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iFAST

New RF Amplifiers based on GaN Semiconductors

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on behalf of the FREIA laboratory

Workshop on efficient RF sources

04-06 July 2022, CERN, Chateau de Bossey, Switzerland

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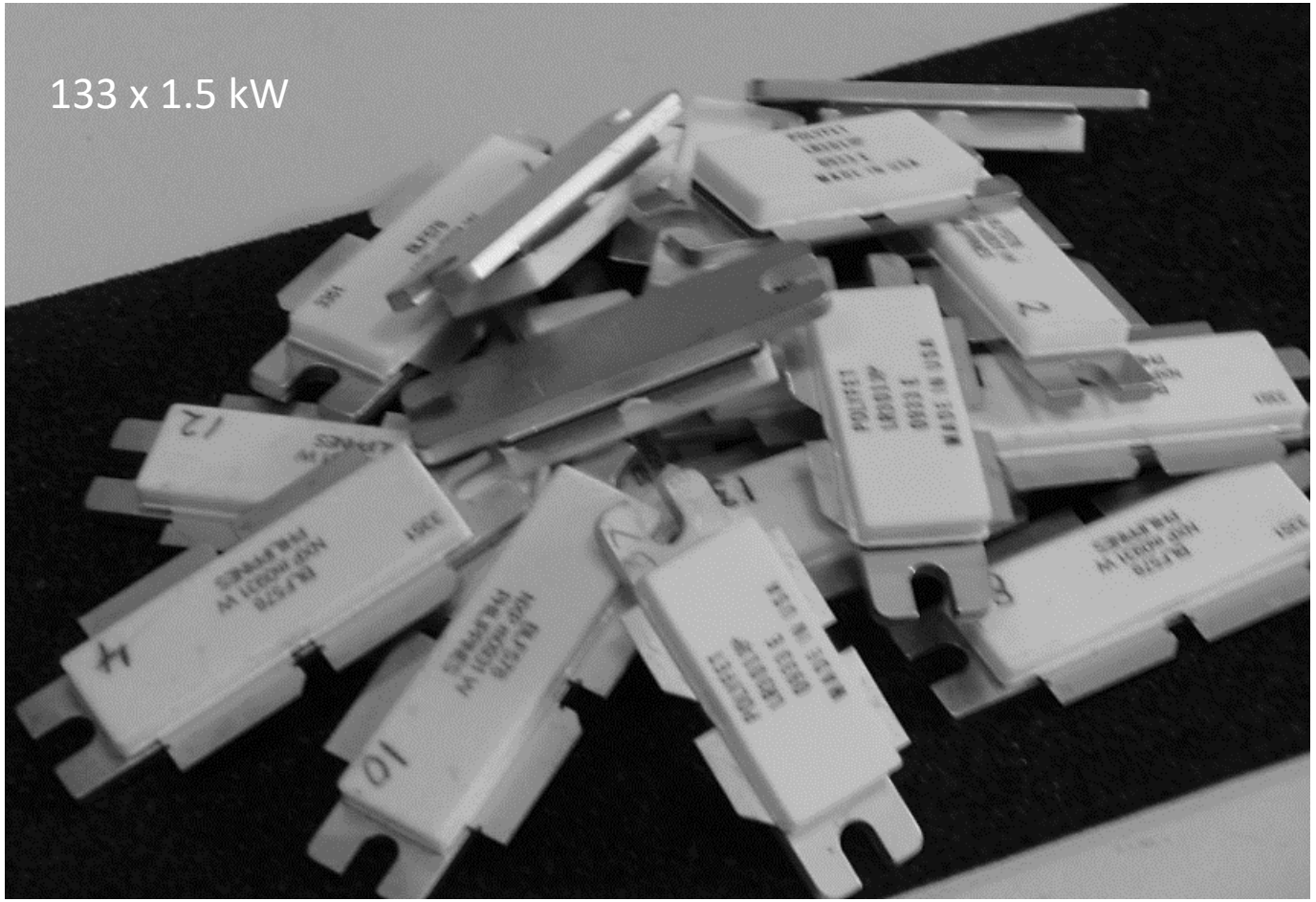
Research Programme @ FREIA on SSPAs improve SoA of transistor amplifiers for accelerators



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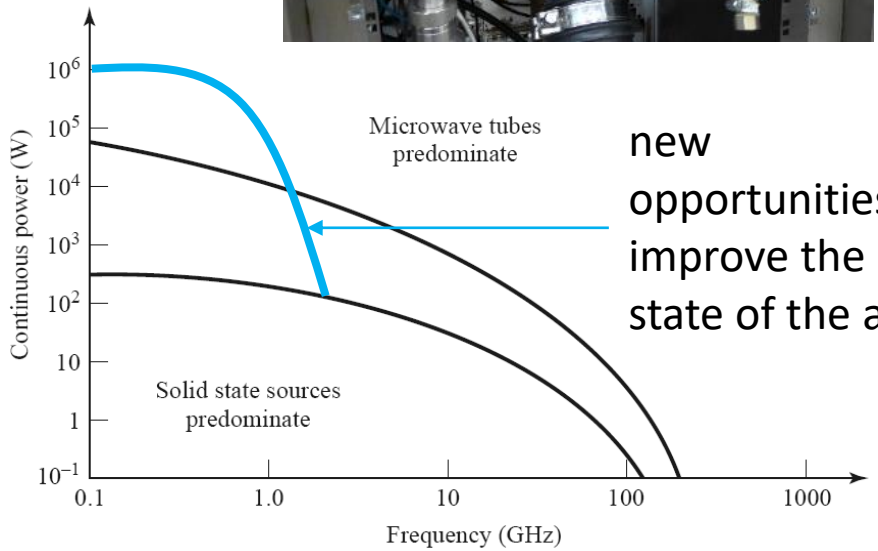

new opportunities to improve the state of the art !

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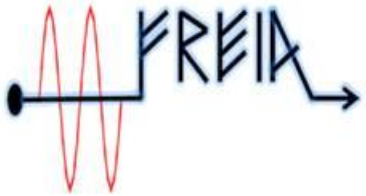
SSPA projects at FREIA*



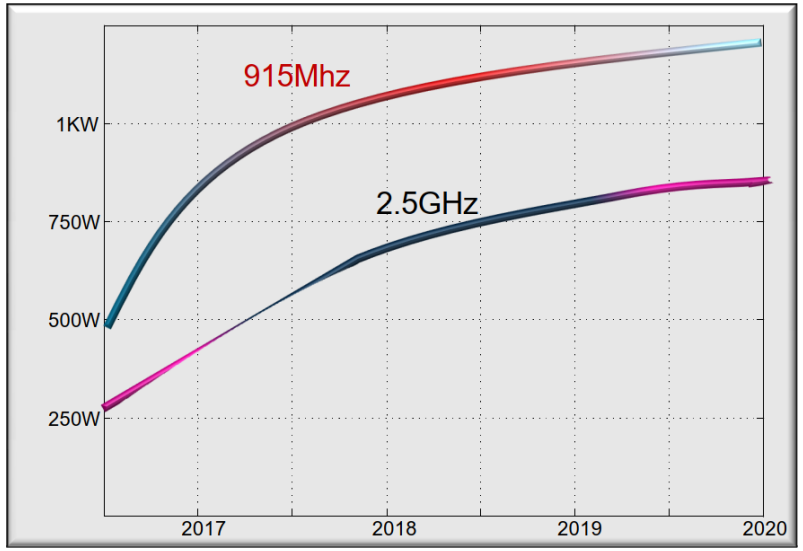
- 352 MHz – ESS
  - 1.25 kW module – single ended architecture
  - Gysel combiner 10 kW
  - 10 kW 5% DC – prototype
  - Gysel combiner 20 kW – air stripline technology
  - 100 kW non-resonant circular power combiner
- 27 MHz – 1 kW module GE Healthcare – EUROSTARS project
- 100 MHz – 10 kW amplifier GE Healthcare – EUROSTARS project

