SSA Developments at SOLEIL

Workshop on Efficient RF sources

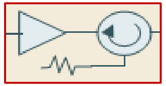
Château de Bossey, 4-6 July 2022

Massamba DIOP

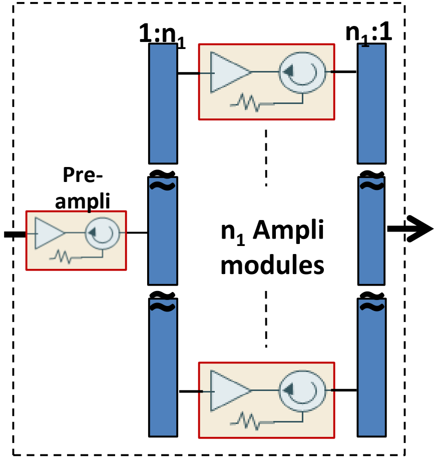
On Behalf of the RF & LINAC Group

SSPA Principle

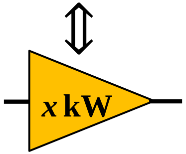
Combining in // a number of elementary amplifier modules (or pallets) of a few 100 W (up to ~ 1 kW)

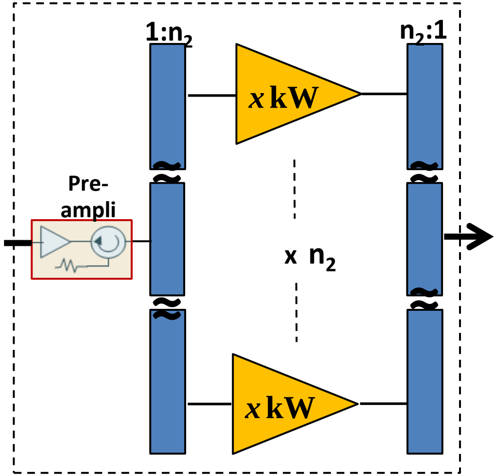


- MOSFET (V_d = 30 - 65 V) → **No HV & Low phase ripple**
- Circulator & its load to ensure a good isolation (even a small residual VSWR can affect the MOSFET power capability !!)

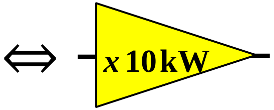


Few kW unit

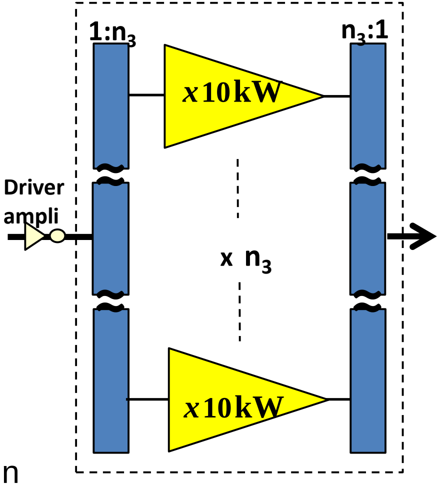




Few 10 kW unit



The number of pre-ampli depends on the module gain



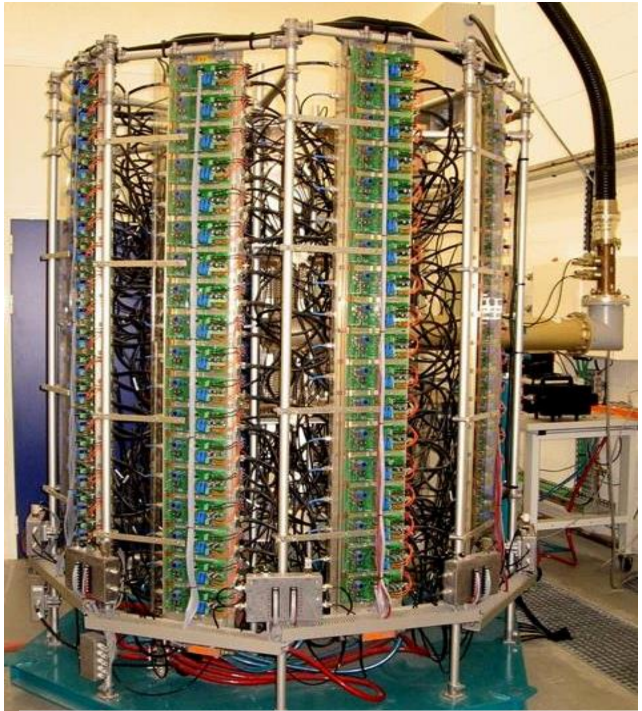
Few 100 kW unit

SOLEIL Booster first SSPA (P_{nom} = 35 kW @ 352 MHz) :

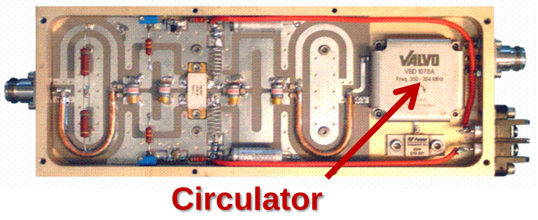
P_{mod} ≈ 300 W ; n_1 = 8 → 2.4 kW ; n_2 = 8 → 19 kW ; n_3 = 2 → 146 RF modules (128 Ampli + 18 Pre-A) → P_{out} ≈ 38 kW

→ Modularity & Redundancy inherent to such a design

Booster original 35 kW SSPA

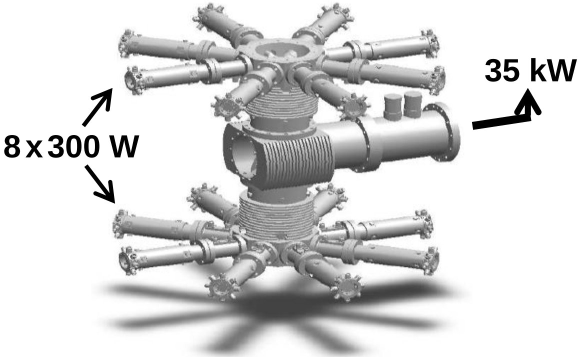


In 2005, world record for a SSPA



330 W CW - 352 MHz
amplifier module
VDMOS D1029UK05
from SEMELAB
(**G = 11 dB, η = 62 %**)

600 W - 280 / 28 V dc
power converter



Power combiner
(8 x 8 x 2)
8 dissipaters of
16 + 2* modules
* Pre-amplifiers

All amplifier components were designed in house and the mass production contracted to industry

~ 86 000 running hours over 13 years and only one single trip from the SSPA, in August 2016, due to a loose connection on a monitoring cable (down time ~ 2.10^{-5} and MTBF ~ 48 000 hours)
~ 1 module failure / year, without impact on the operation, thanks to the modularity and redundancy

Booster new SSPA's (2 x 60kW)

Booster RF system was originally designed for standard operation

The 35 kW amplifier drives a 5-cell copper cavity => V_{RF} = 1 MV (P_{diss} = 20 kW; P_{beam} = 5 kW → P_{tot} = 25 kW)

