CERN: European Organisation for Nuclear Research
LIU: LHC Injector Upgrade
SPS: Super Proton Synchrotron accelerator, 1976, 7 km
SSPA: Solid State Power Amplifiers

6th Workshop Energy for Sustainable Science at Research Infrastructures

6TH WORKSHOP ENERGY FOR SUSTAINABLE SCIENCE AT RESEARCH INFRASTRUCTURES (ESSRI 2022)

CERN LIU-SPS, 200 MHZ RF SSPA

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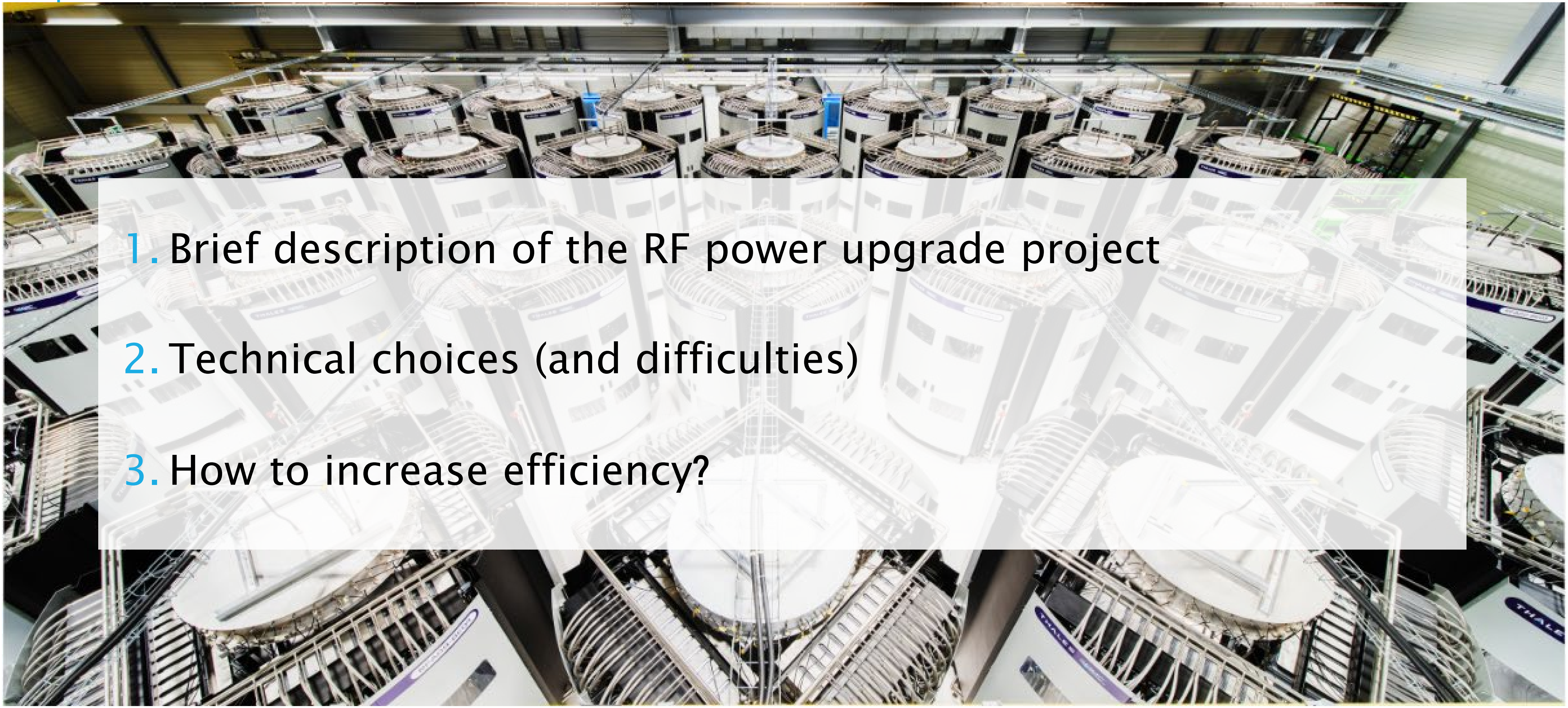
Thanks to all teams members (CERN and Thales), with special thanks to:
Charles Julie, Gino Cipolla (CERN), Patrick Goguillon, Laurent Lachater, Franck Chahbazian, Didier Lebas (Thales)
Top managers (Thales and CERN)

OUTLOOK



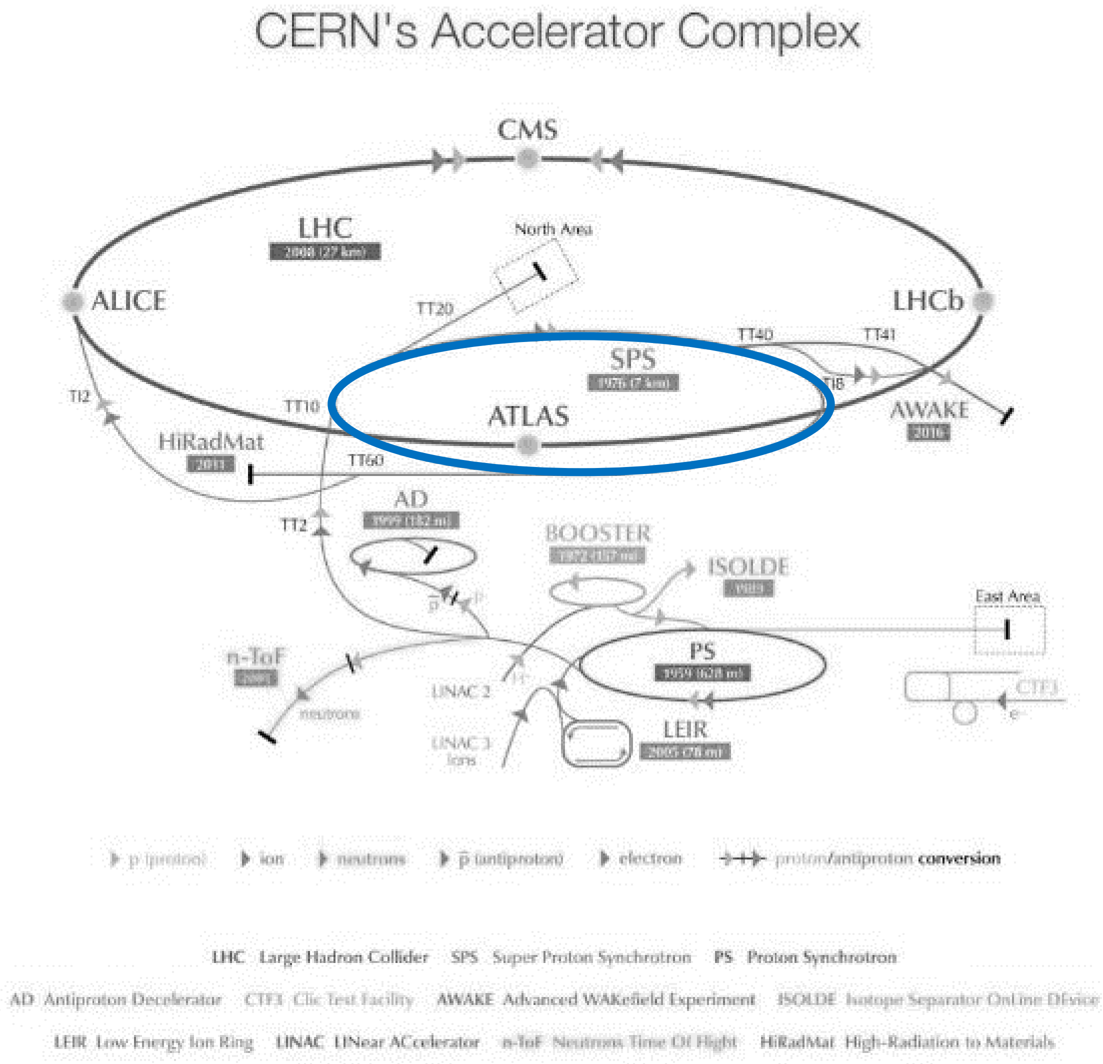
1. Brief description of the RF power upgrade project
2. Technical choices (and difficulties)
3. How to increase efficiency?

