UPPSALA UNIVERSITET

Radiofrequency Power Transistor Amplifiers

Wednesday, May 8, 2019

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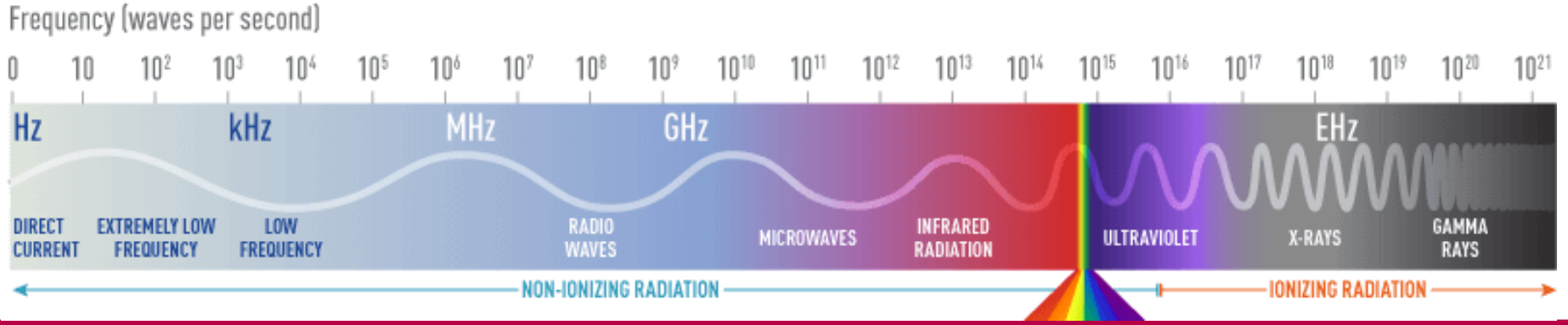
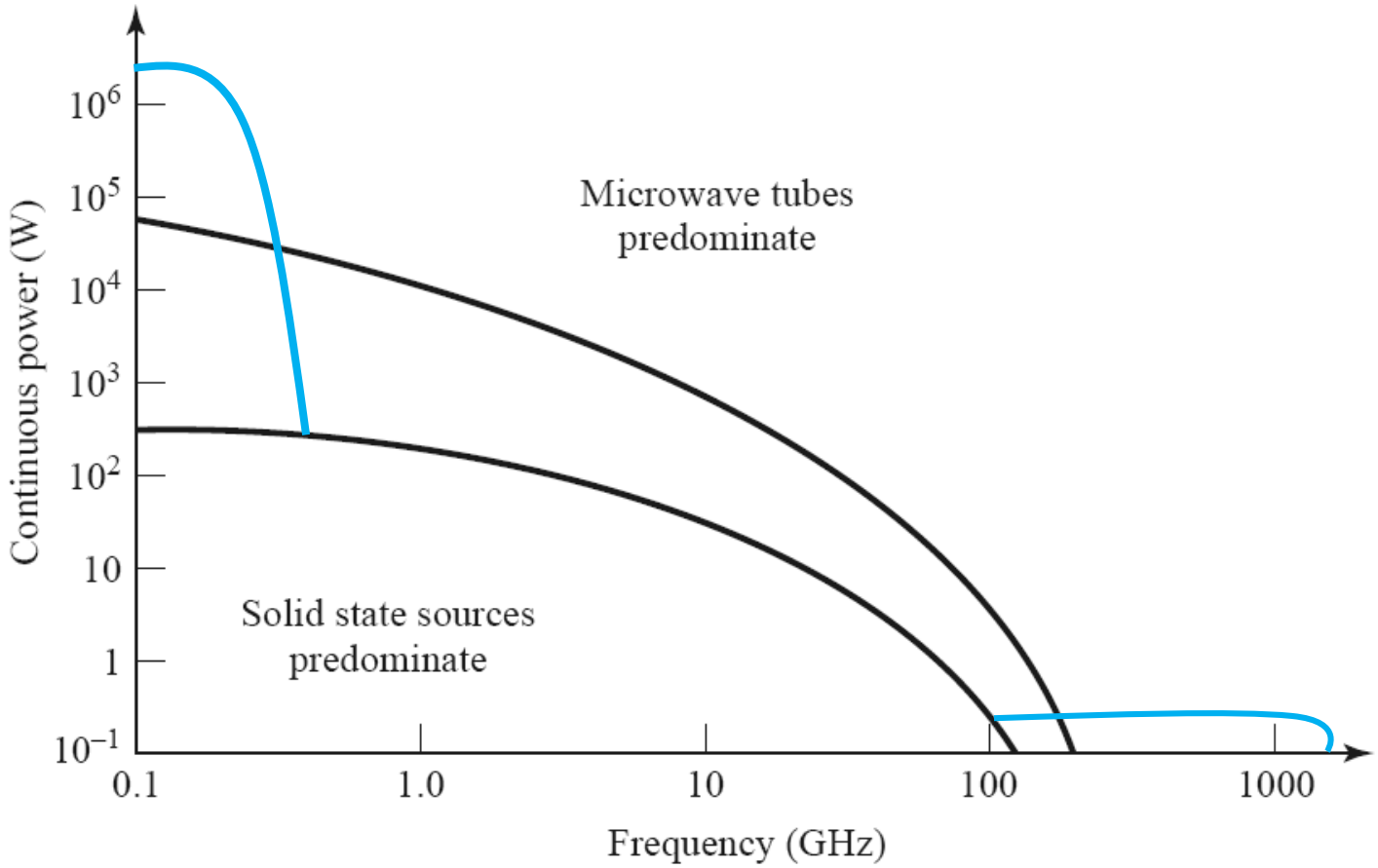
Introduction

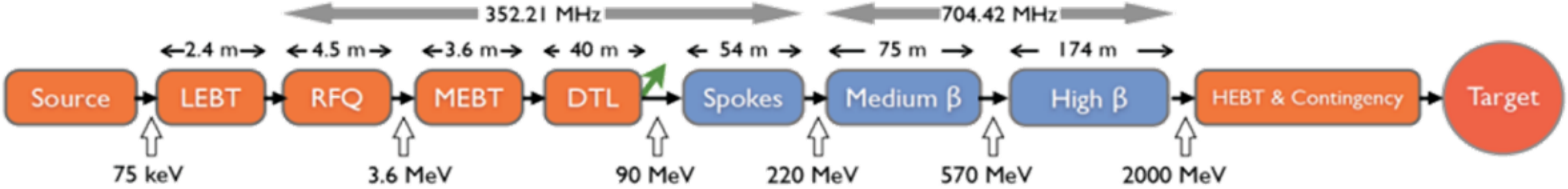
- Radio Frequency (RF) range from very high frequency (VHF) (30–300 MHz) to ultra high frequency (UHF) (300–3000 MHz)
- The term *microwave* is typically used for frequencies between 3 and 300 GHz, with a corresponding electrical wavelength between $\lambda = c/f$ = 10 cm at 3 GHz and λ = 1 mm at 300 GHz
- Signals with wavelengths on the order of millimeters are often referred to as *millimeter waves (*λ = 3 mm at 100 GHz and λ = 5 mm at 60 GHz*)*