But low-*α* operating mode suffered from a low injection efficiency (15-20%) due to the long BO bunches

→ Heavy safety radiation constraints

→ Prevents more beam lines to join this operating mode

2nd RF station installed to increase V_{RF} from 1 MV up to 3 MV in winter 2017-2018

- Shorter bunch length → *SR injection efficiency improved by a factor of ~ 2 in low-α operation*
  - Former spare cavity installed in one straight section of the Bo ring and powered with 60 kW (V_{RF} = 1.8 MV)
  - New 60 kW - 352 MHz SSPA, identical to a standard tower of our SR amplifiers (10 dissipaters of 16 modules, built from 160 RF modules of 400 W with BLF574XR transistors and their dc-dc converters made available by the SR SSPA refurbishment)
  - SSPA and its associated LLRF & control (replica of the actual one) inside the Bo RF room
  - Increase V_{RF} of the existing plant from 1 MV up to 1.2 MV → P_{RF} ~ 30 kW (P_{beam} ~ 0)

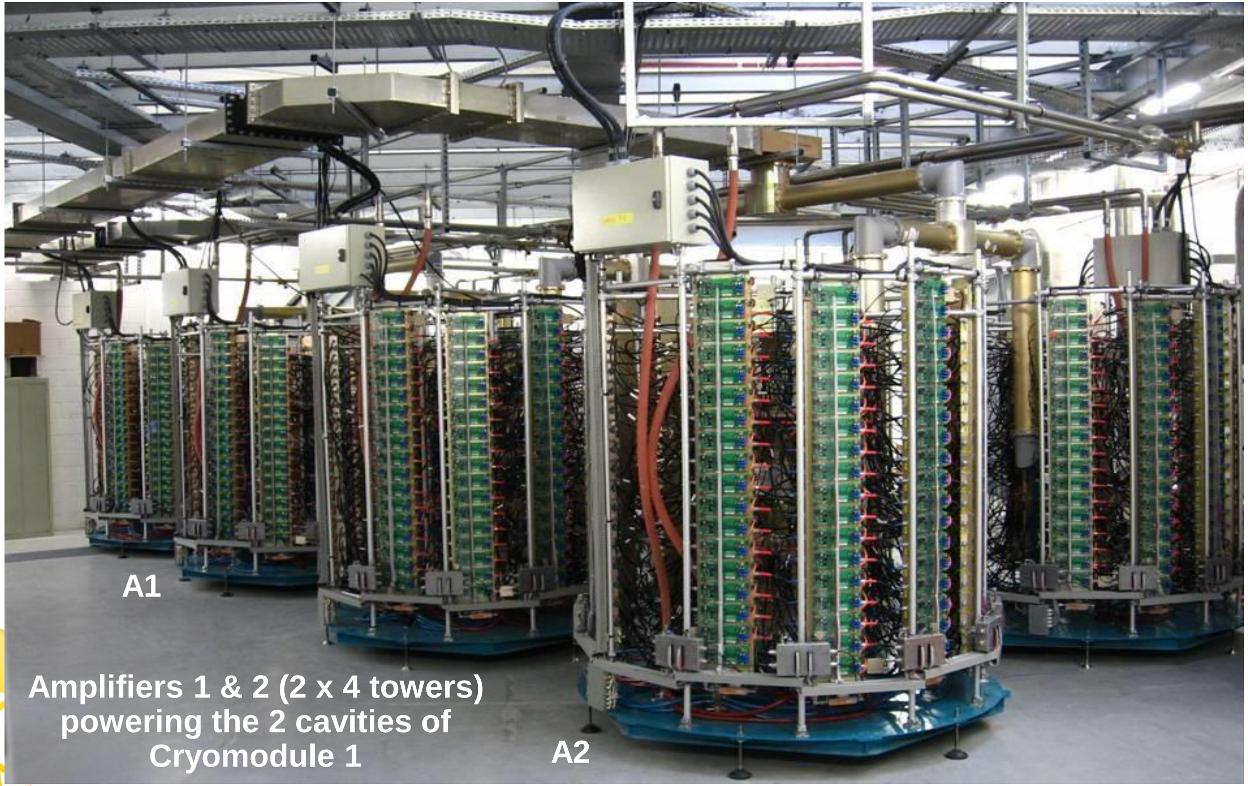
Original 35 kW Booster SSA upgrade up to 60 kW → increase total V_{RF} from 3 MV up to 3.6 MV in October 2019

'Upgraded' Low-*α* operating mode available for users
with V_{RF} = 3.6 MV (SR injection efficiency = 35% instead of 18% before)
+ power savings and redundancy in all other operating modes

SOLEIL SR 180 kW SSPA's

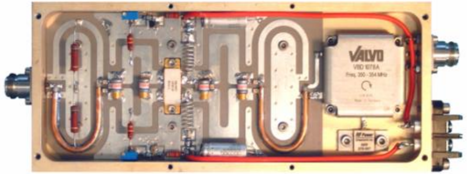
Same principle as the BO one but extended to 4 towers of 45 kW:

- → 10 dissipaters of 18 modules per tower
- → 726 modules / amplifier x 4 cavities → 16 towers & ~ 3000 modules

