Status and efficiency of the 400 kW Solid-State Power Amplifier at 352 MHz for the European Spallation Source (ESS)

PRESENTED BY BRUNO LAGOGUEZ ON BEHALF OF THE PROJECT TEAM

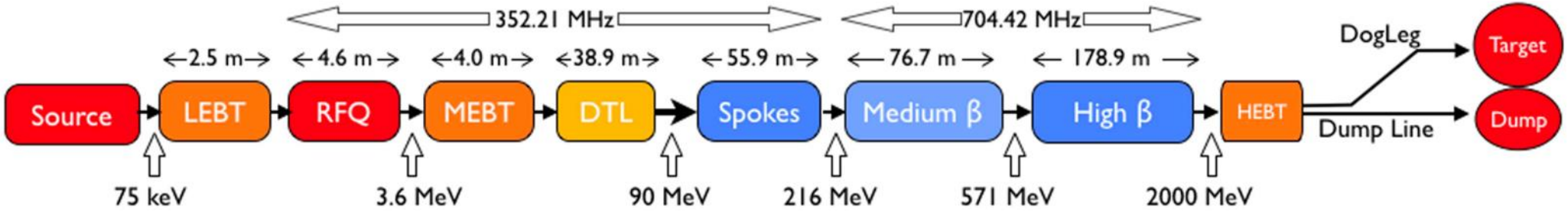
2024-09-25

Agenda

1. Background and Project Motivation
2. Technical Background
3. Planning and Direction
4. Efficiency consideration
5. Work in Progress and Summary

Background and Project Motivation

Background and Project Motivation



Spoke Power Stations

- 26 Stations in total
- 52 high power, high frequency tetrodes

- Power stations have suffered with a variety of reliability and technical challenges

- Many technical challenges have been resolved however the use of tetrodes, with a single supplier, is still considered a significant risk

Risk reduction

ESS initially picked klystrons as an alternative however this was changed to SSPA technology

Key motivators:

- New klystron development needed
- Risk of single supplier
- Power and frequency is in range of SSPA

- Review of commercial (technical and cost), in house development and continuation of Uppsala development carried out

ESS SSPA station goals:

High Level Goals:
Build on and extend technical solution developed at Uppsala
Cost effective (< 3 EUR/W)
Designed for high availability
Achieve a scalable design for high volume production

Key Technical Goals
400 kW capable for ESS pulse parameters
Designed to be a plug compatible with existing Spoke power stations
Compatible with exiting footprint and support structures.

Uppsala University

- Uppsala has worked on SSPA technology development for approx. 10 years.
- Received funding for part of the hardware of the first 400 kW unit.

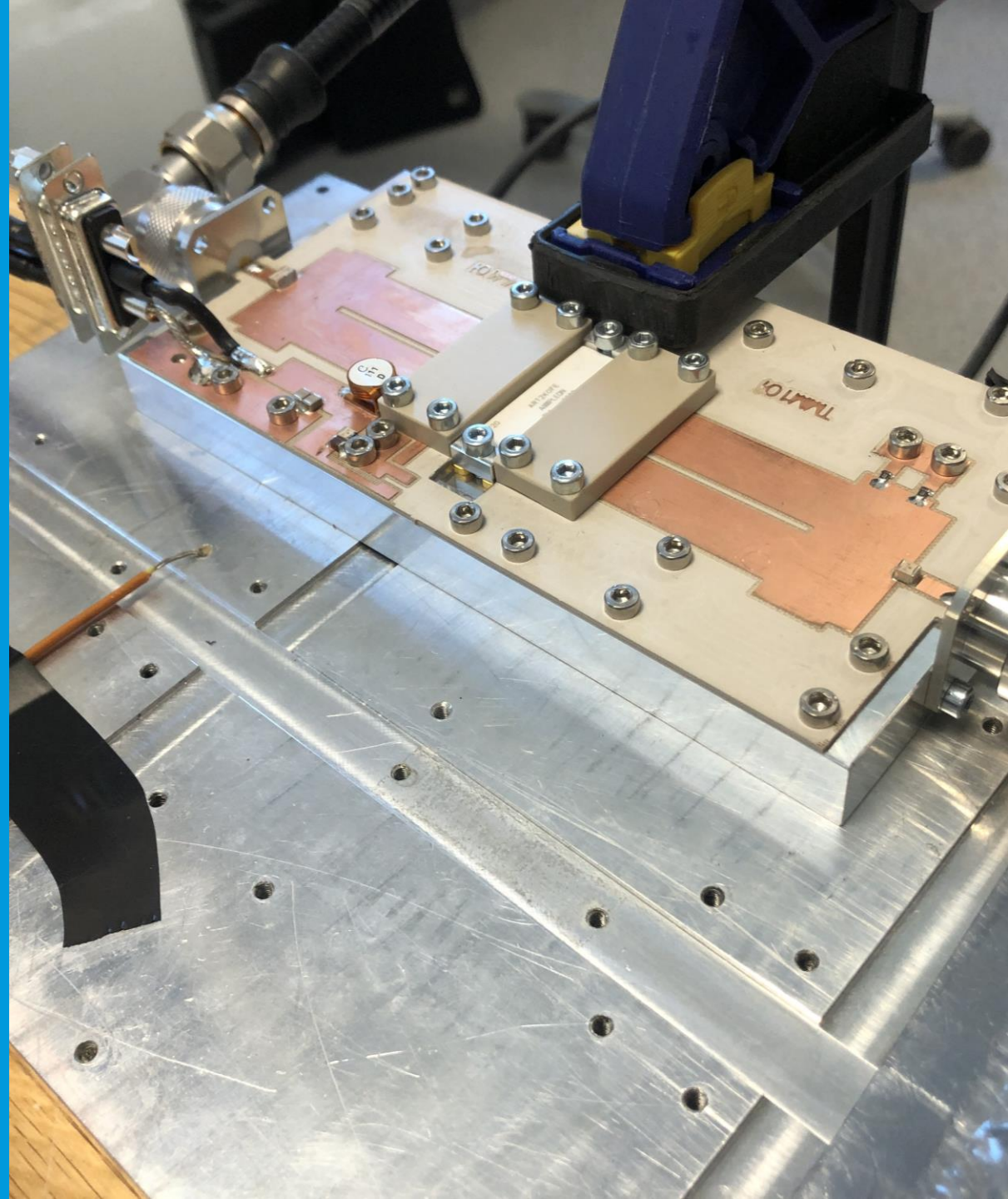
ESS Approved funding for Technology Demonstrator

- Project timeline 2 years

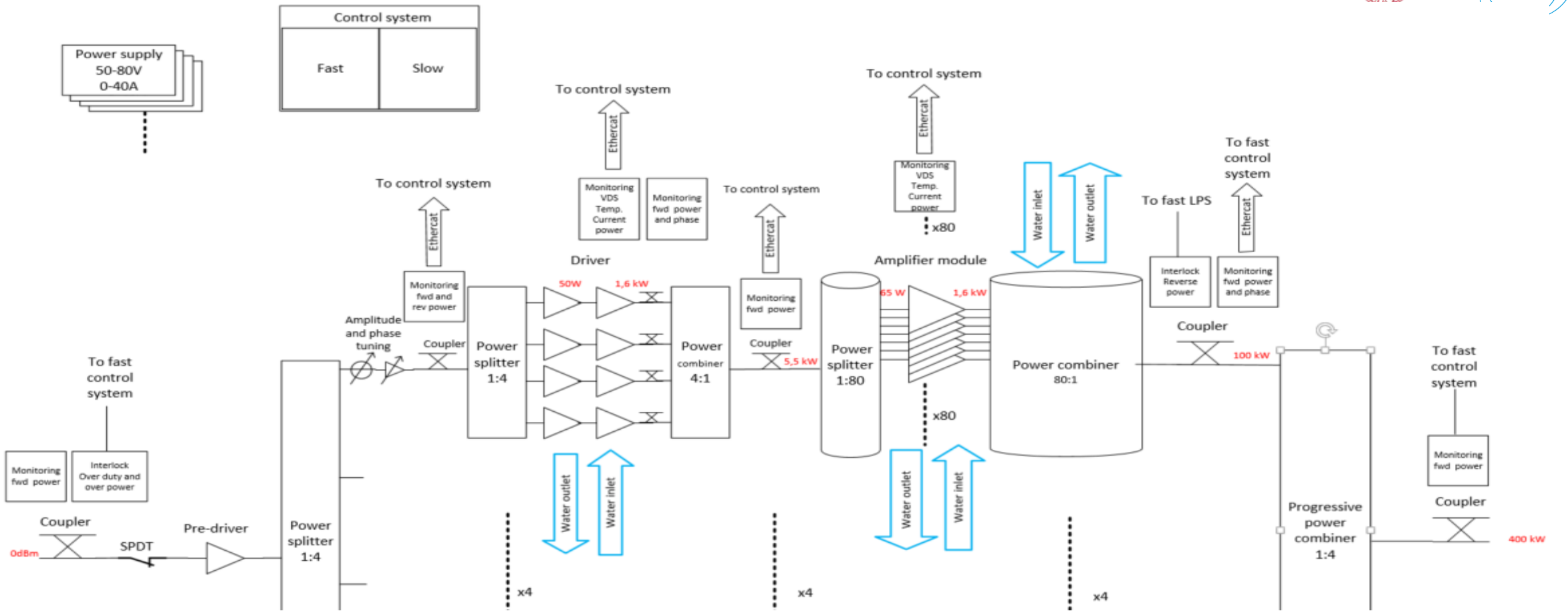
Key Specifications

Operating frequency	352.21 MHz
-1 dB bandwidth	≥ ±1 MHz
Peak output power, Max.	400 kW
RF pulse width	Up to 3.5 ms
Minimum RF Pulse Width	140 µs
Repetition rate	Up to 14 Hz
Gain	≥ 88 dB
Nominal RF Drive	-2 dBm
Harmonic content	< -30 dBc
Spurious and sideband in ± 20 MHz	< -60 dBc
Input/output impedance	50 Ω
Input VSWR	≤ 1.2:1
Load max RL	-26 dB
Gain flatness	ΔG ≤ ±2 dB
Phase flatness	≤ 15°(over 10dB dynamic)

Technical Background



Architecture



Driver Stage

- Pre-driver 4:1
- 4:1 Splitter
- Amp and Phase tuning
- 4:1 Splitter
- Dual stage driver
- 4:1 Combiner