Amplifiers - power v.s. frequency trends



Transistor Amplifier Development for ESS



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

Development of high power RF stations at ESS specifications

352.21 MHz, 400 kW, 14 Hz, 3.5 ms, 200 kHz bandwidth

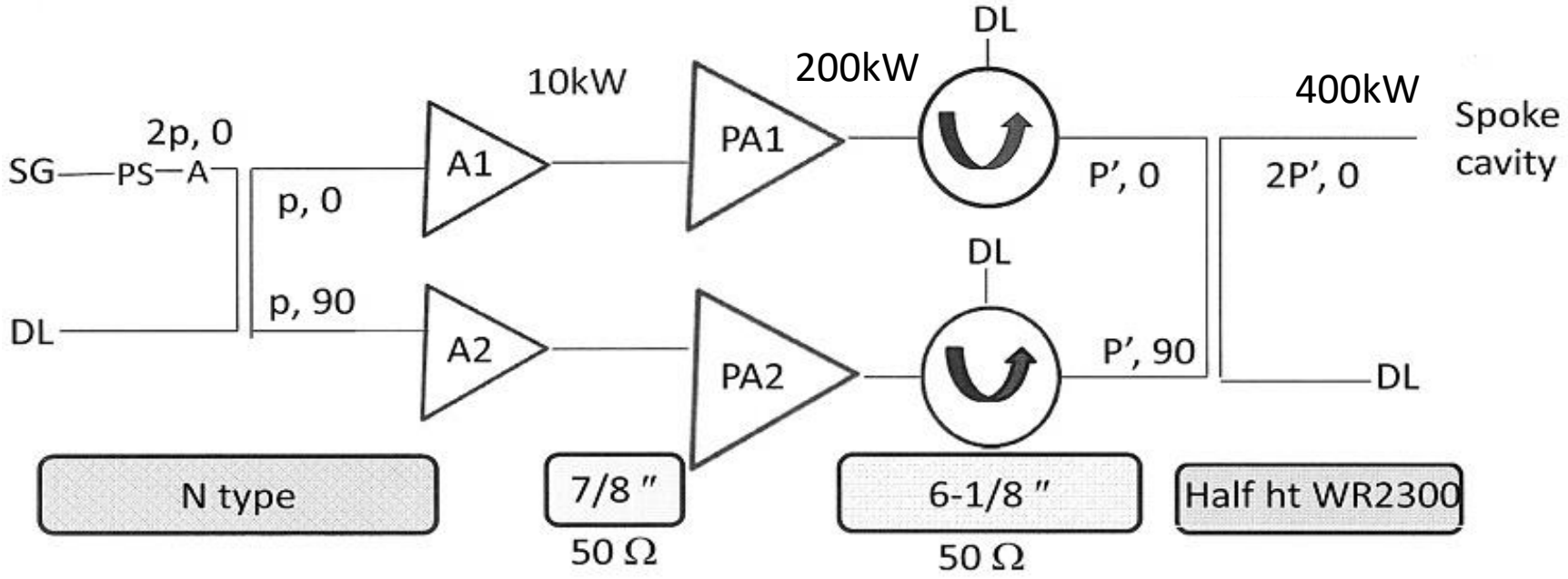
FREIA at Uppsala University

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 is a key-parameter (50-60%)

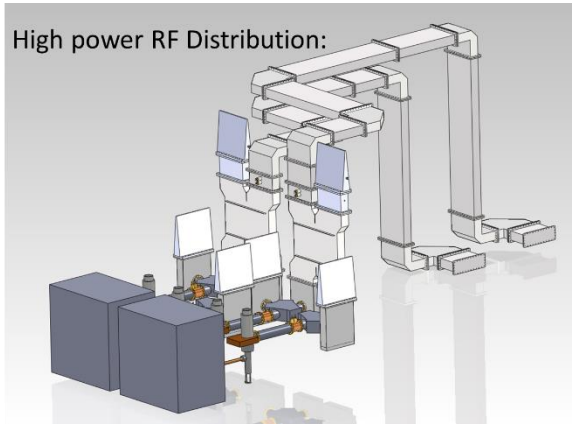
400 kW RF Power Station – tetrode

- only one commercial manufacturer of tetrode tubes
- only 3 for klystrons
- this gives a commercial and cost uncertainty



- 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

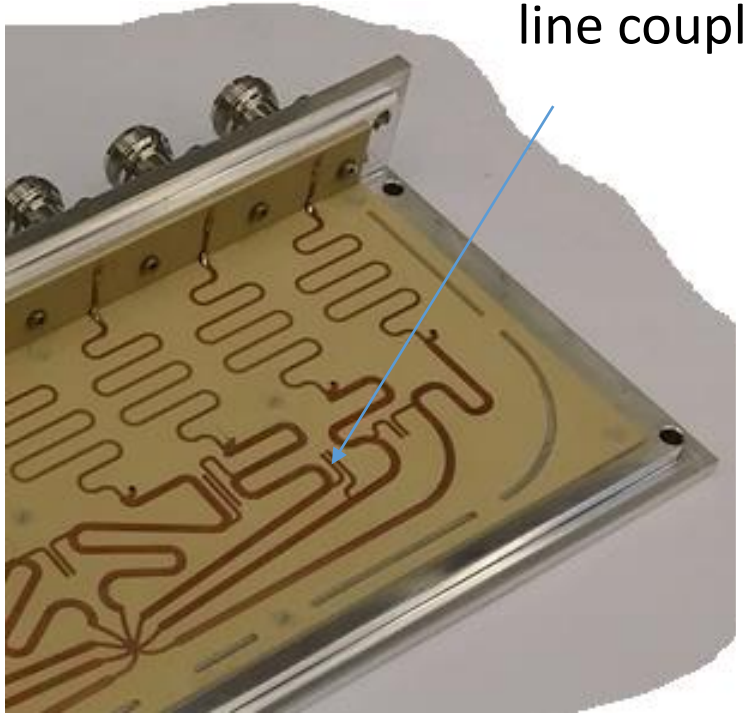


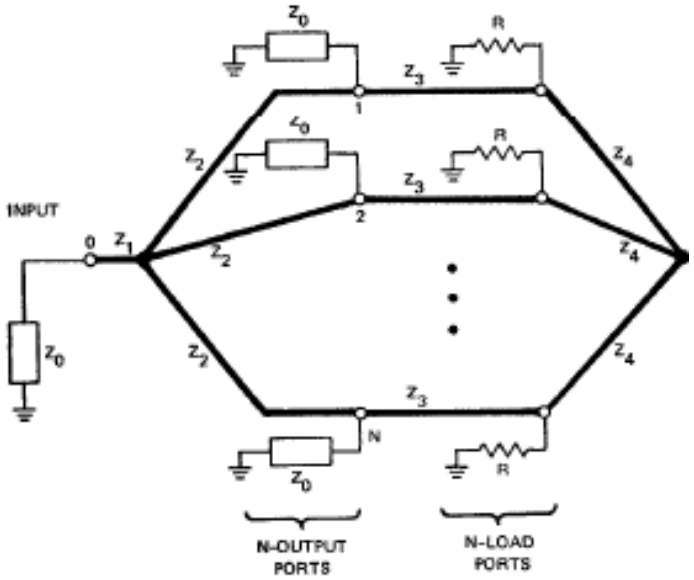
It takes a handful of transistors (200) to replace one tetrode.

Solves the redundancy problem with one tube --> station down (as opposed to many transistors)

10 kW planar Gysel Combiner (352 MHz)

line coupling compensates parasitic coupling





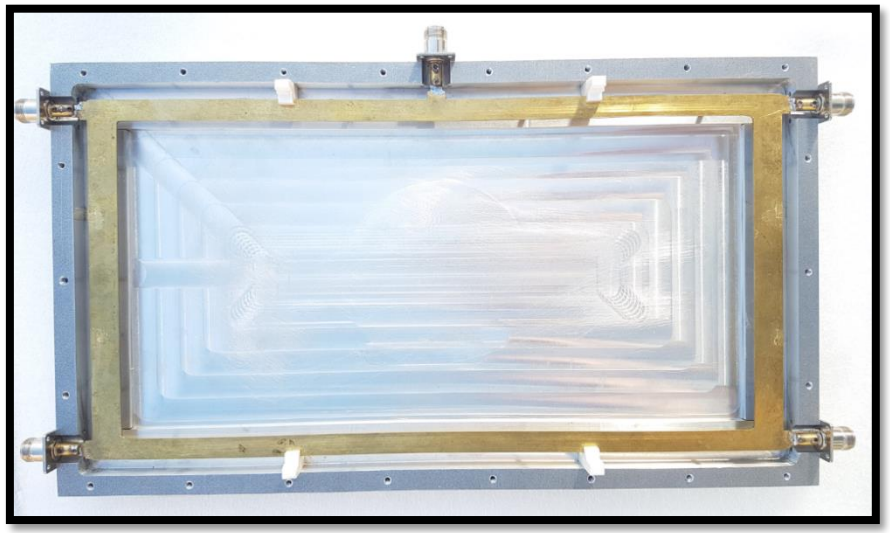
Measured Performance

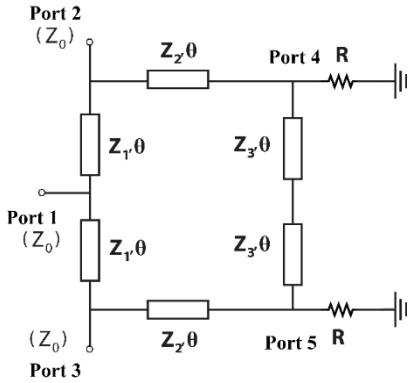
	1	2	3	4	5	6	7	8
Phase [deg]	121	117	117	120	120	117	117	121
Mag [dB]	-9.24	-9.32	-9.24	-9.16	-9.19	-9.27	-9.29	-9.15