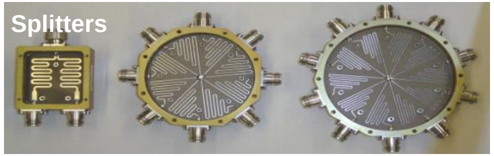


LDMOS LR301 from POLYFET

P = 315 W, G = 13 dB, η = 62 %

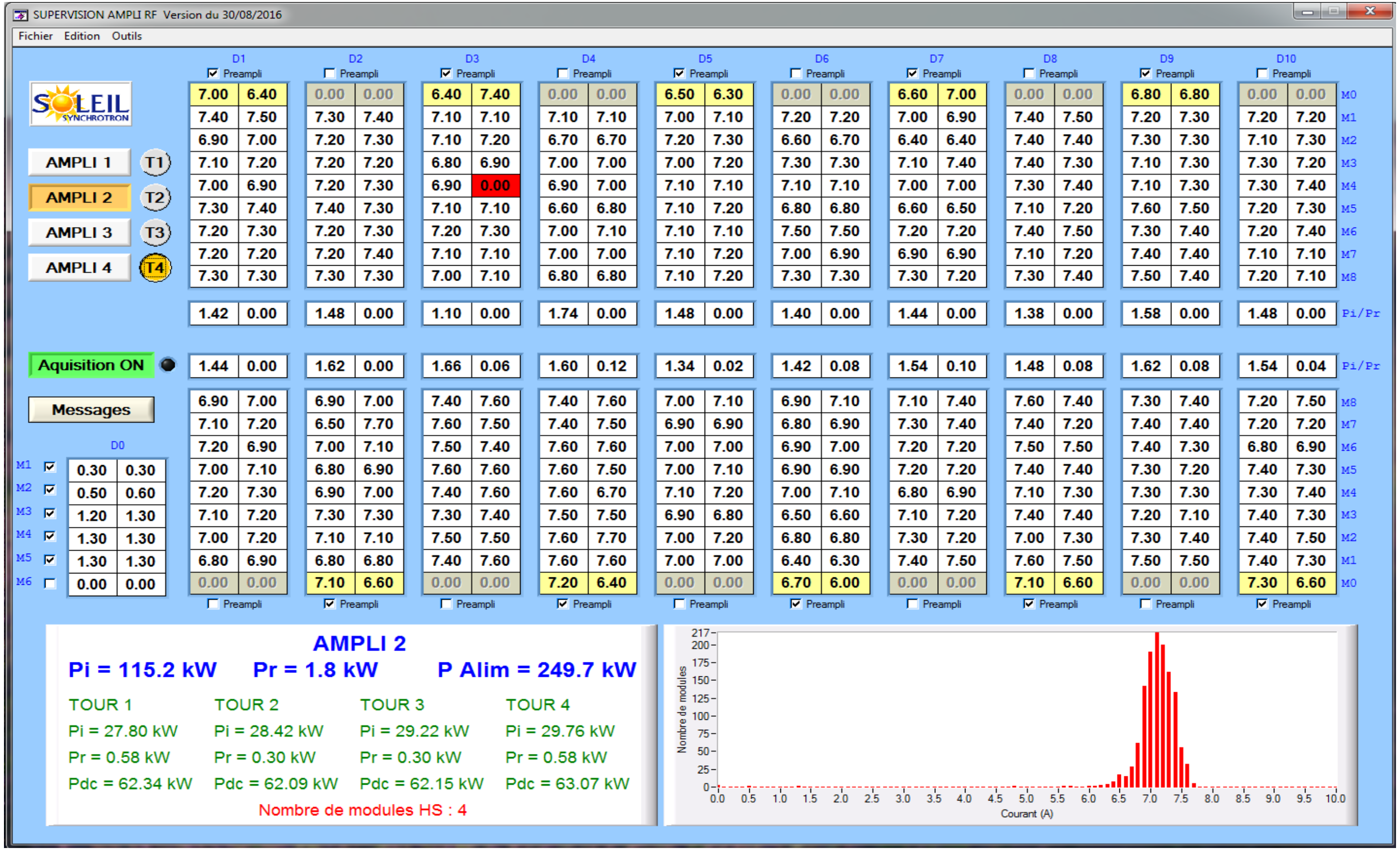


600 W - 280 Vdc / 28 Vdc



SR SSPA Control

Multiplexing (I x 2 x 680 mod. + P_i & P_r x 80) → single µcontroller for 1 complete amplifier (4 towers)



Tower T4 of Amplifier 2

Top transistor currents

Pi & Pr 2.5 kW combiner

Bottom transistor currents

180 kW SSPA's Refurbishment

The failure rate of our original LR301 transistors remains significant ~ 3% a year.

2 types of failures identified : - Transistor breakdown
- Damaged soldering due to thermal fatigue

→ **Module refurbishment from 2013 to 2020** (rate of 5 towers a year with SOLEIL staff + external resources)

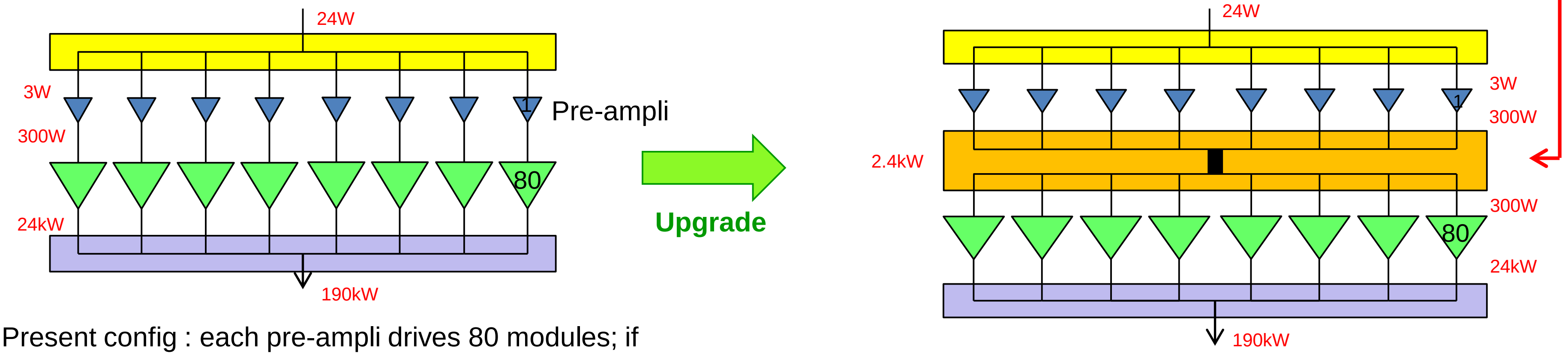
LR301 replacement by 6th generation BLF574XR (V_d = 50V instead of 30V *with better performances*)

- More robust transistor and lower thermal stress → longer lifetime → less maintenance
  → ***failure of a single « new » transistor (~ 8 years of operation)***
- + 7 dB transistor gain → 160 modules & their dc PS are got back for the new BO SSA
- P_{mod} increased : 315 W → 330 W for SR and 330W → 400W for BO
- *Electrical power savings (efficiency RF/DC: 48 % → 57%) compensated the investment cost in < 3 years*

SSPA power increased from 180 to 200 kW
→ More redundancy allowing to store full beam (500 mA) with 3 running SSPA's out of 4

180 kW SSPA's Refurbishment

- Cure the lack of redundancy in the pre-amplification stage → develop a "combiner-divider"



Present config : each pre-ampli drives 80 modules; if one of them fails the amplifier is stopped

Thanks to the combiner-divider, the failure of a pre-ampli does not affect the functioning anymore

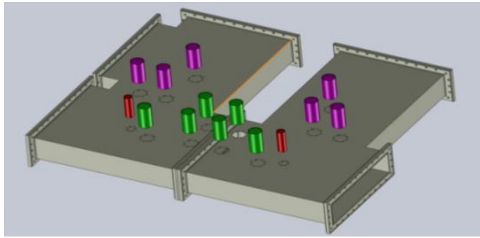
- **Modification of the 2.5 kW combiners** (welded → screwed connections) to increase their power capability and robustness

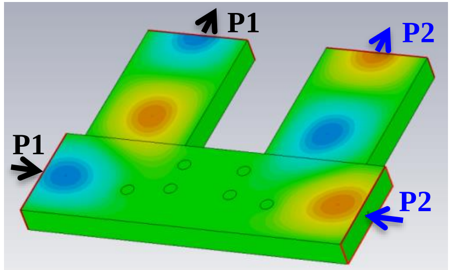
Storing 450 mA using a single CM

Modification of the waveguide network to combine the power from two amplifiers into one cavity

