Superconducting cavity control and operation

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Cavity RF control

There are numerous applications of superconducting cavities:

- Pulsed machines, electrons, protons
- Low-Q cavities in high current synchrotrons
- High-Q cavities in radioactive beam facilities, crabs etc.

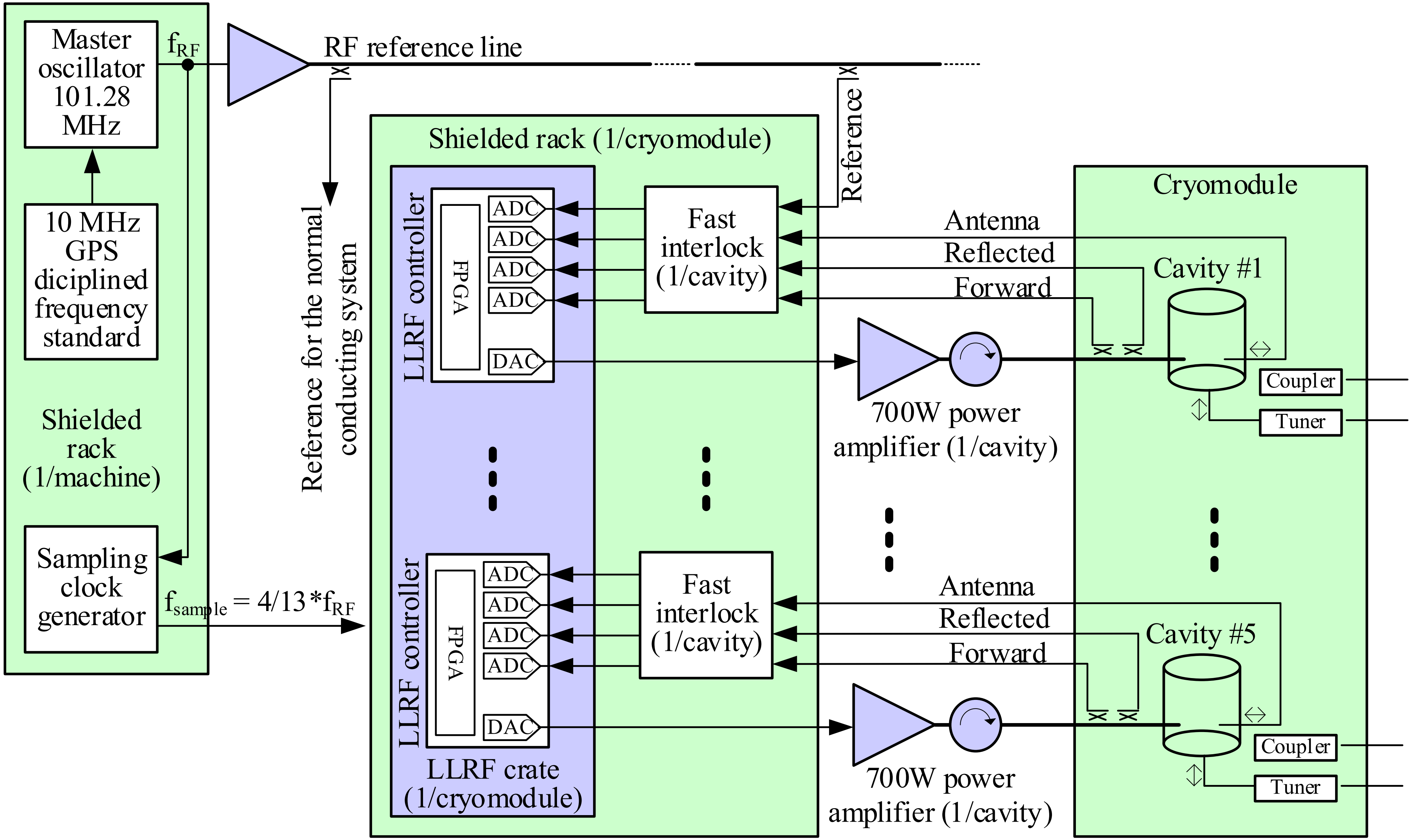
This tutorial focuses on narrow bandwidth, continuous wave cavities, operated with low beam loading

Concepts are the same, but each field has its specific set of challenges and caveats

Cavity RF control

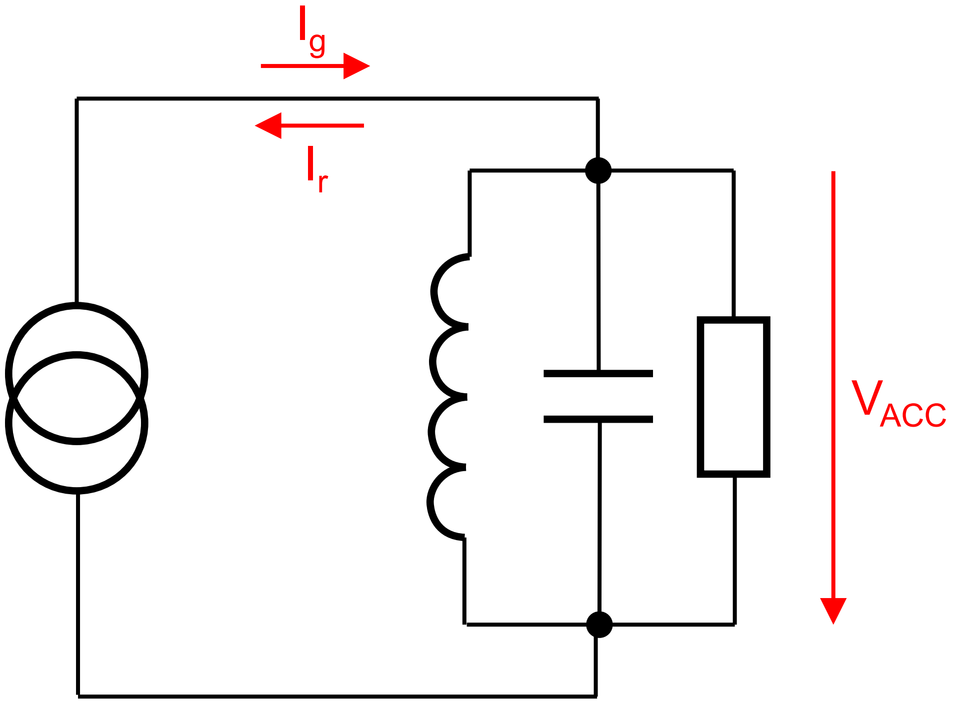
What do we want to control?

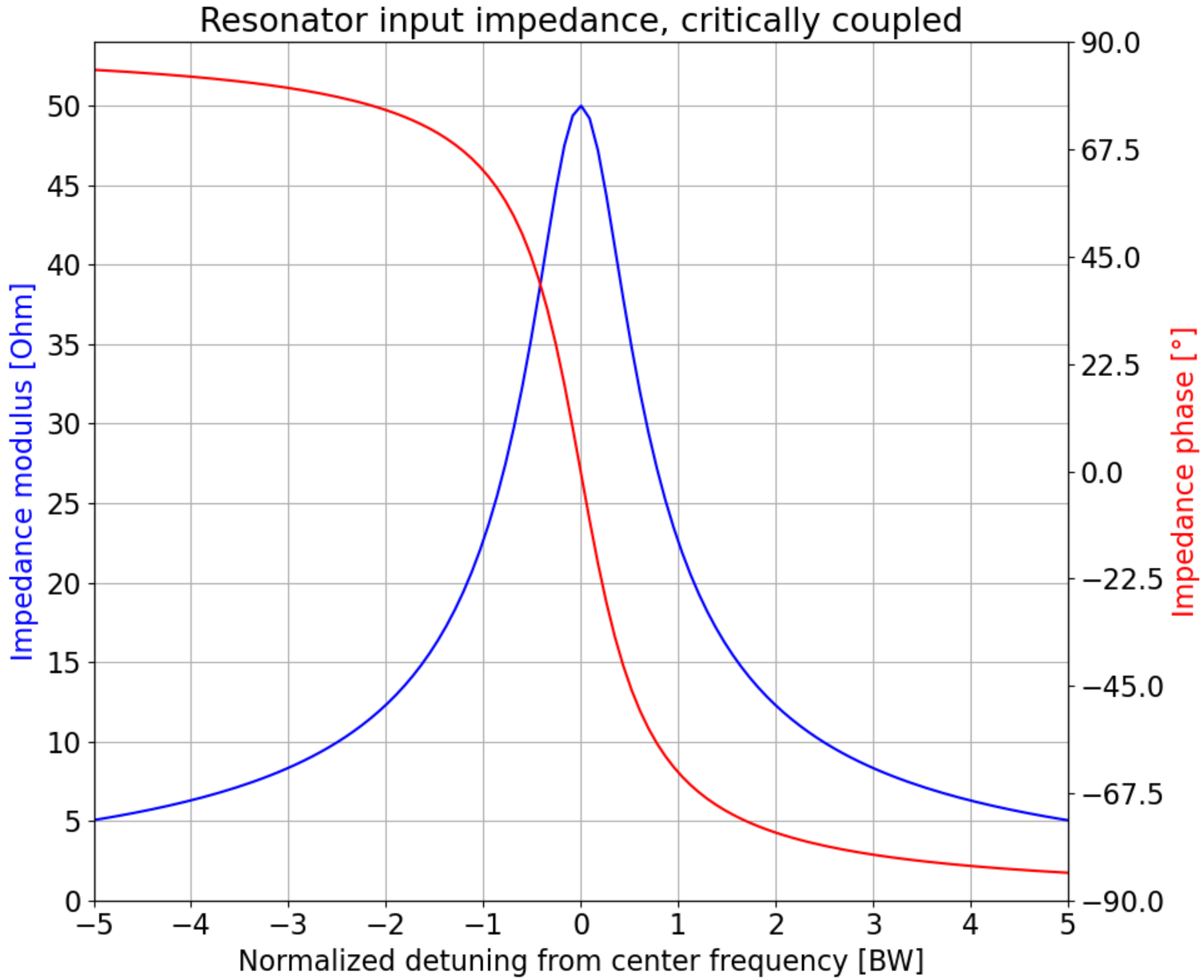
- For cavities at the test stand, R&D
- While testing and qualifying the finished cavities and cryomodules
- Cavities in the machine


Master oscillator 101.28 MHz
f_{RF}
RF reference line
10 MHz GPS diciplined frequency standard
Shielded rack (1/machine)
Sampling clock generator
$f_{sample} = 4/13*f_{RF}$
Reference for the normal conducting system
Shielded rack (1/cryomodule)
Reference
LLRF controller
FPGA
ADC
ADC
ADC
ADC
DAC
Fast interlock (1/cavity)
Antenna
Reflected
Forward
700W power amplifier (1/cavity)
Cryomodule
Cavity #1
Coupler
Tuner
LLRF controller
FPGA
ADC
ADC
ADC
ADC
DAC
Fast interlock (1/cavity)
Antenna
Reflected
Forward
700W power amplifier (1/cavity)
Cavity #5
Coupler
Tuner
LLRF crate (1/cryomodule)

Accelerating cavity as an ideal device

Nothing else than a resonant circuit…





Accelerating cavity as an electrical device

Few important parameters:

- Q_0, Q_L, R/Q…
- Required accelerating gradient
- Lorentz force detuning and the sensitivity to
- Sensitivity to microphonics and amount of external mechanical perturbation
- Sensitivity to liquide He pressure variations
- Tuning range
- …

Accelerating cavity as an electrical device

RF power requirement to obtain desired accelerating voltage [3]

$$I_g = \left[\frac{V}{2(R/Q)} \left(\frac{1}{Q_{ext}} + \frac{1}{Q_0} \right) + I_{b,DC} F_b \sin(\phi) \right] + i \left[I_{b,DC} F_b \cos(\phi) - \frac{V \Delta\omega}{\omega (R/Q)} \right]$$

$$I_r = \left[\frac{V}{2(R/Q)} \left(\frac{1}{Q_{ext}} - \frac{1}{Q_0} \right) - I_{b,DC} F_b \sin(\phi) \right] - i \left[I_{b,DC} F_b \cos(\phi) - \frac{V \Delta\omega}{\omega (R/Q)} \right]$$

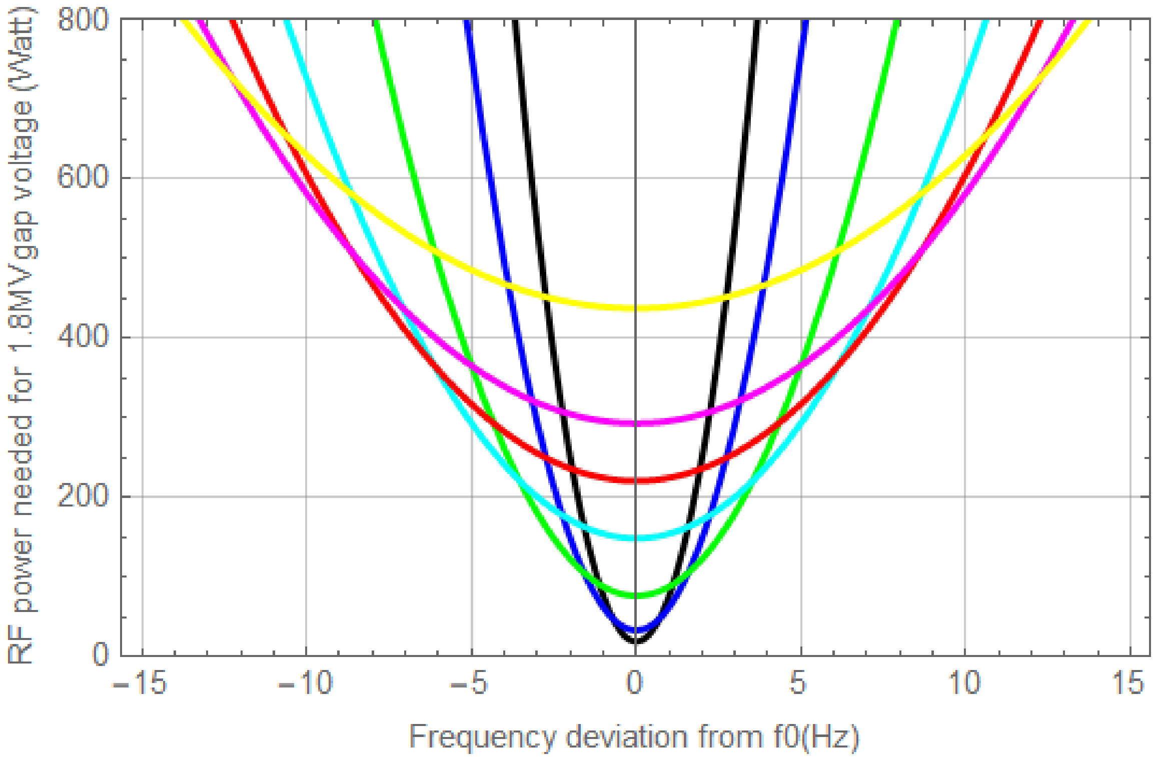
$$P_g = \frac{1}{2} (R/Q) Q_{ext} \left| I_g \right|^2$$

$$P_r = \frac{1}{2} (R/Q) Q_{ext} \left| I_r \right|^2$$

… but this is not the required amplifier power!

Accelerating cavity as an electrical device

In a real world system if we can chose the Q_{LOADED}



Cavity forward power Pg as a function of the operational bandwidth. Black 1Hz, blue 2Hz, green 5Hz, cyan 10Hz, red 15Hz, magenta 20Hz, yellow 30Hz

HIE Isolde QWR band-width (Hz)	Q_{loaded}	Forward power P_g (W) in resonance	Reflected power P_r (W) in resonance	Dissipated power by resonator (W)	Required P_g (W) for 1 BW detuning	Required P_g (W) for 2 BW detuning
1	1.012×10^8	19.2	10.3	8.86	33.7	77.0
2	5.060×10^7	33.5	24.6	8.86	62.4	149
5	2.024×10^7	76.7	67.9	8.86	149	366
10	1.012×10^7	149	140	8.86	293	727
15	6.747×10^6	221	212	8.86	438	1088
20	5.060×10^6	293	284	8.86	582	1449
30	3.373×10^6	438	429	8.86	871	2172

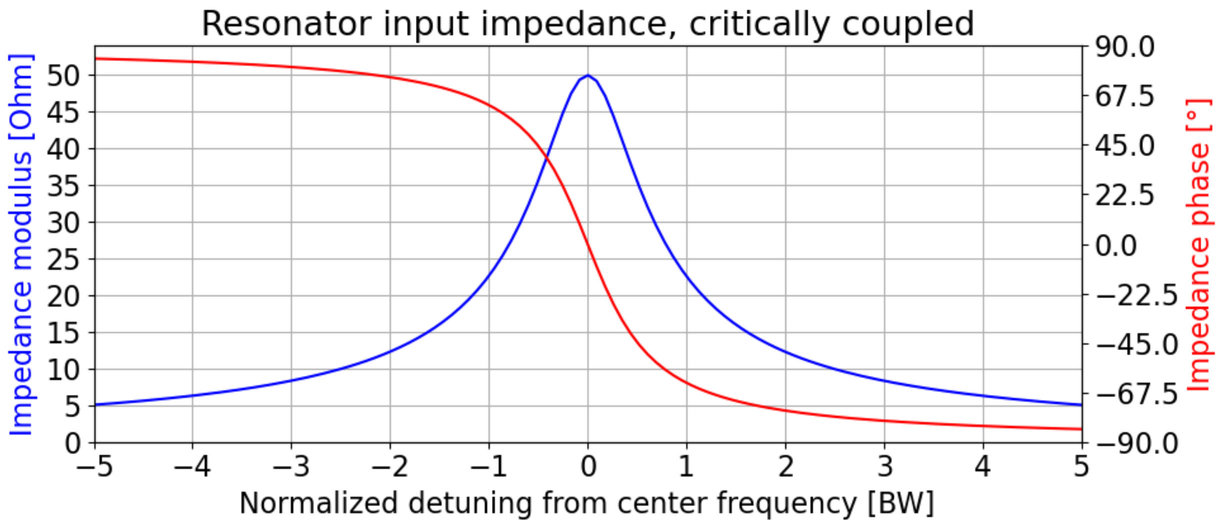
Powering the cavity

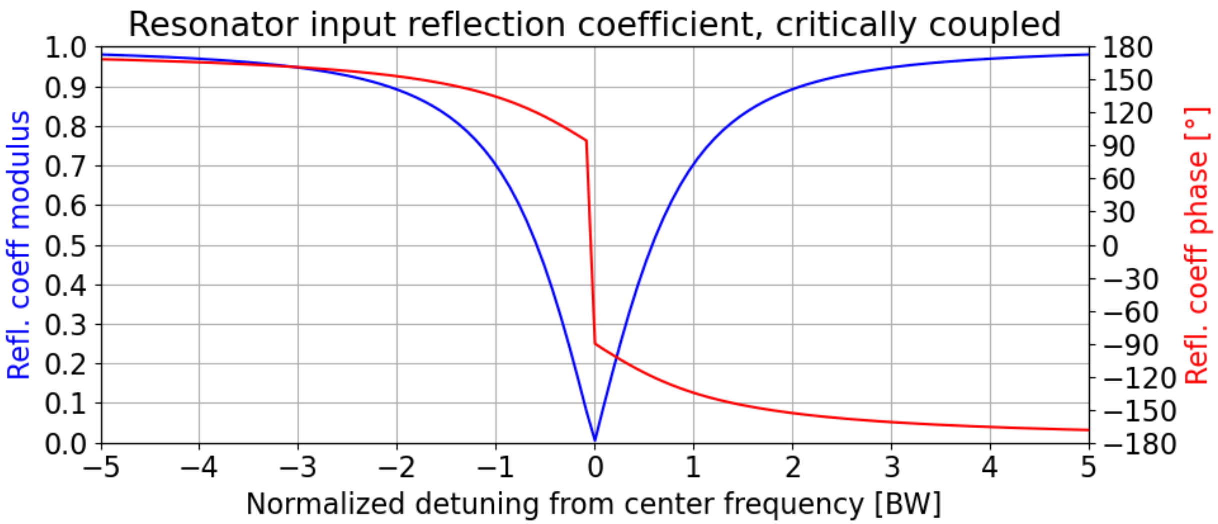
In order to excite field in the cavity, we need to:

1. Provide RF power
2. Cavity must accept it

The generator usually runs at a fixed and defined frequency.

Cavity is typically in an undefined state (in terms of resonant frequency).





Powering the cavity – two modes

Generator driven mode:

- We inject a defined amount of power at the generator frequency.

- Cavity may, or may not accept it, depending on its tune state

Mode used for operation in an accelerator

Powering the cavity – two modes

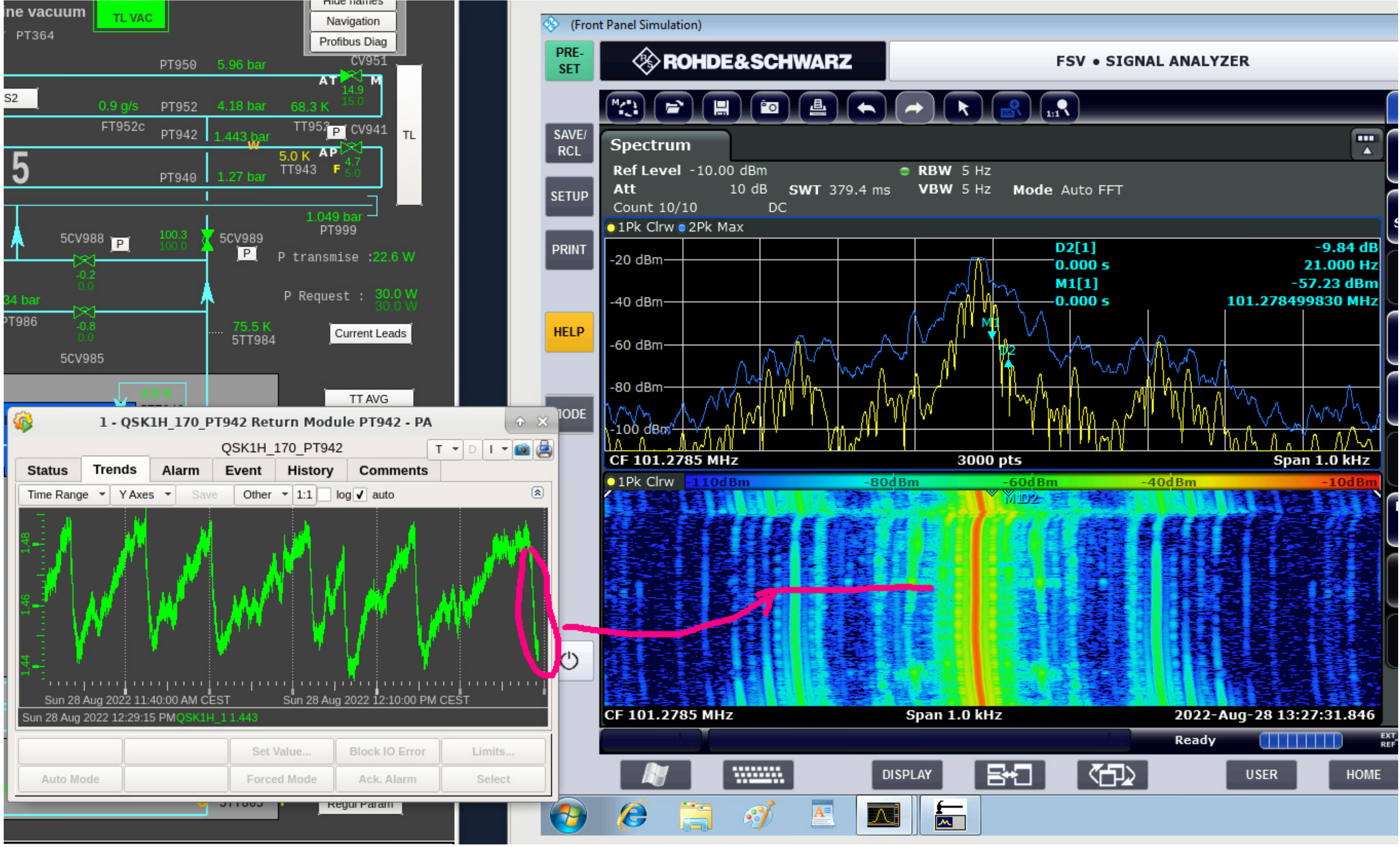
Self-excited mode:

- By means of an active feedback, we inject a defined amount of power at a frequency, which is defined by the instantaneous cavity resonant frequency
- Cavity is always “on tune”, so it accepts all the power
- The loop tracks the cavity resonant frequency

Mode used for testing/measurement/R&D, or starting up sequence in a machine

Powering the cavity – two modes

Self-excited mode:



1 - QSK1H_170_PT942 Return Module PT942 - PA

QSK1H_170_PT942

Sun 28 Aug 2022 12:29:15 PM QSK1H_1 1.443

P transmise :22.6 W

P Request : 30.0 W

Spectrum

Ref Level -10.00 dBm RBW 5 Hz

Att 10 dB SWT 379.4 ms VBW 5 Hz Mode Auto FFT

Count 10/10 DC

D2[1] -9.84 dB
0.000 s 21.000 Hz
M1[1] -57.23 dBm
0.000 s 101.278499830 MHz

CF 101.2785 MHz 3000 pts Span 1.0 kHz

CF 101.2785 MHz Span 1.0 kHz 2022-Aug-28 13:27:31.846

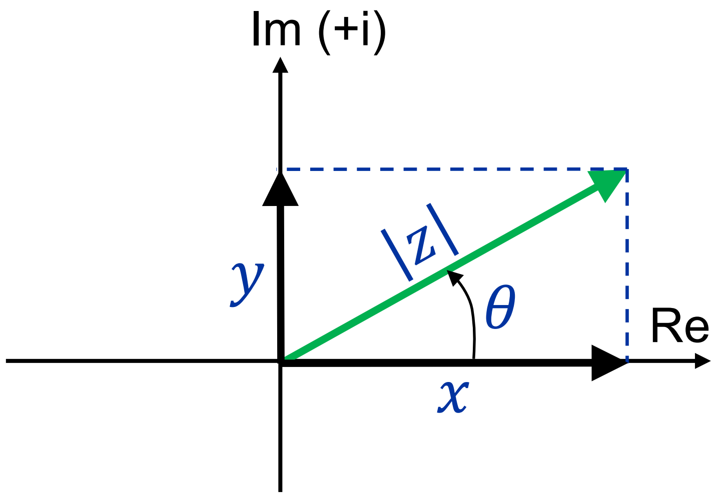
On complex numbers…

We always want to control the accelerating gradient as a phasor.

