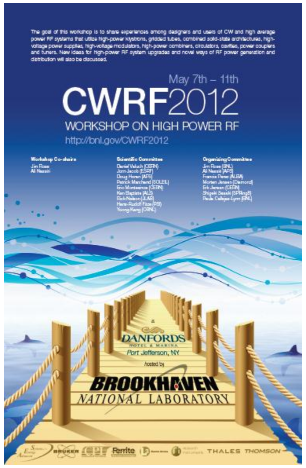


CWRF 2012

150 kW SSA for ESRF Booster Upgrade (Elta – Areva)

May 7th – 11th 2012

Brookhaven National Laboratory

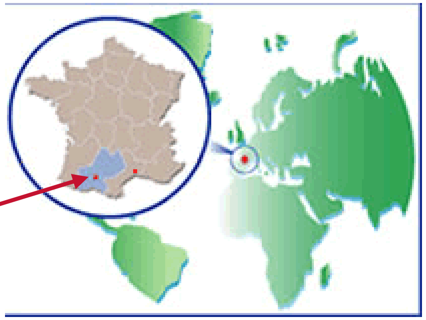
Jean-Paul ABADIE : jean-paul.abadie@areva.com
Alain CAUHEPE : alain.cauhepe@areva.com

Short Presentation of ELTA - AREVA

- **ELTA is an AREVA (66%) and OHB-GmBh (34%) subsidiary, specialized in Electronics - located in Toulouse (France).**

  → AREVA: nuclear energy

  → OHB GmBh: small satellites



- **ELTA is a 250 employees company with more than 30 years heritage in :**
  - **Radio-Frequency for Aeronautic, Space & Scientific applications**
  - **Instrumention and Control (I&C) for Defence and Transportation markets**
  - **High Power Supplies for Defence and Aeronautic markets**
  - **Water Analysers for Nuclear market**

- **Design tools :**
  - **Design tools : RF (AWR + 3D tool AXIEM), Analog, Digital simulation, 3D CAD, PCB Design Software,**
  - **Test Equipments (vector/spectrum analysers, RF I&Q modulator/demodulator) up to 40 GHz)**

ESRF project: Main steps

- October 2010 : Signature of the contract for:
  - 4 SSA at 352,2 MHz / 150kW each for the Booster (Ramped signal)
  - 3 SSA at 352,2 MHz / 150kW each for the Storage Ring (CW)
- May - June 2011 :
  - Test of the first 75kW Tower (1/2 SSA) in Booster and Storage mode (CW)
  - Qualification of the first 75kW Tower in Booster mode
- Sept – Dec 2011 :
  - Installation and SAT (Site Acceptance Test) of the 4 x SSA for the Booster
  - SAT performed on ESRF H-Tuner (simulate any VSWR and phase)
  - SAT performed successfully in Booster mode and in line with ESRF schedule
- April 2012 : Final SAT in line with ESRF schedule
  - Final SAT performed in operational configuration with 4 x SSA connected to Booster cavities