CERN SPS LIU PROJECT

The LHC Injectors Upgrade should plan for delivering reliably to the LHC the beams required for reaching the goals of the HL-LHC

Translated to SPS-RF

re-arrangement of the cavities and construction of new RF power stations



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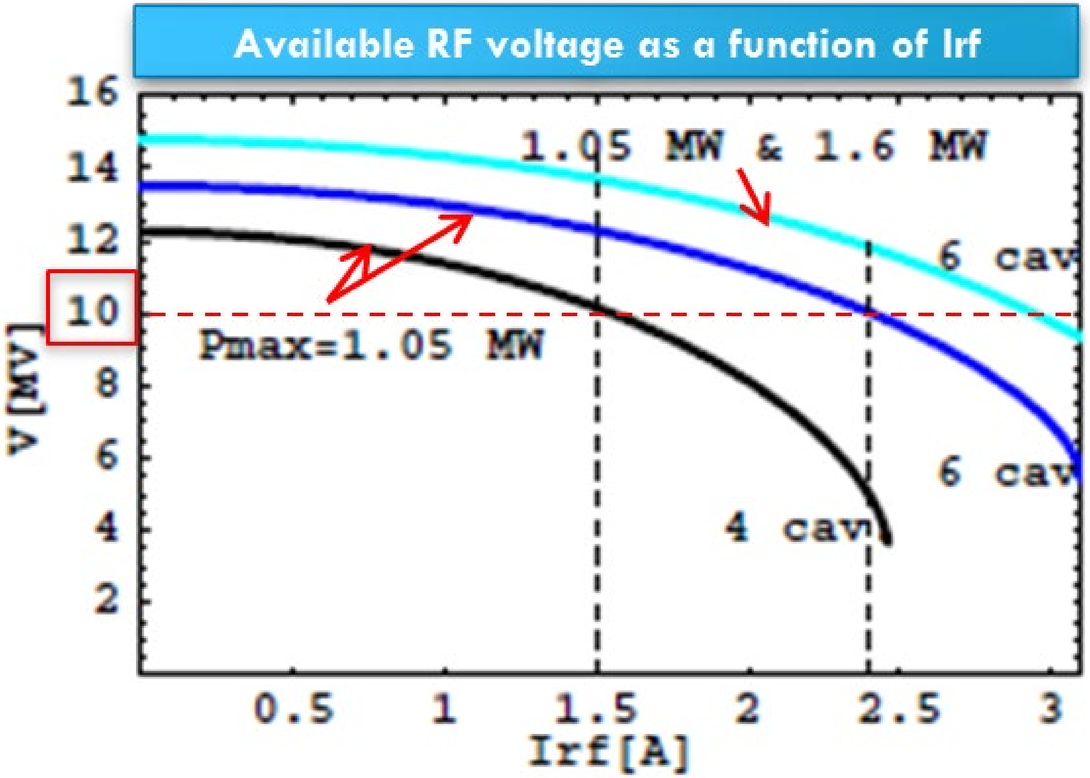
DESCRIPTION OF THE RF POWER UPGRADE PROJECT

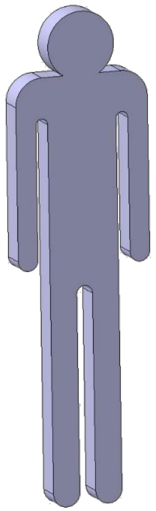
First definition of the project (2011)

- Four existing amplifiers upgraded to 1.05 MW* feeding four cavities
- Two New power amplifiers delivering 1.6 MW* feeding two additional cavities
- A new RF building
- A new LSS3 distribution (Long Straight Section #3)
- *All RF power levels being peak power operating with a 50% duty cycle at 42 kHz or 172 kHz, CW operation at average power (half peak power) is also requested

