

Solid State RF High Power Amplifier Developments at SOLEIL

Ti RUAN, on behalf of SOLEIL RF Group

CWRF10

CELLS-ALBA Barcelona Spain

May 04-07 2010

History Review



- 2004 Success of Booster 35 kW SSA (Solid State Amplifier) encouraged us to design 180 kW SSA. (Unconditional Stability, Drop-in Circulator etc.)
- SR: Four 180 kW amplifiers
- Vacuum tubes (Klystron, IOT, Diacrode) not commercially available at 352 MHz
- Selection of solid state technology
- Challenge: No Transistor available
- Collaboration with Polyfet to develop the highest power UHF LDMOS LR301

Advantages of SSA



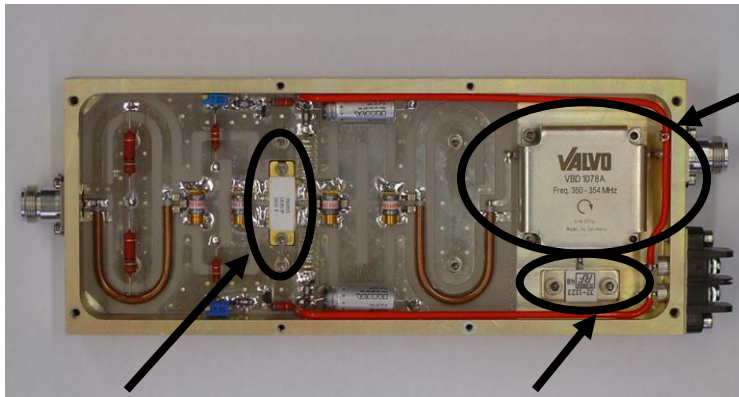
- High Reliability
- Modularity
- No DC High Voltage → No X Ray Radiation
- No High Power Circulator
- Easy Maintenance
- Very Simple Spare Parts
- Good Performance
- Low Phase Noise

352 MHz 2.5 kW Amplifier



315 W Module

Low Loss Wideband
Circulator



LDMOS

50 Ohm
Termination

Main Specifications
 RF power 315 W CW
 Frequency 352 MHz
 Gain 13 - 14.5 dB
 Phase tolerance 15°
 Efficiency 63%
 Unconditional Stability

DC/DC Converter

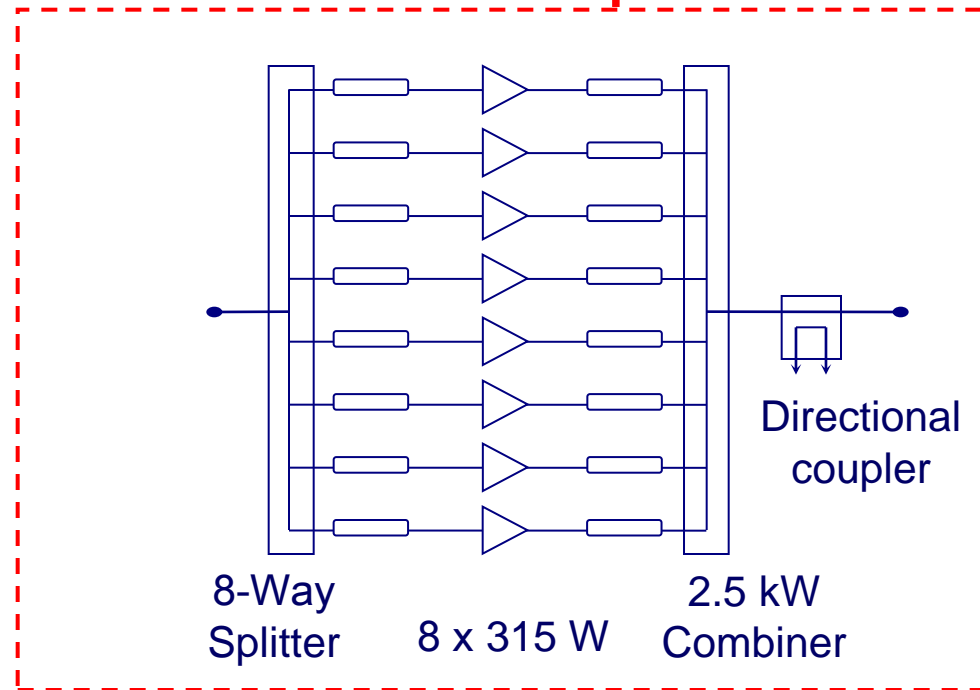


Input
280V DC

Control &
Measurement

Output
28V DC

2.5 kW Group



N-Way Power Combiners

2,5 kW

25 kW

100 kW

200 kW



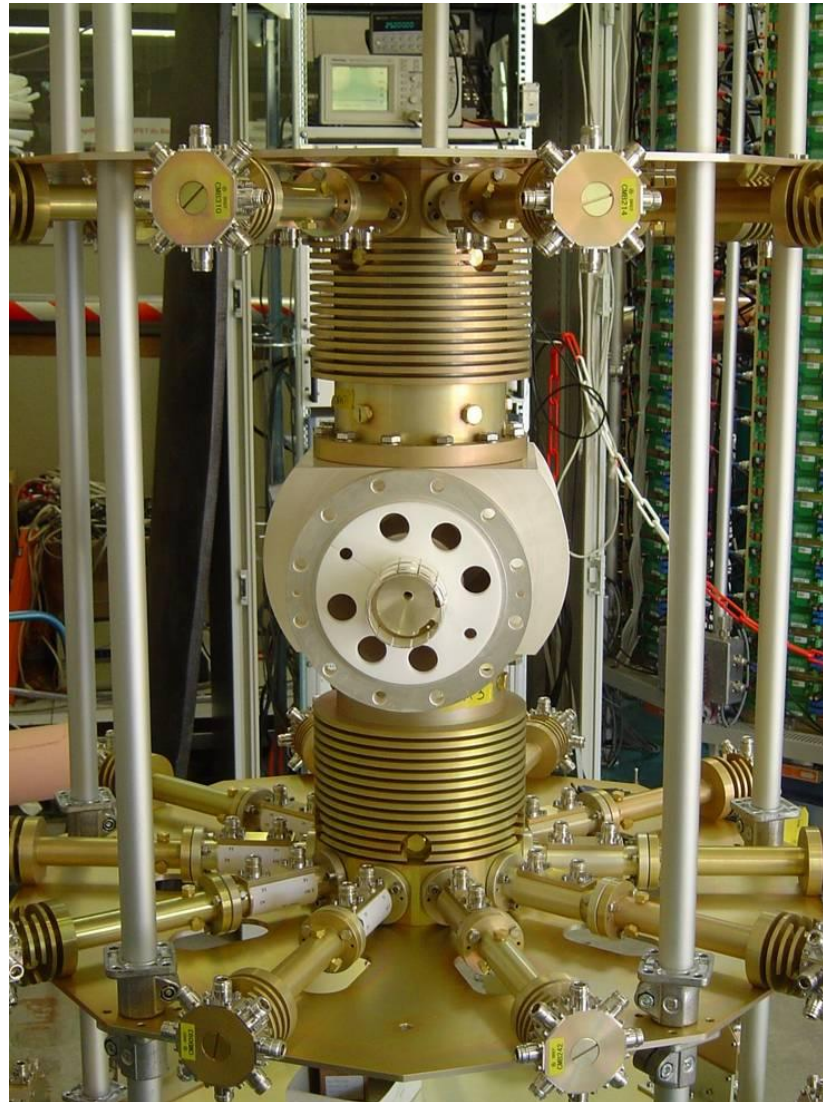
Combination Advantages :

