Twelfth Continuous Wave and High Average Power RF Workshop

12.-14.9.2022
CERN
Geneva, Switzerland
http://cern.ch/CWRF22

ESS-Bilbao New Development in RFQ Coupler and a Novel SSPA RF Power System for our ECR ION Source

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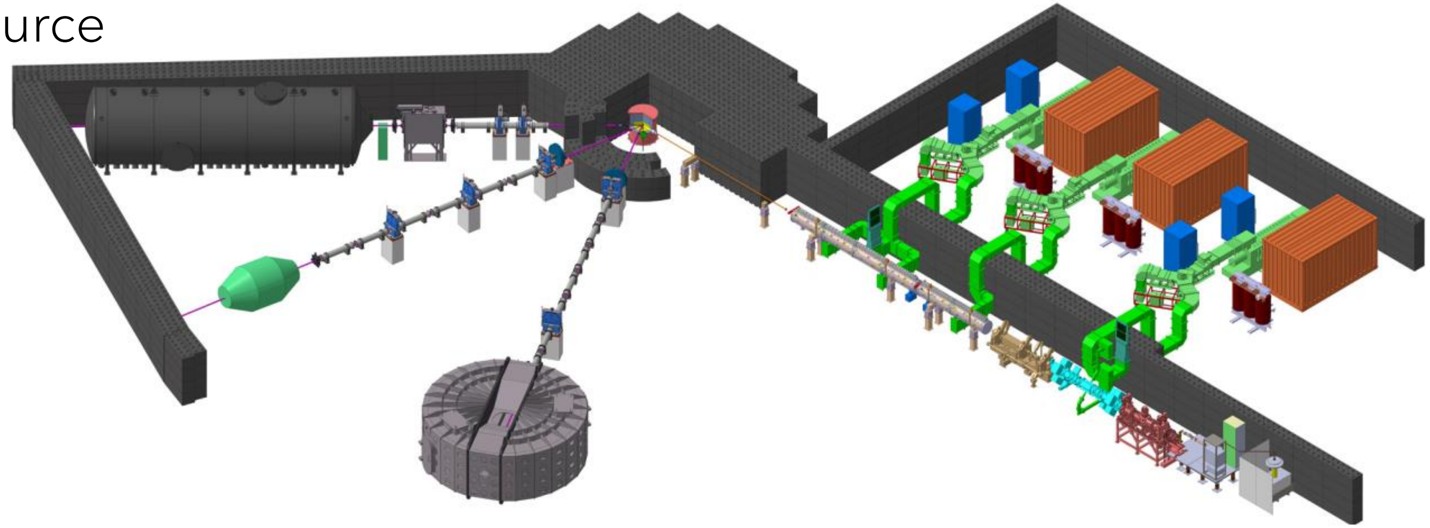
Outline

1. ESSB RFQ Power Coupler
   - ARGITU Project
   - Coupler Design
   - Coupler Fabrication
2. Solid-State RF Power System for ARGITU ECR ION source
   - RF System Design and Implementation
   - Pre-Distortion Technique to Flatten the RF Pulse
3. Summary and some ongoing Projects

ARGITU

- The ARGITU project is one of the initiatives framed within the European strategy to develop the next generation of high-intensity accelerator-driven compact neutron sources (HICANS)

- The ARGITU light-ion linear accelerator aims to provide a 30 MeV, 32mA proton beam as a multi-purpose neutron source



- **More info:** M. Perez et al., " ARGITU compact accelerator neutron source: A unique infrastructure fostering R&D ecosystem in Euskadi", Neutron News, Vol. 31, issue 2-4, pp. 19-25, Dec. 2020, (https://doi.org/10.1080/10448632.2020.1819140)

Injector / RFQ

- The ARGITU injector comprises of:
  - An Electron Cyclotron Resonance (ECR) proton ion source and a Low Energy Beam Transport (LEBT), which already are under operation at the ESS Bilbao premises. They can provide a proton beam of up to 40 mA at energy of 45 kV.
  - The next LINAC section is a Radio Frequency Quadrupole (RFQ), which is currently under manufacturing

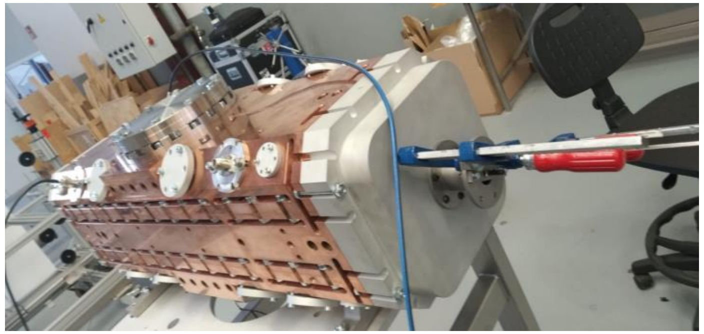
2.7 GHz

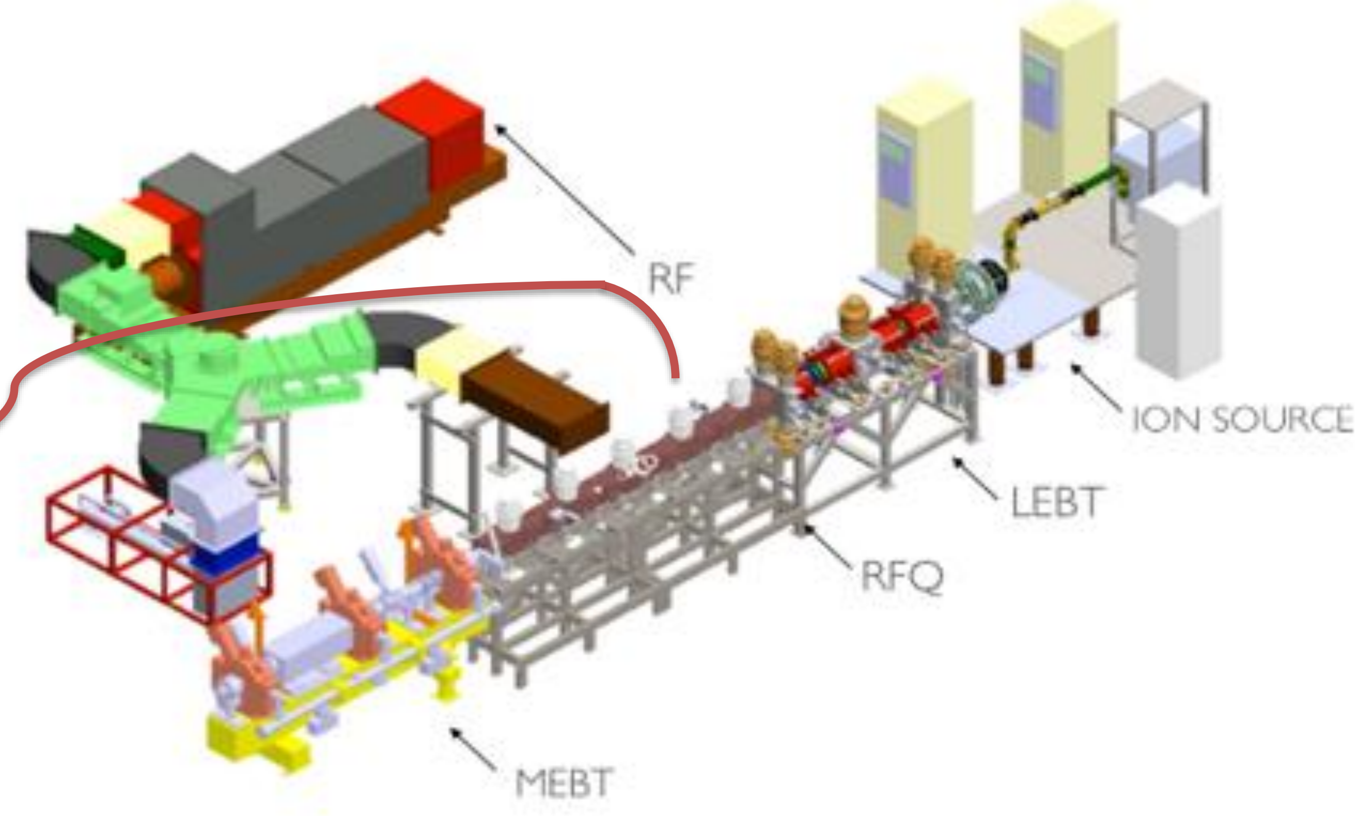
RFQ Specs →

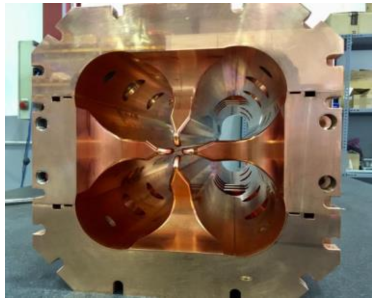
Parameter	Value
Specimen	H+
Beam current	32 mA
Beam energy	45 keV→3 MeV
RF Frequency	352.2 MHz
Pulse Operation	30 Hz; 1.5 ms; 4.5 %
Total length	3.12 m
Inter-vane Voltage	85 kV
Kilpatrick	1.85
Input emittance	0.25 π mm rad

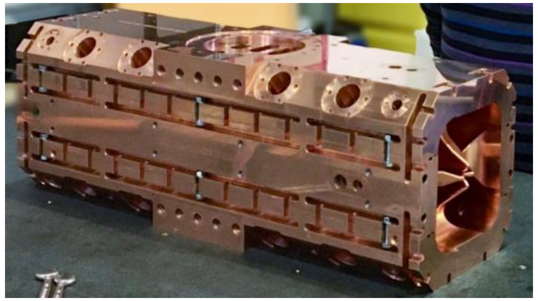
LINAC Section

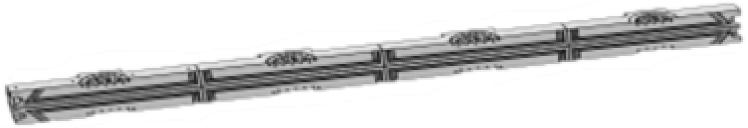
- The 2.8MW CPI klystron is at the manufacturer workshop for repair due to a vacuum leak
- If the klystron couldn't be repaired, the alternative will be 2 x 300 kW solid-state amplifier to feed the the RFQ

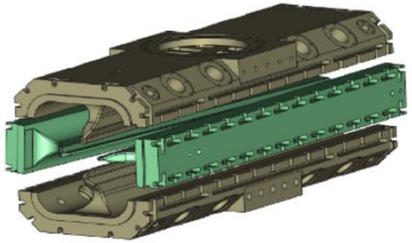












Coupler Design

- Two power couplers should be designed and fabricated for the following power requirements:
- Optimistic power loss in the copper walls derived by simulation with $Q_0 \approx 10000$ and the copper surface resistance of 0.0052 Ω including tuners is: P_{cu}=350 kW.
- The fabricated and assembled RFQ is expected to have higher losses, a value closer to 450 kW is more realistic.
- With 3MeV kinetic energy and 45mA beam current, the power to be delivered to beam will be some 150kW approx.

- $P_{loss} = 450\ kW$
- $P_{beam} = 150\ kW$

$\Rightarrow P_{total} = 600\ kW$

Power Per Coupler
Duty Cycle = 5%

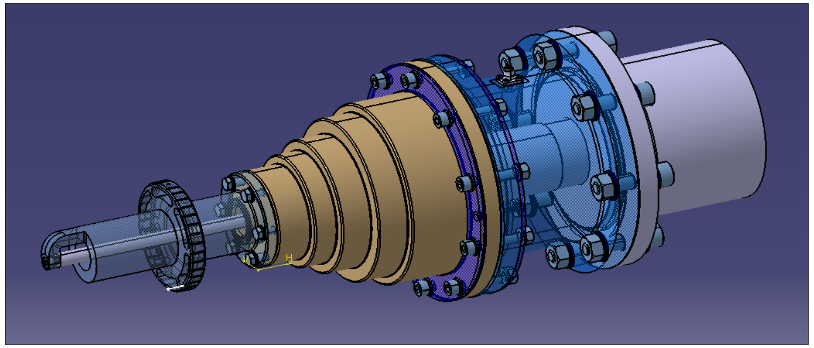
$\Rightarrow$

- $P_{peak} = 300\ kW$
- $P_{avg} = 15\ kW$

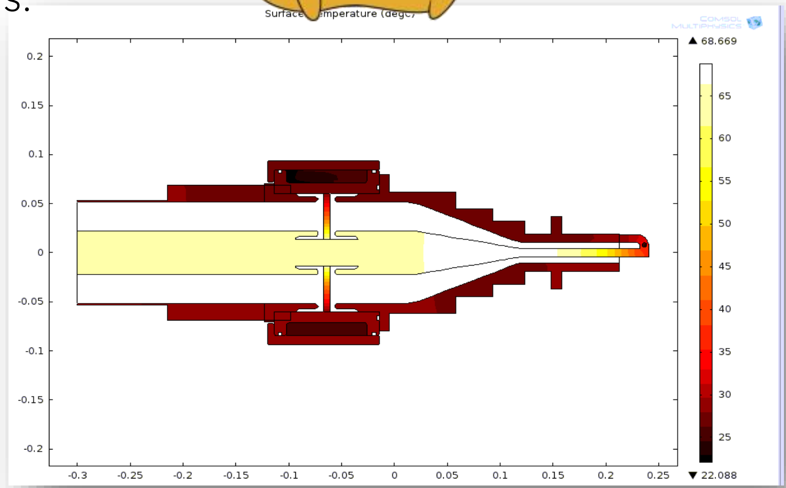
$\rightarrow$ 4-1/2" coaxial

Pikachu

- <u>Challenge:</u>
- In this power level (15kW avg.) we must have cooling for internal conductor and the loop.
- But due to the small coupler port of the RFQ which is 37.6mm and hence an internal conductor of some 9mm of diameter, it is very difficult to have cooling tubes passing through the loop.
- It is decided to develop a prototype coupler which can handle the peak power but with no cooling and with "Peek" material for window to avoid brazing complications.
- This coupler shall be called "Pikachu"!