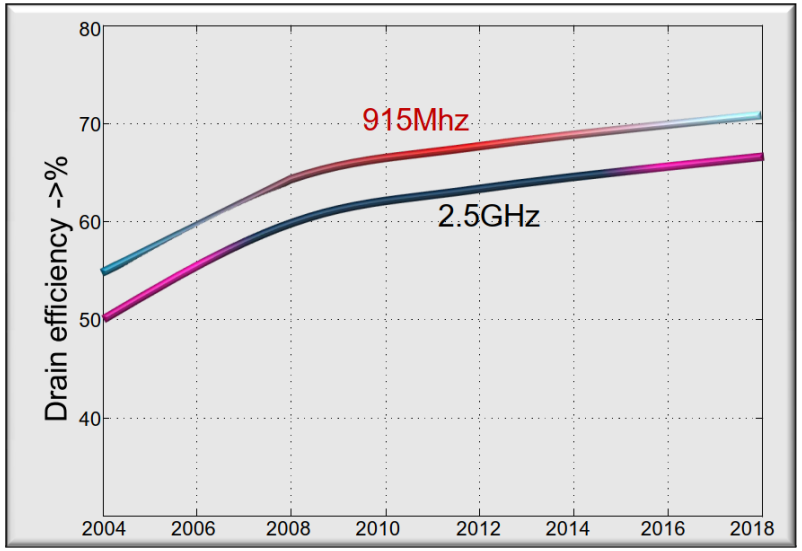
AMPLEON

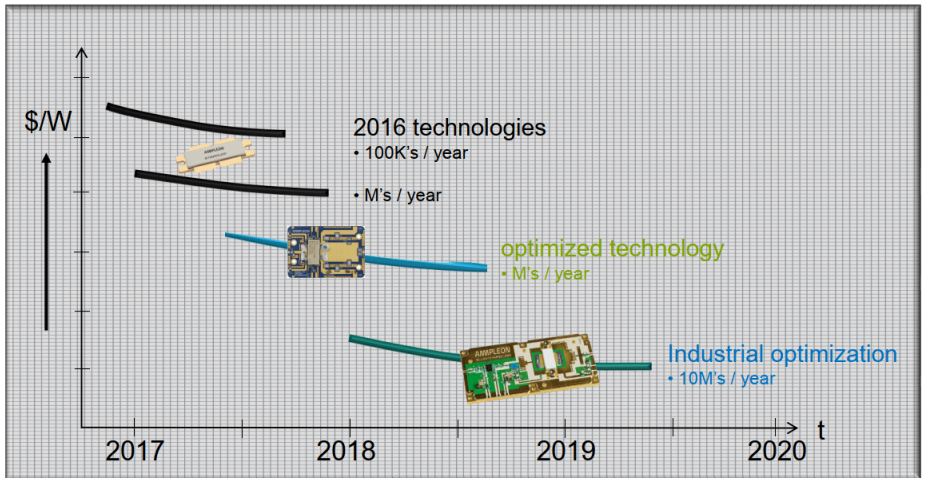
eurostars™

*all are previous LDMOS developments

Power development LDMOS transistors e.g. AMPLEON







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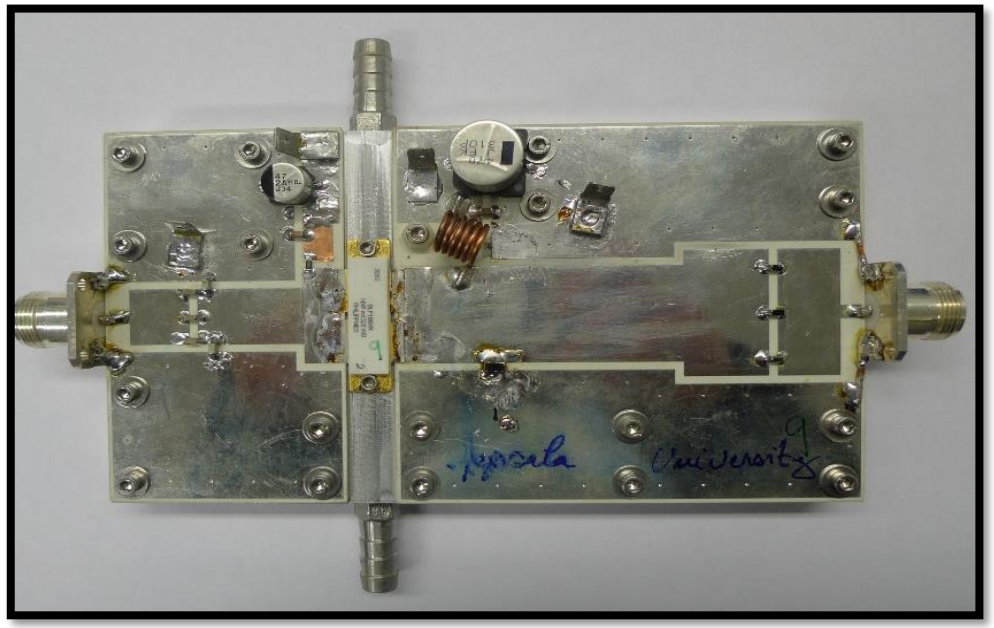
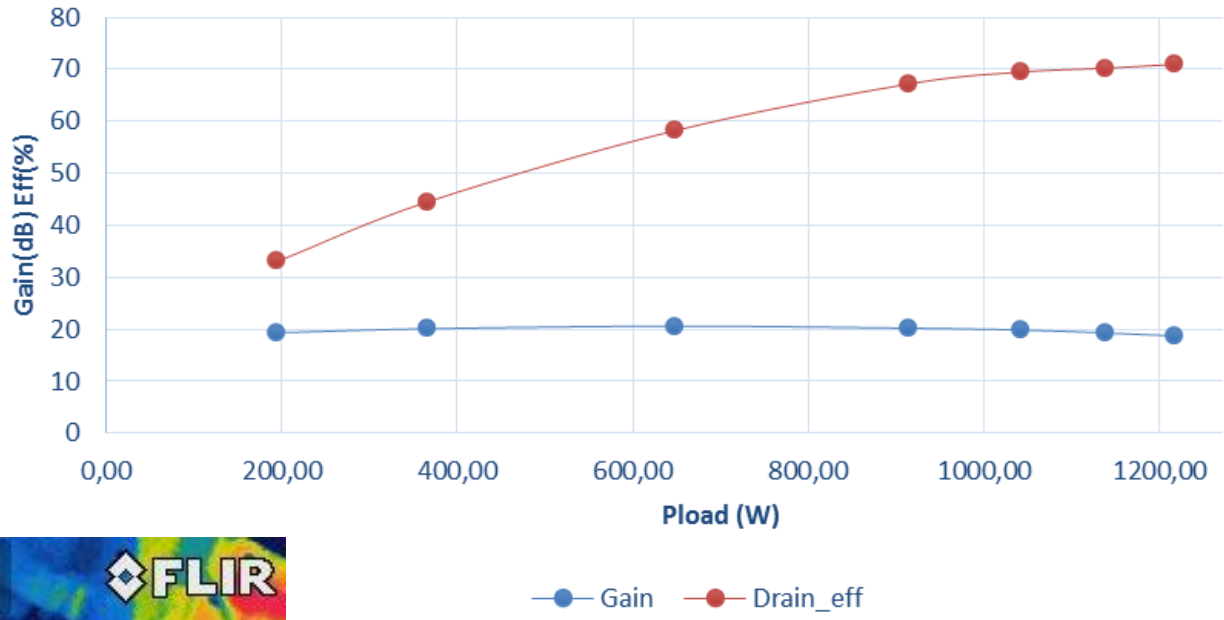
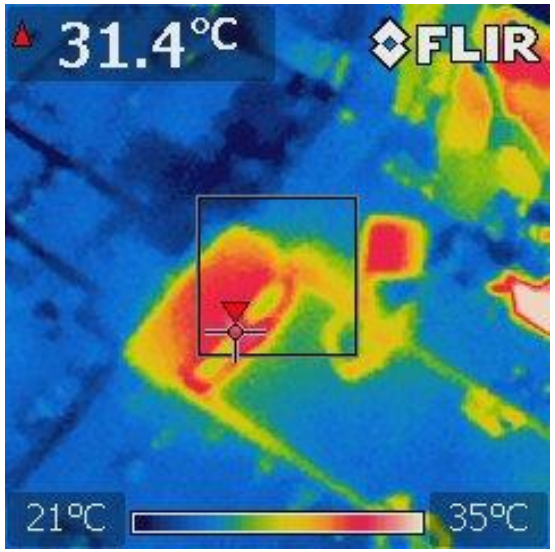
Single ended RF power amplifier 352 MHz 1250 kW - 70% eff.

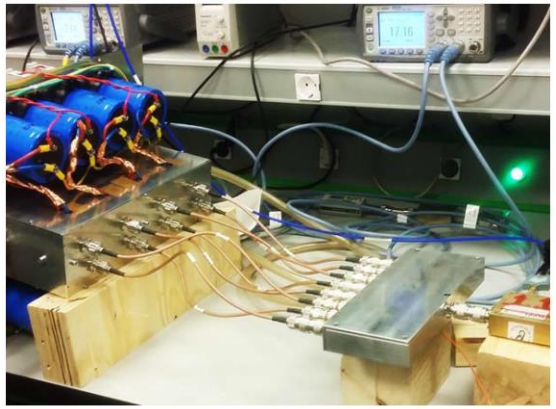






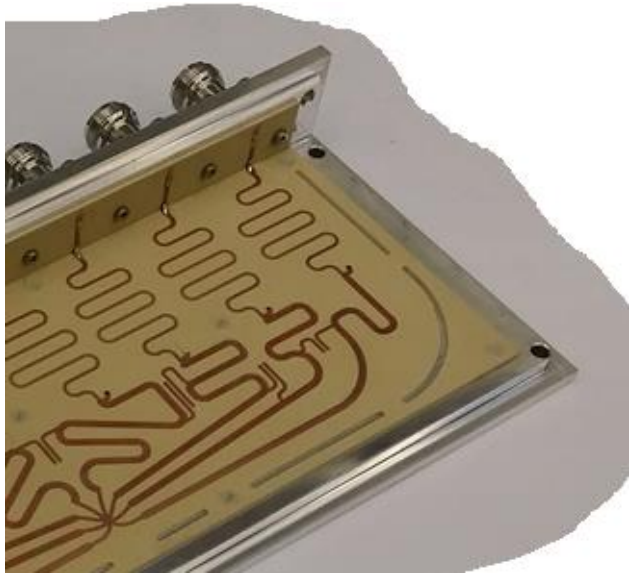
L. Haapala, A. Eriksson, L. D. Hoang and D. Dancila, "Kilowatt-level power amplifier in a single-ended architecture at 352 MHz," 2016, Electronics Letters, Vol. 52, no 18, p.1552-1553.

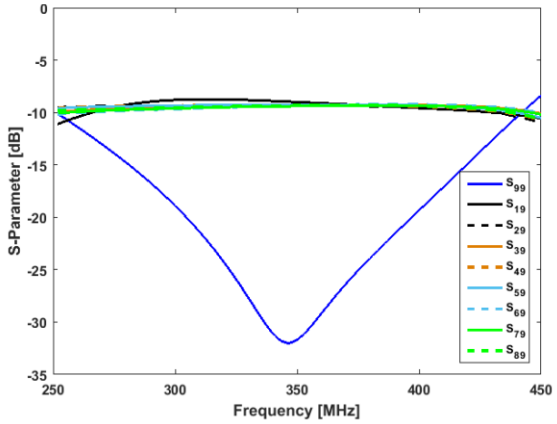
Gysel Power Combiner 10 kW

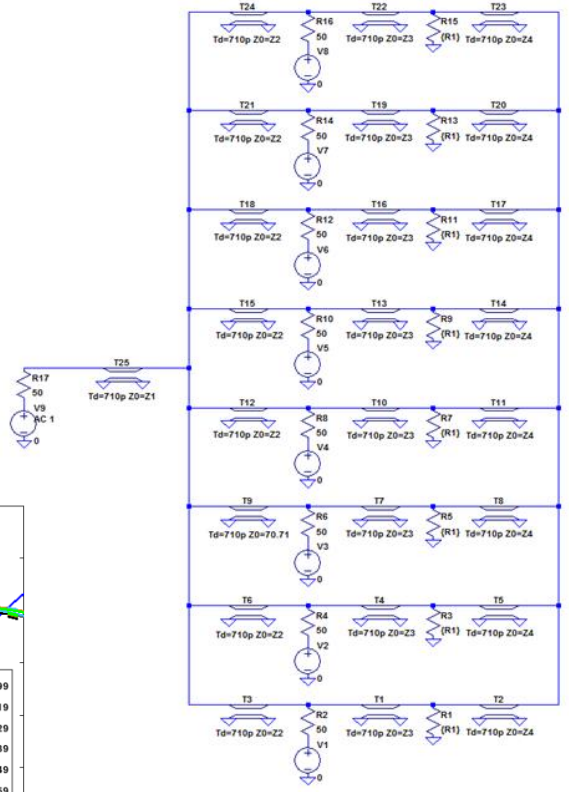


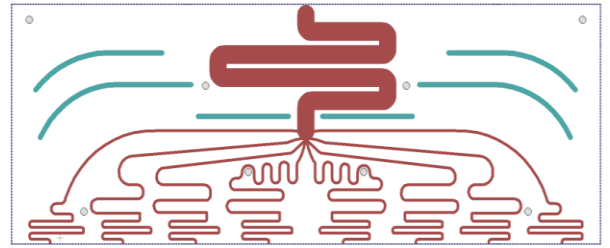
Key Parameters

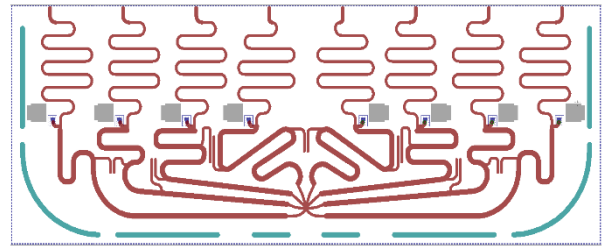
- S_{NN} < -20 dB
- Losses < 0.1 dB
- High Power Handling
- 240 x 100 x 30 mm

