# *X-band pulse compressor: tuning and high-power operation*

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THE UNIVERSITY OF
MELBOURNE

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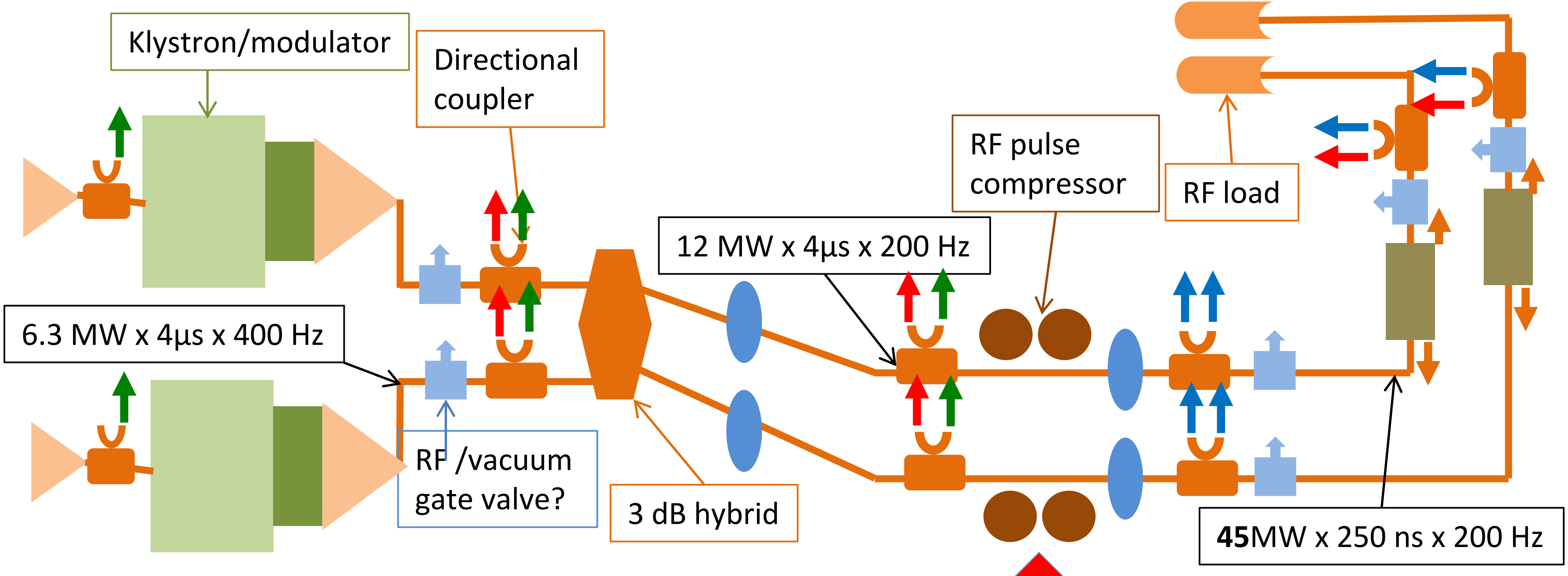
# Xbox-3 RF Signals to Acquire

**To reach 45Mw we need PCs!**



Klystron/modulator

Directional coupler

RF pulse compressor

RF load

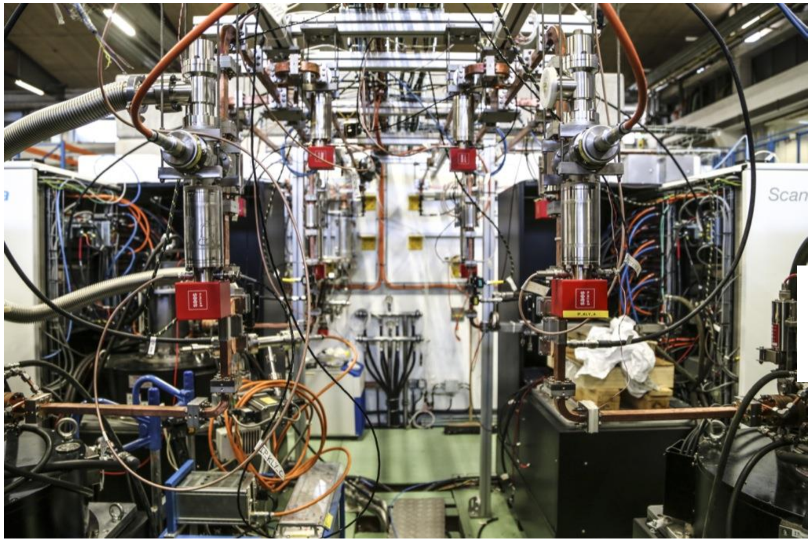
12 MW x 4µs x 200 Hz

6.3 MW x 4µs x 400 Hz

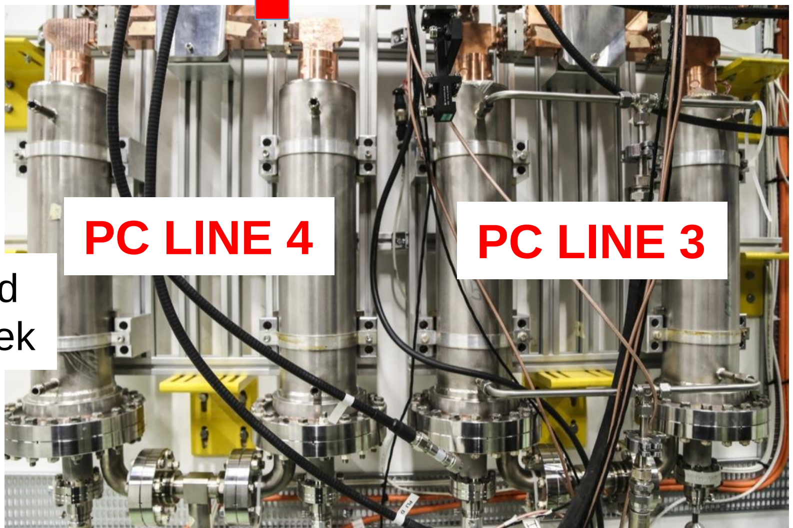
RF /vacuum gate valve?

3 dB hybrid

**45**MW x 250 ns x 200 Hz



Installed last week

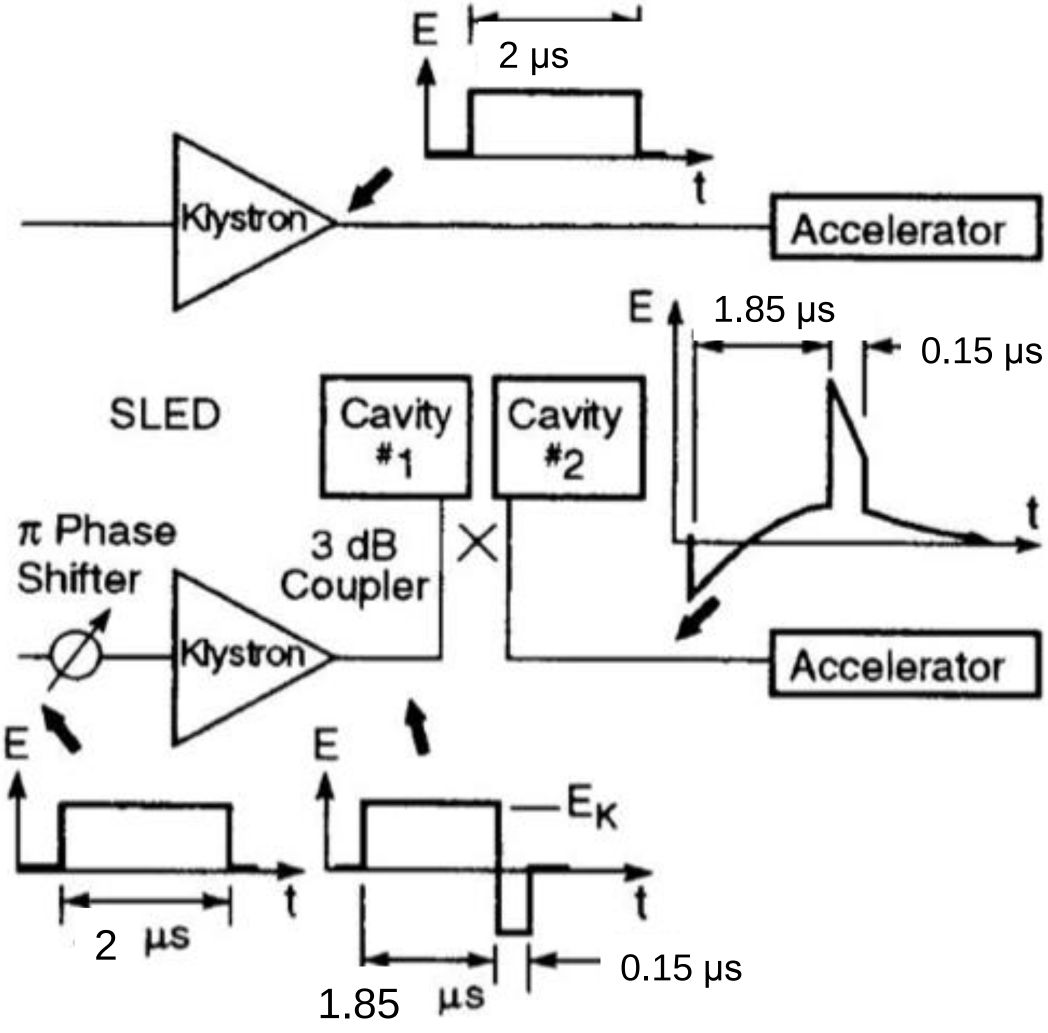


Installed 11/2016

# Pulse compressors with resonant cavity (SLED type)

- Power from the klystron goes to 2 resonant cavities for storage
  because the cavity coupler reflects almost all power, there's a surge of reflected energy which goes to the accelerator.

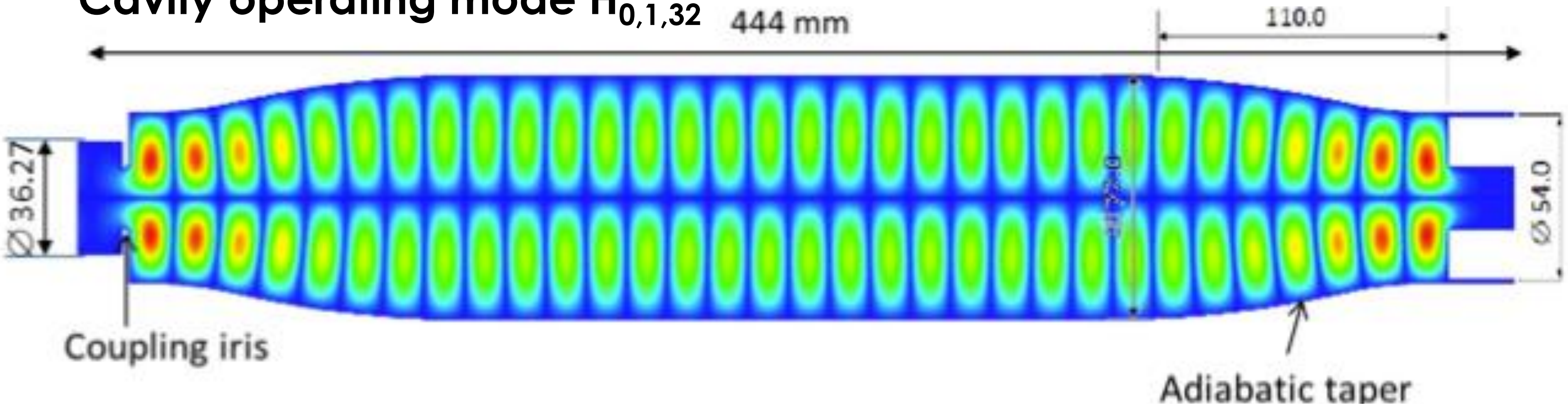
- As the SLED system fills, its emitted power destructively interferes with the klystron reflected power.
  At some point in the klystron pulse, the phase of the klystron is reversed so that the stored energy interferes constructively...



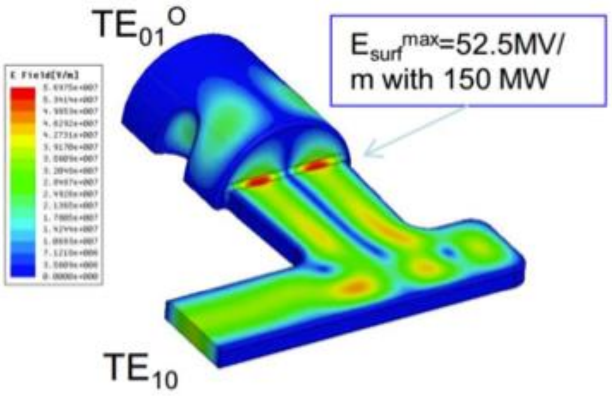
# SLED-I type

- Storage cavities with adiabatic tapers at each end to ensure that unwanted modes are not produced.
  - Trapped modes can cause resonances, whose electric and magnetic field nodes can induce unwanted breakdowns or surface heating.