- TEM Quarter Wave-Length Mode
- Lowest Losses and Lowest Cost
- Best Balance and Minimum Dimension
- Without Rejection Power Load

N-Way Power Splitters



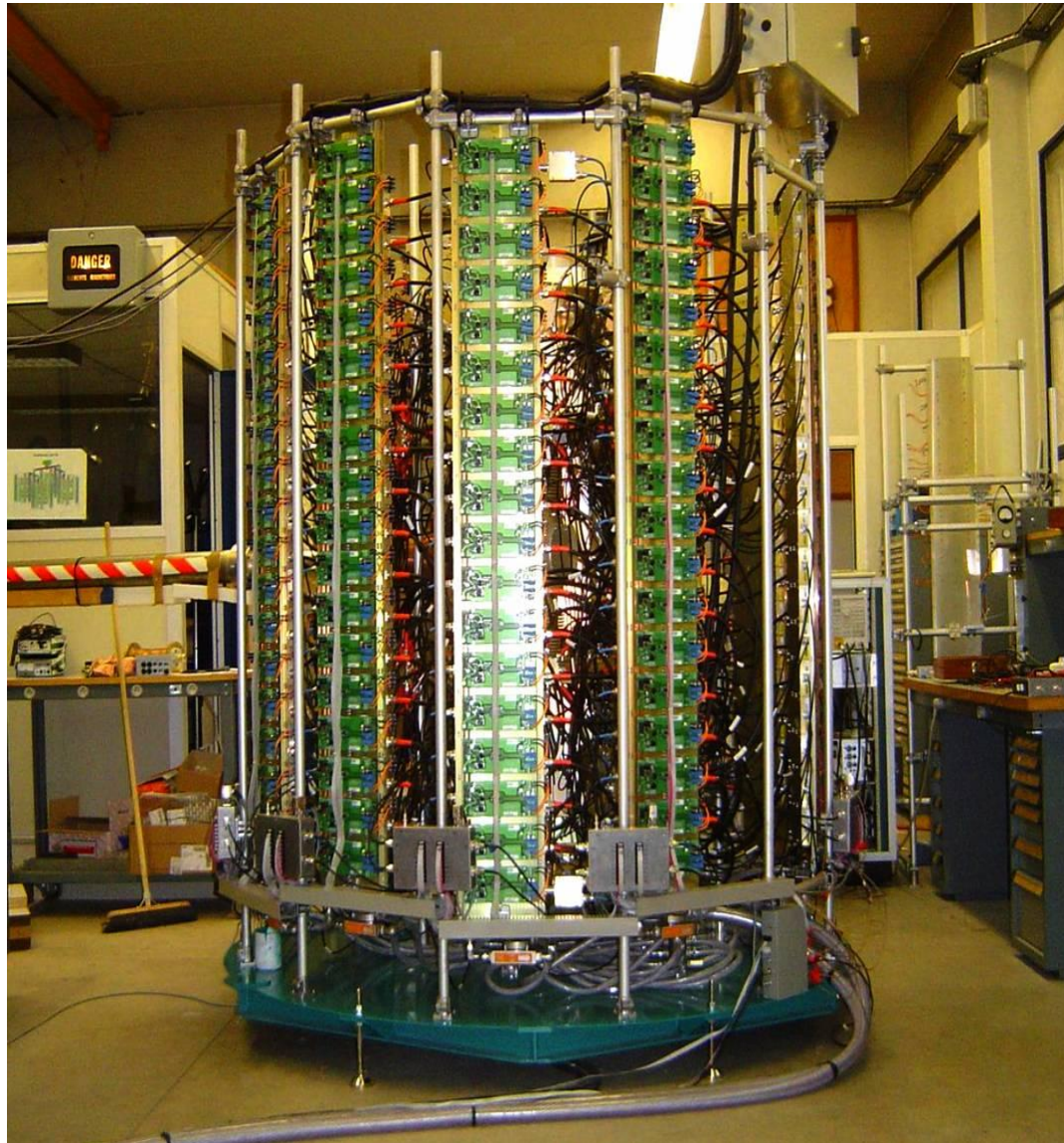
