20th European Synchrotron Light Source Radio-Frequency Meeting
PSI, November 16th-17th, 2016

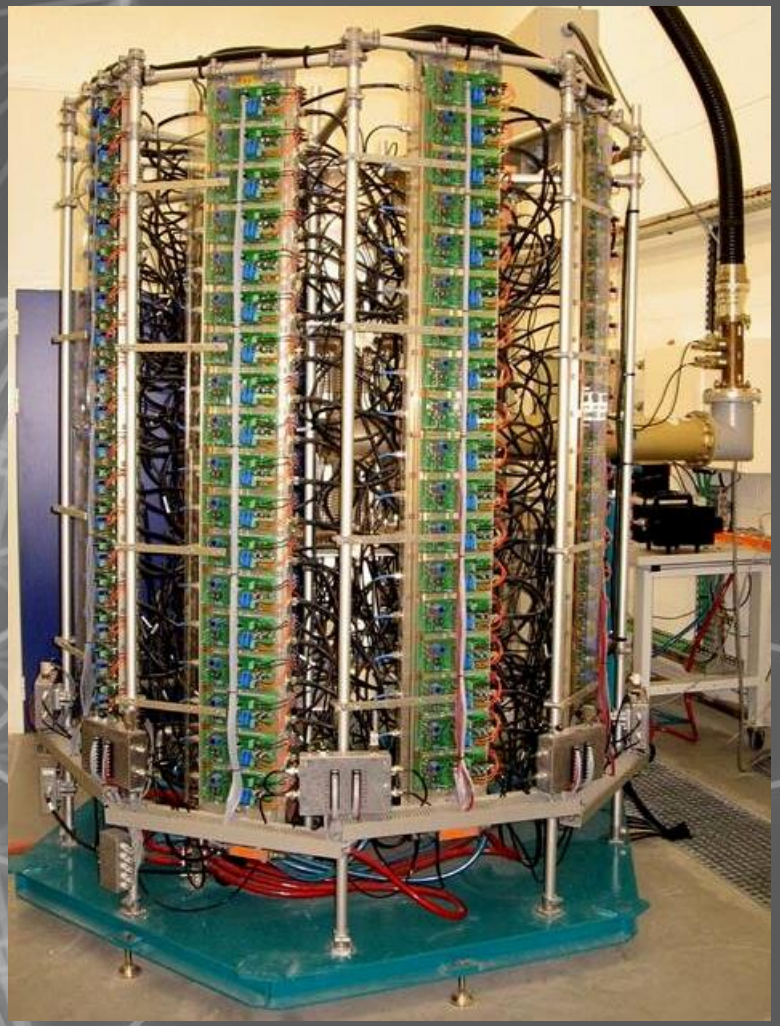
STATE-OF-THE-ART RF SOLID STATE POWER AMPLIFIERS (SSPA's)

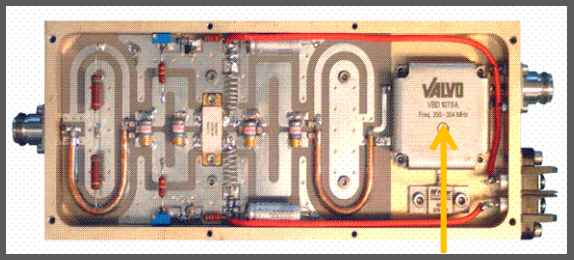
M. DIOP, on behalf of the RF group

- **Experience with the SOLEIL 352 MHz SSPA's**
- **R&D with SSPA's at SOLEIL → transfer of technology**
- **Review of used or planned SSPA's in other facilities**

35 kW SSPA of the SOLEIL Booster

146 modules of 330 W @ 352 MHz with their individual power supplies, mounted on 8 water cooled dissipaters.
All the components were designed in house and the series production contracted to the industry

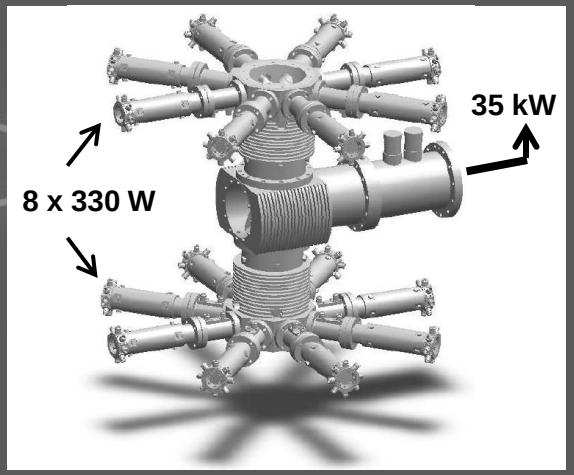




330 W CW - 352 MHz
amplifier module
VDMOS D1029UK05
from SEMELAB
(G = 11 dB, η = 62 %)

1 circulator per transistor : this is the key to success

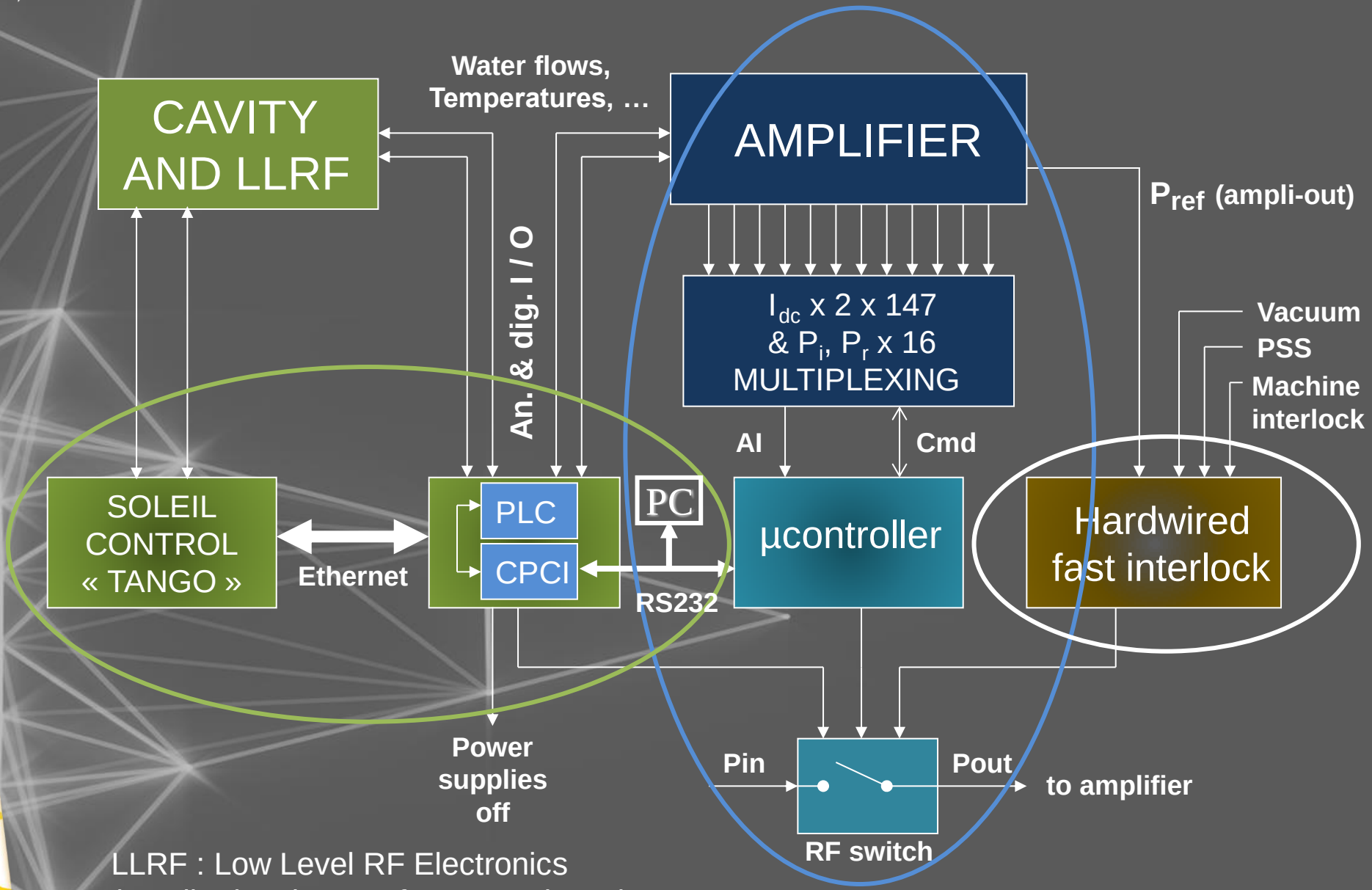
600 W - 280 / 28 V dc
power converter



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

~ 60 000 running hours over 10 years operation: only one single trip from the 35 kW SSPA in September 2016 due to a loose connection on a monitoring cable.