→ *Possibility of storing 450 mA using a single CM*

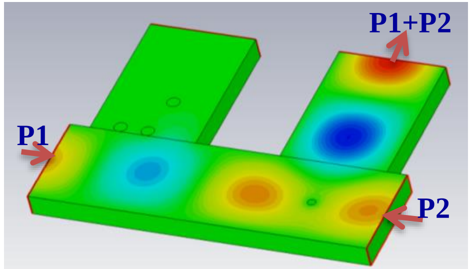
« **Magic Switch** »

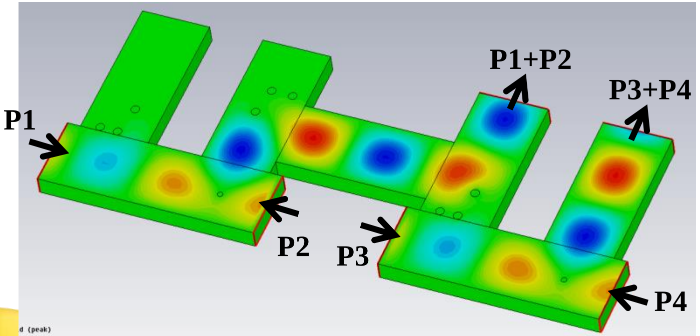




OR

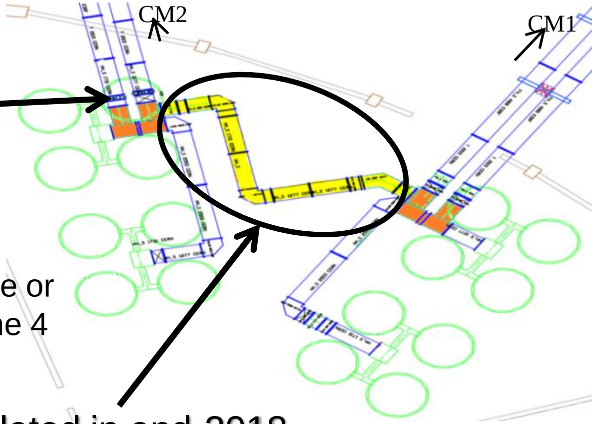
depending on the post configuration





Connecting 2 Magic Switches

Waveguide network layout to power one or the other CM with 300 kW / cav from the 4 SSPA's, combined by pairs



- The 2 Magic Switches implemented and waveguide distribution completed in end-2018

SR SSPA's Operational Results

4 x 200 kW SSPA's
- Investment cost = 3 M€ + 350 k€ for refurbishment
- Operational cost = 400 k€ per year → 6 M€ from installation
- Maintenance annual cost = 5 k€

MTBF & beam downtime, cumulated by the 4 SR SSPA's over ~ 95 000 running hours in ~ 15 years

Equipment	MTBF	Downtime	Comments
a) 4 x RF amplifiers	~ 13 500 h	~ 8.10^{-5}	Failures from preamplifiers and 1st stage combiners (solved) + supervision issues
b) 4 x Power supply 500 kVA thyristor-based with 680 DC/DC converters	~ 6 300 h	~ 3.10^{-4}	Single rectifier per amplifier + aging DC/DC converters
a) + b) 4 x RF transmitters	~ 4 300 h	~ 4.10^{-4}	

Already excellent MTBF and operational avaibility, but still perfectible by :

1) Providing some **more redundancy in the ac-dc power conversion**, which originally consists in a single 500 kW rectifier per SSPA and DC/DC converters

2) **Upgrading the amplifier supervision system**

→ **Cures for these "weaknesses" in our new design**

Rectifier + DC/DC converters replacement by direct AC/DC converters

→ **Redundancy,** easy maintenance, reduced time to repair, solved obsolescence issues and cost reduction

→ **Efficiency improvement**

Total actual efficiency = 87% (96% rectifier and 90% DC/DC converters)

Increased to 96% with new AC/DC converters

→ AC/DC converter voltage remote control allows to match for maximum efficiency over whole power range (impossible presently: components set to reach max efficiency only at max power – 1dB compression)

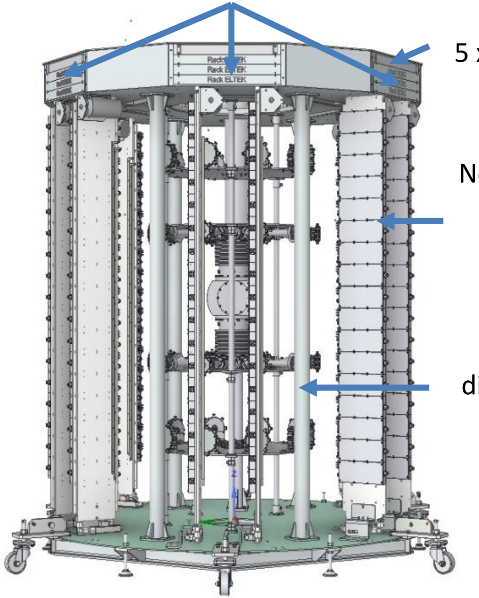
Power supply upgrade plan

From mid-2023, 1 x 50 kW will be installed every 2-3 months in the SR to benefit from **four fully upgraded 200 kW SSA'S by the end of 2026 for SOLEIL Upgrade**

Power Supply Upgrade

8 x 3 kW power converters

5 x 24 kW AC/DC racks (19" 3U)



5 x SSA control rack (19" 1U)

New dissipater orientation to optimize and reduce power cable length

Support pipes with bigger diameter, adapted to the new power supply weight

3D view of a future upgraded SSA RF tower with new AC/DC power converters

Beam current	450 mA	500 mA
RF power into the beam	506 kW	562 kW
Electrical power (4 SSA's + rectifiers and converters in present SOLEIL machine)	1148 kW	1278 kW
Electrical power (4 upgraded SSA's @ 50 V)	1019 kW	1081 kW
Electrical power (4 upgraded SSA's @ 44 V)	894 kW	952 kW
Maximum consumption reduction (44 V)	**22.1%**	**25.5%**

- **Power savings of 1.75 GWh max per year**
- **130 k€ savings per year**

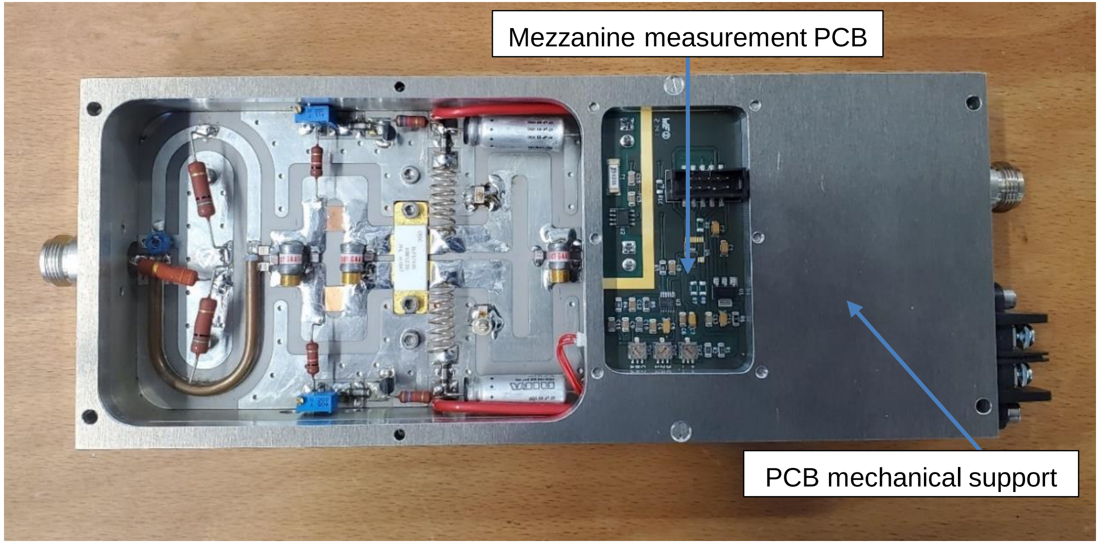
Compensate the investment cost in ~ 6 years

Current measurements were initially done in the DC/DC converter.

