ARIES Workshop on Energy Efficient RF
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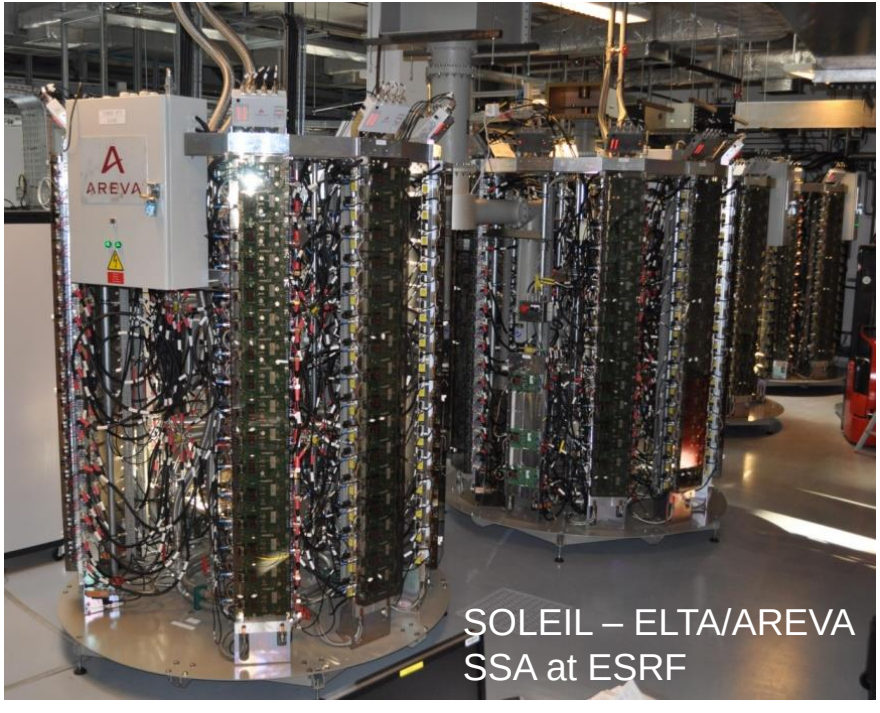
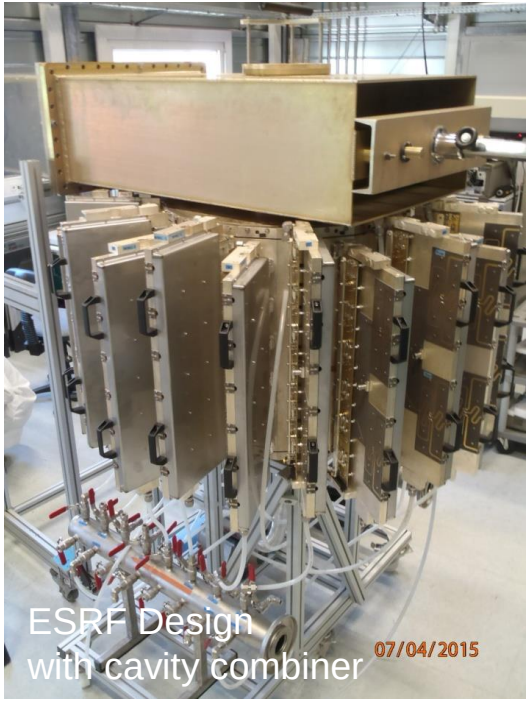
ESRF Experience with Solid State Amplifiers and Combiners

Jörn Jacob

on behalf of ESRF RF Group

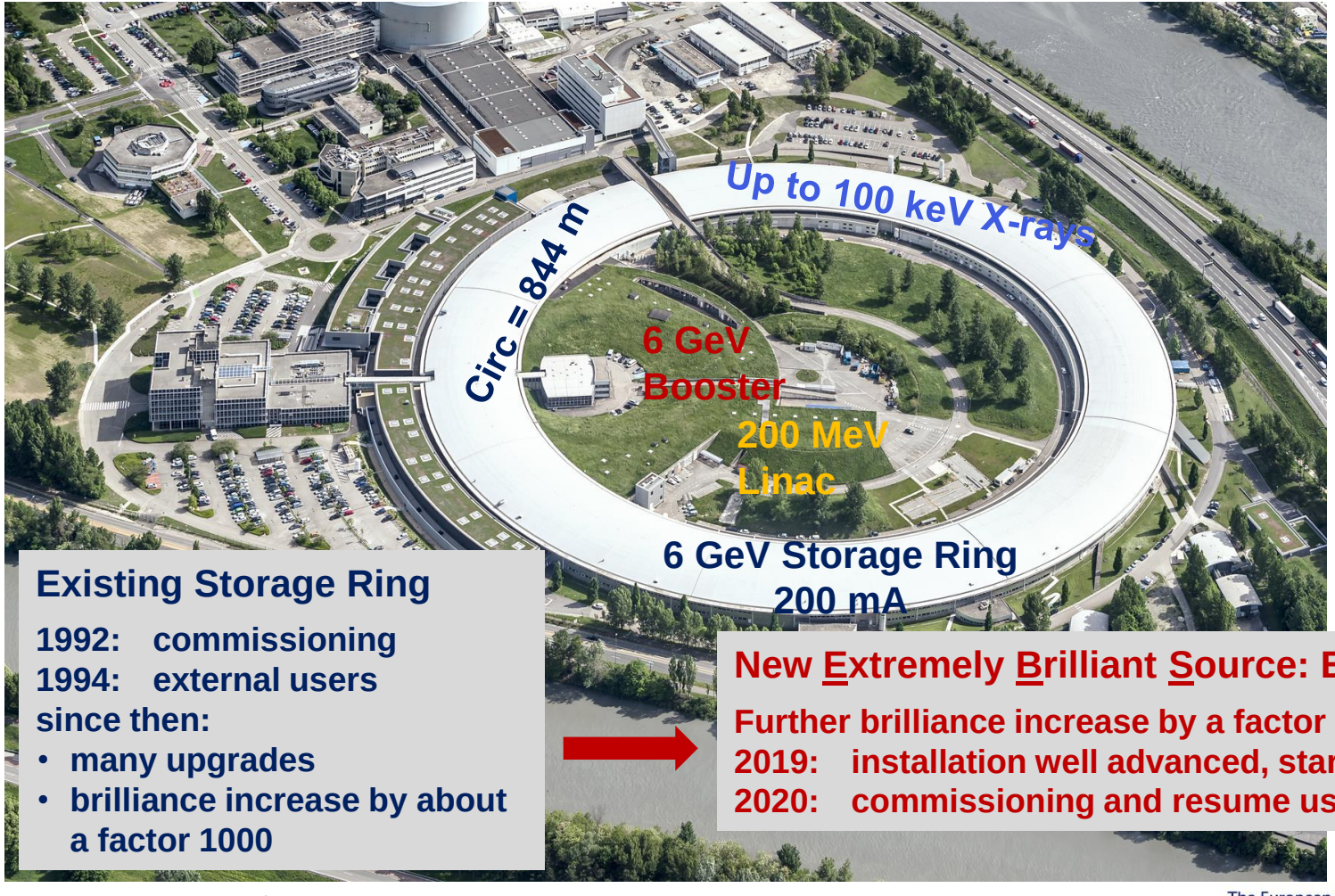


SOLEIL – ELTA/AREVA SSA at ESRF



ESRF Design with cavity combiner

ESRF: FIRST 3rd GENERATION, BECOMES 4th GENERATION LIGHT SOURCE



Existing Storage Ring

1992: commissioning
1994: external users
since then:

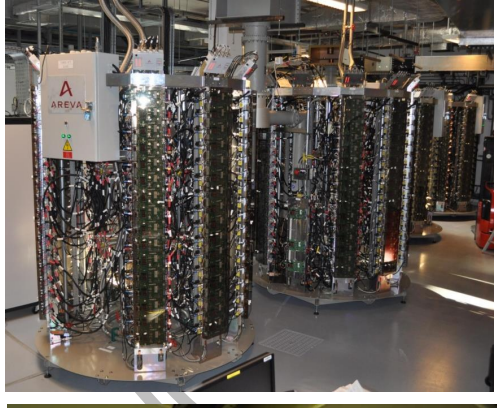
- many upgrades
- brilliance increase by about a factor 1000

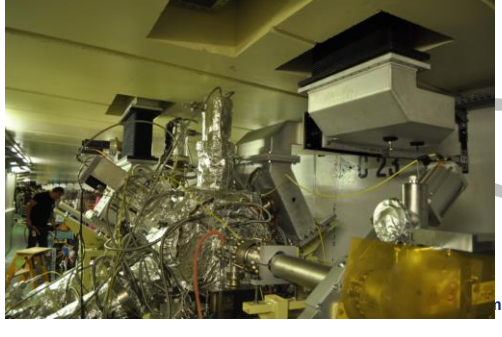
New Extremely Brilliant Source: EBS

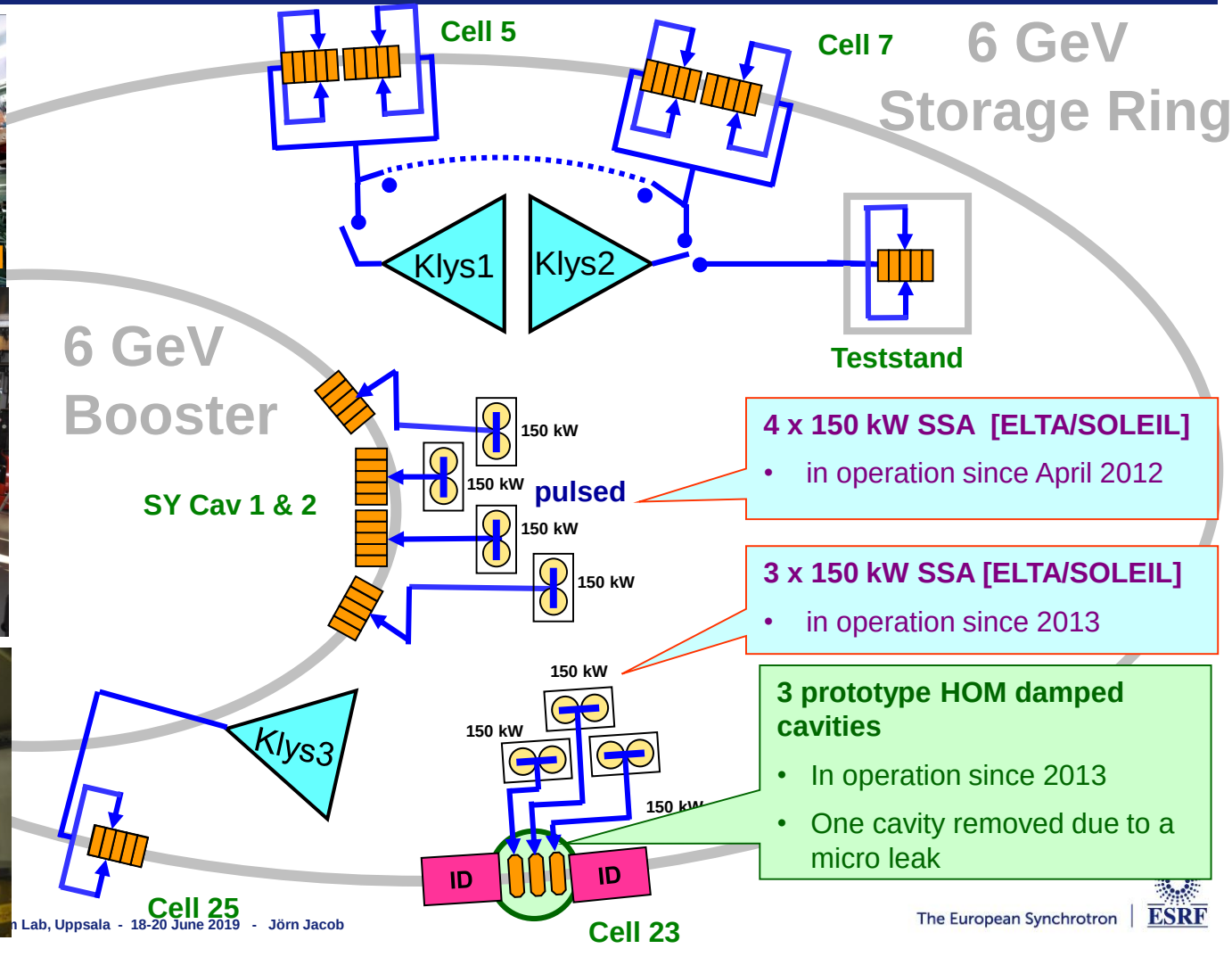
Further brilliance increase by a factor 100
2019: installation well advanced, start up in Dec.
2020: commissioning and resume user service

RF LAYOUT → UNTIL DECEMBER 2018

5-cell cavities: strong HOM







4 x 150 kW SSA [ELTA/SOLEIL]

- in operation since April 2012

3 x 150 kW SSA [ELTA/SOLEIL]