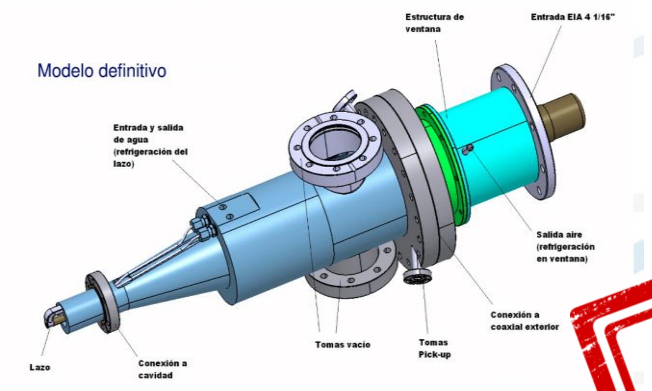


Cooling of internal conductor is difficult due to small diameter



Previous Designs

2011-2013



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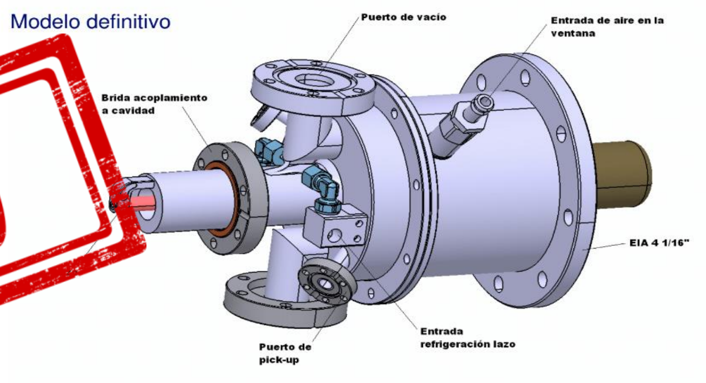
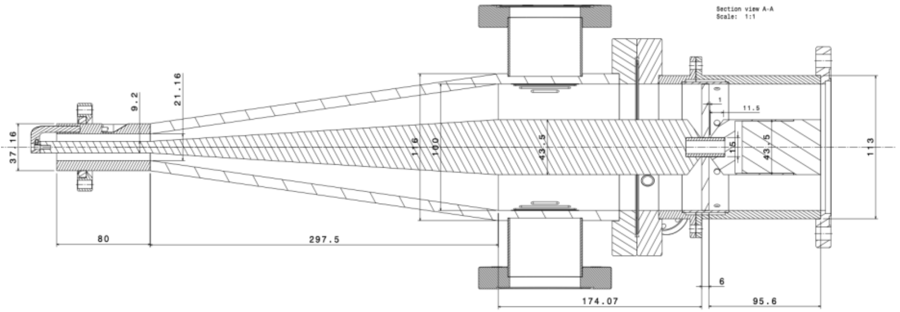
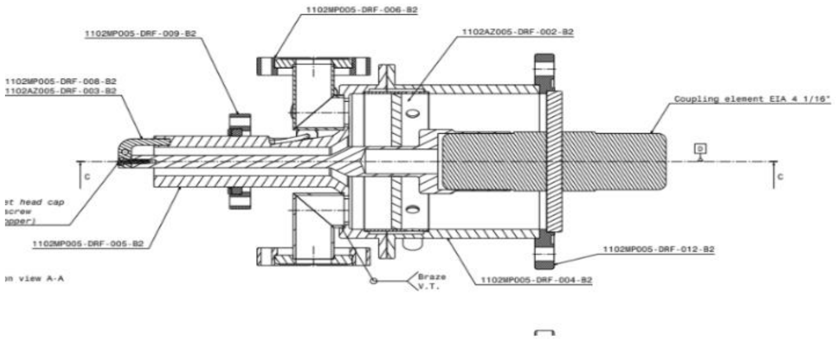


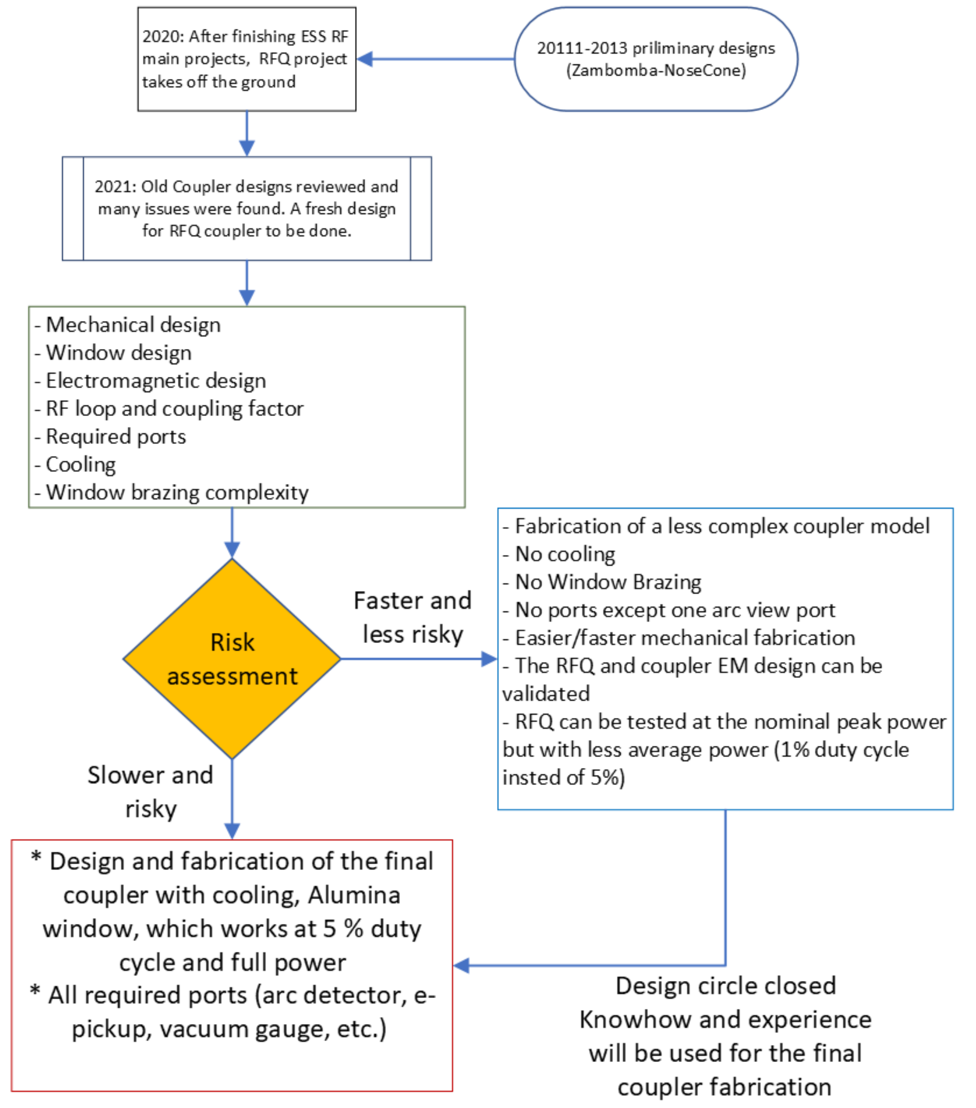
Nose-Cone

Zambomba





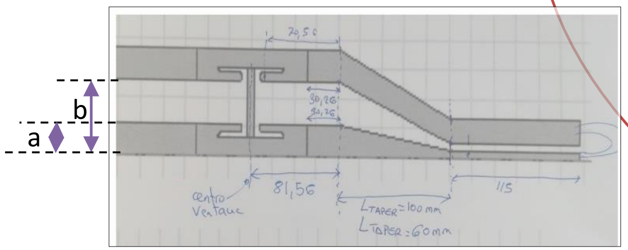
Risk Assessment — Pikachu vs. Final version

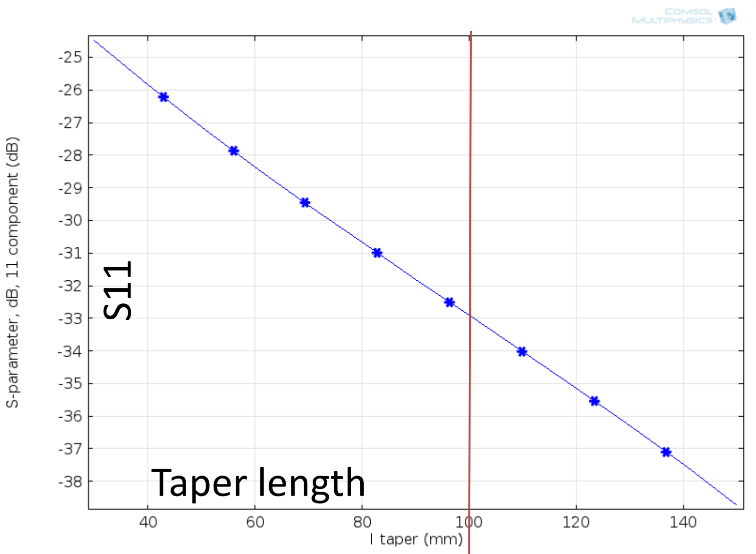


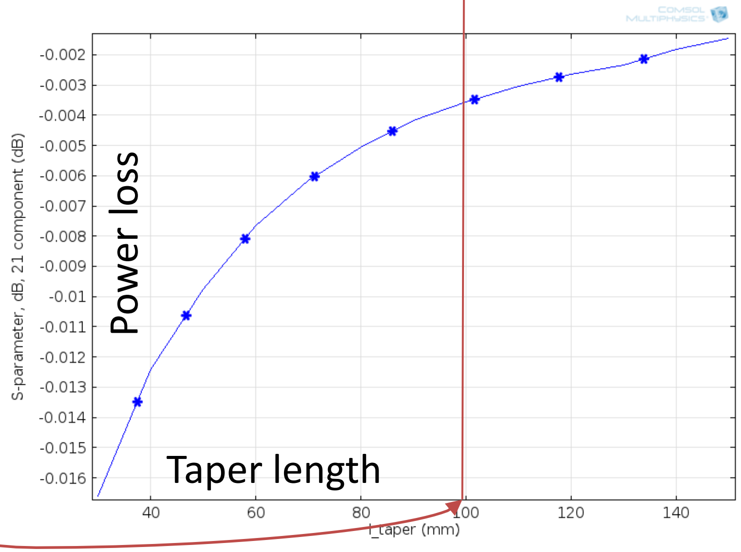
Parameter	Pikachu version	Final version
Number of couplers	2	2
Frequency of operation	352.2 MHz	352.2 MHz
Peak power (each coupler)	300 kW	300 kW
Peak voltage	85 kV	85 kV
RF Duty Cycle max.	1%	5%
Pulse width max.	1 ms	1,66 ms
Pulse repetition rate max.	10 Hz	30 Hz
Coupling type	Loop	Loop
Input flange	4-1/2" EIA	4-1/2" EIA
RFQ / test box input port	DN 40CF	DN 40CF
Arc detector ports	one port on air side	One on airside, one on vacuum side
Electron Pick-up/vacuum gauge ports	No port	CF DN 16, on vacuum side
Temperature sensor	Yes	Yes
Vacuum	10^-7 mbar	10^-7 mbar
Material	Copper	Copper
Window	PEEK material (polyetheretherketone)	Alumina HA-95 (TBC)
Cooling	No	Water for loop, air for window

Taper Section

- With the existing limitations, coupler should match a 4-1/2" coaxial to a 37.6 mm coaxial at the RFQ port, while the 50 Ω impedance is maintained:
- For a coaxial line: $Z = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\, ln\frac{b}{a} \approx 60 \cdot ln\frac{b}{a}$
- To keep the $Z = 50\Omega$ along the taper, we should have:
- $Z(z) = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\, ln\frac{b(z)}{a(z)} = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\, ln\frac{b_1+z*(b_2-b_1)/L}{a_2+z*(a_2-a_1)/L} = 50$ for all z
- Taper length is selected to be 100mm as a trade-off between mechanical limitations and return loss

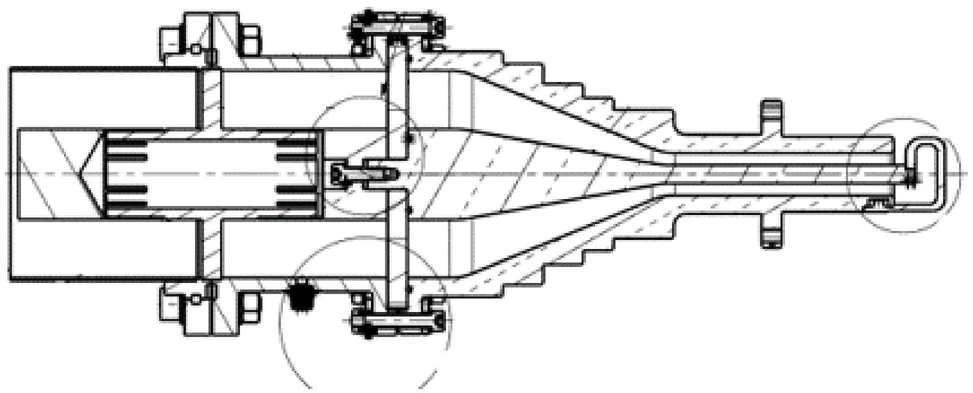


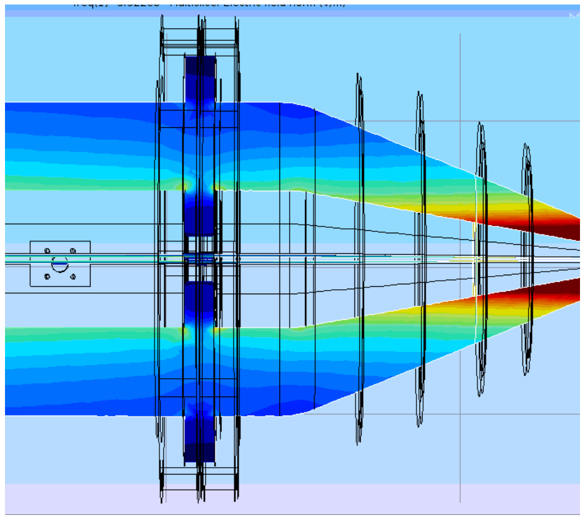




Window section

- Now that due to lack of cooling, the average power will be low, and to avoid brazing, PEEK material is chosen for the window.
- After a survey and simulation, thickness=10mm
- Simulation parameters: ϵ_r=3.2, and $tan\delta$= 0.0005
- To keep Z constant in $Z = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}ln\frac{b}{a}$ when ϵ is higher in the window area, we should either increase b or decrease a or both at the same time.





