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The PSI Compact 500MHz 65kW High Power Solid-State Amplifier

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Solid-State Amplifier Technology Overview

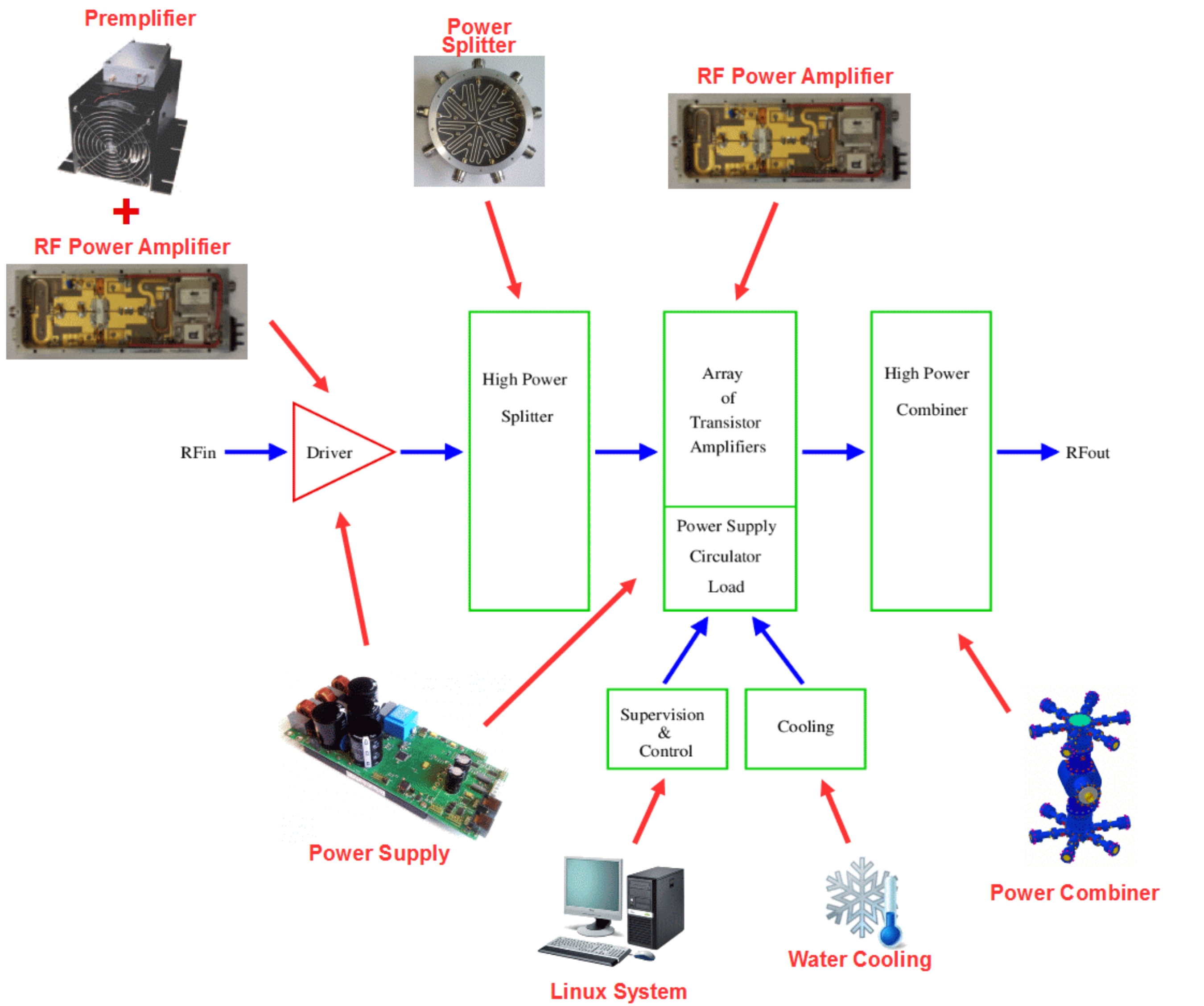
Solid-State Amplifier Technology:

Advantages:

- Modern technology in evolution.
- No high voltage
- No radiation issues
- Price already low and going down.
- Good optimization possibilities
- Redundancy.
- Compact.
- Simple cooling.
- Distributed circulator and load.
- Low phase noise.
- No vacuum.

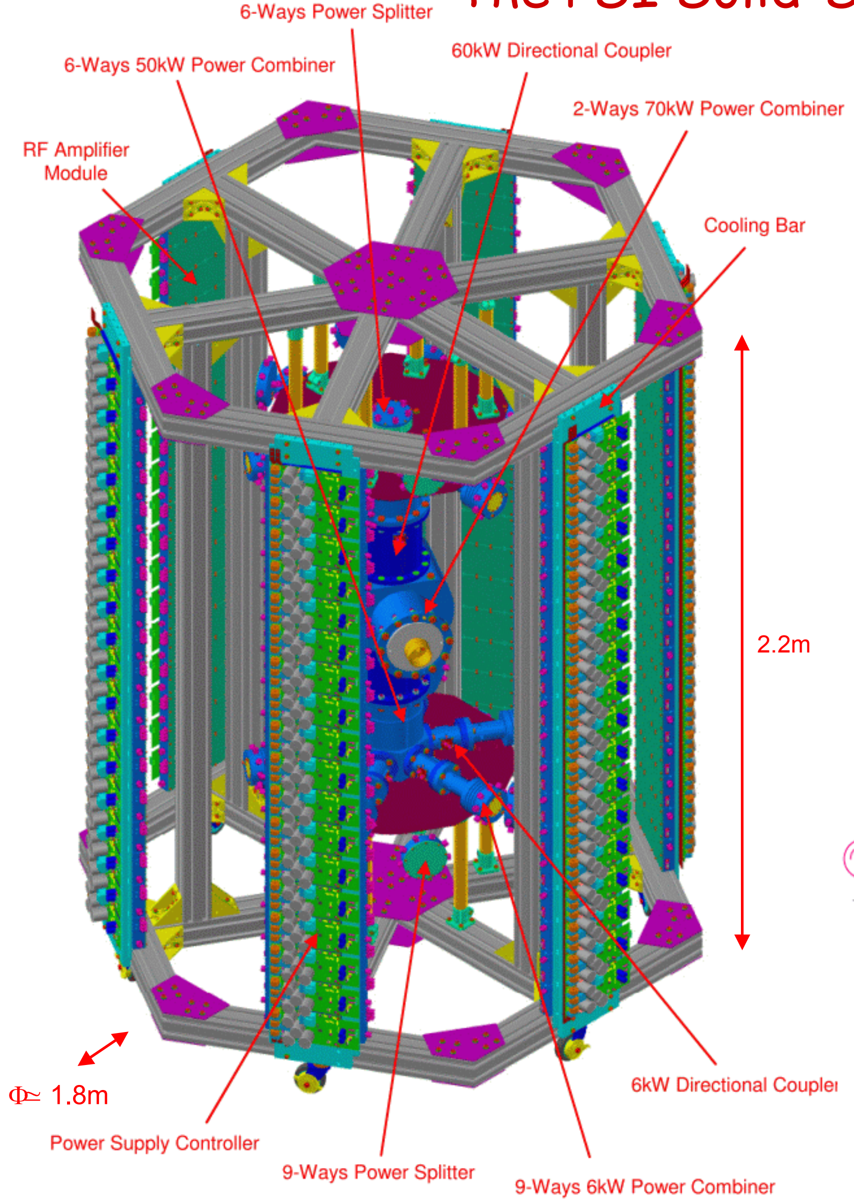
Disadvantages:

- Not enough experience acquired.
- Not well known technology.
- Not enough reliability data.

