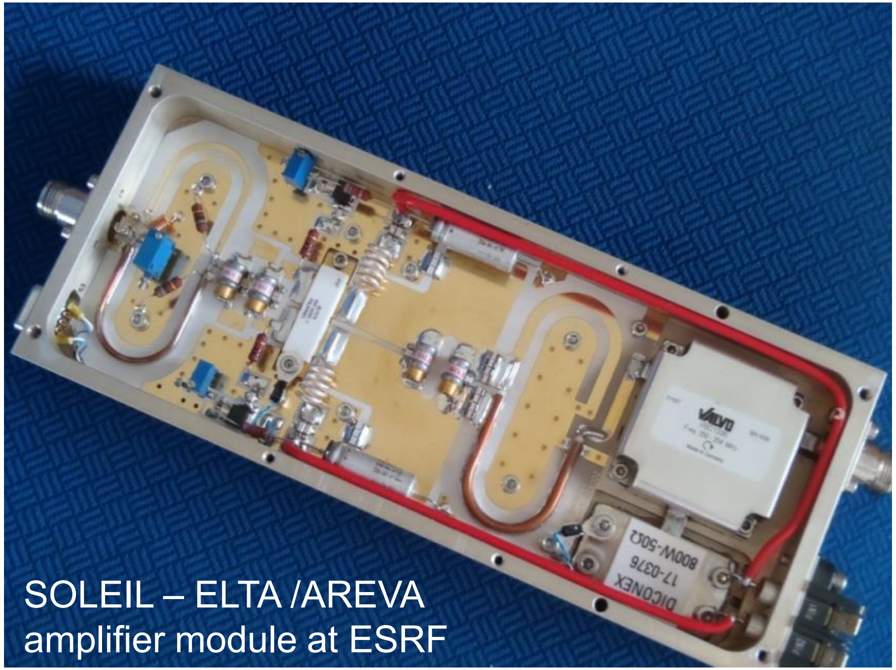
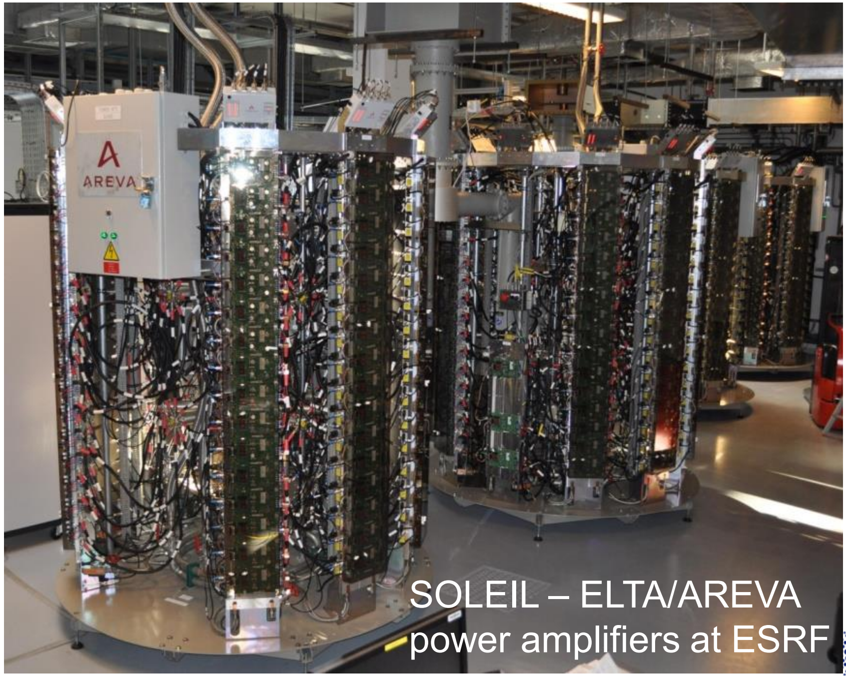
60th ICFA Advanced Beam Dynamics Workshop – **FLS 2018**
Shanghai Institute of Applied Physics, 5 - 9 March 2018

High Power RF Solid State Amplifiers for Accelerators and Storage Rings

Jörn Jacob, ESRF



SOLEIL – ELTA /AREVA
amplifier module at ESRF



SOLEIL – ELTA/AREVA
power amplifiers at ESRF

REFERENCES FOR RF SOLID STATE POWER AMPLIFIERS (SSPA)

4th ESLS RF Meeting at ESRF, Grenoble, October 2000

- **Ti Ruan** (LURE, then SOLEIL) presented 352 MHz - 40 kW SSPA for the SOLEIL booster

☞ Pioneering and advocating RF SSPA for accelerators

☞ Finally built 2 x 180 kW SSPA for SOLEIL storage ring

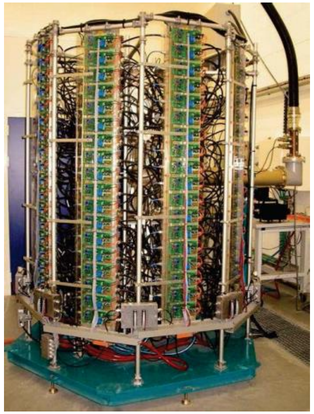
Ti Ruan (1936 - 2014)

IPAC 2017, Copenhagen

- Invited talk and very nice overview by **Patrick Marchand**, SOLEIL:

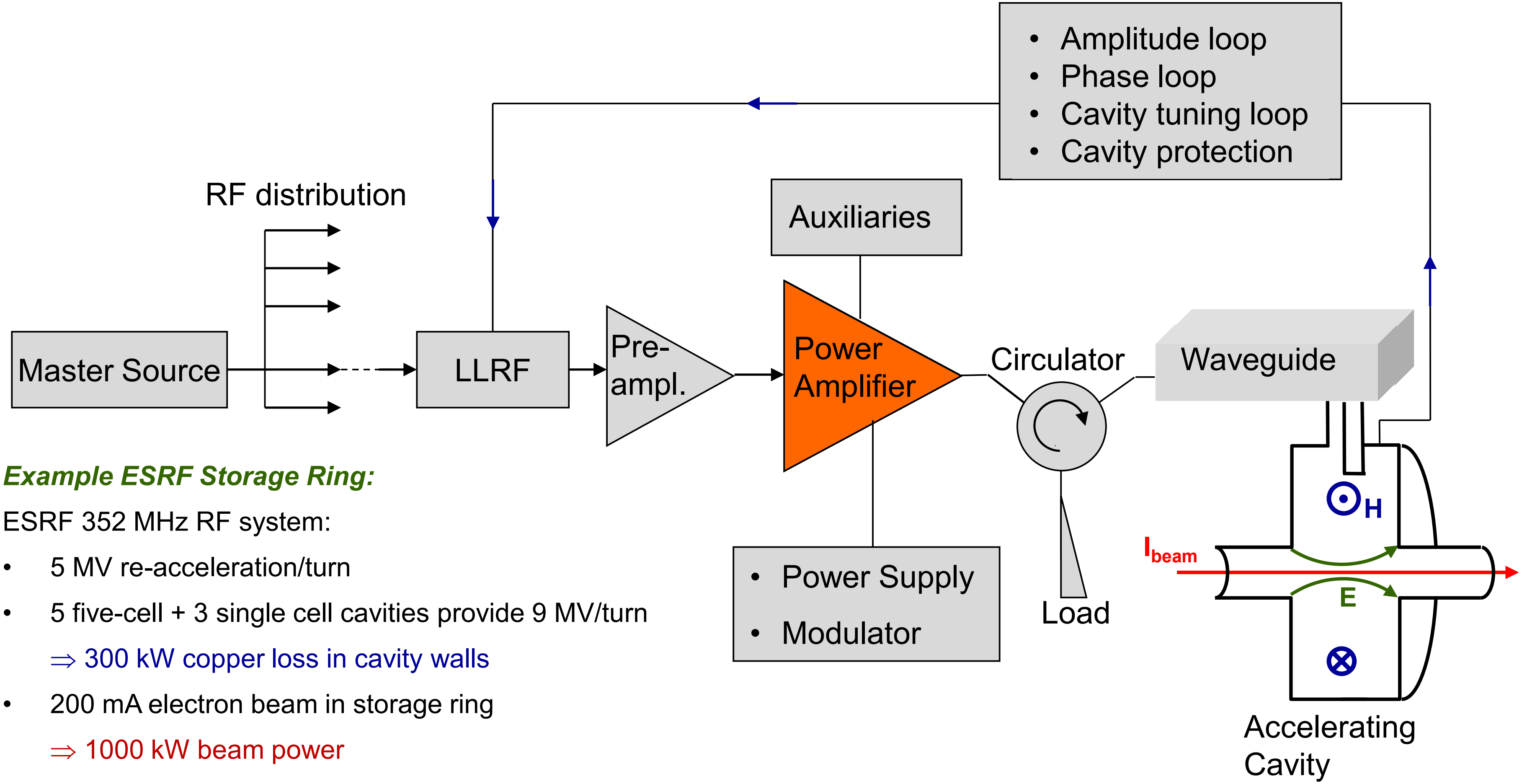
  "Review and Prospects of RF Solid State Power Amplifiers for Particle Accelerators"

☞ Examples cited in this talk other than ESRF are mainly taken from P. Marchand's review



40 kW SSPA of SOLEIL Booster

RF TRANSMITTERS FOR ACCELERATING CAVITIES

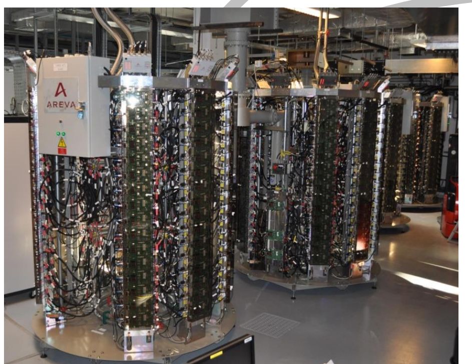


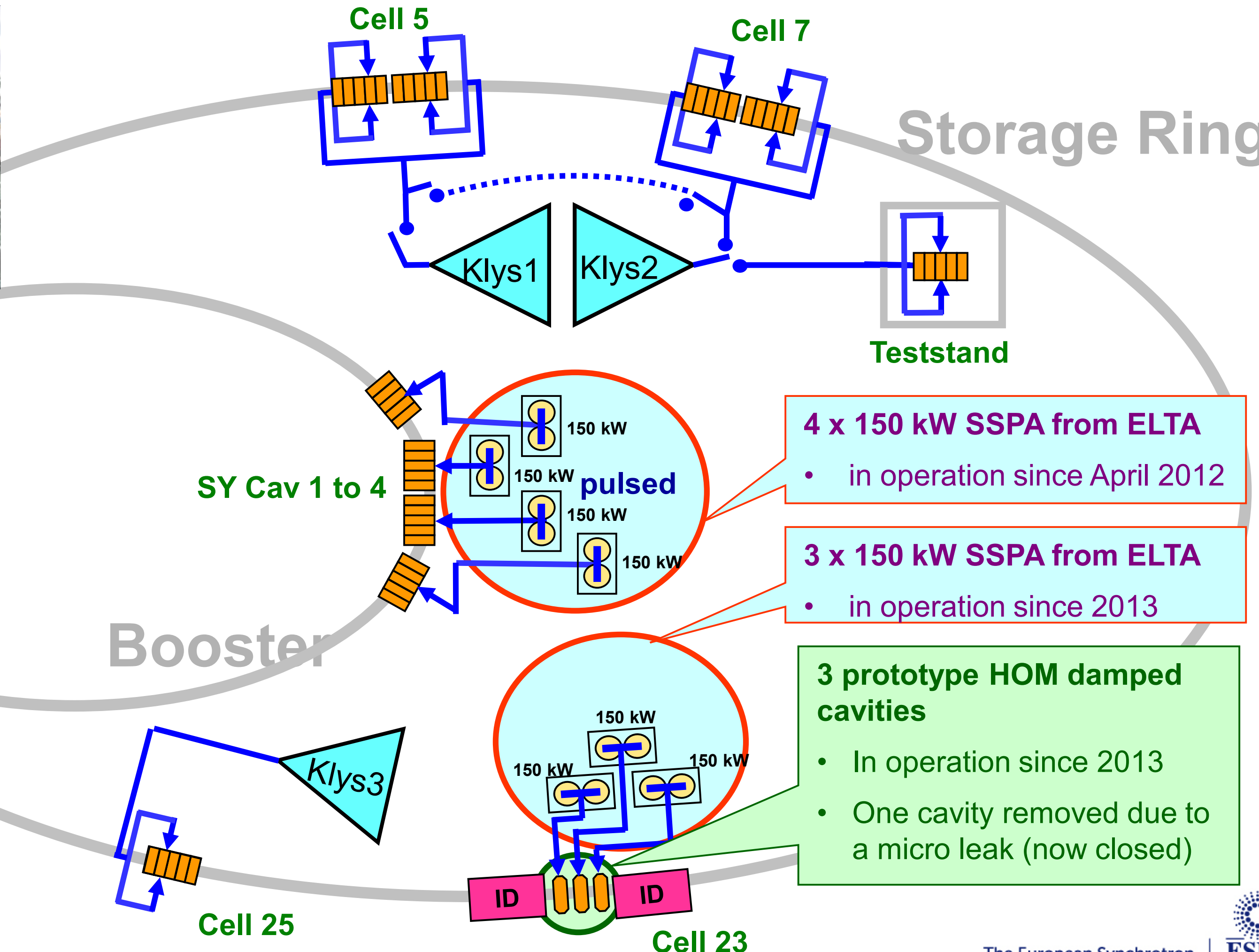
Example ESRF Storage Ring:

ESRF 352 MHz RF system:

- 5 MV re-acceleration/turn
- 5 five-cell + 3 single cell cavities provide 9 MV/turn
  - ⇒ 300 kW copper loss in cavity walls
- 200 mA electron beam in storage ring
  - ⇒ 1000 kW beam power
- RF power from 1.1 MW klystrons and SSPA

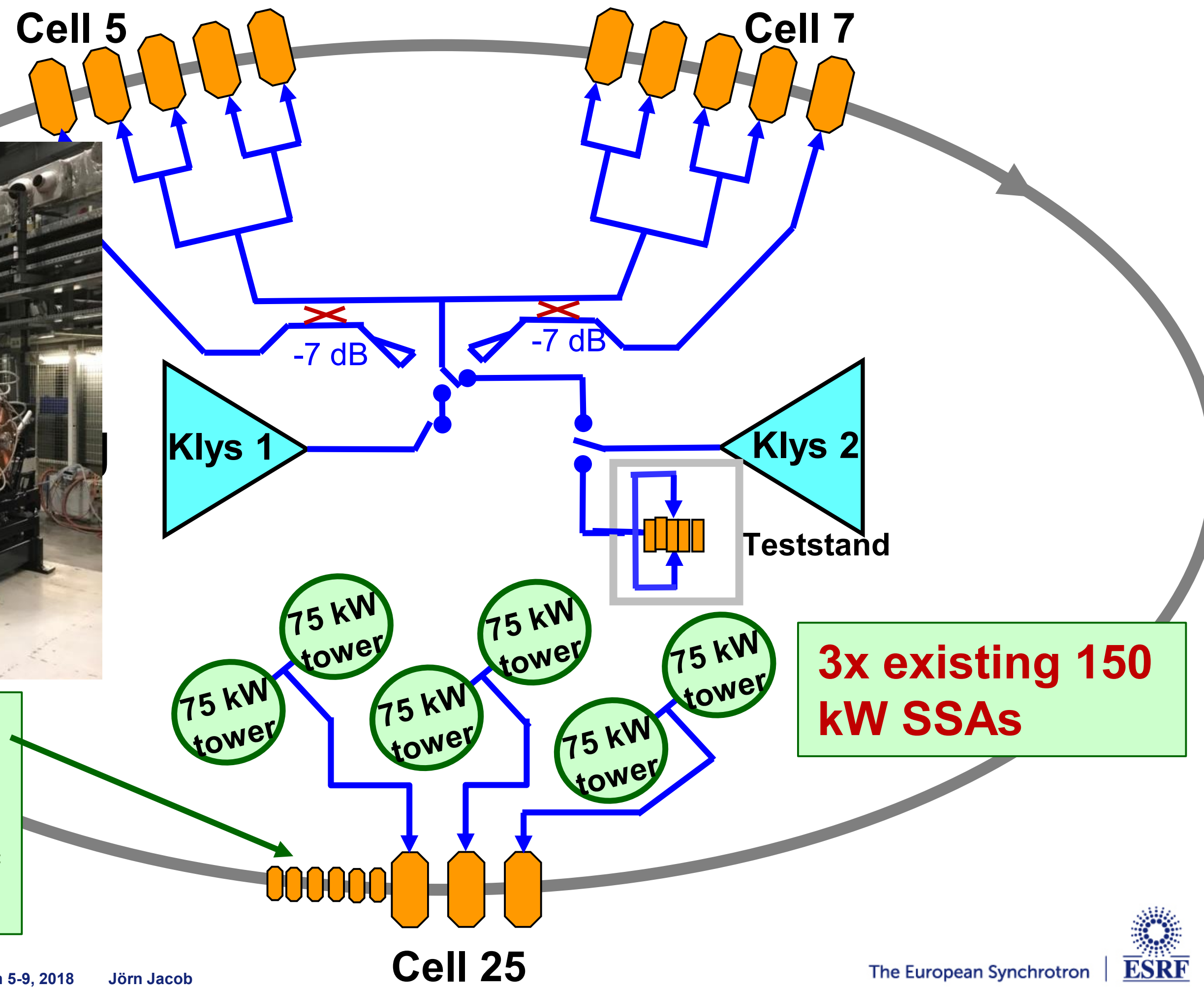
EXAMPLE: ESRF (UNTIL DECEMBER 2018)





RF SYSTEM FOR ESRF- EBS (INSTALLATION IN 2019)

☞ EBS = new Extremely Brilliant Source: see talk by Thomas Perron, ESRF

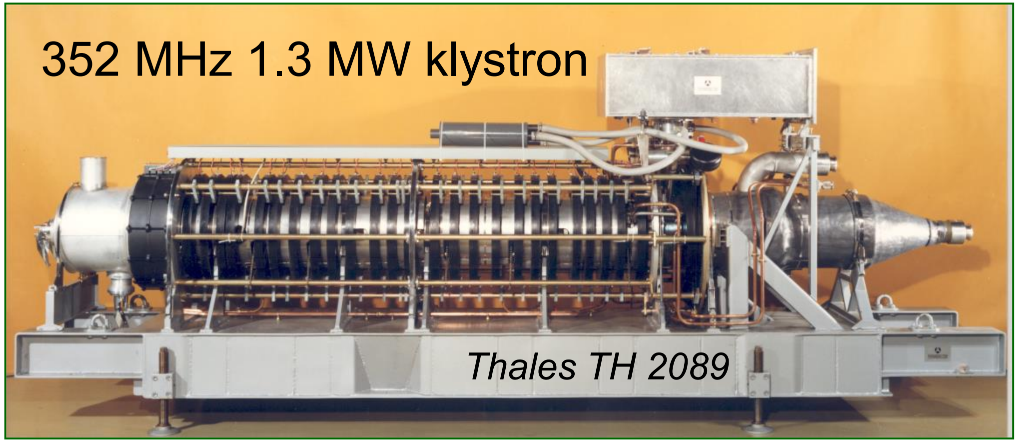


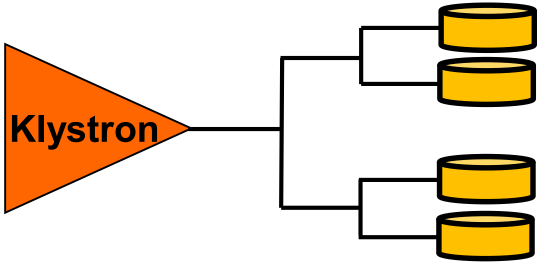
3x existing 150 kW SSAs

3rd harmonic RF system

- Still under study:
  5 to 6 active NC cavities
- SSA development started: ≈ 40 kW per cavity

KLYSTRONS IN OPERATION AT THE ESRF





- ≈1 MW ⇒ power splitting between several cavities
- Any failure trips the complete system: no redundancy

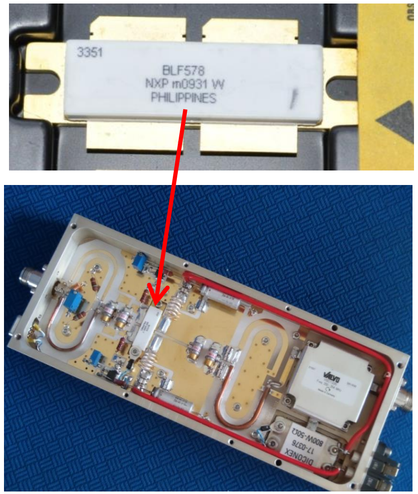
→ η_{typ} = 62 % (DC to RF)
→ G_{typ} = 42 dB ⇒ $P_{in} \lesssim 100$ W

Requires:

- 100 kV, 20 A dc High Voltage Power Supply
  - ☞ with crowbar protection (ignitron, thyratron)
- Modern alternative: IGBT switched PS
- Auxilliary PS's (modulation anode, filament, focusing coils, …)
- High voltage ⇒ X-ray shielding !

150 kW – 352 MHz SSPA AT ESRF

Pair of transistors in push-pull



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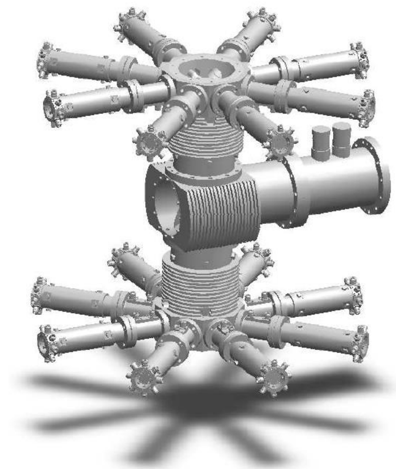

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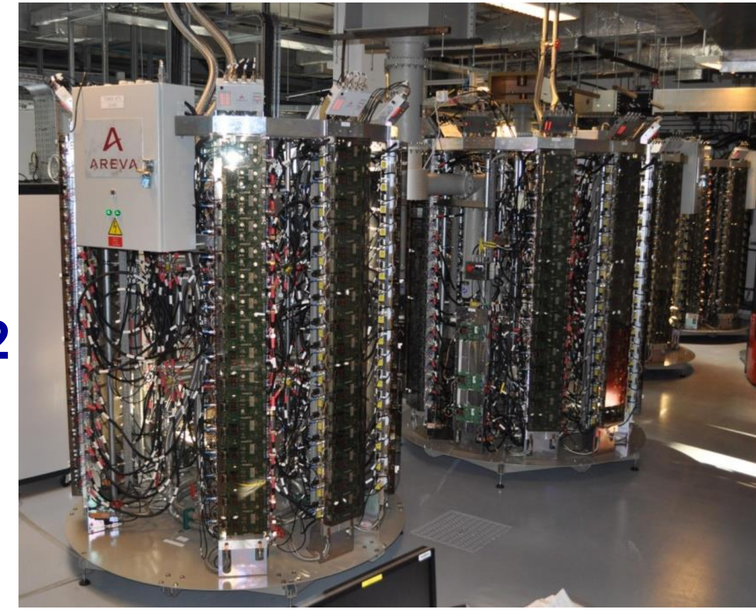


650 W RF module

- DC to RF: η = 68 to 70 %

75 kW coaxial power combiner tree

150 kW - 352.2 MHz SSPA

DC to RF: η > 55 % at nominal power

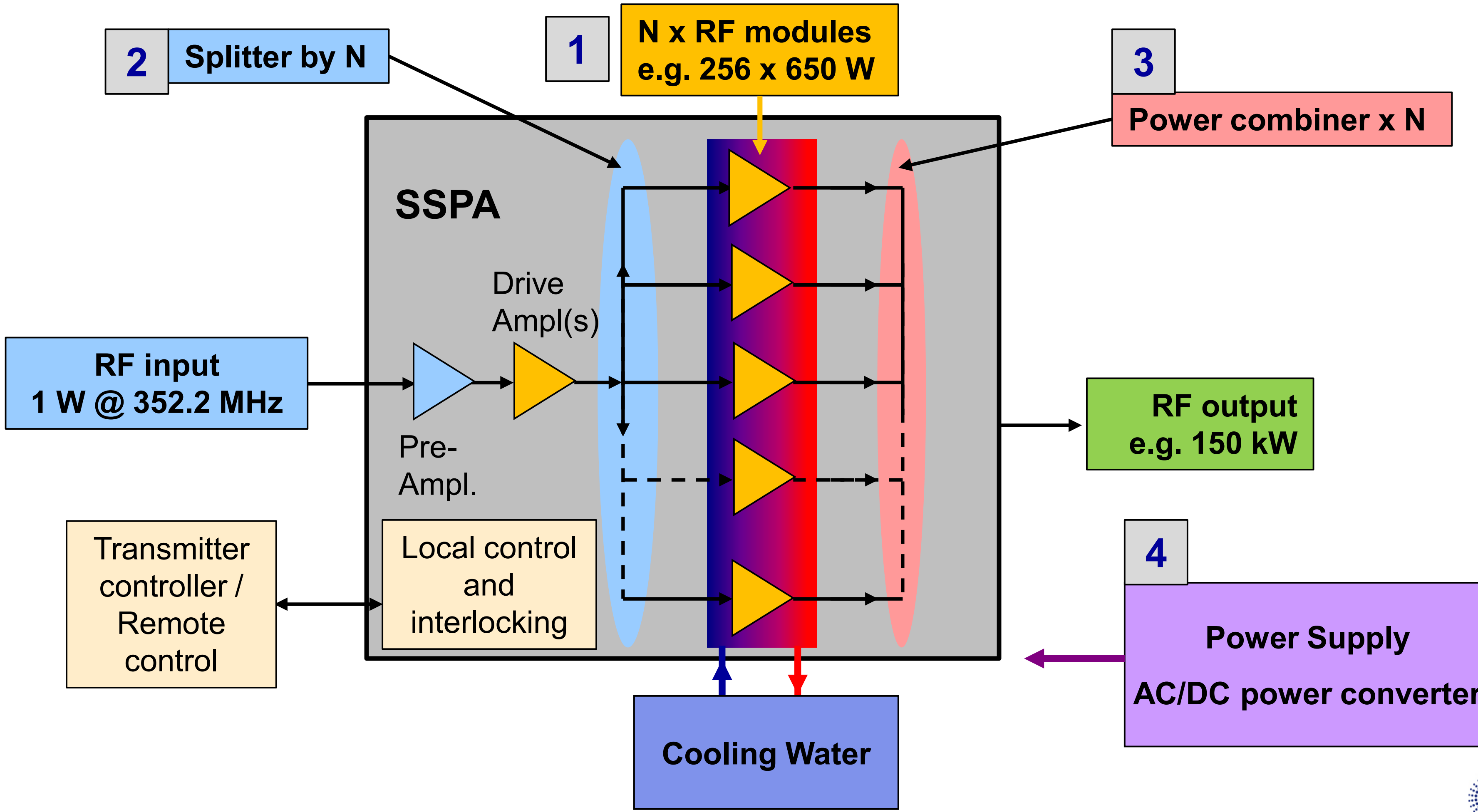
☞ **7 such SSAs in operation at the ESRF!**