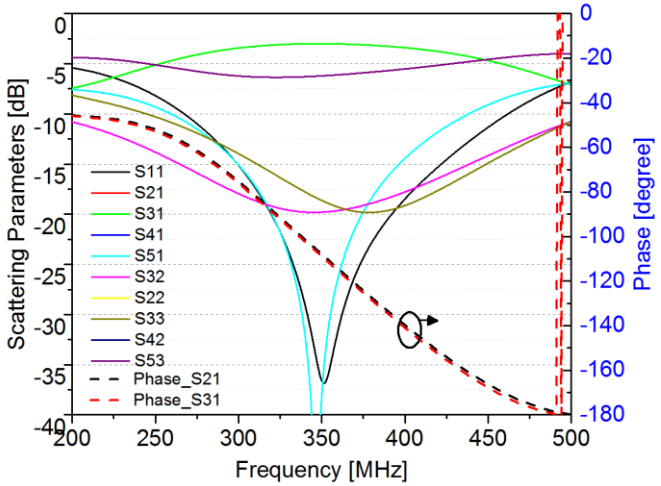
	1	2	3	4	5	6	7	8
1	-21*	-24.7	-23.7	-24.2	-24.1	-23.7	-23.4	-22.7
2		-24*	-27.5	-26.8	-26.3	-24.8	-24.9	-23.6
3			-21*	-26.4	-27.3	-25.2	-24.9	-23.3
4				-23*	-30.6	-27.1	-26.1	-24.1
5					-25*	-26.2	-26.5	-24.2
6						-25*	-27.1	-23.7
7							-26*	-24.9
8								-26*

M. Jobs, D. Dancila, J. Eriksson and R. Ruber, ”A 8-1 Single Stage 10 kW Planar Gysel Power Combiner at 352 MHz,” 2017, submitted to IEEE Transactions on Components, Packaging and Manufacturing Technology

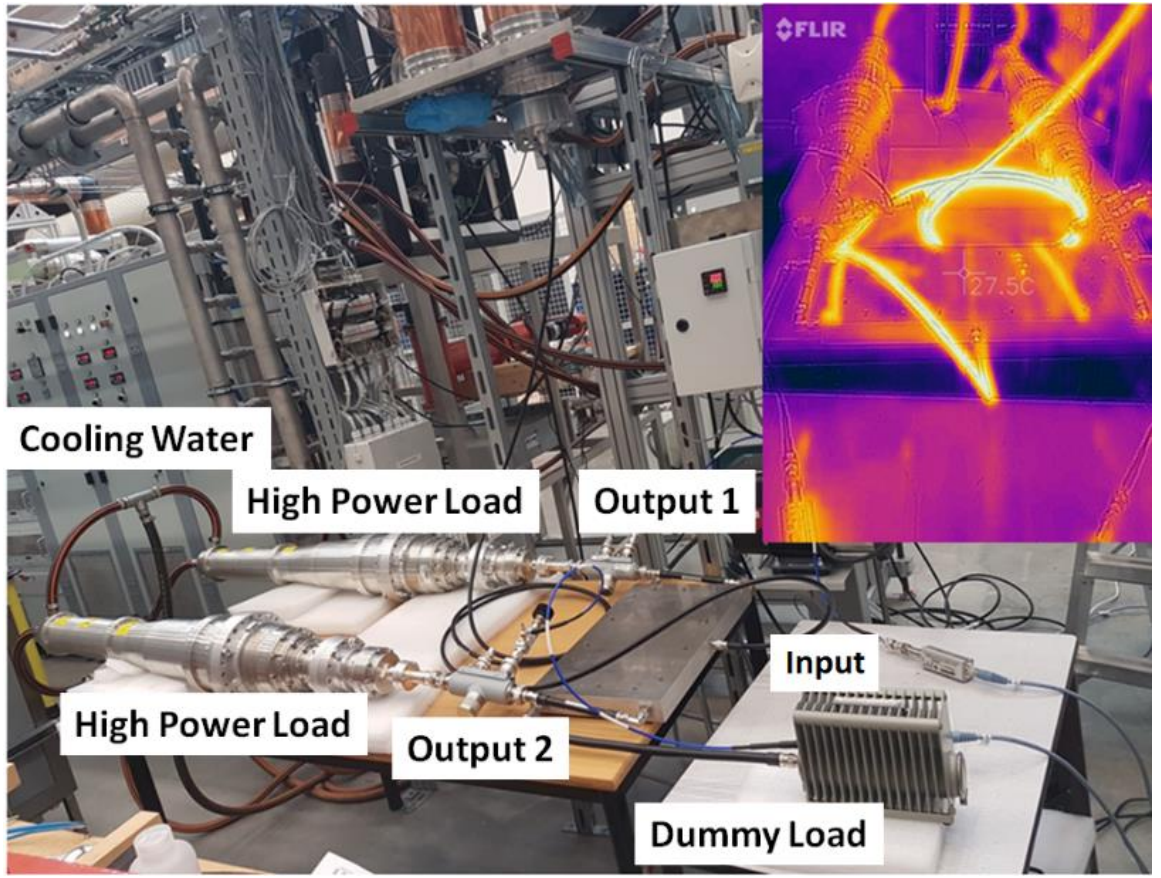
20 kW Gysel combiner (352 MHz)





