High Power Solid State Amplifier for SOLEIL Synchrotron

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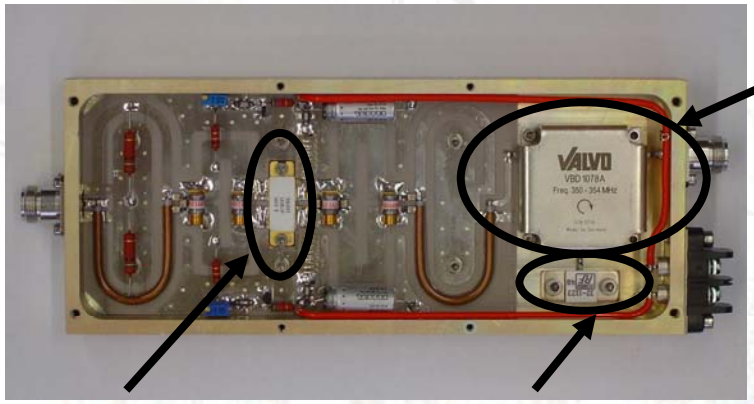
CWRF08 CERN Geneva
25-28 March 2008

Principle of Amplifier

352 MHz 330 W Module



Wideband Circulator

Transistor

50 Ohms Termination

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

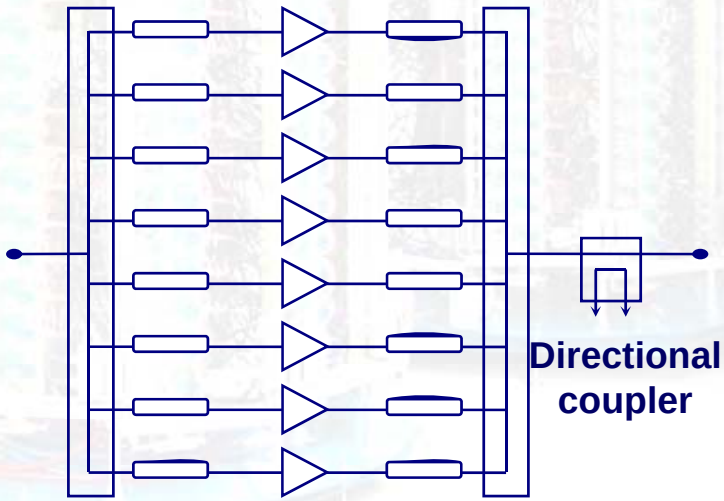
DC/DC Converter

Input 280V DC

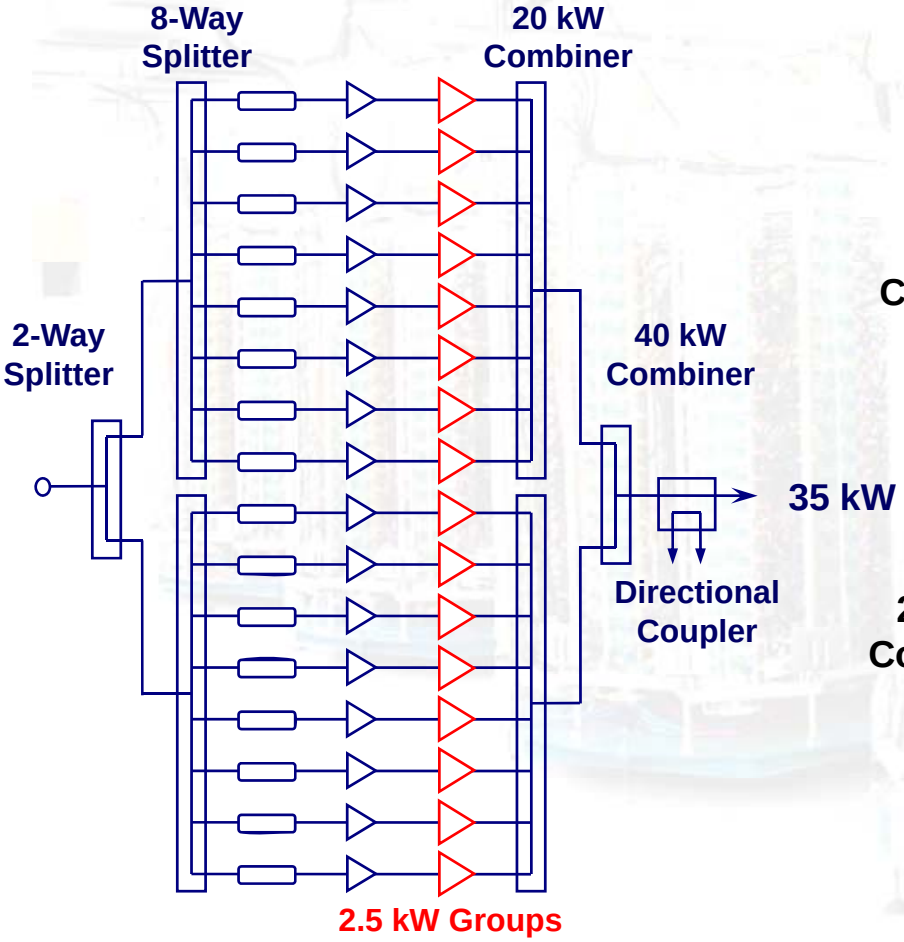
Control & Measurement

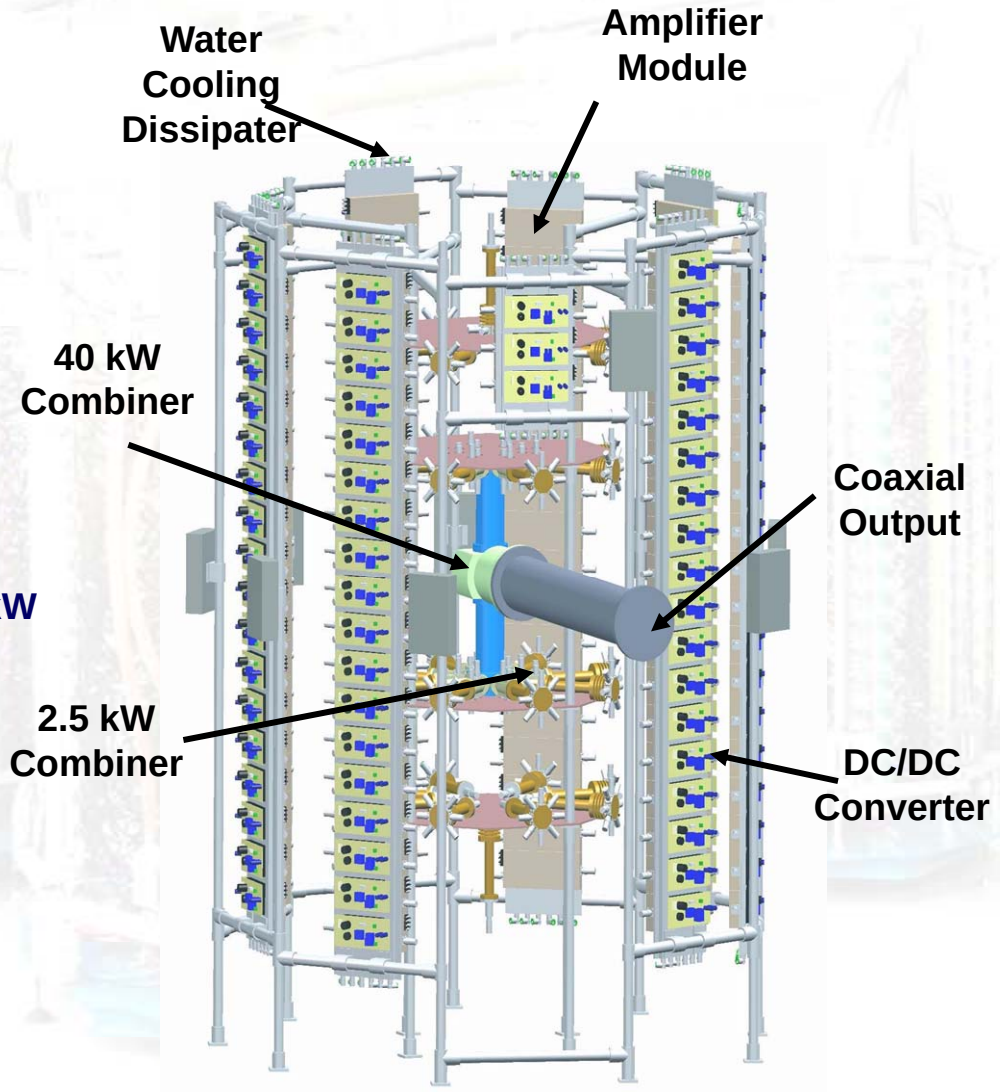
Output 28V DC

2.5 kW Group



Booster RF Amplifier Design





Booster RF Amplifier Tests

Specifications

RF power 35kW

CW

