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Paul Scherrer Institut

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Solid-state power amplifier developments in PSI

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Solid-State Amplifier Technology Overview

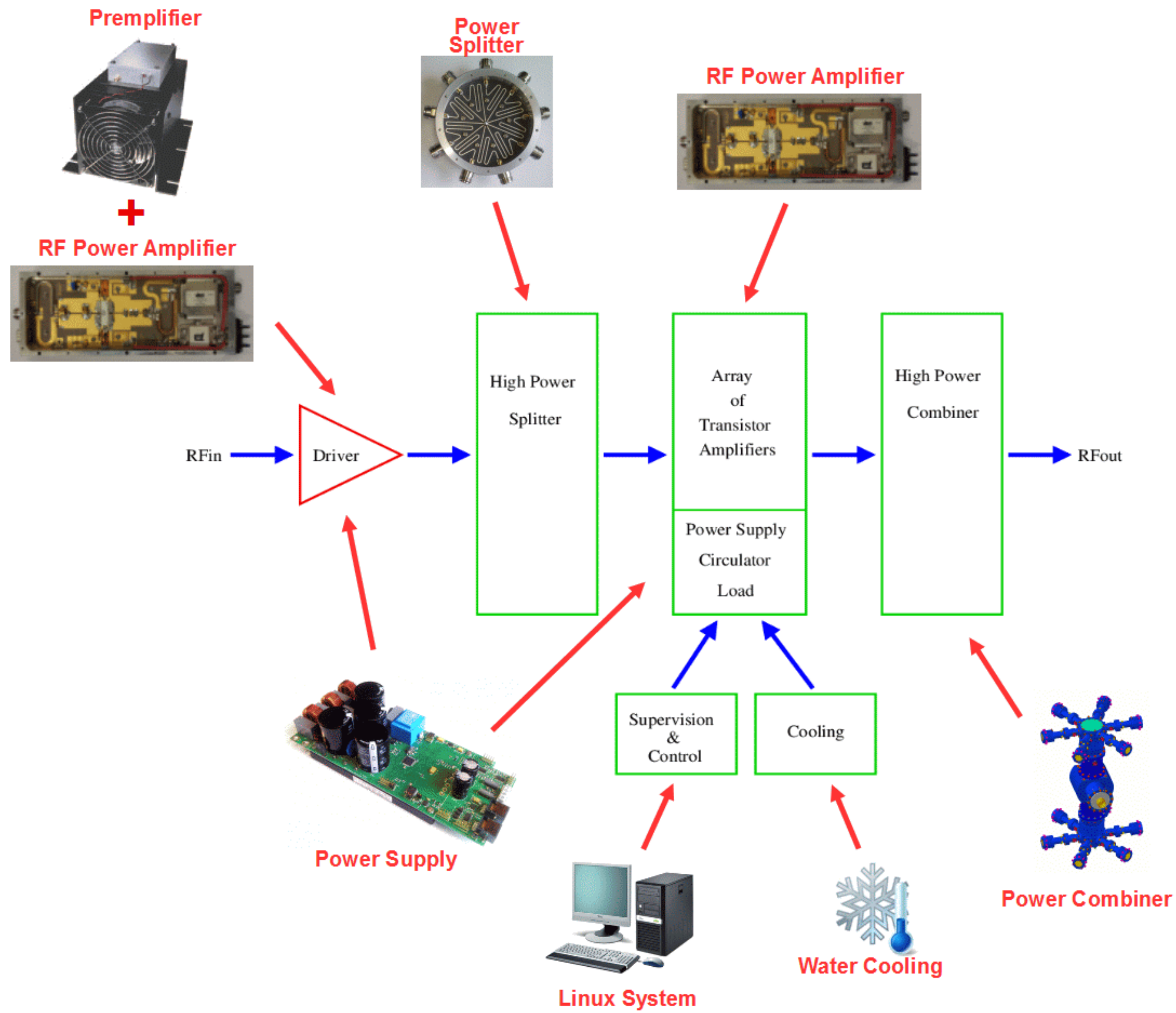
Solid-State Amplifier Technology:

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.

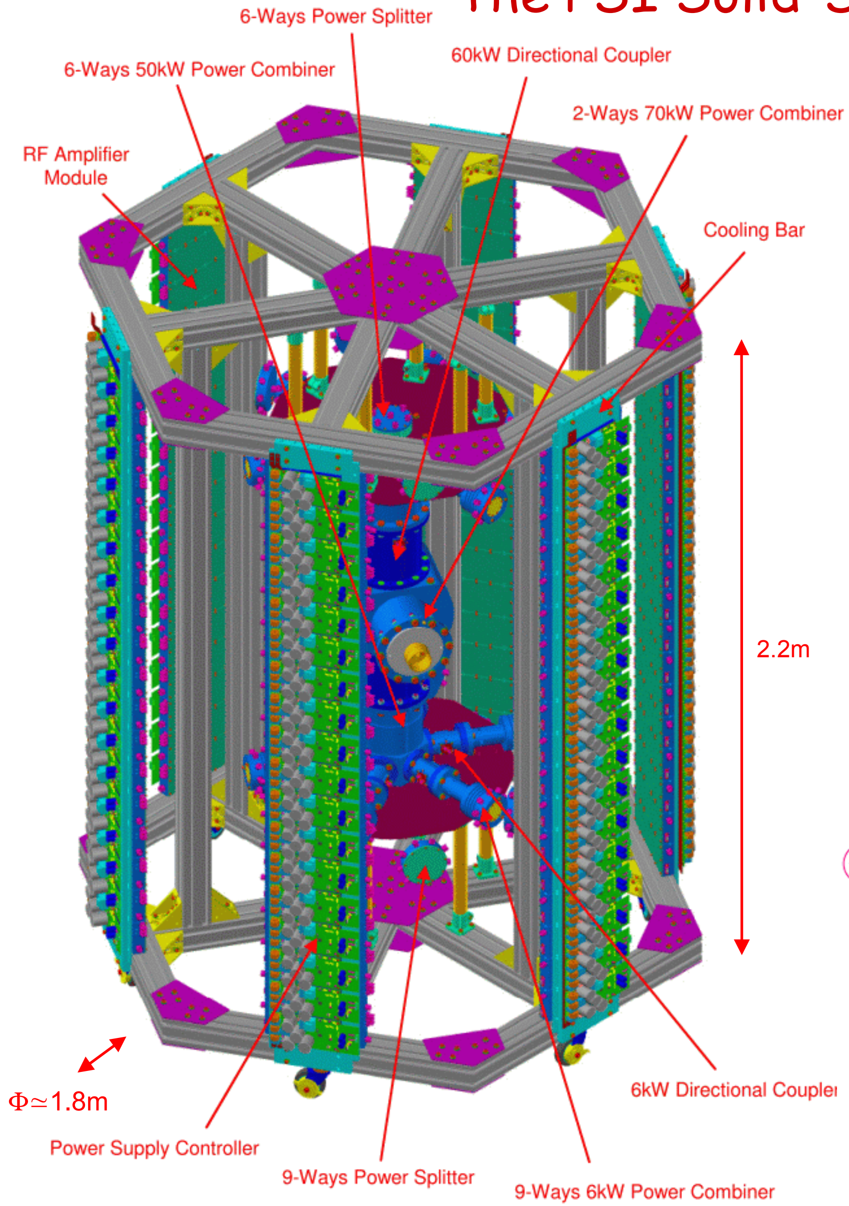
Disadvantages:

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

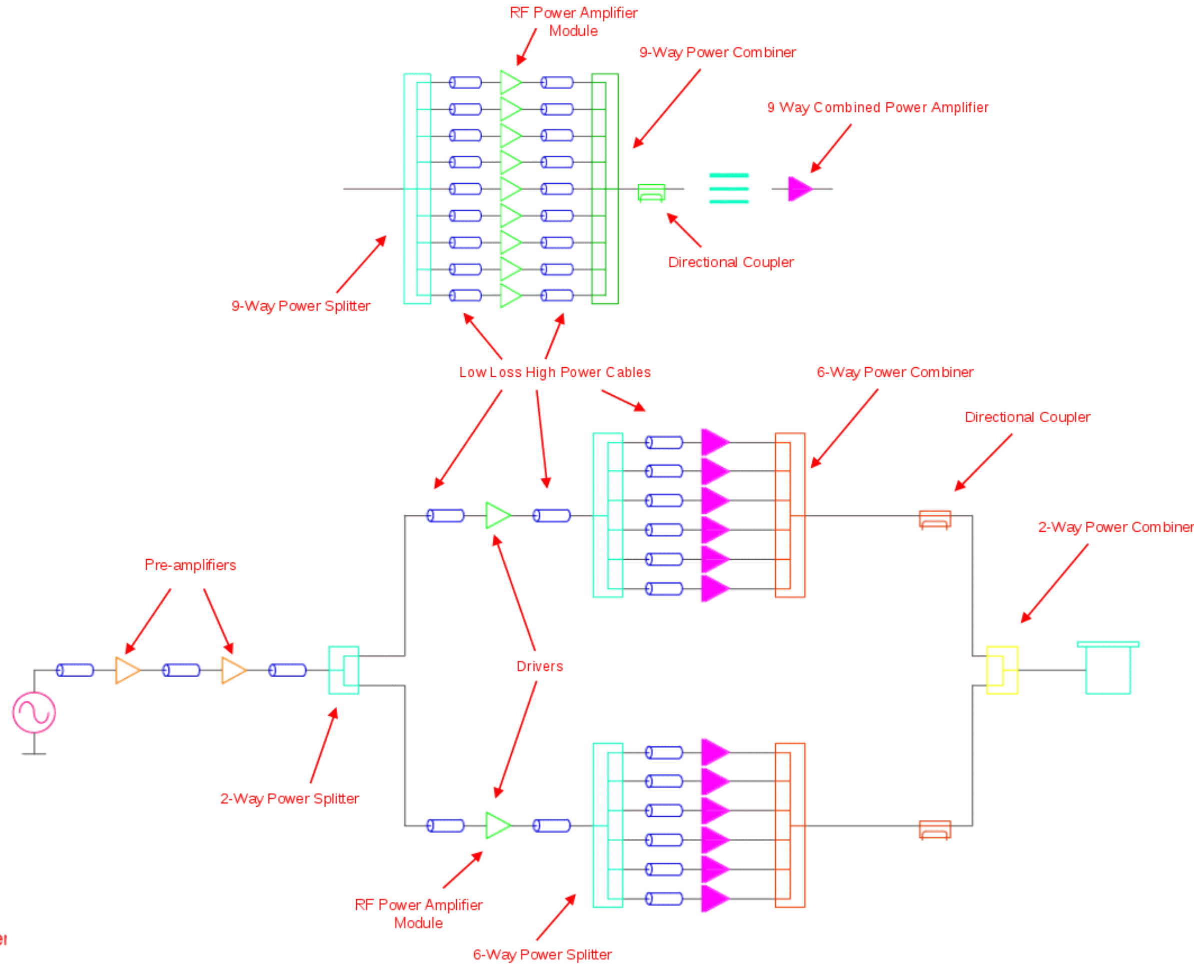


Solid-State Amplifier: Simplyfied Block Diagram

The PSI Solid-State Amplifier System Overview

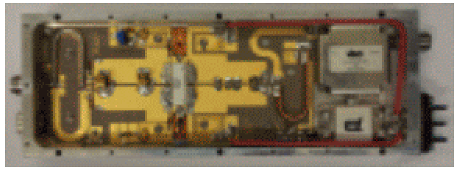


3D-View of 65kW 500MHz Amplifier System



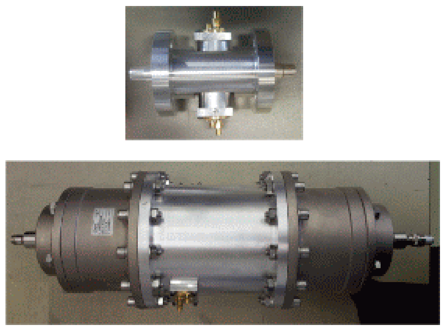
Block Diagram of 65kW 500MHz Amplifier System