The Loop

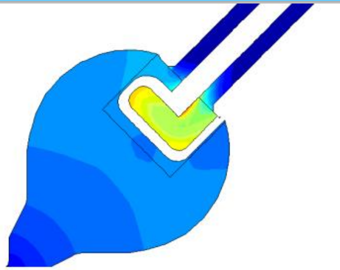
- To design the loop first we should know the required coupling factor
- The coupling factor is calculated as:

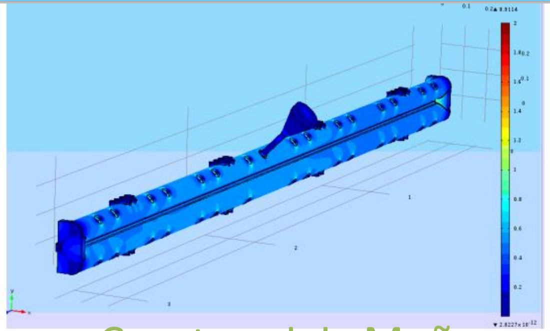
$$\beta_0 = \frac{P_{Cu}+P_{beam}}{P_{Cu}}$$

- Different scenarios:

Q_0	P_{Cu} (kW)	I_{beam} (mA)	P_{beam} (kW)	Optimum beta, β_0
10000	300	45	135	1.45
10000	300	20	60	1.2
7500	400	45	135	1.3375
7500	400	20	60	1.15

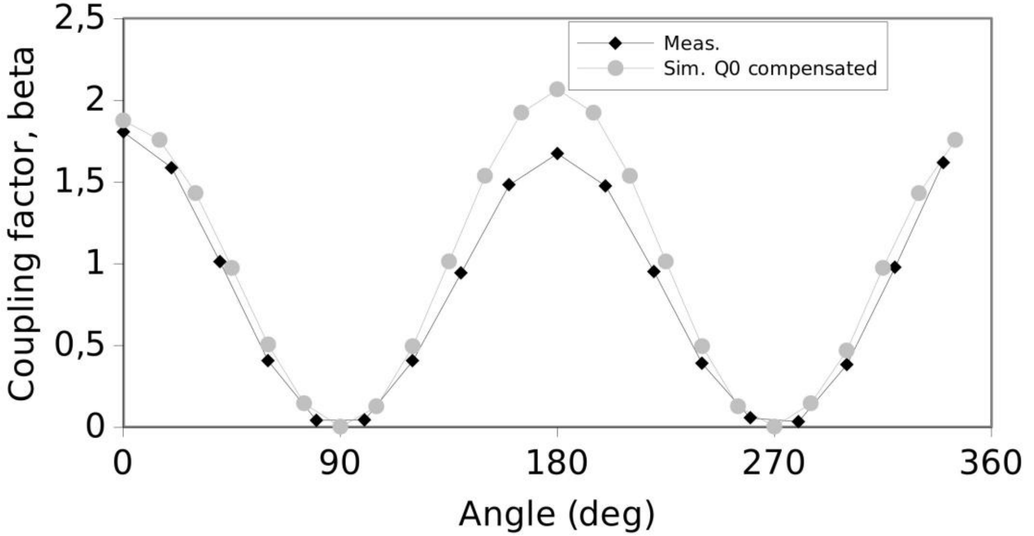
- To be on the safe side, we have maximized the loop size.
- With using Balleyguier method in simulation, the coupling factor can reach to 4, so it will support all the scenarios





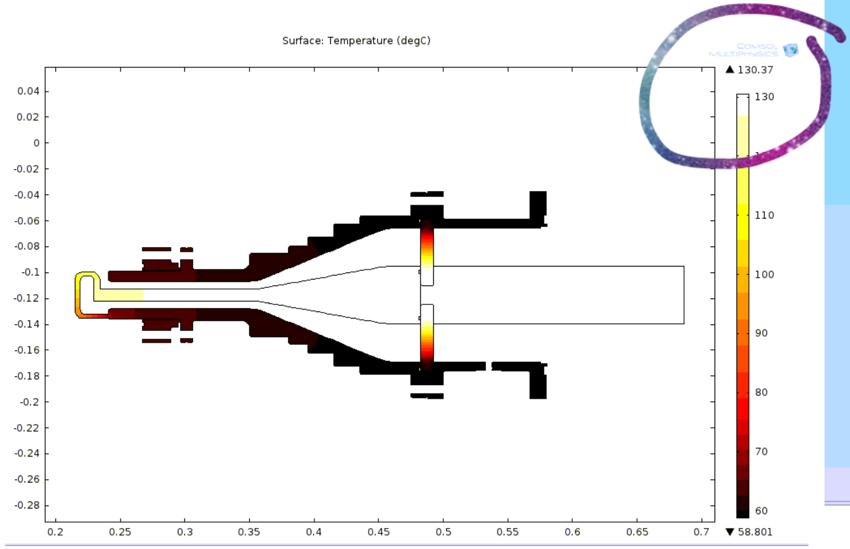
Courtesy J. L. Muñoz

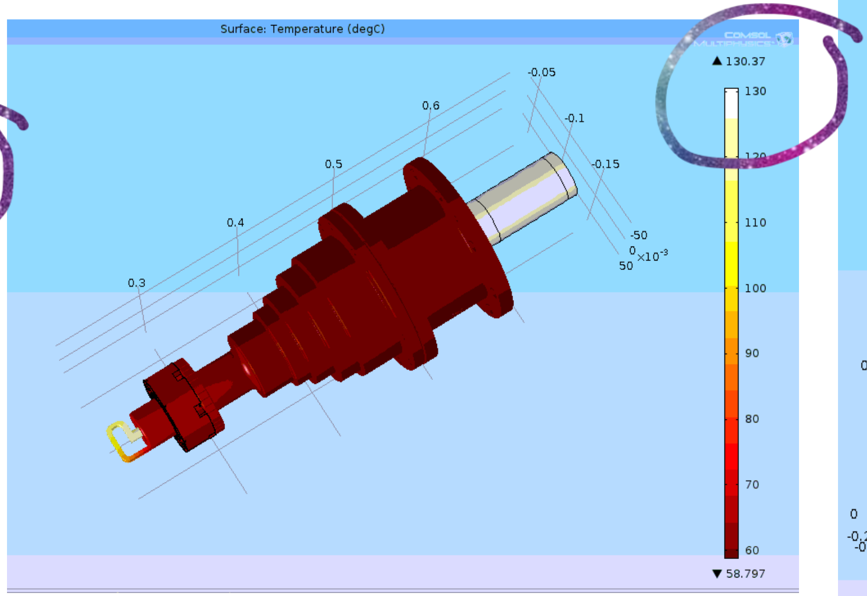
```
>> get_balleyguier_results (model)
Frequencies:
Model A (PEC), f = 351910411.467554
Model B (PMC), f = 352089774.412816
Quality factors:
Model A (PEC), Q0 = 10233.875287
Model B (PMC), Q0 = 10249.587807

Q1 = 2020.552346, Q2 = 479.518991
beta_1 = 4.093433 (A), 4.099718 (B)

ans =

  4.0934
```

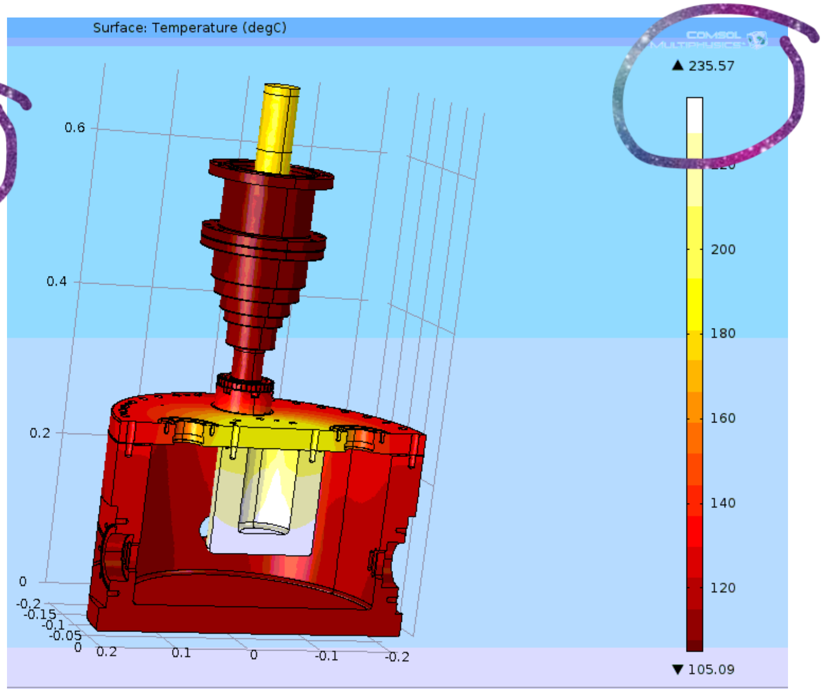


Temperature

- For 3kW average power (300kW peak power, 1% duty cycle)
- Internal conductor temperature reaches 130°C in the coupler, and up to 230°C in the test box



