TIARA Workshop on RF Power Generation for Accelerators

DEVELOPMENTS OF HIGH POWER CW SSAs at SOLEIL

Uppsala, June 17th - 19th, 2013

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OUTLINE

- **SSA operation at SOLEIL**
  - BOOSTER 35 kW
  - STORAGE RING 180 kW
- **SOLEIL 352 MHz SSA State of the Art**
- **500 MHz SSA R&D and new projects**
  - **LNLS** : 2 x 45 kW (476 MHz)
  - **SESAME** : 2 x 75 kW
  - **THOM-X** : 50 kW
- **R&D at other frequencies**

SOLEIL OVERVIEW

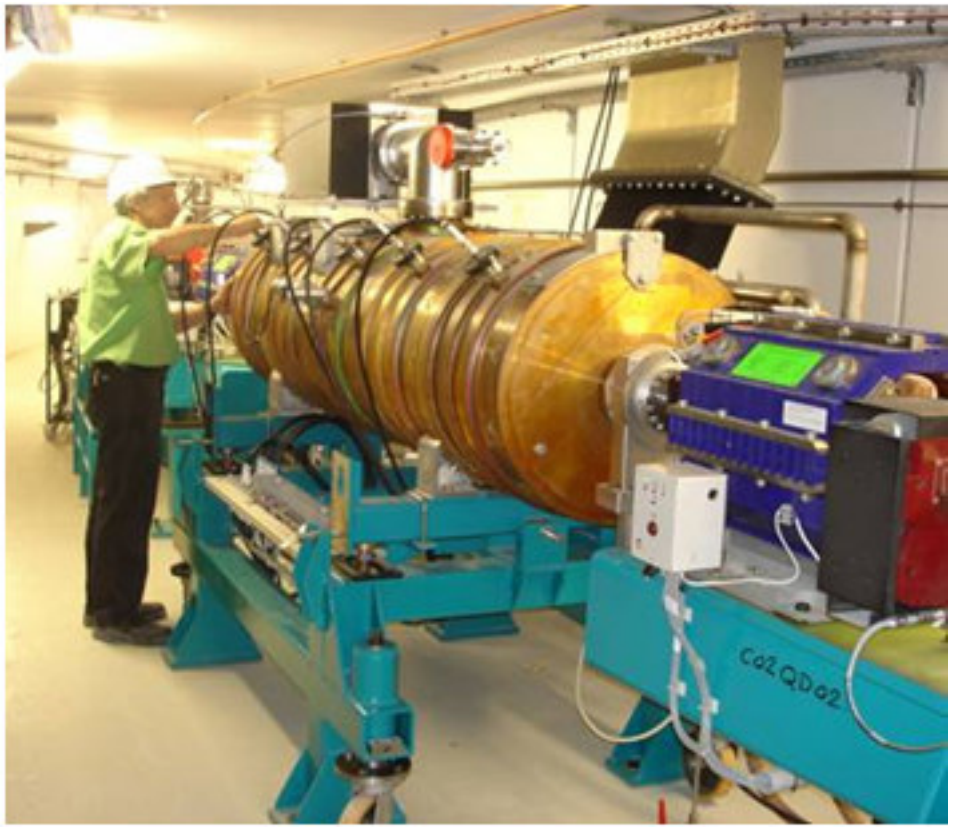
- S-Band (3 GHz) LINAC
- BOOSTER: 100 MeV => 2,75 GeV (3 Hz)
- 2,75 GeV STORAGE RING (500 mA)

- **Opened to users since 2007**

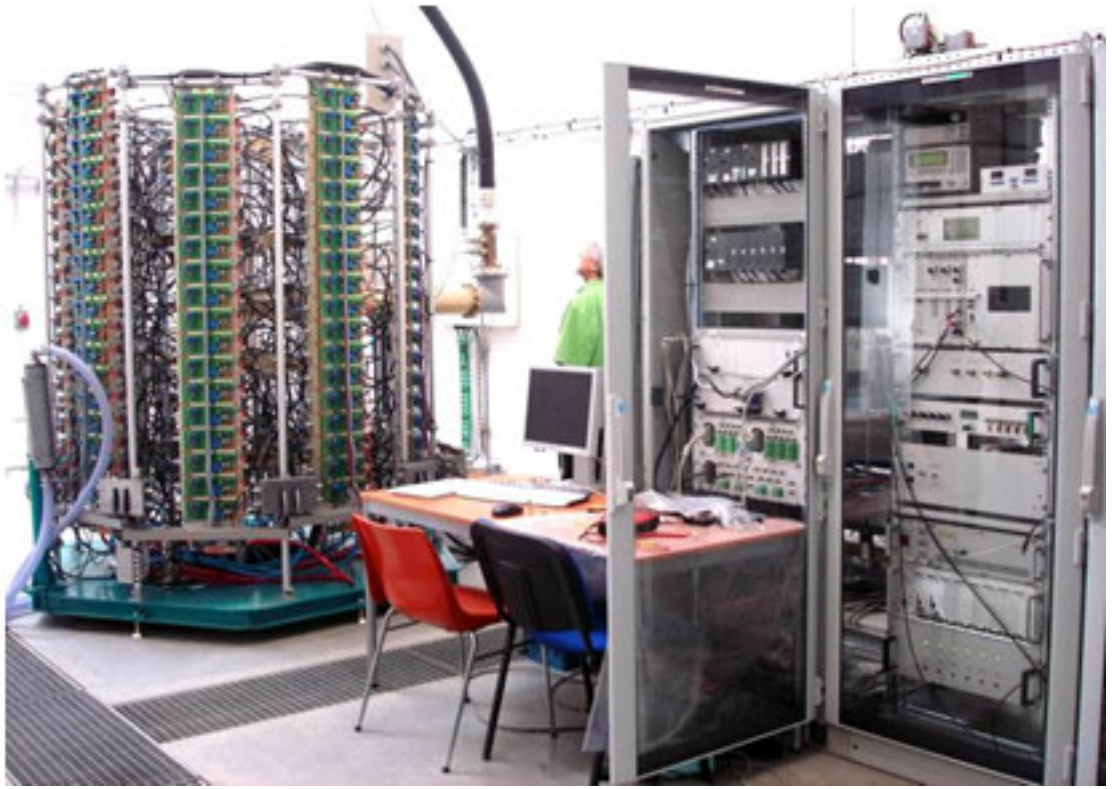
  26 beamlines funded: 18 with insertion devices and 8 with bending magnets
- **2012: 22 beamlines opened to users**

BOOSTER (BO) RF SYSTEM

- E_n : 100 MeV → 2.75 GeV (rep. 3 Hz) ; V_{cav} : 100 → 900 kV @ 352 MHz
- 1 x 5-cell Cu cavity (CERN LEP) → P_{tot} : 20 kW (P_{dis} : 15 kW, P_{beam} : 5 kW)
- 1 x solid state amplifier → 35 kW CW @ 352 MHz (developed in house)



Cavity in the BO ring

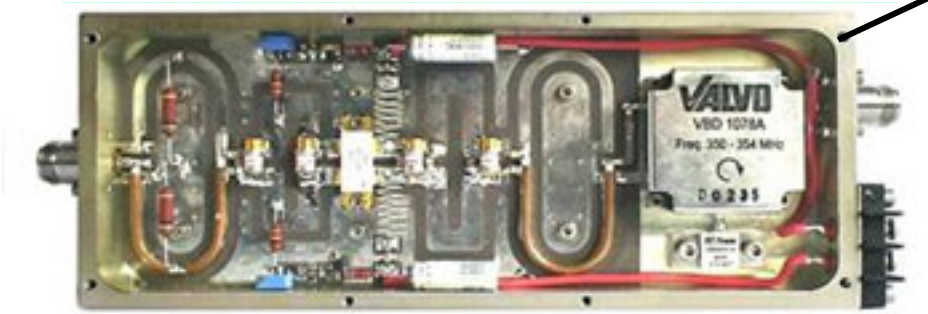


BO RF room (amplifier & LLRF)