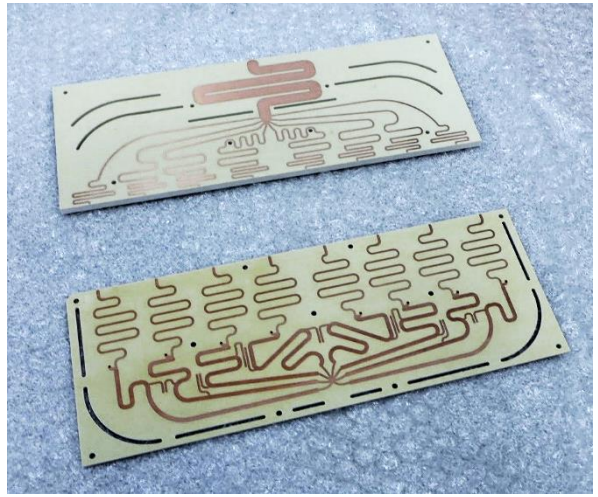






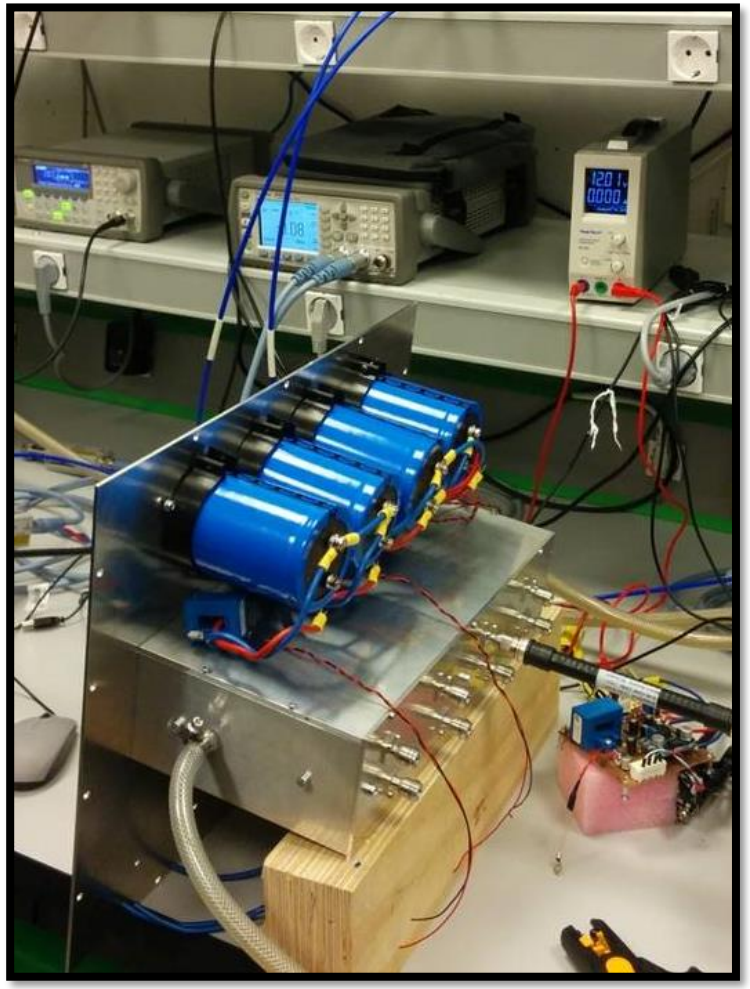


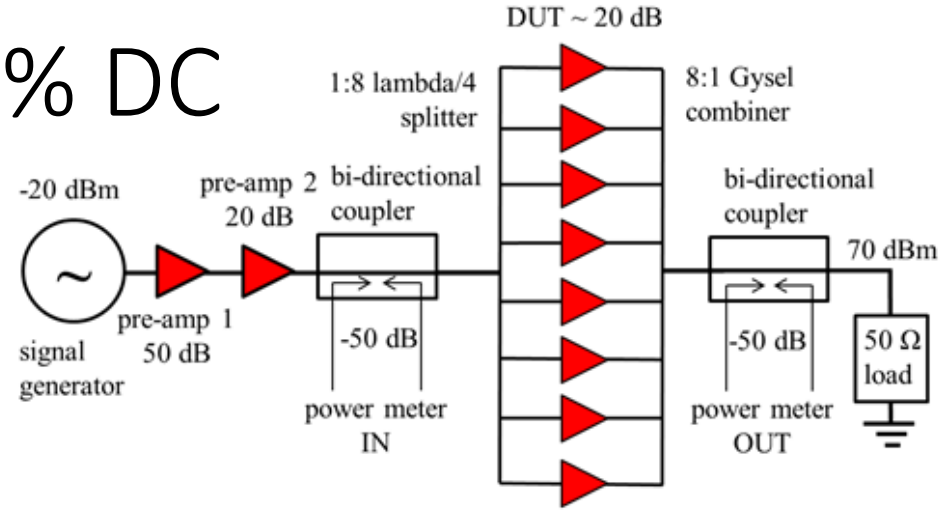


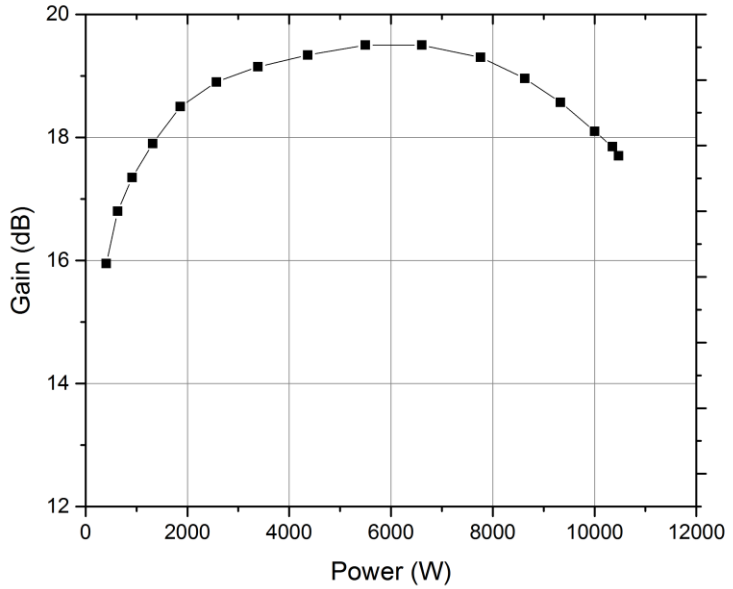


M. Jobs, D. Dancila, J. Eriksson and R. Ruber, "An 8-1 Single-Stage 10-kW Planar Gysel Power Combiner at 352 MHz," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 8, no. 5, pp. 851-857, May 2018.

10 kW HPA 352 MHz pulsed 5% DC

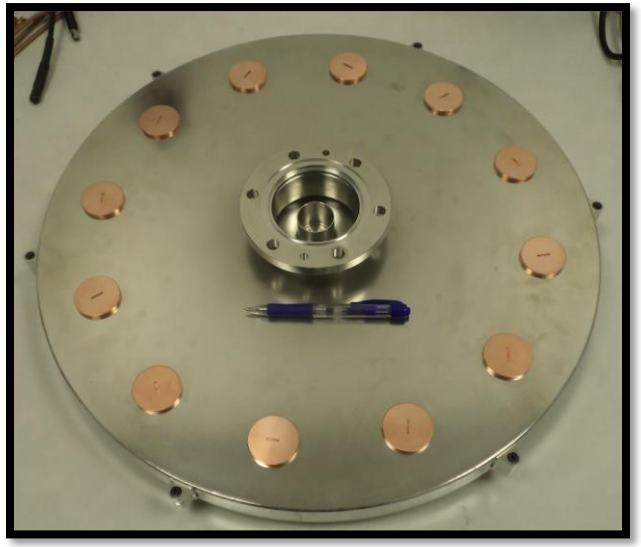




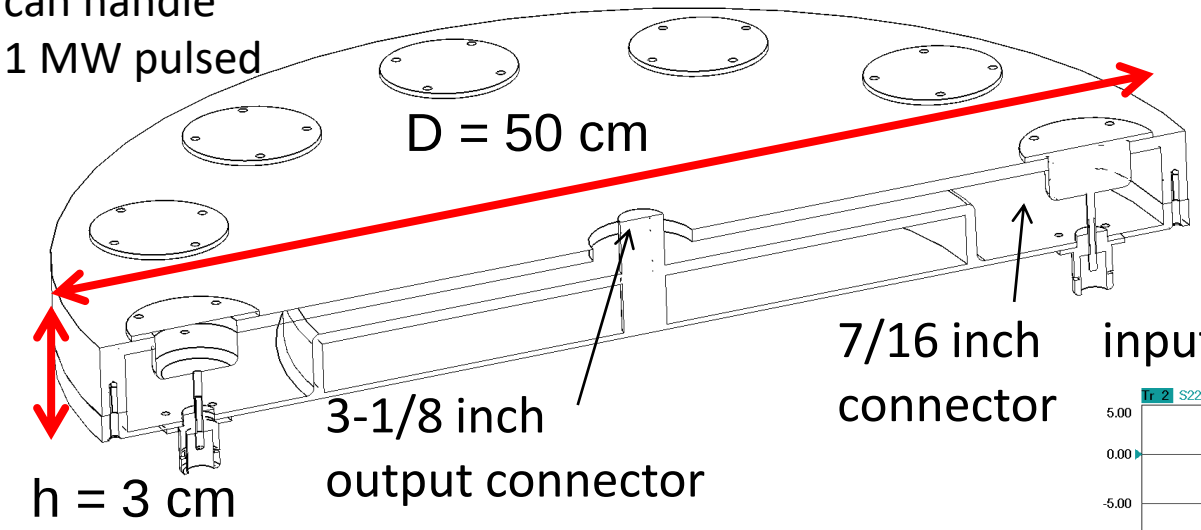


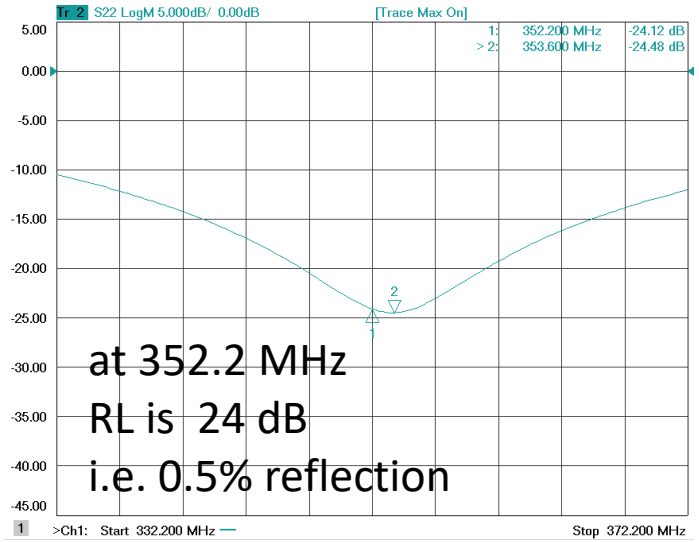
D. Dancila et al, "A compact 10 kW solid-state RF power amplifier at 352 MHz," 2017 IOP Conf. Series: Journal of Physics: Conf. Series, vol. 874, 012093