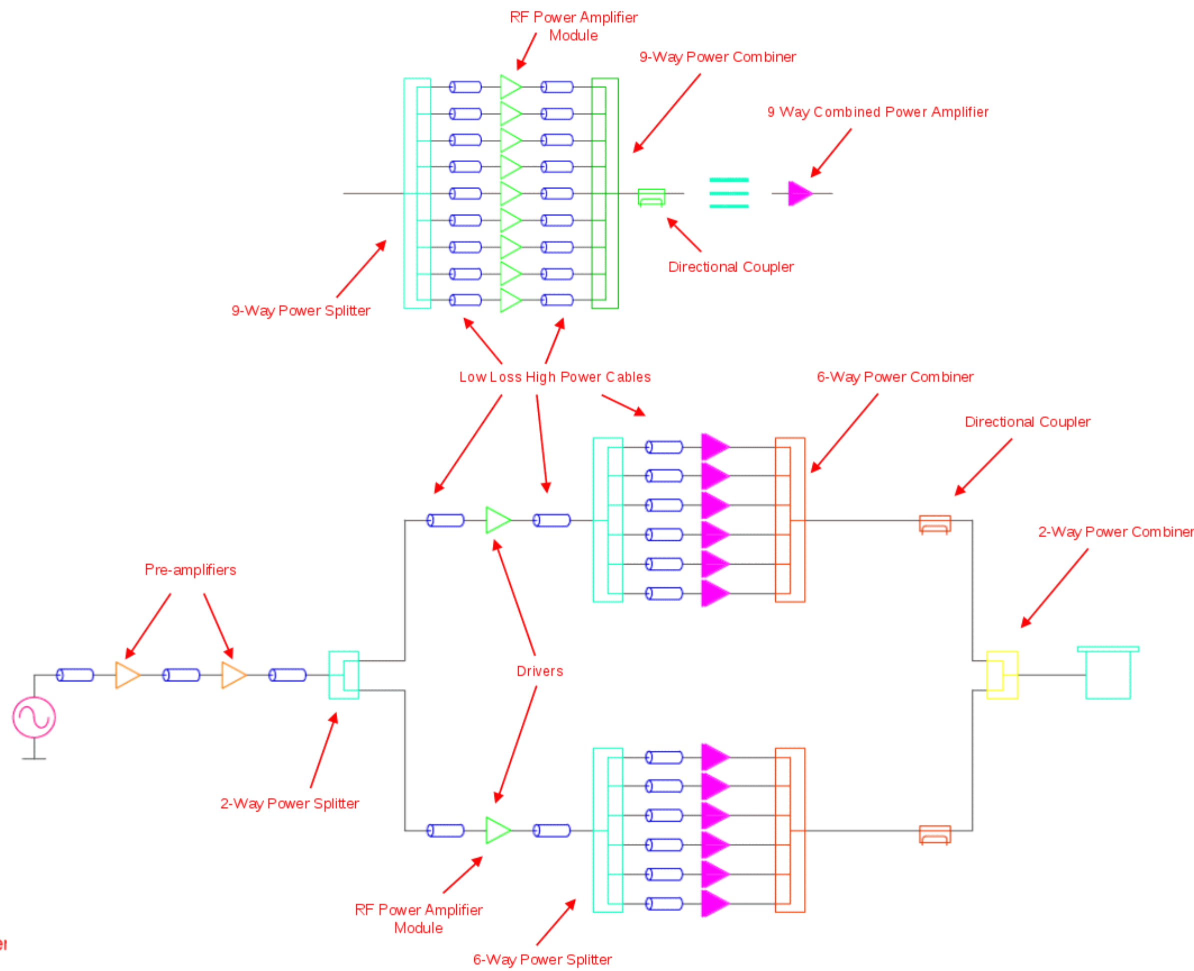


Solid-State Amplifier: Simplyfied Block Diagram

The PSI Solid-State Amplifier System Overview

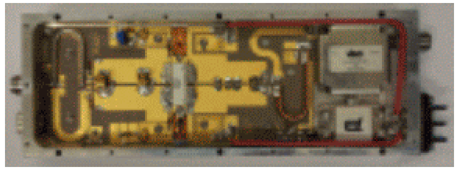


3D-View of 65kW 500MHz Amplifier System



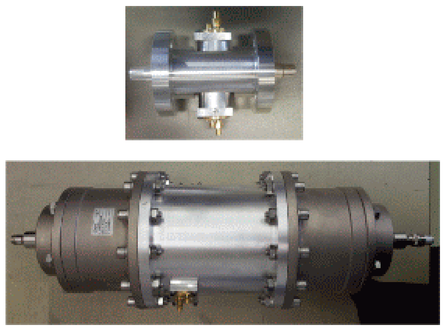
Block Diagram of 65kW 500MHz Amplifier System

Main Components

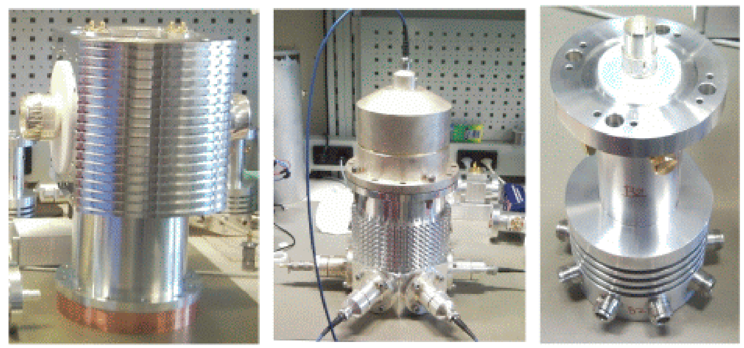


RF Power Amplifier

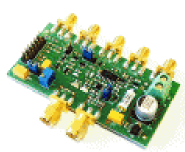
Power Splitters



Power Directional Couplers

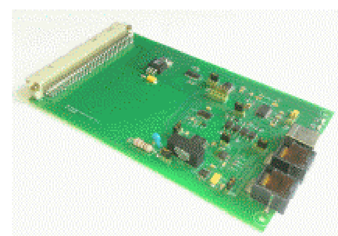


Power Combiners



Power Meter

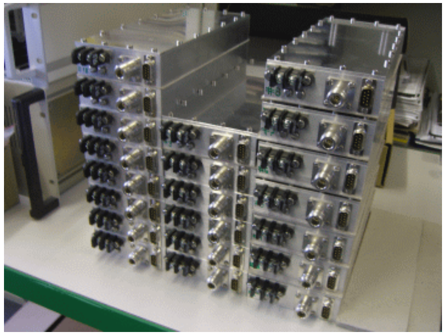
PS Controller



Master Controller

** All components designed by the author in PSI

Solid-State Amplifier Module Overview

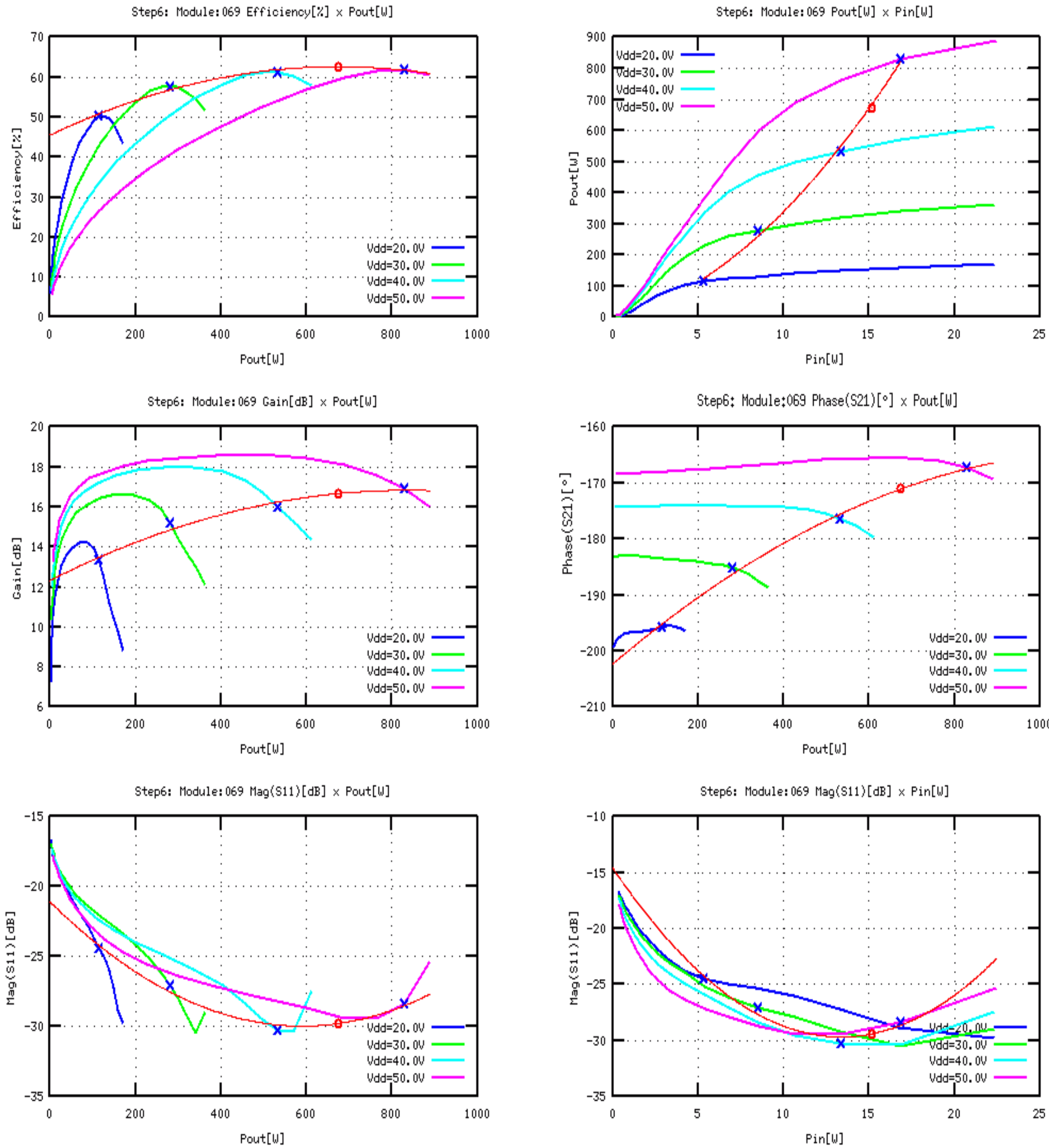


- 120 assembled in neighboring company.
- Design made in PSI using BLF578 transistor.
- Simulations made using transistor model created in PSI.
- All tests and alignements made in PSI.
- Circulator is included (IL~4%).
- Maximum output power > 820W (most of the amplifiers)
- Drain efficiency: 62% (average)
- Phase spread among RF amplifiers ~ 1 degree (sigma)
- Return loss < -25dB

