SOLEIL Solid State Ampilfier Supply For SESAME

TTC Workshop

QST Rokkasho Fusion Institute, 25-27 January 2022

Massamba DIOP

On Behalf of the RF & LINAC Group

COLLABORATION CONTEXT

- **SOLEIL pionneered the development and exploitation of SSPAs for Particule Accelerators**
- Following the success of the SOLEIL 352 MHz SSPAs, several collaboration demands to build SSPA : LNLS (2x50 kW@476 MHz), ESRF (7x150 kW@352 MHz), ThomX (50 kW@500 MHz)
- And lab support for call for tender specification writings and troubleshooting advices

- **2013: official start of SOLEIL/SESAME collaboration for SSPA supply**

SESAME (**S**ynchrotron-light for **E**xperimental **S**cience and **A**pplications in the **M**iddle **E**ast) is a 2.5 GeV synchrotron light source located in Amman (Jordan)

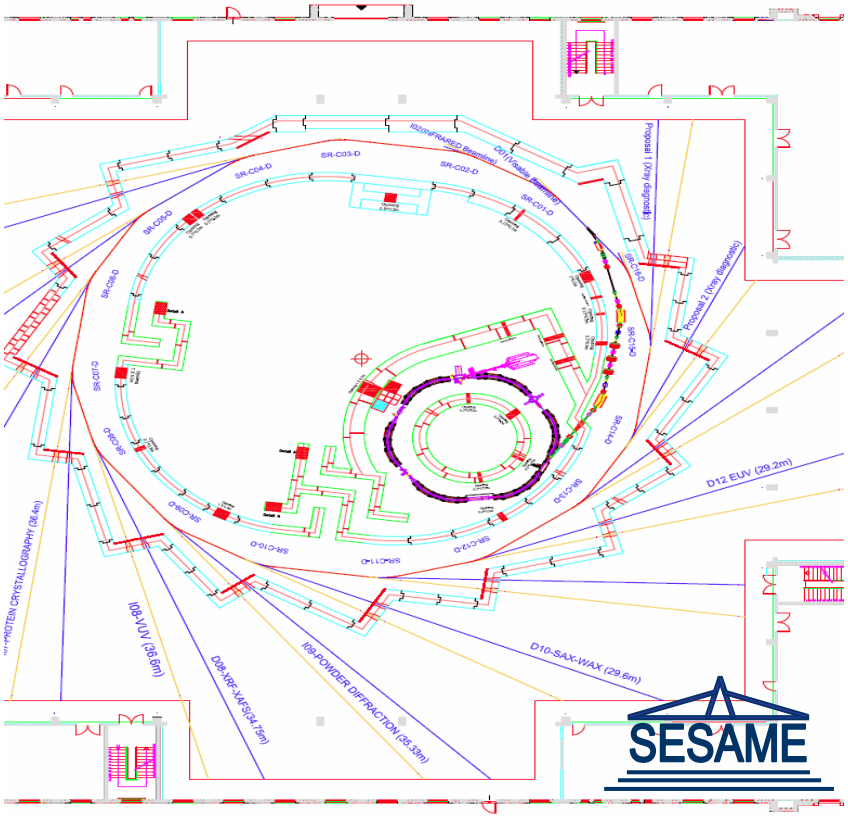
Officialy opened to users on May 2017

Current members

COLLABORATION CONTEXT

SESAME Storage Ring main parameters

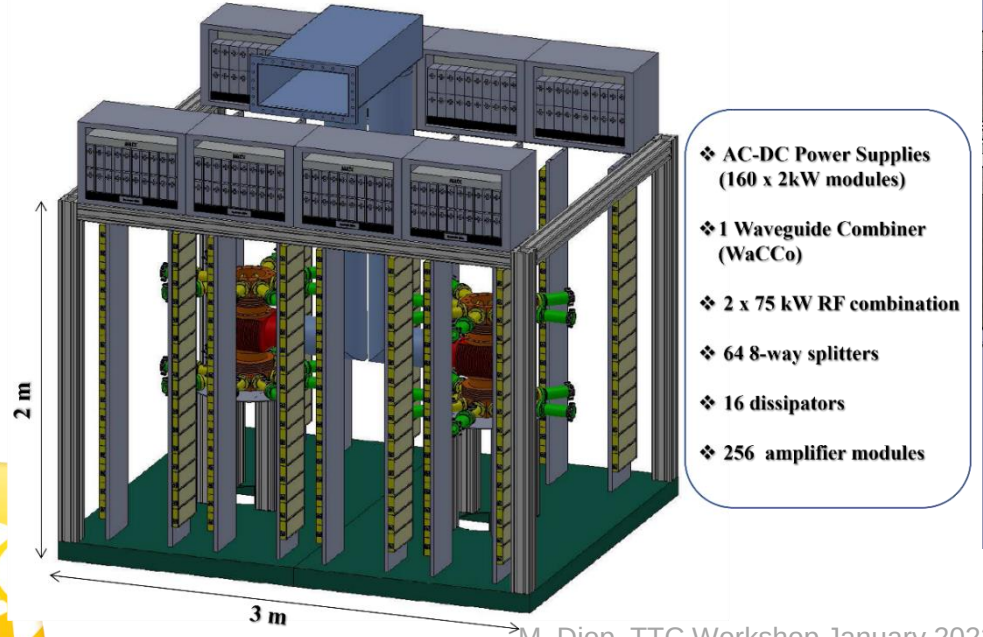
Parameter	Value
Energy	2.5 GeV
Circumference	133.20 m
Super Periods #	8
Bending Dipole	1.45545 T
Radiation loss/turn	590 KeV
Beam current	400 mA
Beam power loss	236 kW
Total RF voltage	2.4 MV
Harmonic number	222
Mom. Comp. factor	0.00828
Energy acceptance	1.45 %
Nat. Emittance ε_x / ε_z	25.74/0.2574
Energy Spread rms	0.1073%
Beam Lifetime	21.5h