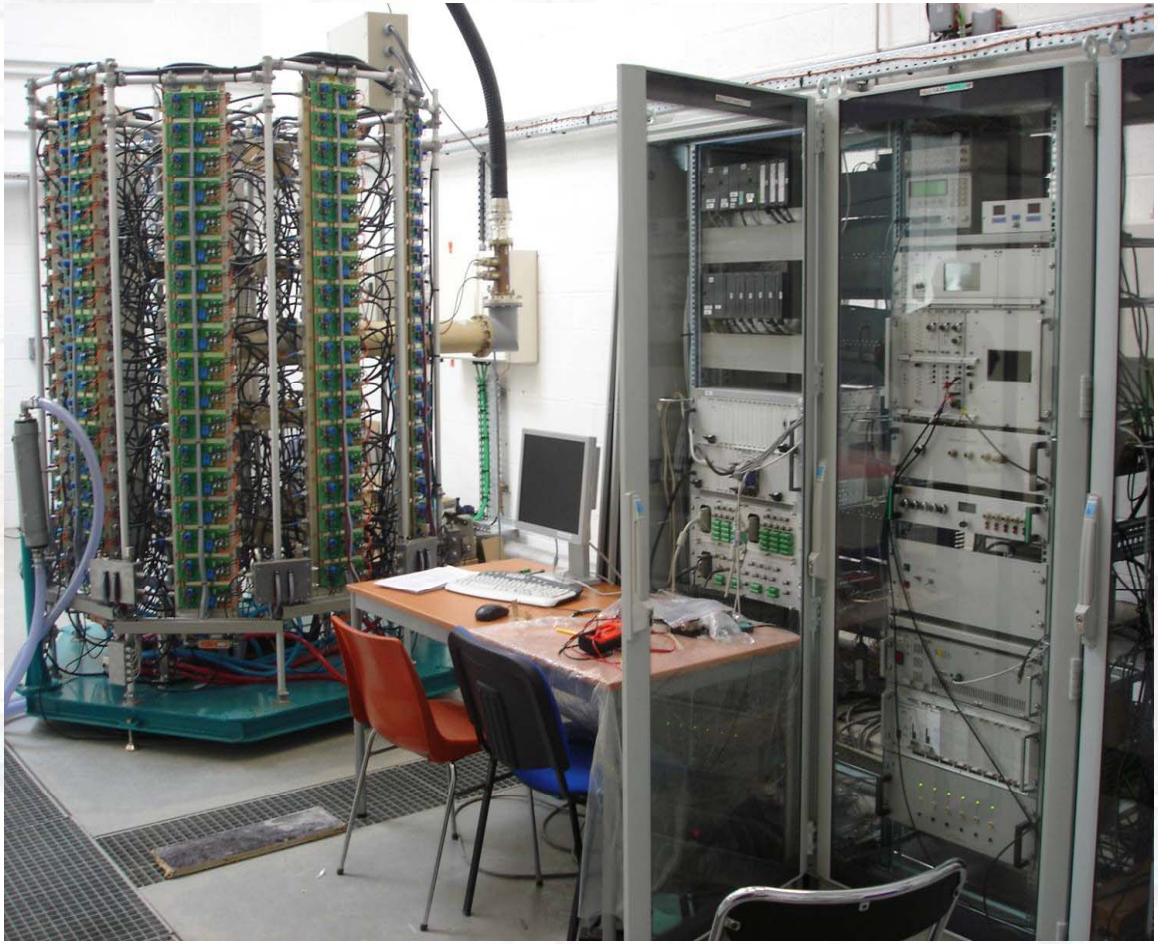
Frequency 352 MHz

Gain 33 dB

Total efficiency 50%

- **Spring 2004 Assembly and test all parts at LURE**
- **Summer 2004 Test power up to 37 kW CW on Dummy Load**
- **Autumn 2004 Power Accelerating Cavity at 30 kW for > 1500 Hours**
- **Dec. 2004 Transport Amplifier Tower to SOLEIL**

Booster RF Amplifier in RF Hall



- July 2005 Complete Installation and test with LLRF
- Since 2005, during more than 9500 h operation, just one interruption due to human mistake

From Booster Amplifier to Storage Ring Amplifier

On CWRF04, we have reported our 200 kW amplifier design special for accelerator application. We haven't modified it.

