





Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

M. Gaspar

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

marcos.gaspar@psi.ch



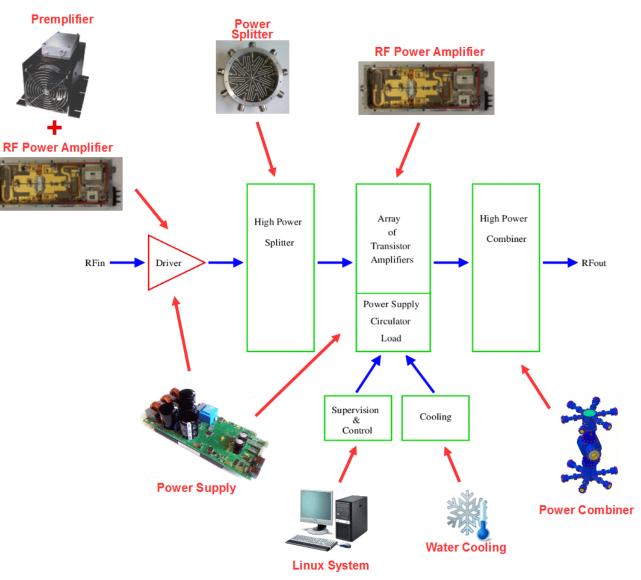
Solid-State Amplifier Technology Overview

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.

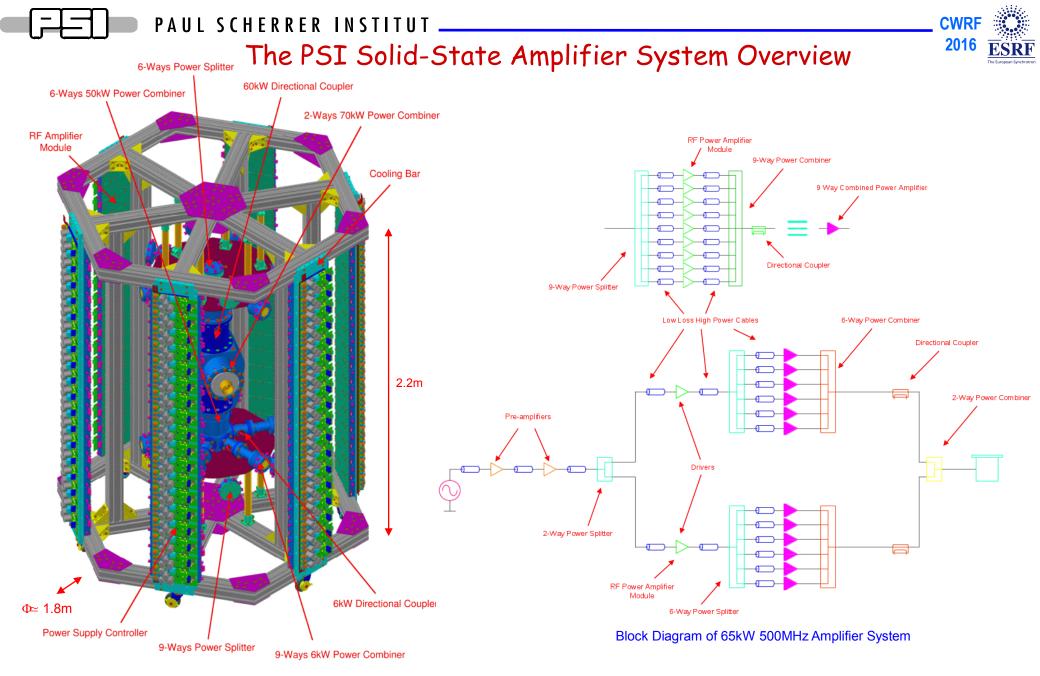
Disadvantages:

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



Solid-State Amplifier: Simplyfied Block Diagram

2016



3D-View of 65kW 500MHz Amplifier System



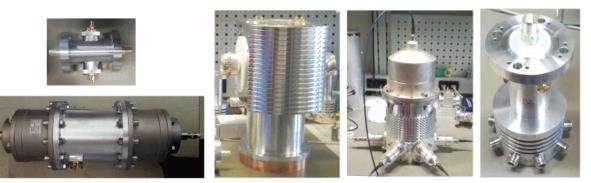


Main Components



RF Power Amplifier

Power Splitters



Power Directional Couplers

Power Combiners



** All components designed by the author in PSI

PAUL SCHERRER INSTITUT ____

Solid-State Amplifier Module Overview

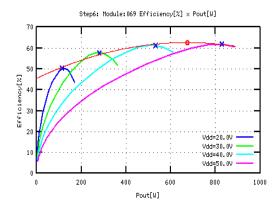


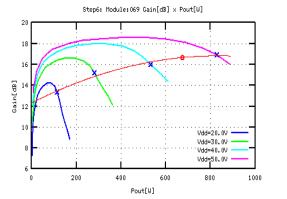
- 120 assembled in neighboring company.
- Design made in PSI using BLF578 transistor.
- Simulations made using transistor model created in PSI.
- All tests and alignements made in PSI.
- Circulator is included (IL~4%).
- Maximum output power > 820W (most of the amplifiers)
- Drain efficiency: 62% (average)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

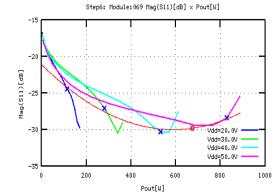
Typical Performance Parameters (Module 069)

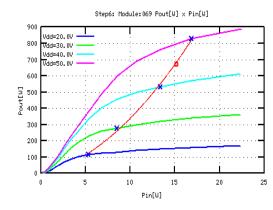
Vdd [V]	Pout [W]	Pin [W]	Gain [dB]	Pdc [W]	Efficiency [%]	Phase(S21) [°]	Mag(S11) [dB]
44.06	630	14.6	16.3	1006.3	62.6	-172.4	-29.55
45.99	630	11.7	17.3	1022.9	61.6	-169.9	-29.74
47.80	669	11.7	17.6	1100.0	60.8	-168.1	-29.64
45.47	674	15.1	16.4	1075.3	62.7	-171.1	-29.41
48.00	674.9	11.7	17.6	1104.4	61.1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

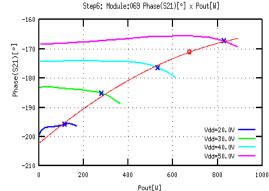


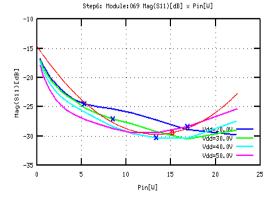






CWRF 2016

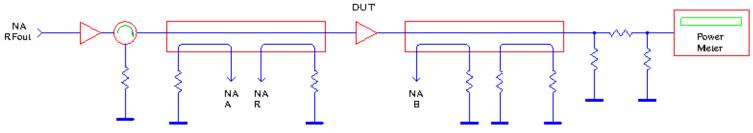






Amplifier Test Set-up

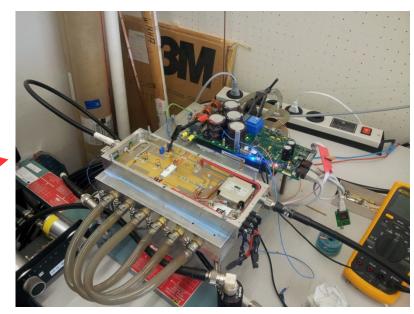




Measurement using External Bridge



Full Test Set-up

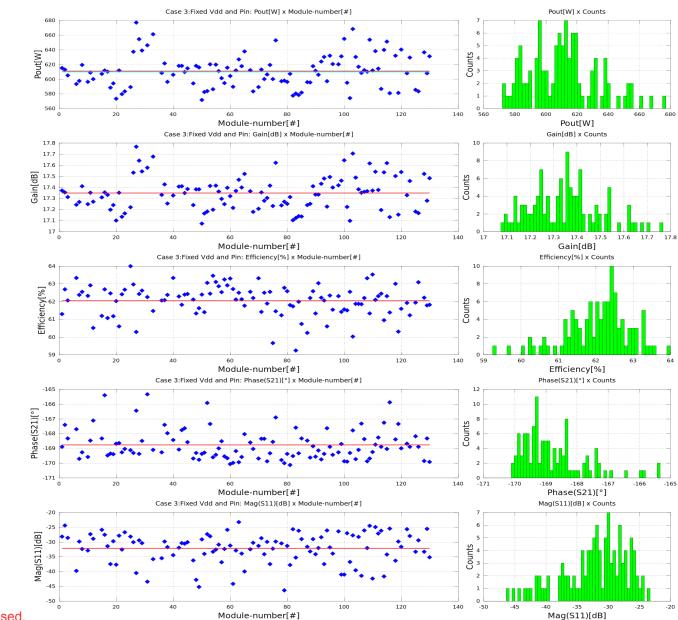


Amplifier under Test

- 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.