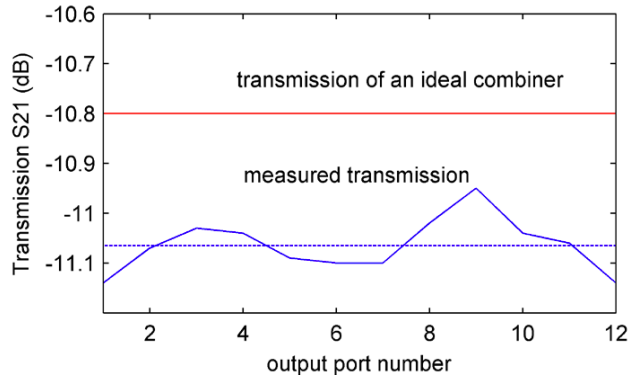
100 kW non-resonant power combiner with door-knob couplers at 352 MHz



can handle
1 MW pulsed



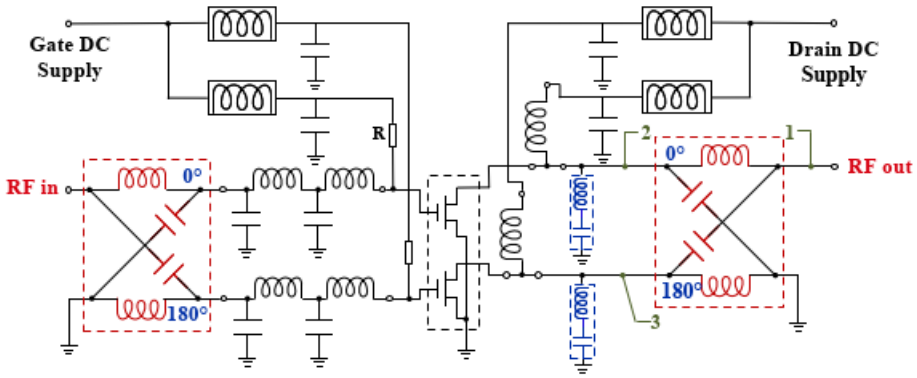


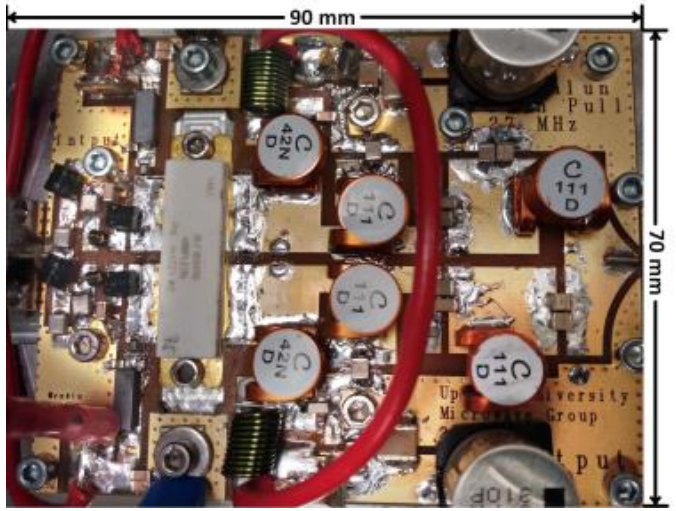


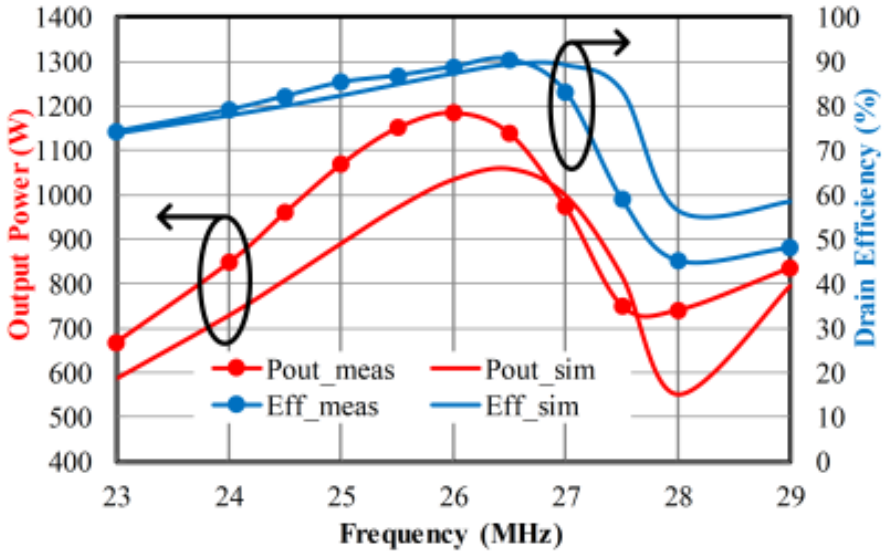
at 352.2 MHz
IL is 0.3 dB i.e. 6% losses

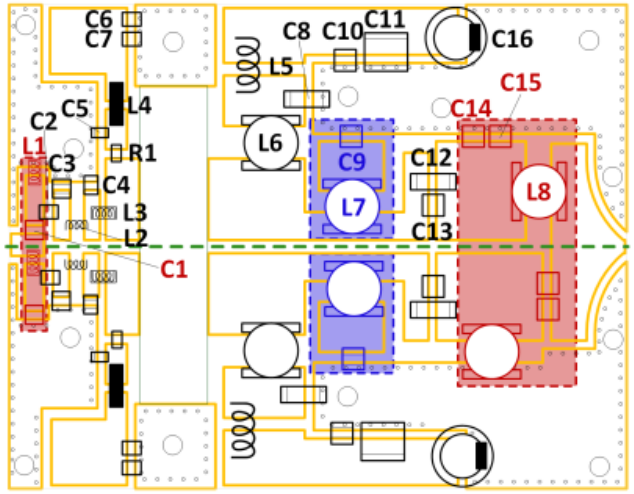
V. A. Goryashko, D. Dancila, A. Rydberg, R. Yogi & R. Ruber (2014): A megawatt class compact power combiner for solid-state amplifiers, Journal of Electromagnetic Waves and Applications.

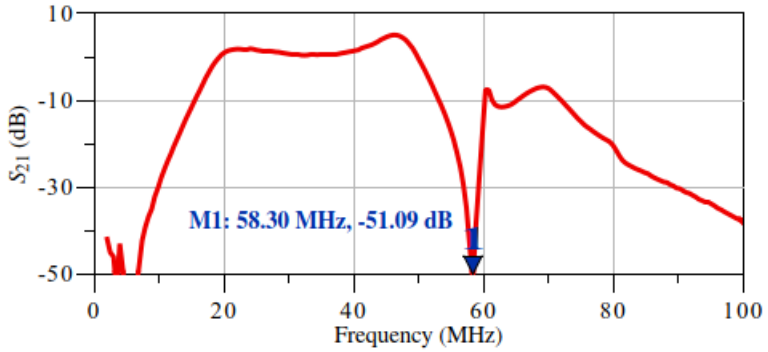
SSPA at 27 MHz – 1kW – 90% eff.





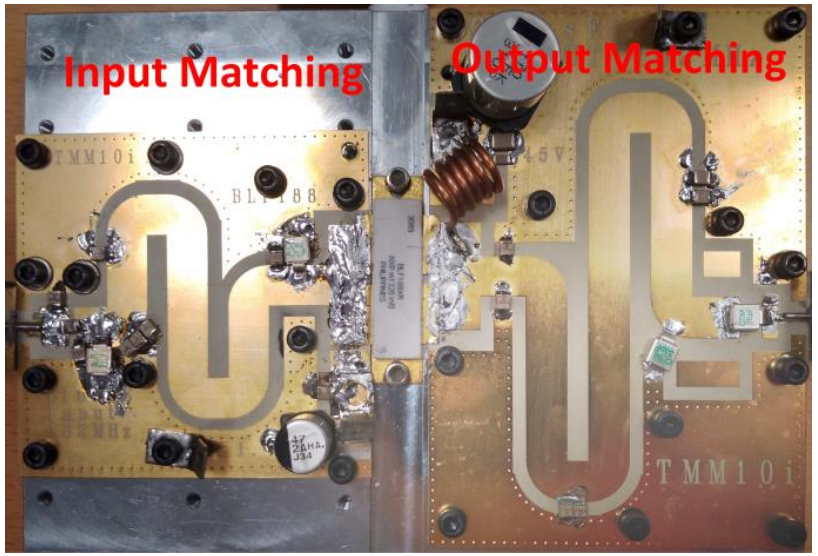






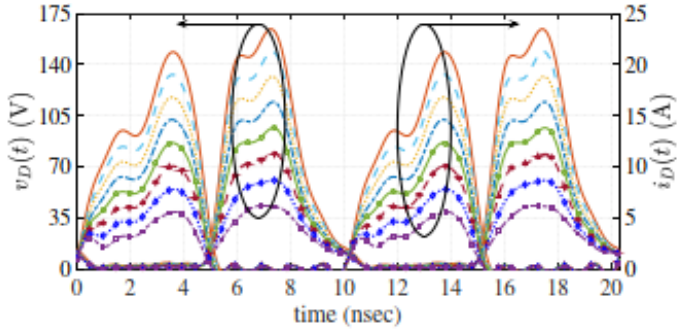
R. Tong and D. Dancila, “Compact and Highly Efficient Lumped Push-pull Power Amplifier at Kilowatt level with Quasi-static Drain Supply Modulation” in IEEE Transactions on Microwave Theory and Techniques, 2020.

