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High Power RF Solid State Amplifiers at FREIA

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Oct. 4 – meeting with Scandinova

FREIA Laboratory, Uppsala University

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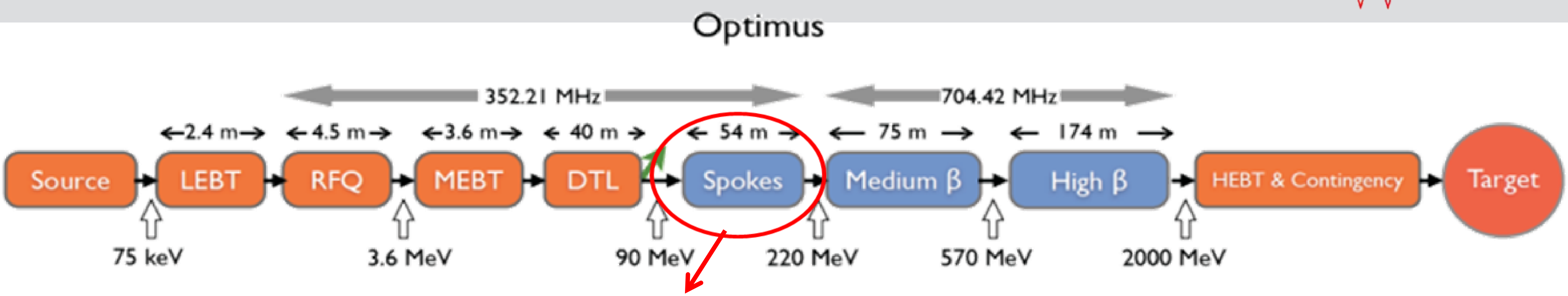
RF Source Development - FREIA



Testing prototype superconducting accelerating cavities (26 SC in final LINAC), cryomodules and high power RF stations

- High power RF stations at ESS specifications
  352.21 MHz, 400 kW, 14 Hz, 3.5 ms, 200 kHz bandwidth

ESS - Lund

Uppsala University

FREIA Uppsala

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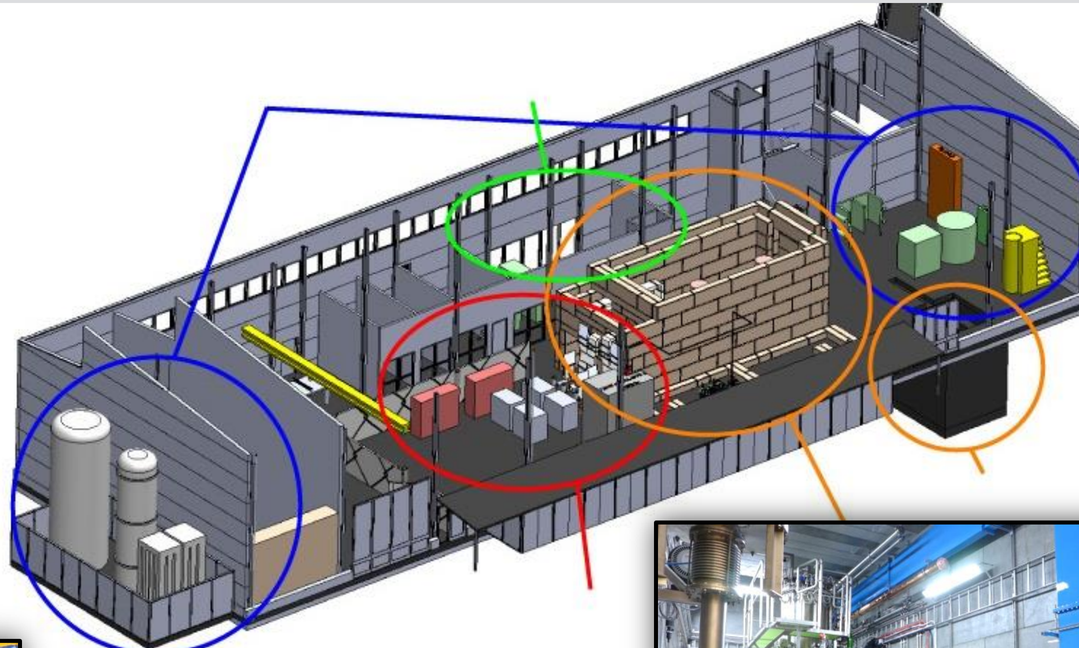
Cryogenics

- Liquid Nitrogen
- Helium liquefaction (150 l/h)
- 2000 l storage dewar

RF Power Stations

- 400 kW 3.5 ms pulses at 14Hz
- Dual TH595 tetrodes
- Load pull



Spoke Cavity

- Operating at 352.21 MHz
- Q > 10^9
- Operating gradient 9 MV/m

Control System

- Closed-loop LLRF system
- Cryogenics control

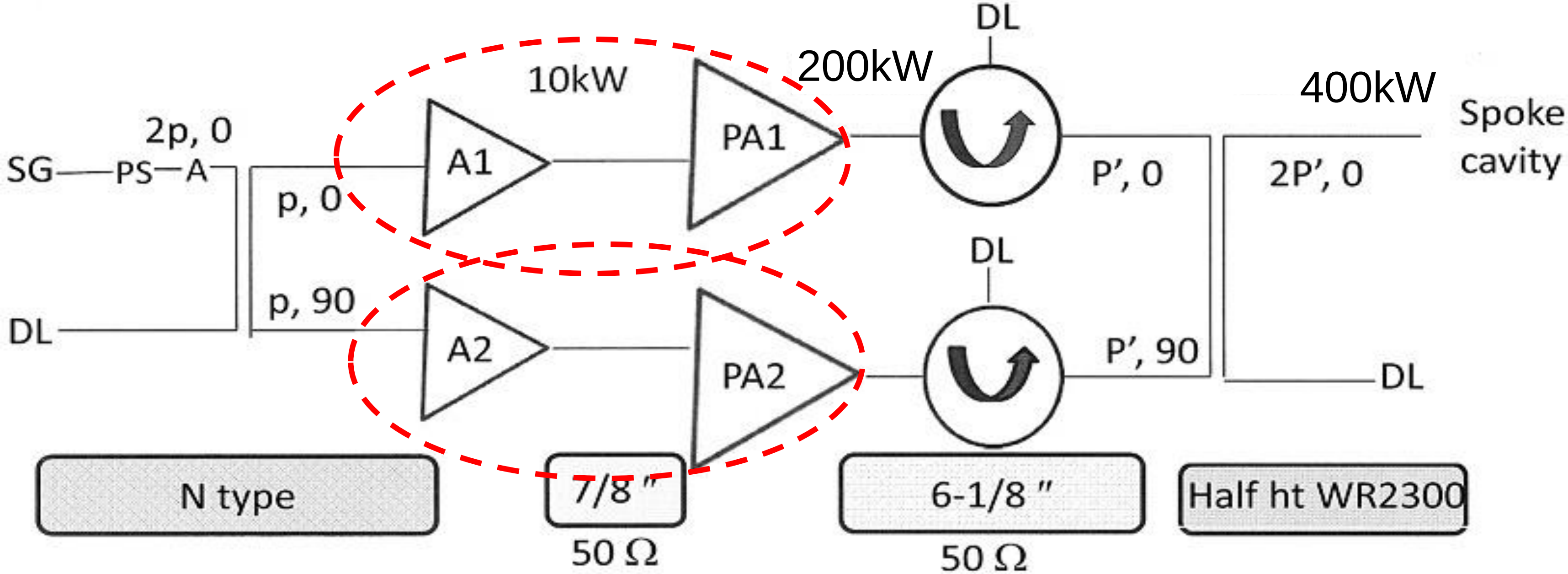
Horizontal Cryostat

- Operating at 1.8 to 4.5 K
- 16 mbar pressure

400kW RF Stations

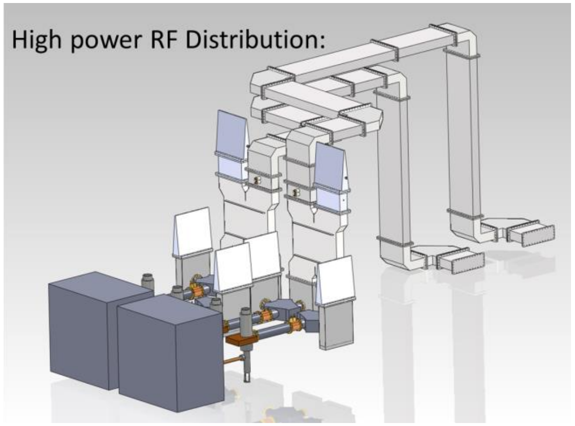
- Tetrode based (Dual TH595)
- 400 kW 3.5 ms pulses at 14Hz
- 20 kV 40 A anode power supplies
- Class AB
- Cost Efficient/Reliability
- Efficiency a key-parameter

RF Power Station – SSA

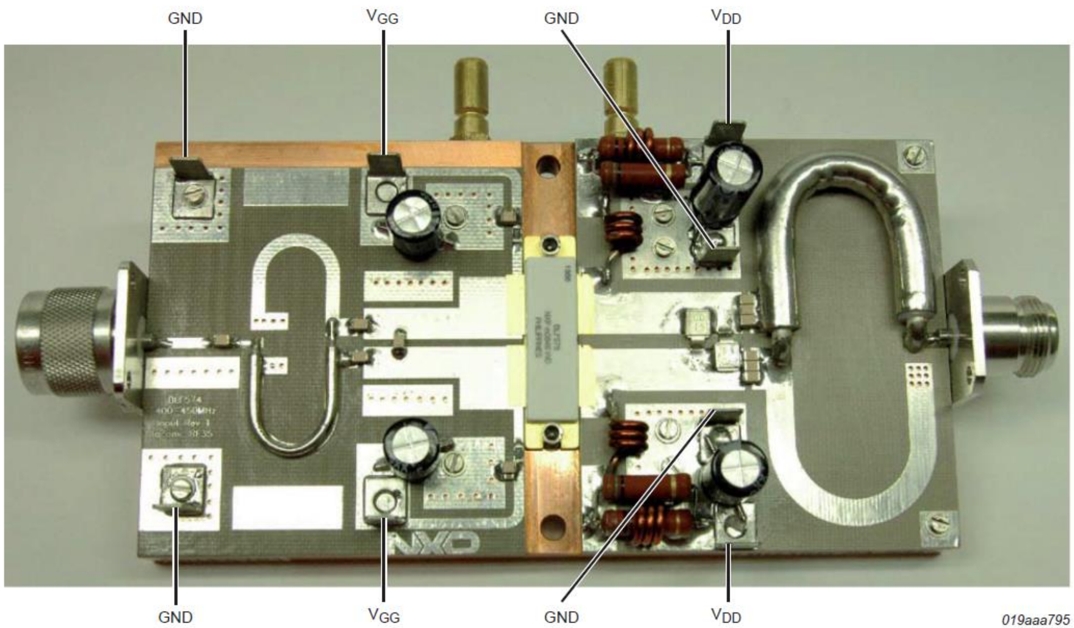


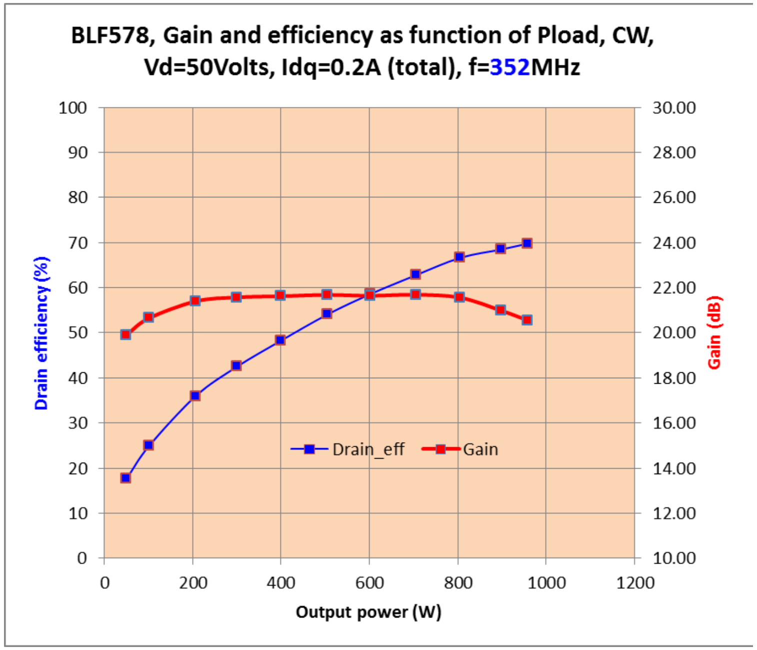
- No presurization and ferrite dummy loads
- Power Distribution at 3 levels
  - Half height WR2300: 400kW
  - 6-1/8 inch, 50 Ω coax: 200 kW
  - 7/8 inch, 50 Ω coax: 10 kW
- Pre amp. Efficiency: 50 - 55 % (class AB)
- Amp. Efficiency > 67 % (class AB)