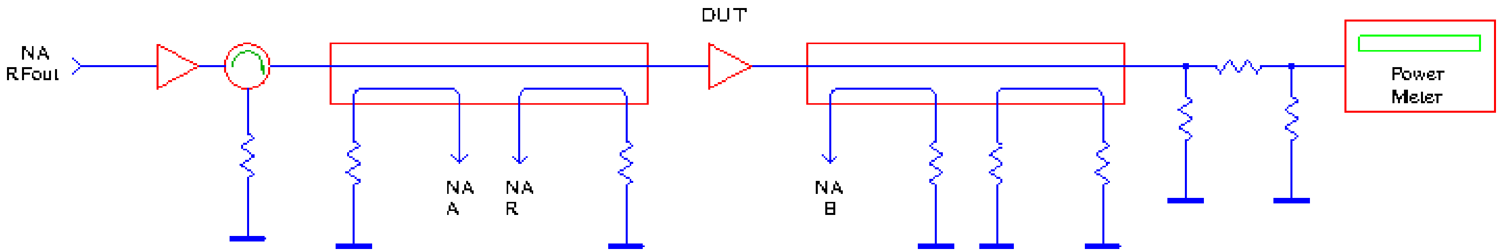
Typical Performance Parameters (Module 069)

Vdd [V]	Pout [W]	Pin [W]	Gain [dB]	Pdc [W]	Efficiency [%]	Phase(S21) [°]	Mag(S11) [dB]
44.06	630	14.6	16.3	1006.3	62.6	-172.4	-29.55
45.99	630	11.7	17.3	1022.9	61.6	-169.9	-29.74
47.80	669	11.7	17.6	1100.0	60.8	-168.1	-29.64
45.47	674	15.1	16.4	1075.3	62.7	-171.1	-29.41
48.00	674.9	11.7	17.6	1104.4	61.1	-167.8	-29.62
50.03	890	22.4	16.0	1468.9	60.6	-169.4	-29.35

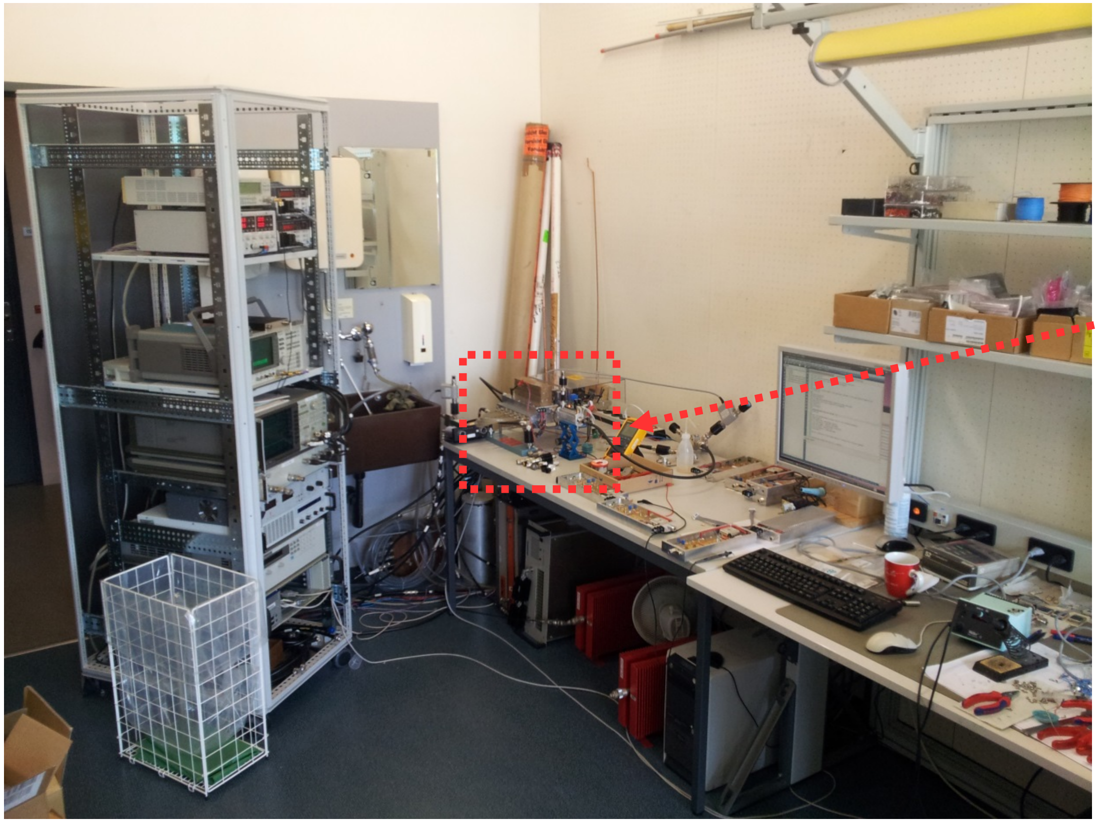
RF Amplifier Measurement Results – Step 6 - Module 069