160-Way Power Combiners



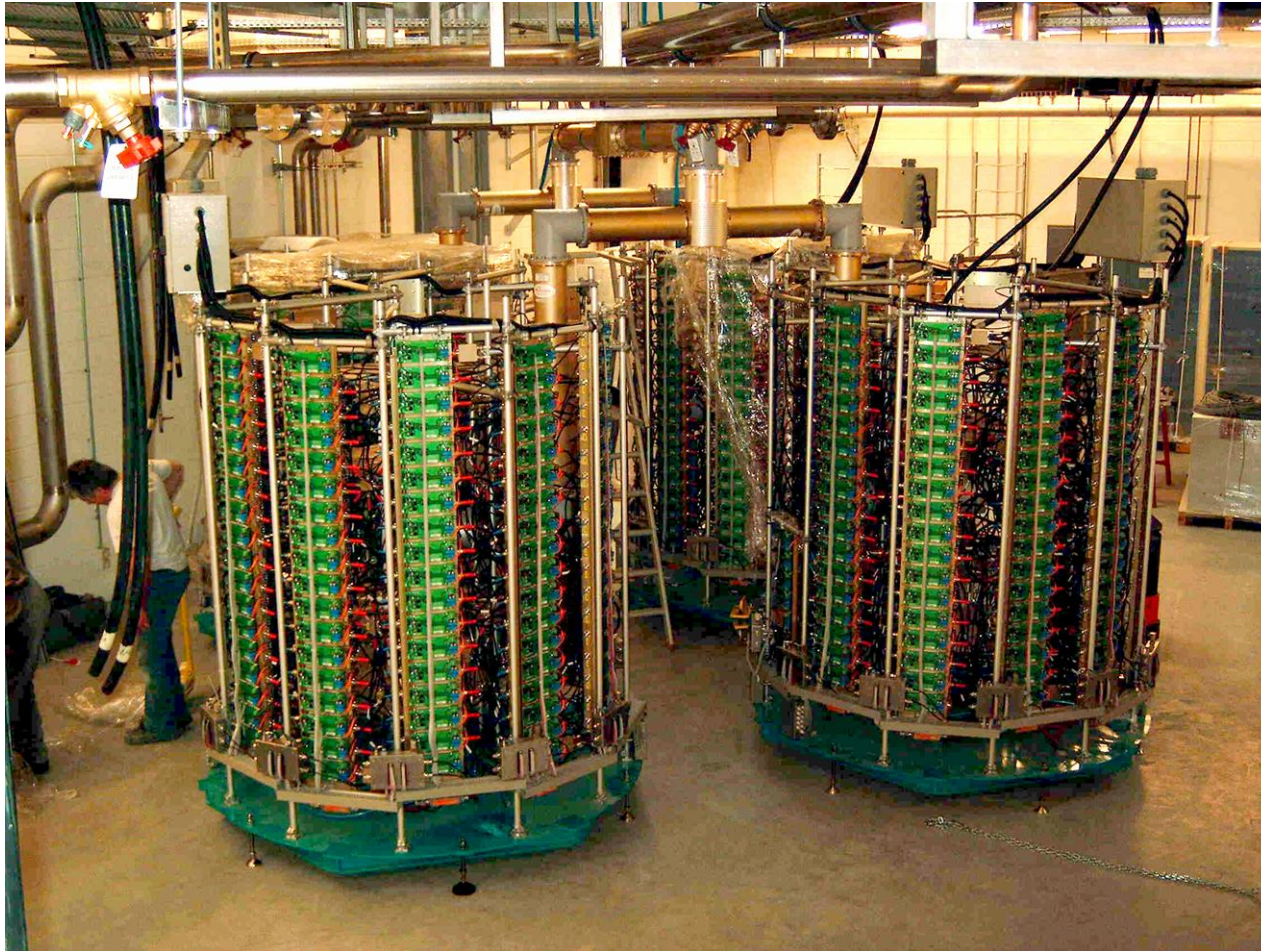
10-Way and 8-Way Power Splitters



352 MHz 50 kW Amplifier



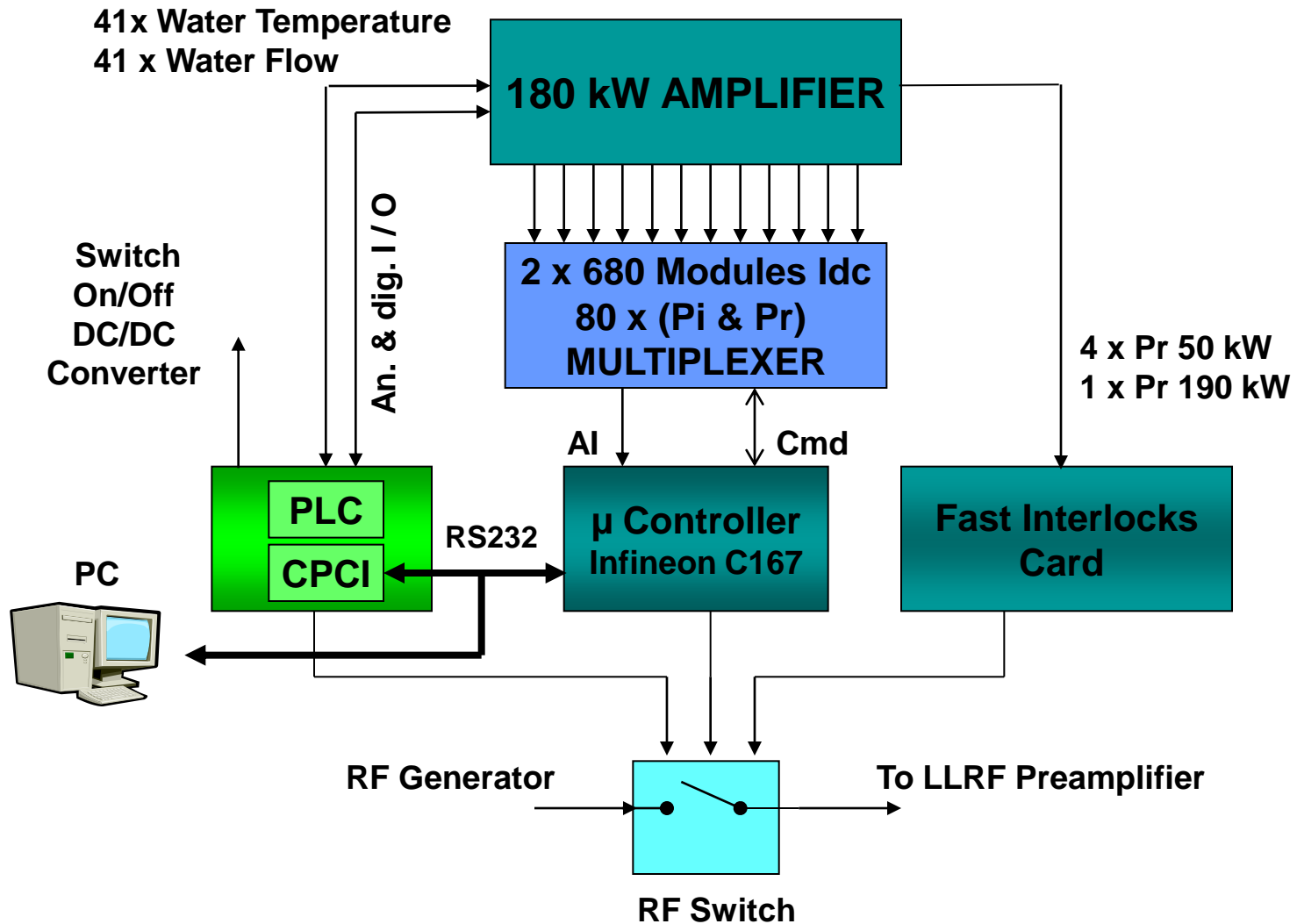
352 MHz 180 kW Amplifier under Installation