TH 595



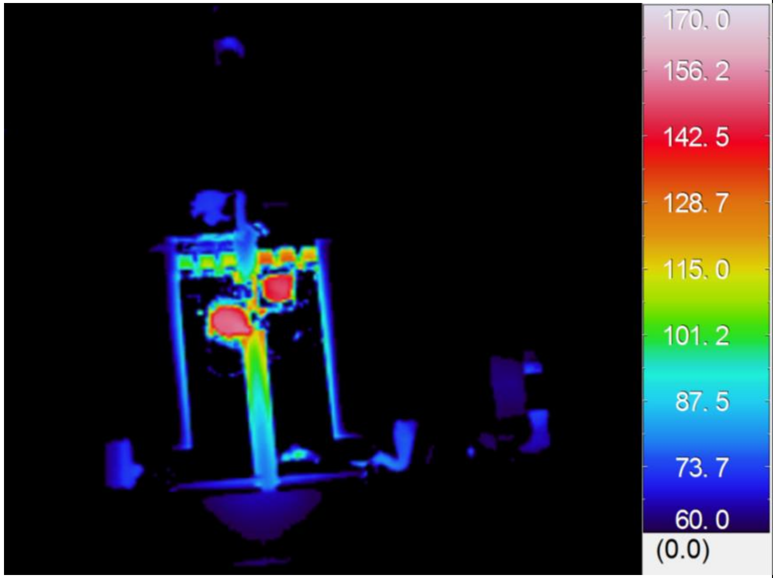
SSA research: collaboration with NXP(now Ampleon) and ESRF



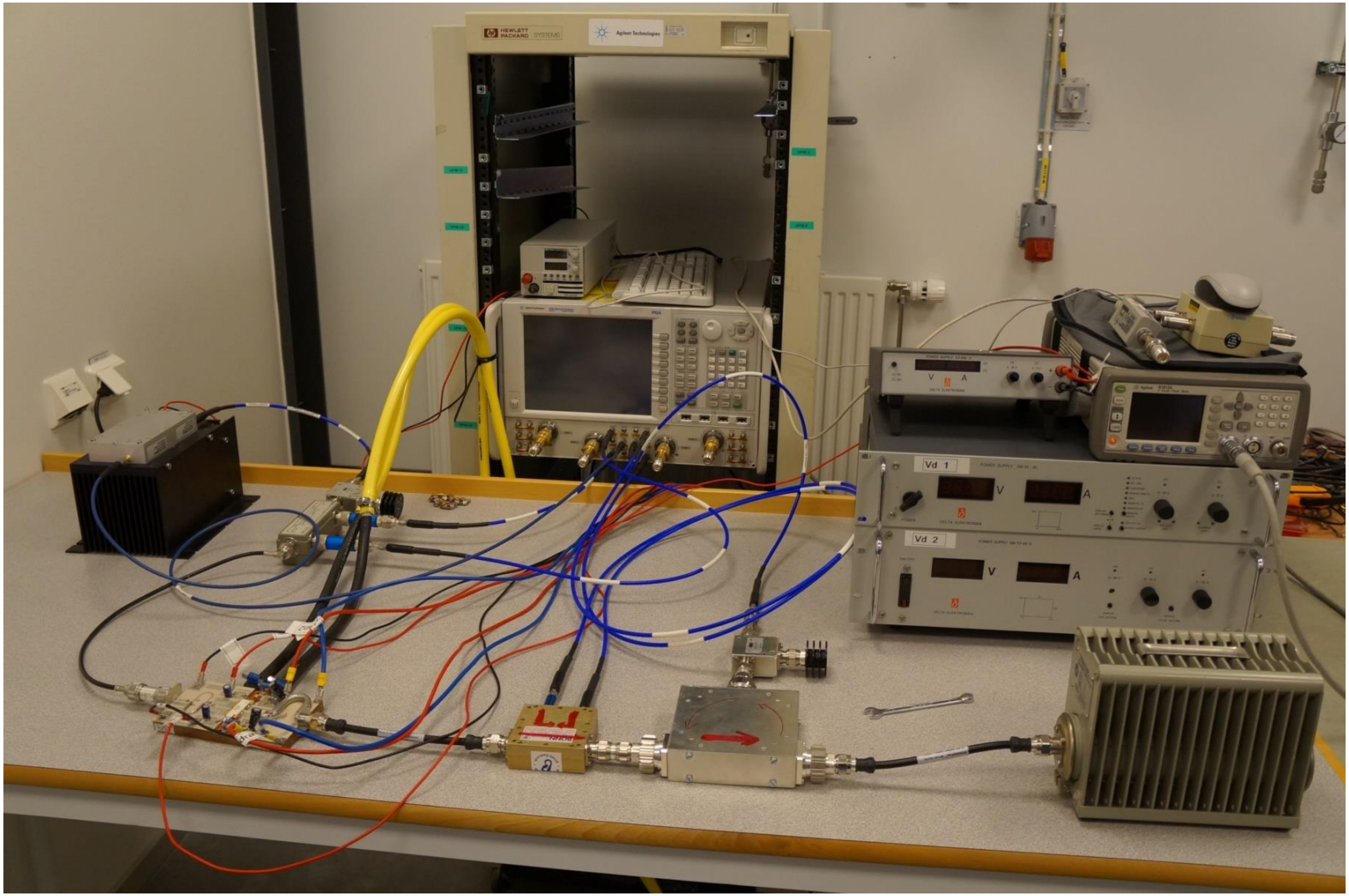


AN10967 is a demo board designed and manufactured by NXP for the BLF578 LDMOS transistor.

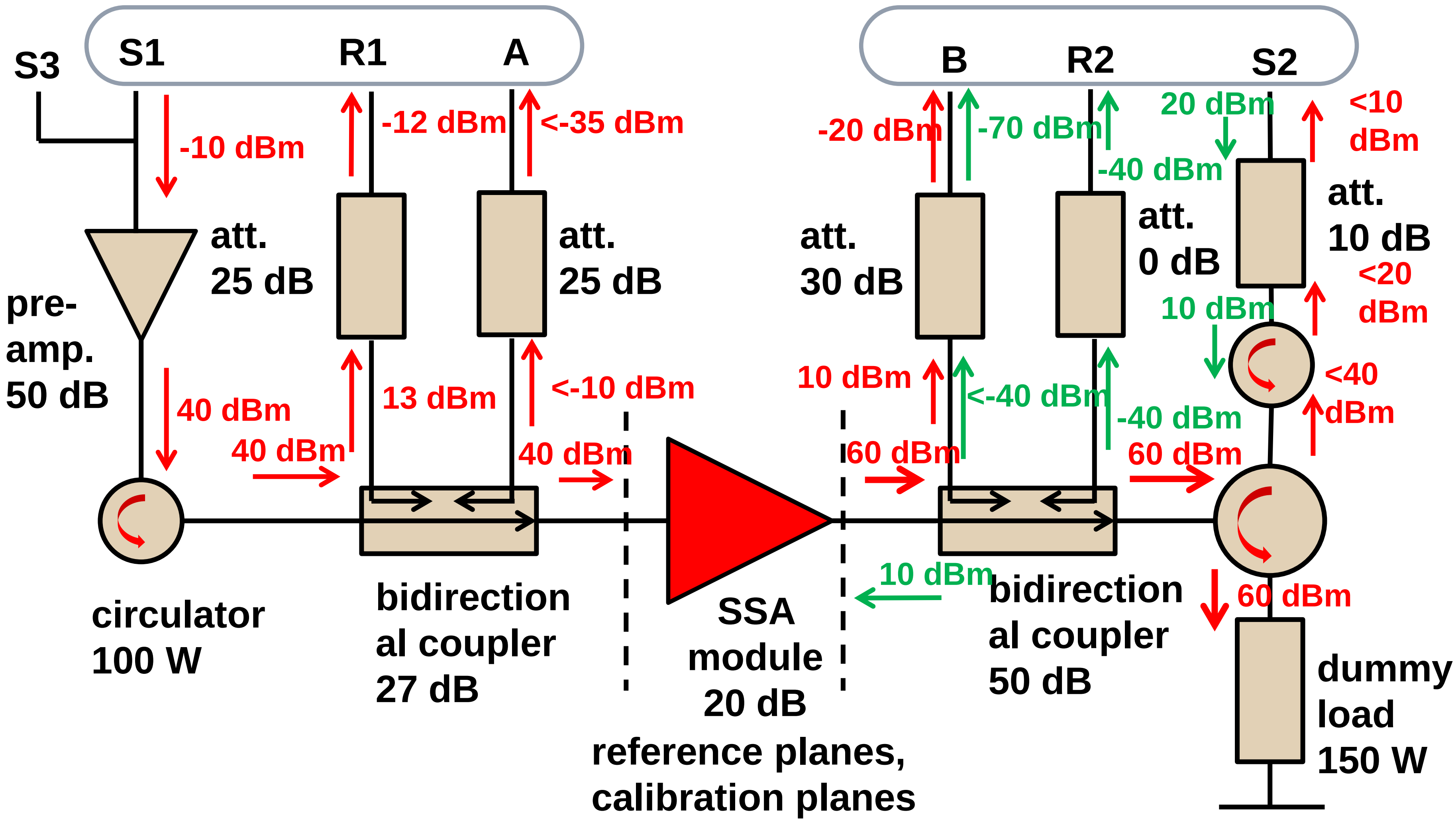
- push-pull configuration, class AB
- delivering 1000 W in CW
- Max efficiency: 70%
- Gain: 20 dB
- Highest temp spot: 145C (15l/min water)



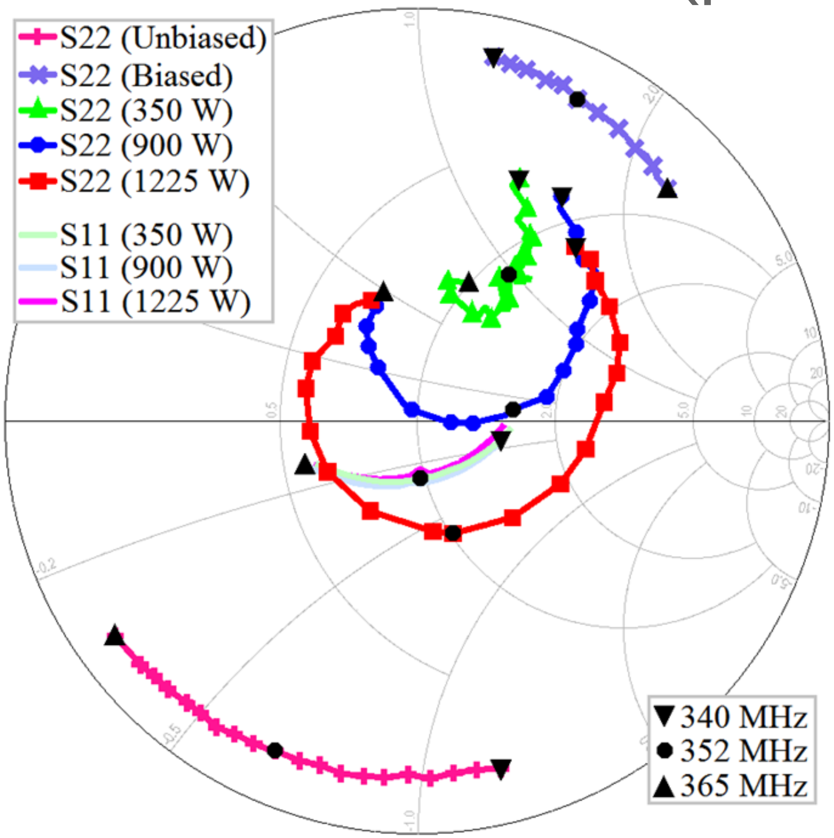
1kW level Hot S-parameters measurements (pulsed)