SSPA design principles at 100 MHz – 1kW – 93% eff. waveform engineering

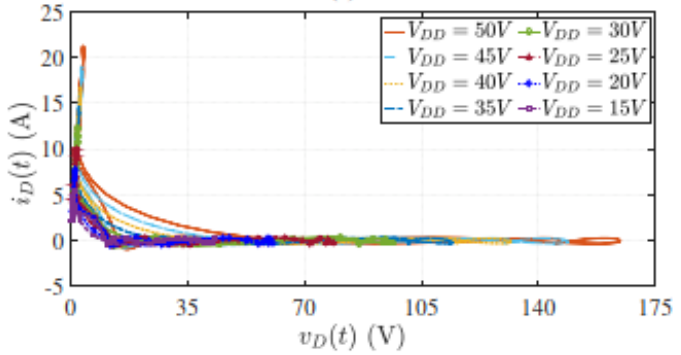


$$v_D(t) = V_{DD} \cdot \left[1 - \sqrt{2}\cos(\omega t) + 0.5\cos(2\omega t)\right] \cdot [1 + \sin(\omega t)] \quad (1)$$

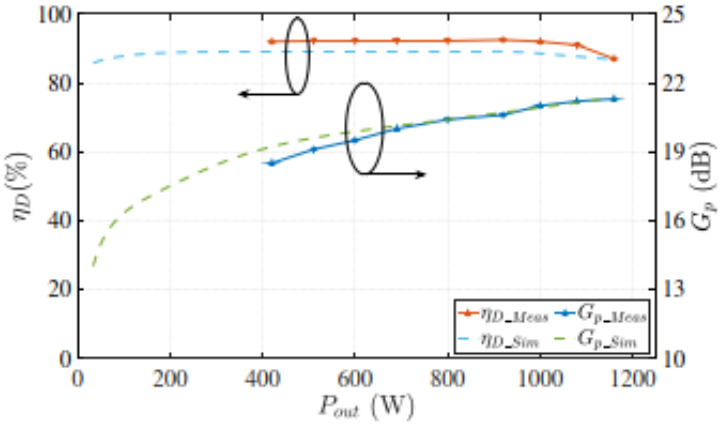
$$\begin{aligned} i_D(t) = & I_{max} \cdot [0.274 + 0.406\cos(\omega t) + 0.117\cos(2\omega t) \\ & - 0.075\cos(3\omega t) - 0.077\cos(4\omega t) \\ & + 0.003\cos(5\omega t) + \cdots] \cdot [1 + 0.34\sin(\omega t)] \end{aligned} \quad (2)$$



(a)



(b)



$$Z_{nf_0} = -\frac{V_{d,n}}{I_{d,n}}$$

R. Tong, O. Bengtsson, A. Bäcklund and D. Dancila, "*Highly Efficient Kilowatt Power Amplifier Module as RF Source for Radioisotope Production Cyclotron System",* IEEE Transactions on Microwave Theory and Techniques, 2021.

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Ongoing SSPA projects at FREIA*

- 352 MHz
  - 400 kW 10% DC – prototype fabrication – VR project
- 704 MHz
  - 1 kW CW – conceptual level - MYRRHA
- 750 MHz
  - 1 kW CW – 200 W module in GaN technology for EU I.FAST project
- 3 GHz
  - 400 W pulsed – AWAKE project (plasma wake field accelerator) – klystron driver
- 12 GHz
  - 1000 W pulsed – AWAKE project (plasma wake field accelerator) – klystron driver

* in yellow, new GaN based developments

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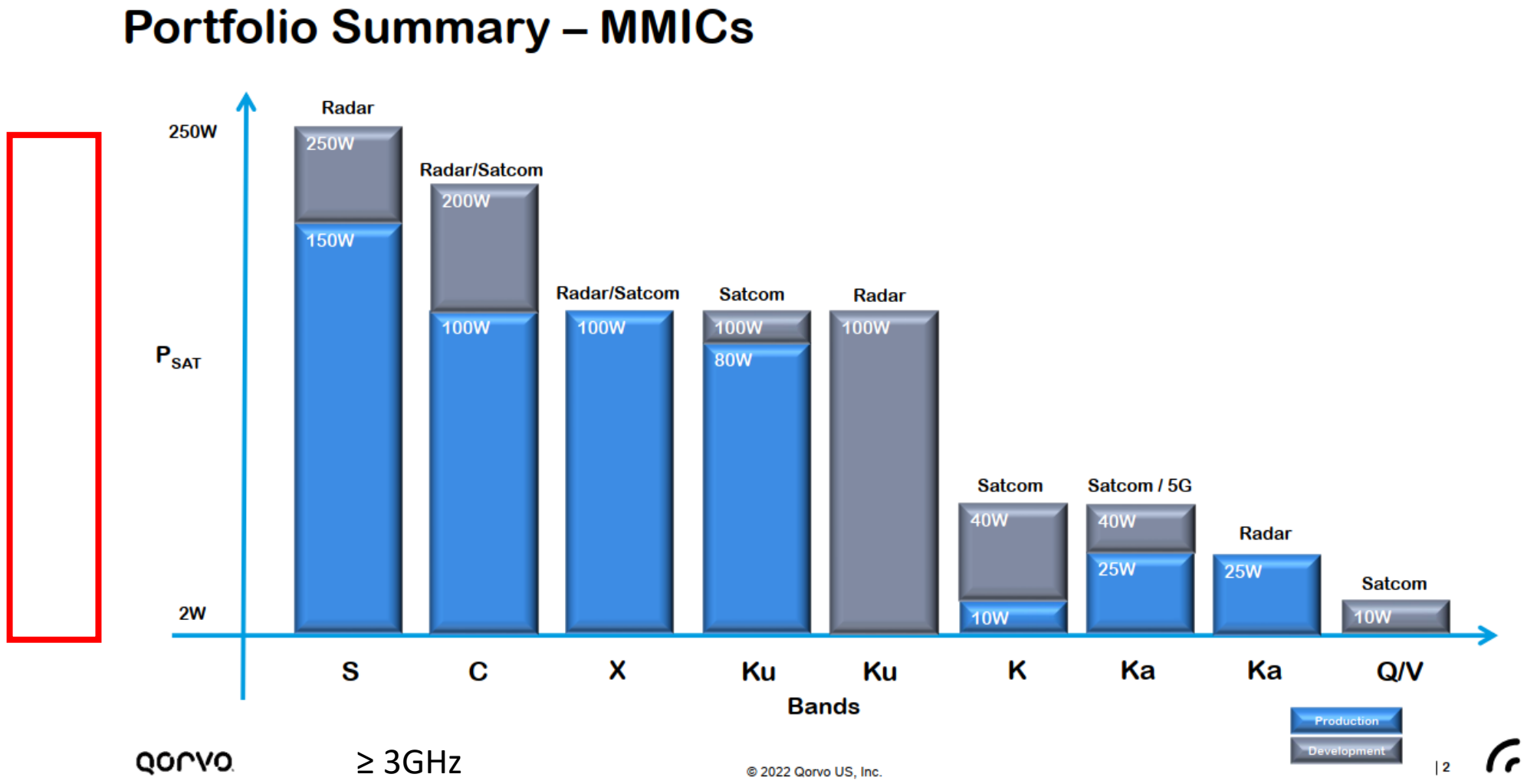
State of the Art - GaN modules at 750 MHz

No.	Operating class	F_{min} (MHz)	F_{max} (MHz)	Operation Voltage (V)	P_{out} (dBm)	Gain (dB)	PAE_{min} (%)	Chip	F_{max} of chip (MHz)	V_{DS} max	Technology	Package	Institution
2020[8]	Class E	400	-	145	63.6	22	70	-	-	500	GaN	Die	Integra Tech. - CA
2018[9]	Class E	680	750	28	47	-	80	CGH35030F	3900	120	GaN	packaged	U. of Cantabria
2017[11]	Harmonic tuned	420	450	75	60	40 (two stages)	75	-	-	-	GaN	Packaged	Integra Tech. – CA
2017[12]	Class E	670	900	28	44.7	-	70	CGH35030F	3900	120	GaN	packaged	U. of Cantabria
2016[13]	Class F	704	-	-	58	-	79	-	-	-	GaN	packaged	Green Mountain Radio Research
2016[14]	Class F	550	950	28	40	15	75	CGH40010F	4000	120	GaN	packaged	U. of Calgary
2011[15]	Class F	550	1100	28	40	10	74	CGH40010F	4000	120	GaN	packaged	Cardiff U.

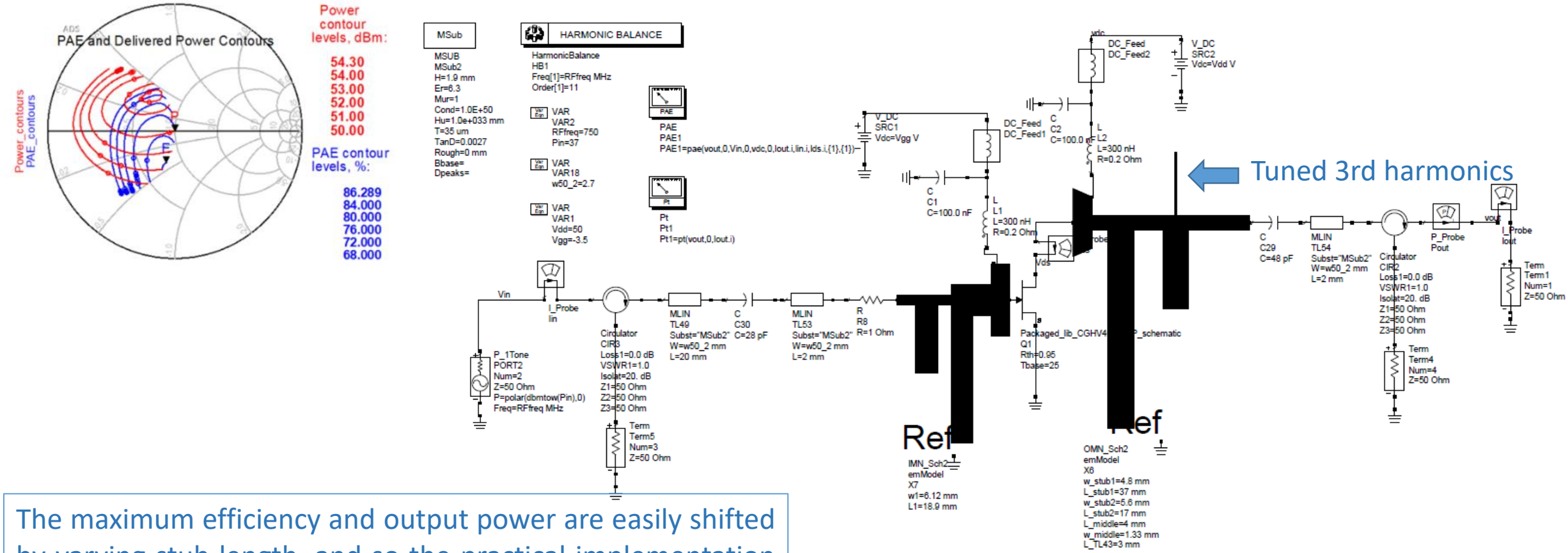
GaN transistors from e.g. Ampleon, Qorvo, Cree - Wolfspeed, NXP Semiconductors, Infineon, etc. are available at high power / high freq.