4 X 726 LDMOS modules including 43 standby modules

Supervision and Protection

(5808 Idc + 320 Pi + 320 Pr)



2 Sets of 180 kW Amplifier



Power and Current of 50 kW Amplifier



AMPLI ANNEAU

D0		D1		D2		D3		D4		D5		D6		D7		D8		D9		D10		Préamplis
		<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	
		6.8	6.7	0.0	0.0	6.9	6.8	0.0	0.0	7.0	6.9	0.0	0.0	7.0	6.8	0.0	0.1	6.8	6.8	0.1	0.1	0
0.0	0.0	9.2	9.2	9.2	9.3	9.0	9.2	8.9	9.0	9.0	9.3	9.3	9.3	9.2	9.3	8.9	9.0	8.9	9.2	9.2	9.1	1
0.0	0.0	9.4	9.3	9.1	9.4	8.8	9.1	8.9	9.3	9.4	9.4	9.0	9.3	9.1	9.2	9.2	9.3	9.2	9.2	8.9	9.0	2
0.0	0.0	9.0	9.0	9.2	9.4	9.0	9.1	8.9	8.9	9.1	9.2	9.1	9.1	9.0	9.3	9.1	9.1	9.3	9.5	9.0	9.0	3
0.0	0.0	9.1	9.1	9.0	9.3	8.9	9.1	8.9	8.9	9.2	9.2	9.2	9.4	9.1	9.3	9.1	9.3	9.3	9.3	9.1	9.2	4
0.0	0.0	9.0	9.2	9.1	9.2	9.2	9.1	9.0	9.1	9.1	9.2	9.0	9.2	8.9	9.3	9.1	9.3	9.1	9.4	9.1	9.2	5
4.2	4.0	9.1	9.3	9.0	9.2	8.8	9.3	8.9	9.2	9.1	9.2	9.1	9.3	9.1	9.3	9.0	9.1	9.3	9.3	9.3	9.1	6
		8.8	9.2	9.1	9.0	9.0	9.3	9.1	9.3	8.8	9.0	9.0	9.2	9.1	9.1	9.1	9.3	9.1	9.3	9.0	9.2	7
		9.2	9.3	9.1	9.1	9.2	9.3	8.8	8.9	8.9	9.0	9.3	9.1	9.1	9.4	9.0	9.3	9.0	9.0	8.9	9.2	8
		2.3	0.0	2.6	0.0	2.2	0.0	2.6	0.0	2.4	0.0	2.4	0.0	2.6	0.0	2.2	0.0	2.4	0.0	2.3	0.0	Pi/Pr
		2.5	0.0	2.4	0.0	2.6	0.0	2.5	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.4	0.0	2.2	0.0	2.2	0.0	Pi/Pr
		8.9	9.1	9.2	9.2	9.4	9.5	9.0	9.2	9.4	9.4	9.1	9.4	8.9	9.1	9.3	9.5	9.4	9.6	9.2	9.5	8
		9.1	9.1	9.2	9.3	9.0	9.3	9.0	9.1	9.2	9.2	9.2	9.3	9.3	9.5	9.2	9.4	9.0	9.2	9.2	9.3	7
		8.7	9.0	9.3	9.1	8.9	9.2	9.3	9.1	9.5	9.4	9.1	9.4	9.0	9.1	9.4	9.5	9.1	9.1	9.2	9.2	6
		9.1	9.1	9.2	9.3	9.2	9.2	9.2	9.1	8.9	8.9	9.2	9.2	9.2	9.1	9.2	9.3	9.1	9.2	9.5	9.6	5
		9.0	9.3	8.9	9.0	9.0	9.2	9.1	9.3	8.9	9.2	9.0	9.1	9.1	9.3	9.3	9.4	9.1	9.4	8.9	9.2	4
		8.9	8.9	9.2	9.3	9.0	9.1	9.1	9.1	9.1	9.0	9.2	9.3	8.9	9.2	9.3	9.3	9.1	9.2	9.3	9.3	3
		8.9	9.1	8.8	9.3	9.2	9.1	9.2	9.2	9.2	9.3	9.1	9.2	8.9	9.2	9.6	9.5	9.0	9.3	9.0	9.0	2
		9.0	9.1	9.2	9.4	9.4	9.3	9.2	9.3	9.2	9.4	9.0	9.0	9.1	9.1	9.2	9.3	9.1	9.4	9.2	9.3	1
		7.2	7.1	0.0	0.1	6.9	7.1	0.1	0.0	7.3	7.3	0.0	0.0	7.2	7.3	0.0	0.0	7.6	7.7	0.0	0.0	0
		<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input checked="" type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	<input type="checkbox"/> On/Off	Préamplis

TOUR ACTIVE

T1 ON

T2 OFF

T3 OFF

T4 OFF

Durée de cycle (s)

10.00

PORT RS232

COM2 COM1

ACQUISITION

ON

SEUILS ALARME

9.60 I (A)

0.30 Pr(kw)

Pi T = 48.00 kW PiMax = 2.60 kW D2 PrMax = 0.00 kW D3

Pr T = 0.00 kW PiMin = 2.20 kW D3 PrMin = 0.00 kW D1

Pdc = 84.28 kW IMax = 9.60 A D8 IMin = 6.80 A D1

H

A

U

T

B

A

S

COPY
GRAPH
SAVE BMP
SAVE FILE
PRINT
QUIT

Power and Current at 500 mA



Courants 1 et 2

Delta courants

Somme courants

AMPLI 1 T1

AMPLI 2 T2

AMPLI 3 T3

AMPLI 4 T4

D0

M1	1.80	1.70	<input checked="" type="checkbox"/>
M2	6.90	7.20	<input checked="" type="checkbox"/>
M3	7.00	7.00	<input checked="" type="checkbox"/>
M4			<input type="checkbox"/>
M5			<input type="checkbox"/>
M6			<input type="checkbox"/>