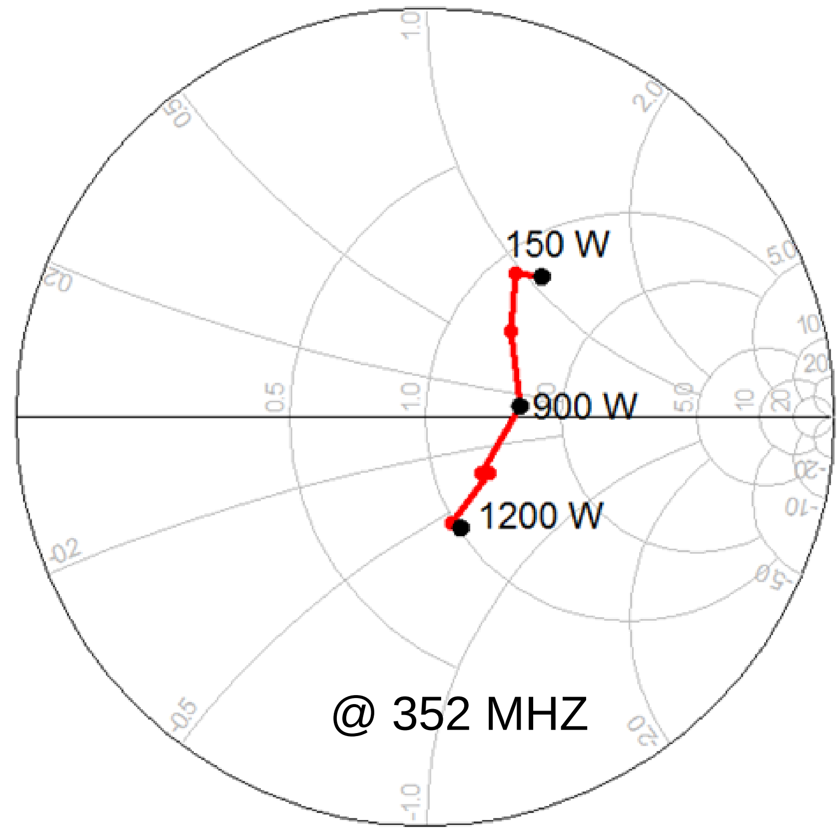


1kW level Hot S-parameters measurements (pulsed)



1kW level Hot S-parameters measurements (pulsed)





- Using Hot S-parameters measurements we can characterize the output impedance at different output power levels.
- The impedance is changing quite dramatically with the output power and this needs to be taken in to account for power combination.

(BLF578 measurements realized in pulsed mode with ESS parameters)

SSA development at UU: single ended RF power amplifier – 1250 W and 70% efficiency

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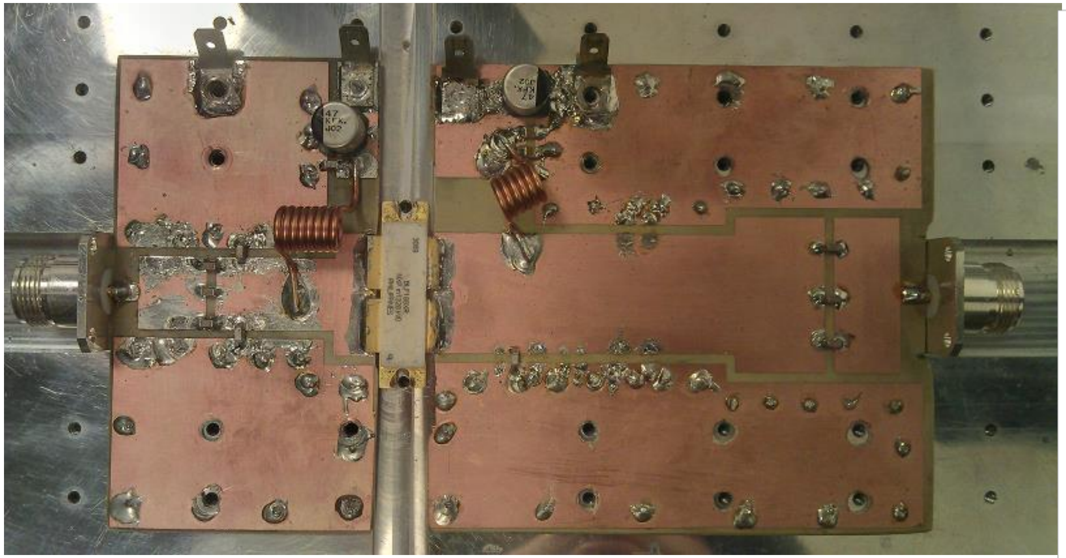
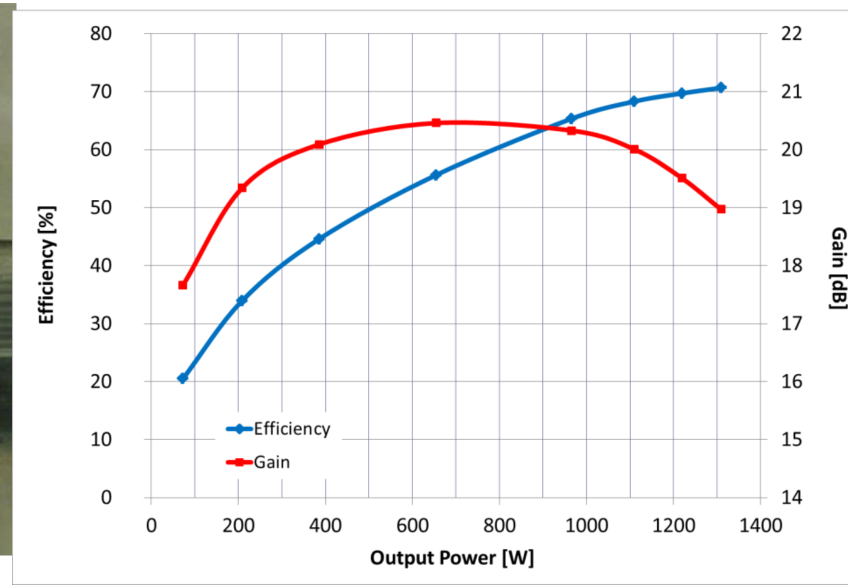
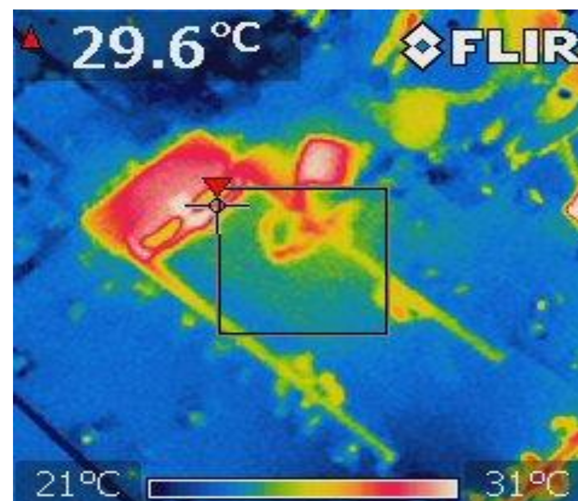


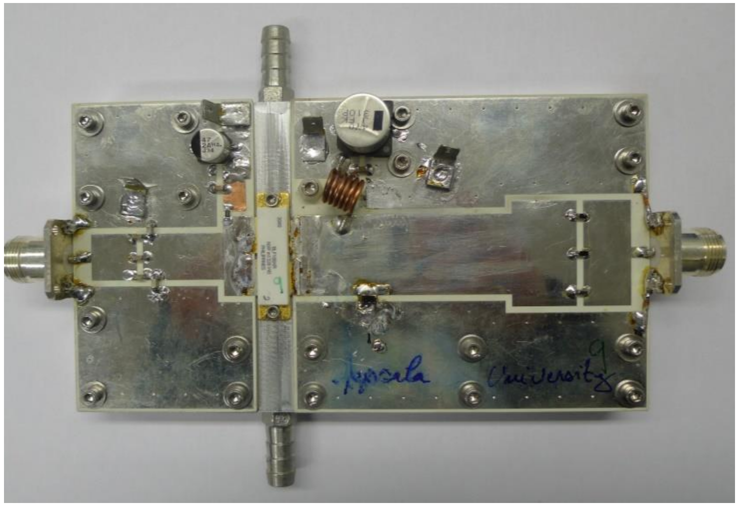


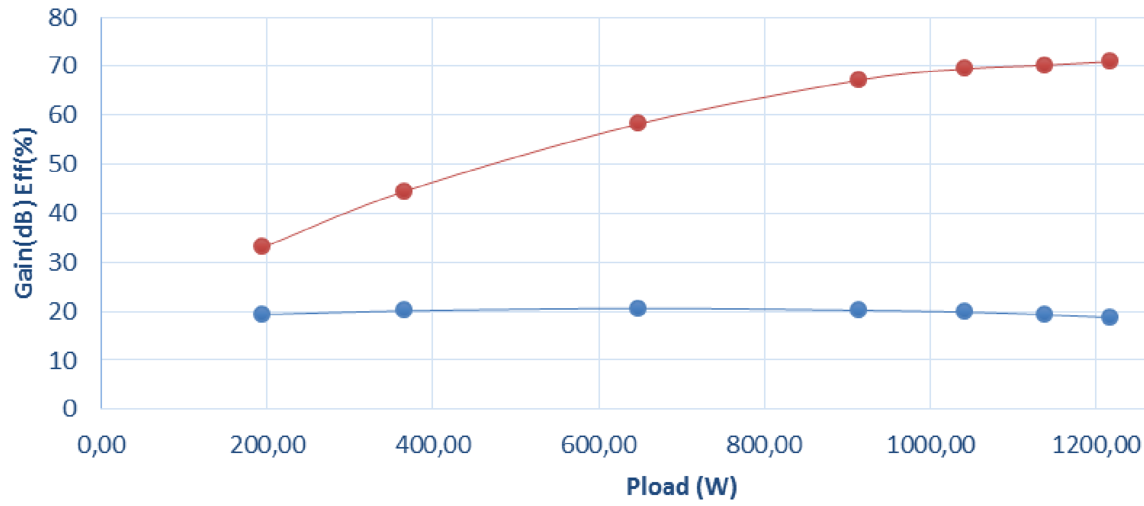
Tested in pulsed mode with ESS characteristics (14 Hz, 3.5 ms) delivering up to 1300 W.

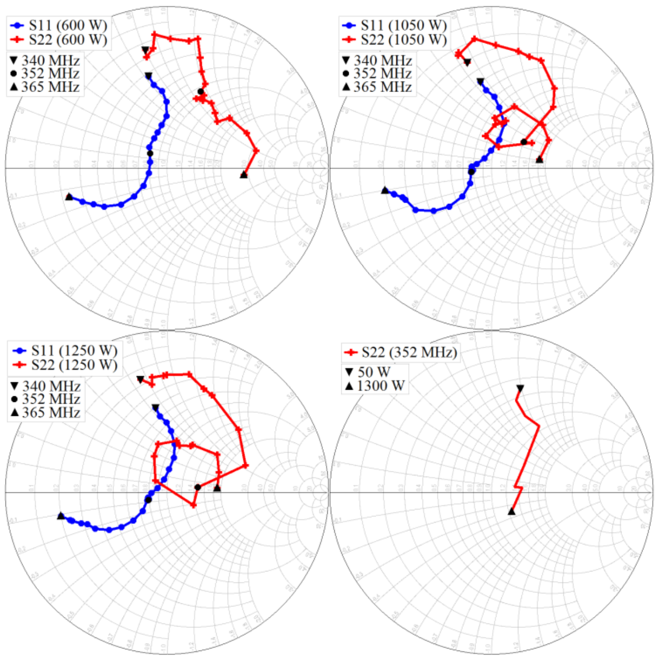
- BLF188XR - excellent ruggedness
- Max efficiency: 71%
- Gain: 19 dB (at 1.5 dB comprsession)
- Highest temp spot: 30 ºC (15l/min water)
- Excellent nonlinear behavior: second harmonic at -34dBc - no balun



Single ended RF power amplifier – 1250 W and 70% efficiency – 8 amplifiers for 10 kW demonstrator



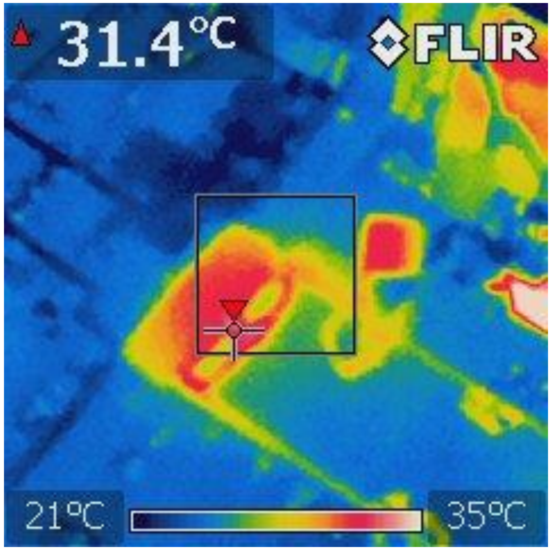




quiescent drain current, I_{Dq}=0.1 A and drain voltage, V_{DS}=50 V.