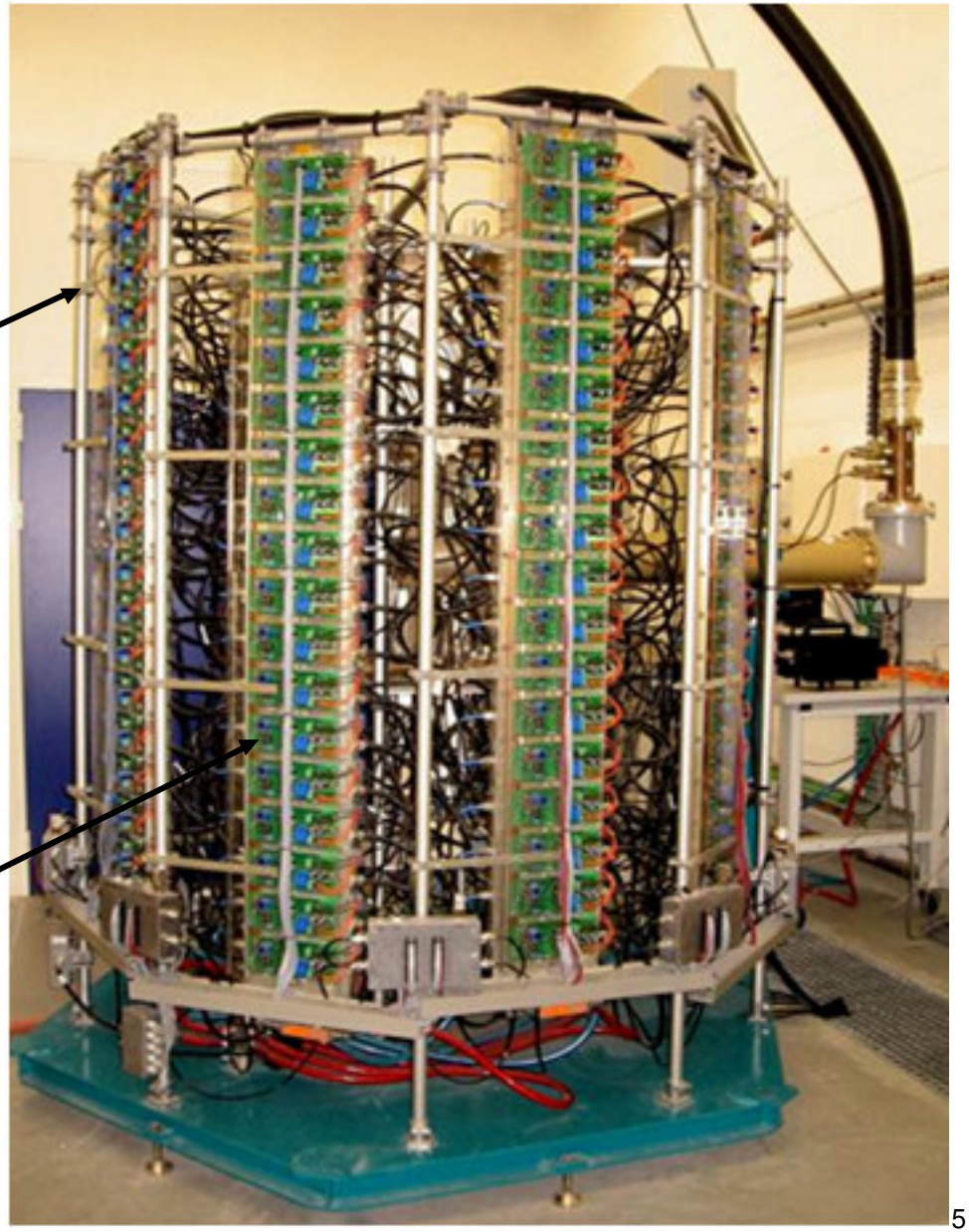
35 kW SSA OF THE SOLEIL BOOSTER

- 147 amplifier modules and power supplies on 8 water-cooled dissipaters

330 W amplifier module -
(VDMOS Transistor - Semelab D1029UK05)



600 W, 300 Vdc / 30 Vdc converter



35 kW SSA Power Combination

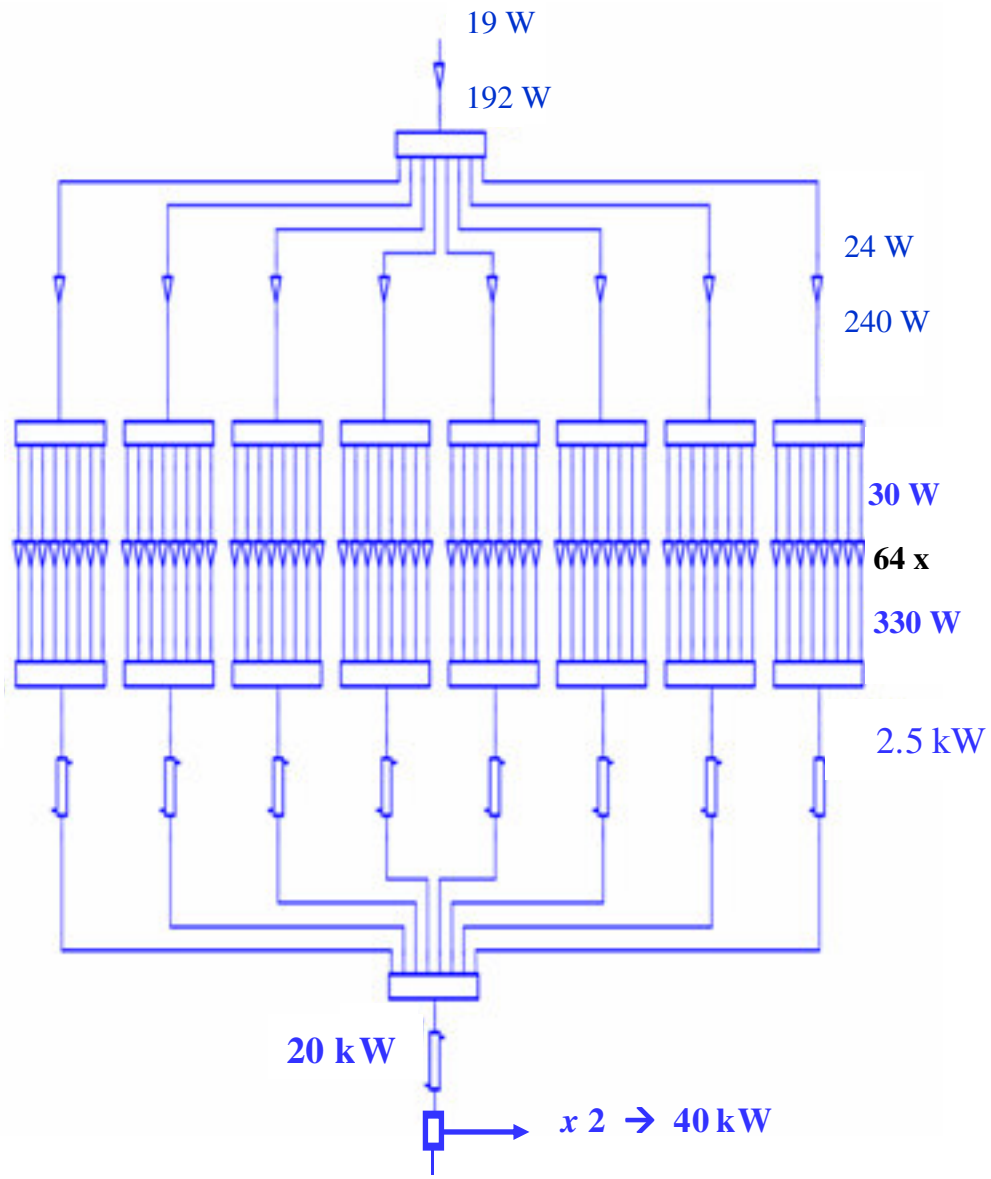
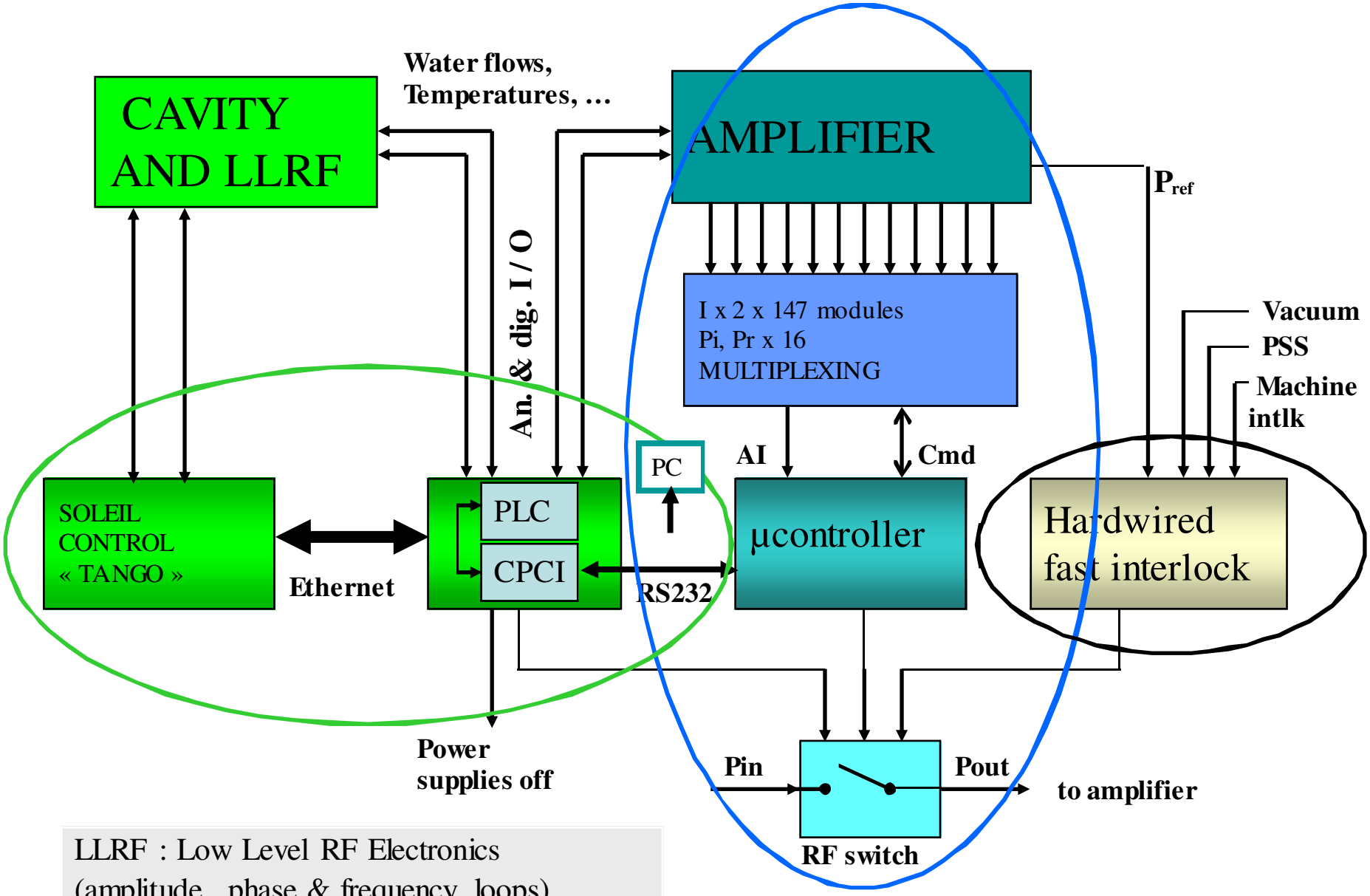


DIAGRAM OF THE BO RF CONTROL SYSTEM



LLRF : Low Level RF Electronics
(amplitude, phase & frequency loops)

OPERATIONAL EXPERIENCE WITH THE BO RF SYSTEM

The Booster RF plant is in operation since mid 2005.
Up to date, after 7 years operation (> 44 000 running hours),
only a single trip in operation, due to a human mistake (2006)

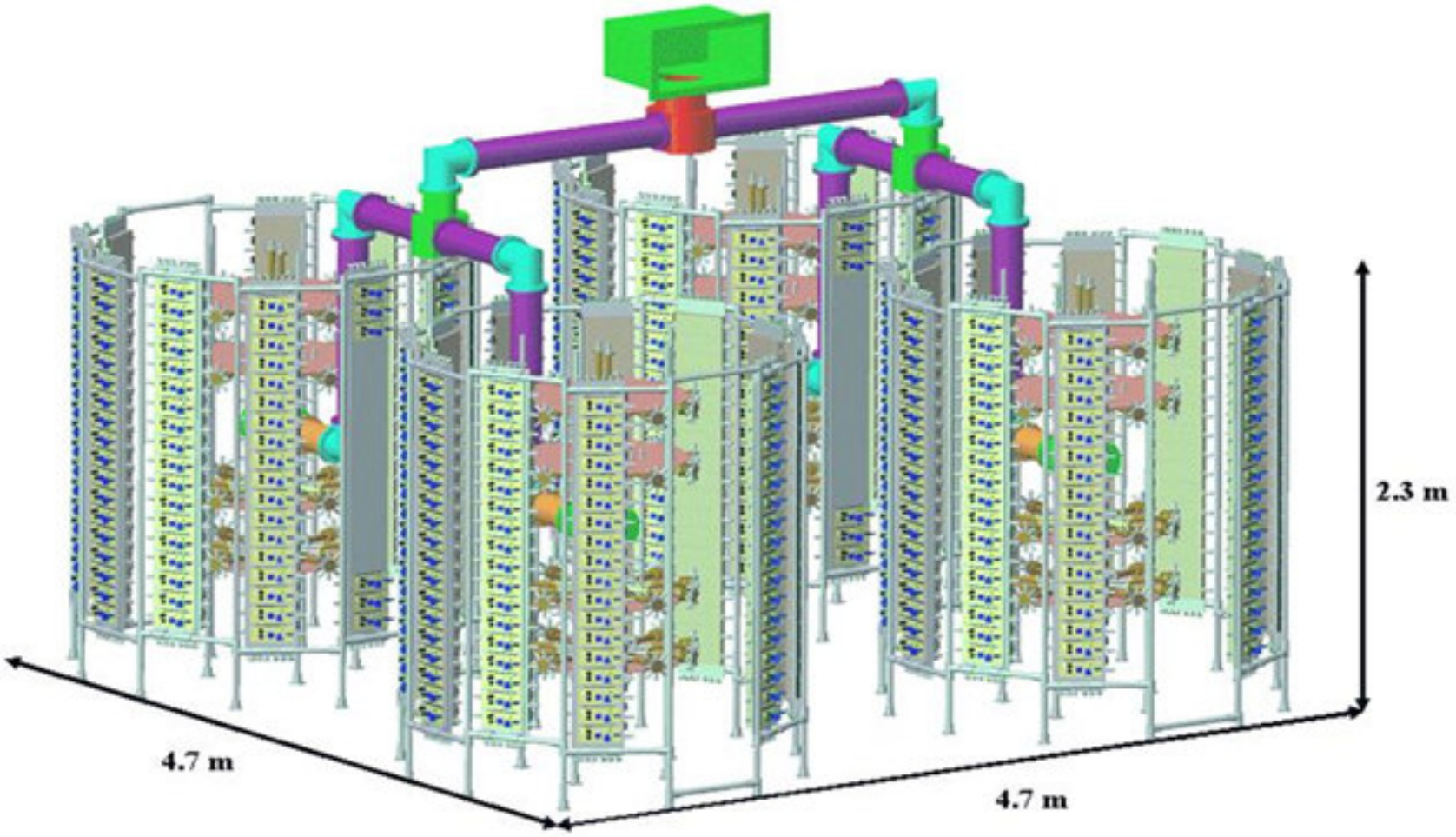
The 35 kW solid state amplifier has proved to be very reliable.
Only 8 (out of 150) module failures: 5 bad solder quality and 3 broken transistors,
which did not affect at all the operating conditions
and could be quickly repaired during scheduled machine shutdowns.