New architecture → RF module modifications :

- Electronic mezzanine card for supervision (1 x T° sensor on circulator load to evaluate reflected power + 1 current sensor)

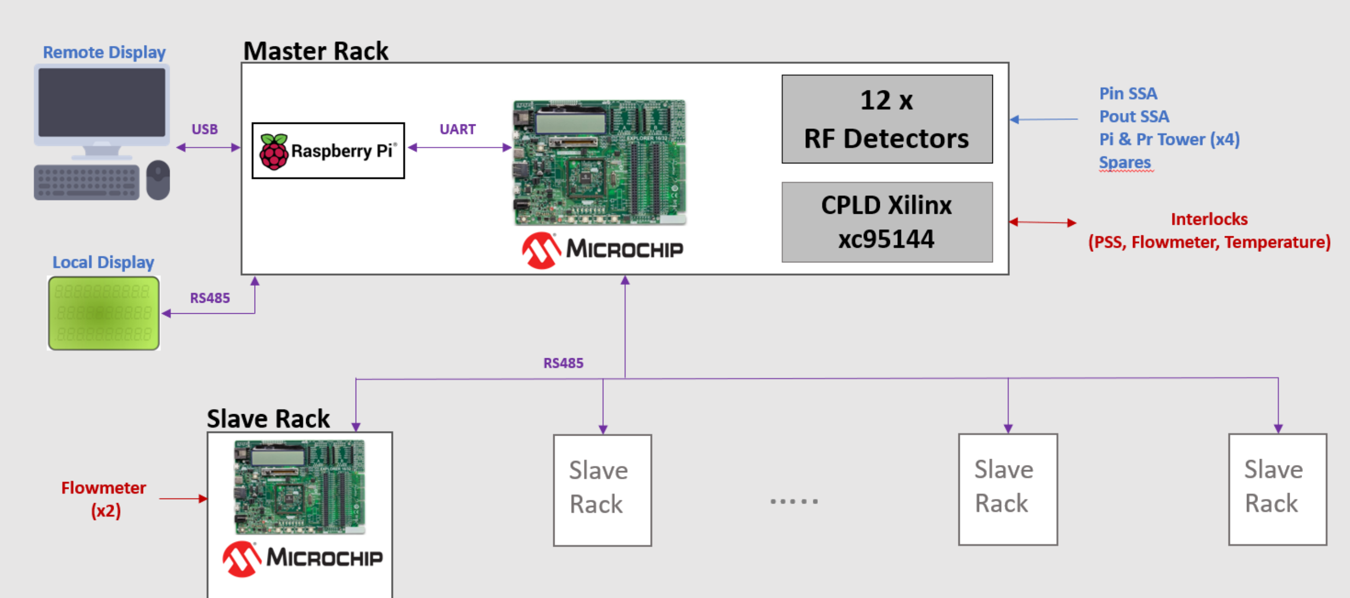
+ T° sensor on the dissipater (interlock purpose)



Module modifications

Upgrade of the SSA supervision system

<u>Architecture modification</u> : Single µcontroller for 1 complete amplifier → 1 "slave" ucontroller for 2 dissipaters
+ 1 "master" for the complete amplifier

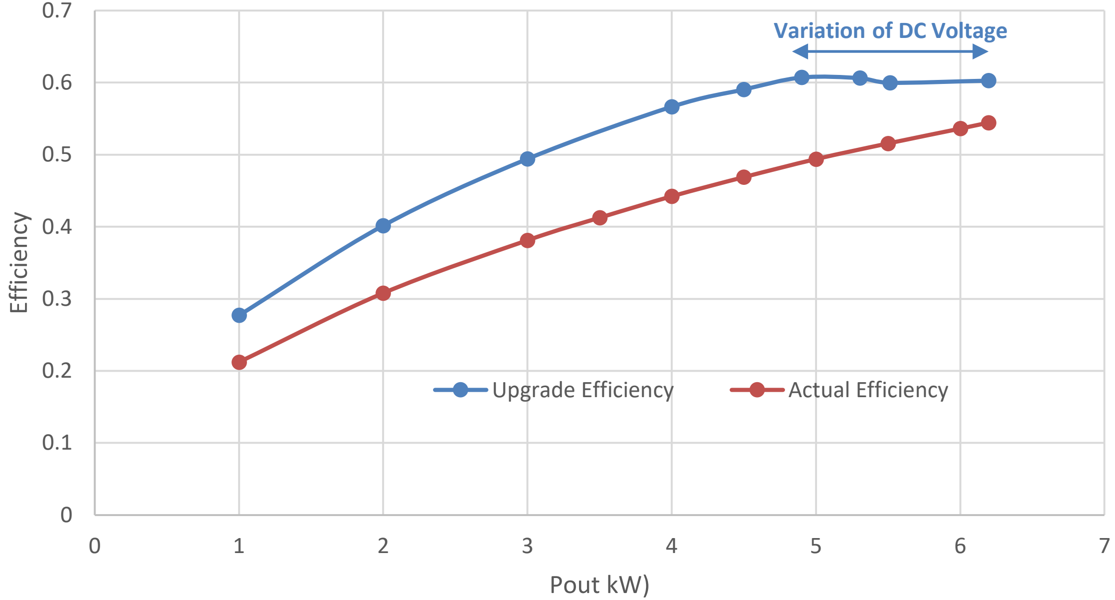


Timing : Configurable cycle time (min=2ms)
Configurable addressing µcontroller position