- Tolerates failures: no trip even at maximum power with up to 6 faulty modules

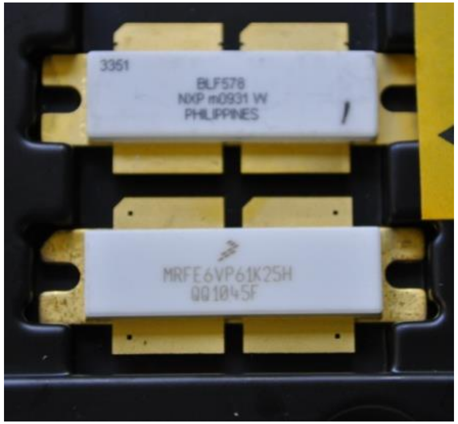
⇒ High redundancy

- Initially developed by SOLEIL
- Transfer of technology to ELTA / AREVA
- RF modules & coaxial lines built by BBEF (PRC)

COMPONENTS OF RF SSPA

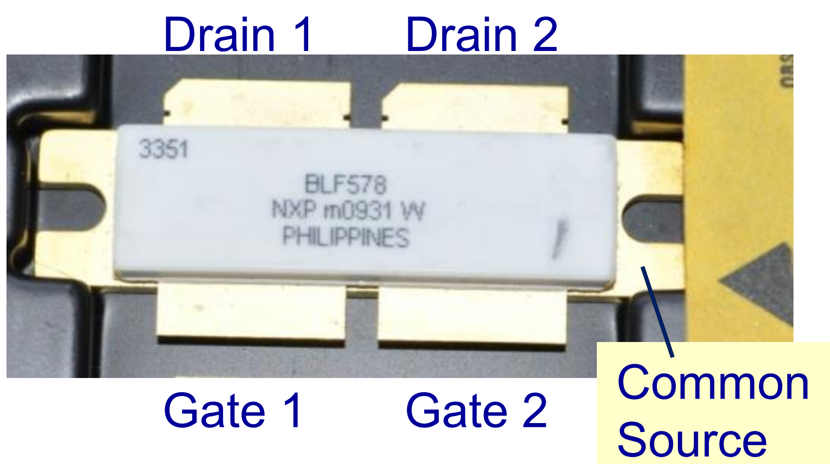


RF AMPLIFIER MODULE: TRANSISTOR

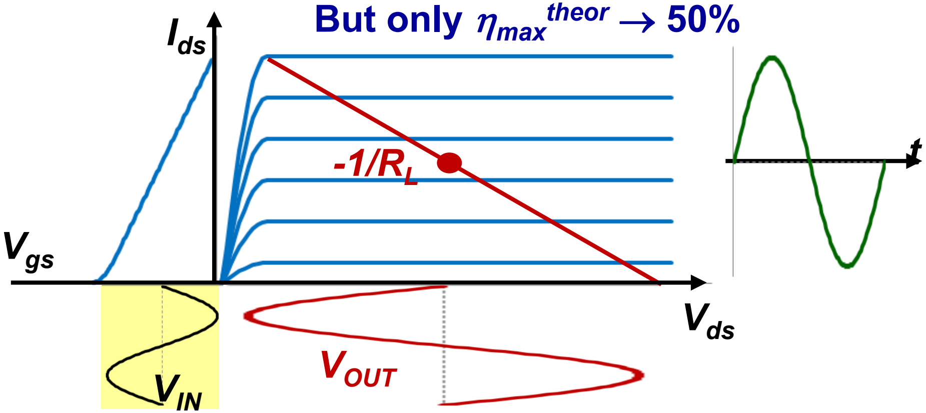


SOLEIL / ELTA module for ESRF SSPA

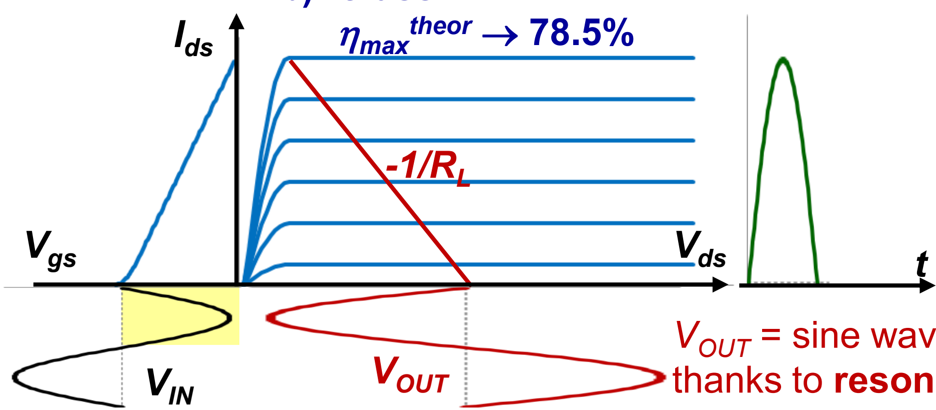
- Pair of Push Pull Si-MOSFET transistors operated in class AB:
- 6^{th} generation 50 V LDMOSFET for 1 kW CW at 225 MHz from NXP-Freescale or Ampleon
- ESRF: BLF578 (~~NXP~~ → Ampleon): 650 W / module at 352 MHz
- GaN transistors for high frequencies



a) **Class A: good linearity, But only $\eta_{max}^{theor} \rightarrow 50\%$**

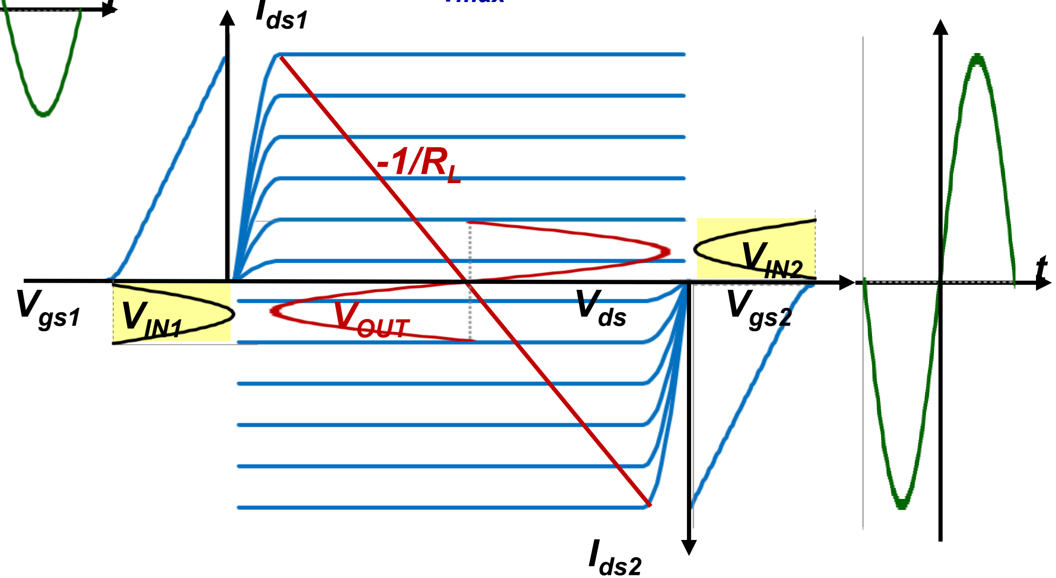


b) **Class B: $\eta_{max}^{theor} \rightarrow 78.5\%$**



V_{OUT} = sine wave thanks to **resonant output circuit**

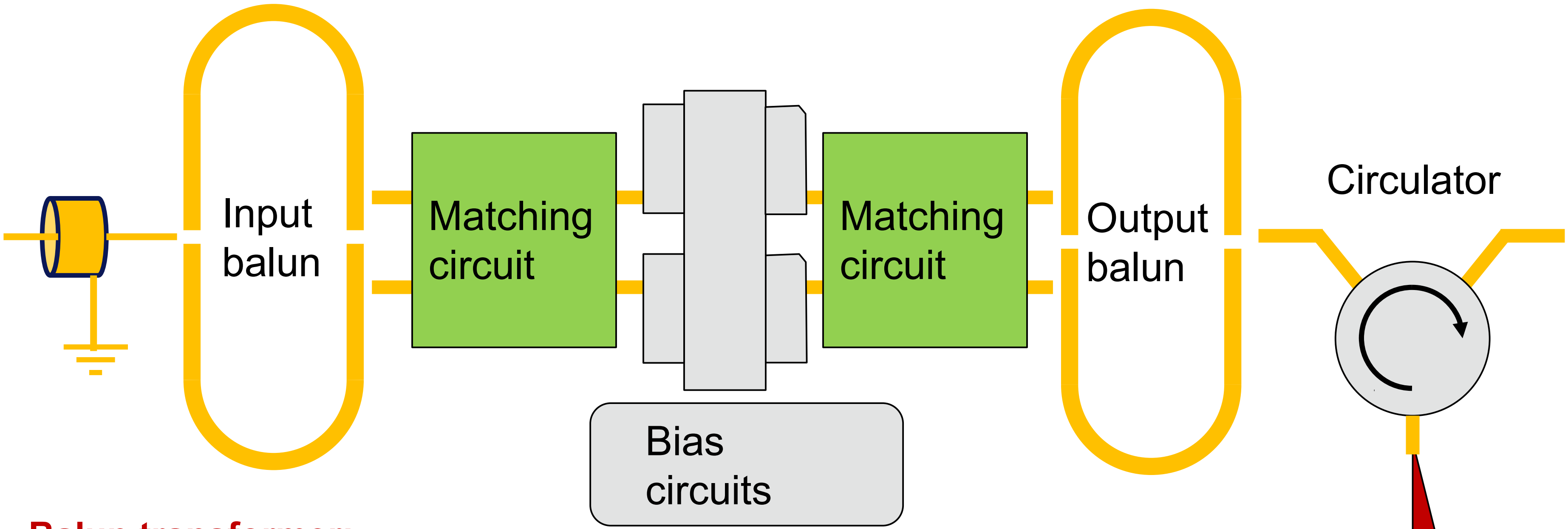
c) **Push-pull in class B: $\eta_{max}^{theor} \rightarrow 78.5\%$**



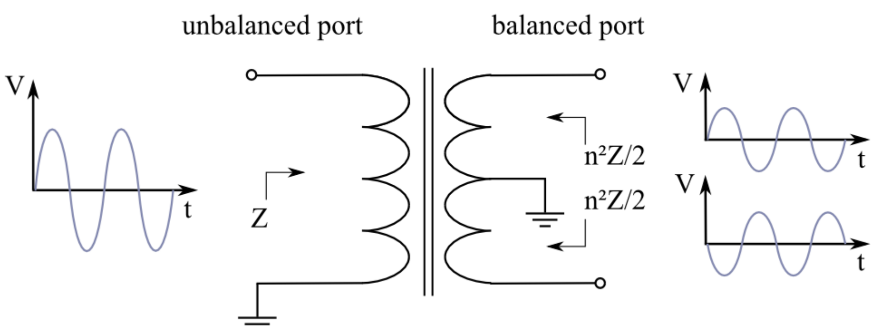
☞ **In fact push-pull in class AB for less distortion near zero crossing and lower harmonic content**

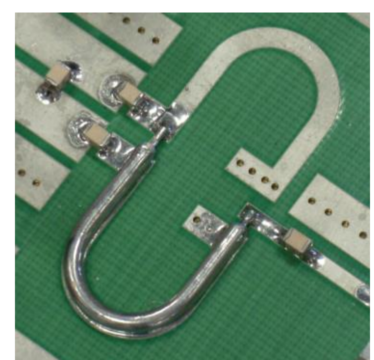
➢ Gate bias: 0.1 … 0.4 A/transistor without RF