→ Advantage of the high modularity and redundancy

STORAGE RING (SR) RF SYSTEM

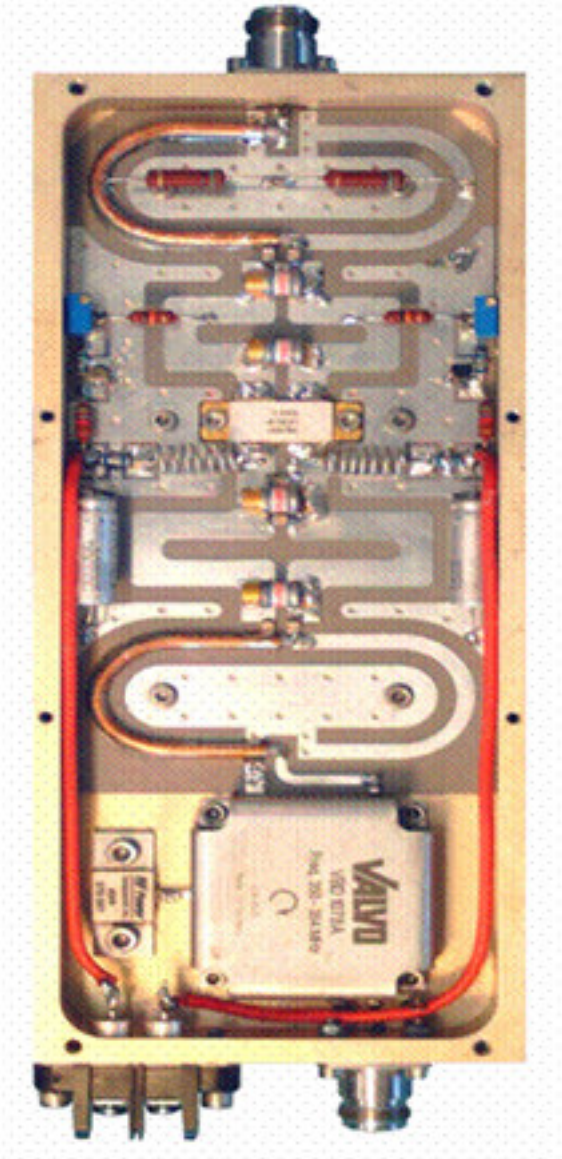
- E = 2.75 GeV, ΔE = 1.2 MeV, I_b = 500 mA
  → P_{RF} = 600 kW & V_{RF} = 4 MV @ 352 MHz
- 2 cryomodules (CM), each containing a pair of single-cell s.c. cavities
- Each cavity is powered with a 180 kW solid state amplifier
- Both CM supplied with LHe (4.2 K) from a single cryo-plant

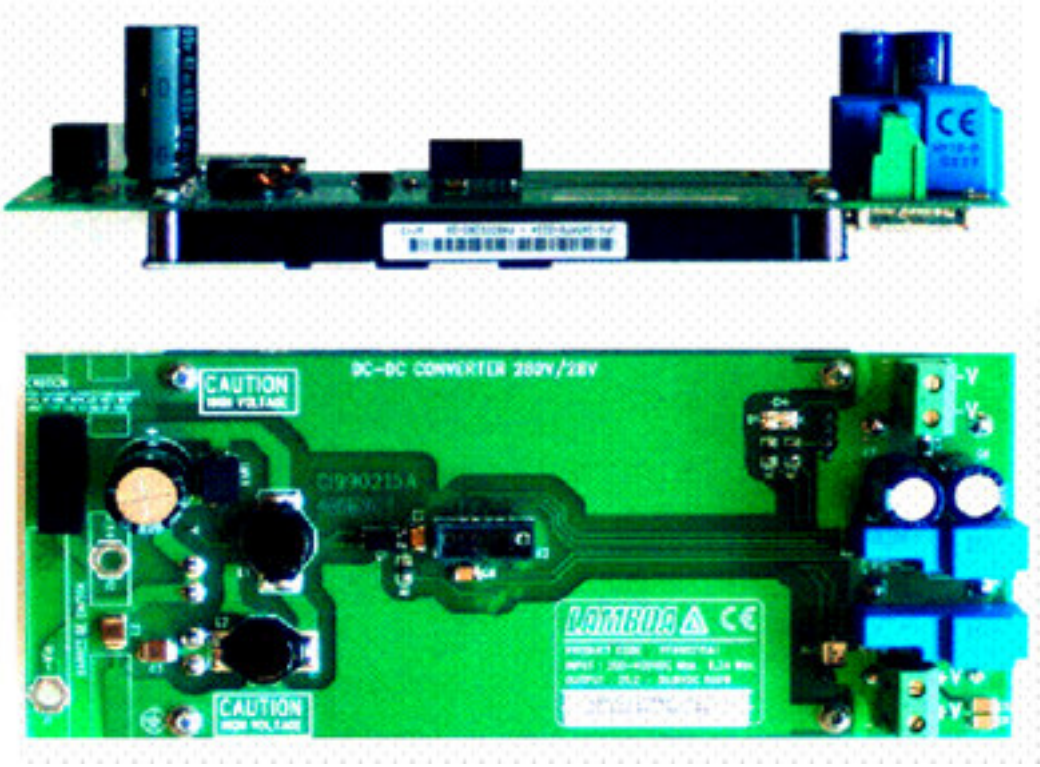
SR 180 kW RF SYSTEM



Same principle as for the BO one, extended to 4 towers of 45 kW
→ 726 modules / amplifier *x* 4 cavities → 16 towers & ~ 3000 modules

COMPONENTS OF THE SR AMPLIFIER



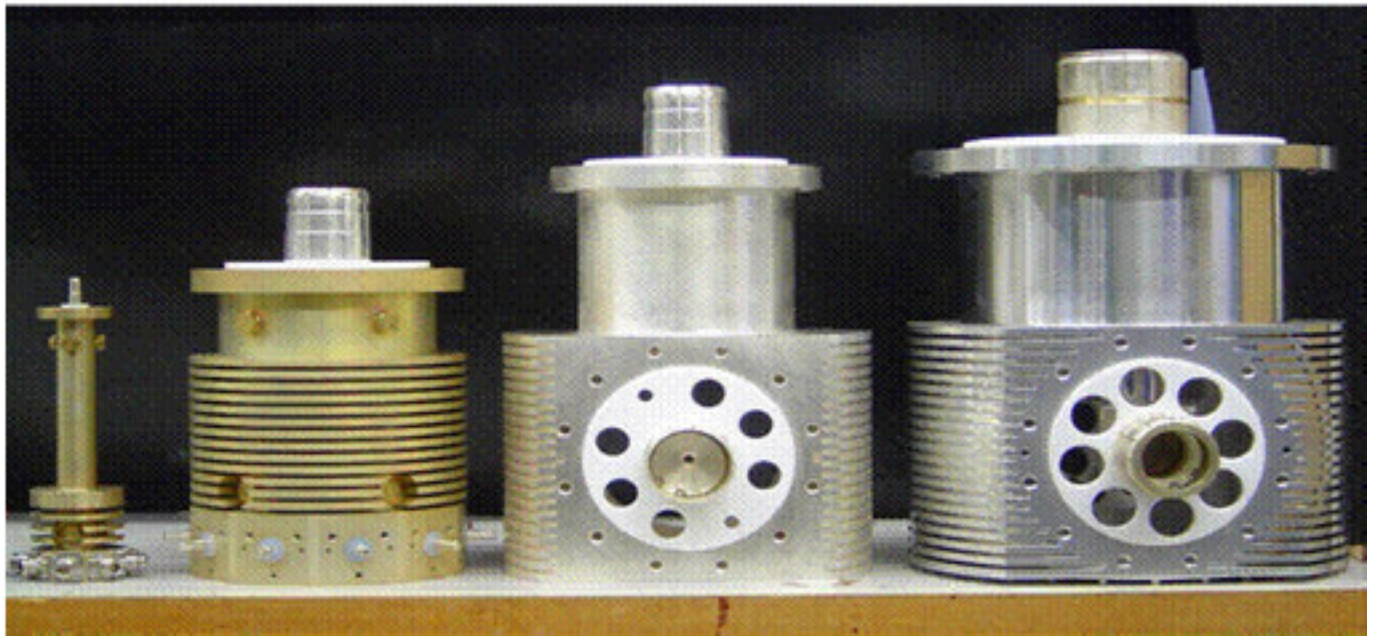


600 W – 280 Vdc / 28Vdc converter

352 MHz - 315 W amplifier module
(LDMOS transitor - Polyfet LR301)

COMPONENTS OF THE SR AMPLIFIER

Power splitters
2 , 8 and 10 ways
(90, 350 & 20 pcs, respectively)



Power combiners
2.5, 25, 100, 200 kW;
320, 34, 26 & 6 pcs, respectively
(S11 < - 30 dB)