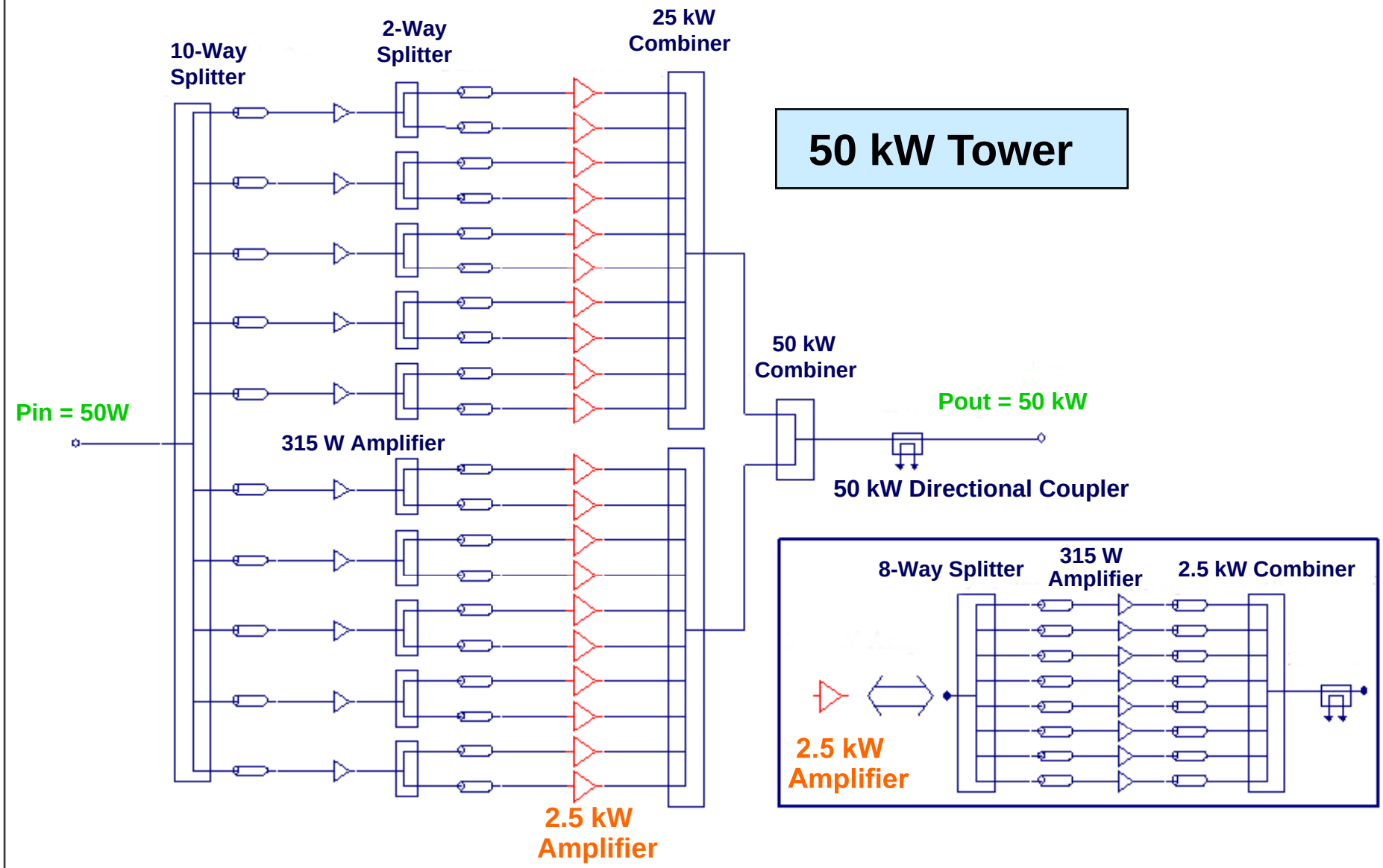
<u>The advantage of our solid state amplifier</u>:

- **High Reliability**
- **Unconditional Stability**
- **No High Voltage in RF Hall, No Cabinets**
- **No High Power Isolator (Circulator with Termination)**
- **Modular Design**
- **Easy and Fast Maintenance**
- **Low Cost (Simple Power combiners, Simple Spare Parts, Maintenance)**
- **Digital supervision and protection system**
- **Pure RF Spectrum (Harmonics, Phase Noise etc.)**

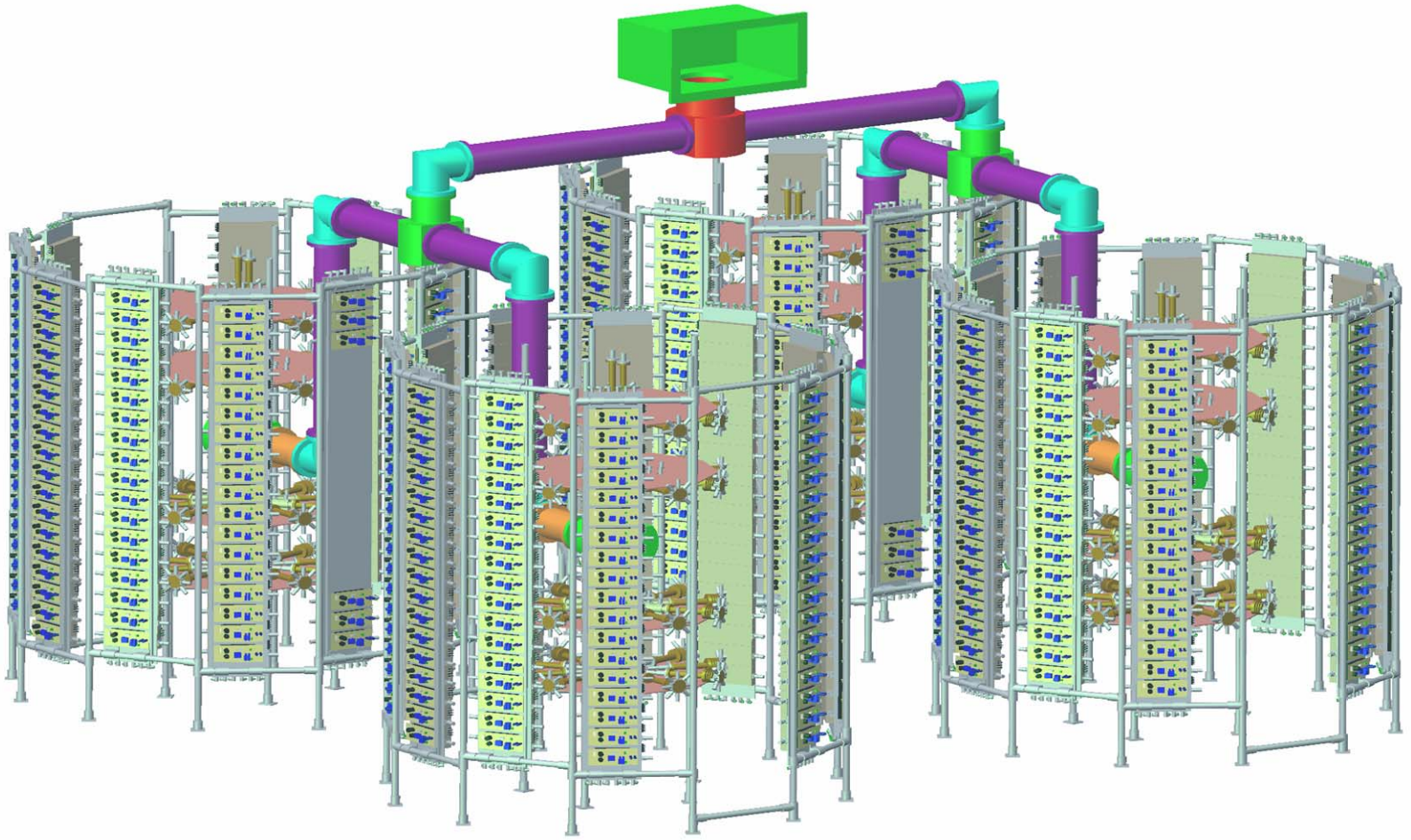
In fact, at that time (CWRF04), it was still a dream for us. So a back up solution with LEP klystron was ready, in case the solid state amplifier would end in failure.

In Summer 2004, the success of Booster 35 kW Amplifier encouraged us to complete Solid State 200 kW Amplifier. It was a real challenge for us, because SOLEIL Plan Time Schedule was fixed.