Booster RF control system



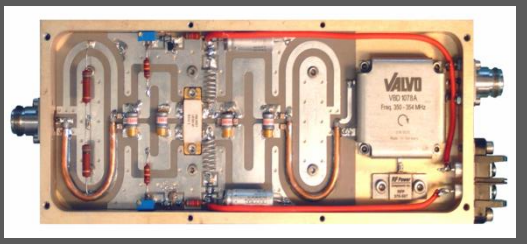
LLRF : Low Level RF Electronics
(amplitude, phase & frequency loops)

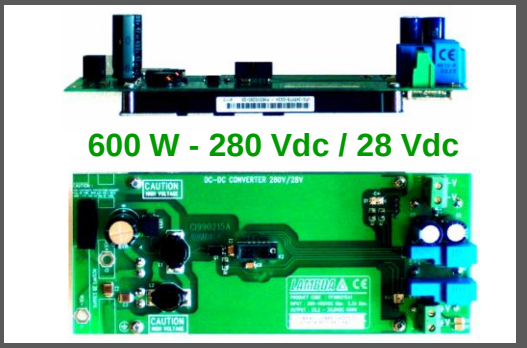
SOLEIL SR 180 kW SSPA's

Same principle as for the BO one, extended to 4 towers of 45 kW
→ 10 dissipaters of 18 modules per tower
→ 726 modules / amplifier x 4 cavities → 16 towers & ~ 3000 modules

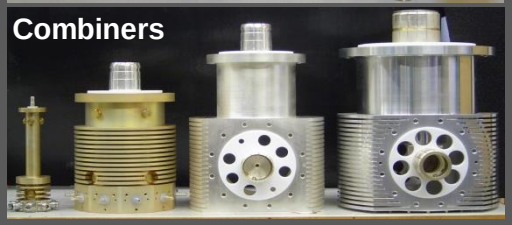
Amplifiers 1 & 2 (2 x 4 towers) powering the 2 cavities of Cryomodule 1

LDMOS LR301 from POLYFET
G : 13 dB, η : 62 %





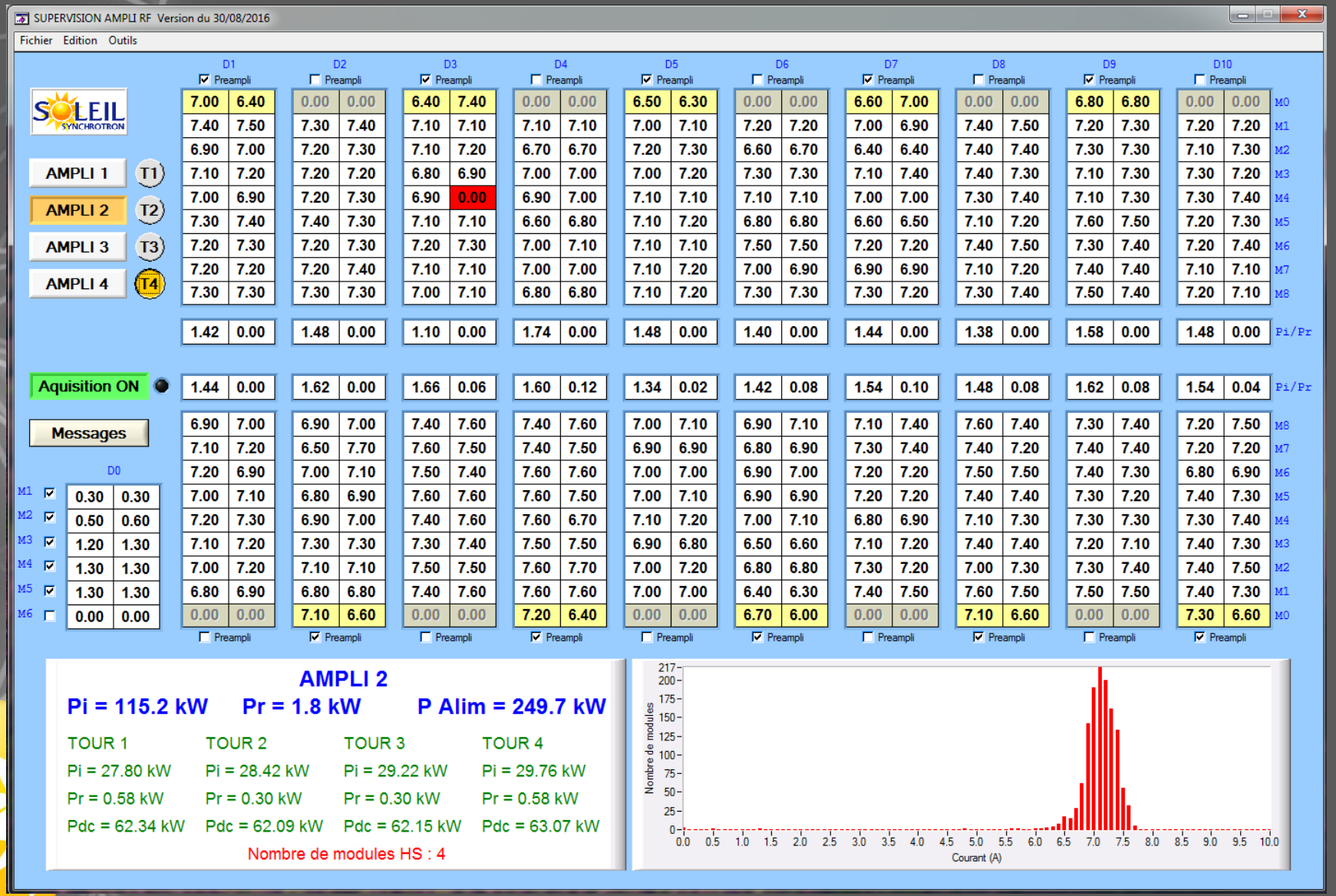
600 W - 280 Vdc / 28 Vdc



All the amplifier components were designed in house & the series production contracted to the industry

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 combiners

Bottom transistor currents

SR SSPA's operational experience

Beam downtime caused by failures from the SR SSPA's over ~ 60 000 running hours in ~ 10 years

Equipment	Downtime	Comments
a) 4 x RF amplifiers	~ $1\ 10^{-4}$	~ 6 h in 5 short events due to **preamplifiers** **MTBF > 10 000 h** (cumulated by 4 amplifiers)
b) 4 x 500 kVA power supplies (230 Vac / 270 Vdc rectifiers)	~ $4\ 10^{-4}$	~ 23 h in 6 faults from the **power supply control**
a) + b) = 4 x RF transmitters	~ $5\ 10^{-4}$	**MTBF ~ 5 000 h** (cumulated by 4 transmitters)

Already excellent operational avaibility and MTBF, but still perfectible
→ Improvements brought in our new generation of amplifiers :

- **Replace modular dc/dc converters + single ac/dc rectifier by modular ac/dc converters, in 2 kW units, directly connected on the mains → redundancy**
- **Use a "combiner-divider" in order to cure the lack of redundancy in the preamplification stage**

The failure rate of our original LR301 transistors remains rather high, ~ 2-3% a year
Thanks to the redundancy, the operation is not affected (except for preamplifiers)
It is mainly a matter of maintenance : ~ 5 k€ of material + 3 men.week / year
→ Largely improved with the 6th generation transistors (Vd : 50 V instead of 30 V)

- **ESRF experience with BLF578 transistors shows a huge reduction in failure rate Not yet a single one after ~ 4 years of operation with ~ 1 800 transistors !!**
- **The refurbishment of the SOLEIL SSPA's with BLF574 transistors is in progress**

Upgrade of the SOLEIL SR SSPA's

Take advantage of using a transistor of 6th generation, the BLF574XR from NXP, which is much more robust and has higher performance than the LR301 → Low cost upgrade

Change only the transistor + "module retuning", re-use old PCB → ~ 10% of amplifier cost

→ Electrical power savings (efficiency : 50 % → 60%) compensate the investment cost in < 3 years

+ 7 dB transistor gain → 160 preampli modules & their dc PS are got back for the new BO SSPA

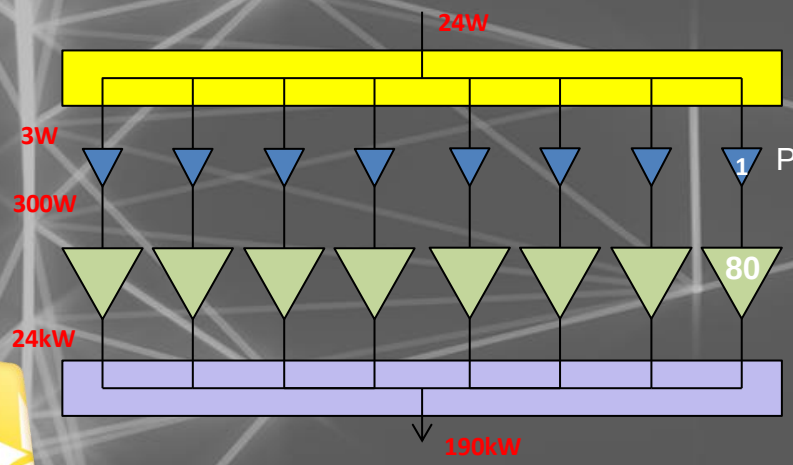
+ More robust transistor & lower thermal stress → much less module failures → less maintenance

+ Higher power capability (max P_{mod} : 310 W → 450 W) → 500 mA with only 3 running SSPA's

The first SSPA (4 towers) has now been upgraded → 5th tower in mid-2017 → go on at a rate of 1 - 2 towers a year

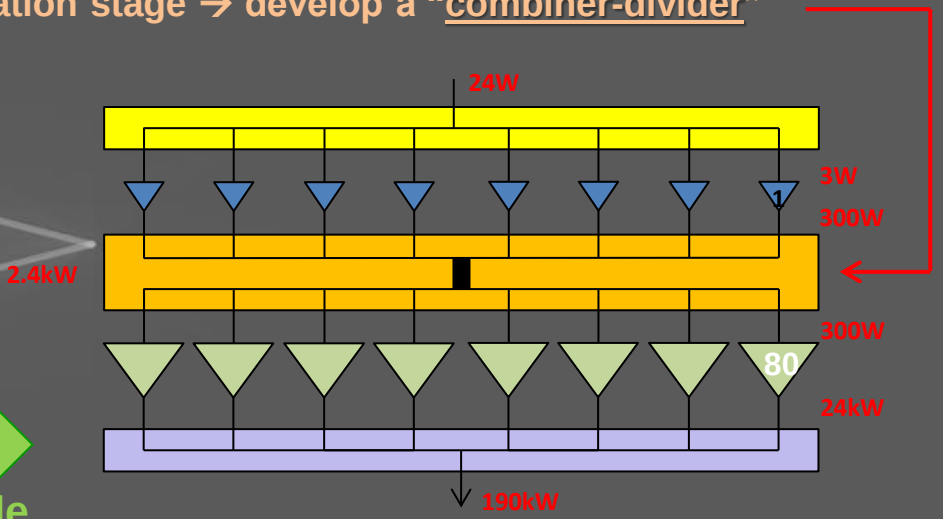
Not a single failure of a « new » transistor until now (~ 2 years of operation)

