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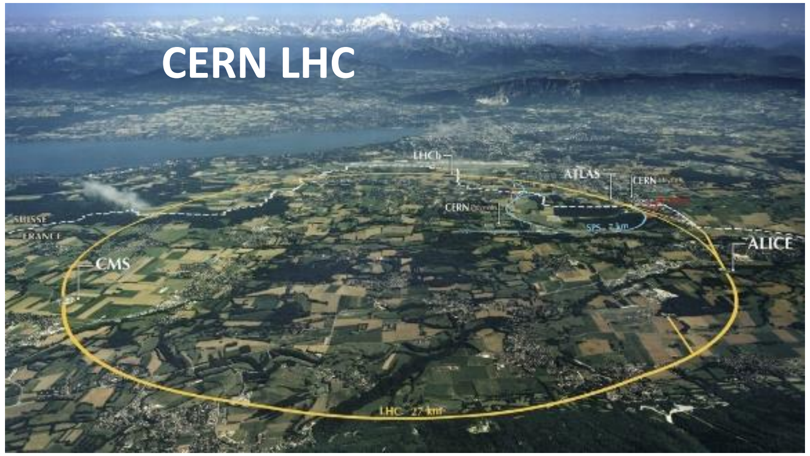
High efficiency SSPA development at Uppsala University

Dragos Dancila

On behalf of the Microwave group, FREIA and ESS

2024 Sept. 25

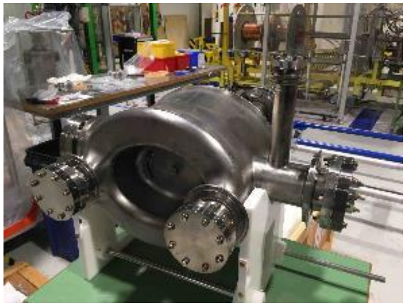


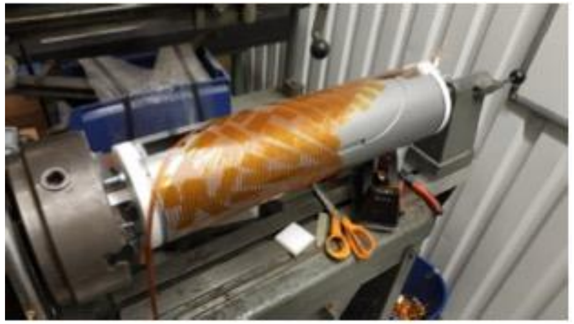
Scientific infrastructure

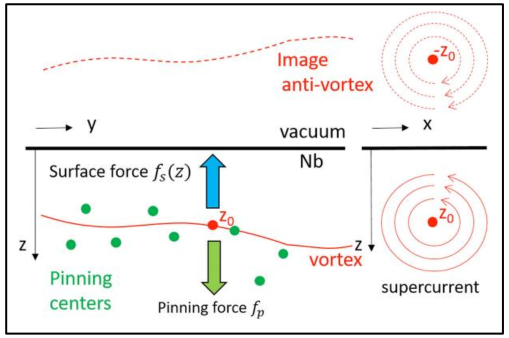
Particle physics
Nuclear physics

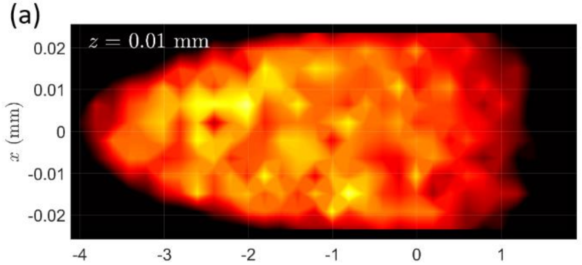
Condensed matter physics
Material science

Basic R&D





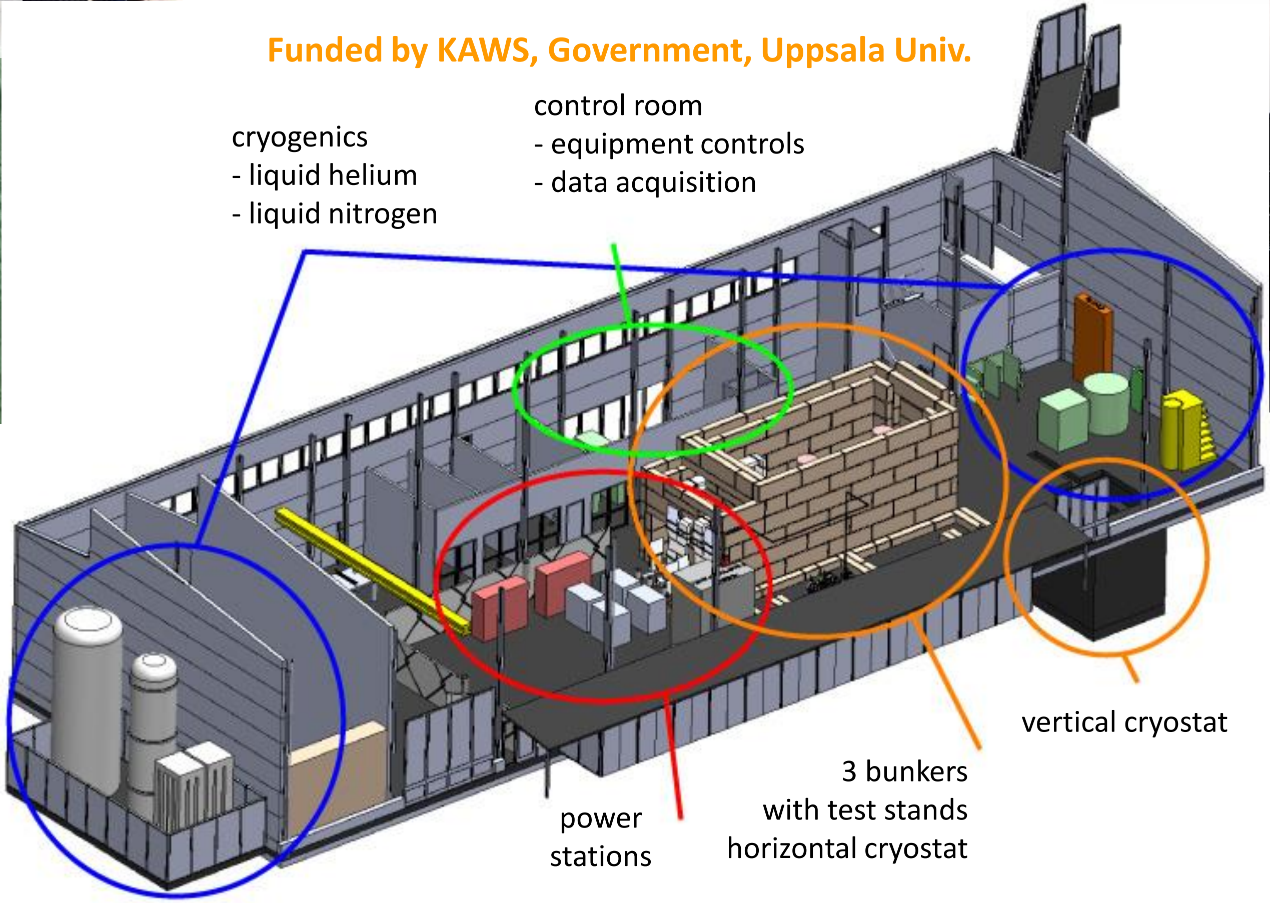


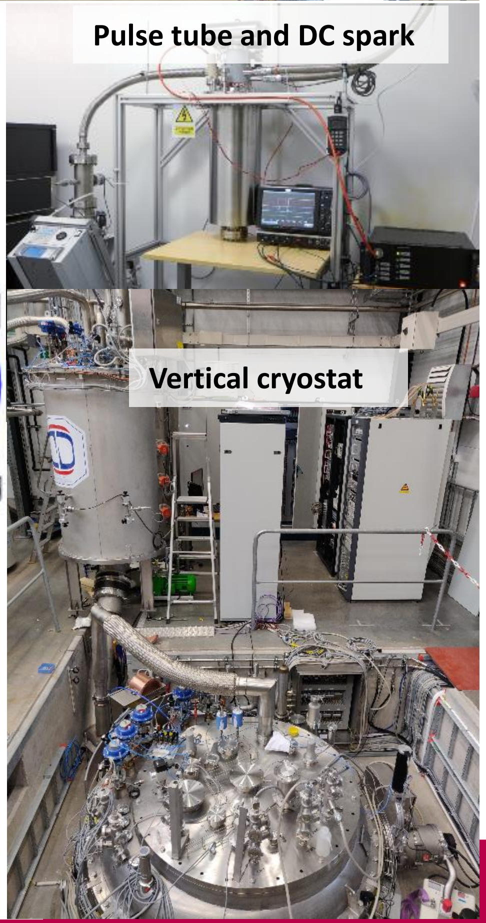


FREIA infrastructure

R. Ruber et al 2021 JINST 16 P07039

Funded by KAWS, Government, Uppsala Univ.





Solid State Power Amplifiers (SSPA) for particle accelerators and industrial applications

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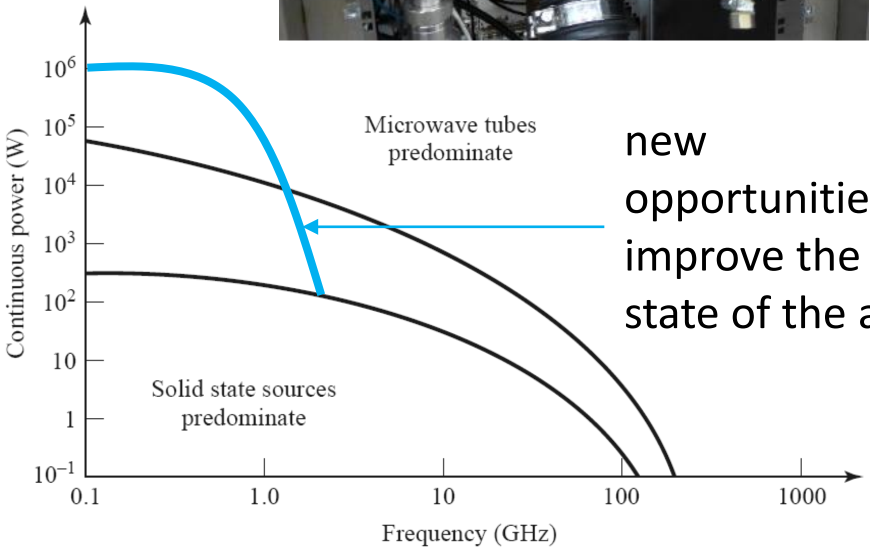

new opportunities to improve the state of the art !

The RF Power Amplifier role is to transfer all Input Power, idealy just DC Power, into RF Output Power

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$Power\ Added\ Efficiency\ (PAE\ or\ \eta_{PAE})$

- $PAE = \frac{RF\ Power_{out} - RF\ Power_{in}}{DC}$
- $PAE = (G-1)\frac{RF\ Power_{in}}{DC}$

$Power\ Efficiency, PE = \frac{RF\ Power_{out}}{DC}$

- $\eta_{PAE} = \frac{(G-1)}{G}\eta_{PE} = \eta_{Gain} \times \eta_{PE}$

$Power\ Efficiency$ is limited by many factors:

- $\eta_{PAE} = \eta_{Gain} \times \eta_{PE} = \eta_{Gain} \times \eta_{knee} \times \eta_{loss} \times \eta_{mode,BW}$

Wall plug efficiency, $\eta_{tot} = \eta_{PAE} \times \eta_{AC\ to\ DC} \times \eta_{combiner}$

high efficiency is not simple to achieve:
$(97{,}5\%)^4 \approx 90\%$
$(94{,}5\%)^4 \approx 80\%$
$(91{,}5\%)^4 \approx 70\%$
$(90\%)^4 \approx 66\%$

(these can be compared to the efficiency of the vacc. tube, only)

adapted from Paul Tasker, Cardiff University at ARIES 2019

Definition of the Efficiency of the SSPA – η_{tot}: wall plug efficiency

- $\eta_{tot} = \eta_{PAE} \times \eta_{AC\ to\ DC} \times \eta_{combiner} = \eta_{Gain} \times \eta_{knee} \times \eta_{loss} \times \eta_{mode,BW} \times \eta_{AC\ to\ DC} \times \eta_{combiner}$

- for high η_{Gain}:

  we need high Gain > 16 dB for $\eta_{Gain} > 0.975$

  if Gain > 10 dB for $\eta_{Gain} > 0.9$ $\left(\eta_{Gain} = \frac{(G-1)}{G}\right)$

- η_{knee} : Linked to the impact of the knee voltage
- η_{loss} : Linked to the impact of matching network, passive components losses
- $\eta_{mode,BW}$: Linked to mode chosen and bandwidth/impedance of matching network
- $\eta_{AC\ to\ DC}$: Linked to losses in DC power supply
- $\eta_{combiner}$: Linked to the power combiner losses, external to PAE, but required when more than one PA