200 kW (4 x 50 kW)



200 kW Amplifier Design



Symmetrical Configuration: Short RF Connection, Same RF Phase
No Cabinet (No High Voltage): Easy Maintenance
Modules and DC/DC Converters fixed on Cooling Bar

Dimension:
4.7 x 4.7 x 2.3 m (without waveguide)
4.7 x 4.7 x 3.6 m (with waveguide)

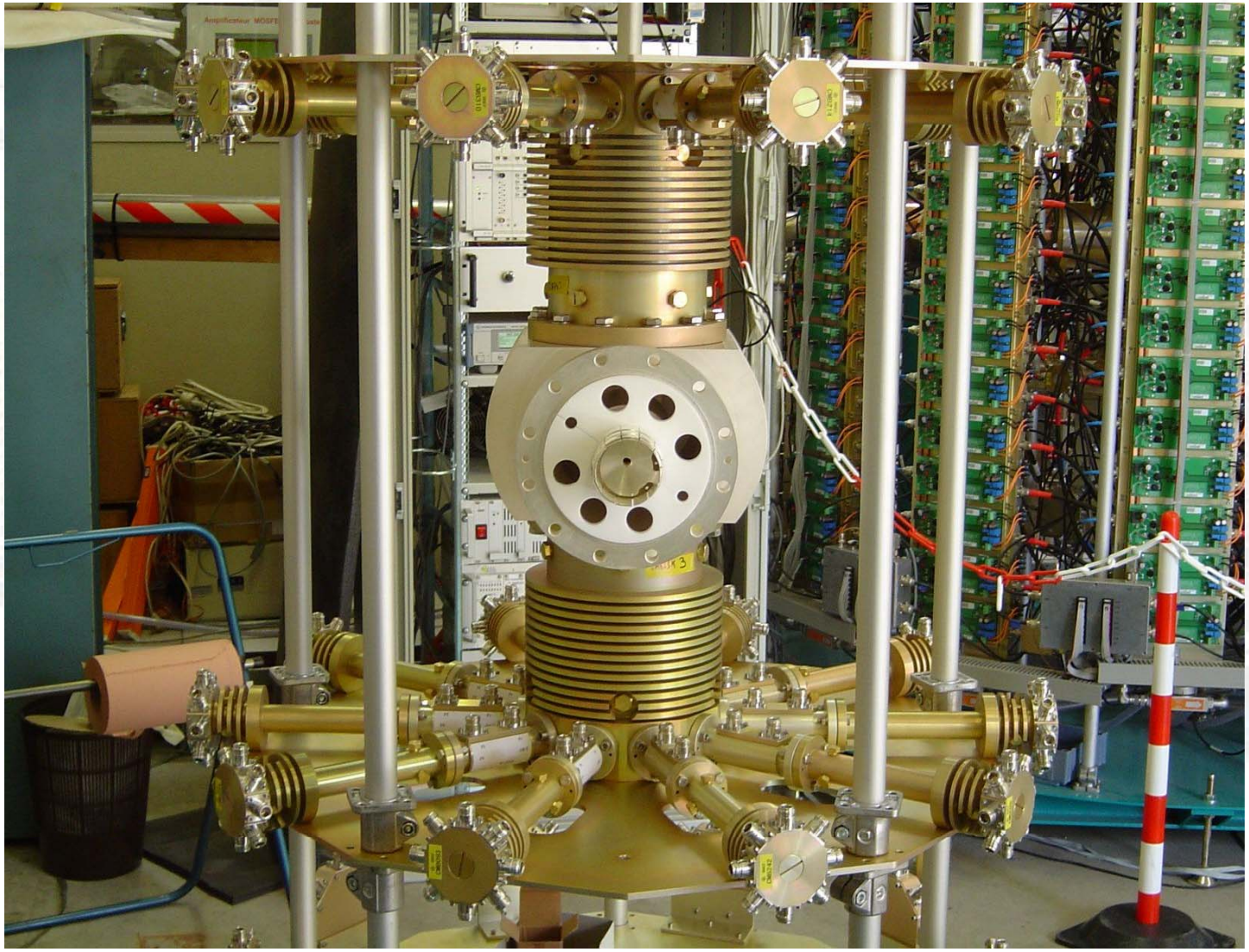
Power Combiners

2.5 kW | 25 kW | 100 kW | 200 kW

Manufacture 320 sets of 2.5 kW Combiners
Manufacture 34 sets of 25 kW Combiners
Manufacture 32 sets of 100 kW Combiners
Manufacture 6 sets of 200 kW Combiners

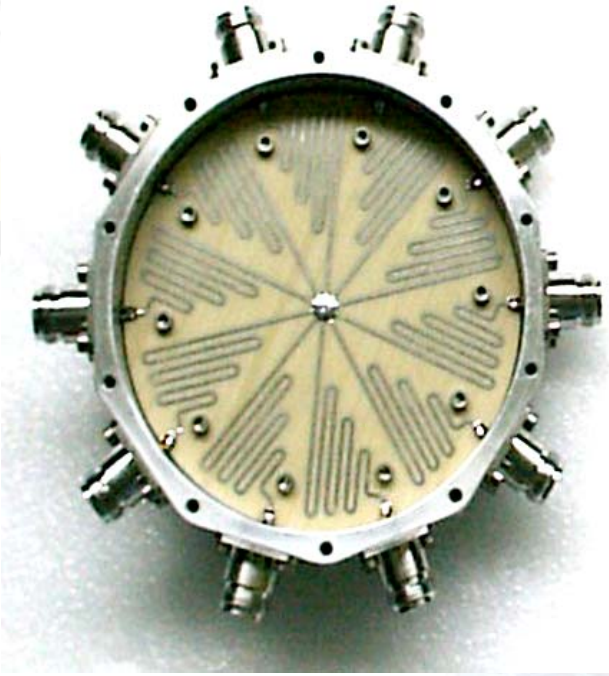
Characteristics of Combiners
Excellent Reflection (S11 < -30 dB)
Very Low Losses (Silvering on Al)
Very Low Amplitude and Phase difference
IEC Standard Coaxial Connector

160-Way Combiner



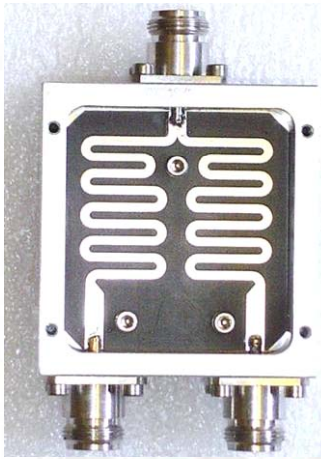
Power Splitters

10-Way



8-Way

2-Way



Manufacture 350 sets of 8-Way Splitters
Manufacture 90 set of 2-Way Splitters
Manufacture 20 sets of 10-Way Splitters

<u>Splitter Characteristics</u>:
Low reflection (S11 < -20 dB)
Low Amplitude & Phase Difference
N connector
Low Cost

VDMOS and LDMOS

Semelab VDMOS D1029UK (selected) has been used in Booster Amplifier. But it has problem with gain degradation at high level output, and Semelab Co. had no capability to supply us 300 pieces per month.

Since Oct. 2003, we have been collaborating with Polyfet to develop the newest 300 W LDMOS LR301. Its version 1 and 2 has lower current. At the beginning of 2004, Version 3 got good characteristics: High Gain and High Efficiency.