AQUISITION

OFF

	D1 <input checked="" type="checkbox"/> Preampli		D2 <input type="checkbox"/> Preampli		D3 <input checked="" type="checkbox"/> Preampli		D4 <input type="checkbox"/> Preampli		D5 <input checked="" type="checkbox"/> Preampli		D6 <input type="checkbox"/> Preampli		D7 <input checked="" type="checkbox"/> Preampli		D8 <input type="checkbox"/> Preampli		D9 <input checked="" type="checkbox"/> Preampli		D10 <input type="checkbox"/> Preampli			
	5.90	5.80			5.70	5.80			6.00	6.00			5.80	5.80			5.90	5.90			MO	
	7.30	7.50	7.60	7.70	7.50	7.40	7.30	7.40	7.40	7.50	7.40	7.40	7.60	7.70	7.40	7.40	7.30	7.40	7.30	7.40	M1	
	7.60	7.70	7.70	7.60	7.70	7.30	7.20	7.30	7.20	7.50	7.30	7.60	7.30	7.50	7.60	7.30	7.30	7.30	7.20	7.40	7.40	M2
	7.50	7.60	7.60	7.70	7.60	7.50	7.20	7.30	7.50	7.50	7.40	7.40	7.50	7.40	7.30	7.40	7.30	7.30	7.30	7.50	7.30	M3
	7.50	7.60	7.60	7.60	7.30	7.40	7.40	7.40	7.50	7.50	7.60	7.60	7.40	7.40	7.30	7.40	7.50	7.30	7.30	7.30	7.30	M4
	6.80	7.00	7.70	7.80	7.30	7.50	7.30	7.50	7.40	7.40	7.80	7.70	7.50	7.60	7.60	7.70	7.50	7.40	7.40	7.40	7.50	M5
	7.80	8.00	7.60	7.60	7.40	7.30	7.40	7.50	7.40	7.50	7.30	7.60	7.40	7.50	7.20	7.20	7.30	7.00	7.40	7.50	7.50	M6
	7.50	7.70	7.30	7.30	7.50	7.40	7.40	7.40	7.50	7.40	7.60	7.50	7.30	7.30	7.30	7.40	7.30	7.40	7.20	7.30	7.30	M7
	7.60	7.50	7.60	7.80	7.40	7.50	7.30	7.70	7.50	7.50	7.50	7.40	7.30	7.40	7.40	7.40	7.40	7.20	7.40	7.40	7.40	M8
	1.56	0.06	1.70	0.12	1.56	0.12	1.56	0.12	1.68	0.10	1.64	0.12	1.62	0.06	1.40	0.08	1.44	0.06	1.48	0.10	Pi Pr	
	1.66	0.14	1.46	0.08	1.66	0.10	1.44	0.16	1.70	0.12	1.66	0.14	1.46	0.14	1.74	0.16	1.52	0.10	1.70	0.10	Pi Pr	
	7.30	7.30	7.80	7.80	7.40	7.60	7.40	7.30	7.40	7.50	7.40	7.50	7.60	7.50	7.30	7.30	7.50	7.40	7.40	7.40	7.40	M8
	7.30	7.20	7.40	7.30	7.40	7.40	7.50	7.60	7.40	7.60	7.40	7.50	7.40	7.40	7.30	7.50	7.60	7.50	7.30	7.30	7.30	M7
	7.40	7.50	7.30	7.30	7.40	7.60	7.40	7.40	7.60	7.50	7.60	7.60	7.60	7.60	7.20	7.20	7.40	7.50	7.50	7.40	7.40	M6
	7.40	7.30	7.20	7.30	7.50	7.50	7.70	7.50	7.60	7.60	7.50	7.60	7.50	7.60	7.40	7.10	7.50	7.50	7.60	7.50	7.50	M5
	7.20	7.50	7.80	7.80	7.50	7.50	7.50	7.40	7.50	7.70	7.50	7.50	7.40	7.40	7.30	7.40	7.40	7.40	8.00	8.20	8.20	M4
	7.50	7.60	7.40	7.30	7.40	7.40	7.50	7.40	7.50	7.50	7.30	7.30	7.40	7.40	7.50	7.80	7.40	7.50	7.30	7.30	7.30	M3
	7.50	7.60	7.30	7.40	7.40	7.40	7.40	7.50	7.50	7.50	7.60	7.50	7.60	7.80	7.40	7.50	7.30	7.50	7.30	7.30	7.30	M2
	7.30	7.50	7.30	7.30	7.40	7.50	7.40	7.60	7.50	7.50	7.60	7.60	7.40	7.40	7.30	7.30	7.60	7.60	7.60	7.40	7.40	M1
			5.90	5.80			5.90	5.90			6.20	6.20			6.10	6.00			6.20	6.30	6.30	MO

Preampli

Preampli

Preampli

Preampli

Preampli

Preampli

Preampli

Preampli

Preampli

Preampli

Pi T1 = 32.48 kW Pi T2 = 31.68 kW Pi T3 = 31.64 kW Pi T4 = 33.18 kW

Pr T1 = 2.20 kW Pr T2 = 1.08 kW Pr T3 = 2.18 kW Pr T4 = 1.62 kW

Pi Amp2 = 129.0 kW Pr Amp2 = 7.1 kW P Alim2 = 286.0 kW

CONFIG

MESSAGES

STATS

GRAPHES

ARCHIVAGE

COPIER

SAUVE IMG

SAUVE DATA

IMPRIMER

QUITTER

- Nominal Power: 180 kW
- Efficiency: ~ 50% including losses of circulators and DC /DC converters (54% without DC/DC converters)
- Gain: 53 dB
- Linearity: $\Delta G = 2$ dB; $\Delta\Phi = 10^\circ$
- Phase Noise (rms) $< 0.04^\circ (< 8$ kHz);
 $< 0.06^\circ (< 1$ GHz)
- Harmonics: - 50 dBc
- Parasitic Modulation: - 60 dBc (> 200 kHz random phase)

RF Power Modules

	Amplifier 1 ** & 2 (CM1)			A 3 & 4 (CM2)
	2006 - 2007	2008	2009	2008 - 2009
Operation hrs	~ 6 000	~ 6 000	~ 6 000	~ 8 000
Transistor *	4%	3%	0.9%	1.3%
Soldering *	<1%	2.2	3.5%	<1%

* A few modules failed due to filter, capacitors problem etc.