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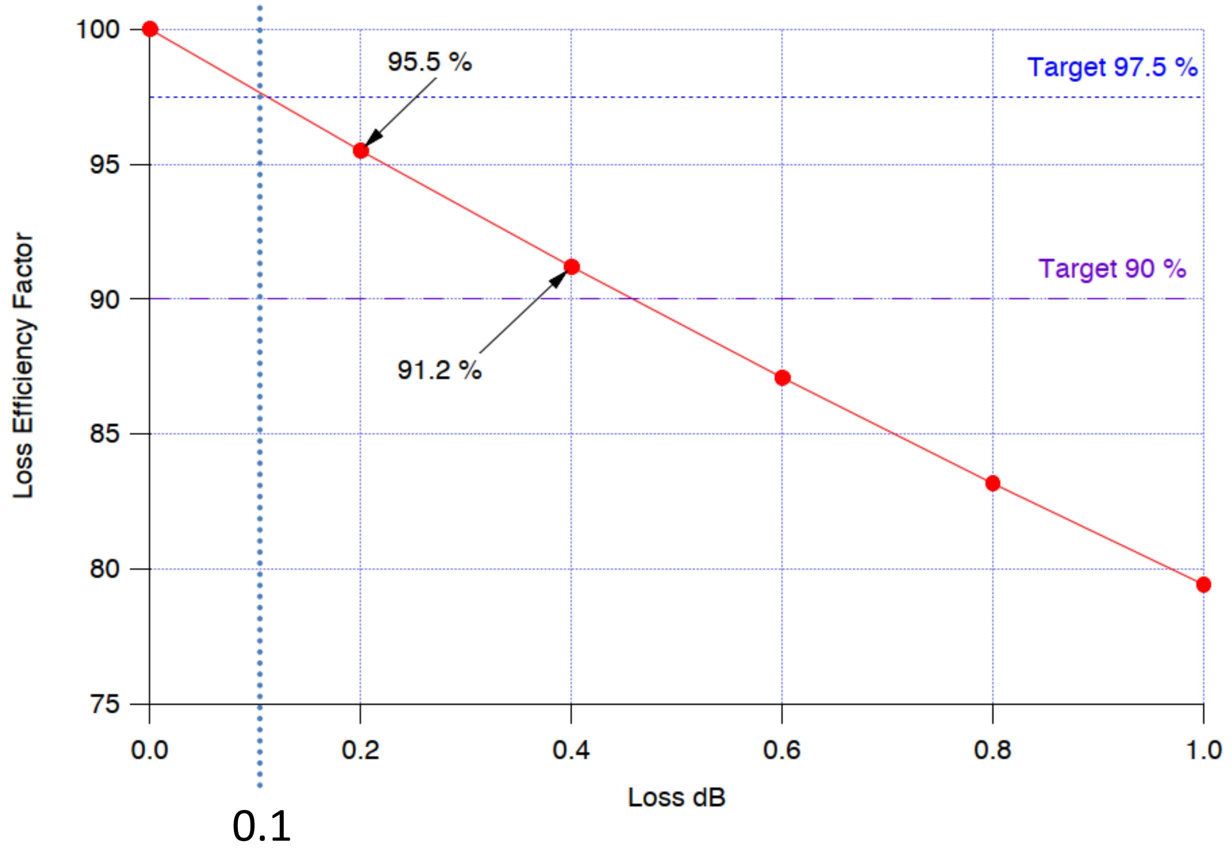
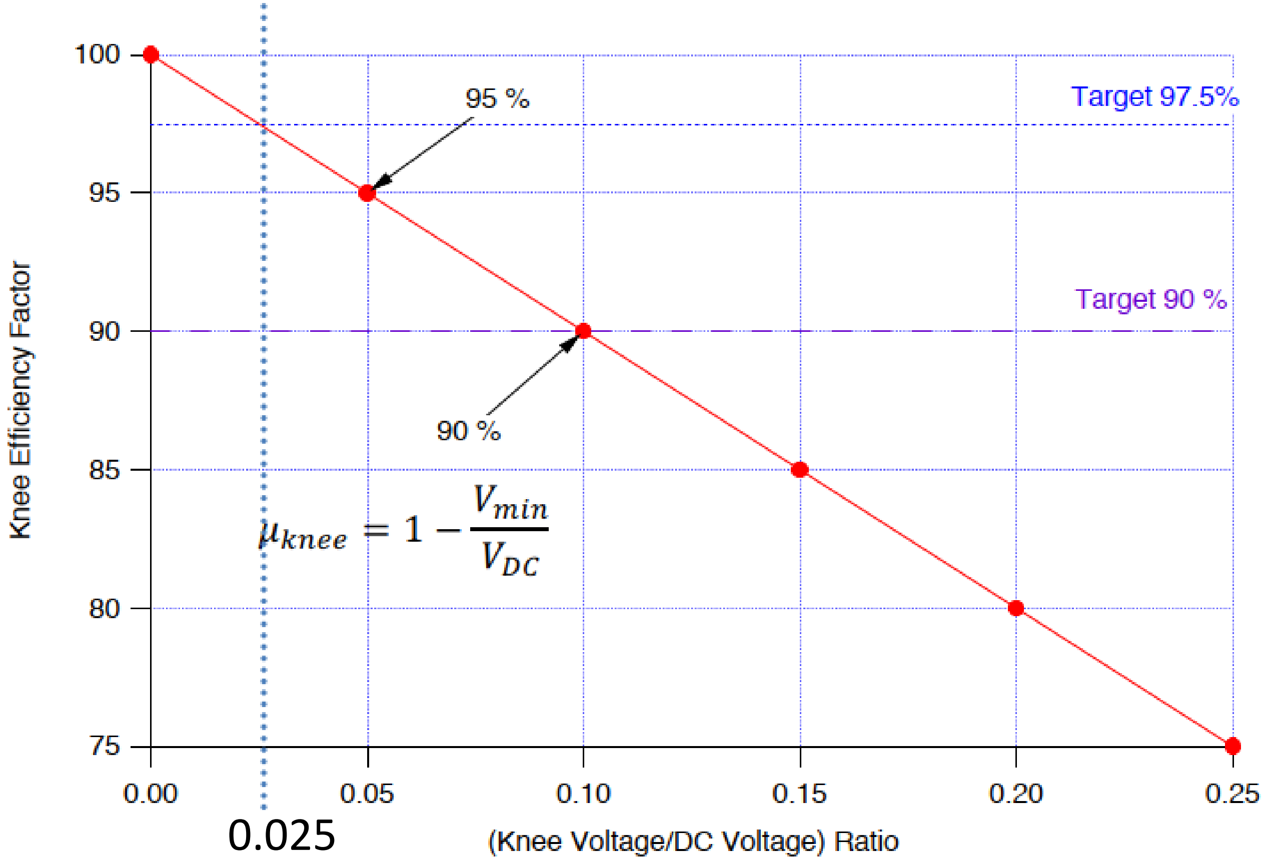
η_{loss} : Impact of Matching/Combining Losses

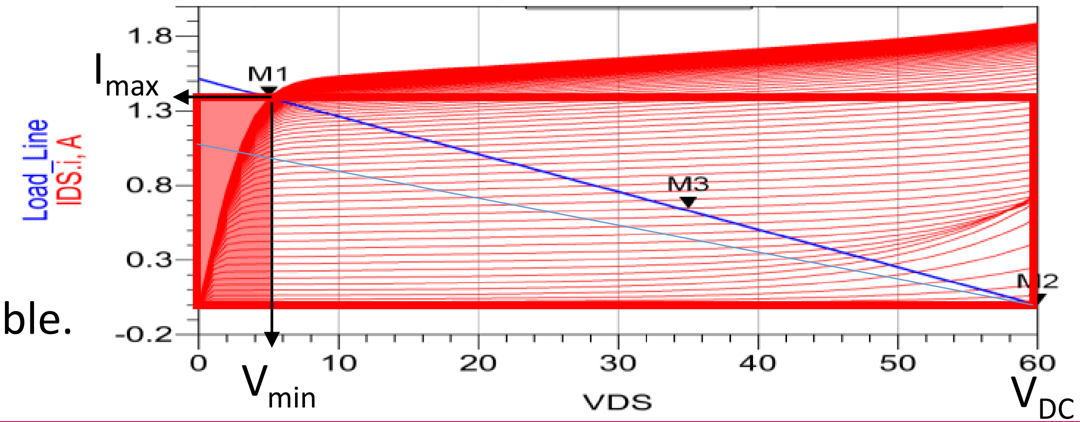


- If Overall Efficiency Target is 90% these must be kept below 0.1 dB
- Difficult in the case of complex modes that require harmonic matching - RF I-V Waveform Engineering (class F or F^{-1})
- Difficult in the case of high powers which require a high impedance ratio matching (50 Ω to 1 Ω)
- Strong motivation to drive up the transistor Power Density

η_{knee}: Impact of knee region



- In an ideal transistor when the RF waveform swings to the maximum current the voltage swings to a ZERO minimum.
- In practice because of a finite Ron, the minimum voltage is greater than ZERO = V_{min}
- $\eta_{knee} = 1 - \frac{V_{min}}{V_{DC}}$
- Consider LDMOS, targeting V_{DC} = 65 V, so looking for V_{min} < 3 V
- Consider GaN, targeting V_{DC} = 100 V, so looking for V_{min} < 5 V



Focus on driving up the operating voltage. Target V_{min} < 5% V_{DS}
In order to target a knee factor < 0.1, operation to I_{max}, is not feasible.
Typically a current of <75% of I_{max} is selected.

$\eta_{mode,BW}$: Mode Selection

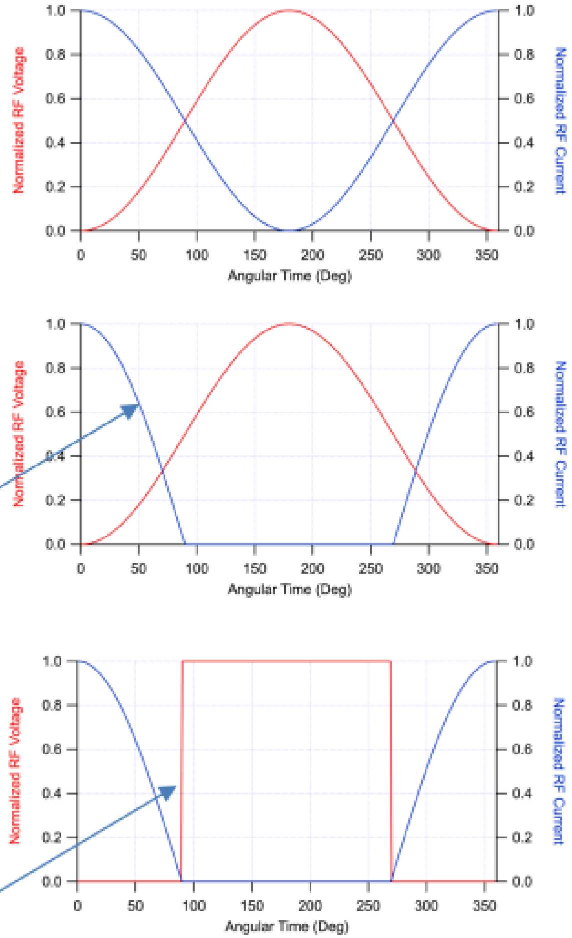
Class A

Class B

Reduce DC by $^{2}/_{\pi}$

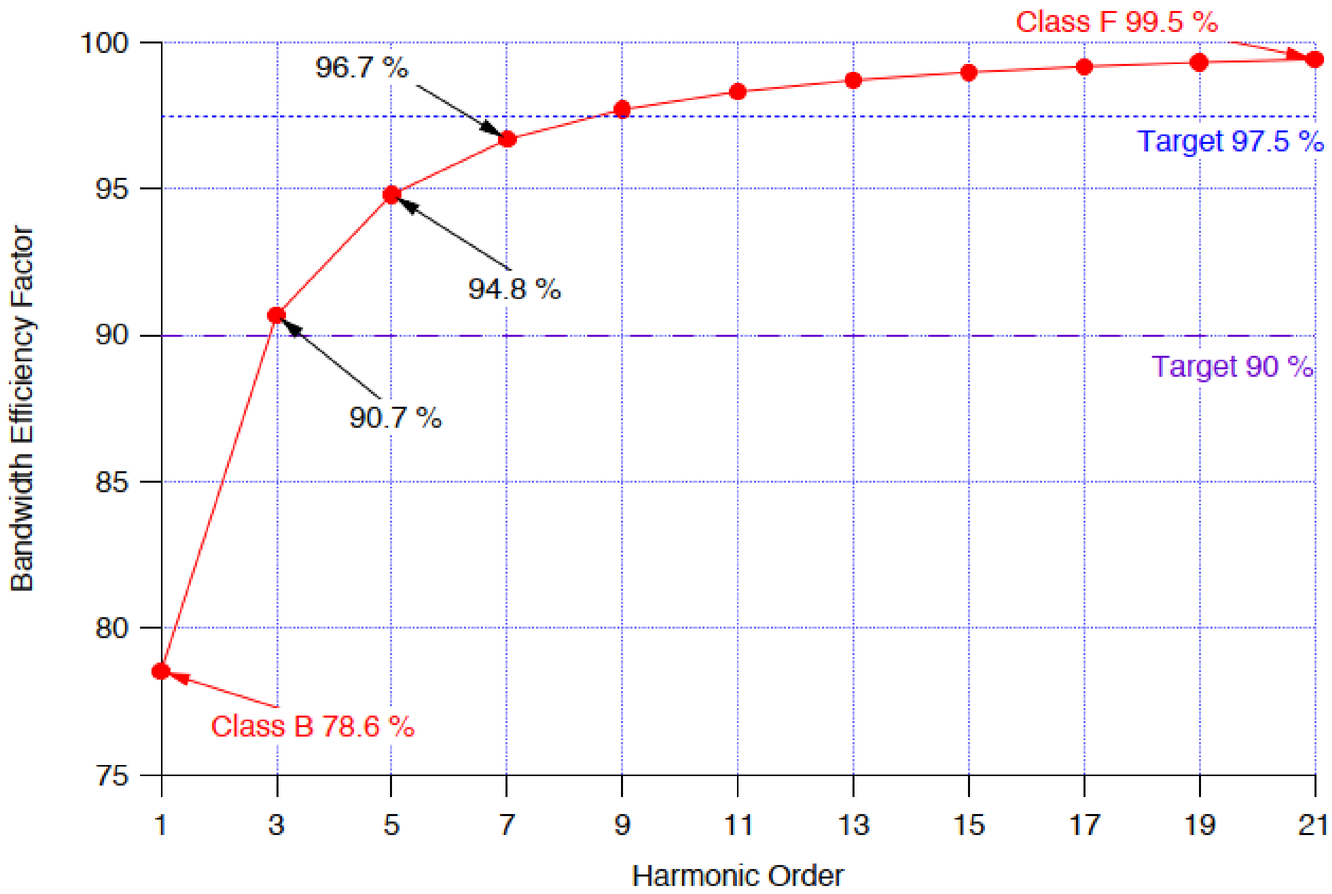
Class F

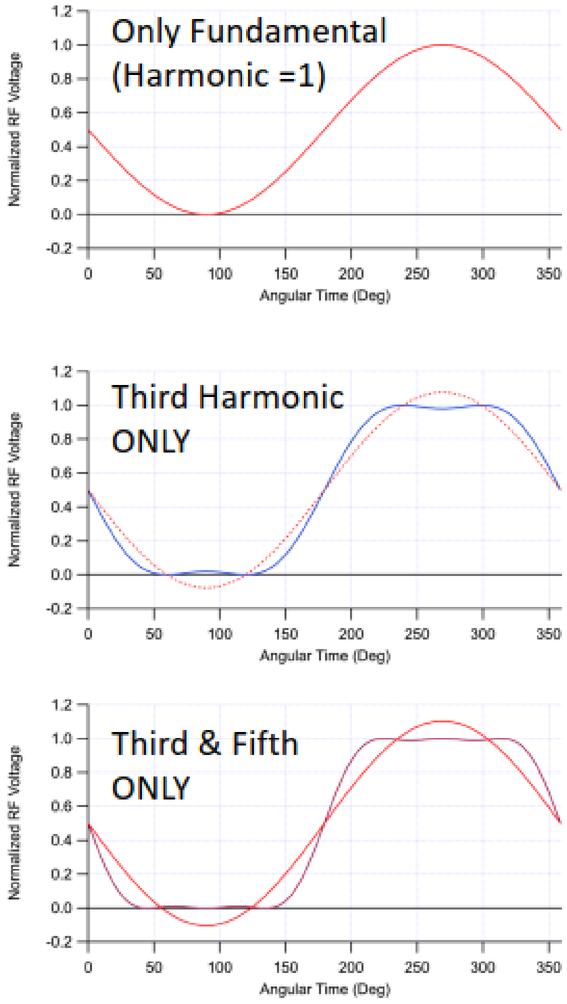
Increase rf by $^{4}/_{\pi}$



- Solution for Infinite Bandwidth
  - Class A - 50%
  - Class B - 78.5%
  - Class F - 100%
- So to achieve a drain efficiency > 90% we will need to target the highest efficiency modes, hence Class F or F^{-1}.
- This requires design involving harmonics
- Matching could be simplified by the use of the continuous mode variant of Class F (including Class E, J, F^{-1}, etc.)