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

Upgrade



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

SOLEIL R&D with SSPA
→ Transfers of technology

SOLEIL R&D with 352 MHz SSPA's

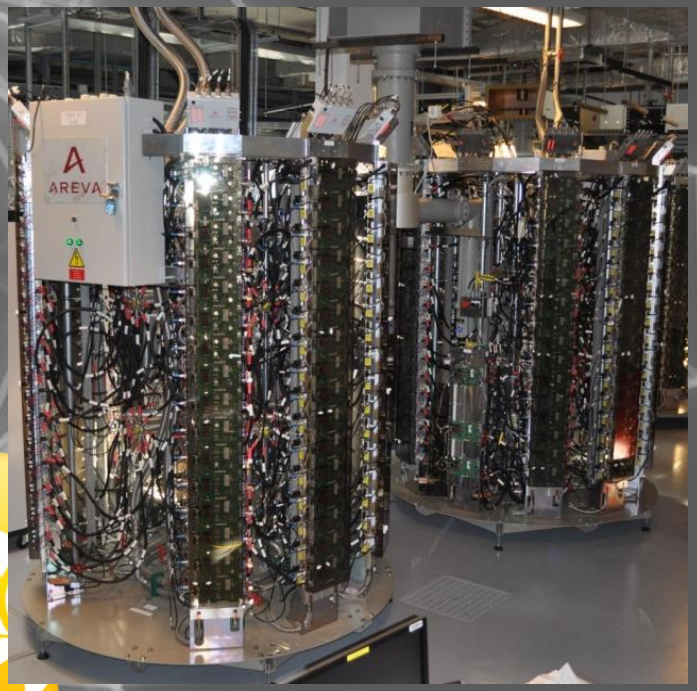
Development of new RF modules, based on 6th generation LDMOS (Vd = 50V)

→ 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)
& thermal stress strongly reduced (ΔT : - 60 °C) → longer lifetime

ESRF upgrade → Replace 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

BO : 4 x 150 kW SSPA's in use since January 2012
2 trips in ~ 5 years of operation → refill postponed

SR : 3 x 150 kW SSPA's in use since October 2013
2 trips in ~ 3 years of operation → beam loss

Trips, due to youth problems, which are now fixed

BO + SR : ~ 1 800 transistors → not a single failure !

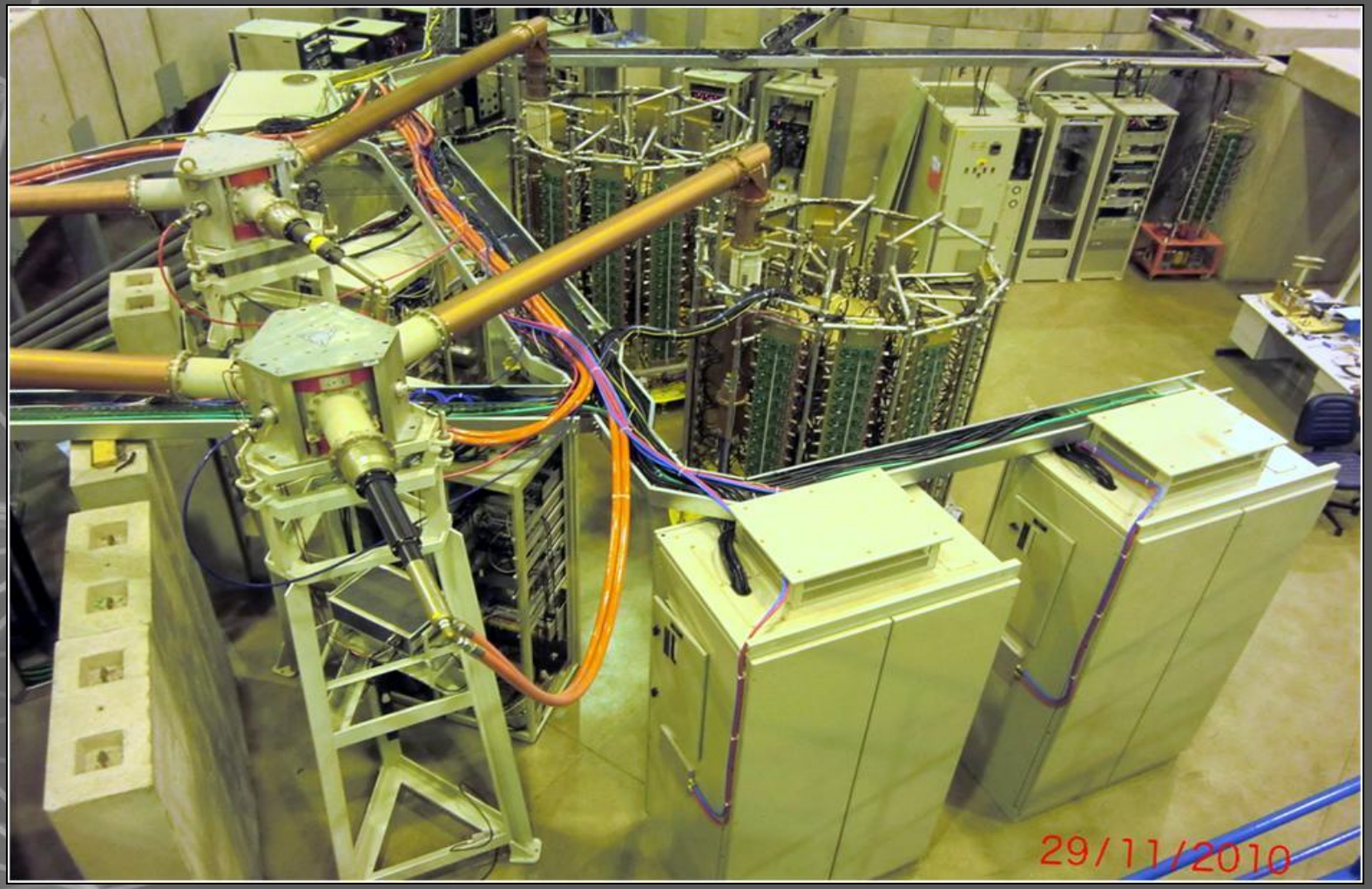
Efficiency (dc to RF) : 58% (dc-dc converters)
With new ac-dc converters → η (overall ac to RF) > 60%

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

LNLS 50 kW RF plants



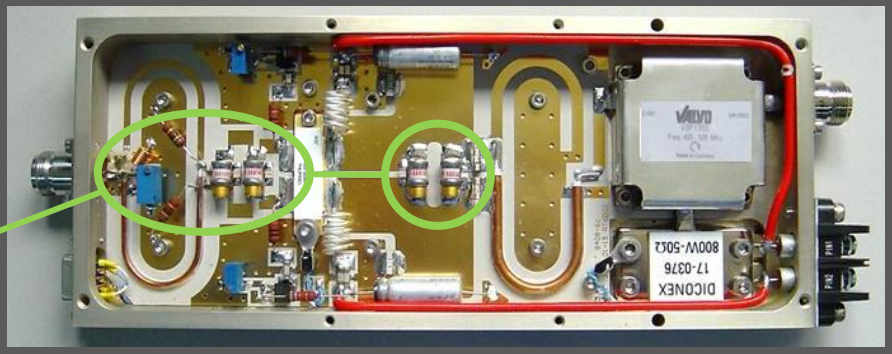
The two 50 kW SSPA's have run satisfactorily on the LNLS SR for ~ 6 years
→ Use of SSPA's (500 MHz) for SIRIUS, their new light source

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)

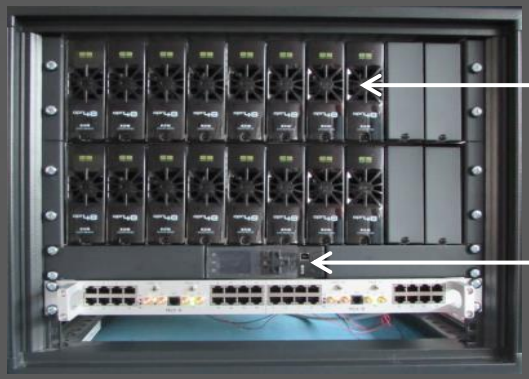
** + 10 pts in efficiency lead to electrical power savings over 10 years of operation ≈ full amplifier cost*

- 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 (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 »

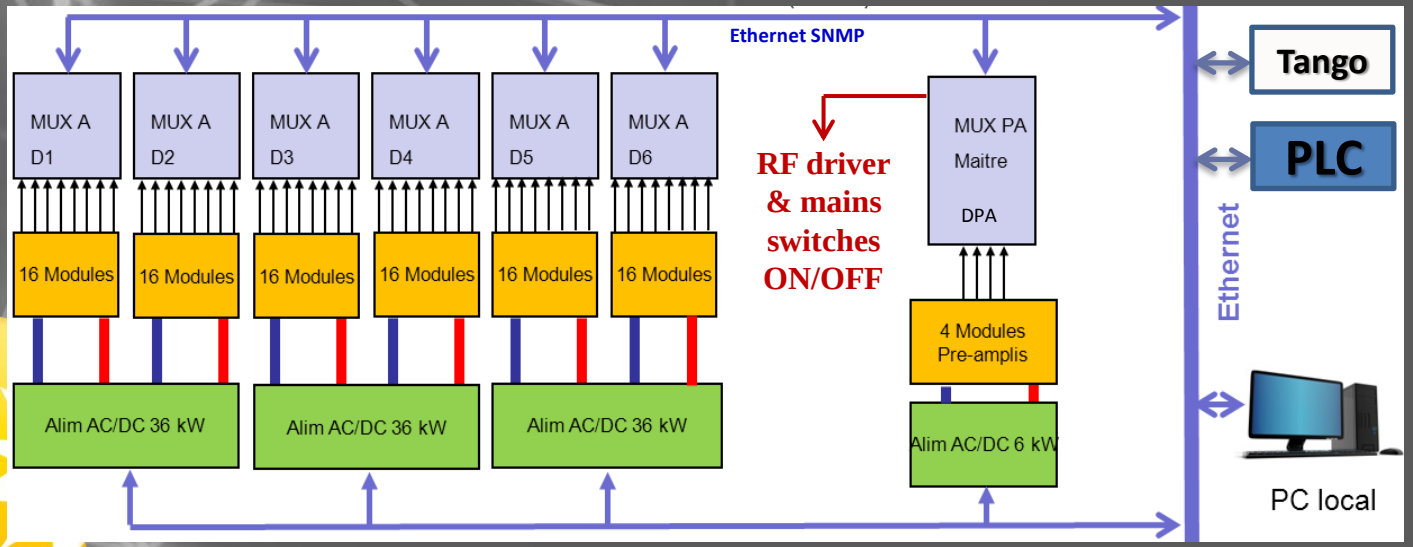
R&D with 500 MHz SSPA at SOLEIL

- Change from tower to cabinet assembly, better suited with the *new power supplies* while keeping the exchangeability at the lowest level, i.e. the elementary module
  → optimum modularity / redundancy and spare inventory management