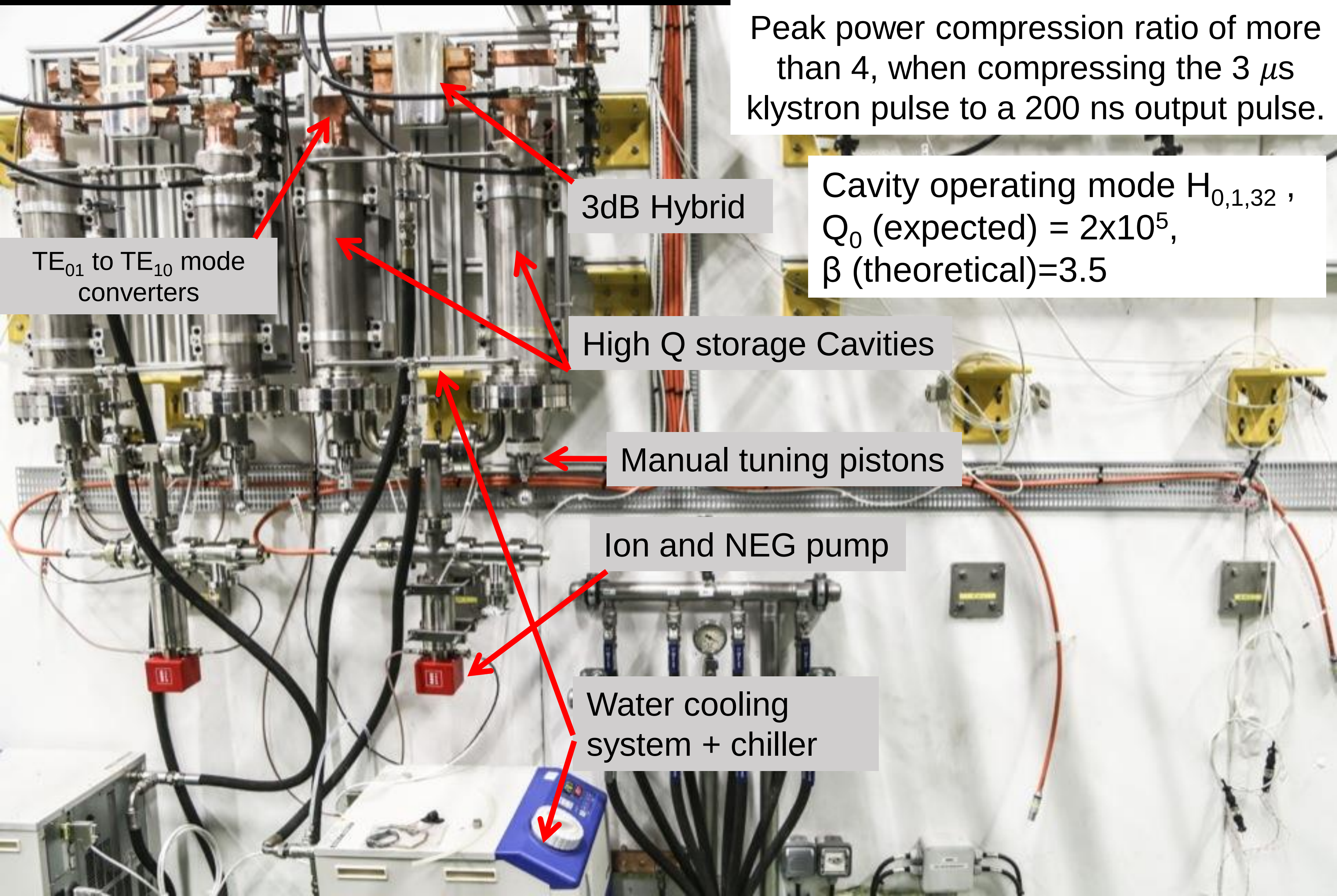
**Cavity operating mode $H_{0,1,32}$**



- Adiabatic tapers at each end of the cavity reduce the radius such that the TE02 and TE03 modes are below the cut-off frequency.
- Compact mode converters.



# PC installed at Xbox-3



Peak power compression ratio of more than 4, when compressing the 3 $\mu$s klystron pulse to a 200 ns output pulse.

Cavity operating mode $H_{0,1,32}$ ,
$Q_0$ (expected) = $2 \times 10^5$,
β (theoretical)=3.5

$TE_{01}$ to $TE_{10}$ mode converters

3dB Hybrid

High Q storage Cavities

Manual tuning pistons

Ion and NEG pump

Water cooling system + chiller

# Characteristics

- High Q cavities have a narrow bandwidth making them susceptible to small volumetric changes.

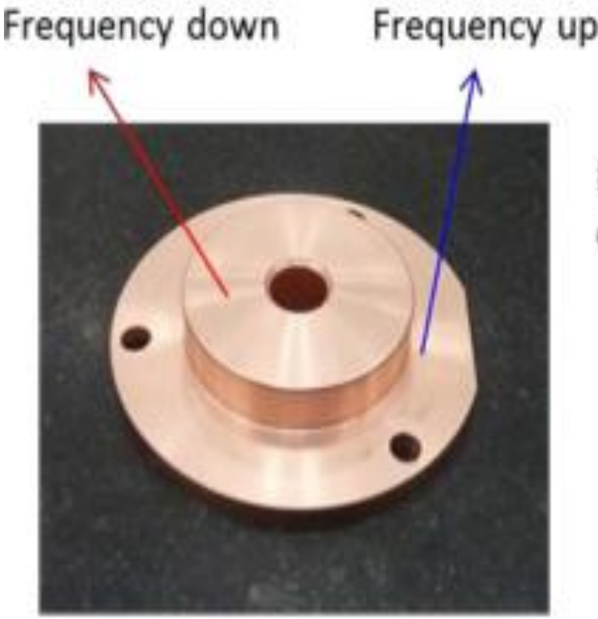
- Small temperature changes (+1C° = -200KHz) perturb the resonant frequency, lowering the compression efficiency and adversely affecting the output pulse shape.
  - An increase in temperature would make the cavities expand and thus lower the resonant frequency.

- The end section of the cavity is a piston, able to move freely in order to tune the cavity frequency.

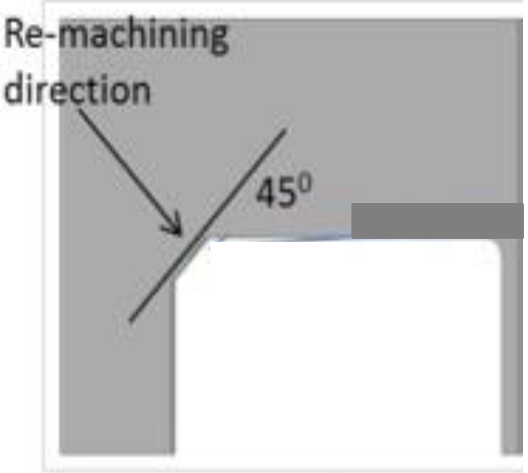
- The frequency of the RF in the cavities is necessarily identical to the filling frequency of the klystron.
  - However, the RF in the cavity acquires a phase shift which depends on the difference between the klystron frequency and the cavity's natural frequency.

# Pulse compressors tuning

- The end of the cavity is a removable copper plate that can be machined on its inside face to increase the cavity volume, or machined on the outer edge in order to decrease the cavity volume.



Coarse tuning



Fine tuning

De-tuning plungers increase the mode frequency then the pulse compressor will be transparent

to the incoming RF pulse.

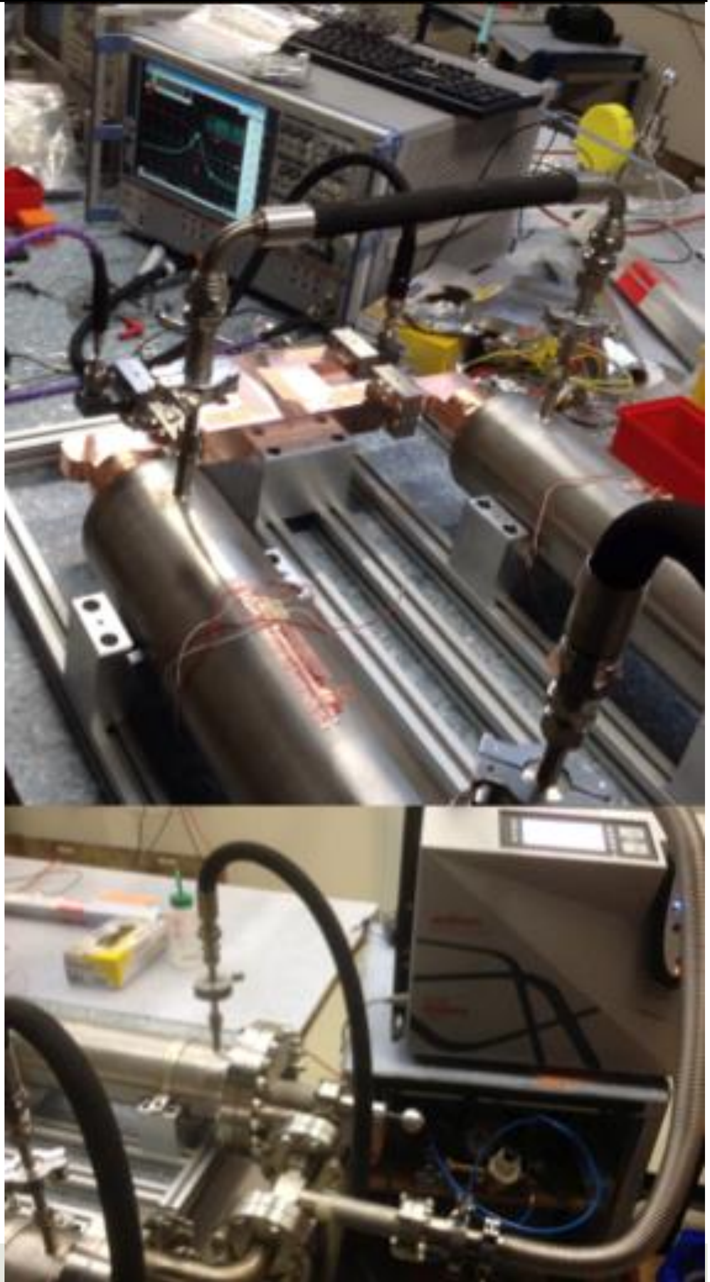
- The coarse tuning will impart a frequency variation of 20 MHz/mm, while the fine frequency tuning of the chamfer is 1.1 MHz/mm.

# Pulse Compressor Tuning

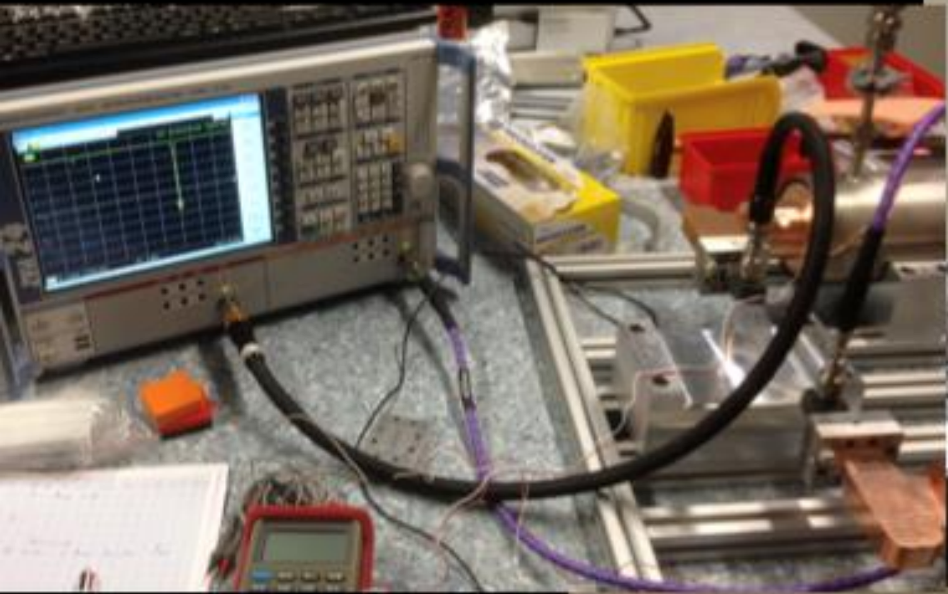
- Rohde and Schwarz ZVA24 VNA was connected to each cavity in order to measure their S-parameters as a function of frequency.
  - Standard WR90 waveguide calibration kit, using the through, reflect, line (TRL) technique.