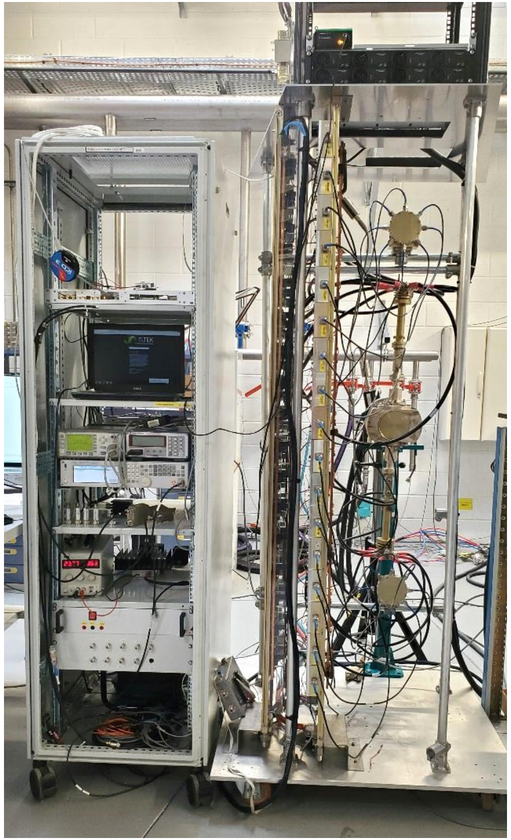
Moved from dsPIC33f to **PIC32MZ to increase performances**
(processing speed, calculation precision, number of communication buses)

Power Supply and supervision system Upgrade

6 kW prototype test



Efficiency comparison results



6 kW prototype test stand

Next steps

- 60 kW prototype mounting and tests – September 2022
- Implementation in present SOLEIL Booster – October 2022
- 2nd Booster SSA installation – January 2023

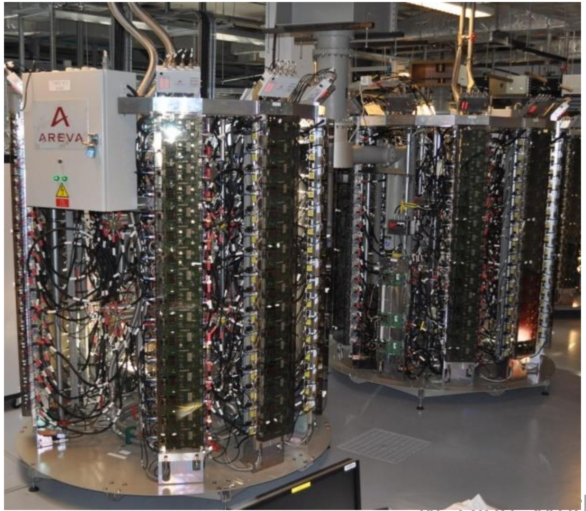
SOLEIL SSPA R&D
Scientific Collaborations and Technology Transfers

SOLEIL R&D with 352 MHz SSPA's

Development of new RF modules, based on 6th generation LDMOS (Vd = 50V)
→ **P_{mod} ~ 700 W, G ~ 20 dB, η > 70% at 352 MHz**
[With original LR301 (28V), P_{mod} = 315 W, G = 13 dB, η = 62 % @ 352 MHz]

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

ESRF project of partly replacing its 1 MW klystrons by 150 kW SSPA's (1 per cavity)
→ 2009, SOLEIL transfer of technology with ELTA-AREVA
→ 7 SSPA's of 150 kW, built by ELTA under SOLEIL license



ESRF 150 kW 352 MHz SSPA from ELTA/SOLEIL
2 towers of 75 kW ↔ 260 RF modules of 700 W

BO : 4 x 150 kW SSPA's in use since 2012

SR : 2 x 150 kW SSPA's in use since 2013

BO + SR : ~ 1 820 transistors

DC-to-RF efficiency of 58%, dc-dc converters included
With new ac-dc converters → η (overall ac to RF) > 60%

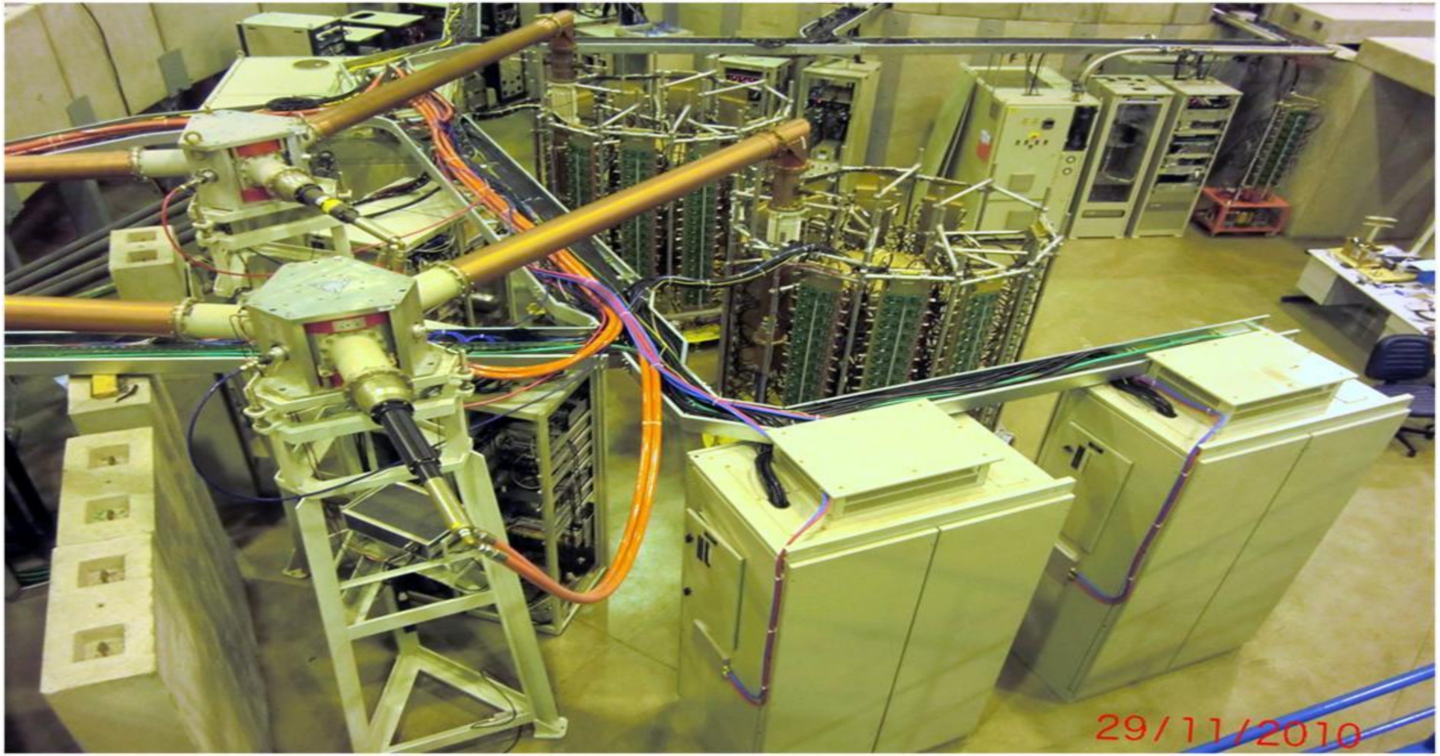
LNLS - SOLEIL Collaboration

Two SSPA's of 50 kW @ 476 MHz for LNLS (Brazilian LS) SR * with components designed by SOLEIL
(400 W modules with BLF574)