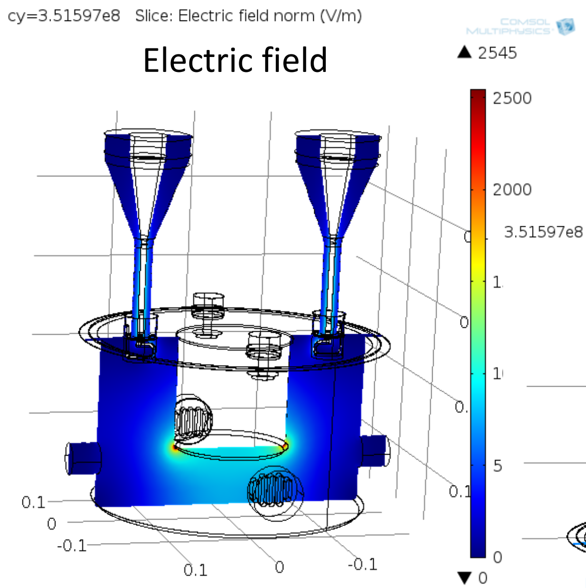


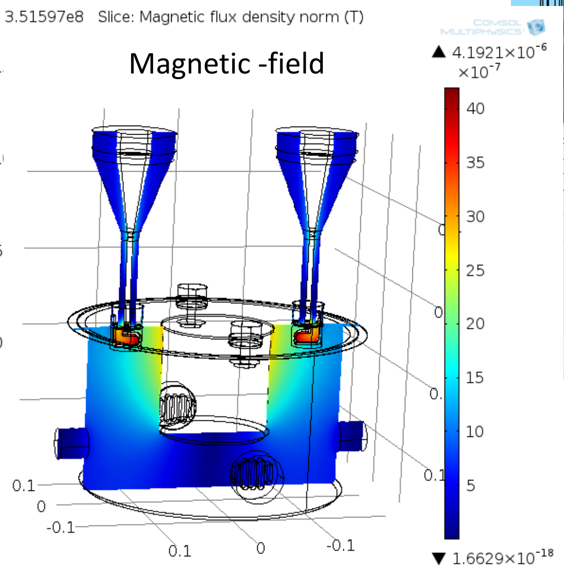


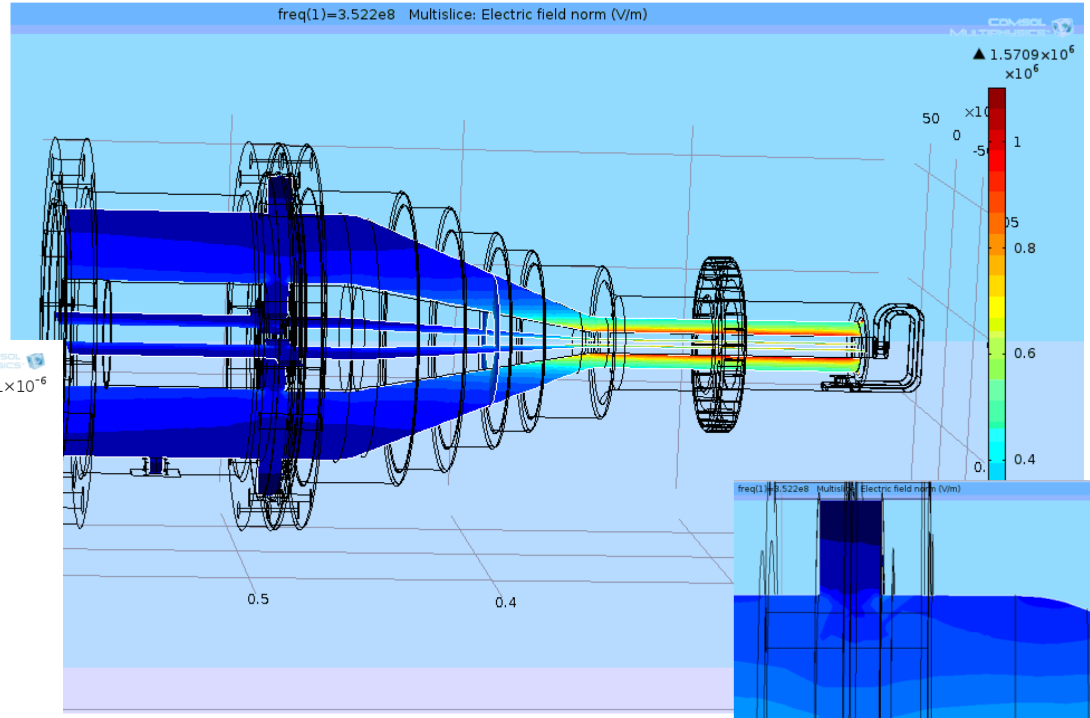
Courtesy J. L. Muñoz

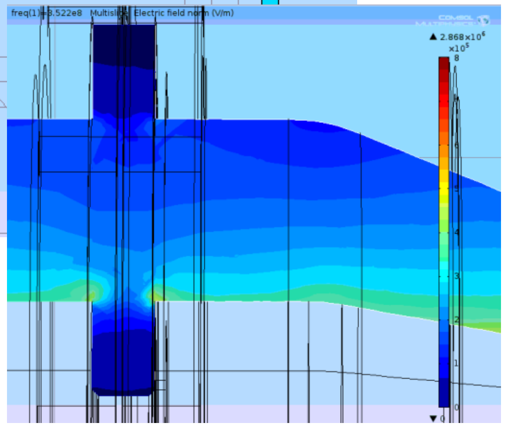
Electromagnetic Simulation

- The values of the electric field in the air and vacuum regions are well below standard limits.
- For the air region the most critical part is the PEEK window area. With a power input of 1.0 MW (4 x 250 kW), the E-field in this region is below 0.4 MV/m









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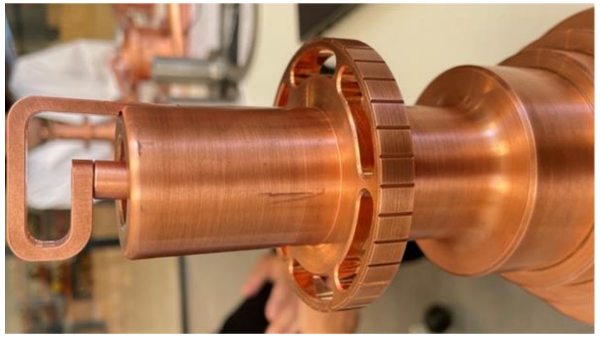
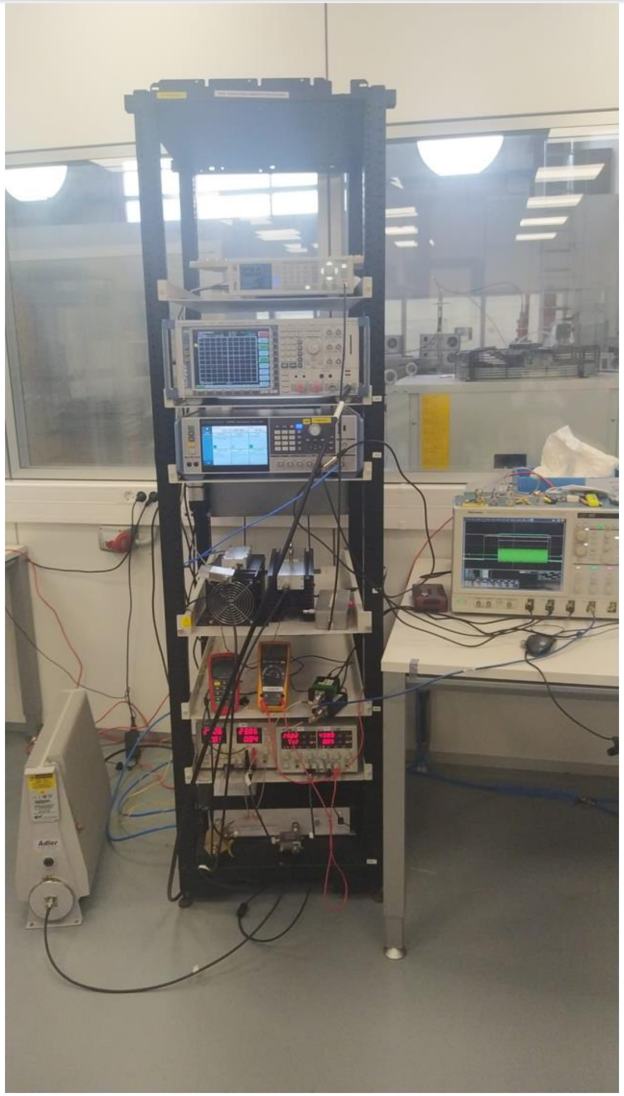
Fabrication

- Two Pikachu couplers have been fabricated
- Low power tests are in good match with the simulation results
- High power tests still pending to be done