$\eta_{mode,BW}$: Mode Realization





3rd harmonic ONLY is typical, hence practically limits $\eta_{mode,BW}$ <90 %

considering the 5th harmonic helps achieve $\eta_{mode,BW}$ <95 %

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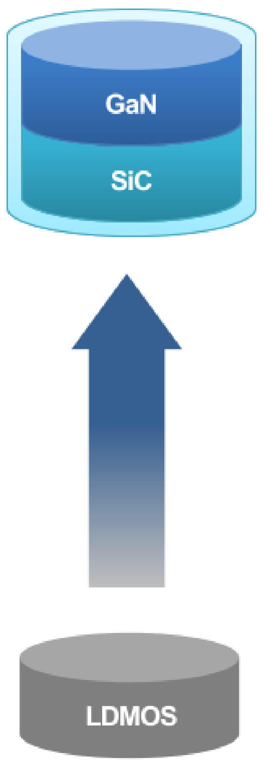
Comparison of GaN on on SiC with LDMOS



GaN on SiC
A structure of GaN (gallium nitride) deposited on a silicon carbide (SiC) substrate

- **Size 50%** Down
- Thermal Conductivity **5 Times Higher**
- **10%** More Efficient
- Electric Use **10%** Down

Si (LDMOS)
Silicon epitaxial wafer,
Low-priced & easy change of electrical characteristics

Category	Si (LDMOS)	SiC	GaN
Eg Bandgap [eV]	1.1	3.3	3.4
Power Density [W/mm]	0.2	10	>30
Thermal Conductivity [W/cmK]	1.5	4.9	2.0
RF Usable Frequency	~ 3GHz	~ 40GHz	

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Operation at Higher Drain Voltage

A Highly Manufacturable 75–150 VDC GaN-SiC RF Technology for Radars and Particle Accelerators

Gabriele F. Formicone, *Senior Member, IEEE*

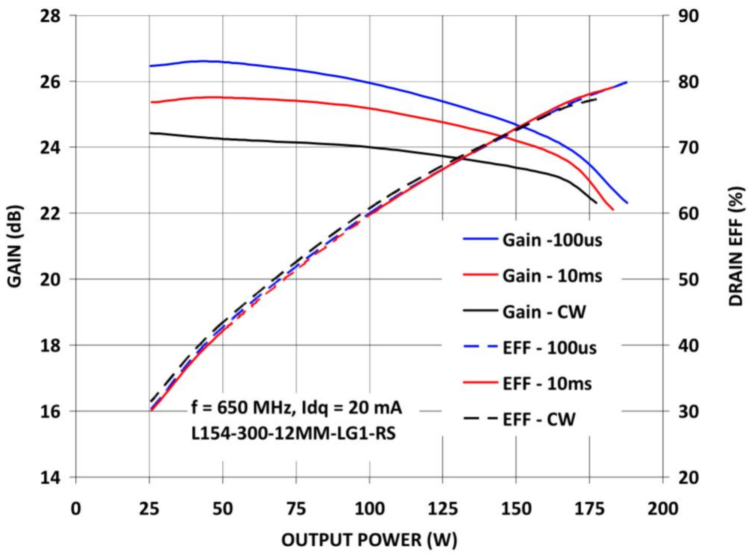


Fig. 13. Measured RF gain and drain efficiency versus output power for the 12 mm die characterized at 100 V bias and 650 MHz. In CW operation, only ~2dB compression is tested.

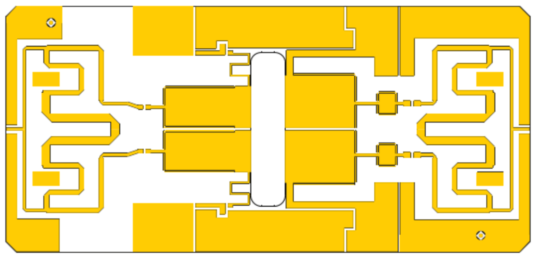
IGNP0912S5000 | RF Power Amplifier Pallet

INTEGRA
RF POWER DEVICES

L-Band, GaN/SiC, RF Power Amplifier Pallet

960 - 1220 MHz | 6000 W typ | 75% Efficiency typ | 19 dB Gain typ | 125 V | 32µs Pulse Length, 4% Duty Cycle

IGNP0912S5000 is a high power RF power amplifier pallet that has been desIgned to suit the unique needs of TACAN, DME and IFF/SSR avionics systems. Under 32µs, 4% duty cycle pulse conditions, it supplies 5000 W of peak output power, with 18dB of associated gain and 70% efficiency. It operates from a 125 V supply voltage.



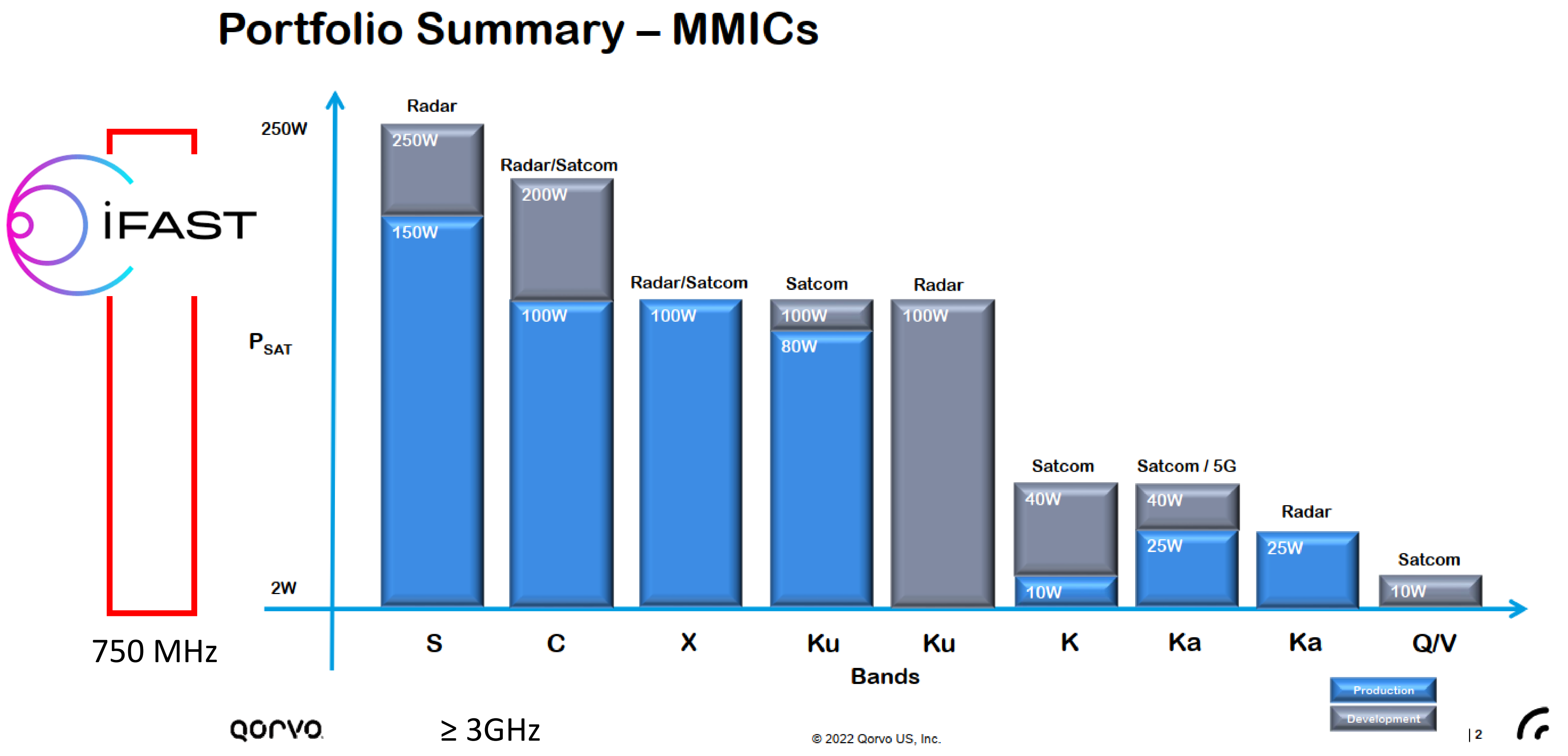
FEATURES

- GaN on SiC HEMT Technology
- Output Power >5000 W
- Input impedance fully matched to 50Ω
- High Efficiency - up to 75% during the RF pulse
- 100% RF Tested

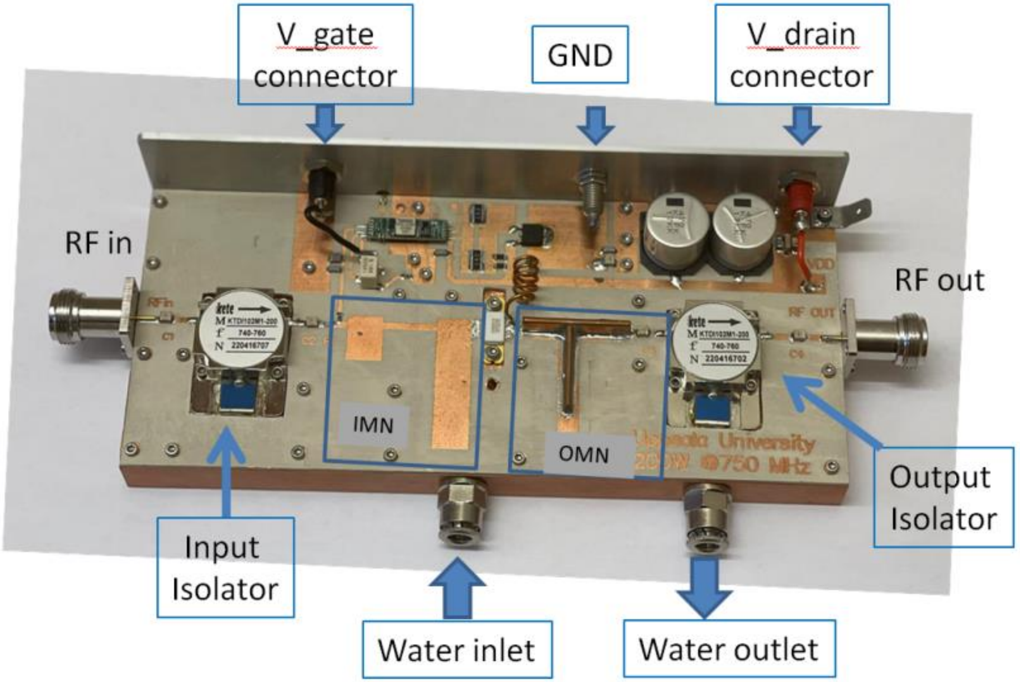
6 kW! (under 32µs, 4% duty cycle pulse…)
VDS = 125V
Target V_{min} < 5% VDS
Efficiency typ 75%