RF AMPLIFIER MODULE: RF CIRCUIT



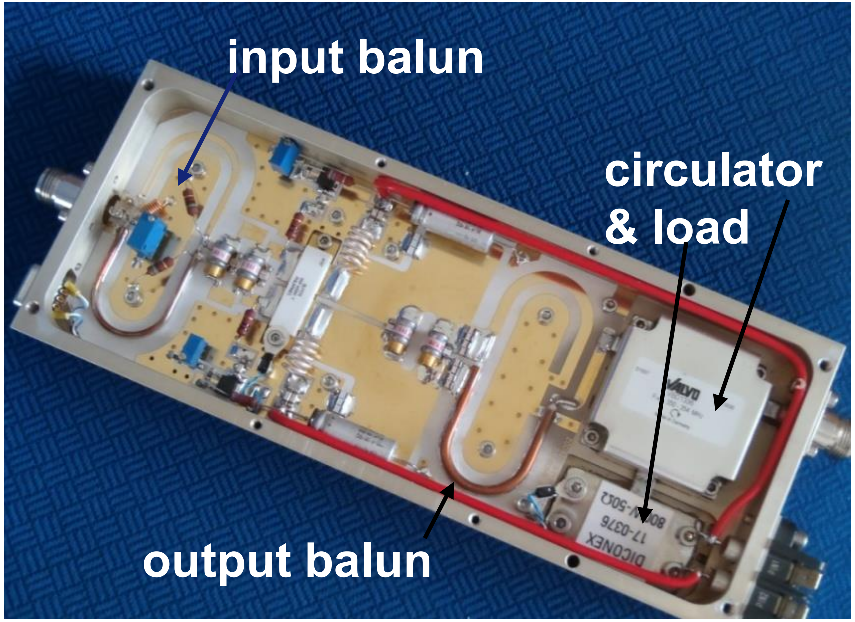
Balun transformer:

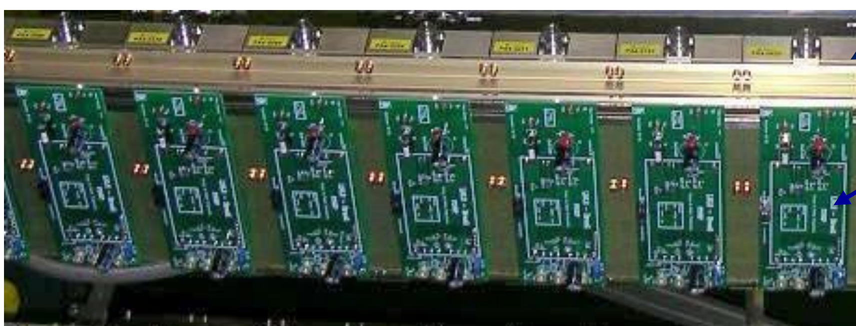




Coaxial balun implementation

RF MODULE ON SOLEIL/ELTA SSA FOR ESRF



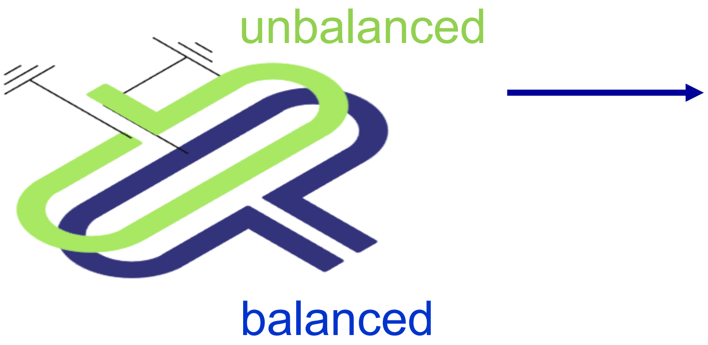


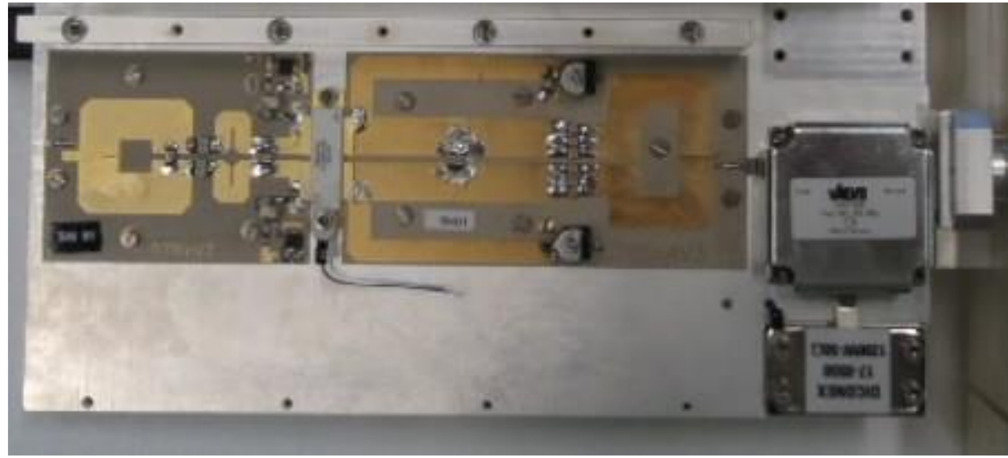
- Protection of RF module against reflected power by a circulator with 800 W load (SR: 1200 W)
  - ➢ No high power circulator after the power combiner !
- Input and output BALUN transformers with hand soldered coaxial lines
- Individual shielding case per module
- Temperature sensors on transistor socket and circulator load
- Performance: **650 W, η = 68 to 70 %, full reflection capability**

- **RF module** mounted on rear side of **water cooled plate**
- **Each transistor** powered by one **280 Vdc / 50 Vdc converter** (2 dc/dc converters per RF module), installed with interface electronics on front side of water cooled plate
  - ➢ **SSA powered with 280 Vdc**, which is distributed to the dc/dc converters

RF AMPLIFIER MODULE: ESRF IN HOUSE DEVELOPMENT

Motorola patent





ESRF fully planer design:

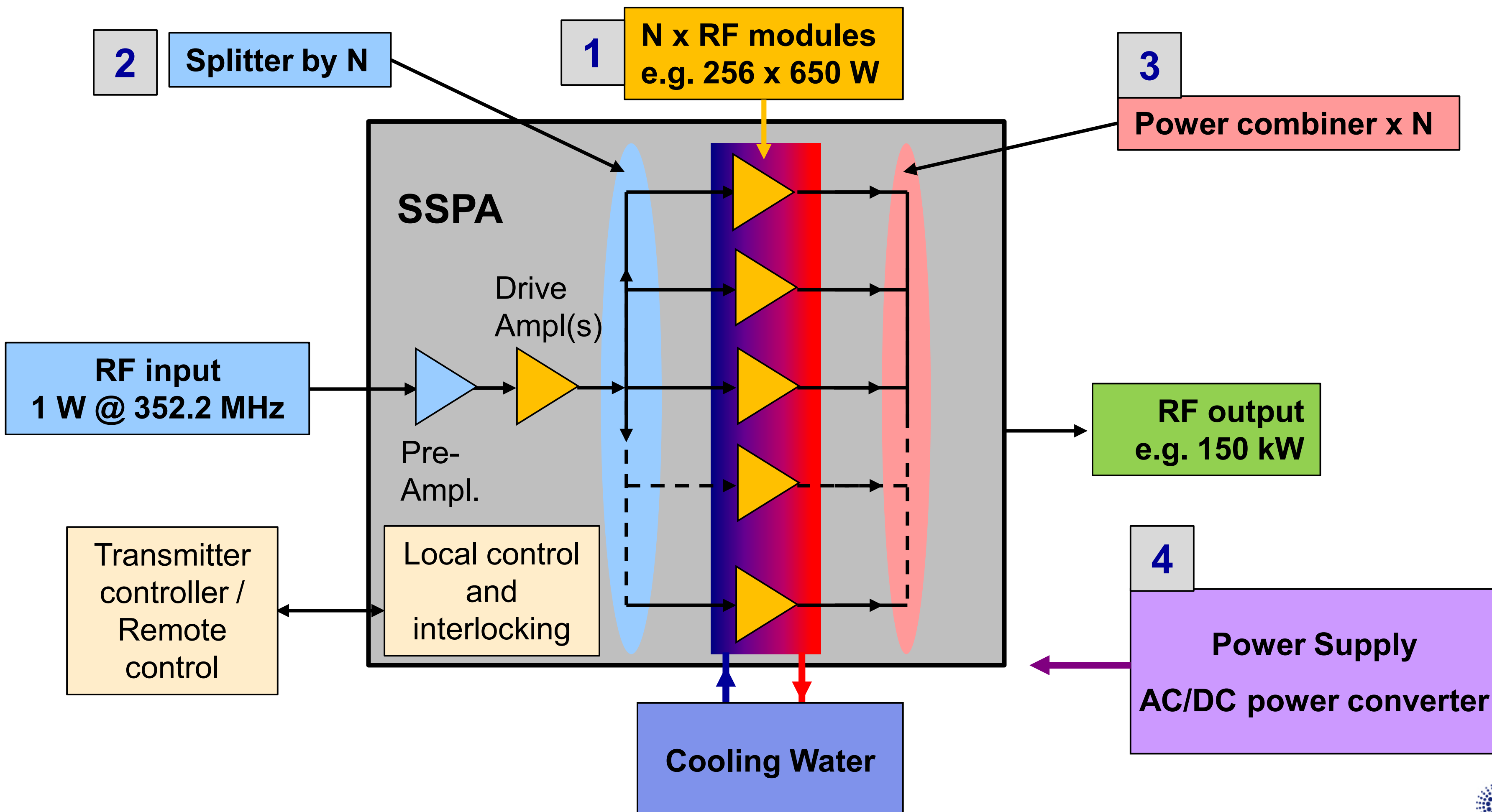
- Printed circuit baluns
- RF drain chokes replaced with "quarter wave" transmission lines.
- Very few components left, all of them SMD and prone to automated manufacturing

⇒ Reduced fabrication costs

18 modules incl. output circulator	Average Gain	Average Efficiency
at P_{RF}^{out} = 400 W	20.6 dB	50.8 %
at P_{RF}^{out} = 700 W	20.0 dB	64.1 %

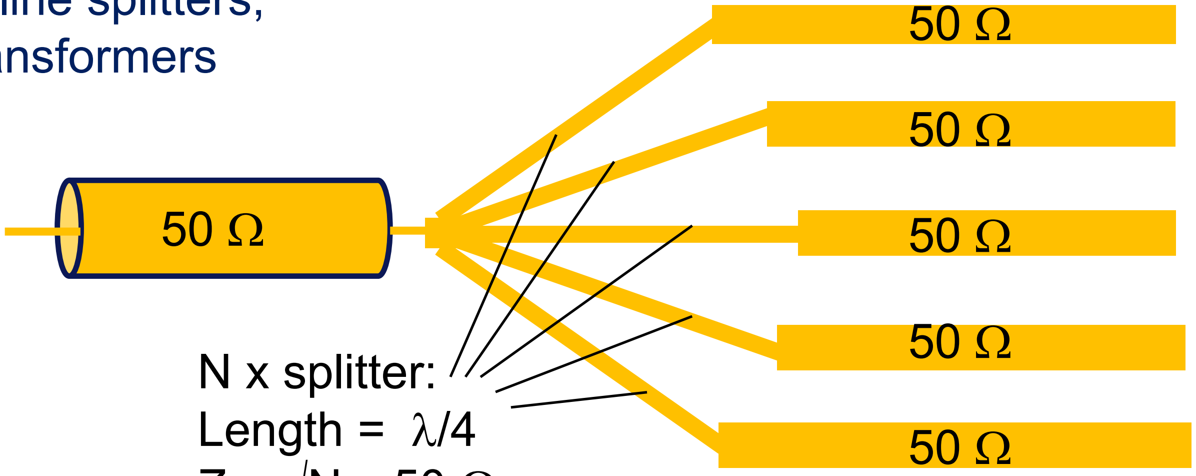
[M. Langlois, ESRF]

COMPONENTS OF RF SSPA



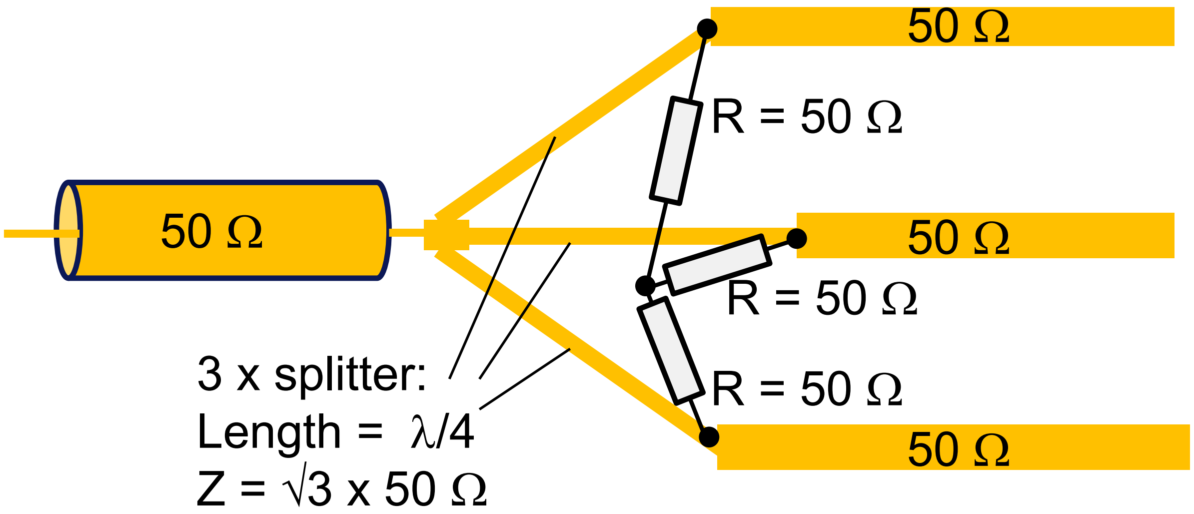
POWER SPLITTERS FOR THE RF DRIVE DISTRIBUTION