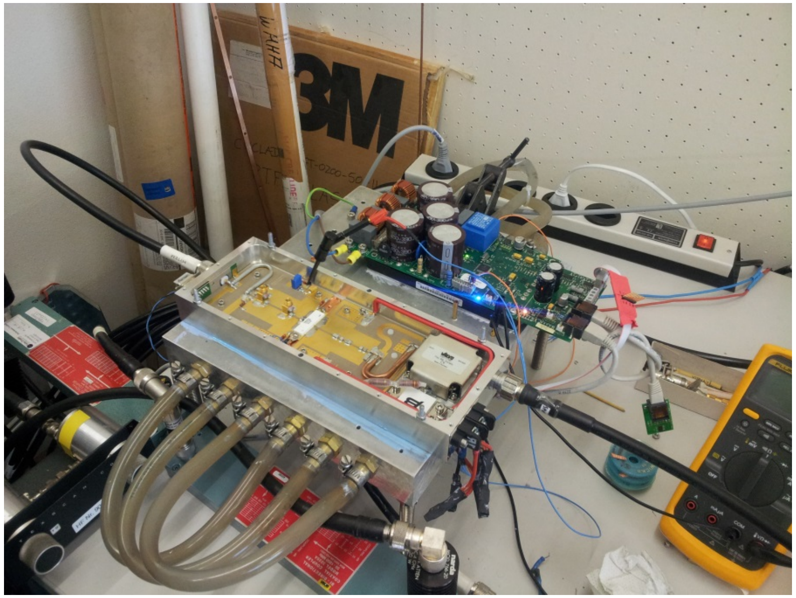
Amplifier Test Set-up



Measurement using External Bridge



Full Test Set-up



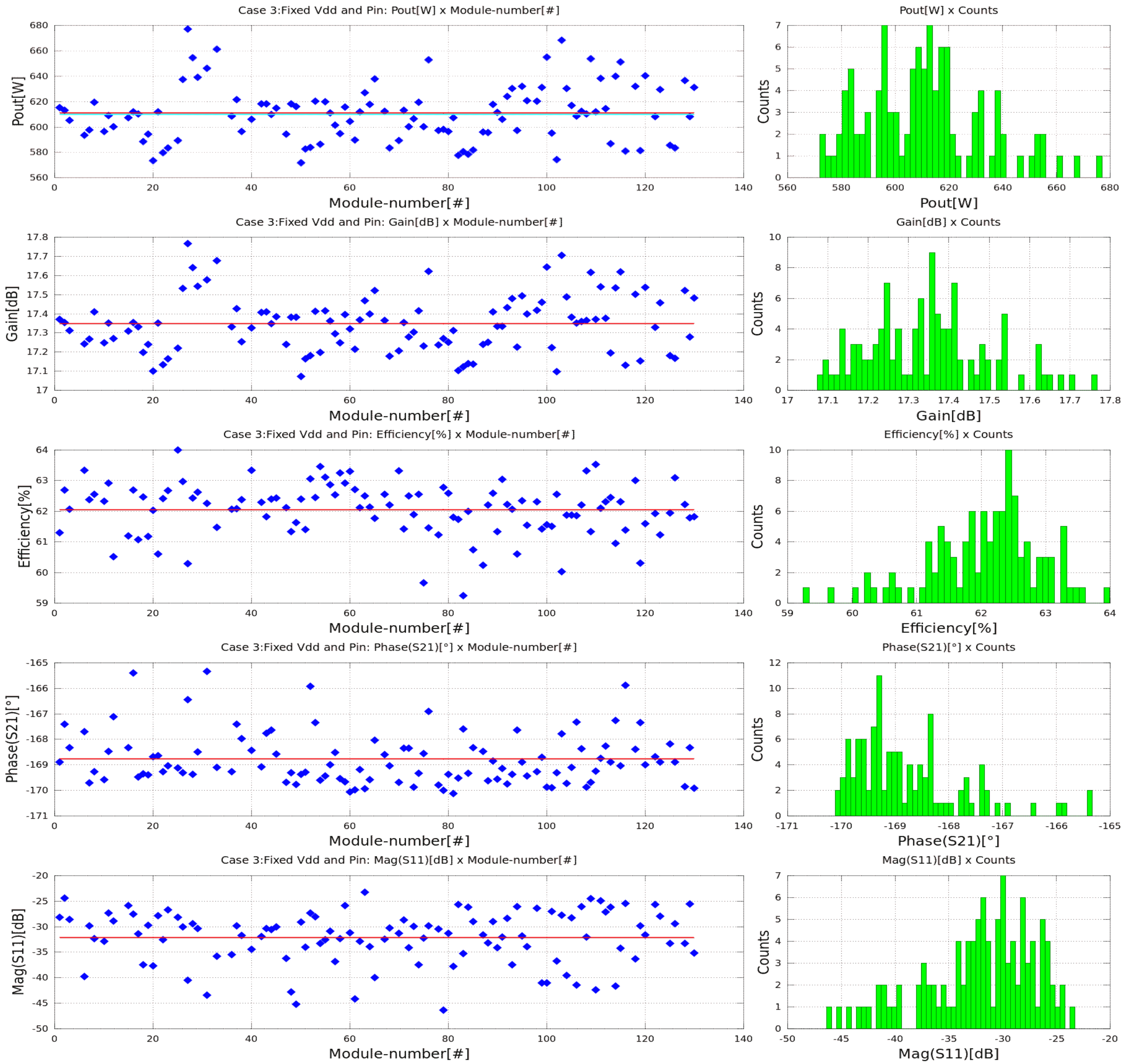
Amplifier under Test

- Tests, alignement, and also acquisition of measured data from all RF amplifiers assisted by a software specialy designed in PSI.
- Duration of tests – 3 months.
- Number of RF amplifiers produced – 120.
- Manpower required – 1 technician.

Performance parameters of all produced RF amplifier modules

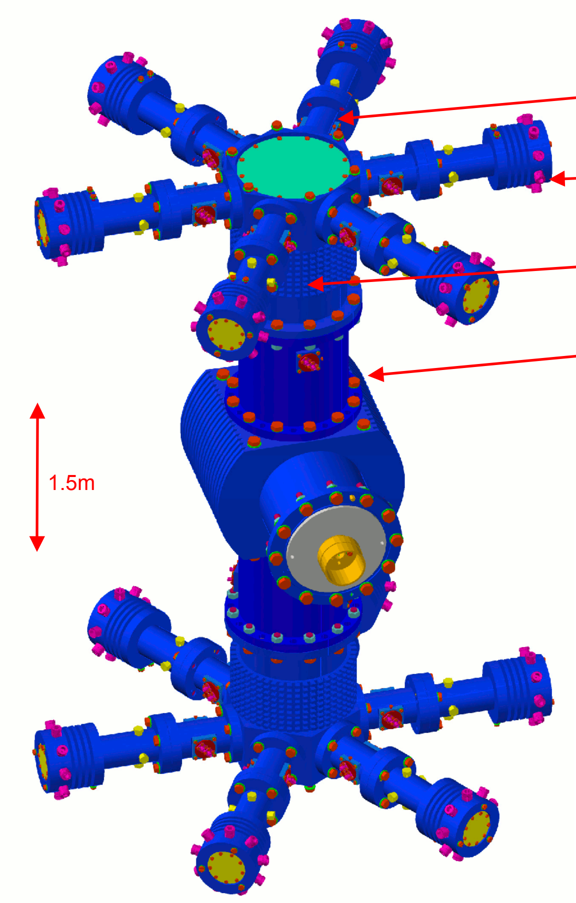
Vdd=48V

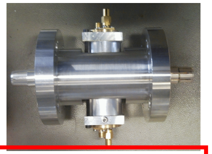
Pin=11.7W



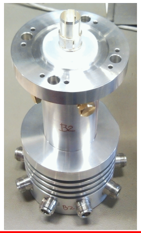
** some serial numbers not used.

High Power Combiner

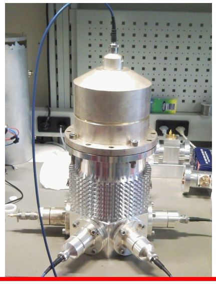




10kW Directional Coupler



9-Way 10kW Power Combiner

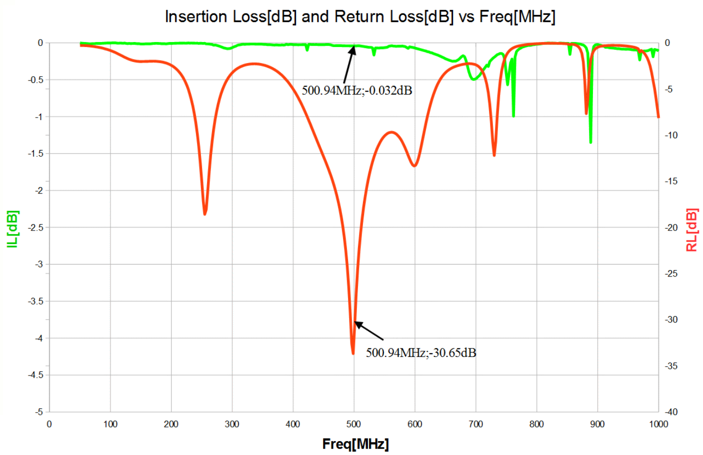


6-Way 60kW Power Combiner

2-Way 70kW Power Combiner

3D View – Complete Combining Structure

Complete Combiner Structure: Insertion Loss and Return Loss vs Frequency



Performance Parameters of Combiner Components

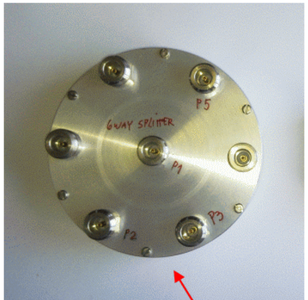
Combiner Component	RL [dB]	IL [dB]	BW (RL<-25dB) [%]
Complete Combiner Structure	-30.65	-0.031	2.94
9-Way Combiner	-35.6	-0.018	5.53
6-Way Combiner	-39.7	-0.01	7.15
2-Way Combiner	-37.3	-0.005	7.98 **
1 5/8 Directional Coupler	-30.9	-0.002	-
6 1/8 Directional Coupler	-36.8	-0.007	-

**Value limited by the measurement set-up.

Input Power Splitter Components

Produced Devices

6-Way Splitter



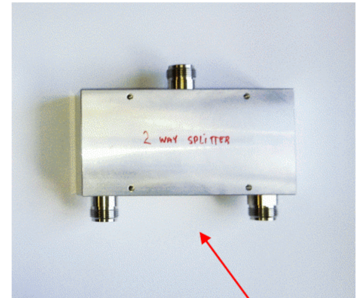
Type 2

9-Way Splitter

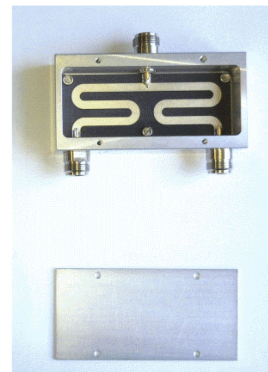
Type 2

Type 1

2-Way Splitter



Type 1



Performance Parameters of Splitter Components

Splitter Component	RL [dB]	IL [dB]	BW (RL<-25dB) [%]
9-Way Splitter	-42.6	-0.063	5.28
6-Way Splitter	-22.7	-0.01	6.34
2-Way Splitter	-35.8	-0.051	19.2

Power Supply Controller

(and Complete Monitoring System)