See next talk: RF GaN/SiC Technology from Integra by Tom Kole

GaN high power transistors – e.g. Qorvo

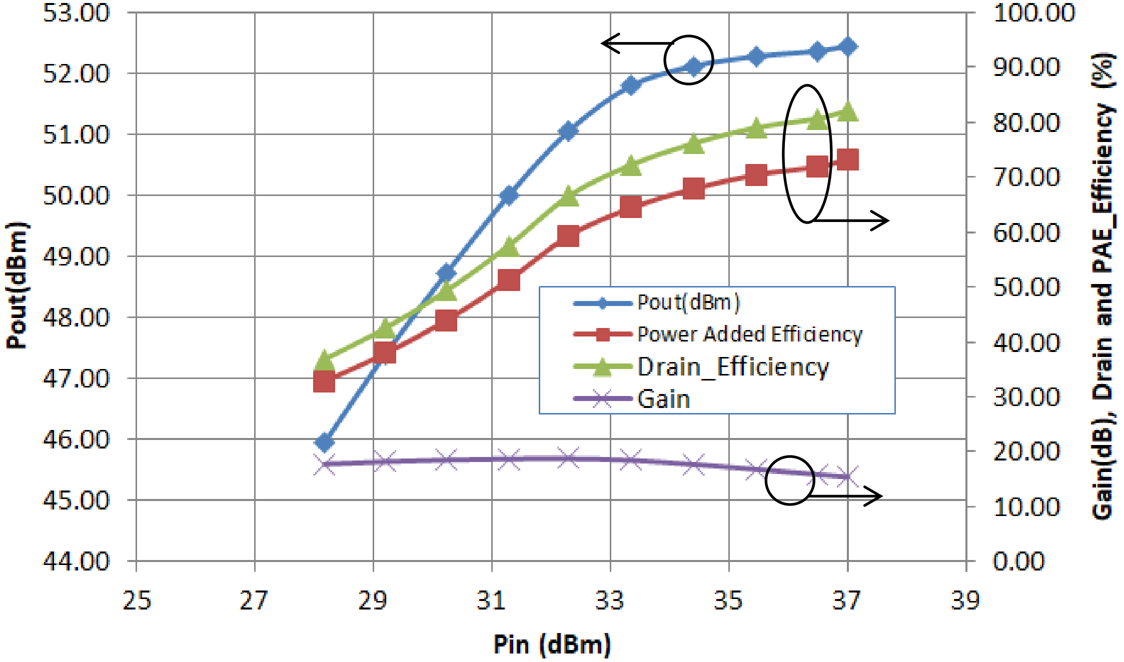


GaN RF Amplifier Module 200 W



Fabricated 200W solid-state RF power amplifier at 750-MHz

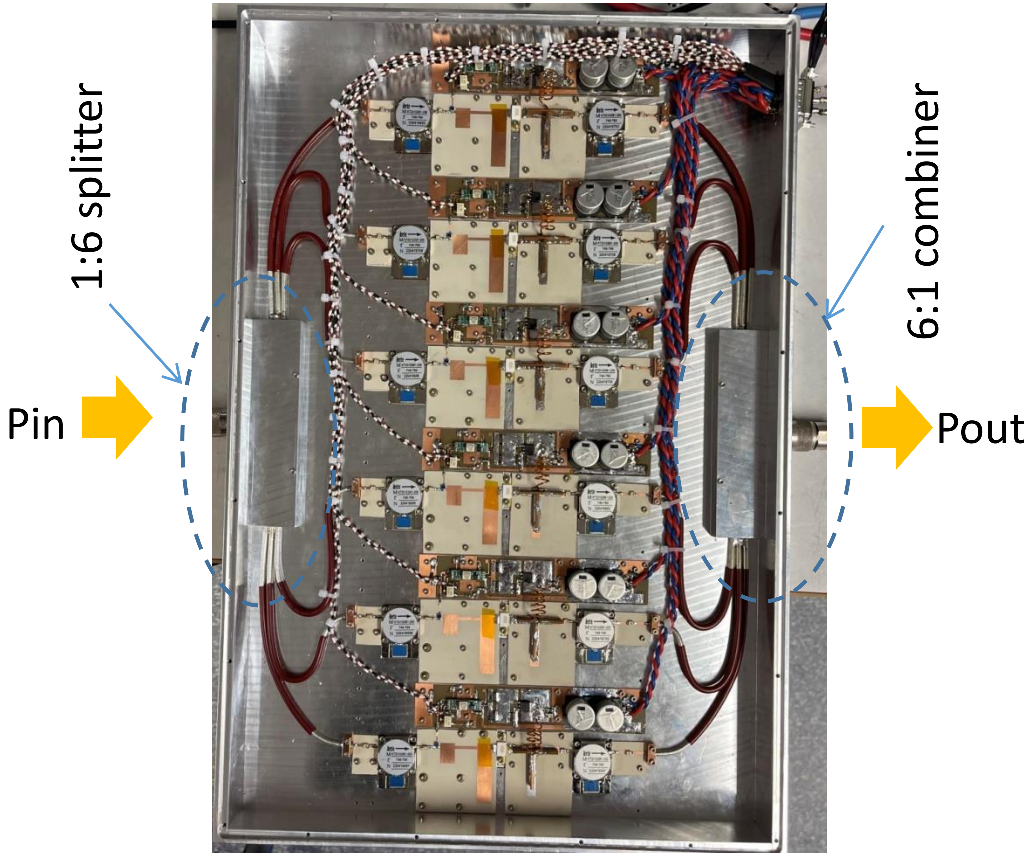
Pout > 200 W, PEff > 83 %



Measurement results of 200W solid-state RF power amplifier at 750 MHz

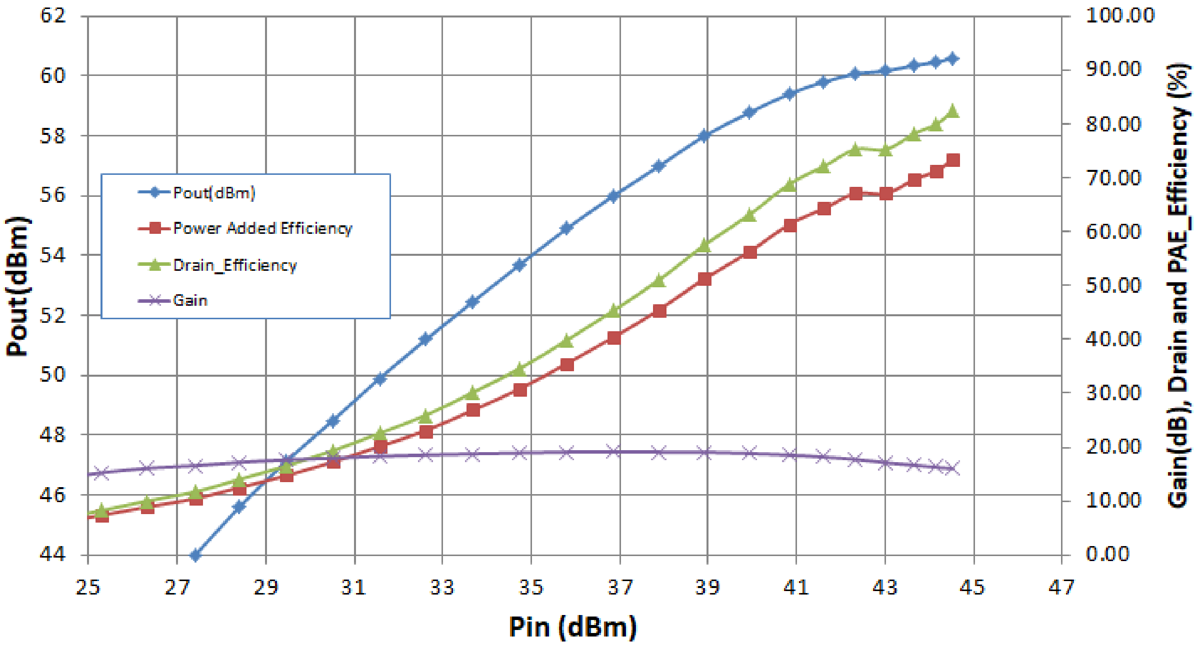
Alireza Kasaei and Dragos Dancila, "High-efficiency high-power Gallium Nitride amplifier modules", 3rd I.FAST Annual Meeting, 18 April 2024, Paris.

GaN RF Amplifier at kW level



Implemented 1kW RF high power solid-state amplifier including DC bias circuits, 6 x 200-W RF power amplifiers, and the RF splitter and combiner.

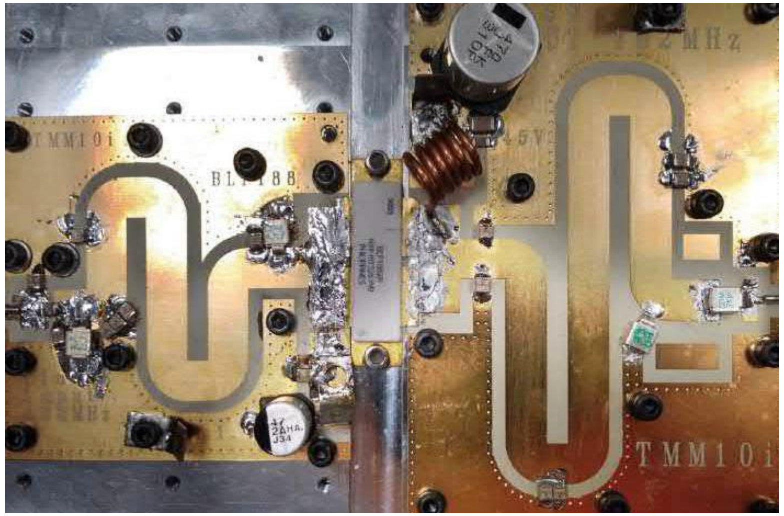
Pout > 1150 W, PEff > 82.5 %



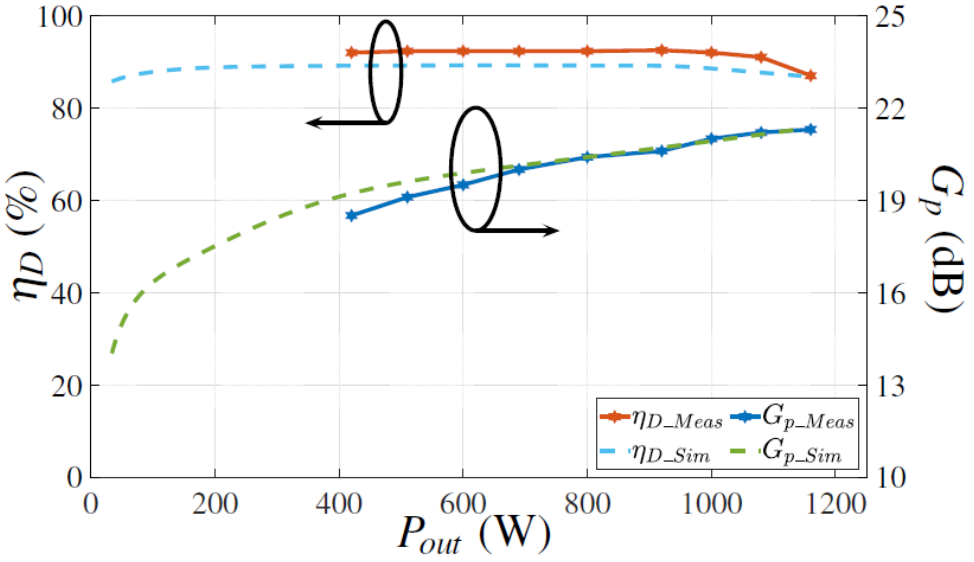
$P_{in(dBm)}$	Pout(dBm)	Pout (W)	PAE(%)	I_Drain (A)	DE (%)	Gain
43.02	60.17	1039.92	67.09	31	75.28	17.15
43.66	60.35	1083.93	69.71	31.1	78.21	16.69
44.16	60.46	1111.73	71.26	31.2	79.96	16.30
44.53	60.60	1148.15	73.48	31.25	82.45	16.07

Measurement Results including Signal Gain, Output Power, Drain Efficiency, and Power Added Efficiency at 750MHz.

Waveform engineering: design principles at 100 MHz – 1kW – 93% eff.



- PA designed and fabricated for operation around 98 MHz
- Obtained state-of-the-art peak efficiency of 93%, with a gain >20dB and an output power of 980W.
- Efficiency maintained above 90% up to 5dB backoff using drain supply variation from 30 to 50V.



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.

Efficient Multimode PA Module at 100 MHz

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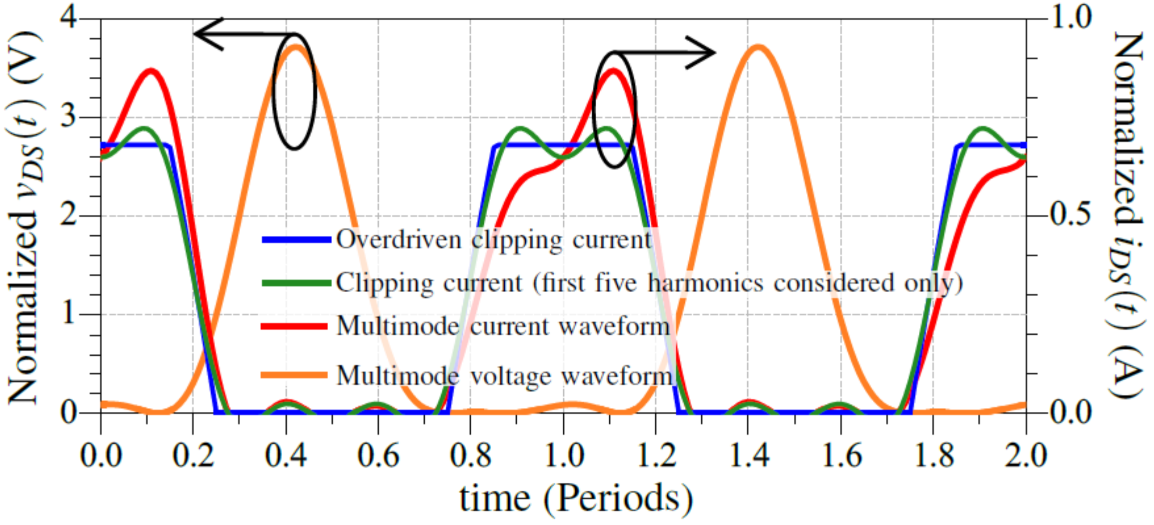
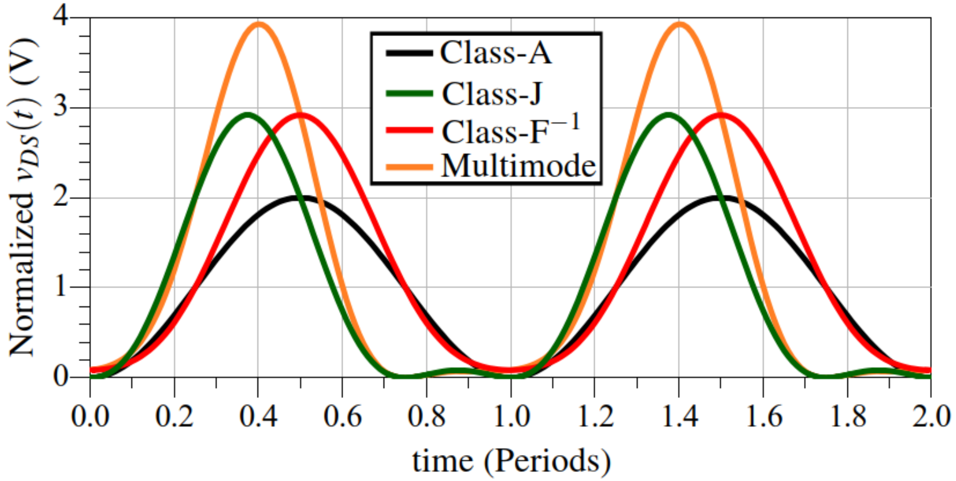
- Multimode PAs defined in terms of time-domain waveform engineering
- Background of different classes (F^{-1}, J)
- Theory for multi-mode operation and a combination of F^{-1} and J modes chosen for the final single-ended PA design





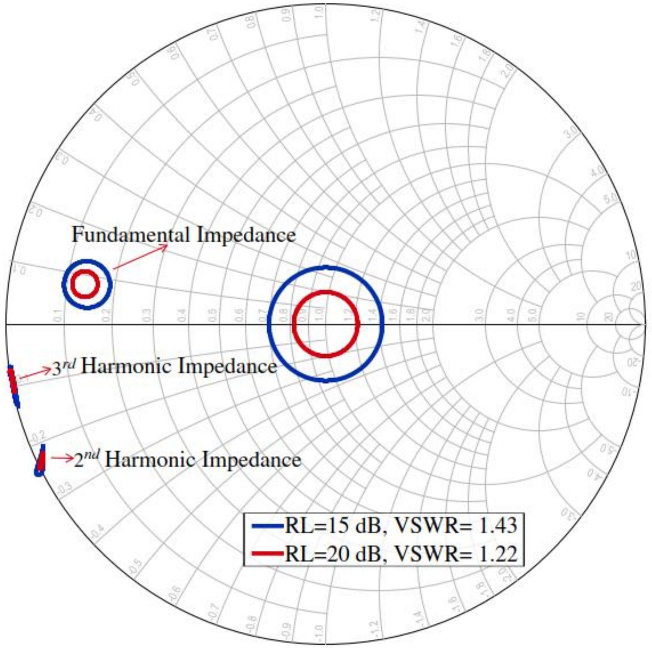
$$v_{DS}(t) = V_{DD} \cdot \left[1 - \sqrt{2}\cos(\omega t) + 0.5\cos(2\omega t)\right] \cdot [1 + \sin(\omega t)]$$

Efficient Multimode PA Module at 100MHz

Specification		Operation Mode		
		Class-F^{-1}	Class-J	Multimode
$Z_{nf_0} = $ $Z_{f_0} \cdot R_{opt}$ (Ω)	Z_{f_0}	$3.29 + j0$	$2.0 + j2.0$	$3.1 + j2.4$
$Z_{2f_0} \cdot R_{opt}$ (Ω)	Z_{2f_0}	Inf *+ $jInf$	$0 - j2.36$	$0 - j6.0$
$Z_{3f_0} \cdot R_{opt}$ (Ω)	Z_{3f_0}	$(0 + j0)^{*}$	$(0 + j0)^{*}$	$0 - j2.8$
Efficiency, η_D (%)		**90**	78	**91**
Output Power (dBm)		P_o ‡	$P_o - 0.3$	$P_o - 1$
Matching complexity		Hard	**Easy**	**Easy**

* "Inf" means infinity large impedance here, i.e, open circuit. While $(0 + j0)$ represents "short circuit".