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

** A 2.5 kW 476 MHz SSA had already been built for the LNLS Booster*

LNLS - SOLEIL Collaboration



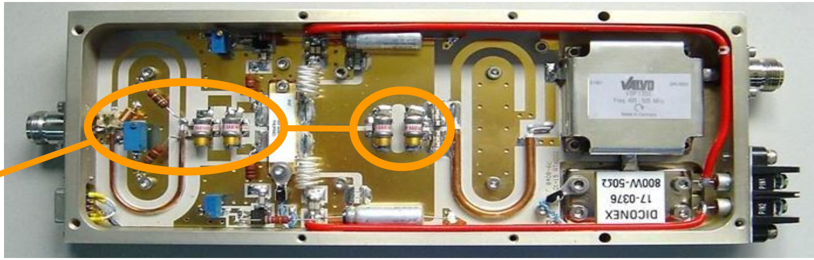
The two 50 kW SSPA's of the LNLS SR have run satisfactorily for > 10 years
→ Use of SSPA's @ 500 MHz at SIRIUS

R&D with 500 MHz SSPA at SOLEIL

Experience feedback →
1) **Increase effort on the modularity/redundancy and the efficiency ***
2) **Moderate power for long lifetime (thermal stress → soldering degradation)**

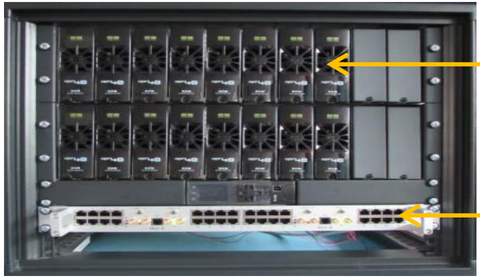
** + 10 pts in efficiency lead to electrical power savings over 10 years of operation ≈ full amplifier cost*

- **New 650 W - 500 MHz modules** using 6th generation (Vd : 50V) LDMOS BLF578 from NXP
  - RF output power, P_n : 650 W CW
  - Input return loss : - 40 dB at P_n
  - Unconditional stability (K >10 dB)
  - Gain : 17 dB at P_n (1 dB compression)
  - Efficiency ≈ 62 % at P_n
  - Gain dispersion : +/- 0.2 dB at P_n
  - Phase dispersion : +/- 5° at P_n



Mandatory for good combining efficiency → Components for gain and phase adjustments

- Modular dc-dc converters + single power rectifier replaced by **modular 230 V_{ac} / 50 V_{dc} converters**, in 2 kW units, 96% efficiency, voltage remote control
  → optimized efficiency for any operating power : 56% (overall) @ P_{max} and 50% @ 0.6 P_{max}



- Modularity brought in the preamplification stage by inserting the « divider-combiner »

500 MHz SSPA for THOMX[1] and SESAME[2]

[1] *ThomX : Compton X-ray source under construction in Orsay, France*
[2] *SESAME : Jordan Synchrotron light source*

ThomX 50 kW SSPA
(6 x 16 RF modules + 3 x 15 PS)

- Fully modular 50V power supplies → 230 V_{ac} / 50 V_{dc} converters, in 2 kW units, 96% efficiency, with voltage remote control for efficiency optimization
- Change from the tower to cabinet assembly, better suited with the new power supplies
- Control upgrade → stand-alone, self-protected and more modular (1 µcontroler per dissipater)

SESAME 80 kW SSPA
(10 x 16 RF modules + 5 x 16 PS)

✓ For SESAME SR : 4 x 80 kW SSPA → 1st one built by SOLEIL as a demonstrator
→ 3 others on the same model by SigmaPhi Electronics (former SOLEIL licensee)
Status : all in operation (first pair since end 2016 and 2nd one since May 2017)

✓ The ThomX 50 kW SSPA is also completed and commissioned

1.3-1.4 GHz SSPA R&D

RF Power Source requirements for LUCRECE* : 20 kW CW SSPA @ 1.3 GHz

** RF R&D program for the French FEL project LUNEX5*

- Comparison between GaN and LDMOS technology

Transistor performance measurements in CW mode

	Old Gen GaN	Old Gen GaN	New Gen LDMOS	New Gen GaN
V_d (V)	50	50	50	50 (65Vpulse)
P_{out} (W @ 1 dB comp.)	71.2	150.2	700	400
P_{out} (W @ 3 dB comp.)	425.9	430.9	X	1000
Gain (dB)	14.11	18.33	18.16	17
Efficiency (%)	55.6	65	62	71

X: not measured

R&D @ 1.4 GHz

On going tests at 40V to limit dissipated power on the dice → 740W at 3dB comp. with 65% efficiency and expected to go up to 900W

Perspective : Possible adaptation of LUCRECE SSPA for SOLEIL Upgrade if the harmonic system is active (1.41 GHz)

Summary and Conclusions

- **SOLEIL has pioneered the use of SSPA's in particle accelerators**
  Original home-made design (35 kW in the BO and 4 x 180 kW in the SR) has operated for about 15 years with outstanding **operational MTBF >> 1 year**

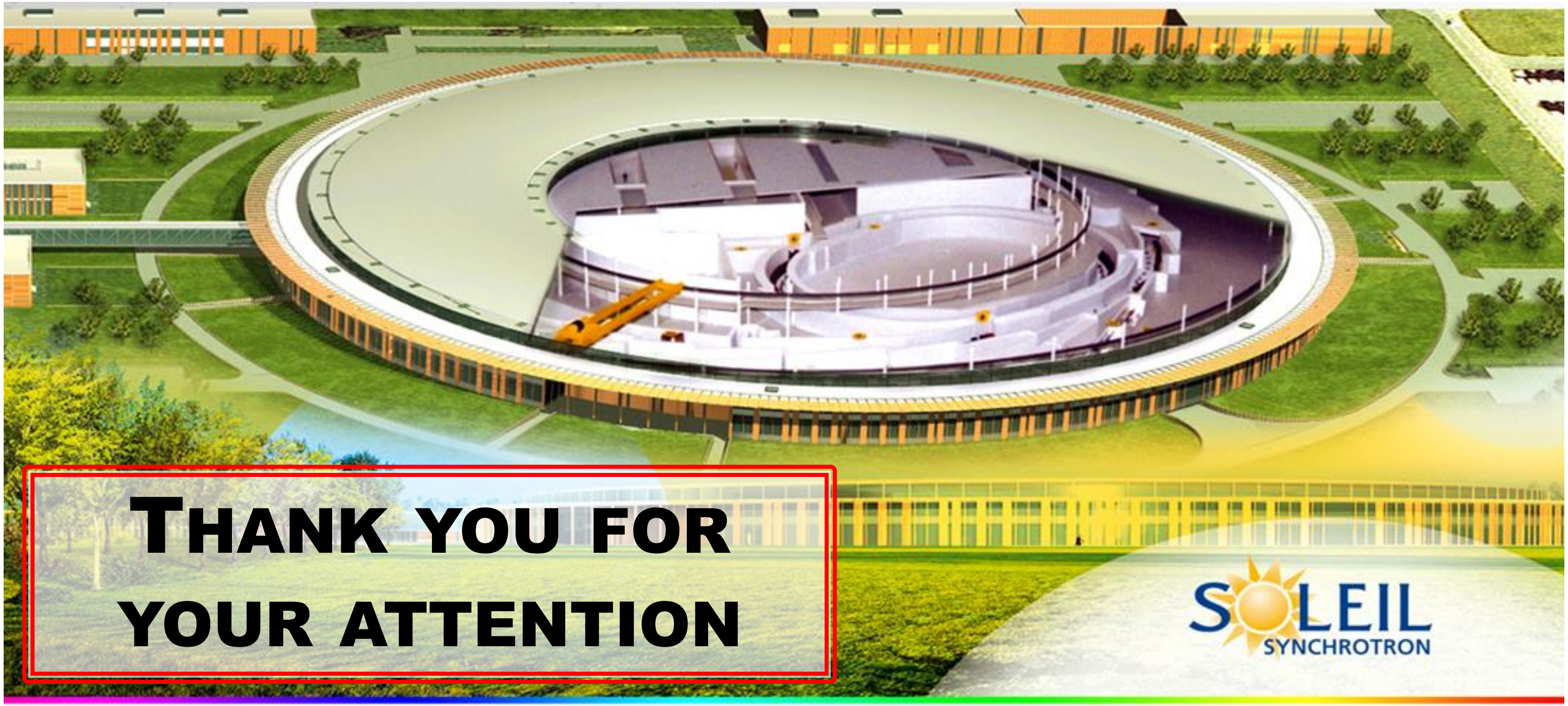
- **BO RF upgrade** : → 2 RF plants with 60 kW SSPAs → Redundancy + SR injection efficiency improvement in low-α operating mode (~ factor of 2)

