

Model-Driven Control for High-Stability Magnetron RF Sources

LLRF Topical Workshop on Advanced Feedback Control (TWoAFC)

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Context: EPITA project & Magnetrons

Enabling
Partnerships for
Innovation & accelerator
Technology
Advancement

EPITA

↳ **WP6** - Advanced RF Technologies

↳ **T1** - Locked Magnetron Sources for
SRF Systems

↳ EHU will develop phase-locking
techniques to enable cost-effective
amplitude and phase noise stabilization.



Magnetrons: High-Power and Efficient at Low Cost

Magnetrons, compact and cost-effective microwave sources, are a promising alternative to solid-state amplifiers (SSAs) and klystrons for efficient, low-cost RF power delivery, particularly in systems requiring multiple RF sources, such as linacs.

	Magnetron	Klystron
Peak Power	Lower	High
Average power	Lower	High
Gain	Lower	High
Tuneable range	Large	Small
Instantaneous bandwidth	Smaller	Small
Noise	Higher	Lower
Best Efficiency L band	~ 90%	ILC ~ 69%
Best Efficiency X band	~ 50%	XL5 = 40%
Pushing figure	Significant	Significant
Pulling figure	Significant	
Amplifier cost	Low	high
Modulator & magnet cost	Lower	high

You would not use a magnetron if capital and running costs are not an issue.

A. Dexter, Phase Locked Magnetrons For Accelerators. Linac 2014

Magnetrons

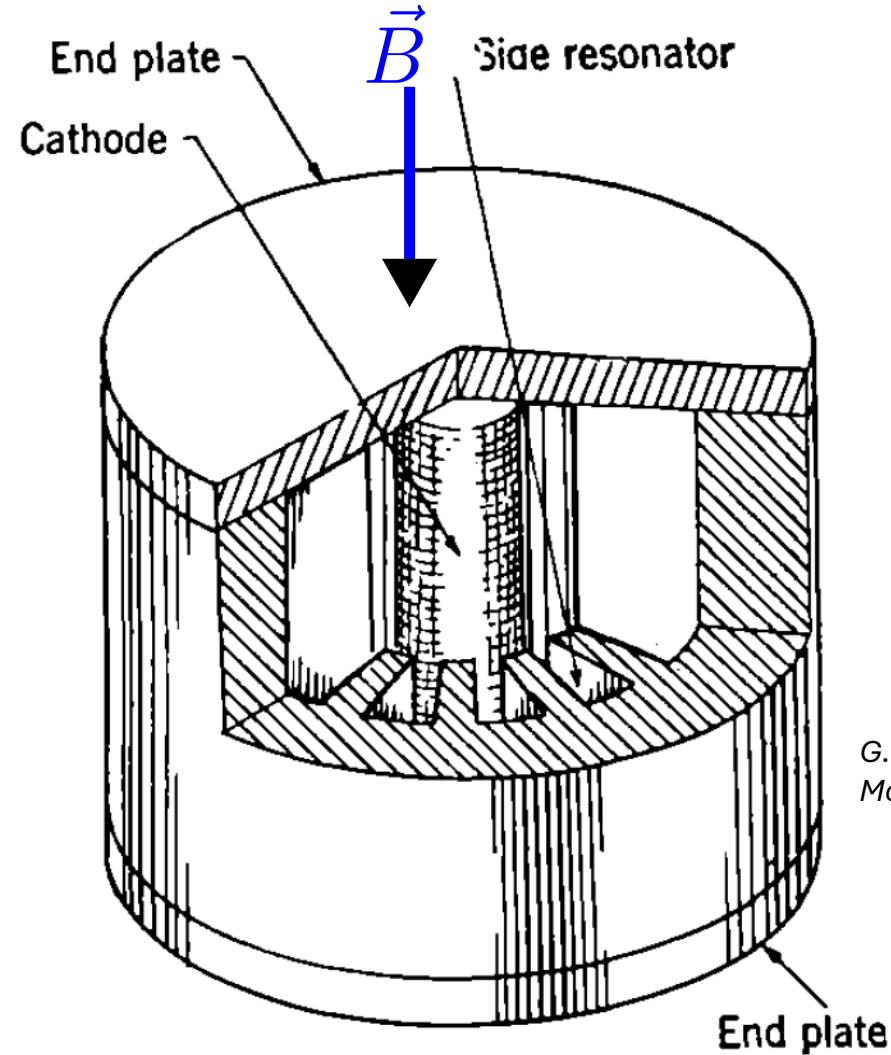
Vacuum sealed resonant cavity
with

An **anode** composed of several
coupled **side resonators**,

an **electron** emitting **cathode**,

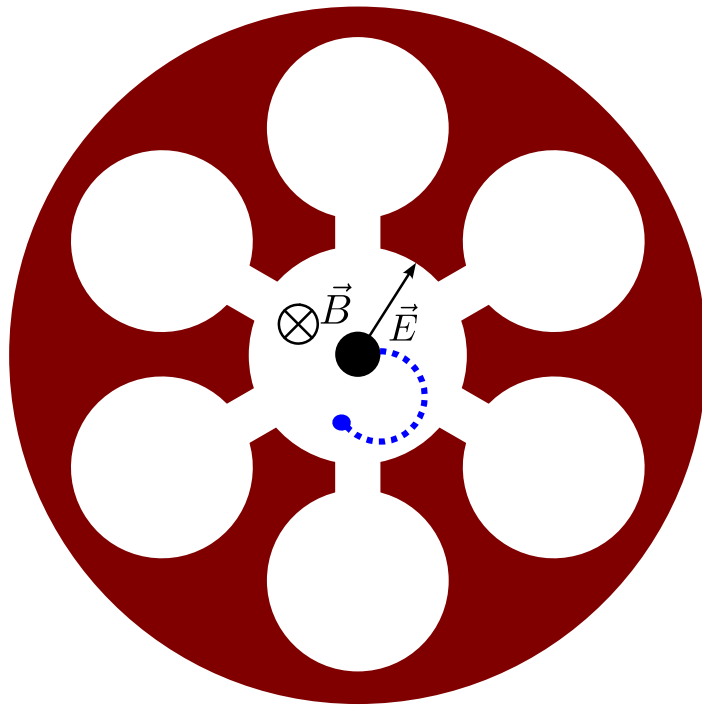
a **High-Voltage** potential
between anode and cathode,

And a perpendicular **magnetic
field**.