50 kW SSA for ThomX
(6 dissipaters x 16 mod)

80 kW SSA for SESAME
(10 dissipaters x 16 mod)

- Improved control and supervision



1 MUX per dissipater
MUX : analogic comparators & multiplexers + a µcontroller which monitors all data from a dissipater (16 mod & their PS) + CPLD for the interlocks

→ Fully stand-alone & self-protected

Other SOLEIL SSPA projects

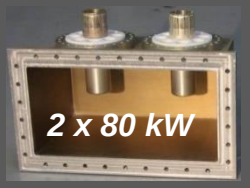
- We've completed the ThomX and first SESAME SSA's; the 3 other ones for SESAME are being built by SigmaPhi Electronics (SPE), the SOLEIL licensee

- The 150 kW-500 MHz SSA is already in the SPE catalogue
  → 2 x 75 kW (2 x 8 dissipaters of 16 modules) combined by means of a wave guide to coaxial combiner, the WaCCo

- 2 x 60 kW - 186 MHz SSPA's for the LUNEX5 photocathode gun
  900 W RF modules using circulators, developped with Valvo

- 1.3 GHz SSA for LUCRECE (R&D for LUNEX5)
  SPE has already built SSA's at 1.3 GHz (P_{mod} ~ 200 W)
  9 x 10 kW for ELBE & 1 x 16 kW for bERLinPro
  SOLEIL - SPE → 20 kW - 1.3 GHz SSA ,
  P_{mod} > 400 W using GaN transistor

Essential for higher frequency

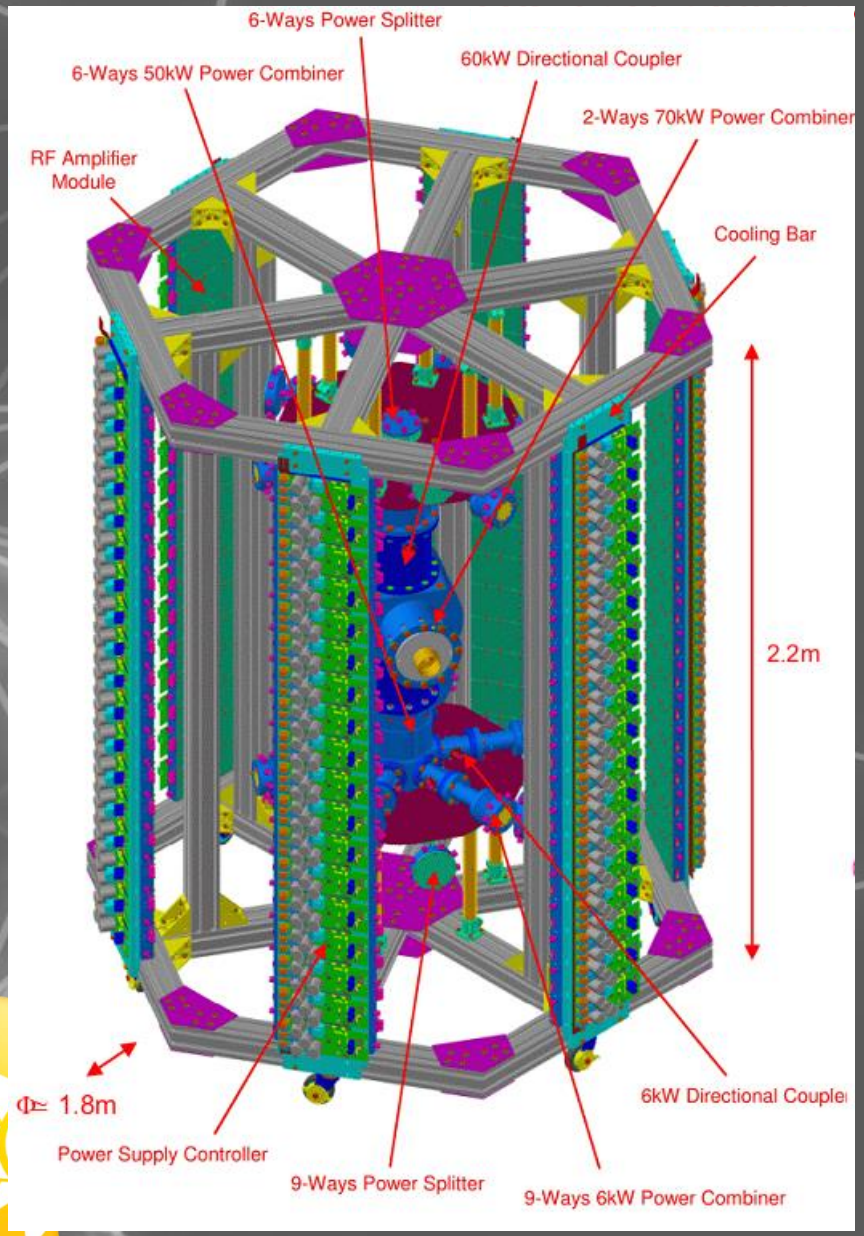


WaCCo

- SOLEIL upgrade towards DLSR and VSR
  → harmonic cavities 1.76 GHz (h = 5) & 1.94 GHz (h = 5.5)
  → 10 kW SSAs using GaN transistors

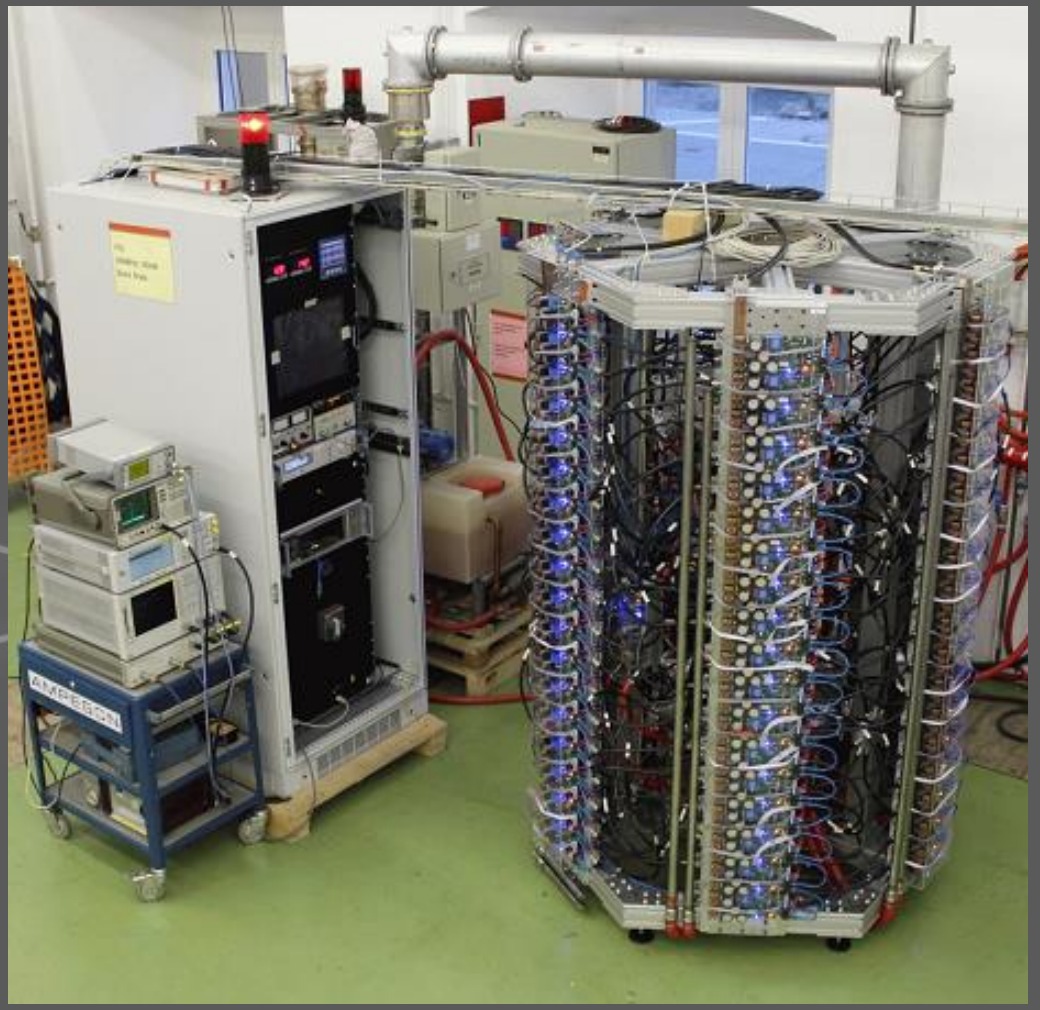
Used or planned SSPA's in other facilities

PSI 60 kW - 500 MHz SSPA



Home made, following the SOLEIL 352 MHz design but specificity of the control system

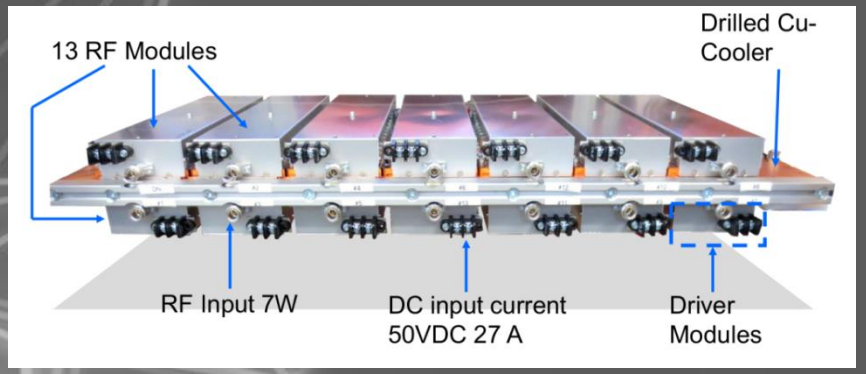
Under test → Replace SLS Booster klystron