Overlook on the 150 kW SSA

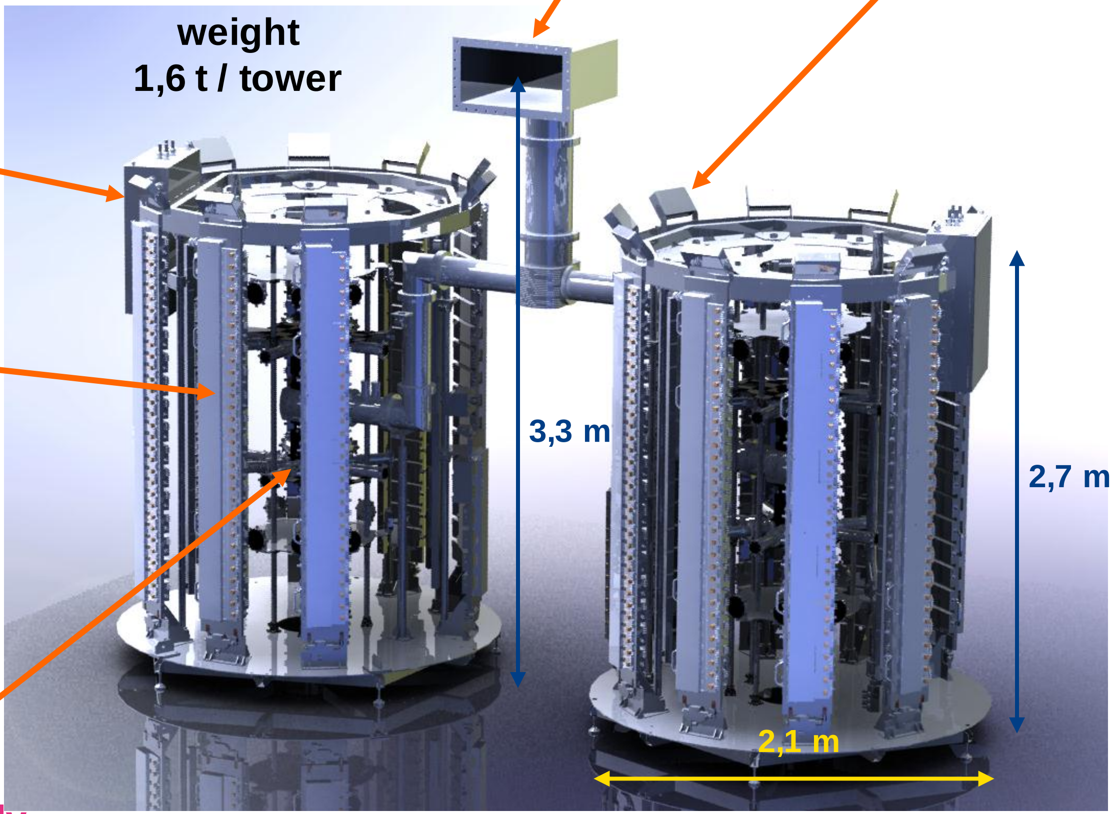
General Presentation

150kW output
WR2300

Control
Mux-Box

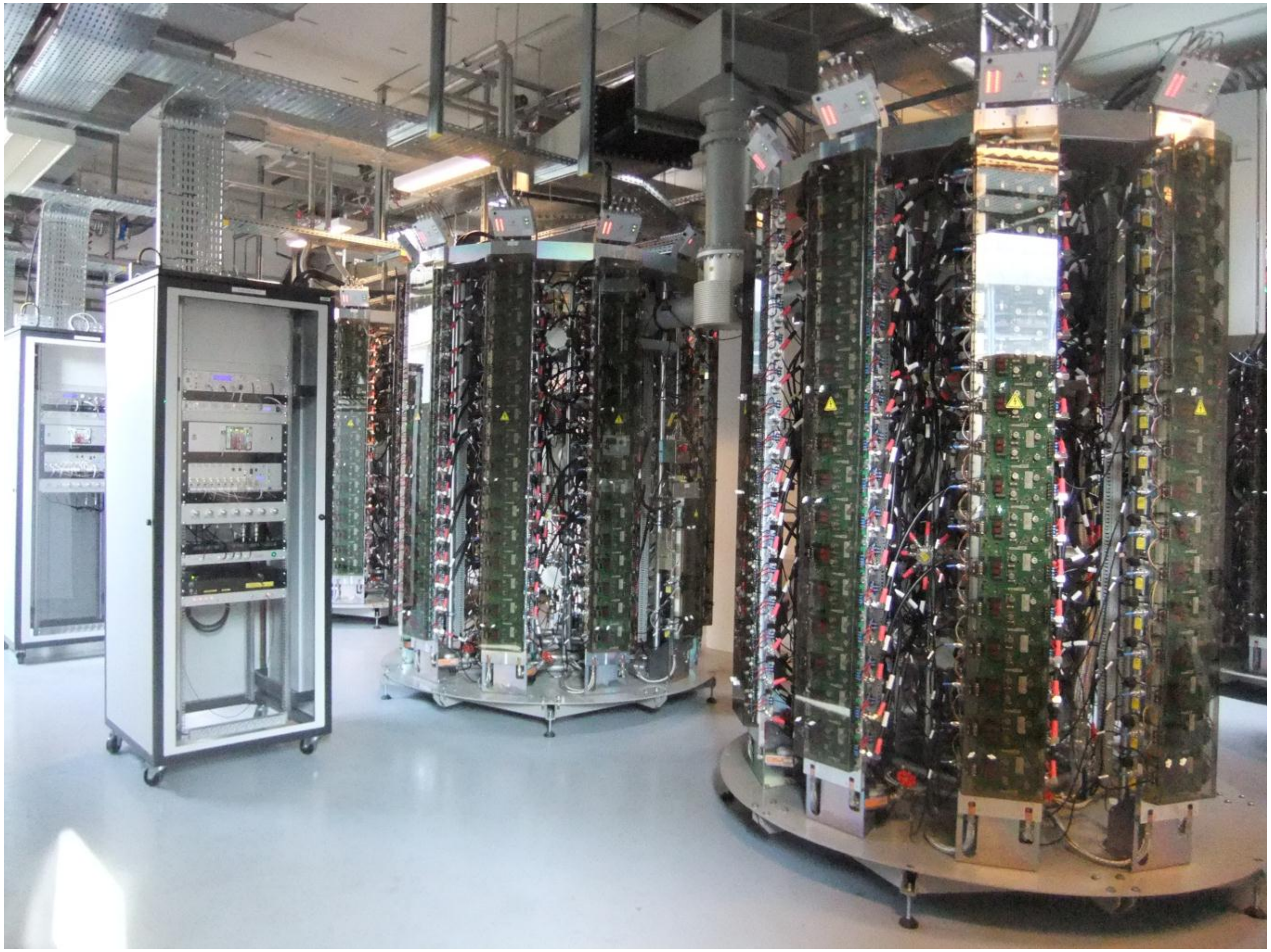
Electrical Box

Cold Plate Assembly
16 Amplifier Modules
16 DC-DC Converters



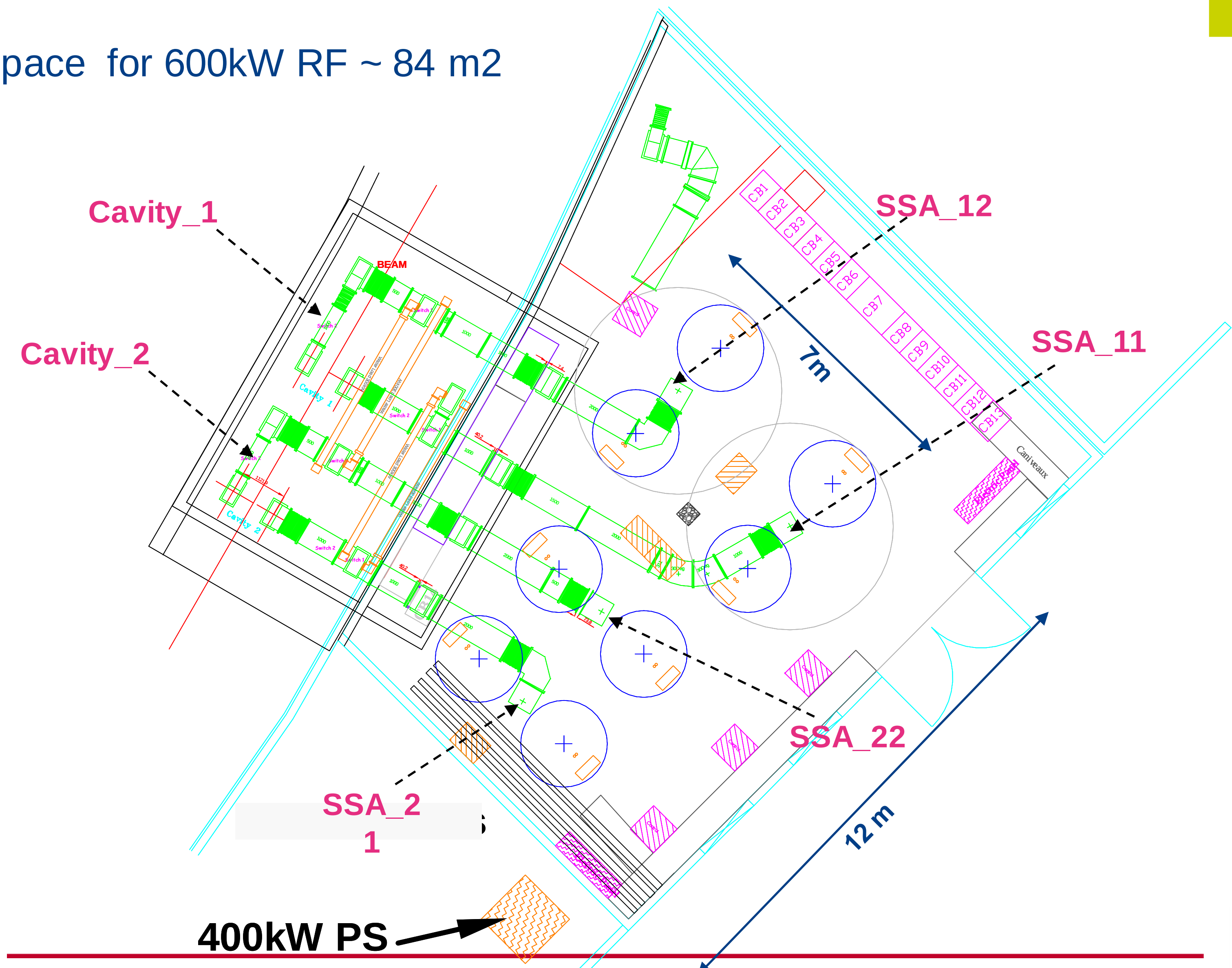
