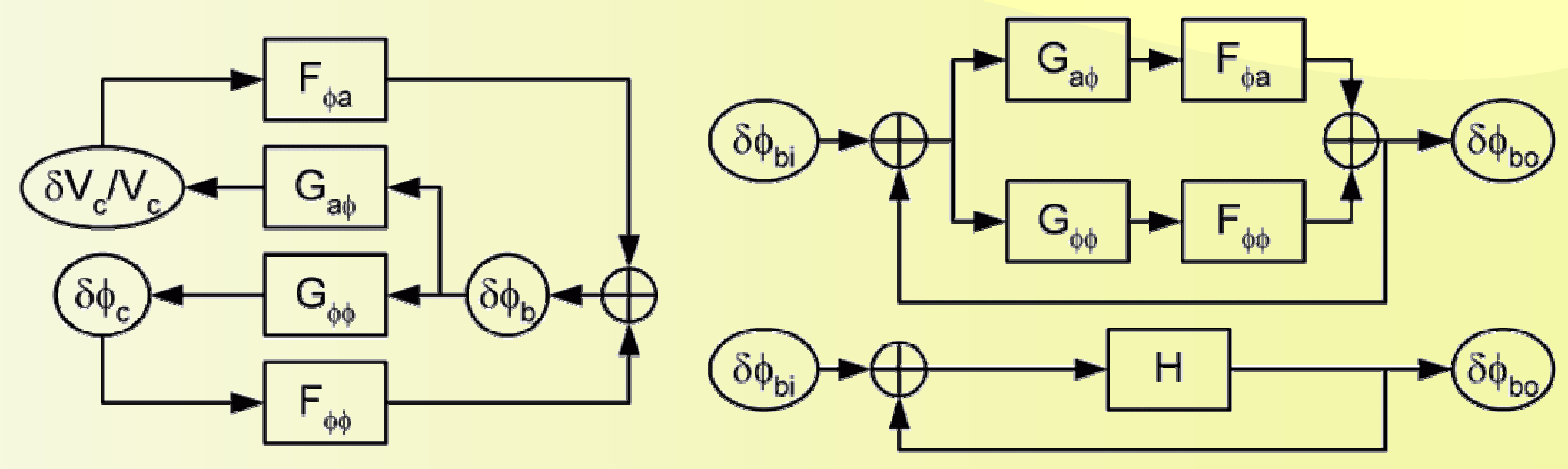
$$\delta\phi_b=F_{\phi a}\frac{\delta V_c}{V_c}+F_{\phi\phi}\delta\phi_c$$

$$F_{\phi a}=-\frac{1}{\tan\phi_s}\frac{\omega_s^2}{p^2+\omega_s^2}\qquad F_{\phi\phi}=\frac{\omega_s^2}{p^2+\omega_s^2}$$

$$G_{aa} = G_{\phi\phi} = G_1\cos\phi_s + G_2\sin\phi_s$$

$$G_{a\phi} = -G_{\phi a} = G_1\sin\phi_s - G_2\cos\phi_s$$

G_1, G_2 depend on the feedbacks



For a direct feedback with delay :

$$H_d(p)=\frac{-\omega_s^2 Y\tan\psi}{\sin\phi_s(p^2+\omega_s^2)((1+G(1-\tau_d p+\tau_d^2p^2/2)+\tau p)^2+\tan^2\psi)}$$

Characteristic equation : 1 - H = 0

Poles ⇒ Robinson damping time vs. the gain

Time domain analysis (Simulink model)

First order cavity model

$$\dot{V}_{cr} = \frac{1}{\tau}\left[V_{gr}-V_{cr}-\tan\psi.V_{ci}\right]$$

$$\dot{V}_{ci} = \frac{1}{\tau}\left[V_{gi}-V_{ci}+\tan\psi.V_{cr}\right]$$

Beam loading

$$V_{cr}^{+} = V_{cr}+\omega_{RF}\left(\frac{R}{Q}\right)q\cos\phi_b$$

$$V_{ci}^{+} = V_{ci}+\omega_{RF}\left(\frac{R}{Q}\right)q\sin\phi_b$$

Synchrotron motion

$$\Delta E_i^{n+1} = \Delta E_i^n - V_c\cos\left[\phi_{b0}+(\delta\phi_b)_i^n-\phi_c\right]-\left(U_0+D\,\Delta E_i^n\right)$$

$$(\delta\phi_b)_i^{n+1} = (\delta\phi_b)_i^n - \frac{2\pi f_{RF}\,\alpha}{f_0\,E_0}\left\{\Delta E_i^n - V_c\cos\left[\phi_{b0}+(\delta\phi_b)_i^n-\phi_c\right]-\frac{U_0+D\,\Delta E_i^n}{2}\right\}$$