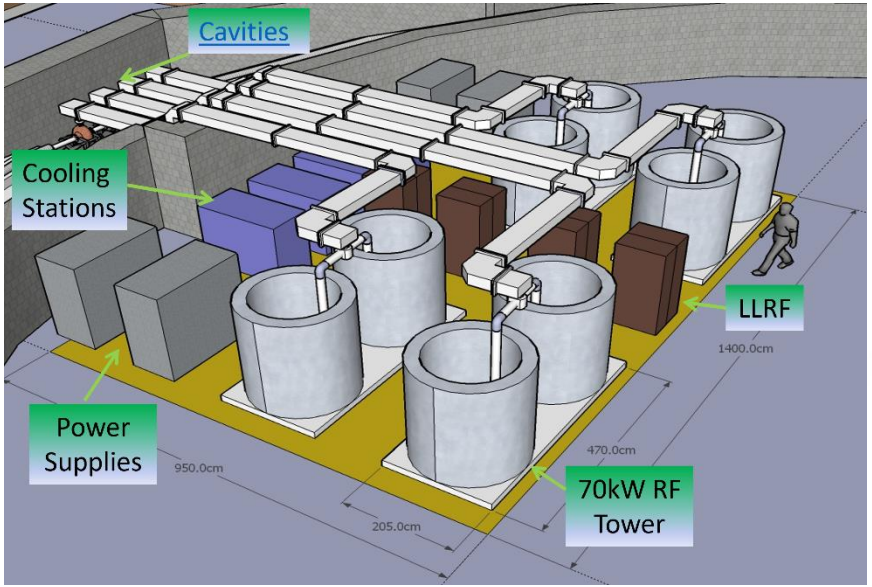


SESAME Machine layout

COLLABORATION CONTEXT

- **SOLEIL RF initial contribution demand** :
  - 140 kW SOLEIL SSPA demonstrator @ 500 MHz (2 x 70 kW towers)
  - Training for maintenance and support for the realization of 3 other SSPA from SOLEIL former industrial partner, Sigmaphi Electronics (SPE)
  - Refurbishment of 2 ELLETRA cavities

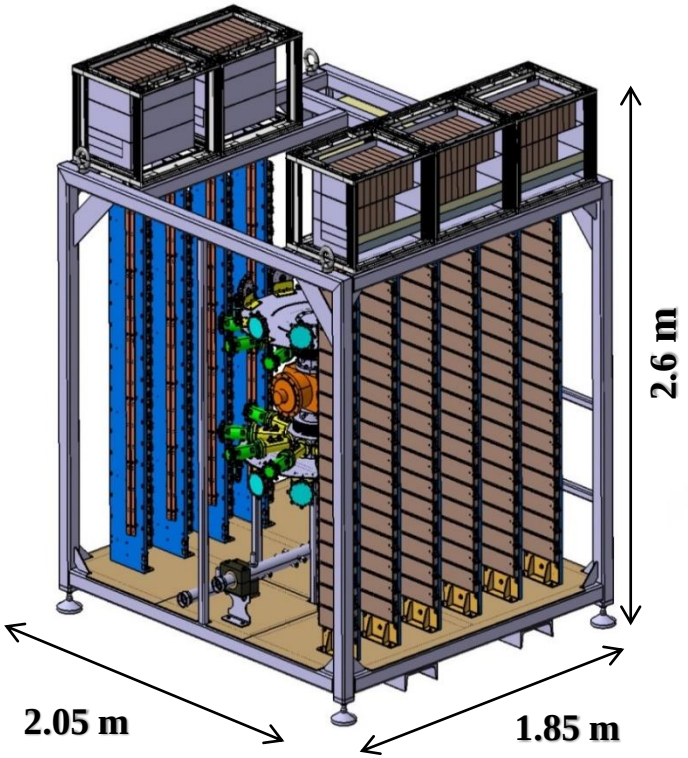




COLLABORATION CONTEXT

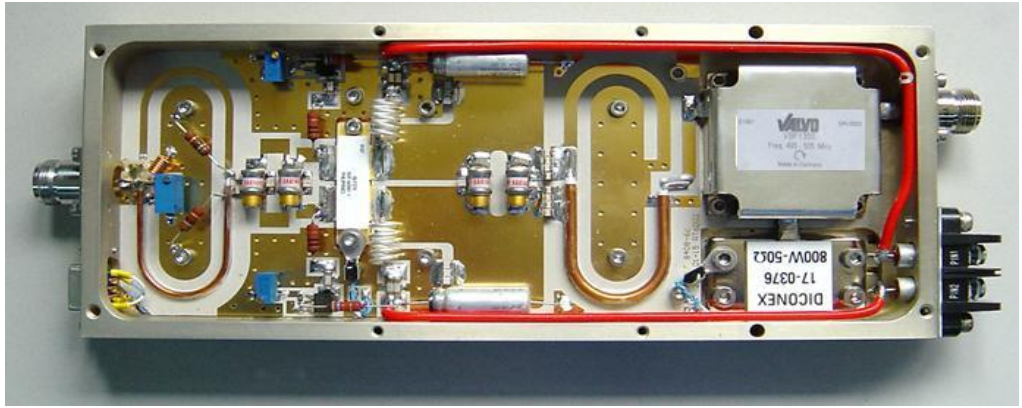
- **SSPA contribution modification in 2012**
  - Motivated by cost reduction
  - Replacement of 140 kW SSPA with 80 kW units
    → 4 x 80 kW SSPAs needed for the storage ring