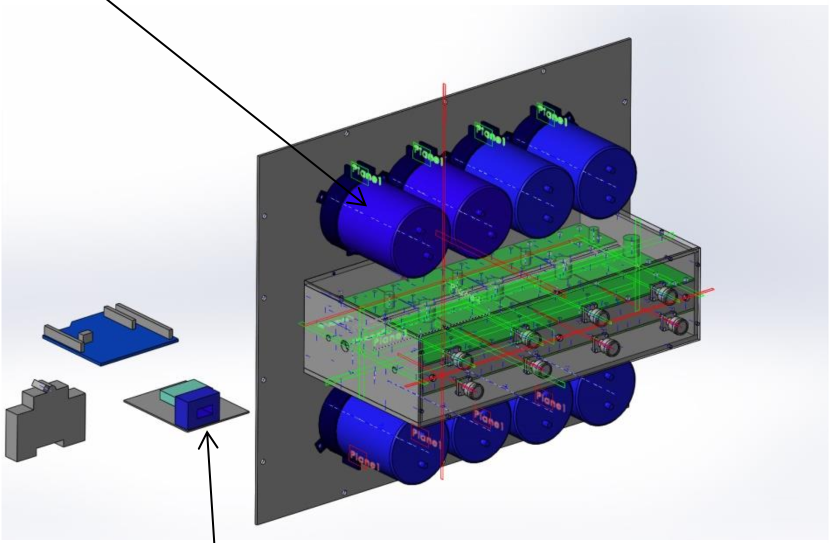
temperature rises for only few degrees, to about 30ºC

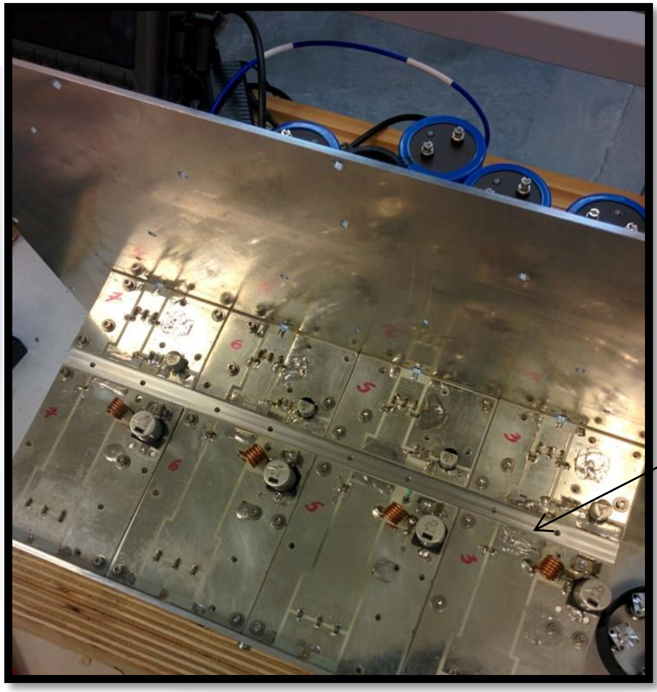
Hot S-parameters measured at different output power at 352MHz

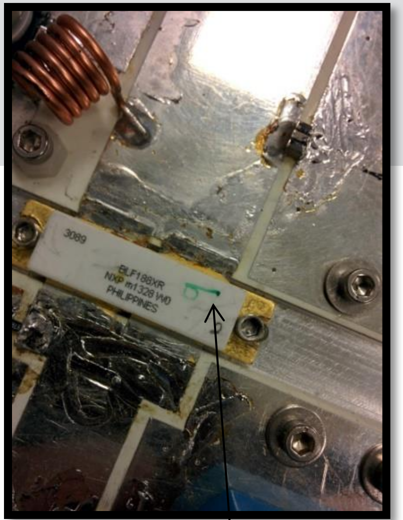


10 kW – SSA demonstrator

capacitor bank



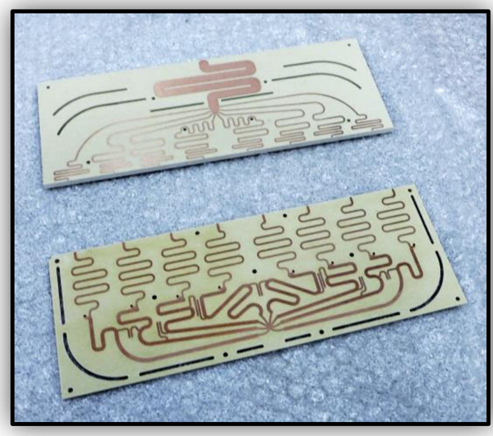




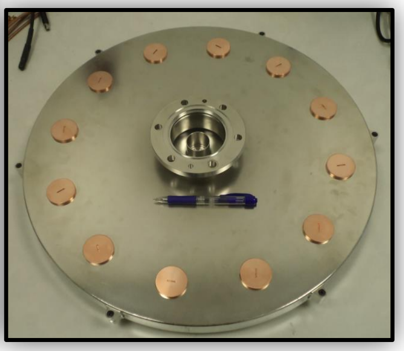
8 x 1.25 kW

Monitoring circuits:

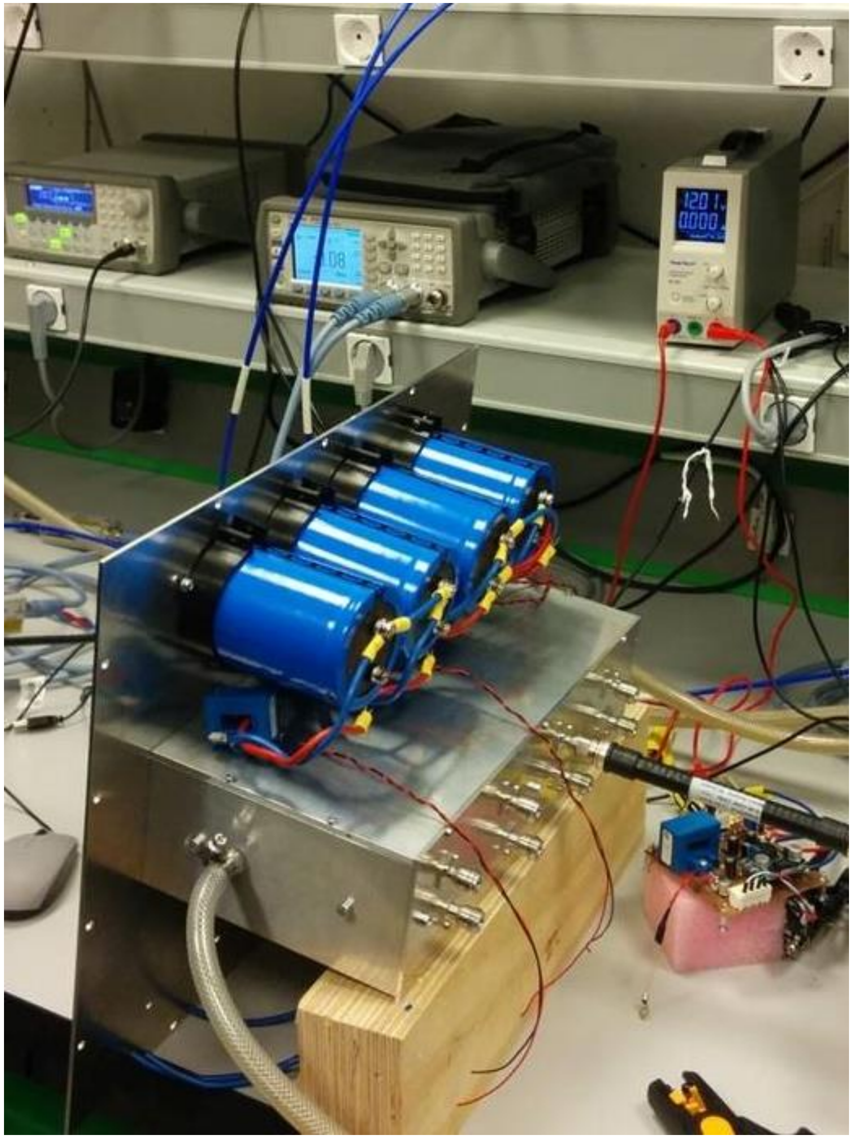
- drain voltage
- drain current
- temperature



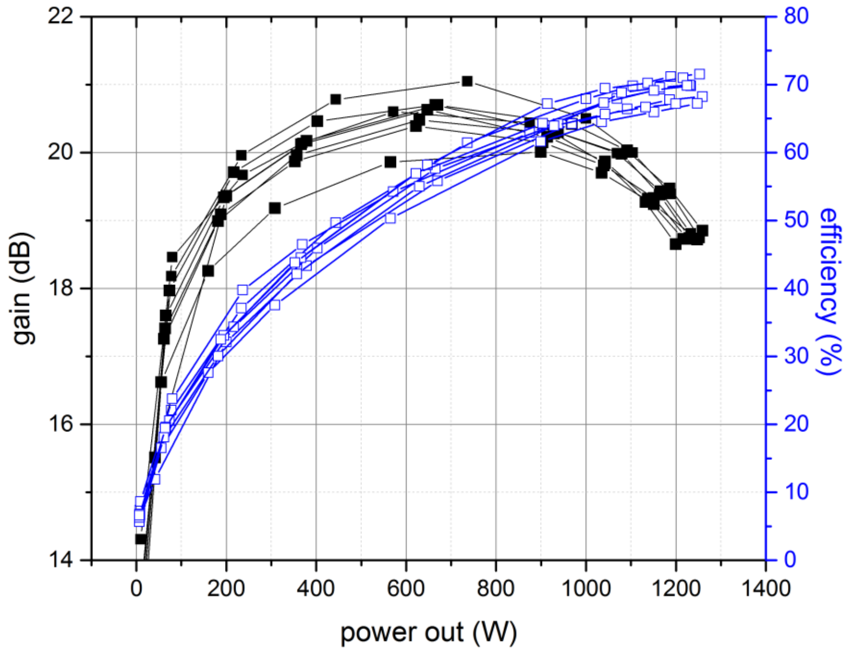
Combiners
Planar and WG

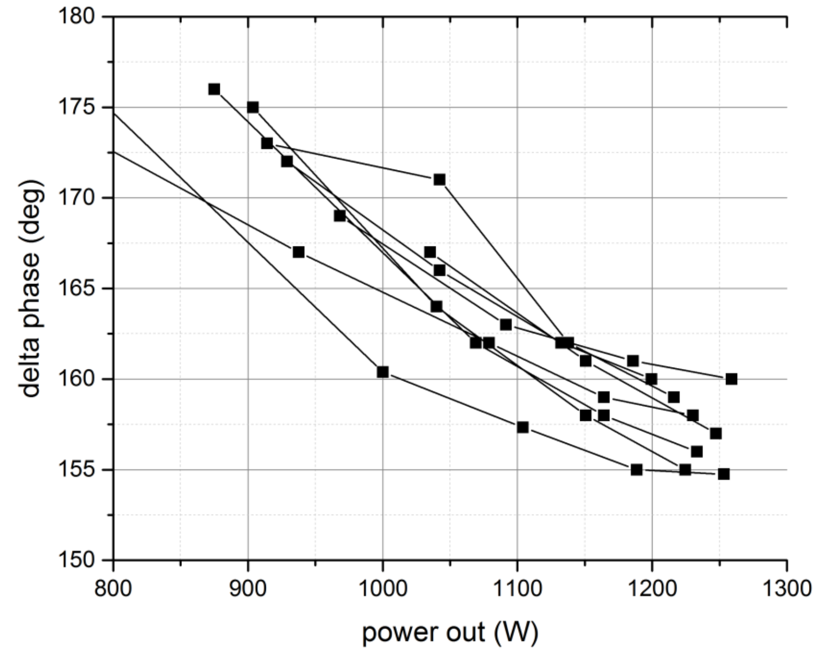


10 kW amplifier under construction



Drain efficiency and phase of the 8 modules of the 10 kW amplifier demo





A small variation in both gain (< 0.5 dB) and phase (< 5º) is measured for the 8 modules of the 10 kW demonstrator.