SOLEIL stripline splitters,
using λ/4 transformers

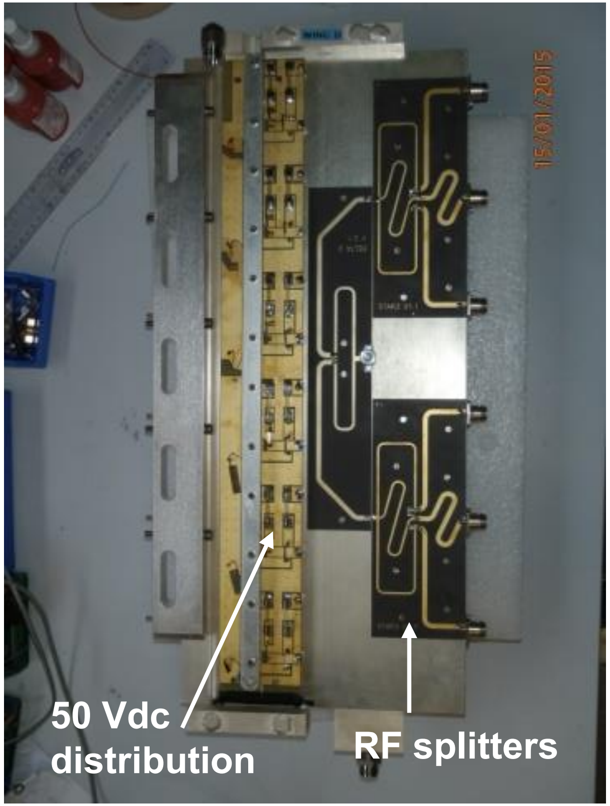


N x splitter:
Length = λ/4
$Z = \sqrt{N} \times 50\ \Omega$

WILKINSON SPLITTER FOR THE RF DRIVE DISTRIBUTION



Addition of resistors to absorb differential signals without perturbing the common mode, thereby decoupling the connected outputs from each other



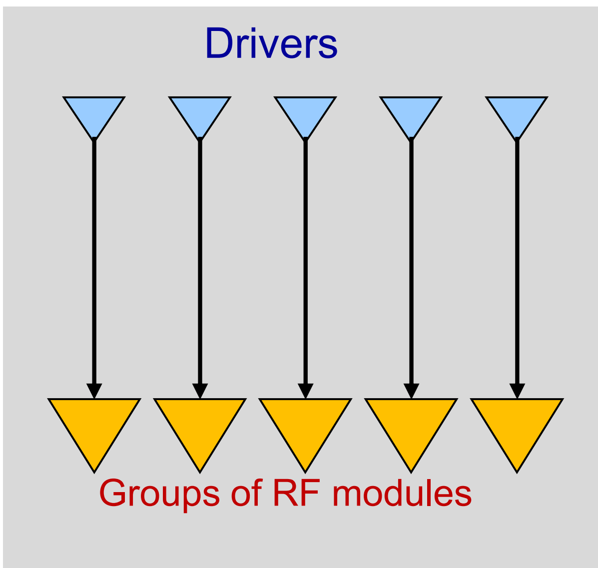
Water cooled wing with 6 RF modules, developed at ESRF

[M. Langlois, ESRF]

IMPROVEMENT: REDUNDANCY IN THE PRE-AMPLIFICATION STAGE

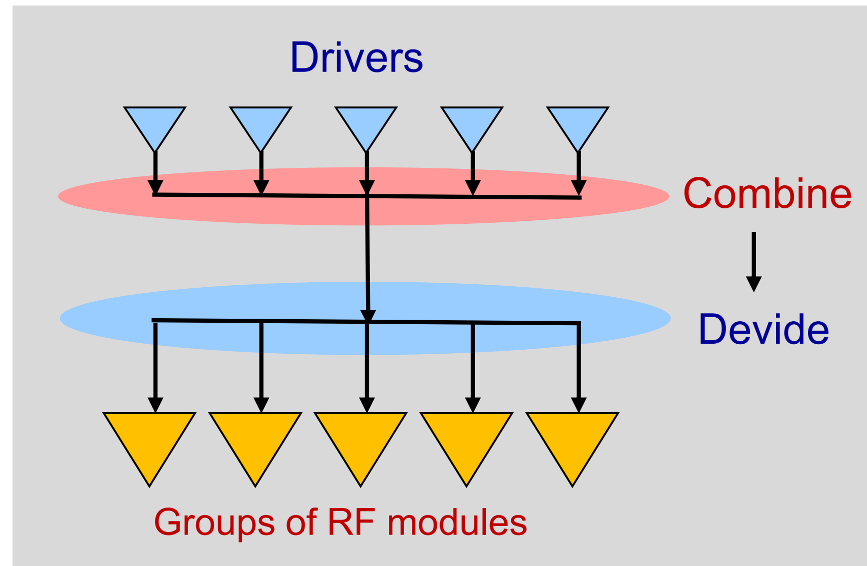
Most SSPA: 1 Drive amplifier feeds a group of RF modules

⇒ 1 Drive failure trips the whole SSPA



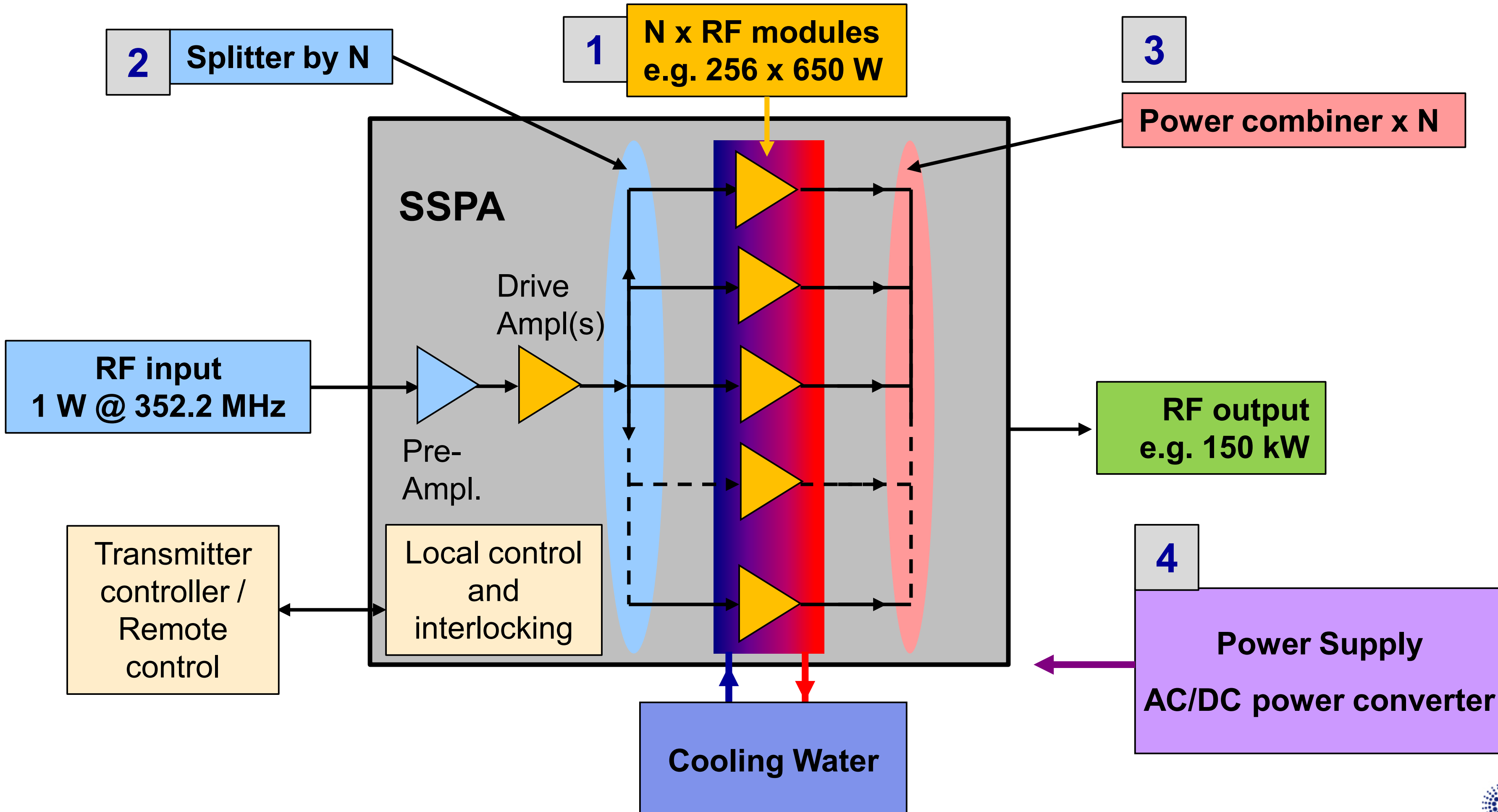
New SOLEIL configuration: Drive redundancy

⇒ 1 Drive failure does not affect the functioning of the SSPA

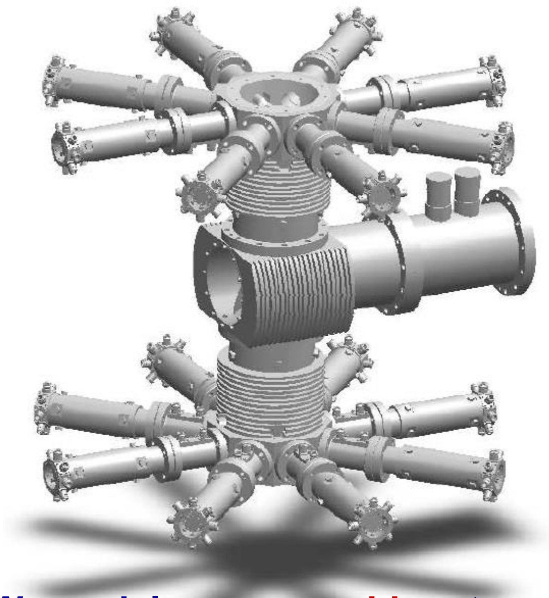


[P. Marchand, IPAC 2017]

COMPONENTS OF RF SSPA



COAXIAL COMBINER FOR SOLEIL/ELTA SSPA AT ESRF



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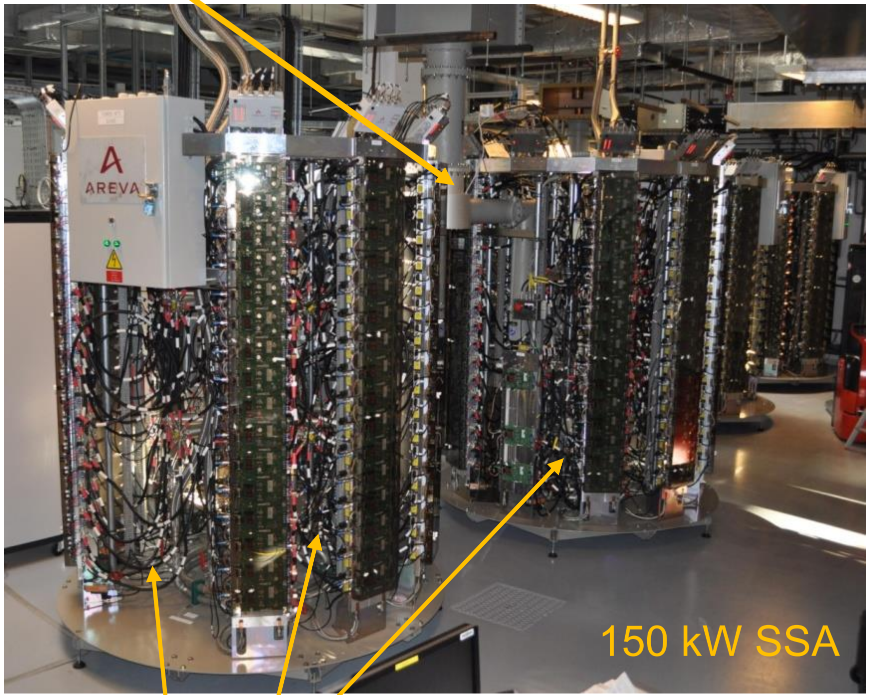
➢ EIA 9"3/16 for 160 kW (2 x 80 kW)