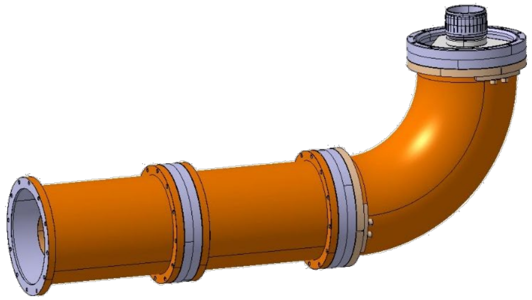
Courtesy Elena Chapochnikova



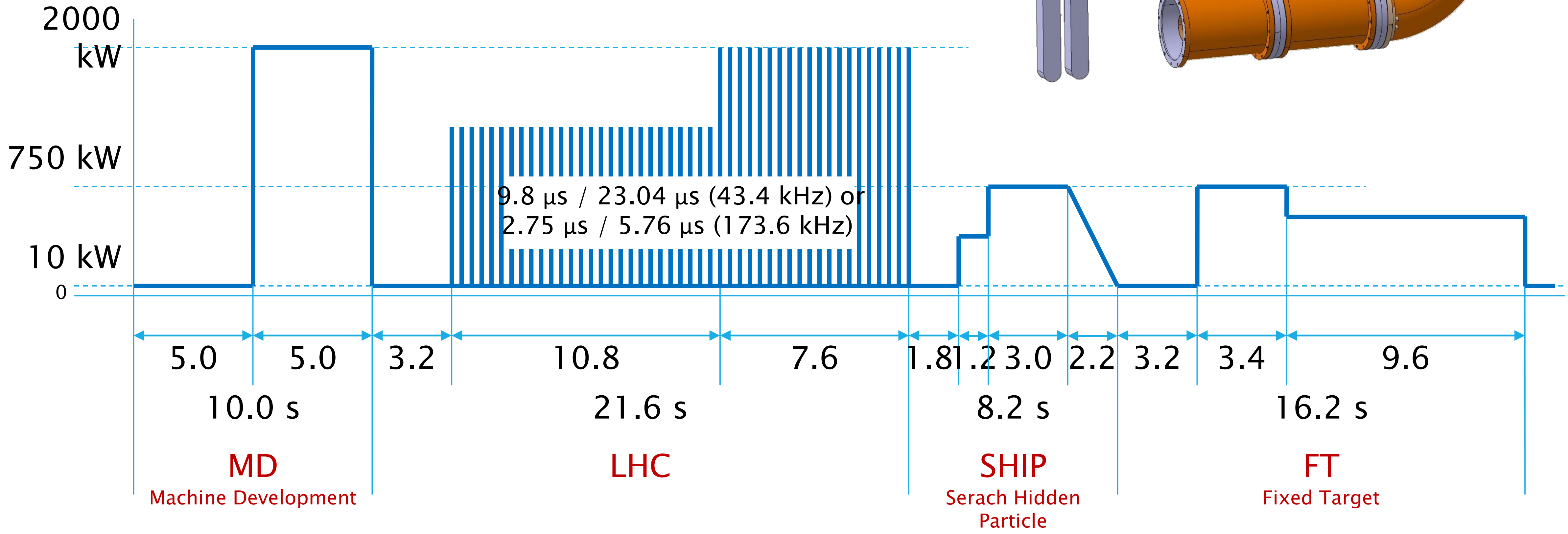
SPS SUPERCYCLE



Average power limited to 750 kW due to 350 mm coaxial lines



Terrible cycle for all RF power stations!



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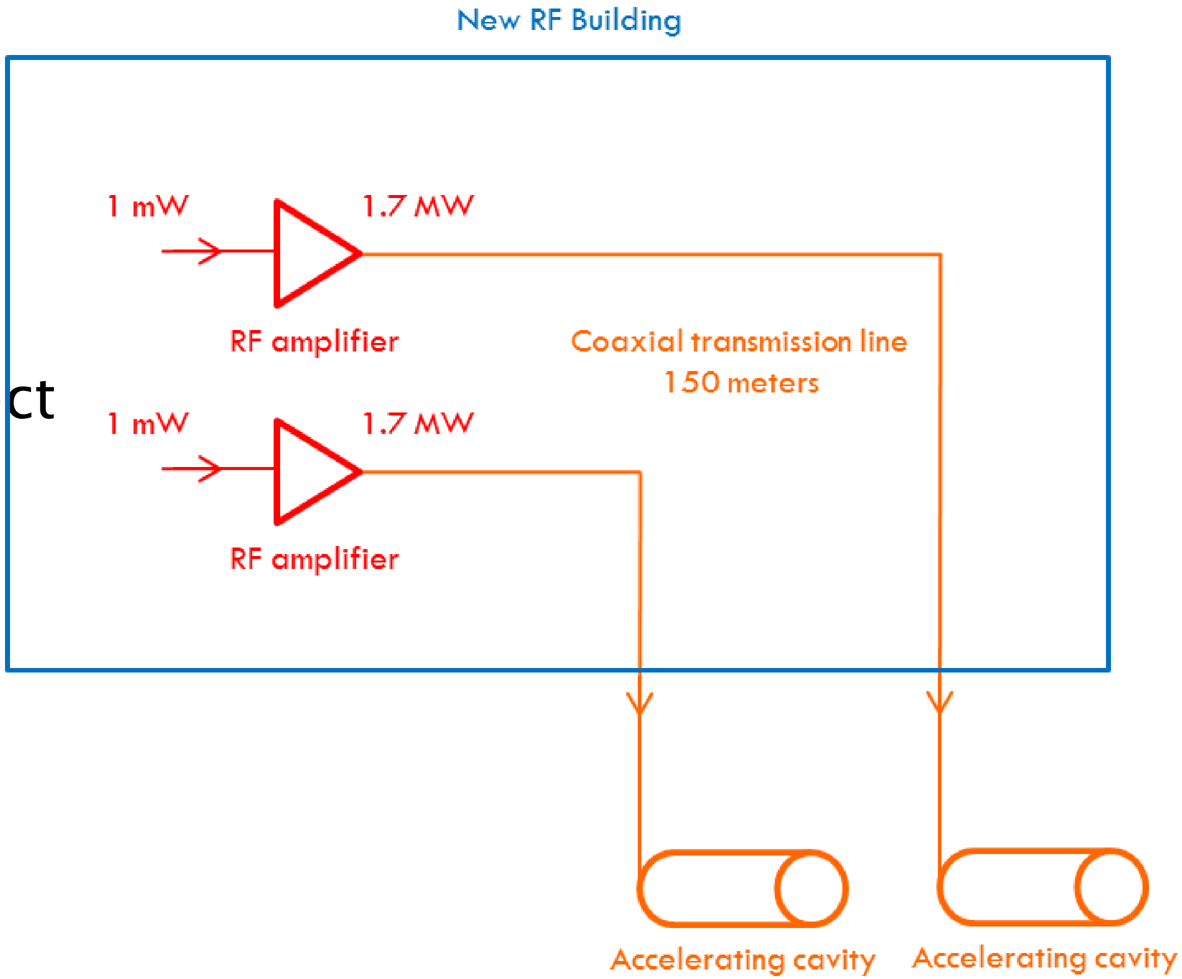
DESCRIPTION OF THE RF POWER UPGRADE PROJECT