Main Features

Output Power: 1.2kW

Output Voltage Range: 23V to 53V

Input Voltage Range: 85Vac to 265Vac

Power Factor Compensation: PF > .98

Efficiency: ~ 90%

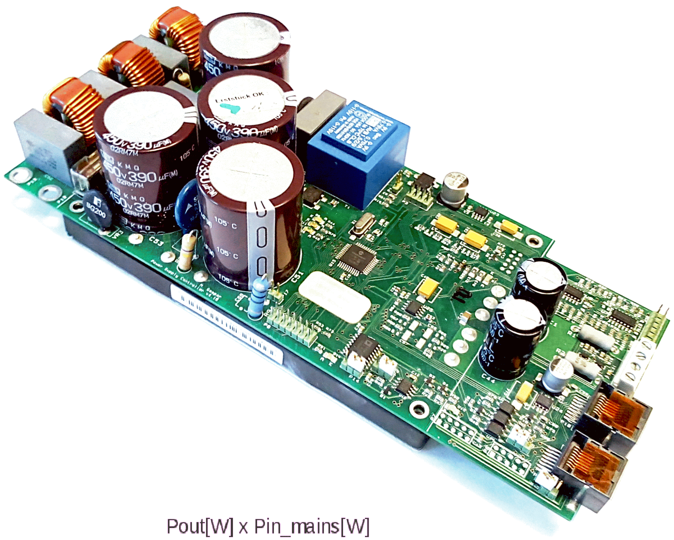
Can be Remotely Programmed and Monitored

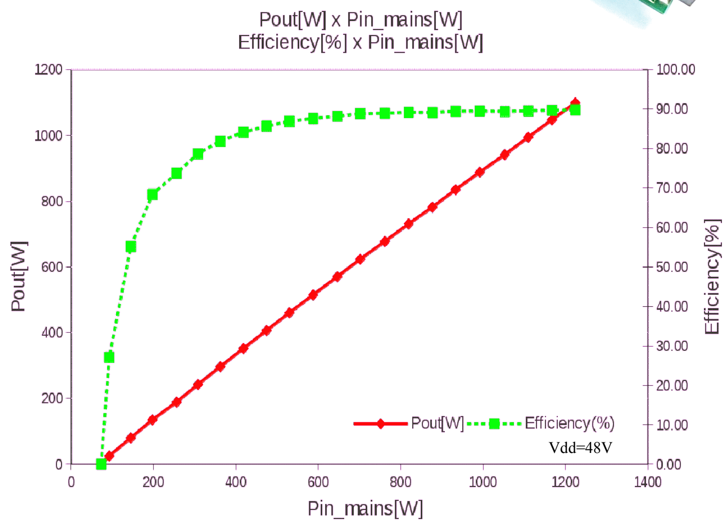
Extra Analog and Digital I/Os

Multi-tasking Script Operating System (**SOS**)

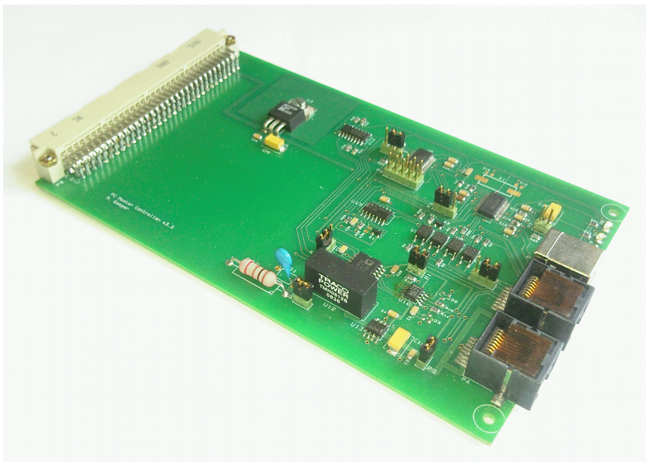
Interlock Reaction Time: ~ 1uS

Full Monitoring Loop Time: ~ 150mS





Master Controller



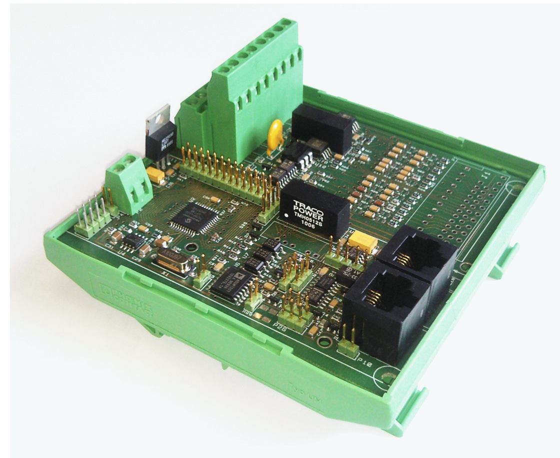
Main Features

Output Isolated Power: 15V 1A

External Connections: USB and RS232

Interlock Monitoring through Signaling Lines

IO Interface



Main Features

Optoisolated Analog I/O Channels: 3

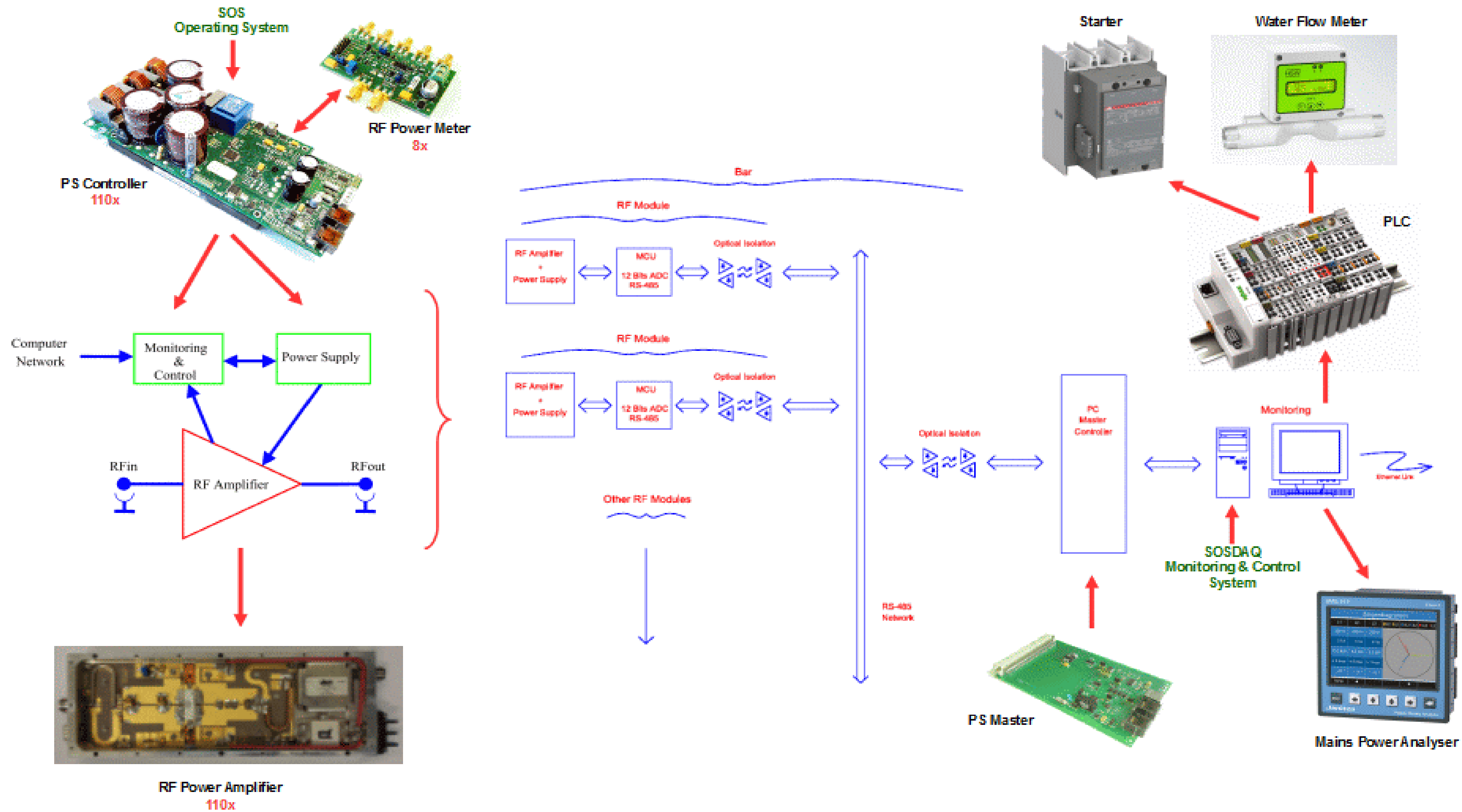
Optoisolated Digital I/O Channels: 4 or 8