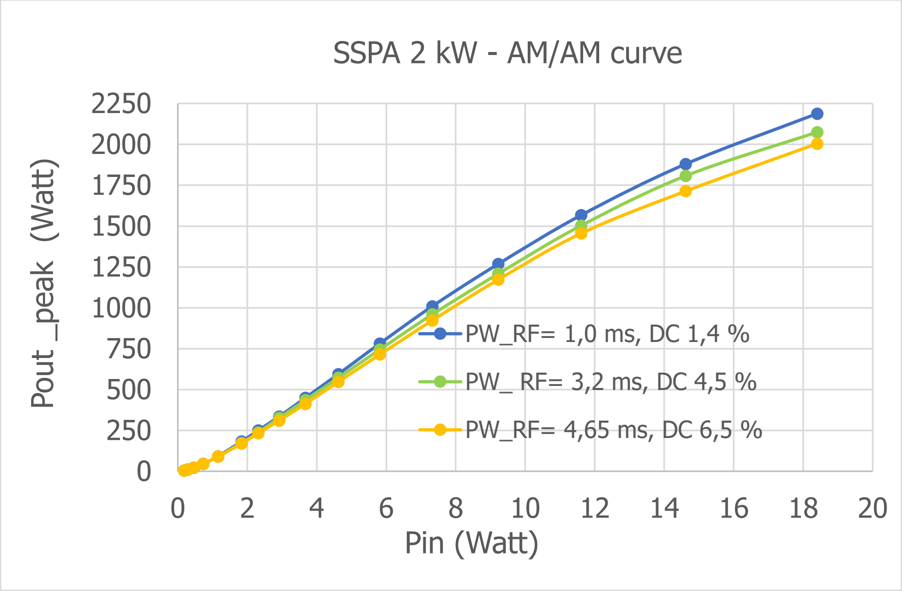


2kW Test Stand

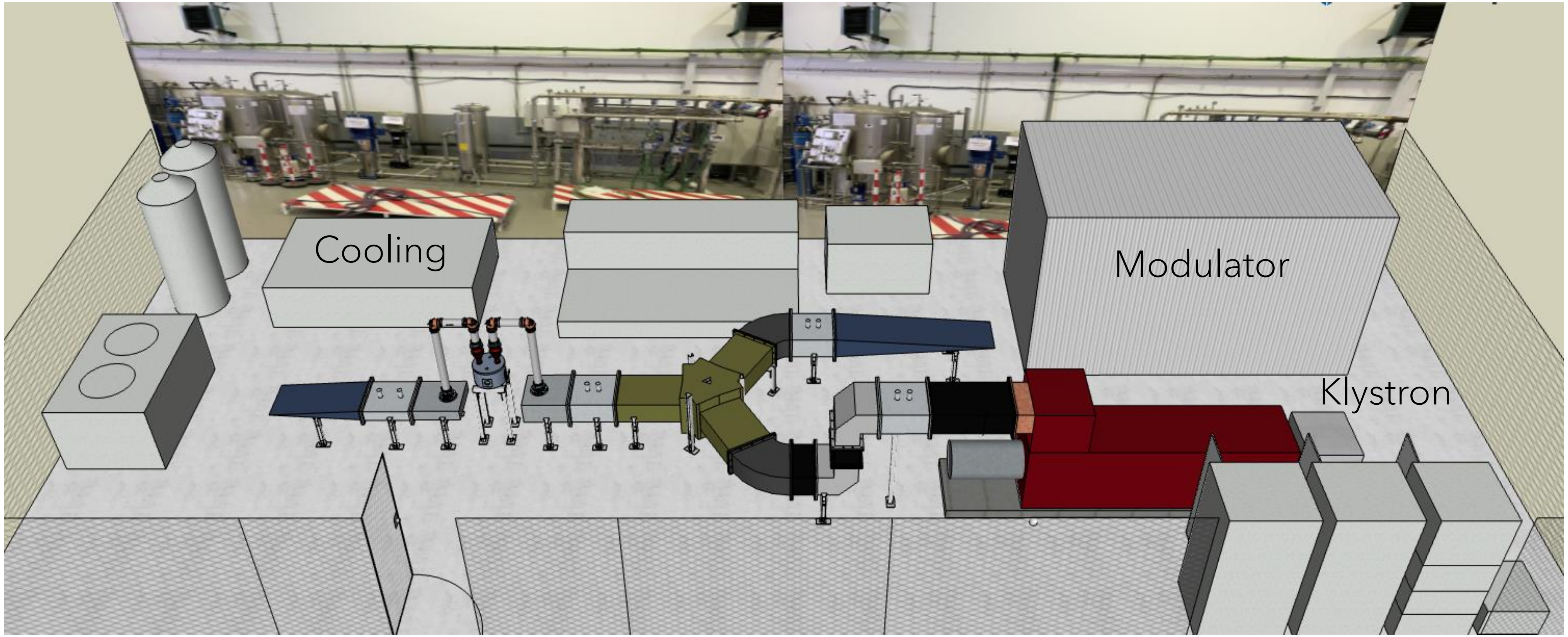


In-house developed 2kW amplifier

2 x Pikachu couplers and the test box

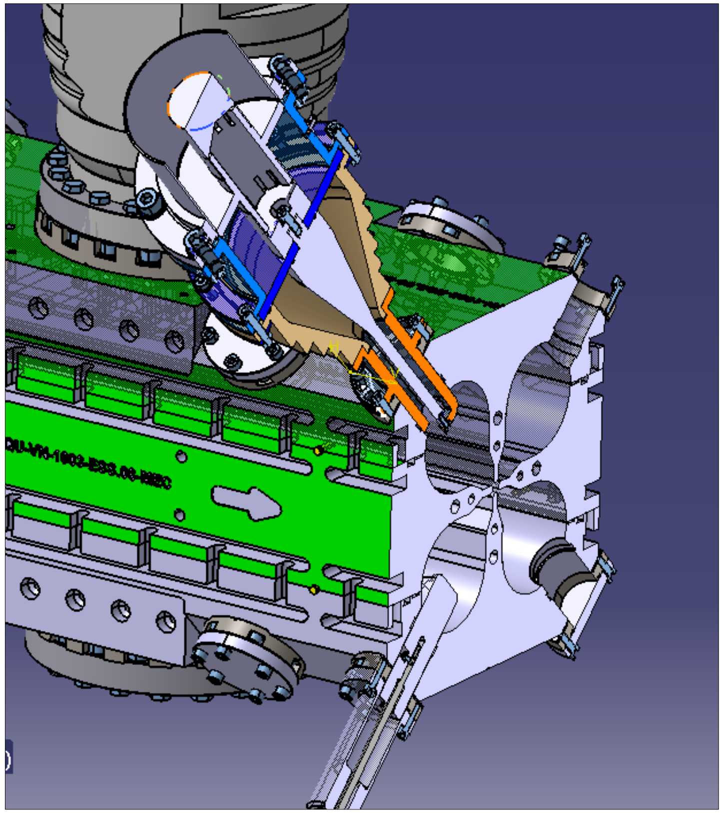


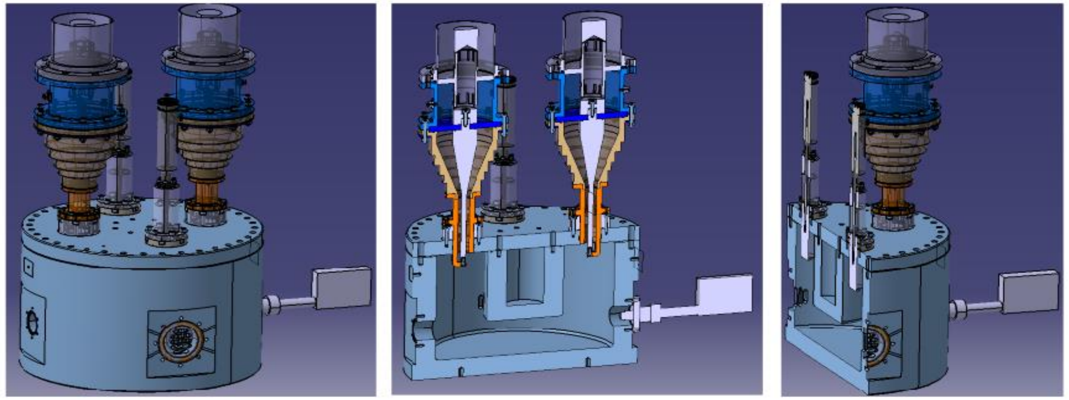
1.2MW Test Stand

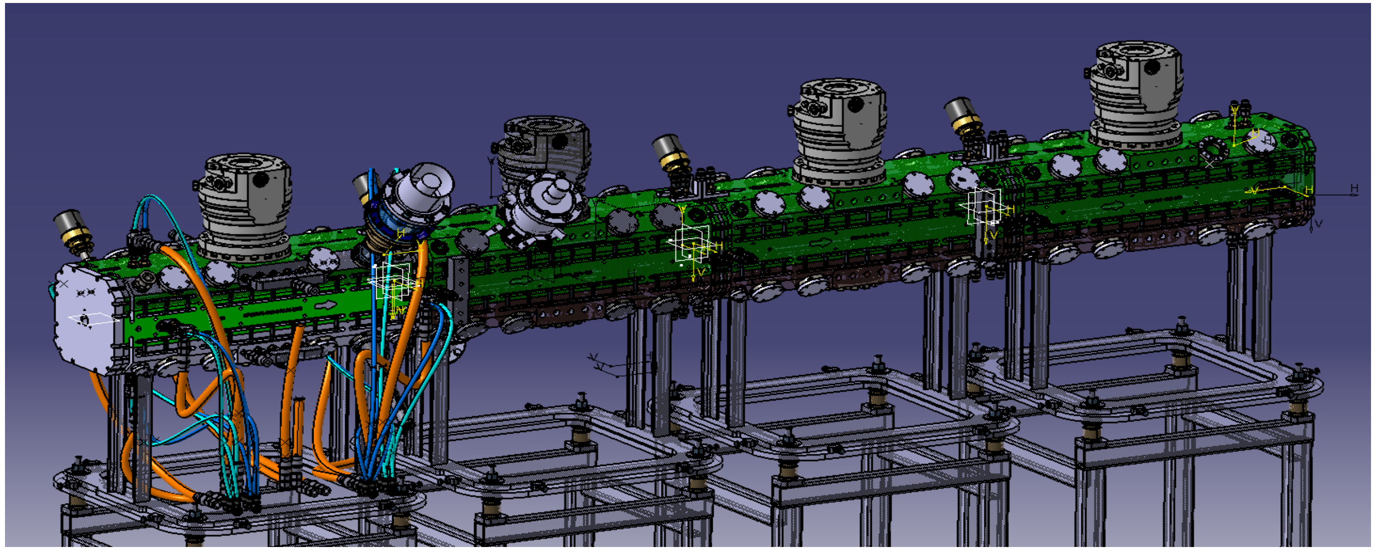


Control racks

Coupler Assembly







The Coupler Team

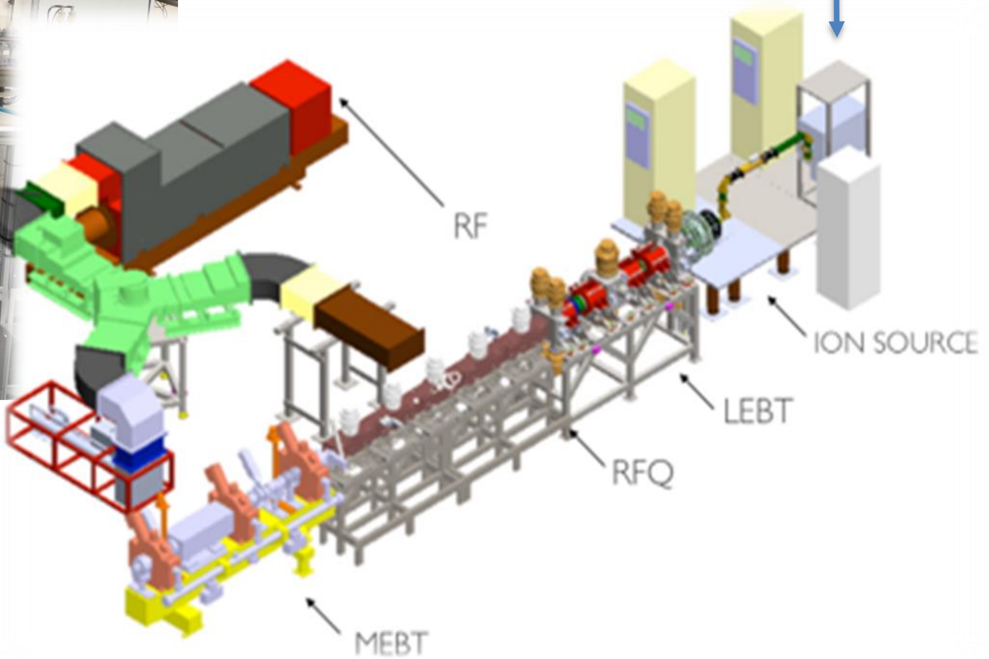
- Ibon Bustinduy
- Pedro González
- Javier Martin
- Arash Kaftoosian
- Nagore Garmendia
- Juan Luis Muñoz

SSPA for ION Source

- The plan is to replace the 1kW klystron amplifier with a SSPA for the ECR ION source

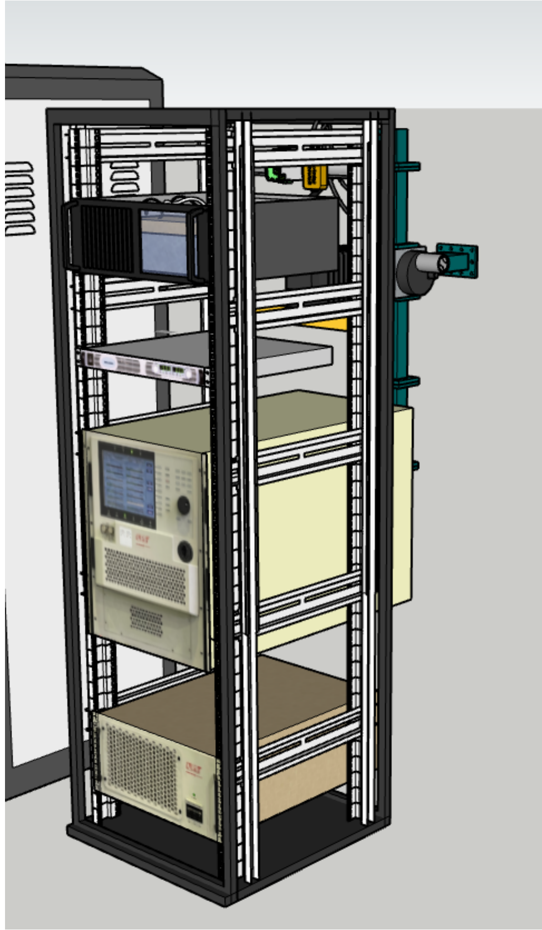
2kW CW klystron and its P.S.

2.7 GHz

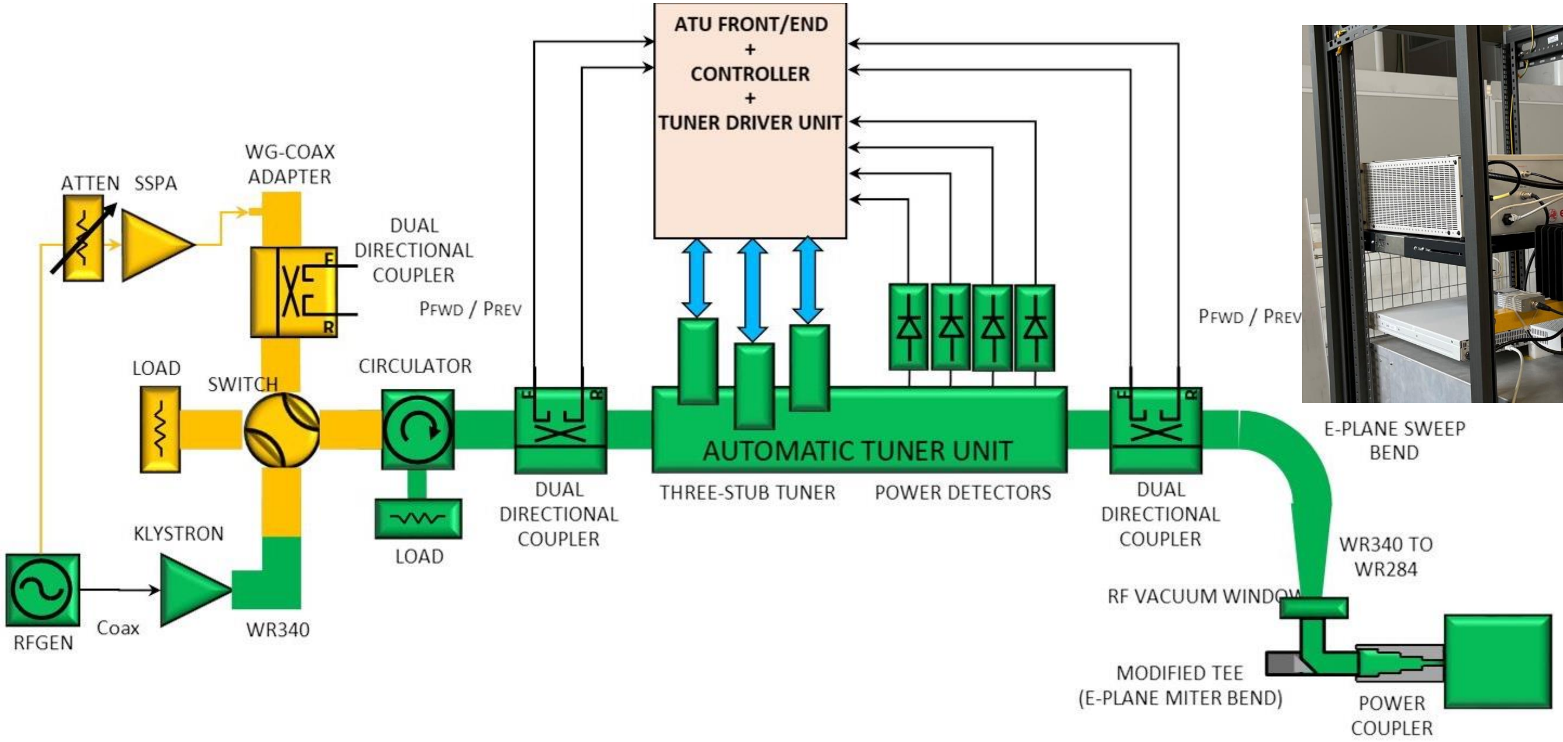


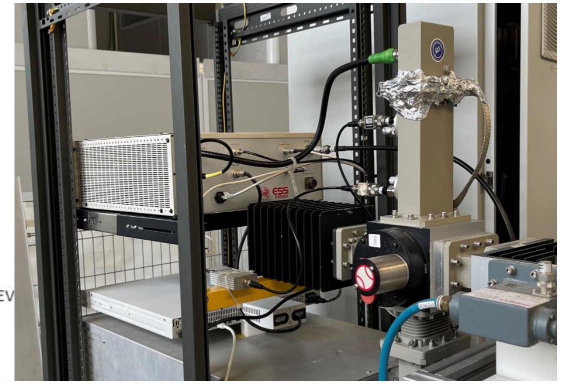
ECR ION Source Improvement

The ion source RF system is based on a commercial 2kW klystron from CPI basically for 2.7GHz satellite communication (both CW and pulsed RF). Due to its lifetime and some recent issues, it is decided to redundant the power source by adding a SSPA.