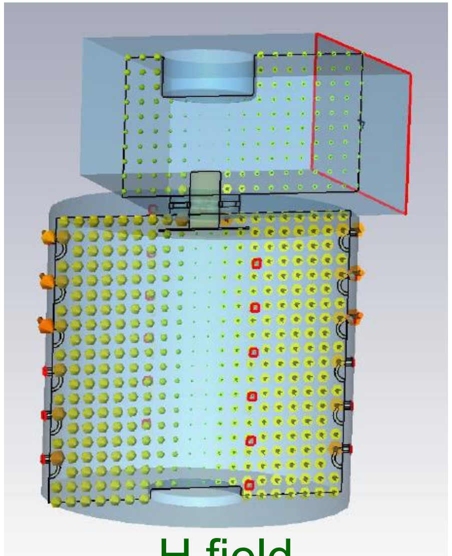
75 kW coaxial power combiner tree with

- λ/4 transformers like splitters but used in reverse
- Coaxial diameter adapted to power level:
  - ➢ EIA 1"5/8 for 6 kW power level (8 x 650 W)
  - ➢ EIA 6"1/8 for 40 kW (8 x 5.2 kW)
  - ➢ EIA 6"1/8 for 80 kW (2 x 40 kW)

Each RF module is connected to its 6 kW combiner by means of a 50 Ω coaxial cable:

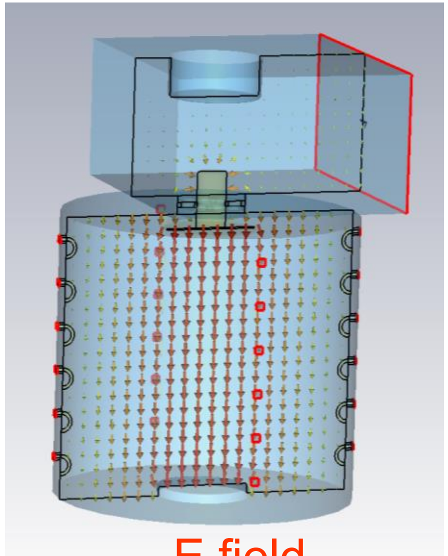
→ **256 coaxial cables** for 650 W full reflection, with tight phase (length) tolerance

ESRF DESIGN USING A CAVITY COMBINER *



H field

Homogenous magnetic coupling of all **input loops**



E field

Strong capacitive coupling to **the output waveguide**

Strongly loaded E_{010} resonance

- Modest field strength
- Cavity at atmospheric pressure
- 1 dB - Bandwidth ≈ 0.5 … 1 MHz

For 352.2 MHz ESRF application:

- **6** rows x **22** Columns x **700 W** per transistor module

  $\Rightarrow$ **85 kW** nominal

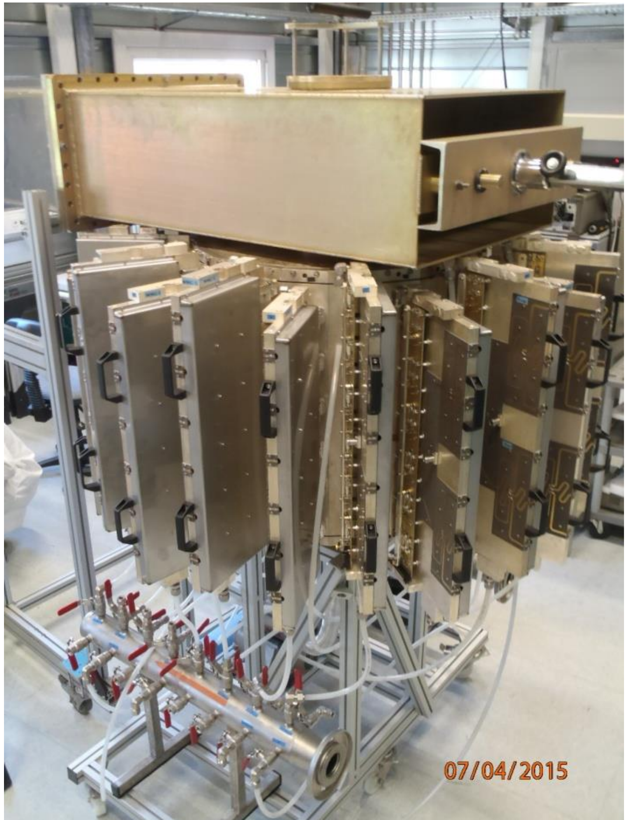
- More compact than coaxial combiners

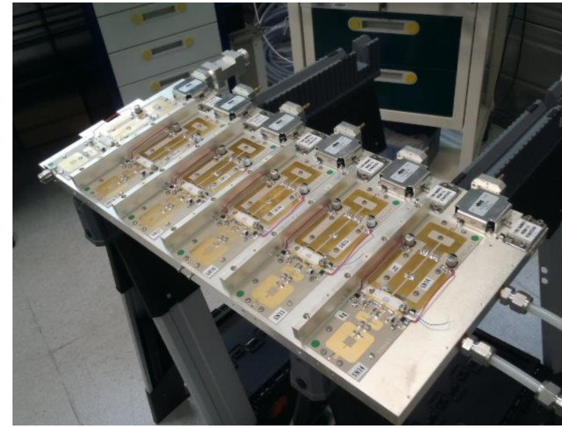
  $$\beta_{waveguide} \approx n_{module} \times \beta_{module} >> 1$$

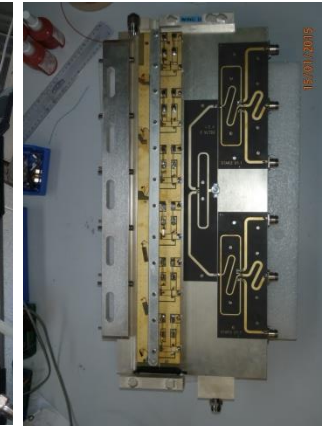
- Easy to tune if n_{module} is varied
- Substantial reduction of losses $\Rightarrow$ higher η

* *Received funding from the EU as work package WP7 of the FP7/ ESRFI/CRISP project*

ESRF DESIGN USING A CAVITY COMBINER *







$\eta_{RF/DC}$ = 62 % at P_{nom} = 85 kW

P_{test} = 90 kW

P_{nom} obtained with 1 wing off

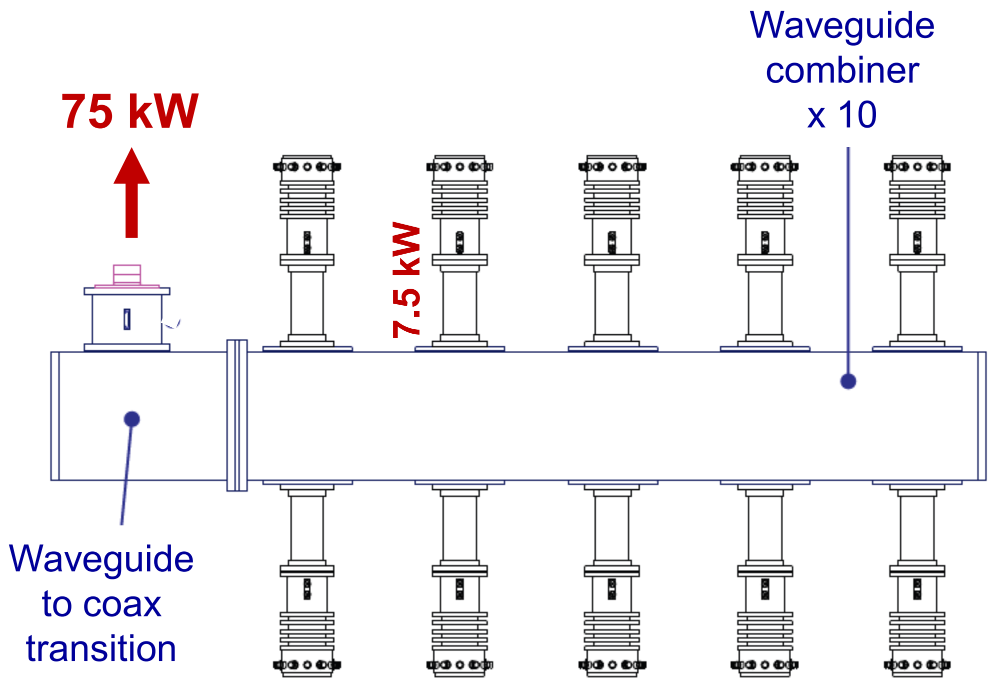
Direct coupling of RF modules to the cavity combiner:

- No coaxial RF power line
- Very few, sound connections
- 6 RF modules are supported by a water cooled "wing"
- The end plate of the wing is part of the cavity wall with built on coupling loops
- One collective shielding per wing
- **Less than half the size of a 75 kW tower with coaxial combiner tree**

[M. Langlois, ESRF]

HIGH POWER WAVEGUIDE COMBINER

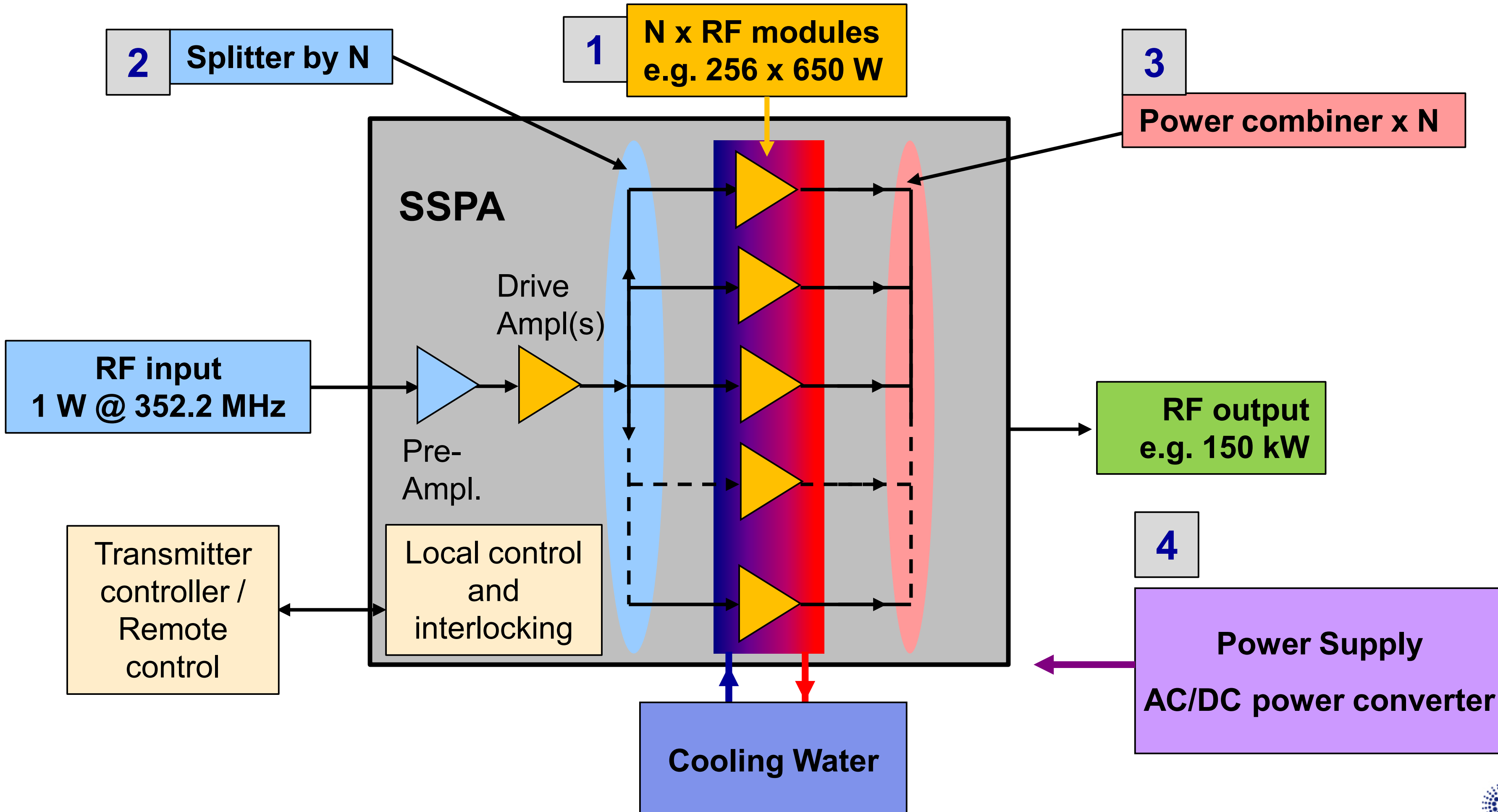
Example: BESSY II 500 MHz – 75 kW SSPA, built by Cryoelectra GmbH