Multipurpose Application: PLC/Crate/Daughter Card

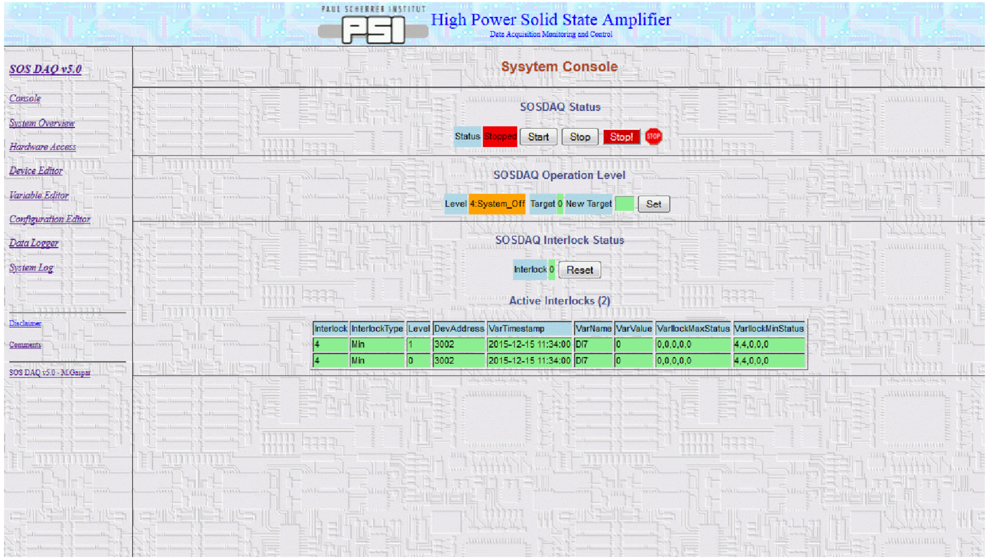
Interlock Reaction Time: < 1uS

Full Monitoring Loop Time: ~ 70mS

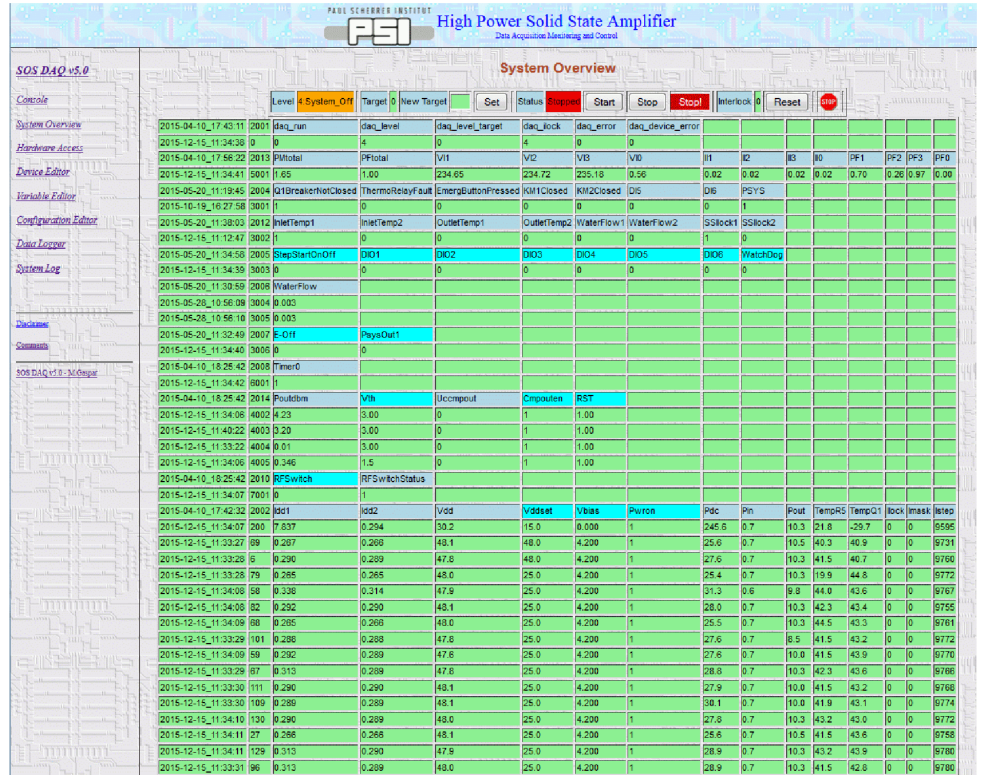
Supervision System Configuration



SOSDAQ - Supervision System User Interface



System Console



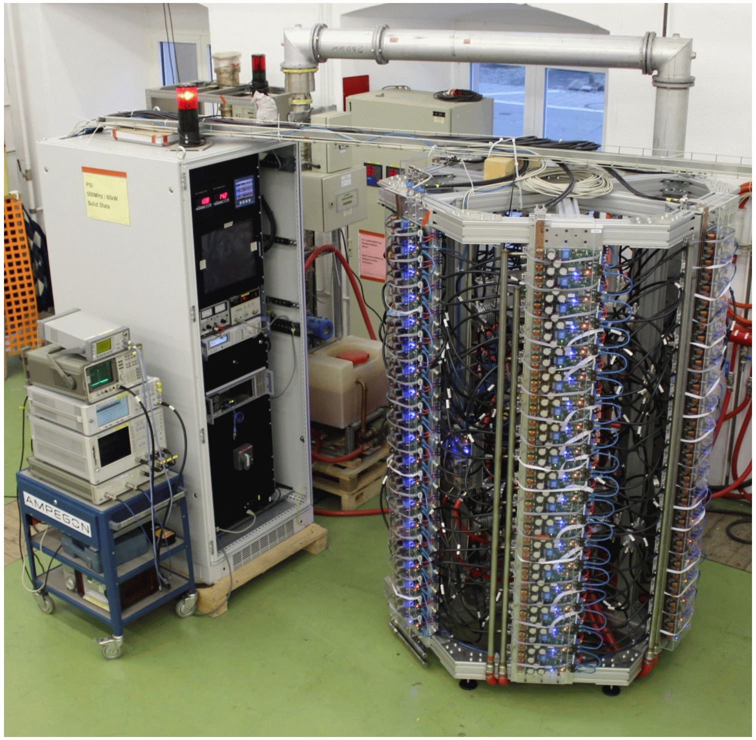
System Overview

SOSDAQ system performance parameters

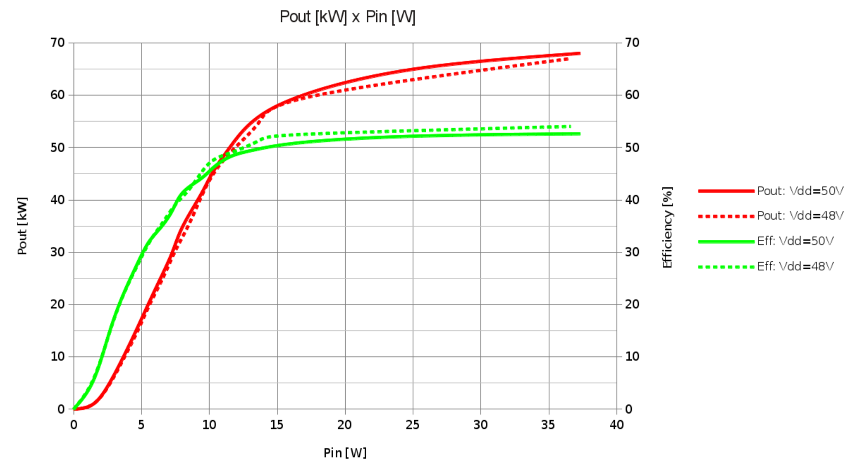
Parameter	Value
Channel update rate	≈ 200 channels/s
Number of channels	≈ 2000 channels
Number of operating levels	5
Average time to change level	5s
Fast interlock reaction time	10ns
Slow interlock reaction time	5s
Server request rate (minimum)	>100 requests/s

- A web-server is used to provide the user interface by means of standard web-browsers giving access to the different services provided by the SOSDAQ, such as, system console, system overview, hardware access, variable editor, system configuration editor, datalogger, etc.
- Languages: Only Shell-script, C and Javascript. Full cross-platform compatibility. Less vulnerability to software updates and upgrades.
- Distributed processing, supervision and monitoring system.
- Successful efficiency optimization of the complete system using the proposed software.

Performance Results of the Complete System



65kW 500MHz Amplifier System in Operation.