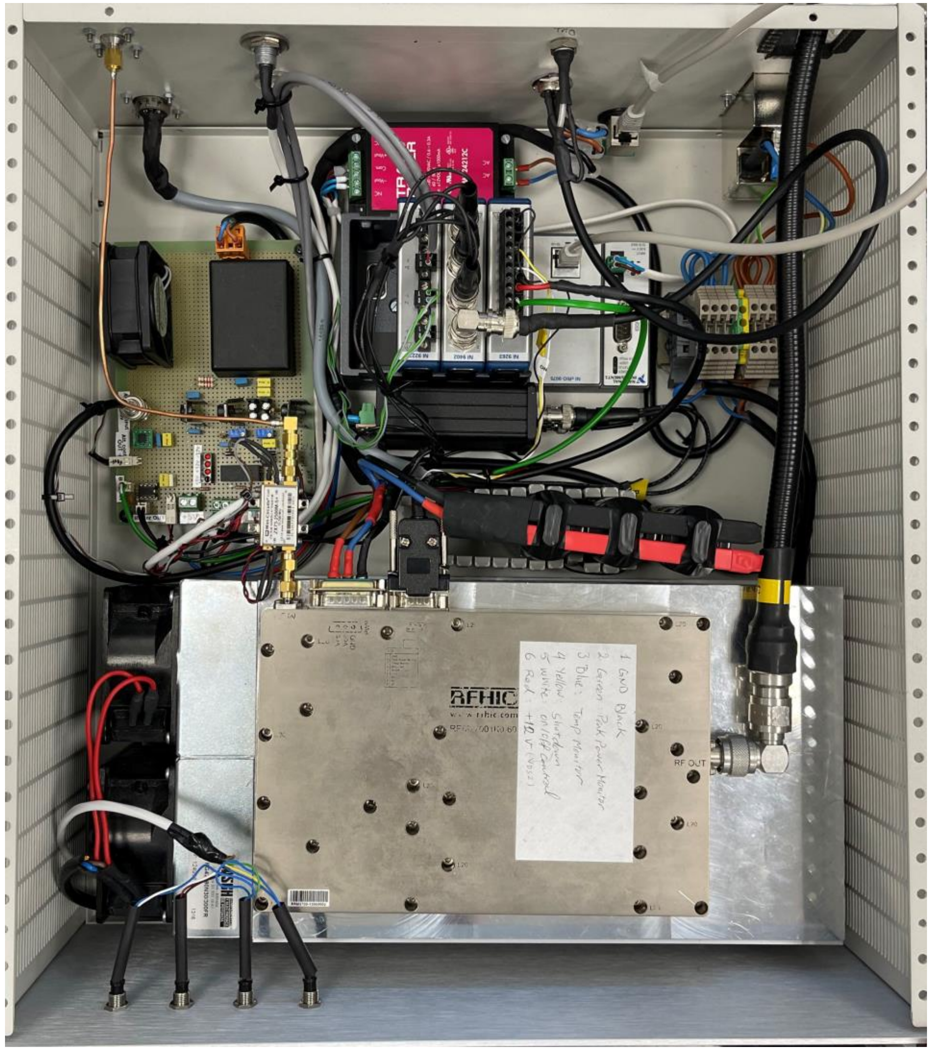
The yellow section are the added parts: SSPA, directional coupler and RF switch. With the new configuration, SSPA or klystron can be selected remotely to operate as the RF power source for plasma generation and then proton extraction.



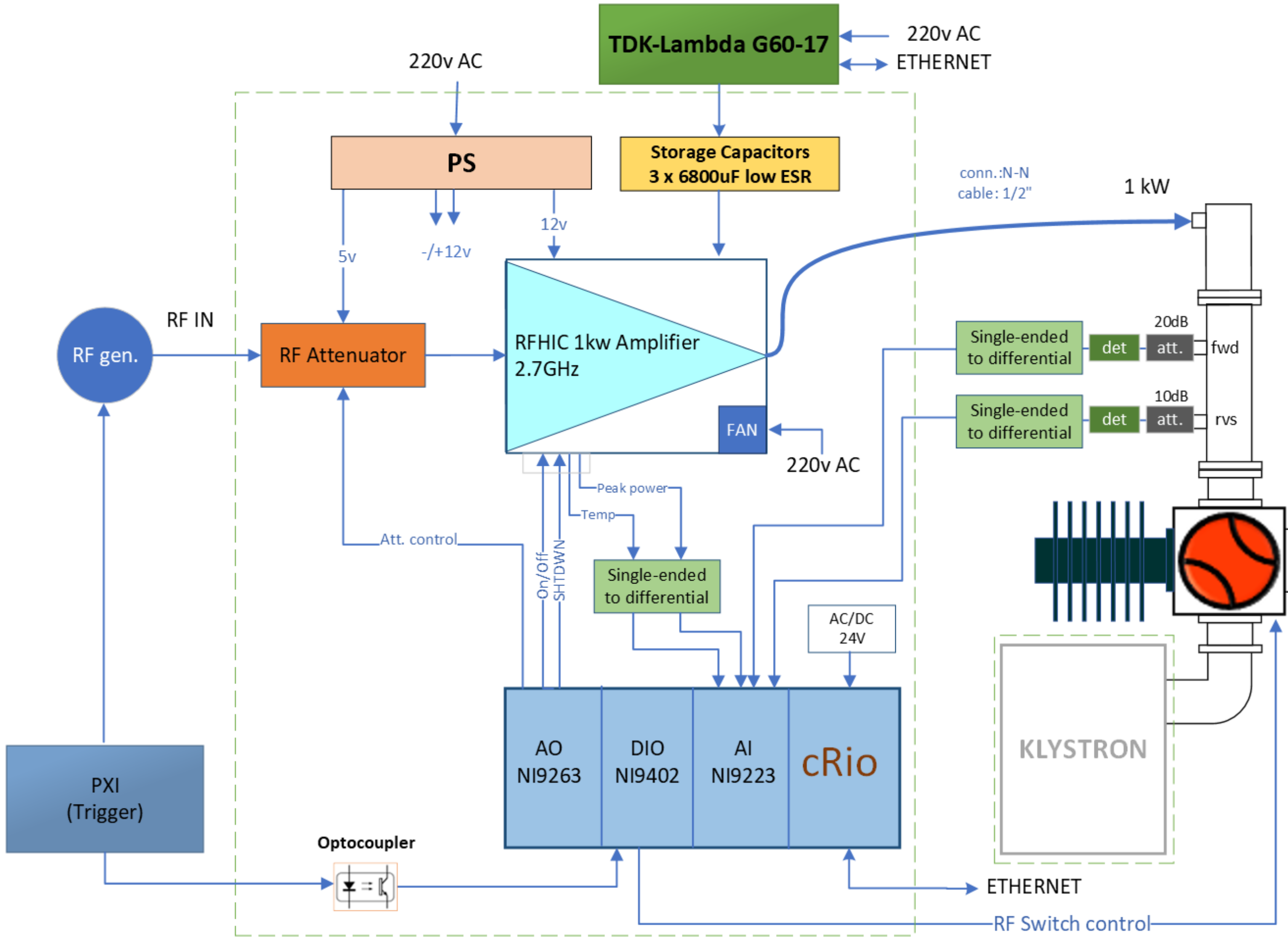


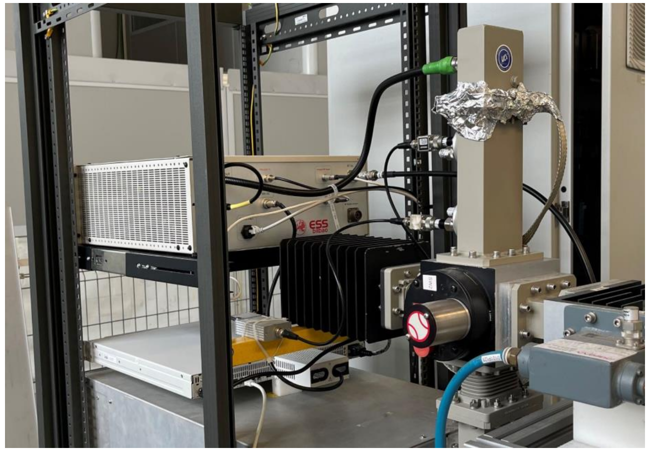
SSPA Unit

- Typical klystron limitations: limited number of manufacturers, high voltage requirement, lifetime, maintenance, etc.
- Typical Solid-State Power Amplifier (SSPA) advantages: no HV, thus more compact system, less protection required, more flexible in terms of control, modularity which allows to expand the RF power or increase reliability by redundancy. Also, longer lifetime, less running cost and better MTBF.
- This SSPA module consists of a voltage-controlled RF attenuator, a 1kW (2.7GHz) solid-state pulsed RF amplifier from RFHIC, a Compact-Rio including AO, AI and DIO modules, plus auxiliary electronics and single-ended to differential signal converters.
- SSPA control system has been developed using three main tools: LabVIEW for signal digitalization and the SSPA control; EPICS for data transfer and Python for control system execution.



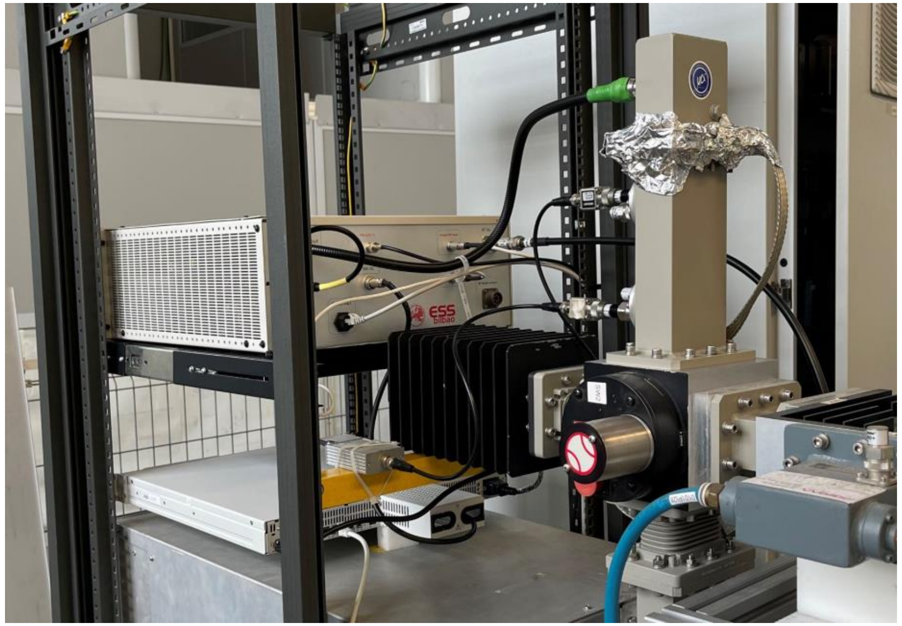
RF Source Block Diagram





Technical Specifications

Specifications	
Frequency	2.7 GHz
Bandwidth	20 MHz
Power output (max.)	1000 W
Power input (max.)	-3 dBm
Gain	63 dB
Duty cycle (max.)	10%
RF pulse (max.)	1.5 ms
Pulse droop without correction mechanism	0.5 dB
Pulse droop with correction mechanism	Flat pulse
Efficiency	35%
Rise/fall time	200 ns
Input return loss	20 dB



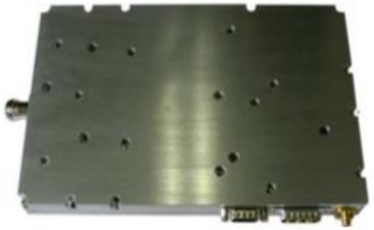
Pulse Amp Module **RRM27001K0-60** **RFHIC**

Product Features

- Frequency from 2690 ~ 2710GHz
- GaN HEMT
- 50 Ohm Input/Output impedance
- High efficiency