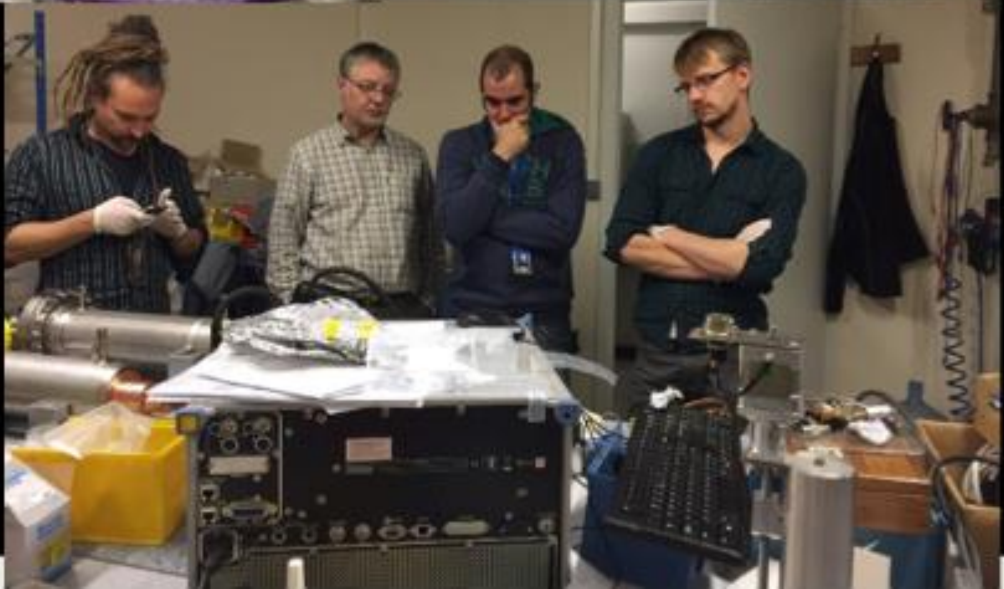
- In order to stabilise the temperatures of the cavities they were connected via their water circuit to SMC, HRS024-AF-20 chiller units, which were able to stabilise the water temperature to within 0.1 $C^0$.
  - The same chiller can be used for high power operation because it has a cooling capacity of 2.1 kW, which is more power than will be dissipated in the pulse compressor under load.

- Vacuum leak tests before the installation.



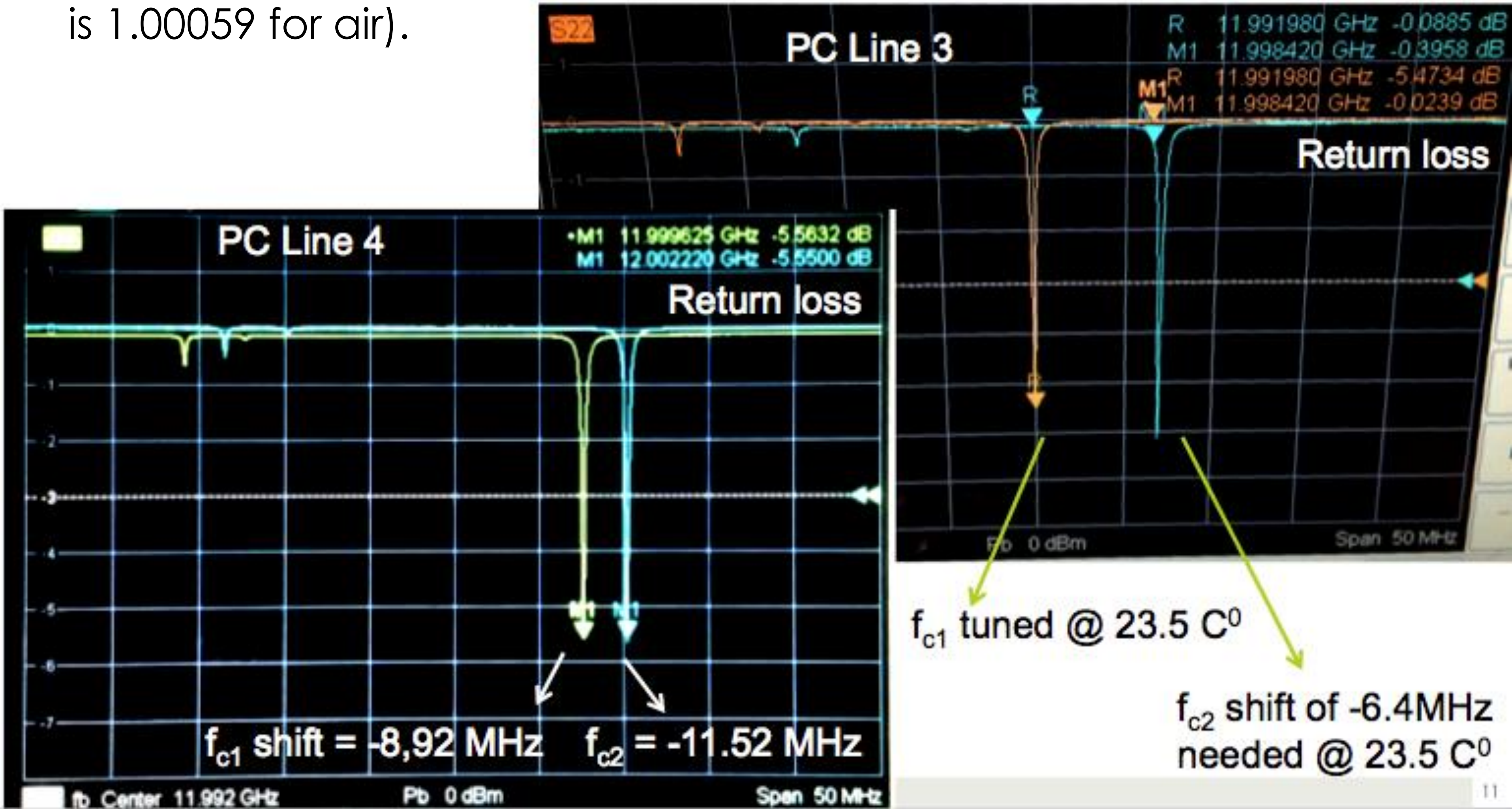
# People at work





# PC tuning, individual cavities

- The design frequency of the cavities is 11.9942 GHz at 30 C$^0$ under vacuum. This translates to approximately 11.9907 GHz in air (the frequency scales with the square root of relative permittivity, which is 1.00059 for air).



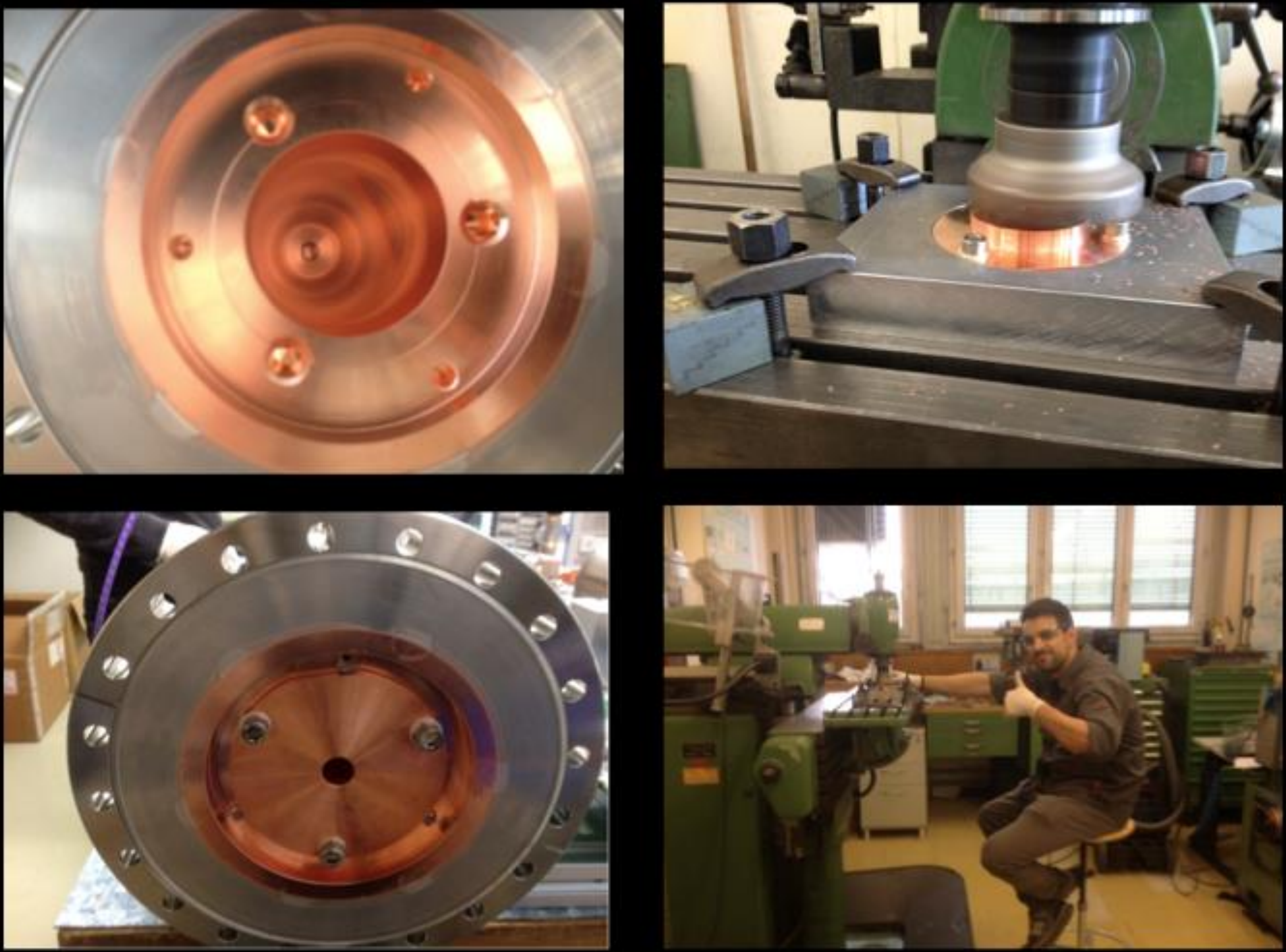
$f_{c1}$ shift = -8,92 MHz

$f_{c2}$ = -11.52 MHz

$f_{c1}$ tuned @ 23.5 C$^0$

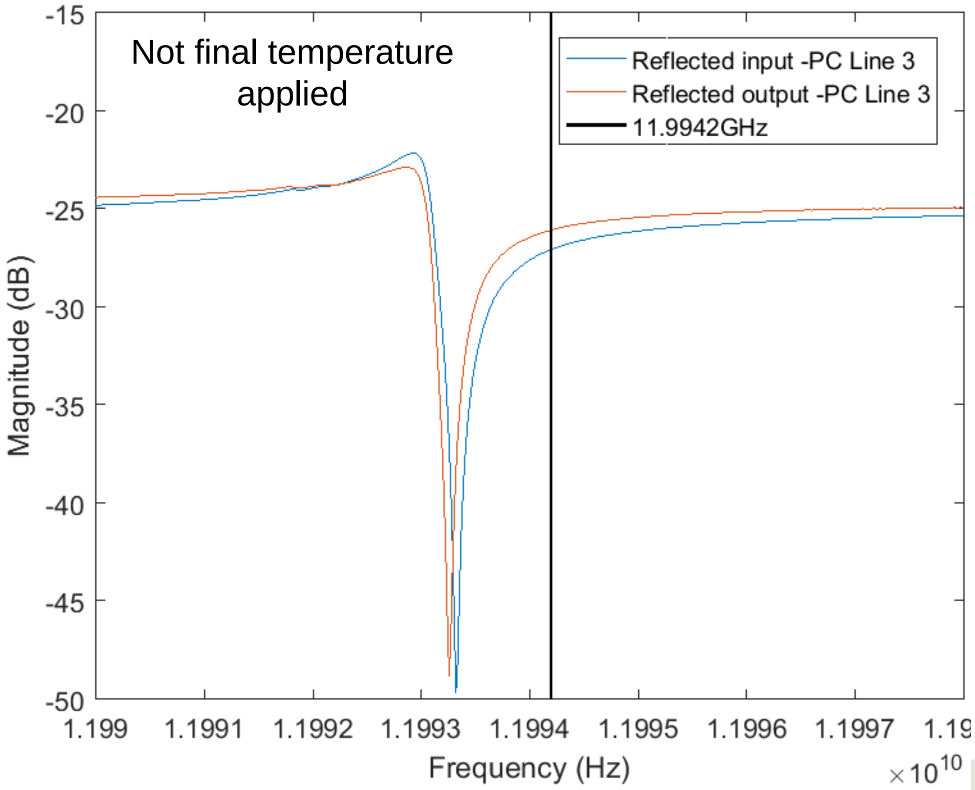
$f_{c2}$ shift of -6.4MHz needed @ 23.5 C$^0$