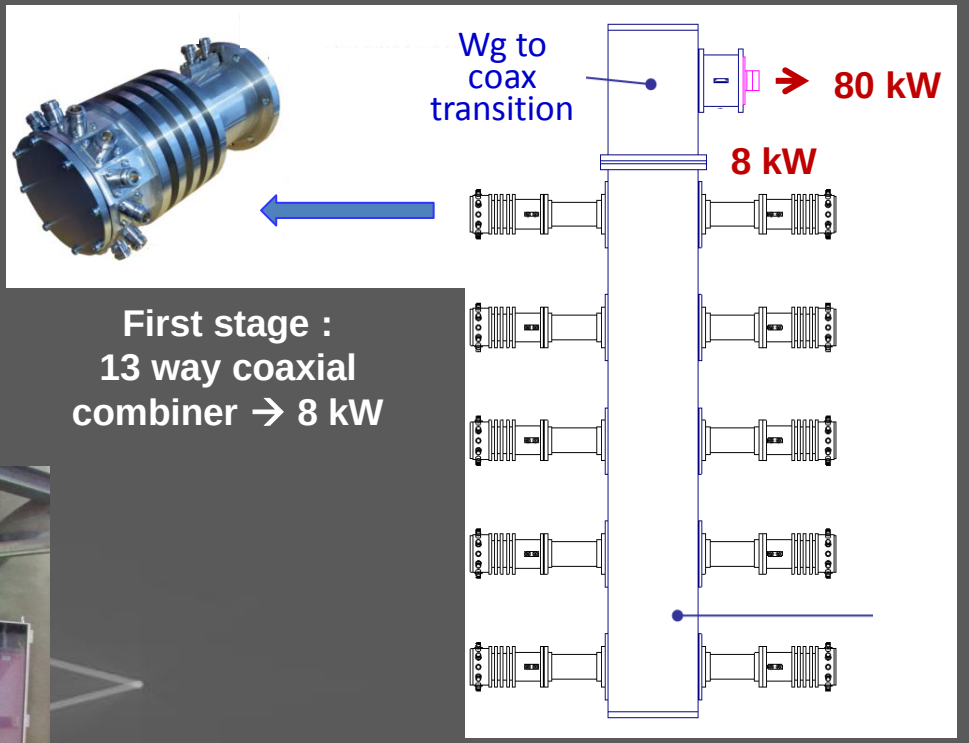


HZB - BESSY II 500 MHz SSPA's

At HZB, replacement of the BESSY II 500 MHz klystrons by SSPA's
4 x 80 kW (SR) + 1 x 40 kW (Booster), supplied by Cryoelectra GmbH

13 modules of 650 W + 1 driver per dissipater
(x 10 dissipaters)



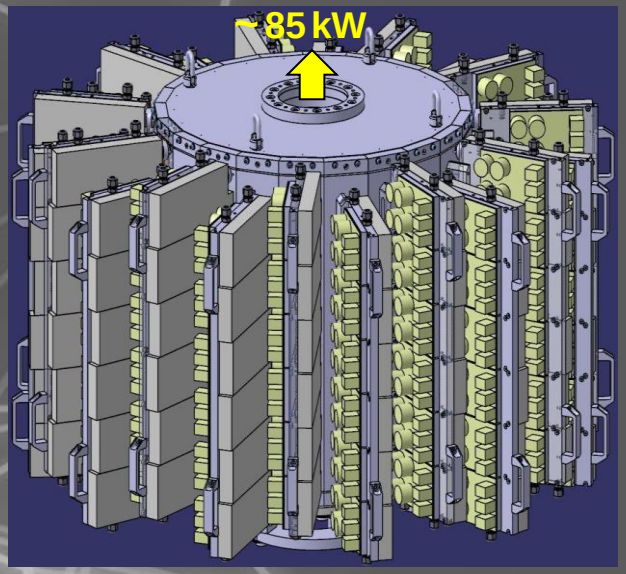


First stage :
13 way coaxial
combiner → 8 kW

2nde stage : 10 way coaxial
to waveguide combiner

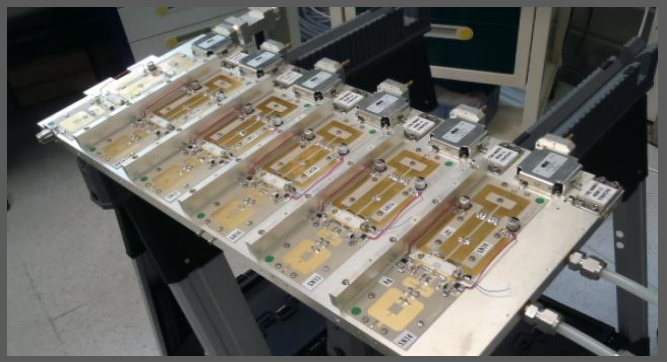
80 kW SR SSPA (efficiency ~ 50 %)
4 plants in operation since end 2015

R&D with cavity combiner for 352 MHz SSPA's at ESRF



The cavity is made of 22 water cooled "wings"
On each wing, 6 modules of ~ 700 W
Each module is magnetically coupled (loop) to the cavity

} ~ 85 kW



Tests on prototype

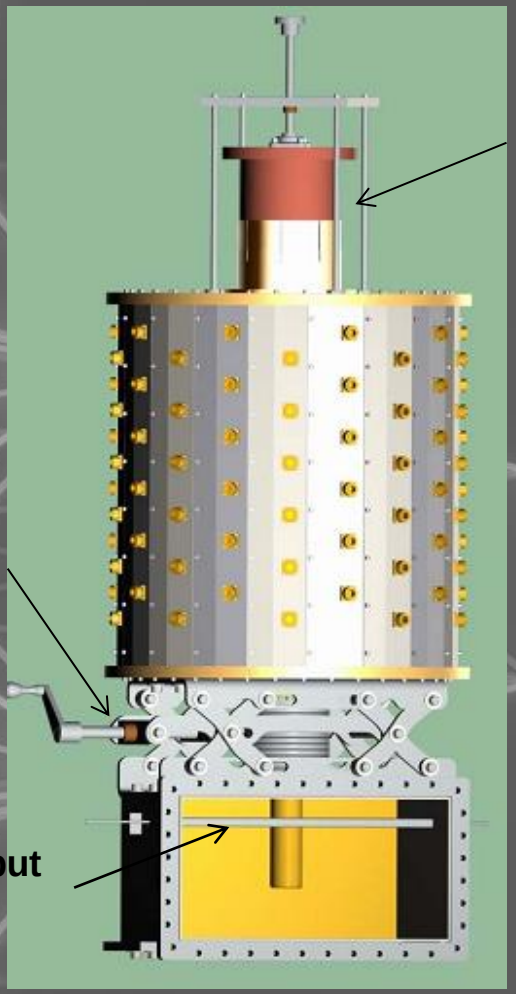
"Fully planar" module efficiency ~ 65%
22 x 8 kW PS (1 / wing) in separate cabinet
At 85 kW drain efficiency : 64.5% ; 56% overall

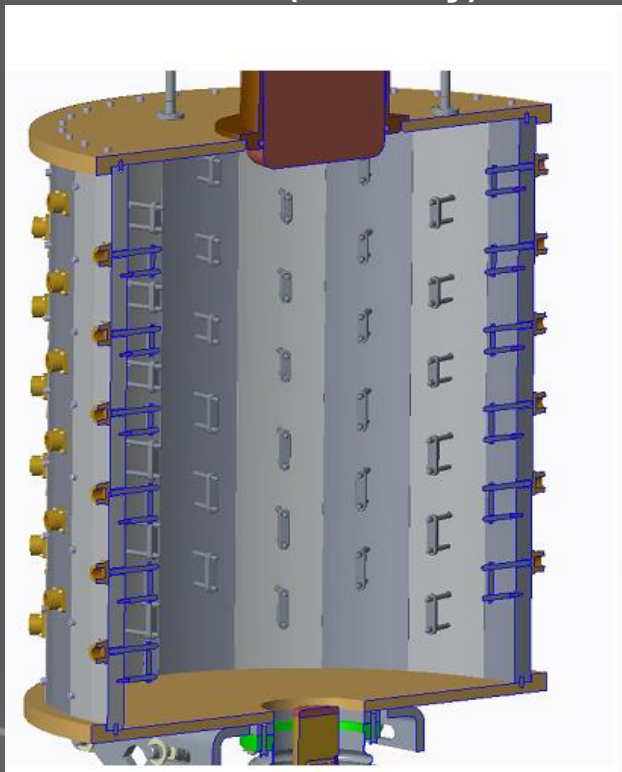
PRO / CON

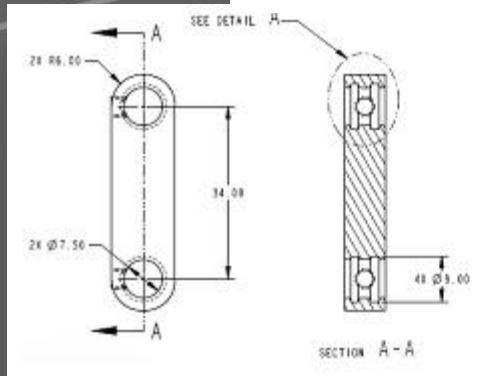
(+) Eliminates power coaxial cables & more compact
(-) Lower tolerable VSWR
(-) "Narrow" bandwidth (~ 500 kHz)
(-) Replacing a failing component → remove a wing of 6 modules
(-) Wing RF contacts on cavity body → RF leaks (?)
(-) Coupling dispersion → individual loop size (or adjustment)

R&D with cavity combiner for 352 MHz SSPA's at APS

- Replace 1 MW - 352 MHz klystron amplifiers with 200 kW SSPA's (1 / cavity)
- SSPA based on 2 kW LDMOS (Vd : 60 V) modules
- 108 : 1 cavity combiner (top & bottom plates + output coupler Te bar are water cooled)