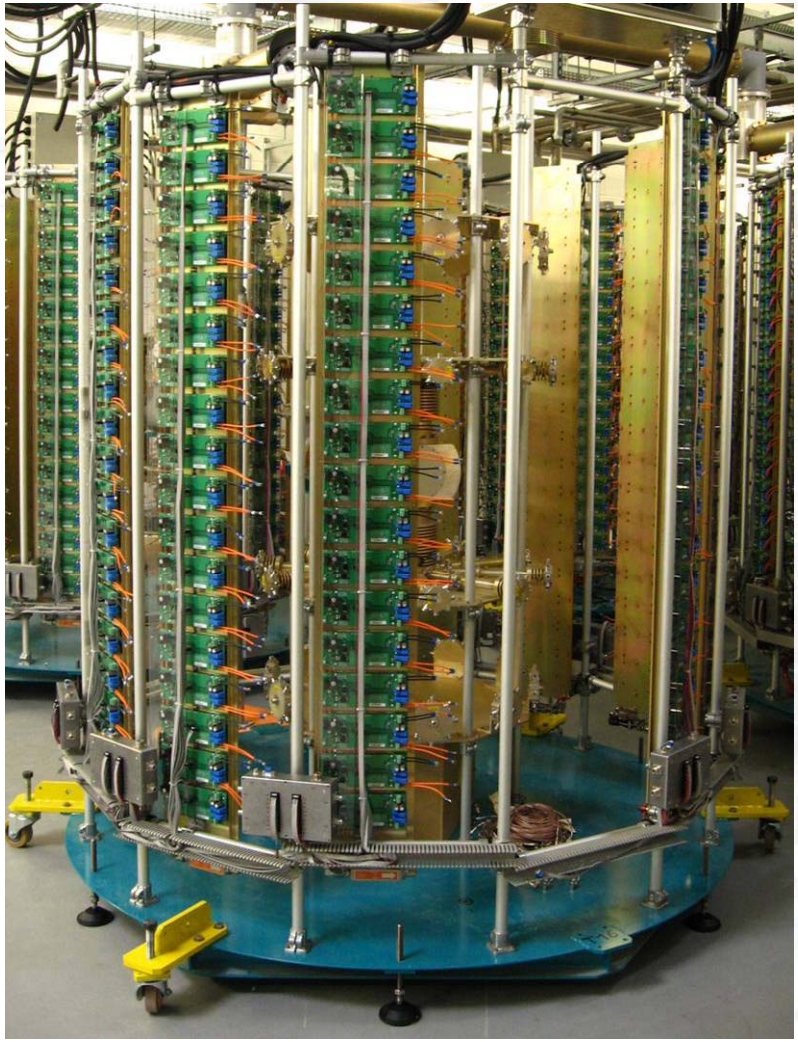
LDMOS LR301 was a very new type, nobody has used it. Hence Spring 2004, when we called for tenders for 3000 Amplifier Modules, we still considered 2 types of transistor, i.e. VDMOS D1029UK and LDMOS LR301.

Summer 2004, we decided to use LR301. In fact, we had no possibility of choice.

Spring 2005, First 50 kW Tower was completed with LR301 Version 3. We have tested it up to 48 kW CW. Failure Rate of 15/180 over 1000 h, not acceptable.

May 2005, Polyfet decided to develop Version 4, its gain 1 dB lower than Version 3, but its voltage is higher, more ruggedness expected. Test result: Failure rate about 3 times lower than with Version 3. Go on with Version 4.

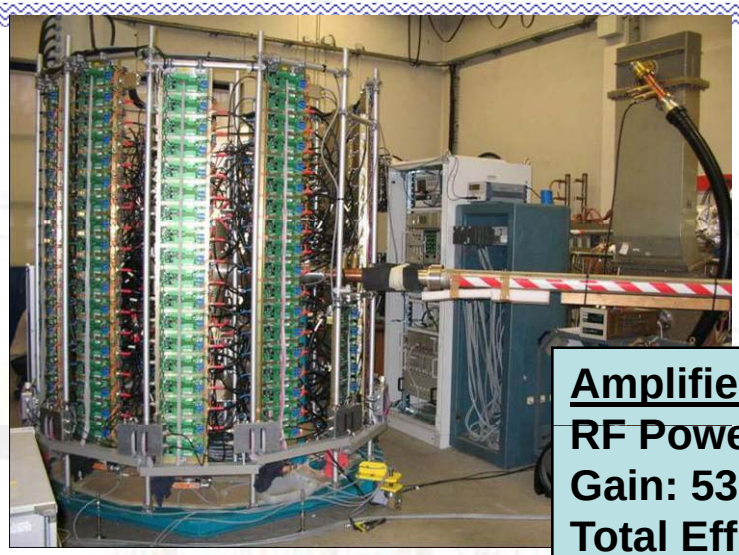
Installing Amplifier



50kW Tower in assembling course

Spring 2005 Linking up 50kW Towers

Put into Operation of 2 sets of 200 kW Amplifier



Till Feb. 2006 :

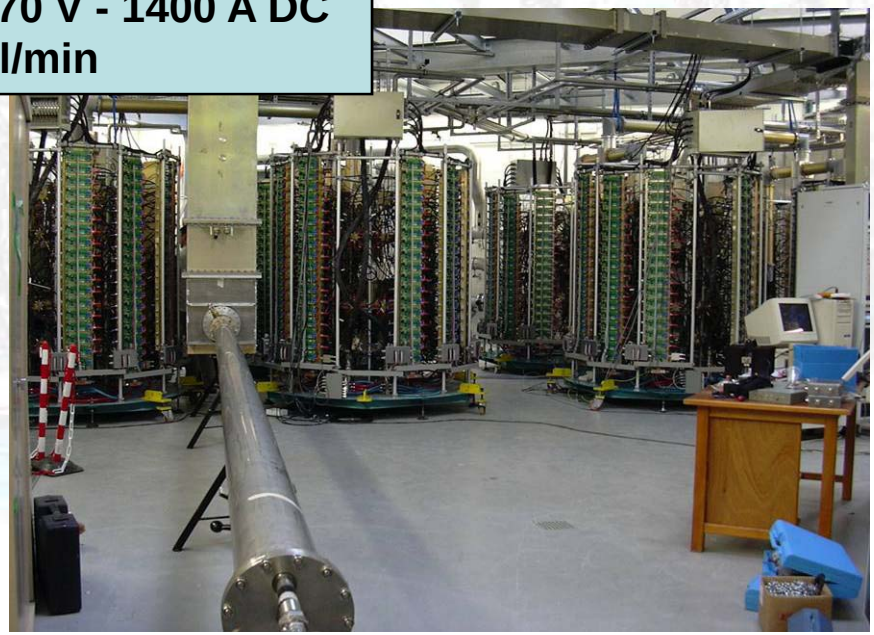
- 8 towers were assembled and tested up to 45 kW CW one by one
- Time of assembling and testing one tower was about 5 weeks

Amplifier specifications :

RF Power: 180 kW
Gain: 53 dB
Total Efficiency ~ 50 %
Power Supply: 270 V - 1400 A DC
Water Flow: 500 l/min

Till the end of March 2006:

- Installed 2 sets of amplifier (2 x 4 Towers) and connected to electric mains & water cooling system



Beginning of April 2006 (Before CWRF06)