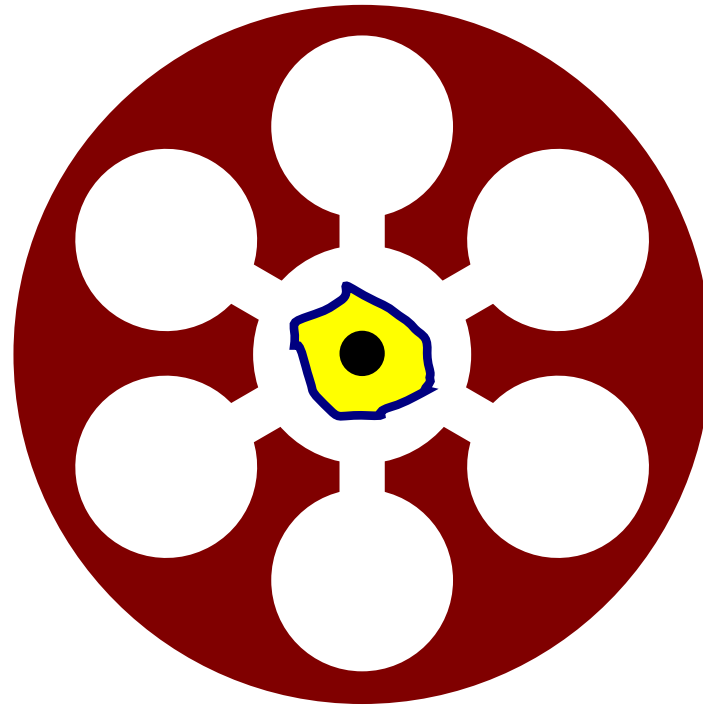


*G. Collins, Microwave Magnetrons.
McGraw-Hill Book Company, 1948.*

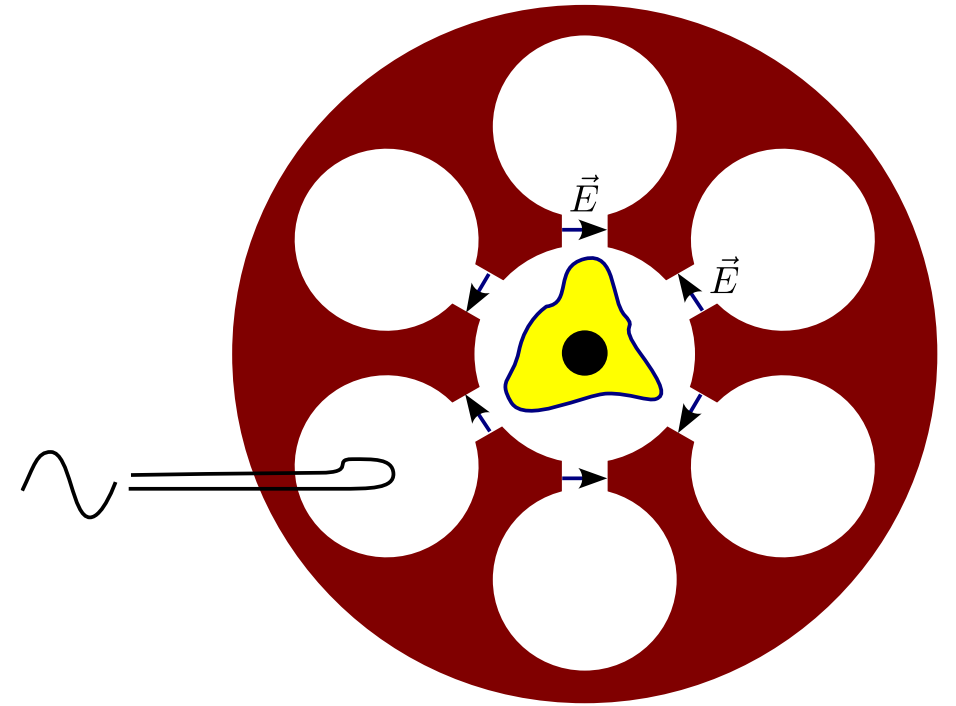
Magnetron working principle I



1. Electrons are emitted from the cathode, accelerated by the electric field towards the anode, and with a curved trajectory due to the magnetic field.



2. An electron cloud is formed around the cathode.



3. The resonant cavity gets excited by the electrons. The resonant mode shapes the electron cloud, allowing even more energy to be transferred from the electrons to the resonant mode. Energy can be taken from the system by an antenna.

Magnetron working principle II

The magnetrons signal **gets affected by:**

- Thermal noise of the electrons
 - The geometry of the cavity
- } Inherent Noise/Instability sources
- The Voltage difference and current between Anode and Cathode
 - The magnetic field
- } Pushing effects
- The extraction of signal
 - The Injection of signal
- } Pulling effects

Magnetron Pushing Effects

3 main sources:

- Anode-Cathode Voltage
- Anode-Cathode Current
- Magnetic Field

Pushing can be used to **control** the output signal of magnetrons, but

all **noise** present in pushing sources **will affect the output** of the magnetron

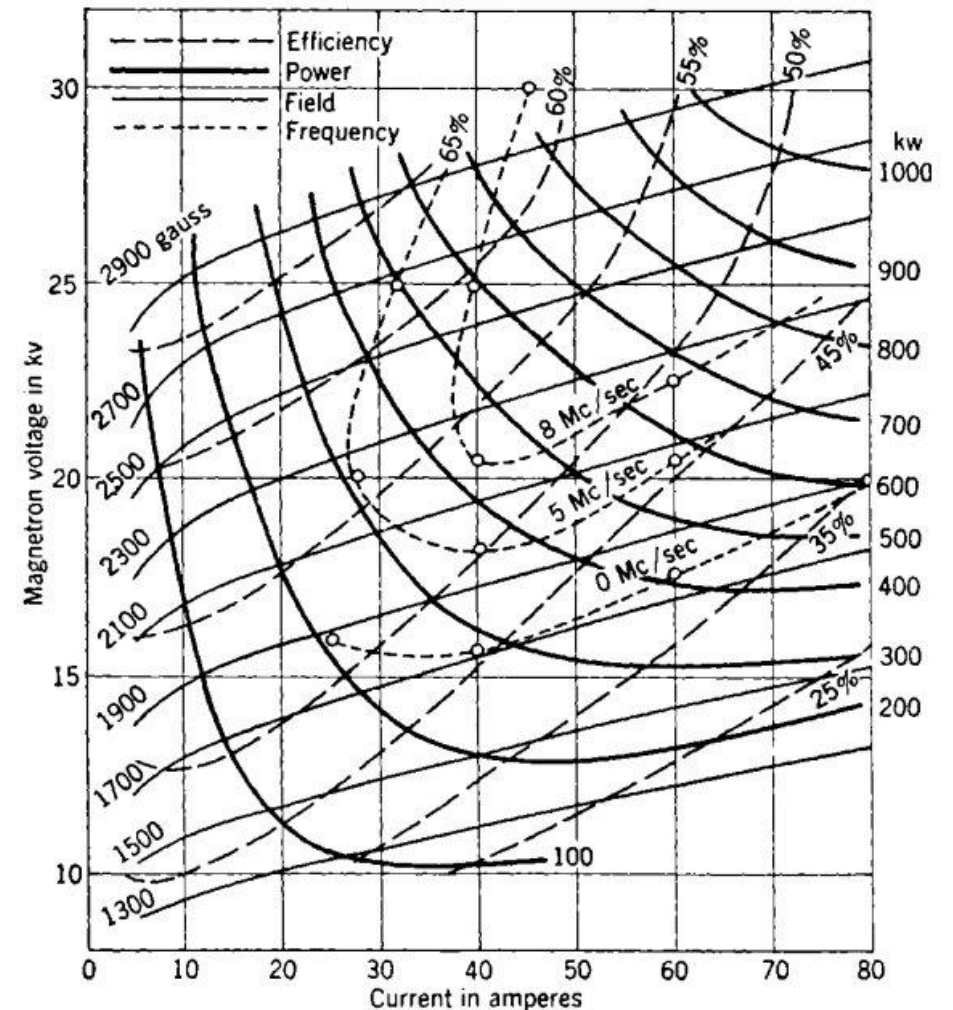
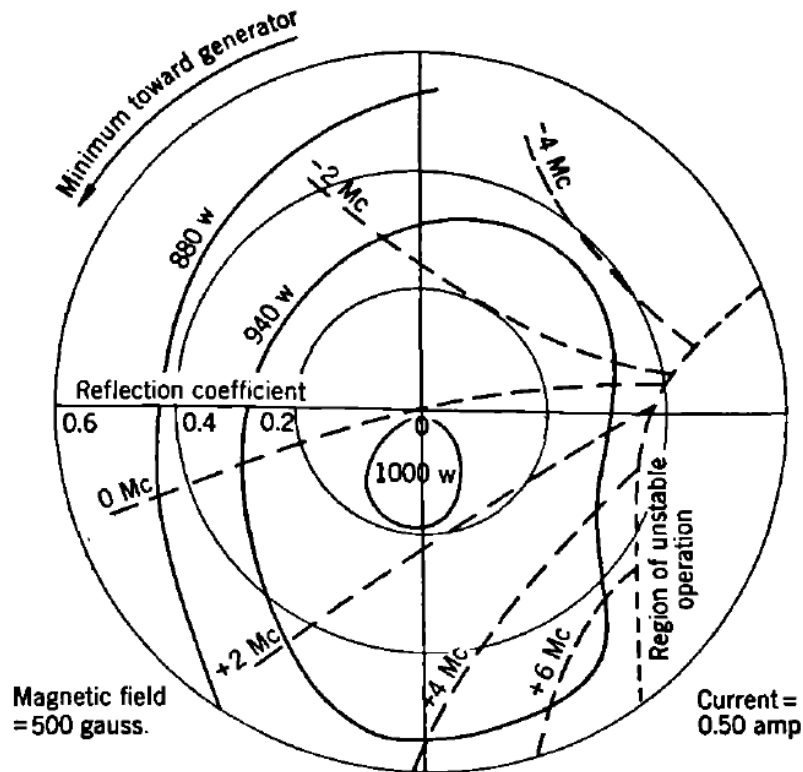


FIG. 1-30.—Typical performance chart of a magnetron (4J31).