100 kW Stage

- HP Amplifier modules
- 80:1 Splitter
- 80:1 Splitter
- 100 kW Output

400 kW Stage

- 4:1 HP Combiner
- 400 kW Output

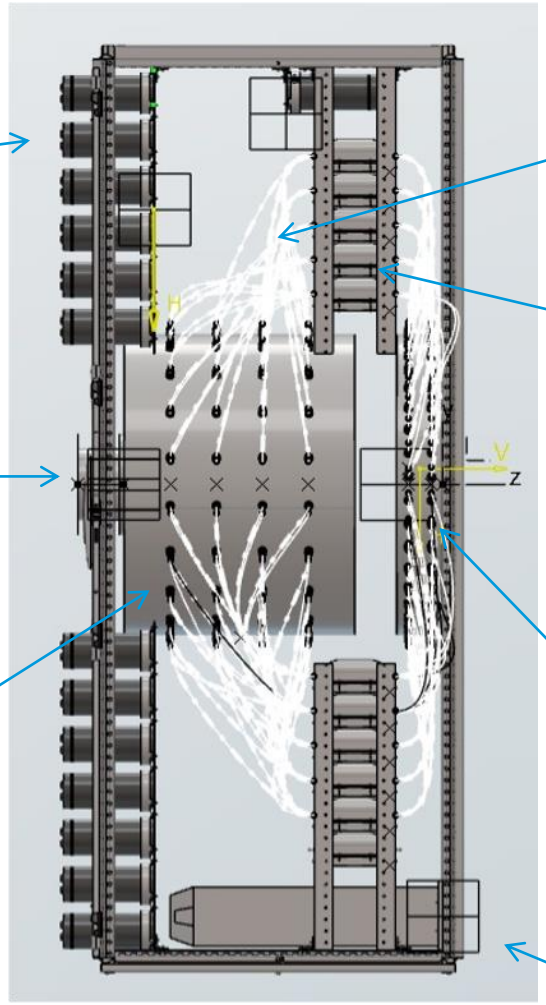
SSPA: 400 kW Station at 352 MHz

distributed capacitor bank for 10% DC

6-1/8" Coaxial cable

100 kW RF output

Cavity Combiner 64:1 (now 80:1)



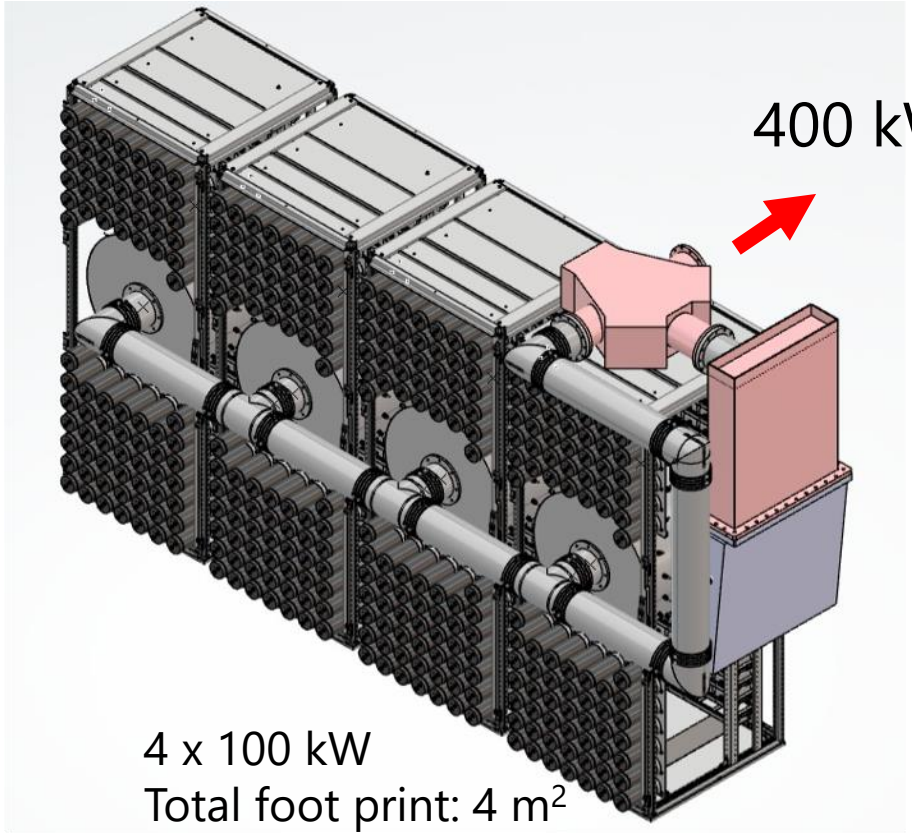
semi-rigid cables

PA modules 64 x 1.6 kW

Cavity splitter 1:64 (now 80:1)

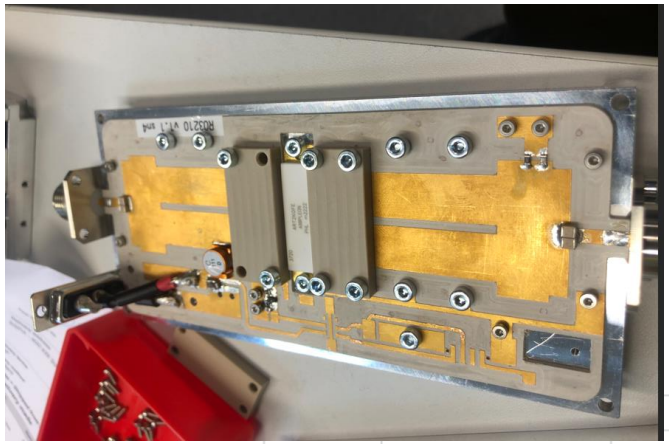
DC power supply, 15 kW

Circulator and water cooled load (same as for tetrode stations)



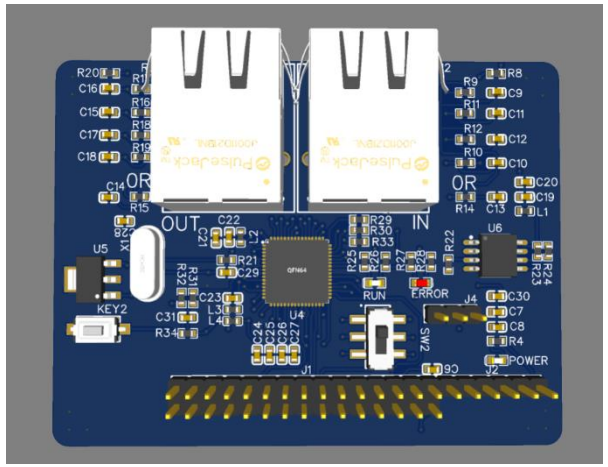
4 x 100 kW
Total foot print: 4 m^2

1.6 kW RF Power Amplifier Module
(15 manufactured and tested)