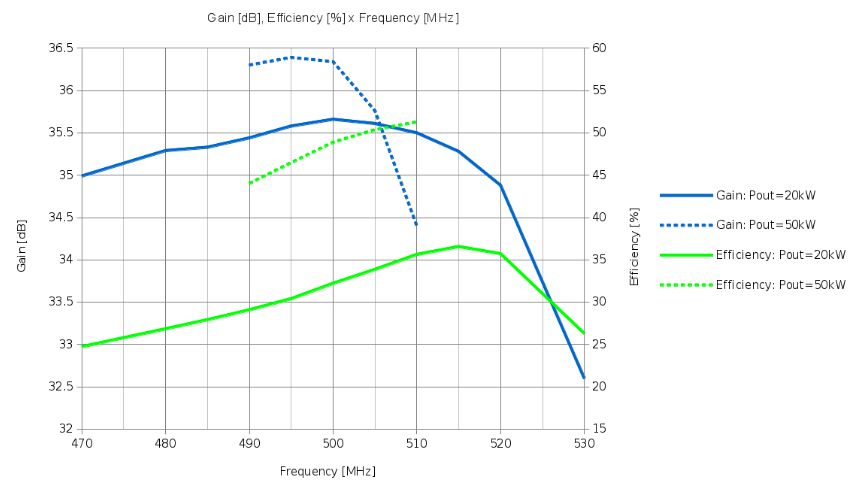


Full 65kW Amplifier System Measurement Results:
Pout and Efficiency vs Pin

65kW 500MHz Amplifier System Performance

Vdd[V]	Pout[kW]	Pmains[kW]	Efficiency[%] (wall plug)**	Efficiency[%] (DC to RF)	Pin[W]
48	**67**	**124**	**54**	**60.4**	**36.6**
50	**68**	**129.2**	**52.6**	**58.8**	**37.3**

** Wall plug efficiency: ratio of RF power delivered to load (Pout) to mains AC power consumption (Pmains).



Full 65kW Amplifier System Measurement Results:
Gain and Efficiency vs Frequency

Efficiency Performance of Various Components

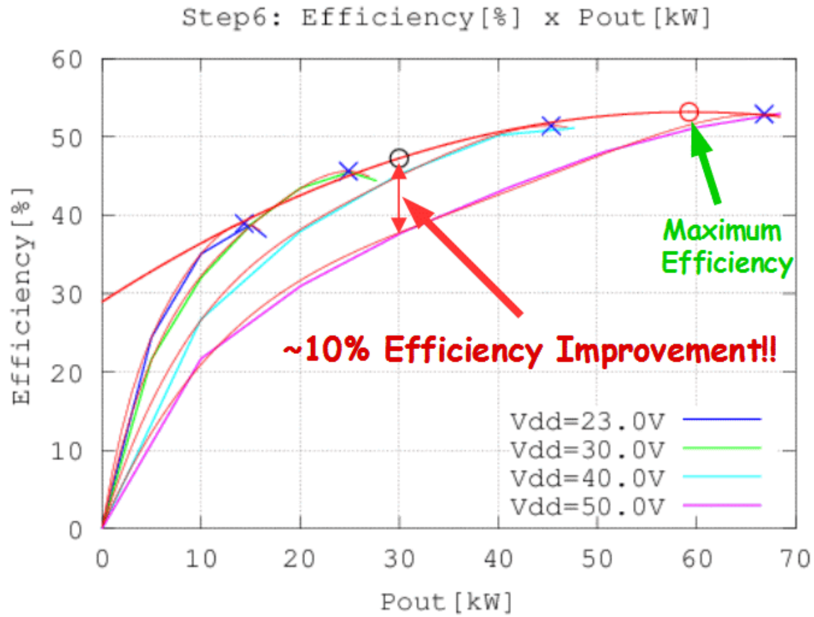
System Component	RL [dB]	IL [dB]	Efficiency [%]
Transistor RF power amplifier (including circulator)	-	-	61 - 64
High power coaxial cables	< -35	-0.084	98.10
Complete Combiner Structure	-30.65	-0.031	99.29
PS Controller (AC/DC converter + Supervision)	-	-	88 - 91
9-Way Combiner	-35.6	-0.018	99.59
6-Way Combiner	-39.7	-0.01	99.77
2-Way Combiner	-37.3	-0.005	99.88
9-Way Splitter	-42.6	-0.063	98.56
6-Way Splitter	-22.7	-0.083	98.10
2-Way Splitter	-35.8	-0.051	98.83
1 5/8 Directional Coupler	-30.9	-0.002	99.95
6 1/8 Directional Coupler	-36.8	-0.007	99.84
Other Components (Estimated)	-	-0.1	98
Total (Estimated for Pout=65kW)	-	-	51 - 54

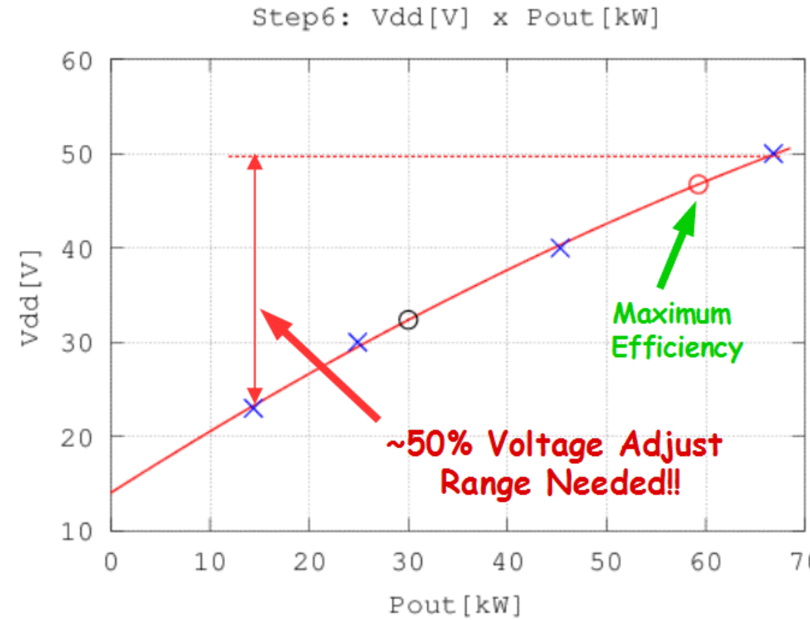
** Precision of measurements limited by specific measurement set-ups.

Efficiency Optimization

Psi 500MHz 65kW Solid-state High Power Amplifier

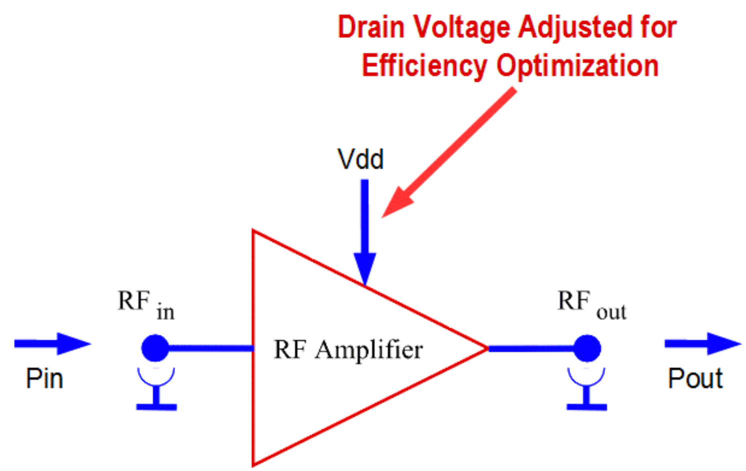
SSPA Example: Efficiency optimization at 30kW (black marker) and Maximum Efficiency Operation (red marker)



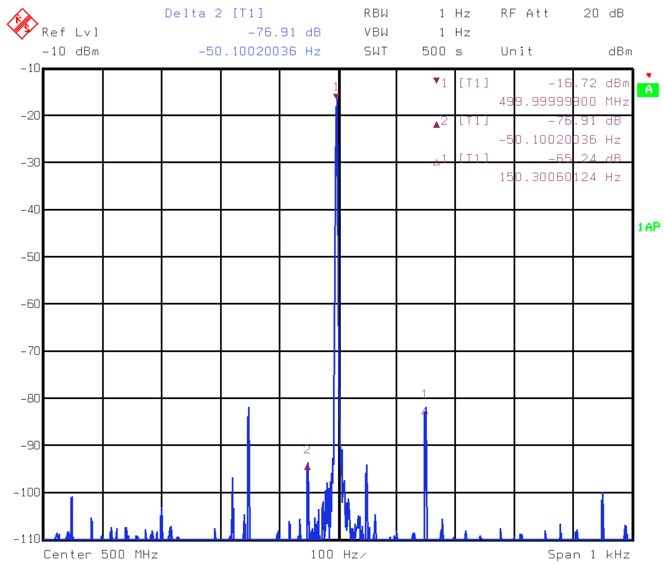


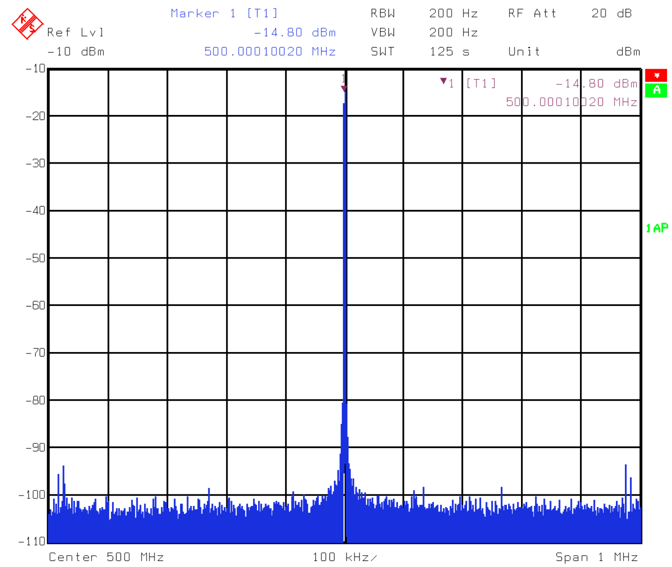
Comparison: Klystron Amplifier (incl. accessories) vs. SSPA (with efficiency optimization)