« Core »
Combiner Assembly

SSA installed at ESRF facility



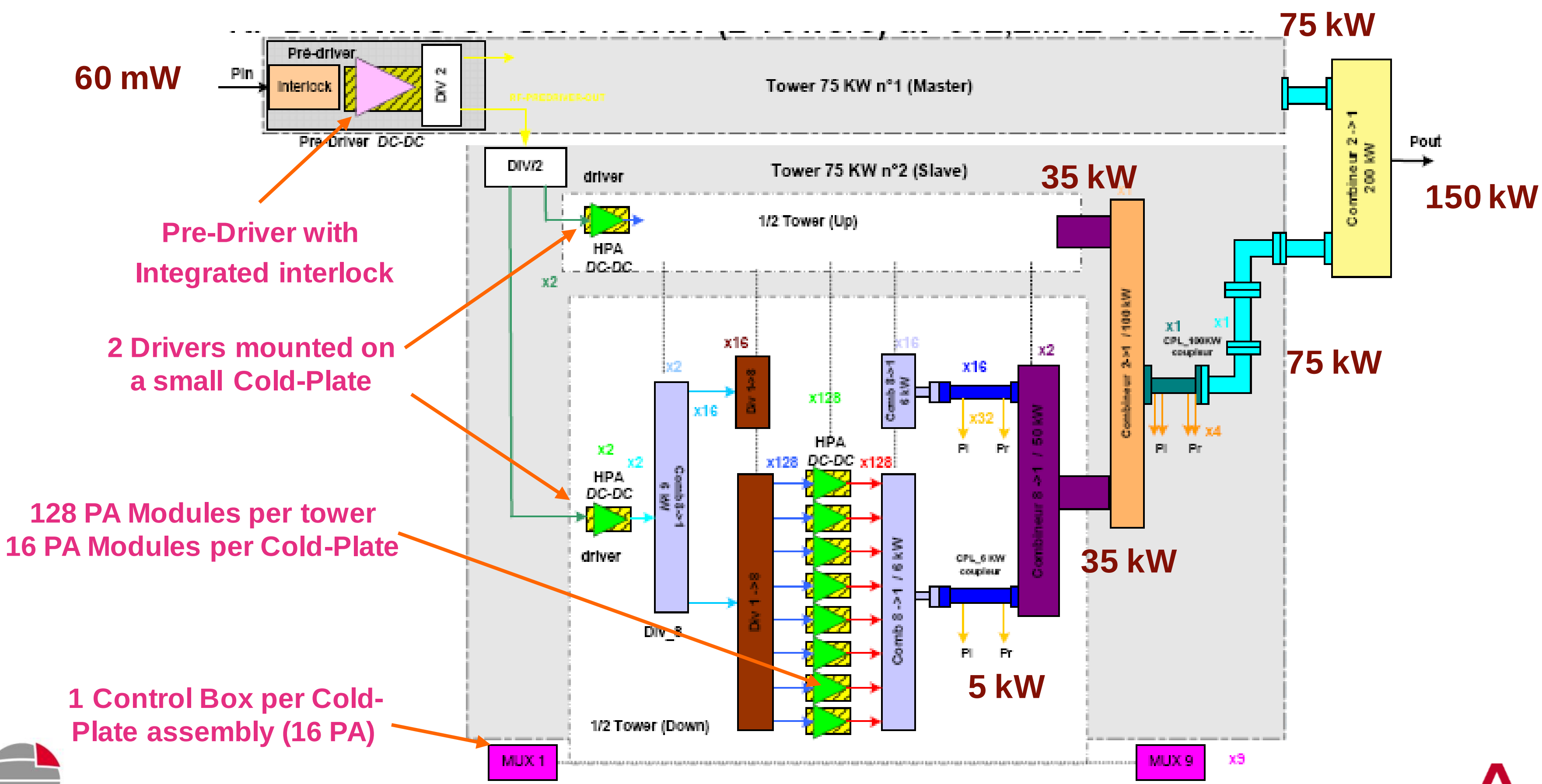
ESRF: SSA Position for Booster

Space for 600kW RF ~ 84 m2



150 kW SSA for ESRF Booster

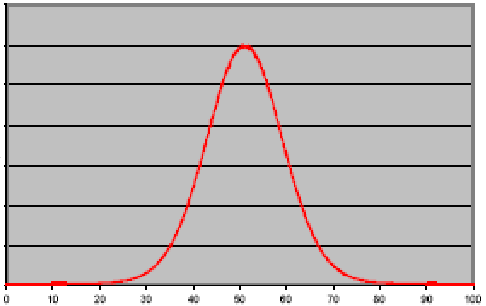
- **RF Architecture of the 150 kW SSA Power Amplifier**