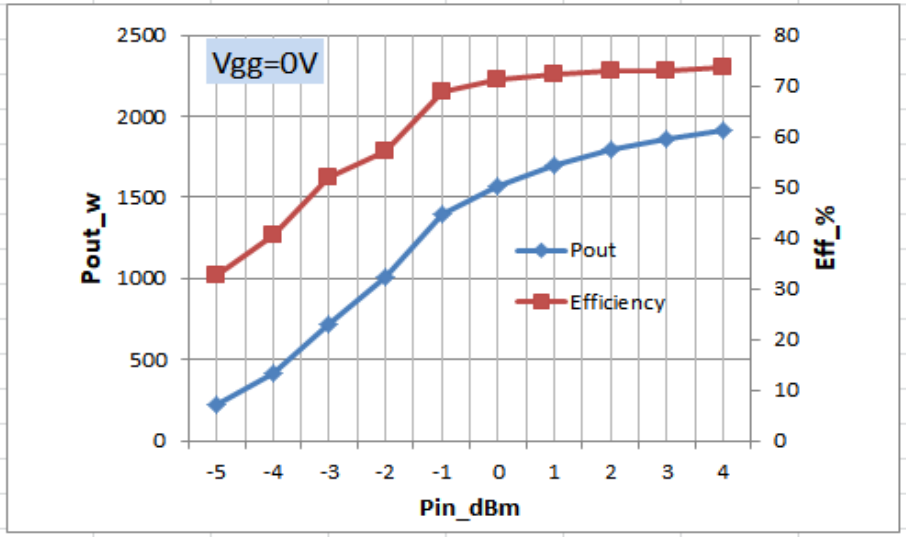
1.6 kW amplifier

Control board

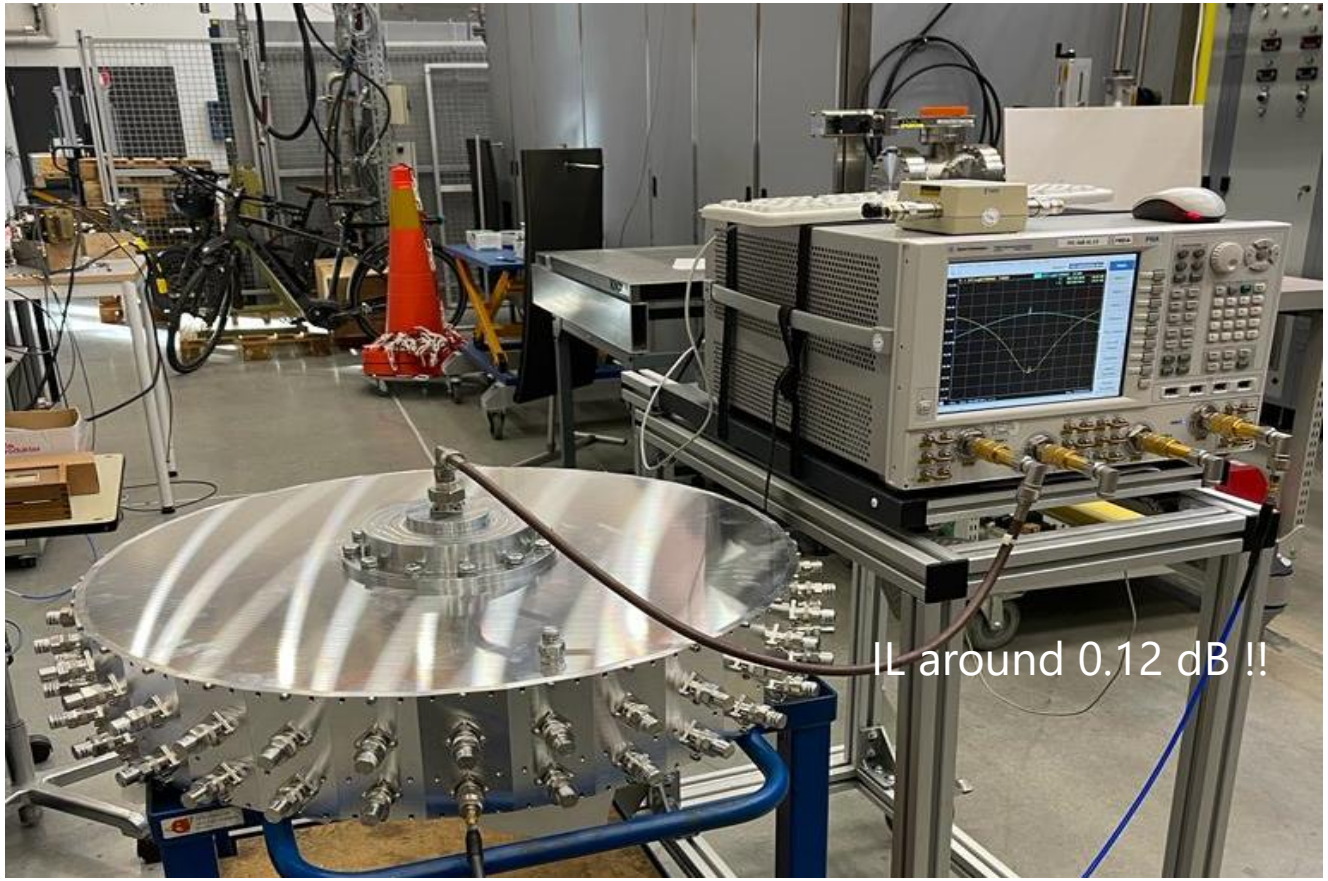


Pout > 1.6 kW
Eff > 72 %

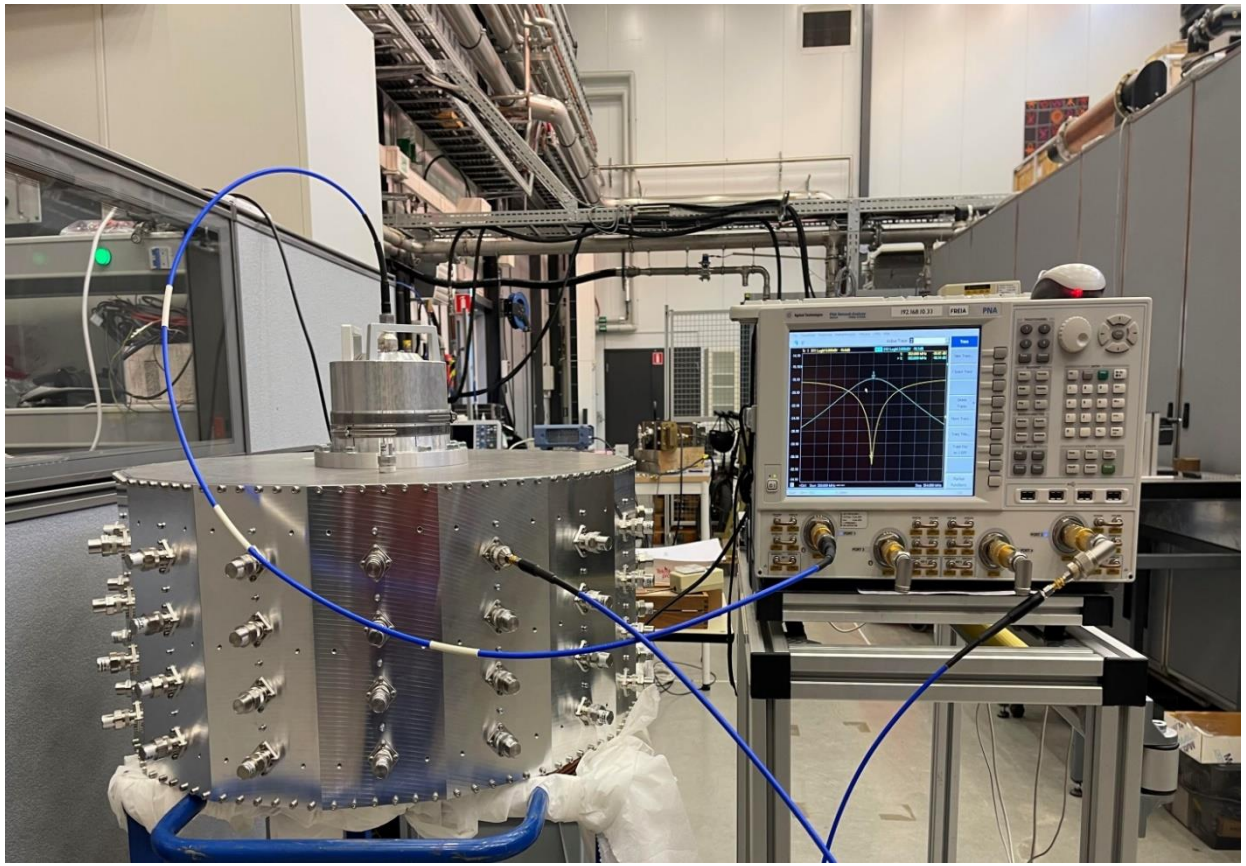
Vdd= 75		PRF= 100Hz, 1%	
Vgg= 0		Freq= 352MHz	
Pin	Pout_w	Idc_Peak_Amp	Eff_%
-5	218	8.9	32.66
-4	421	13.8	40.68
-3	716	18.4	51.88
-2	1013	23.6	57.23
-1	1400	27.1	68.88
0	1571	29.4	71.25
1	1700	31.4	72.19
2	1792	32.7	73.07
3	1860	33.9	73.16
4	1917	34.7	73.66

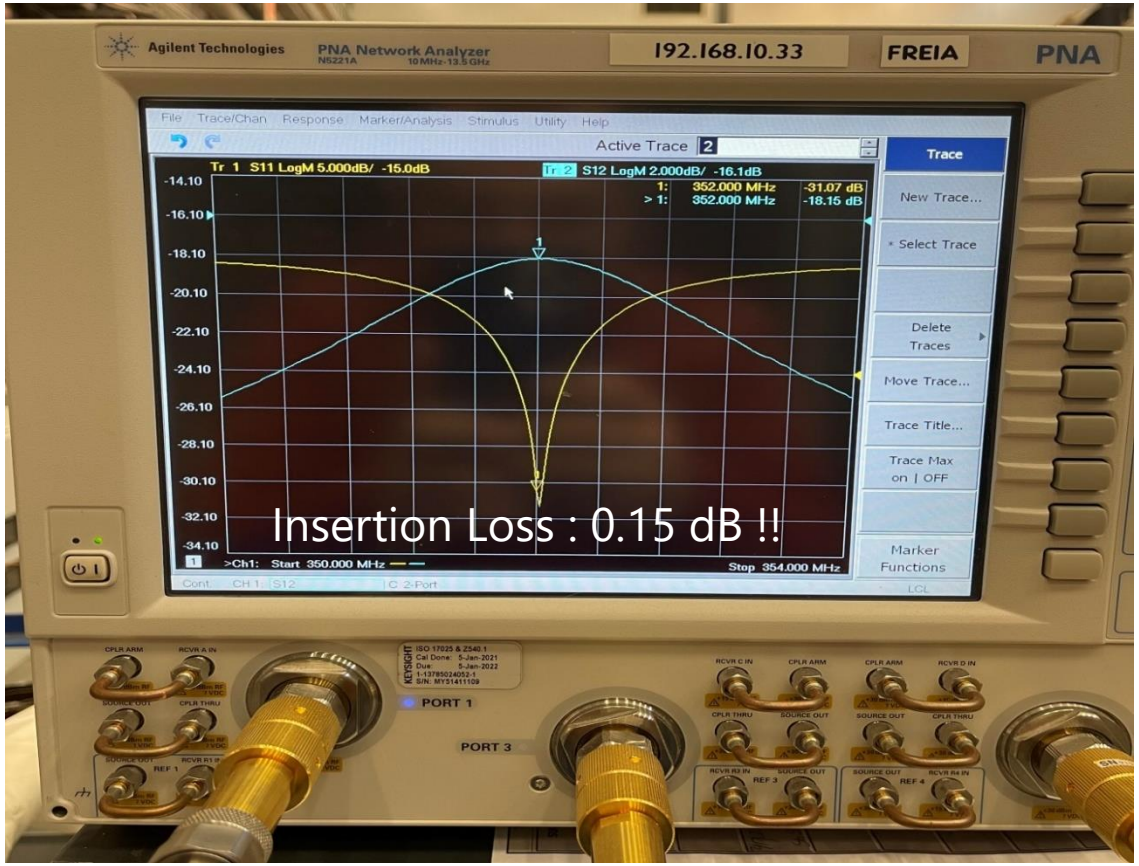


1:64 power splitter (First unit manufactured and tested)



64:1 power combiner - 100-kW (two units manufactured and tested)