Paul Scherrer Institut • 5232 Villigen PSI

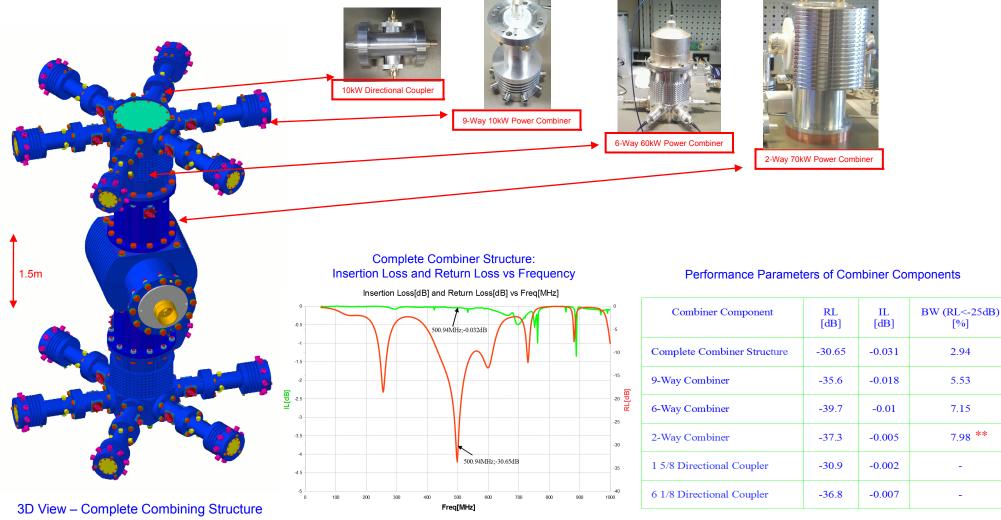
M. Gaspar – June 2016 - 7/20

CWRF 2016



PAUL SCHERRER INSTITUT _____

High Power Combiner



**Value limited by the measurement set-up.

[%]

2.94

5.53

7.15

-

_

7.98 **

CWRF 2016



Input Power Splitter Components



Produced Devices

9-Way Splitter

6-Way Splitter













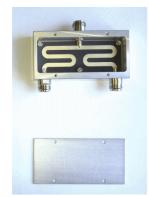


Type 1

2-Way Splitter







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



PAUL SCHERRER INSTITUT _____



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%

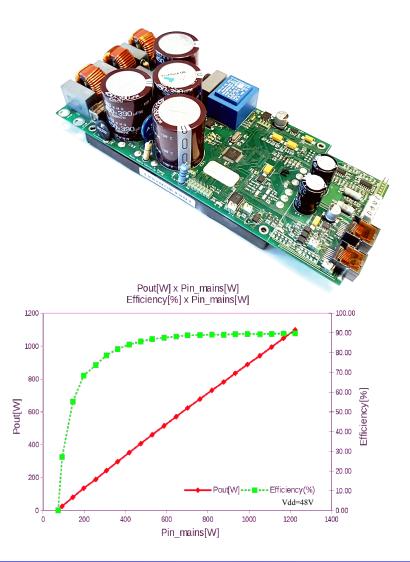
Can be Remotely Programmed and Monitored

Extra Analog and Digital I/Os

Multi-tasking Script Operating System (SOS)

Interlock Reaction Time: ~ 1uS

Full Monitoring Loop Time: ~ 150mS



Master Controller

IO Interface



Main Features

Output Isolated Power: 15V 1A External Connections: USB and RS232 Interlock Monitoring through Signaling Lines