Main Components

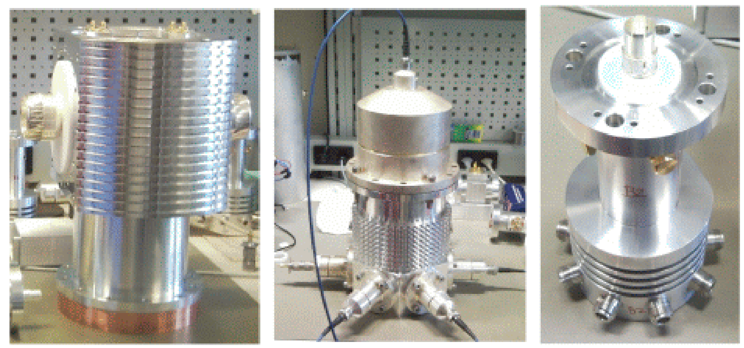


RF Power Amplifier

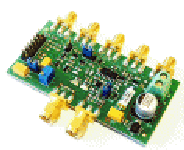
Power Splitters



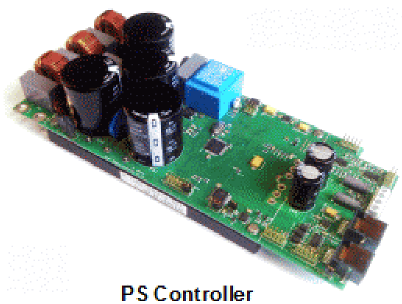
Power Directional Couplers



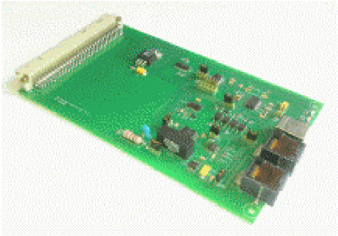
Power Combiners



Power Meter



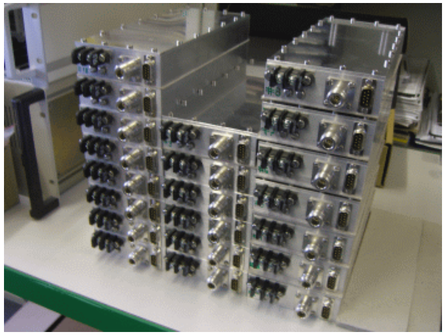
PS Controller



Master Controller

** All components designed by the author in PSI

Solid-State Amplifier Module Overview

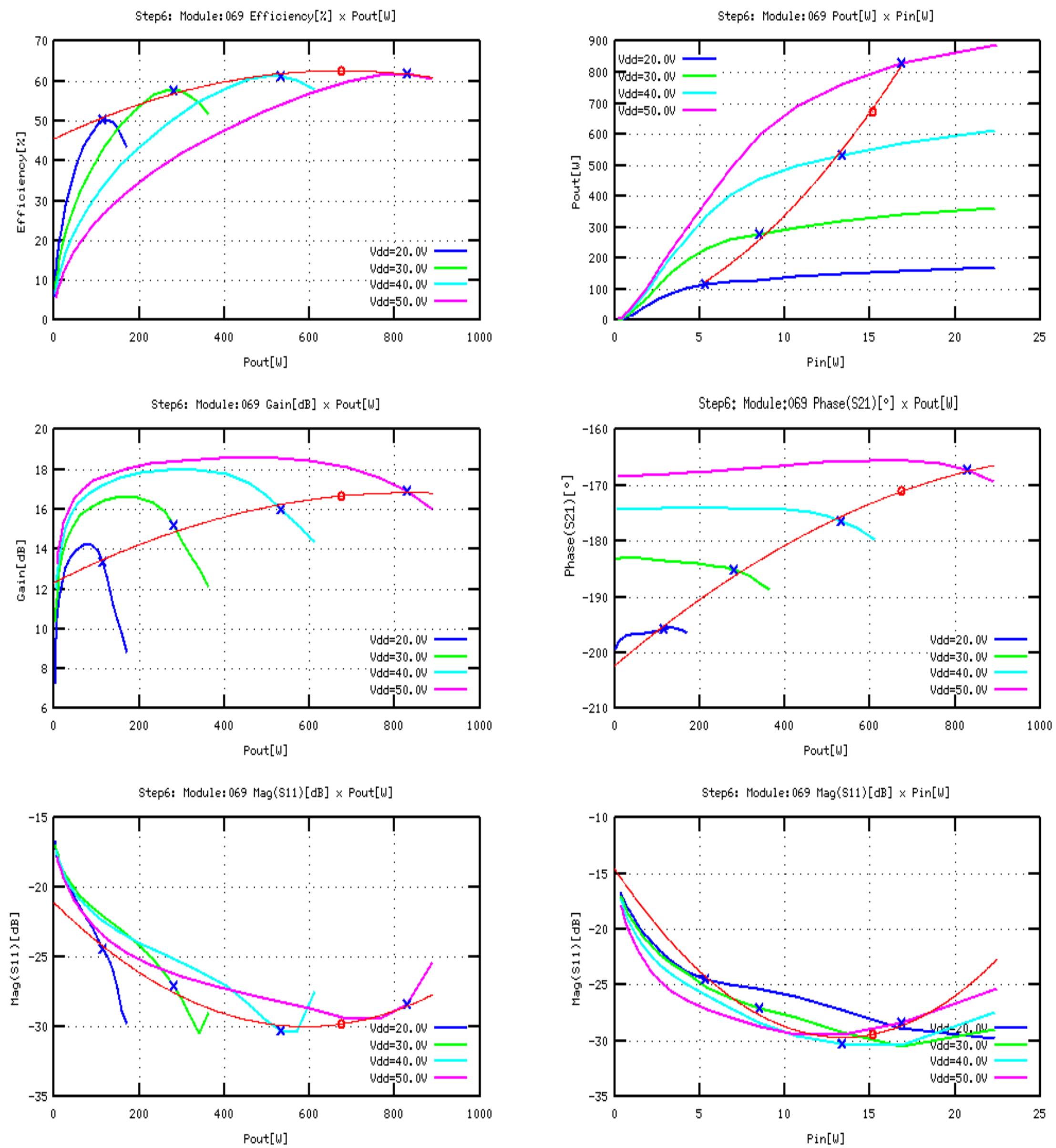


- 120 assembled in neighboring company.
- Design made in PSI using BLF578 transistor.
- Simulations made using transistor model created in PSI.
- All tests and alignements made in PSI.
- Circulator is included (IL~4%).
- Maximum output power > 820W (most of the amplifiers)
- Drain efficiency: 62% (average)
- 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

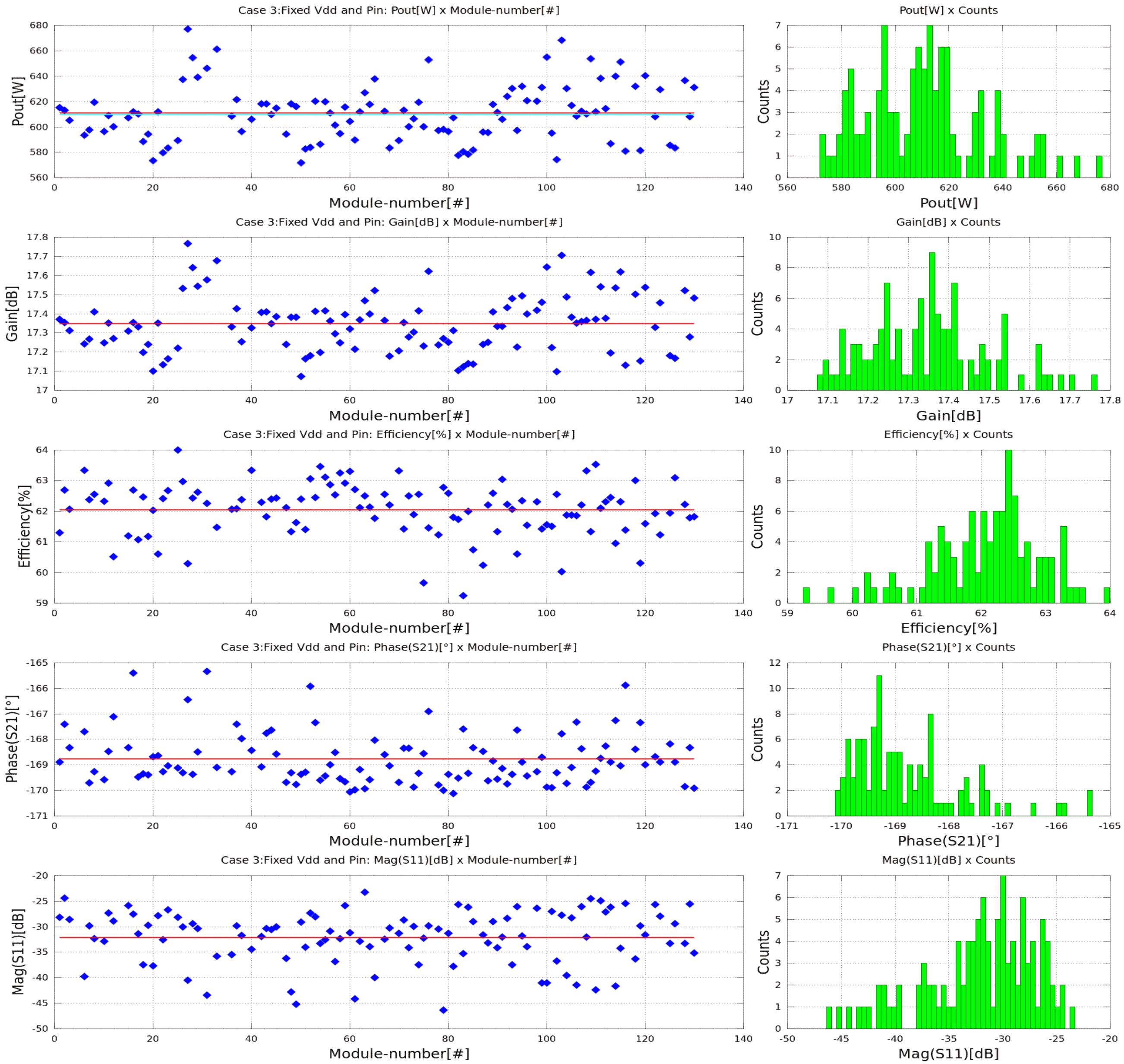
RF Amplifier Measurement Results – Step 6 - Module 069