GaN high power transistors – e.g. Qorvo



≥ 3GHz

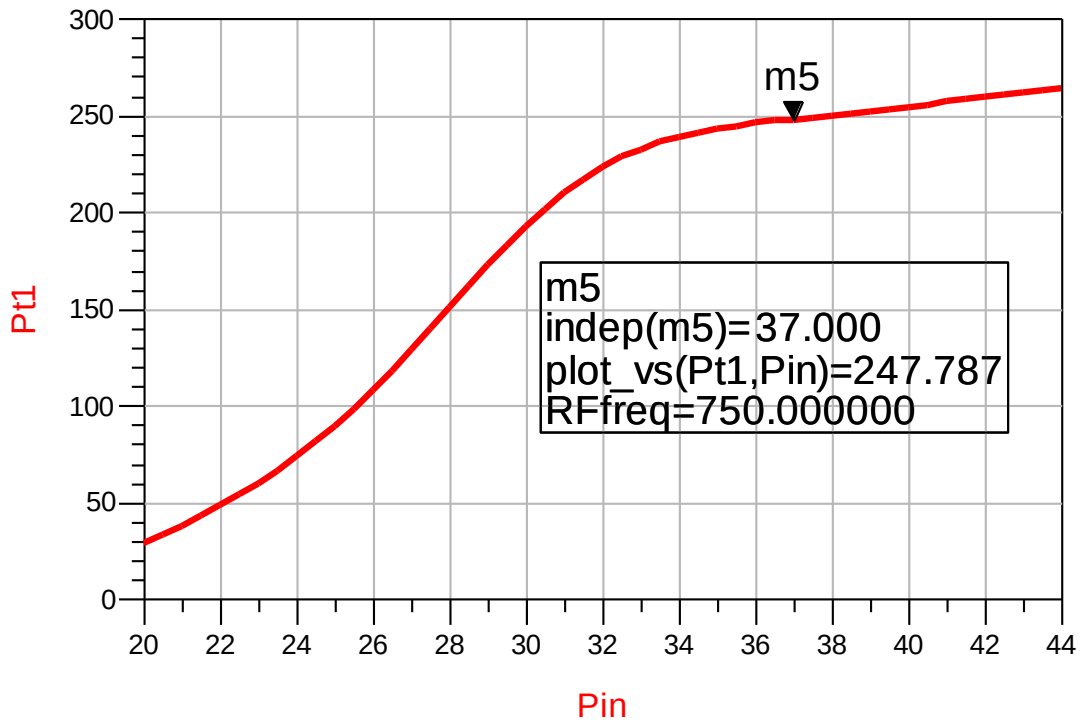
Load pull simulations and harmonics optimization



The maximum efficiency and output power are easily shifted by varying stub length, and so the practical implementation of the PA will meet the targeted specifications.

Simulation results of the GaN SSPA at 750 MHz

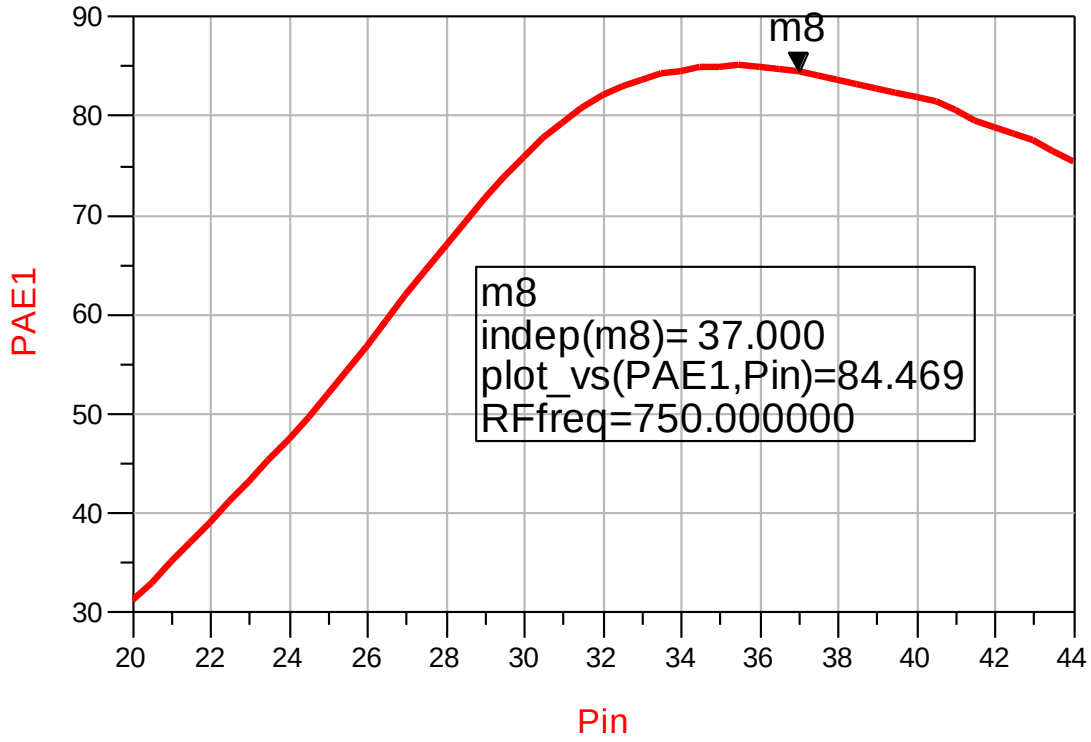
Output power versus input power



Pout=247 W (54 dBm) @ Pin=37 dBm

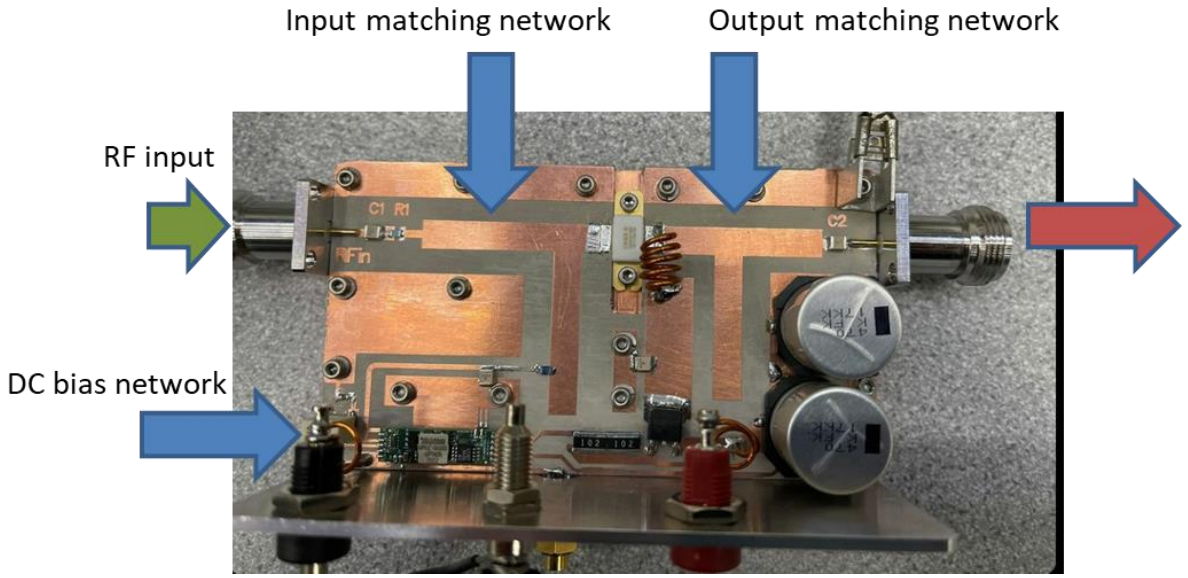
Gain = 17 dB

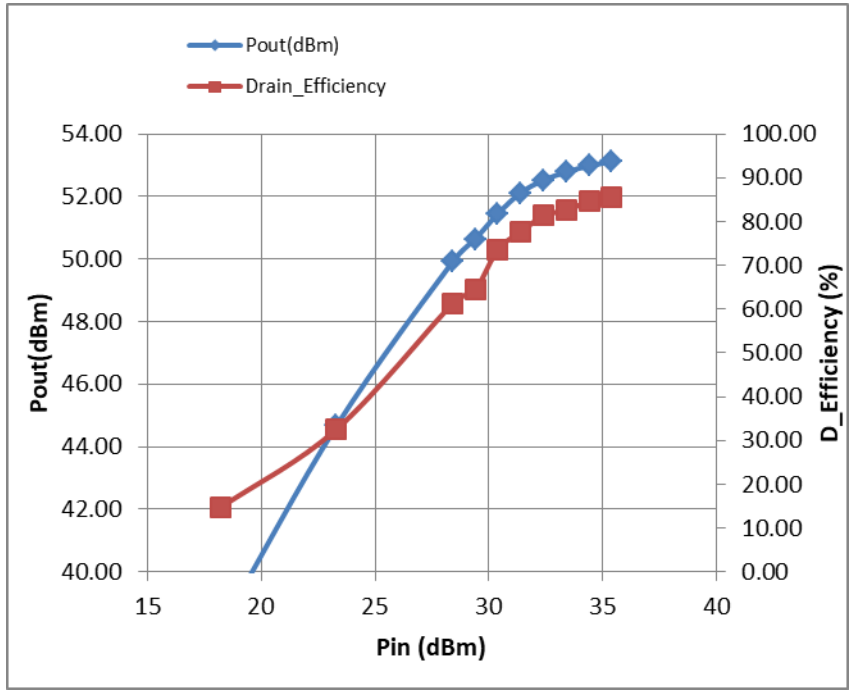
Power added Efficiency (PAE) versus input power