Direct feedback

$$\tilde{V}_g=\tilde{V}_{g0}+G\left(V_{c0}-\hat{D}\,\tilde{V}_c\right)$$

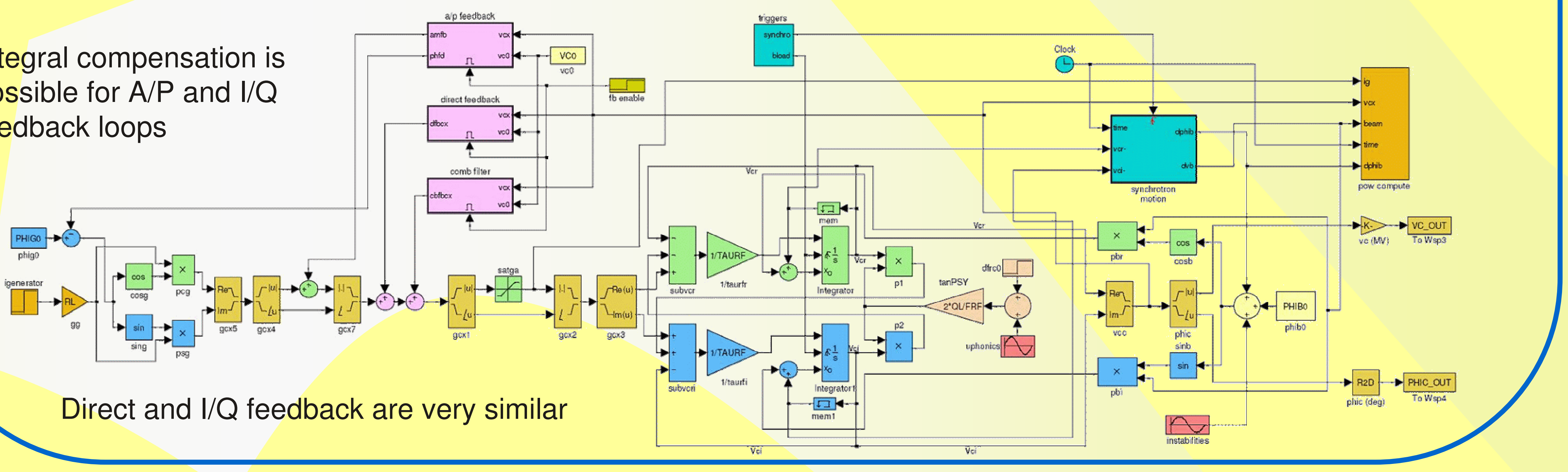
Slow amplitude/phase loops

$$\tilde{V}_g=\left[\left|\tilde{V}_{g0}\right|+G_A\hat{H}_A\left(V_{c0}-\hat{D}\left|\tilde{V}_c\right|\right)\right]\exp j\left(\phi_{g0}-G_P\hat{H}_P\hat{D}\,\phi_c\right)$$

Fast I/Q feedback

$$\tilde{V}_g=\tilde{V}_{g0}+G_I\left(V_{c0}-\hat{D}\,V_{cr}\right)-j\,G_Q\hat{D}\,V_{ci}$$