- **Organisation**
  - First 80 kW amplifier (demonstrator) designed and built at SOLEIL
  - This amplifier consists in a combination of 160 modules, which can provide 550W each – tested by SOLEIL and SESAME RF teams at SOLEIL
  - SOLEIL had concluded an agreement of transfer of know-how on SSA with SPE, which will build the 3 other amplifiers for SESAME after the validation of the first one



SSA R&D at 500 MHz

Modules of 650 W at 500 MHz using 6th generation LDMOS BLF578 from NXP



- RF Output Power: 650 W CW
- Gain : 17 dB
- Efficiency ≈ 63 % 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)

230 V_ac - 50 V_dc power converters
96% high efficiency 2 kW modules basis

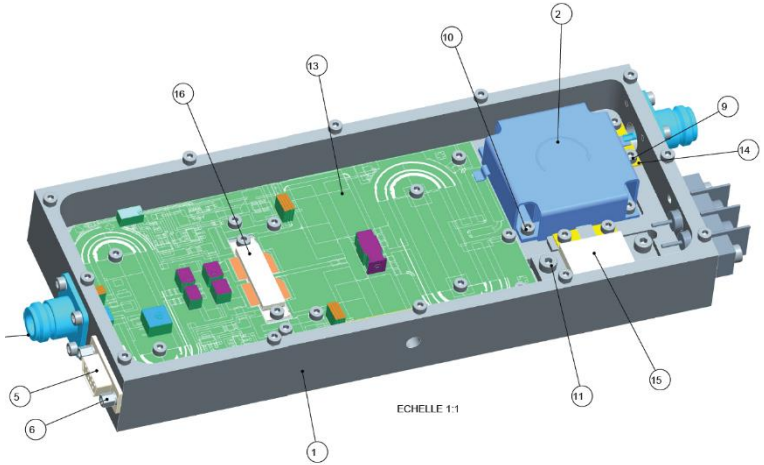
Remote voltage control
→ optimum amplifier efficiency for different operating power

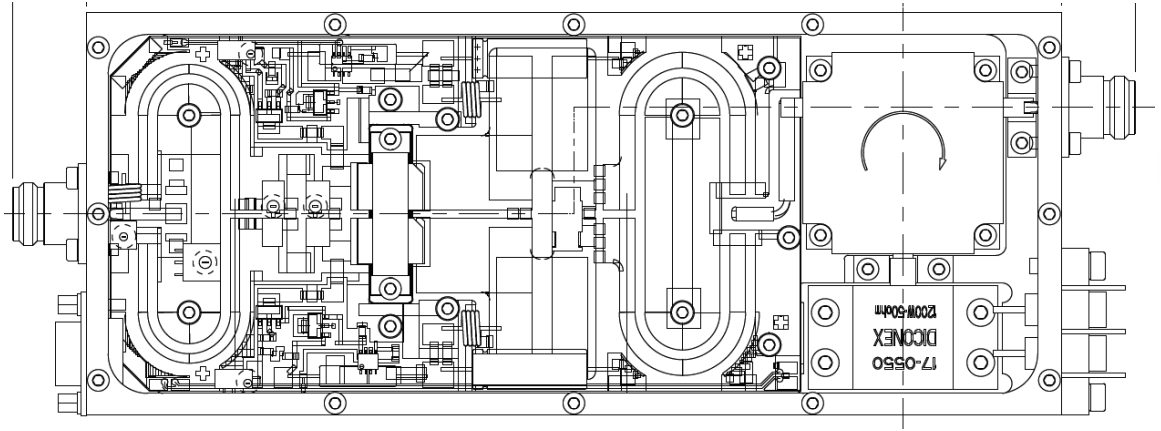
SOLEIL original module modifications

- **SESAME demand for all amplifiers to be identical**
- To reduce manufacturing costs and for warranty purpose, SPE proposed a few modifications on the original design:

Modifications for SESAME module:

- 2 PCBs added for circulator pins
- Position of RF chokes
- New SMD components
- Output RF connector
- Number of cover's screws