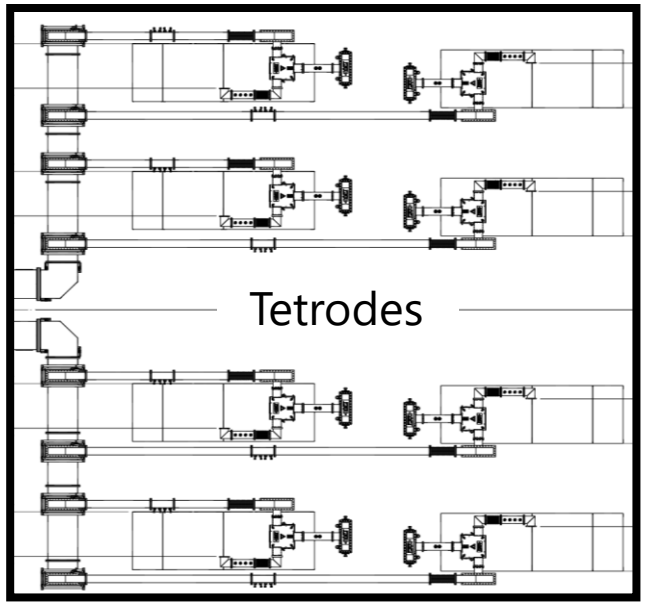


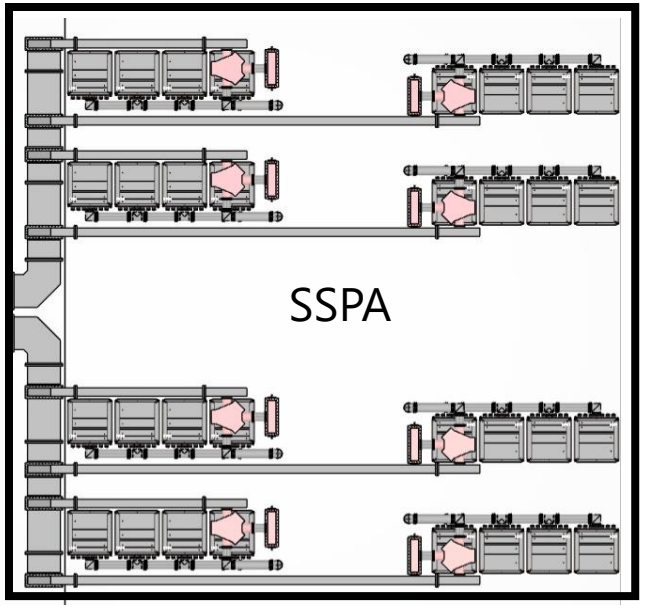


Planning and Direction

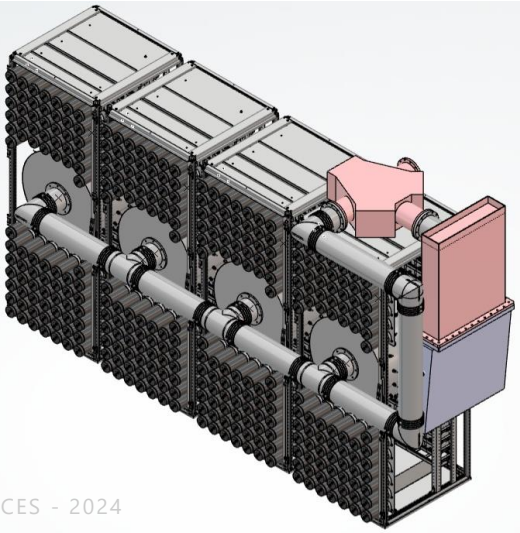
Layout in the Gallery

Plan view of Current Layout with tetrodes

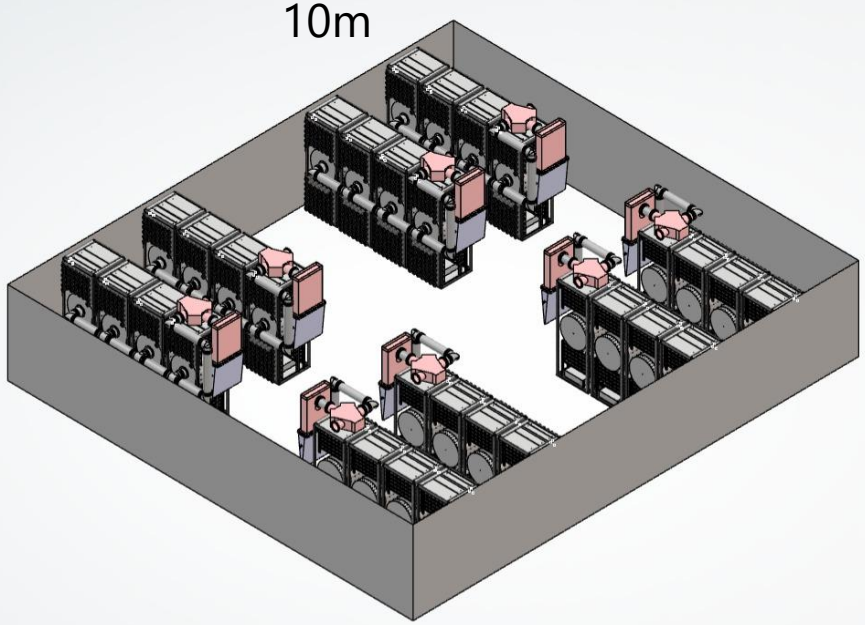




Anticipated Layout with SSPAs



Single 400 kW unit



Planning

Project formally started February 2024

3 main milestones obtained so far

- 1.6 kW module (tested up to 2 kW)
- Combiner and splitter with 64 inputs
- Combiner qualification at 100 kW

Dec 2024/ January 2025: 100 kW 1st rack

- Order 100 PCBs in September – start by manufacturing in-house RF boards
- Design of the combiner and splitter with 80 inputs in order to start the manufacturing
- Start manufacturing of boxes, cooling plates, and 4:1 splitter in October.

End 2025/ Beg 2026: 400kW prototype

- Successful qualification of the 1st rack (100 kW): March 2025
- Control system HW design done: March 2025

Key Directions and Challenges

Use of LDMOS for cost, robustness and market availability

Full power/gain budget was reviewed: power per module evaluated at 1600 W to 1850 W.

- 64:1 splitter/combiner cavities changed to 80:1
  - 256 power modules increased to 320.
- 1850 W may be OK but puts the drain voltage out of specification (70 V).
  - Priority on lower risk with option to test at higher power ahead of future production

Current measurement changed to reduce cost

Low cost, on board RF power measurement

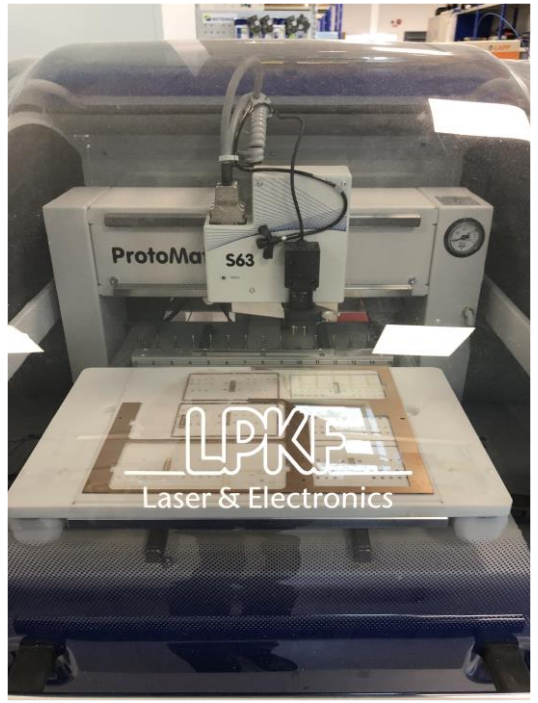
PCBs milled in-house to reduce cost and control risk

Full module, housing, monitoring and controls integrated and designed ease of maintenance

Stepwise soak testing in progress.

New technical developments are considered as opportunities for personal development where it aligns with other ESS technologies

In-house PCB production



Efficiency consideration

Class AB or class C

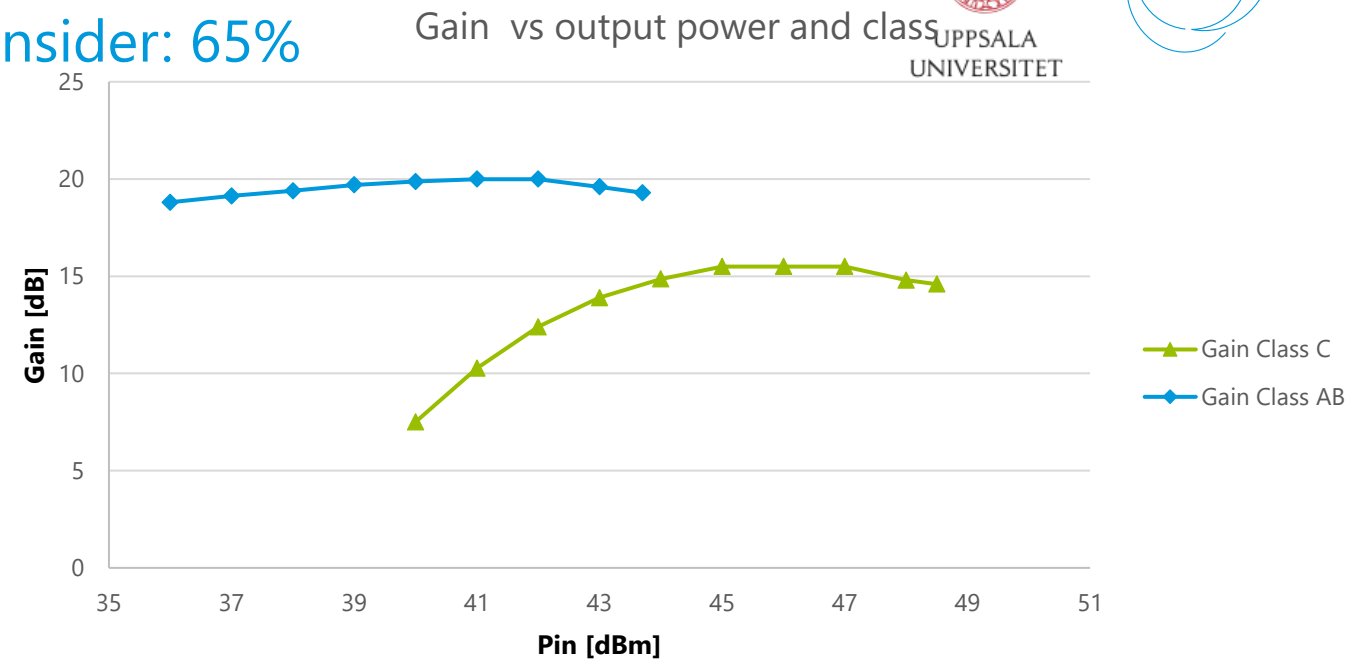
In operation Module efficiency to consider: 65%