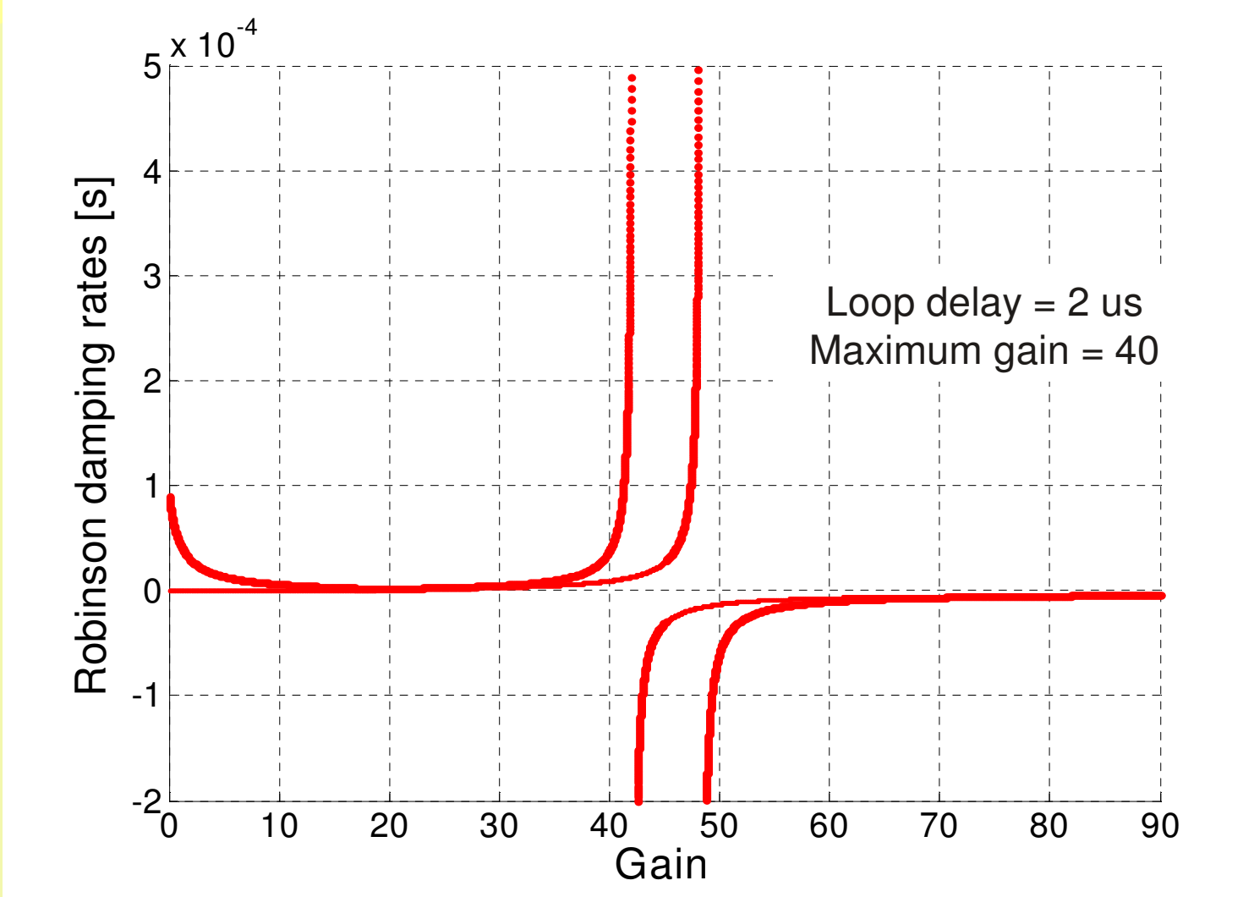
Integral compensation is possible for A/P and I/Q feedback loops