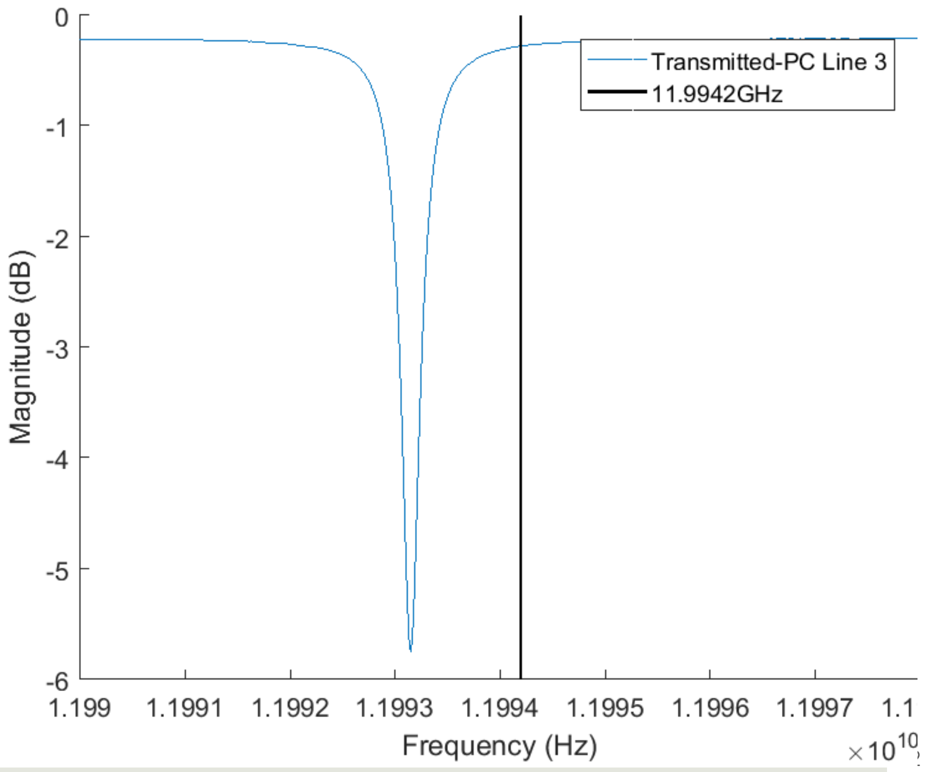
# Copper plate machining



# PC line 3 tuning whole system

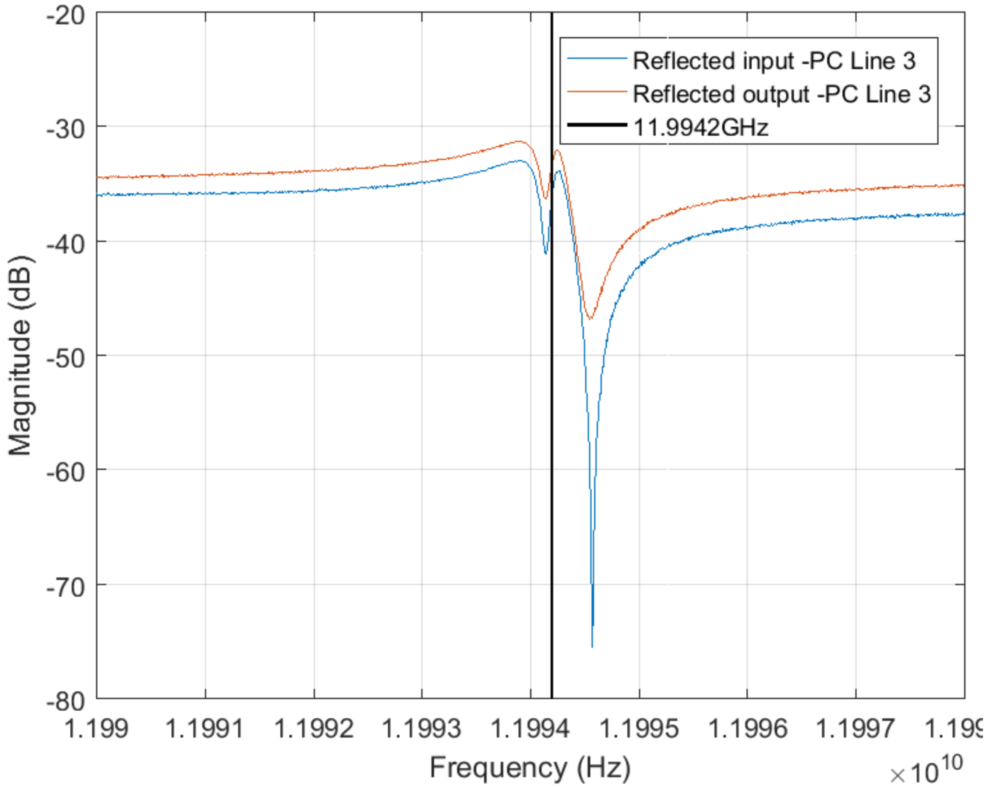
- Cavities tuned iteratively.
  - After adjusted the plates, the cavities were attached to the -3 dB hybrid.
  - Vacuum rough pumping was performed to remove most of the air and the S-parameter measurements were repeated.
  - Fine tuning under the vacuum and stable temperature is done with one of the pistons if needed.

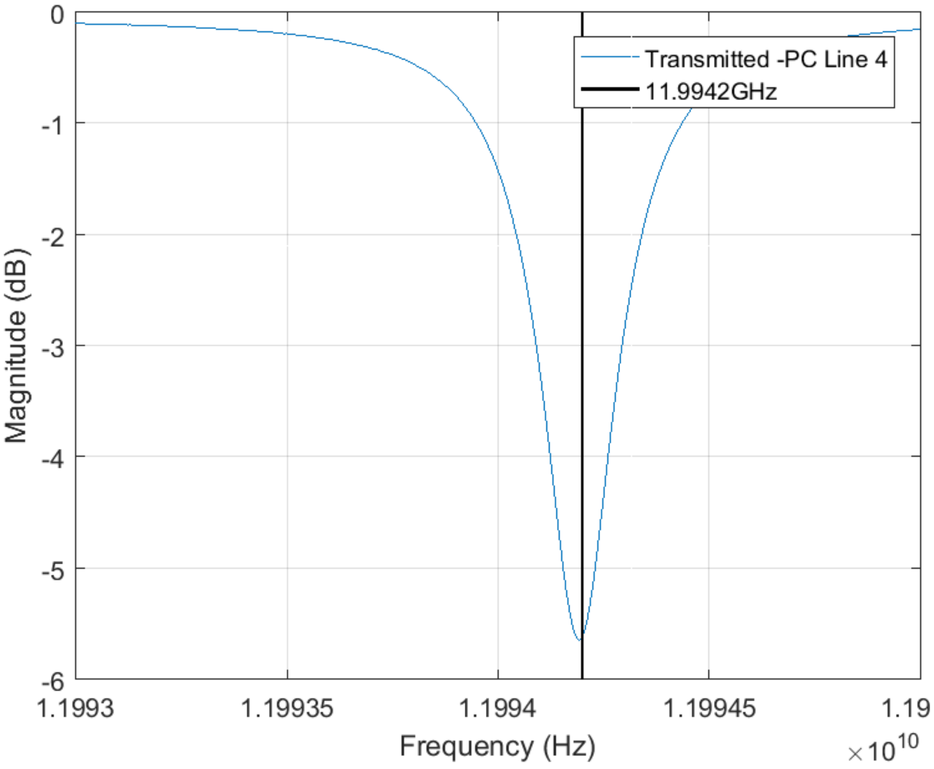

Not final temperature applied



# PC Line 4 tuning whole system

- Better reflections ($S_{11}$ $S_{22}$) in PC of line 4 than line 3.
- Cavity frequencies are similar in both PC.
- Transmitted signal ($S_{12}$) ~ -6dB in both PCs.





# Intrinsic Q-factor

- The loaded-Q value $Q_L$ is given as :

$$Q_L = \frac{f_o}{\Delta f}$$

- where $\Delta f$ is the width of the resonance at half power and $fo$ is the resonant frequency.
- The coupling factor for an over coupled cavity (as all useful pulse compressors are) can be found using:

$$\beta = \frac{1 + S_{12}}{1 - S_{12}}$$

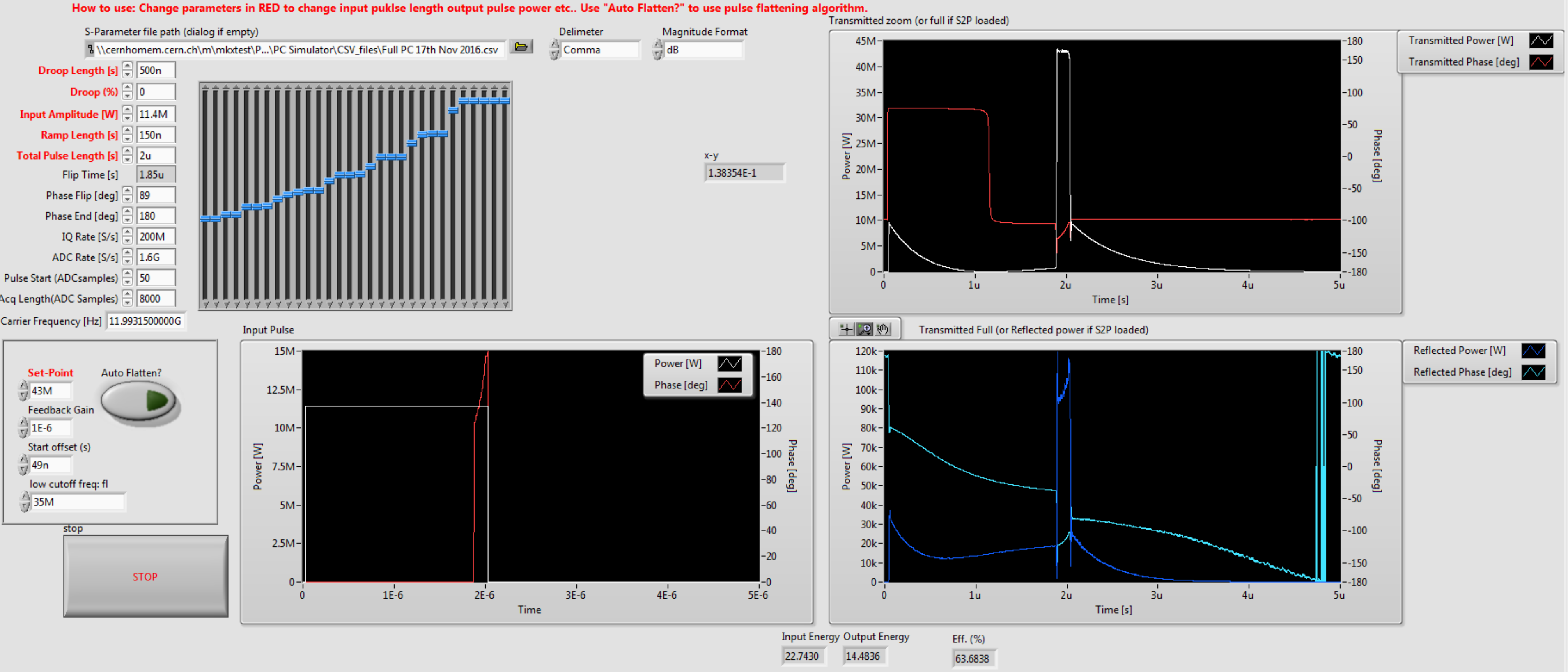
- The intrinsic Q-factor is then $Q_0 = Q_L(1+\beta)$

| PC | Coupling factor ( β) | $Q_0$ |
|---|---|---|
| Line 3 | 3,1 | $1 \times 10^5$ |
| Line 4 | 3,2 | $1{,}8 \times 10^5$ |

- The pulse compressors perform very closely to the design.

# Pulse compressor simulation

- The **S-parameters** can be used to simulate the output pulse shape.