Popular complex number representations

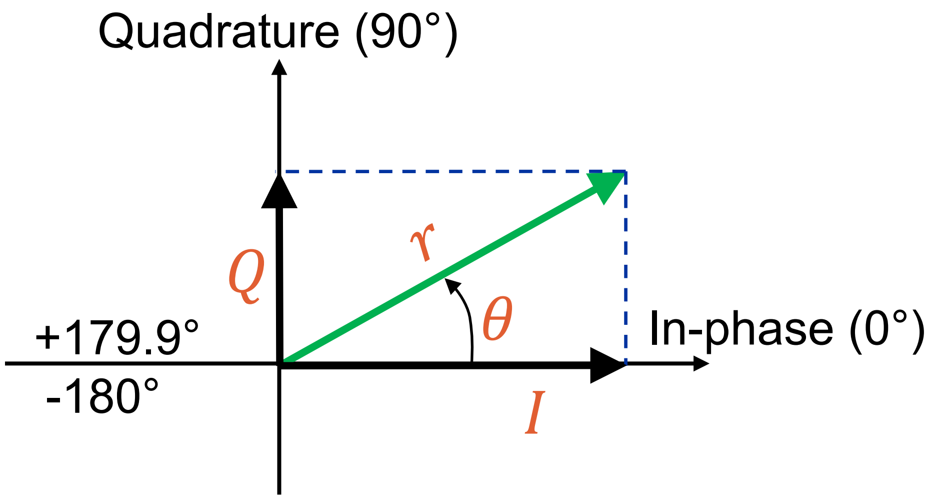
In mathematics:

$$z = x + iy = |z|e^{i\theta}$$



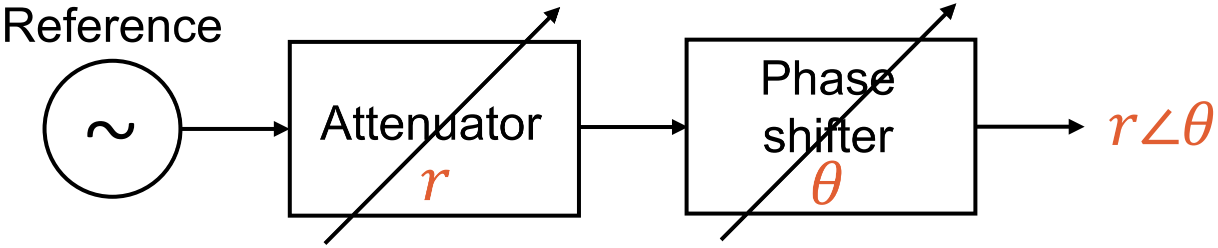
In engineering:

$$z = I + jQ = r\angle\theta$$

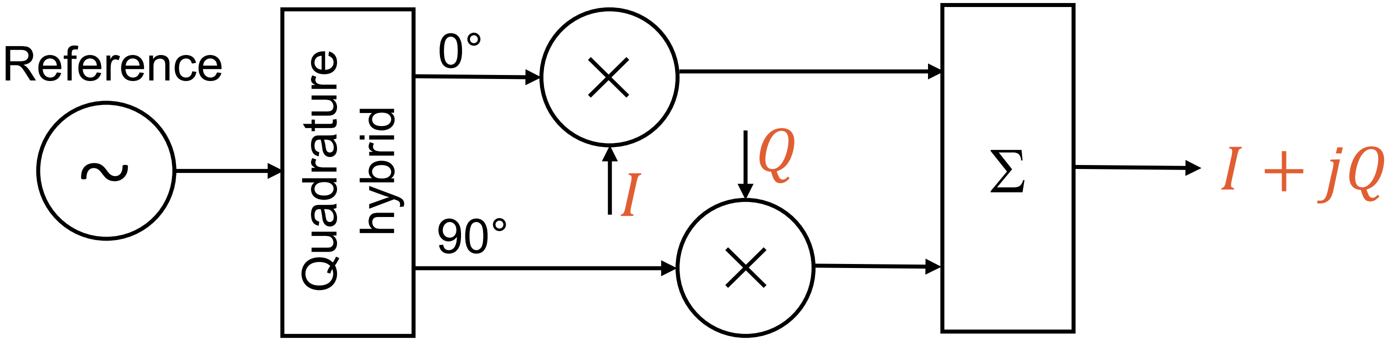


Complex numbers in engineering

In analogue world:



In digital world:

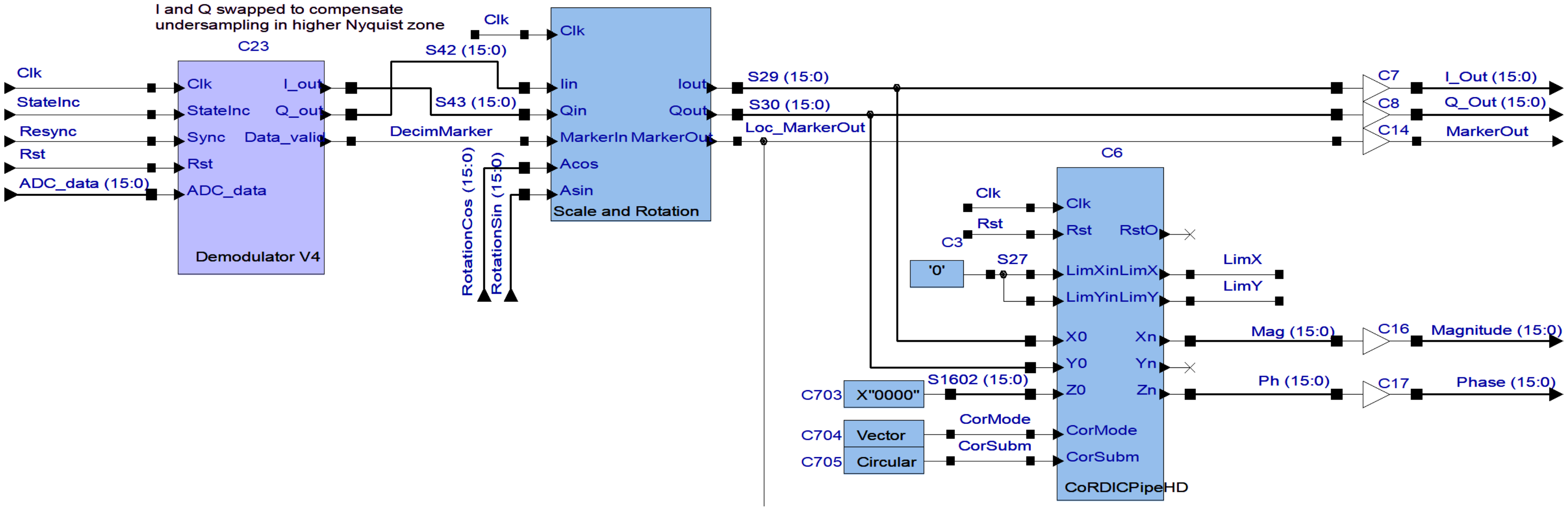


Complex numbers in engineering

Operators want to set degrees and megavolts

CAV1	OFF	STANDBY	READY	ON	Set Mag ▲ 5.000	Set Ph ▲ -103.0	ON		5.000	-103.0	4.999	-103.2	75.0	65.5
CAV2	OFF	STANDBY	READY	ON	Set Mag ▲ 4.500	Set Ph ▲ -128.0	ON		4.500	-128.0	4.501	-128.4	61.0	55.3

But feedback loops work in I and Q. Bit of a headache as sin/cos are difficult in digital.



I and Q swapped to compensate undersampling in higher Nyquist zone

Feedback loop

Function of a feedback loop is to make value of the measured quantity equal to the value of the setpoint.

Credits: Camran Iqbal: Introduction to Control Systems [1]

Feedback loop

Function of a feedback loop is to make value of the measured quantity equal to the value of the setpoint.

In accelerators, we want to control at least:

- **Phasor of the Accelerating gradient (i.e. amplitude and phase)**
- **Cavity tune state**

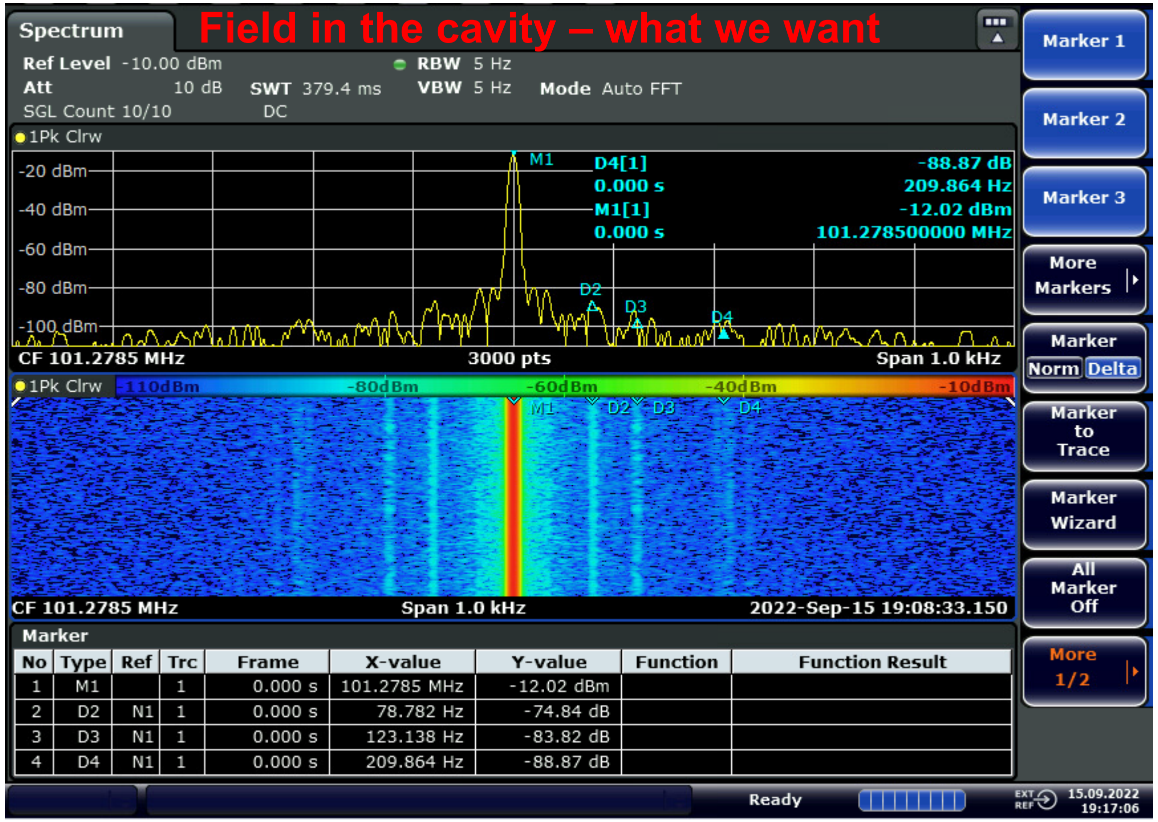
These setpoints can change in time

Cavity can be very sensitive to fast changes

Credits: Camran Iqbal: Introduction to Control Systems [1]

Feedback loop

Function of a feedback loop is to make value of the measured quantity equal to the value of the setpoint.



Field in the cavity – what we want

Ref Level -10.00 dBm
Att 10 dB
SWT 379.4 ms
RBW 5 Hz
VBW 5 Hz
Mode Auto FFT
SGL Count 10/10
DC

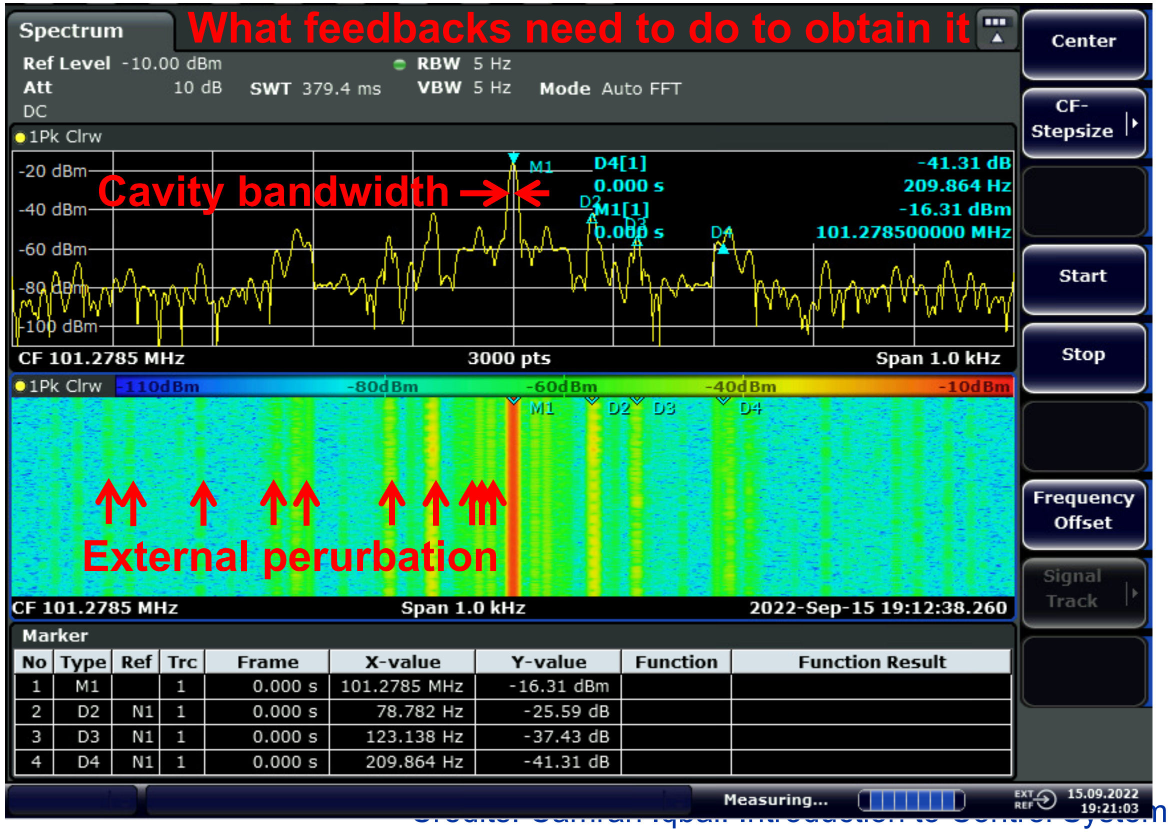
D4[1] 0.000 s -88.87 dB 209.864 Hz
M1[1] 0.000 s -12.02 dBm 101.278500000 MHz

CF 101.2785 MHz
3000 pts
Span 1.0 kHz
2022-Sep-15 19:08:33.150

Marker

No	Type	Ref	Trc	Frame	X-value	Y-value	Function	Function Result
1	M1		1	0.000 s	101.2785 MHz	-12.02 dBm		
2	D2	N1	1	0.000 s	78.782 Hz	-74.84 dB		
3	D3	N1	1	0.000 s	123.138 Hz	-83.82 dB		
4	D4	N1	1	0.000 s	209.864 Hz	-88.87 dB		

Ready
15.09.2022 19:17:06



What feedbacks need to do to obtain it

Cavity bandwidth

External perurbation

Ref Level -10.00 dBm
Att 10 dB
SWT 379.4 ms
RBW 5 Hz
VBW 5 Hz
Mode Auto FFT
DC

D4[1] 0.000 s -41.31 dB 209.864 Hz
M1[1] 0.000 s -16.31 dBm 101.278500000 MHz

CF 101.2785 MHz
3000 pts
Span 1.0 kHz
2022-Sep-15 19:12:38.260

Marker

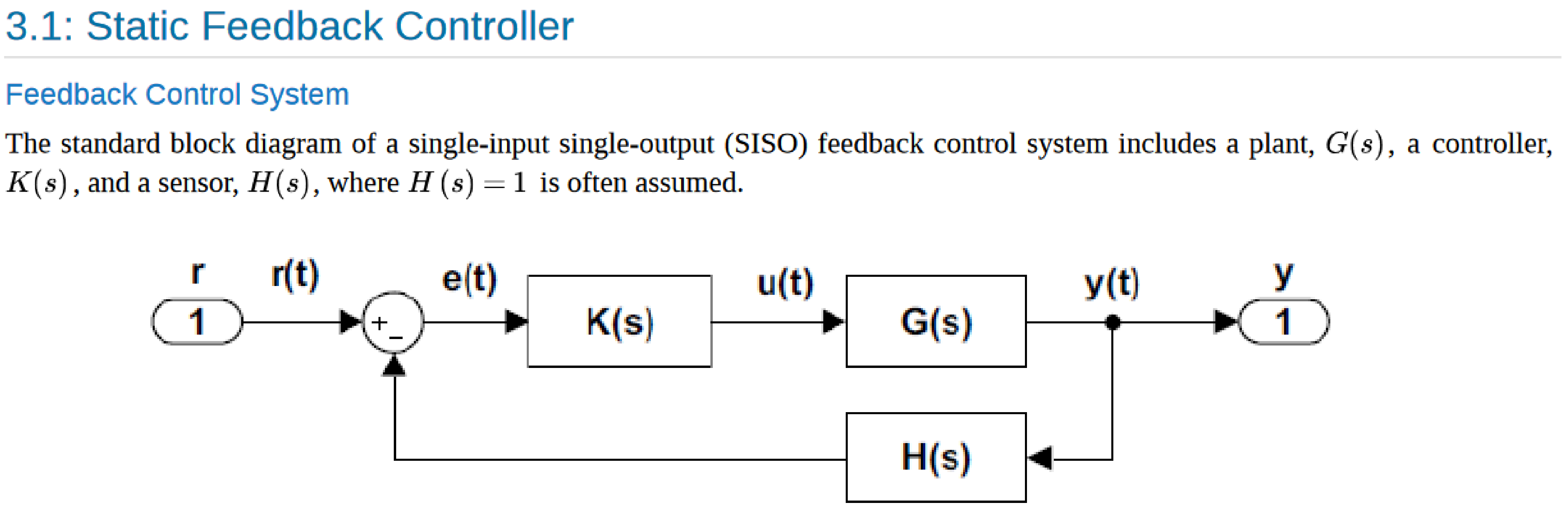
No	Type	Ref	Trc	Frame	X-value	Y-value	Function	Function Result
1	M1		1	0.000 s	101.2785 MHz	-16.31 dBm		
2	D2	N1	1	0.000 s	78.782 Hz	-25.59 dB		
3	D3	N1	1	0.000 s	123.138 Hz	-37.43 dB		
4	D4	N1	1	0.000 s	209.864 Hz	-41.31 dB		

Measuring...
15.09.2022 19:21:03

ms [1]

Feedback loop

Function of a feedback loop is to make value of a measured quantity equal to the value of the setpoint.



3.1: Static Feedback Controller

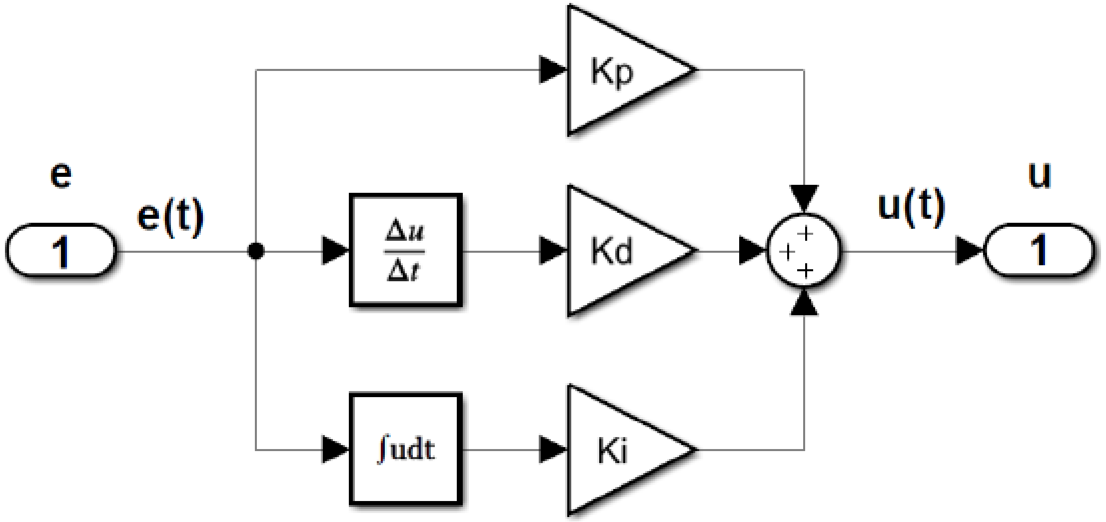
Feedback Control System

The standard block diagram of a single-input single-output (SISO) feedback control system includes a plant, $G(s)$, a controller, $K(s)$, and a sensor, $H(s)$, where $H(s) = 1$ is often assumed.

Credits: Camran Iqbal: Introduction to Control Systems [1]

Feedback loop

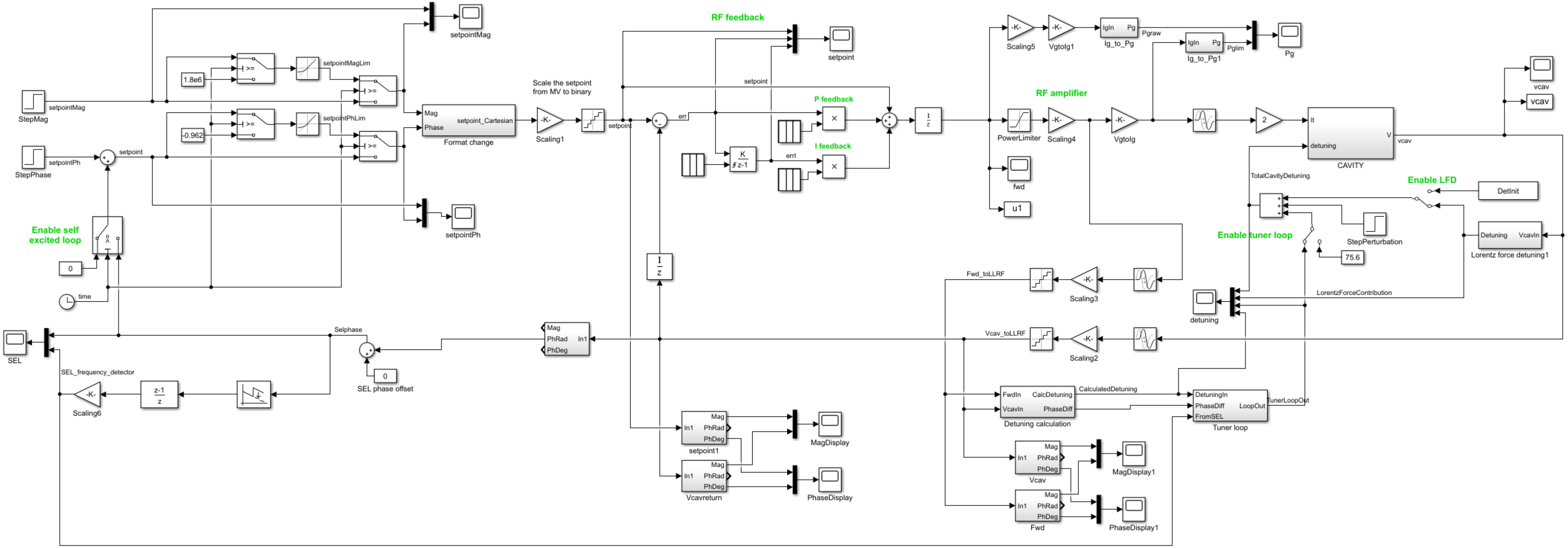
Controller K(s) – e.g. a simplest PID regulator



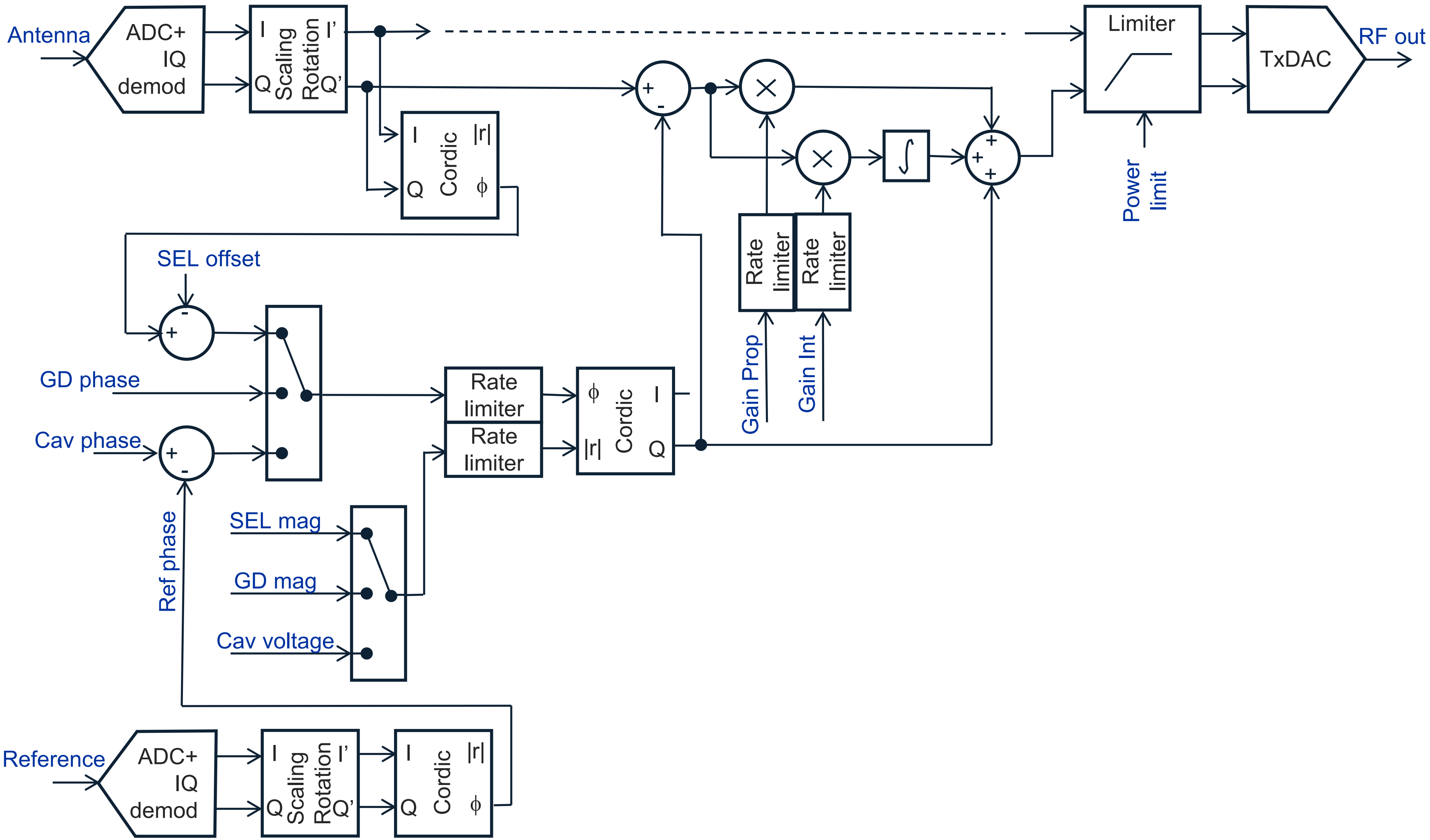
Credits: Camran Iqbal: Introduction to Control Systems [1]