Direct and I/Q feedback are very similar

SIMULATION RESULTS

Direct feedback loop without disturbance



Slow A/P loop characteristics

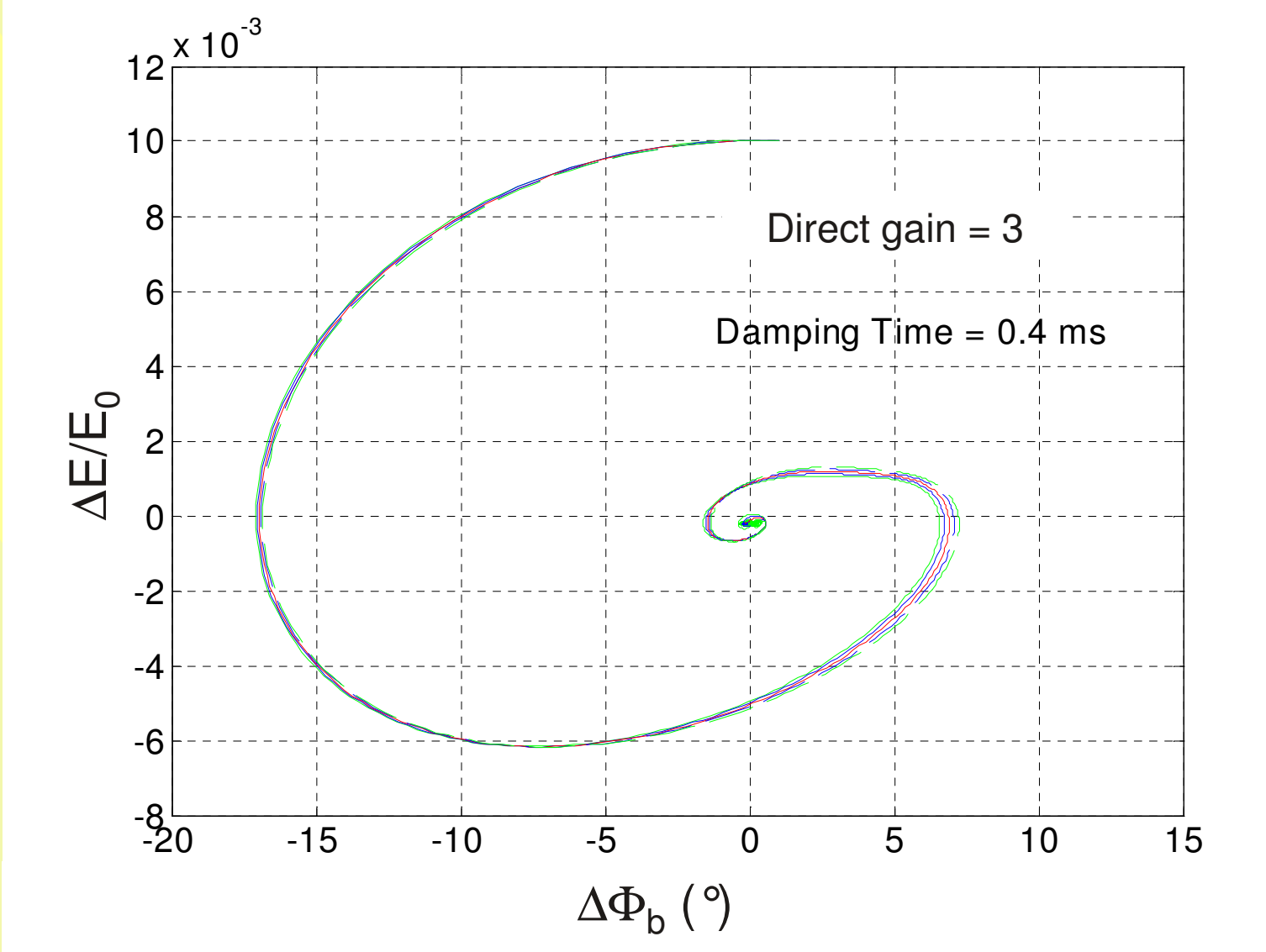
	Amplitude	Phase	Frequency
Accuracy	± 0.25 %	± 0.4°	± 30 Hz
3 dB BW	12 kHz	7 kHz	5 Hz