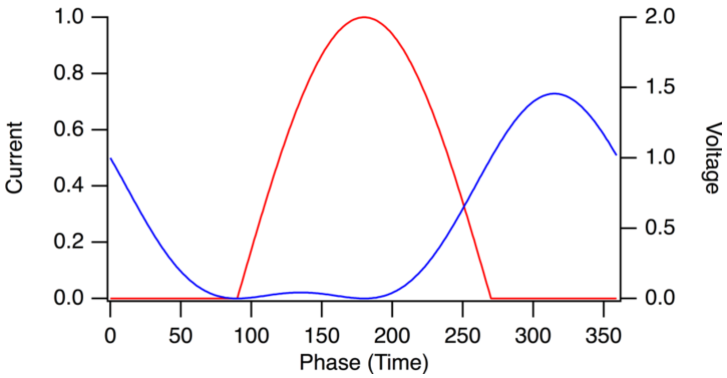
‡ P_o represents the output power for Class-F^{-1} as a benchmark for other modes.

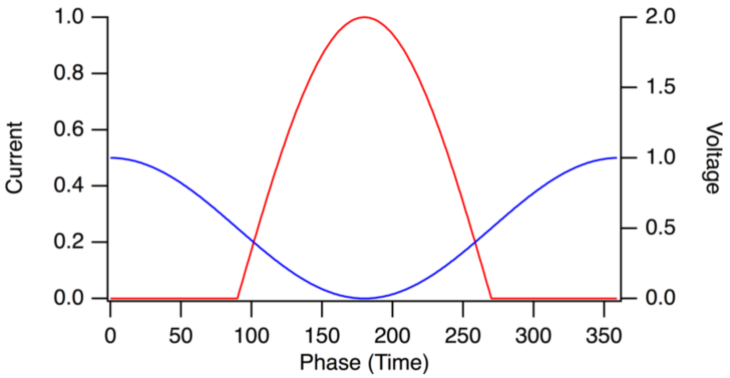


PA module load mismatch of 15 dB and 20 dB and their respective intrinsic impedance transformation for the fundamental, 2nd and 3rd harmonic through the package and output matching network.

RF I-V Waveform Engineering

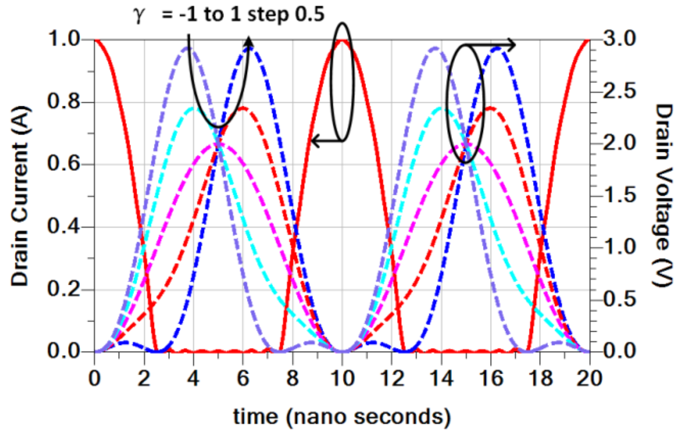
- Class B Waveforms delivering high Efficiency verified:



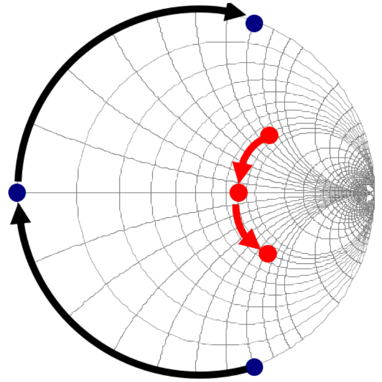


- Other Waveforms delivering high Efficiency have also been observed: Class E, Class J, Class F and Class F^{-1}, etc.
- These modes had the same; RF Power, DC values, hence efficiency, $\eta_{mode,BW}$.
- There are multiple similar performance waveform solutions and we can see classical modes as just one case of a set of continuous solutions.

The Continuous Mode Concept

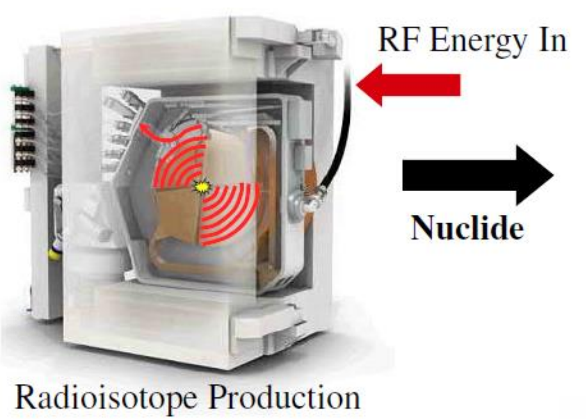


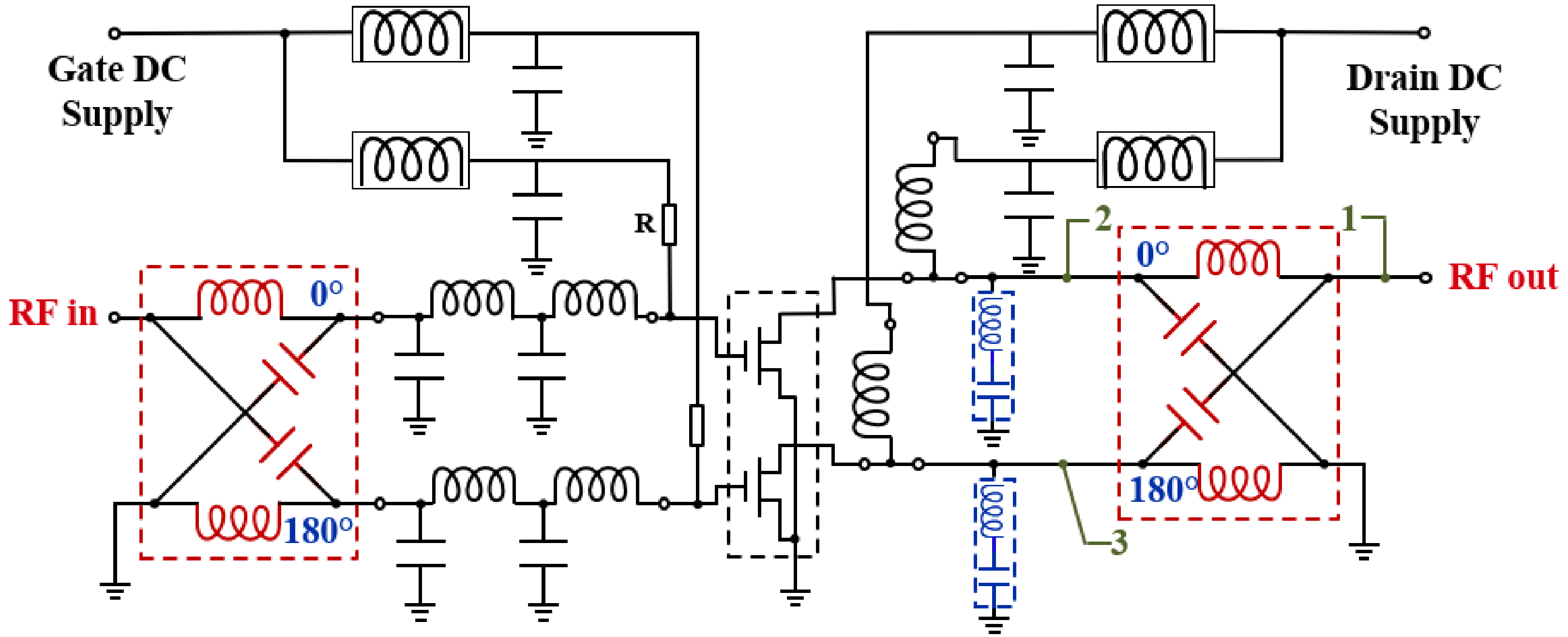
$$V_{ds}(t) = (1 - \frac{V_{rf}}{V_{DD}} * \cos(2\pi f t)) * (1 - \gamma * \sin(2\pi f t))$$



Cripps & Tasker, IEEE MWCL 2009

Efficient and Compact Push-Pull SSPA Module using lumped matching networks



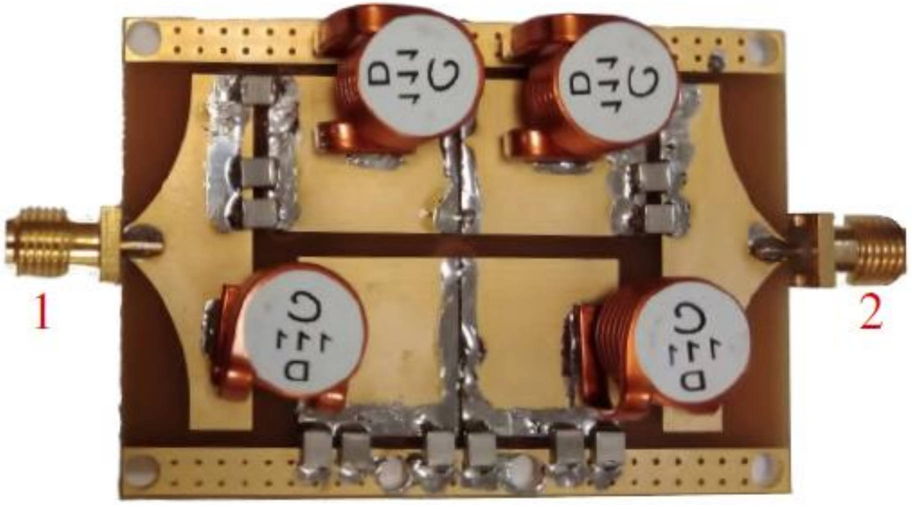


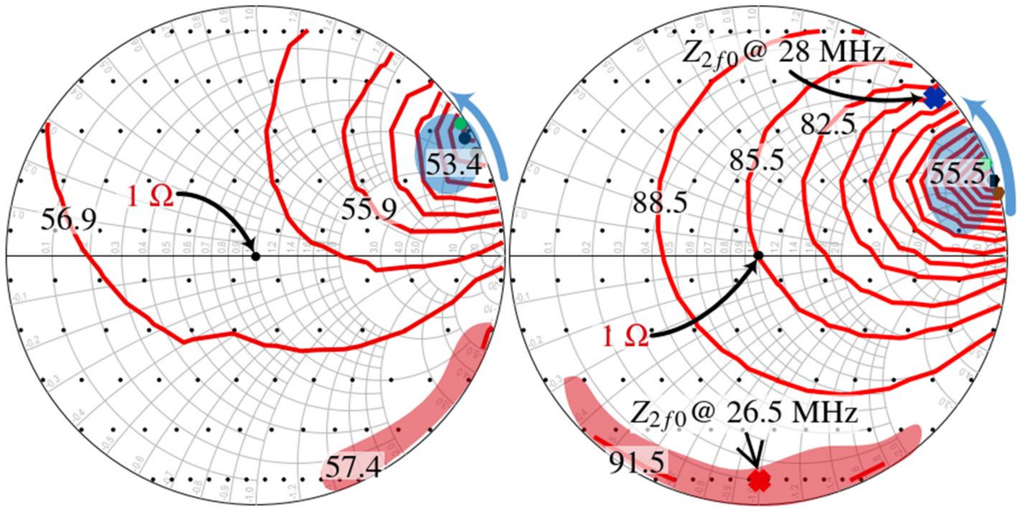
Tong, Renbin, et al. "Compact and highly efficient lumped push-pull power amplifier at kilowatt level with quasi-static drain supply modulation. " IEEE/MTT-S International Microwave Symposium (IMS). IEEE, 2020.

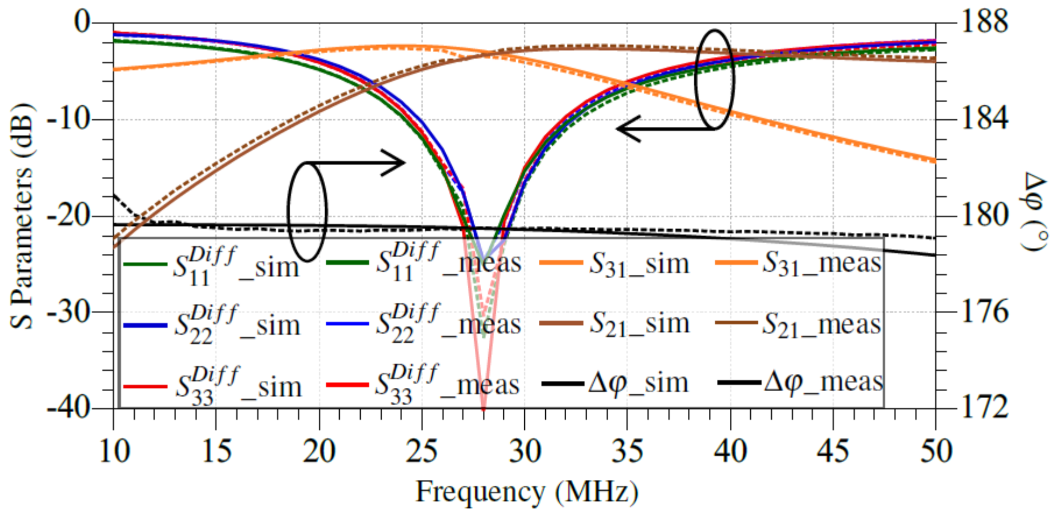
Tong, Renbin, et al. "Compact and highly efficient kilowatt lumped push–pull power amplifier for cyclotron in radioisotopes production." IEEE Transactions on Microwave Theory and Techniques 69.1 (2020): 723-731.