- in operation since 2013

3 prototype HOM damped cavities

- In operation since 2013
- One cavity removed due to a micro leak

EBS RF SYSTEM LAYOUT – START UP DECEMBER 2019

EBS Storage Ring

Cell 5

Cell 7

Symmetric 3dB splitting using existing magic T's

-7 dB

-7 dB

KLYS 1

KLYS 2

NEW RF power Teststand

75 kW tower

75 kW tower

75 kW tower

75 kW tower

75 kW tower

75 kW tower

3x existing 150 kW SSAs

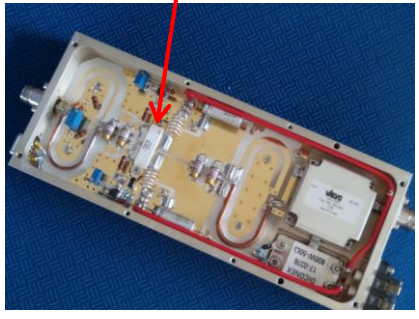
Cell 25

Space for 3rd or 4th harmonic RF system

- Still under study:
  5 to 7 active (?) NC cavities
  or passive Super3HC type
- ≈ 40 kW per NC cavity from SSA

150 kW – 352 MHz SSA AT ESRF

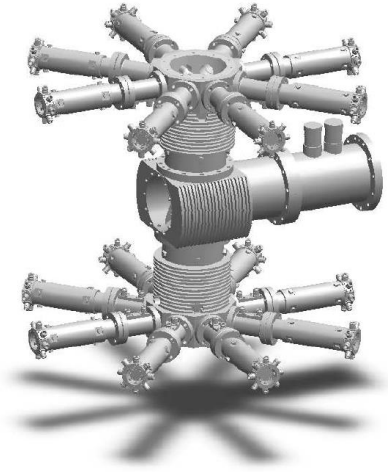
Pair of transistors in push-pull
(BLF578 from NXP, now produced by Ampleon)



650 W RF module

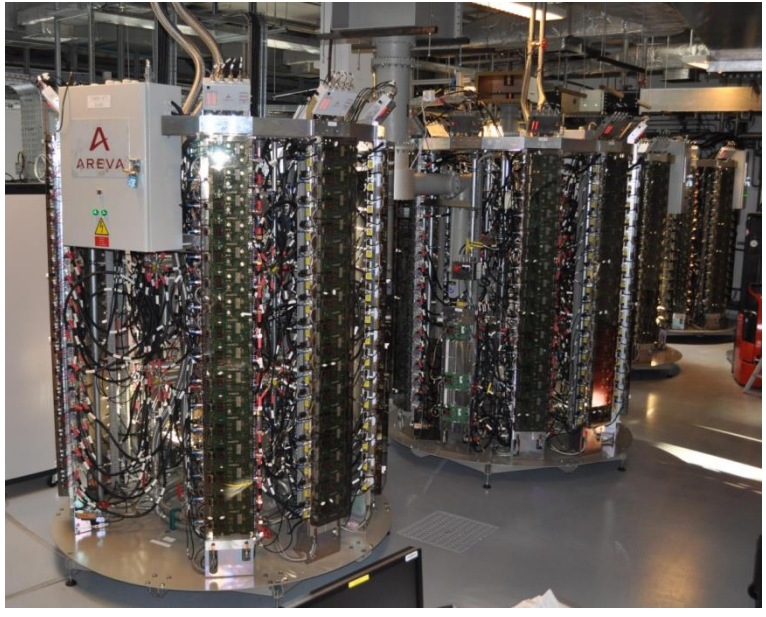
- DC to RF: η = 68 to 70 %

x 128



75 kW coaxial power combiner tree

x 2



150 kW - 352.2 MHz SSA

DC to RF: η = 58 %, G = 63.3 dB at P_{nom}

☞ **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)

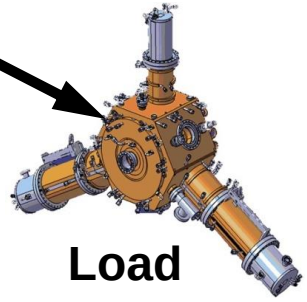
COMPARISION SSA versus KLYSTRON IN OPERATION