** The failure rate of Amplifier 1 is much higher than others

Other components

DC/DC	2 / ~ 3000
2.5 kW Power Combiner	4 / 320
Multiplexer	1 / 180

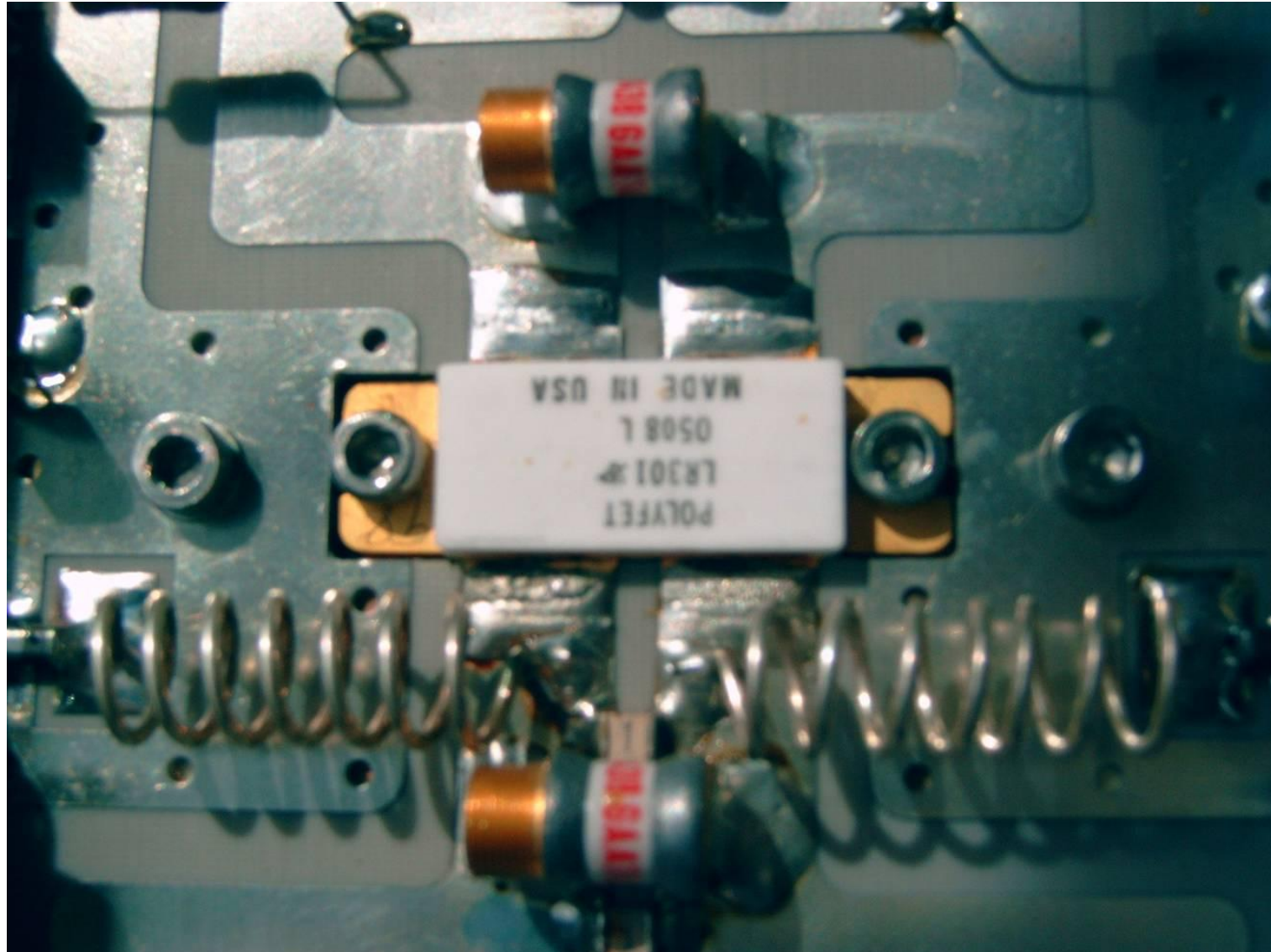
Module Failure Rate



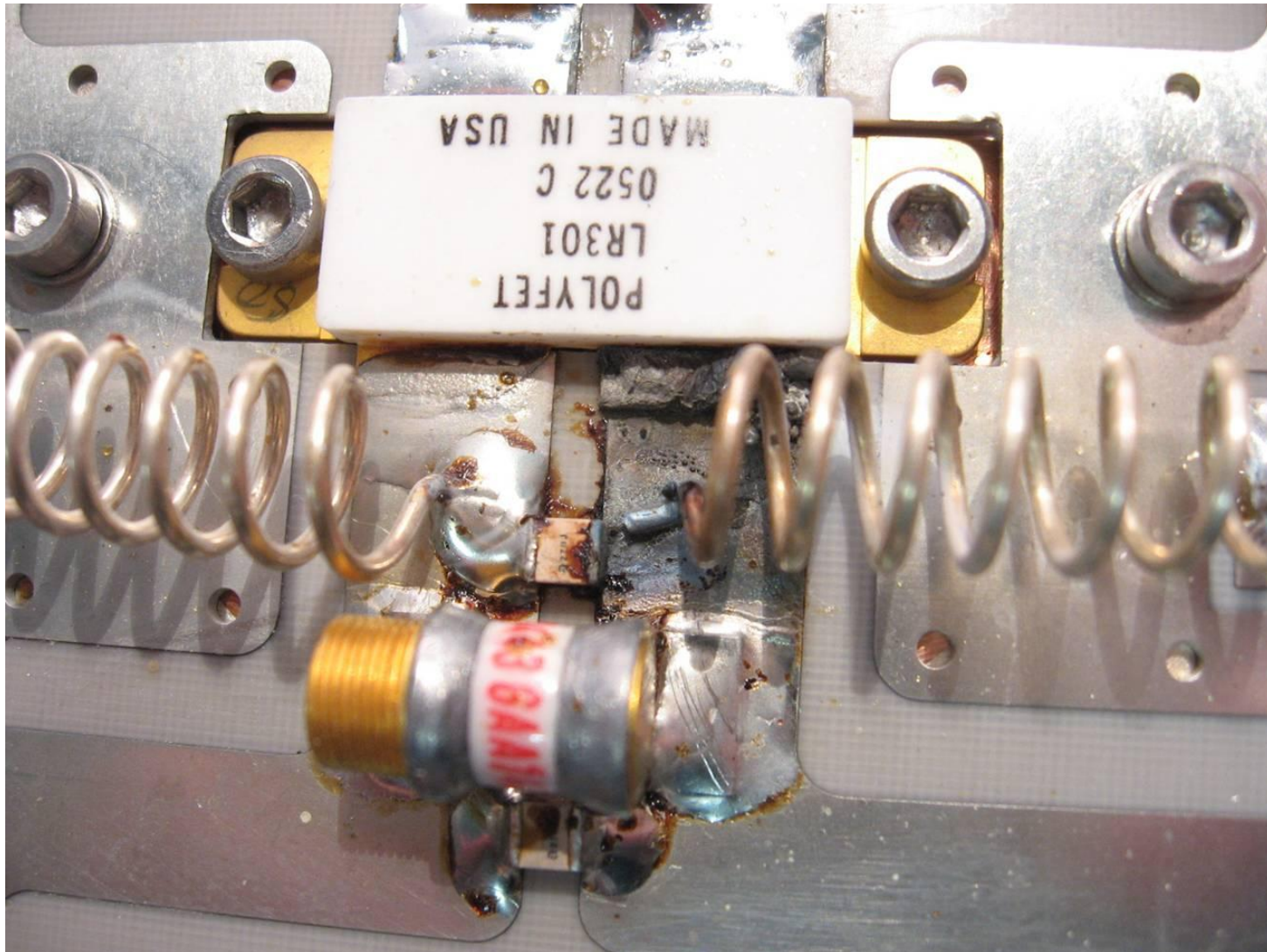
- Transistor failure rate ~ 1.5 % per year
→ Replacement of ~ 50 transistors per year
(maintenance cost: ~ 5000 Euros)
- Soldering failure rate ~ 1.5 % per year due to thermal fatigue and soldering fault.
→ Re-solder and Take Super High Q Capacitors nearby Drains to repair them.