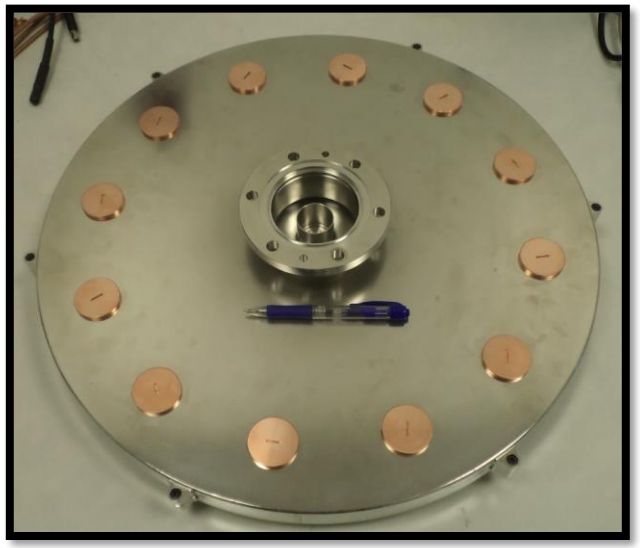


Tested up to 20 kW
IL 0.1 dB

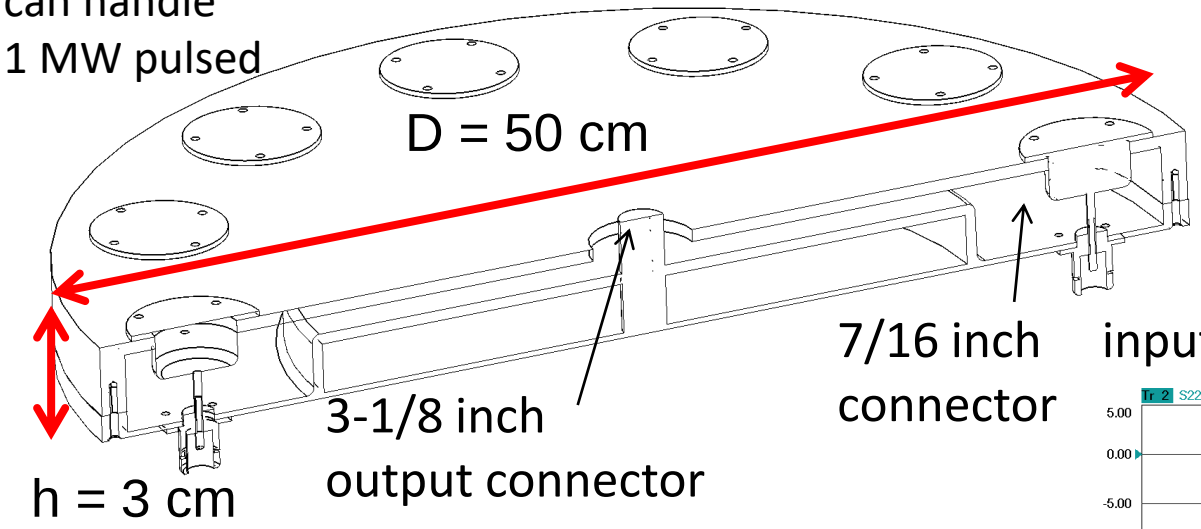


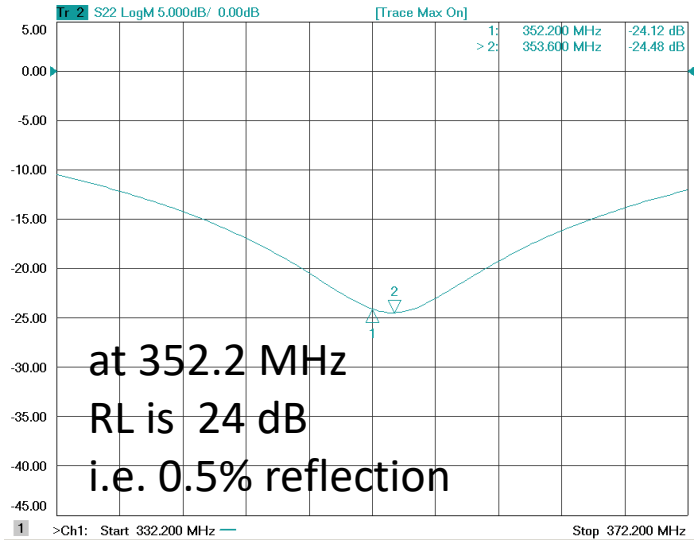
L. Hoang Duc et al., “A new high-power low-loss air-dielectric stripline Gysel divider/combiner for particle accelerator applications at 352 MHz,” 2017, Journal of Engineering.

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

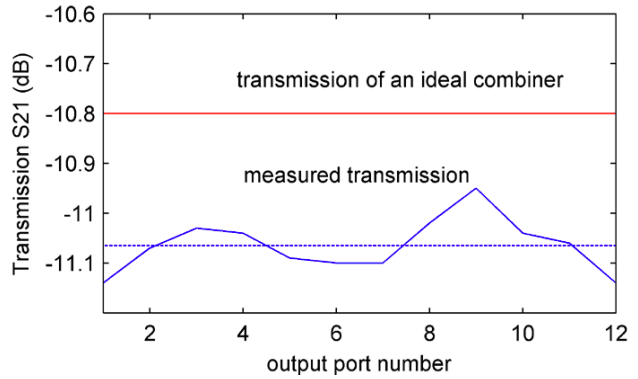


can handle
1 MW pulsed





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.

SSPA based on high power transistors

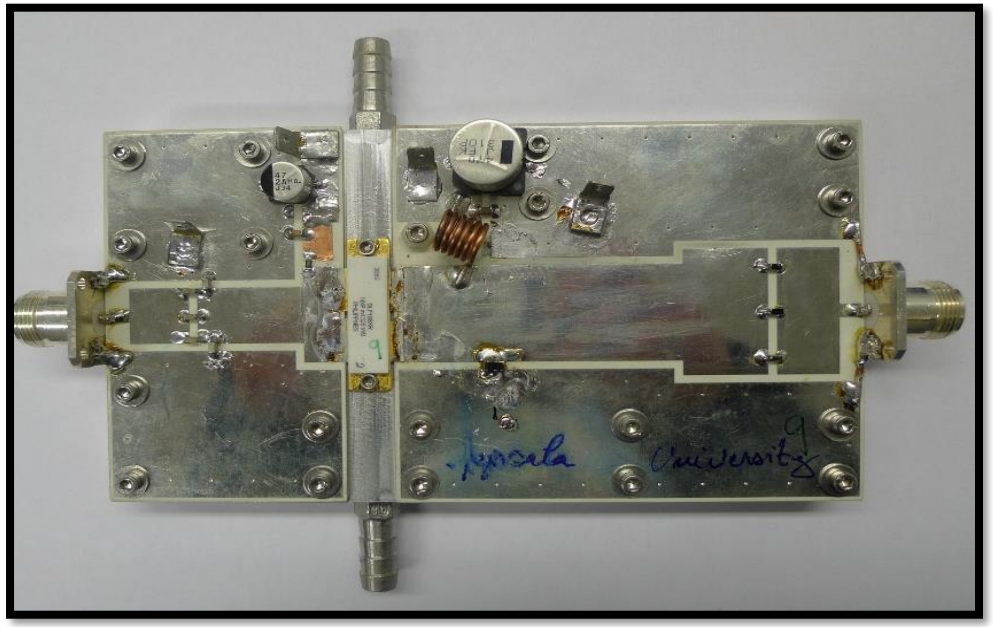
- >1000 W output power
- 27 MHz, 100 MHz, 352 MHz, 704 MHz etc.
- High efficiency >70%

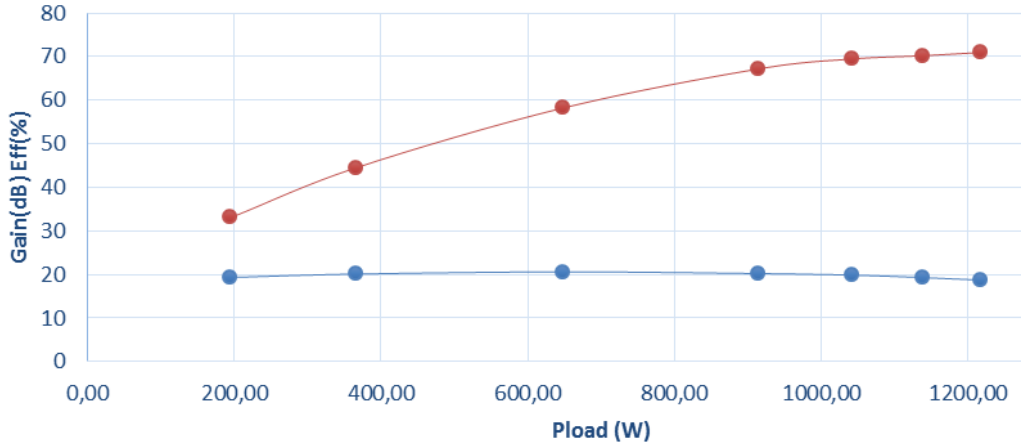
e.g. Ampleon BLF188XR LDMOS transistor, other NXP, Infineon, etc.

- High breakdown voltage (140 V)

RF amplifiers developed at FREIA

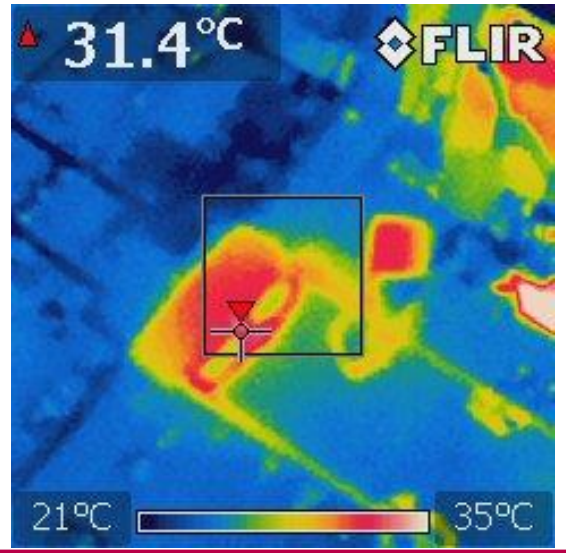
Single ended RF power amplifier class B 1250 W and 70% efficiency





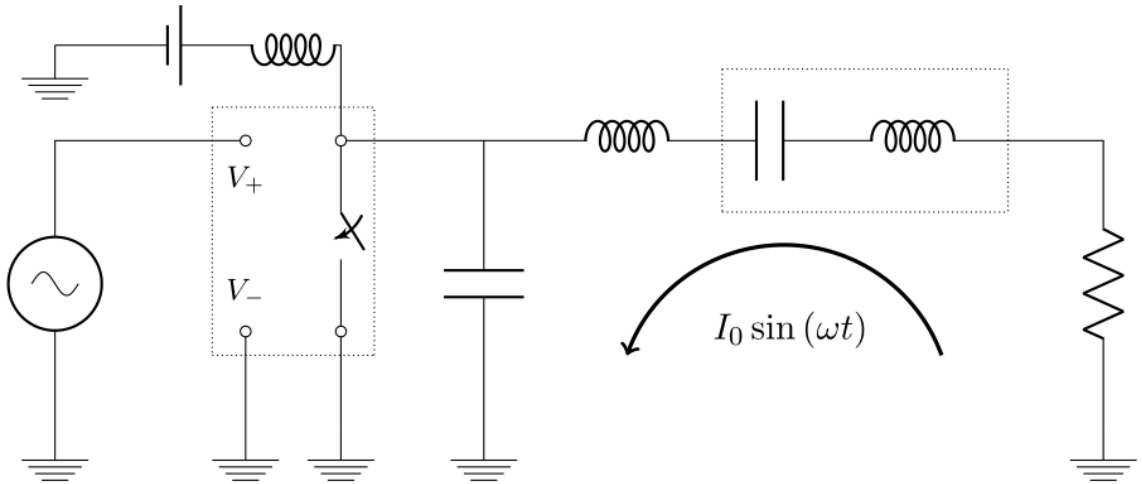
quiescent drain current, I_{Dq}=0.1 A and drain voltage, V_{DS}=50 V.