Push-pull PA for a kW module at 27 MHz

- Designed lumped balun for push-pull PA and characterized it in back-to-back configuration/compared with simulations.
- Investigated in simulations regions of second harmonic impedance for efficient operation.







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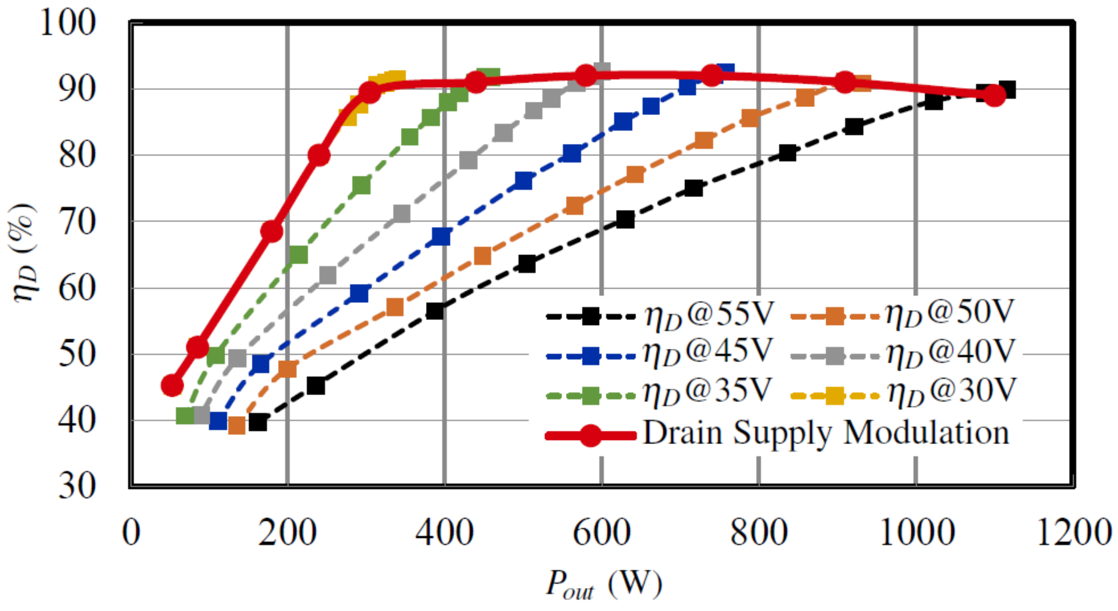
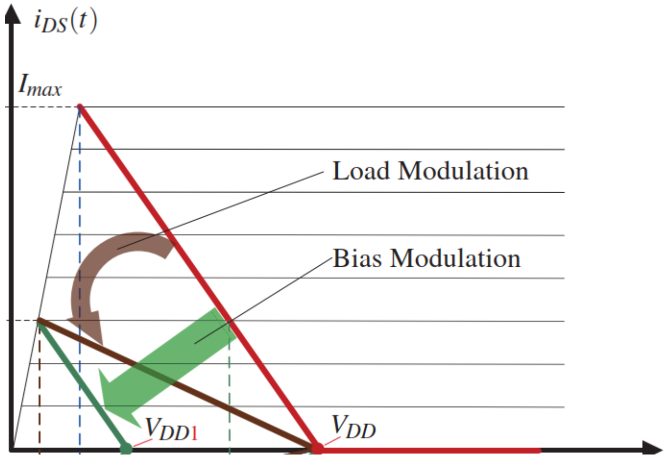
Supply Modulation for Efficiency in Backoff

- 89% efficiency 1150 W output power at 26.5 MHz achieved
- > 83% efficiency with > 960 W achieved from 24.5 to 27 MHz
- Quasi-static supply modulation shaping function obtained



- Drain supply modulation results in > 90% drain efficiency over a 5 dB back-off power range.



Push-Pull Module at 27 MHz

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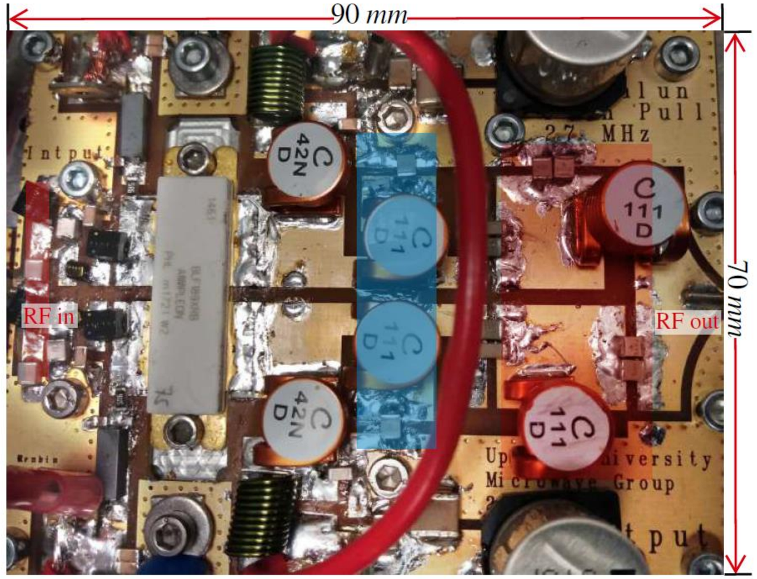
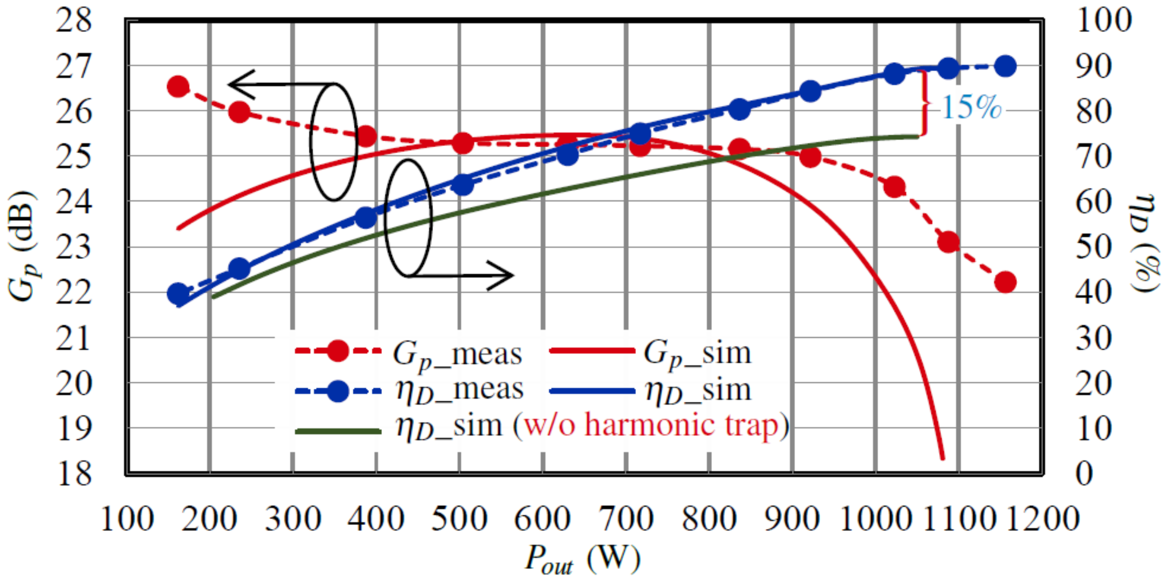
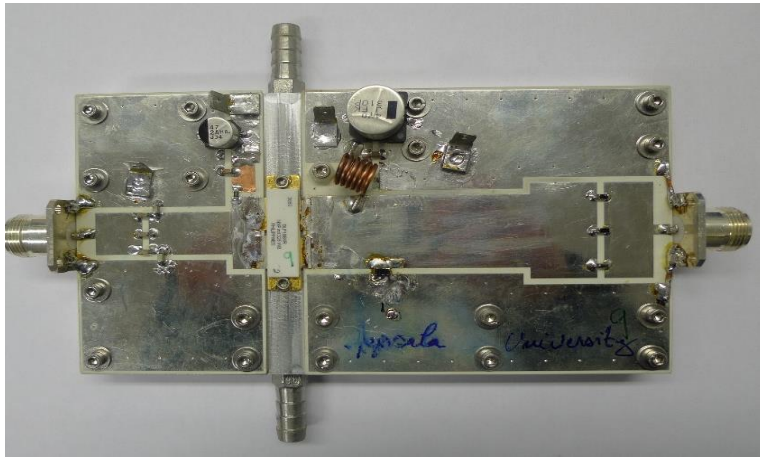


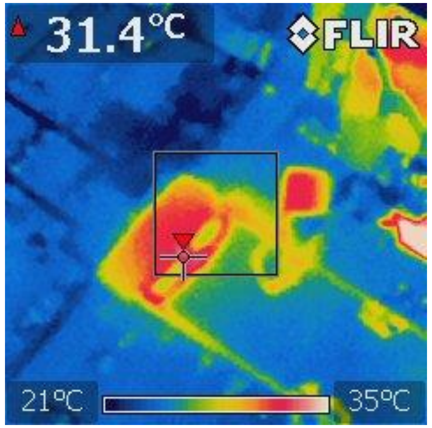
- Matching circuits including harmonic trap to ensure high efficiency in class F
- Final circuit is very compact
- Demonstrated close to 1kW between 24 and 27 MHz

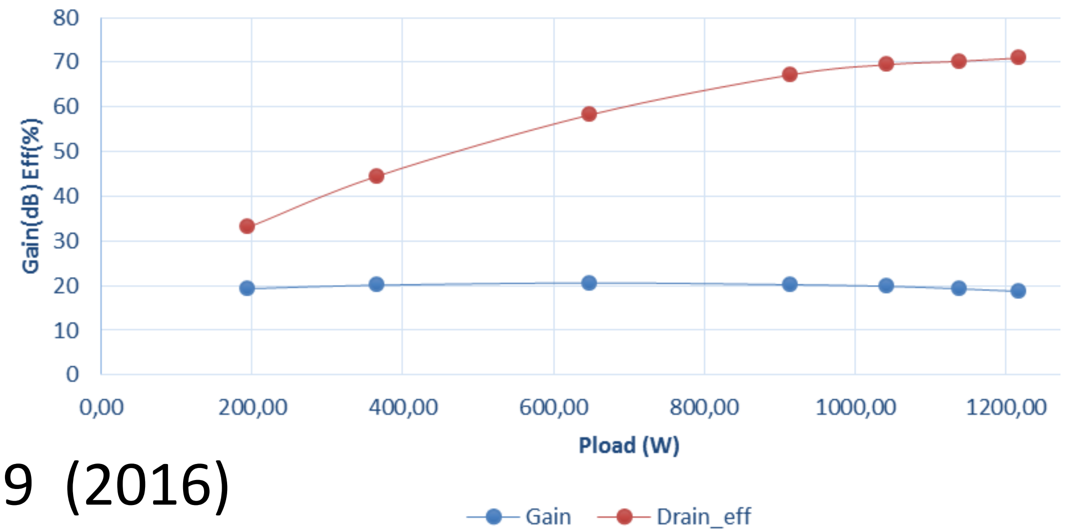


See next talk: Industrial usage of high efficiency SSPAs by Jan Kovermann

Single ended RF power amplifier 352 MHz

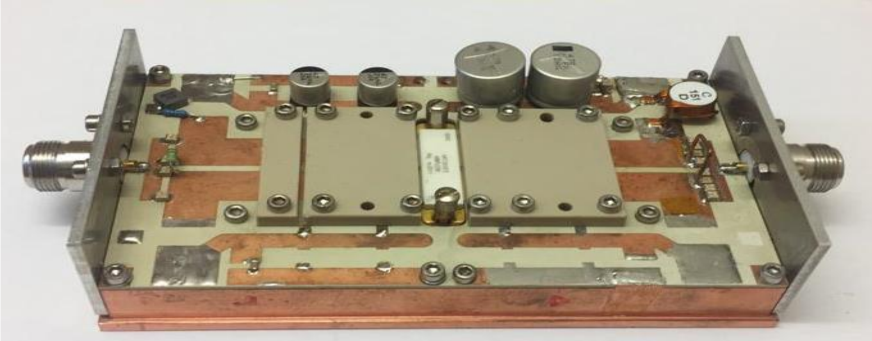






BLF189 (2016)

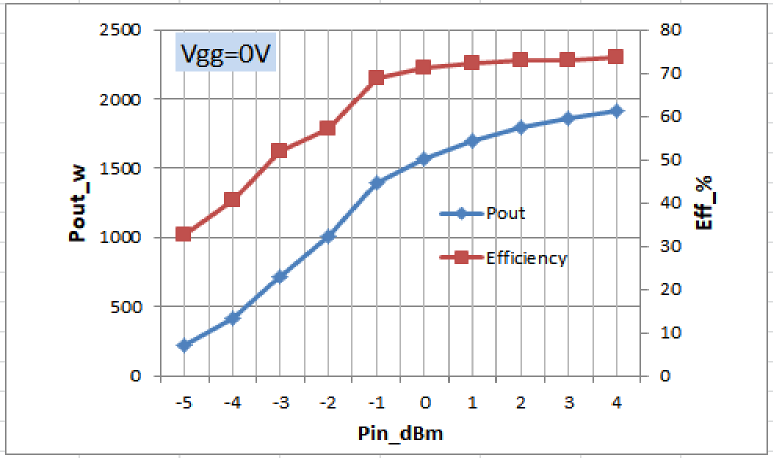
Pout > 1.25 kW, Eff > 70 %



ART2K (2024)