**How to use: Change parameters in RED to change input puklse length output pulse power etc.. Use "Auto Flatten?" to use pulse flattening algorithm.**

S-Parameter file path (dialog if empty): \\cernhomem.cern.ch\m\mkxtest\P...\PC Simulator\CSV_files\Full PC 17th Nov 2016.csv

Delimeter: Comma

Magnitude Format: dB

**Droop Length [s]**: 500n

**Droop (%)**: 0

**Input Amplitude [W]**: 11.4M

**Ramp Length [s]**: 150n

**Total Pulse Length [s]**: 2u

Flip Time [s]: 1.85u

Phase Flip [deg]: 89

Phase End [deg]: 180

IQ Rate [S/s]: 200M

ADC Rate [S/s]: 1.6G

Pulse Start (ADCsamples): 50

Acq Length(ADC Samples): 8000

Carrier Frequency [Hz]: 11.9931500000G

x-y: 1.38354E-1

**Set-Point**: 43M

Feedback Gain: 1E-6

Start offset (s): 49n

low cutoff freq: fl: 35M

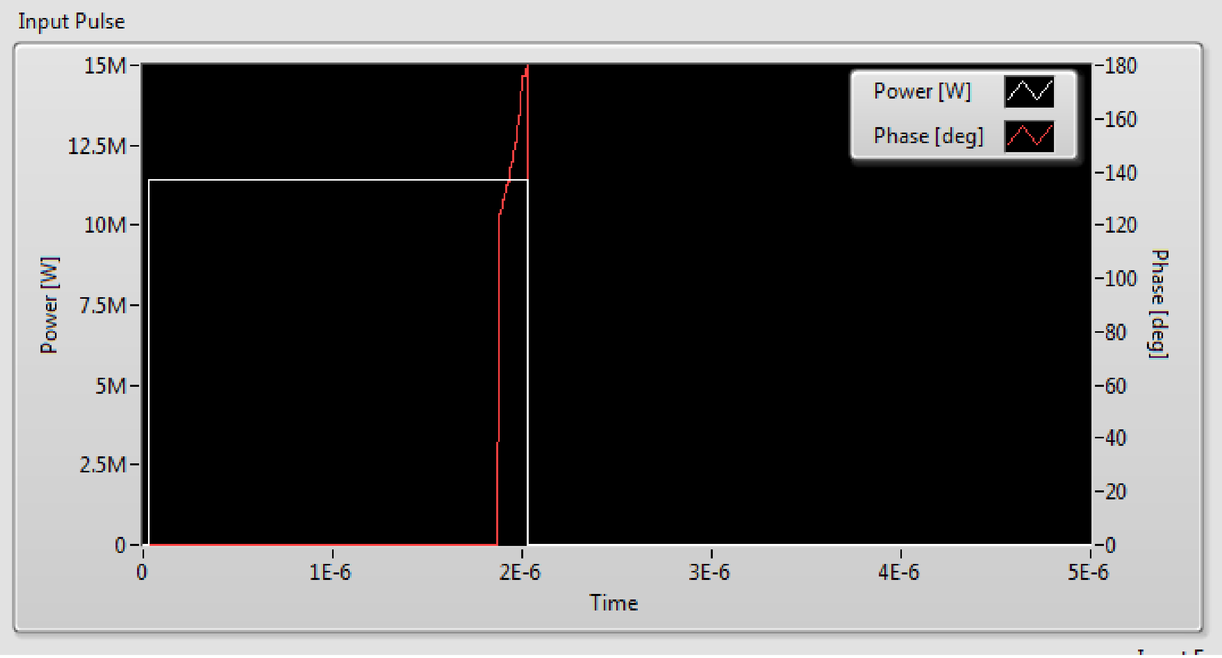
Input Energy: 22.7430

Output Energy: 14.4836

Eff. (%): 63.6838

# Pulse compressor simulation

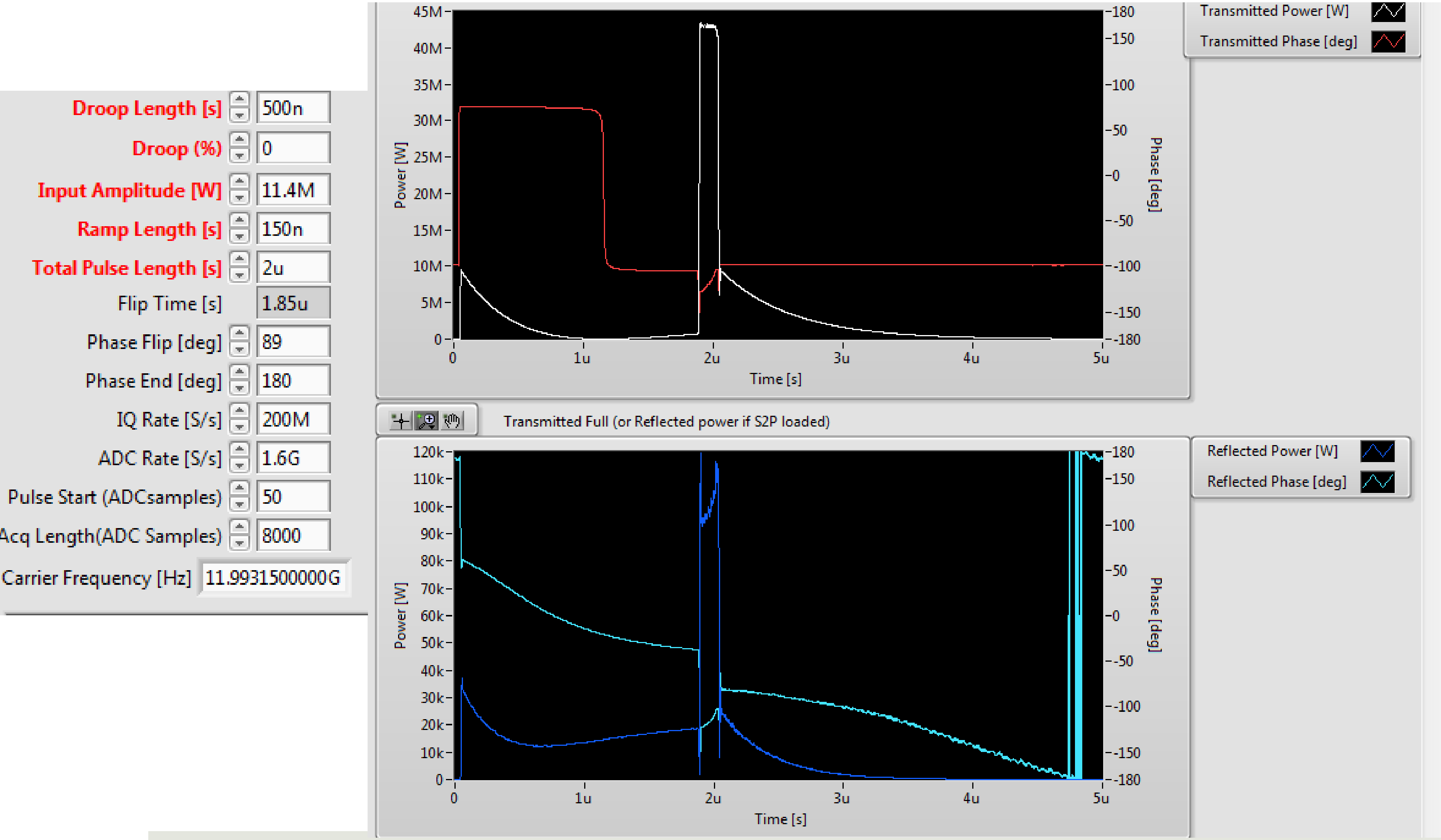
- The pulse compressor's input pulse can be Fourier transformed into the frequency domain.



- The resultant complex frequency spectrum is then multiplied by the S-parameters for transmission and reflection.
- The spectra are then inverse Fourier transformed to the time domain to obtain the transmitted and reflected pulses.

# Pulse compressor simulation

- A simulation was performed using LabVIEW.
  - Resultant transmitted and reflected pulses.



**Droop Length [s]** 500n

**Droop (%)** 0

**Input Amplitude [W]** 11.4M

**Ramp Length [s]** 150n

**Total Pulse Length [s]** 2u

Flip Time [s] 1.85u

Phase Flip [deg] 89

Phase End [deg] 180

IQ Rate [S/s] 200M

ADC Rate [S/s] 1.6G

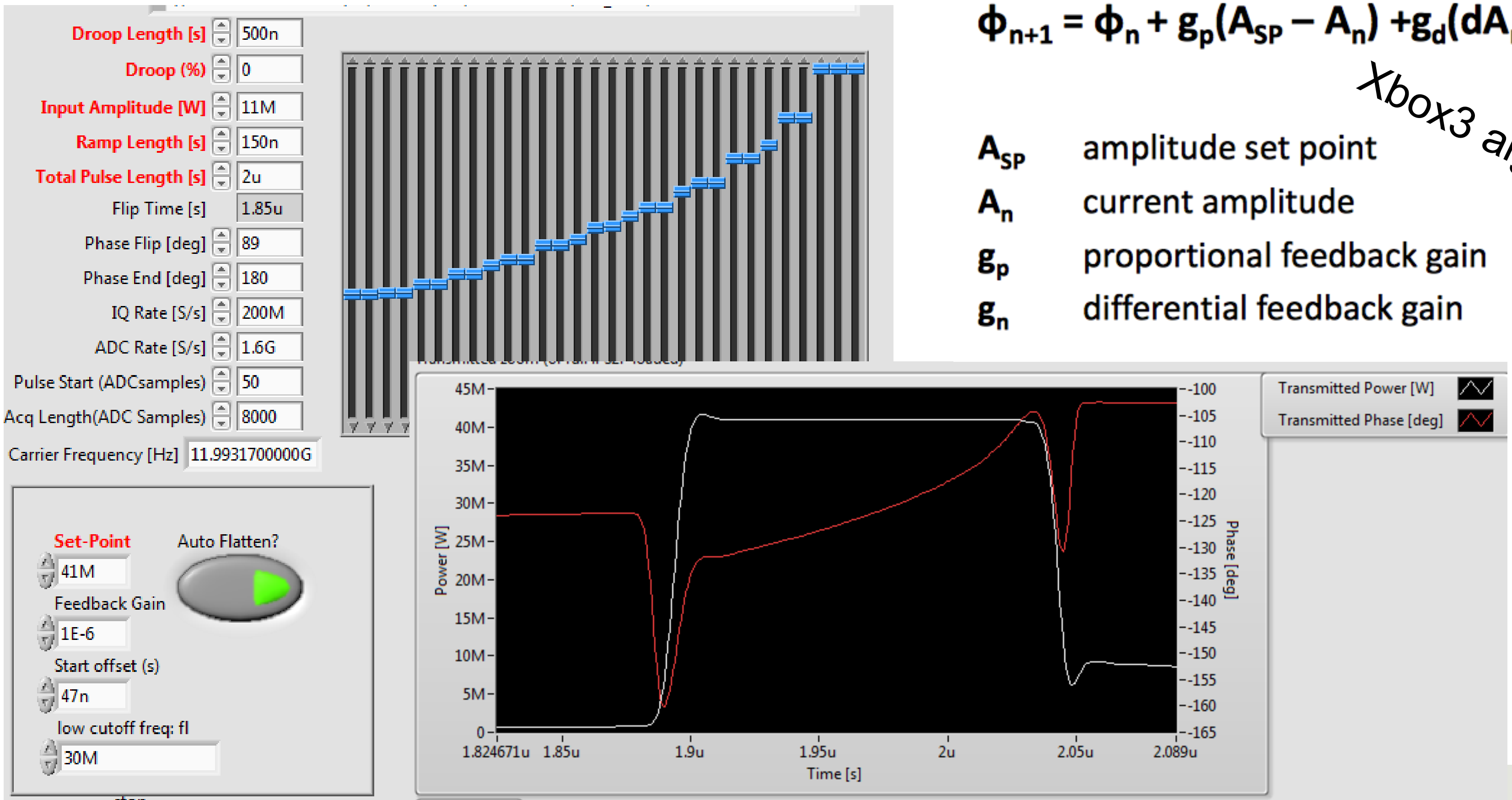
Pulse Start (ADCsamples) 50

Acq Length(ADC Samples) 8000

Carrier Frequency [Hz] 11.9931500000G

# Pulse Flattering algorithm

- Change in the pulse slope is done with the temperature control or with the manipulated input pulse’s phase profile.
  - Methods used when running the test stand.
  - Immediate response by changing the input phase profile.
  - The algorithm will use a simple integral feedback loop.



| | |
|---|---|
| Droop Length [s] | 500n |
| Droop (%) | 0 |
| Input Amplitude [W] | 11M |
| Ramp Length [s] | 150n |
| Total Pulse Length [s] | 2u |
| Flip Time [s] | 1.85u |
| Phase Flip [deg] | 89 |
| Phase End [deg] | 180 |
| IQ Rate [S/s] | 200M |
| ADC Rate [S/s] | 1.6G |
| Pulse Start (ADCsamples) | 50 |
| Acq Length(ADC Samples) | 8000 |
| Carrier Frequency [Hz] | 11.9931700000G |
| Set-Point | 41M |
| Feedback Gain | 1E-6 |
| Start offset (s) | 47n |
| low cutoff freq: fl | 30M |