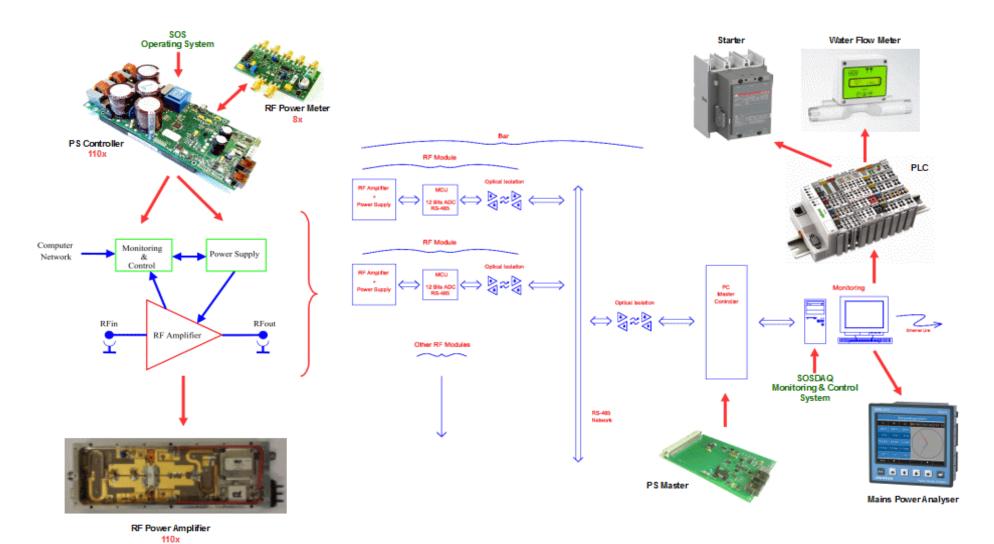


Main Features

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



CWRF 2016

SRF





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

			2001		daq_ievei	daq_ievel_target			dad_device_error								
1		015-12-15_11:34:38		o	4	0	4	0	0								
E L	20	015-04-10_17:56:22	2013	PMtotal	PFtotal	VII	V12	VB	V10	11	112	113	10	PF1	PF2 P	¥F3	PFO
	20	015-12-15_11:34:41	5 0 01	1.65	1.00	234.65	234.72	235.18	0.56	0.02	0.02	0.02	0.02	0.70	0.26 0	.97	0.00
	20	015-05-20_11:19:45	2004	Q1BreakerNotClosed	ThermoRelayFault	EmergButtonPressed	KM1Closed	KM2Closed	DIS	D16	PSYS						
	20	015-10-19_16:27:58	3001	1	0	0	0	0	0	0	1						
	20	015-05-20_11:38:03	2012	InletTemp1	InletTemp2	OutletTemp1	OutletTemp2	WaterFlow1	WaterFlow2	SSlock1	SSIOCK2						
	20	015-12-15_11:12:47	3002	1	0	0	0	0	0	1	0						
	20	015-05-20_11:34:58	2005	StepStartOnOff	DIO1	0102	DIO3	DIO4	DI05	DIO6	WatchDog						
	20	015-12-15_11:34:39	3003	0	0	0	0	0	0	0	0						
	20	015-05-20_11:30:59	2006	WaterFlow													
	20	015-05-28_10:56:09	3004	0.003													
	20	015-05-28_10:56:10	3005	0.003													
	20	015-05-20_11:32:49	2007	E-Off	PsysOut1							_					
	20	015-12-15_11:34:40	3006	0	0												
	20	015-04-10_18:25:42	2008	Timer0													
	20	015-12-15_11:34:42	6001	1													
	20	015-04-10_18:25:42	2014	Poutdbm	Vth	Ucompout	Cmpouten	RST									
	20	015-12-15_11:34:06	4002	4.23	3.00	0	1	1.00								_	
	20	015-12-15_11:40:22	4003	3.20	3.00	0	1	1.00									
	20	015-12-15_11:33:22	4004	0.01	3.00	0	1	1.00								_	
	20	015-12-15_11:34:06	4005	0.346	1.5	0	1	1.00						_	i i		<u> </u>
	20	015-04-10_18:25:42	2010	RFSwitch	RFSwitchStatus							_			i i		
	20	015-12-15_11:34:07	7001	0	1							_				_	<u> </u>
	20	015-04-10_17:42:32	2002	ldd 1	kld2	Vdd	Vddset	Vbias	Pwron	Pdc	Pin	Pout	TempR5	TempQ1	llock in	mask	Istep
	20	015-12-15_11:34:07	200	7.837	0.294	30.2	15.0	0.000	1	245.6	0.7	10.3	21.8	-29.7	0 0	5	9595
	20	015-12-15_11:33:27	00														_
			09	0.267	0.266	48.1	48.0	4.200	1	25.6	0.7	10.5	40.3	40.9	0 0	•	9731
	20	015-12-15_11:33:28				and a second		4.200 4.200				_			00		9731 9760
	1.1		6	0.290	0.289	47.8	48.0		1	27.6	0.7	10.3	41.5	40.7		D	
Ser.	20	015-12-15_11:33:28	6 79	0.290 0.265	0.289 0.265	47.8 48.0	48.0 25.0	4.200	1	27.6 25.4	0.7 0.7	10.3 10.3	41.5 19.9	40.7 44.8	0 0	0	9760
112 - 112	20	015-12-15_11:33:28 015-12-15_11:33:28	6 79 58	0.290 0.285 0.338	0.289 0.265 0.314	47.8 48.0 47.9	48.0 25.0 25.0	4.200 4.200	1 1 1	27.6 25.4 31.3	0.7 0.7 0.6	10.3 10.3 9.8	41.5 19.9 44.0	40.7 44.8 43.6	00	0 0 0	9760 9772
112 11	20 20 20	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:33:08	6 79 58 82	0.290 0.265 0.338 0.292	0.289 0.265 0.314 0.290	47.8 48.0 47.9 48.1	48.0 25.0 25.0 25.0	4.200 4.200 4.200	1 1 1	27.6 25.4 31.3 28.0	0.7 0.7 0.6 0.7	10.3 10.3 9.8 10.3	41.5 19.9 44.0 42.3	40.7 44.8 43.6 43.4	0 0 0 0	0 0 0	9760 9772 9767