RF 352MHz

Low Level RF

Power Amplifier

What we compare



Load

Driver RF 100W

95kV/18A

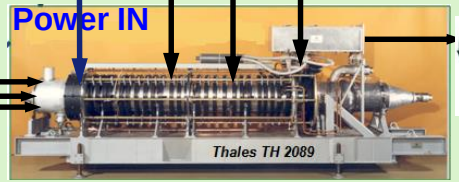
2 Focusing Power Supplies 2 X 130V/8A

IP Power Supply

5kV

Filament 25V/25A

Power IN

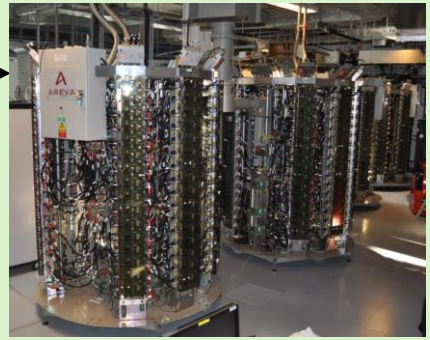


Power OUT

CIRCULATOR

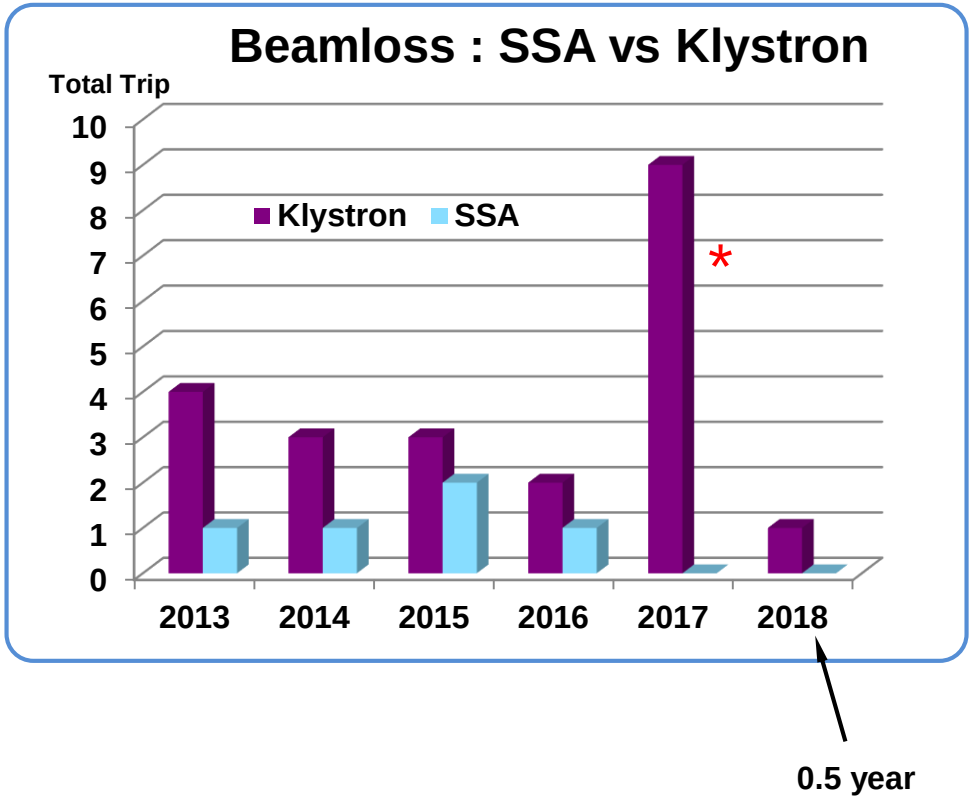
Modulating Anode 60kV/2mA

1.3 MW KLYSTRON



ELTA/SOLEIL Solid State Amplifier

SSA versus KLYSTRON – TRIP RATE



Including auxiliaries and Power supplies

KLYSTRON average failure: **4** trips / year

SSA average failure: **0.9** trips/ year

* When a klystron begins to be sick it can generate several beam interruptions in a short time lapse

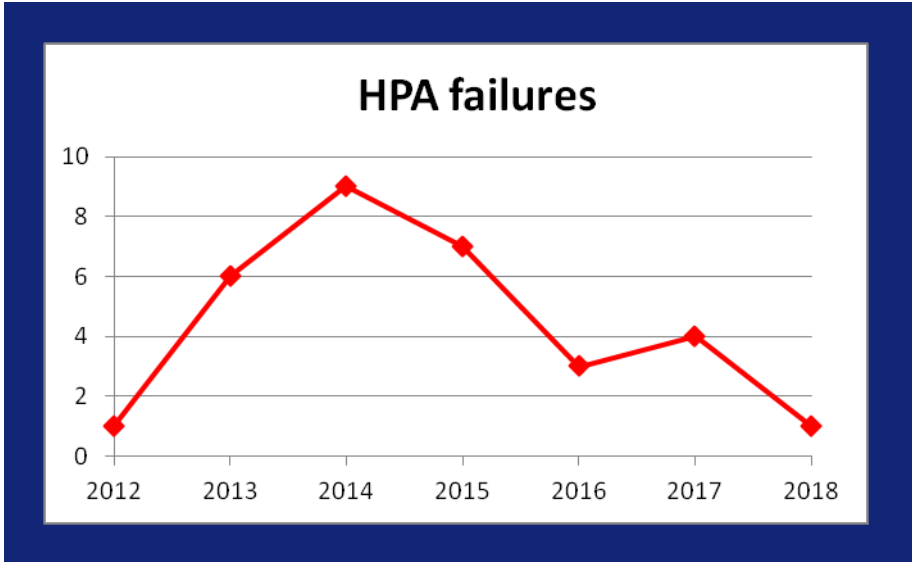
OPERATION EXPERIENCE WITH 7 x 150 kW SSA

- Booster → **4 x 150 kW SSA**, since January 2012 (**6,400 hr**), Top-up since April 2016
- SR → **3 x 150 kW SSA**, since October 2013 (**32,000 hr**), 1 stopped after a few months due to cavity
- So far **not a single transistor failure !**
- Nominal Power Efficiency DC→RF: 58%, Gain 63.3 dB – No variation in time detected so far

Component	Event count	Disturb Operation ?	Comment
HPA 650W (filter)	SR 22 SY 9	No No	CMS filters stressed when soldering on the PCB. Youth problem, now fixed with time. Last failure: February 2018.
DC/DC Converter 280V/50V	SR 12 SY 3	No No	Primary filter capacitors (C12 & C24).
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 3 No	The SSA trips when the fuse blows because the relays for cooling interlocks are fed by this interface. *This is a weakness of the system, which can be improved.*
Water Cooling	SR 1 SY 2	No Yes 1	Fortunately it happened outside of machine operation
TOTAL	**SR 38** **SY 23**	**3** **2**	**1 in 2014 + 1 in 2015 + 1 in 2016 → Beam loss** **2 in 2012 → Refill postponed**

SSA : 650 W - HPA Failures

Year	SY	SR	Total
2012	1		1
2013	3	3	6
2014	2	7	9
2015	3	4	7
2016	0	3	3
2017	0	4	4
2018	0	1	1



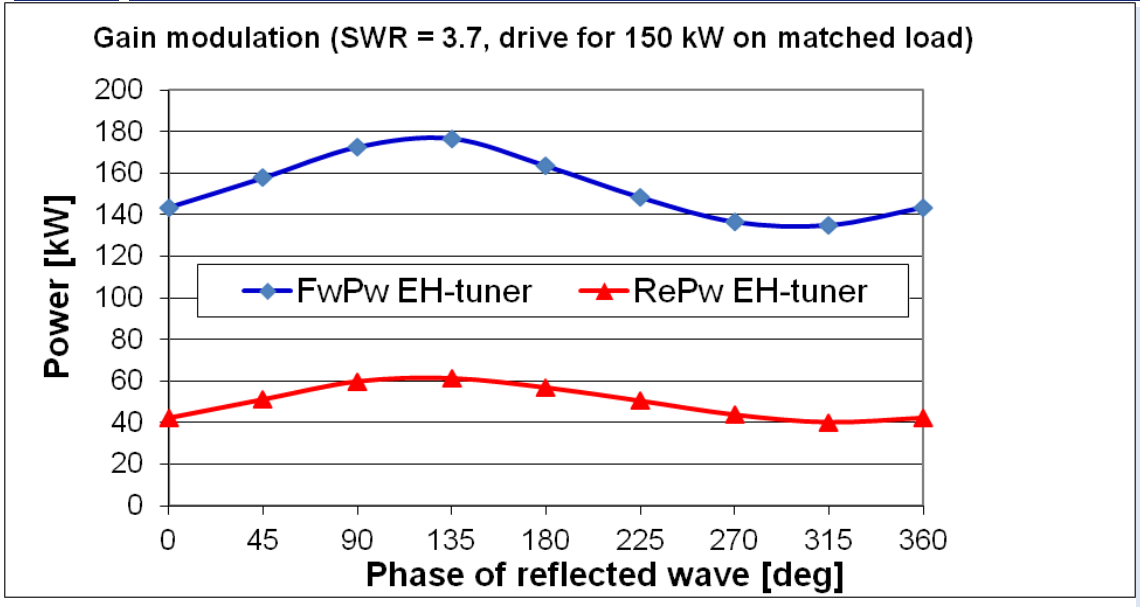
Average 5 HPA failures per year for a total of 1820 HPA (128+2 / tower)