Efficiency is around 70% at 1250 W (pulsed conditions 14 Hz, 3.5 ms)

Phase measurements performed using the hot S-parameters set-up.

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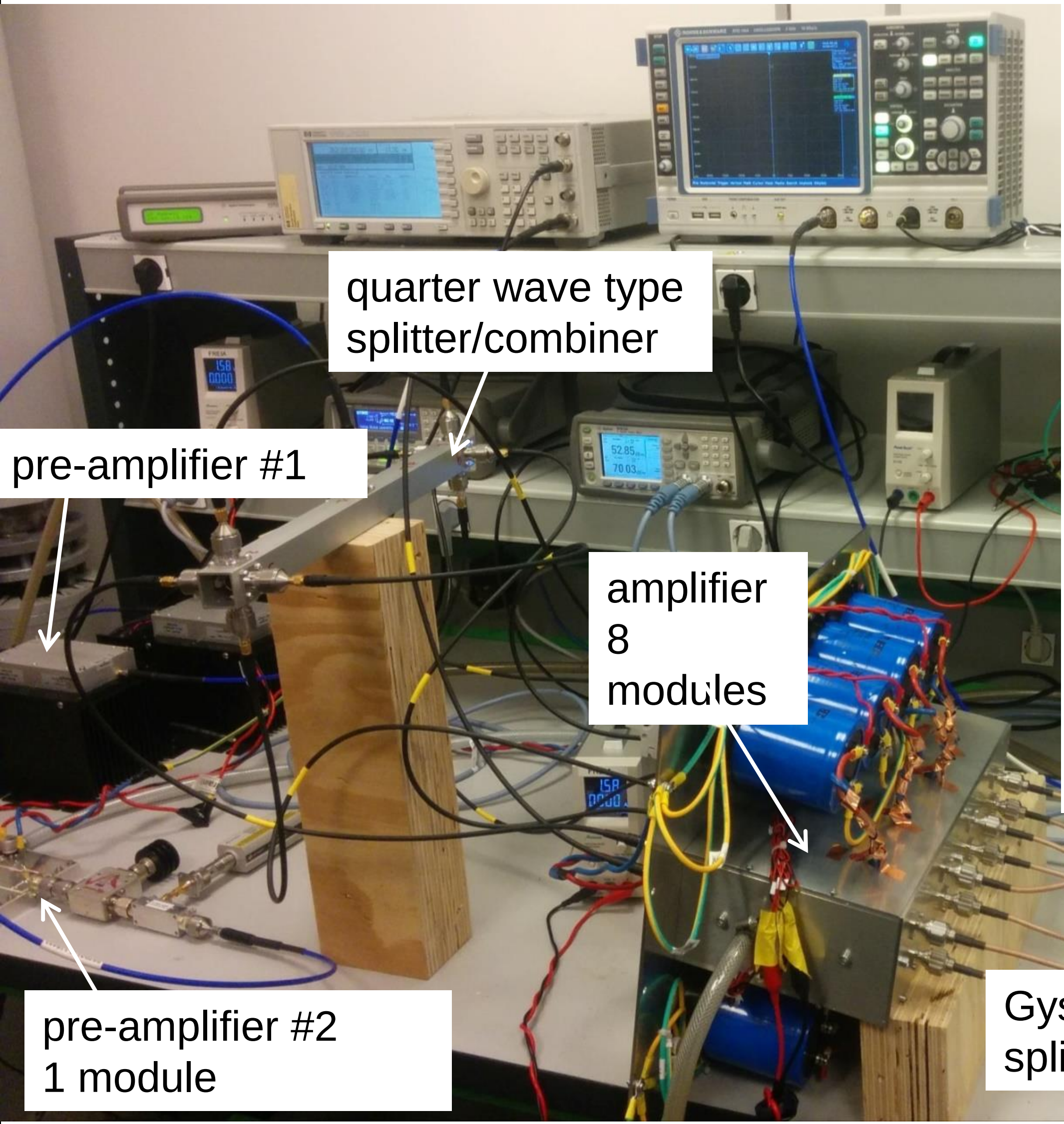
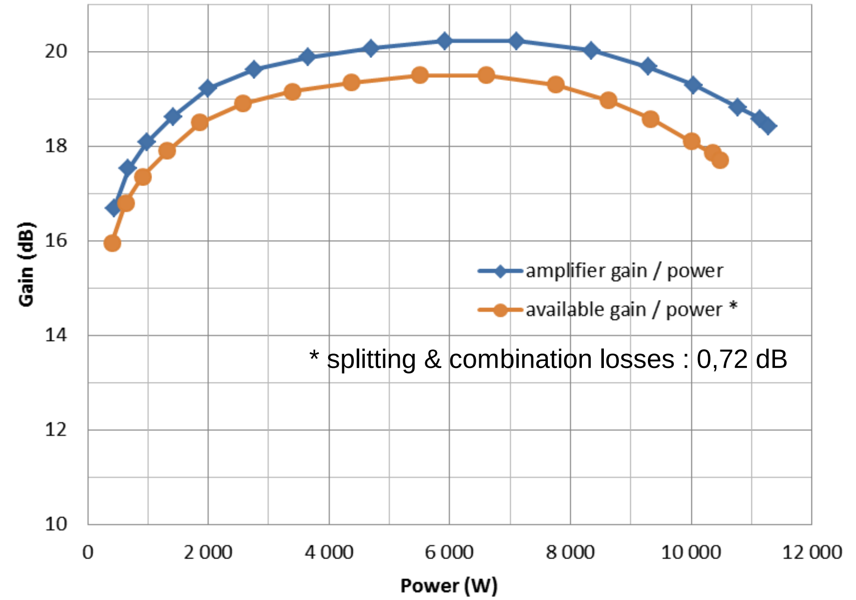
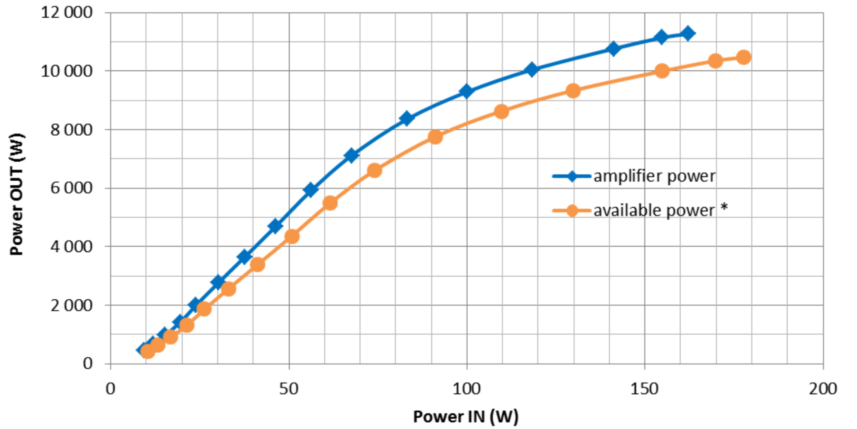
10 kW 352 MHz amplifier







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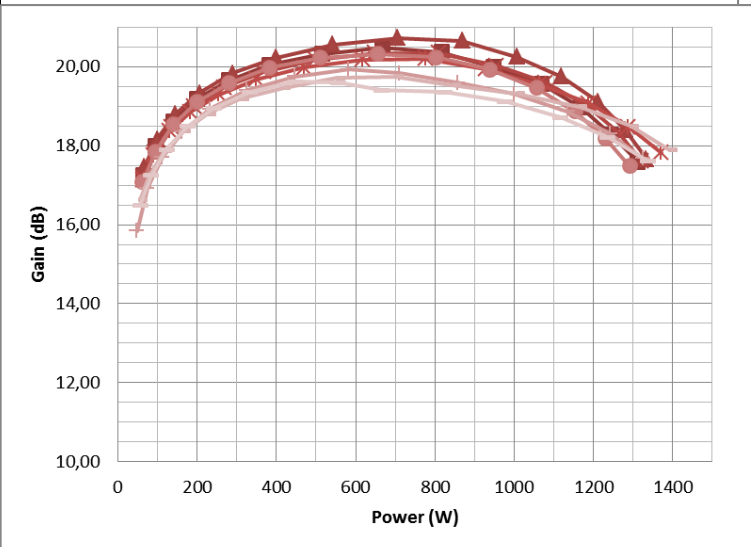
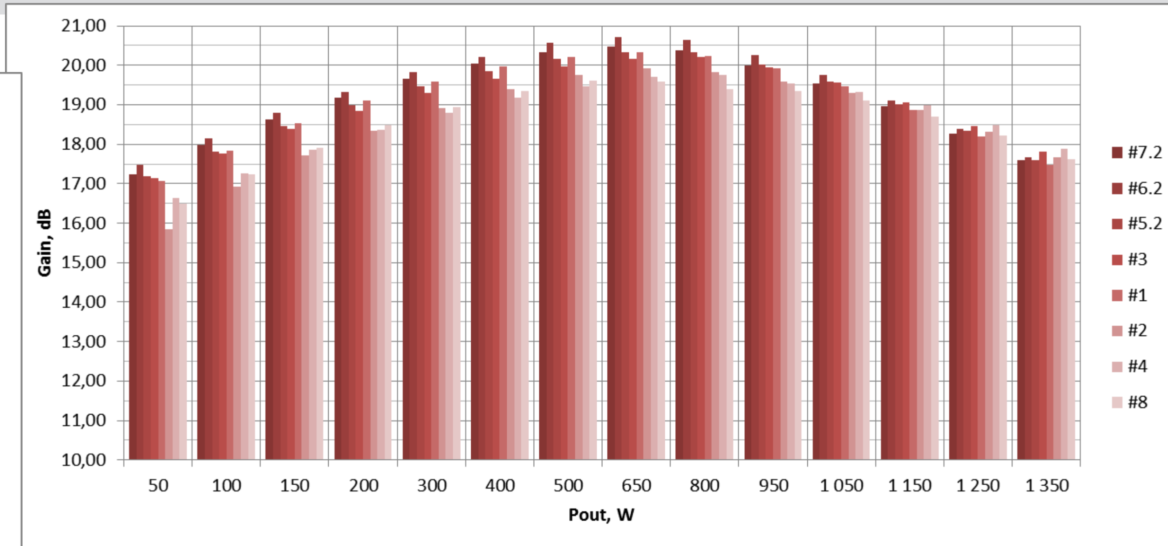
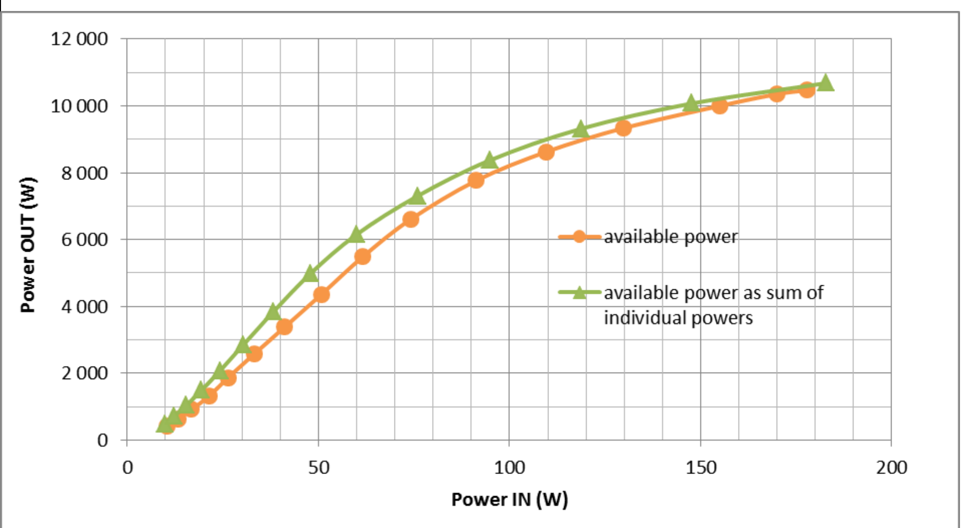
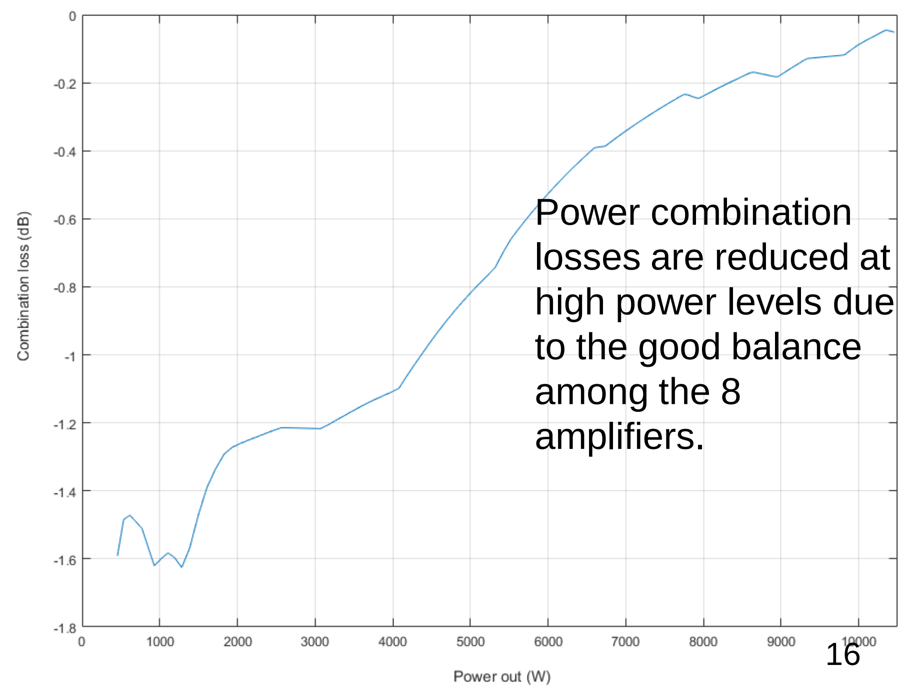
Spread among the 8 amplifiers