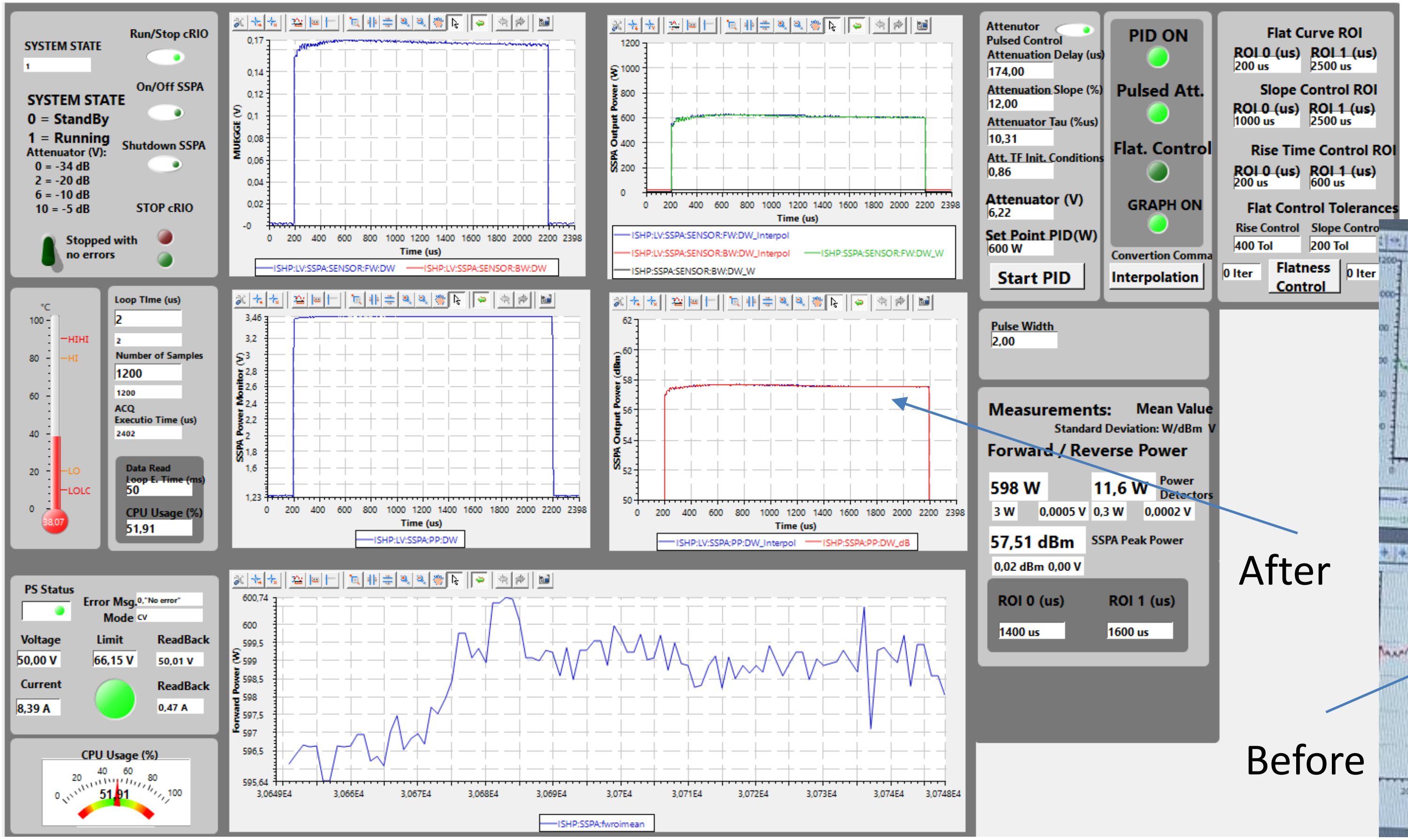
Applications

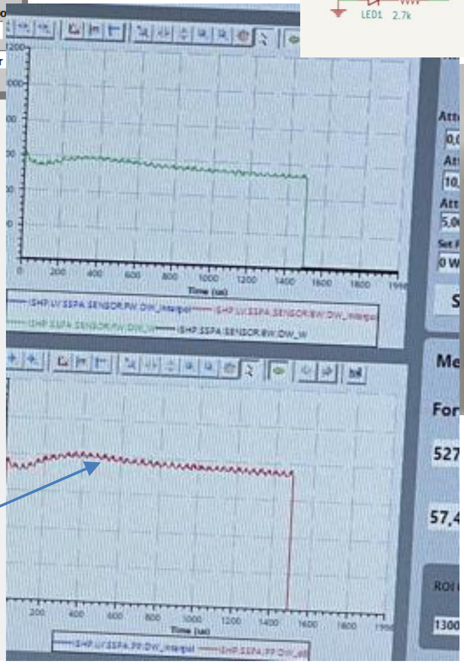
- Radar system

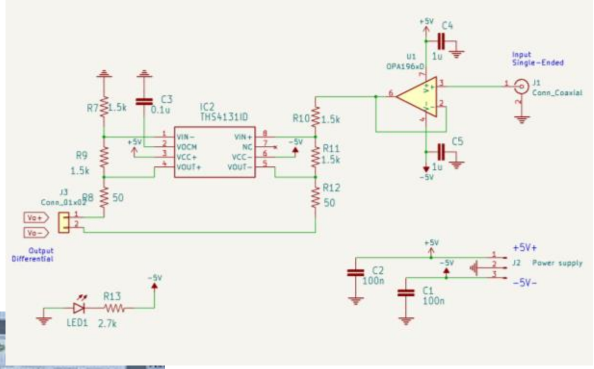


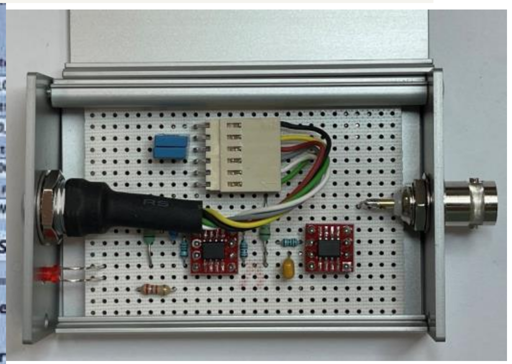
Single ended to Differential

- Using single-ended to differential circuits based on THS4131 ICs for signals going to AI modules of cRIO, improved the noise.





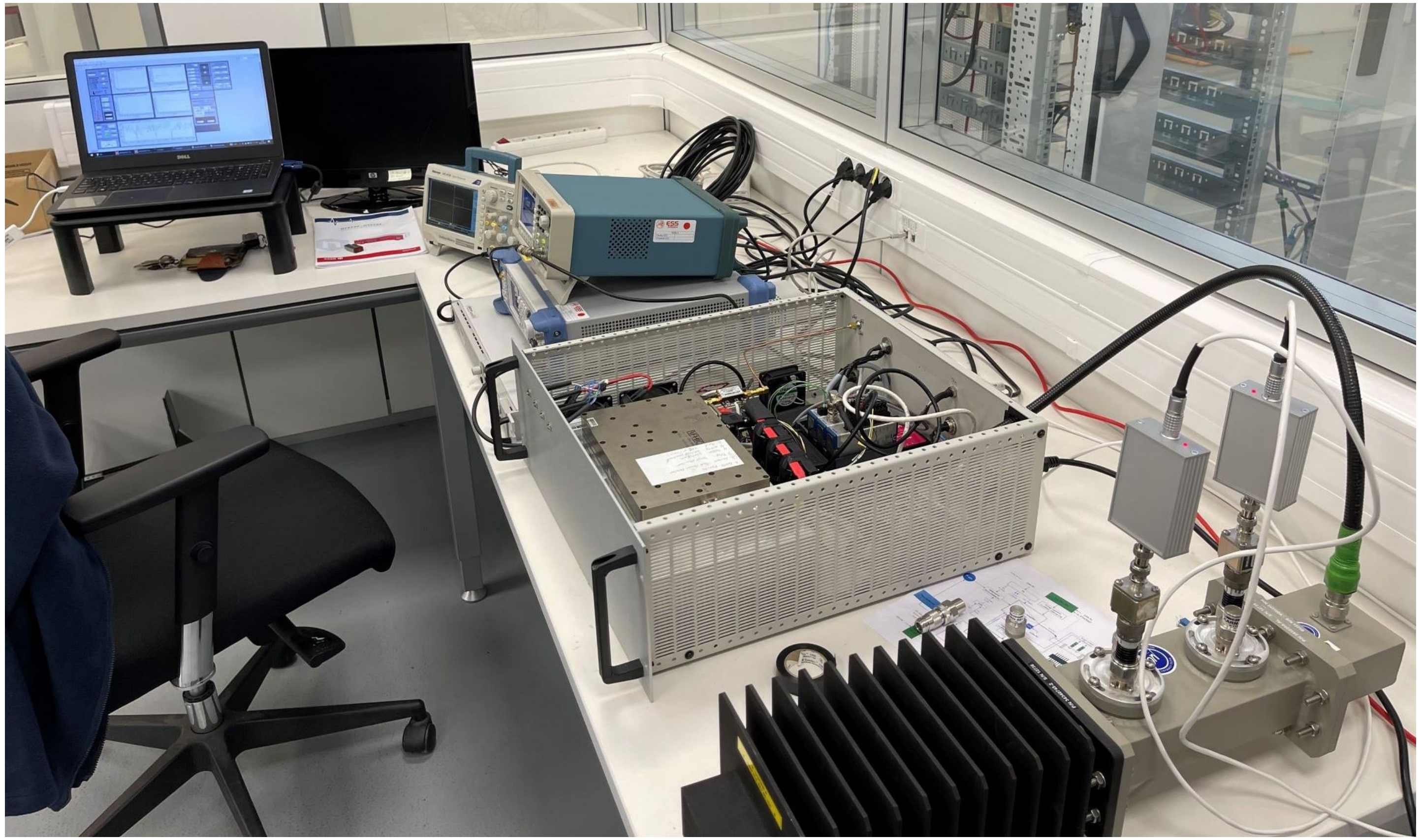




After

Before

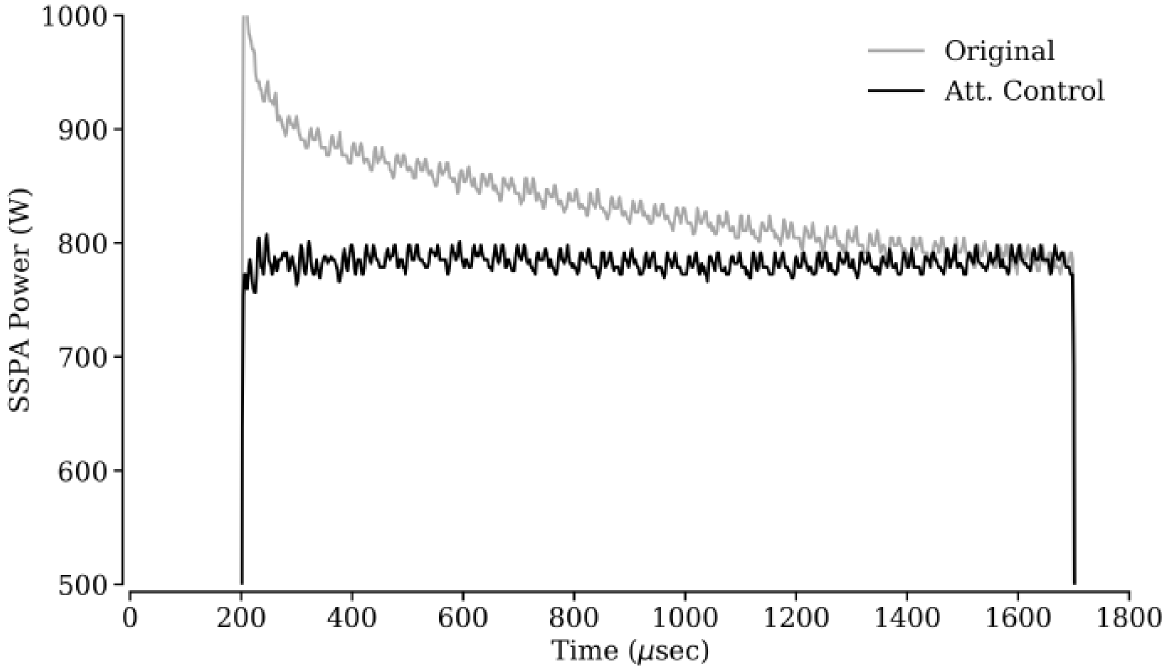
Test and Installation



Pre-Distortion

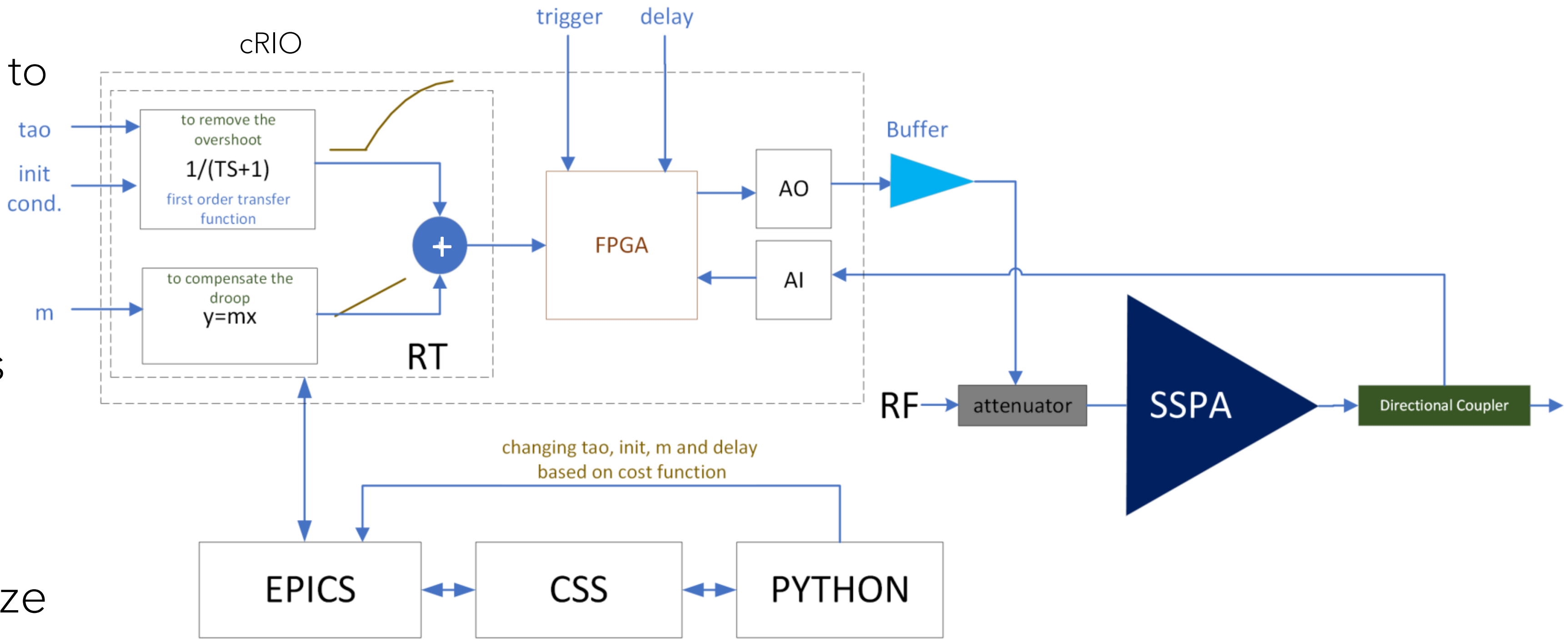
- To remove the overshoot at the beginning of the RF high power pulse and also compensate the pulse droop, a pre-distortion technique is used by controlling the input voltage-controlled attenuator. With this correction, we can have a flat RF output pulse, or any other desired pattern if required.

- In principle the AO module, with the help of RT and FPGA of the cRIO, generates a combination of basic transfer function and a slope signals to vary the attenuation value at the SSPA input, so that the high-power output pulse will be completely flat.