Performance parameters of all produced RF amplifier modules

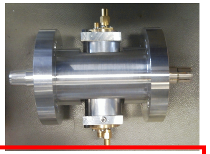
Vdd=48V

Pin=11.7W

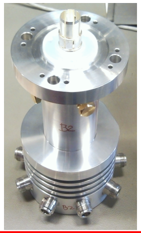


** some serial numbers not used.

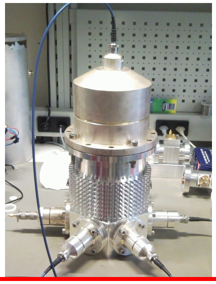
High Power Combiner



10kW Directional Coupler

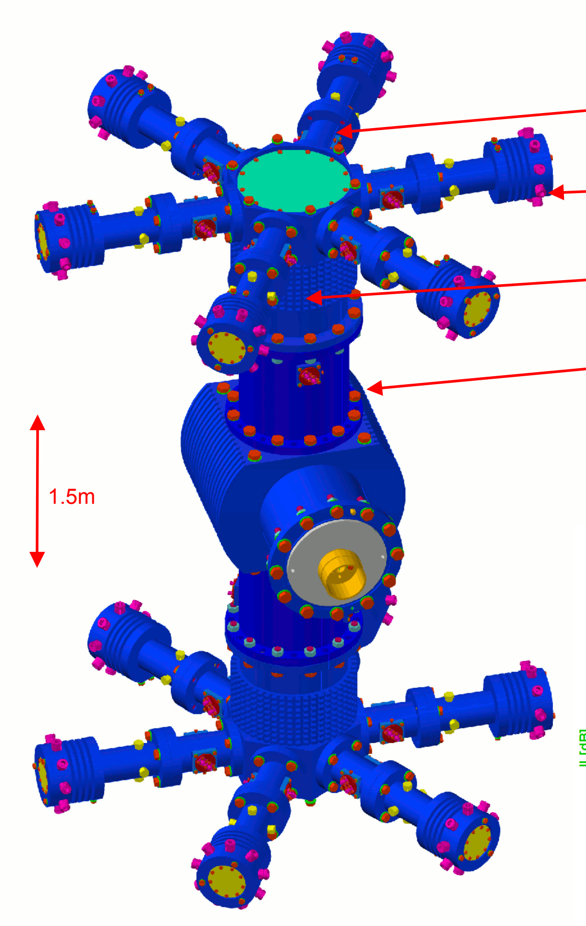


9-Way 10kW Power Combiner



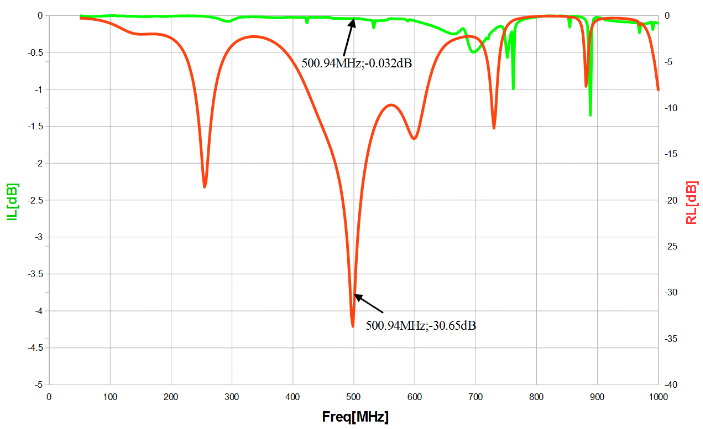
6-Way 60kW Power Combiner

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

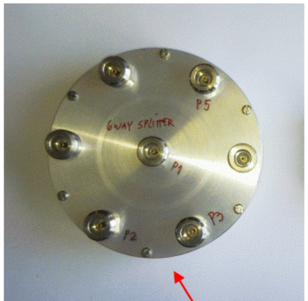
Combiner Component	RL [dB]	IL [dB]	BW (RL<-25dB) [%]
Complete Combiner Structure	-30.65	-0.031	2.94
9-Way Combiner	-35.6	-0.018	5.53
6-Way Combiner	-39.7	-0.01	7.15
2-Way Combiner	-37.3	-0.005	7.98 **
1 5/8 Directional Coupler	-30.9	-0.002	-
6 1/8 Directional Coupler	-36.8	-0.007	-

**Value limited by the measurement set-up.

Input Power Splitter Components

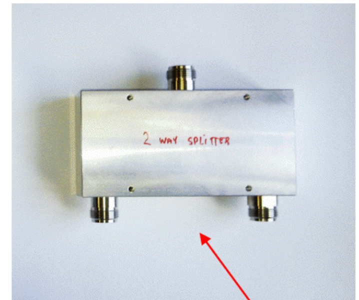
Produced Devices

6-Way Splitter



9-Way Splitter

2-Way Splitter

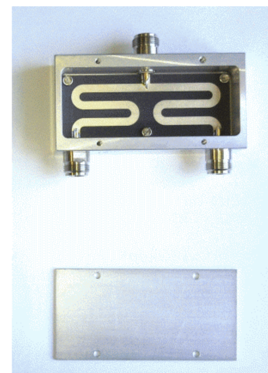


Type 2

Type 2

Type 1

Type 1

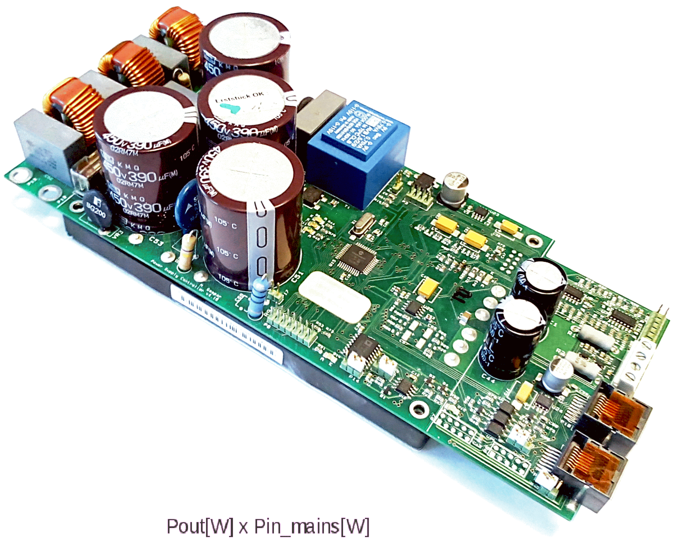


Performance Parameters of Splitter Components

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%

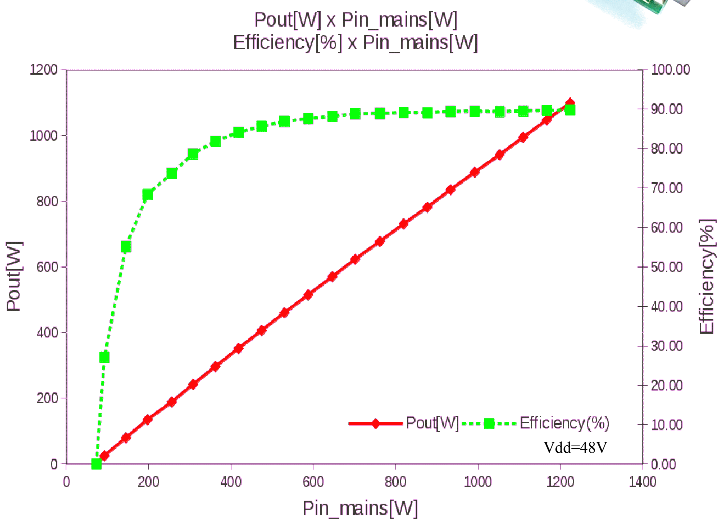
Can be Remotely Programmed and Monitored