G. Collins, *Microwave Magnetrons*. McGraw-Hill Book Company, 1948.

Magnetron Pulling Effects

Load mismatch



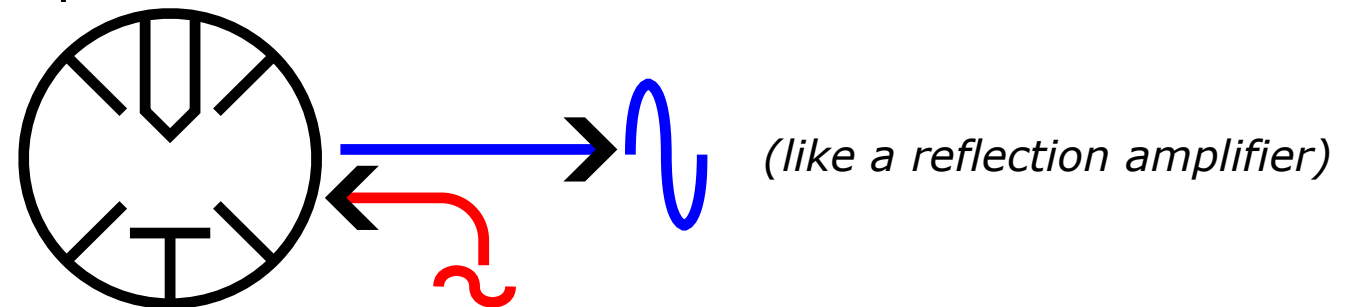
Frequency of 0 Mc contour = 896.5 Mc/sec

FIG. 19-4.—Rieke diagram for LCW magnetron.

G. Collins, *Microwave Magnetrons*. McGraw-Hill Book Company, 1948.

Injection Locking

By injecting a small signal to the magnetron we can control the phase of the output signal and improve noise performance



It has a limited locking bandwidth

$$\left| \frac{f_{\text{mag}} - f_{\text{inj}}}{f_{\text{mag}}} \right| < \frac{1}{2Q} \sqrt{\frac{P_{\text{inj}}}{P_{\text{mag}}}}$$

And a phase offset

$$\sin(\alpha) = 2Q \frac{f_{\text{mag}} - f_{\text{inj}}}{f_{\text{mag}}} \sqrt{\frac{P_{\text{mag}}}{P_{\text{inj}}}}$$

f_{mag}	Magnetron
P_{mag}	free-running
	parameters
f_{inj}	Injection
P_{inj}	parameters

EPITA proposal Control Loop

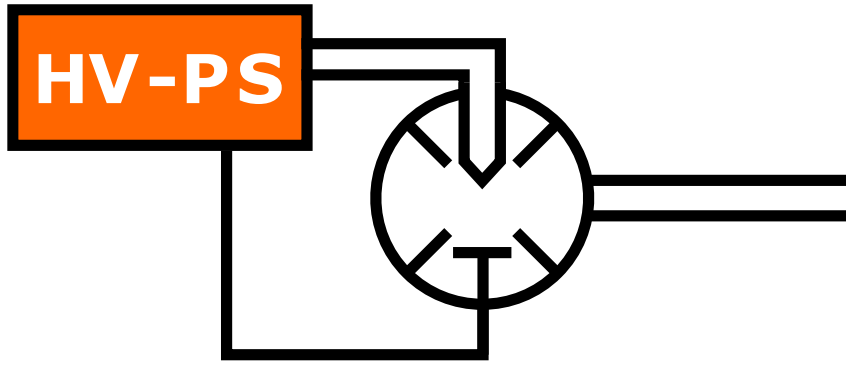
An uncontrolled Magnetron has random phase.

Locking techniques allow to set the phase but Pushing & Pulling effects modify it.

Active Injection Locking fixes this and allows to set an exact phase at the output of the magnetron.

	Free-Running	Locked Magnetron	Active Injection Locked (LLRF)
External circuit needed	No	Yes (signal source)	Yes (LLRF)
Phase Control	No	Partial	Yes
Pushing & Pulling Effects	Not corrected	Not corrected	Yes