Thermal Fatigue

(After working for 20000 hrs)



Thermal Fatigue Failure



After 4 years of running, the operational experience proved to be **fully satisfactory**. Almost **no down-time** during operation.

But we have continued developing a new generation solid state RF amplifier

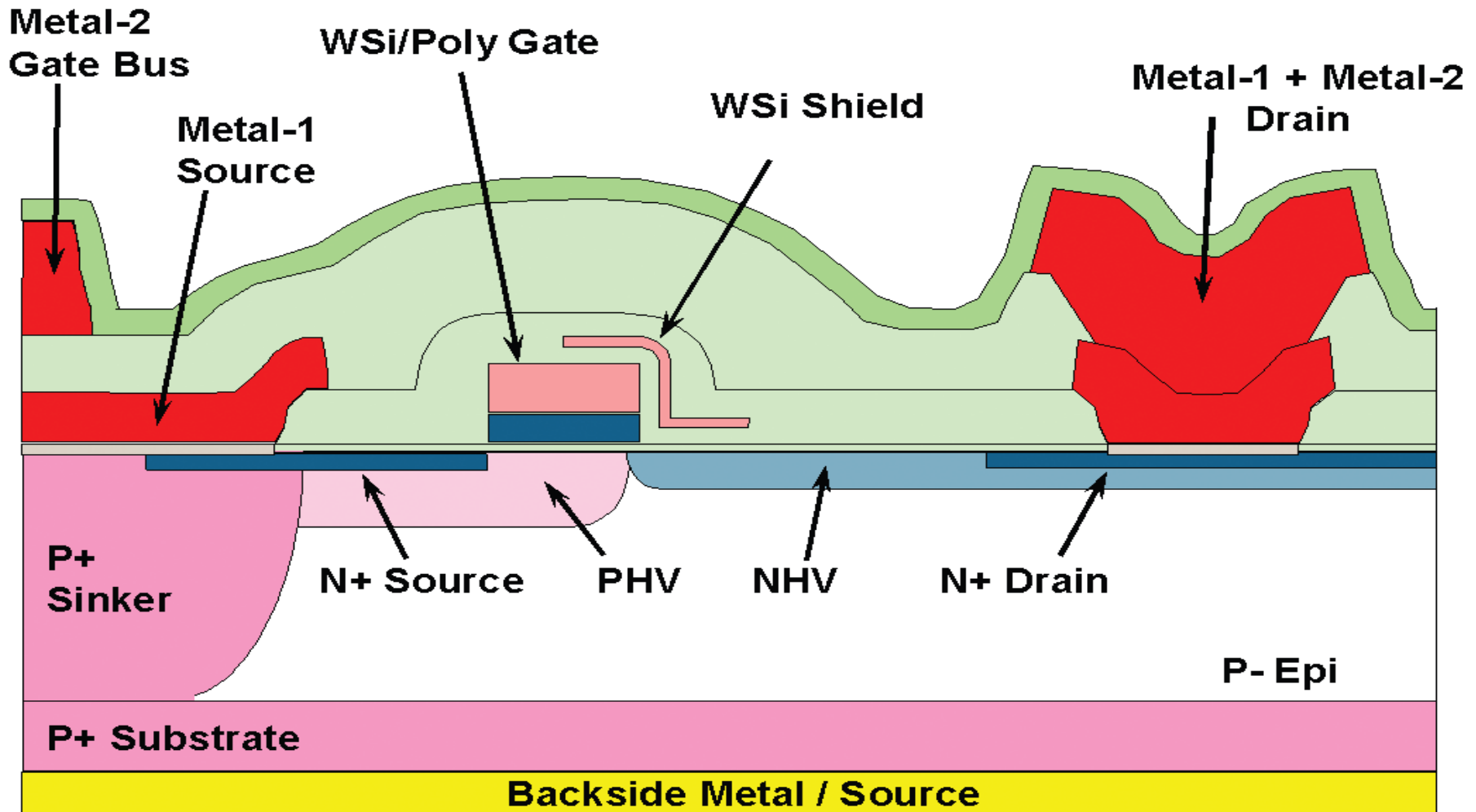
Fortunately the 6th Generation LDMOS has come out

6th Generation RF LDMOS (Laterally Diffused MOS)