ELTA/SOLEIL SSA TESTS - OVERDRIVE

- **Avoid overdrive conditions**
  - High peak drain voltage can damage the transistor [according to NXP]
  - Explains gain and efficiency degradation observed on first 75 kW tower under test at the ESRF, according to ELTA *)
  - Taken into account by ELTA for the fabrication of the 2nd batch of 3 x 150 kW SSA for the ESRF storage ring:
    - No degradation observed after 3500 hours of fatigue test with 8 amplifier modules at maximum power *)
    - Paid with 1 to 2 % less efficiency of the RF modules and about 1 % less efficiency at nominal power for a complete SSA
- **Short pulses (20 μs)**
  - Transient gain increase up to ≈1.3 dB
  - Risk of overdrive
  - ⇒ Overdrive protection needs to be adjusted carefully

* [J.-P. Abadie & A. Cauhepe, ELTA / AREVA]

ELTA/SOLEIL SSA TESTS – GAIN MODULATION FOR MISMATCHED LOAD



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 (confirmed by simulation)
- Partially due to imperfect circulators on RF modules:

  ⇒ modulation of load impedance

  ⇒ RF module gain modulation

Specification:

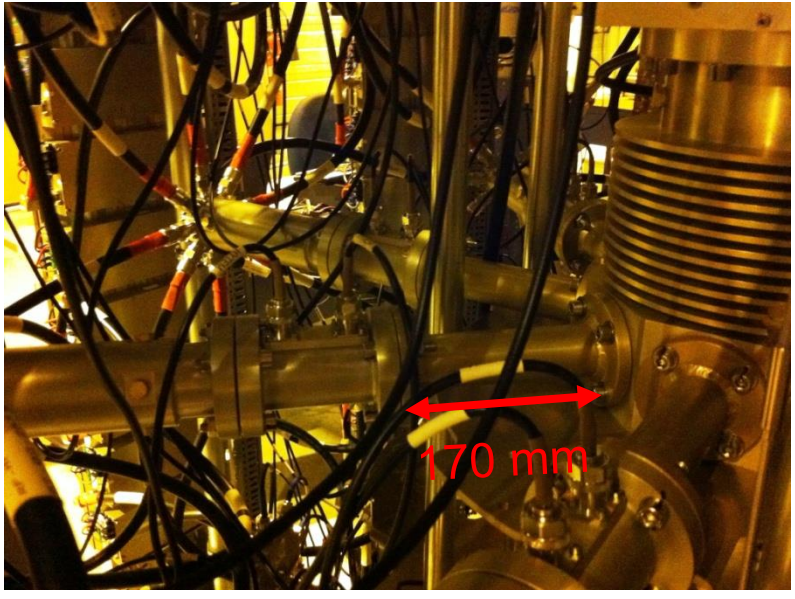
- SWR = 3.7 → P_{refl} / P_{fwd} = 50 kW / 150 kW, all phases (☞ EH – tuner)
- Full reflection at all phases specified and tested for 80 kW (movable short circuit)

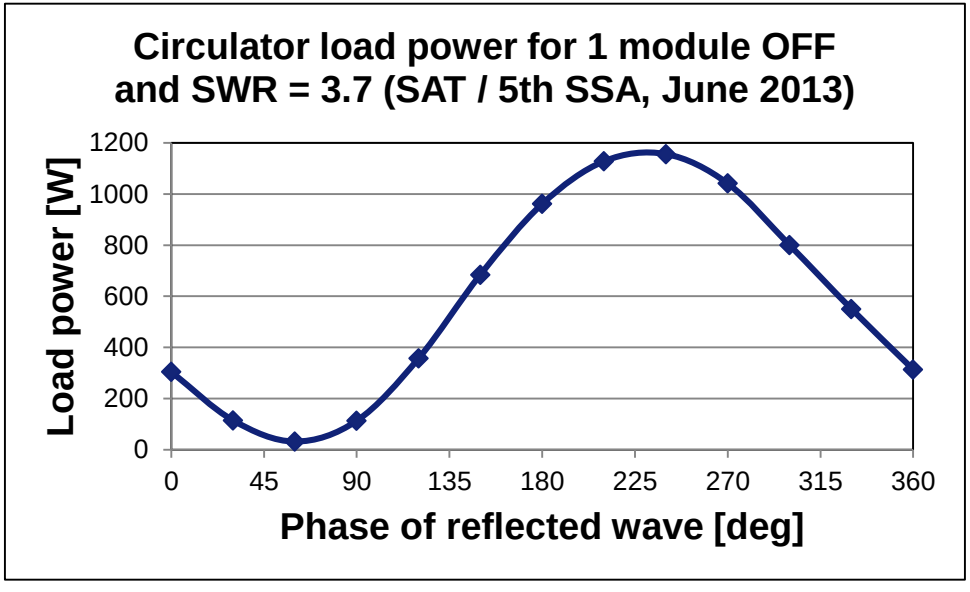
Test results:

- ✓ **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

ELTA/SOLEIL SSA TESTS – OVERLOAD OF UNPOWERED RF MODULES

- **SWR = 3.7 (Spec)** → P_{refl} / P_{fwd} = 50 kW / 150 kW, all phases (☞ EH – tuner)
  - ✓ Operation with up to 6 unpowered modules (redundancy in case of defect)
  - ➢ But: overpower on circulator load depending on phase of mismatch: up to 1700 W