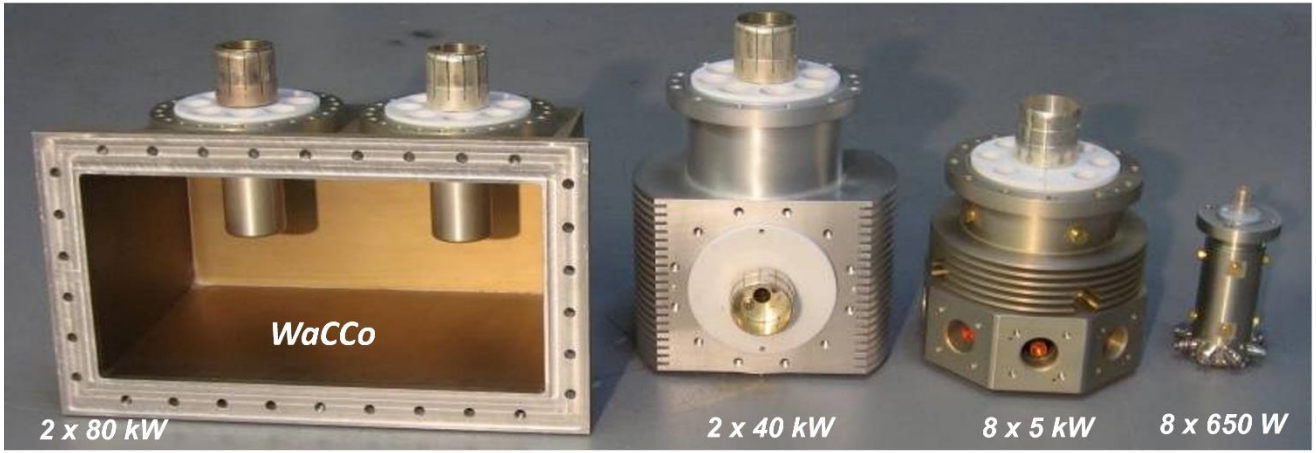


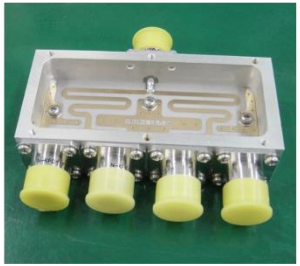


- SOLEIL implementation and SPE validation

Power combination components

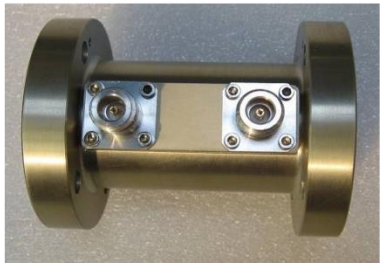
Power combiners





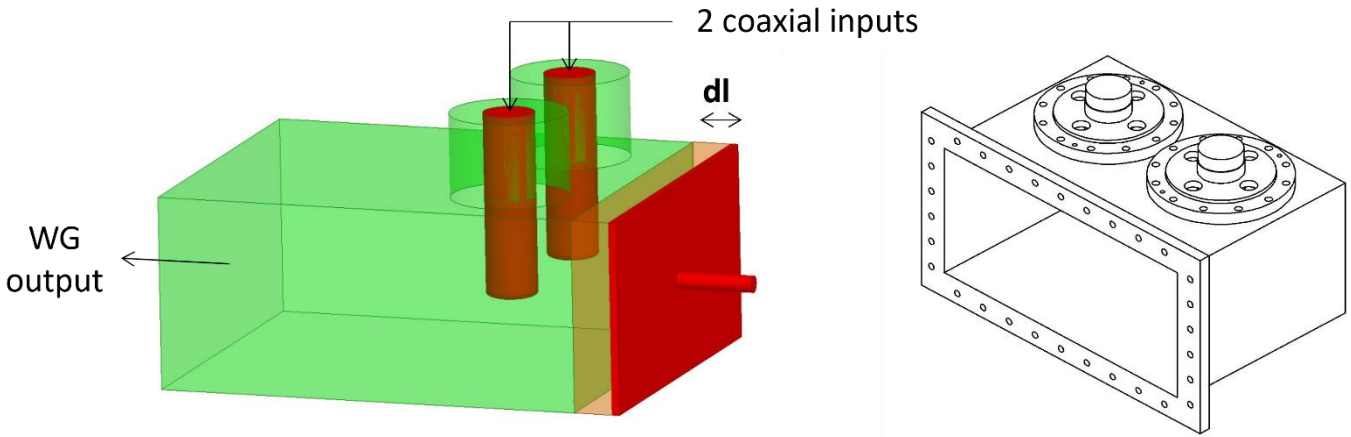
2 & 4 - way splitters

8-way splitter



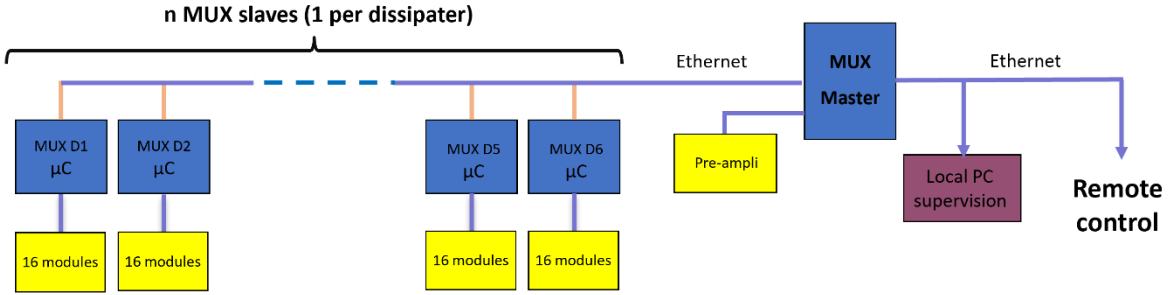
P_i - P_r monitoring coupler

Waveguide to Coaxial Combiner (WaCCo)