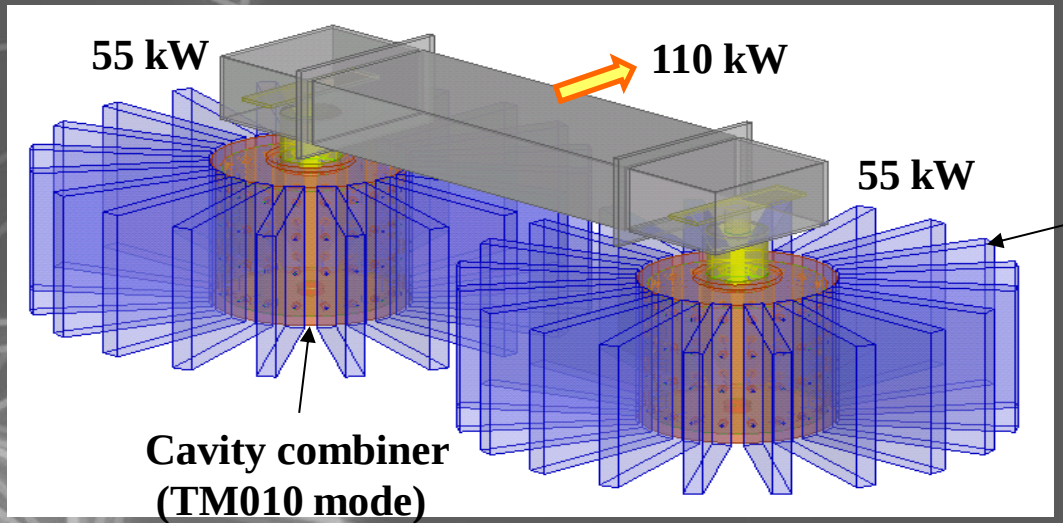




Adjustable input coupling loops

R&D with cavity combiner for 500 MHz SSPA's at SPRING8

SPRING8 II → replace 1 MW - 500 MHz klystron amplifiers with 16 SSPA's of 110 kW (1 / cavity)



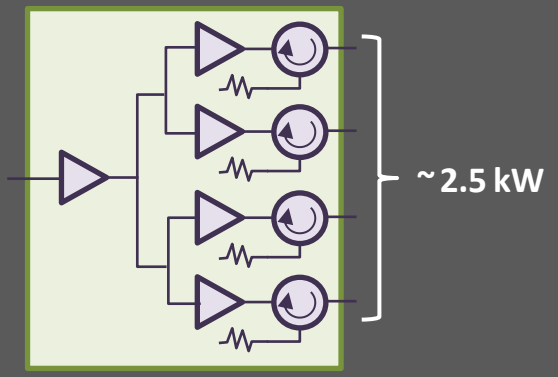
<u>110 kW 500 MHz SSPA</u> :

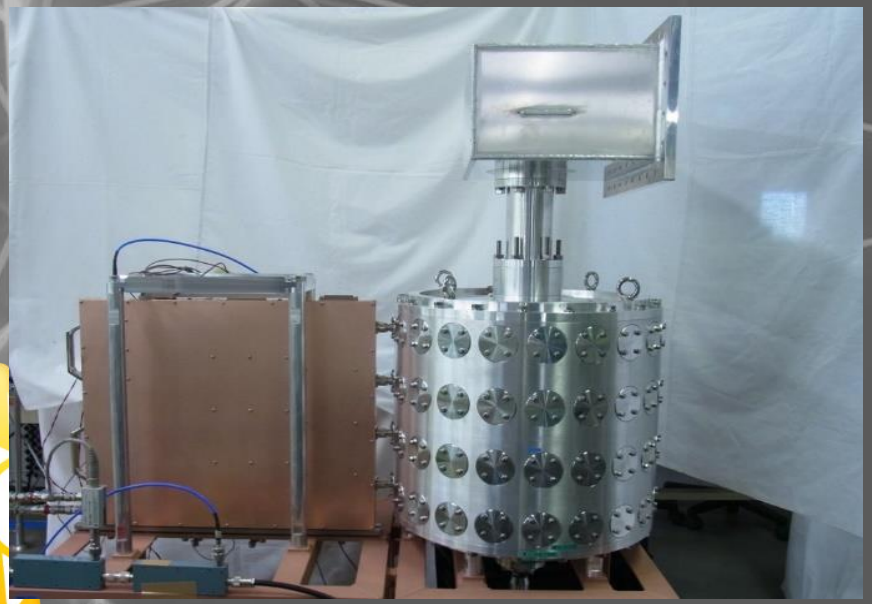
Combination of two 55 kW cavities

20 wings on each cavity

Each SSA wing includes :

- 1 pre-amp
- 4 LDMOS
- 4 circulators



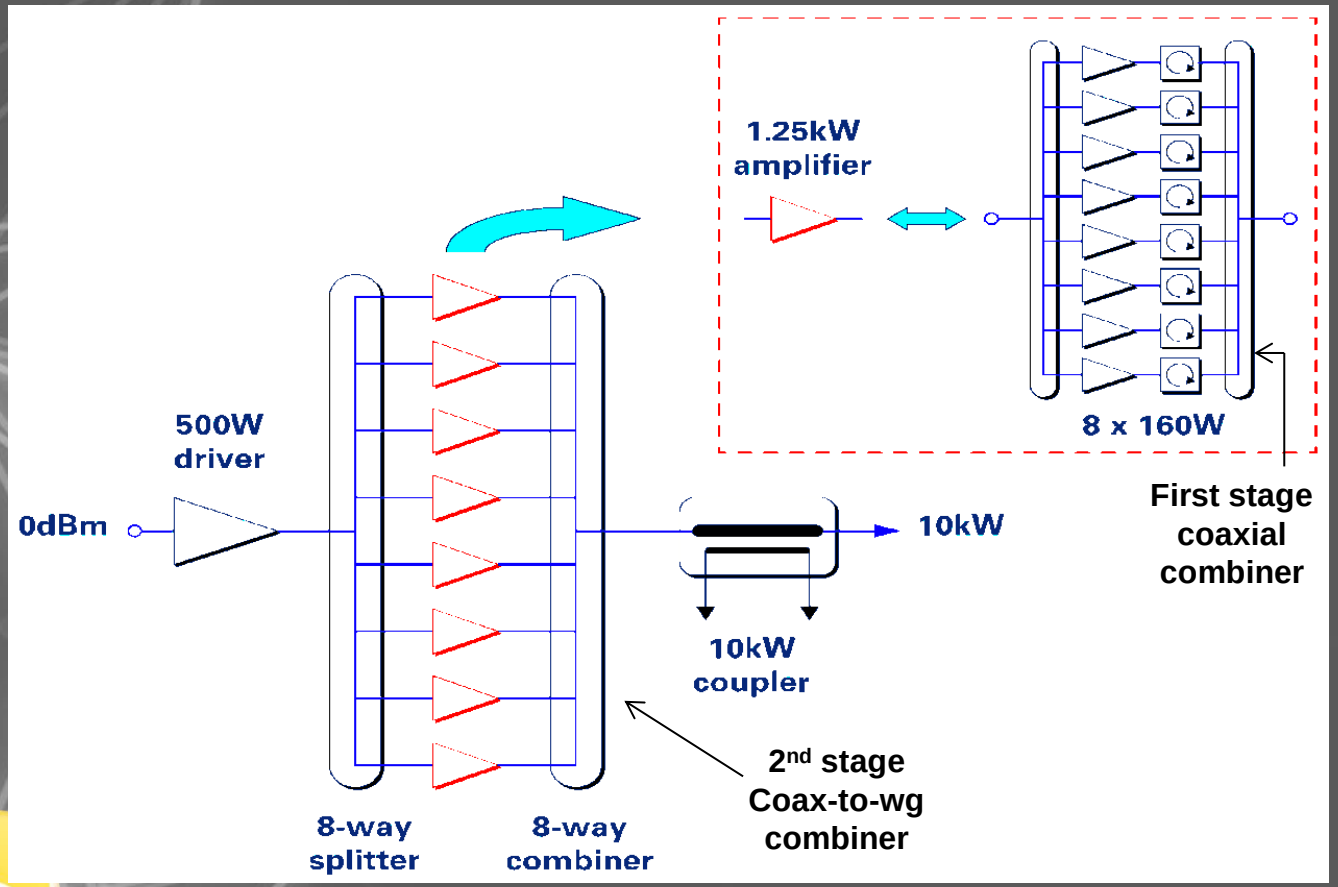


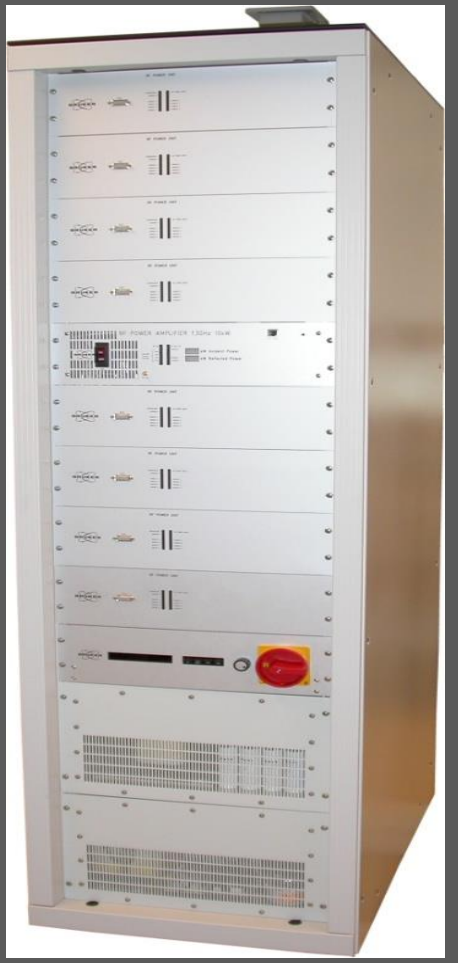
Prototype (only 1 wing) under low power tests

To limit the coupling dispersion, adjustment by loop rotation

10 kW-1.3 GHz SSPA's for ELBE-HZDR

10 SSPA's of 10 kW @ 1.3 GHz supplied by Bruker, now SIGMAPHI ELECTRONICS, operational in ELBE at HZDR since beg. 2012 ; two 10 kW SSA's combined on one cavity