Power combination losses are reduced at high power levels due to the good balance among the 8 amplifiers.

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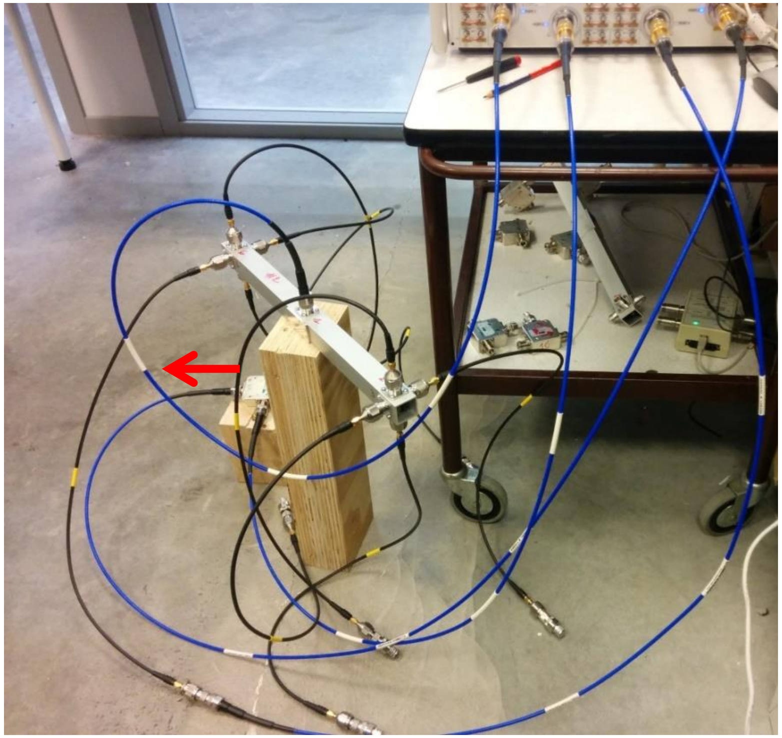
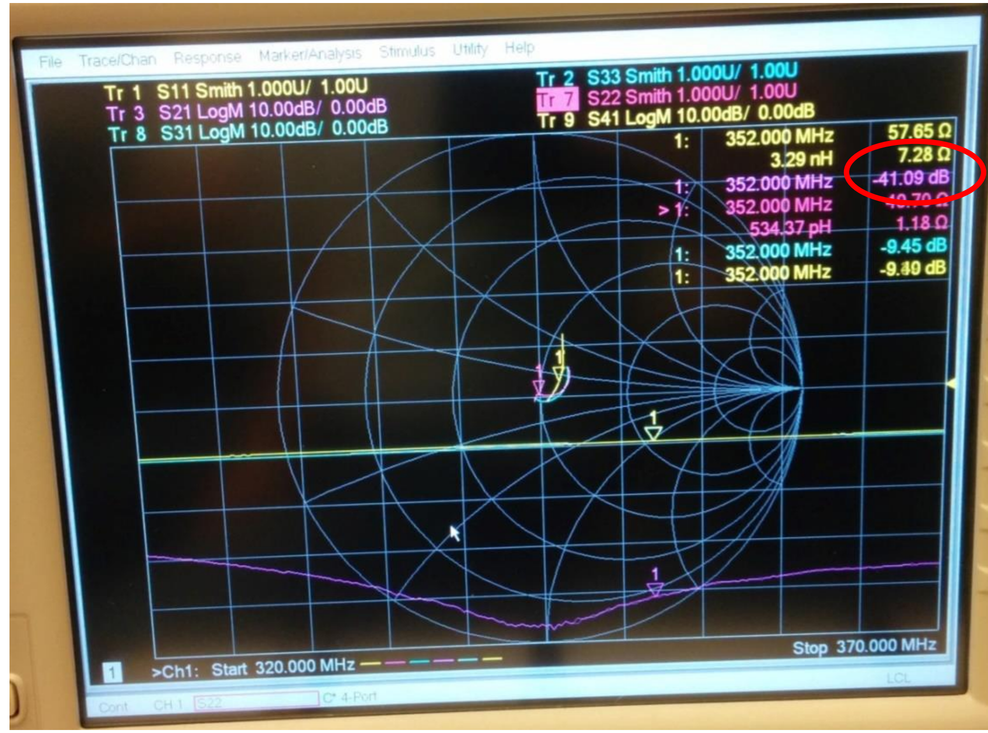
FREIA

8:1 λ/4 splitter/combiner





1:8 splitter connected to 8 loads.
Circulator is used to measure RL

RL is at -41 dB level
we can deduce the RL of the combiner at -32 dB

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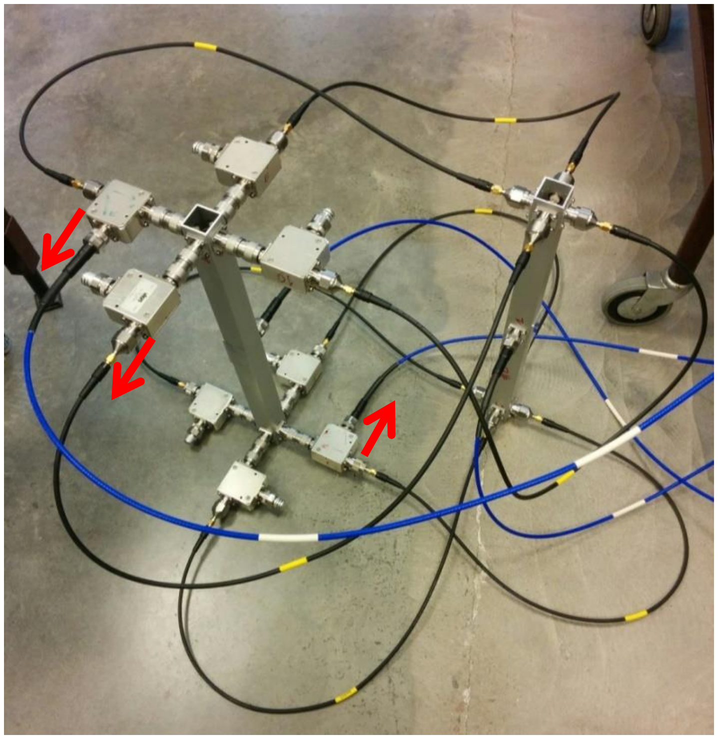
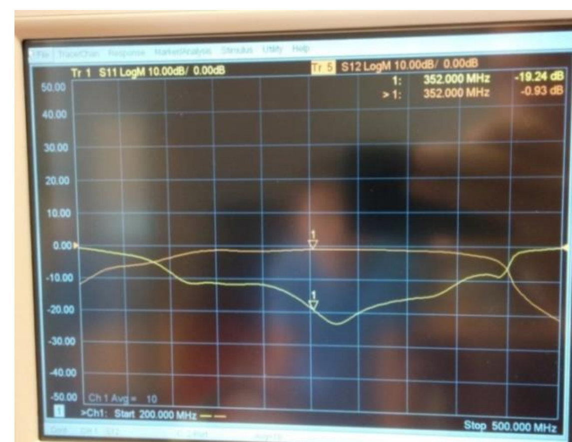
8:1 λ/4 splitter/combiner



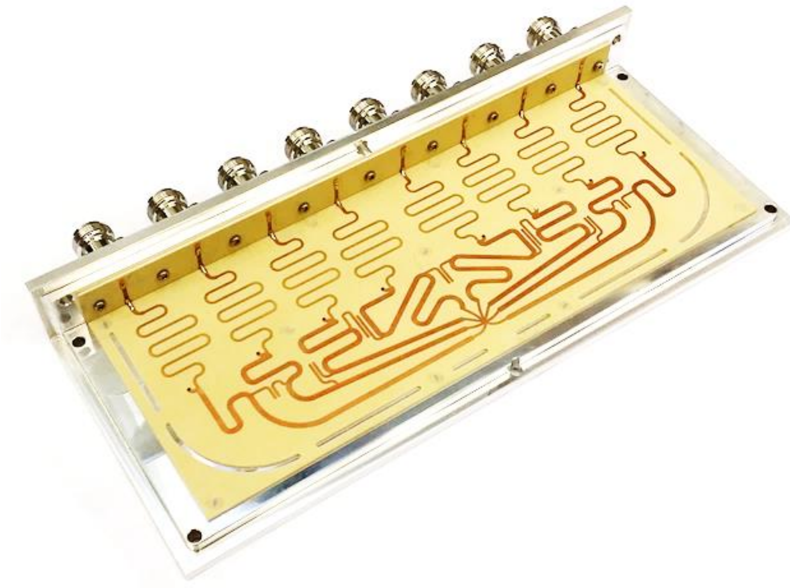
RL is at -28 dB level
considering 1:8 splitting/combination
we can deduce the RL of the combiner at -17 dB
higher RL due to slightly phase and amplitude imbalances

1:8 splitter connected with circulators to the 8:1 combiner

Measured IL 0.93 dB (with cables 0.3 dB and circulator 0.2 dB)
we deduce the splitter/combiner IL = 0.2 dB



Gysel Combiner



- Aluminum Casing
- High Integration Factor
- Integrated Loads
- Easily Reproducible
- Average Insertion Loss (IL): 0.2dB
- Peak Power (Tested): 10 kW