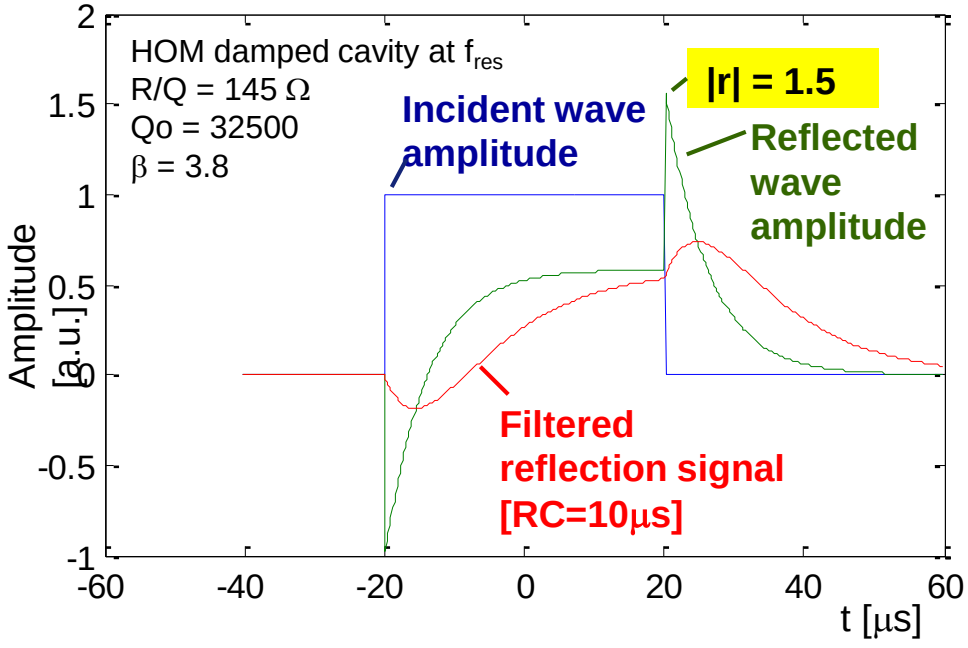




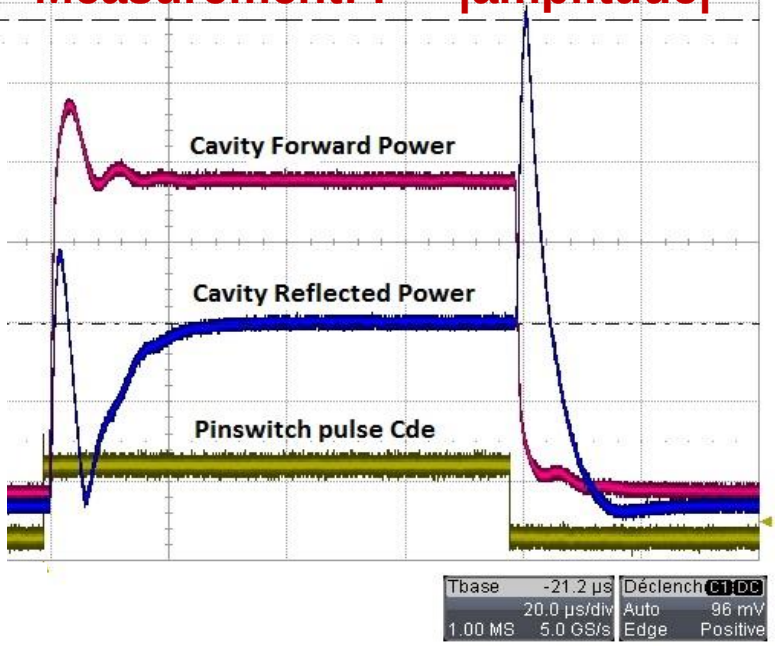
Adjusting the length of the 2nd stage in the combiner tree by +170 mm ⇒ Limit of peak reverse power to 1200 W = capacity of circulator load

TRANSIENT REFLECTIONS FOR PULSED CAVITY CONDITIONING

Computation: amplitude



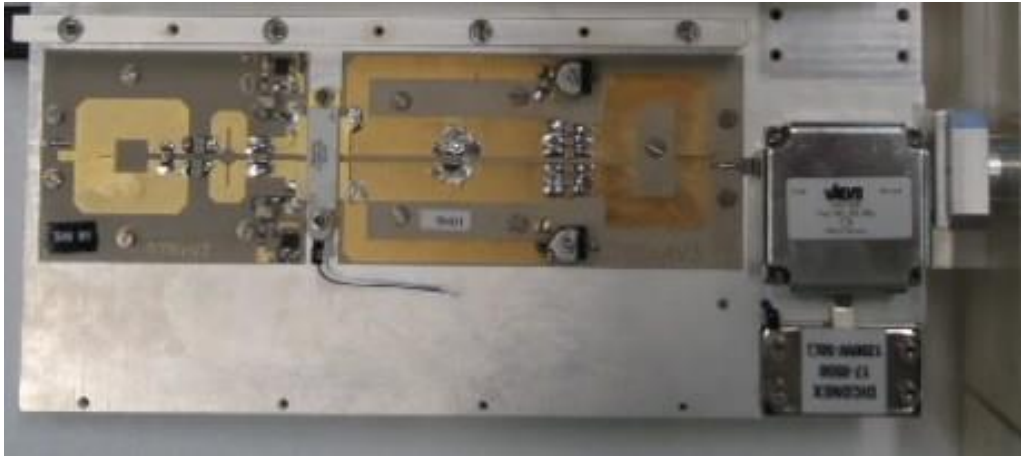
Measurement: P = |amplitude|²



- 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)

RF AMPLIFIER MODULE: ESRF IN HOUSE DEVELOPMENT

Motorola patent



ESRF fully planer design:

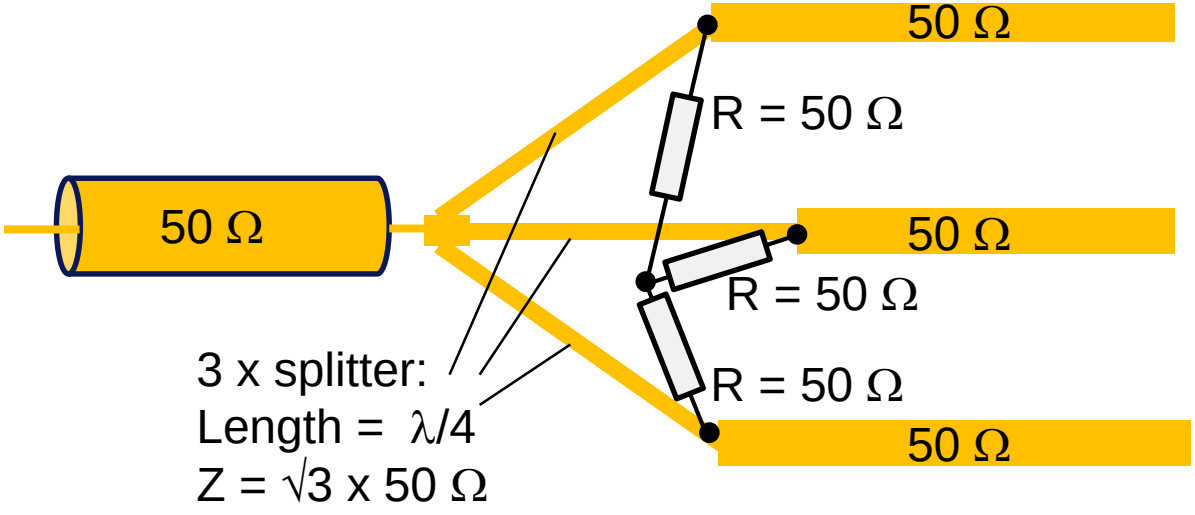
- Printed circuit baluns
- RF drain chokes replaced with “quarter wave” transmission lines.
- Very few components left, all of them SMD and prone to automated manufacturing