Extra Analog and Digital I/Os

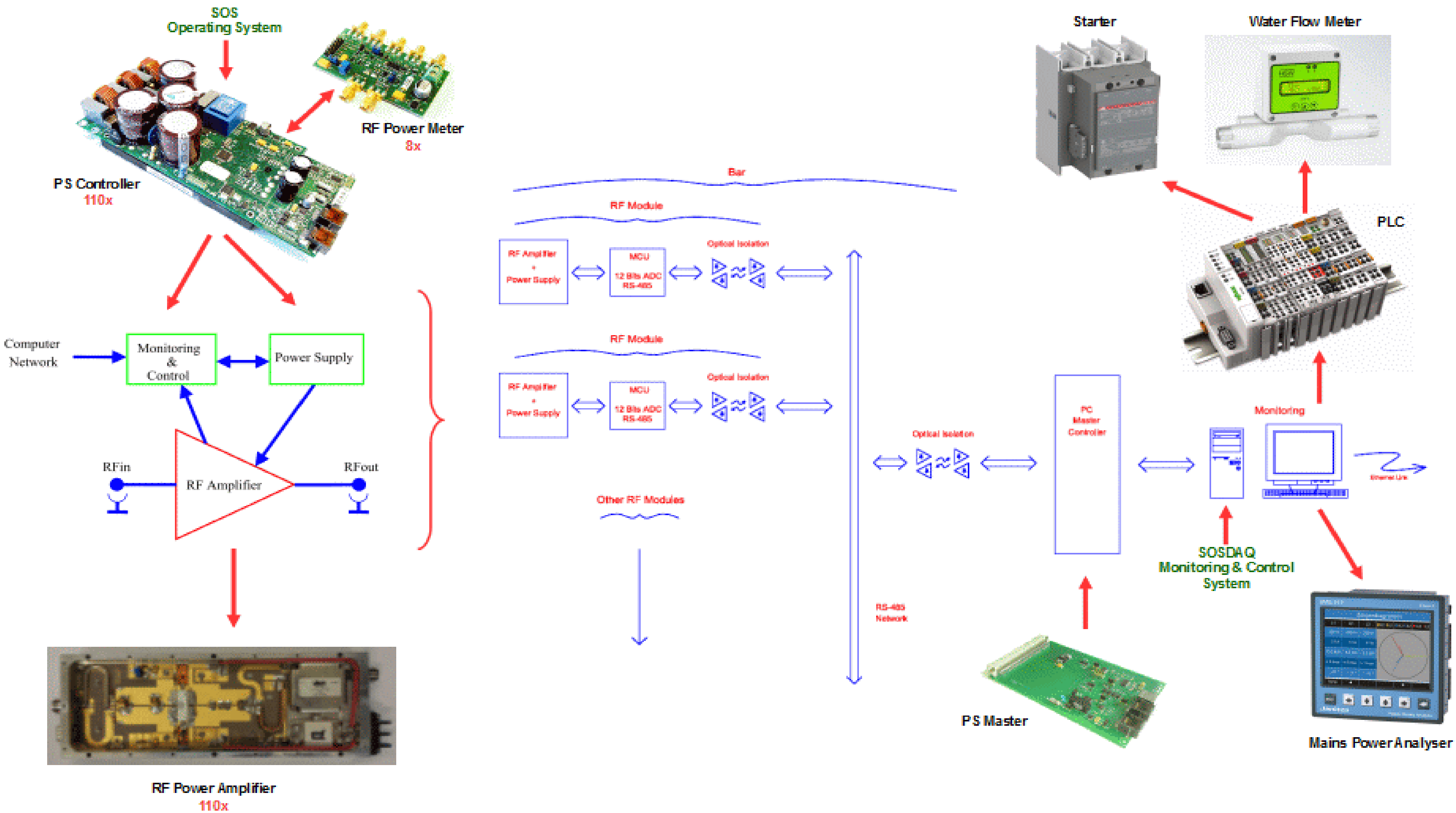
Multi-tasking Script Operating System (**SOS**)