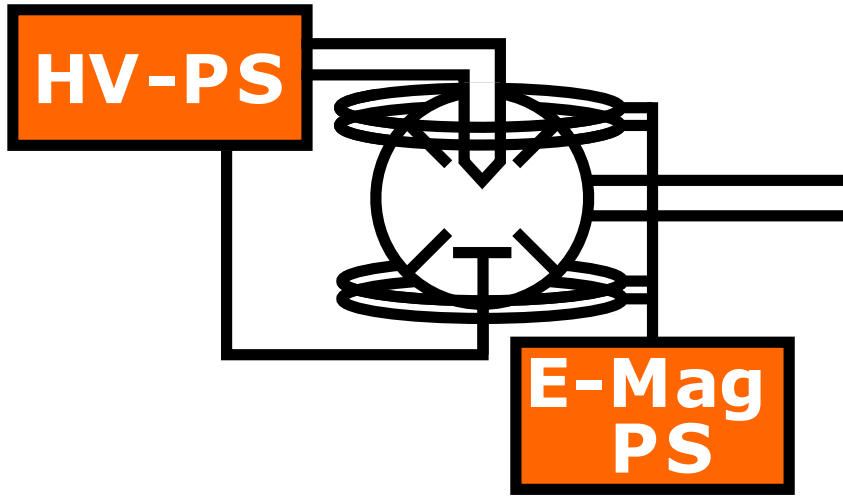
EPITA proposal Control Loop



HV-PS: High Voltage Power Supply

- Pushing Phenomena based Control

EPITA proposal Control Loop

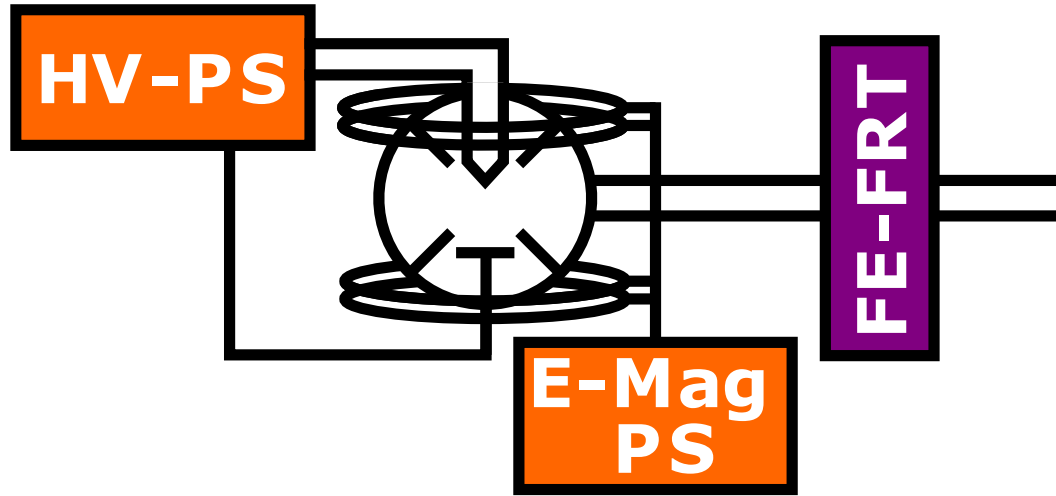


HV-PS: High Voltage Power Supply

E-Mag PS: Electro Magnet Power Supply

➤ Pushing Phenomena based Control

EPITA proposal Control Loop



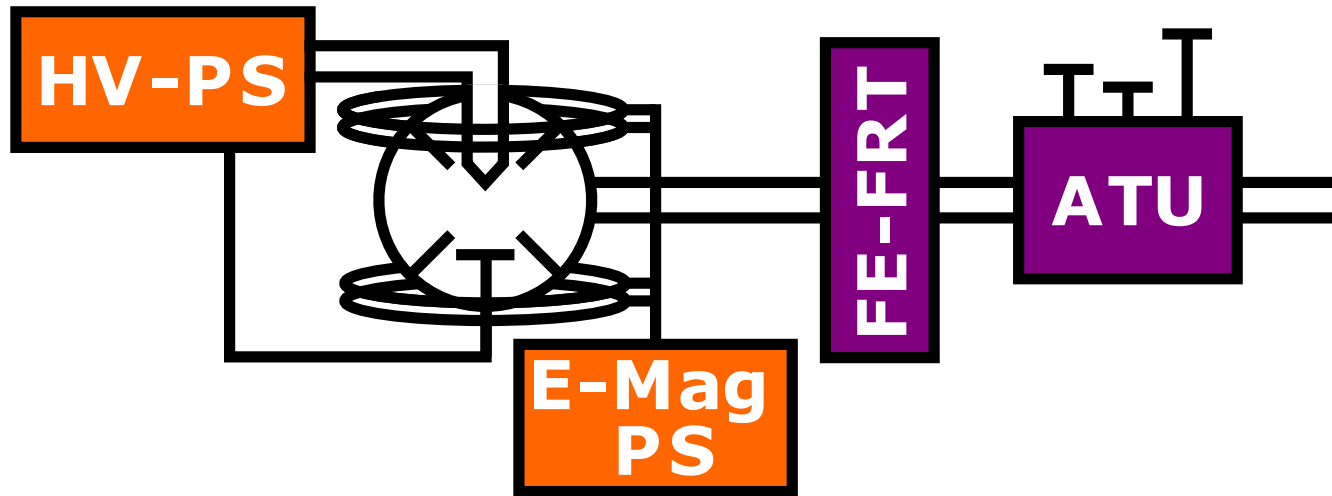
HV-PS: High Voltage Power Supply

E-Mag PS: Electro Magnet Power Supply

FE-FRT: Ferro-Electric Fast Reactive Tuner

- Pushing Phenomena based Control
- Pulling Phenomena based Control

EPITA proposal Control Loop



HV-PS: High Voltage Power Supply

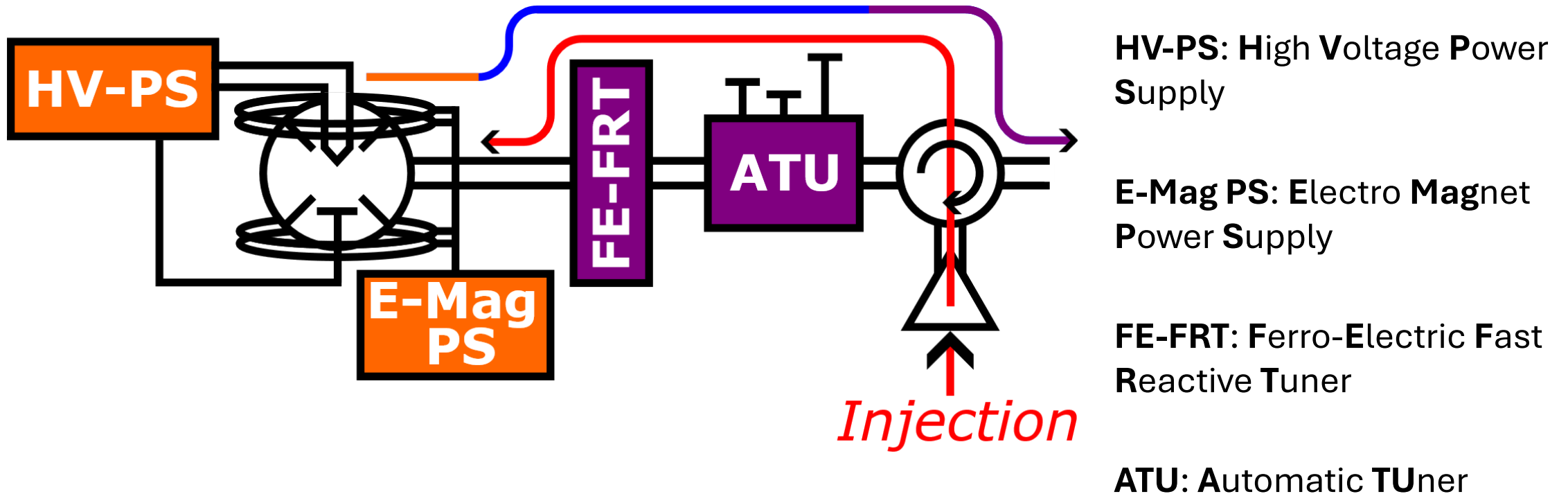
E-Mag PS: Electro Magnet Power Supply

FE-FRT: Ferro-Electric Fast Reactive Tuner

ATU: Automatic Tuner

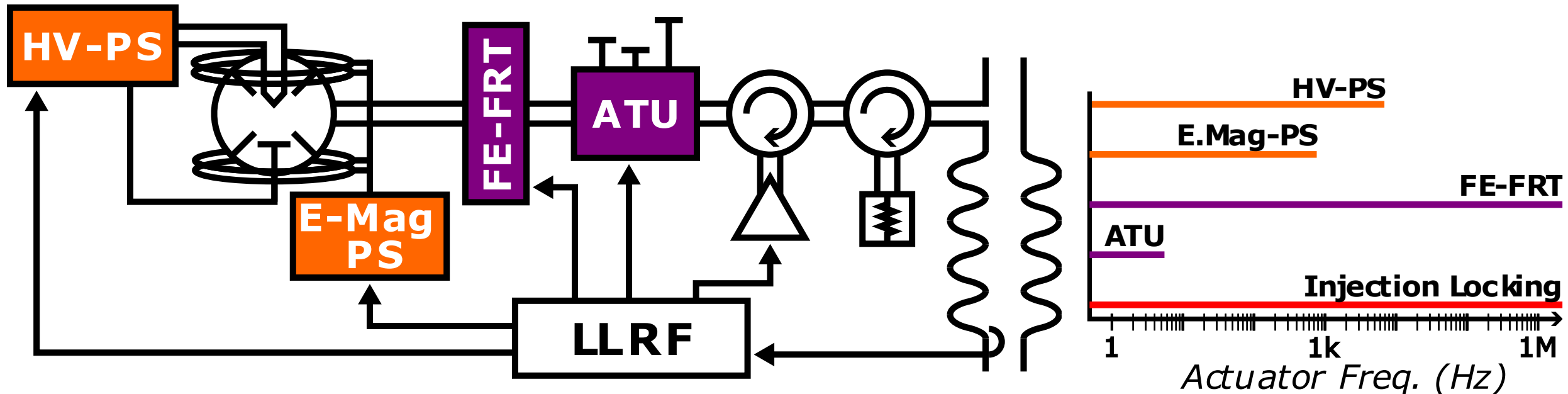
- Pushing Phenomena based Control
- Pulling Phenomena based Control