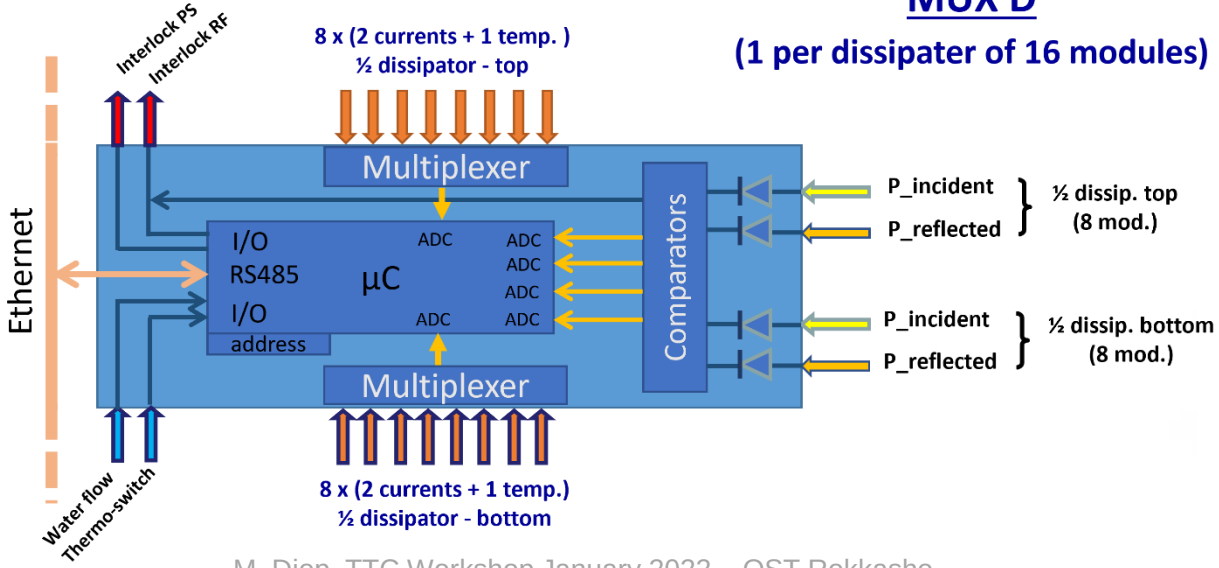
- Two 6 inches coaxial input ports (2 x 80 kW) → 1 WG output
- Replace a coaxial combiner + a coaxial-to-WG transition
- Design optimization with HFSS and Microwave Studio
  → A 500 MHz prototype has been validated at low power
- **<u>Movable SC</u> → adjustable coupling for matching different configurations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

SSPA control



MUX D

(1 per dissipater of 16 modules)



PLANNING

➢ **Schedule** :

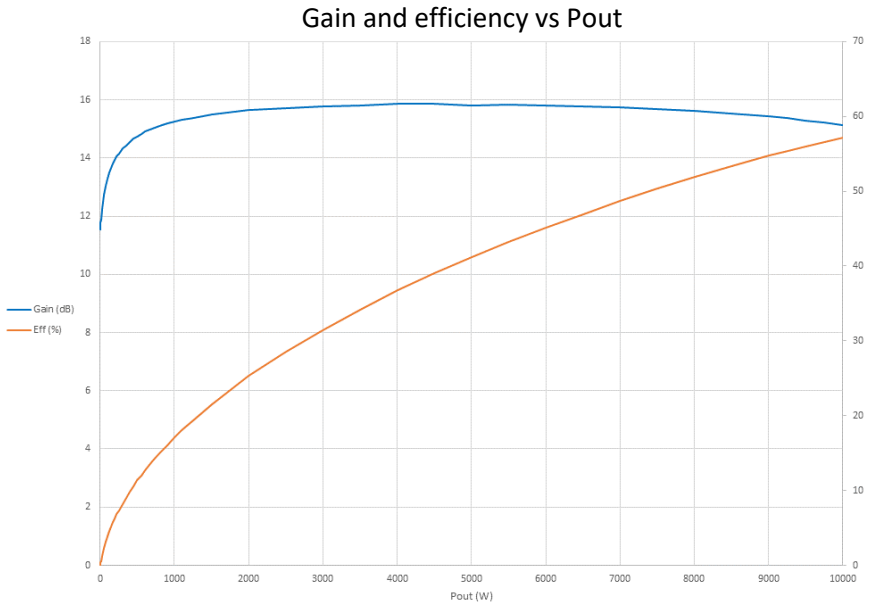
- Component order for the first 80 kW SSPA demonstrator (AMP1) - end of 2013
- AMP1 mounting and FAT at SOLEIL - end of 2015
- 2 X 80 kW SSPA FAT (AMP3 and 4) at SPE – beginning of summer 2016
- AMP1, AMP3 and AMP4 shipment to SESAME – end of summer 2016
  → Issues with AMP1 due to module oxidation during transportation
- AMP3 and AMP4 SAT at SESAME – September 2016
- AMP2 FAT at SPE – December 2016
- Shipment of AMP2 and components to repair AMP1 – January 2017
- AMP1 and AMP2 SAT at SESAME – April 2017

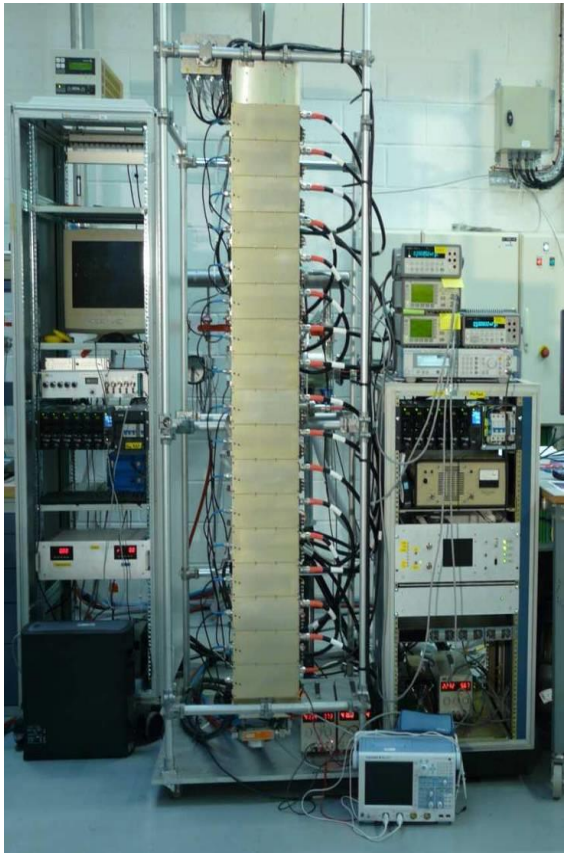
Financial support through OPEN-SESAME project (under EU's H2020 framework programme)