Disturbance parameters

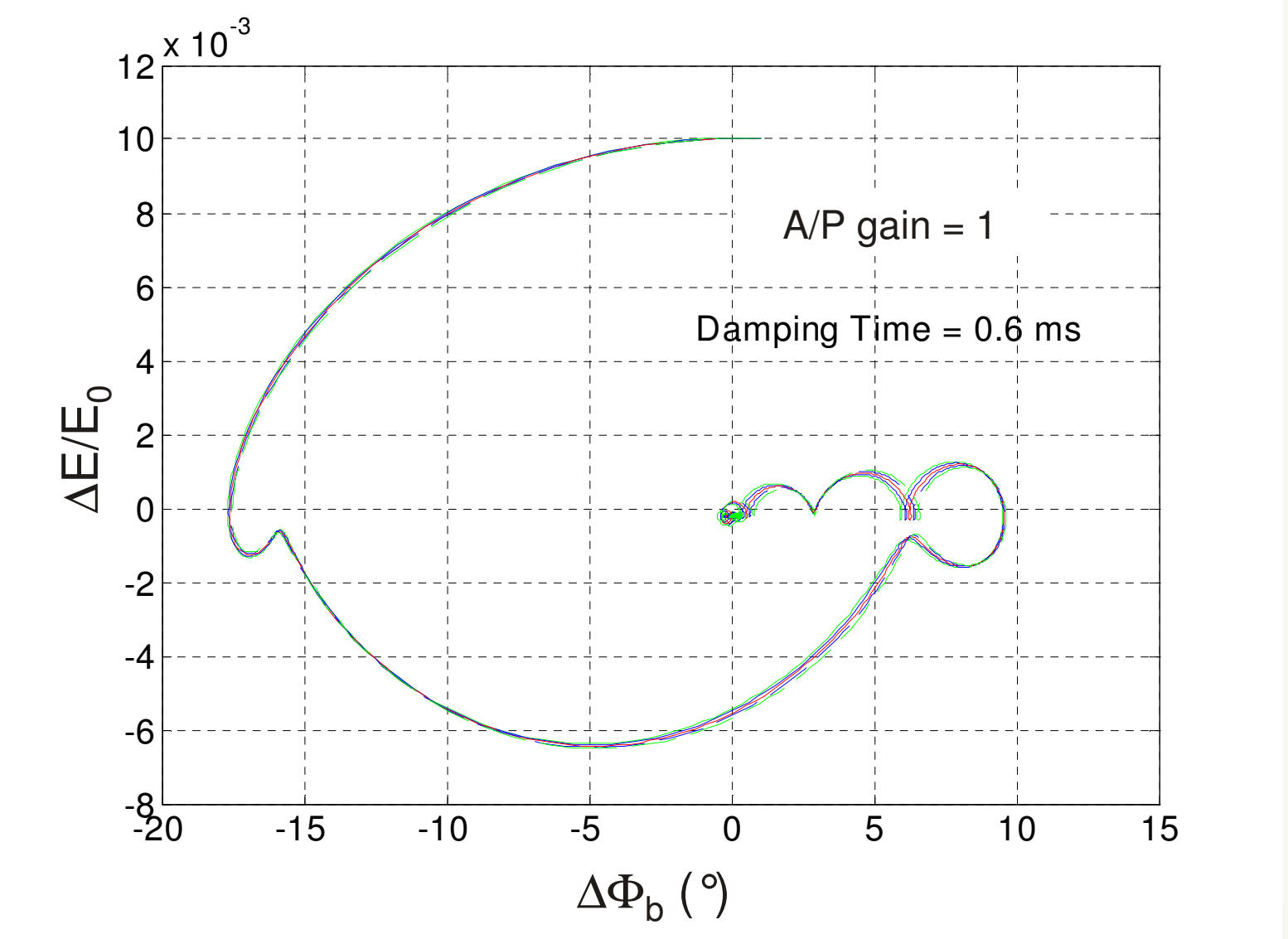
Injection phase error (°)	1
Relative injection energy error (%)	1
Microphonics (freq =200 Hz | Amp = 20 Hz)	