$$\phi_{n+1} = \phi_n + g_p(A_{SP} - A_n) + g_d(dA_n/dt)$$

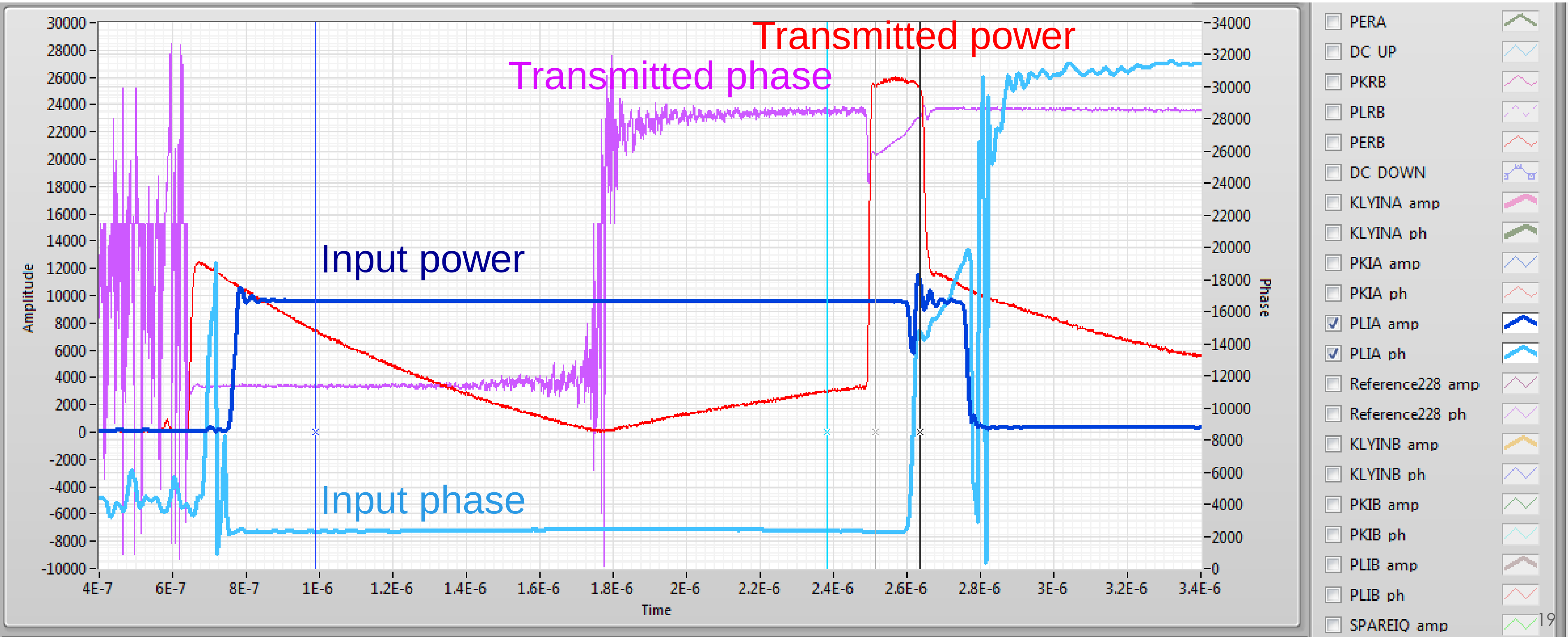
Xbox3 algorithm

| | |
|---|---|
| $A_{SP}$ | amplitude set point |
| $A_n$ | current amplitude |
| $g_p$ | proportional feedback gain |
| $g_n$ | differential feedback gain |

# PC performances in Line 3 of Xbox-3

Data

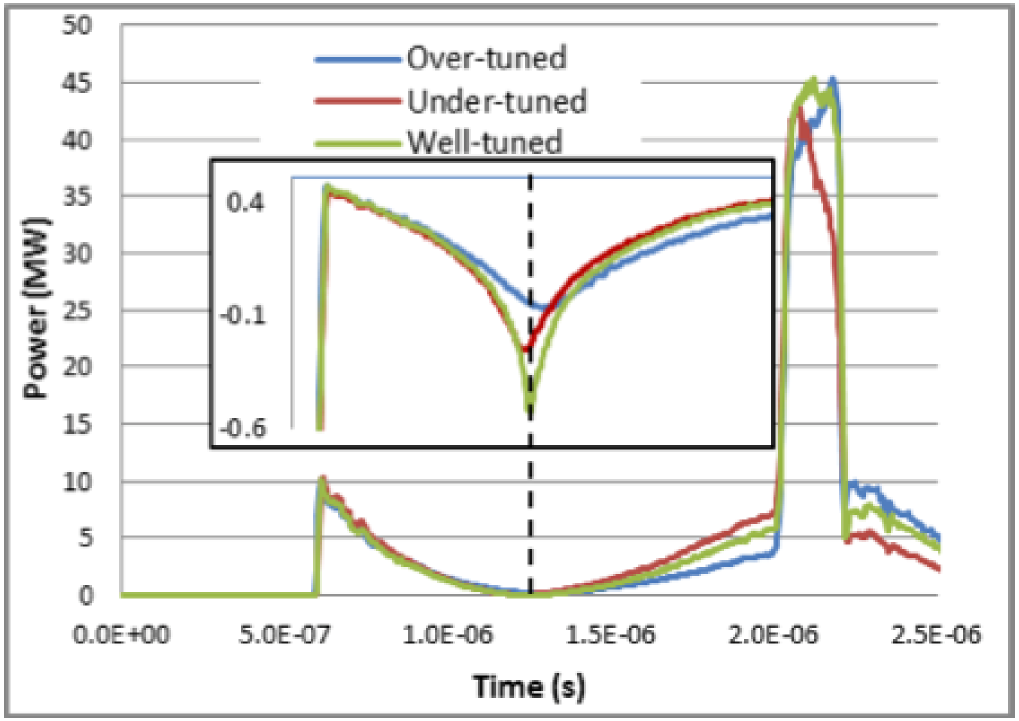
- Both the reflected and output pulse shapes are monitored in order to perform the tuning.
- The output pulse shape corresponds to the average frequency of the two cavities.

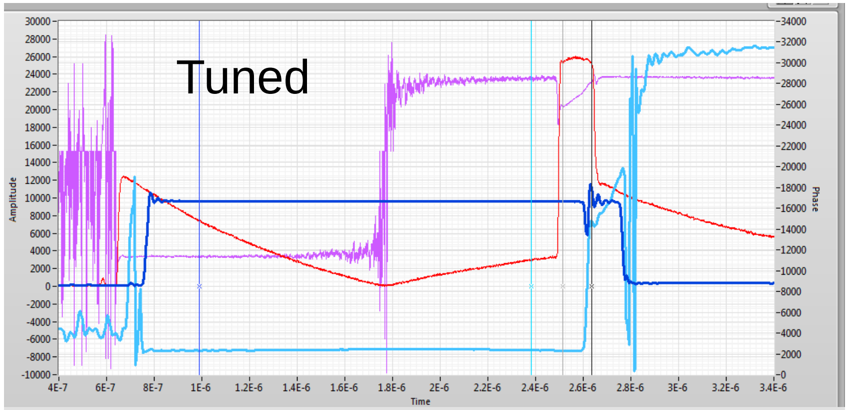


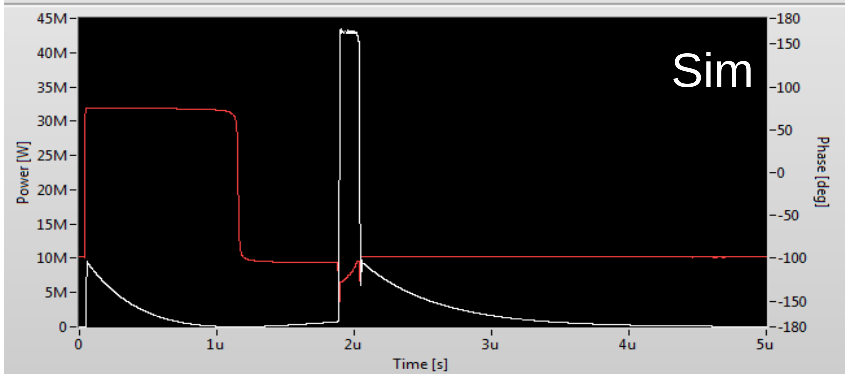
☐ PERA
☐ DC UP
☐ PKRB
☐ PLRB
☐ PERB
☐ DC DOWN
☐ KLYINA amp
☐ KLYINA ph
☐ PKIA amp
☐ PKIA ph
☑ PLIA amp
☑ PLIA ph
☐ Reference228 amp
☐ Reference228 ph
☐ KLYINB amp
☐ KLYINB ph
☐ PKIB amp
☐ PKIB ph
☐ PLIB amp
☐ PLIB ph
☐ SPAREIQ amp

# When phase doesn't flip correctly

- Any change in the average RF power (such as RF power interruption due to an RF breakdown) caused the pulse compressor to cool and detune.
  - In Xbox-I was developed software to tune the pistons automatically. Different design of cavities respect Xbox-2 and 3.
  - Xbox-2 run at 50Hz => flat top stable after a cluster of BD
  - Xbox-3 we observe a detuning we are investigate the best solution

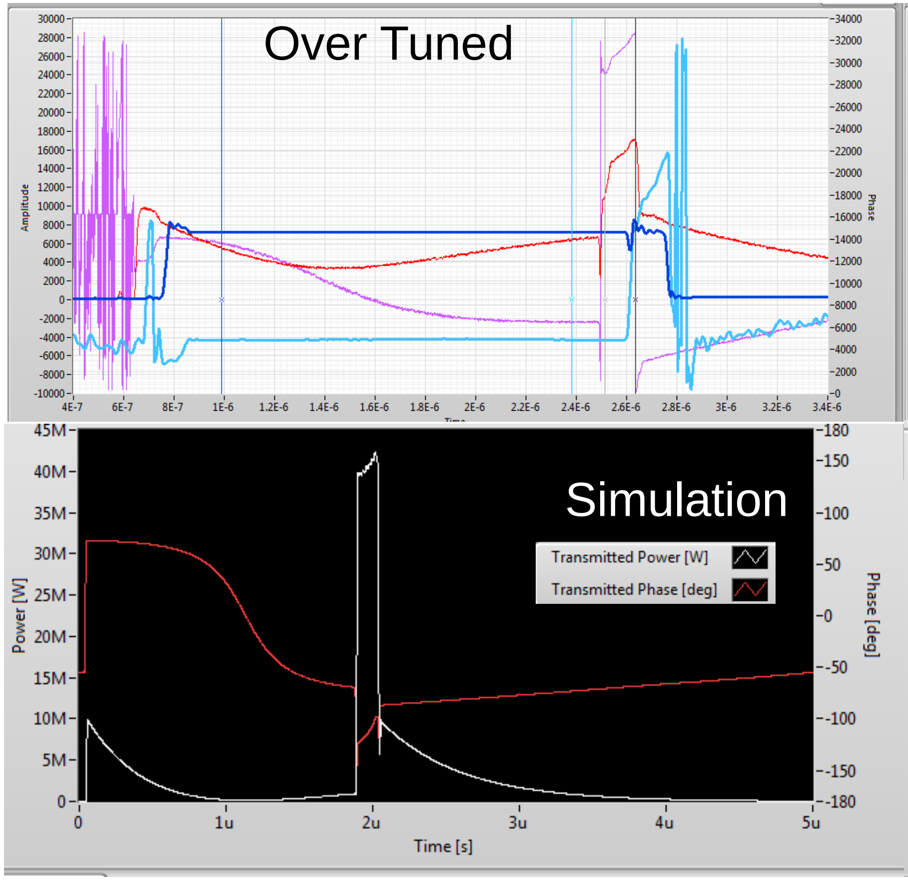




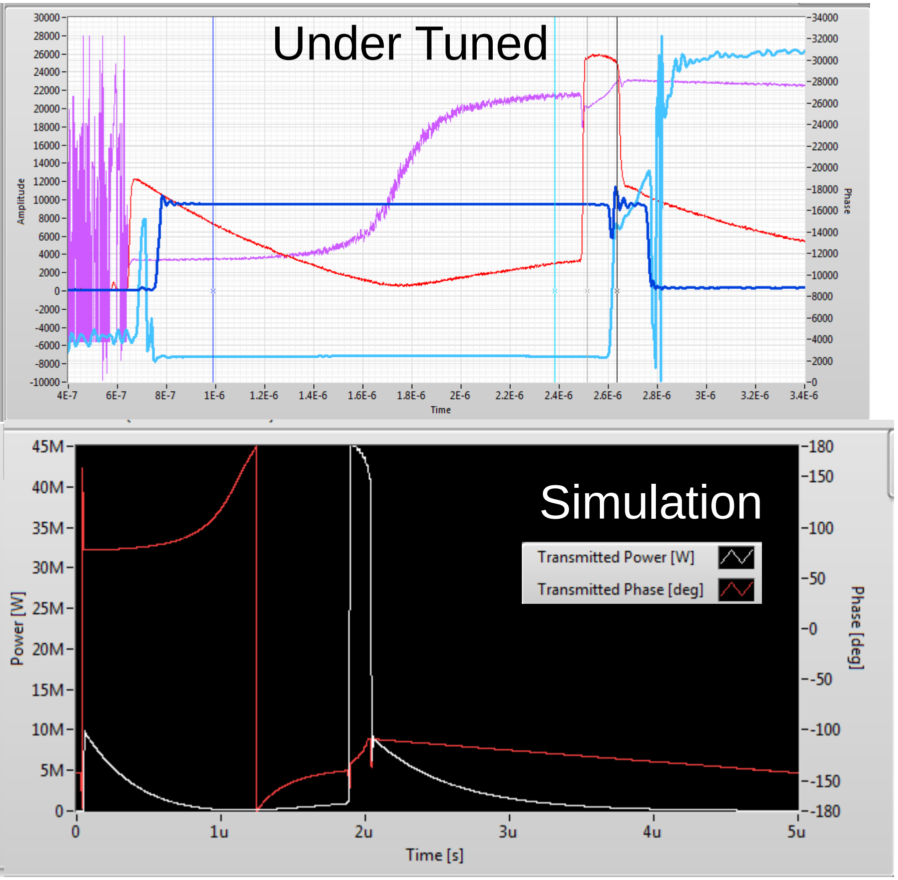


# Over tuned and under tuned

- **Over tuned** means that the filling phase shift is negative so that the phase flip is smaller than the desired value of about 90 degrees, while **under tuned** means that the filling phase shift is positive so that the phase flip is larger than the desired value of $90^0$