the loss 1	20 20 20 20	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:34:08 015-12-15_11:34:08	6 79 58 82 68	0.290 0.265 0.338 0.292 0.265	0.289 0.265 0.314 0.290 0.266	47.8 48.0 47.9 48.1 48.0	48.0 25.0 25.0 25.0 25.0 25.0	4.200 4.200 4.200 4.200	1 1 1 1 1	27.6 25.4 31.3 28.0 25.5	0.7 0.7 0.6 0.7 0.7	10.3 10.3 9.8 10.3 10.3	41.5 19.9 44.0 42.3 44.5	40.7 44.8 43.6 43.4 43.3	0 0 0 0 0 0	0 0 0 0	9760 9772 9767 9755
the main in	20 20 20 20 20	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:33:08 015-12-15_11:34:08 015-12-15_11:34:09	6 79 58 82 68 101	0.290 0.285 0.338 0.292 0.265 0.288	0.289 0.265 0.314 0.290 0.266 0.288	47.8 48.0 47.9 48.1 48.0 47.8	48.0 25.0 25.0 25.0 25.0 25.0 25.0	4.200 4.200 4.200 4.200 4.200	1 1 1 1 1 1 1	27.6 25.4 31.3 28.0 25.5 27.6	0.7 0.7 0.6 0.7 0.7 0.7	10.3 10.3 9.8 10.3 10.3 8.5	41.5 19.9 44.0 42.3 44.5 41.5	40.7 44.8 43.6 43.4 43.3 43.2	0 0 0 0 0 0 0 0	D D D D D D	9760 9772 9767 9755 9761 9772
The second second	20 20 20 20 20 20 20	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:34:08 015-12-15_11:34:09 015-12-15_11:33:29	6 79 58 82 68 101 59	0.290 0.285 0.338 0.292 0.285 0.288 0.288 0.292	0.289 0.265 0.314 0.290 0.266 0.288 0.289	47.8 48.0 47.9 48.1 48.0 47.8 47.8 47.8	48.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0	4.200 4.200 4.200 4.200 4.200 4.200	1 1 1 1 1 1 1 1 1	27.6 25.4 31.3 28.0 25.5 27.6 27.6	0.7 0.7 0.6 0.7 0.7 0.7 0.7 0.7	10.3 10.3 9.8 10.3 10.3 8.5 10.0	41.5 19.9 44.0 42.3 44.5 41.5 41.5	40.7 44.8 43.6 43.4 43.3 43.2 43.9	0 0 0 0 0 0 0 0	0 0 0 0 0 0	9760 9772 9767 9755 9755
The first water	20 20 20 20 20 20 20 20 20 20 20 20 20 2	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:34:08 015-12-15_11:34:08 015-12-15_11:34:09 015-12-15_11:33:29 015-12-15_11:34:09	6 79 58 82 68 101 59 67	0 290 0 285 0 338 0 292 0 285 0 288 0 292 0 313	0.289 0.265 0.314 0.290 0.266 0.268 0.289 0.289	47.8 48.0 47.9 48.1 48.0 47.8 47.8 47.8 47.8	48.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25	4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200	1 1 1 1 1 1 1 1 1	27.6 25.4 31.3 28.0 25.5 27.6 27.6 28.8	0.7 0.7 0.6 0.7 0.7 0.7 0.7 0.7 0.7	10.3 10.3 9.8 10.3 10.3 8.5 10.0 10.3	41.5 19.9 44.0 42.3 44.5 41.5 41.5 42.3	40.7 44.8 43.6 43.4 43.3 43.2 43.9 43.6	0 0 0 0 0 0 0 0 0 0 0 0	D D D D D D D D D D	9760 9772 9767 9755 9761 9772 9770 9770
and the state of the state	20 20 20 20 20 20 20 20 20 20	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:34:08 015-12-15_11:34:08 015-12-15_11:34:09 015-12-15_11:33:29 015-12-15_11:33:29 015-12-15_11:33:29	6 79 58 82 68 101 59 67 111	0.290 0.285 0.338 0.292 0.285 0.286 0.288 0.292 0.313 0.290	0.289 0.285 0.314 0.290 0.266 0.268 0.289 0.289 0.289 0.290	47.8 48.0 47.9 48.1 48.0 47.8 47.8 47.8 47.8 47.8 48.1	48.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0	4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200	1 1 1 1 1 1 1 1 1	27.6 25.4 31.3 28.0 25.5 27.6 27.6 28.8 27.9	0.7 0.7 0.6 0.7 0.7 0.7 0.7 0.7 0.7 0.7	10.3 10.3 9.8 10.3 10.3 8.5 10.0 10.3 10.0	41.5 19.9 44.0 42.3 44.5 41.5 41.5 42.3 41.5	40.7 44.8 43.6 43.4 43.3 43.2 43.9 43.6 43.2	0 0 0 0 0 0 0 0 0 0 0 0 0 0	D D D D D D D D D D D D D D	9760 9773 9761 9761 9761 9773 9776 9776 9766