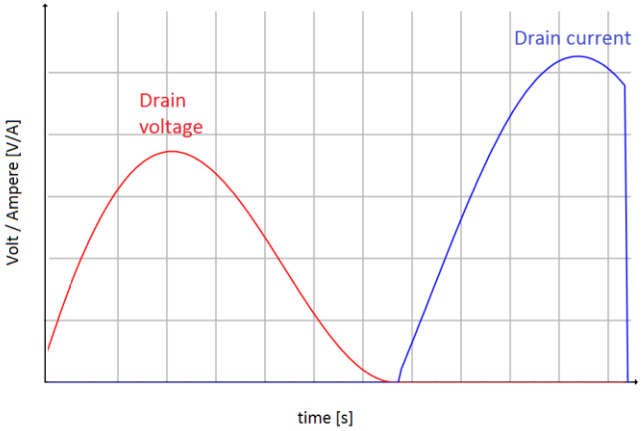
temperature rises for only few degrees, to about 30°C

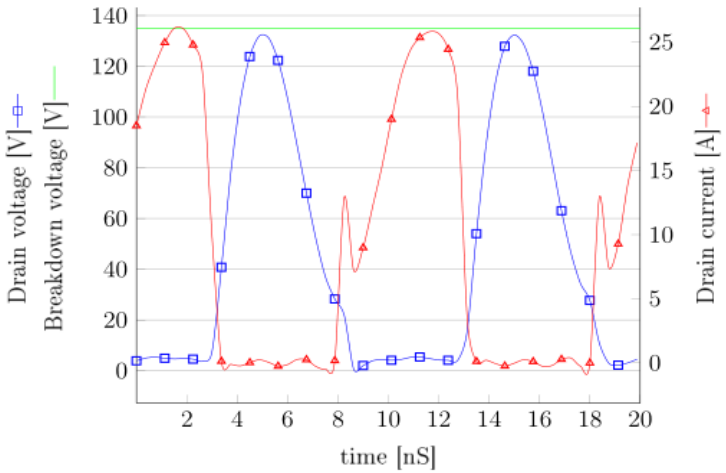


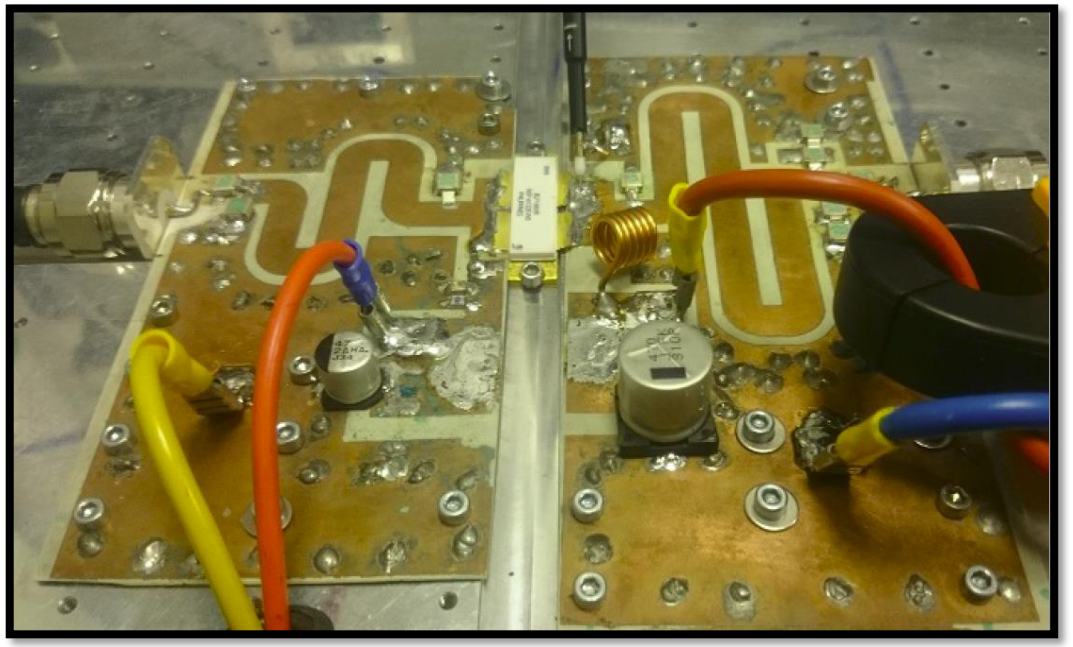
Hot S-parameters measured at different output power at 352MHz