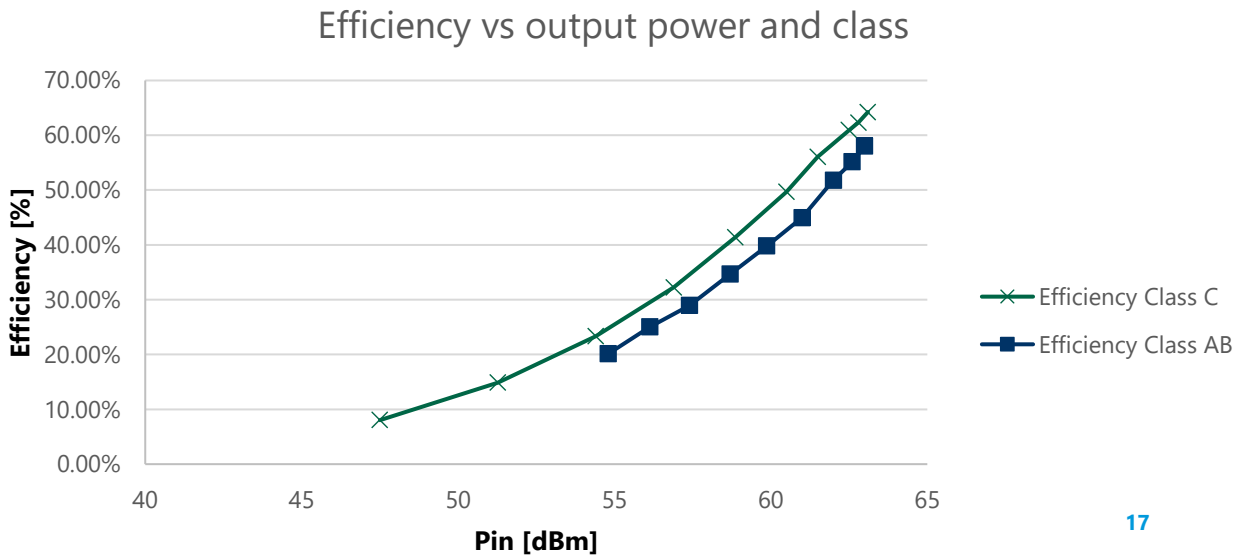
Class C

- Efficiency
- Linearity
- Gain
- Less components
- Reliability

Class AB

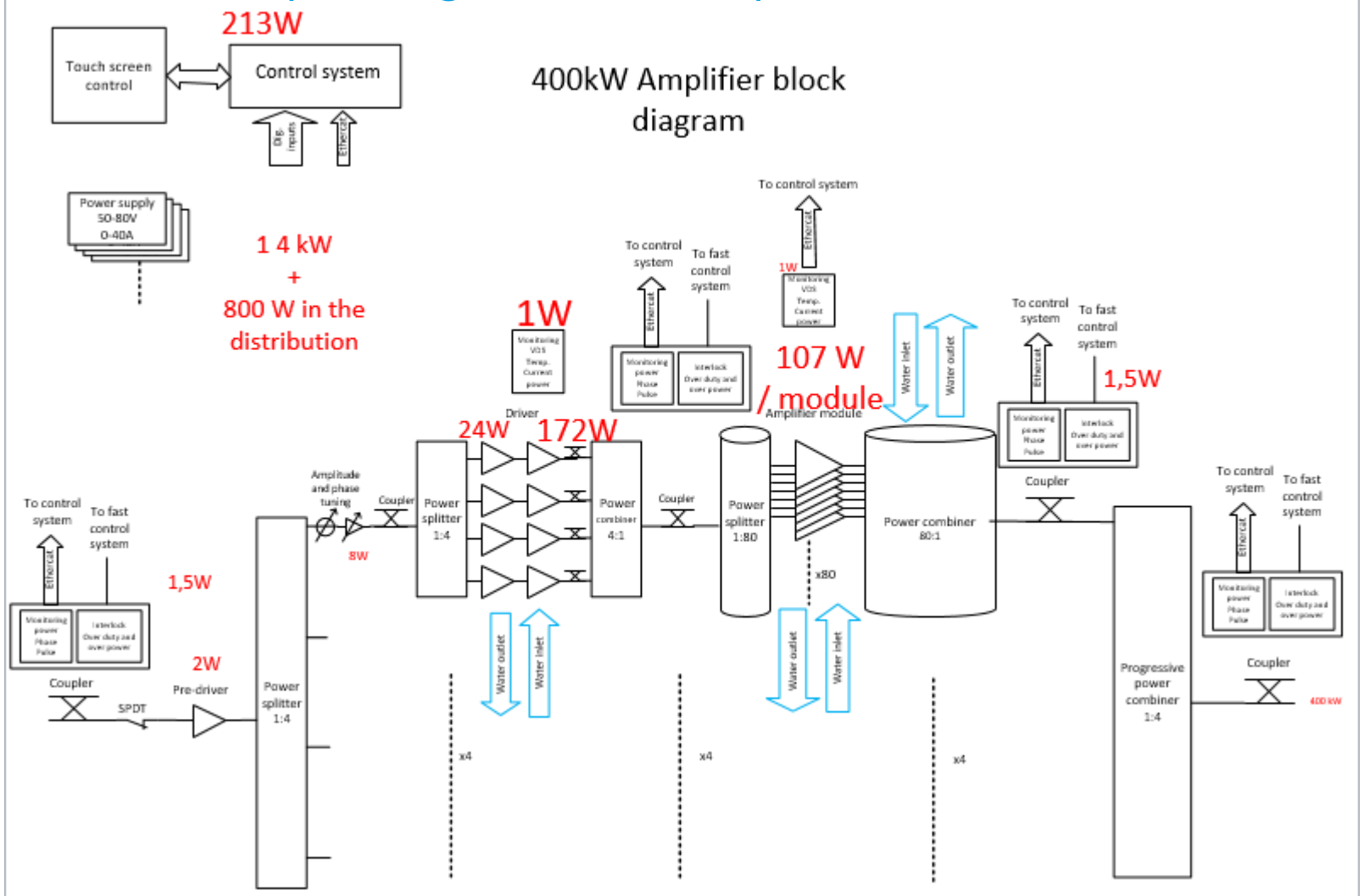
- Linearity
- Efficiency
- Gain





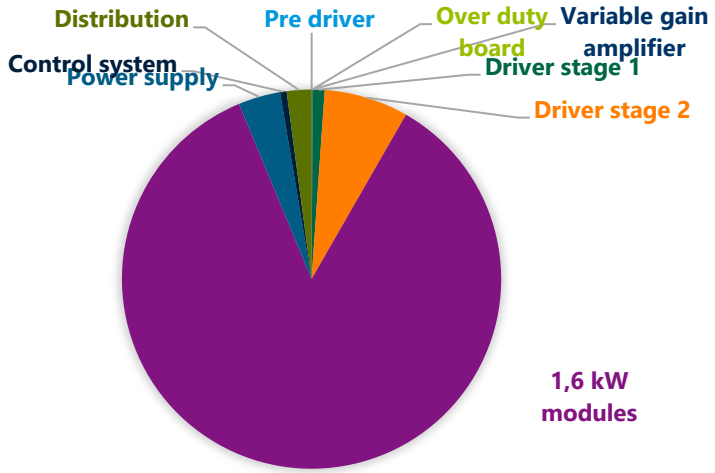
Global efficiency

From power grid to RF output



Electrical consumption	Per Unit	nb of Unit	Total	
Pre driver	2	1	2	W
Variable gain amplifier	8	4	32	W
Over duty board	1,5	4	6	W
Driver stage 1	24	16	384	W
Driver stage 2	172	16	2752	W
1,6 kW modules	102,2	320	32711	W
Power supply	4,1	336	1374	W
Control system	213	1	213	W
Distribution	2,4	336	806	W
Total			38280	W
Eff			52,2%	

DISTRIBUTION THE CONSUMPTION



Loss between the amplifier module and the output are a key point: 0,5dB is 5% on the global eff.

Class C or Class B

We need flexibility

Class C Eff Module: 65%

Electrical consumption	Per Unit	nb of Unit	Total	
Pre driver	2	1	2	W
Variable gain amplifier	8	4	32	W
Over duty board	1,5	4	6	W
Driver stage 1	24	16	384	W
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Power supply	4,1	336	1374	W
Control system	213	1	213	W
Distribution	2,4	336	806	W
Total			38280	W
Eff			52,2%	

Class AB Eff Module: 55%

Electrical consumption	Per Unit	nb of Unit	Total	
Pre driver	2	1	2	W
viariable ampi	8	4	32	W
over duty	1,5	4	6	W
driver syage 1	24	4	96	W
driver stage 2	121,4	4	486	W
1,6 kW module	121,4	320	38864	W
power supply	4,9	324	1574	W
control system	213	1	213	W
distribution	2,4	324	778	W
Total			42050	W
Eff			47,6%	

Work in Progress

Rack Layout

Rack layout with 80 modules

It will be challenging to get the cables in place.

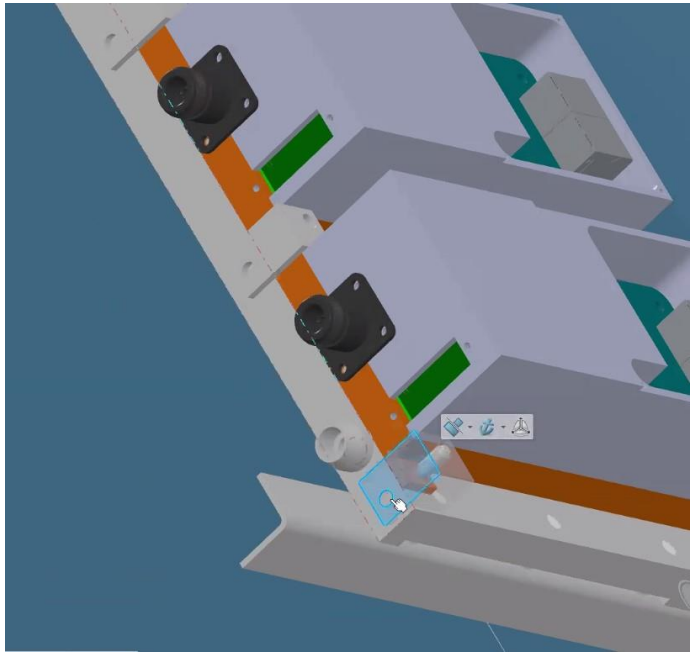
Cooling plate design in progress

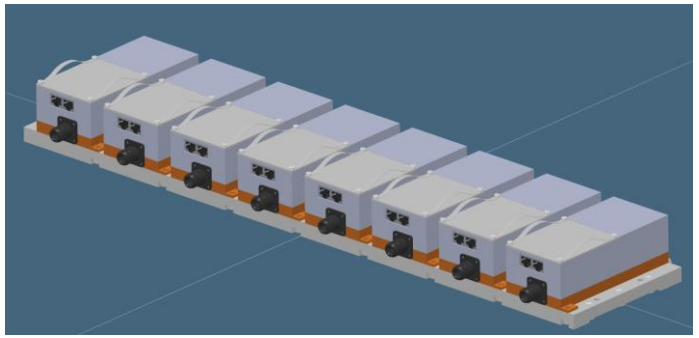
Design of the heat sink and box for the module - completed

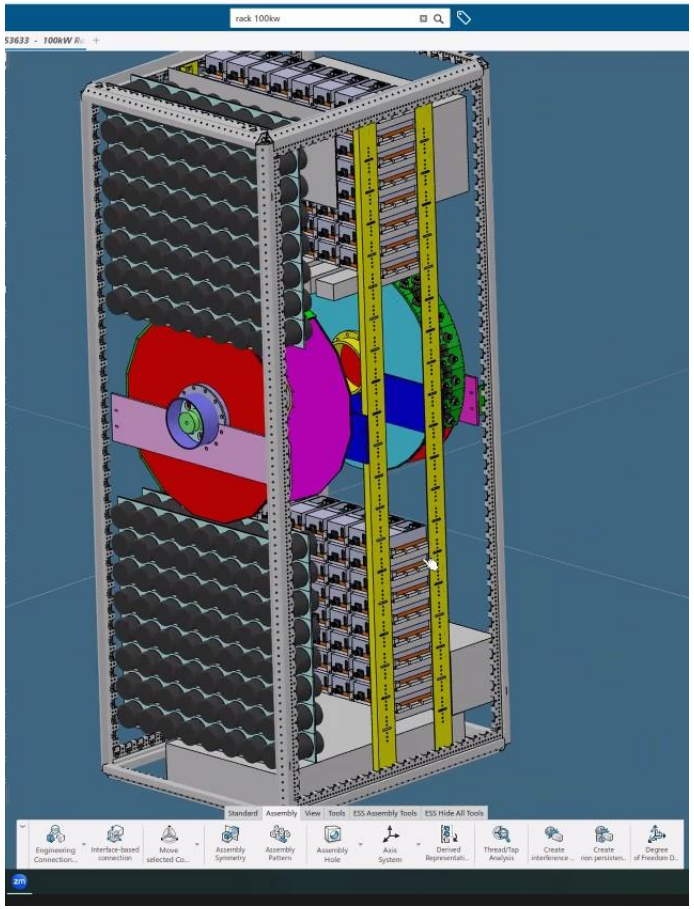
Working on a easy solution to get the module in and out for easy repair

Investigation with 128 modules (not yet possible)