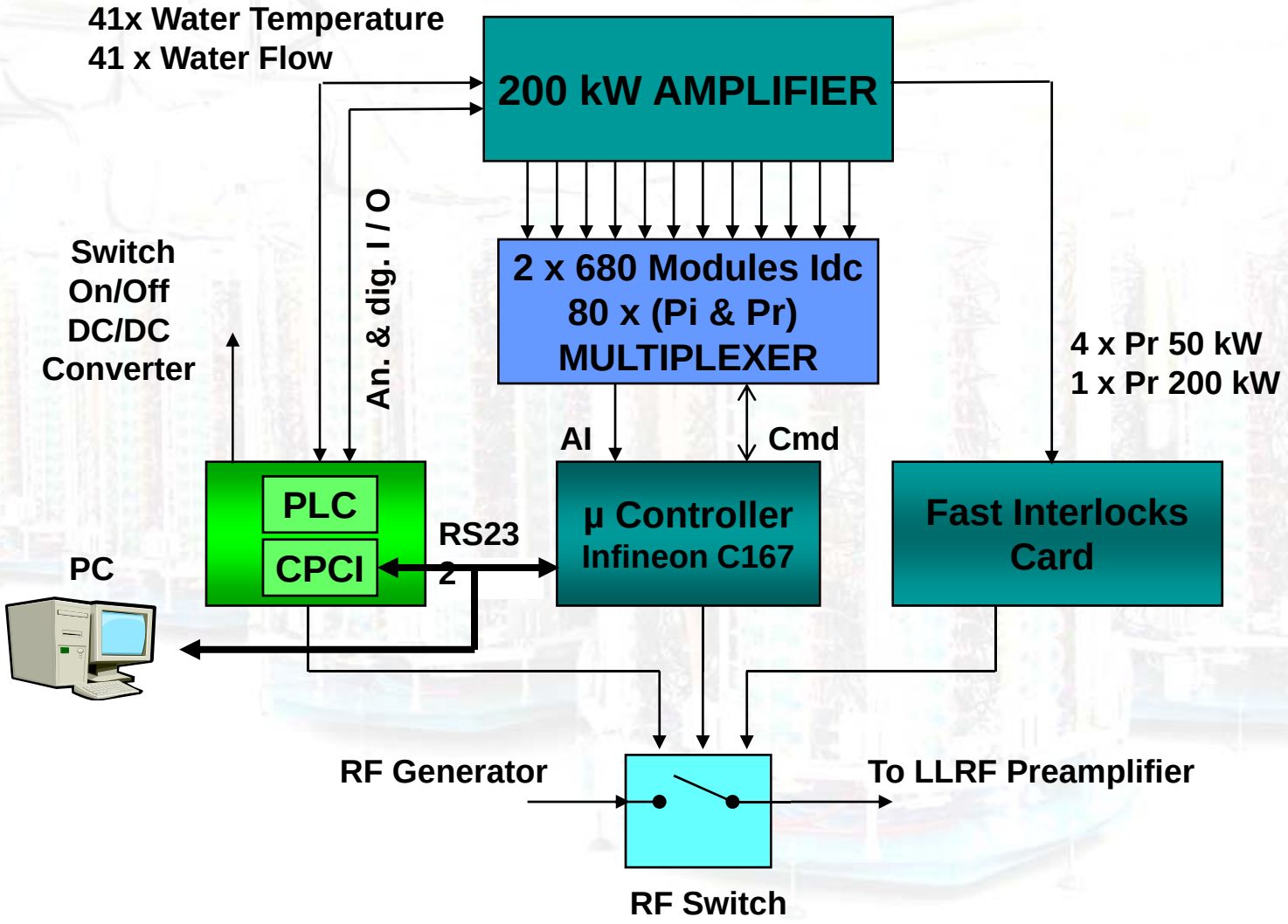
- 2 sets of amplifier were tested up to 180 kW (World Record) on dummy load
- «Acceptance Test» of Bruker 500 kVA 270 V DC Power Supply for 100 hours

Tests with SC Cavity

Beginning of Mai 2006 : **2 sets of Amplifier were connected on SC cavities, RF Power of each Amplifier was 80kW at Full Reflect Condition.**
Till this step, about total 30 transistors failed out of 1400 modules

End of May 2006 to March 2008 : **Working with beam current (7500 hours)**
56 modules failed, just one interruption of beam current. It means that in Early Period Operation, Failure rate of 5.2 % on Amplifier 1 and 1.7 % on Amplifier 2. 2 overdrive accidents on Amplifier 1 due to lack of safety interlock when testing RF feedback → transistors partially damaged.

Supervision and Protection
5808 Idc + 320 Pi + 320 Pr



Supervision of Amplifier
2.75 GeV 250 mA

Selection of 50 kW Tower

DC Current of 2 Stages of Preamplifiers

3rd Stage

Final Stage

Pin & Pr of 2.5 kW Group

Final Stage

3rd Stage

	D1		D2		D3		D4		D5		D6		D7		D8		D9		D10		
	Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		
M0	5.80	5.70			5.50	5.40			5.80	5.80			5.40	5.40			5.70	5.50			M0
M1	7.60	7.60	7.40	7.50	7.50	7.40	7.20	7.30	7.20	7.40	7.40	7.50	7.20	7.30	7.20	7.30	7.10	7.20	7.00	7.00	M1
M2	7.40	7.40	7.30	7.50	7.50	7.60	7.10	7.20	7.20	7.30	7.40	7.40	7.10	7.10	7.10	7.10	7.20	7.10	7.10	7.10	M2
M3	7.50	7.50	7.50	7.40	7.30	7.40	7.30	7.40	7.20	7.30	7.30	7.50	6.90	6.90	7.20	7.20	7.10	7.10	7.40	7.10	M3
M4	7.30	7.40	7.40	7.40	7.40	7.50	7.40	7.40	7.10	7.20	7.40	7.40	7.30	7.30	7.20	7.10	7.40	7.60	7.40	7.40	M4
M5	7.50	7.50	7.40	7.40	7.30	7.40	7.30	7.30	7.20	7.10	7.30	7.30	7.20	7.20	7.20	7.20	7.20	7.20	7.10	7.20	M5
M6	7.40	7.40	7.40	7.50	7.20	7.40	7.20	7.20	7.10	7.10	7.50	7.50	6.90	6.90	7.20	7.10	7.20	7.40	7.20	7.30	M6
M7	7.50	7.40	7.40	7.50	7.30	7.30	7.40	7.40	7.30	7.40	7.30	7.60	7.20	7.00	7.10	7.20	7.10	7.30	7.00	7.10	M7
M8	7.30	7.40	7.30	7.40	7.30	7.30	7.20	7.30	7.20	7.20	7.40	7.60	7.20	7.10	7.30	7.30	7.30	7.30	7.30	7.30	M8
Pi Pr	1.48	0.04	1.52	0.04	1.52	0.04	1.74	0.02	1.46	0.02	1.64	0.04	1.56	0.04	1.46	0.02	1.58	0.02	1.48	0.04	Pi Pr
Pi Pr	1.64	0.04	1.74	0.04	1.48	0.06	1.46	0.04	1.40	0.00	1.54	0.00	1.60	0.04	1.56	0.08	1.66	0.04	1.56	0.02	Pi Pr
M8	7.40	7.20	7.00	7.30	7.40	7.20	7.20	7.20	7.10	7.20	6.70	6.90	7.30	7.40	7.50	7.50	7.00	7.20	7.30	7.50	M8
M7	7.40	7.30	7.20	7.20	7.20	7.30	7.30	7.40	7.30	7.30	6.90	7.20	7.20	7.20	7.30	7.40	7.20	7.20	7.20	7.30	M7
M6	7.50	7.60	7.50	7.60	7.30	7.40	7.20	7.30	7.00	7.10	7.30	7.10	7.60	7.50	7.60	7.60	7.30	7.30	7.20	7.20	M6
M5	7.10	7.30	7.30	7.20	7.20	7.30	7.10	7.20	7.10	7.10	7.30	7.40	7.30	7.40	7.30	7.40	7.30	7.20	7.30	7.30	M5
M4	7.40	7.30	7.30	7.40	7.10	7.20	7.20	7.20	7.00	7.10	6.90	7.10	7.20	7.30	7.50	7.50	7.50	7.40	7.20	7.00	M4
M3	7.40	7.60	7.30	7.40	7.30	7.20	7.30	7.60	7.10	7.10	7.40	7.30	7.20	7.20	7.30	7.30	6.90	7.10	7.30	7.40	M3
M2	7.20	7.30	7.40	7.50	7.30	7.20	7.20	7.30	7.60	7.60	6.90	6.90	7.50	7.60	7.40	7.40	7.10	7.00	7.10	7.30	M2
M1	7.40	7.50	7.30	7.30	7.20	7.30	7.20	7.20	7.20	6.70	7.00	7.00	7.20	7.20	7.50	7.60	7.20	7.50	7.10	7.20	M1
M0			5.60	5.60			5.70	5.50			5.60	5.50			5.70	5.70			5.60	5.60	M0
	Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		Preampli		