Feedback loop

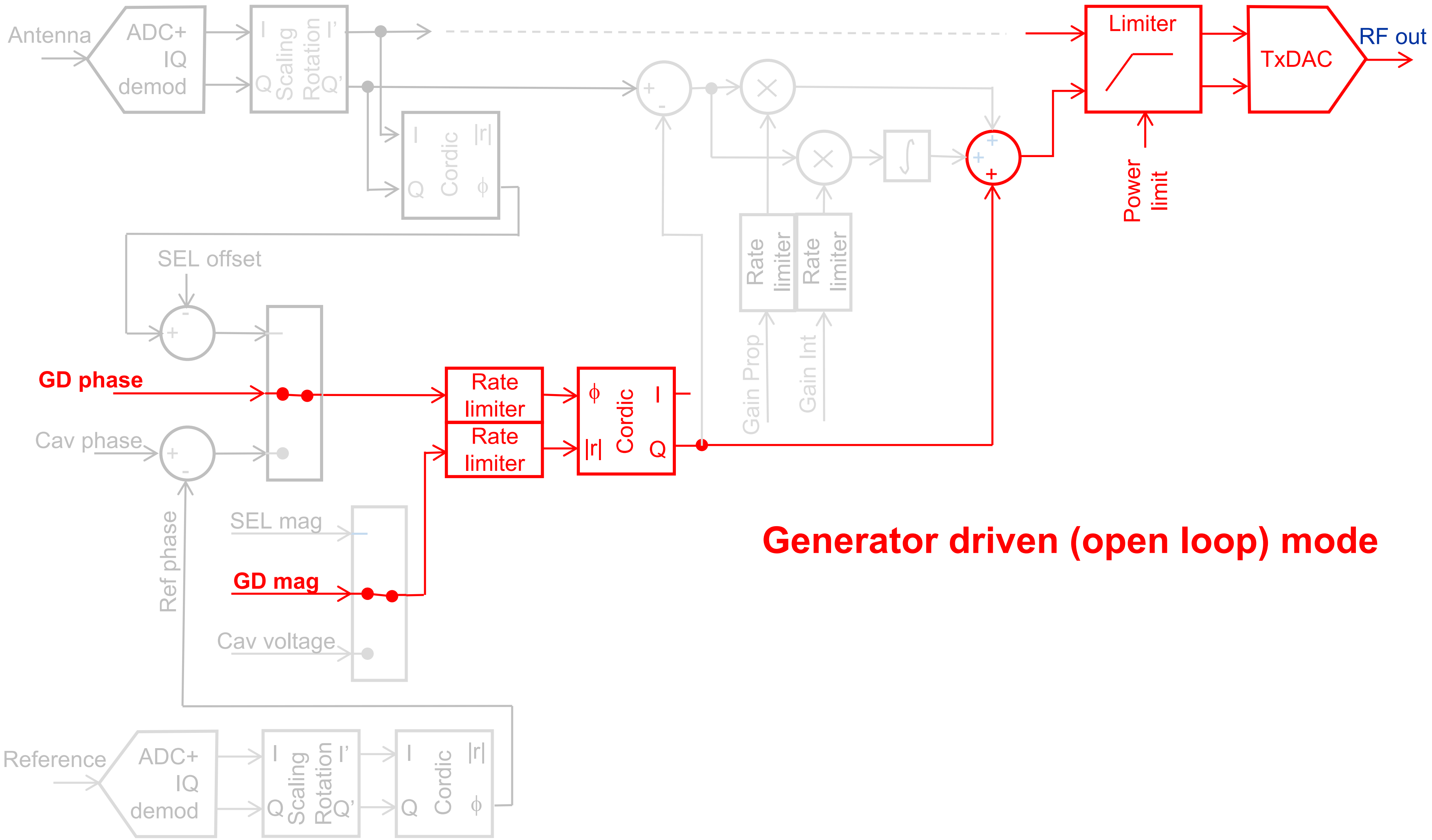
Simulink model of the HIE-Isolde LLRF controller



Example of a feedback controller – HIE Isolde

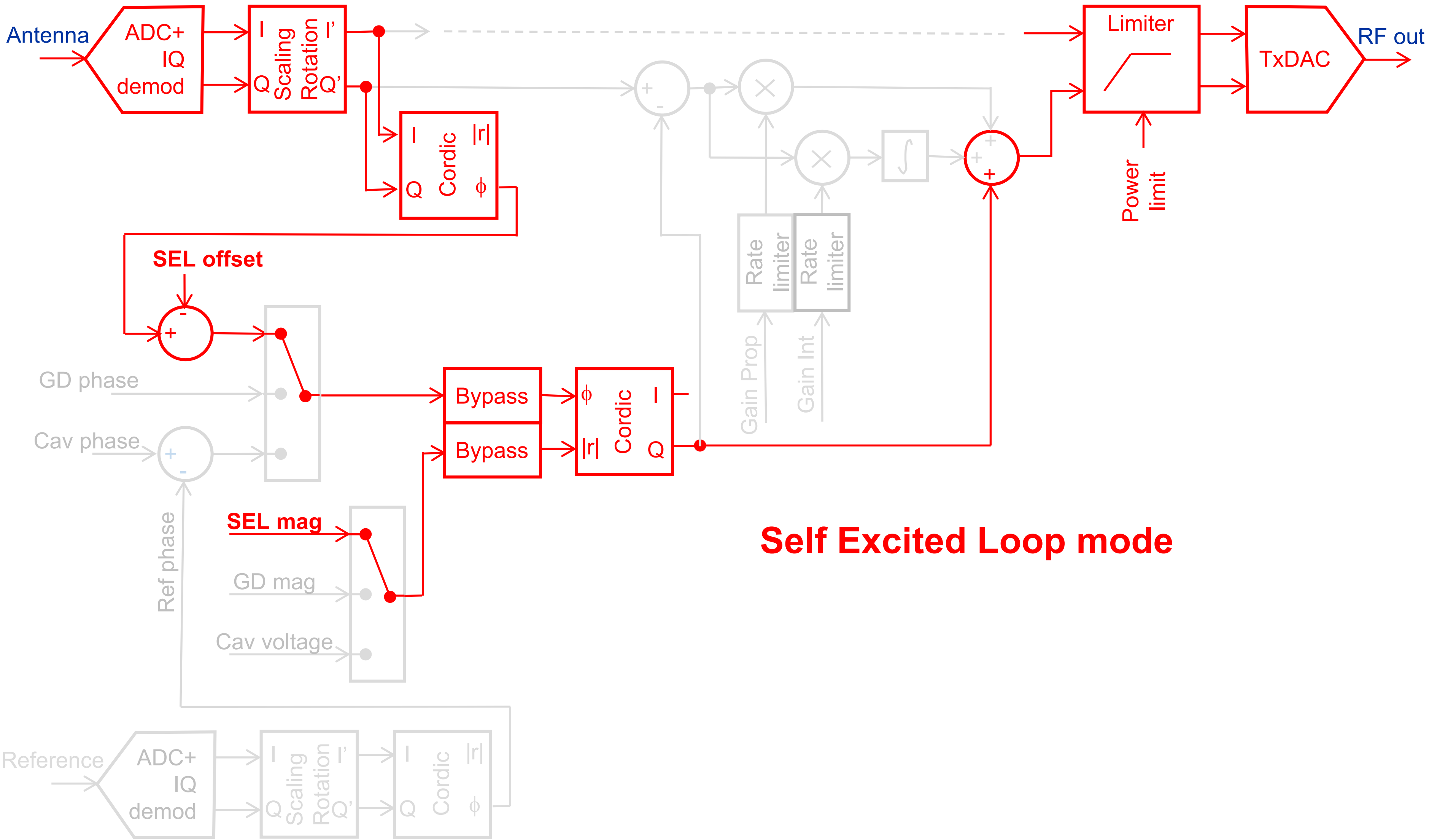


Example of a feedback controller – HIE Isolde



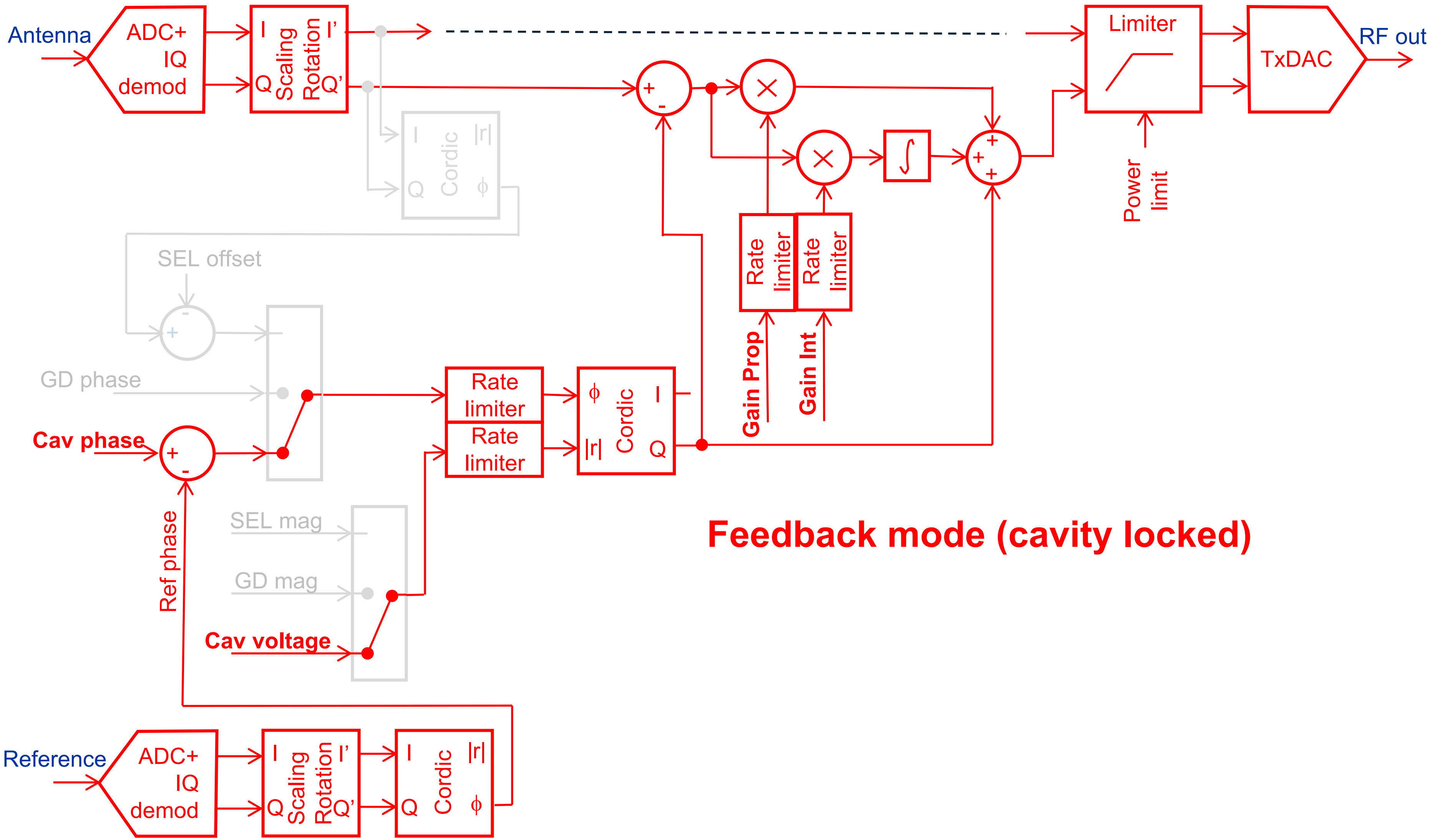
Generator driven (open loop) mode

Example of a feedback controller – HIE Isolde



Self Excited Loop mode

Example of a feedback controller – HIE Isolde



Feedback mode (cavity locked)

Feedback loop gain limits

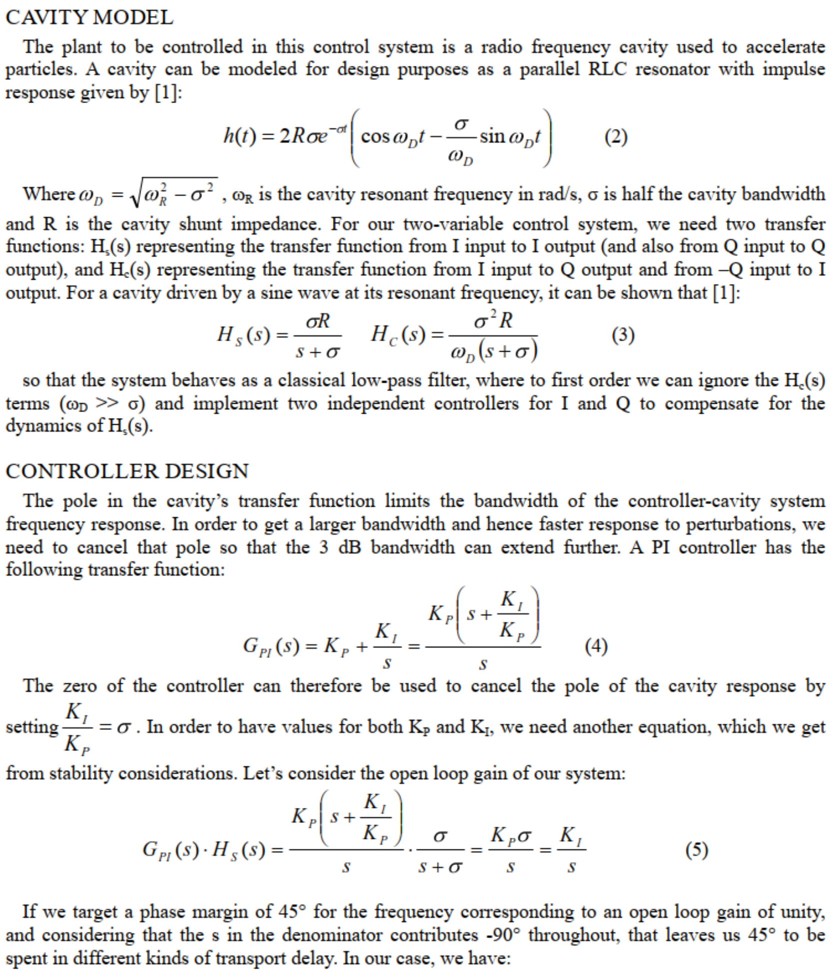
Loop gain defines the field quality and suppression of external perturbations

Maximum feedback loop gain is limited by gain/phase margin of the loop

Contributing factors:

- **Loop delay**
- **Cavity bandwidth**

For more details - one of (many) readings e.g. [2]



CAVITY MODEL

The plant to be controlled in this control system is a radio frequency cavity used to accelerate particles. A cavity can be modeled for design purposes as a parallel RLC resonator with impulse response given by [1]:

$$h(t) = 2R\sigma e^{-\sigma t}\left(\cos\omega_D t - \frac{\sigma}{\omega_D}\sin\omega_D t\right) \qquad (2)$$

Where $\omega_D = \sqrt{\omega_R^2 - \sigma^2}$, ω_R is the cavity resonant frequency in rad/s, σ is half the cavity bandwidth and R is the cavity shunt impedance. For our two-variable control system, we need two transfer functions: $H_s(s)$ representing the transfer function from I input to I output (and also from Q input to Q output), and $H_c(s)$ representing the transfer function from I input to Q output and from –Q input to I output. For a cavity driven by a sine wave at its resonant frequency, it can be shown that [1]:

$$H_S(s) = \frac{\sigma R}{s+\sigma} \qquad H_C(s) = \frac{\sigma^2 R}{\omega_D(s+\sigma)} \qquad (3)$$

so that the system behaves as a classical low-pass filter, where to first order we can ignore the $H_c(s)$ terms ($\omega_D >> \sigma$) and implement two independent controllers for I and Q to compensate for the dynamics of $H_s(s)$.

CONTROLLER DESIGN

The pole in the cavity's transfer function limits the bandwidth of the controller-cavity system frequency response. In order to get a larger bandwidth and hence faster response to perturbations, we need to cancel that pole so that the 3 dB bandwidth can extend further. A PI controller has the following transfer function:

$$G_{PI}(s) = K_P + \frac{K_I}{s} = \frac{K_P\left(s + \frac{K_I}{K_P}\right)}{s} \qquad (4)$$

The zero of the controller can therefore be used to cancel the pole of the cavity response by setting $\frac{K_I}{K_P} = \sigma$. In order to have values for both K_P and K_I, we need another equation, which we get from stability considerations. Let's consider the open loop gain of our system:

$$G_{PI}(s) \cdot H_S(s) = \frac{K_P\left(s + \frac{K_I}{K_P}\right)}{s} \cdot \frac{\sigma}{s+\sigma} = \frac{K_P\sigma}{s} = \frac{K_I}{s} \qquad (5)$$

If we target a phase margin of 45° for the frequency corresponding to an open loop gain of unity, and considering that the s in the denominator contributes -90° throughout, that leaves us 45° to be spent in different kinds of transport delay. In our case, we have:

Feedback loop gain limits - example

Assume cavity QL = 10^7, i.e. bandwidth 10 Hz

System RF frequency f_{RF} = 101.28 MHz, sampling frequency f_{sample} = 81.024 MHz

Amplifier delay 100 ns, both forward and antenna cables 25 m / 97.5 ns

Digital quadrature demodulation 4 clk periods, Feedback controller 4 clk periods

DAC and modulator delay 4 clk periods

```
Delay demodulator 49.37 ns
Delay modulator + DAC 49.37 ns
Total loop delay 443.1 ns
Feedback parameters Ki=1772491, Kp=55707.08
```

Feedback loop gain limits - example

Assume cavity QL = 10^7, i.e. bandwidth 10 Hz

System RF frequency f_{RF} = 101.28 MHz, sampling frequency f_{sample} = 81.024 MHz

Amplifier delay 100 ns, both forward and antenna cables 25 m / 97.5 ns

Digital quadrature demodulation 32*4 clk periods, Feedback controller 4 clk periods

DAC and modulator delay 4 clk periods + 1.2 μs (e.g. TxDAC)

```
Delay demodulator 1579.78 ns
Delay modulator + DAC 1249.37 ns
Total loop delay 4703.9 ns
Feedback parameters Ki=166967, Kp=5247.54
```

Feedback loop gain limits - example

Assume cavity QL = 20000, i.e. bandwidth 10 Hz

System RF frequency f_{RF} = 400.8 MHz, sampling frequency f_{sample} = 80.000 MHz

Amplifier delay 150 ns, both forward and antenna cables 35 m / 136.5 ns

Digital quadrature demodulation 4 clk periods, Feedback controller 4 clk periods

DAC and modulator delay 4 clk periods

```
Delay demodulator 50.00 ns
Delay modulator + DAC 50.00 ns
Total loop delay 573.0 ns
Feedback parameters Ki=1370677, Kp=21.77
```

Feedbacks for other SRF cavity applications

Machines with high beam loading, or pulsed operation require more sophisticated control

- LQG (Linear–quadratic–Gaussian control)
- Kalman filters
- Adaptive feed forward
- One turn feedback
- …