Cavity too cold

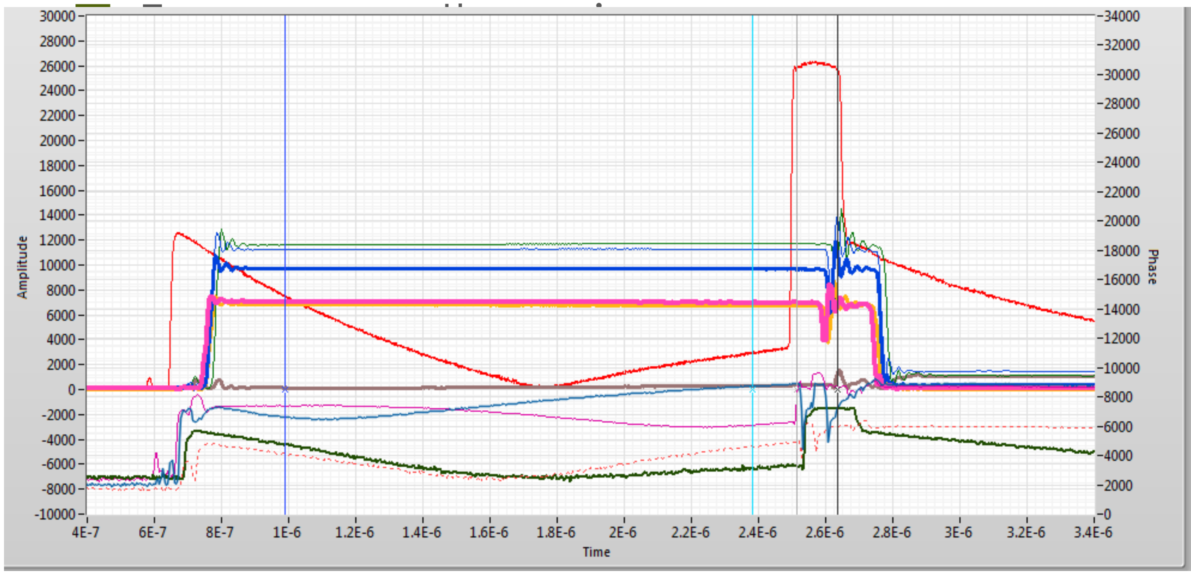


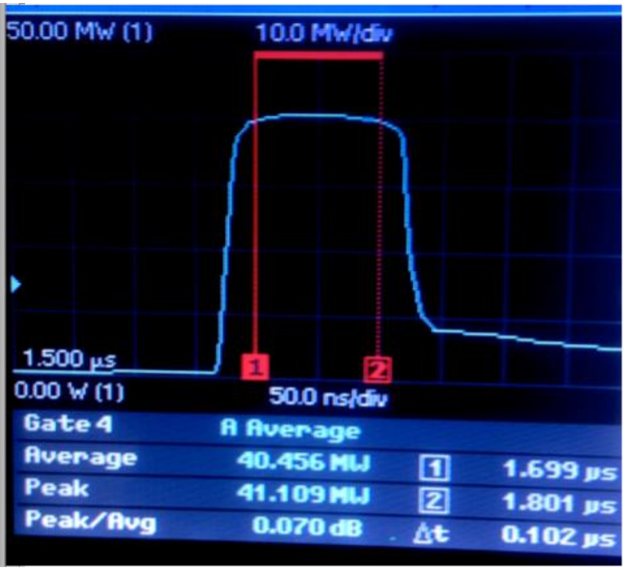
Cavity too hot

# Xbox-3 line 3 performances (data)

- With a pulse width of 2µs and a flat top of 150ns we reached an average power of 40.5MW with an input power of 11.4MW
  - Gain 3.55

- Power measured at the structure (few meters after the PC)





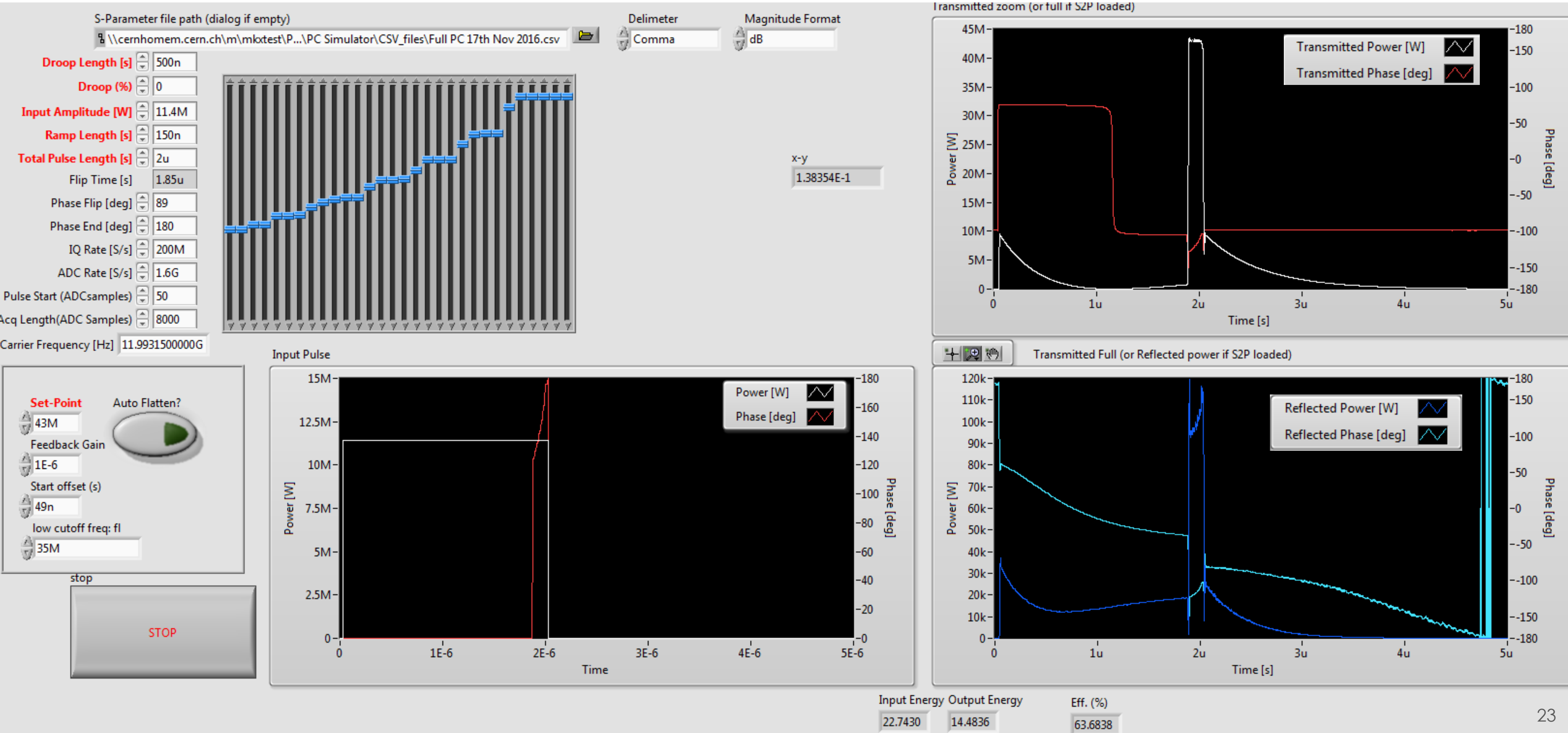
- Transmission and reflections: values are used in the simulation with the same input parameters

# Line 3 PC simulation

- Transmitted power @PC 43MW. Attenuation of the waveguide (~0.4 dB)
  - Power attenuated ~ 40 Mw in agreement with the measurements

- Efficiency ~ 60% ratio between the output and input power

- Note: peak reflection ~ 100KW



S-Parameter file path (dialog if empty): \\cernhomem.cern.ch\m\mkxtest\P...\PC Simulator\CSV_files\Full PC 17th Nov 2016.csv

Delimeter: Comma

Magnitude Format: dB

**Droop Length [s]** 500n

**Droop (%)** 0

**Input Amplitude [W]** 11.4M

**Ramp Length [s]** 150n

**Total Pulse Length [s]** 2u

Flip Time [s] 1.85u

Phase Flip [deg] 89

Phase End [deg] 180

IQ Rate [S/s] 200M

ADC Rate [S/s] 1.6G

Pulse Start (ADCsamples) 50

Acq Length(ADC Samples) 8000

Carrier Frequency [Hz] 11.9931500000G

x-y 1.38354E-1

**Set-Point** 43M

Auto Flatten?

Feedback Gain 1E-6

Start offset (s) 49n

low cutoff freq: fl 35M

stop

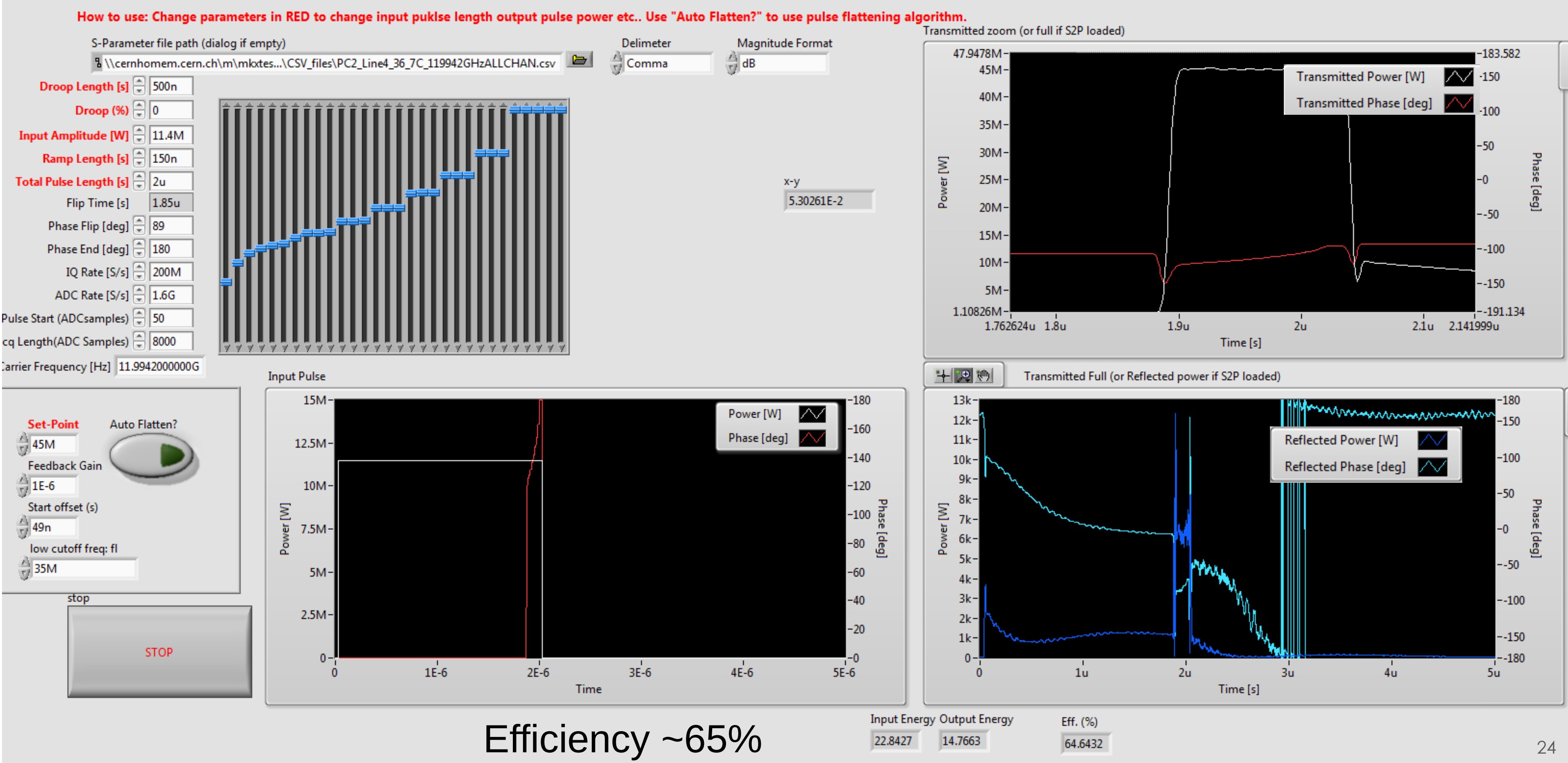
Input Energy 22.7430

Output Energy 14.4836

Eff. (%) 63.6838

# Line 4 PC simulation only

- Max power 45MW , we will expect 2 MW more than PC on line 3
  - We reduce the peak reflection ~ 6KW ,the reflected pulse reacts to the frequency difference between the two cavities. We achieve a better frequency tune.
  - Reflection also depends on the hybrid performances



**How to use: Change parameters in RED to change input puklse length output pulse power etc.. Use "Auto Flatten?" to use pulse flattening algorithm.**