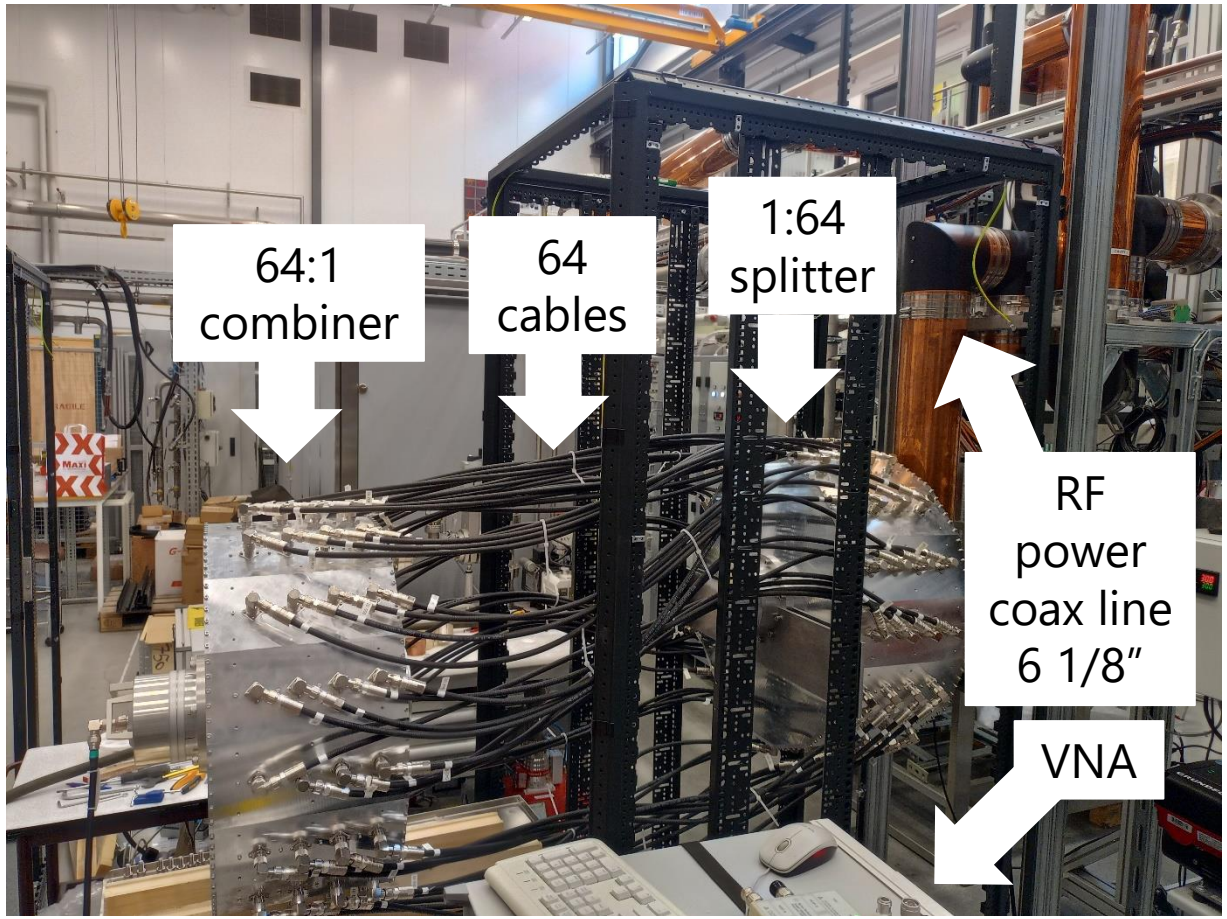
- Would allow doubling of power per rack

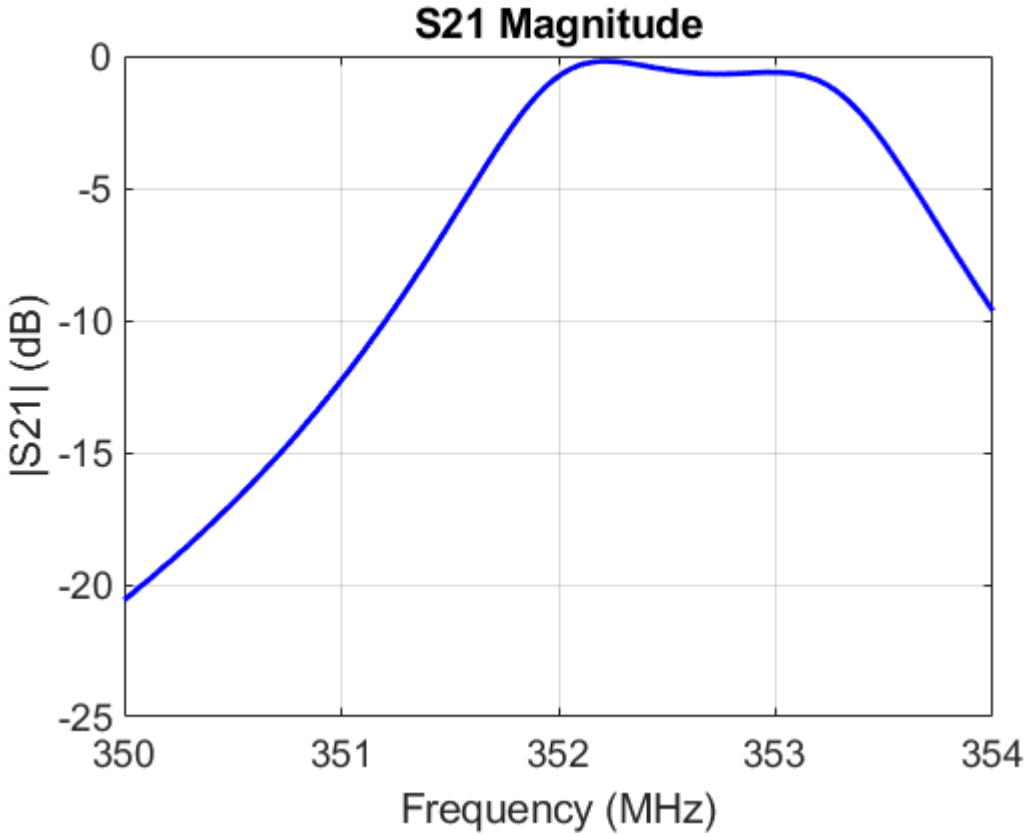






Back to back combiner test: low power

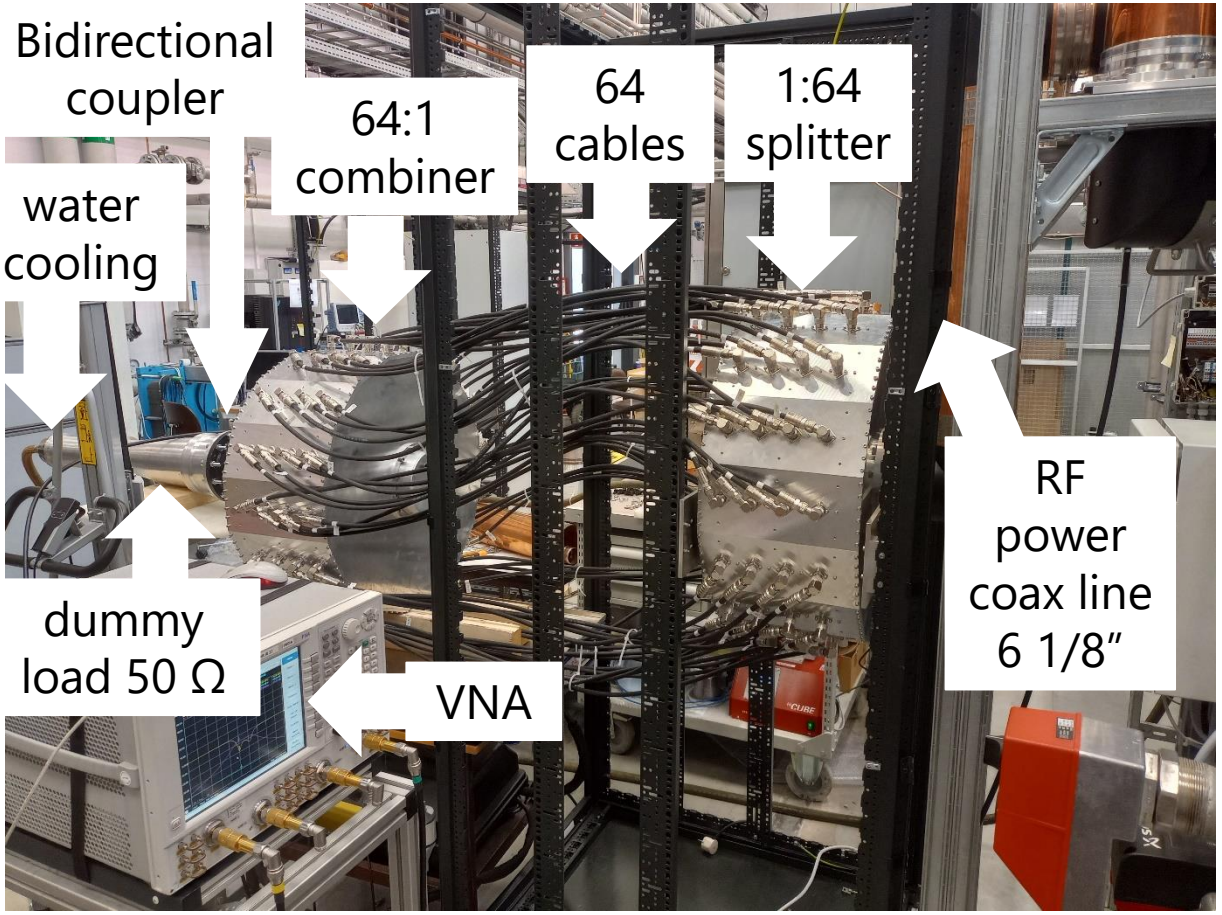


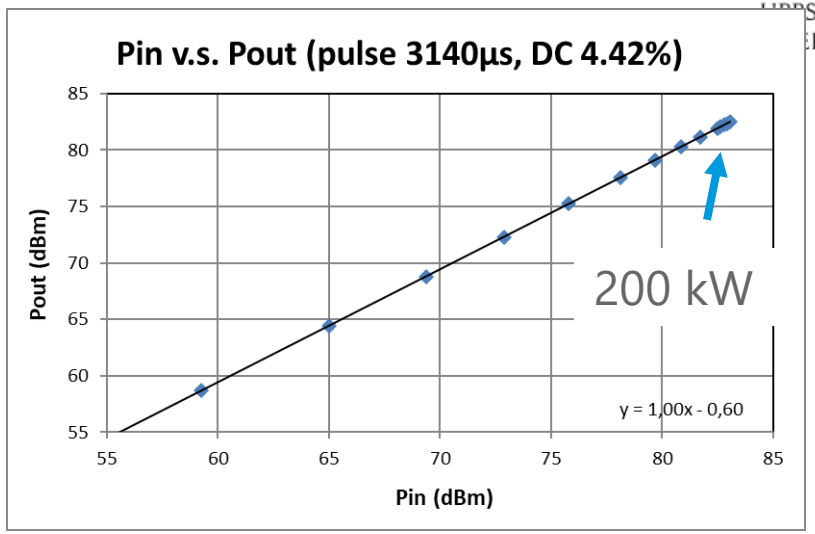


IL = 0.3 dB (calibrated: i.e. wo cables, connectors, etc.)