100 MHz – 1kW – class E SSPA – 87% eff.





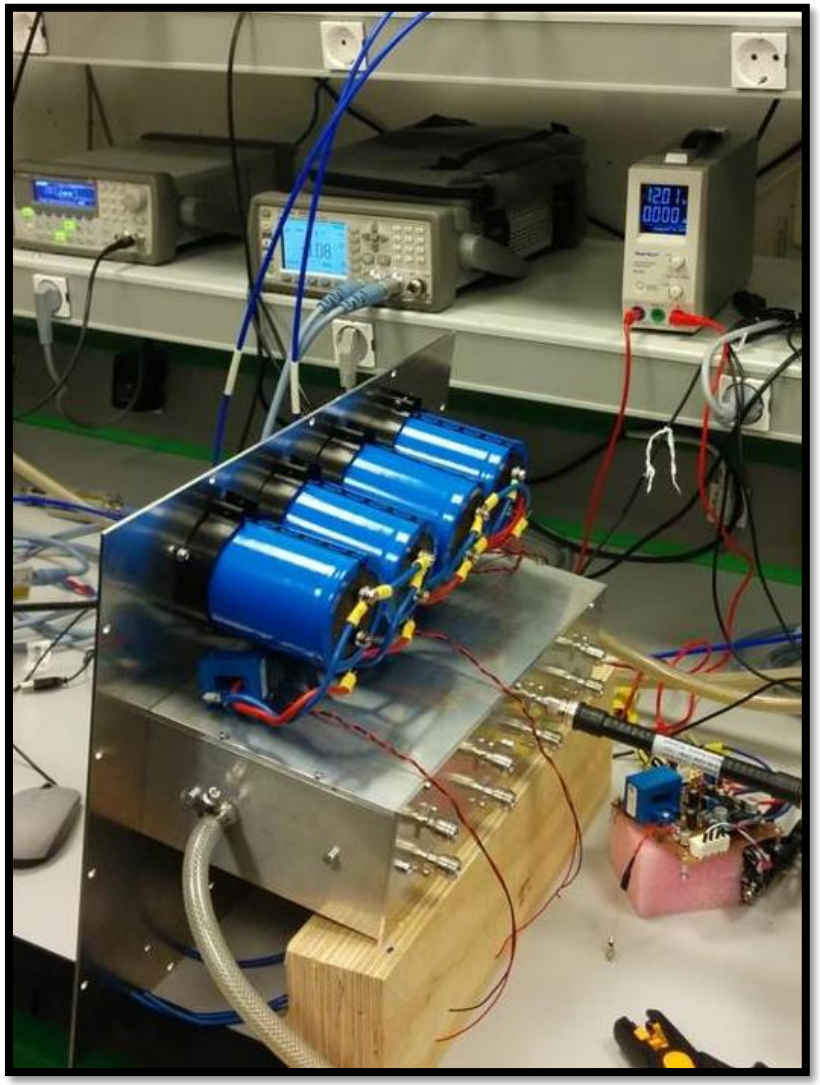




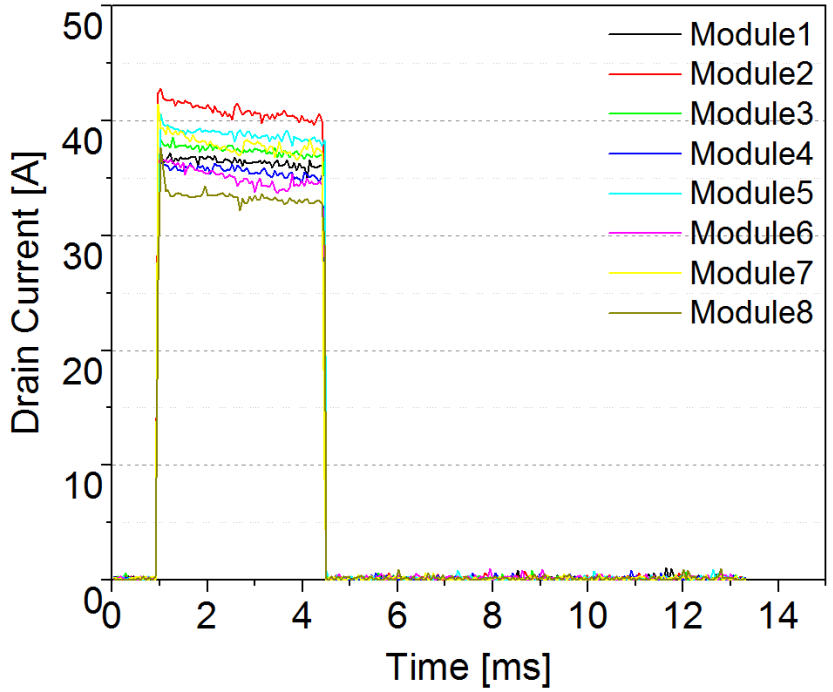
Measured 1010 W peak output power at 87% drain efficiency with 22 dB gain at 102 MHz operation (V_{ds} peak = 140.5 V). The measurements were performed with a 5% duty cycle, using 3.5 ms pulses at repetitions of 14 Hz i.e. similar to ESS operation conditions.

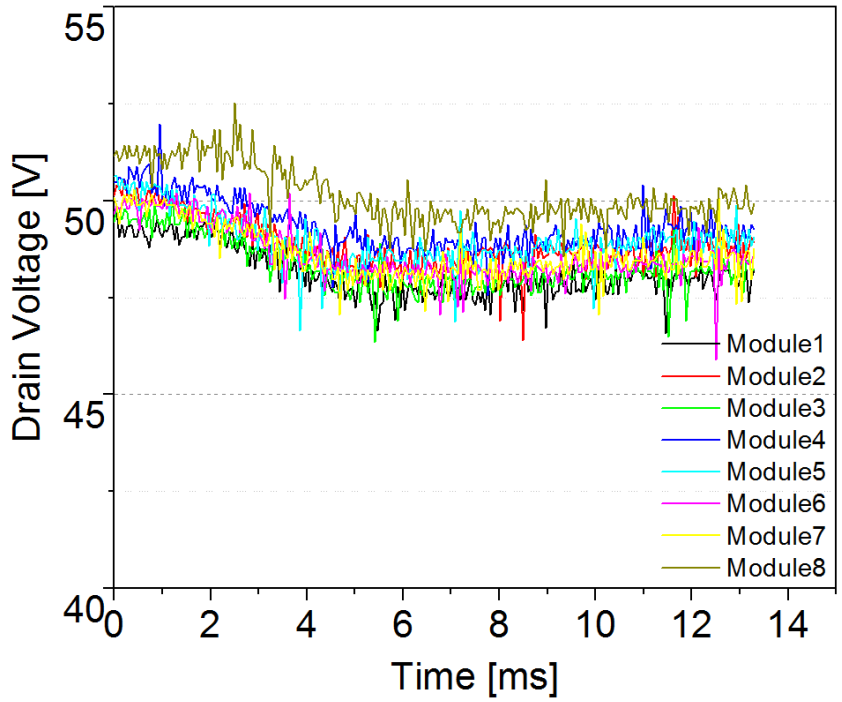
Master work Stefan Book

10 kW SSPA power source



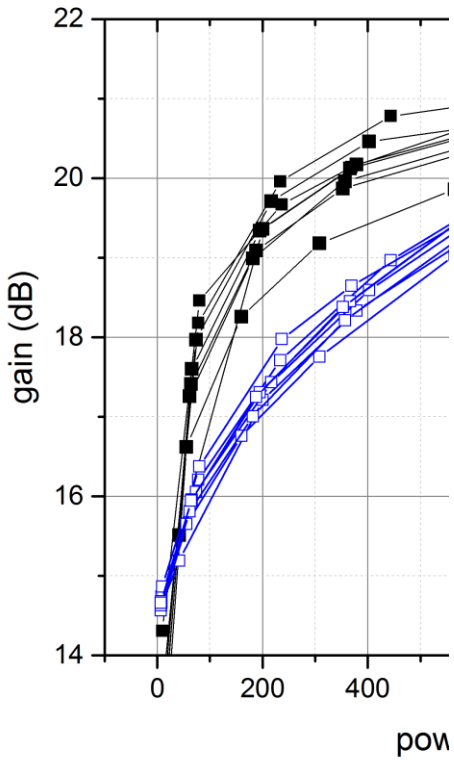
Time-multiplexed measurements of voltages and currents for all 8 modules

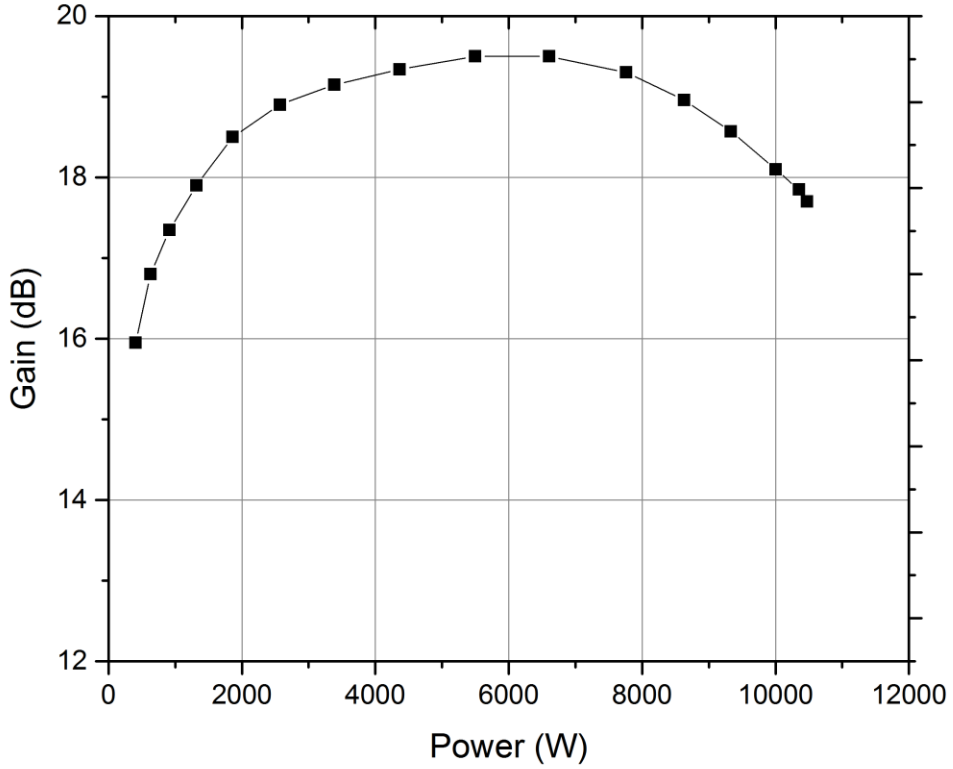


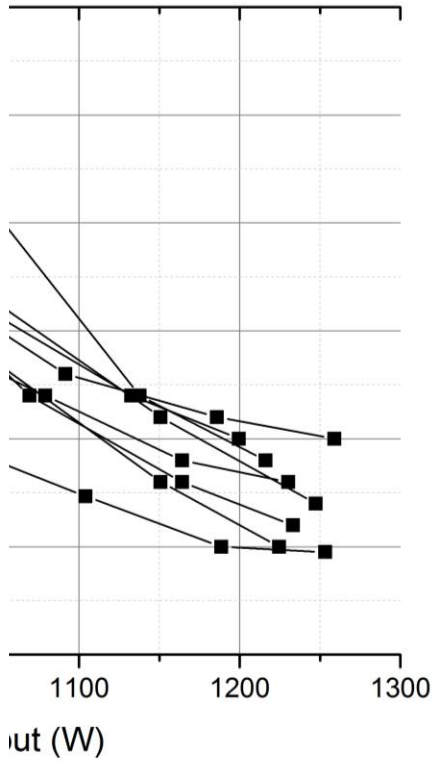


L. Hoang Duc, A. Bhattacharyya, V.A. Goryasko, R Ruber, A. Rydberg, J. Olsson and D. Dancila, “Time Domain Characterization of High Power Solid State Amplifiers for the Next Generation Linear Accelerators,” 2017, Microwave and Optical Technology Letters.