SESAME staff training at SOLEIL

2012 measurement training session

- Gain and efficiency vs Pout (elementary module and prototype measurements)
- Module setting to change the operating point





10 kW prototype

➢ Module degradation tests with thermal cycles

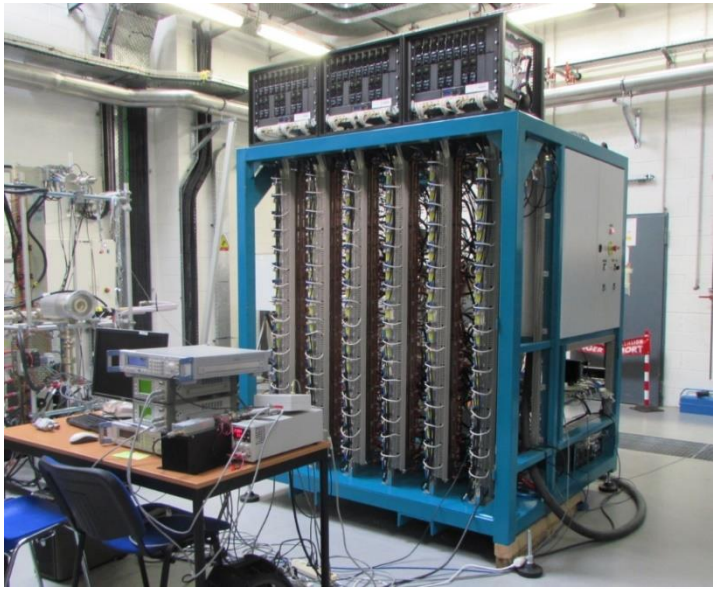
- Two groups of 8-Modules each were prepared.
- First group was tested with 650 W to give a total output of 5.2 kW for 1000 h.
- Second group was tested with 725 W to give a total output of 5.8 kW for 1000 h.
- The results of tests showed stable performance after 1000 h.
- After the 1000 h test, each module was tested individually to check all its parameters in details.

SESAME staff training at SOLEIL

ThomX Amplifier: 50kW @ 500MHz - Based on 530 W modules ➔ 96 modules mounted on 6 dissipaters

Schedule

- Oct. 2014: Finalization of the amplifier design with the cabinet integration
- Feb 2015: Mounting with the assistance of SESAME colleagues
- March 2015: First tests on dummy load up to 52kW CW
- April 2015: All measurements achieved (pulse & CW, with full reflection and VSWR of 2.5:1)



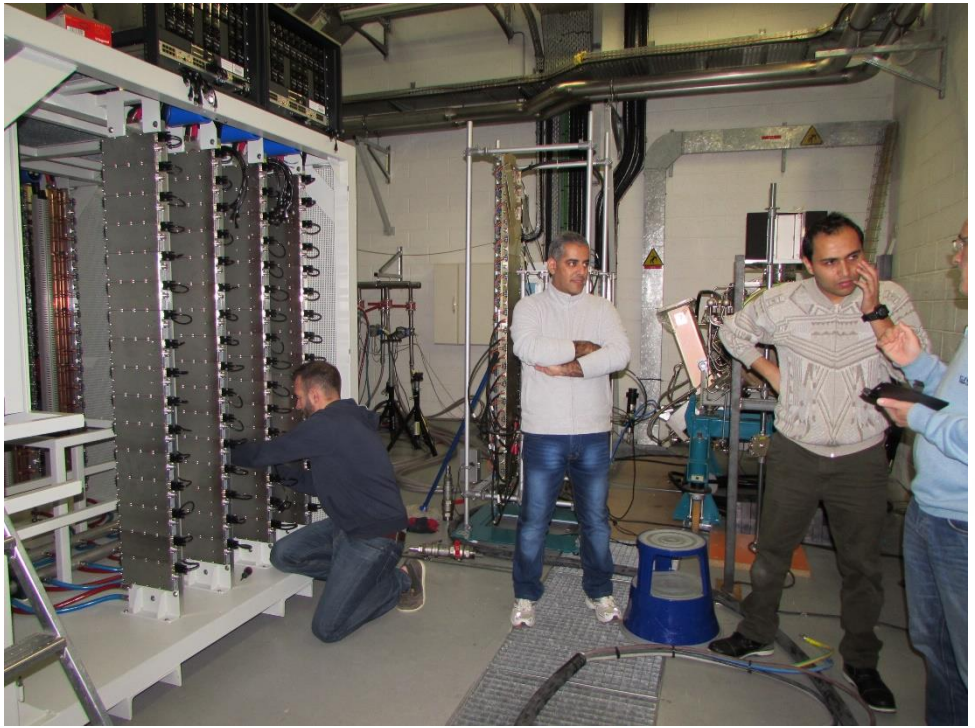
80 kW demonstrator assembly

Demonstrator (AMP1) assembly at SOLEIL, December 2015

Issues encountered with:

- Grease residues remaining on 40 kW combiners
- Cable connector crimping
- Polarization current decrease on several transistors even with no RF

- Cleaning of combiners
- Defect cables have been replaced
- NXP communication and official warranty approval to keep on using their transistors with no specific modifications nor repair



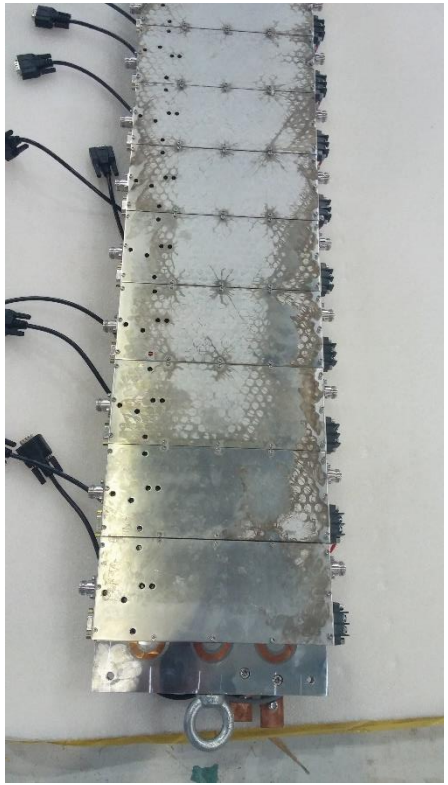
80 kW demonstrator FAT report

Factory Acceptance Test
500 MHz Solid State Amplifier
SOLEIL 04.03.2016
Present:
SOLEIL:
SESAME:
Pre-amplifier input: 4.5 mW
Pre-amplifier output: 37 W
Pre amplifier module output: 400 W
Amplifier module output: 4 kW
Amplifier output: 80 kW
Achieved efficiency for 80 kW: 60 %
Phase and gain as a function of dynamic range.
2 h stability.
500 h stability.
Interlock test:
water off Main off
5 modules off RF off
DC power off RF off
High reflection (0 dBm 100 µs, 0.3 dBm 30 µs for switching off)
Pressure difference: 11-4 bar
Water flow: 120-130 l/min
Temperature difference: 30-26 °C

	Specification	Achieved		Accepted
Frequency	500 MHz	500 MHz	demonstrated	yes
1 dB bandwidth	0.25 MHz	14 MHz	demonstrated	yes
Max Power	80 kW	80 kW	demonstrated	yes
Efficiency @ 80 kW	52 %	55 %	demonstrated	yes
Input Power@ 80 kW	< 1 W	5 mW	demonstrated	yes
Harmonic Content	< -25 dBc	< -36 dBc	demonstrated	yes
Phase Noise	< -60 dBc	< -75 dBc (50 Hz)	demonstrated	yes
Time full reflection @ 80 kW	< 10 µs	< 100 µs	demonstrated	yes
Full reflection @ 30 kW	DC	DC	demonstrated	yes
Maximum VSWR at @ 80 kW	< 1.15	< 1.35	demonstrated	yes
80 kW operation with 3 modules off	yes	yes	demonstrated	yes

AMP1 issue report after shipment to SESAME

Observation at SESAME when unpacking the demonstrator (end of summer 2016) :
presence of oxidation on 32 modules



- Caused by draining default on 2 dissipators before shipment
  → SAT postponed to focalise on AMP3 and AMP4 needed to begin machine commissioning

Cure :

- Module and dissipator replacement

SAT at SESAME

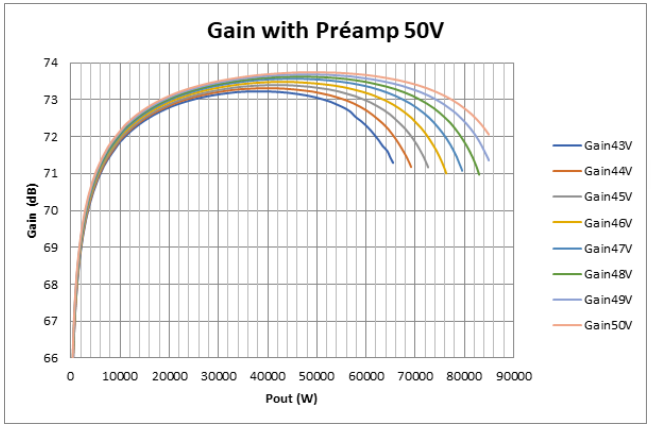
Goals:

- Measurements of all the monitored amplifier parameters vs Pout up to 80 kW on a matched load for DC voltages from 43 V up to 50 V (module currents and temperature, Pi and Pr on the 8 module - combiners, amplifier efficiency and gain)
- Dynamic range of last stage, 2 last stages and overall : gain and phase vs input power (Pout from 8 W up to 80 kW)

- ✓ September-October 2016 : SAT for AMP3 and AMP4
- ✓ April 2017 : SAT for AMP1 and AMP2
- ✓ Training of SESAME RF team for SAT measurements, coupler calibration, use and configuration of the supervision application, etc…

+ Waveguide connections to cavity and SOLEIL support for cavity conditioning (CAV3 up to 550 kV and CAV4 up to 450 kV)

AMP1 measurements



SAT at SESAME

SUMMARY & CONCLUSIONS

SOLEIL/SESAME collaboration purpose :