Three main sub-tasks

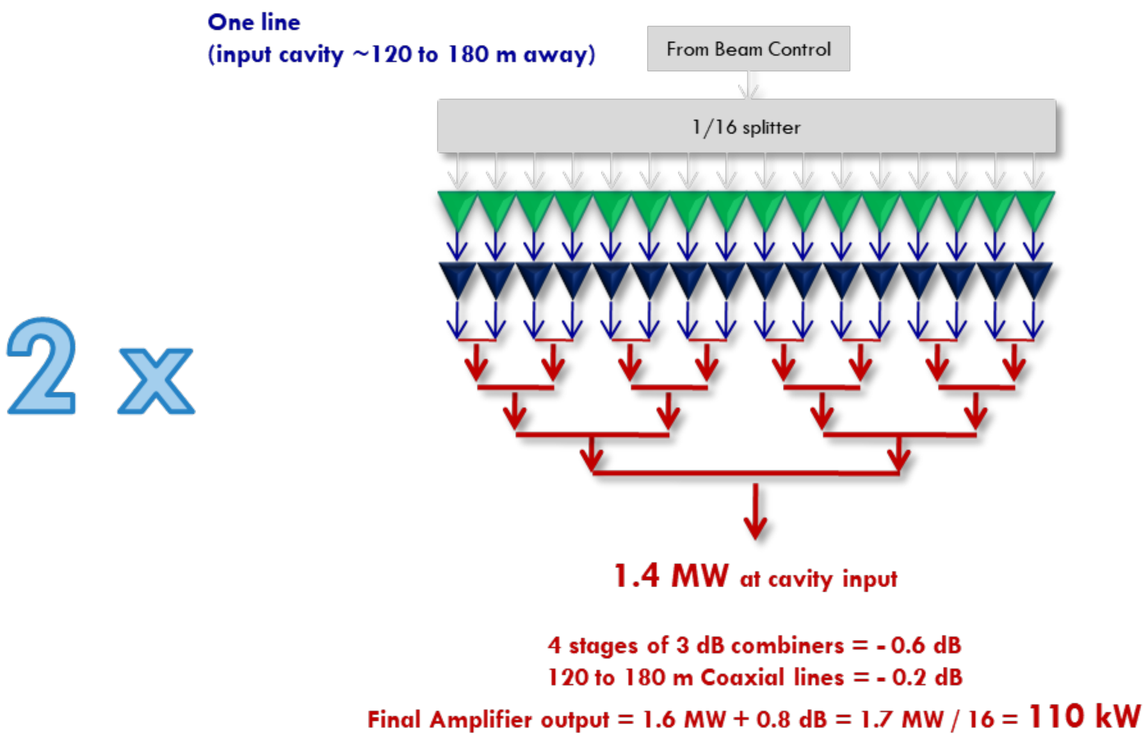
1) New RF Building project

2) Cavities re-arrangement project
   - LSS3
   - Coaxial lines
   - Cavities
   - Fundamental Power Couplers

3) RF Power Amplifiers project
   - Present amplifiers upgrade
   - New amplifiers



NEW SYSTEMS 2 x 1.7 MW @ 200 MHZ



Three contracts

Drivers :
- 2 x 16 x SSPA

Finals :
- Tetrode : 2 x 16 x 110 kW
- IOT : 2 x 16 x 110 kW
- SSPA : 2 x 16 x (110 x 1 kW)
- Diacrode : 2 x 2 x 850 kW
- No klystron at 200 MHz

Combiners + lines :
- 3 dB hybrids
- 850 kW power loads

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OUTLOOK

1. Brief description of the RF power upgrade project
2. Technical choices (and difficulties)
3. How to improve efficiency?

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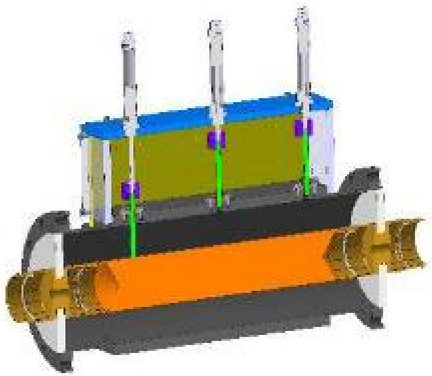
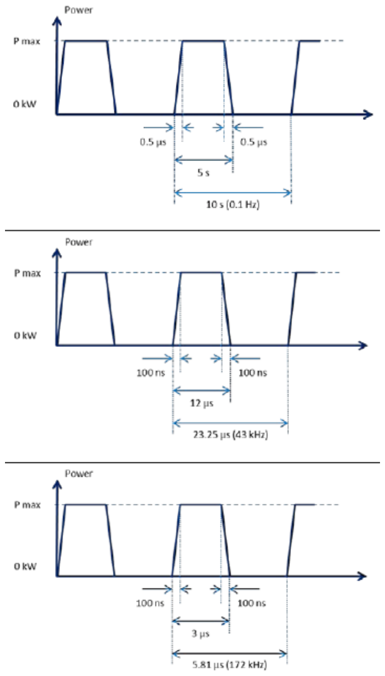
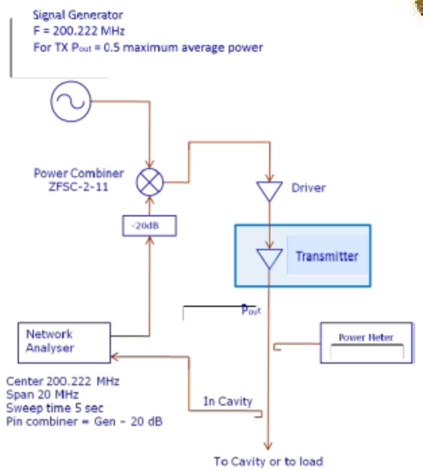
TECHNICAL REQUIREM

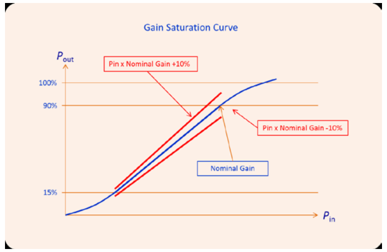
Requirements

- Integration within the given building
- Repetition rate 0.1 Hz to 500 kHz (require a CW and a pulsed amplifier)
- Full reflection all phases 100 ms (equivalent to 4 time the power level along the lines)
- Non conventional way to measure the BW (required by LLRF and TWC)
- Very good linearity