Drain efficiency, gain and phase variation of 10 kW amplifier at 352 MHz realised at FREIA



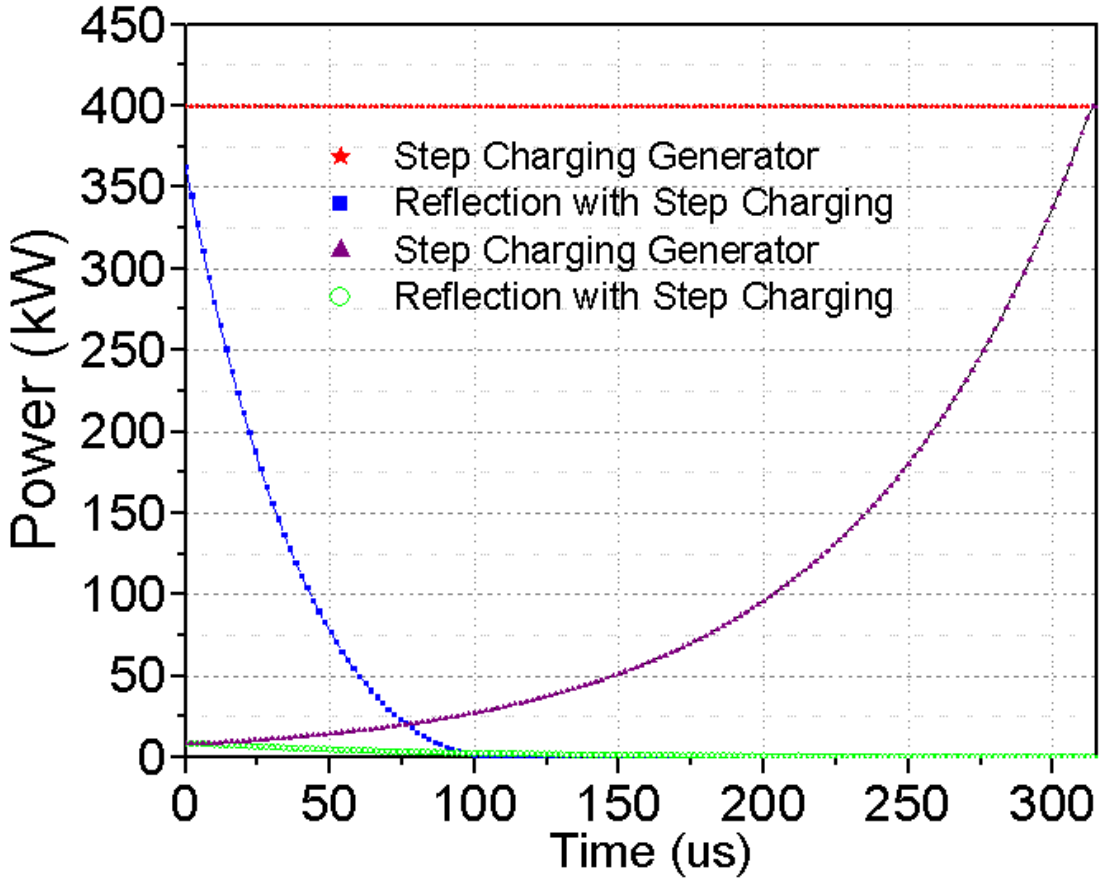




A small variation in both gain (< 0.5 dB) and phase (< 5º) is measured for the 8 modules of the 10 kW demonstrator.

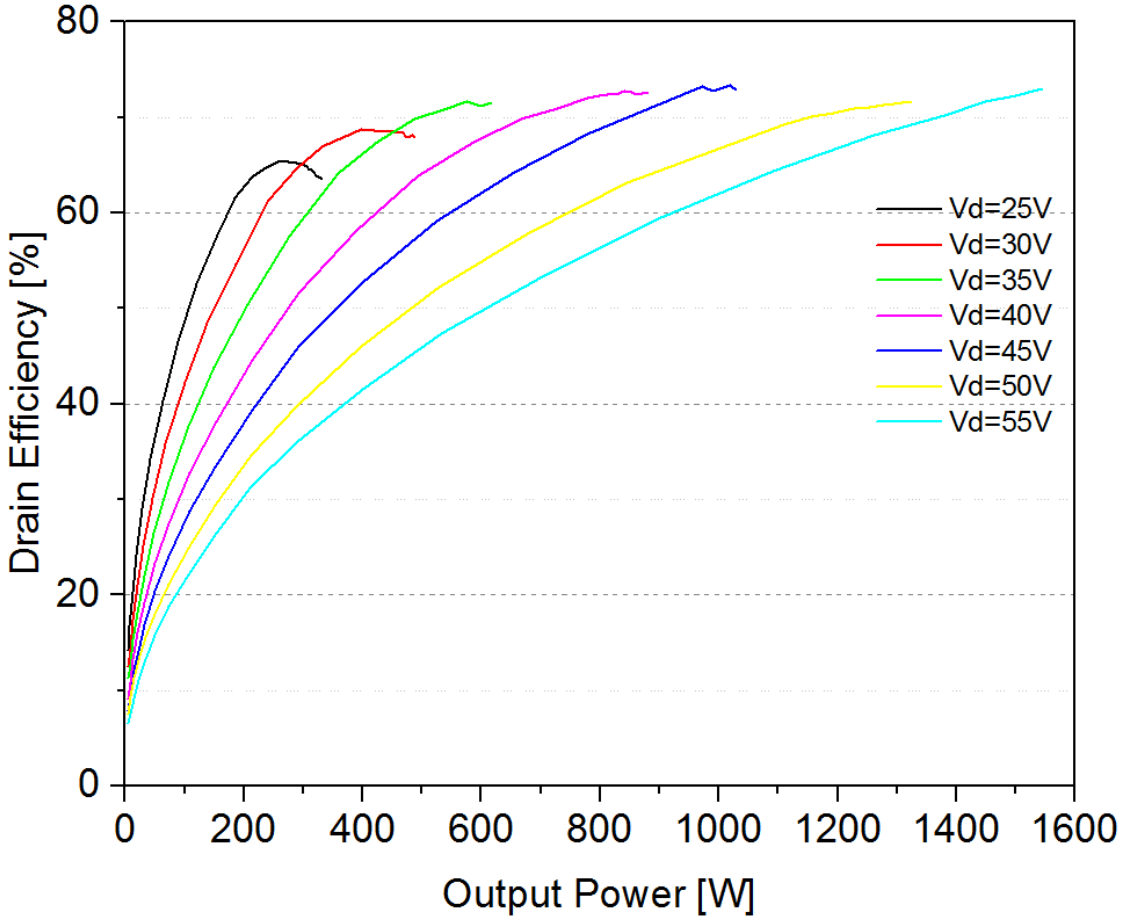
D. Dancila et al, "A compact 10 kW solid-state RF power amplifier at 352 MHz," 2017 IOP Conf. Series: Journal of Physics: Conf. Series, vol. 874, 012093