PAE = 84.5 % @ Pin=37 dBm

750 MHz GaN amplifier in EU project I.FAST fabrication and first measurements

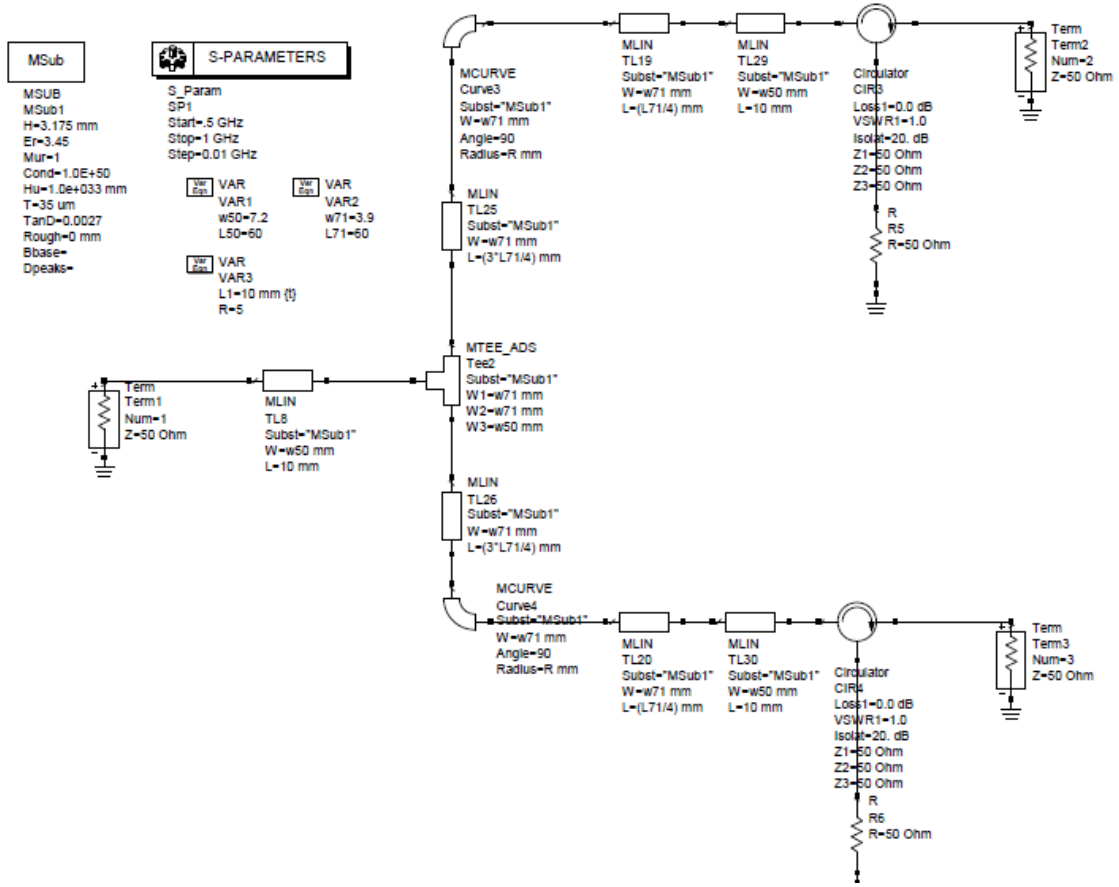


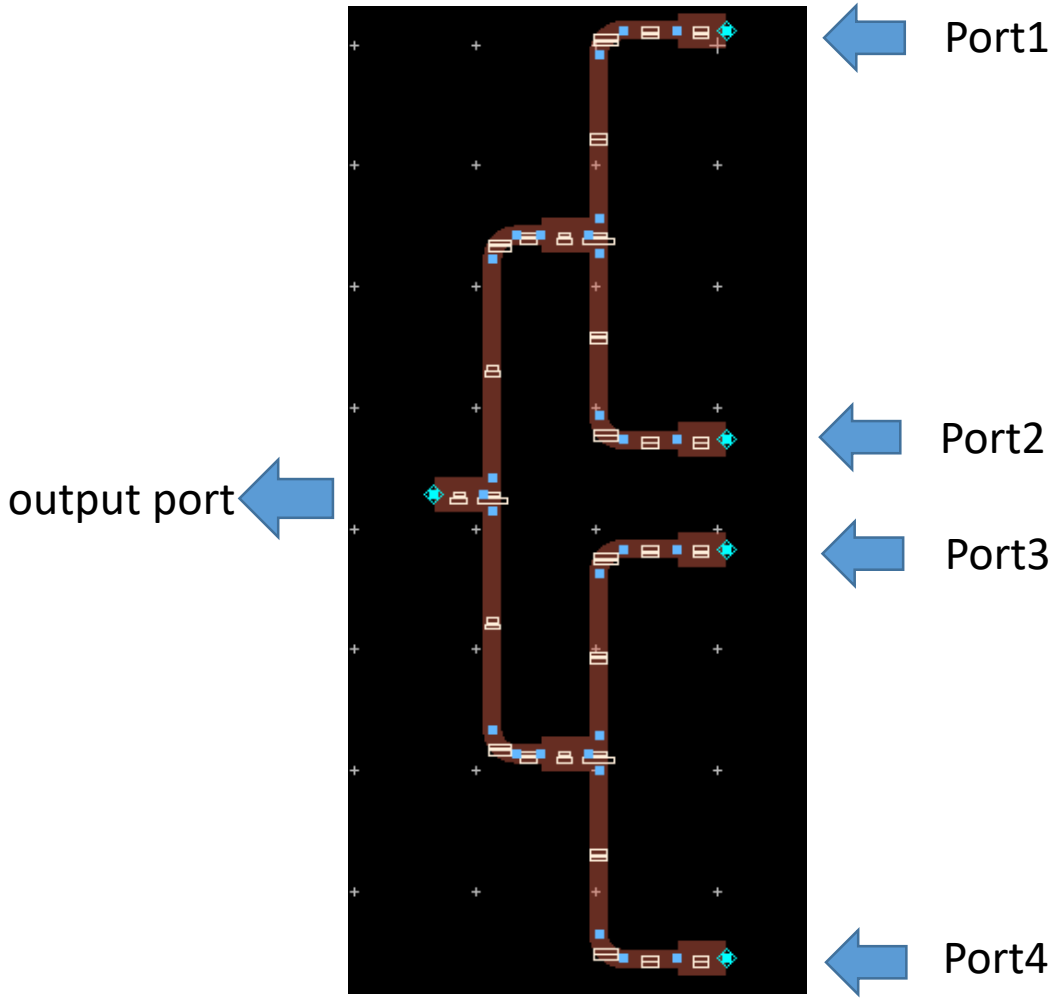


- A measured output power of 205 W was possible, with a signal gain of 17 dB and an efficiency of 84% in compression.
- This is improving the State of the Art.

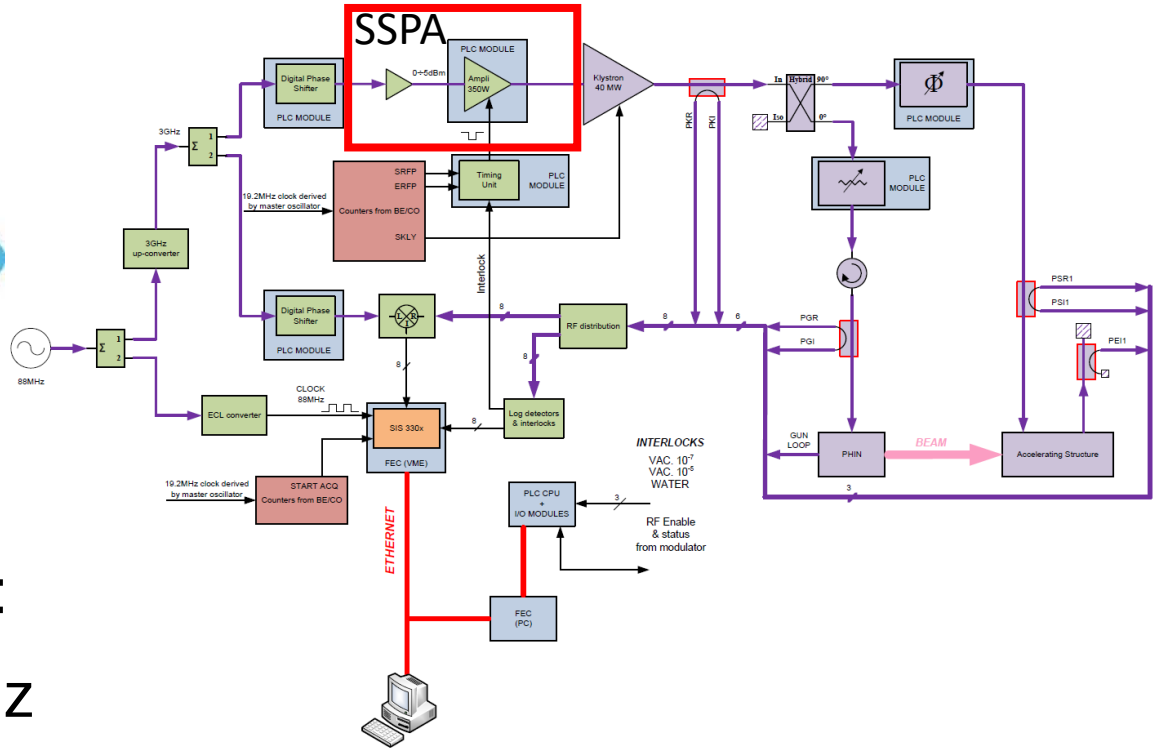
Pout = 53 dBm (60 dBm with combiner) / PAE = 84% @ 750 MHz

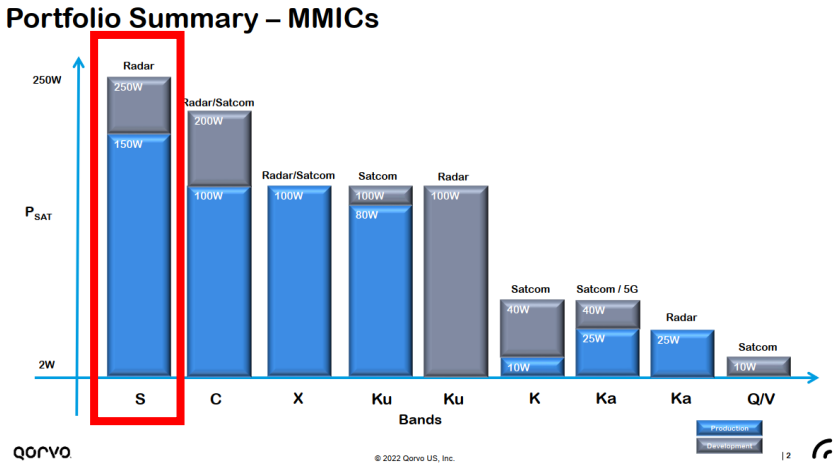
Plannar Wilkinson power combiner 2:1, 4:1 and 6:1





Development of SSPA - drivers for the klystrons





Specifications:

@3 GHz

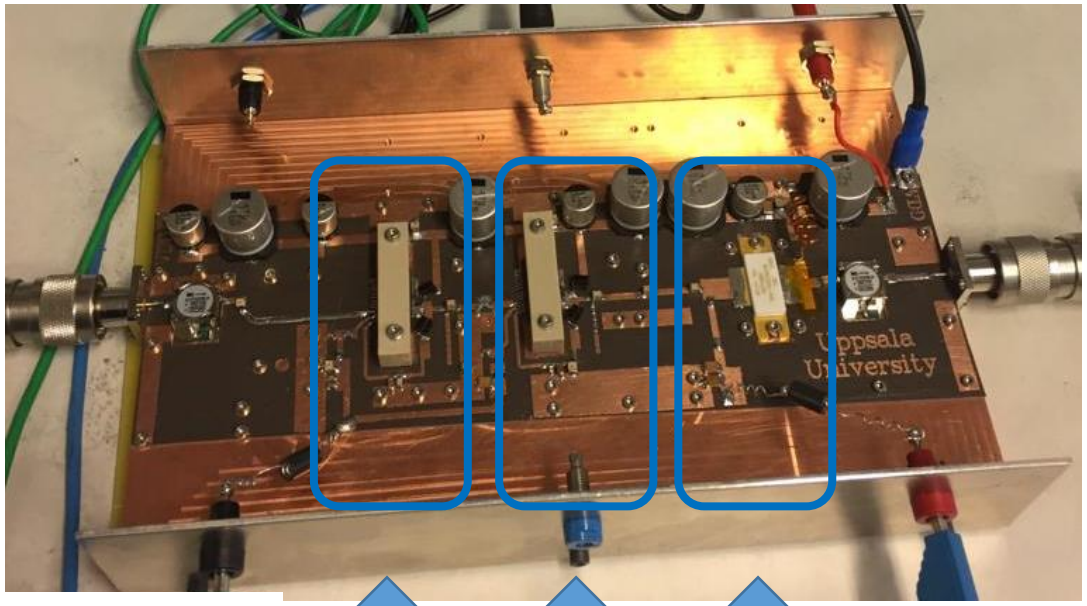
1) 200W at the input of the 6 or 7.5 MW S-band klystron