S-Parameter file path (dialog if empty): \\cernhomem.cern.ch\m\mkxtes...\CSV_files\PC2_Line4_36_7C_119942GHzALLCHAN.csv

Delimeter: Comma

Magnitude Format: dB

**Droop Length [s]**: 500n

**Droop (%)**: 0

**Input Amplitude [W]**: 11.4M

**Ramp Length [s]**: 150n

**Total Pulse Length [s]**: 2u

Flip Time [s]: 1.85u

Phase Flip [deg]: 89

Phase End [deg]: 180

IQ Rate [S/s]: 200M

ADC Rate [S/s]: 1.6G

Pulse Start (ADCsamples): 50

cq Length(ADC Samples): 8000

arrier Frequency [Hz]: 11.9942000000G

x-y: 5.30261E-2

**Set-Point**: 45M

Feedback Gain: 1E-6

Start offset (s): 49n

low cutoff freq: fl: 35M

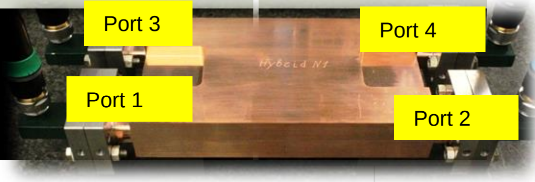
Input Energy: 22.8427

Output Energy: 14.7663

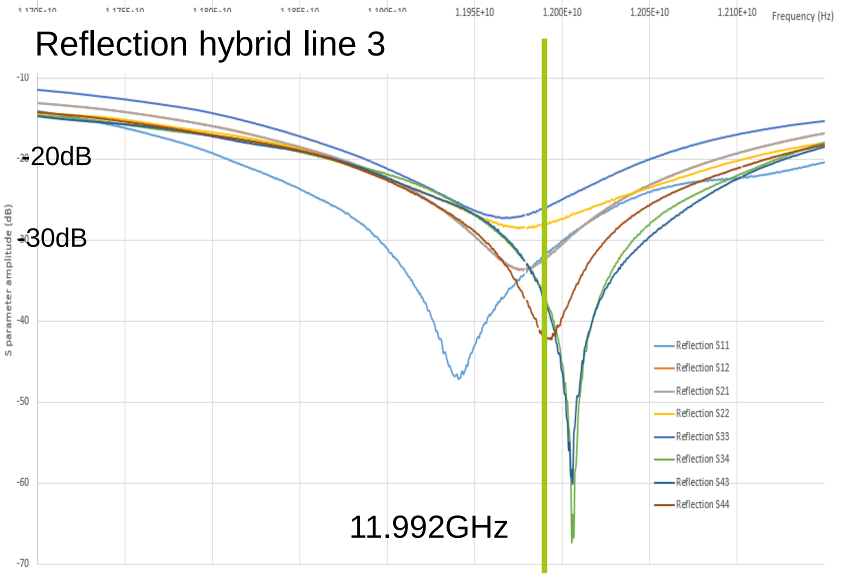
Eff. (%): 64.6432

Efficiency ~65%

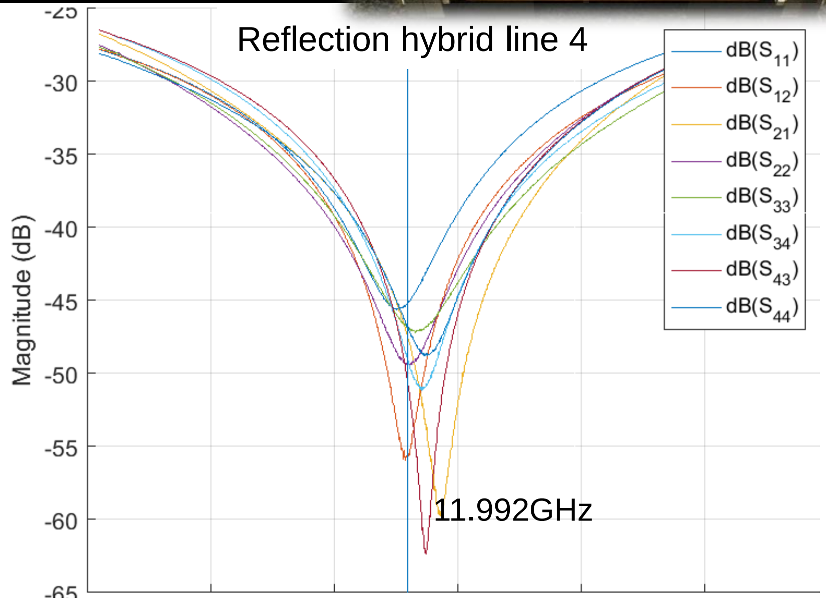
# Hybrid reflections



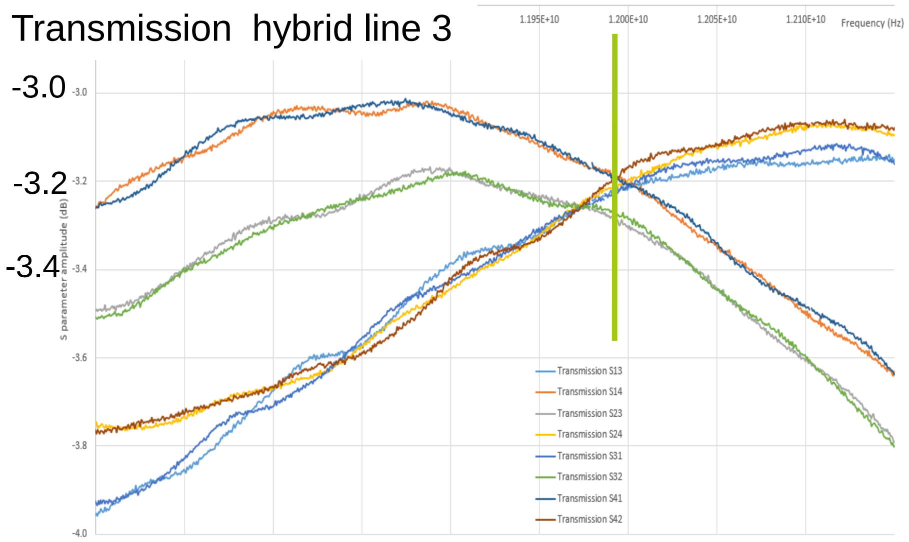
Reflection hybrid line 3



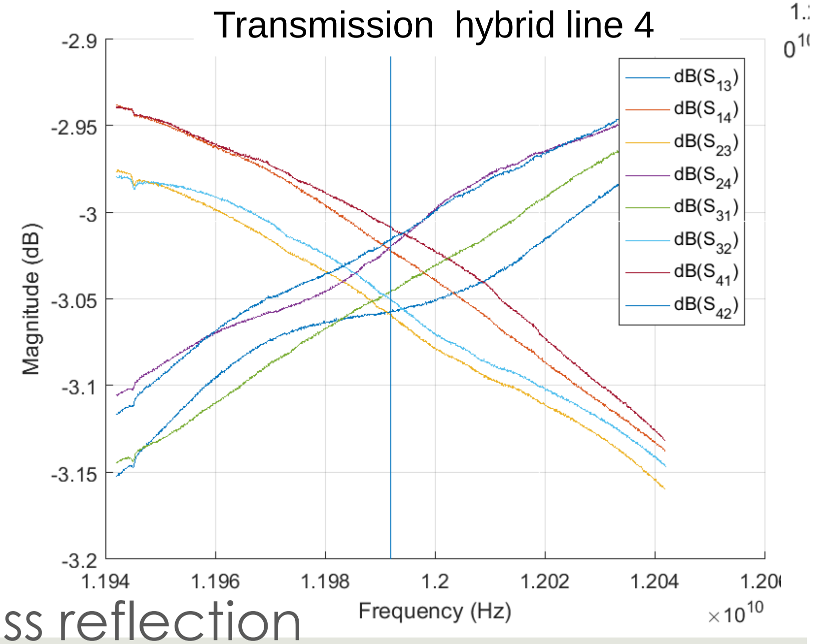
Reflection hybrid line 4



Transmission hybrid line 3



Transmission hybrid line 4



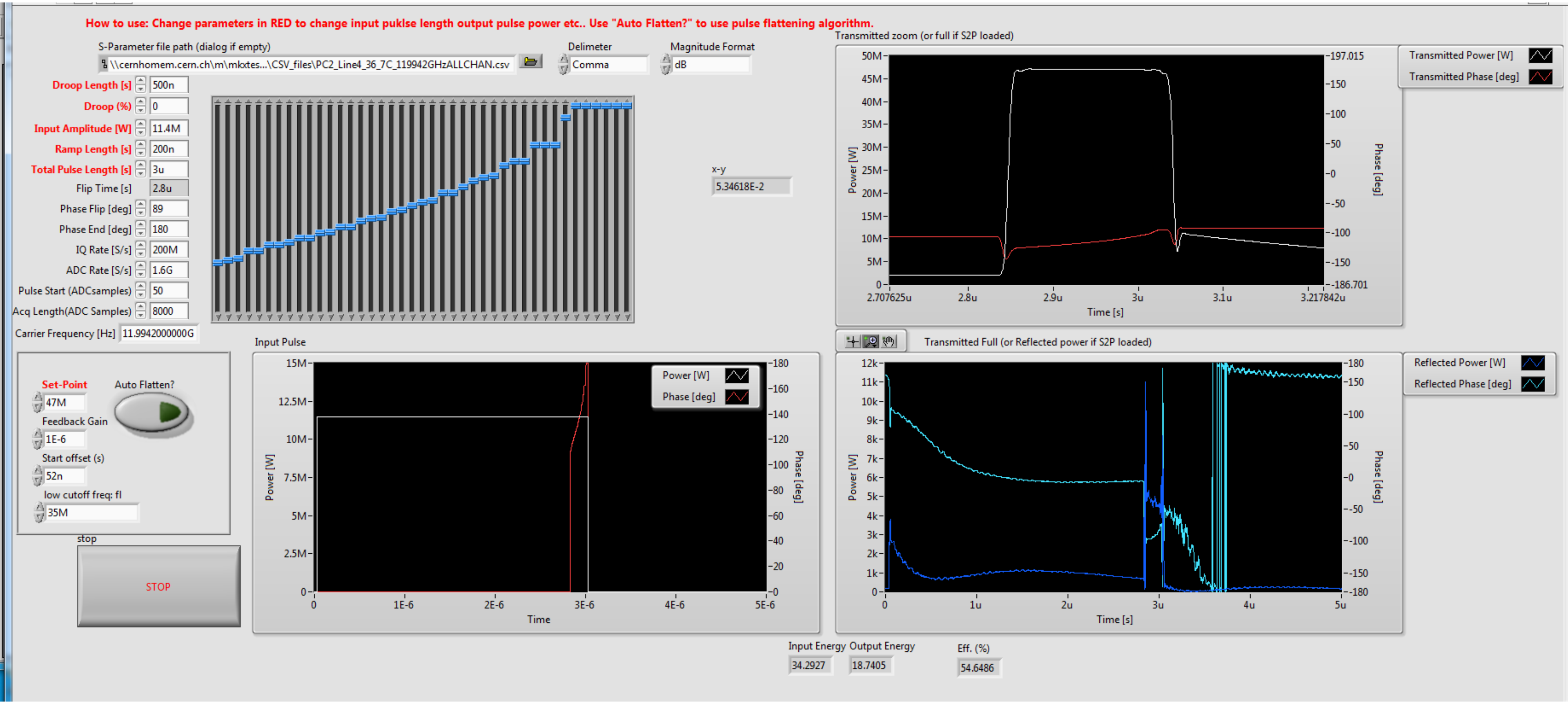
- The hybrid installed in PC line 3 has less reflection

# Conclusion

- Two PCs have been tuned and installed in line 3 and 4 of Xbox3
- We commissioned line 3 up to 40 MW with a pulse width of 2us and a flat top of 150ns
  - PC performances in agreement with the simulation.
- A second PC is tuned last week and installed in line 4. We will expect 2 MW more than Line 3.
  - Better tuned with less reflection in the -3dB hybrid
- Soon we will tune the PC for line 1 and 2.

# Extra slides

# Max gain



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S-Parameter file path (dialog if empty): \\cernhomem.cern.ch\m\mkxtes...\CSV_files\PC2_Line4_36_7C_119942GHzALLCHAN.csv

Delimeter: Comma

Magnitude Format: dB

**Droop Length [s]**: 500n

**Droop (%)**: 0

**Input Amplitude [W]**: 11.4M

**Ramp Length [s]**: 200n

**Total Pulse Length [s]**: 3u

Flip Time [s]: 2.8u

Phase Flip [deg]: 89

Phase End [deg]: 180

IQ Rate [S/s]: 200M

ADC Rate [S/s]: 1.6G

Pulse Start (ADCsamples): 50

Acq Length(ADC Samples): 8000

Carrier Frequency [Hz]: 11.9942000000G

x-y: 5.34618E-2

**Set-Point**: 47M

Feedback Gain: 1E-6

Start offset (s): 52n

low cutoff freq: fl: 35M

Input Energy: 34.2927

Output Energy: 18.7405

Eff. (%): 54.6486