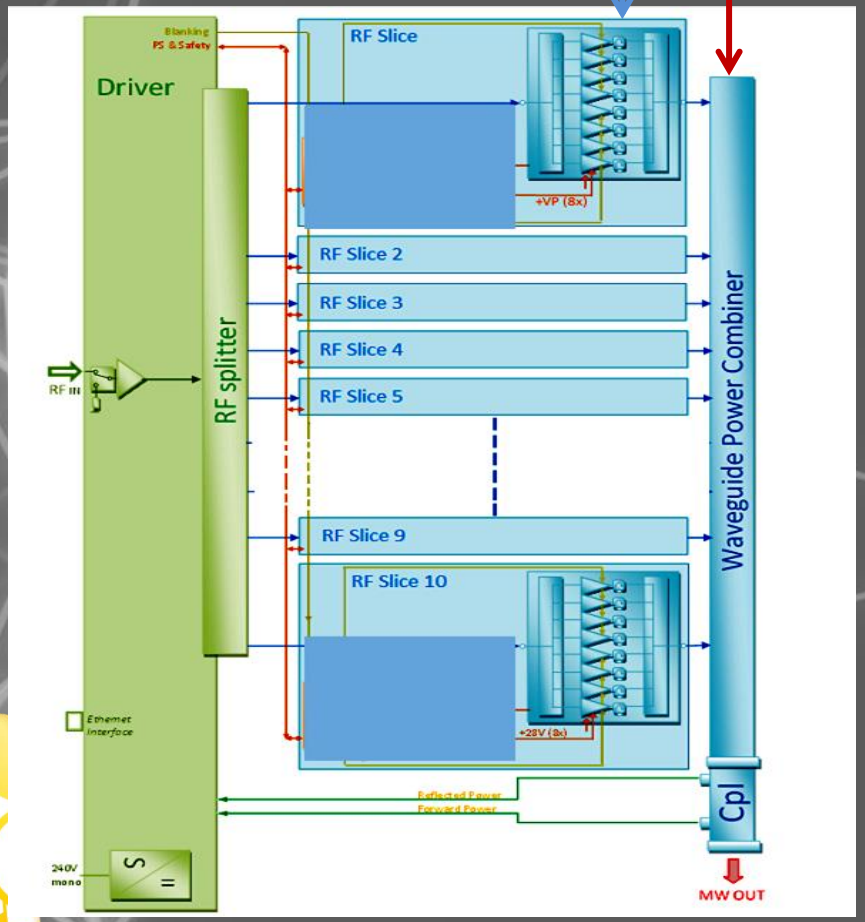


16 kW @ 1.3 GHz for BerlinPro - HZB

Upgraded version supplied by SIGMAPHI ELECTRONICS to HZB, intended to BerlinPro, presently used in HoBiCaT

New generation transistor (50 V) → ~ 200 W / module

Power combination : 200 W x 8 x 10 → 16 kW



16 kW - 1.3 GHz SSPA from SIGMAPHI ELECTRONICS

A similar one is being built by SPE for MESA

1.3 GHz - 3.8 kW SSA's for LCLS II

In SLAC LCLS II s.c. LINAC, need for 284 SSA's of 3.8 kW at 1.3 GHz

The 3.8 kW SSPA is based on 20 (or 24) LDMOS & circulators, combined with a coaxial combiner + 1 circulator at the output

Prototypes from different suppliers

15 units already delivered
6 more in October
Then delivery of 14 / month

3.8 kW SSA from R&K
Overall efficiency ~ 40%

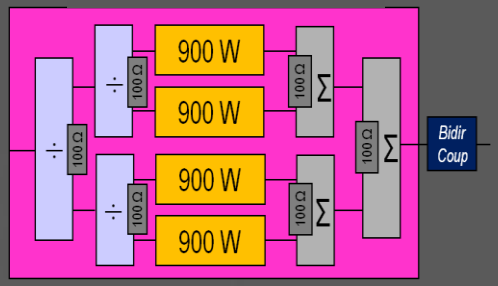
GANIL - SPIRAL2 SSPA's @ 88 MHz

GANIL SPIRAL2 sc LINAC needs four types of 88 MHz amplifiers :
7 x 2.5 kW, 2 x 5 kW, 6 x 10 kW et 14 x 19 kW

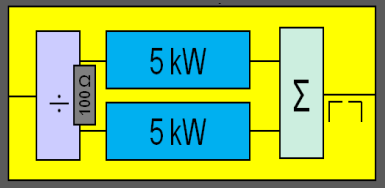
Use of SSPA's, supplied by BRUKER, now SIGMAPHI ELECTRONICS

2.5 kW base module 4 x BLF578 with isolated 3dB combiners

2.5 kW amplifier

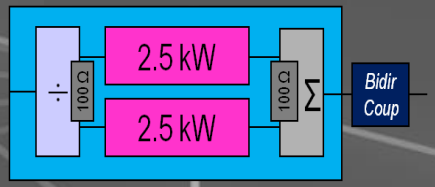


10 kW amplifier

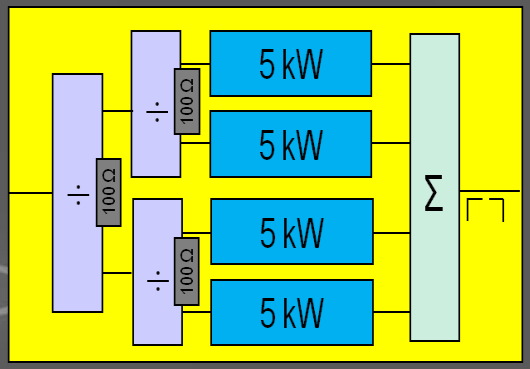


10 kW and 19 kW with non isolated combiners

5 kW amplifier



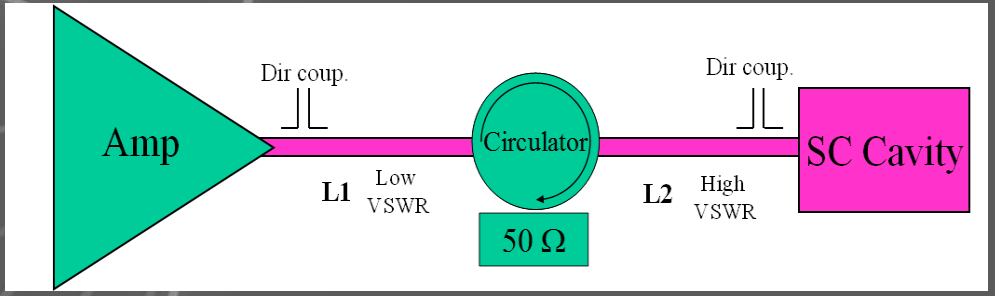
19 kW amplifier



The amplifier modules have no built-in circulator

- **UHF range (350 & 500 MHz, 1.3 GHz) → Use of 1 circulator per transistor is the key to success**
- **At lower freq. difficult to build ~ 1 kW compact circulators → FM - audio transmitter technology (without circulator & with 3 dB hybrid combiners), well suited for medium power into a matched load, but not for high power under mismatched conditions; the SSPA is very sensitive to VSWR !!**

GANIL - SPIRAL2 SSPA's @ 88 MHz



1) Isolation and impedance of the power circulator significantly depends on the cavity operating conditions (VSWR in L2)
2) As the amplifier modules have no built-in circulator, the resulting VSWR in L1 is high enough to affect the amplifier performance

3) That requires adjusting L1 & L2 to limit P_r < 4 % (VSWR < 1.5) + oversizing of the amplifier in order to achieve the nominal power under any operating conditions

All the amplifiers have passed the SAT and are ready for the machine commissioning with cavities & beam.
Overall efficiency ~ 66 %

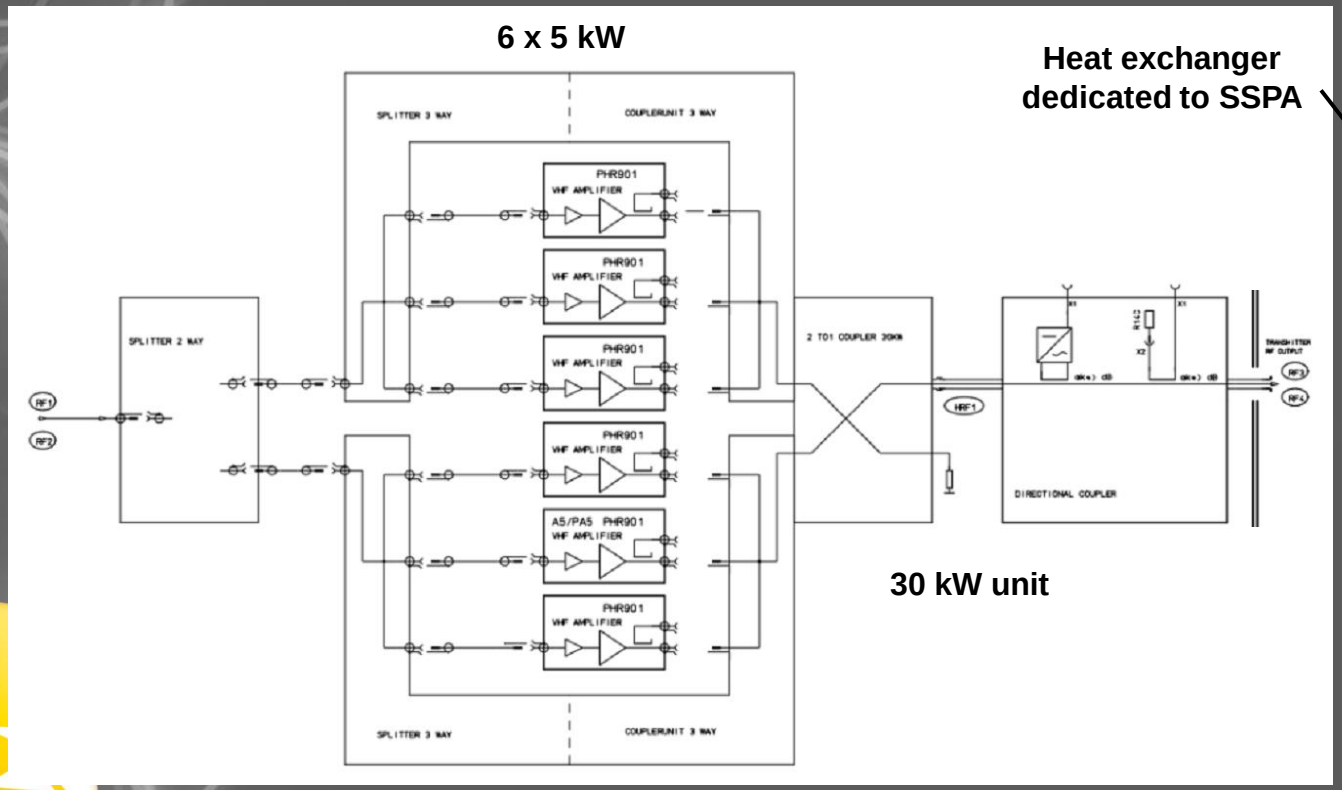
100 MHz SSPA's in MAX IV

SSPA's of 60 kW @ 100 MHz from Rhode & Schwarz

1.5 GeV ring : **2 cavities, each powered with a 60 kW SSPA ***

3 GeV ring : **6 cavities, each presently powered with a 60 kW SSPA → *Phase 2 :* 120 kW / cav from two 60 kW SSPA's, combined with 3 dB hybrid**