- Build and install a 80 kW SSPA demonstrator
- Train SESAME RF team for maintenance and provide support to handle the realization of 3 x 80 kW SSPA from SPE, the former SOLEIL licensee

✓ 10 kW prototype testing, module degradation with thermal cycles, 50 kW ThomX SSPA mounting + FAT measurements

✓ Demonstrator FAT and SAT for all the 4 x 80 kW SSPA at SESAME

- SESAME RF team handles SSPA exploitation with SOLEIL support if needed
- Very fruitfull and interesting collaboration (positive human and technical experience)
- Still communication for general advices

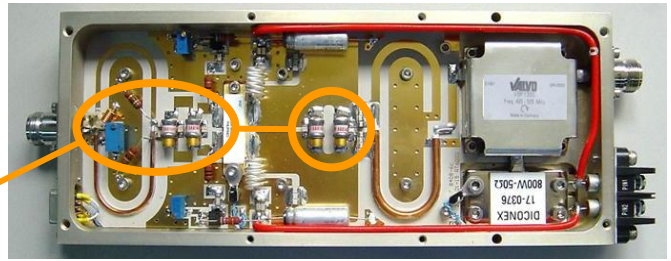

THANK YOU FOR
YOUR ATTENTION
SOLEIL
SYNCHROTRON

BACKUP SLIDES

SSA R&D at 500 MHz

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

- **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 (1dB compression)**
  - **Efficiency ≈ 62 % at P_n**
  - **Gain dispersion : +/- 0.2 dB at P_n**
  - **Phase dispersion : +/- 5° at P_n**

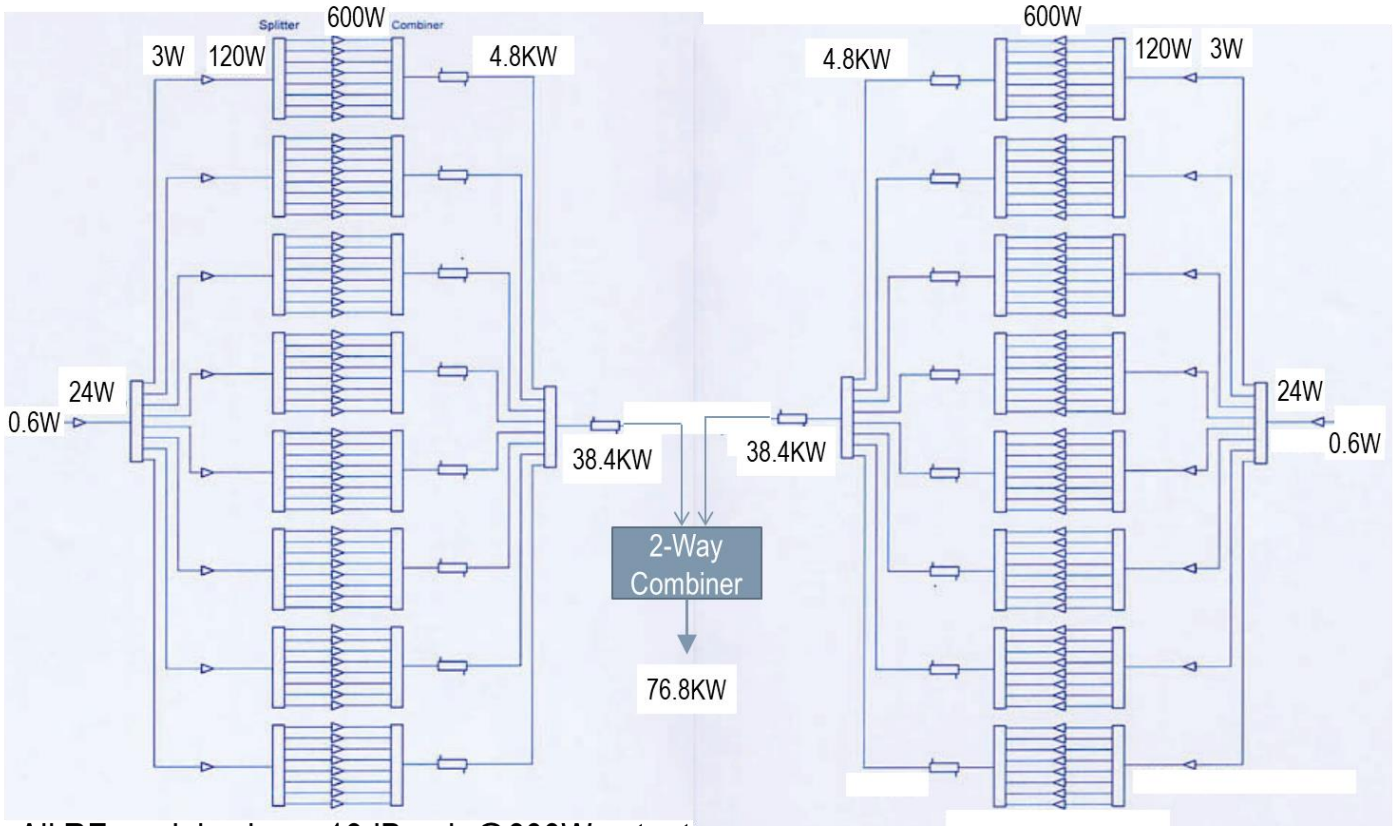


This is mandatory for good combining efficiency → Components for gain and phase adjustments

- **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 »**

SESAME SSA architecture



All RF modules have 16dB gain@600W output.