1442 (m 1 m 1 m 1 m	20 20 20 20 20 20 20 20 20 20 20 20 20 2	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:34:08 015-12-15_11:34:08 015-12-15_11:34:09 015-12-15_11:33:29 015-12-15_11:33:29 015-12-15_11:33:30	6 79 58 82 68 101 59 67 111 109	0.290 0.285 0.338 0.292 0.285 0.288 0.292 0.313 0.290 0.313 0.290	0.289 0.265 0.314 0.290 0.266 0.288 0.289 0.289 0.289 0.289 0.289	47.8 48.0 47.9 48.1 48.0 47.8 47.8 47.8 47.8 48.1 48.1	48.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25	4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200	1 1 1 1 1 1 1 1 1 1 1 1	27.6 25.4 31.3 28.0 25.5 27.6 27.6 28.8 27.9 30.1	0.7 0.7 0.6 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	10.3 10.3 9.8 10.3 10.3 8.5 10.0 10.3 10.0 10.0	41.5 19.9 44.0 42.3 44.5 41.5 41.5 42.3 41.5 41.5 41.9	40.7 44.8 43.6 43.4 43.3 43.2 43.9 43.6 43.2 43.2 43.2 43.1		D D D D D D D D D D D D D D	9760 9772 9767 9765 9761 9772 9770
and and and and and and	20 20 20 20 20 20 20 20 20 20 20 20 20 2	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:34:08 015-12-15_11:34:08 015-12-15_11:34:09 015-12-15_11:33:29 015-12-15_11:33:29 015-12-15_11:33:30 015-12-15_11:33:30	6 79 58 82 68 101 59 67 111 109 130	0 290 0 285 0 338 0 292 0 285 0 285 0 286 0 292 0 313 0 290 0 289 0 289 0 280	0.289 0.265 0.314 0.290 0.288 0.288 0.289 0.289 0.289 0.289 0.289	47.8 48.0 47.9 48.1 48.0 47.8 47.6 47.6 47.6 48.1 48.1 48.1 48.1	48.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25	4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200	1 1 1 1 1 1 1 1 1 1 1 1 1 1	27.6 25.4 31.3 28.0 25.5 27.6 27.6 28.8 27.9 30.1 27.8	0.7 0.7 0.6 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	10.3 10.3 9.8 10.3 10.3 8.5 10.0 10.3 10.0 10.0	41.5 19.9 44.0 42.3 44.5 41.5 41.5 41.5 41.5 41.9 43.2	40.7 44.8 43.6 43.4 43.2 43.9 43.6 43.2 43.9 43.6 43.2 43.1 43.0	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	D D D D D D D D D D D D D D D D D D D	9760 9772 9767 9761 9761 9770 9770 9766 9766 9774
and a state of the	20 20 20 20 20 20 20 20 20 20 20 20 20 2	015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:33:28 015-12-15_11:34:08 015-12-15_11:33:29 015-12-15_11:33:29 015-12-15_11:33:29 015-12-15_11:33:30 015-12-15_11:33:30 015-12-15_11:33:30	6 79 58 82 68 101 59 67 111 109 130 27	0 290 0 285 0 338 0 292 0 295 0 292 0 292 0 313 0 290 0 290 0 290 0 290 0 290 0 290 0 290	0.289 0.265 0.314 0.290 0.266 0.288 0.289 0.289 0.290 0.289 0.290 0.289 0.289 0.289 0.289 0.289	47.8 48.0 47.9 48.1 48.0 47.8 47.8 47.8 47.8 47.8 48.1 48.1 48.1 48.1	48.0 25.0 25.0 25.0 25.0 25.0 25.0 25.0 25	4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200 4.200	1 1 1 1 1 1 1 1 1 1 1 1 1	27.6 25.4 31.3 28.0 25.5 27.6 27.6 27.6 27.9 30.1 27.8 25.6	0.7 0.7 0.6 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	10.3 10.3 9.8 10.3 10.3 8.5 10.0 10.3 10.0 10.0 10.3 10.5	41.5 19.9 44.0 42.3 44.5 41.5 41.5 41.5 41.5 41.9 43.2 41.5	40.7 44.8 43.6 43.4 43.3 43.2 43.9 43.6 43.2 43.1 43.0 43.6	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	D D D D D D D D D D D D D D D D D D D	9760 9772 9767 9765 9761 9772 9770 9776 9766 9766 9768 9774 9772