AMPLIFIERS 1 & 2 => 2 CAVITIES OF CM1

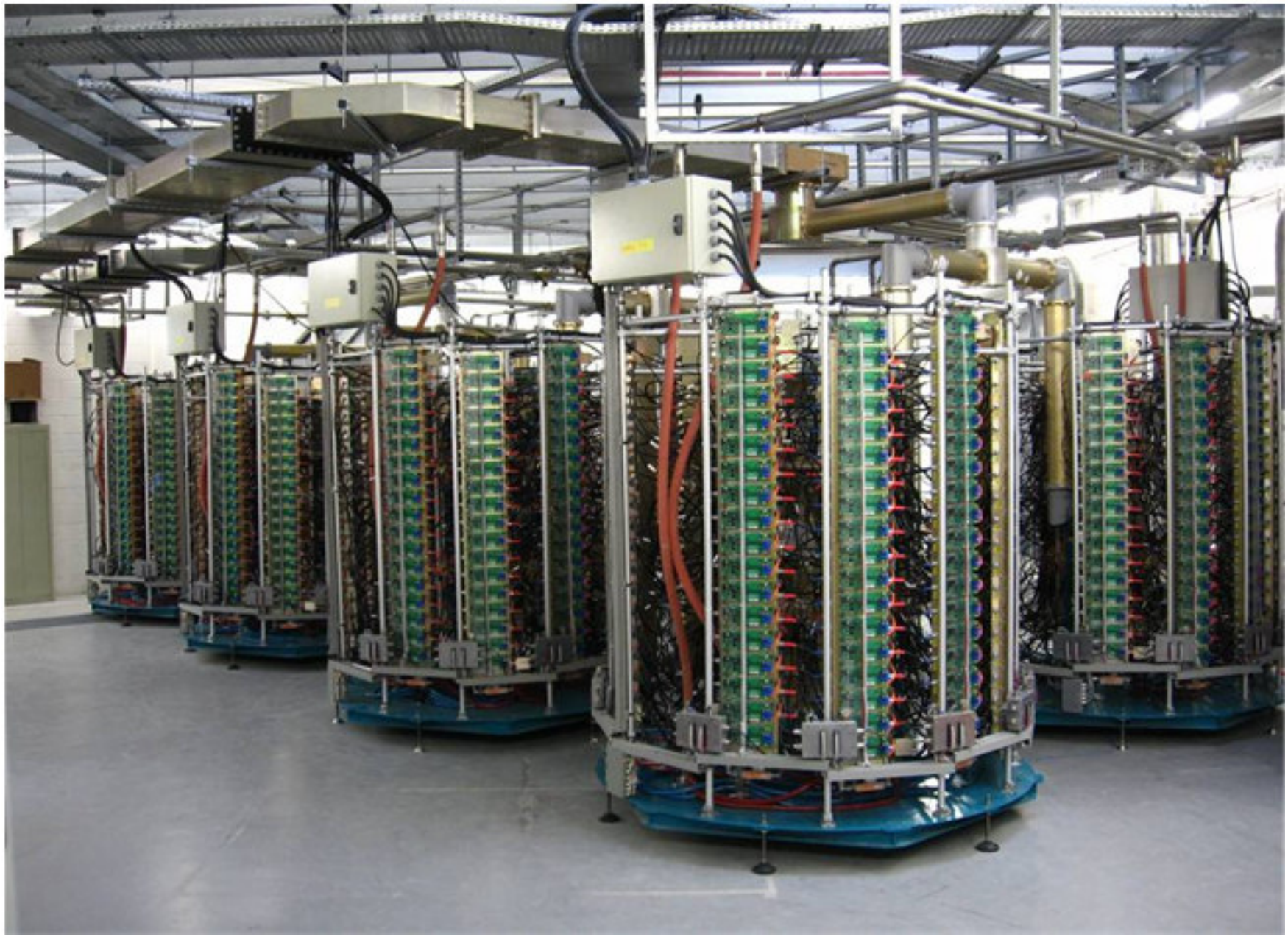
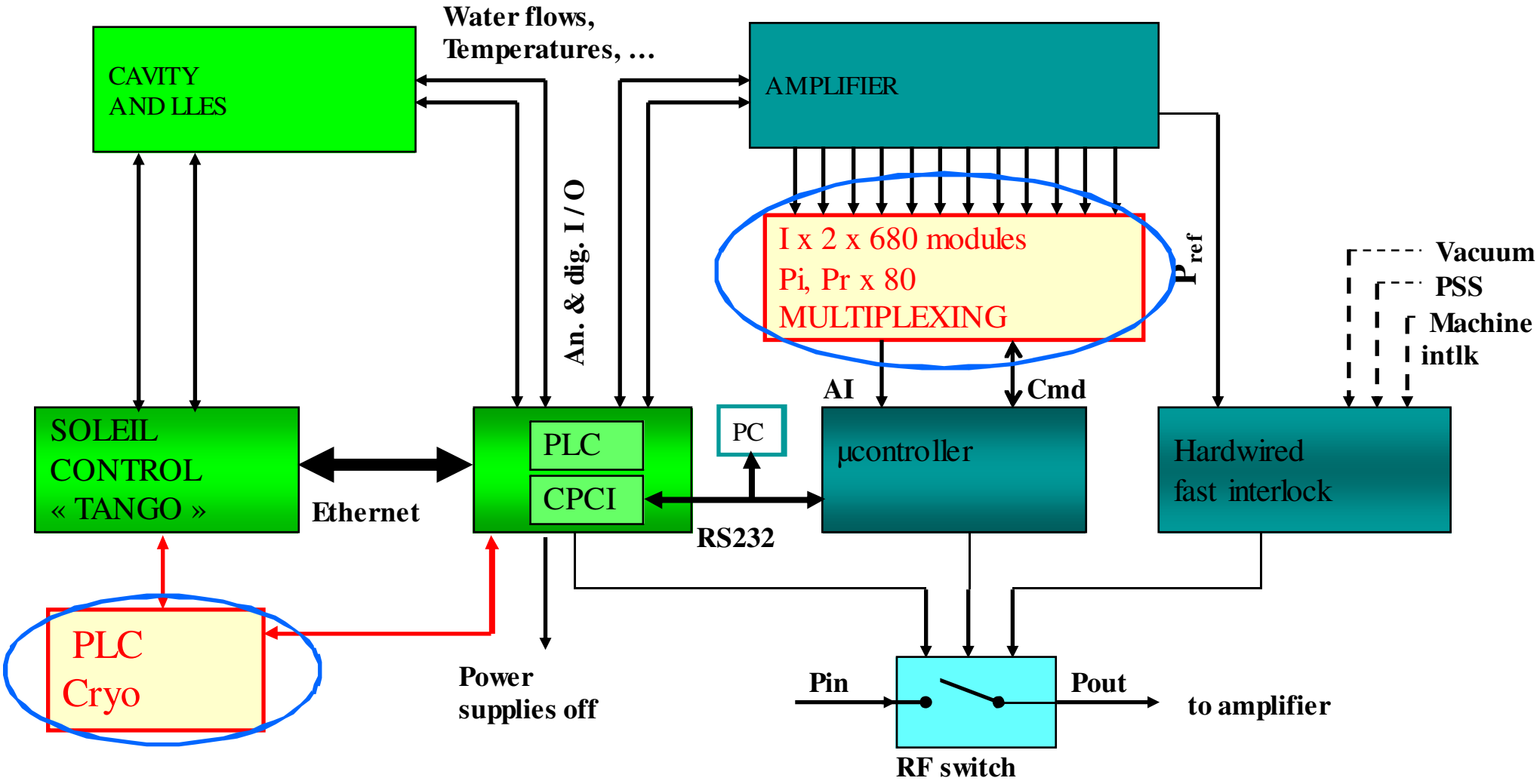


DIAGRAM OF THE SR RF CONTROL SYSTEM



AMPLIFIER CONTROL via the UCONTROLLER
Transistor Currents, Pi, Pr For A Tower

SUPERVISION AMPLI RF Version du 02/03/2011

Fichier Edition Outils

Courants 1 et 2
Delta courants
Somme courants

AMPLI 1 T1
AMPLI 2 T2
AMPLI 3 T3
AMPLI 4 T4

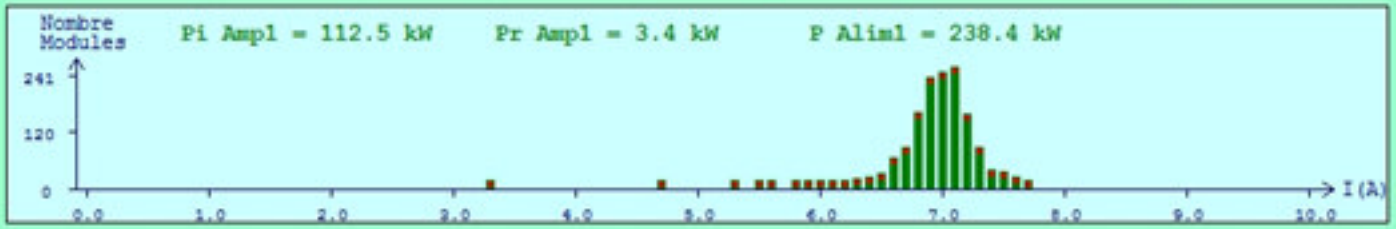
ARCHIVAGE
05/06/2013 à 12:00:00

	2.90	2.70			2.90	2.80			2.90	2.70			2.90	2.70			2.90	2.80			M0
	6.90	6.80	7.00	7.10	6.90	7.10	6.90	7.00	7.20	7.20	6.80	7.00	7.00	7.10	6.80	6.80	6.90	7.10	7.10	7.20	M1
	7.00	7.10	6.60	6.80	6.80	7.00	6.90	7.00	7.00	7.10	7.10	7.30	6.70	6.70	6.90	6.90	6.70	6.80	7.00	7.10	M2
	7.10	7.10	6.90	7.20	6.90	7.00	6.70	6.90	7.10	7.10	7.60	7.60	7.00	7.20	7.00	7.00	6.90	7.00	6.80	6.90	M3
	6.70	7.00	7.10	7.20	6.70	6.80	7.00	7.10	7.10	7.10	7.00	7.20	6.90	6.90	6.60	6.90	6.90	7.00	7.10	7.10	M4
	6.70	6.90	7.00	7.00	6.70	6.80	6.80	6.90	6.80	6.90	7.10	7.10	6.80	6.90	6.50	6.70	6.80	6.90	7.10	7.20	M5
	6.70	7.10	6.90	7.10	7.00	7.10	6.90	7.00	7.30	7.10	7.20	7.30	6.90	6.90	6.60	6.70	7.00	7.00	6.90	7.00	M6
	6.80	7.00	6.90	7.00	6.90	7.00	6.90	7.10	7.10	7.20	7.10	7.10	6.70	6.80	6.10	6.90	6.50	6.60	7.30	7.40	M7
	6.80	7.10	6.90	7.10	7.00	7.00	6.80	7.00	6.80	7.00	7.20	7.30	7.00	7.10	6.90	6.90	7.00	6.80	6.90	7.10	M8
	1.32	0.00	1.32	0.00	1.30	0.02	1.34	0.02	1.42	0.00	1.48	0.04	1.42	0.02	1.44	0.04	1.42	0.00	1.42	0.00	Pi Pr
	1.44	0.04	1.34	0.06	1.44	0.04	1.40	0.02	1.22	0.04	1.46	0.00	1.24	0.02	1.42	0.00	1.50	0.00	1.76	0.02	Pi Pr
	7.00	7.20	6.80	6.90	7.00	7.20	6.70	6.90	6.60	6.20	7.00	7.20	6.90	6.90	6.80	6.90	6.90	7.00	7.00	7.10	M8
	7.20	7.00	6.90	7.00	7.00	7.00	6.80	6.90	6.40	6.40	7.30	7.30	6.60	6.60	7.10	7.20	7.00	7.10	7.10	7.00	M7
	7.00	7.10	7.00	7.10	6.90	6.90	6.80	7.00	3.30	4.70	7.00	6.90	6.80	6.90	7.00	7.00	6.80	7.00	6.80	7.00	M6
	6.70	6.80	6.90	6.90	7.10	7.30	6.90	6.90	6.60	6.60	6.90	7.00	7.00	7.20	6.80	7.00	6.80	7.00	7.00	7.20	M5
	6.90	7.00	6.80	7.00	7.10	7.10	6.60	6.80	6.60	6.70	7.10	7.10	6.70	6.80	6.80	6.80	6.80	6.80	7.20	7.30	M4
	7.10	7.20	6.90	7.10	7.60	7.60	6.30	6.30	6.60	6.60	7.20	7.10	7.20	7.10	7.00	6.90	6.90	6.90	7.20	7.30	M3
	7.00	7.10	6.80	6.90	7.10	7.10	7.10	7.20	7.10	7.10	7.30	7.40	6.50	6.60	6.90	7.10	6.90	6.80	7.10	7.10	M2
	7.00	7.20	6.90	7.00	7.00	7.10	6.80	7.00	6.60	6.80	7.10	7.20	7.00	7.00	6.60	6.70	6.90	6.90	7.10	7.10	M1
			3.00	2.90			3.00	2.70			3.00	2.80			2.70	2.90			3.00	2.70	M0
	D0		D1		D2		D3		D4		D5		D6		D7		D8		D9		D10