150 kW SSA for ESRF Booster

Main RF Characteristics (1) :

- Nominal RF power (spec) = 150 kW
- RF power increased up to 170kW during tests
- Efficiency at 150kW → ~ 58% (spec at 55%)
  at 100kW → ~ 48% (spec at 45%)
- Operation with high mismatch conditions and all phases (no HPA missing):
  → 50kW Reverse power at 150kW Forward permanently in CW mode
  → full Reverse power at 150 kW Forward during 20 µsec
  → full Reverse power at 80kW permanently in CW mode,
- Operational modes
  → Booster : Ramped signal at 10Hz
  → Storage : CW
  → Cavity Conditionning : Square Pulse (20us to 10ms at 50 Hz)



10ms/div

- Forward level at 150kW with up to 6 HPAs missing in Booster mode at 150kW and with mismatch conditions

150 kW SSA for ESRF Booster

- **Efficiency on Matched Load :**

EFFICIENCY CW @ 280Vdc	SPEC	SSA 12	SSA 21	SSA 22	SSA 11
150 kW on Matched Load all HPA ON	>55%	58,5%	58,1%	59,2%	57,2%
100 kW on Matched Load all HPA ON	>45%	48,5%	48%	49%	48%
150 kW on Matched Load all HPA ON after 24 h except 200 h for SSA1	>55%	57,8%	57,8%	59%	57%
150 kW on Matched Load 6 x HPA missing	>55%	57%	57,3%	58,5%	56,2%

150 kW SSA for ESRF Booster

- Output Power versus Load Mismatch at worst phase conditions:

Mode	all HPA ON	SPEC	SSA 12	SSA 21	SSA 22	SSA 11
CW	150 kW Forward Power 50 kW Reverse Power	Fwd > 150kW	C	NC ? (1)	C	C (2)
CW	80 kW Forward Power Full Reflection	Fwd > 80 kW	C	C	C	C
PULSE 20 µsec	150 kW Forward Power Full Reflection	Fwd >150kW	C	C	C	C

- (1) Power at SSA21 is less than 150kW for the worst phase condition, whereas losses of the combining core are compliant (combining losses less than 3%).
- (2) First, the test fails and then pass after taking into account corrective losses due to some mismatch of waveguide bend inserted in the test circuit

150 kW SSA for ESRF Booster

- Output Power with 6 HPA missing and versus Load Mismatch at worst phase conditions - Booster mode:

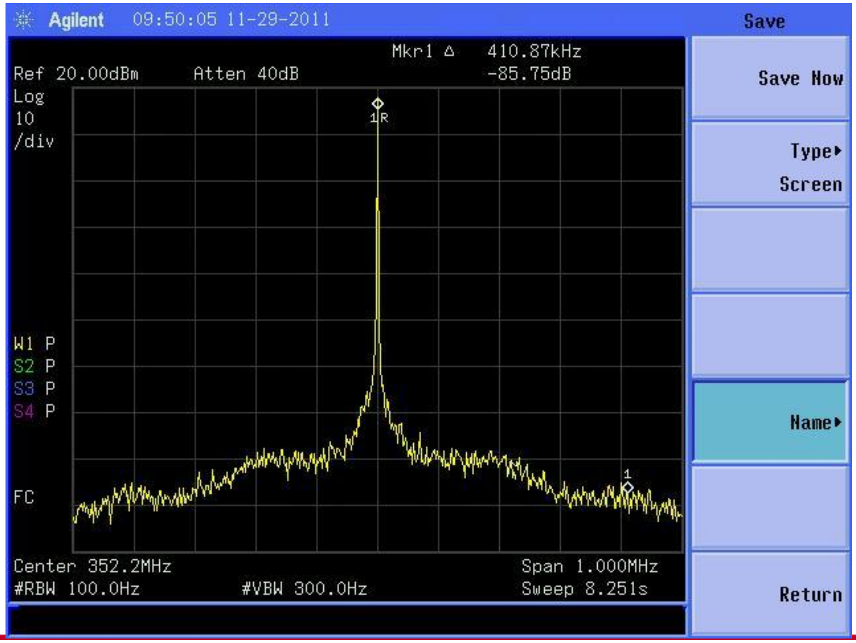
6 x HPA missing	SPEC	SSA 11
150 kW Forward Power 50 kW Reverse Power	No degradation + Fwd > 150 kW	C Booster (1)
80 kW Forward Power Full Reflection	No degradation + Fwd > 150 kW	C Booster (1)
150 kW Forward Power Full Reflection Pulse Mode 20 µsec	No degradation + Fwd > 150 kW	C Pulse (1)

- (1) Mismatch test any phases, in Booster mode, has been performed on SSA_11 only

150 kW SSA for ESRF Booster

RF Characteristics :

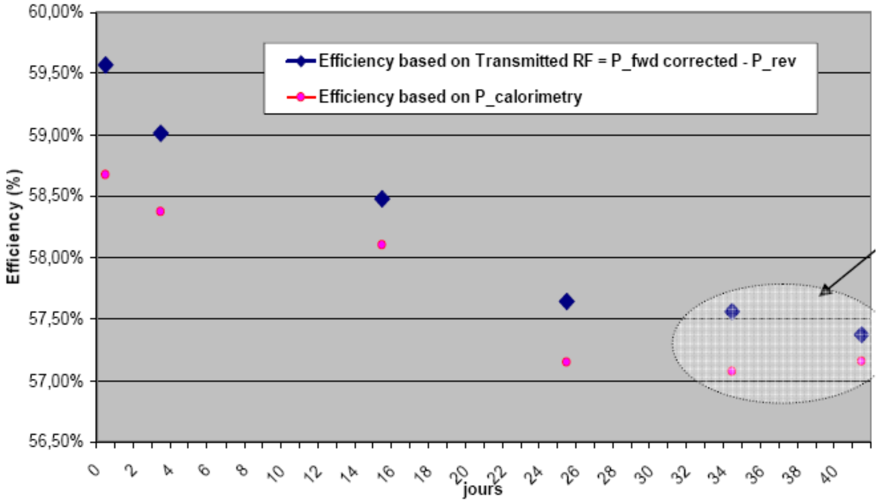
- Gain = 64 dB
- Gain flatness in ± 0,5 MHz ~ 0,1dB
- Output range > 35dB
- Phase shift from 47W to 150kW < 15°
- Compression at 150kW < 0,5dB
- Harmonics 2 < -36dBc & Harmonic 3 < -50dBc
- Spurious < -70dBc