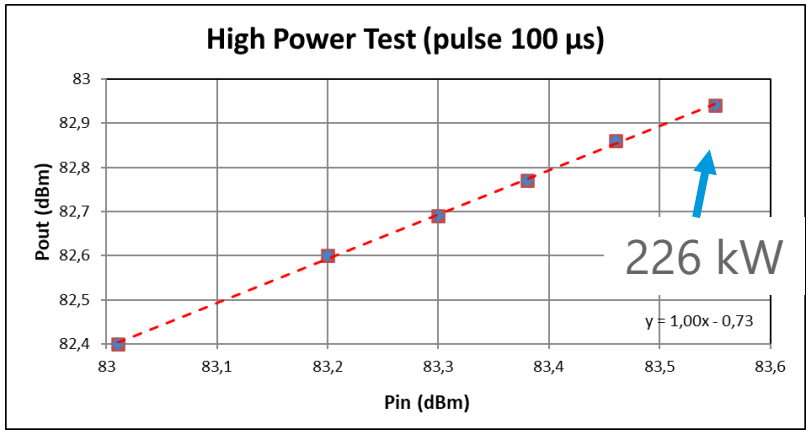
Back to back combiner test: high power

Verification of High Power Output Coupler





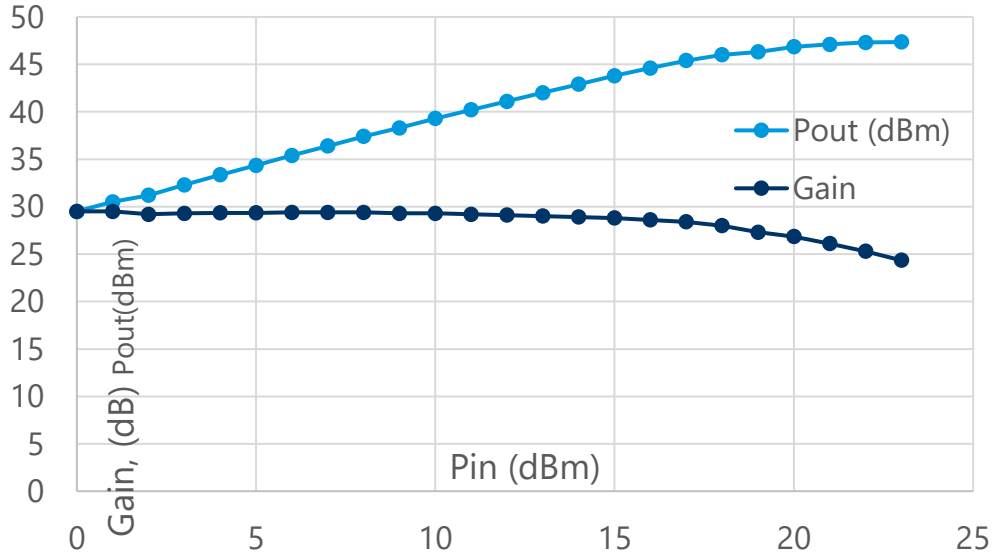
IL = 0.58 dB (with cables, connectors, etc.)

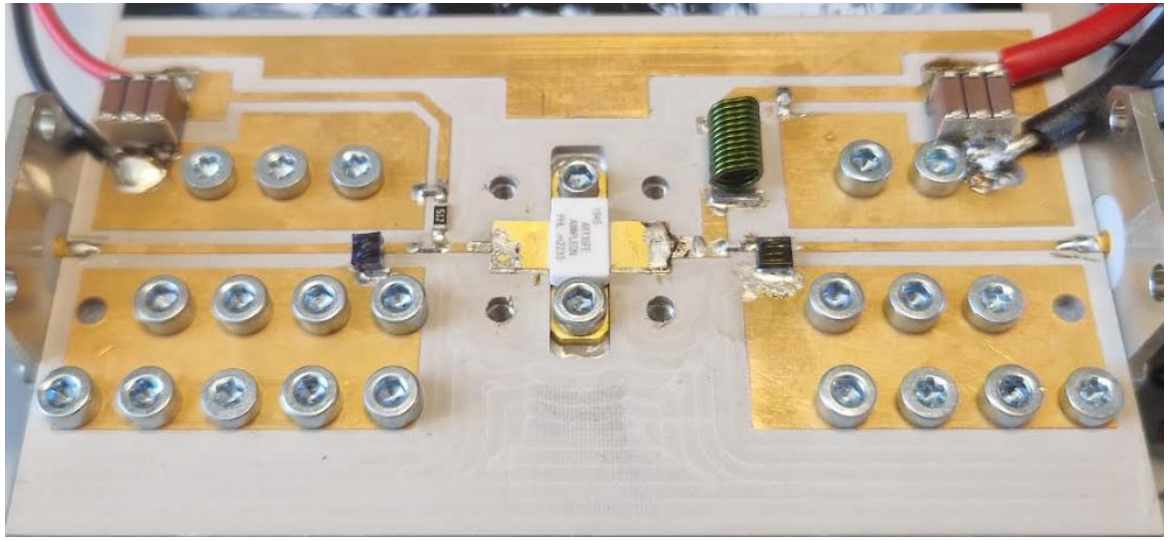


IL = 0.61 dB (with cables, connectors, etc.)

Test successfully carried out to 220 kW without incident. (100 kW is required)

Driver 50W based on LDMOS ART35FE

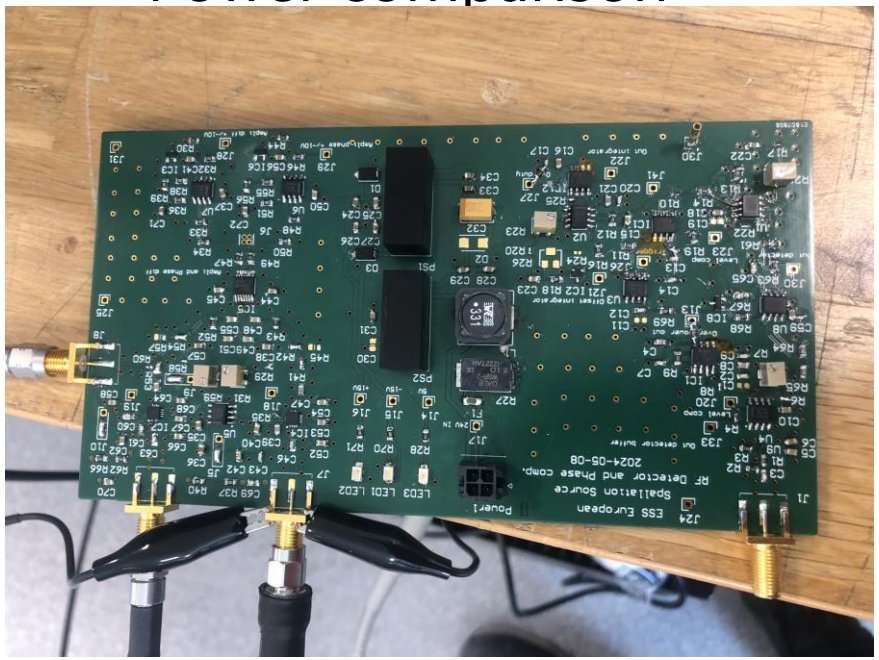




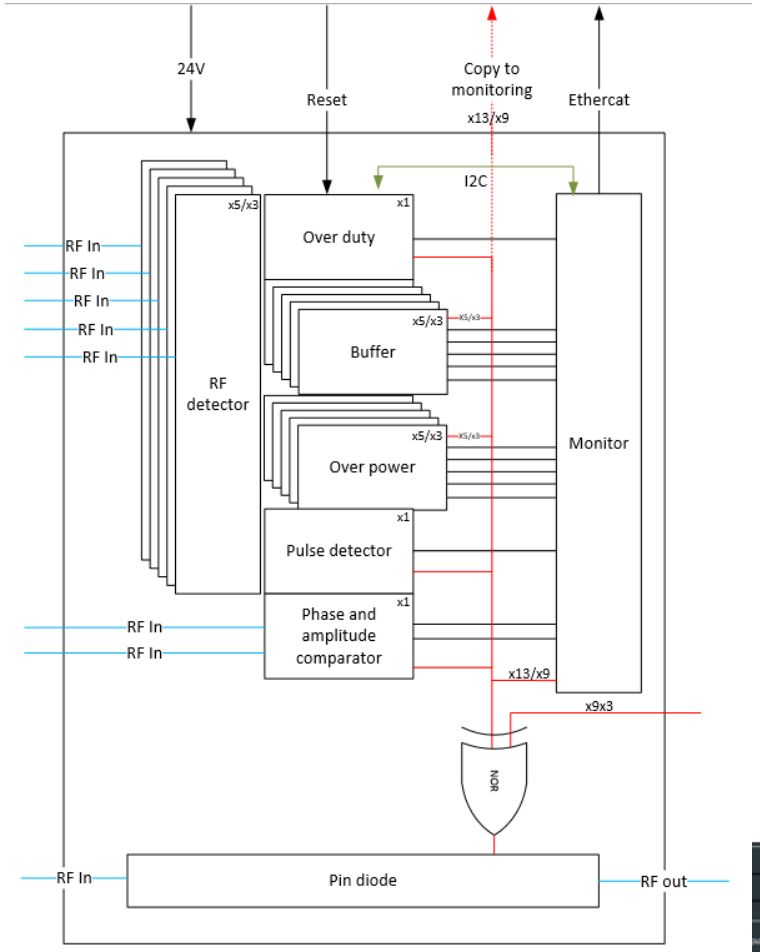
Design Parameters	Specifications	Simulation Results	Measurements
Operational frequency	352.21 MHz	352.21 MHz	352.21 MHz
Gain at nominal power 50 W output	27 dB min	27.1 dB	26.85 dB
Efficiency	>50%	65%	62%
Input/output impedance	50 Ω	50 Ω	50 Ω
Gain flatness (over 10dB dynamic)	ΔG ≤ ±0.5 dB		ΔG : +/- 1,6 dB
2nd, 3rd Harmonic content	<-30 dBc	-20 dBc -26 dBc	-20 dBc -26 dBc
Input VSWR	≤ 1.12:1	1.07:1	1.12:1
Output VSWR	≤ 1.12:1	3:1	3.5:1