EPITA proposal Control Loop



- Pushing Phenomena based Control
- Pulling Phenomena based Control

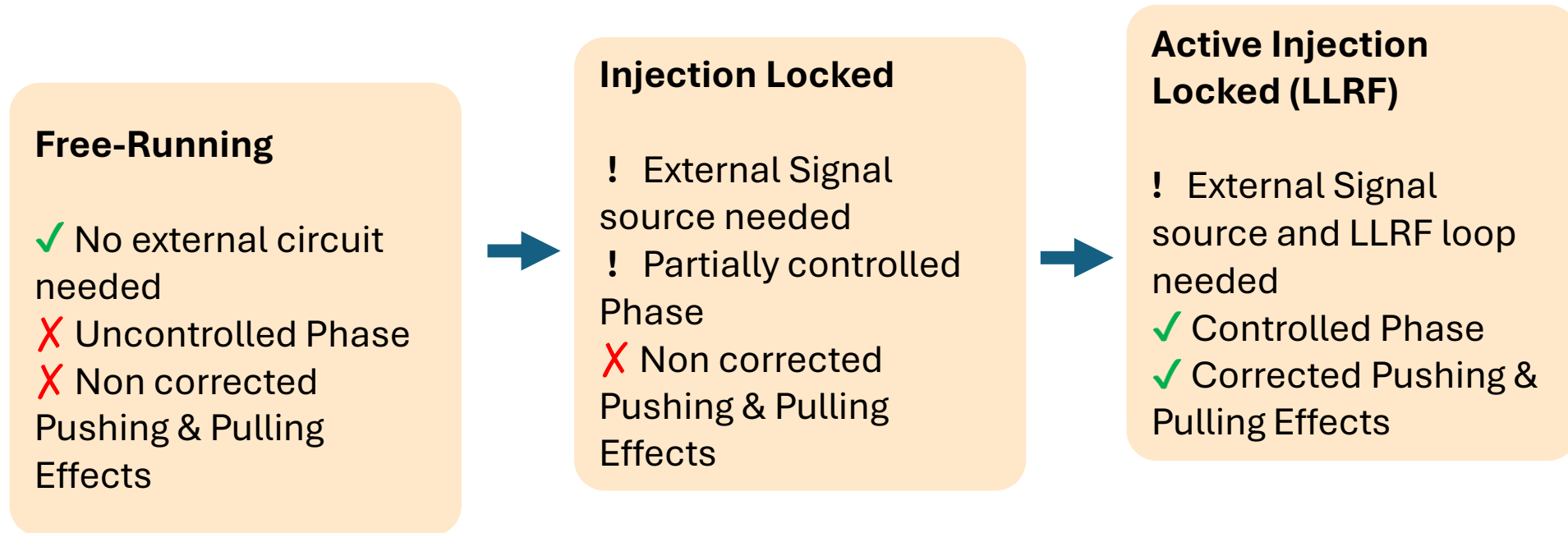
EPITA proposal Control Loop



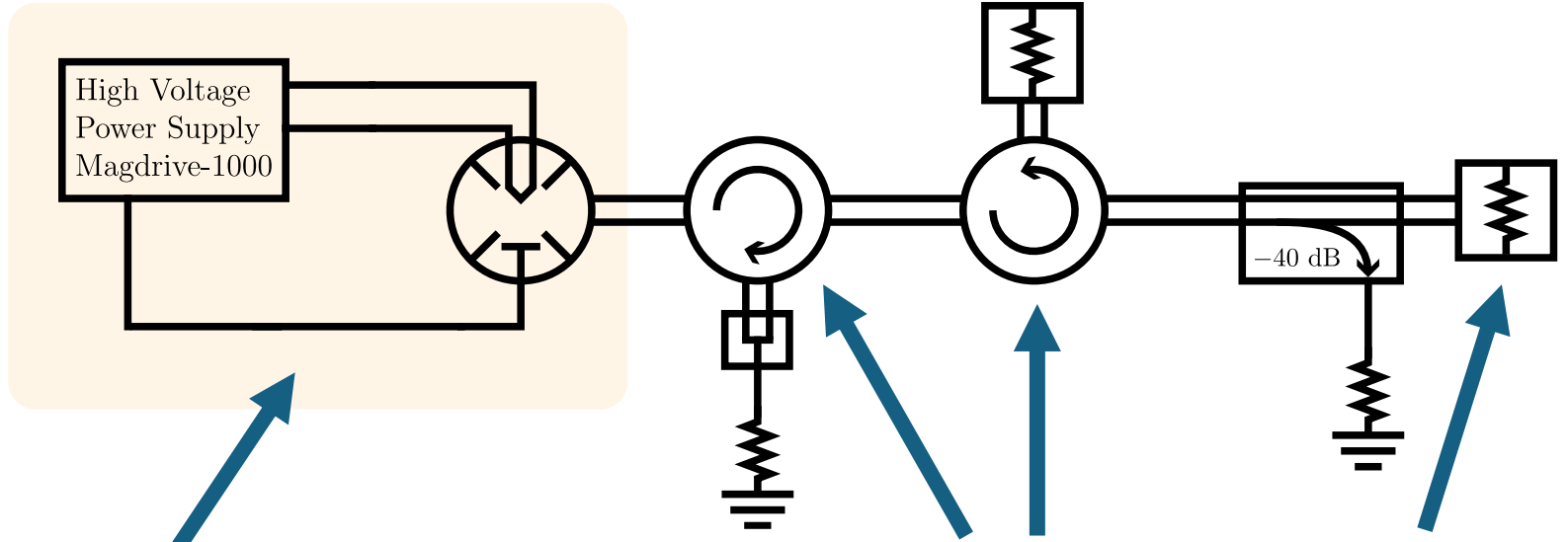
Active Injection-Locking Testbench

The testbench is a first step towards EPITA's Control loop.

We have implemented a LLRF Active Injection Locking loop capable of correcting the pushing deviations generated by the ripple present in the power supply



Testbench Schematic



Water Loads and isolators in the magnetrons output: No pulling effect expected



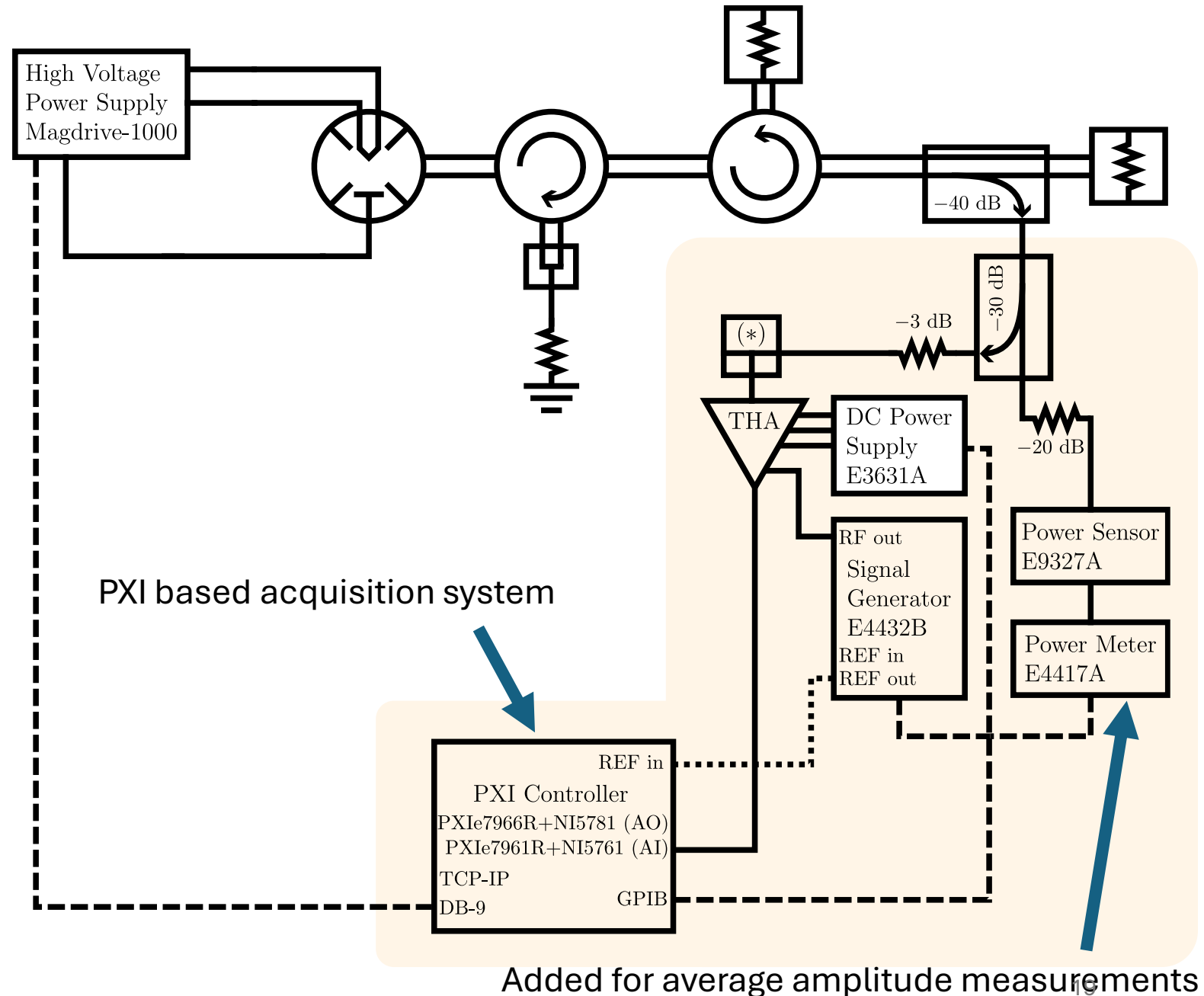
Magnetron and HV-PS: Magdrive Start Kit

- Magnetron: 2.45 GHz 1 kW (Nominal)
- HV-PS: 4 – 4.15 kV, 60 – 300 mA Anode to Cathode