M1	0.60	0.60
M2	1.40	1.30
M3	1.30	1.40
M4	1.50	1.40
M5	1.50	1.40
M6		

Messages

Aquisition OFF

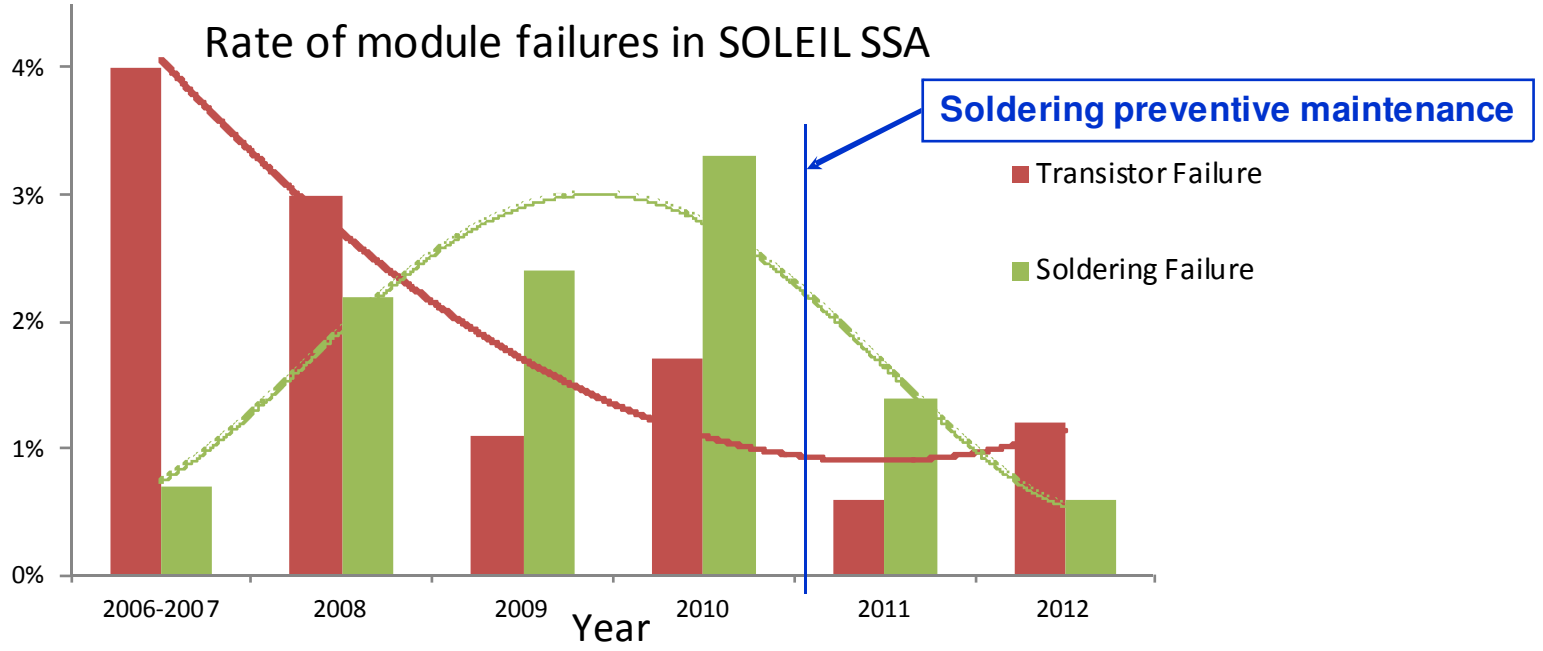


STORAGE RING OPERATIONAL EXPERIENCE

RF power amplifiers

- Proved to be very reliable : after > 38000 running hours over ~ 7 years, only 5 short beam dead times → ~ 100 % operational availability, MTBF > 1 year

- Module failure rate of ~ 3.5 % per year → ~ no impact on the operation
  → Matter of maintenance : 1 hour @ each shutdown for ~ 10 mod. change
  → Yearly repair cost of ~ 5 k€ (for the four 200 kW amplifiers)



Significant improvement expected from the new generation modules with more robust transistors and less thermal stress

SOLEIL RF STATUS

- After 7 years of operation, SSA innovative design has proved itself and demonstrated that it is an **attractive alternative to the vacuum tube amplifiers**, featuring an outstanding reliability and a MTBF (> 1 year).

- Thanks to the acquired expertise and the arrival of the 6th generation LDMOS, SOLEIL has carried out developments which led to doubling the power of the elementary module (650 W) while improving the performance in terms of gain, linearity, efficiency and thermal stress.

- **Advantages of SSA technology:** low phase noise, good linearity, high reliability, long life time, easy maintenance, simple spare parts, no HV, no X ray.

=> UPGRADE to benefit from 6th generation improvements

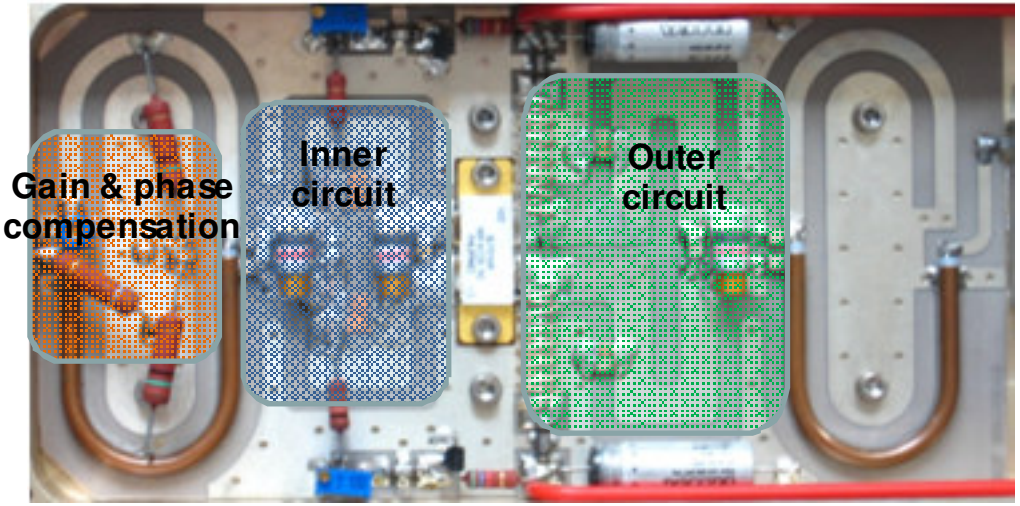
Why SSA upgrade at SOLEIL?

- Easier maintenance, better performances
  - Low gain and phase dispersion (+/-0,2dB and +/-5° instead of +/-1,5dB and +/-7,5°)
  - More power capability => optional operation with 2 or 3 amplifiers out of 4
  - More robust transistors
  - Transistor supply made easier (NXP, Freescale…)
- Cost savings
  - 6% increase in module efficiency => less modules => electrical power savings
    => compensation for upgrade costs within 4 years
  - Old PCB re-used and only transistors are changed => less than 10% of the amplifier cost

At the beginning, we thought about replacing only the damaged modules with new transistors. But the very strong performance and cost advantages made us change our strategy for a controlled and planned massive upgrade.

SSA upgrade at SOLEIL in details

- Transistor LR301 replaced by BLF574XR
  - Same footprint as LR301
  - Up to 500W CW (high power margin)
  - Better robustness and relialibity
- Add gain and phase compensation circuits
- Components change for matching



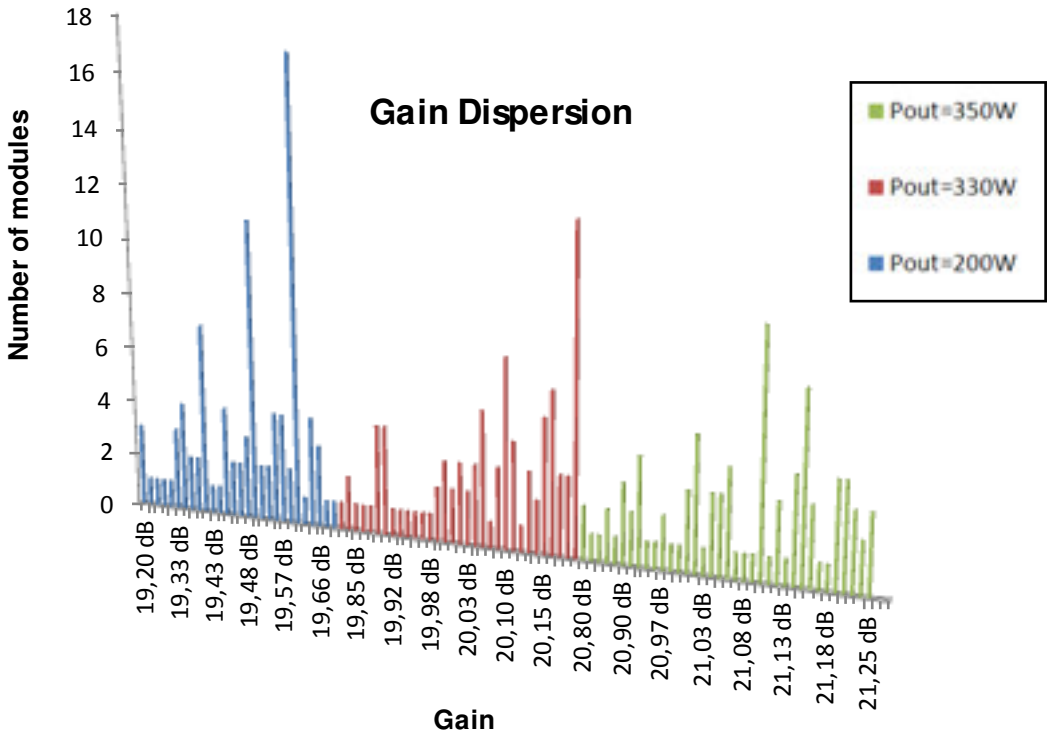
Comparison LR301 vs BLF574XR

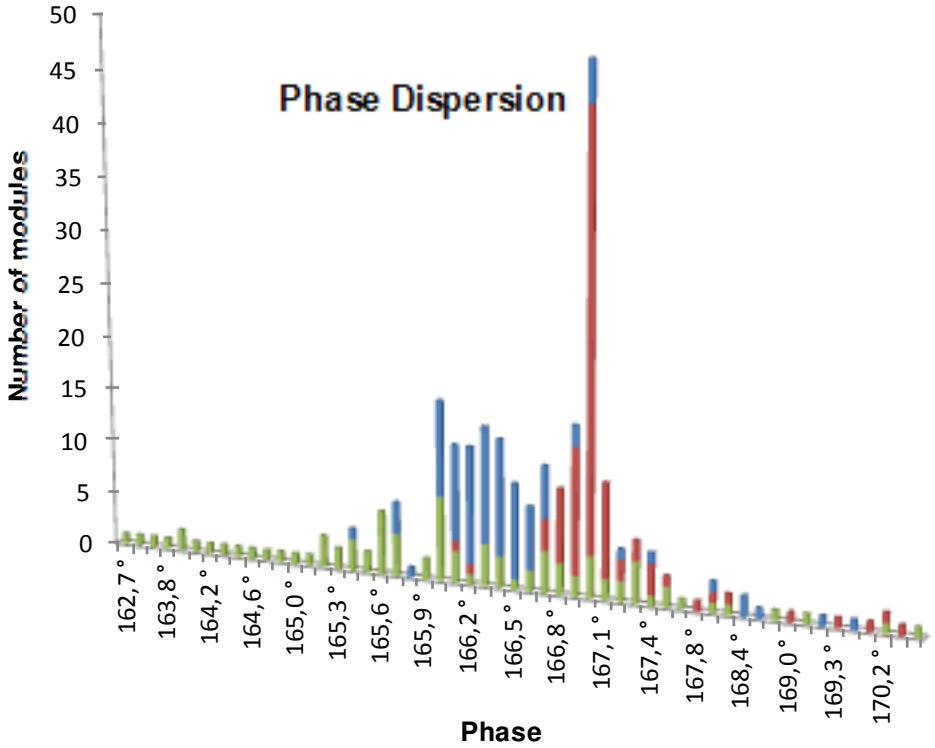
RF parameters	LR301	BLF574XR	Advantages of BLF574XR
Gain	13,7	20	Less drivers (+0,5% for overall efficiency)
Efficiency	62%	68%	Better efficiency (+4,5% for overall efficiency)
Output power	315W (350W tested)	330W (450W tested)	More Power Margin
Gain Dispersion	+/-0,8dB at Pnom	+/-0,2dB at Pnom	No sorting
Phase Dispersion	+/-7,5 at Pnom	+/-5 at Pnom (+/-2,5 expected)	Better combining efficiency

- Test of 10 BLF574XR samples:
  - Assembling and test of 2,5kW unit based on BLF574XR modules during 4000h on dummy load
  - Mounting them in our amplifier (AMP1) since one year in operation without any problem

SSA upgrade at SOLEIL in details

Distribution of 100 first BLF574XR modules





- Jan-Feb 2013: Supplying all components (RF capacitors, transistor, etc…)
- March & April 2013 : Modifications and adjustments of 100 modules
- May 2013 : Replacement of 90 drivers on two 180kW amplifiers
- Oct 2013 : Replacement planned of 90 drivers on two last 180 kW amplifiers
- Replacement of last stage modules ~ 4-8 years (1 or 2 tower per year)