Cavity dynamic behaviour

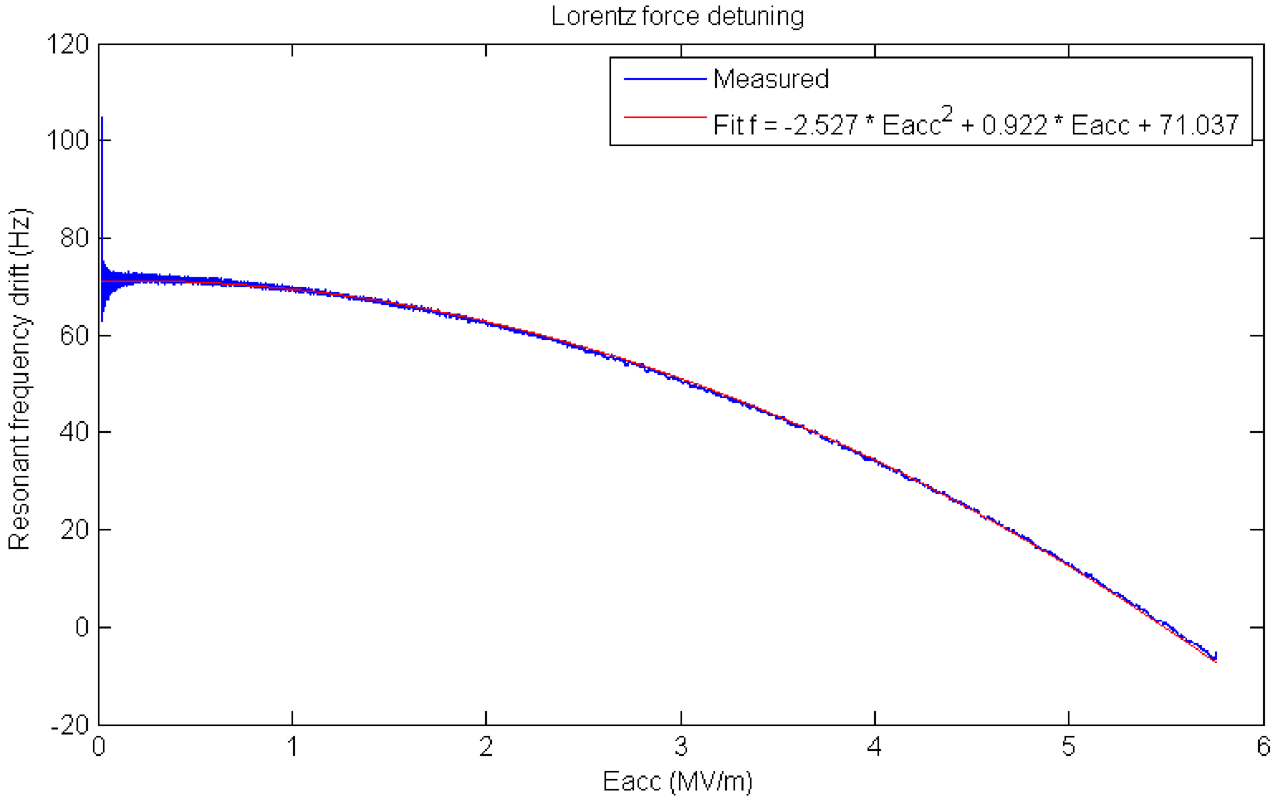
Lorentz force detuning

Ponderomotive instability

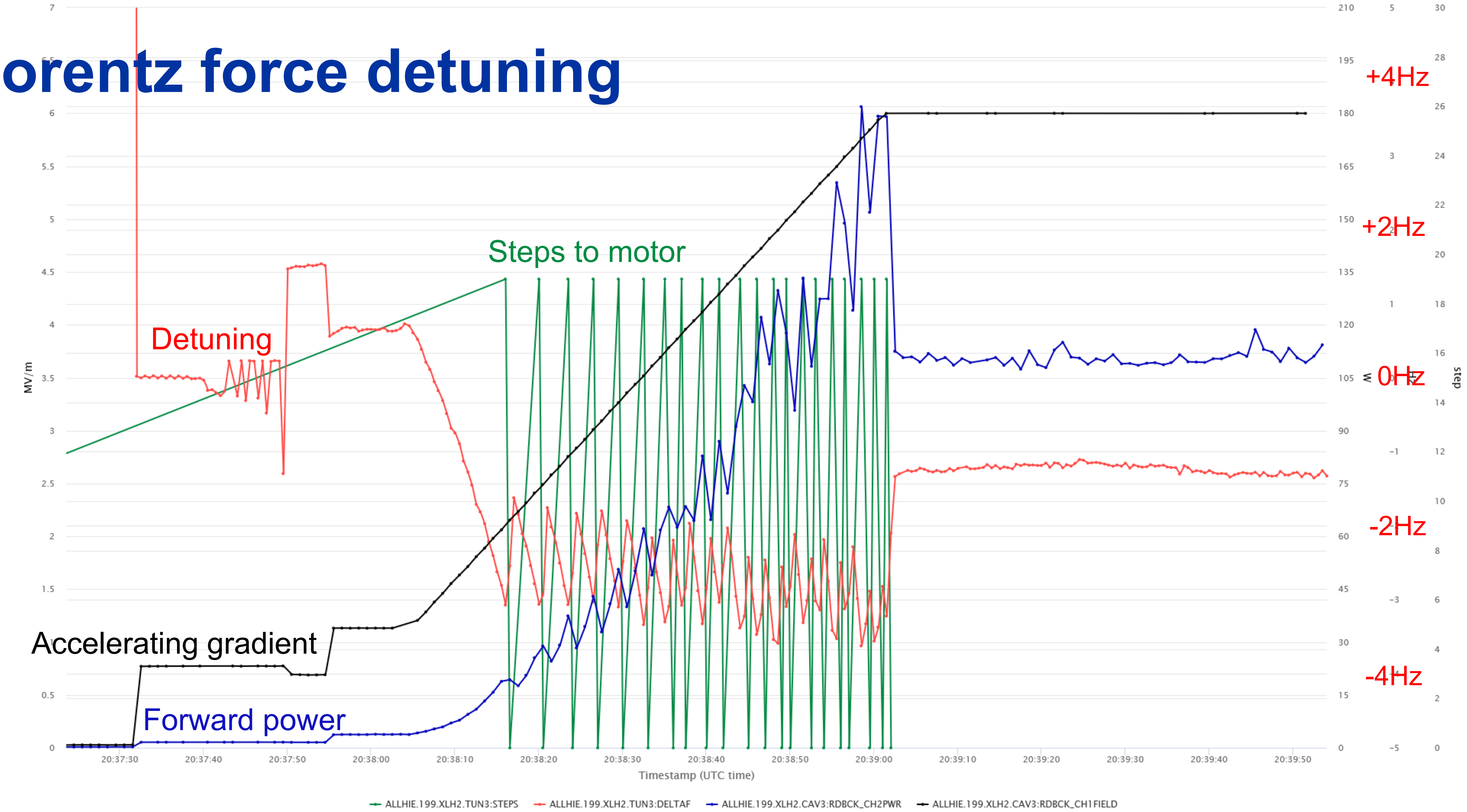
Microphonics

Lorentz force detuning

Instantaneous frequency shift $\Delta f \propto K_L |E_{acc}|^2$

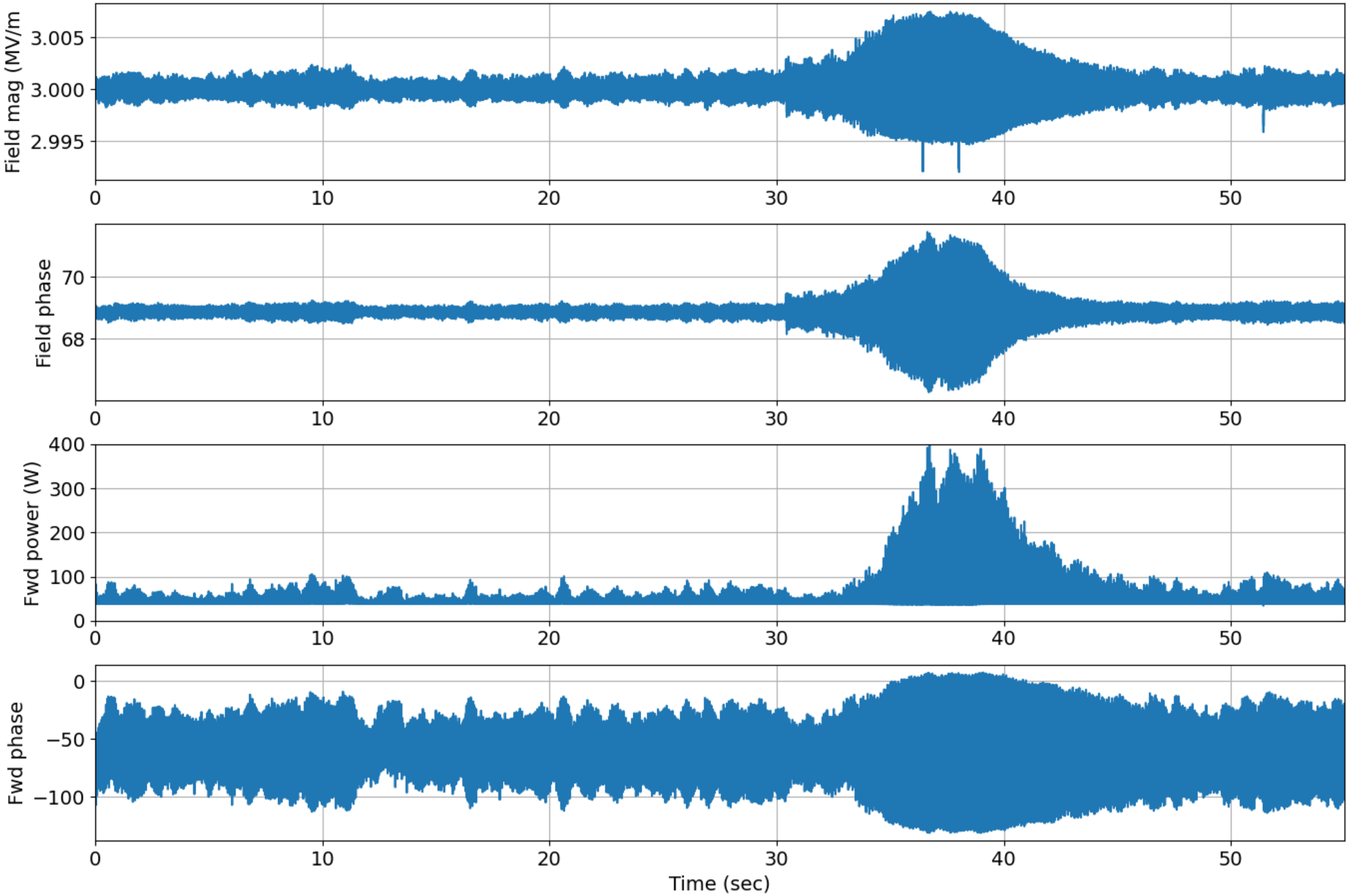


Lorentz force detuning



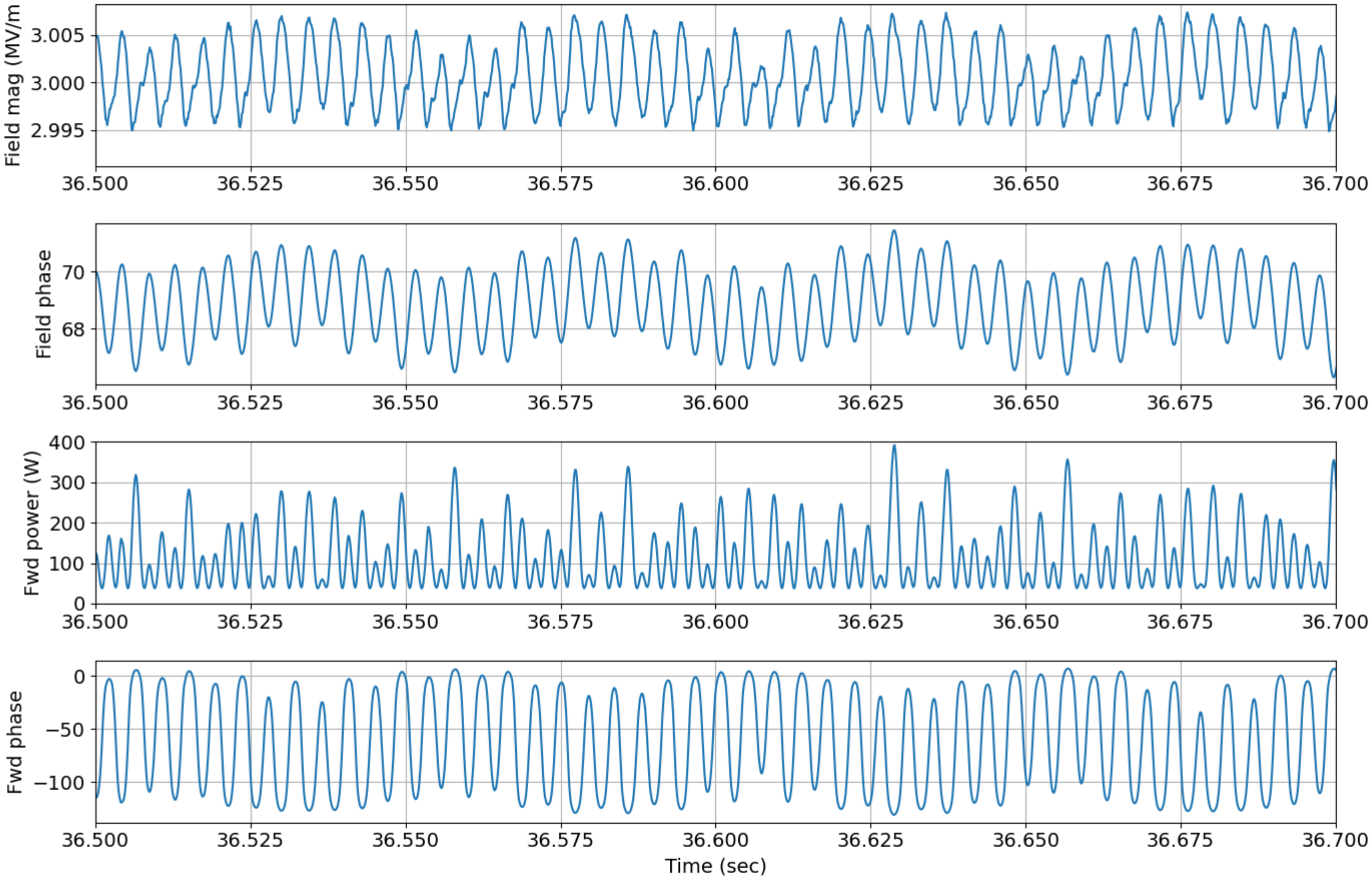
Ponderomotive instability

Lorentz force detuning and mechanical properties of the cavity (stiffness, mechanical resonant frequency) may lead to a field driven electromechanical resonance



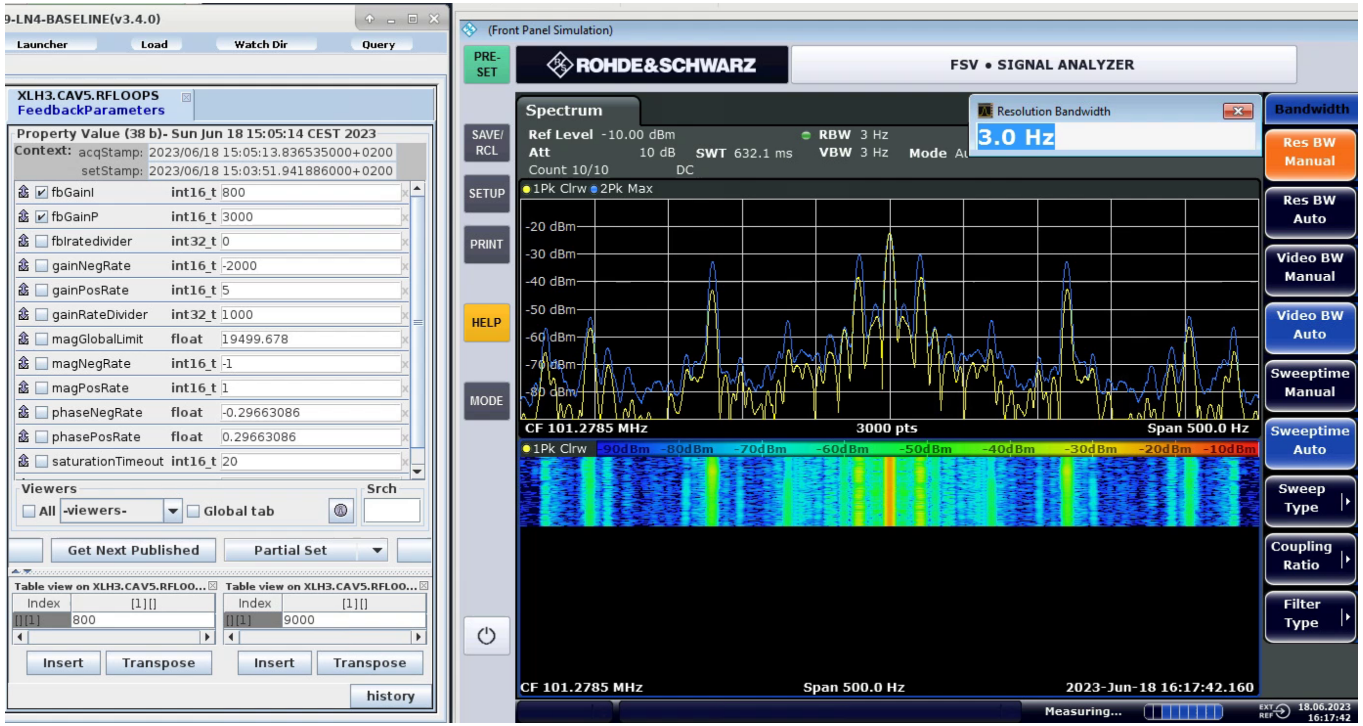
Ponderomotive instability

Lorentz force detuning and mechanical properties of the cavity (stiffness, mechanical resonant frequency) may lead to a field driven electromechanical resonance



Ponderomotive instability

ponderomotive_instability___Record_2023_06_18_15_05_35_719.mp4



9-LN4-BASELINE(v3.4.0)

XLH3.CAV5.RFLOOPS FeedbackParameters

Property Value (38 b)- Sun Jun 18 15:05:14 CEST 2023

Context: acqStamp: 2023/06/18 15:05:13.836535000+0200
setStamp: 2023/06/18 15:03:51.941886000+0200

☑	fbGainI	int16_t	800
☑	fbGainP	int16_t	3000
☐	fbIratedivider	int32_t	0
☐	gainNegRate	int16_t	-2000
☐	gainPosRate	int16_t	5
☐	gainRateDivider	int32_t	1000
☐	magGlobalLimit	float	19499.678
☐	magNegRate	int16_t	-1
☐	magPosRate	int16_t	1
☐	phaseNegRate	float	-0.29663086
☐	phasePosRate	float	0.29663086
☐	saturationTimeout	int16_t	20

Table view on XLH3.CAV5.RFLOO… Index [1][] [][1] 800

Table view on XLH3.CAV5.RFLOO… Index [1][] [][1] 9000

(Front Panel Simulation)

ROHDE&SCHWARZ FSV • SIGNAL ANALYZER

Spectrum

Ref Level -10.00 dBm
Att 10 dB
SWT 632.1 ms
Count 10/10
DC
RBW 3 Hz
VBW 3 Hz
Mode Au

Resolution Bandwidth 3.0 Hz

1Pk Clrw 2Pk Max

CF 101.2785 MHz 3000 pts Span 500.0 Hz

CF 101.2785 MHz Span 500.0 Hz 2023-Jun-18 16:17:42.160

Measuring...

18.06.2023 16:17:42

Resonance control

Resonant frequency of the cavity is moving all the time

- Fast variation – microphonics
- Slow variation – l-He pressure fluctuations, Lorentz force detuning
- LFD can be very nasty to control…

Small changes (<BW) are compensated by LLRF. It is fast and costs only RF power

Large changes (>BW) must be compensated by tuners. Comparably slow and rather complex process…

Resonance control

Knowledge of the instantaneous cavity resonant frequency is the key

Observables: Forward, Reflected, Antenna (probe) phasors

Methods:

1. **Transmitted power method (Fwd, Ant)**
2. **Reflection coefficient method (Fwd, Rfl)**
3. **Alternative methods (e.g. internal regulator signals)**

Resonance control – Transmitted power method

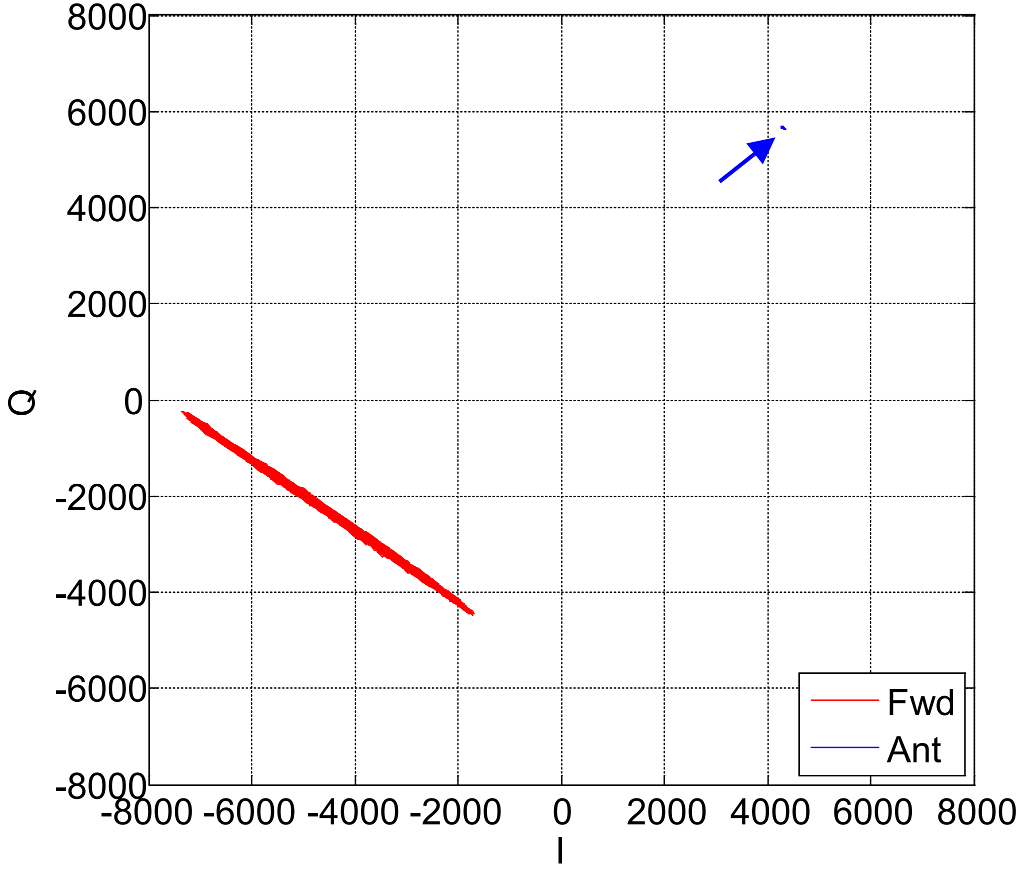
The instantaneous cavity tune state can be calculated from the forward and antenna signals.

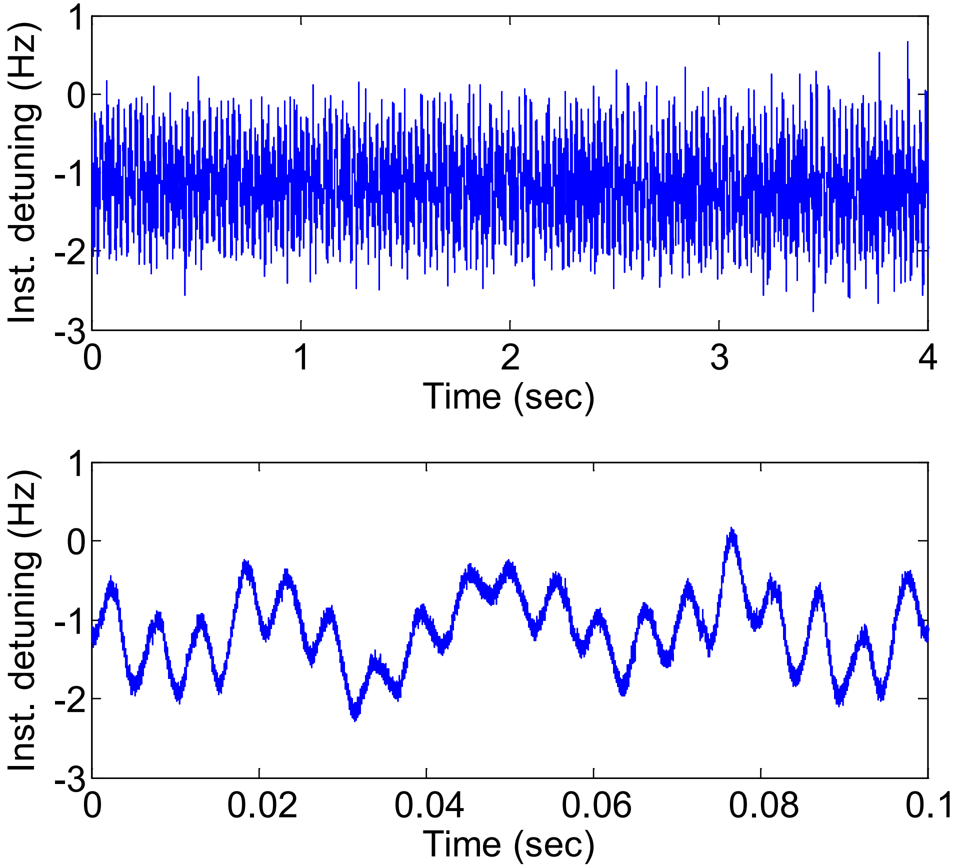
At least some transmission is needed to get started – fails for large detuning

$$\Delta f = \frac{1}{2} BW \frac{\left|V_{fwd}\right|}{\left|V_{ant}\right|} \sin\left(\varphi_{ant} - \varphi_{fwd}\right)$$

Resonance control – Transmitted power method

Not trivial if cavity bandwidth ≈ microphonics





Resonance control – Reflection coefficient method

The instantaneous cavity tune state can be calculated from the measured complex reflection coefficient.

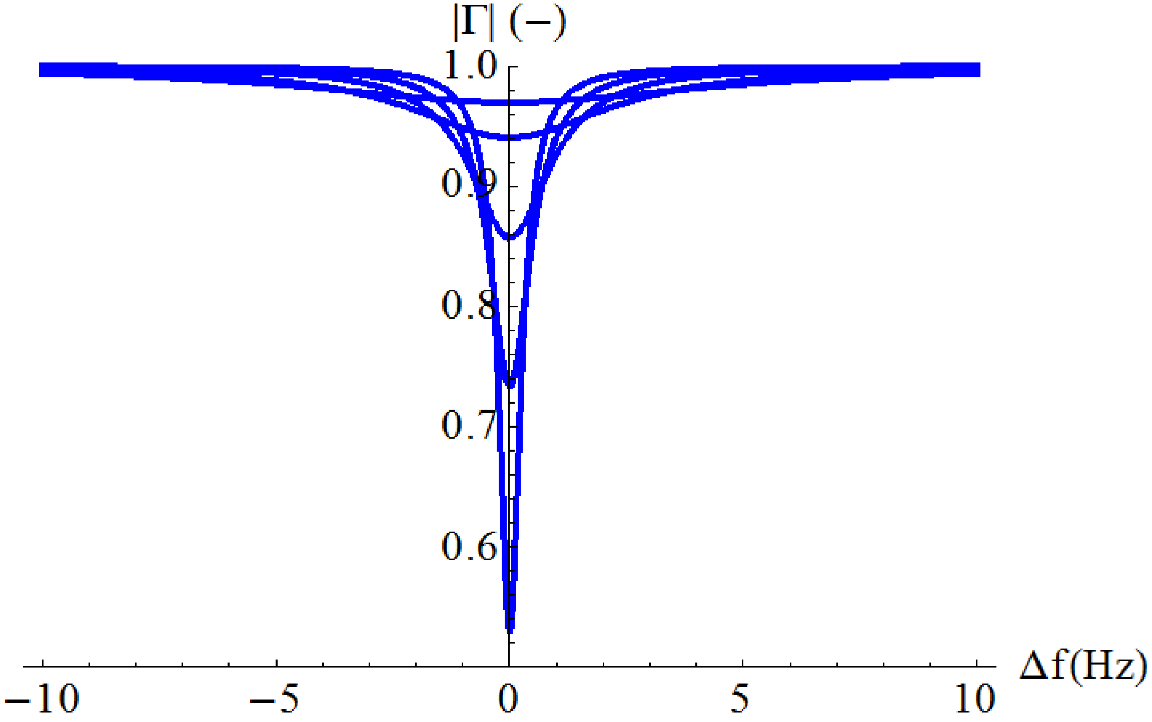
Best results for critically coupled cavities.

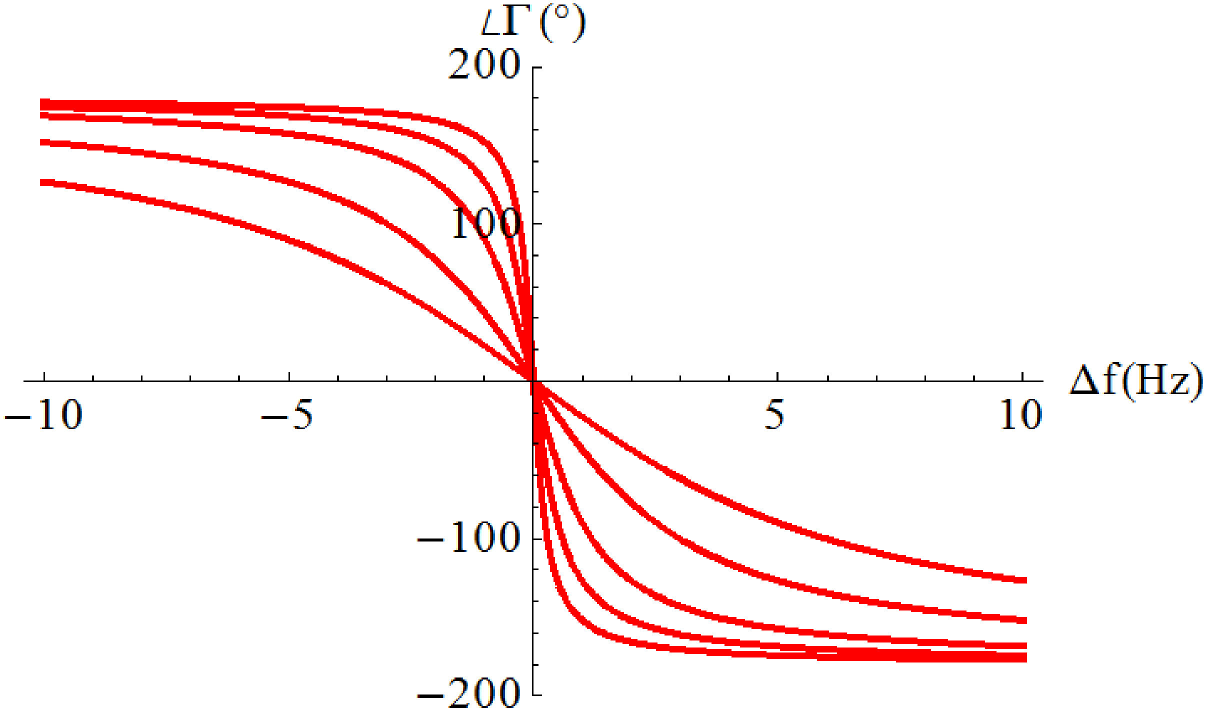
Difficult for strongly overcoupled SC cavities $|\Gamma| \sim 1$

Resonance control – Reflection coefficient method

The instantaneous cavity tune state can be calculated from the measured complex reflection coefficient.