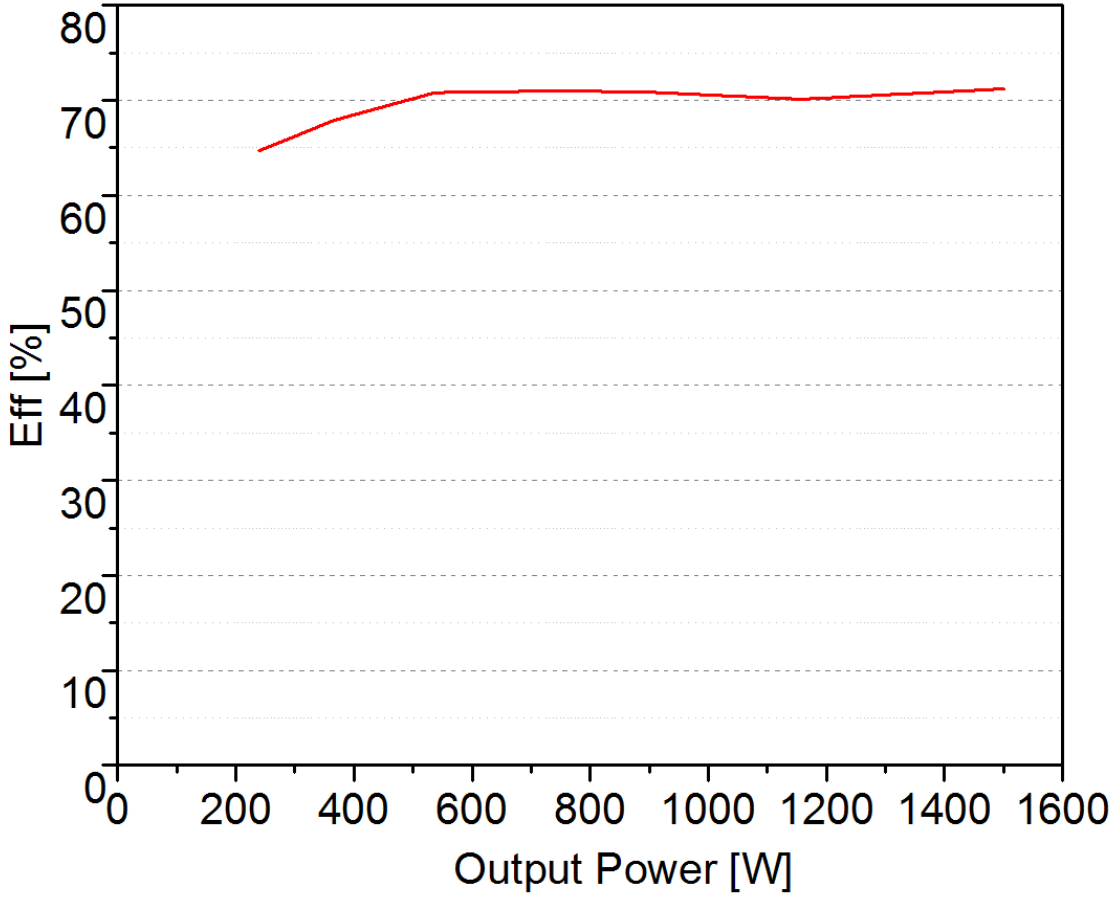
Energy efficient charging of superconductive cavity resonators



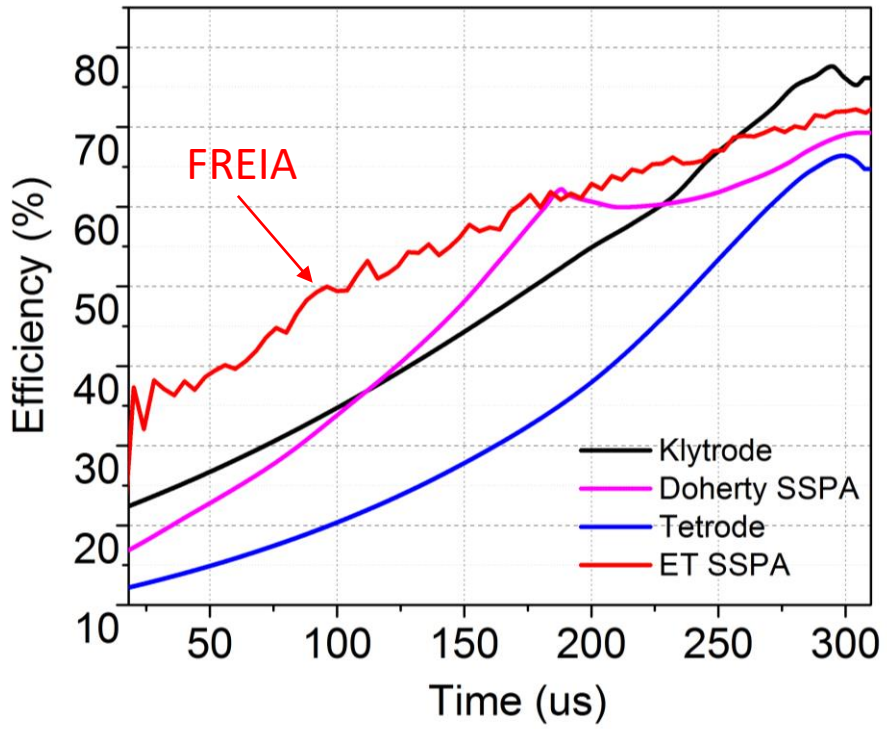
A. Bhattacharyya et al, "Minimization of power consumption during charging of superconducting accelerating cavities," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 801,pp. 78 – 85, 2015.

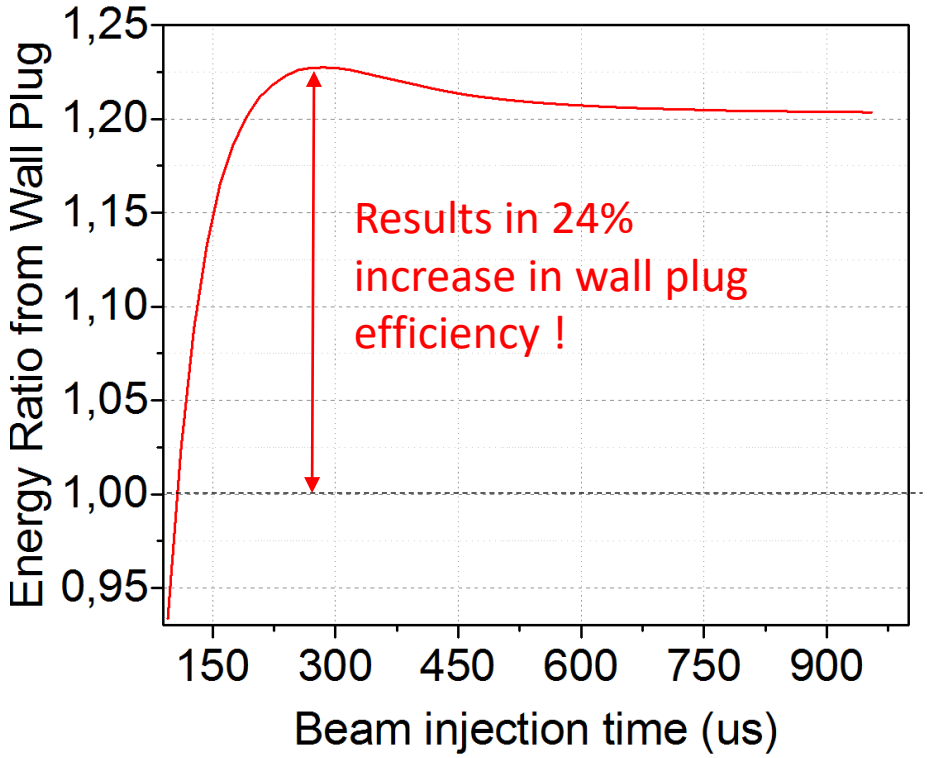
Drain Voltage Modulation of Solid State Power Amplifiers – agregated efficiency curve





Optimal Power Consumption during the Charging of Superconducting Cavities using Drain Voltage Modulation ofSolid State Power Amplifiers





Long et. al, Swedish Microwave Conference, Lund. 2018 (first results)

Conclusions and Strategy

- **High Power SSPA Design:**
  - need to increase the efficiency of solid-state amplifiers using
  - waveform engineering
  - active load pulling
- **RF power combiners:**
  - need to implement highly efficient combiner topologies
  - protection to the transistors without using circulators
  - adapt to 400 kW power station, as for ESS
- **Ongoing projects**
  - 27 and 101 MHz amplifiers for cyclotron - radioisotopes production – Eurostars projects
  - high power microwaves for material processing: carbon fiber composites, rocks fracturing
- **Future projects**
  - SSPA 400kW for the update of ESS