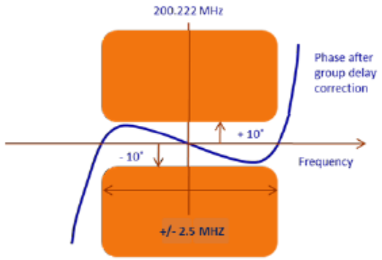


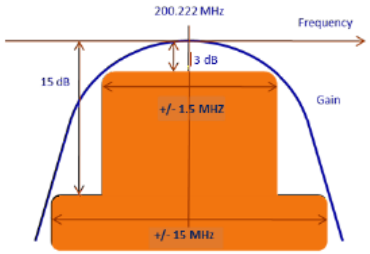


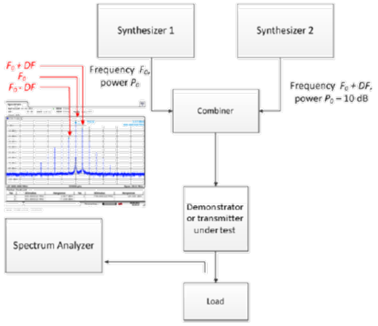


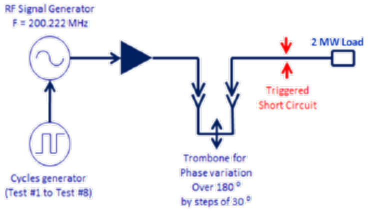
A lot of tests to qualify the amplifiers

- Supercycle test, short circuit test, BW, linearity, …
- Short duration tests to qualify an Amplifier within one week
- Long duration tests to check reliability over 1000 hours









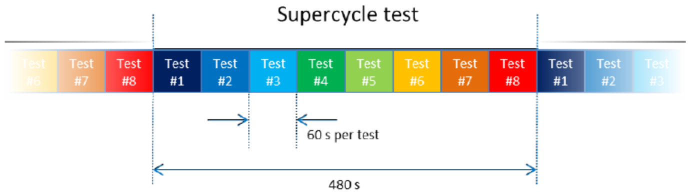
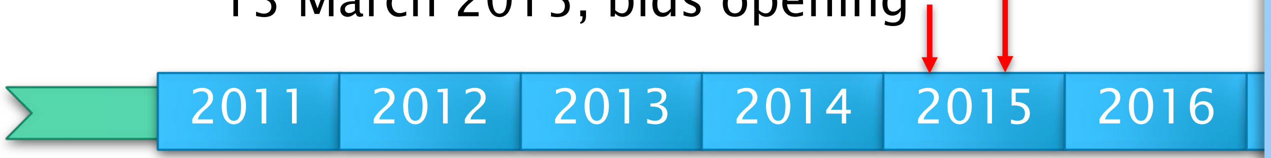


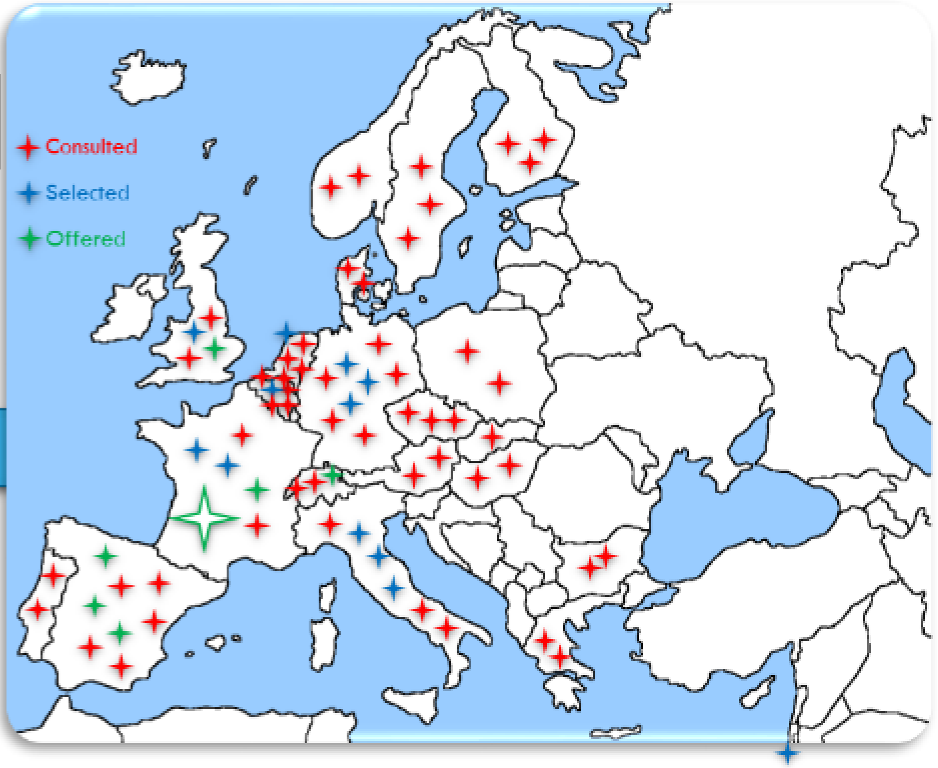
Figure 7: Supercycle test

INVITATION TO TENDER

17 September 2015, FC approval

13 March 2015, bids opening





74 companies consulted within the CERN's Member states

19 selected

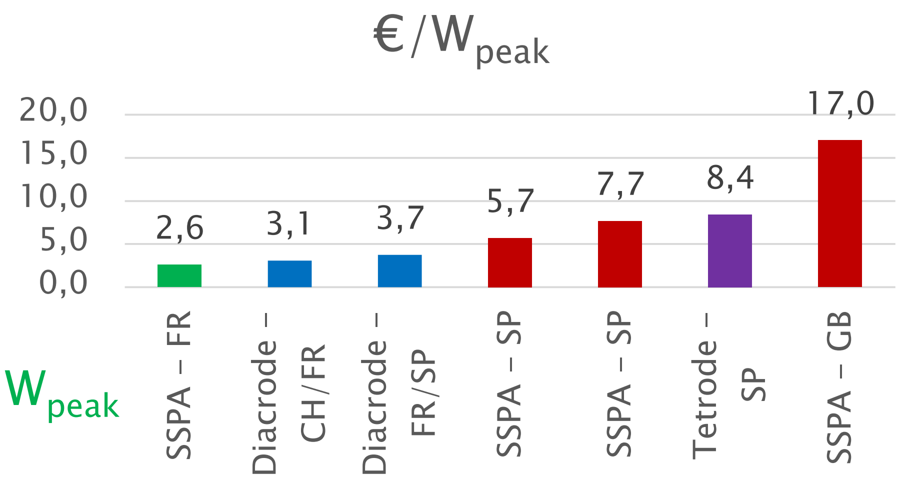
8 declined

7 offers

March 2015 lowest bid was Thales Communication & Security

Very careful verification of the offer

September 2015 CERN FC approval



2.6 €/W_{peak}

TRANSISTOR POWER RATINGS –

PERSONAL VIEW OF FUTURE PERSPECTIVE (2016)