Measured Performance

	1	2	3	4	5	6	7	8
Phase [deg]	121	117	117	120	120	117	117	121
Mag [dB]	-9.24	-9.32	-9.24	-9.16	-9.19	-9.27	-9.29	-9.15

	1	2	3	4	5	6	7	8
1	-21*	-24.7	-23.7	-24.2	-24.1	-23.7	-23.4	-22.7
2		-24*	-27.5	-26.8	-26.3	-24.8	-24.9	-23.6
3			-21*	-26.4	-27.3	-25.2	-24.9	-23.3
4				-23*	-30.6	-27.1	-26.1	-24.1
5					-25*	-26.2	-26.5	-24.2
6						-25*	-27.1	-23.7
7							-26*	-24.9
8								-26*

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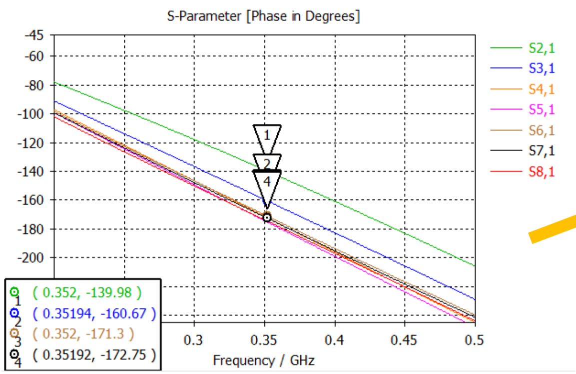
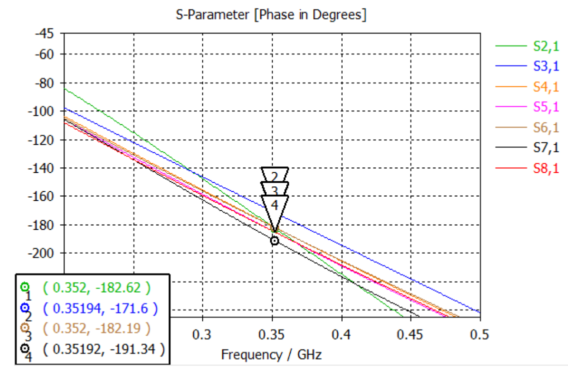
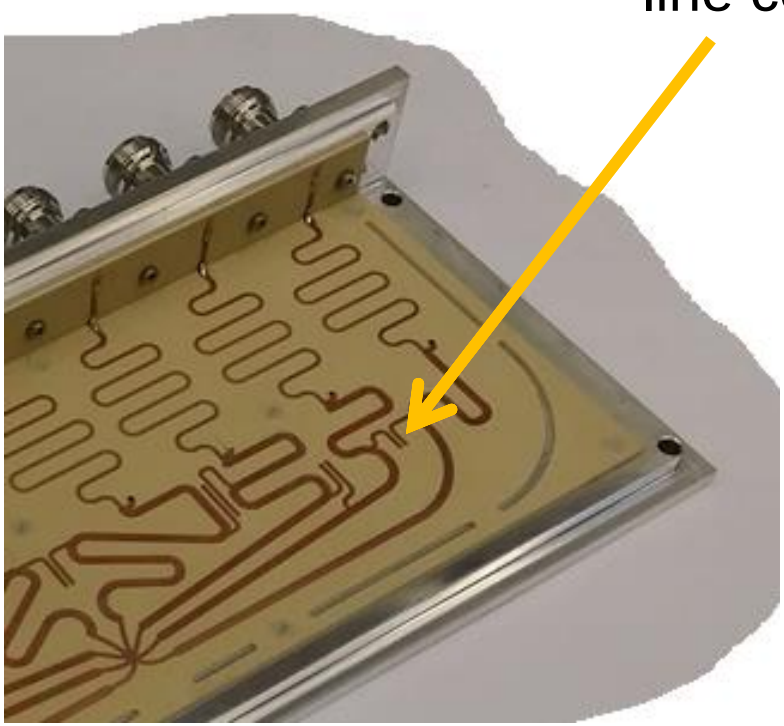
Gysel Combiner

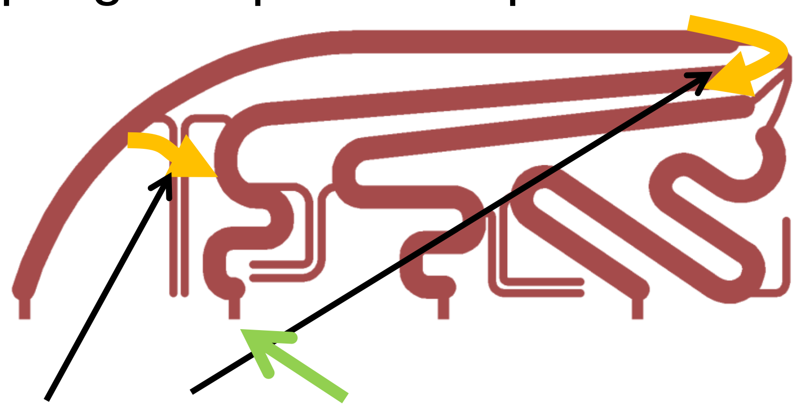


Phase Balancing



line coupling compensates parasitic coupling





$$U_{out}e^{-j(\omega t+\theta)} = U_0 e^{-j\omega t} + U_1 e^{-j(\omega t+\gamma)}$$

$$efficiency = 1 - (\alpha - \alpha^2) * \sin^2(\frac{\gamma}{2})$$

$$phase = -\mathrm{atan}(\frac{\sin(\gamma)}{({}^{1}/_{\alpha} - 1) + \cos(\gamma)})$$

FREIA development: 100 kW non-resonant power combiner with door-knob couplers

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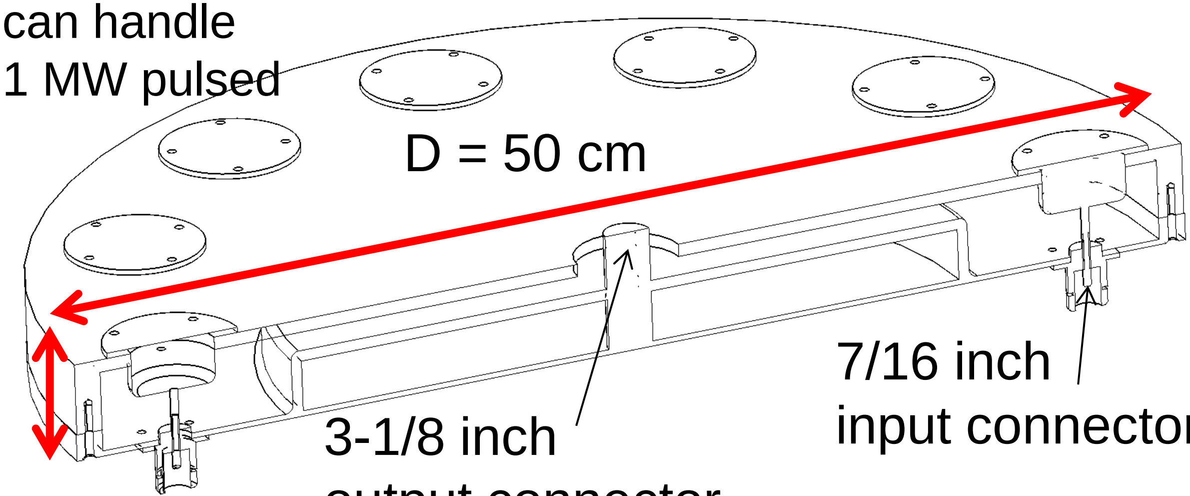
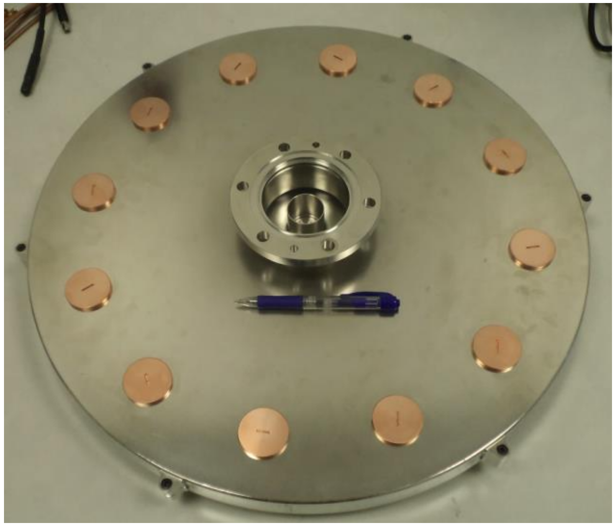
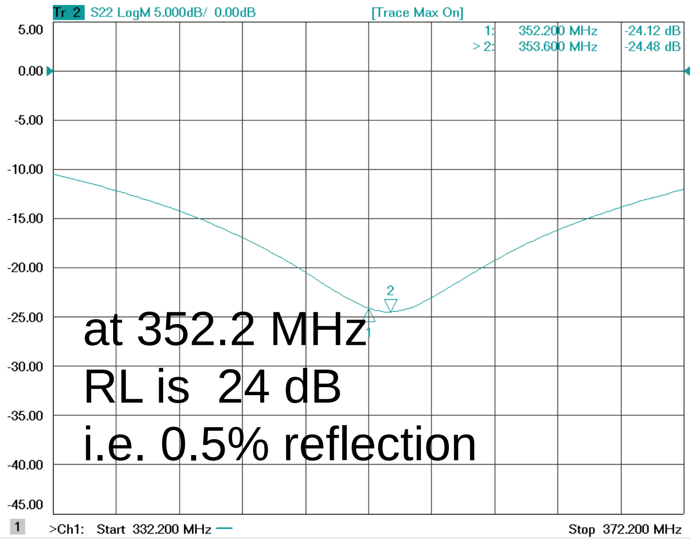
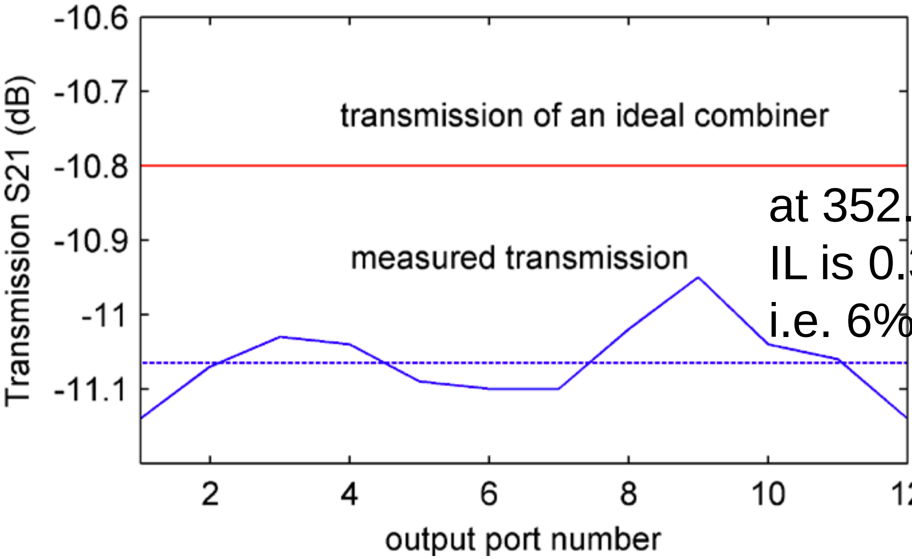
can handle
1 MW pulsed







at 352.2 MHz
RL is 24 dB
i.e. 0.5% reflection



at 352.2 MHz
IL is 0.3 dB
i.e. 6% losses

V.A. Goryashko, D. Dancila, A. Rydberg, R. Yogi & R. Ruber (2014): A megawatt class compact power combiner for solid-state amplifiers, Journal of Electromagnetic Waves and Applications, DOI: 10.1080/09205071.2014.962187