Testbench Schematic

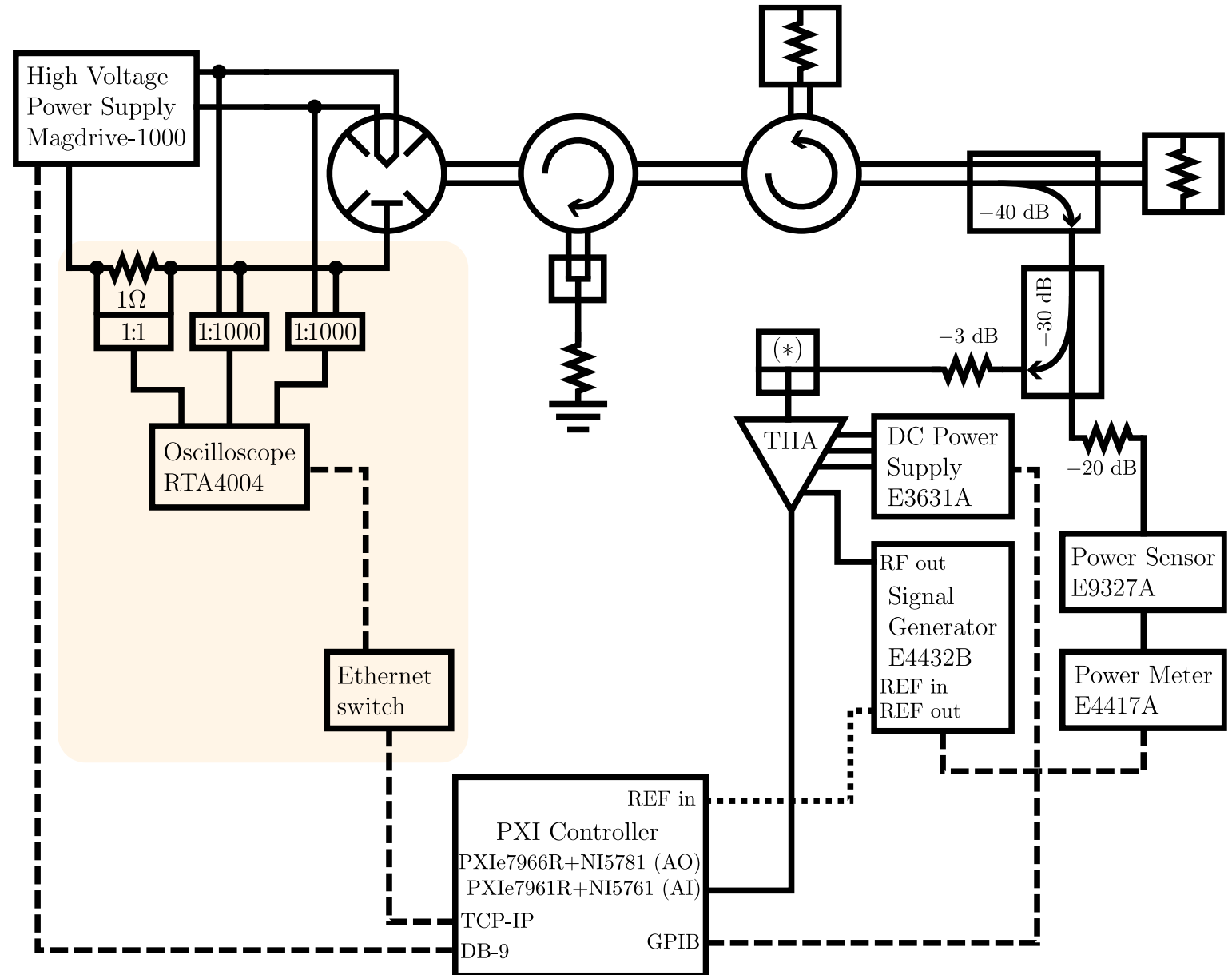
Magnetron signal is measured using:

- **Undersampling** techniques. 2.45 GHz signal sampled at 250 MHz.
- **Track-And-Hold amplifier** to increase the acquisition bandwidth of the ADC.
- **Quadrature Demodulation** to ease the burden on the FPGA (and reduce latency)



Testbench Schematic

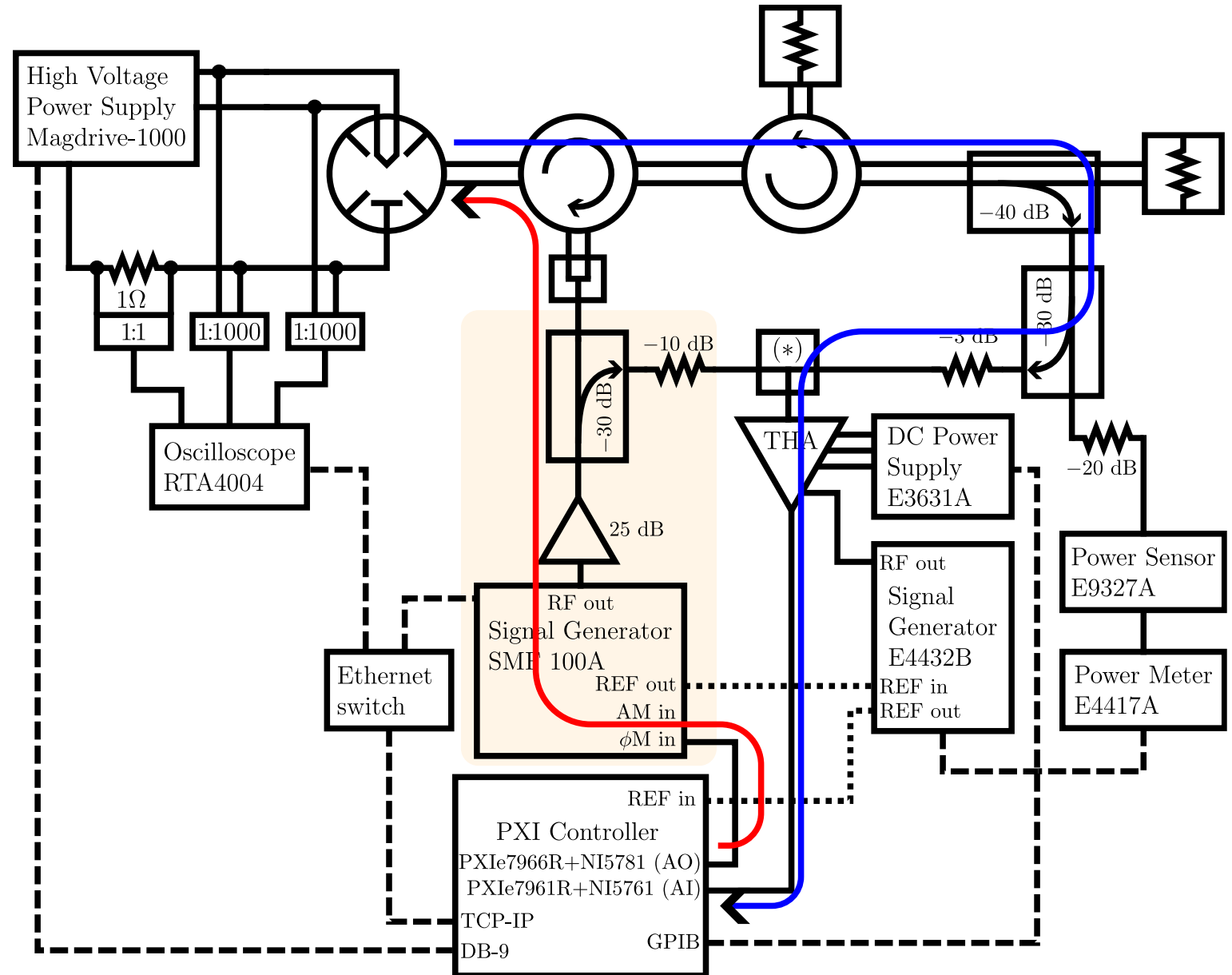
HV-PS voltage and current measurements added, to study the cause of pushing effects



Testbench Schematic

LLRF control loop:

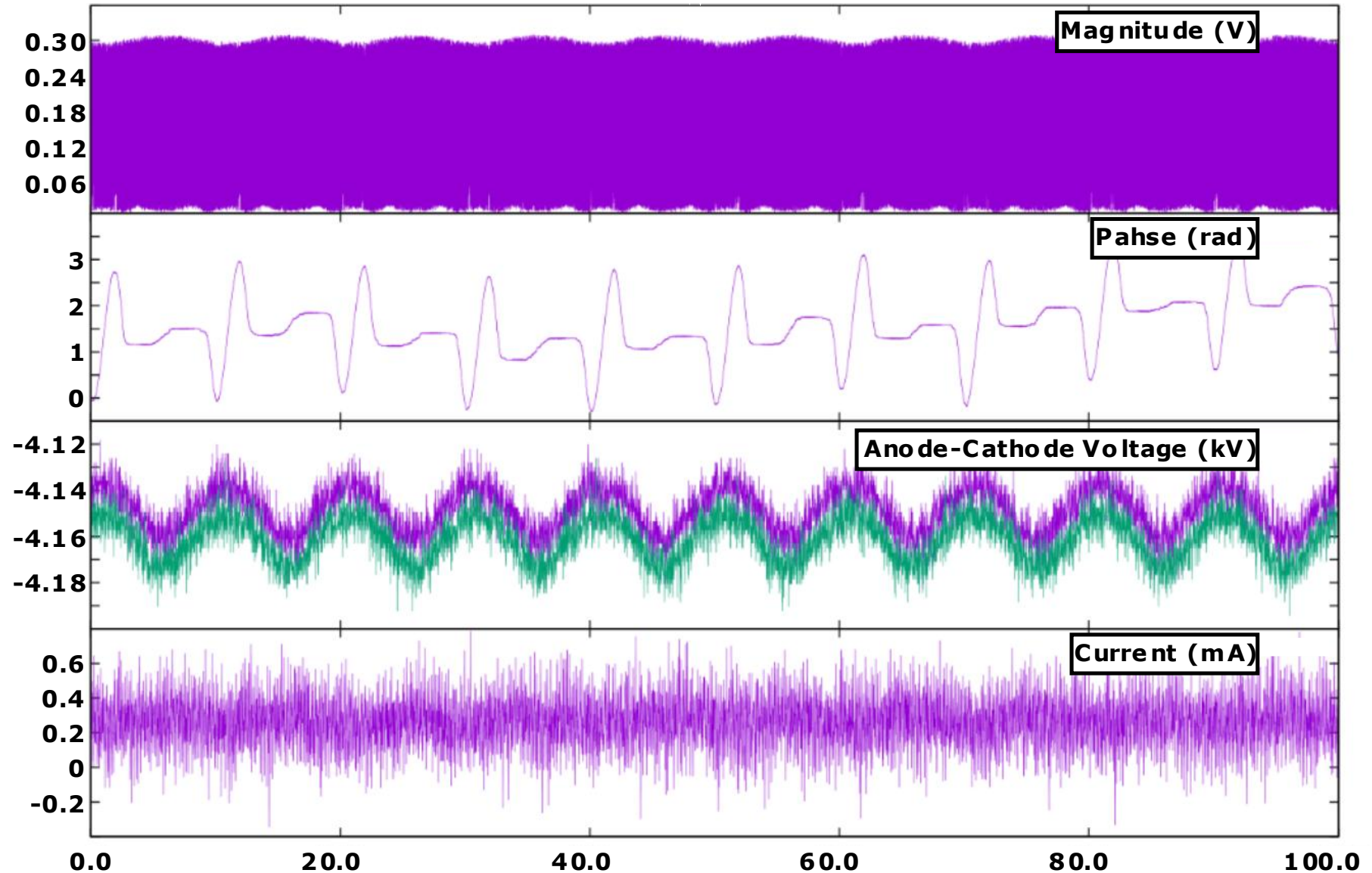
- **Magnetrons signal is measured**
- **The phase of the signal is compared against a setpoint and the necessary correction is added to the generators PM modulation**
- **A maximum of 5 W are used to lock the magnetron ($P_{inj}/P_{mag} = 0.5$)**