Single high power circulator at the amplifier output

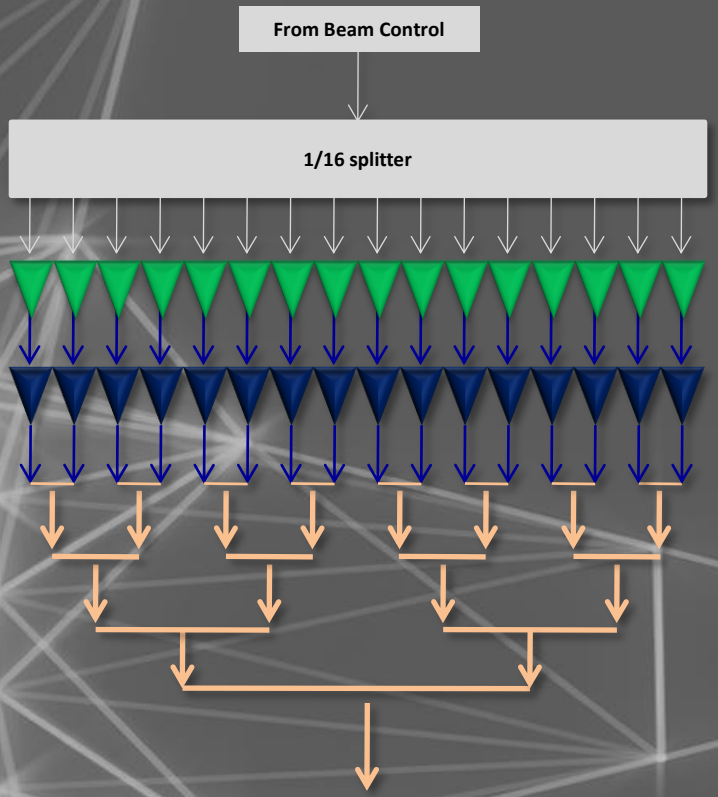


60 kW SSPA = 2 units of 30 kW combined with a 3 dB hybrid (efficiency ~ 66 %)

**** Same thing in SOLARIS, which is a replica of 1.5 GeV - MAX IV***

1.6 MW - 200 MHz SSPA's for CERN - SPS

CERN SPS needs for 1.6 MW peak (50% duty cycle) at 200 MHz x 2 cavities



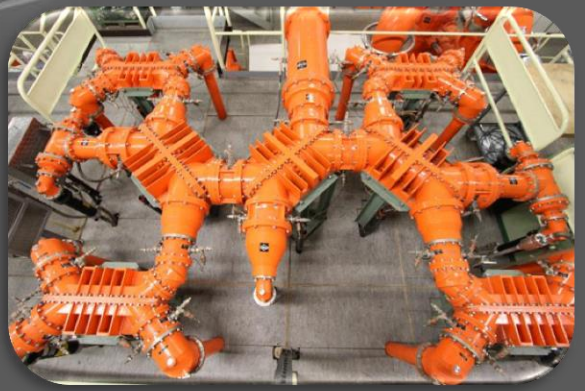
1.6 MW at cavity input
4 stages of 3 dB combiners = - 0.6 dB
120 to 180 m Coaxial lines = - 0.2 dB

16 x 1.25 kW preamplifiers

16 x 140 kW amplifiers

140 kW SSPA from THALES
80 : 1 cavity combiner
80 x 2 kW RF units
2 transistors per unit
First demonstrator delivery in Autumn 2016

4 stages of 3 dB hybrid coaxial combiners (as already existing)



And many other ones, in use, in production or planned

ELETTRA : 1 x 20 kW - 500 MHz for the Booster, in production
DELTA : 1 x 20 kW (booster) and 1 x 75 kW (SR) @ 500 MHz, in production
CLS : 1 x 100 kW - 500 MHz for the Booster → call for tender
DIAMOND : 1 x 80 kW - 500 MHz for the Booster + 1 x 60 kW - 500 MHz for test bench → call for tender
ESS – Bilbao : 3 x 30 kW - 352 MHz for the buncher cavities of ESS → call for tender
MYRRHA : 160 kW - 176 MHz (production) and 1 x 80 kW - 352 MHz (→ call for tender)
SIRIUS : 4 x 60 kW - 500 MHz, planned
ALBA : 4 x 30 kW - 1.5 GHz for 3rd harmonic system, planned
FREIA - Uppsala : R&D with 10 kW - 352 MHz prototype (ESS operational conditions), in production
IPNO - Orsay : 10 kW - 352 MHz prototype from LNL – INFN, used in EURISOL test bench
IFMIF EVEDA : 18 x 200 kW - 175 MHz, planned

GANIL : 7 x 2.5 kW & 2 x 5 kW & 6 x 10 kW & 14 x 20 kW @ 88 MHz
SESAME : 4 x 80 kW @ 500 MHz
HZDR : 10 x 10 kW @ 1.3 GHz
HZB : 1 x 15 kW @ 1.3 GHz
MESA : 1 x 15 kW @ 1.3 GHz
BARC (India) : 1 x 25 kW @ 75 MHz
FERMILAB : 1 x 75 kW @ 162 MHz & 1 x 10 kW @ 325 MHz
IAP Frankfort : 1 x 12 kW @ 176 MHz & 1 x 10 kW @ 88 MHz
BNL : 1 x 20 kW @ 704 MHz
JLAB : 1 x 10 kW @ 748 MHz
TARLA (Turkey) : 2 x 4 kW @ 1.3 GHz
…….
…….

Built by SIGMAPHI ELECTRONICS

Summary - Conclusions

- SOLEIL has run for ~ 10 years with 352 MHz SSPA's (35 kW in the BO, 4 x 180 kW in the SR); they have shown an outstanding operational availability (MTBF >> 1 year). This experience has demonstrated that the SSPA can advantageously replace the vacuum tube in such an application, thanks to its inherent modularity/redundancy, the absence of HV and its very low phase noise.
- R&D carried out at SOLEIL allowed improving the original design towards more compactness in doubling the power per modules while reducing the thermal stress, improving the redundancy and the overall (plug to RF) efficiency up to 65 % (resp. 55 %) at 352 MHz (resp. 500 MHz).
- More recently, SOLEIL has built two 500 MHz SSPA's, one 50 kW for ThomX & one 80 kW for SESAME; 3 other identical ones are supplied to SESAME by SigmaPhi Electronics (SPE), the SOLEIL licensee ;

  A 150 kW version is available as well.
- SSPA technology has now reached maturity ; SSPA's have run for a few years in several other places and the operational experience feedback is excellent :
  - 7 x 150 kW - 352 MHz SSPA's from ELTA/SOLEIL, for 5 years in the ESRF BO (3 years in SR);
  - 2 x 50 kW - 476 MHz SSPA's, realized within the frame of a collaboration between SOLEIL and LNLS - Brazil, for 6 years in the LNLS SR;
  - 10 x 10 kW - 1.3 GHz SSPA, built by Bruker, now SPE, for 5 years in ELBE at HZD.
- SSPA technology is being adopted by many other facilities and taken up by the industry for applications ranging from 80 MHz up to 1.5 GHz with power from few 10 kW up to MW.

  At f > 300 MHz, using a circulator per transistor is the key to success ; at lower frequency, the lack of ~ 1 kW compact circulators makes it less easy → VALVO - SOLEIL R&D with circulators.

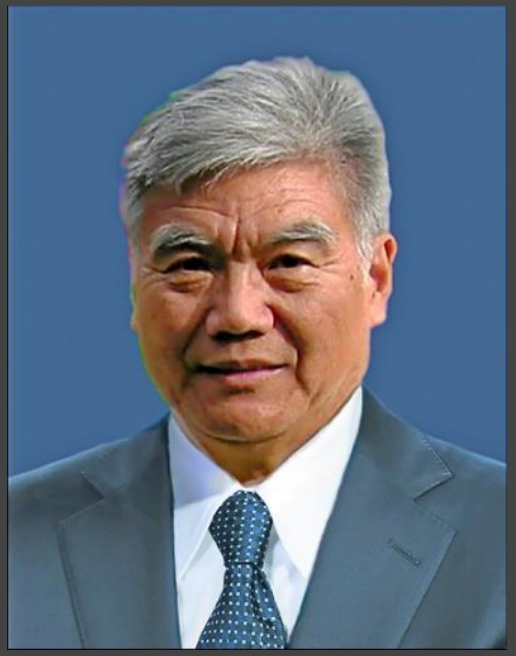
  At f > 1.3 GHz, the GaN transistor supplants the LDMOS → SPE - SOLEIL R&D for LUCRECE.
- R&D's are carried out with cavity combiners, which could be an alternative to coaxial combiners

Acknowledgements

- Wolgang ANDERS (HZB)
  Hartmut BÜTTIG (HZDR)
  Douglas HORAN (APS)
  Marcos GASPAR (PSI)
  Takahiro INAGAKI (SPRING8)
  Jorn JACOB & Michel LANGLOIS (ESRF)
  Michel LECHARTIER (GANIL)
  Lars MALMGREN (MAX IV)
  Eric MONTESINOS (CERN)
  Nico PUPETER (CRYOELECTRA GmbH)
  Cedric SCHAN (SIGMAPHI ELECTRONICS)
  A. Dian YEREMIAN (SLAC-LCLS II)

- SOLEIL RF and LINAC group

Do not forget who was THE pioneer in the domain of high power solid state RF amplifiers



Ti RUAN, 1936 - 2014


Thank you for your attention