AREVA

150 kW SSA in CW mode

- **Efficiency degradation after lifetest in CW mode**
  - Efficiency drops from 59,5% to 57,5 %
  - After 1000 hours, efficiency is still in the specification (> 55%) and seems to stabilize



  - For Booster mode, cumulative 1000 hours represents several years of operation with much more favourable thermal conditions → less critical for Booster mode
  - After investigation, efficiency degradation is due to « abnormal » efficiency degradation of some PA modules. Nevertheless, it shall be considered that an average efficiency loss of ~2% is normal for LDMOS technology.
  - Most probable root cause is an operation of the transistor lightly outside its specified range. → on-going simulation and tests in order to keep the transistor strictly inside its operating range

150 kW SSA in CW mode

Burn-out of the load of the missing PA in CW mode:

- In case of HPA missing and mismatch at SSA output (Forward=150kW and Reverse=50kW), power dissipated in the load of the missing HPA can vary from 150W to 1500W according phase conditions on the reverse power.

- This variation is due to the unbalanced distribution of the reverse power through the different arms of the combining system when one « generator » is missing (this result has been recovered by simulation)

- Several solutions has been envisaged:
  → a high power circulator at SSA output,
  → reducing the max dissipated power around 1200W (combiner optimization)
  + higher power load able to withstand 1200W with enough margin.

- In Booster mode, the load withstands 3200W peak.

150 kW SSA for ESRF Booster

Electrical Circuits

- 280 V dc +/- 20V (nominal)
- Designed for handling current up to 1400 A continuously
- Power supply distribution to the ColdPlate through circuit breakers
- Compliant with European Certification (CE)

Water Cooling

- 160 liters / mn per 75kW Tower (instead of the initial 220 liters/mn)
- Inlet water temperature around 23°C
- Copper or Stainless materials only
- Valves on each Cold Plate for balancing the flow rate through each Cold Plate
- Water distribution based on ring distribution and a ring collector

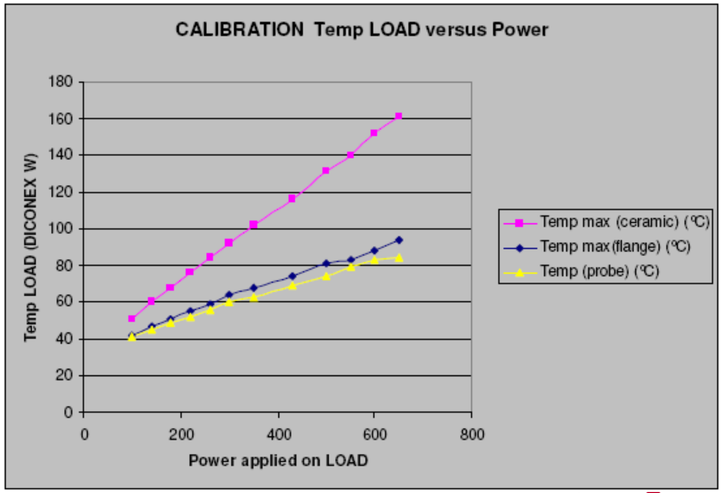
Mechanical Structure:

- Industrial solution based on metal-welded pieces
- Robust structure consolidated by simulation
- Permits an easy accessibility to modules (for maintenance purpose)
- Mechanical tool developped for handling the tower during transportation and installation

Monitoring & Protections

- **RF Monitorings, Protections, Interlocking :**
  - Overdrive detection on the LLRF input (20dBm) : fast hardware detection (< 150 nsec)
  - Interlock on Reverse RF level detected at the output of the Master Tower in case of severe mismatch (fast hardware detection < 200 ns)
  - Monitoring of Forward and Reverse levels at the output of the 6 kW combiners
  - Monitoring of Forward and Reverse levels at Tower output (75 kW bidirectionnal coupler)
  - For RF monitoring, Peak and RMS detectors are implemented

- **Monitoring implemented inside each HPA module :**
  - Current consumptions for Drain_1 and Drain_2
  - Transistor temperature
  - Load temperature → gives a very useful indication of SSA state and behaviour.



- **Thermal and Hydraulic protections :**
  - Thermal Interlocking on each Cold Plate
  - Water Flow Interlocking on each Cold Plate

650 W Power Amplifier Module

- **Designed in partnership with Soleil**
  - Optimized in terms of efficiency
  - Optimized for lowering component temperatures
  - Temperature cartography during PA prototype validation
  - Optimized regarding gain and phase balance

- **RF Characteristics :**
  - Power Output : 650 W (< P_1dB ~ 680W)
  - Frequency : 352,2 MHz
  - Gain : 20, 3 dB
  - Efficiency : > 70 %
  - Gain Dispersion : +/- 0, 2 dB max
  - Phase Dispersion : +/- 5° max
  - Transistor Technology : LDMOS 6th Generation
  - Protected by internal circulator and its associated power load

- **Monitoring :**
  - Drain Currents (2 values / PA modules)
  - Flange temperature of the RF transistor (indicator)
  - Flange temperature of the circulator load

ELTA

AREVA

High Power Combiners

Combiners (designed by Soleil):

- Quarterwave technology
- Advantage : mature technology and easy to implement
- Draw-back : in case of mismatch at SSA output, reverse power through the different arms is not uniformely distributed as soon as an arm is unbalanced (for instance in case of HPA missing)