SOLEIL 352 MHz SSA State Of The Art

6th generation transistors (V_{dc} = 50 V) + SOLEIL expertise → fast progress

→ At 352 MHz, P_{mod} ~ 700 W, G > 20 dB, η > 70%

[Current LR301 mod. (V_{dc} = 28 V) : P = 315 W, G = 13 dB, η = 62 % @ 352 MHz]

→ Huge improvement : P_{mod} x 2.2 , better performance (G , η , linearity)
& thermal stress strongly reduced (ΔT : - 60 C) → longer lifetime

→ Beg. 2009, transfer of technology agreement concluded with ELTA-AREVA

→ ESRF contract for 7 SOLEIL type amplifiers of 150 kW (14 x 75 kW towers)

- June 2010 : A 10 kW unit (16 modules) successfully tested at SOLEIL
- June 2011 : Commissioning of the first 75 kW tower at ESRF
- March 2012 : Commissioning of the 4 x 150 kW amplifiers for the booster, which, up to now, have run quite satisfactorily for 1.5 year
- 2013 – 2014 : Delivery of the 3 amplifiers for the SR, slightly modified as compared to the Booster for handling high CW VSWR (→ Jorn Jacob)

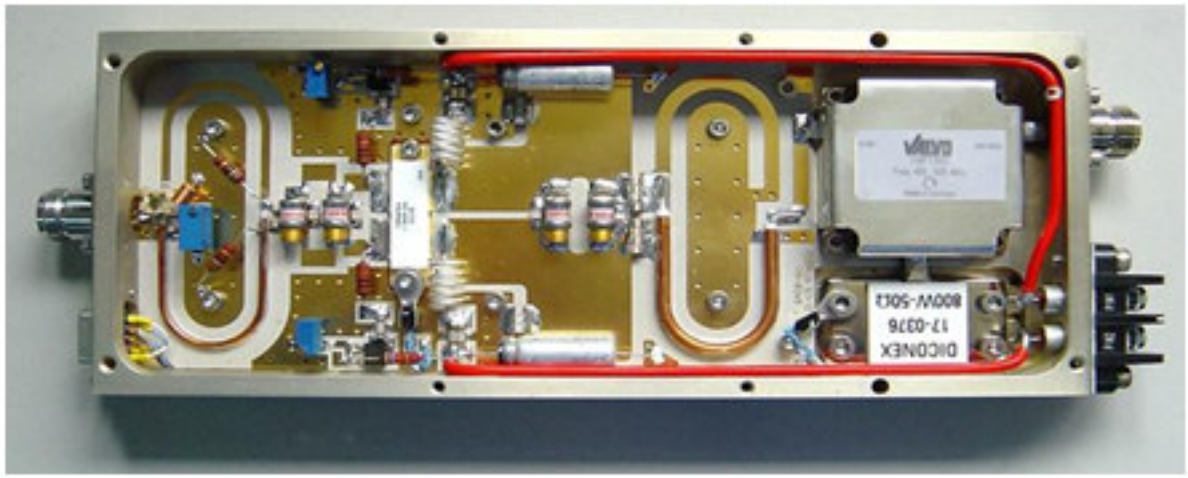
SOLEIL 352 MHz SSA State Of The Art

	Transistor type	Power supply per module	Module Parameters at nominal conditions	Amplifier design & nominal power	VSWR limitation *	Comments
SOLEIL Booster	D1029UK05 ◊ SEMELAB	1 x 600 W 280/28 Vdc	P_{1dB} = 330 W, G = 11 dB η = 60 % , T_{max} = 130 C	1 tower of 8 dis P_{nom} = 35 kW modulated	No limit with SOLEIL Booster duty cycle	1 trip over 7 years due to a human mistake
SOLEIL SR (actual)	LR301 Polyfet	1 x 600 W 280/28 Vdc	P_{1dB} = 315 W, G = 13 dB η = 62 % , T_{max} = 130 C	4 towers of 10 dis P_{nom} = 180 kW cw	70 kW full reflection Pr = 35 kW @ 180 kW	MTBF > 1 year
SOLEIL SR (upgrade)	BLF574XR NXP	1 x 600 W 280/48 Vdc	P_{1dB} = 350 W, G = 22 dB η = 69 % , T_{max} = 90 C	4 towers of 10 dis P_{nom} = 200 kW cw	70 kW full reflection Pr = 32 kW @ 200 kW	Much more robust than LR301
ESRF Booster (800W load)	BLF578 NXP	2 x 600 W 280/48 Vdc	P_{1dB} = 650 W, G = 20 dB η = 71 % , T_{max} << 75 C	2 towers of 8 dis P_{nom} =150 kW modulated	No limit with ESRF Booster duty cycle	In CW Pr limited at 5 kW for Pi = 150 kW
ESRF SR V2 (1.2kW load)	=	=	=	2 towers of 8 dis P_{nom} = 150 kW cw	85 kW full reflection Pr = 50 kW @ 150 kW	→ modified combination → + 1.2 kW load
ESRF SR V3 (power circul)	=	=	=	→ P_{nom} = 140 kW	140 kW CW full reflection	+ 5% power loss - 3% on efficiency Extra costs

- * VSWR limitation: when operating the amplifier at high CW incident power, Pi, with a high VSWR and the worst phase condition, **an unpowered module** (ie, both of its power supplies, or both sides of its push-pull broken) can see a power on its circulator load, Pload > Pi
- ***Rem***: full reflection for a short time (~10 ms) is not a problem (→ Pr interlock)
- 2 PS in series on 2 modules in //
- ◊ VDMOS; all the other cases are LDMOS

500 MHz R&D ON SSA

6th generation LDMOS → BLF578 : 650 W modules



RF characteristics:

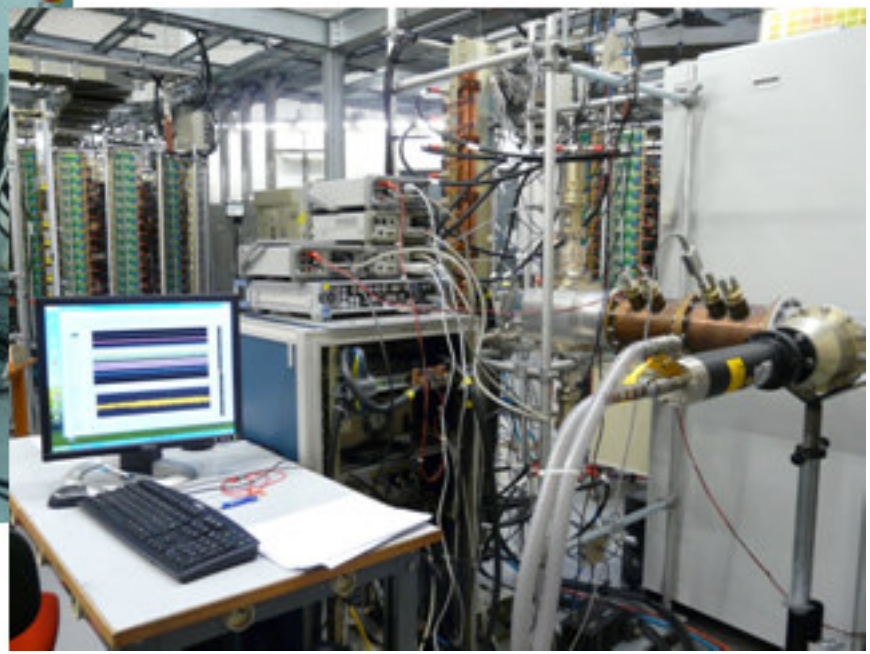
- RF Output Power: 650 W CW at 1 dB
- Gain : 17dB
- Efficiency: > 60% at P_n
- Gain dispersion : +/- 0.2 dB at P_n
- Phase dispersion :+/- 5 at P_n
- Input Return Loss : < - 40 dB at P_n
- Unconditional stability (K>10 dB)

High efficiency (96%) 230 V_ac / 50 V_dc power converters

500 MHz R&D on SSA

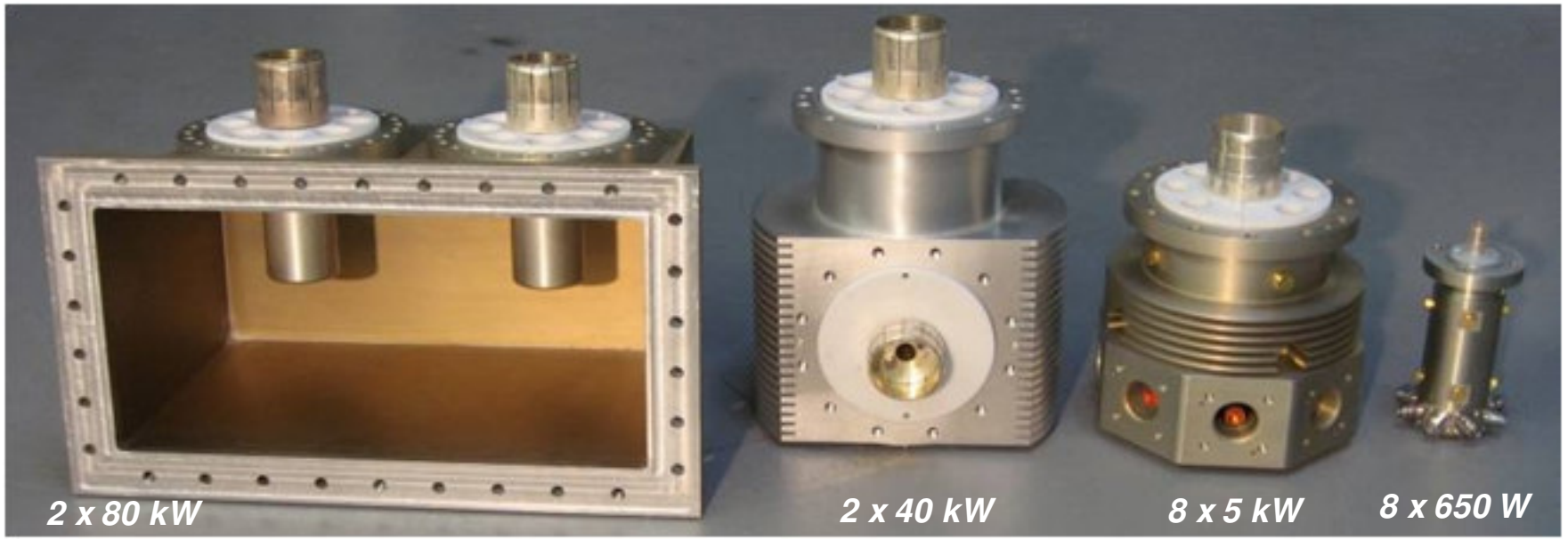
10 kW unit prototype for long term test (> 500 hours)