DISTURBED BEAM STABILITY STUDY

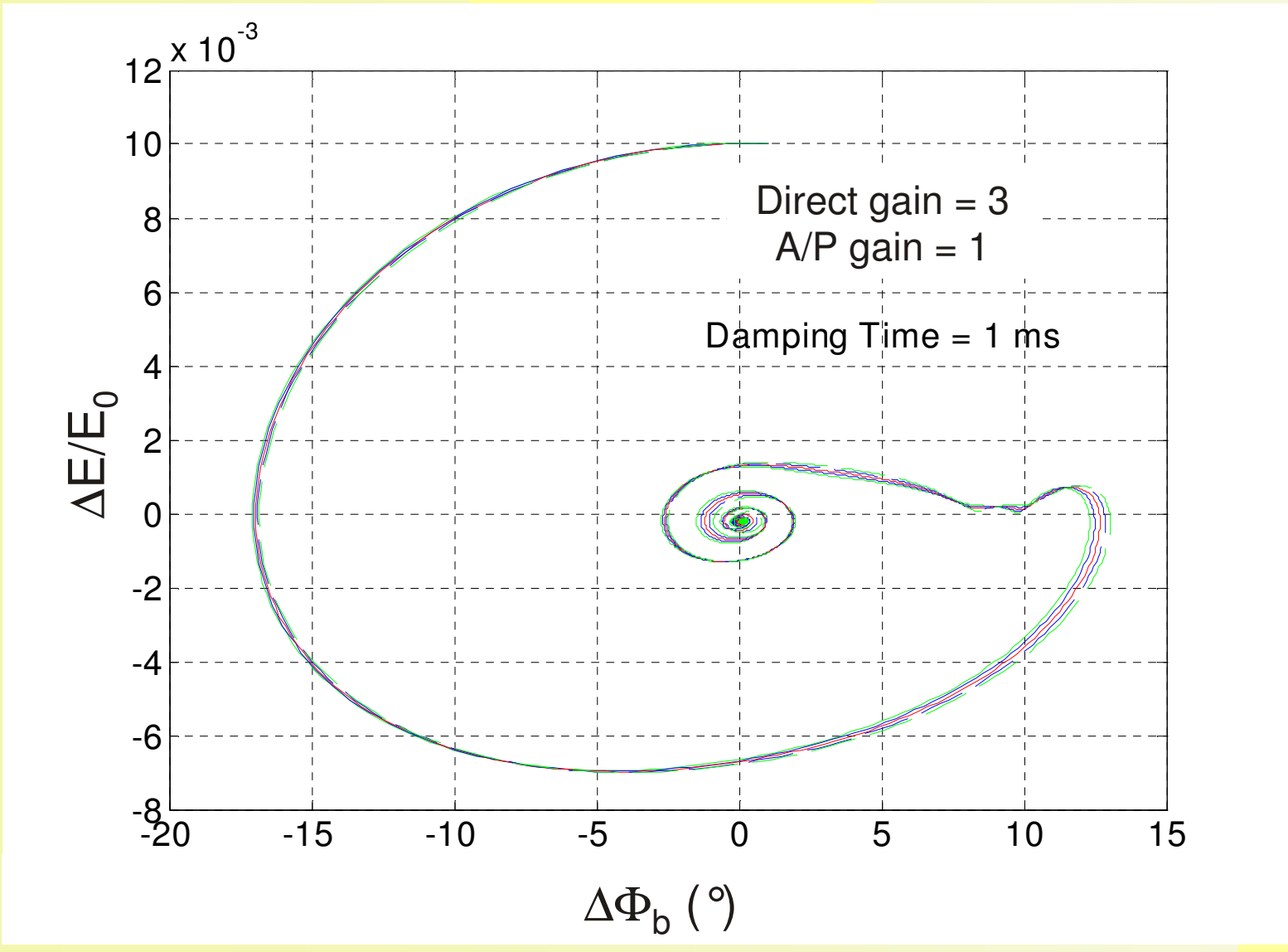
Direct feedback loop performance



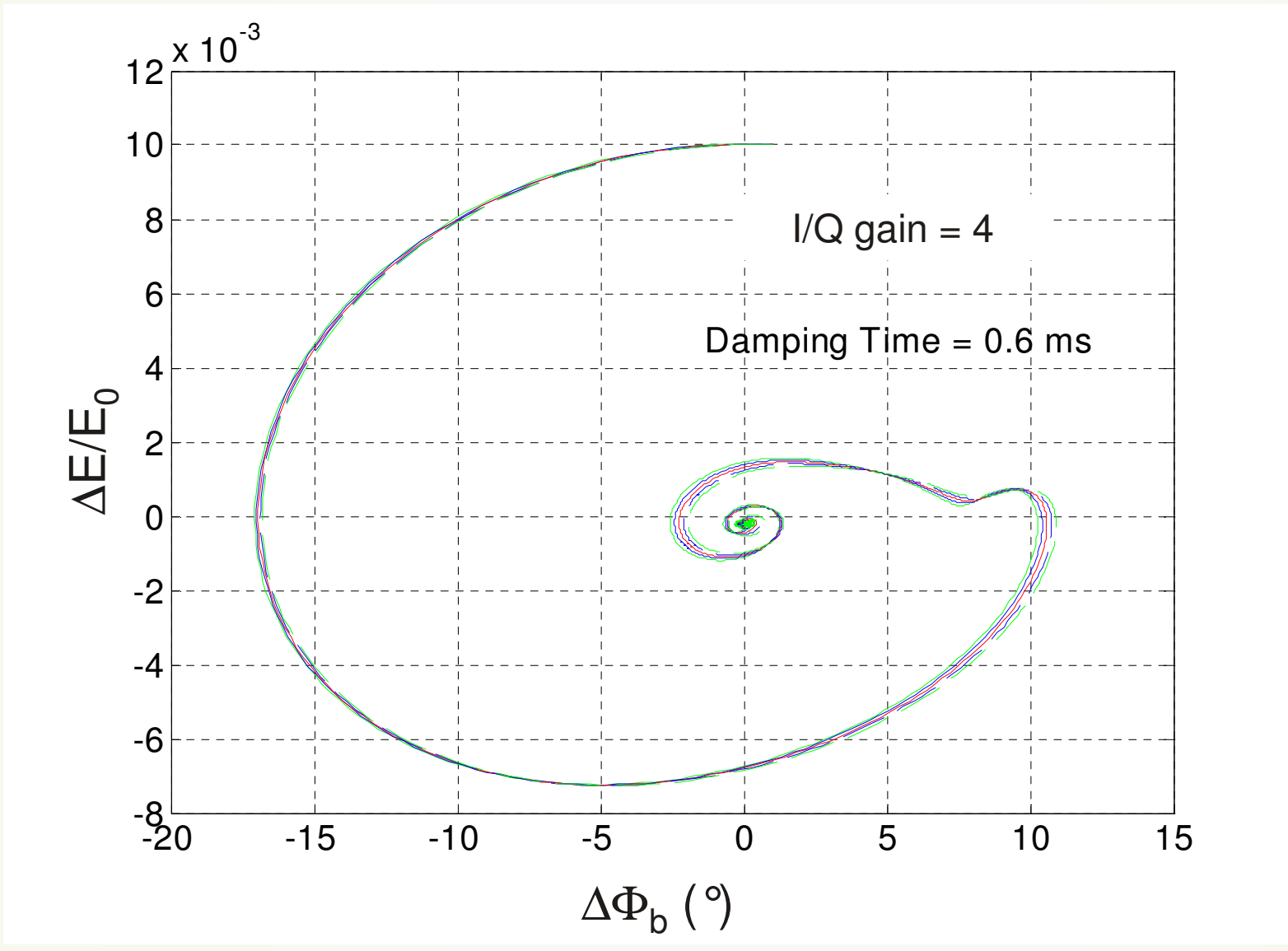
Slow A/P loop performance



Direct feedback + A/P loop performance



Digital I/Q feedback loop performance



STORAGE RING PARAMETERS

	2 CM
RF frequency (MHz)	352.202
Harmonic number	416
Missing bunches	~40
Nominal energy (GeV)	2.75
Energy loss per turn (keV)	944+184(ID)+22(PM)
Momentum compaction factor	4.38 10^{-4}
Energy damping D parameter	6.88 10^{-4}
Cavity loaded quality factor	10^5
R/Q circuit per cavity (Ohm)	45
Beam current (mA)	500
Total cavity voltage (MV)	4
Synchronous phase (°)	73.6
Tuning angle (°)	-77.8

CONCLUSIONS

With superconducting cavities and heavy beam loading, Soleil operates close to the limit of Robinson instability. The stability margin at 500 mA is about 3% in current and 5° in phase.

A Matlab-Simulink based simulation tool has been developed in order to better understand the beam/cavity interferences in presence of disturbances (injection errors, microphonics …) and with different feedback systems.

The first results point out that the beam stability in Soleil can be achieved using either a direct analog feedback (phase 1) or a fast digital I/Q feedback (phase 2) with loop gain lower than 5.

The corresponding hardware designs are described in details in "Control and Low Level RF System of the SOLEIL Synchrotron" (poster presented at this conference).