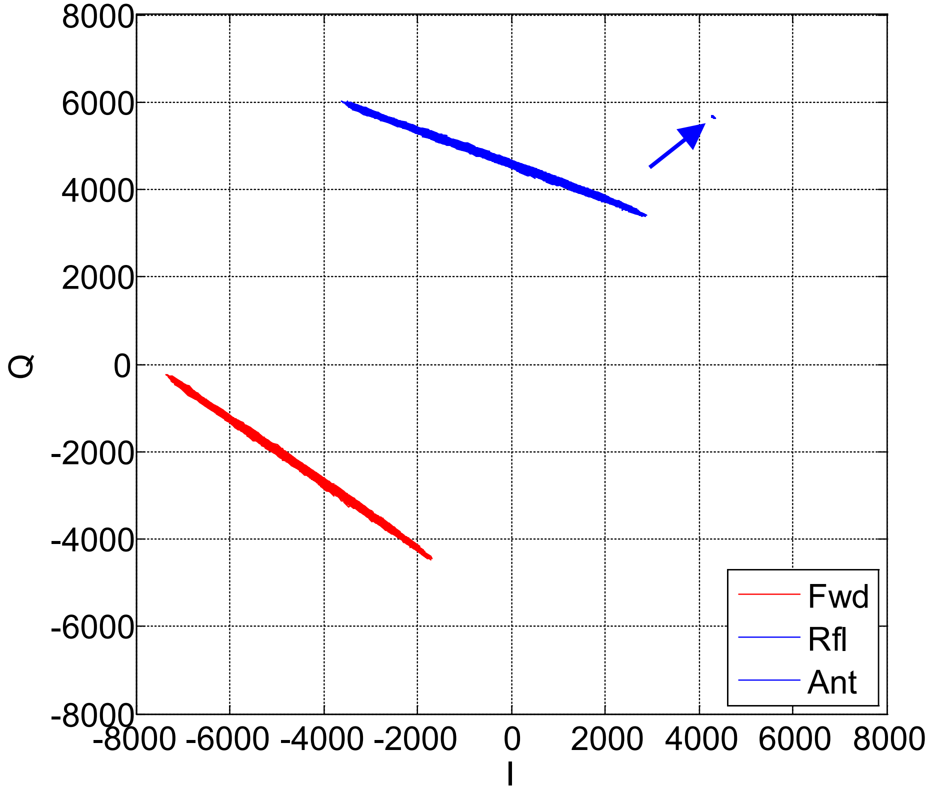
For overcoupled cavities it provides at least the direction where to tune.

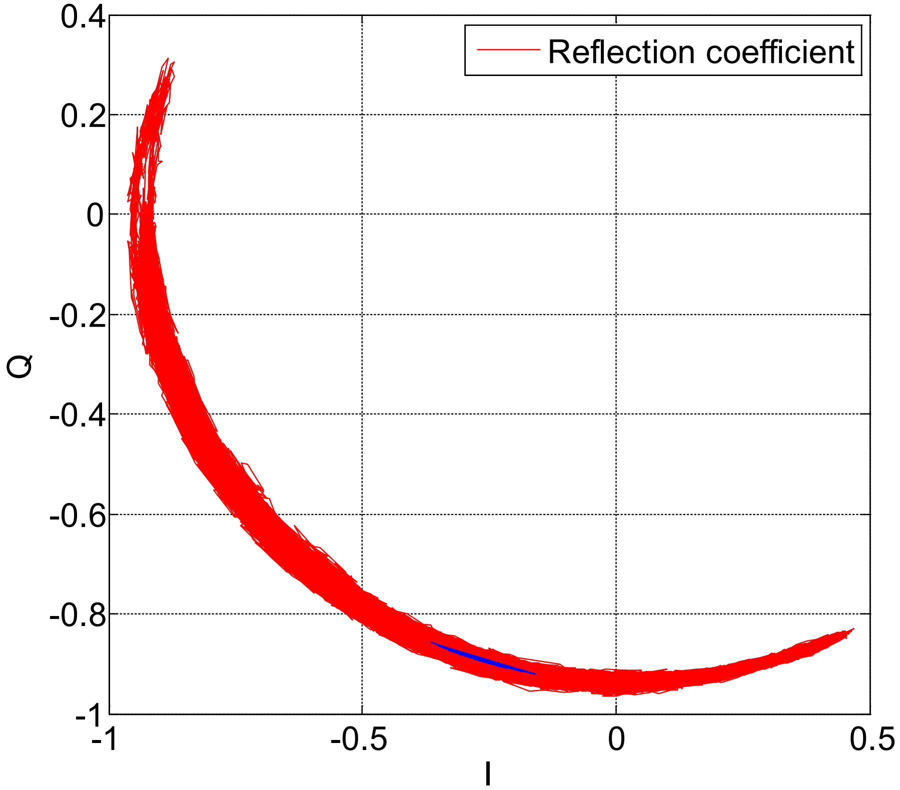




Resonance control – Reflection coefficient method

The instantaneous cavity tune state can be calculated from the measured complex reflection coefficient.





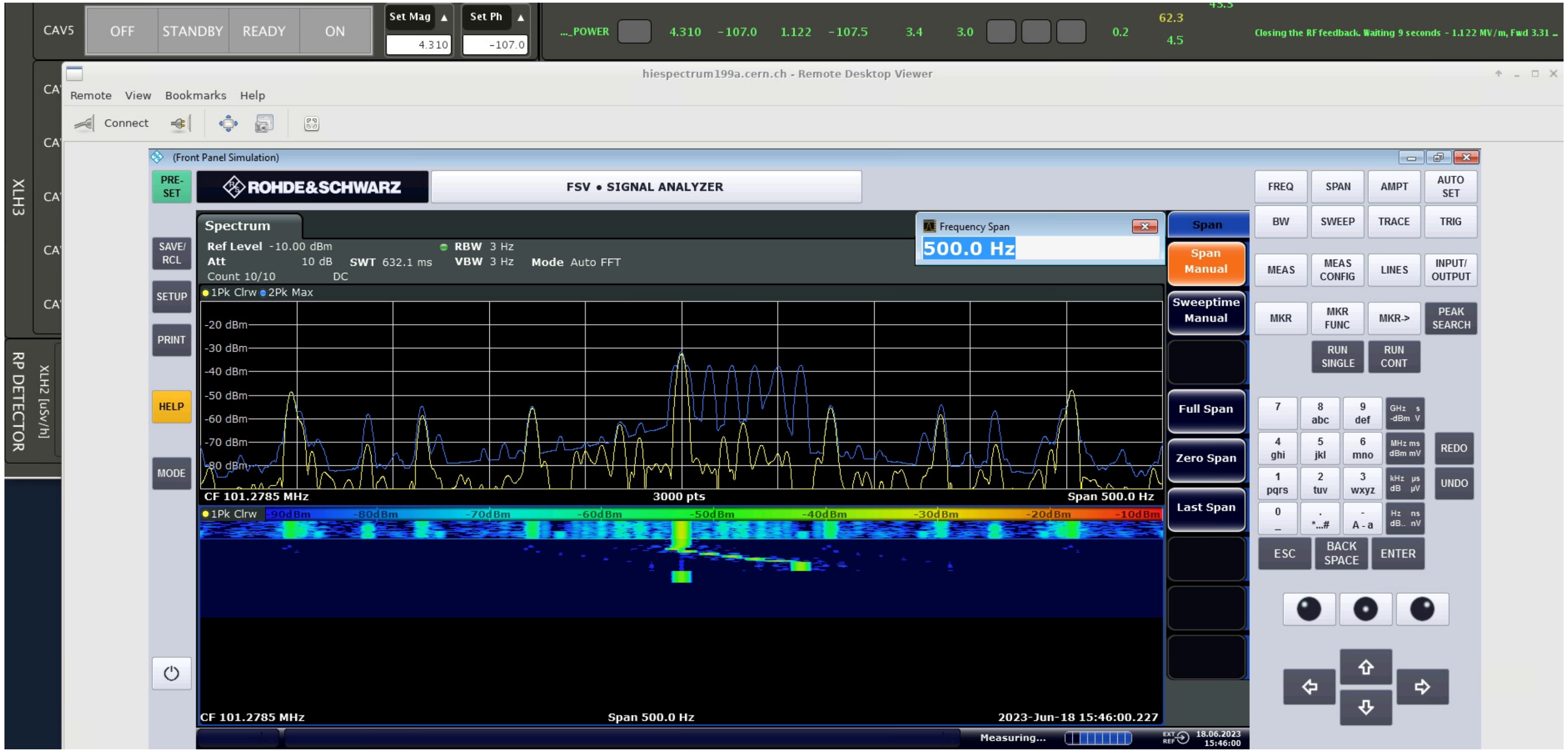
Resonance control – Alternative methods

Modern digital LLRF systems provide access to the direct observables (Fwd, Rfl, Antenna) but also any internal signals from the feedback regulators

Together with computing and signal processing capabilities, one may try alternative methods to find the instantaneous cavity tune state…

Starting up the cavity from “dark and cold” state

Starting up sequence HIE-Isolde



CAV5 OFF STANDBY READY ON

Set Mag 4.310

Set Ph -107.0

Closing the RF feedback. Waiting 9 seconds - 1.122 MV/m, Fwd 3.31 ...

hiespectrum199a.cern.ch - Remote Desktop Viewer

(Front Panel Simulation)

FSV • SIGNAL ANALYZER

Spectrum

Ref Level -10.00 dBm RBW 3 Hz

Att 10 dB SWT 632.1 ms VBW 3 Hz Mode Auto FFT

Count 10/10 DC

Frequency Span 500.0 Hz

CF 101.2785 MHz 3000 pts Span 500.0 Hz

CF 101.2785 MHz Span 500.0 Hz 2023-Jun-18 15:46:00.227

Measuring...

Starting up sequence HIE-Isolde

Clear all interlocks, start up the amplifiers, check LLRF

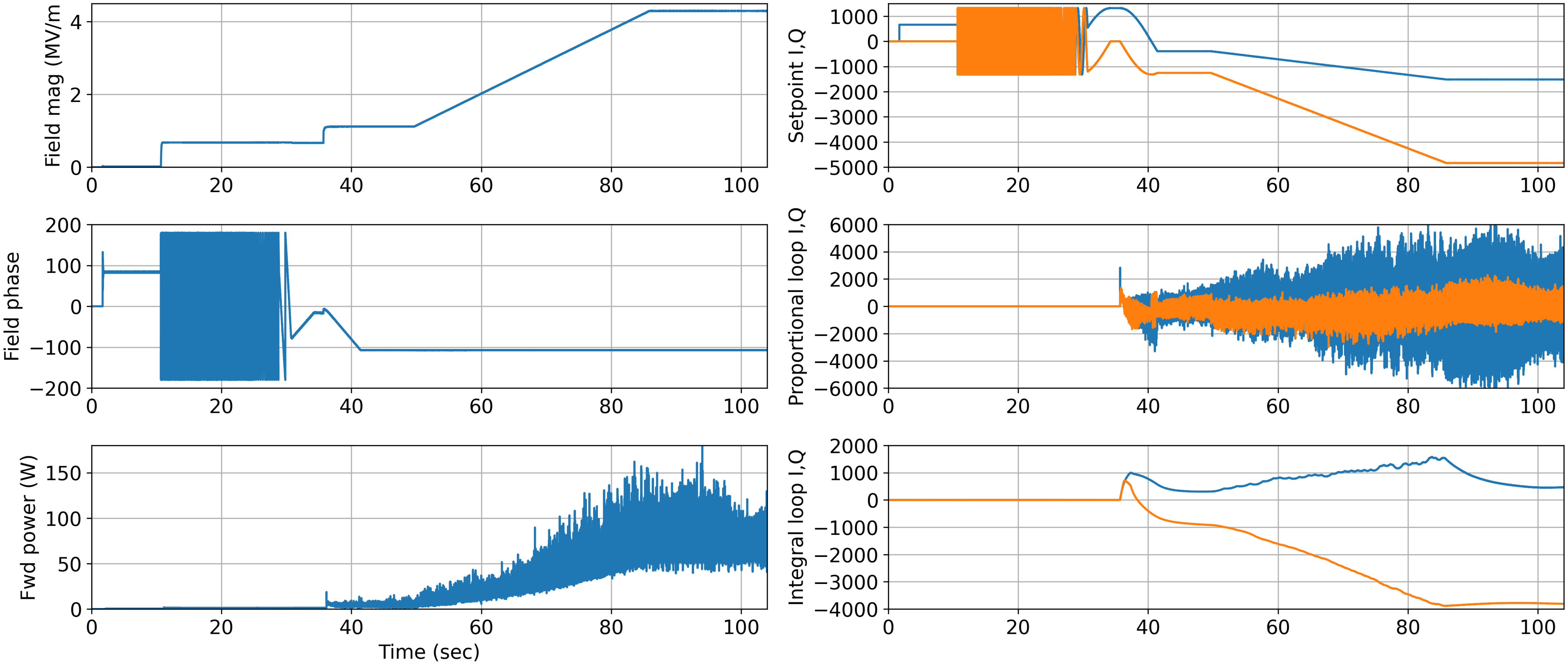
…

```
State STANDBY reached
Lifting RF veto and closing the RF switch. Excitation enabled from now on.
Reference ADC phase is correct
Lifting RF veto and starting up the cavity
Waiting 1 seconds - Field: 0.021 MV/m
Reference DAC phase is correct
Reached intermediate state READY
Lifting RF veto and starting up the cavity
Switching GD off and switching SEL on for device XLH2.CAV5.SEQ
Waiting 30 seconds - Field: 0.682 MV/m
Cavity bandwidth within limits: 6.515 Hz (Limits: 3.000 - 20.000 Hz)
Sending 100 steps to the tuner XLH2.CAV5.TUNER to reach nominal linac frequency
Sending 100 steps to the tuner XLH2.CAV5.TUNER to reach nominal linac frequency
Sending 52 steps to the tuner XLH2.CAV5.TUNER to reach nominal linac frequency
Sending 26 steps to the tuner XLH2.CAV5.TUNER to reach nominal linac frequency
```

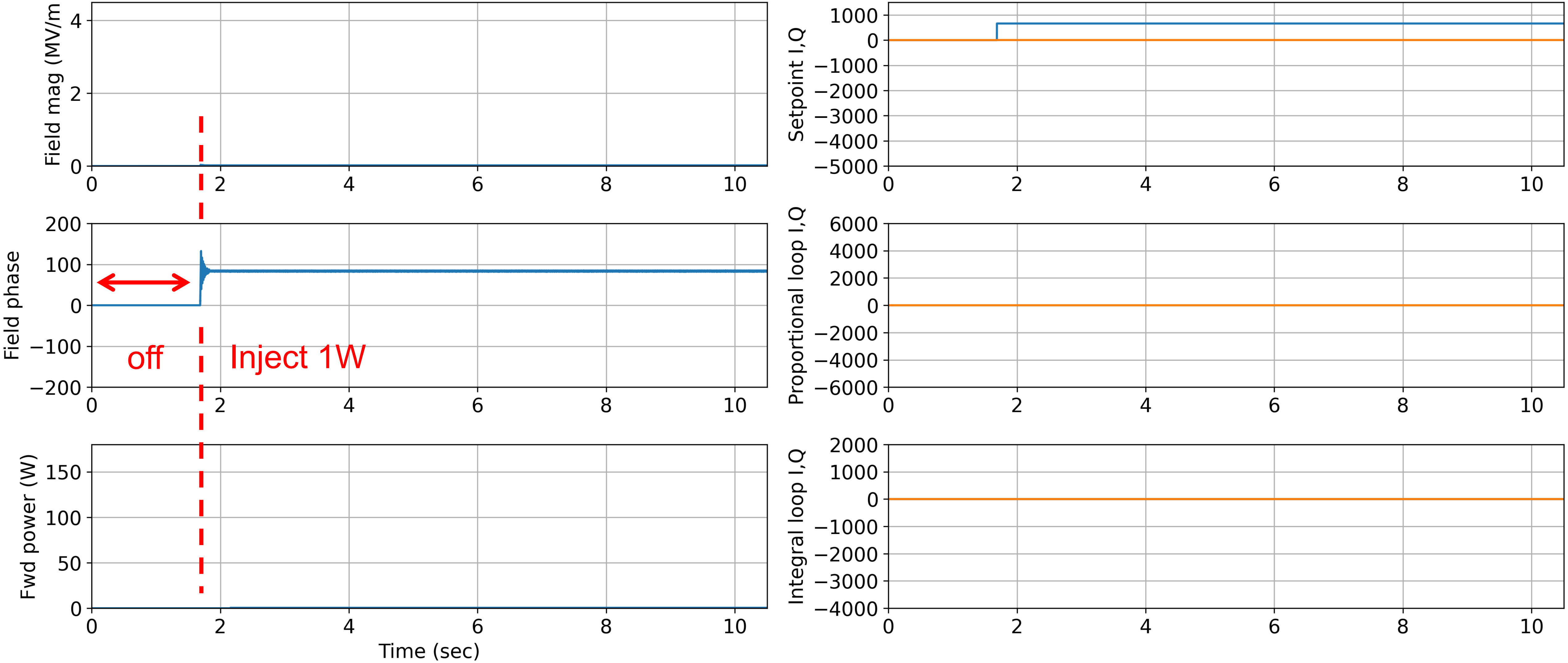
Starting up sequence HIE-Isolde

```
Enabling the tuner loop...
Waiting 3 seconds - 0.671 MV/m, Fwd 1.12 W, Rfl 1.01 W
Waiting 1 seconds - 0.670 MV/m, Fwd 1.11 W, Rfl 1.01 W
Switching over from GD to feedback mode
Waiting 3 seconds - 1.111 MV/m, Fwd 3.48 W, Rfl 3.20 W
Waiting 1 seconds - 1.120 MV/m, Fwd 3.16 W, Rfl 2.94 W
Closing the RF feedback. Waiting 1 seconds - 1.120 MV/m, Fwd 3.12 W, Rfl 2.86 W
Closing the RF feedback. Waiting 9 seconds - 1.122 MV/m, Fwd 3.31 W, Rfl 2.97 W
Setting setpoint cavity voltage and phase
Waiting 3 seconds - 1.190 MV/m, Fwd 4.18 W, Rfl 3.77 W
Waiting 2 seconds - 1.279 MV/m, Fwd 5.27 W, Rfl 4.80 W
Waiting 1 seconds - 1.366 MV/m, Fwd 5.43 W, Rfl 4.83 W
Ramping set points. Waiting 1 seconds - 1.455 MV/m, Fwd 6.78 W, Rfl 6.21 W
Ramping set points. Waiting 36 seconds - 4.309 MV/m, Fwd 50.38 W, Rfl 41.64 W
State ON reached
```

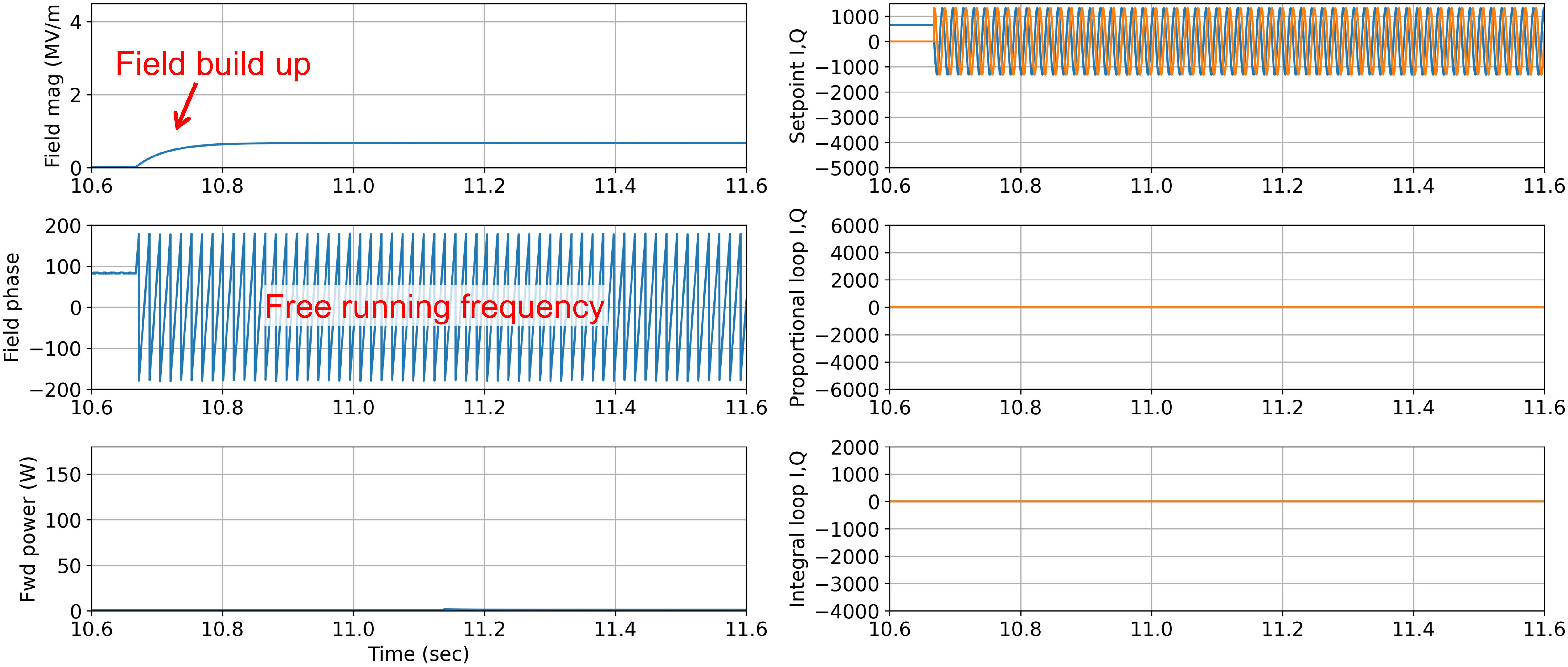
Starting up sequence – overview



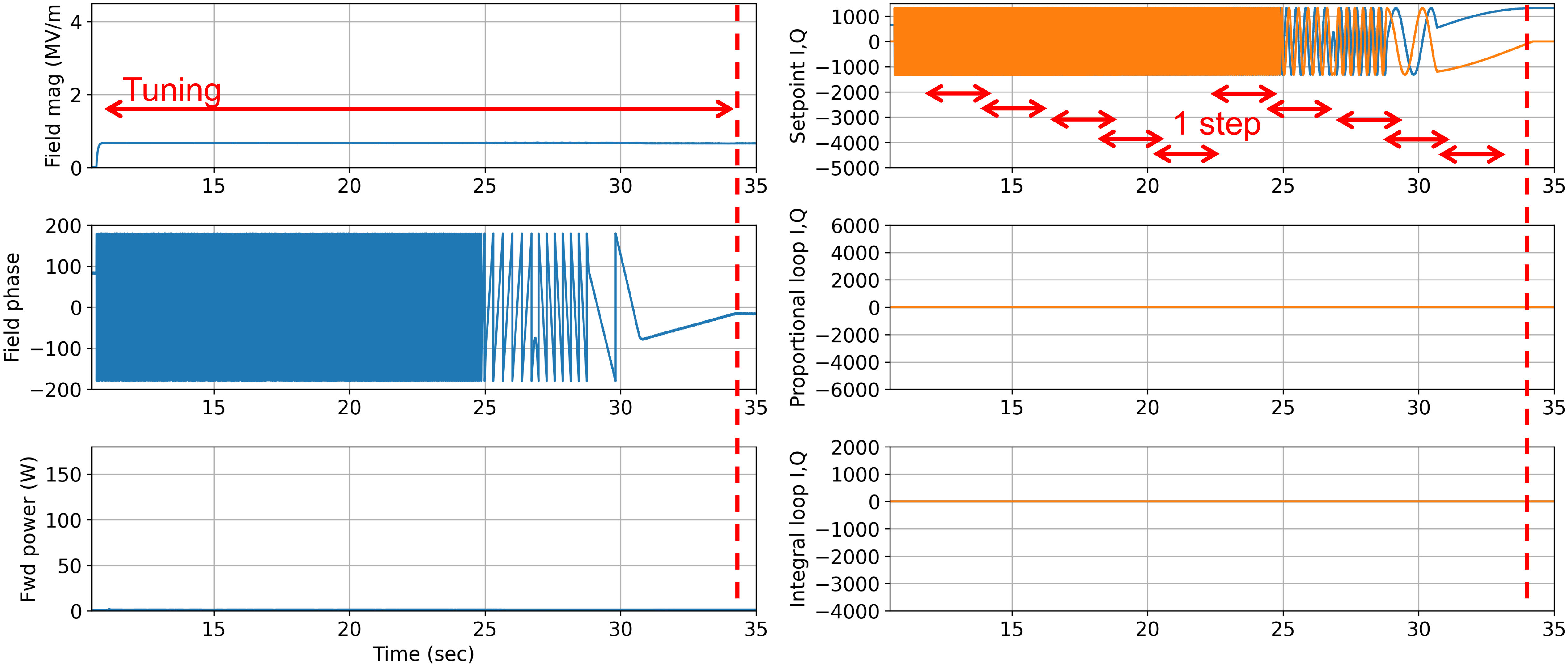
1. Low power checks



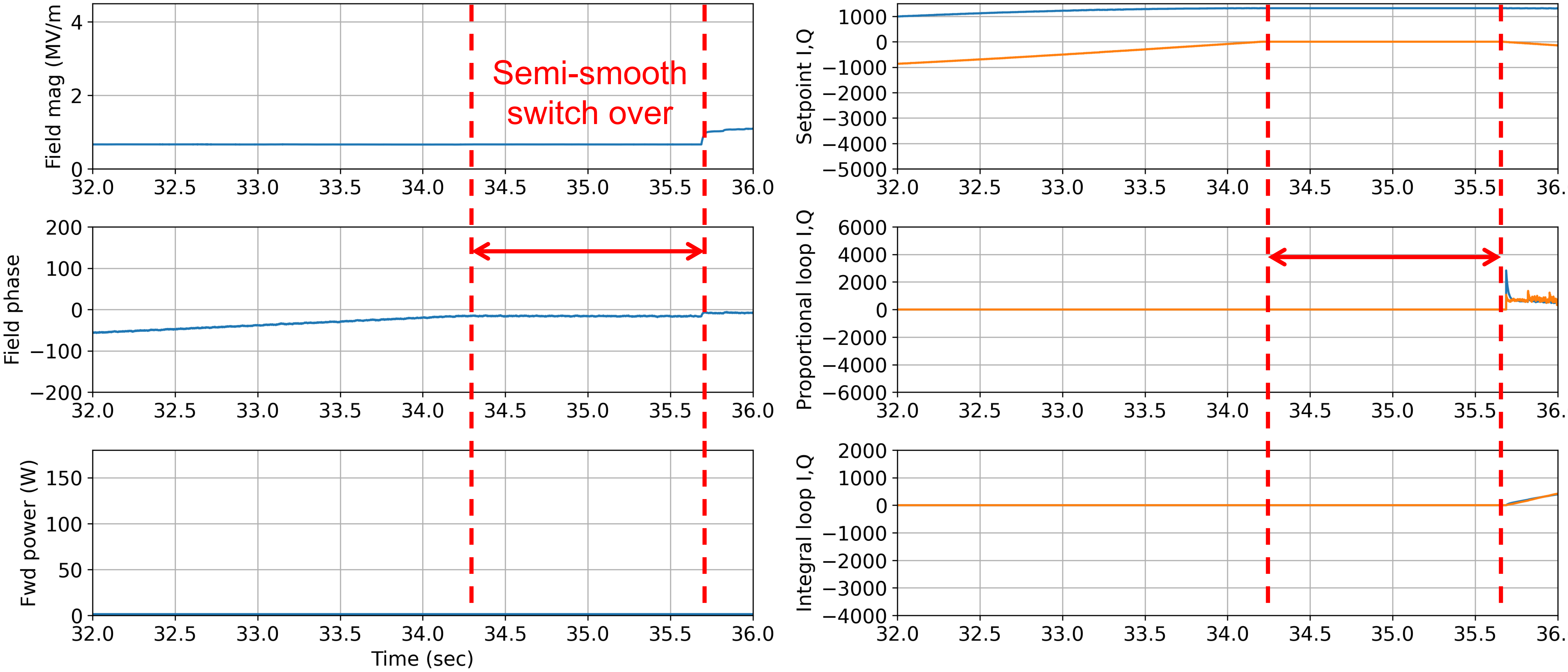
1. Excite field with SEL, measure the cavity frequency