	Booster (pulsed) Duty cicle:50%		Storage Ring (CW) Beam current: 400mA	
	Klystron Amplifier: BO	SSPA 1x60kW System	Klystron Amplifier: SR3	SSPA 2x60kW System
Pout	**36kW**	**36kW**	**100kW**	**100kW**
Efficiency (wall plug)	**11.2%**	**46.5%**	**40%**	**52%**
Price Estimated	**1.8MCHF**	**400kCHF**	**1.8MCHF**	**800kCHF**



Output Frequency Spectrum





2nd harmonic level: -45dBc

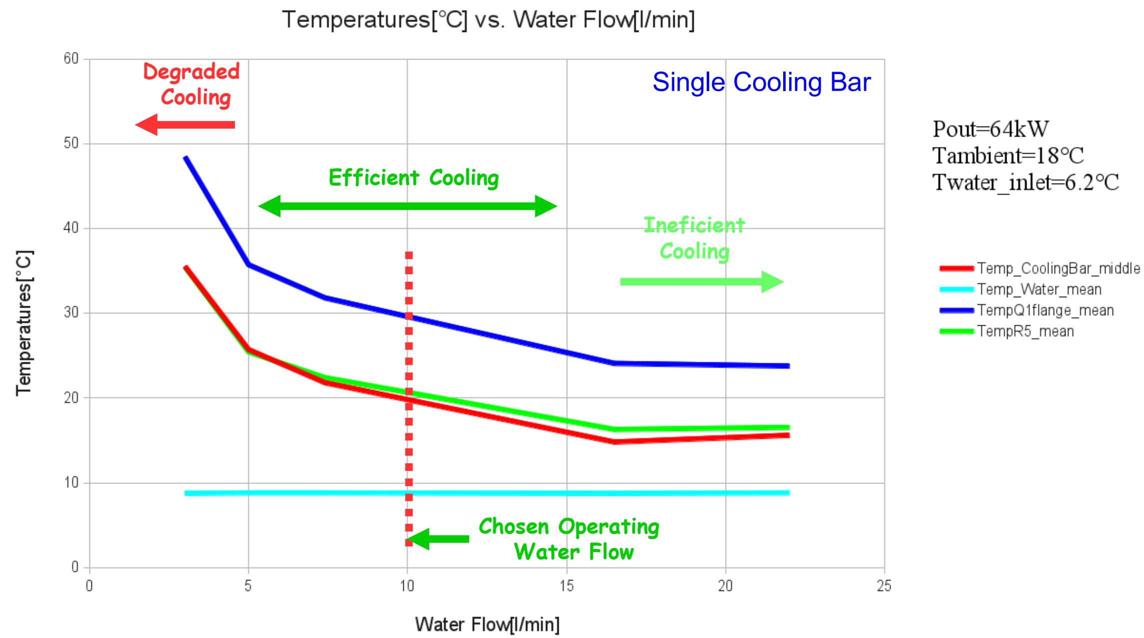
Pout=63kW

3rd harmonic level: absent

Cooling System

Temperature in various components at Pout=63kW

Component	Temperature [°C]	Remark
Cooling Bar A4000 aluminium	31.7	Top
High Power Cable	44	10cm from 9-Way Combiner Input
Water Inlet	7.9	System Inlet
Water Outlet	13.7	System Outlet
Cooling Bar A4000 aluminium	11	Water Pipe Inlet, 20cm from Top
Cooling Bar A4000 aluminium	16.7	Water Pipe Outlet, 20cm from Top
9-Way Combiner Neck	42.5	
9-Way Combiner Back	43.5	
2-Way Combiner Neck	39.2	
2-Way Combiner Back	37.5	
2-Way Combiner Middle	31.6	
6-Way Combiner Neck	40.8	
Output Directional Coupler	42.2	Last Coupler, After 2-Way Combiner
Output High Power Coaxial	42.1	1m from Output Directional Coupler
9-Way Splitter	28.4	Input Connector Side
9-Way Splitter	28.2	Cover Side
PS Controller Capacitor 390uF 450V	55.4	
PS Controller Resistor R1 = 0.01Ω	57.8	RF Amplifier Current Measurement
Transistor Q1 Flange	40.0	Averaged from All Transistors
Resistor R5 Flange	29.8	All R5 Avg., Reflected Power Measurement



Operating parameters at Pout=63kW

Water Flow	up to 150 l/min
Water Pressure	up to 3 Bar
RF Amplifier Power Loss (Average all amplifiers)	Pa_loss=340W
RF Module Output Power (Average all amplifiers)	Pout=610W
Temperature Difference Transistor Flange to Heatsink	ΔT_FH~9.3°C
Thermal Resistance Transistor Flange to Heatsink	Rth_FH=0.027K/W

Gracefull Degradation Tests

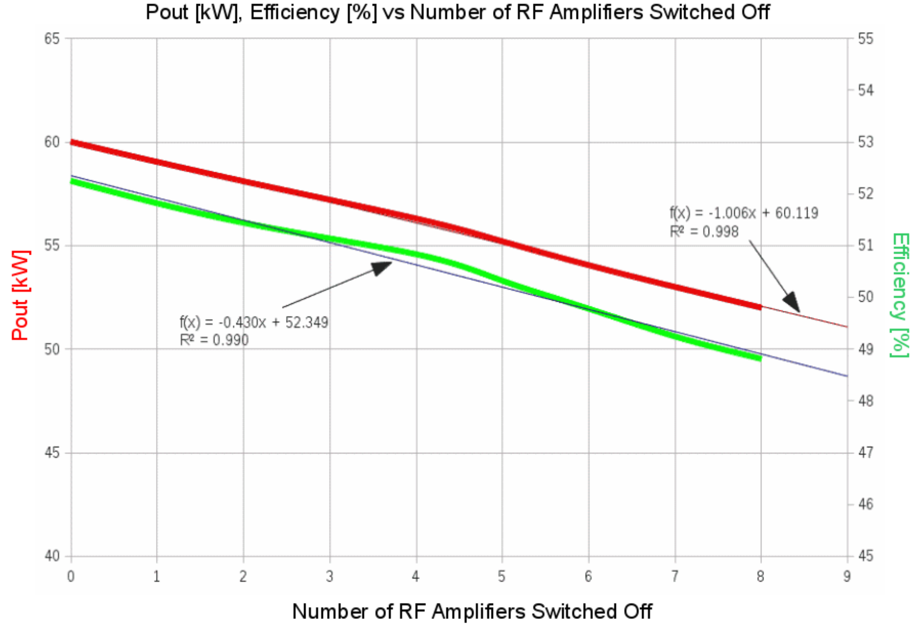
Good agreement with theory:

$$C_{eff} = \frac{P_o'}{P_o} = \left[\sum_{m=1}^{N} \frac{K_{p_m}}{N}\right]^2 = \left[\overline{K_{p_m}}\right]^2$$

No damage with continuous operation up to 8 RF Amplifiers switched off.

1 RF Amplifier damaged when 10 RF Amplifiers were switched off, due to high reflected power in all amplifiers.

The same results obtained independently of the choice of which RF Amplifiers were switched off, i.e., randomly chosen or all connected to the same 9 Way output power combiner.



Full Reflection Tests

Pout	Operating time	Remark
10kW	15min	No damage
20kW	15min	No damage
30kW	15min	No damage
40kW	15min	No damage
50kW	1min	No damage
60kW	30s	No damage

Measurements performed by placing a short circuit at output of the system.

Duration of measurements limited by the cooling system.

Thank you

65kW 500MHz Amplifier System Installed in SLS.

References
[1] M. Gaspar *and T. Garvey.* IEEE-Trans Nucl. Sci., v63,issue2:699-706, (4/2016)
[2] M. Gaspar *and T. Garvey.* IPAC-15, WEPHA027, (2015)
[3] M. Gaspar *et al.*. NIM-A, 637:8–24, (2011)

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