⇒ Reduced fabrication costs

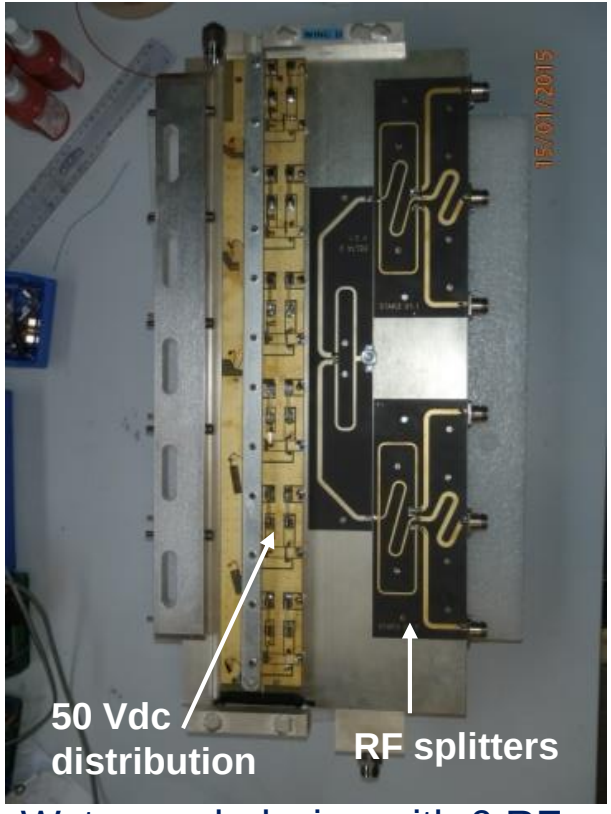
18 modules incl. output circulator	Average Gain	Average Efficiency
at P_{RF}^{out} = 400 W	20.6 dB	50.8 %
at P_{RF}^{out} = 700 W	20.0 dB	64.1 %

[M. Langlois, ESRF]

WILKINSON SPLITTER FOR THE RF DRIVE DISTRIBUTION



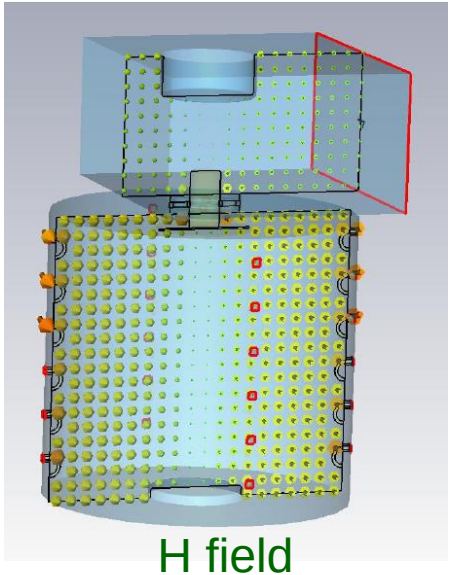
Resistors absorb differential signals without perturbing the common mode, thereby decoupling the connected outputs from each other



Water cooled wing with 6 RF modules, developed at ESRF

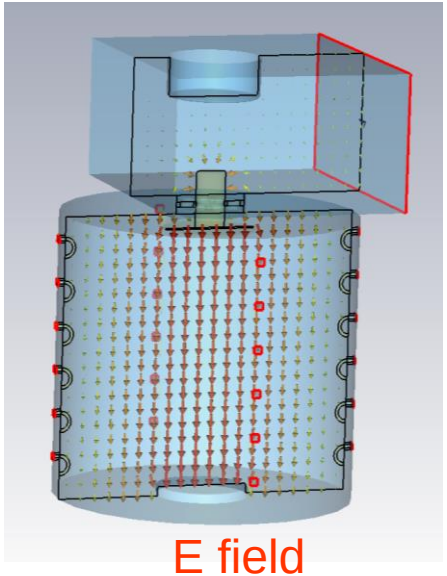
[M. Langlois, ESRF]

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

  ⇒ **85 kW** nominal

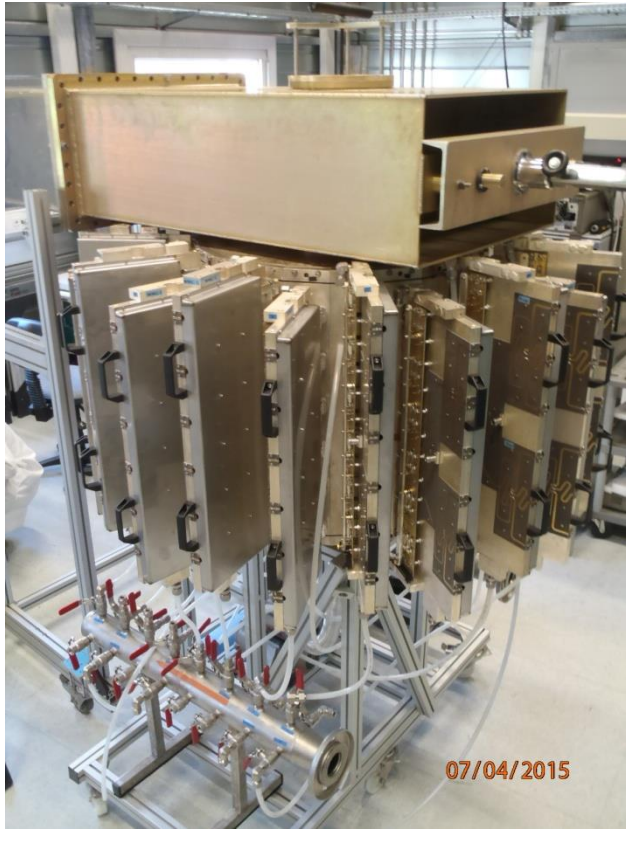
- More compact than coaxial combiners

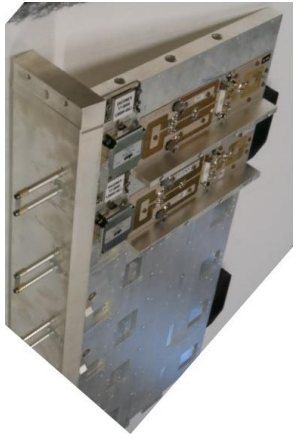
  $$ß_{waveguide} \approx n_{module} \times ß_{module} >> 1$$