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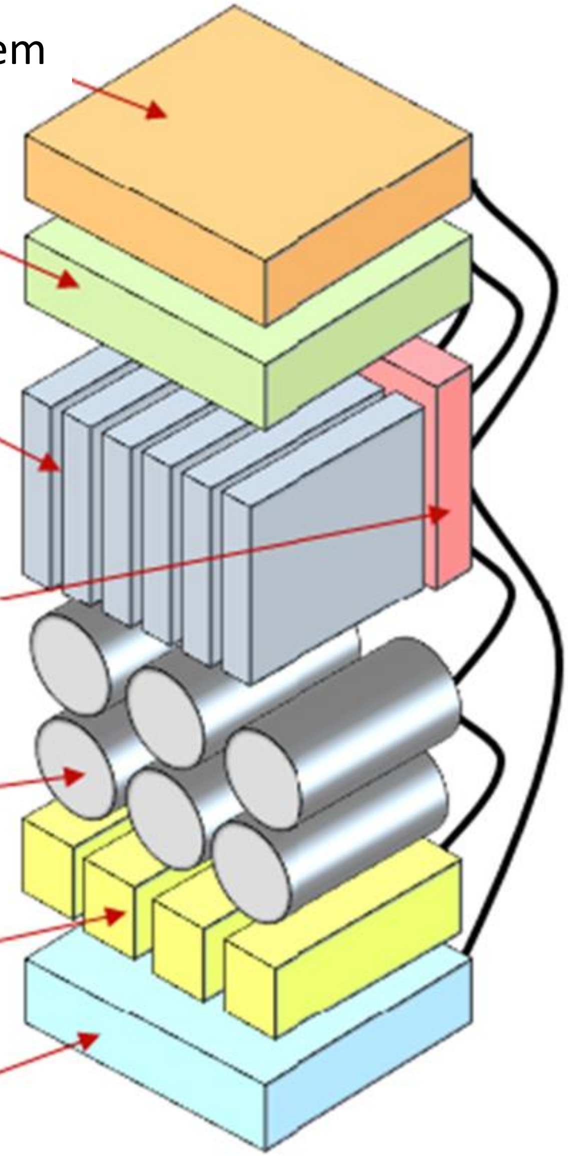
Collaboration



LLRF and
control system

Power splitting +
Power combiner

RF modules
(new transistors
new packaging
intelligent modules)

Connectors
RF + DC + water

(Capacitor tank)

ACDC convertors +
power supply

Water cooling system
(thermal aspects)

Business perspective:

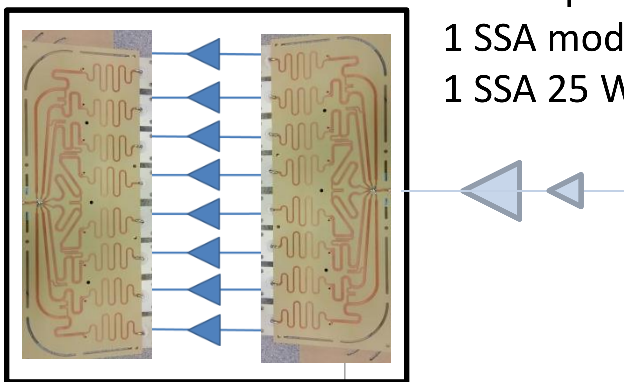
- commercialisation
- distribution

Strategy for power combining – v1

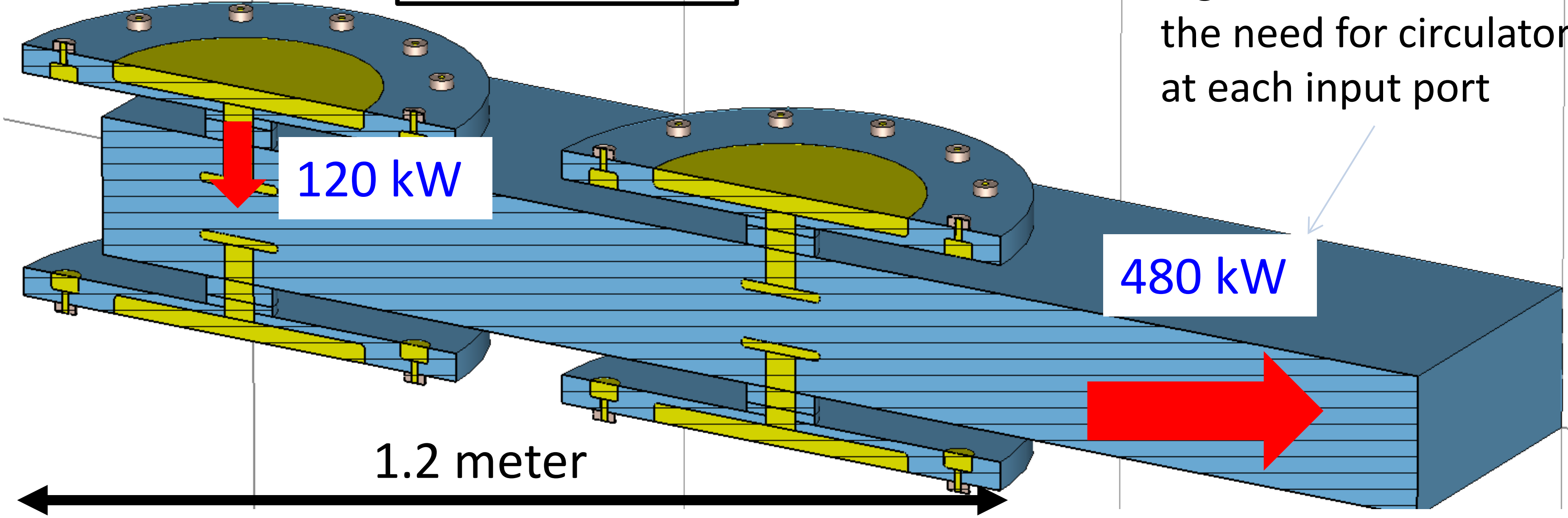
400 kW station
with major components
developed at FREIA

10 kW tile
8 SSA modules
Gysel combiner
& splitter 8:1

300 W pre-amplifier
1 SSA module
1 SSA 25 W amplifier



Standard WR 2300 for high power combining; broadband design, ultra high power handling capability; high isolation to avoid the need for circulators at each input port



Strategy for power combining – v2

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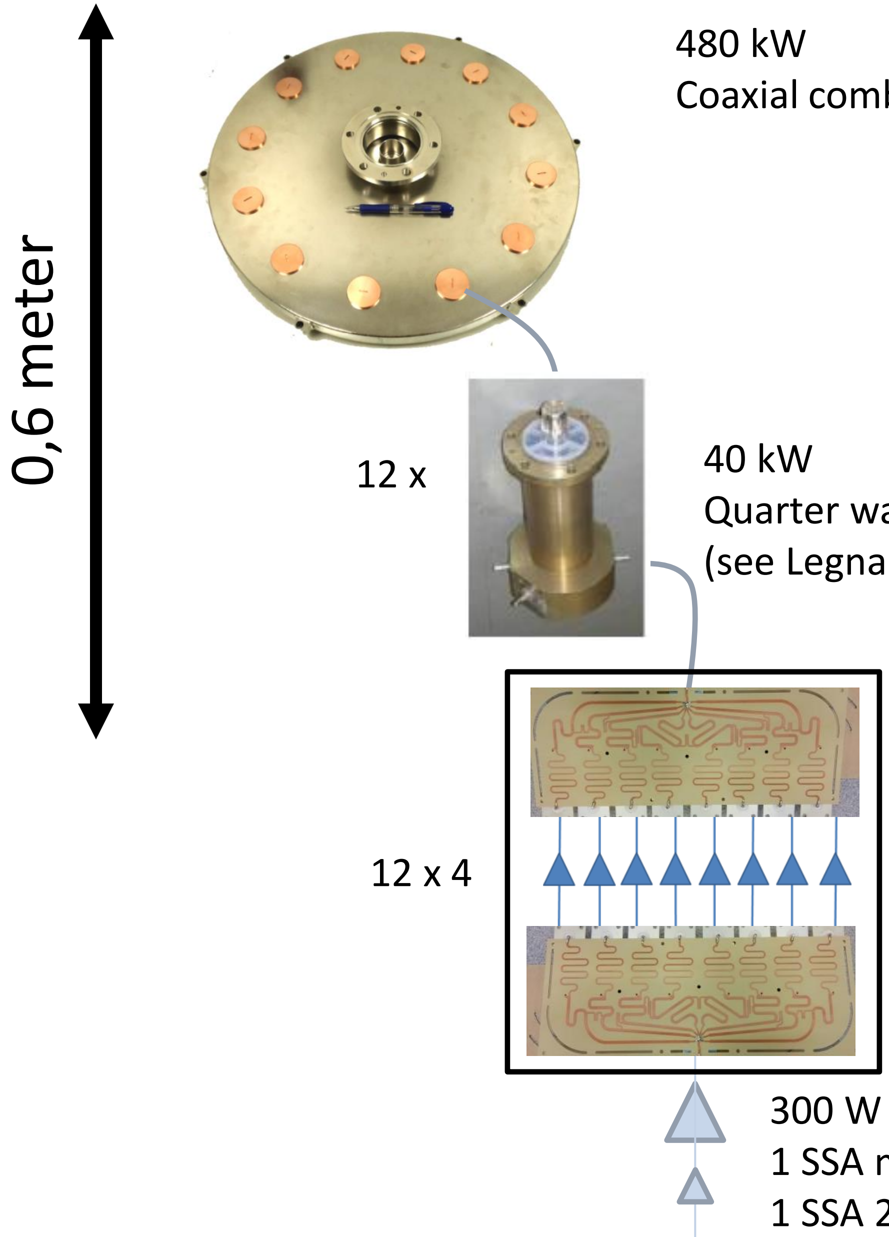
400 kW station
with major components
developed at FREIA



480 kW
Coaxial combiner 12:1

40 kW
Quarter wave combiner 4:1
(see Legnaro 4-ways)

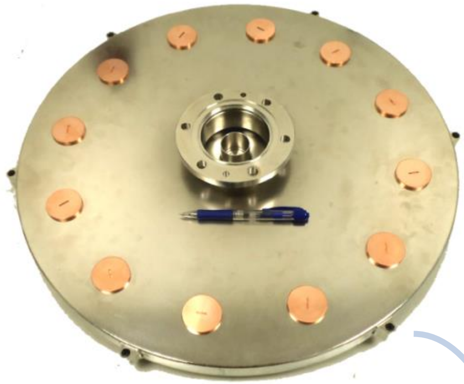
10 kW tile
8 SSA modules
Gysel combiner
& splitter 8:1

300 W pre-amplifier
1 SSA module
1 SSA 25 W amplifier

Strategy for power combining – v3

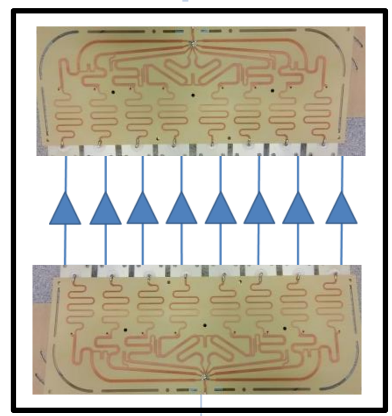
400 kW station
with major components
developed at FREIA

0,6 meter



400 kW
Coaxial combiner 40:1

40 x



10 kW tile
8 SSA modules
Gysel combiner
& splitter 8:1

300 W pre-amplifier
1 SSA module
1 SSA 25 W amplifier

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Conclusions

- A single ended high RF power Solid-State Amplifier was successfully designed and manufactured producing 1.25 kW with an efficiency of 70% at 352 MHz, in ESS operational mode (14 Hz, 3.5 ms). This is a simple and robust design minimizing manufacturing cost towards mass fabrication and industrialization. Joint UU - Ampleon application note.
- Measurement methods have been developed and implemented allowing hot S-parameters measurements.
- A small variation in both gain (< 0.5 dB) and phase (< 5º) is measured for the 8 modules of the 10 kW demonstrator under construction at FREIA.
- A 10 kW demonstrator, using 8 modules is finalized at FREIA. Monitoring circuits and power combiners are under development.
- <u>Strategy for the near future</u>: highly efficient class E amplifiers at 100 MHz for GE's cyclotron nucleotides production – Eurostars application; possibly 400 MHz (for CERN crab cavity tests); development and amplifier design of Latch-Free LIGBT/IGBT high power transistors at UU – Comheat AB (compared with LDMOS, saturation current is presently 15-30 times higher).

Joint UU - Ampleon application note on BLF188XR's site