Interlock Reaction Time: ~ 1uS

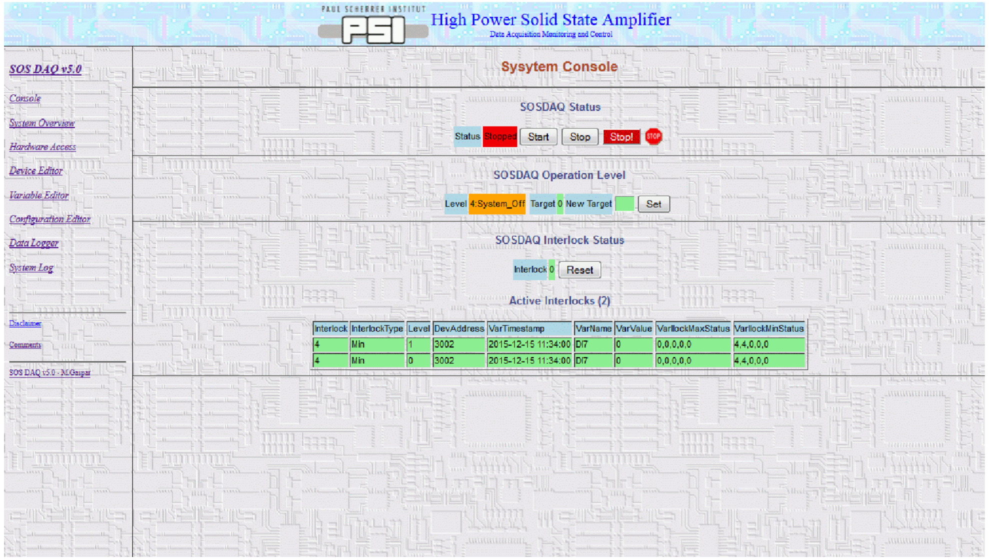
Full Monitoring Loop Time: ~ 150mS



Supervision System Configuration



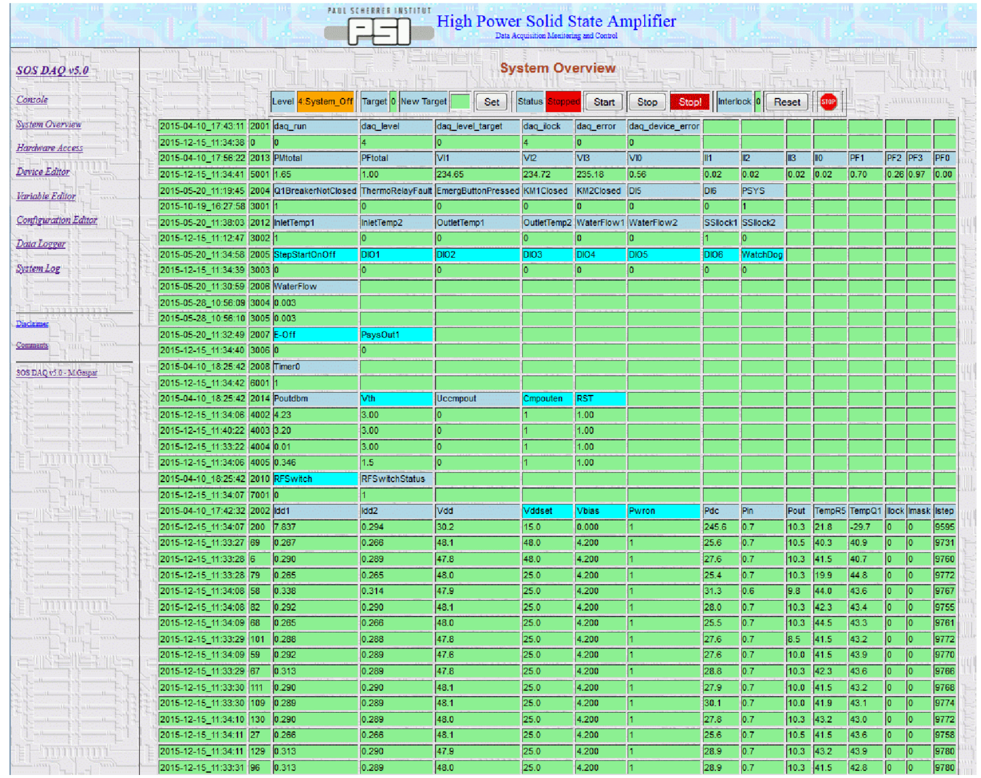
SOSDAQ - Supervision System User Interface



System Console

SOSDAQ system performance parameters

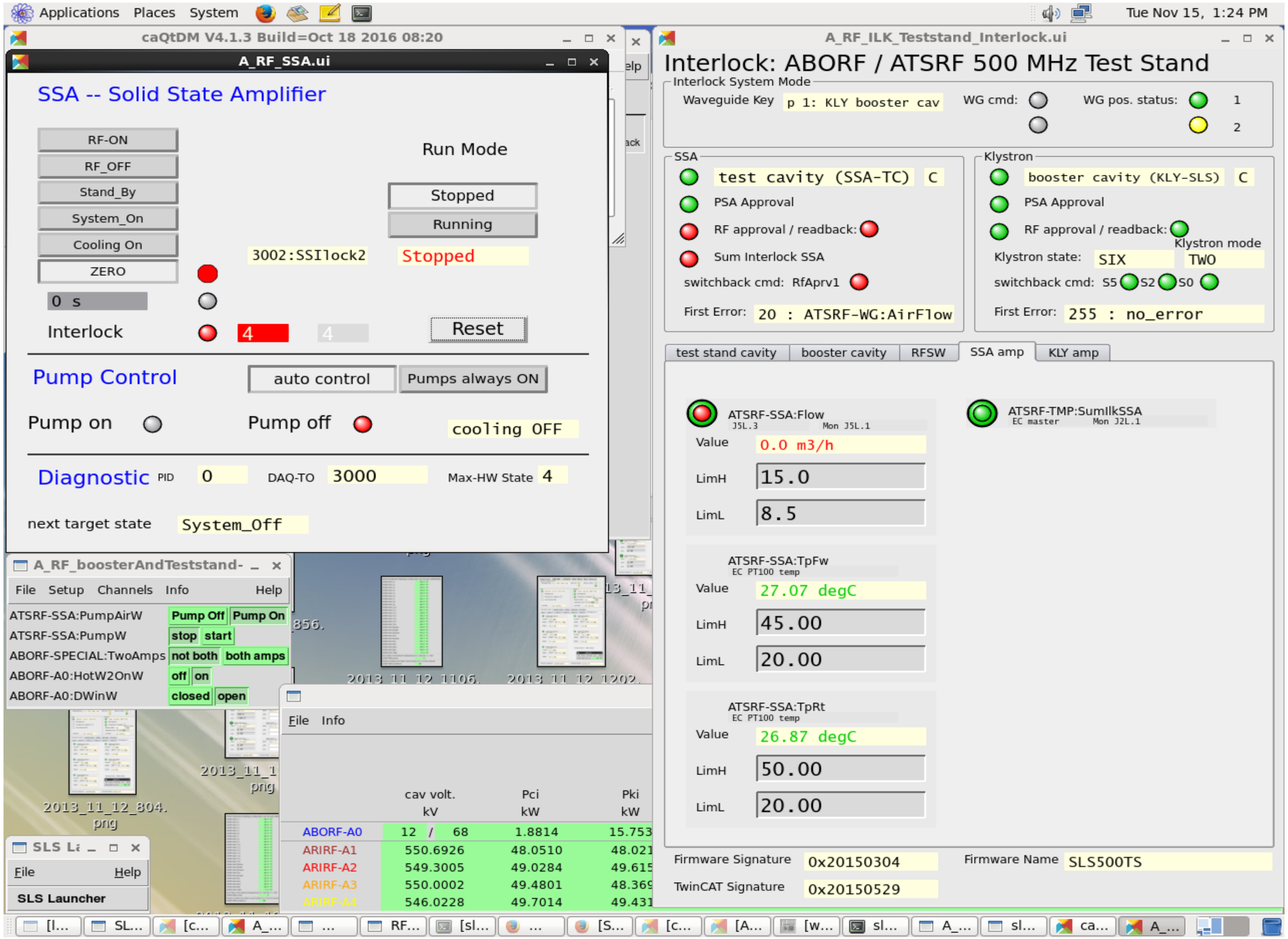
Parameter	Value
Channel update rate	≈ 200 channels/s
Number of channels	≈ 2000 channels
Number of operating levels	5
Average time to change level	5s
Fast interlock reaction time	10ns
Slow interlock reaction time	5s
Server request rate (minimum)	>100 requests/s



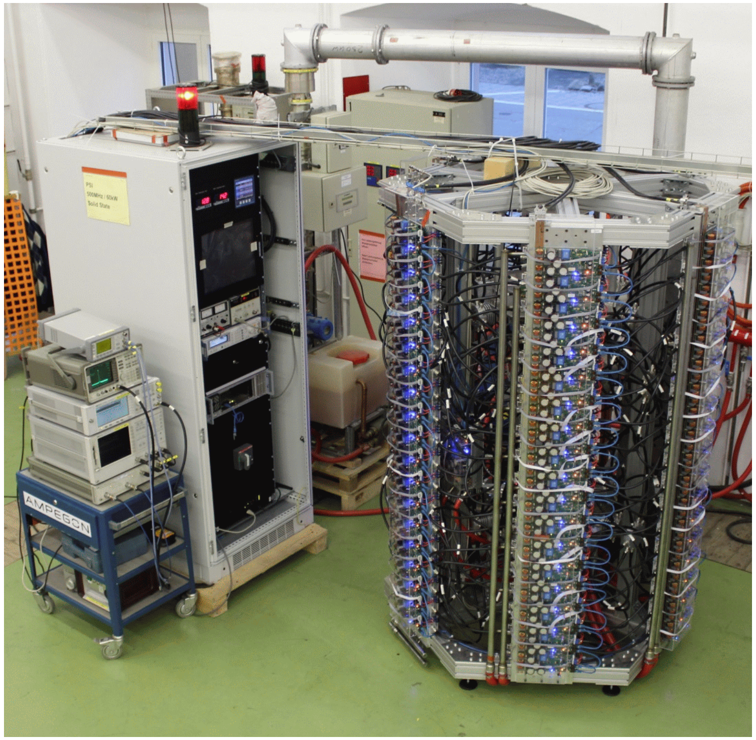
System Overview

- 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.