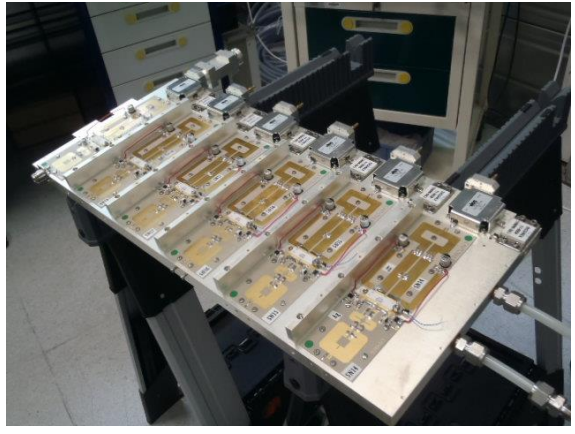
- Easy to tune if n_{module} is varied
- Substantial reduction of losses ⇒ higher η

* *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

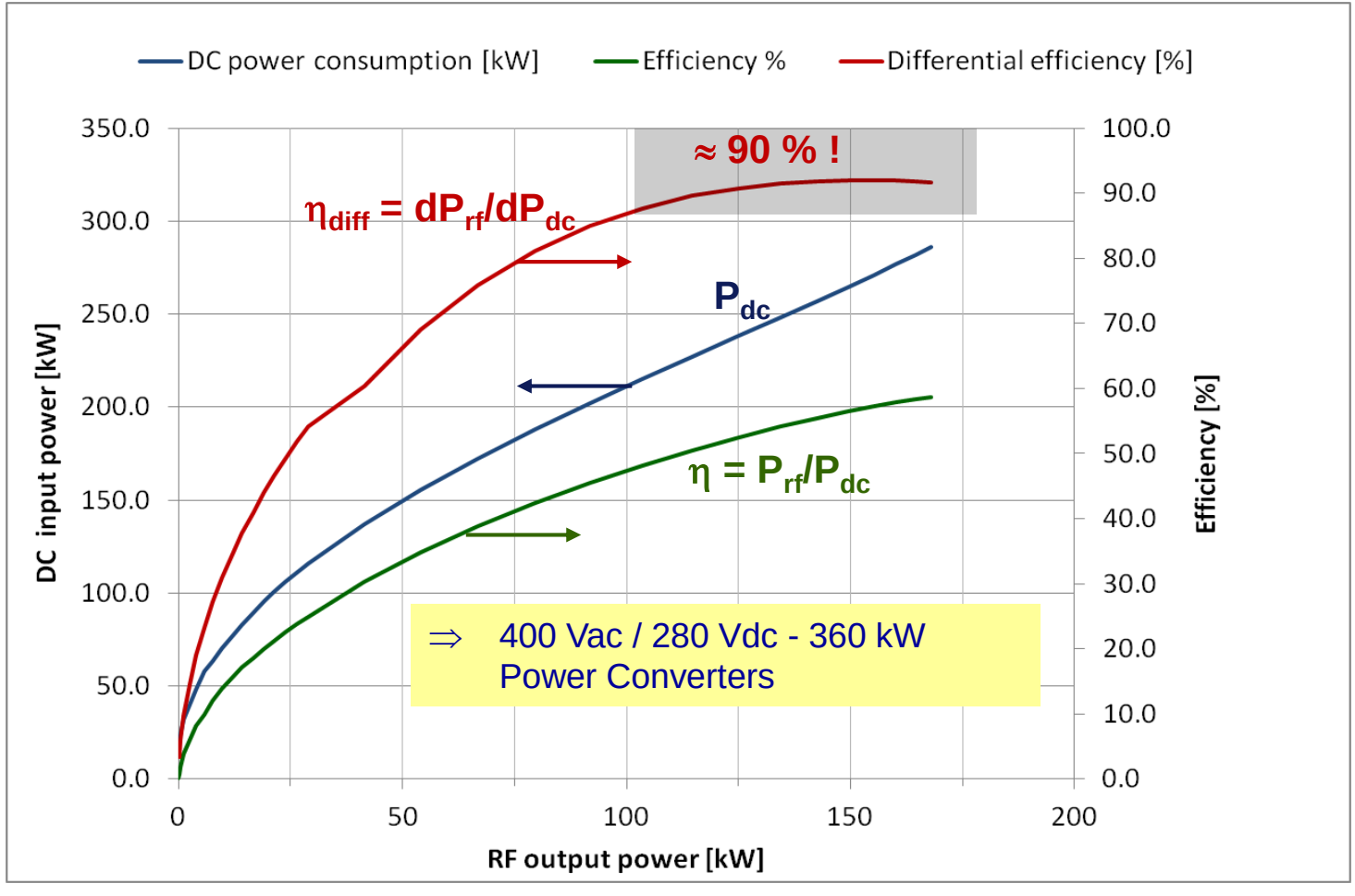
P_{nom} obtained with 1 wing off

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]

DC POWER REQUIREMENT FOR ESRF 150 KW SSPA FROM ELTA

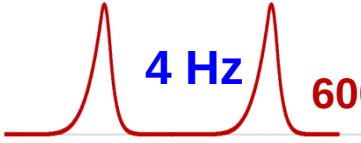


DC SUPPLY OF 4x 150 KW SSPA ON ESRF BOOSTER

Constant AC power
300…400 kW

Average power consumption

Peak DC power
1000…1200 kW

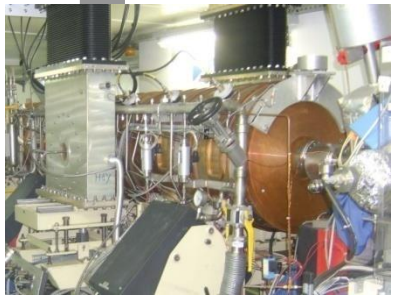


Mains 400 V ac

280 V dc

280 Vdc Supply
400 kW average

Anti-flicker
C = 4.4 F



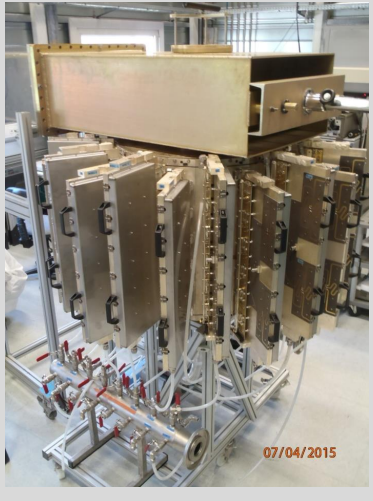
4 booster cavities

- 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]


Thank
you !!!