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



$\eta_{combiner}$: combiner losses

=

IL [dB]	η *combiner*
0.3	93,0%
0.5	89,0%
0.8	83,0%
1.0	79,0%

10 kW HPA 352 MHz pulsed 5% DC

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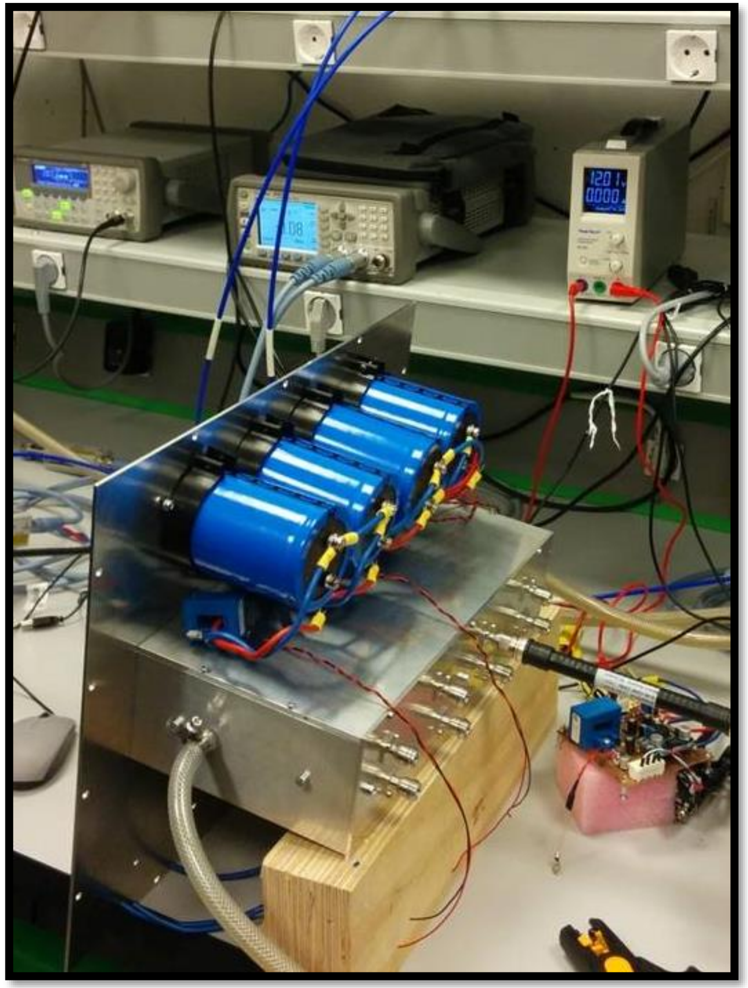

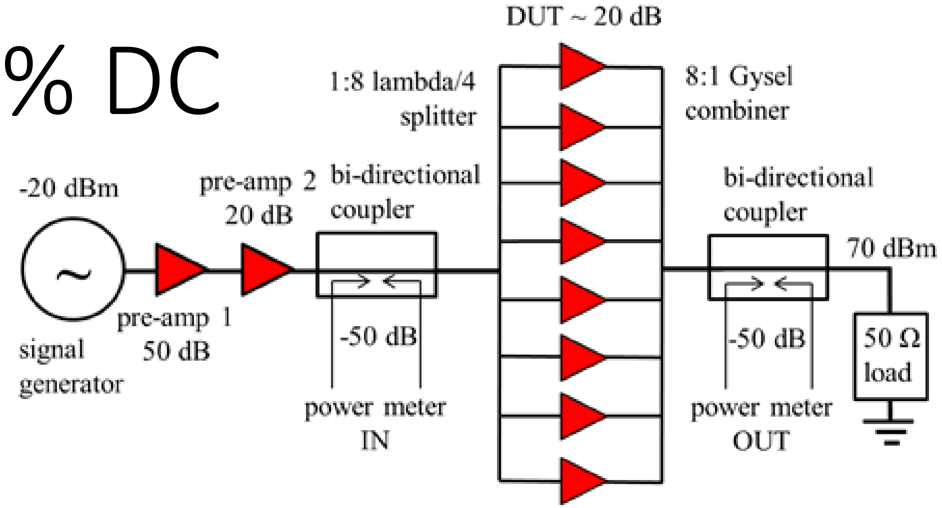

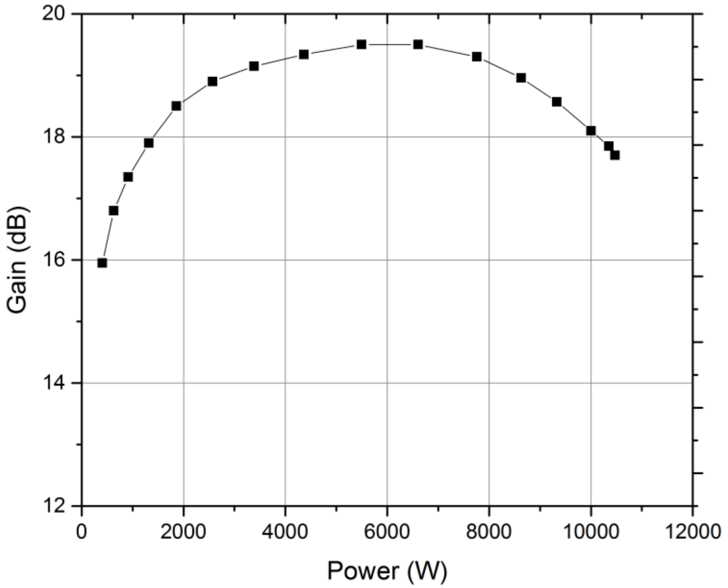

D. Dancila et al, "A compact 10 kW solid-state RF power amplifier at 352 MHz," 2017 IOP Conf. Series: Journal of Physics: Conf. Series, vol. 874, 012093

Gysel Power Combiner 10 kW

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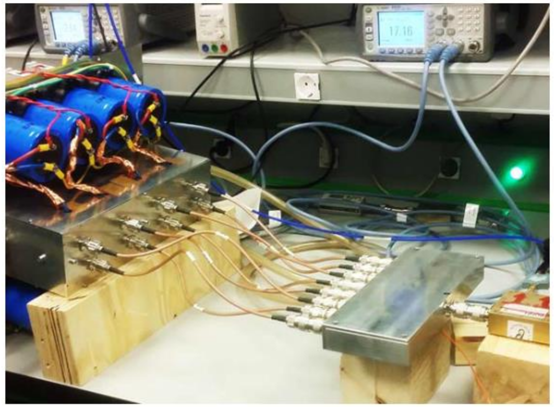
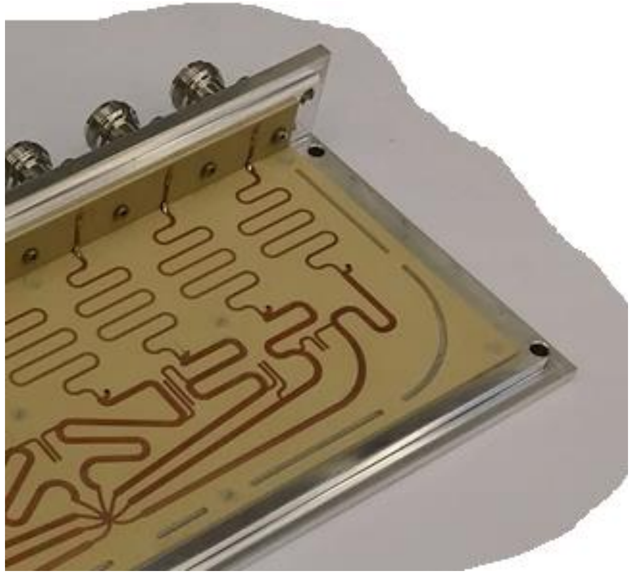
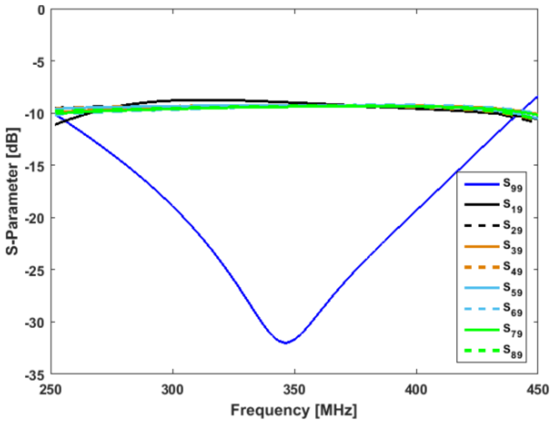
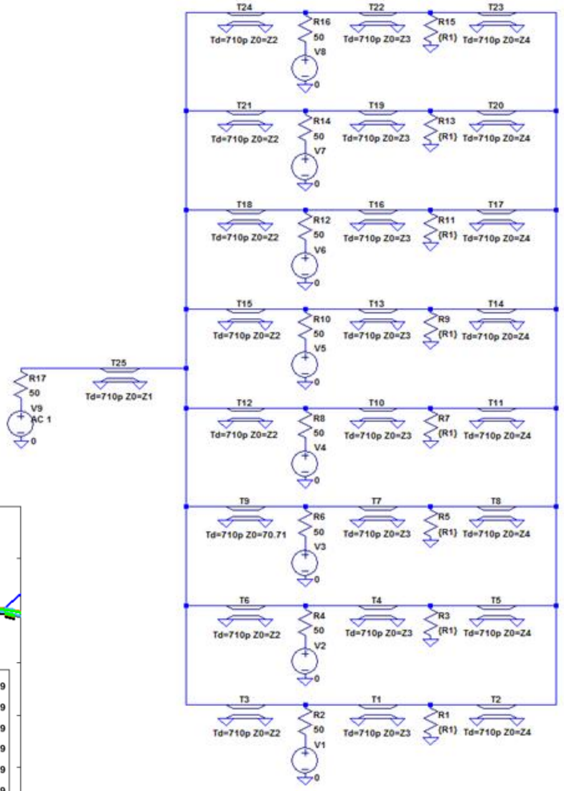


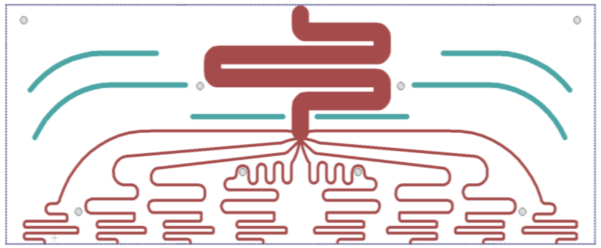
Key Parameters

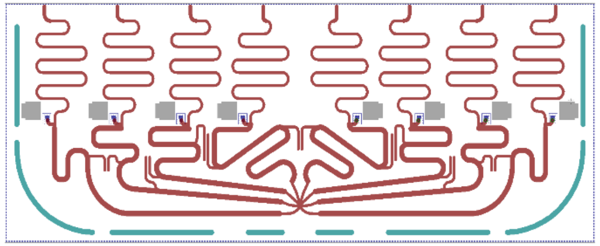
- $S_{NN} < -20$ dB
- Losses < 0.1 dB
- High Power Handling
- 240 x 100 x 30 mm

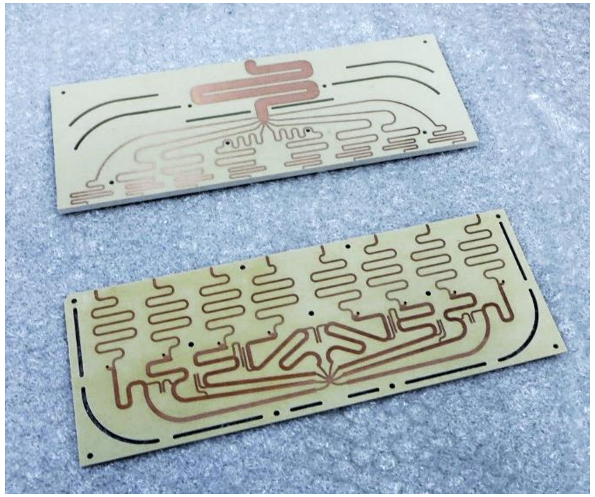












M. Jobs, D. Dancila, J. Eriksson and R. Ruber, "An 8-1 Single-Stage 10-kW Planar Gysel Power Combiner at 352 MHz," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 8, no. 5, pp. 851-857, May 2018.

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

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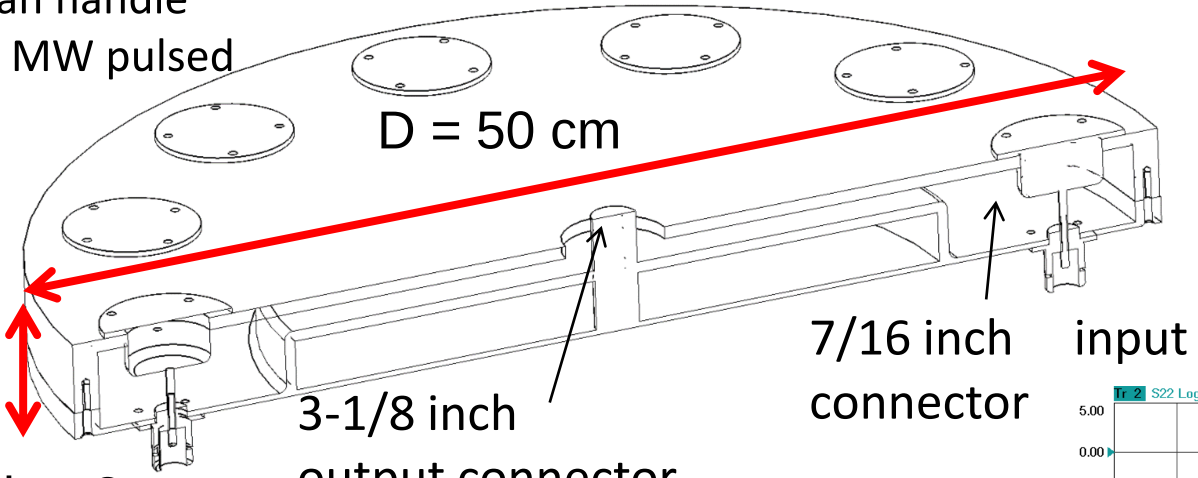
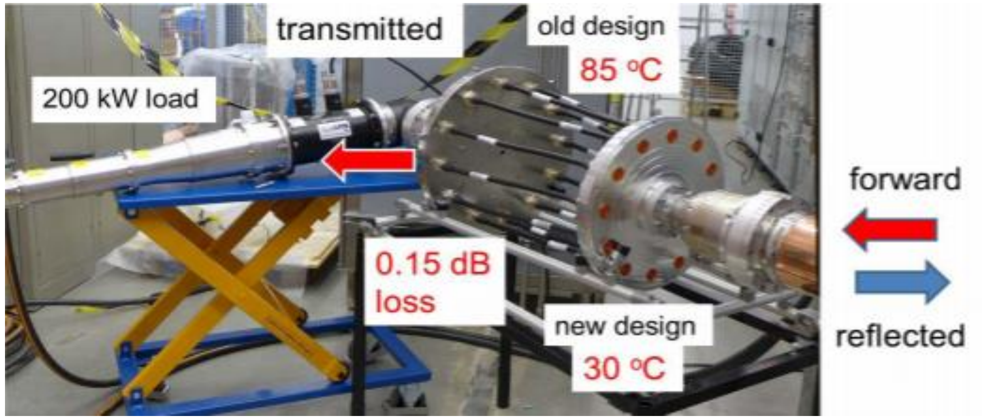
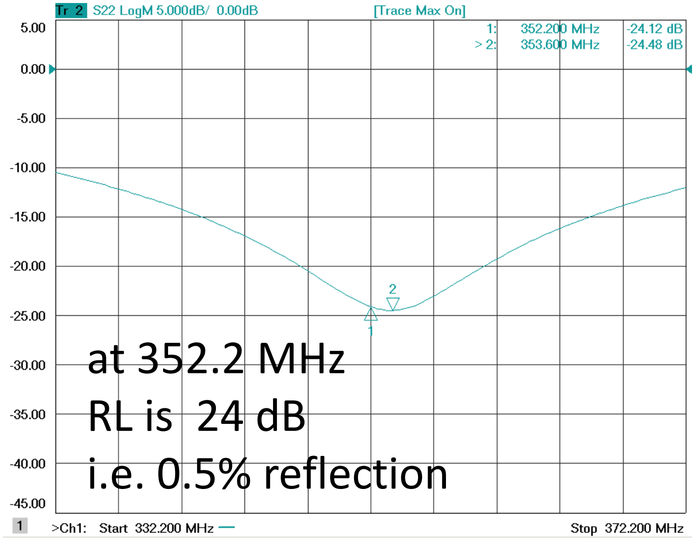
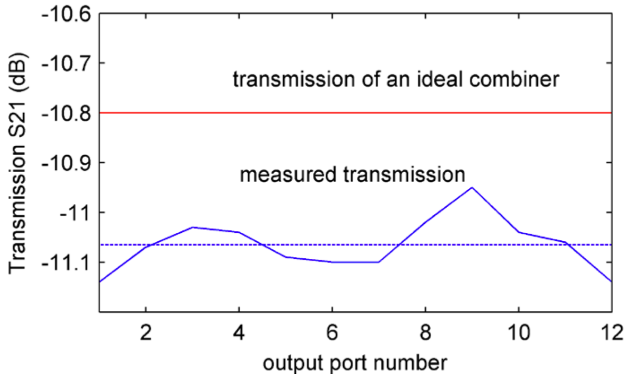