Results

With injection, but without Phase control loop

- HV-PS shows a significant ripple
- Even with injection, the amplitude and phase of the magnetron show a very noticeable ripple



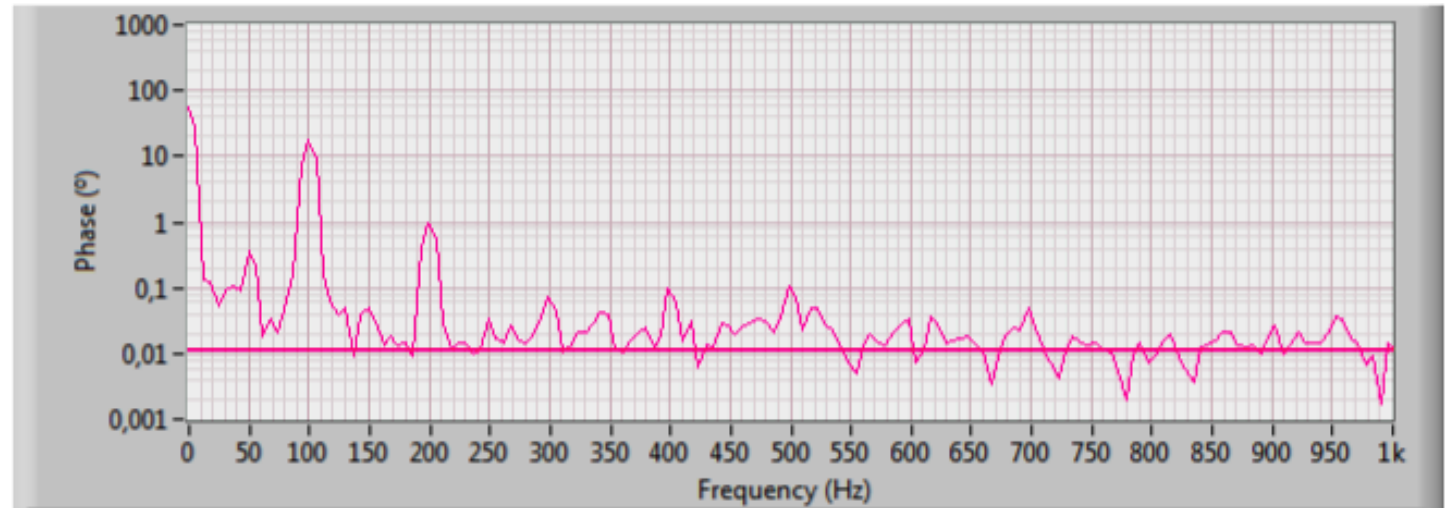
Results II

With active phase locking

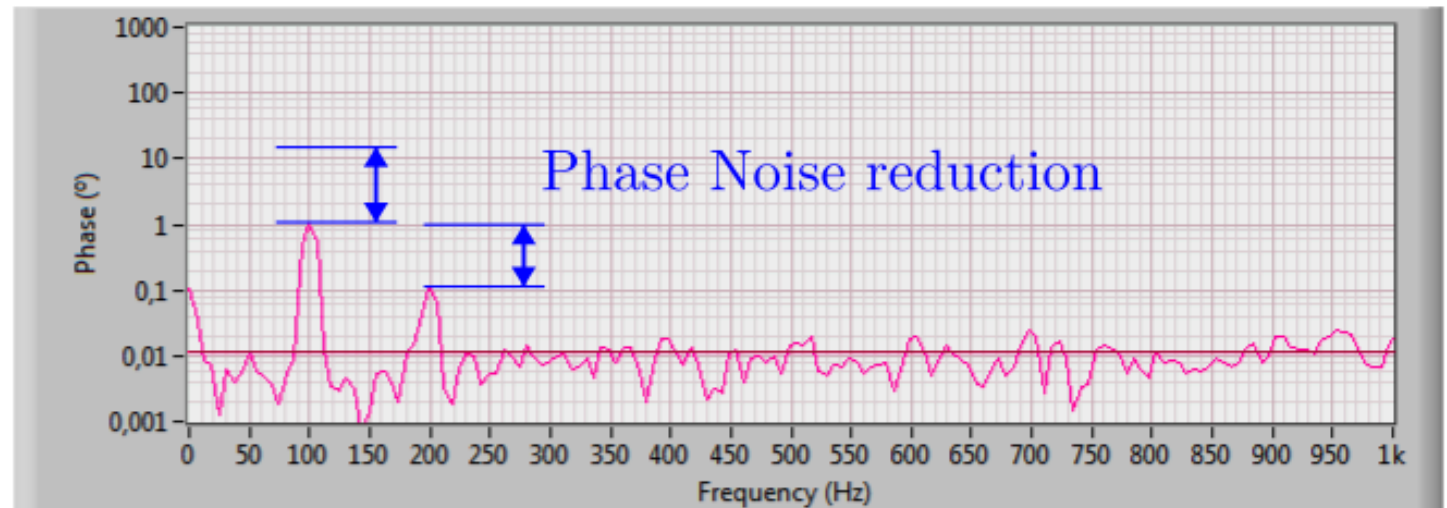
We have targeted the highest power phase deviation: 100 Hz and 200 Hz

- 12 dB improvement in 100Hz
- Highest deviation reduced to 1° RMS

w/o control



w/ control



(*) In this test we have increased the Injected Power compared with the previous slide.

Conclusions

- **Power Supply Ripple is a very significant factor in the stability of a magnetron**
- **Injection Locking alone does not stabilize the output phase of a magnetron. Active correction is needed to do so**
- **The proposed test-bench allows the phase control of a magnetron with phase deviations up to $<1^\circ$ RMS, although magnitude control requires additional considerations**