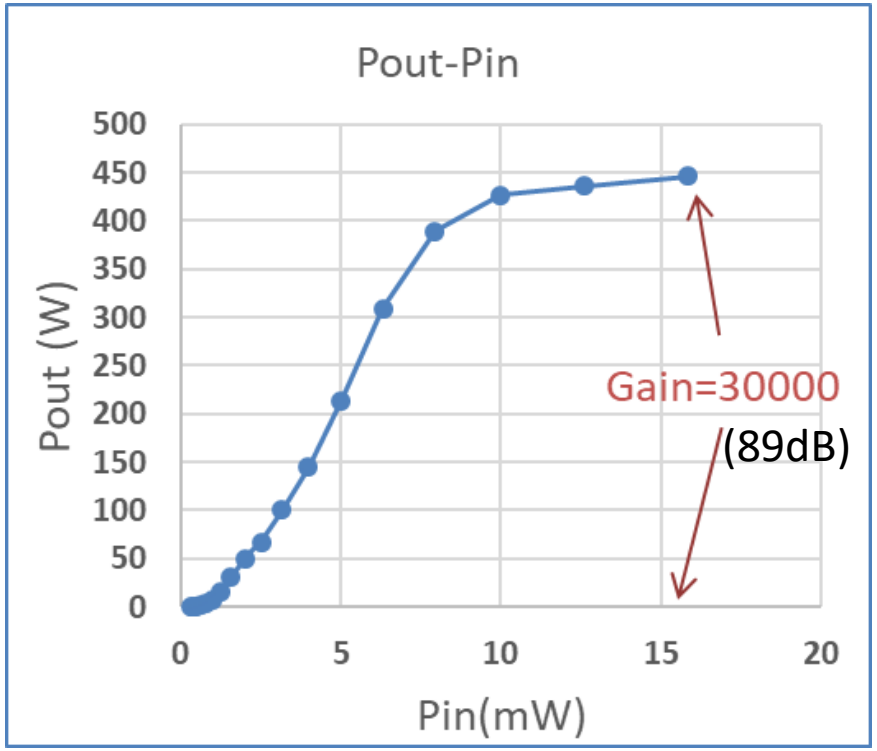
@12 GHz

2) 200 W at the input of the 6 MW X-band klystron

3) 1000 W at the input of the 50 MW X-band klystron

3 GHz – 400 W amplifier at 3 GHz - AWAKE





Pre Driver

Driver

PA

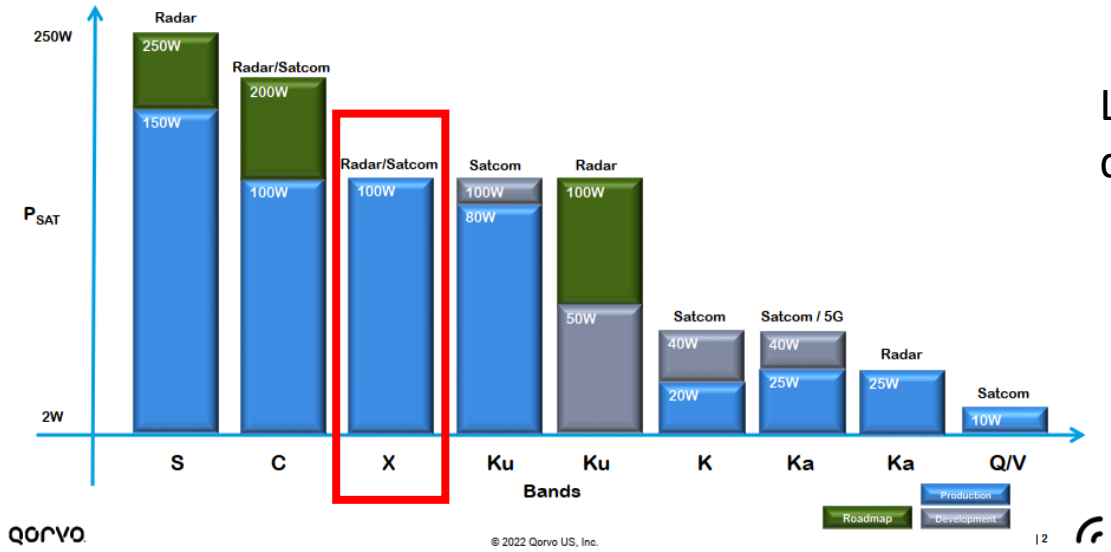
BLM9D2327S-50PB

BLS9G2731L-400

Download datasheet

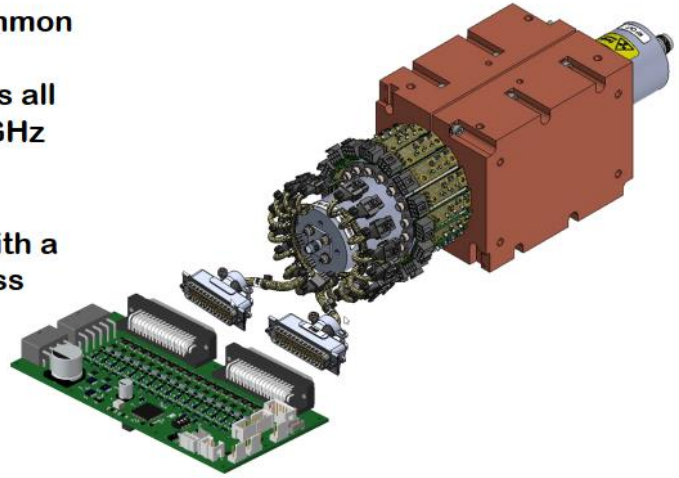
Overview | Product details

12 GHz – 100 W max power available per transistor



Low loss power combiners development is key.

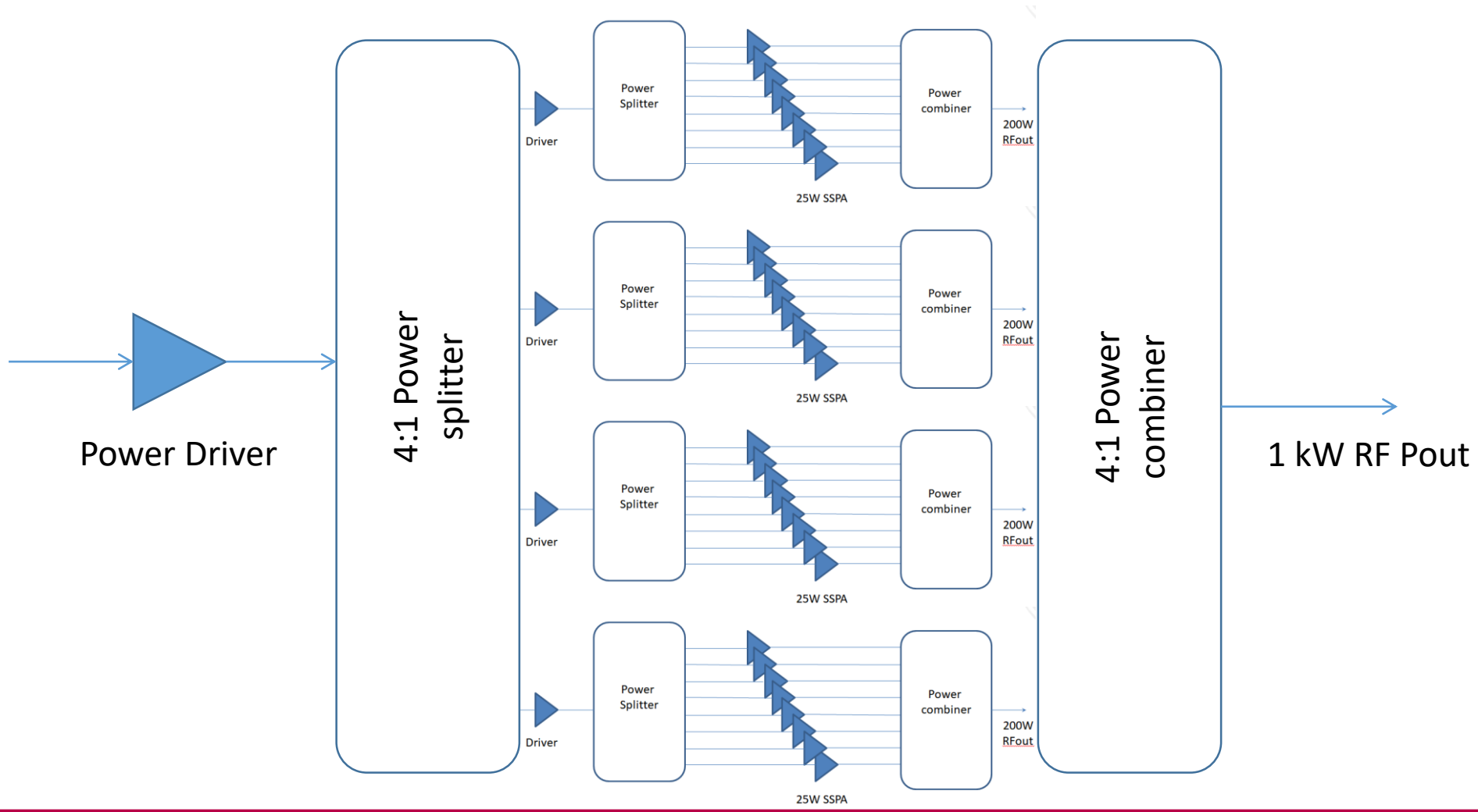
- Qorvo has developed a common Microwave SSPA node for combining 16 MMICs across all or any portion of the 2-20 GHz band
- The SSPA Platform ships with a bias PCB and wiring harness
- The Bias PCB is the SSPA control board



Price tag of this 500 W amplifier is prohibitive, i.e. 50 k$ and we need to combine 2 of them for the klystron needs, i.e. 1000 W.

Thus, we plan to develop our own power amplifier at X band, based on combining 40+ transistors of 25 W each.

X-band SSPA – 1 kW SSPA - AWAKE



TBC …

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Thanks for your attention !

Questions