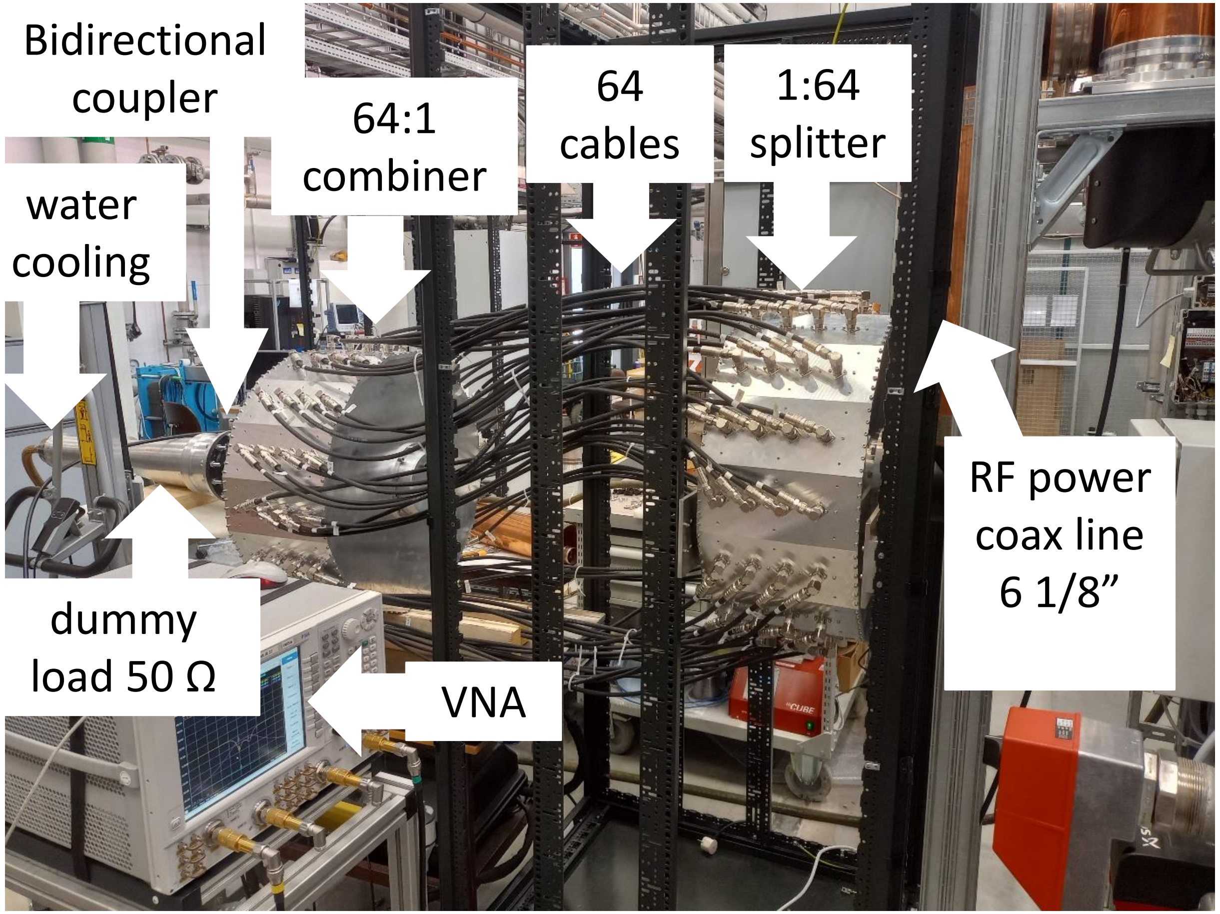
at 352.2 MHz
RL is 24 dB
i.e. 0.5% reflection

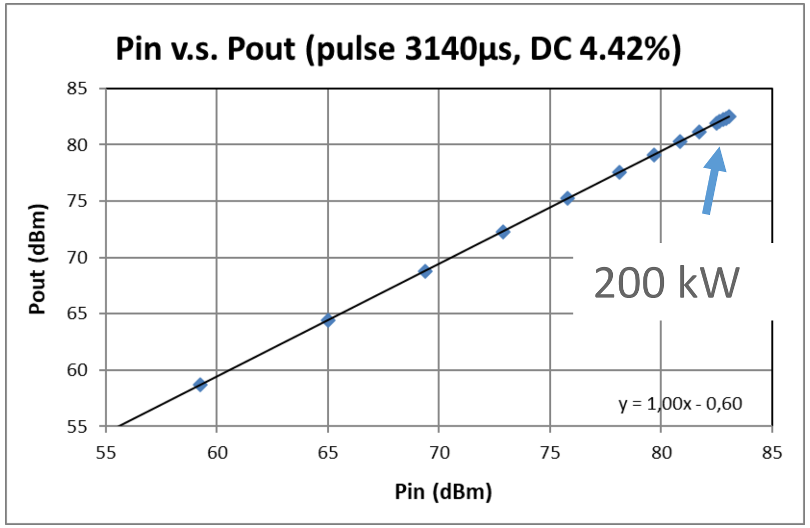


at 352.2 MHz
IL is 0.3 dB i.e. 6% losses

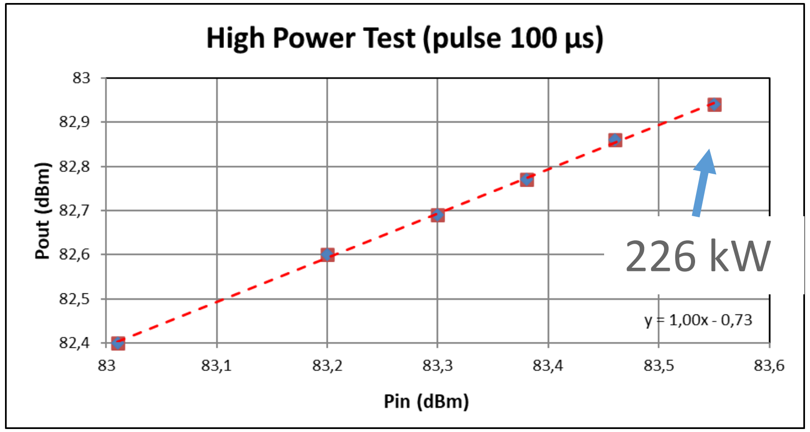
V. A. Goryashko, D. Dancila, A. Rydberg, R. Yogi & R. Ruber (2014): A megawatt class compact power combiner for solid-state amplifiers, Journal of Electromagnetic Waves and Applications.

Back to back combiner test at high power





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)

ESS’ SSPA 400kW station at 352 MHz - 5% DC

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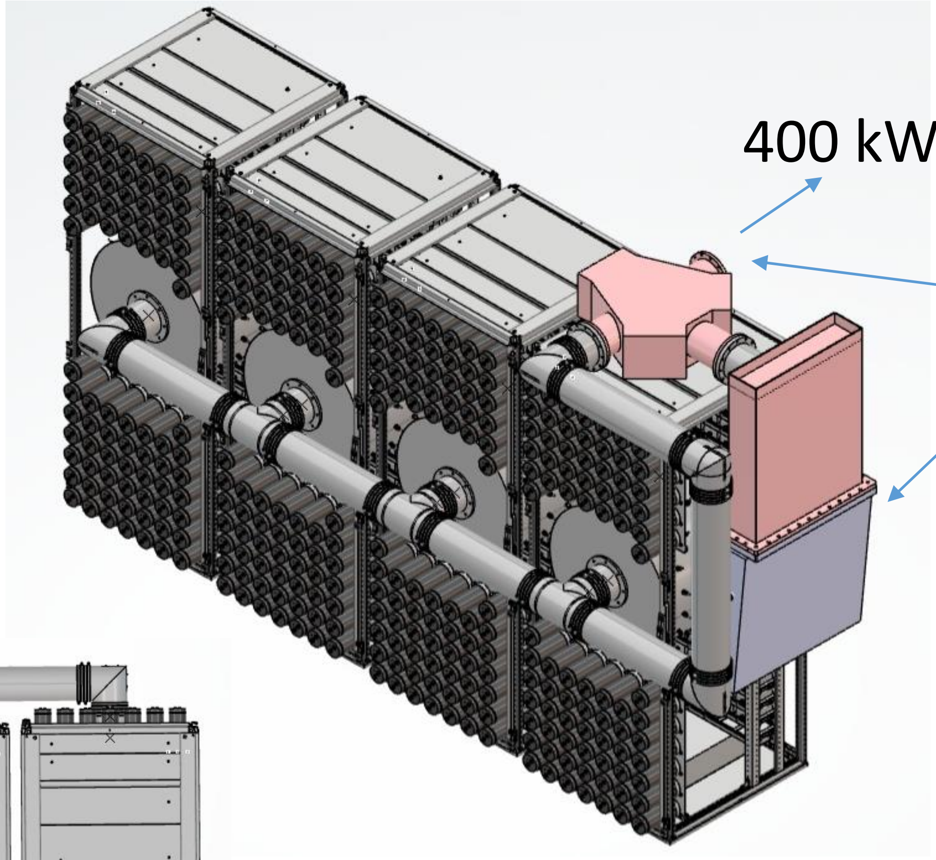
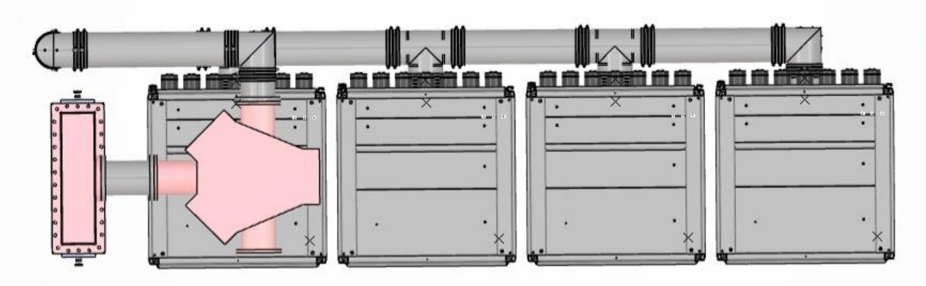
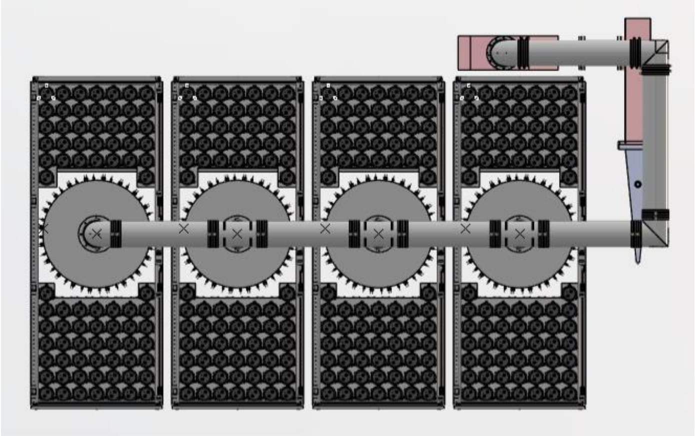


400 kW

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





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

See next talk: Pulsed 400 kW solid state amplifier by Bruno Lagoguez

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Summary

The total, i.e. wall plug efficiency of an SSPA station is influenced by six key factors:

$$\eta_{tot} = \eta_{Gain} \times \eta_{knee} \times \eta_{loss} \times \eta_{mode,BW} \times \eta_{AC\ to\ DC} \times \eta_{combiner}$$

- Understanding waveform engineered in different amplifier topologies allows for optimal amplifier design. Continuous modes remove the constraint of working with just harmonic shorts or open.
- If we target PAE > 90 % the first 4 factors must all be > 97.5 %
  - Need to have Gain > 16 dB rather than >10 dB
  - Need to reduce Knee Voltage by a significant factor down to 0.025 of V_{max}
  - Keep output matching losses < 0.1 dB rather than 0.4 dB
  - Circuit design increased beyond 3rd harmonic to at least 5th harmonic
- Considering a good AC to DC efficiency: $\eta_{AC\ to\ DC} = 96\%$
- Considering combiner losses, the wall plug eff. η_{tot} becomes:

PAE

$(97{,}5\%)^4 \approx 90\%$

$(94{,}5\%)^4 \approx 80\%$

$(91{,}5\%)^4 \approx 70\%$

$(90\%)^4 \approx 66\%$

(see vac tube eff)

PAE	90%	80%	70%	66%
with η ACDC	87%	77%	67%	63%
IL 0.3 dB	81%	71%	63%	59%
IL 0.5 dB	77%	68%	60%	56%
IL 0.8 dB	72%	64%	56%	52%
IL 1.0 dB	69%	60%	53%	50%

Questions ?

Welcome to Uppsala, especially on the last day of April – Valborg.