Power, Phase, Over-duty Measurement Board

A board to measure
- RF power
- Over-duty
- Phase to ref
- Power comparison



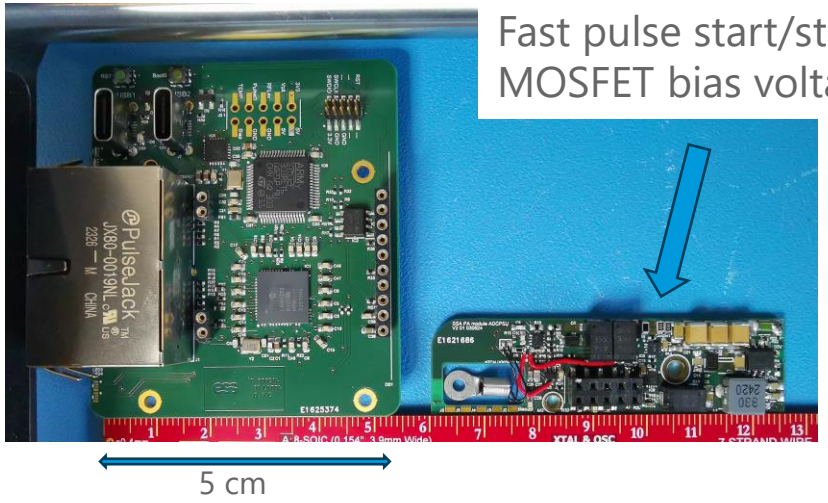
Control board



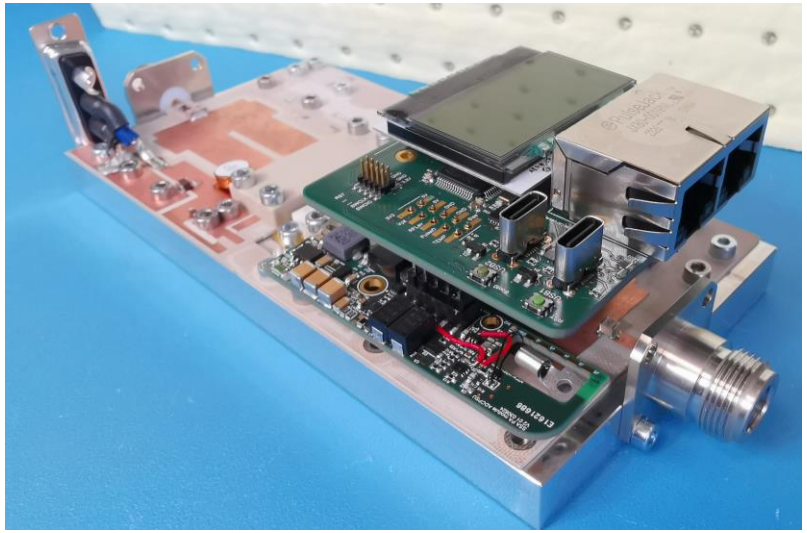
Power measurement
Pulse length
Interlock signal

Monitoring and Control

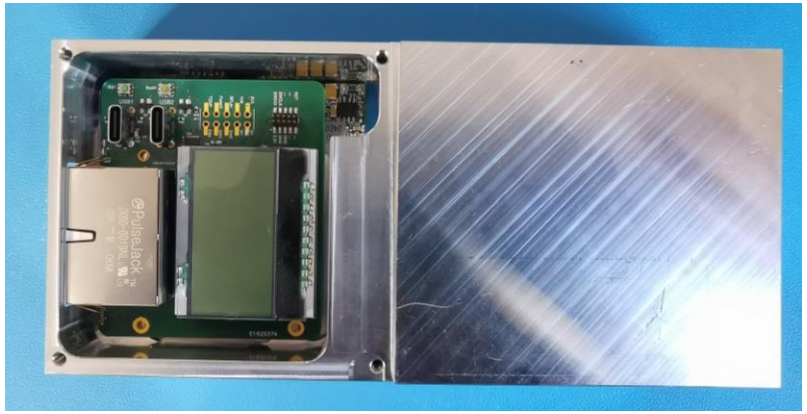
PSU down conversion
Analogue data buffers
NCT linearisation
Fast pulse start/stop detection
MOSFET bias voltage



STM32 MCU for A/D conversion and comms
LAN9252
USB interfaces
(Optional) LCD for debugging and display



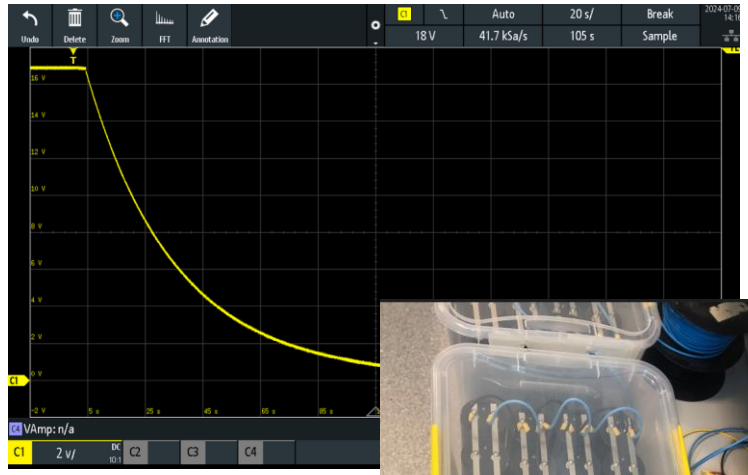
Amplifier Module with control boards

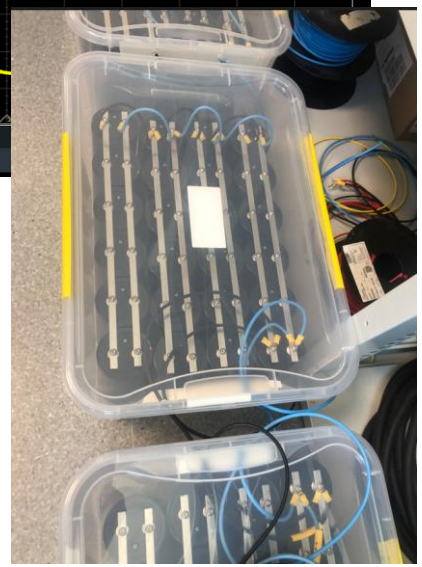


Full integrated assembly

Other Developments

- Power module design optimisation including change of substrate, housing and cooling
- Control system under development. Platform will be common and supported by ESS.
- Electrical Schematics
- 1:80 cavity splitter/combiner (scale from 1:64)
- Rack layout
- Discharge protection circuit
- High Power 4:1 progressive combiner (400 kW stage)
- 4:1 driver combiner
- Soak testing.
- Setting up for in-house assembly and production
- Plus some more…





Tested with 72 capacitors

90% discharged in 85 sec

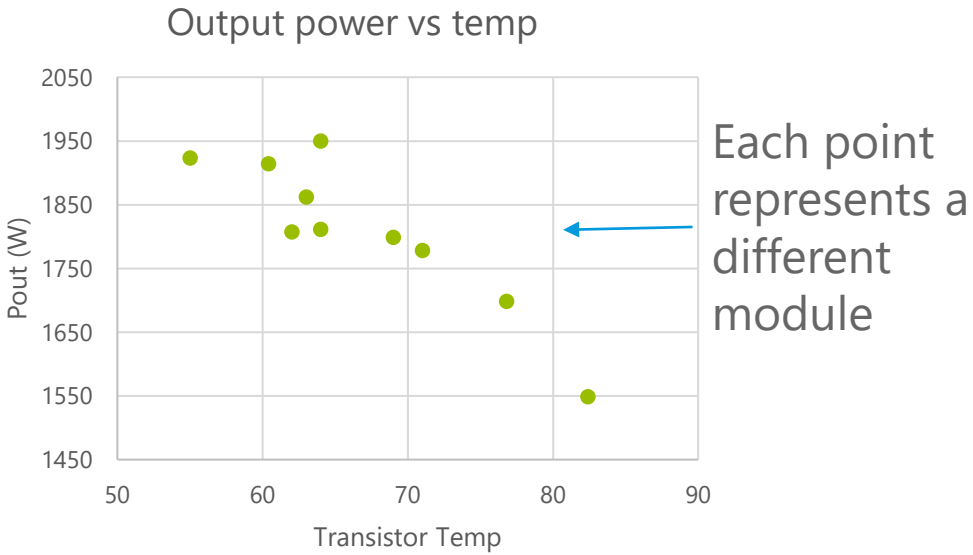
Soak test with 8 modules

Initial difficulties encountered

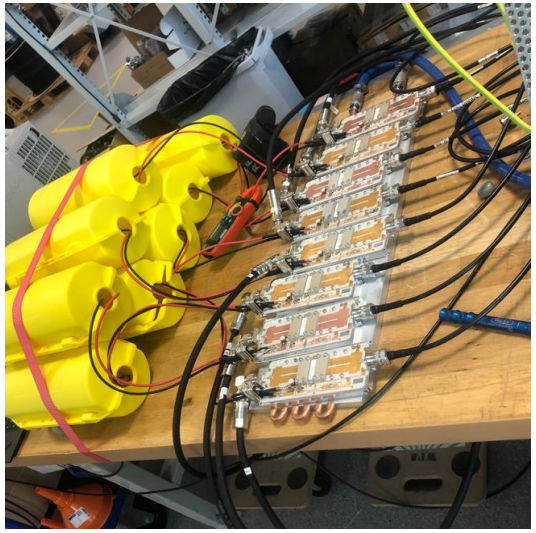
Soak testing using 8:1 combiner (loan from Soleil)
Initially paused due to uneven heating.

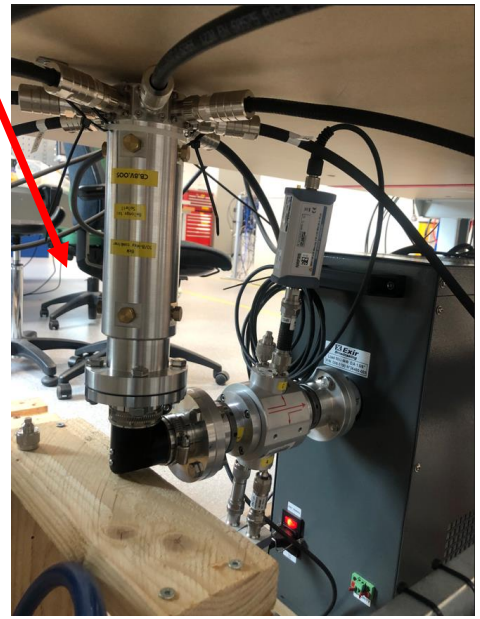
Investigation ongoing:

- Possibly due to output and phase mismatch
- 12 kW achieved



Each point represents a different module





Temperature measurements vs duty cycle

pulse period	transistor temp	Pout (dBm	Pout (W)	dutycycle
1000	25,5	62,6	1 819,70	0,4%
300	28,4	62,52	1 786,49	1,2%
140	35	62,48	1 770,11	2,5%
71	49	62,33	1 710,02	4,9%

Summary

- Technology demonstrator development started in February 2024 as risk reduction to Spoke power stations.
- Development is based on a high power module delivering about 1.8 kW with auxiliaries, low power and high power stages being developed as part of this project.
- Priority on reliability and availability via risk reduction rather than prioritising absolute minimal cost.
- Control strategy is to use supported ESS technology for ease of integration.
- Timescale is challenging (2 years). Good progress made to date.
- Project is providing great staff morale boost, allows for personal development and for enhancing ESS in-house expertise.

Thanks for your attention !

Questions

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