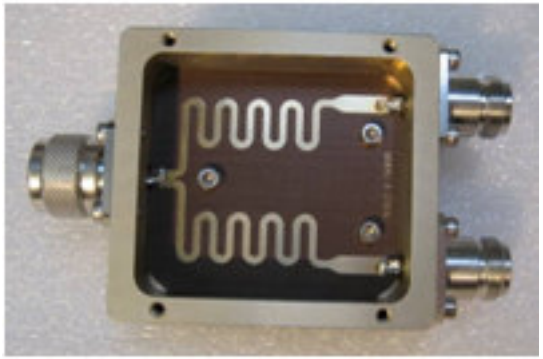
Efficiency ~ 55%



500 MHz R&D ON SSA

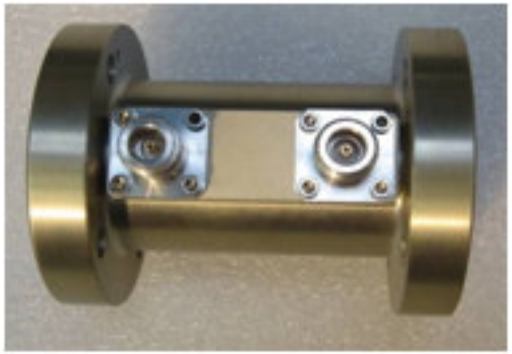
Power combination components





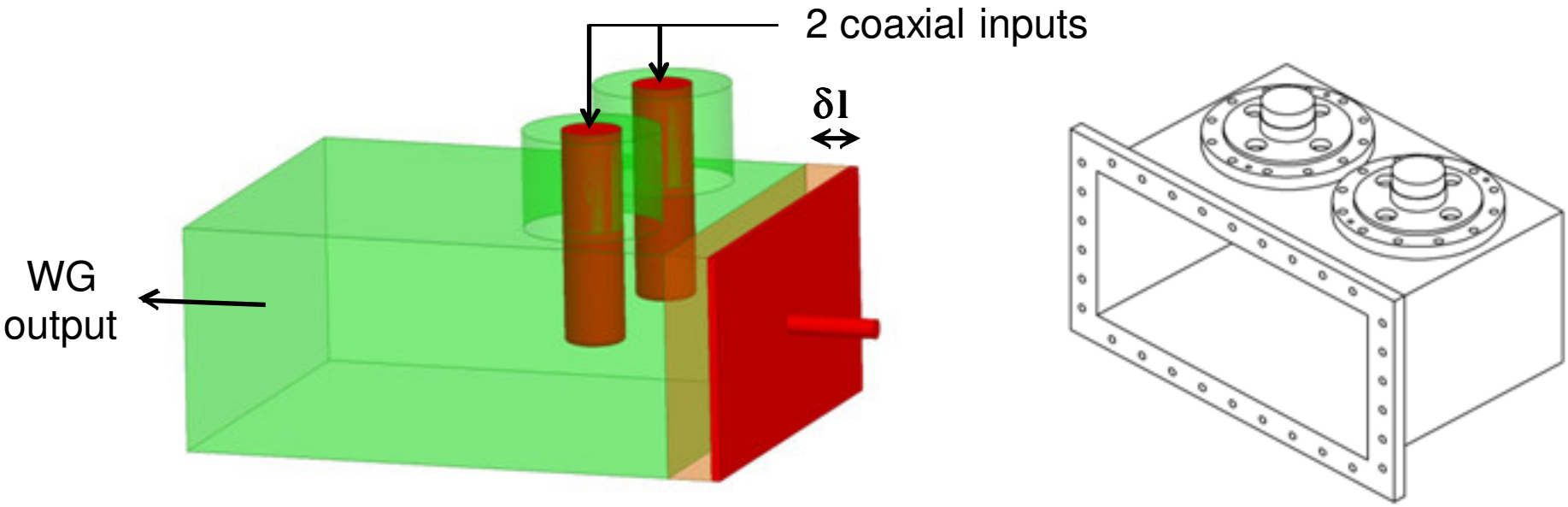
2-way splitter

8-way splitter



P_i - P_r monitoring coupler

WAVEGUIDE-to-COAXIAL COMBINER (WaCCo)



- **Two 6 inches coaxial input ports (2 x 80 kW) → 1 WG output**
- **Replace a coaxial combiner + a coaxial-to-WG transition**
- **Design optimization with HFSS and Microwave Studio**
  → A 500 MHz prototype has been validated at signal level
- **<u>Movable SC</u> → can ensure a good matching for different configurations with diff nb of dissipaters per tower or diff nb of modules per dissipater**

SOLEIL R&D ON SSA

- **Collaboration agreements**
  - **LNLS** (Brazilian LS) : 2 x 45 kW @ 476 MHz, in operation
  - **SESAME** (LS in Jordan) : 4 x 150 kW @ 500MHz
  - **THOM-X** (Compact source of hard rays): 50 kW @ 500MHz

- **R&D at other frequencies**
  - FM band (88 – 108 MHz) → 1 kW module with G > 25 dB and η ~ 80 %
  - L band (1.3 & 1.5 GHz) for 4th generation LS → P_{mod} > 400 W
    - **LUNEX5 :** 20kW @ 1.3 GHz – R&D for the TDR

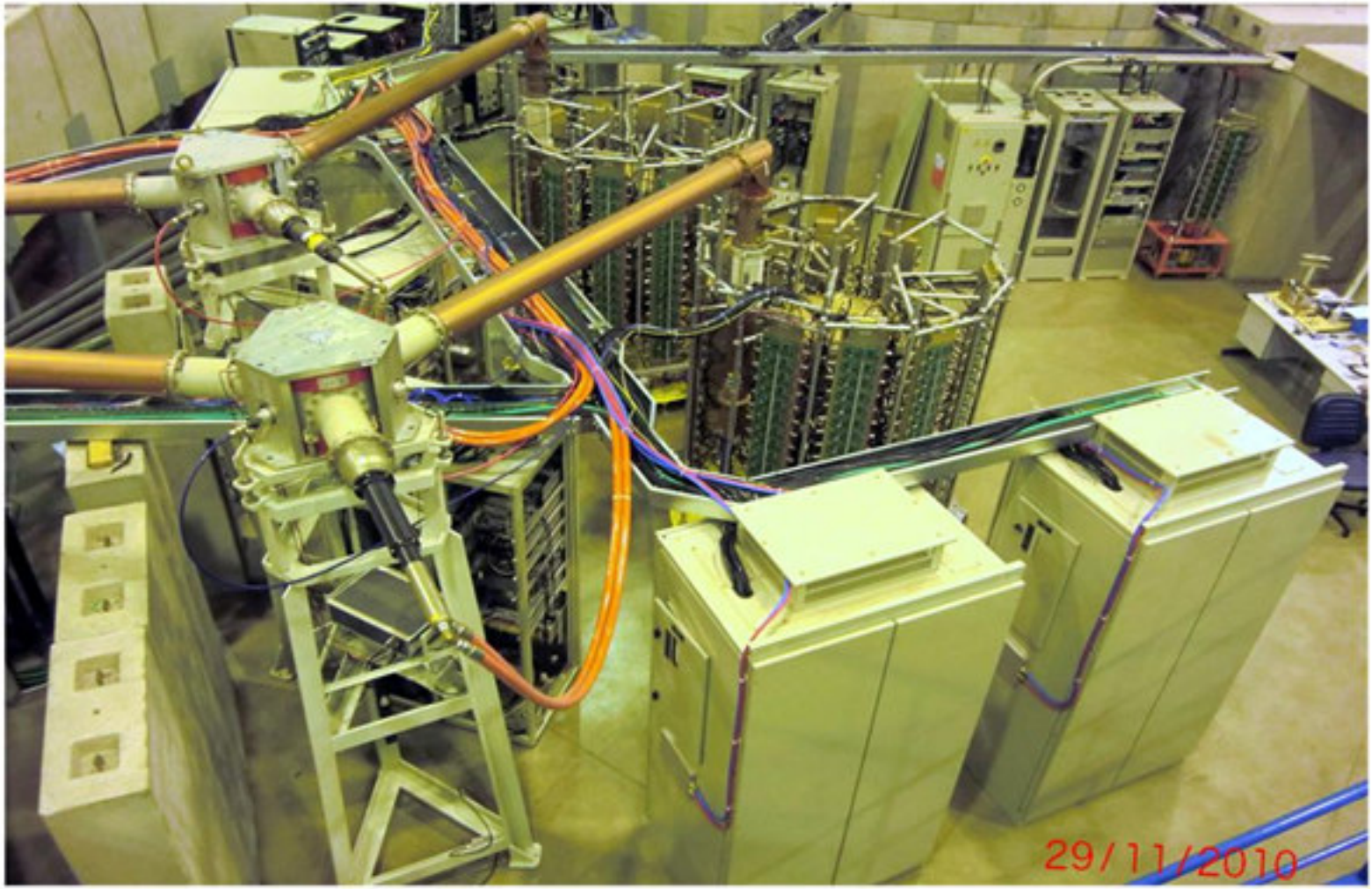
The SSA technology is ideally suited to the ERL requirement, which is typically of a few tens of kW at 1.3 – 1.5 GHz.

SOLEIL-LNLS COLLABORATON

Two amplifiers of 50 kW @ 476 MHz for the LNLS storage ring with components designed by SOLEIL (400 W RF modules with **BLF574**)

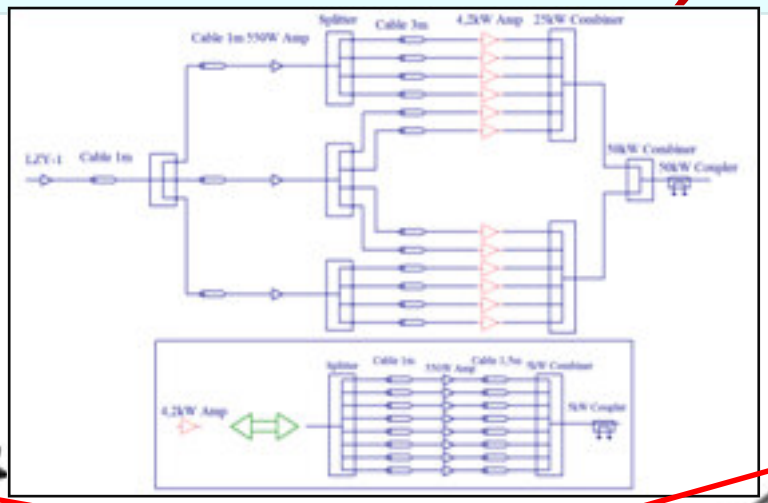
April 2010 : the SOLEIL -LNLS team in Campinas-Brazil, after successful tests of the amplifiers

LNLS 50 kW RF Plants

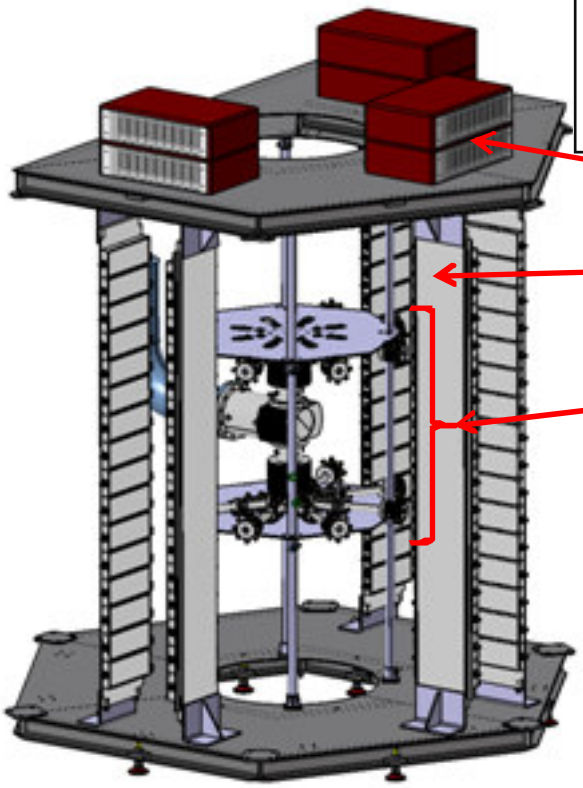


The two 50 kW SSA have run satisfactorily on the LNLS SR for ~ 3 years

THOM-X 500 MHz 50 kW AMPLIFIER (PRELIMINARY DESIGN)