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.



PAUL SCHERRER INSTITUT _____ Performance Results of the Complete System



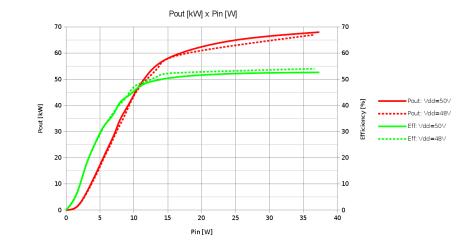


65kW 500MHz Amplifier System in Operation.

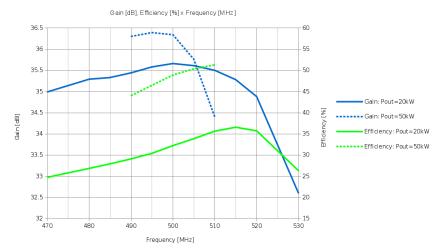
65kW 500MHz Amplifier System Performance

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: Pout and Efficiency vs Pin



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

Paul Scherrer Institut • 5232 Villigen PSI





Efficiency Performance of Various Components

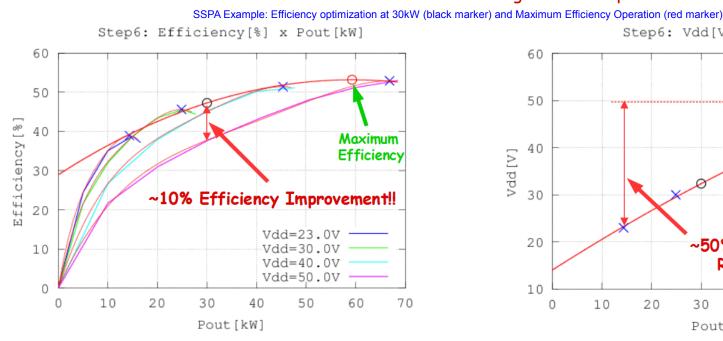
System Component	RL [dB]	IL [dB]	Efficiency [%]
Transistor RF power amplifier (including circulator)	-	-	61 - 64
High power coaxial cables	< -35	-0.084	98.10
Complete Combiner Structure	-30.65	-0.031	99.29
PS Controller (AC/DC converter + Supervision)	-	-	88 - 91
9-Way Combiner	-35.6	-0.018	99.59
6-Way 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