Voltage limits

	2002	2006
900 MHz	41 V/m	
1800 MHz	58 V/m	3 V/m
2100 MHz	61 V/m	

Device	**Distance**	**Power**
Phone	20 km	2 W
Microcell	2 km	10 W
Macrocell	20 km	50W

The tendency is to increase the number of smaller cells in order to keep the phone battery autonomy, increase the data bandwidth, and reduce the exposition of population to too high electromagnetic fields

TRANSISTOR POWER RATINGS – PERSONAL VIEW OF FUTURE PERSPECTIVE (2016)

Transistor supplier main business will not be higher power per transistor

Conclusion : below a GHz, 1 kW per transistor (LDMOS) seems to me a very good goal

1482 Million Smartphones in 2015

6.1 Millions Microcell stations 2009

5.9 Millions Macrocell stations 2009

Freescale + NXP Semiconductors revenue in 2015: $10'000 Millions

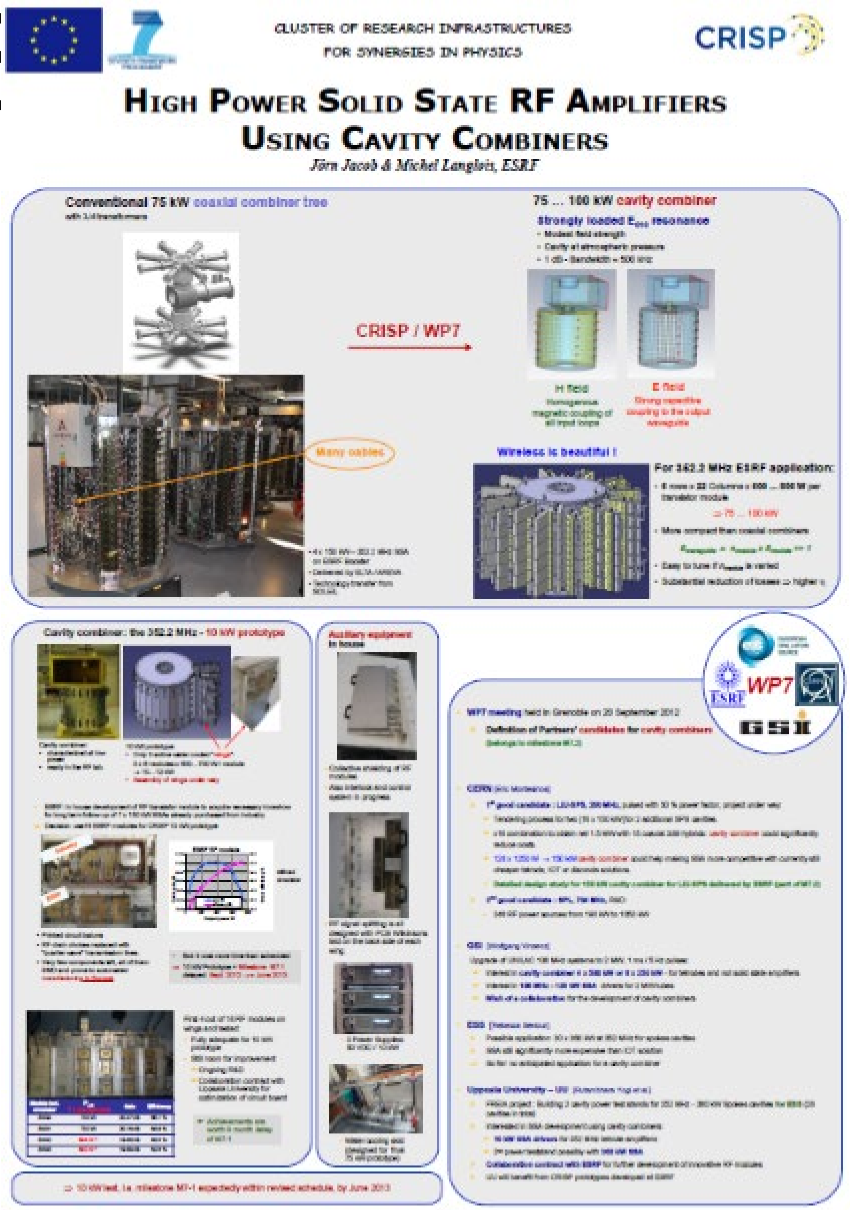
Assumption (with a lot of simplifications)

Machine	# RF stations	Peak power	# 500W LDMOS
ESS	120	1.2 MW	290'000
FCC	400	125 kW	100'000

- Cost of a LDMOS ~ $120
- Revenue for transistors manufacturers $50 Millions
- Over minimum 5 years $10 Millions per year

RF for accelerators could be 0.1 % of main suppliers revenue

CAVITY COMBINERS



CRISP (Sept 2010)

- Jörn Jacob (ESRF) asked for support to the development of cavity combiners receiving funding from the EU as work package WP7 in the framework of the FP7/ESFRI/CRISP program
- CERN immediately supported it

CRISP, 2nd yearly meeting, PSI 18-19 March 2013

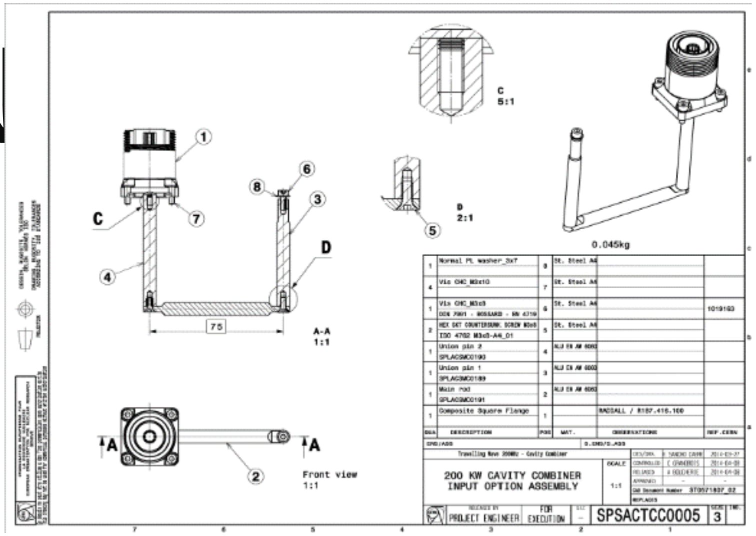
- ESRF cavity combiner
- 144:1 Cavity combiner for CERN-LIU-SPS