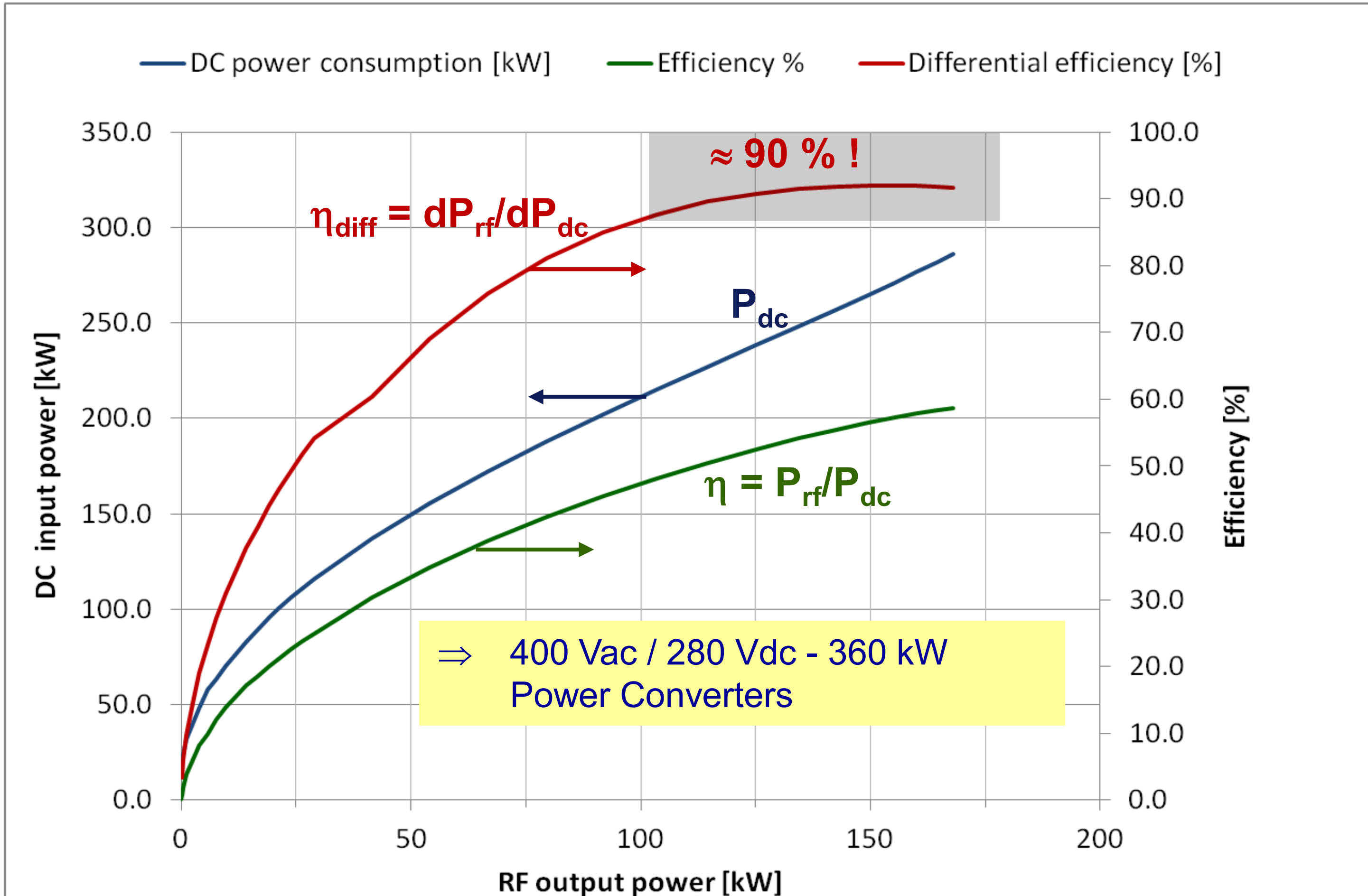
Final combiner stage

[P. Marchand, IPAC 2017]

COMPONENTS OF RF SSPA



DC POWER REQUIREMENT FOR ESRF 150 KW SSPA FROM ELTA



DC SUPPLY OF 4x 150 KW SSPA ON ESRF BOOSTER

Constant AC power
300…400 kW

Average power consumption

Peak DC power
1000…1200 kW

4 Hz

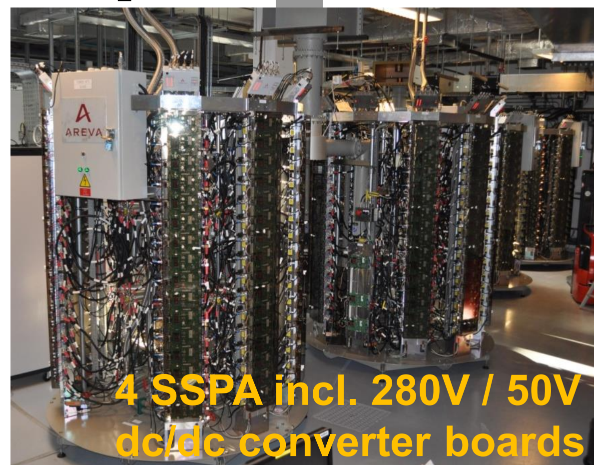
600 kW RF

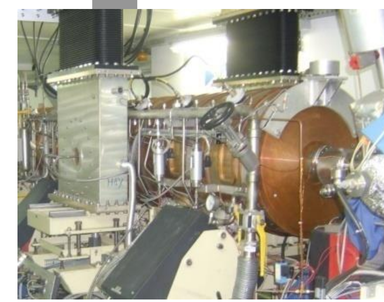
Mains 400 V ac

280 V dc

280 Vdc Supply
400 kW average

Anti-flicker
C = 4.4 F





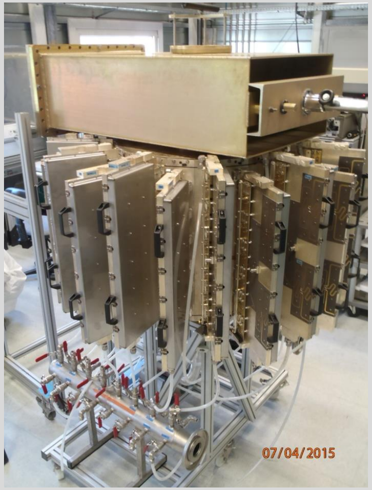
4 booster cavities

- Single 280 V dc / 400 kW PS for the 4 SSPA of the ESRF booster and one back up 360 kW PS
- ☞ Three 280 V dc / 360 kW PS: for the 3 SR SSPA

DC SUPPLIES WITH INCREASED EFFICIENCY, MODULARITY AND REDUNDANCY

ESRF 352 MHz - 85 kW SSPA:

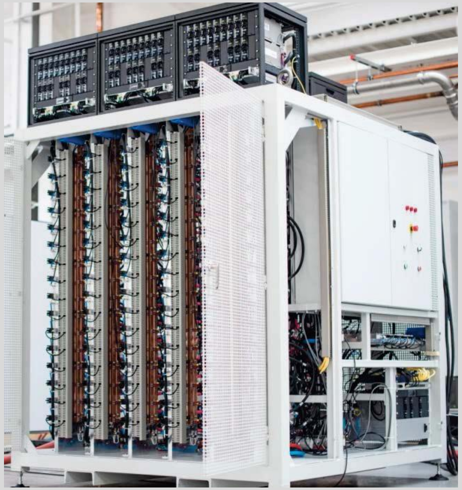
- Direct 400 Vac / 50 Vdc converters from EEI
  - ⇒ Higher efficiency than 2 stages
  - ➢ OK for CW, but antiflicker capacitances for pulsed operation 6x higher at 50 Vdc
- One 160 A / 8 kW PS per wing = 6 RF modules
  - ⇒ Redundancy: can tolerate 1 PS failure at P_{nom} without tripping the SSPA



Recent SOLEIL developments:

- Highly efficient (η = 96 %), modular 2 kW - 240 Vac / 50 Vdc converters, feeding 50 Vdc busses
  - ⇒ High redundancy, tolerates converter failures
- Remote voltage control: allows optimising SSPA efficiency for large range of output power:
  - ⇒ $\eta_{RF/AC}$ **= 56 % at P_{max}** and **50 % at ½ P_{max}**

⇒ Architecture changed from tower to cabinet



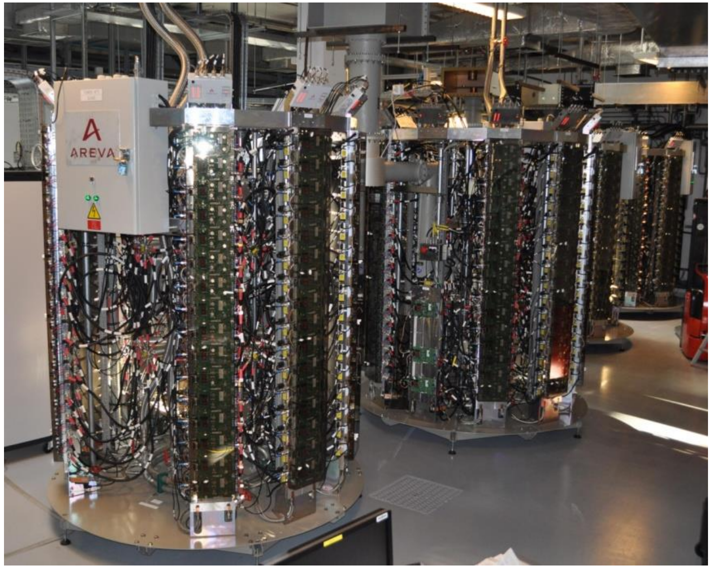
Example:

500 MHz -80 kW SSPA at SESAME:

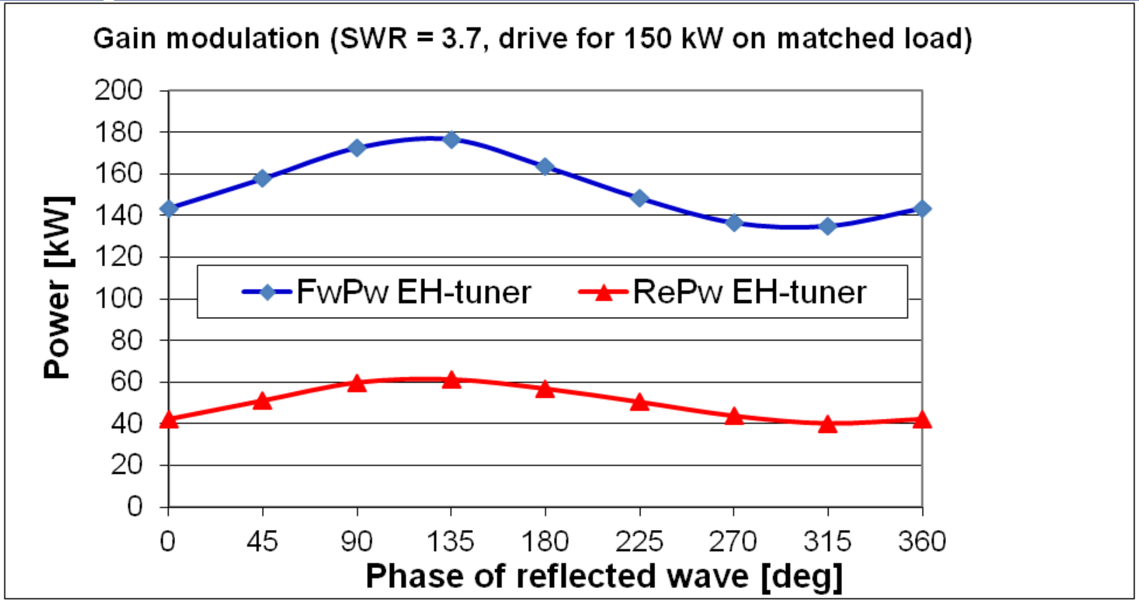
- 1st one built by SOLEIL
- 2nd- 4th under SOLEIL licence by Sigmaphi Electronics

[P. Marchand, SOLEIL]

Operation experience with RF Solid State Amplifiers



OPERATION ON MISMATCHED LOADS – ELTA SSPA AT ESRF



150 kW ELTA SSPA at ESRF

Measurement with constant RF input power level, giving 150 kW on matched load:

⇒ ± 20 kW on FwPw, i.e. **gain modulation**

- Partially intrinsic to non directive coaxial combiner tree
- Partially due to imperfect circulators on RF modules:
  - ⇒ modulation of load impedance
  - ⇒ RF module gain modulation

Specification:

- SWR = 3.7 → P_{refl} / P_{fwd} = 50 kW / 150 kW, all phases (☞ EH – tuner)
- Full reflection at all phases specified and tested for 80 kW (movable short circuit)

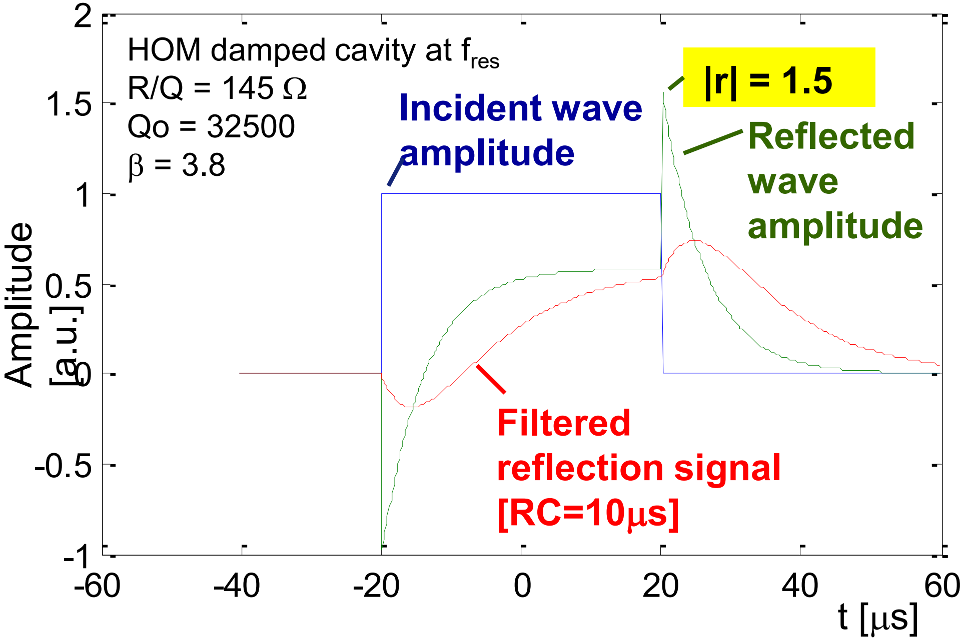
Test results:

✓ **Reflected power well absorbed by circulator loads on RF modules**

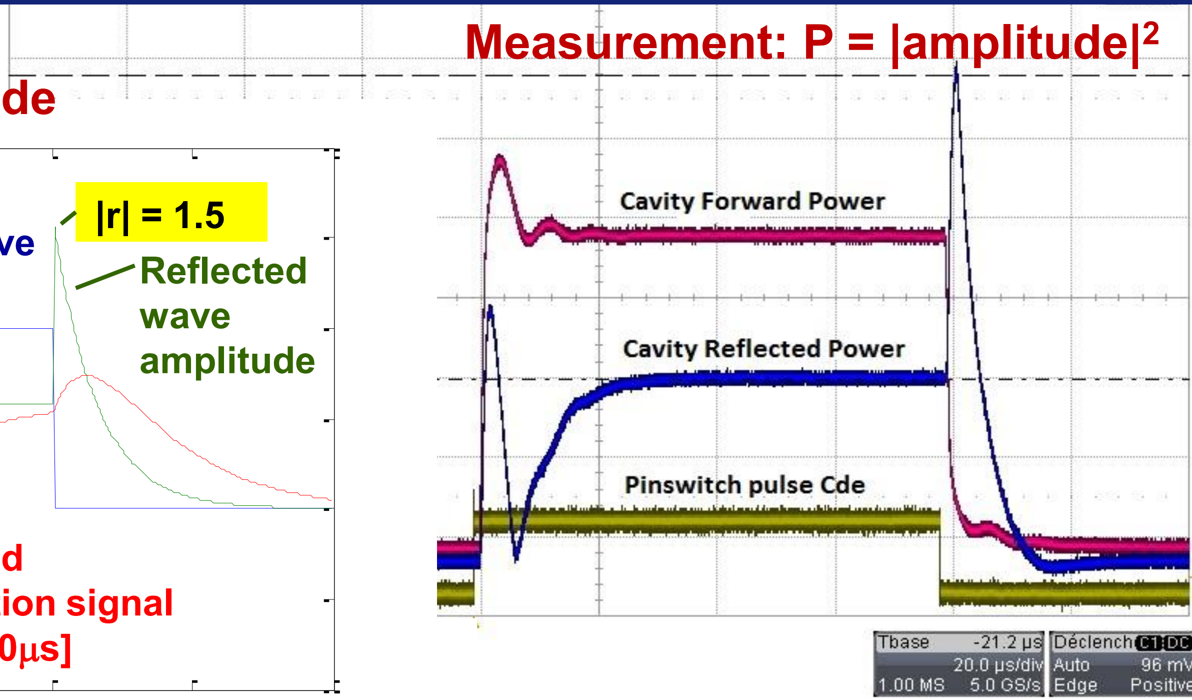
- Despite one circulator per RF module: gain modulation
- ⇒ for some phases: SWR=3.7 test limited to 140 kW and short circuit test limited to 60 kW by overdrive protection

TRANSIENT REFLECTIONS FOR PULSED CAVITY CONDITIONING

Computation: amplitude



Measurement: P = |amplitude|²



- ESRF SSPA from ELTA tested with 20 μs /150 kW pulses at full reflection (spec)
  - ⇒ Fast interlock for P_{refl} > 150 kW
  - ⇒ Interlock on low pass filtered signal for P_{refl} > 50 kW (spec)

11 YEARS OPERATION WITH SSPA AT SOLEIL

SOLEIL booster: 1x 35 kW SSPA, 65000 running hours in 11 years:

- Only 1 single trip due to loose connection of monitoring cable
- 1 module failure / year, without impact on operation thanks to modularity & redundancy

SOLEIL SR: 4x 180 kW SSPA, 63000 running hours in 11 years

Equipment	MTBF	Downtime	Remarks	
a) 4 x RF SSPA	≈ 12 500 h	≈ 1.10^{-4}	Drive amplifier failures	Lack of redundancy on older transmitters
b) 4 x 500 kVA thyristor based 230 Vac/270 Vdc rectifiers	≈ 8 000 h	≈ 4.10^{-4}	Single rectifier per SSPA	
a) + b) 4 x RF transmitters	≈ 5 000 h	≈ 5.10^{-4}		

- 2% original LR301 (Polyfet, 30 V) transistor failures per year, without impact on operation thanks to modularity & redundancy (except for drive amplifiers)
- Improvement with current replacement by 6th generation LDMOS FET
- Further improvement on new SOLEIL developments with PS and Driver redundancy

[P. Marchand, IPAC 2017]

OPERATION EXPERIENCE AT ESRF

- Booster → 4 x 150 kW SSPA in operation since January 2012 , Top-up since April 2016
- SR → 3 x 150 kW SSPA in operation since October 2013, one SSPA shut down due to leaky cavity
- So far **not a single transistor failure** (BLF578)
- thanks to redundancy and modularity, other component failures are mostly transparent to operation

Component	Event count	Disturb Operation	Comment
HPA 650W (filter)	SR 10 SY 9	No No	CMS filters stressed when soldering on the PCB. Youth problem, now fixed with time.
DC/DC Converter 280V/50V	SR 4 SY 3	No No	Fuse blown. OK after replacing the fuse
Pre-Driver	SR 0 SY 5	 Yes 1	Conception problems, which have been fixed: Gain loss, bad soldering, bad logic circuitry …
MUXBOX Control Interface	SR 3 SY 4	Yes 2 No	Fuse blown: trips relays for cooling interlocks fed by this interface ☞ *System weakness that will be improved.*
Water Cooling	SR 1 SY 2	No Yes 1	
TOTAL	**SR 18** **SY 23**	**2** **2**	**1 in 2014 + 1 in 2015 → Beam loss** **2 in 2012 → Refill postponed**

[J.-M. Mercier, ESRF]

TENTATIVE NON EXHAUSTIVE LIST OF SSPA DEVELOPMENTS IN THE WORLD

Where	Supplier	Freq.	Power	Combiner
SOLEIL	In house	352 MHz	35 kW (booster) 160 kW (SR)	Several stage coaxial combiner (40 kW towers)
ESRF	SOLEIL/ELTA	352 MHz	150 kW	Several stage coaxial combiner (75 kW towers)
LNLS & SIRIUS, ThomX, SESAME	In house + transfer to Sigmaphi Electronics	476 MHz 500 MHz	160 kW	Several stage coaxial combiner
BESSY II	Cryoelectra GmbH	500 MHz	40 kW (booster) 75 kW (SR)	Waveguide combiner for last stage
SLS	In house, based on SOLEIL design	500 MHz	60 kW	Several stage coaxial combiner
ESRF	In house, pioneering cavity combiner	352 MHz	85 kW Tested at 90 kW	Cavity Combiner (single stage)
APS R&D	In house	352 MHz	200 kW	Cavity Combiner
SPring8	In house	509 MHz	110 kW	2 Cavity Combiners + waveguide comb x2

[P. Marchand, IPAC 2017]

TENTATIVE NON EXHAUSTIVE LIST OF SSPA DEVELOPMENTS

Where	Supplier	Freq.	Power	Combiner
CERN SPS	THALES	200 MHz	16 x 144 kW = 2 MW, pulsed	1st Stage:80 x 2 kW cavity combiner 2nd stage: 16 x 144 kW 3 dB coaxial hybrid network
GANIL-SPIRAL2	Bruker, now Sigmaphi Electronics	88 MHz	2.5 kW, 5 kW, 10 kW and 19 kW units	3 dB hybrids [Single power circulator $\rightarrow$ Phase shifters adjusted to tolerate cavity reflections]
MAX IV, SOLARIS	Rhode & Schwarz, FM transmitters	100 MHz	2 x 30 kW cabinets	3 dB hybrid

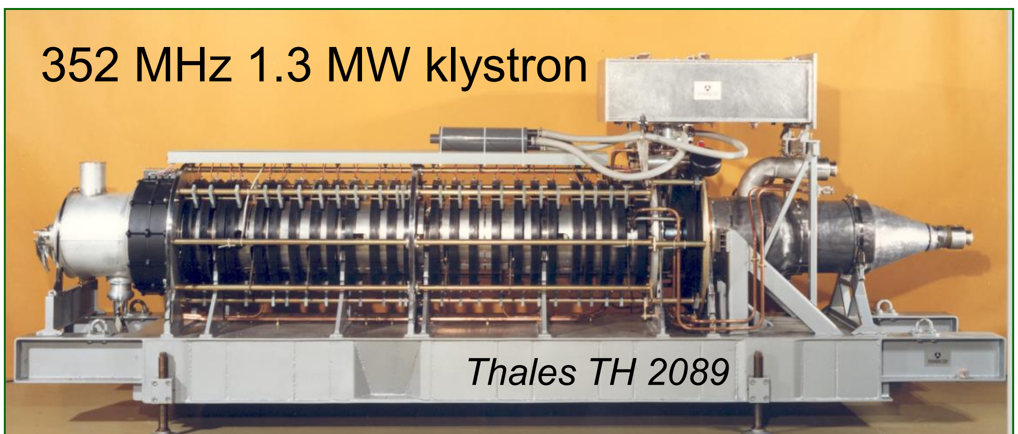
[P. Marchand, IPAC 2017]

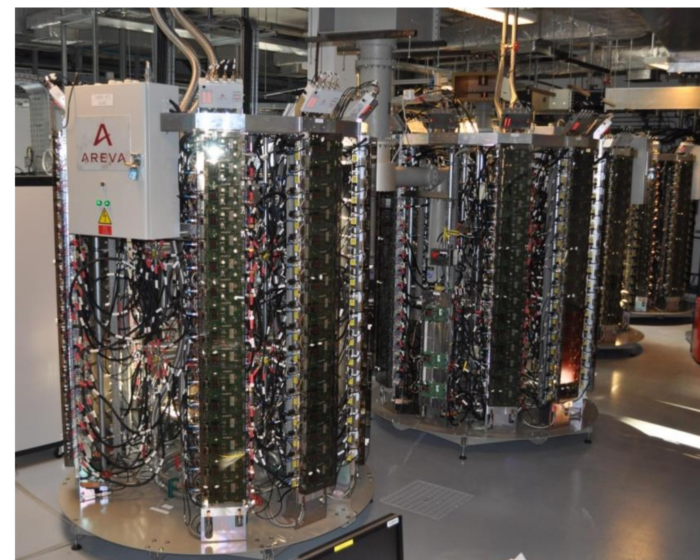
TENTATIVE NON EXHAUSTIVE LIST OF SSPA DEVELOPMENTS

Where	Supplier	Freq.	Power
ELBE FEL	Bruker, now Sigmaphi Electronics	1.3 GHz	20 kW
HoBiCaT / bERLinPro		1.3 GHz	16 kW
Beijing Univ.	In house & BBEF	1.3 GHz	20 kW
LCLS	Call for Tender: R&K, …	1.3 GHz	3.8 kW 284 units
LUCRECE, R&D	SOLEIL & SPE	1.3 GHz CW	20 kW / GaN transistors
JLAB	In house R&D	1.5 GHz	GaN transistors

[P. Marchand, IPAC 2017]

Conclusion
Short comparison Klystron / SSPA





RF SSPA AS ALTERNATIVE TO KLYSTRON/TUBES : PROS & CONS

+ No High voltage (50 V instead of 100 kV)
  + No X-Ray shielding
  + 20 dB less phase noise
+ High modularity / Redundancy
  - ➢ SSA still operational with a few modules in fault
  - ⇒ Increased reliability
– More required space per kW than a tube,
  - ➢ But it is easier to tailor the power to the requirement
  - ➢ Cavity combiners → reduced SSA size
- Durability / obsolescence:
  - ➢ Klystron or other tube: OK as long as a particular model is still manufactured, but problematic in case of obsolescence, development costs of new tubes too high for medium sized labs
  - ➢ SSA: shorter transistor product-lifetime, however guaranteed availability of comparable, possibly better transistors on the market ☞ **requires careful follow up!**
+ **Easy maintenance**, if sufficient spare parts available

- Investment costs:
  – Still higher price per kW than comparable tube solutions, if require tube exists
  + But SSA technology is progressing ☞ e.g. expected cost reduction with planar module design and compact cavity combiner
  + Prices for SSA components should sink
  + Prices for klystrons have strongly increased over the last decades
+ Low possession costs:
  + ESRF spec: Less than 0.7 % RF modules failing per year, most easy to repair
  + so far confirmed by short ESRF experience
- SSA/tubes: Comparable efficiency, must be analyzed case by case
  - High efficiencies such as with IOT or high efficiency klystrons difficult to obtain with transistors in UHF
  + Reduced power consumption for pulsed systems (e.g. Booster), thanks to possible capacitive filtering of the DC voltage

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Thank
you !!!