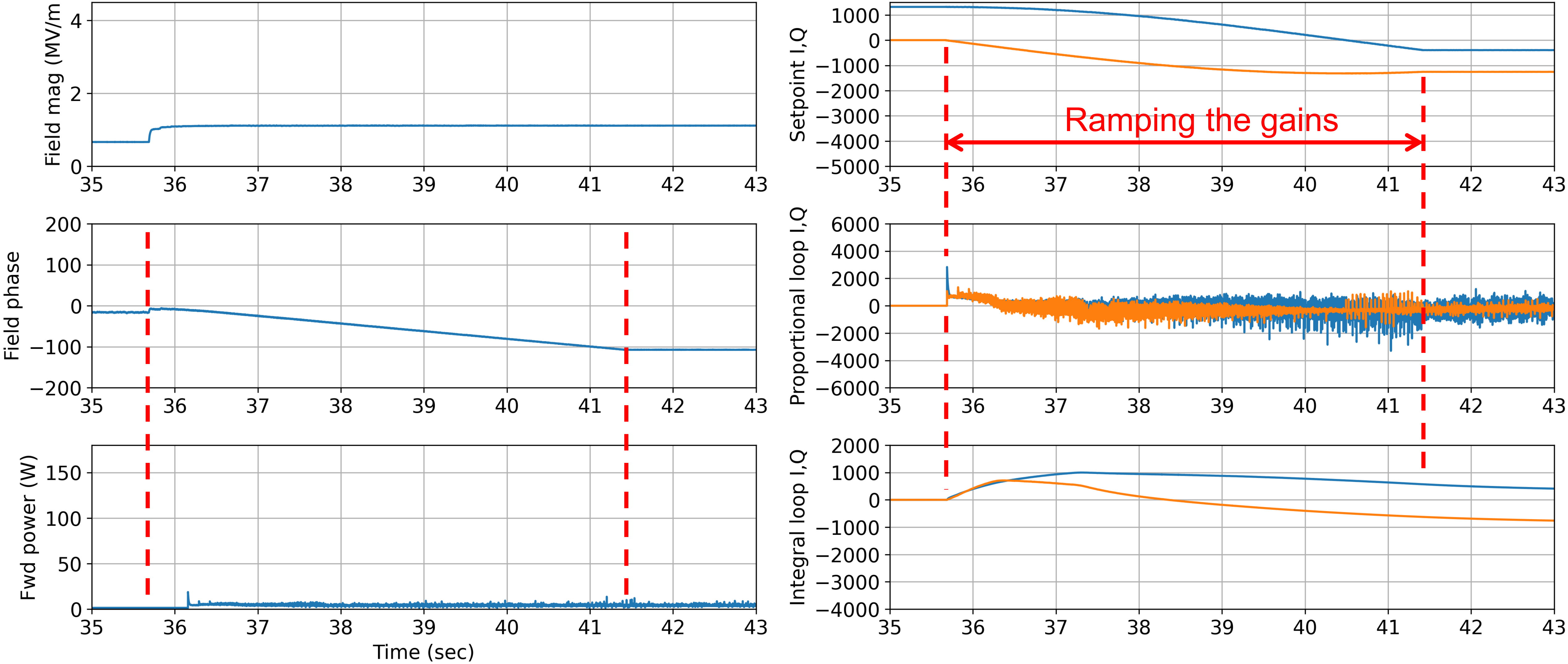
3. Tune to nominal freq.



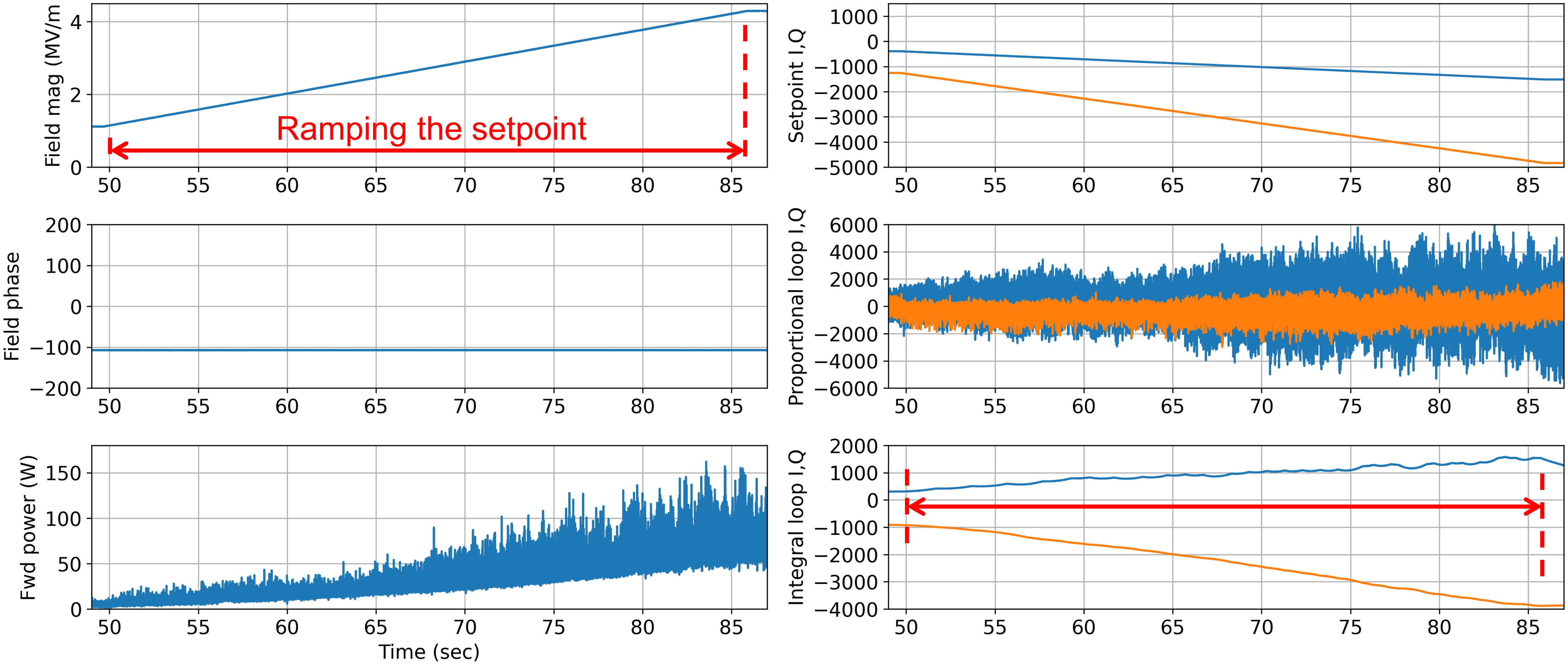
4. Switch to Generator Driven mode



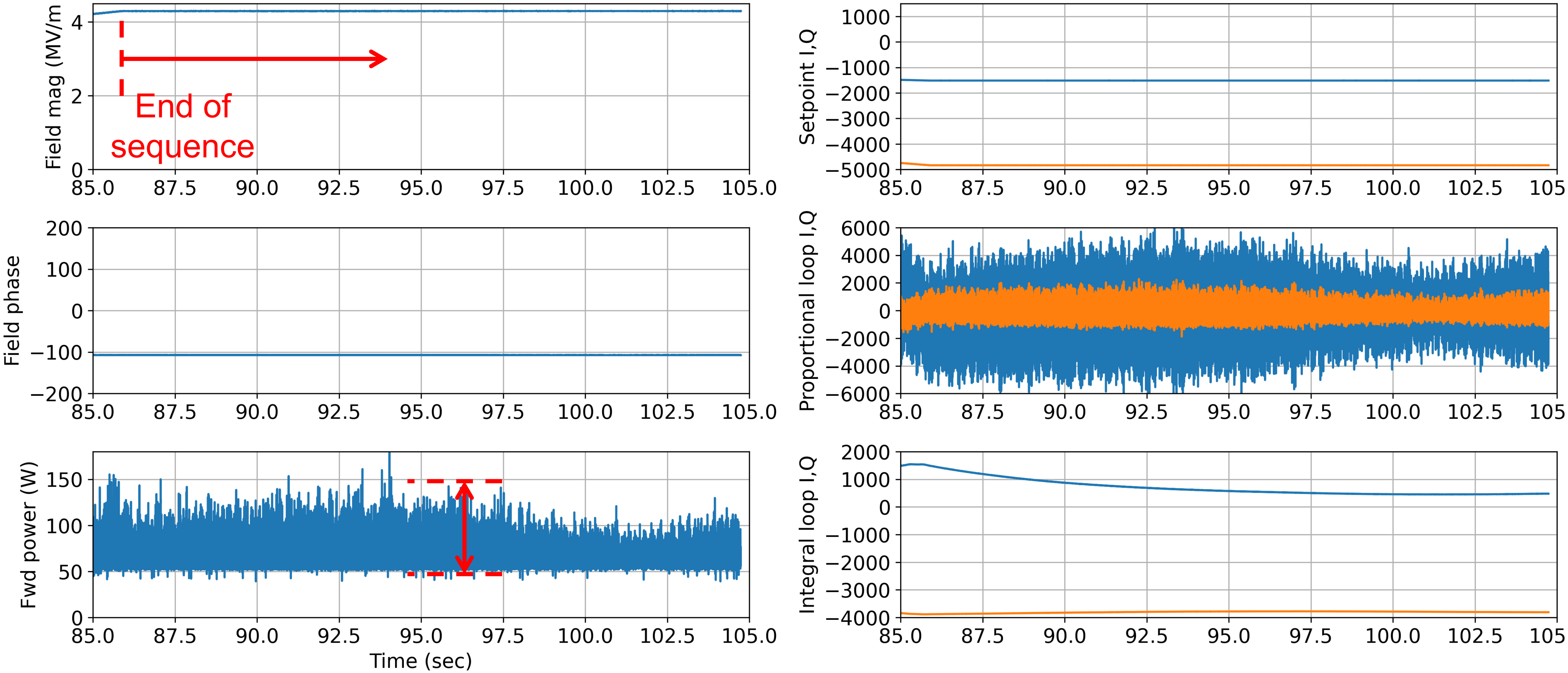
5. Enable feedback and ramp the gain



6. Ramp the setpoint to nom. values (while locked)



7. Fully locked at nominal accelerating gradient



Cavity conditioning

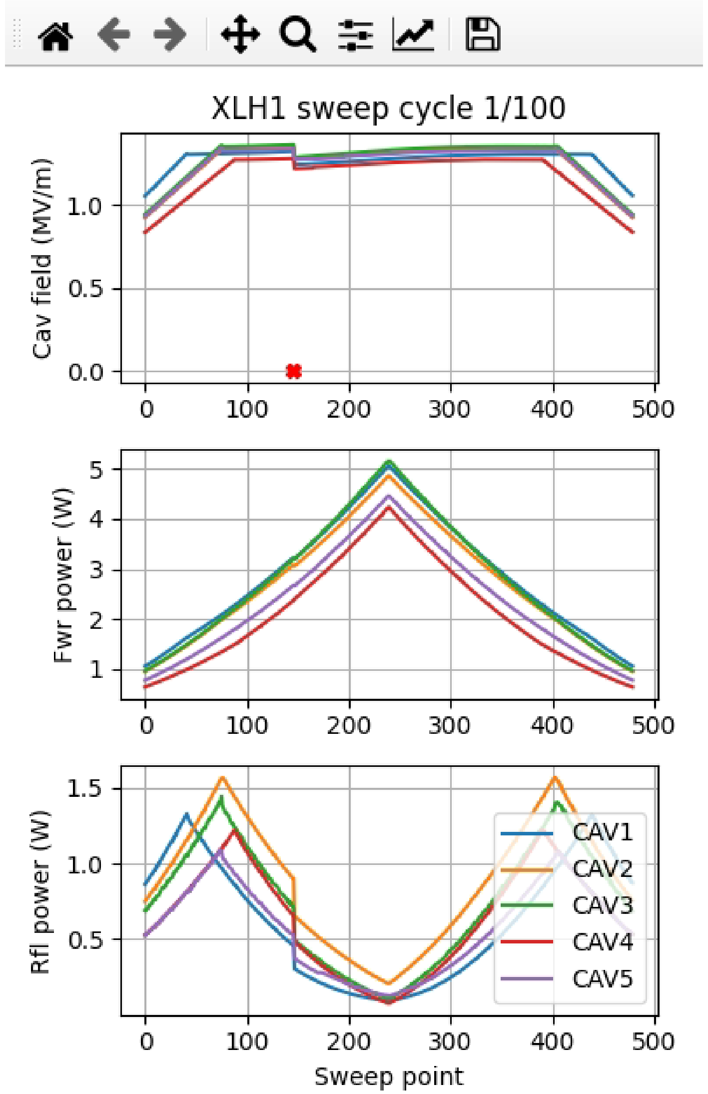
Conditioning of multipacting – “dump” power to reduce SEY of the surface by electron bombardment. Typically low energy phenomena. Q constant, but the power is absorbed, field is not increasing with increased power.

Conditioning of field-emission – “burn” local field emitters. High field, high power phenomena. Field increases with fwd power, but the Q drops. Often very high power, pulsed conditioning.

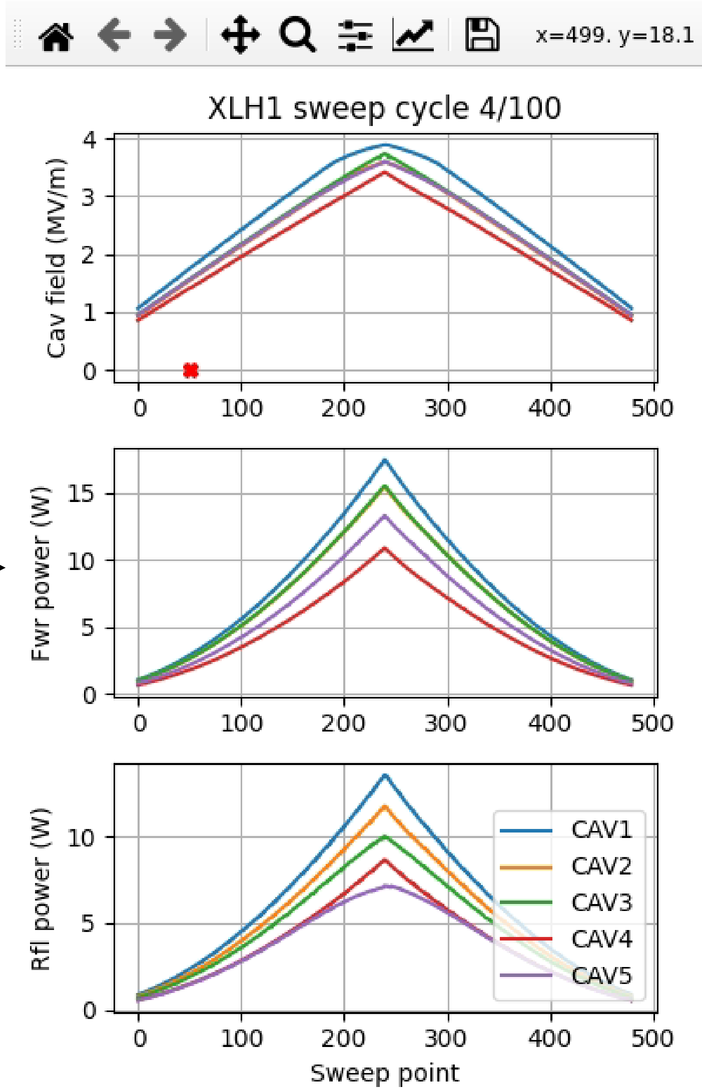
Typically, self excited loop is used, as it naturally follows the cavity parameter fluctuations (Q, fc)

Cavity conditioning

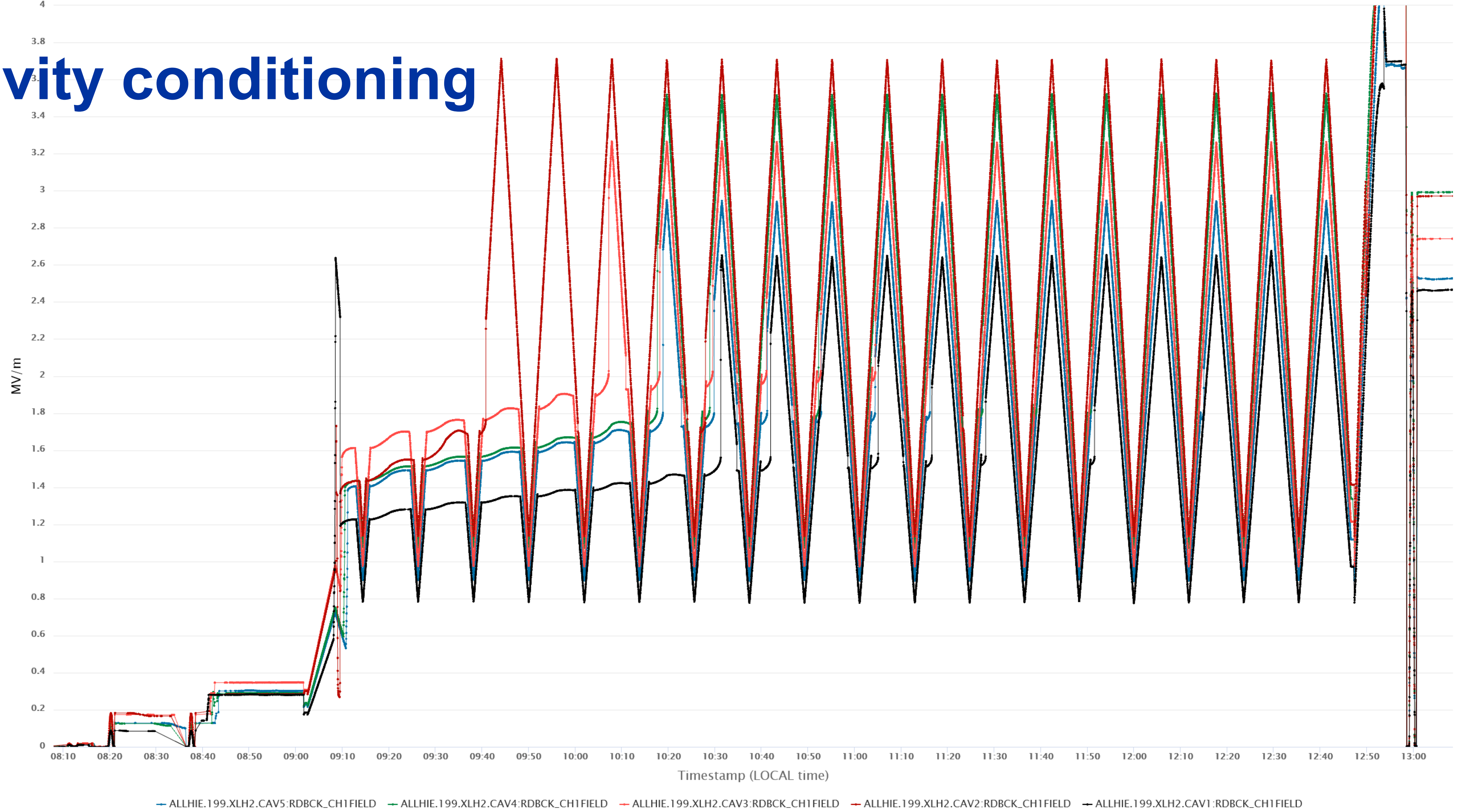
Typically, self excited loop is used, as it naturally follows the cavity fluctuations (Q, fc)



One day later



Cavity conditioning



Few notes on feedbacks

Recap: *Function of a feedback loop is to make the value of the measured quantity equal to the value of the setpoint.*

Feedbacks always try to keep the two equal, until they run out of power or authority

Few notes on feedbacks

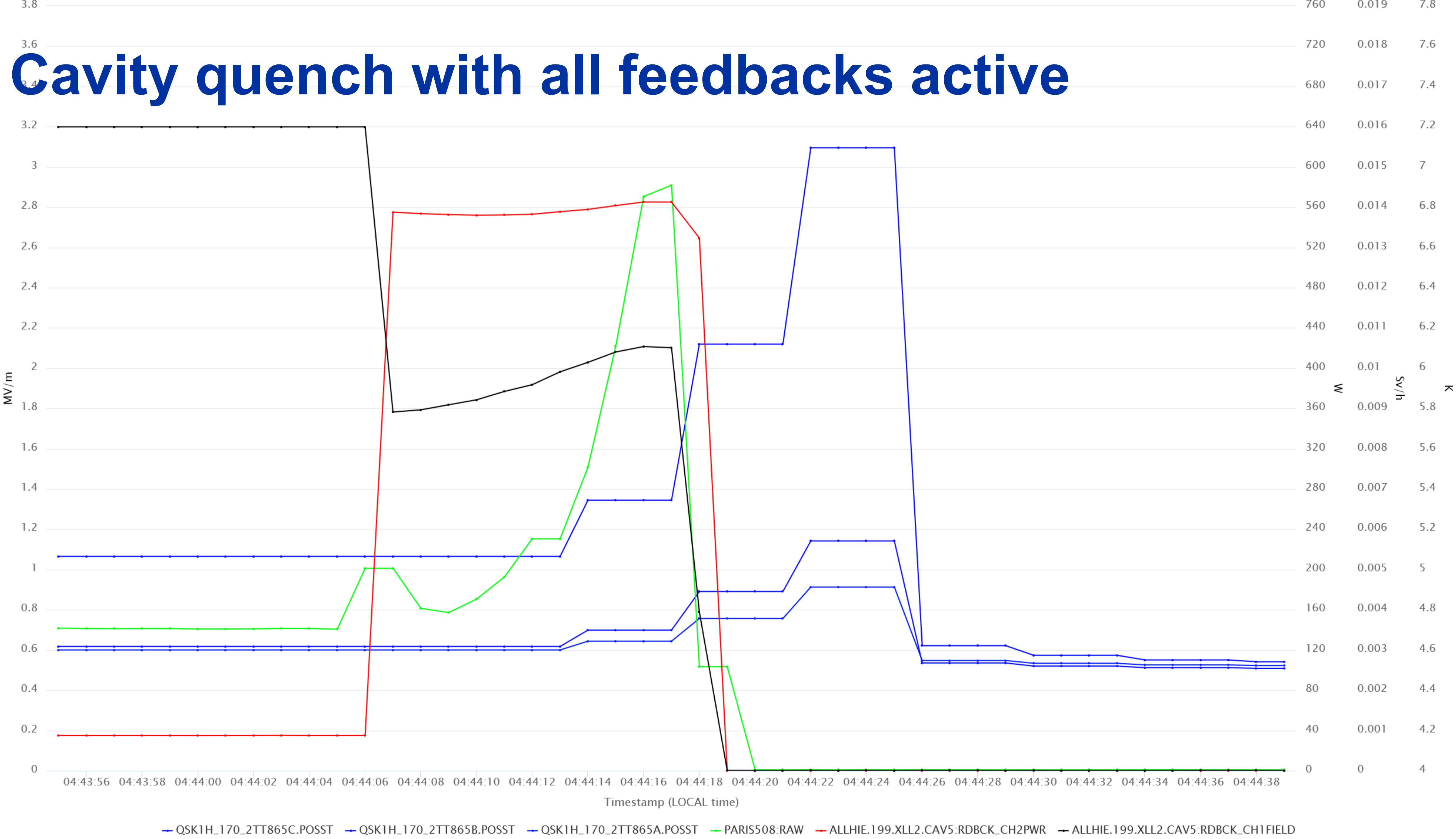
Recap: *Function of a feedback loop is to make the value of the measured quantity equal to the value of the setpoint.*

Feedbacks always try to keep the two equal, until they run out of power or authority

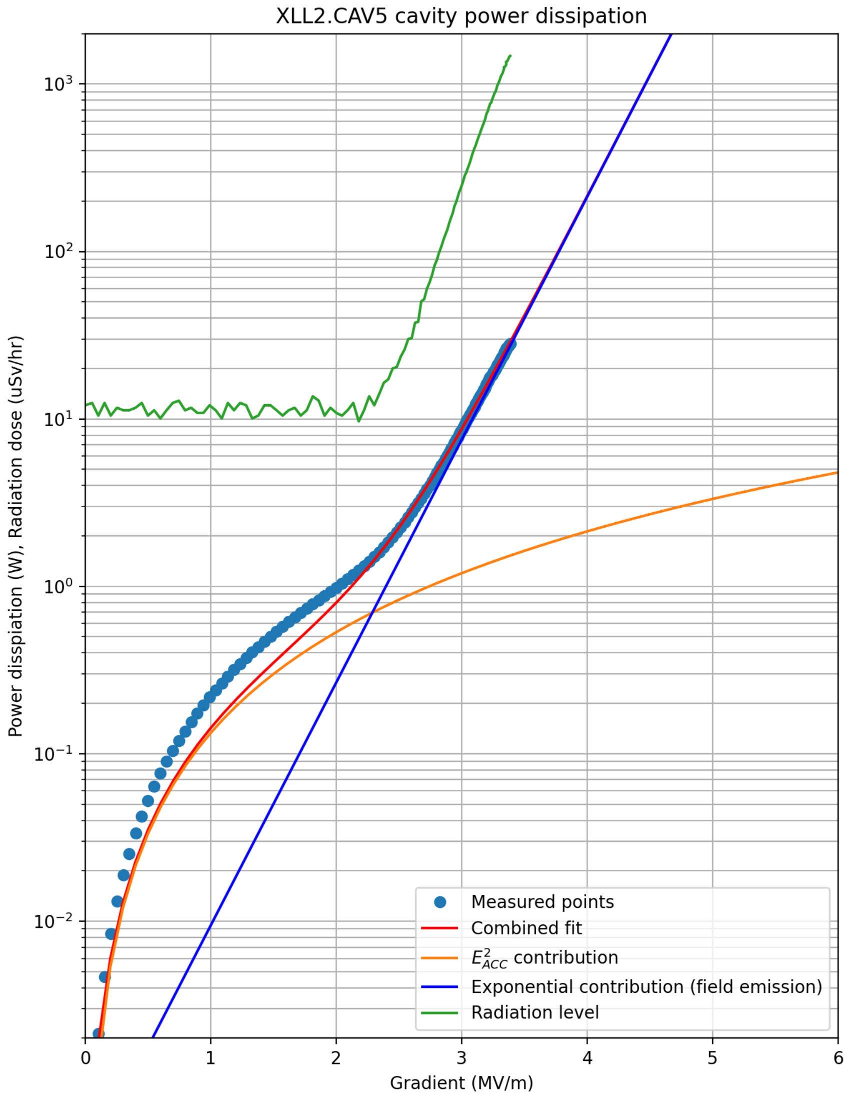
Always think of a "safety net" to catch unexpected behaviour