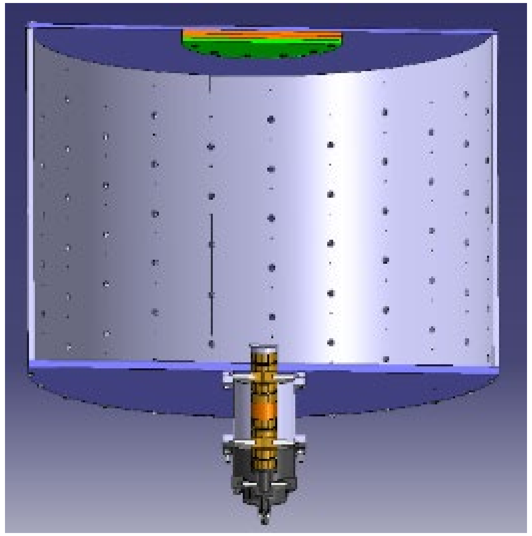
In addition, please refer to two excellent papers from ESRF at IPAC

- MOPC005-IPAC11, 352.2 MHZ – 150 kW Solid State Amplifiers at the ESRF
- WEPFI004-IPAC13, Commissioning of first 352.2 MHz – 150 kW Solid state amplifiers at the ESRF and status of R&D

CAVITY COMBIN

Based on ESRF Technical Note for CERN-LIU-SPS under CRISP in Feb 2013, we built our own 144:1 cavity combiner






CRISP

EUROPEAN SYNCHROTRON RADIATION FACILITY

ESRF

Accelerator & Source

Technical Note

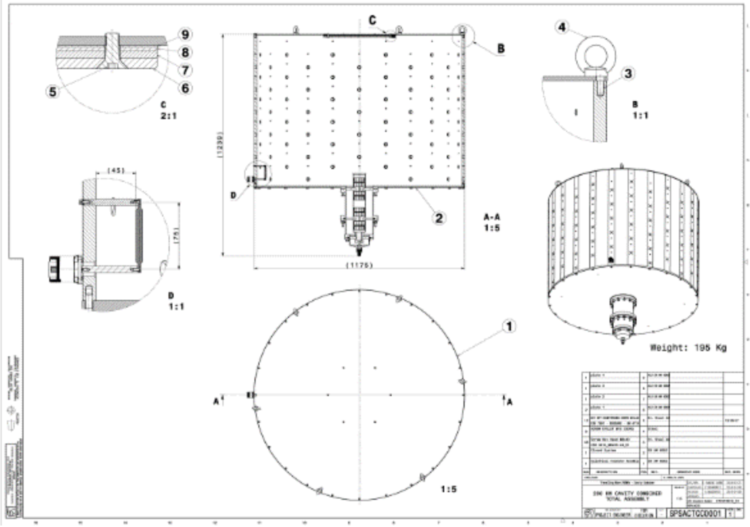
01-13/RF

150 kW Cavity combiner for CERN-LIU-SPS[1]

Author(s): Michel LANGLOIS

Date: February11th, 2013

Distribution: Jörn JACOB, Eric MONTESINOS



AMPLIFIERS FOR CERN

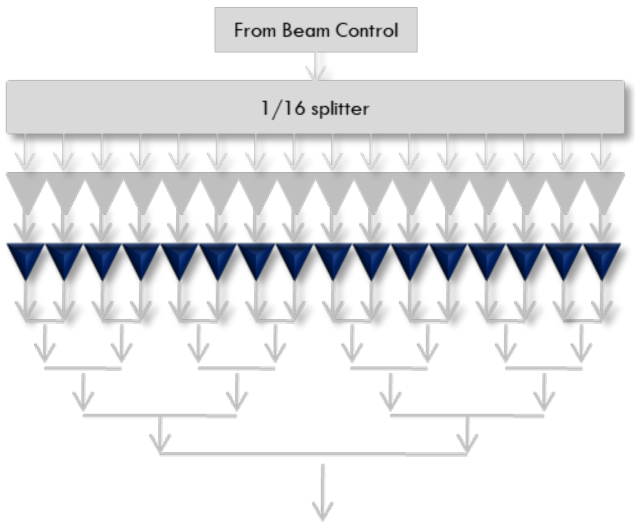
One Transmitter will be composed of
- 16 x 144 kW RF amplifiers

One RF amplifier will be composed of
- 1:80 cavity splitter
- 80 x 1.8 kW RF blocs (160 transistors)
- 80:1 cavity combiner

In total
- Two transmitters
- 32 RF towers
- 2560 RF blocs
- 5120 transistors

TCS proposal fully in line with our own R&D programs
- Small RF units based on 1 kW LDMOS transistors
- Cavity combiners

2 x



1.6 MW at cavity input ~120 to 180 m away

4 stages of 3 dB combiners = - 0.6 dB
120 to 180 m Coaxial lines = - 0.4 dB
Final Amplifier output = 1.6 MW + 1 dB = 2 MW
16 towers of minimum 125 kW