Tower Design

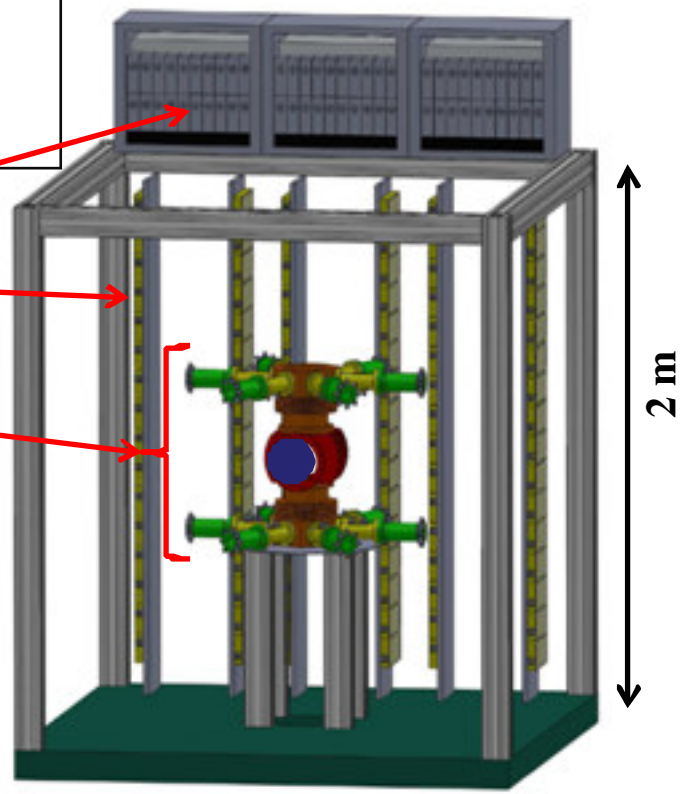


AC-DC Power Supplies

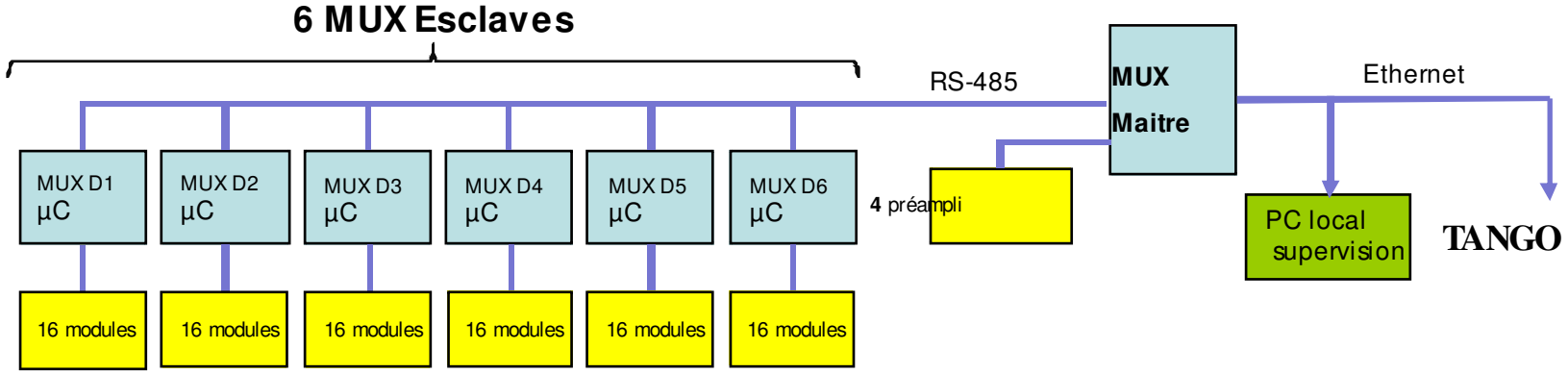
16 Amplifiers per Dissipator

High Power Combination

Cabinet Design

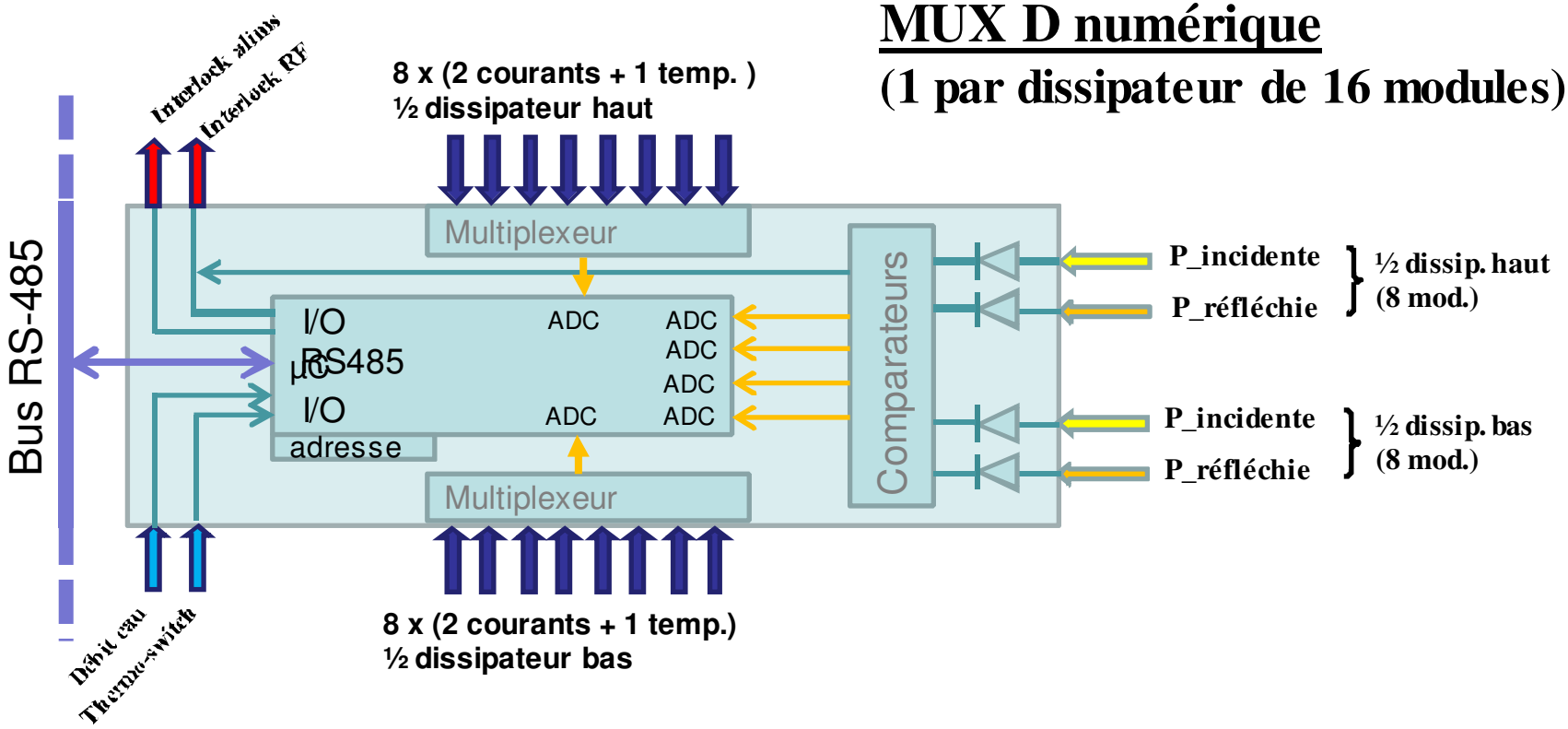


PROPOSAL FOR THOM-X AMPLIFIER CONTROL SYSTEM

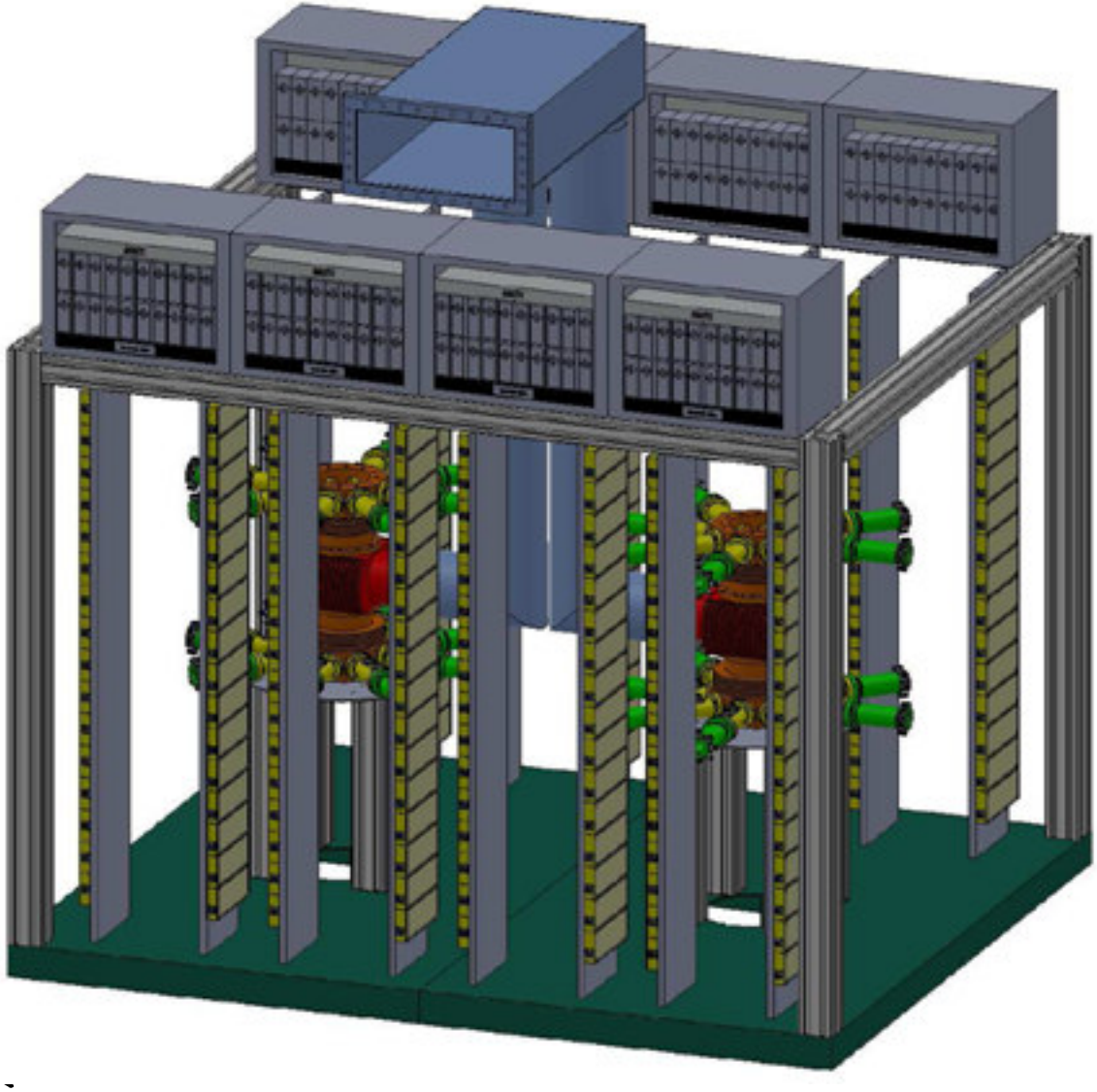


MUX D numérique

(1 par dissipateur de 16 modules)



SESAME 500MHz 140kW AMPLIFIER (PRELIMINARY DESIGN)



- AC-DC Power Supplies (160 x 2kW modules)
- 1 Waveguide Combiner (WaCCo)
- 2 x 75 kW RF combination
- 64 8-way splitters
- 16 dissipators
- 256 amplifier modules

SUMMARY & CONCLUSIONS

- **BOOSTER 35 kW SSA (D1029UK05)**
- **STORAGE RING 180 kW SSA (LR301)**
  - Operation and upgrade to 6th generation BLF574XR
- **SOLEIL 352 MHz SSA State of the Art**
  - P_{mod} ~ 700 W, G > 20 dB, η > 70%
- **500 MHz SSA R&D (BLF578)**
  - P_{mod} ~ 650 W, G ~ 17 dB, η > 60%
- **500 MHz SSA based projects**
  - **LNLS** : 2 x 45 kW (476 MHz)
  - **SESAME** : 2 x 75 kW
  - **THOM-X** : 50 kW
- **R&D at other frequencies**
  - FM band (88 – 108 MHz) → 1 kW module with G > 25 dB and η ~ 80 %
  - L band (1.3 & 1.5 GHz) for 4th generation LS → P_{mod} > 400 W
    - **LUNEX5** : 20kW @ 1.3 GHz

Thank you for your attention