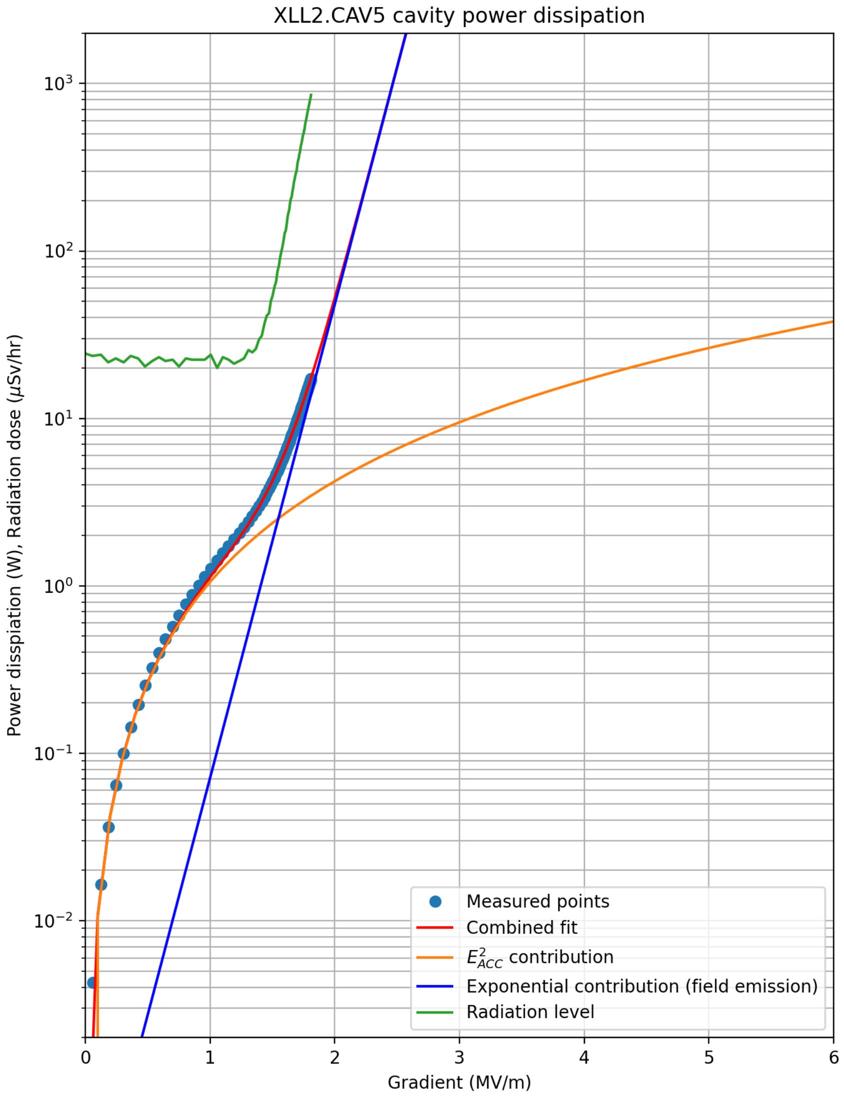
- **Regulator saturation timeout (e.g. in HIE-Isolde 10-15 seconds)**
- **Maximum error timeout (e.g. if error > 5% for 5 sec)**
- **Average power interlock (e.g. in HIE-Isolde 350 W for 5 min, 250 W for 30 min, 200 W for 2 hours)…**

Cavity quench with all feedbacks active

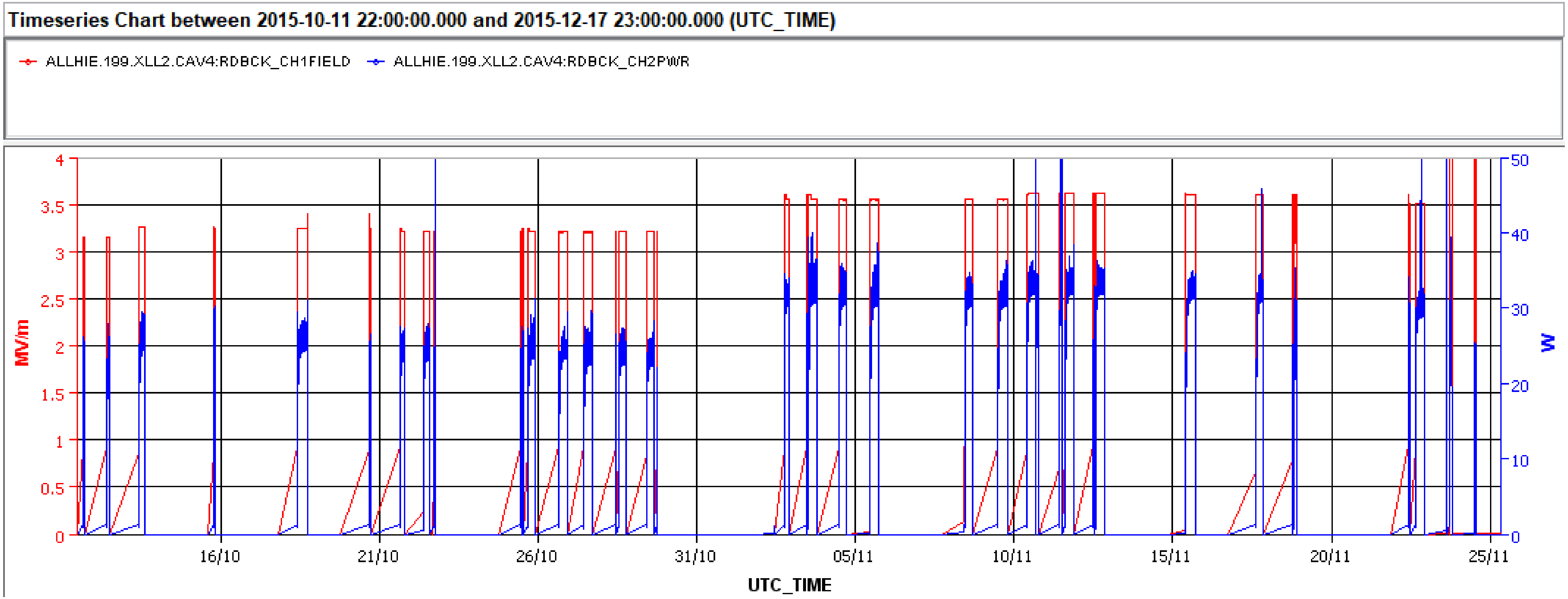


Cavity quench with all feedbacks active



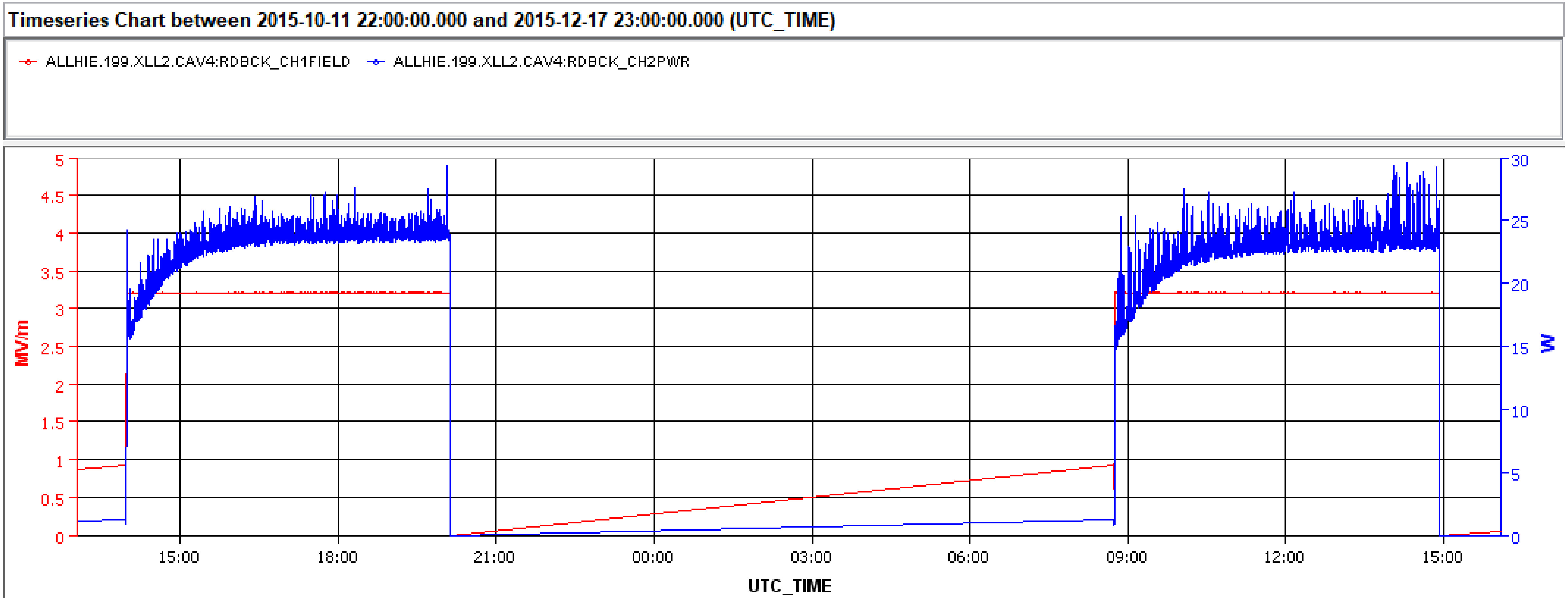


Keeping the field up*

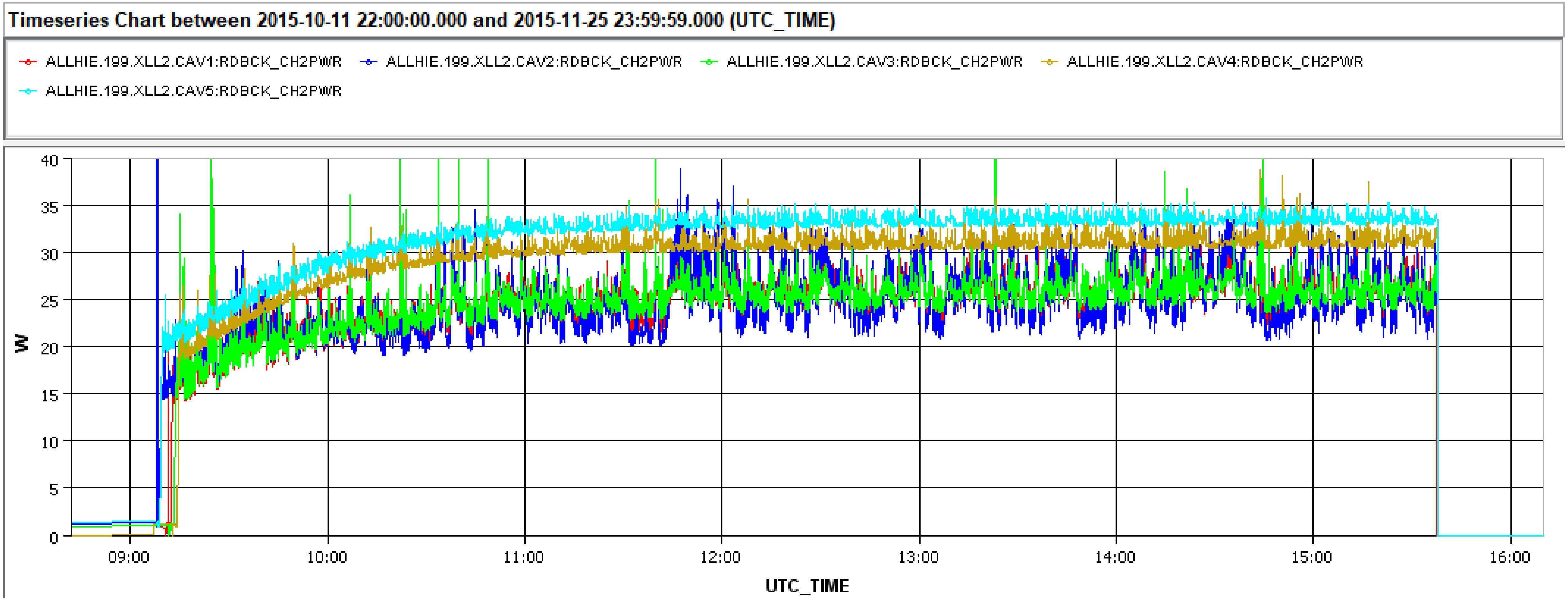


Timeseries Chart between 2015-10-11 22:00:00.000 and 2015-12-17 23:00:00.000 (UTC_TIME)

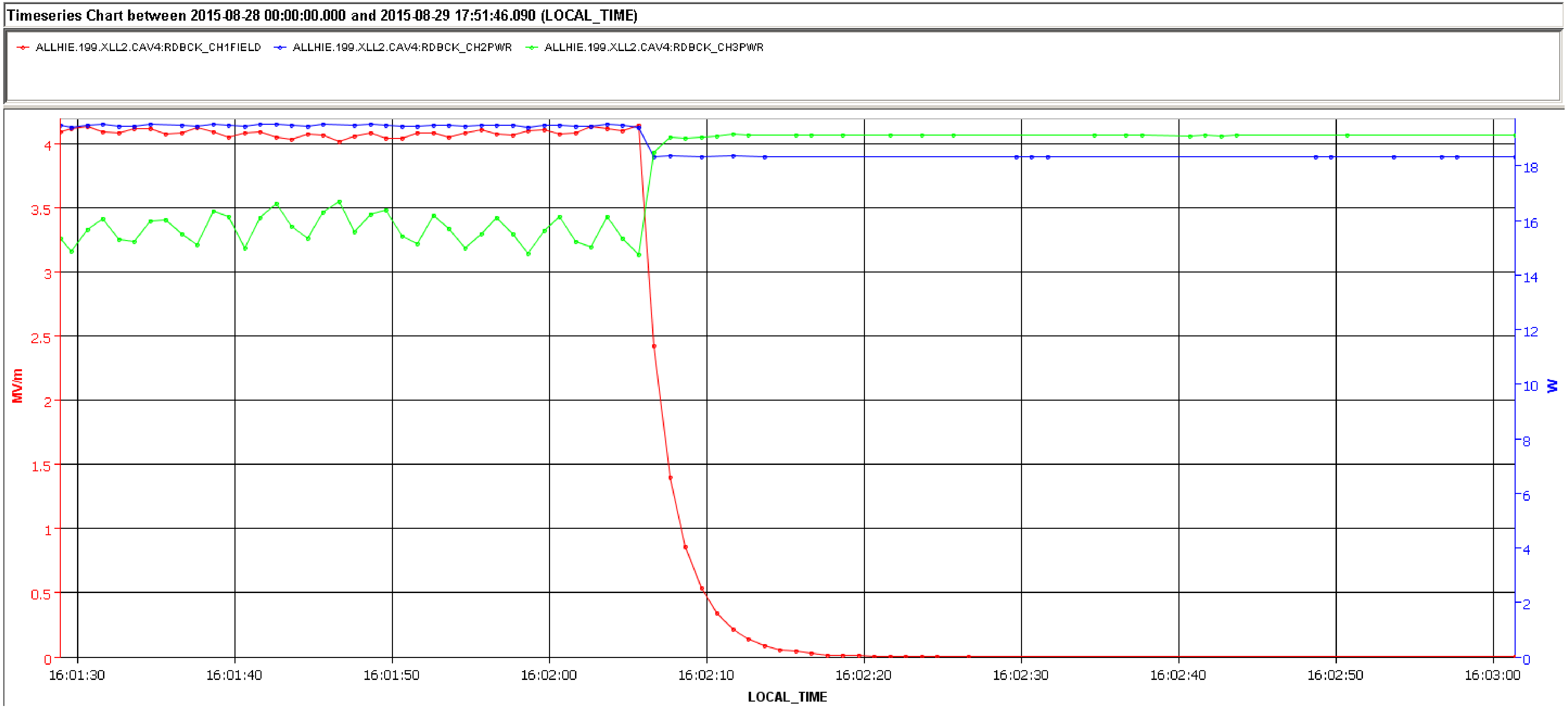
Keeping the field up*



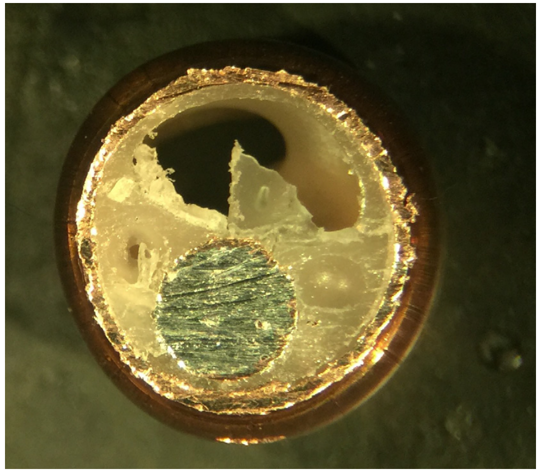
Keeping the field up*

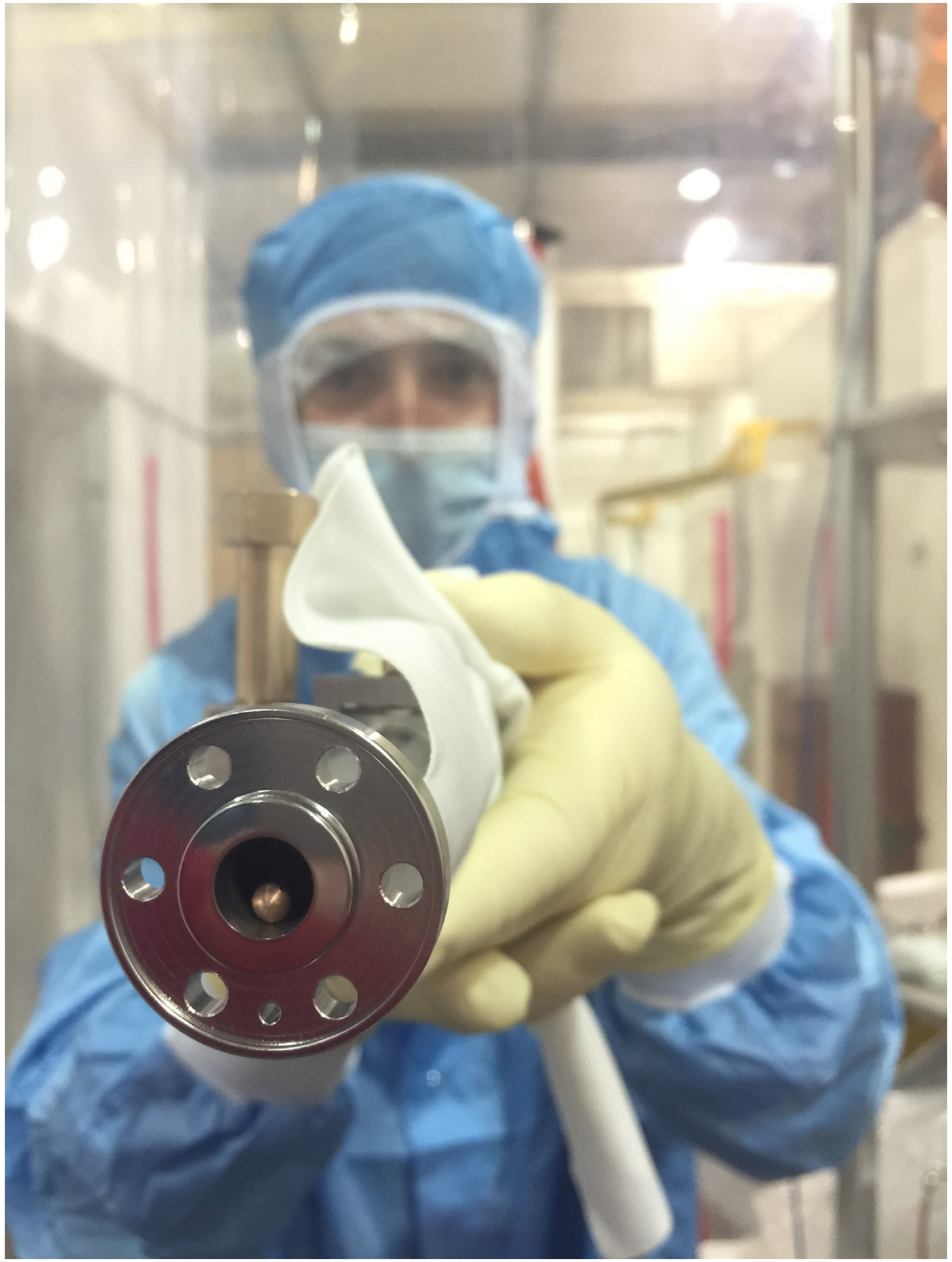

Timeseries Chart between 2015-10-11 22:00:00.000 and 2015-11-25 23:59:59.000 (UTC_TIME)

Keeping the field up*



Keeping the field up*





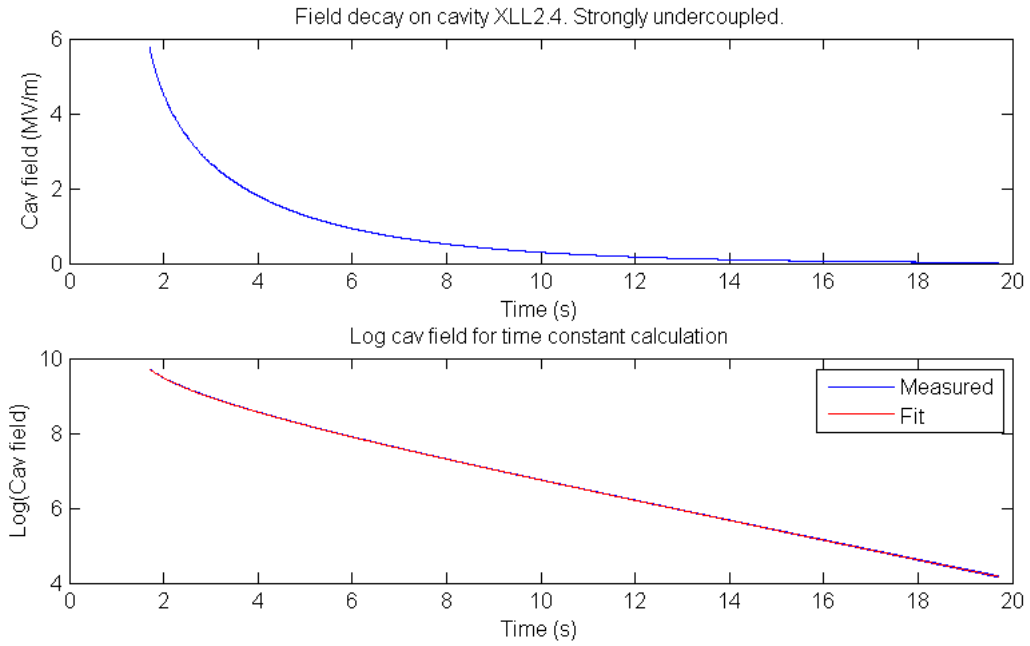
* regardless how much you melt the fundamental power coupler

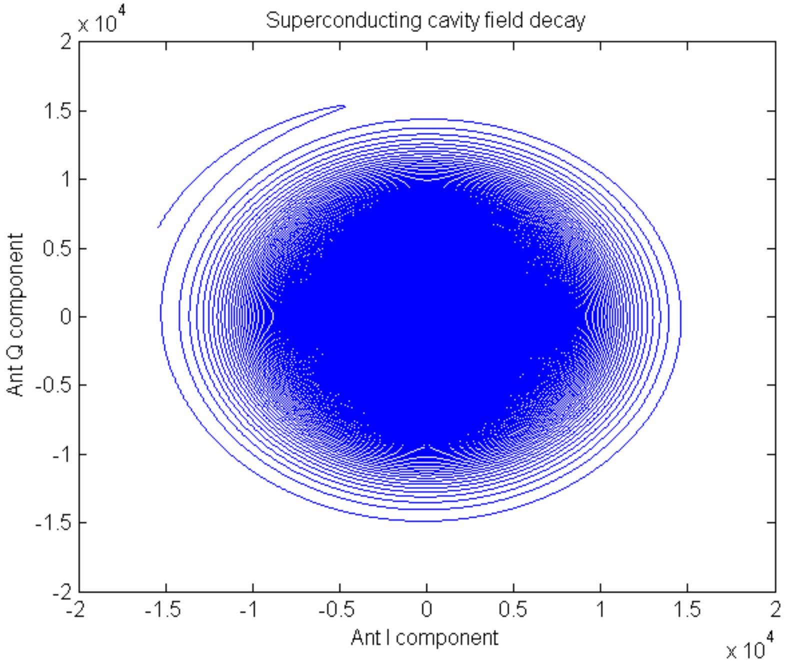
Extracting information from the field decay transient

Digital systems allow to record time series of measured signals

We have forward, reflected and transmitted signals available

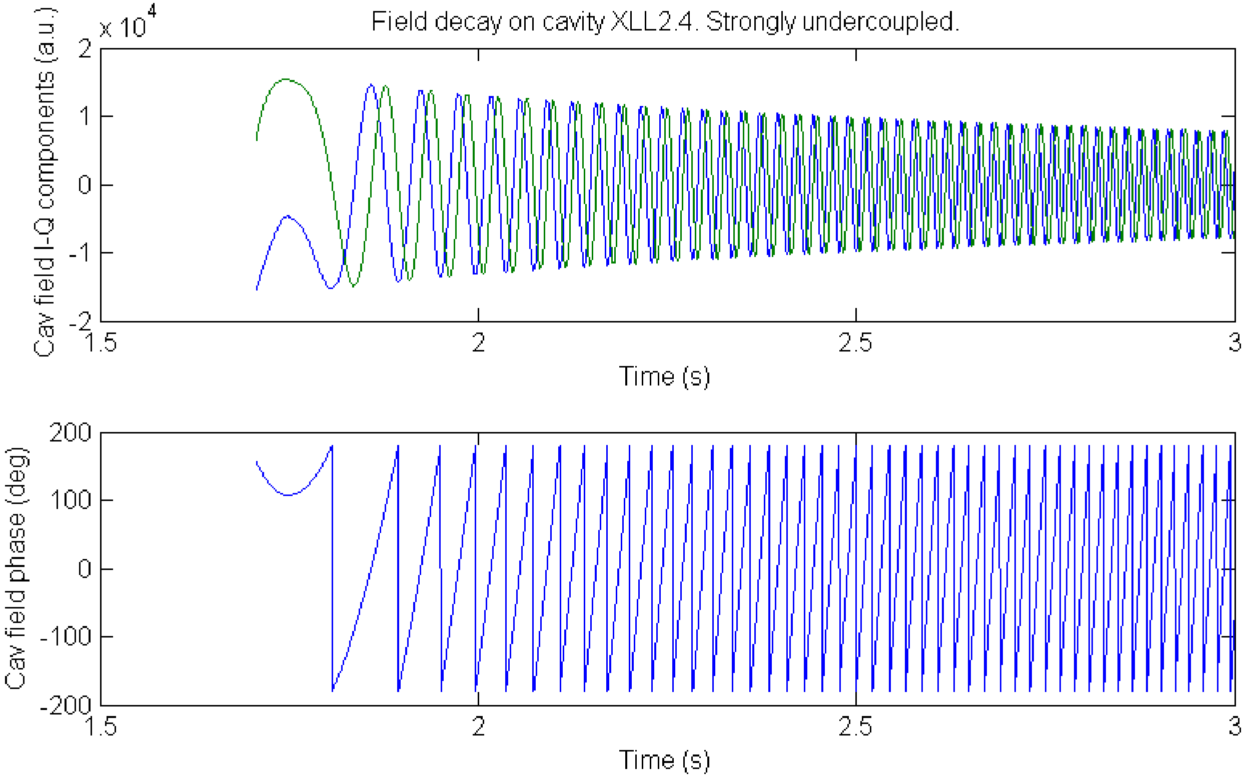
How much information can be extracted from a single field decay transient?