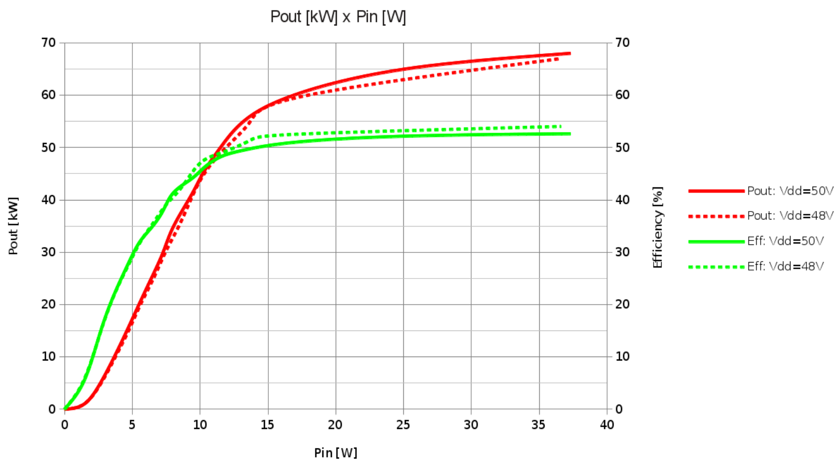
SOSDAQ – Integration with EPICS



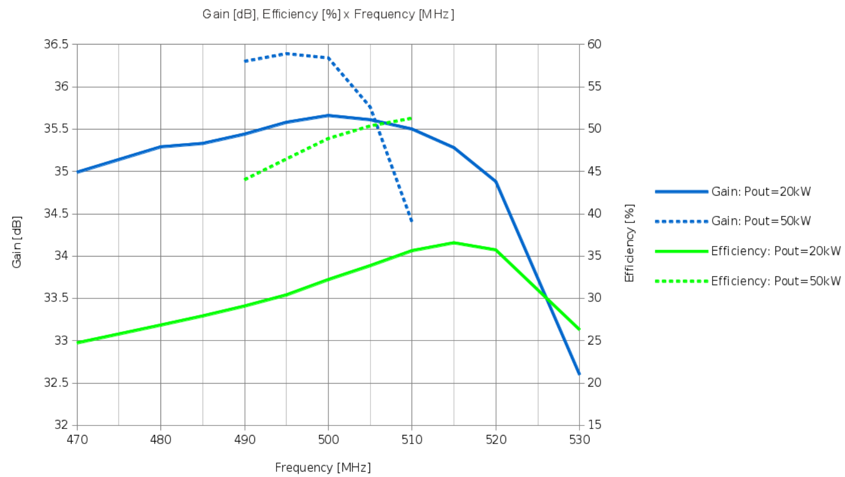
Performance Results of the Complete System



65kW 500MHz Amplifier System in Operation.



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



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

65kW 500MHz Amplifier System Performance

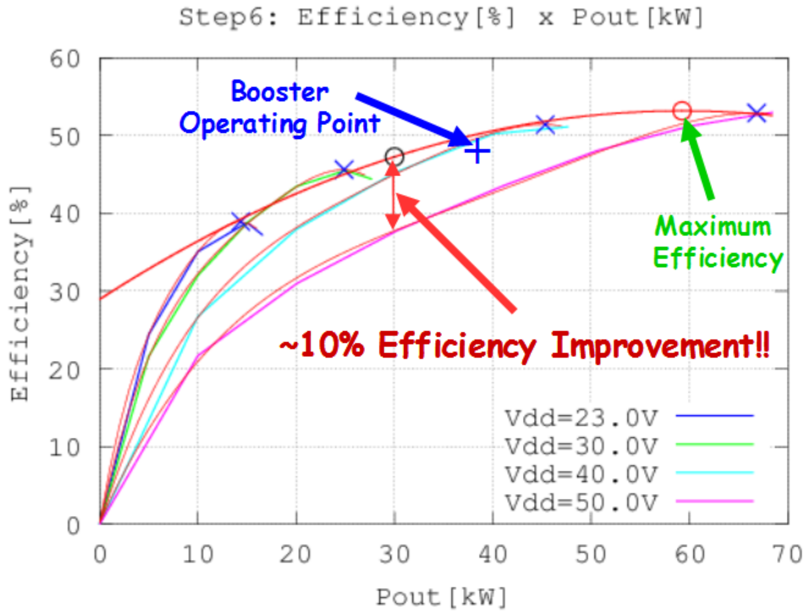
Vdd[V]	Pout[kW]	Pmains[kW]	Efficiency[%] (wall plug)**	Efficiency[%] (DC to RF)	Pin[W]
48	67	124	54	60.4	36.6
50	68	129.2	52.6	58.8	37.3

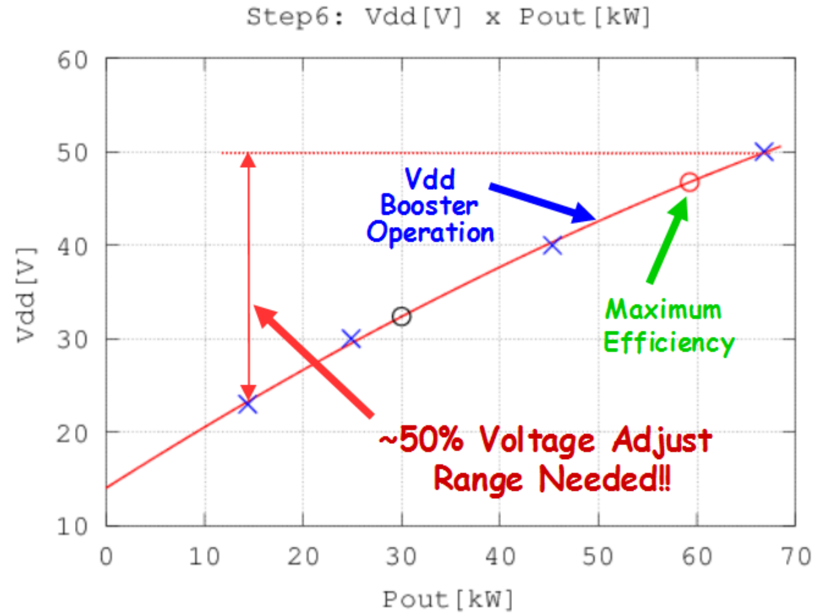
** Wall plug efficiency: ratio of RF power delivered to load (Pout) to mains AC power consumption (Pmains).

Efficiency Optimization

Psi 500MHz 65kW Solid-state High Power Amplifier

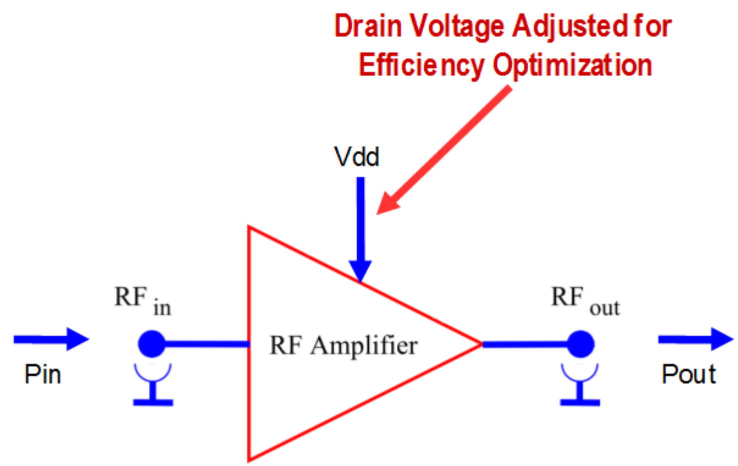
Efficiency optimization at 30kW (black marker), Maximum Efficiency Operation (red marker) and Booster Operating Point (blue marker)