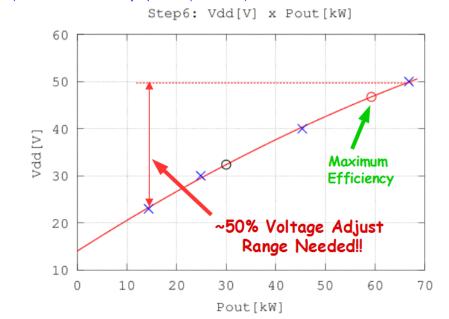
** Precision of measurements limited by specific measurement set-ups.



CWRF 2016

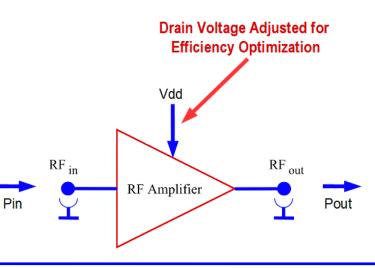
Efficiency Optimization Psi 500MHz 65kW Solid-state High Power Amplifier





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

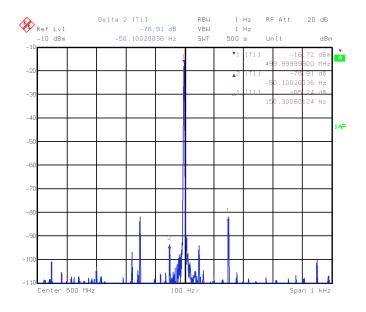
		r (pulsed) icle:50%	Storage Ring (CW) Beam current: 400mA		
	Klystron Amplifier: BO	SSPA 1x60kW System	Klystron Amplifier: SR3	SSPA 2x60kW System	
Pout	36kW	36kW	100kW	100kW	
Efficiency (wall plug)	11.2%	46.5%	40%	52%	
Price Estimated	1.8MCHF	400kCHF	1.8MCHF	800kCHF	

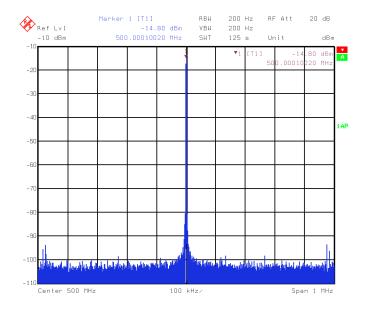


Paul Scherrer Institut • 5232 Villigen PSI



Output Frequency Spectrum





2nd harmonic level: -45dBc

3rd harmonic level: absent

Pout=63kW

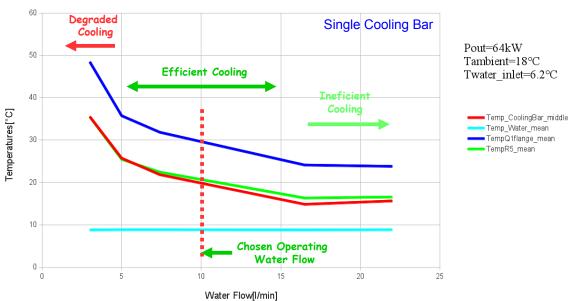


Cooling System



Temperature in various components at Pout=63kW

Component	Temperature [°C]	Remark
Cooling Bar A4000 aluminium	31.7	Тор
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 $R1 = 0.01\Omega$	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



Temperatures[°C] vs. Water Flow[I/min]

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

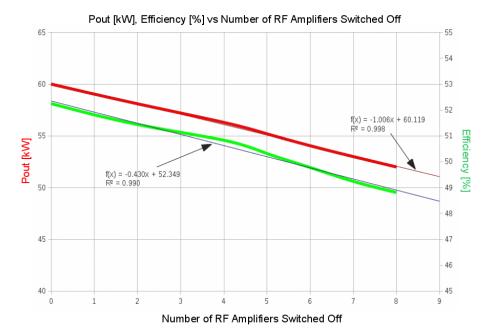
Good agreement with theory:

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

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.

PAUL SCHERRER INSTITUT _____



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)

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