- **SR SSPA refurbishment** : in 2013, start of original transistor replacement by **6th generation LDMOS** (V_d = 50 V instead of 30 V), much more robust and with higher gain and efficiency → **Drastic reduction in module failures, higher power capabilities and efficiency** + available components for the new 60 kW BO SSPA

- **SR SSPA refurbishment** + "Magic switches" (+ Upgraded cavity couplers) → **Additional redundancy**
  Possibility to store I_{beam} using either a single CM (450 mA) or 2 CMs (500 mA) with only 3 running amplifiers/cavities

- SOLEIL R&D on SSPA → improvement of the original design in **compactness, reliability and efficiency**
  Overall (plug to RF) efficiency ~ 60% at 352 MHz or lower frequencies, ~ 56% at 500 MHz and ~ 50% at 1.3 – 1.4 GHz

- Scientific collaborations & technology transfers to the industry (ESRF, LNLS, ThomX, SESAME, LUCRECE, ...)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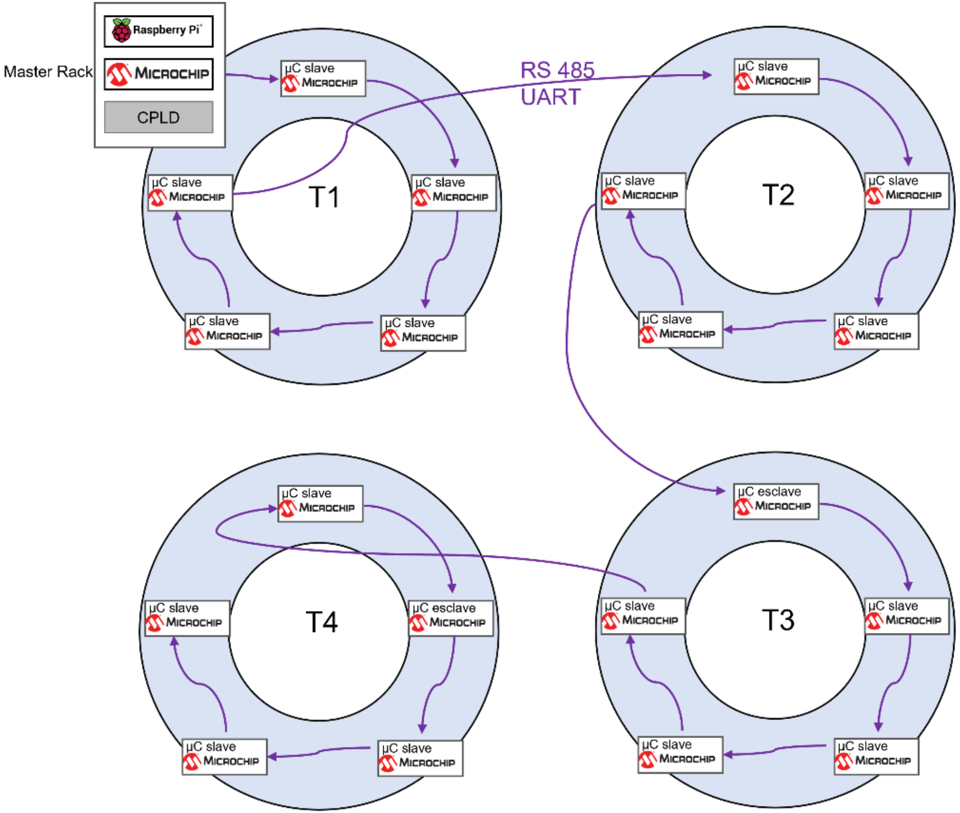
SOLEIL SSA supervision system principle



SOLEIL Upgrade Parameters

	4 (3) NC cavities ESRF-EBS
Length [m]	~ 4.20
Redundancy	Yes
V_{RF} [MV]	1.8
P_b [kW]	362
V_{cav} [kV]	450 (600)
P_{dis} [kW]	4 x 20 (3 x 36)
P_{cav} [kW]	111 (157)
P_{RF} [kW]	444 (471)
Coupling	$ß_c$ = 5
Z_{HOM}	TBD

SOLEIL Upgrade Parameters	V0356 lattice version
Circumference, L [m]	354
Energy, E_n [GeV]	2.75
RF frequency, f_{RF} [MHz]	352
Max beam current, I_b [mA]	500
Energy loss per turn, dU [keV]	722.5 ǂ
RF power into the beam, P_b [kW]	362
Overall RF voltage, V_{RF} [kV]	1800
Cavity voltage, V_{cav} [kV]	650
Coupling factor, $ß_c$	5
Energy spread, s_E / E	$0.9\ 10^{-3}$ *
Momentum compaction factor, α	$1.05\ 10^{-4}$
Emittance, e_x / e_z [pm.rad]	84 / 25 ; 55 / 55 *
RF energy acceptance, $(DE / E)_{RF}$	$7.7\ 10^{-2}$
Longitudinal damping time, t_s [ms]	12.2 *
Transverse damping times, t_x / t_z [ms]	7.7 / 14.4 *
Synchrotron frequency, f_s [kHz]	1.78
Natural RMS bunch length, s_s [ps]	8.5

ǂ *Including 264 keV for the ID's*

** Without ID's contribution*