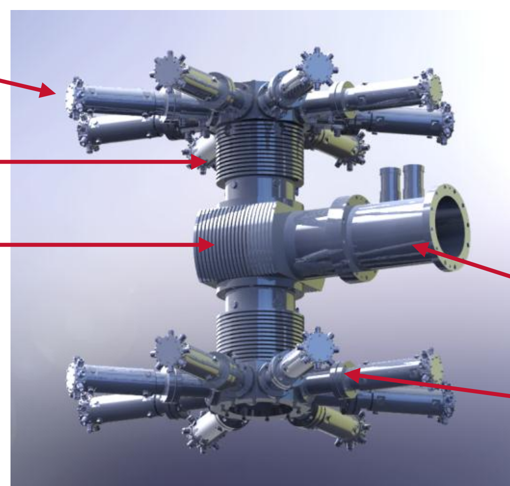
Combining Core Assembly (CAD made by Elta)

- Low loss (~ 3% including RF cables at PA output)
- Optimized for Compact arrangement

6kW Combiner

50 kW Combiner

100kW Combiner



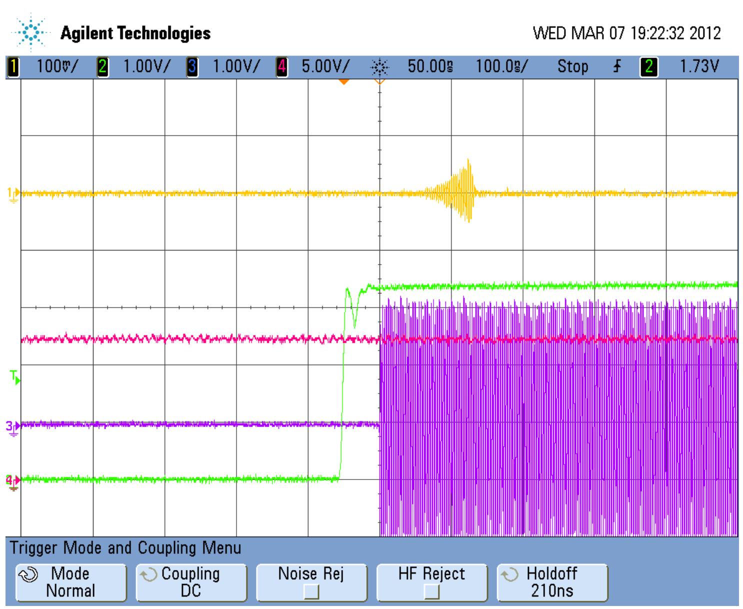
100kW bi-directional Coupler

6kW bi-directional Coupler

Pre-Driver

Pre-Driver :

- Amplification of the input low level signal (18 dBm) up to 2 x 10W
- Internal Interlocking on RF Input level – very fast detection (<150 nsec)
- Internal Band Pass Filter with Time Delay > 150ns.
- Overdrive protection: combined with the very fast detection of excessive input level, the filter permits to switch-off RF signal before it goes through the filter (see picture)
- Internal Interlocking on Reverse Output level (< 10 usec)
- One of the most important module for safety operation of the SSA



green → Pulse
purple → RF_IN
Yellow → RF_OUT
Red → Status P_in

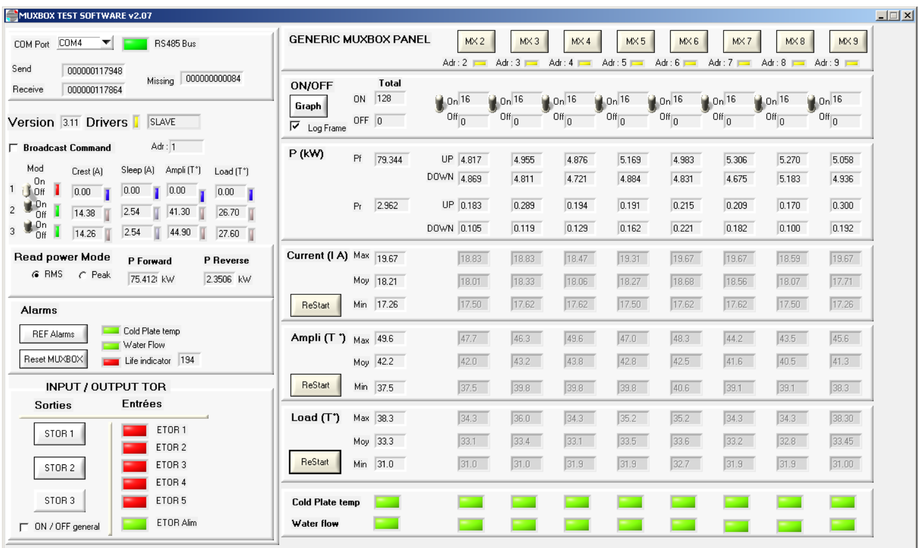
Control (Mux-Box)

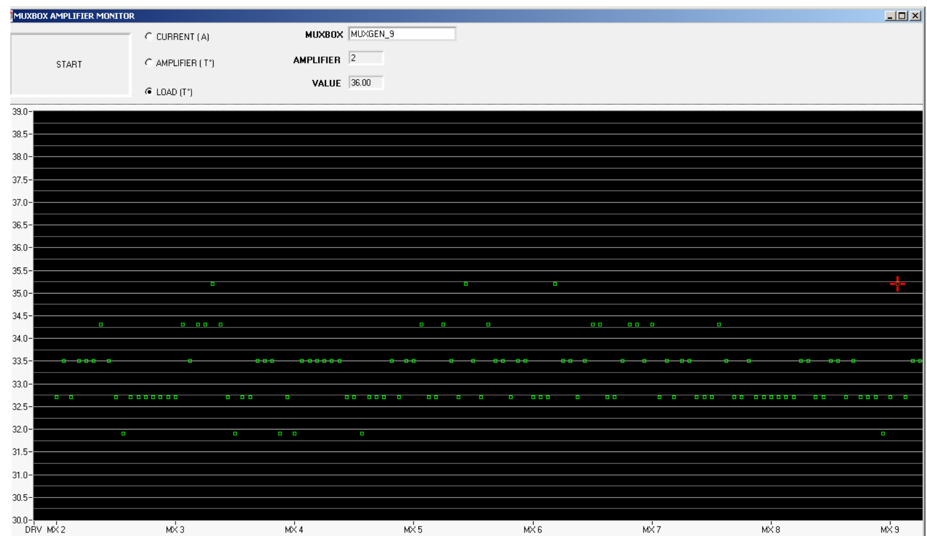
Control Box:

- Distributed Control & Monitoring (1 Mux-Box per Cold Plate), based on DSPIC microcontroller
- Monitors the Amplifier Modules (currents and temperatures)
- Monitoring the Cold Plate Interlockings (Temperature and Water Flow)
- Control the ON/OFF of each Amplifier Modules (Power supply switch-off)
- Interface with Amplifier / DC-DC Modules by I2C bus
- RS485 interface with ESRF Supervisor :
  ModBus RTU at 100kbps (max : 1 Mb/sec)
- Leds indicators give an easy way for controlling the states of the HPA modules and the states of the Cold-Plate Interlocks (temperature & flow rate)
- Hot swapping of the Mux-Box

GUI : Graphical User Interface

- **GUI :**
  - Permits to monitor SSA in operational mode
  - Permits to configure SSA (HPA modules ON/OFF)
  - Permits to eliminate module with degraded performances during pre-tests
  - Permits an easy Fault Location of the failed module
  - Simple processing can be done on the monitored parameters in order to detect drifts or to generate warnings → preventive maintenance

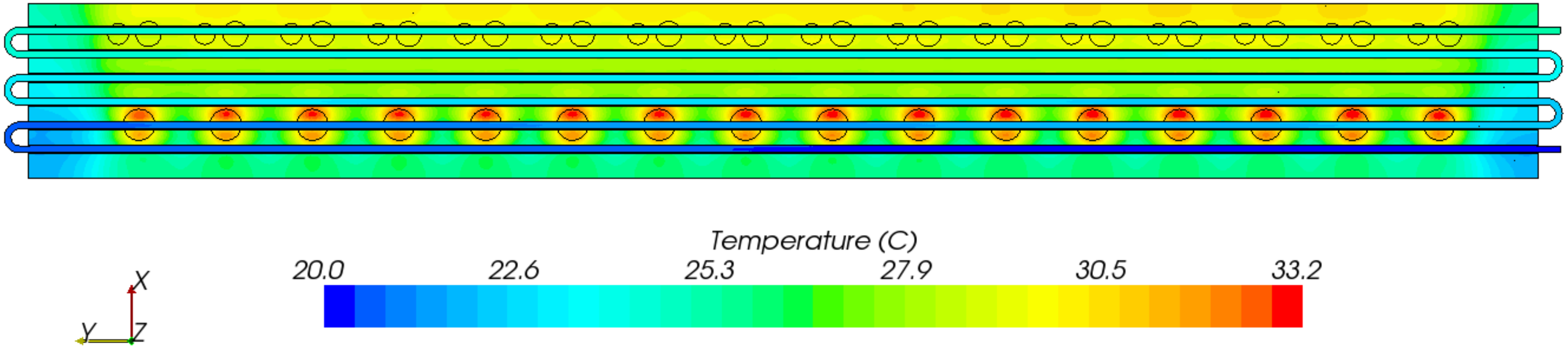




Cold Plate : Thermal simulation

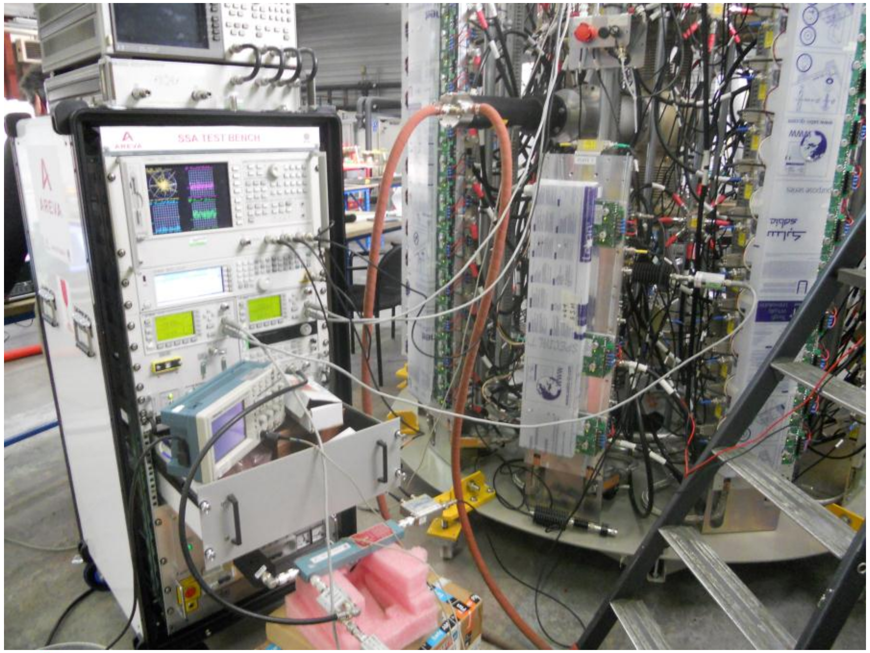
Thermal Simulation performed on the Cold Plate

- Mixed simulation : Thermal & Fluidic (takes into account turbulence)
- Simulation takes into account heat flux through the dissipative component flanges and through the Amplifier package
- Thermal Simulation gives :
  - A global thermal cartography of the Cold Plate
  - Flange temperatures of main dissipative components (transistor, load, circulator, DC-DC converter), in order to estimate junction temperatures
- Consolidated by measurements :
  - T_junction_transistor ~ 120°C