- High Gain with High Stability due to Shield between Gate and Drain
- 50 V DC Voltage: High Power with High Efficiency
- Excellent Linearity
- Excellent Ruggedness
- Integrated ESD Protection
- Broadband Operation up to 500 MHz

6th Generation RF LDMOS (Laterally Diffused MOS)



6th Generation RF LDMOS (Laterally Diffused MOS)



The Gain and Stability of a MOSFET depends on capacitance C_{rss} between Gate and Drain

LDMOS has lower C_{rss} than VDMOS

The 6th Generation LDMOS has only about 20 - 30% of C_{rss} than normal LDMOS

New Generation Modules developed in SOLEIL



Frequency	Output Power	Gain (1 dB)	Efficiency
MHz	W	dB	%
476*	350	19.8	69
500	700	17.9	67
352**	700	20.5	73
88	1000	26.1***	87***

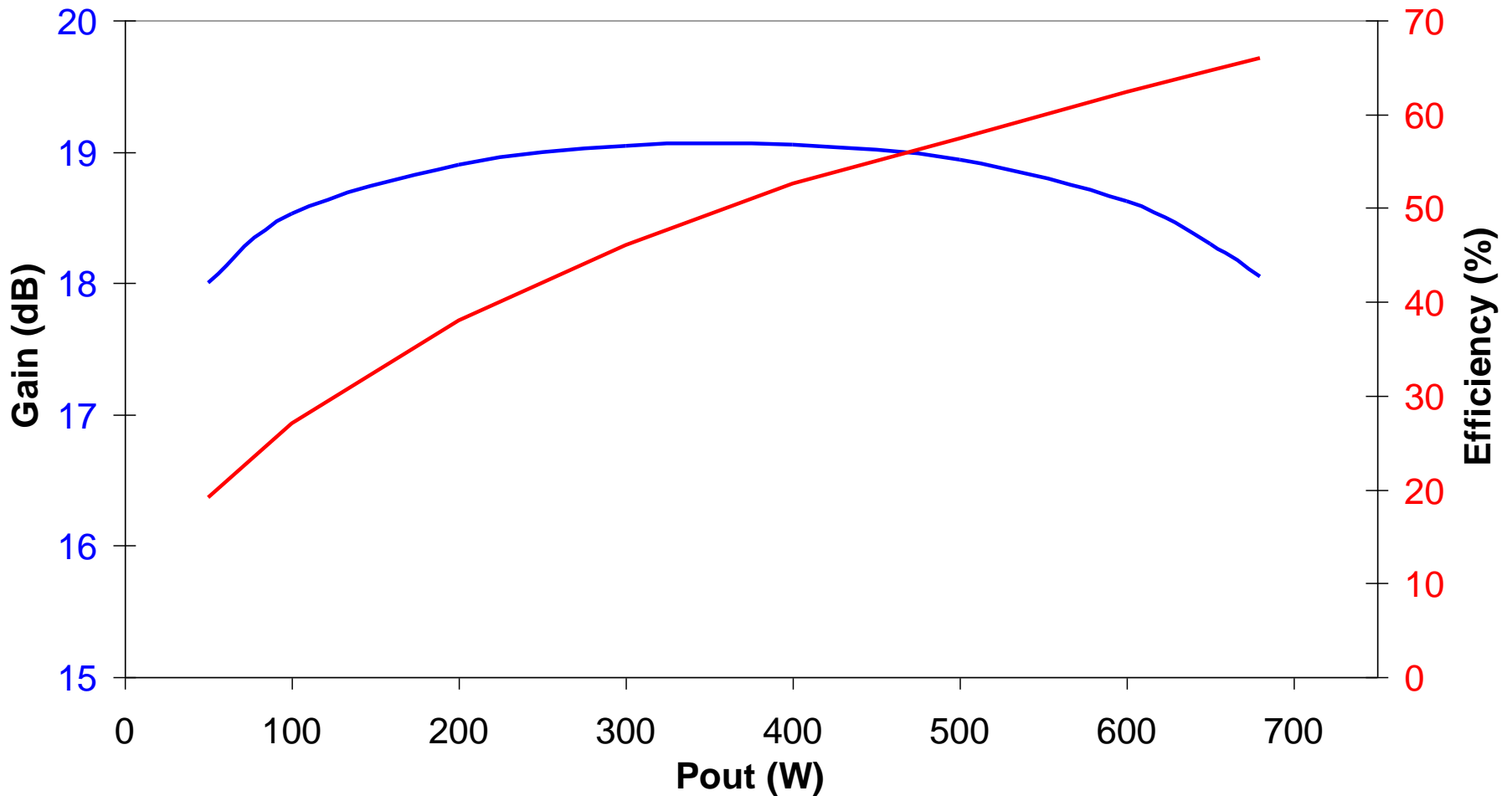
* For LNLS 50 kW Amplifiers

** For ESRF 150 kW Amplifiers

*** Without Circulator and at 2 dB Gain compression

- Higher frequency: Lower Power, Efficiency and Gain
- 1.3 GHz module is being developed

Gain & Efficiency vs Power for 500 MHz Module



Advantages of New Module with 6th Generation LDMOS



- Tolerance: Gain +/- 0.1 dB, Phase +/- 2°
- Anti-Thermal Fatigue (Special PCB Laminate, Super High Q Capacitors etc. Temperature ~ 80°C)
- High Reliability, LDMOS MTBF > 2000 yrs
- Excellent Ruggedness
- High Efficiency
- Good Linearity with Low Phase Noise
- Compact (Double density of RF Power)

- June 2008, collaboration agreement LNLS - SOLEIL to realize two sets of SSA in replacement of the two 476 MHz - 40 kW klystron amplifiers in the SR
- Beg. 2010, 2 sets of SSA fully assembled
- April 2010, successful tests of the first SSA on dummy load:
 - 50 kW CW @ 0.4 dB compression
 - Overall efficiency ~ 60%
 - Gain 40 dB (2 stages)



April 23rd, 2010 at LNLS : SOLEIL – LNLS team

Collaborations:

- LNLS: 2 amplifiers of 45 kW at 476 MHz based on 350 W modules
- SESAME: 4 amplifiers of 150 kW at 500 MHz based on 700 W modules

Transfert of technology to ELTA-AREVA:

- ESRF contract for 7 amplifiers of 150 kW at 352MHz
- High Power Amplifiers at 500 MHz under industrialization

Thanks for your Attention