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



Gracefull Degradation Tests

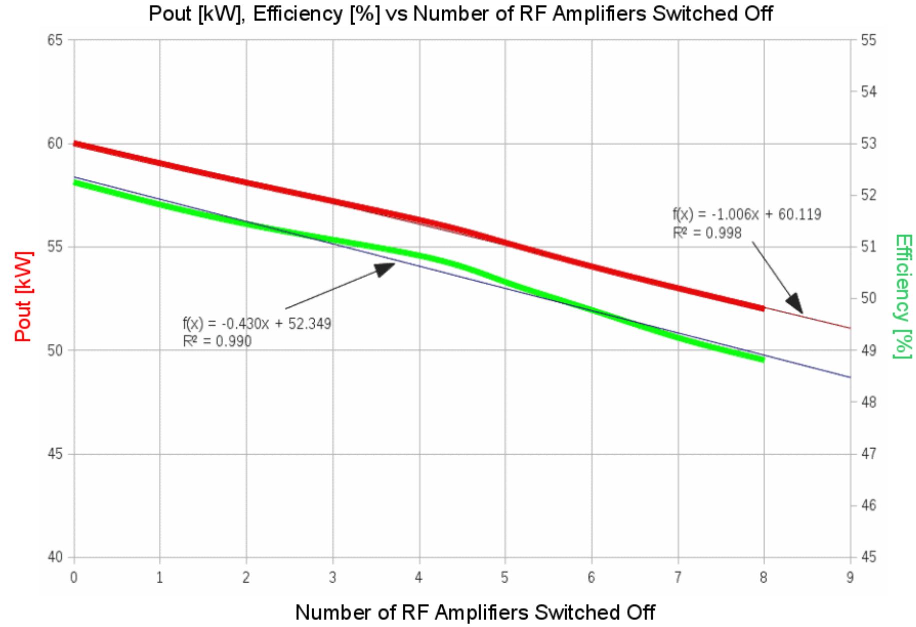
Good agreement with theory:

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

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.

Solid-State RF Power Amplifier Installation in SLS

Amplifier Mains Input

Control Rack
- Step start
- PLC
- Mains input and monitoring
- Circuit breaker
- Protection
- Linux-Debian Computer

Solid-State Amplifier
- Output Power Amplifiers
- Drivers
- Pre-amplifiers
- RF Switch
- Power supplies
- Output power sombiner
- Power splitters
- Directional couplers

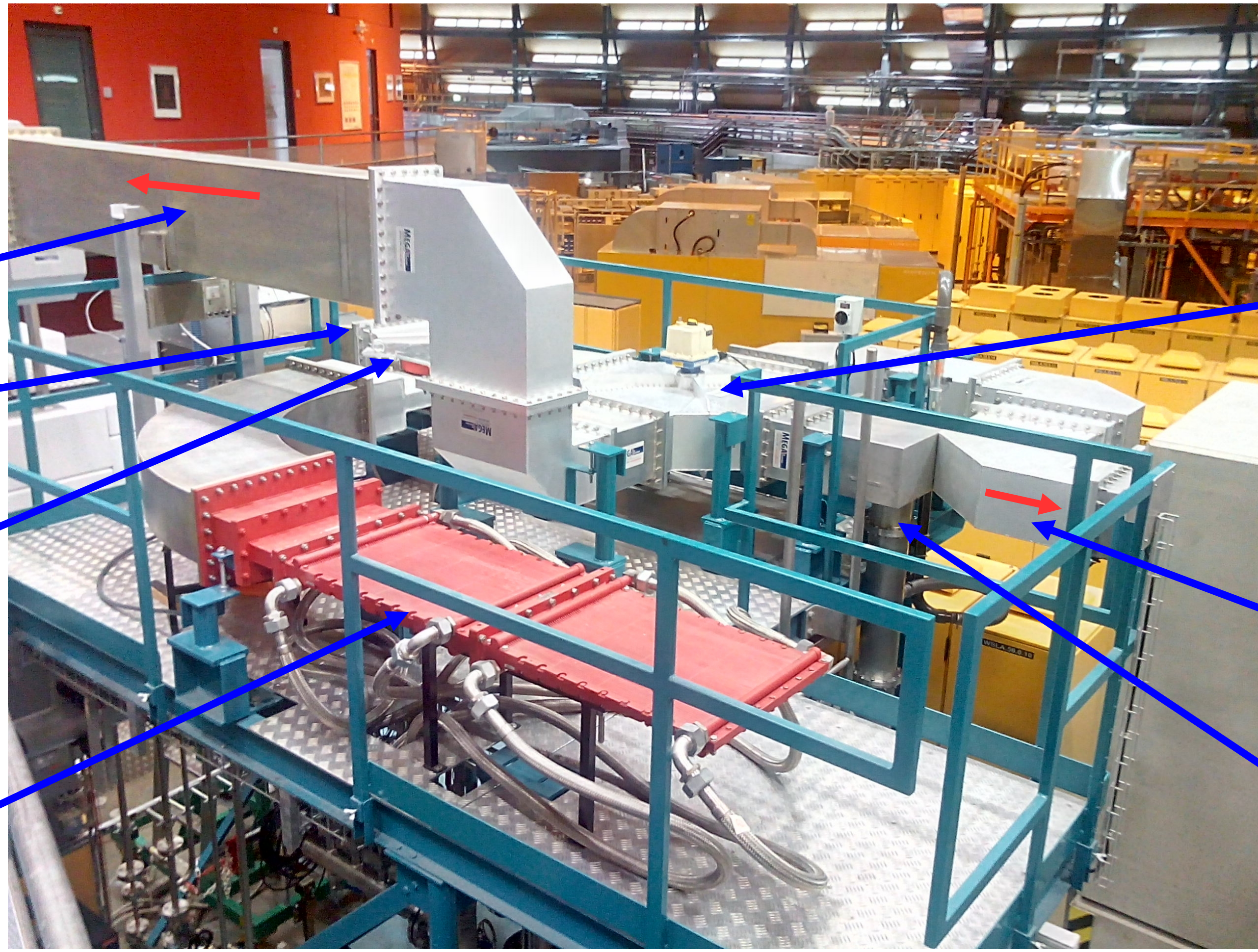
Cooling Rack

Amplifier RF Output

Water inlet and outlet

SLS Teststand

SLS Teststand and Booster RF Distribution



Tests performed after installation in SLS

1- Tests performed with 80kW water cooled RF load.

Succesful operation at RF output power up to 56kW.

RF load damaged due to cooling problems. No damage to the Solid.state amplifier due to full reflextion.

External temperature of the 6 1/8“ output coaxial transmission line exceeds 40°C in long duration operation.

2- Tests performed with the SLS cavity (installed in SLS Teststand).

Cavity conditioning up to 56kW.

Continuous operation at different output power levels, up to around 56kW.

3- Normal operation with the SLS booster.

The feedback loop worked very well after we added a phase shifter to compensate for the phase offset.

Succesful operation with the booster trapezoidal ramp. The ramp was identical to the klystron ramp as expected.

Maximum RF ouput power (top of trapezium) around 40kW.

Up to now the test duration was limited to 2 days.

Thank you

65kW 500MHz Solid-state Power Amplifier System Installed in SLS.

Special Thanks to all members of the PSI High Frequency Section. The realization of this work would not be possible without their help and competence.

* We acknowledge the financial support of the Swiss Commission for Technology and Innovation under grant number 13192.1 PFFLM-IW.

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)