Bench Test

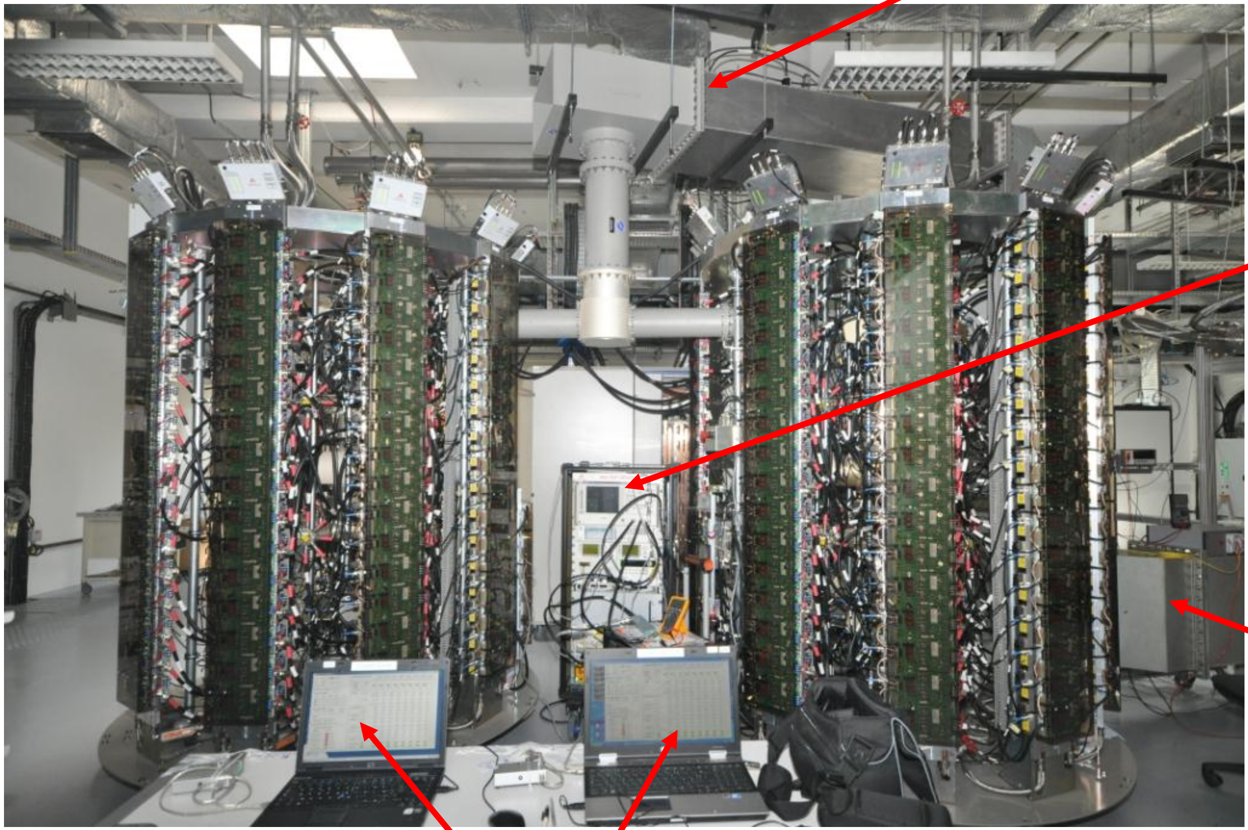
- **Bench Test is a multi purpose bench used for :**
  - Testing and tuning HPA module (for design phase or for maintenance)
  - Performing initial tests before delivery
  - Performing commissioning test at ESRF facilities



150 kW SSA for ESRF Booster

- **Test Set-up during ESRF commissioning**

RF interface with ESRF waveguide



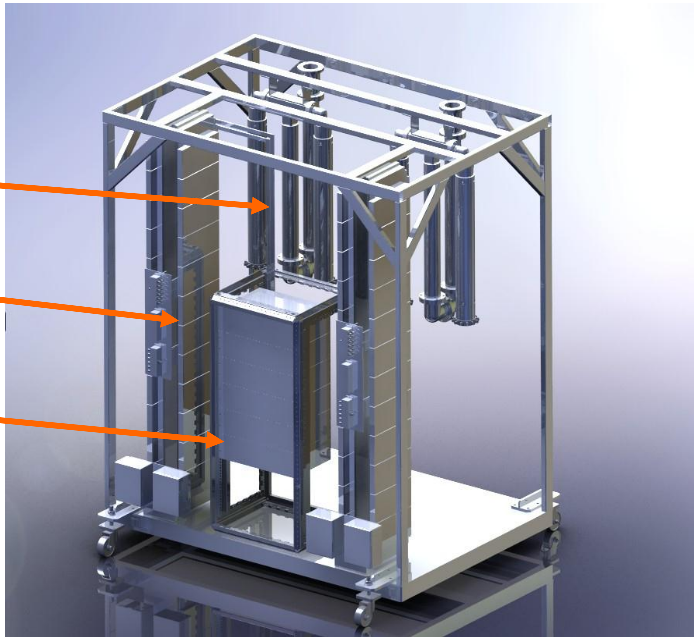
Test Bench (Elta)

H Tuner (ESRF)

Monitoring (Elta)

Versatility of the Modular SSA Architecture

- **Other arrangement can be envisaged if required (cabinet version)**
  - Example of 2 x 20 kW at 88 MHz based on 850 W Amplifier Module



- **Cylinder arrangement offers advantages :**
  - Excellent symetry for RF paths
  - Excellent accessibility for replacing modules

Advantages of the Modular SSA Architecture

- High Beam Availability (full performance with up to 6 failed Amplifier modules)
- Computed MTBF of the overall 150kW Amplifier : 10 000 Hours
- Computed Failure rate of Amplifier Module : less than 0,7% per year
  → 7,2 PA Modules should failed each year among the 1024 PA modules
  → real value at CWRF 2014
- Distributed Heat Dissipation
- No need for High Voltage Power Supply
- No need for High Power Circulator at RF Output for Booster mode (1)
- No need for Warm-up sequence
- Very low Phase Noise
- Easy Maintenance : MTTR < 15 min for most of the modules (except Combining core)
- Flexibilty to fit to different RF Output Power (by reducing the number of PA modules)
- Reduced number of Spare Parts
- Preventive maintenance could be done thanks to the monitored parameters

(1) same for CW mode as far as the PA load and PA circulator are well sized
→ increase of the size of the PA module

Conclusion :

- The ESRF project permits to consolidate the expected performances of the SSA solution on a large industrial scale, since all requirements are fullfiled in Booster mode.
- It permits to demonstrate that maintenance is quite easy, thanks to the monitored parameters and thanks to the good accessibility at the modules.
- It permits to show that performances can be achieved with a good repetitivity on several SSA (no need for accurate tuning)
- The four SSA have been delivered on time even if a large amount of new designs have been undertaken.
- This project has highlighted some weakness in CW mode that can be reasonably solved for the next SSA for the storage ring.

Thank you for your attention