OFF A1 ON A2 OFF A3 OFF A4

OFF T1 OFF T2 OFF T3 ON T4

Imax 9.00 Imin 0.20

Pr 0.30 Delta 0.50

Courants 1 et 2

Delta courants

Somme courants

Stats Tour

Stats Ampli

	D0		
M1			
M2	1.70	1.50	☑
M3	6.20	6.30	☑
M4	6.50	6.50	☑
M5			
M6			

AQUISITION ON

Pi T1 = 29.96 kW Pi T2 = 29.22 kW Pi T3 = 28.70 kW Pi T4 = 31.08 kW

Pr T1 = 0.92 kW Pr T2 = 0.98 kW Pr T3 = 0.32 kW Pr T4 = 0.68 kW

Pi Amp2 = 119.0 kW Pr Amp2 = 2.9 kW P Alim2 = 268.3 kW

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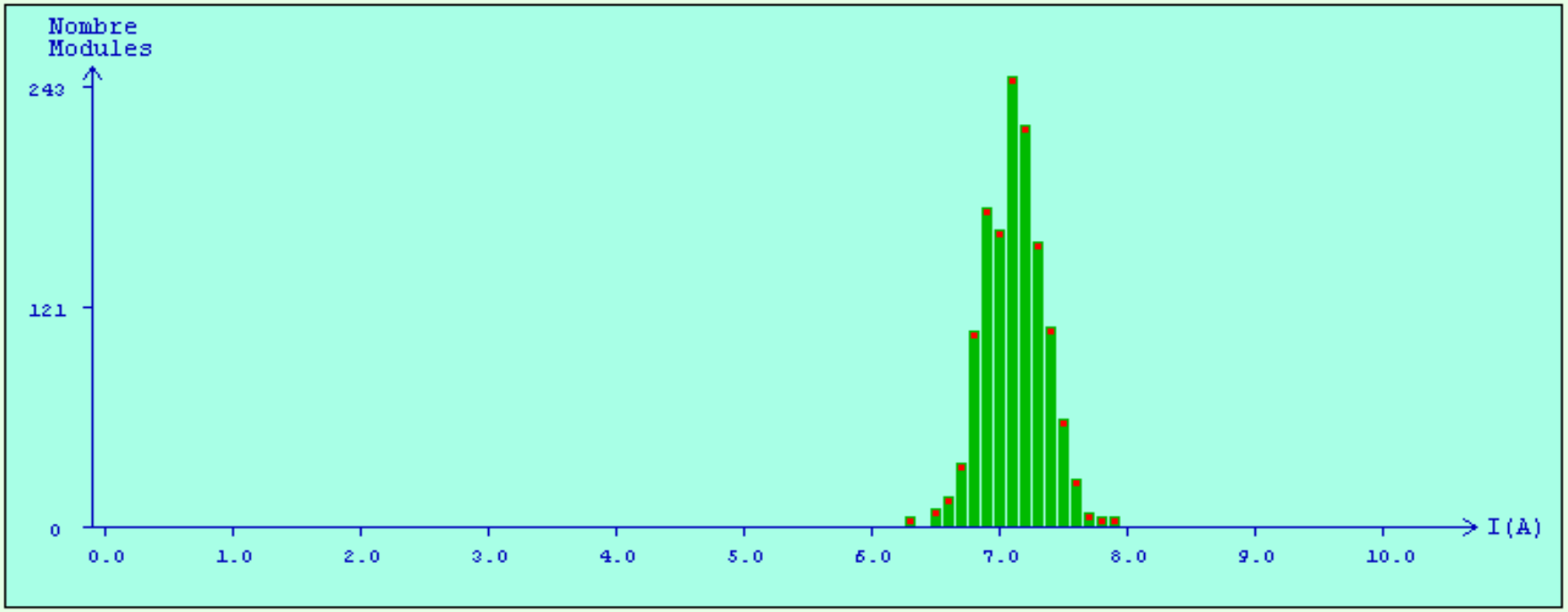
Distribution of DC Currents of Modules in Amplifier 2



- [ ] Courants Modules (I moyen +/- 1A)
- [x] Courants Modules (0 à 10A)
- [ ] Delta Courants des Transistors (0 à 2A)
- [ ] Delta Courants des Transistors (0 à 10A)