Next Steps

Test in Accelerating cavity

Will be tested in
HZB

Improve Controller

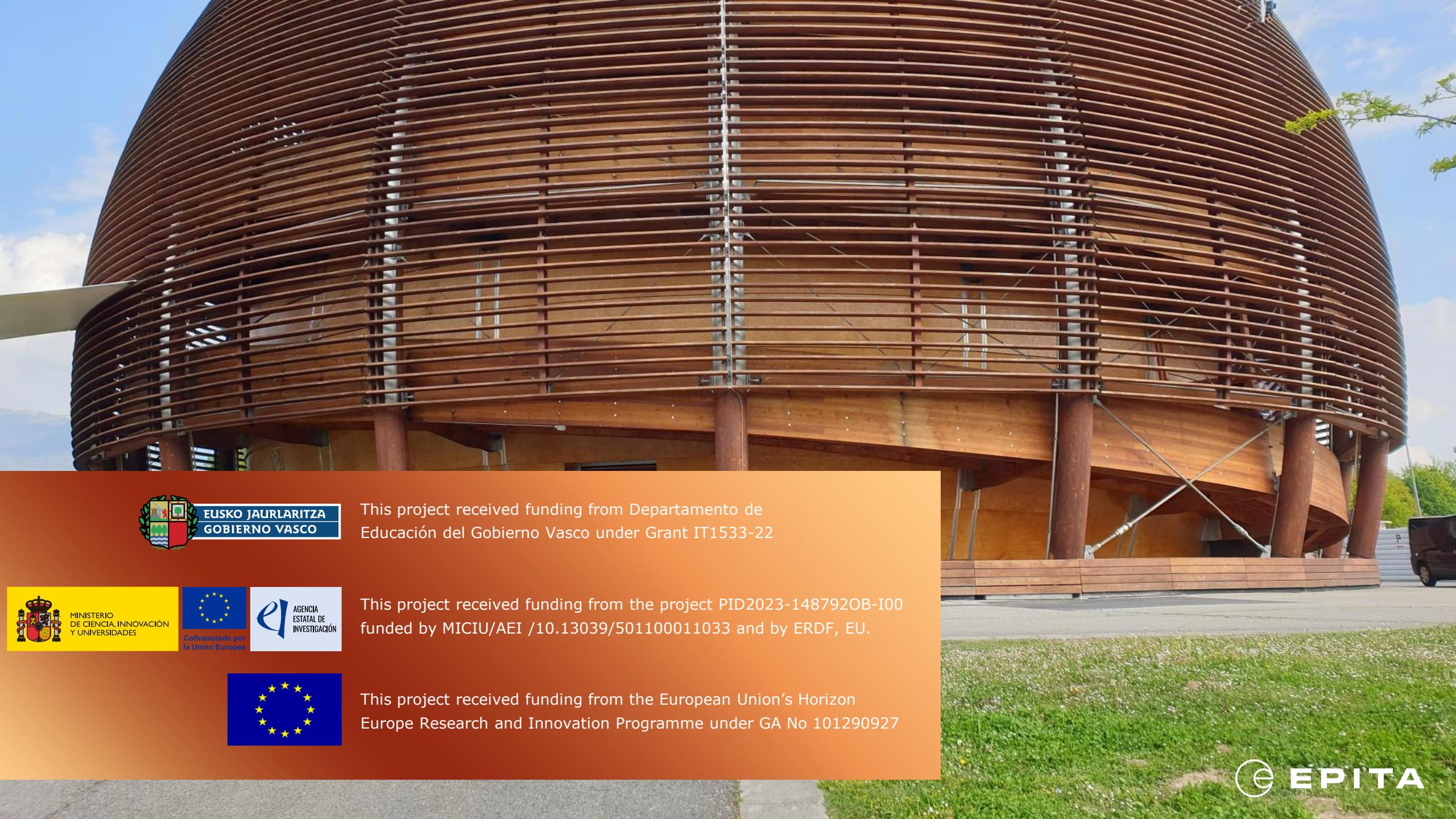
Implement a more
robust control
algorithm based on a
phenomenological
Slater model

Improve measurement system

Step from PXI platform
to AMDs RFSoc
platform

Improve/Redesign HV-PS

The source of most of the
noise. Improving it could
allow to control it in real
time and use the pushing
techniques.



EUSKO JAURLARITZA
GOBIERNO VASCO

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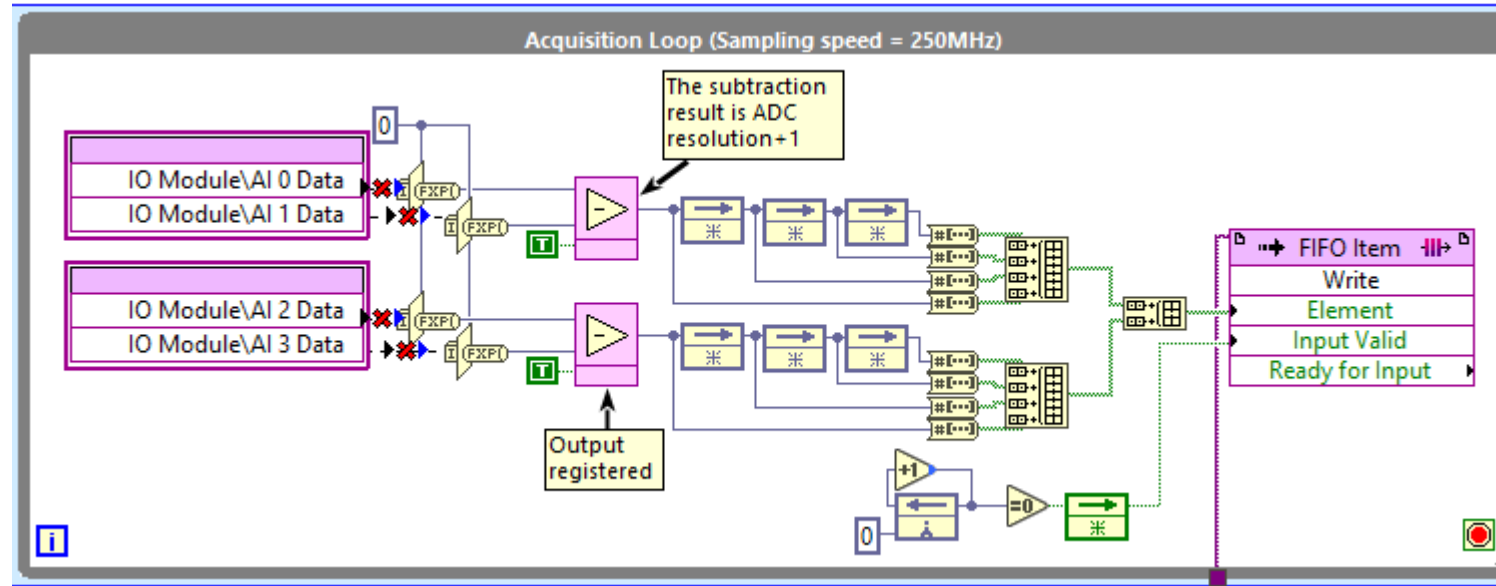


This project received funding from the project PID2023-148792OB-I00 funded by MICIU/AEI /10.13039/501100011033 and by ERDF, EU.

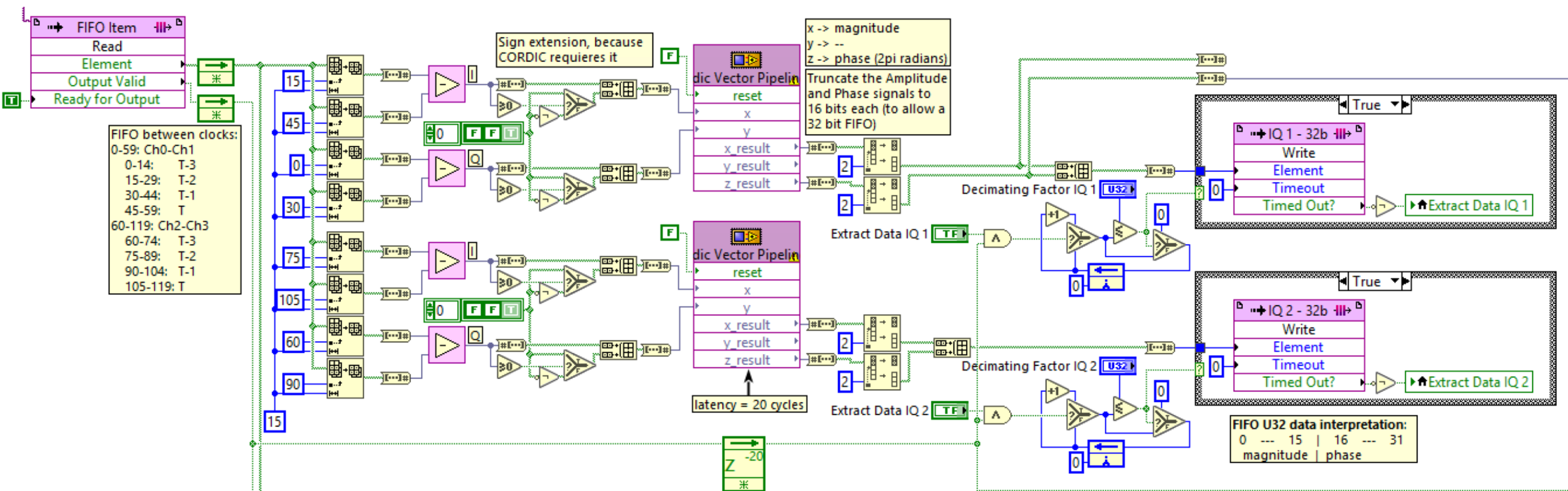


This project received funding from the European Union's Horizon Europe Research and Innovation Programme under GA No 101290927

EXTRA SLIDES



EXTRA SLIDES



EXTRA SLIDES