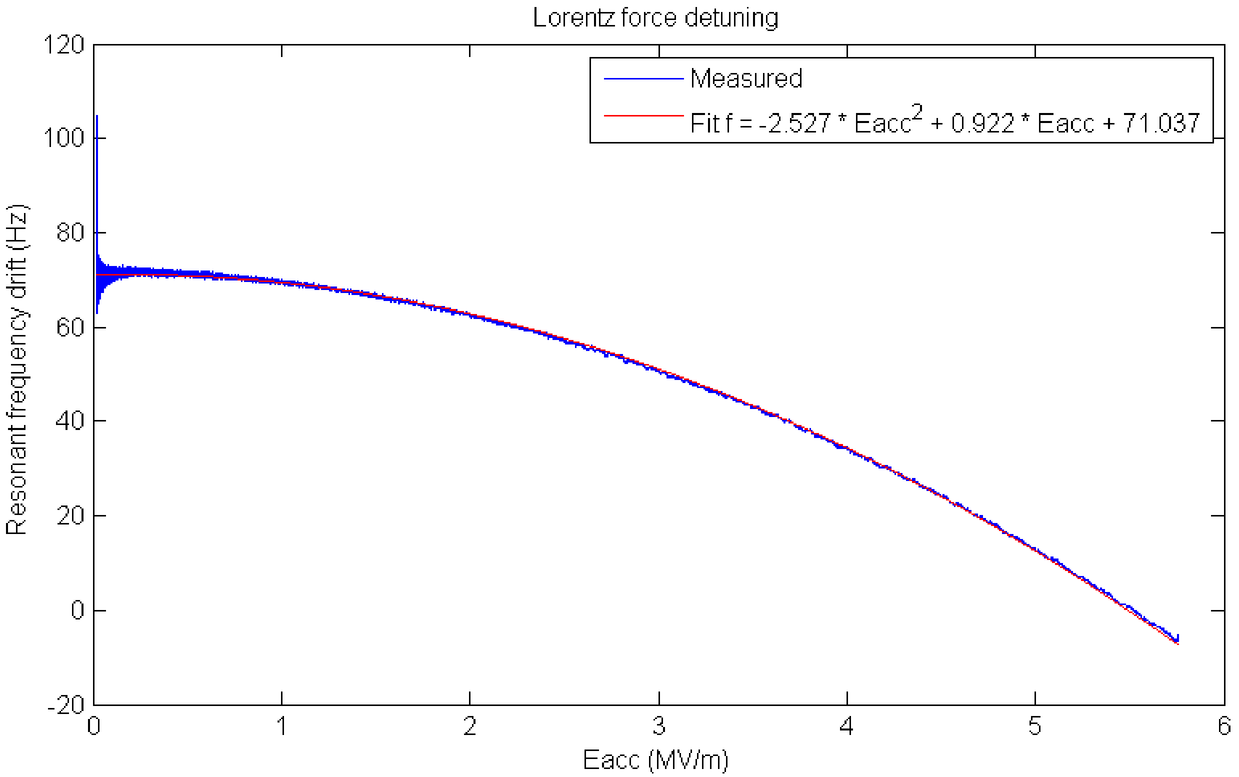




Extracting information from the field decay transient

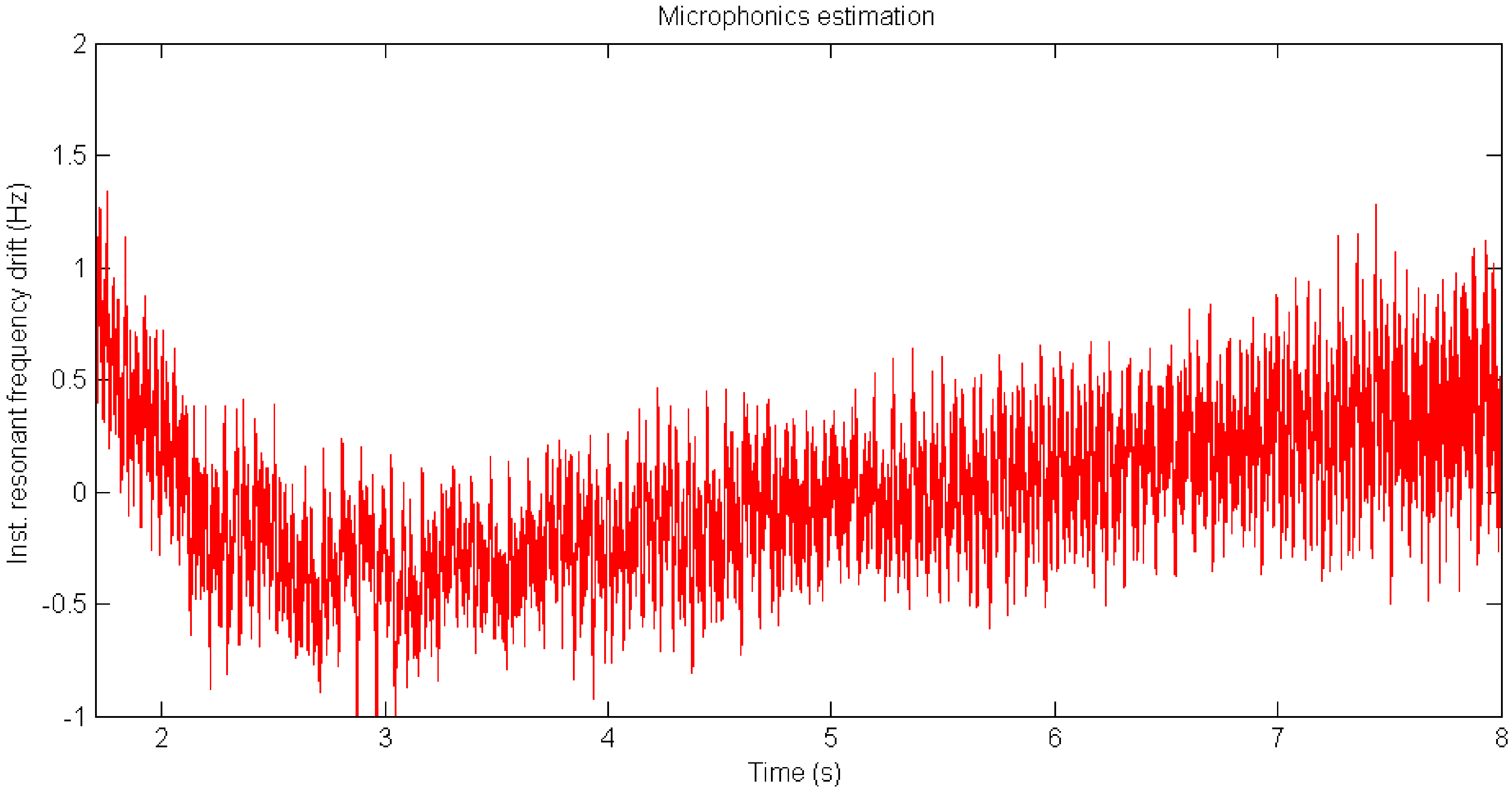
Instantaneous frequency shift $\Delta f \propto K_L \, |E_{acc}|^2$





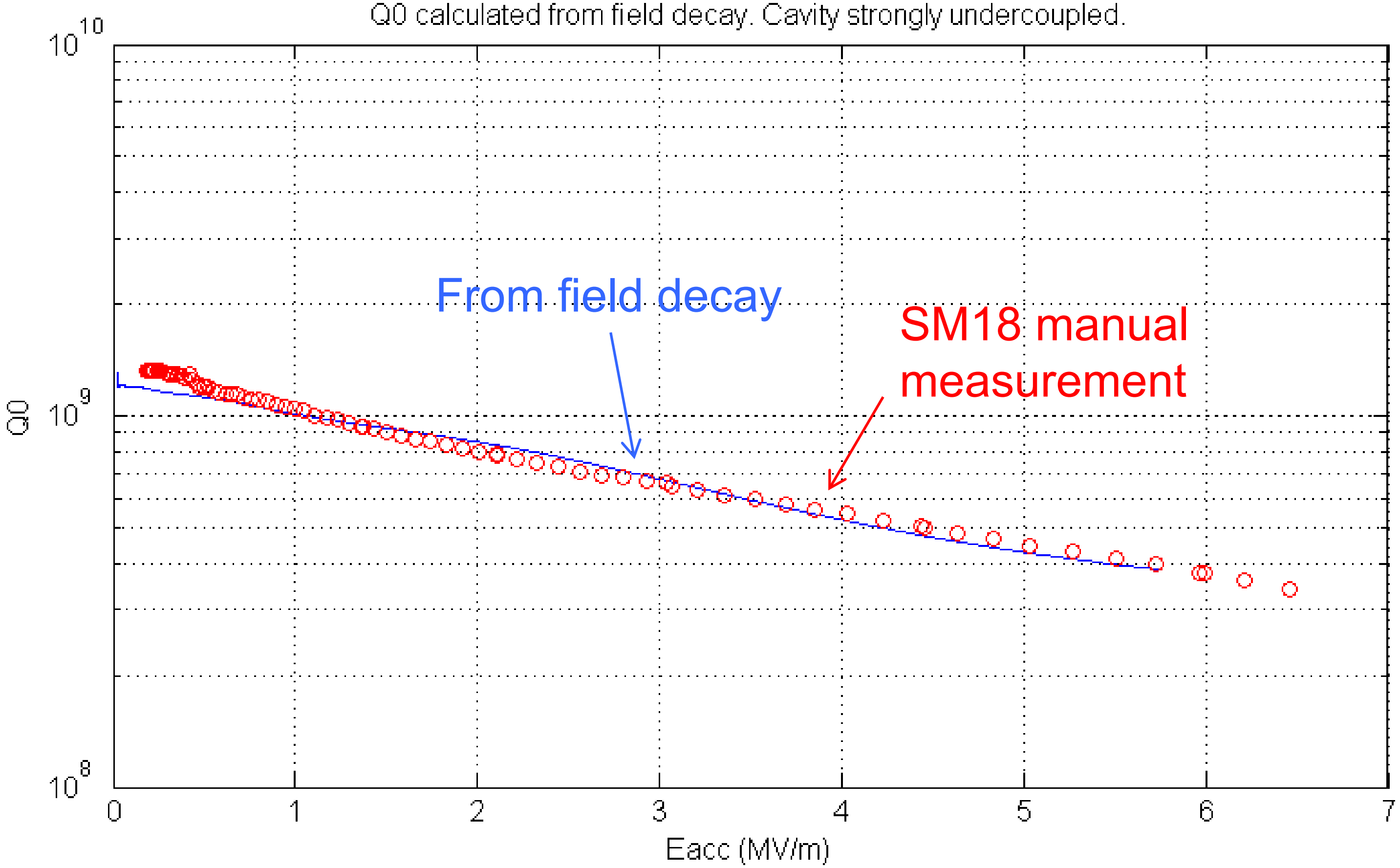
Extracting information from the field decay transient

When the LFD component is removed, we can estimate the cavity microphonics Δf(t)



Extracting information from the field decay transient

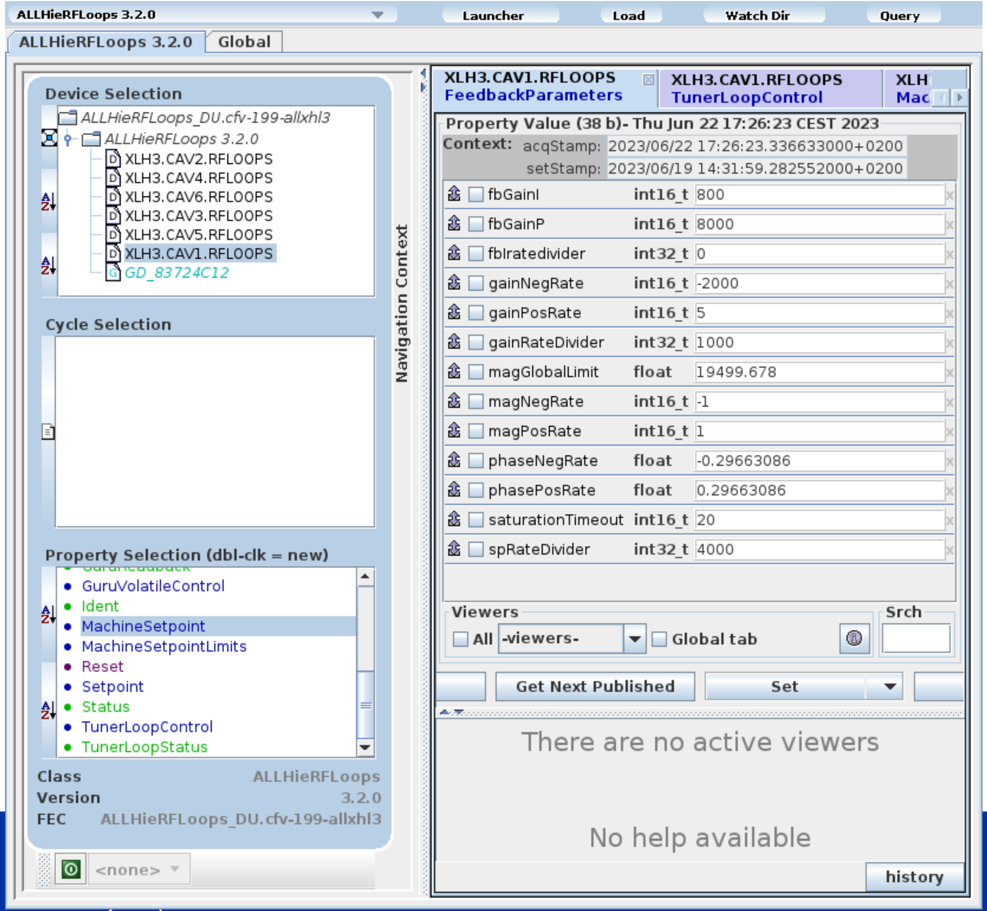
If the cavity is strongly undercoupled, we can directly calculate also the Q_0 vs. E_{acc}



Operator vs. equipment expert view

Control of SC cavity is a complex art.

There can be 100+ parameters to control one single cavity…



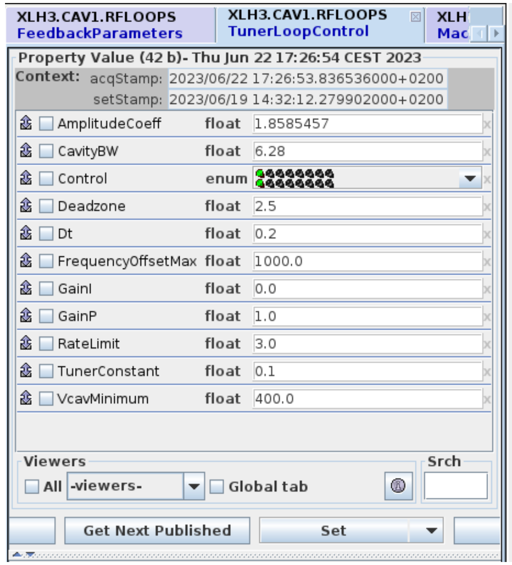
Class ALLHieRFLoops
Version 3.2.0
FEC ALLHieRFLoops_DU.cfv-199-allxhl3

Property Value (38 b)- Thu Jun 22 17:26:23 CEST 2023
Context: acqStamp: 2023/06/22 17:26:23.336633000+0200
setStamp: 2023/06/19 14:31:59.282552000+0200

fbGainI	int16_t	800
fbGainP	int16_t	8000
fbIratedivider	int32_t	0
gainNegRate	int16_t	-2000
gainPosRate	int16_t	5
gainRateDivider	int32_t	1000
magGlobalLimit	float	19499.678
magNegRate	int16_t	-1
magPosRate	int16_t	1
phaseNegRate	float	-0.29663086
phasePosRate	float	0.29663086
saturationTimeout	int16_t	20
spRateDivider	int32_t	4000

There are no active viewers

No help available



Property Value (42 b)- Thu Jun 22 17:26:54 CEST 2023
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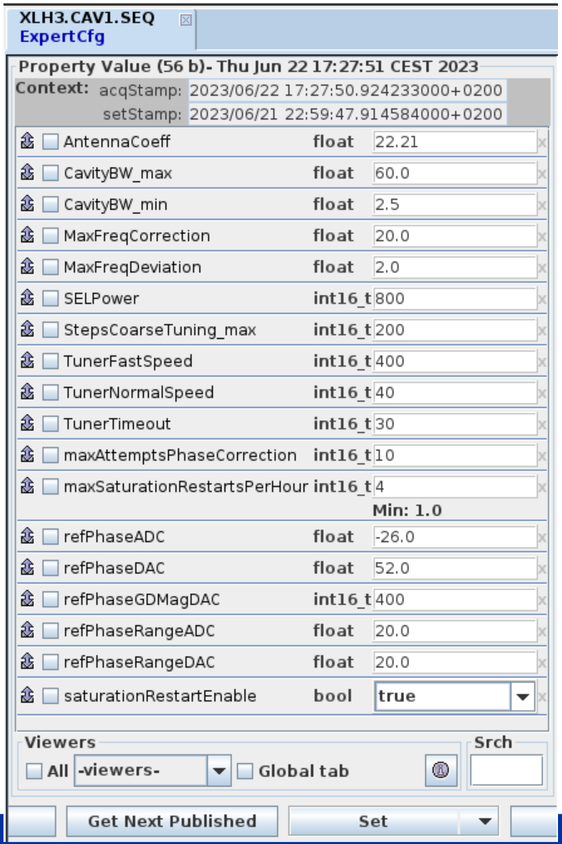
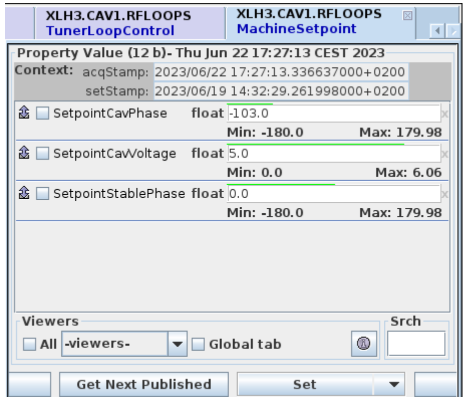
setStamp: 2023/06/19 14:32:12.279902000+0200

AmplitudeCoeff	float	1.8585457
CavityBW	float	6.28
Control	enum	
Deadzone	float	2.5
Dt	float	0.2
FrequencyOffsetMax	float	1000.0
GainI	float	0.0
GainP	float	1.0
RateLimit	float	3.0
TunerConstant	float	0.1
VcavMinimum	float	400.0



Property Value (56 b)- Thu Jun 22 17:27:51 CEST 2023
Context: acqStamp: 2023/06/22 17:27:50.924233000+0200
setStamp: 2023/06/21 22:59:47.914584000+0200

AntennaCoeff	float	22.21
CavityBW_max	float	60.0
CavityBW_min	float	2.5
MaxFreqCorrection	float	20.0
MaxFreqDeviation	float	2.0
SELPower	int16_t	800
StepsCoarseTuning_max	int16_t	200
TunerFastSpeed	int16_t	400
TunerNormalSpeed	int16_t	40
TunerTimeout	int16_t	30
maxAttemptsPhaseCorrection	int16_t	10
maxSaturationRestartsPerHour	int16_t	4 Min: 1.0
refPhaseADC	float	-26.0
refPhaseDAC	float	52.0
refPhaseGDMagDAC	int16_t	400
refPhaseRangeADC	float	20.0
refPhaseRangeDAC	float	20.0
saturationRestartEnable	bool	true



Property Value (12 b)- Thu Jun 22 17:27:13 CEST 2023
Context: acqStamp: 2023/06/22 17:27:13.336637000+0200
setStamp: 2023/06/19 14:32:29.261998000+0200

SetpointCavPhase	float	-103.0 Min: -180.0 Max: 179.98
SetpointCavVoltage	float	5.0 Min: 0.0 Max: 6.06
SetpointStablePhase	float	0.0 Min: -180.0 Max: 179.98

Operator vs. equipment expert view

Equipment expert needs all the knobs…

But how much control the machine operator needs?

Operator vs. equipment expert view

Equipment expert needs all the knobs…

But how much control the machine operator needs?

*** footnote: Use physical units for setpoints**

Operator vs. equipment expert view

LINE			SETPOINT MAG [MV/m]	SETPOINT PHASE [deg]	SEQ STATUS	RUNNING	SETPOINT MAG [MV/m]	SETPOINT PHASE [deg]	CAV FIELD MAG [MV/m]	CAV FIELD PHASE [deg]	RF POWER FWD [W]	RF POWER RFL [W]	LIMIT	RF OUT SATUR	FAST ILOCK	CAV DISS [W]	T CAB [K]	T CAV [K]	He LEV VESSEL [%]	DETAILED STATUS
XLL2	CAV1	OFF STANDBY READY **ON**	Set Mag 4.380	Set Ph 178.0	ON		4.380	178.0	4.379	177.2	63.2	41.8				1.6	51.7	5.2	51.0	State ON reached
	CAV2	OFF STANDBY READY **ON**	Set Mag 5.470	Set Ph 178.0	ON		5.470	178.0	5.471	176.0	93.5	79.2				9.8	67.7	4.9		State ON reached
	CAV3	OFF STANDBY READY **ON**	Set Mag 3.720	Set Ph -126.0	ON		3.720	-126.0	3.720	-126.7	39.8	35.7				2.2	54.0	4.6		State ON reached
	CAV4	OFF STANDBY READY **ON**	Set Mag 4.200	Set Ph 178.0	ON		4.200	178.0	4.200	175.6	57.9	46.2				6.3	59.7	4.7	51.8	State ON reached
	CAV5	OFF STANDBY READY **ON**	Set Mag 1.300	Set Ph -82.0	ON		1.300	-82.0	1.301	-82.6	33.4	28.4				0.2	56.8	4.6		State ON reached
XLH1	CAV1	OFF **STANDBY** READY ON	Set Mag 6.000	Set Ph 144.0	STANDBY		4.000	144.0	0.005	-113.9	0.0	0.0				-0.0	22.1	4.5	51.7	State STANDBY reached due to veto trip
	CAV2	OFF STANDBY READY **ON**	Set Mag 6.000	Set Ph 178.0	ON		6.000	178.0	5.998	177.3	123.4	106.2				9.1	52.3	4.9		State ON reached
	CAV3	OFF STANDBY READY **ON**	Set Mag 3.200	Set Ph 178.0	ON		3.200	178.0	3.198	177.4	34.0	26.8				2.2	21.4	4.6		State ON reached
	CAV4	OFF STANDBY READY **ON**	Set Mag 4.500	Set Ph 178.0	ON		4.500	178.0	4.500	177.3	59.6	52.1				3.5	26.2	4.6	49.9	State ON reached
	CAV5	OFF STANDBY READY **ON**	Set Mag 4.370	Set Ph -127.0	ON		4.370	-127.0	4.371	-127.6	72.5	41.0				3.9	26.2	5.3		State ON reached

Sources

[1] Amran Iqbal: Introduction to Control Systems
https://eng.libretexts.org/Bookshelves/Industrial_and_Systems_Engineering/Book%3A_Introduction_to_Control_Systems_%28Iqbal%29/03%3A_Feedback_Control_System_Models/3.3%3A_PI%2C_PD%2C_and_PID_Controllers

[2] J. Serrano, A. Rohlev, I. Kozsar: FPGA-based low level control of CERN'S LINAC 3 cavities. In 10th ICALEPCS Int. Conf. on Accelerator & Large Expt. Physics Control Systems. Geneva, 10 - 14 Oct 2005, MO4B.1-2O (2005)

[3] Joachim Tuckmantel: Cavity-Beam-Transmitter Interaction Formula Collection with Derivation, CERN-ATS-Note-2011-002 TECH

Thank you for your attention!

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