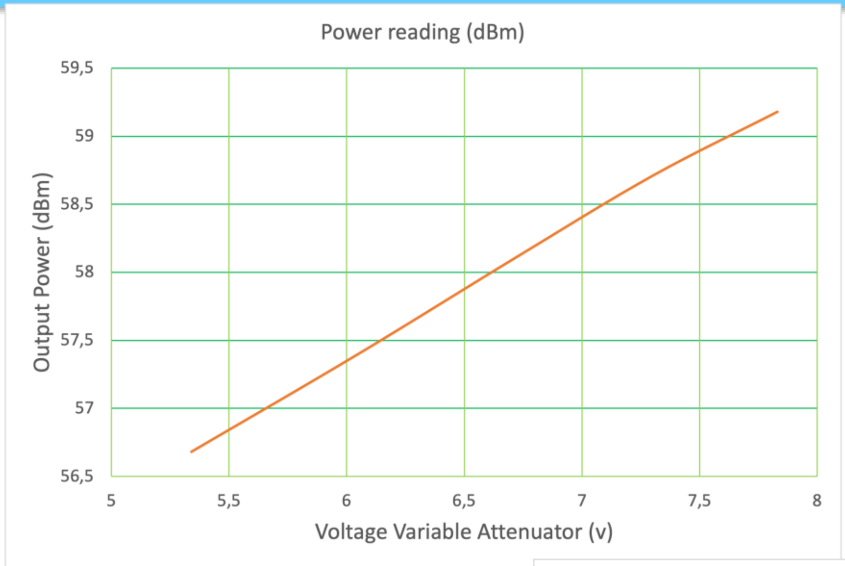


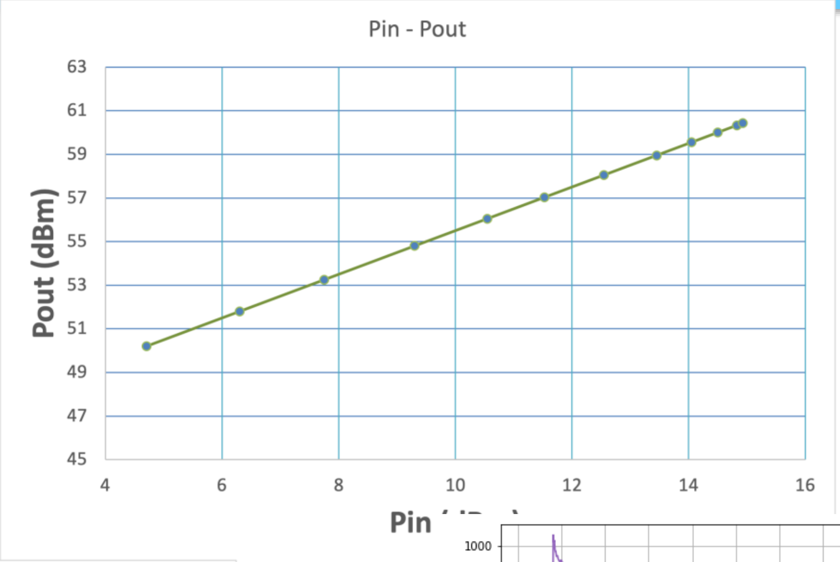
Pre-distortion Mechanism

- The pre-distortion technique consists of two parts:
  - A first order transfer function, to remove the overshoot
  - A slope generator to compensate pulse droop
- To obtain the best parameters in different RF conditions, an error feedback is made by comparing the real pulse and the ideal one and then optimize the parameters (tao, m, init. cond. and delay) in Python (Scipy.optimize/minimize)

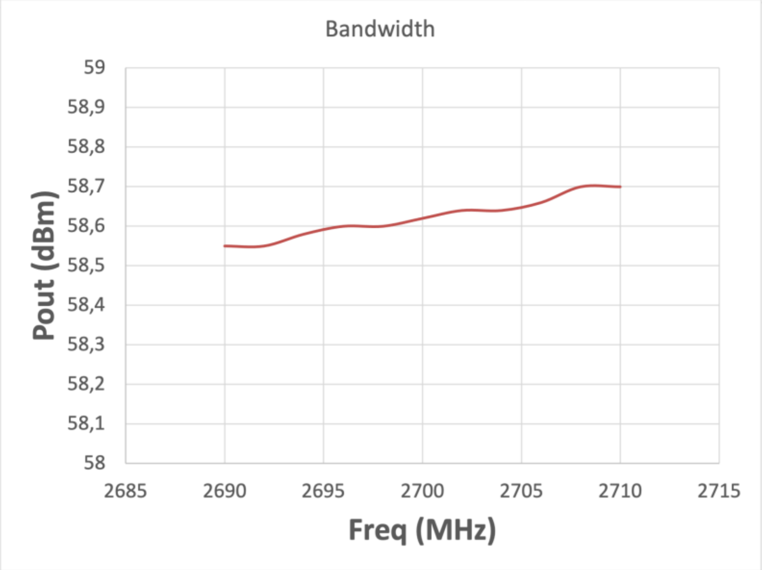


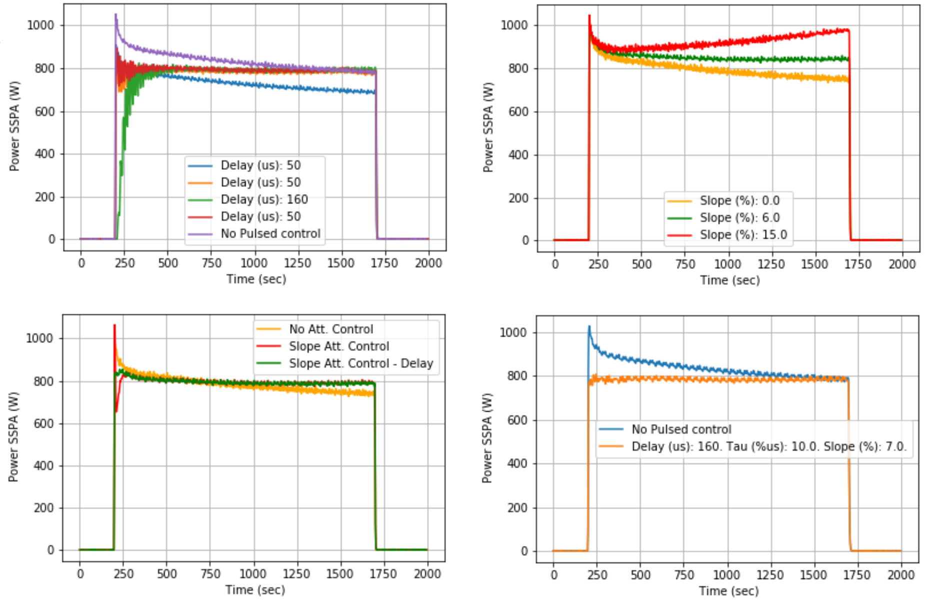
System Behaviour



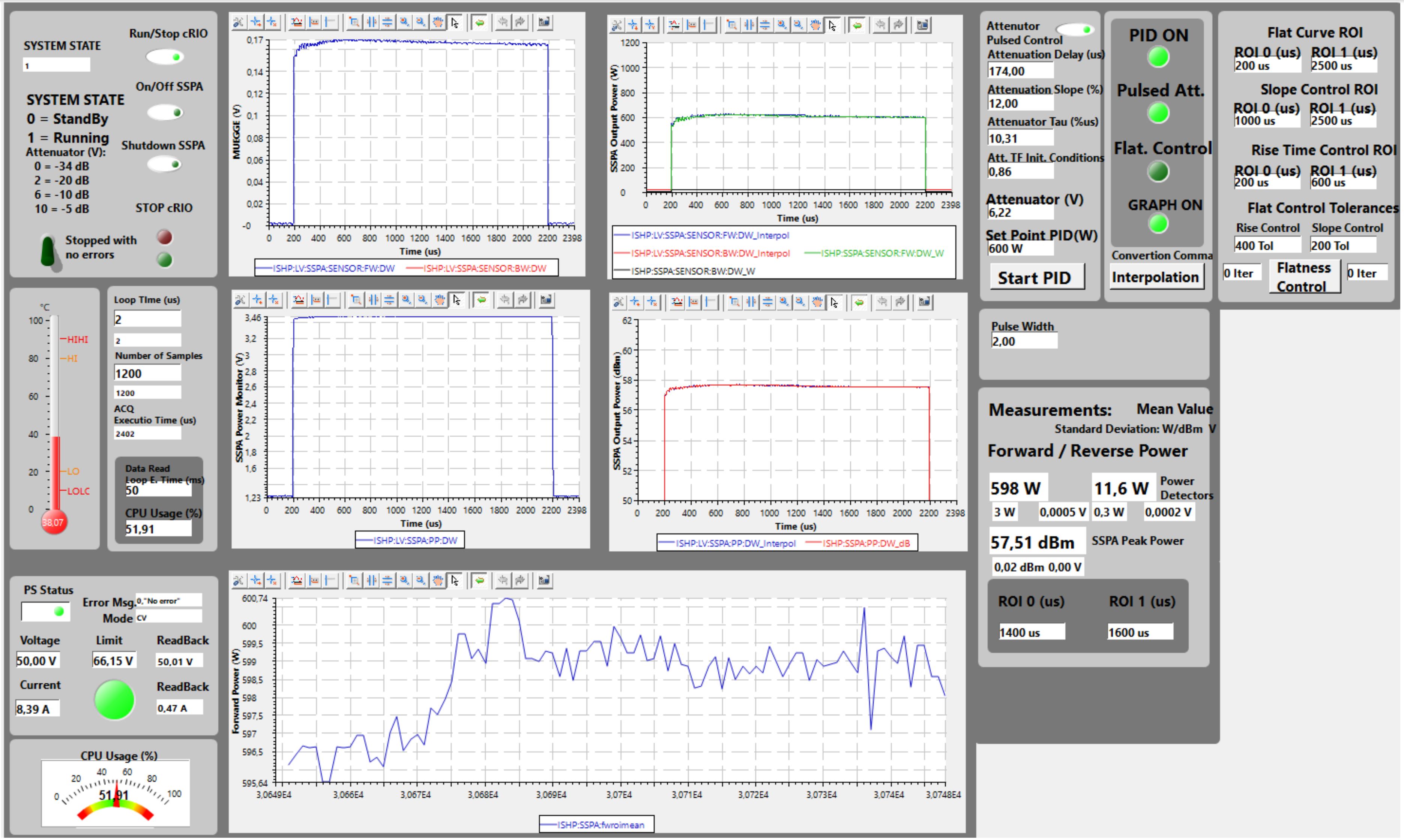


Measured Values





GUI


SYSTEM STATE
Run/Stop cRIO
On/Off SSPA
SYSTEM STATE
0 = StandBy
1 = Running
Attenuator (V):
0 = -34 dB
2 = -20 dB
6 = -10 dB
10 = -5 dB
Shutdown SSPA
STOP cRIO
Stopped with no errors
Loop Time (us)
Number of Samples
1200
ACQ Executio Time (us)
2402
Data Read Loop E. Time (ms)
50
CPU Usage (%)
51,91
HIHI
HI
LO
LOLC
38,07
Time (us)
MUEGGE (V)
SSPA Output Power (W)
SSPA Power Monitor (V)
SSPA Output Power (dBm)
Forward Power (W)
ISHP:LV:SSPA:SENSOR:FW:DW
ISHP:LV:SSPA:SENSOR:BW:DW
ISHP:LV:SSPA:SENSOR:FW:DW_Interpol
ISHP:LV:SSPA:SENSOR:BW:DW_Interpol
ISHP:SSPA:SENSOR:FW:DW_W
ISHP:SSPA:SENSOR:BW:DW_W
ISHP:LV:SSPA:PP:DW
ISHP:LV:SSPA:PP:DW_Interpol
ISHP:SSPA:PP:DW_dB
ISHP:SSPA:fwroimean
Attenutor Pulsed Control
Attenuation Delay (us)
174,00
Attenuation Slope (%)
12,00
Attenuator Tau (%us)
10,31
Att. TF Init. Conditions
0,86
Attenuator (V)
6,22
Set Point PID(W)
600 W
Start PID
PID ON
Pulsed Att.
Flat. Control
GRAPH ON
Convertion Comma
Interpolation
Flat Curve ROI
ROI 0 (us)
ROI 1 (us)
200 us
2500 us
Slope Control ROI
1000 us
2500 us
Rise Time Control ROI
200 us
600 us
Flat Control Tolerances
Rise Control
Slope Control
400 Tol
200 Tol
0 Iter
Flatness Control
0 Iter
Pulse Width
2,00
Measurements:
Mean Value
Standard Deviation: W/dBm V
Forward / Reverse Power
598 W
11,6 W
Power Detectors
3 W
0,0005 V
0,3 W
0,0002 V
57,51 dBm
SSPA Peak Power
0,02 dBm 0,00 V
ROI 0 (us)
ROI 1 (us)
1400 us
1600 us
PS Status
Error Msg.
Mode
CV
Voltage
Limit
ReadBack
50,00 V
66,15 V
50,01 V
Current
ReadBack
8,39 A
0,47 A
CPU Usage (%)
51,91

Summary

- ARGITU is a European project to develop a high-intensity accelerator-driven compact multi-purpose neutron sources (HICANS)
- A 352MHz 3MeV RFQ and two power couplers are under development at ESS-Bilbao. Two lower average-power couplers are ready for high power tests on the test box.
- A 1kW 2.7GHz RF system with ability of providing flat-top RF pulse to feed plasma cavity in the ECR proton source successfully developed and tested at ESS-Bilbao
- Spanish contribution to ESS: Complete MEBT section + RF systems for warm linac of ESS and the Target development are in their final phases. MIRACLES beamline is ongoing.
- A project to generate and amplify a sawtooth signal for multi-harmonics cavity in HIE-ISOLDE of CERN along with its LLRF control system is ongoing at ESS-Bilbao.
- The Emittance Meter Unit (EMU) project (Conceptual Design, Control, Electronics and Integration) for MYRRHA recently delivered to SCK-CEN (Belgian Nuclear Research Centre)

THANK YOU!