- [ ] Modules Hors Service

- [ ] Ampli 1
- [x] Ampli 2
- [ ] Ampli 3
- [ ] Ampli 4

- [x] T1
- [x] T2
- [x] T3
- [x] T4

- [x] Modules sortie
- [ ] Preamplis

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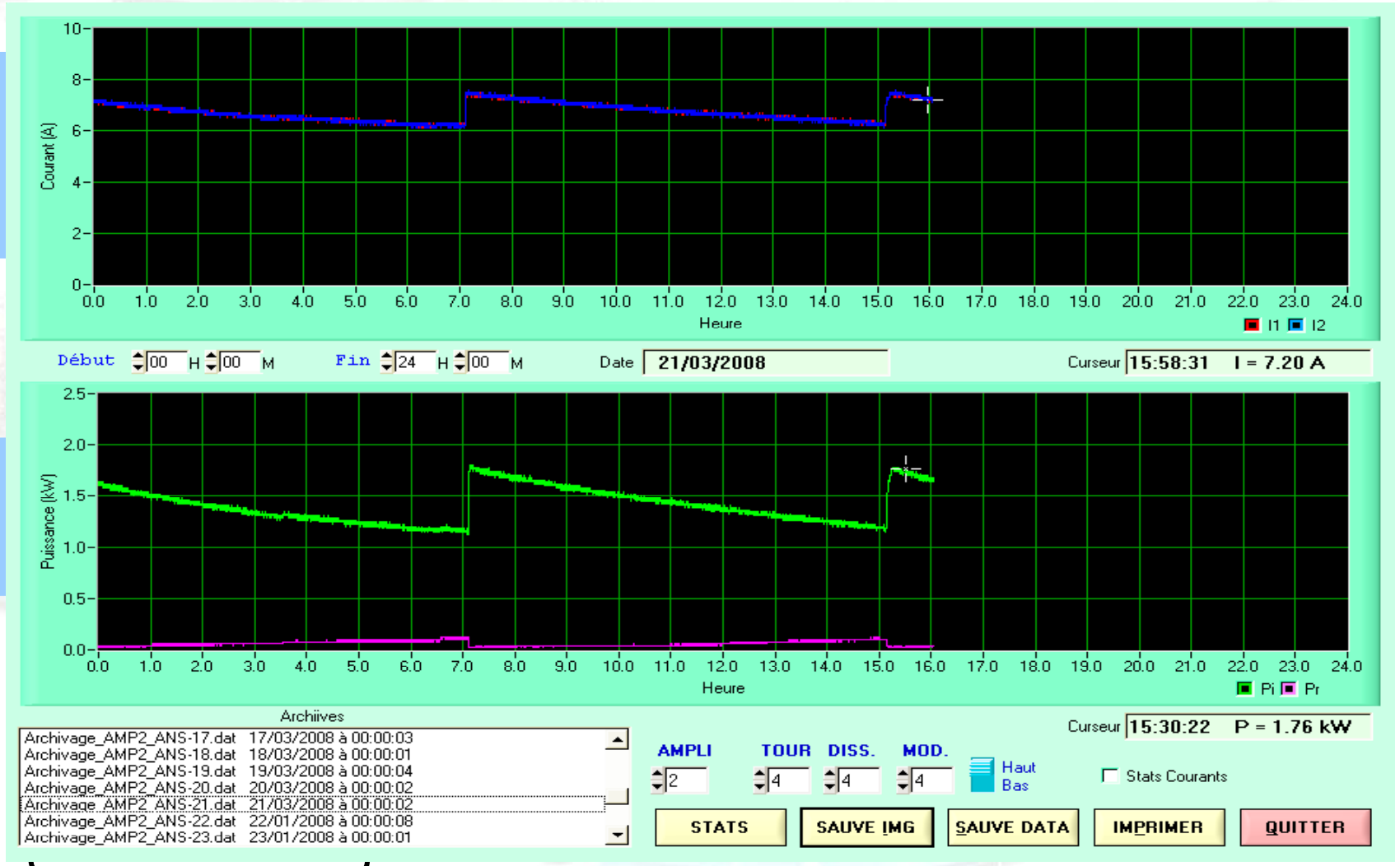
Display of Current and 2.5 kW Group Pin & Pr

Selective Module Currents

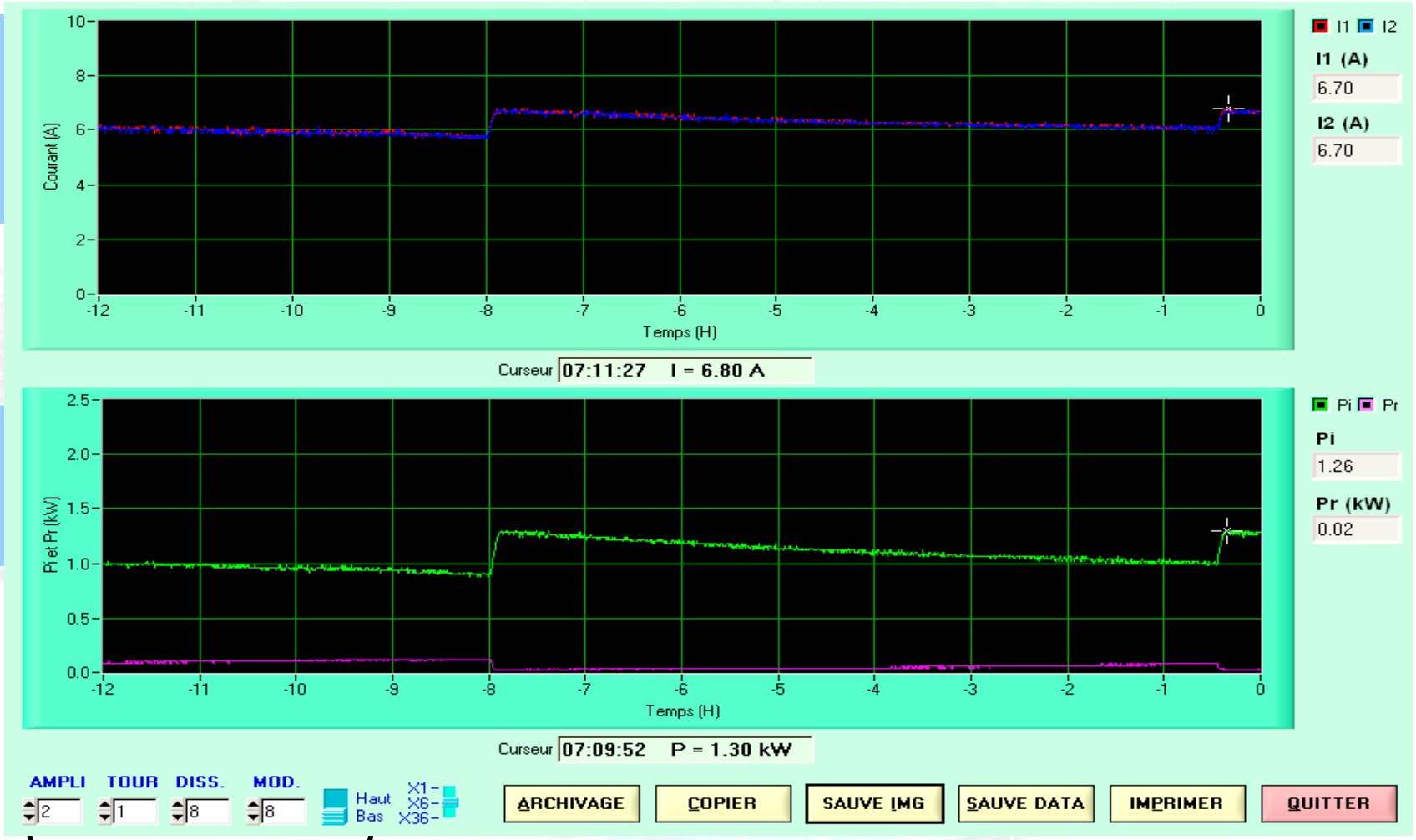
Pin & Pr of 2.5 kW Group



Selective Date

Record of Current and 2.5 kW Group Pin & Pr

Selective Module Currents



Pin & Pr of 2.5 kW Group

Geographic Position of modules

Current Developments

- Develop 352 MHz, 500 MHz and 1.3 GHz CW High Power Solid State Amplifier
- Test the newest Silicon LDMOS (Pay attention to GaN just for 1.3 GHz application)
- Continue to Improve our Design to Increase Ruggedness
- Study Adjustment of Gain and Phase of Module to reduce module characteristic Dispersion in order to reach higher RF Power and Efficiency
- Improve Fast Protection Interlock Circuit and Limit Over Driving
- Another 2 sets of Amplifier will be completed before June 2008

Conclusion

- **Realization of the First 352 MHz 180 kW CW All Solid State Amplifier in the World**
- **High Reliability. During 7500h operation, only one Beam Current Interruption caused from a module failure in 2nd Stage due to higher power than nominal, it has been improved**
- **Unconditional Stability (Never Oscillated)**
- **Pure RF Spectrum:**
  Harmonics < -50 dB
  Phase Noise (rms) < 0.04°(< 8 kHz); < 0.06° (< 1 GHz)
- **Low Cost Design, No External High Power Circulator, Easy Maintenance**
- **At 300 mA Beam Current in Storage Ring, both Amplifiers Work well at 150 kW CW to SC. 4 Sets of Amplifier will not be a problem for 500 mA Nominal Beam Current operation**
- **Transistor Failure Rate is about 3.5 % per operation year (6300 h) and it is getting better → expectation around 1%**