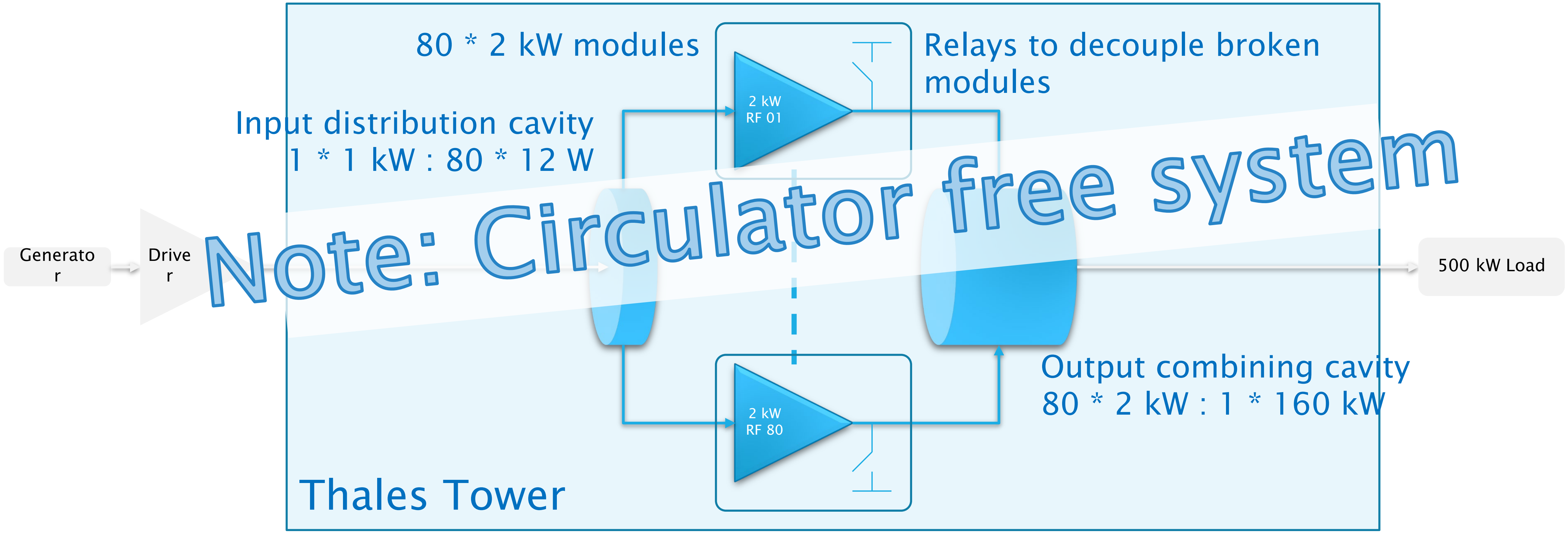
Three contracts

Drivers :
2 x 16 x SSPA

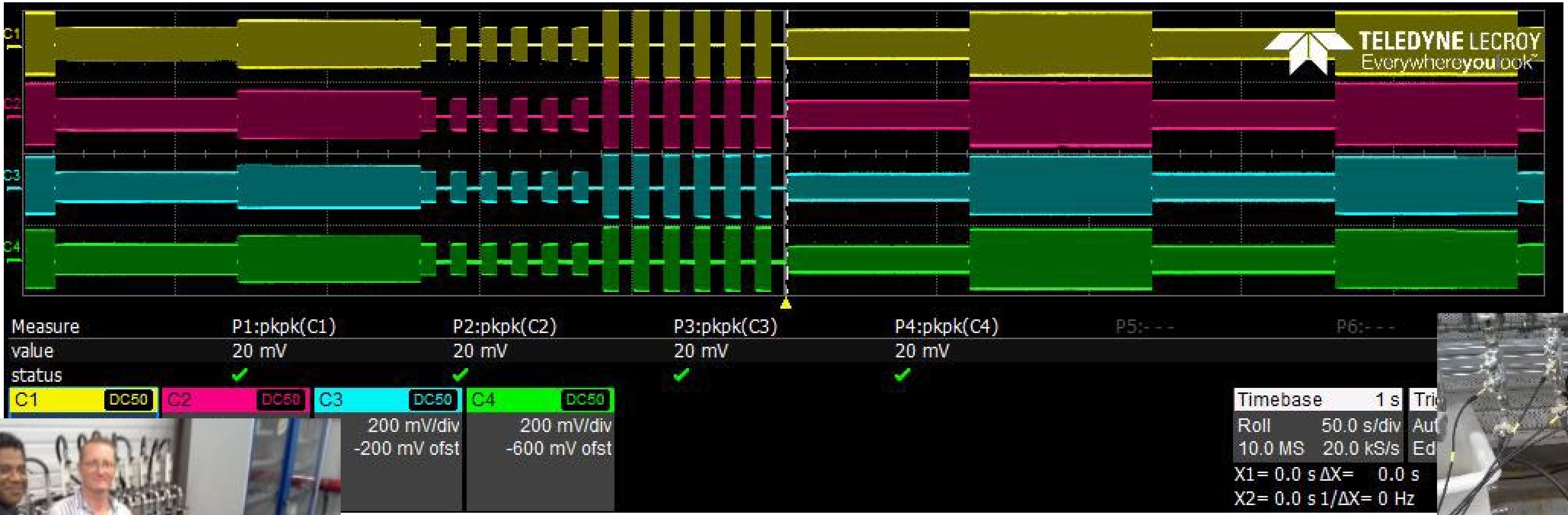
Finals :
SSPA : 2 x 16 x (80 x 1.8 kW)

Combiners + lines :
3 dB hybrids
850 kW power loads

THALES SYSTEM ARCHITECTURE

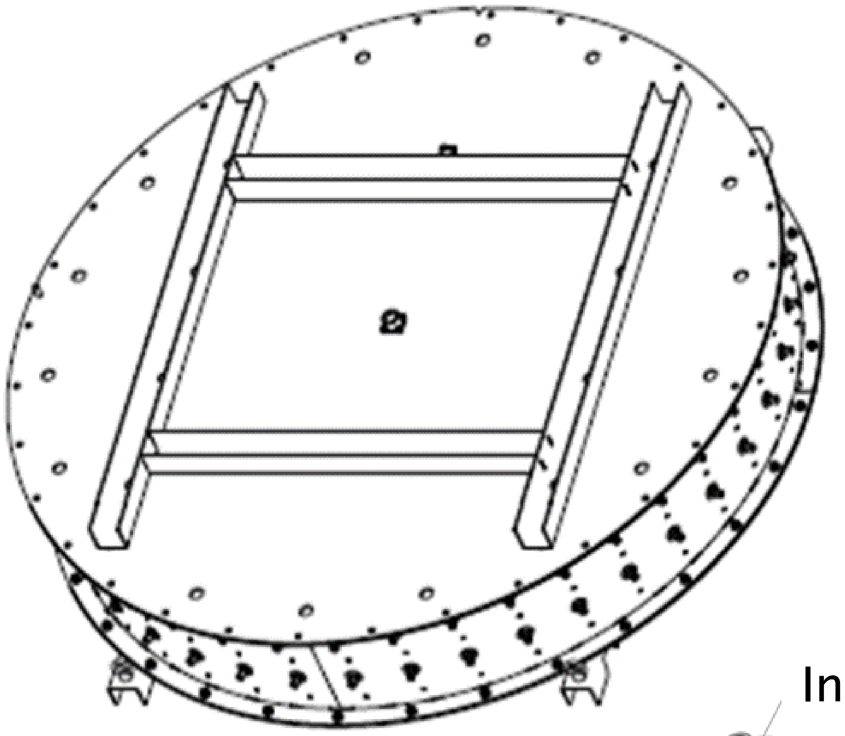


THALES V1 PROTOTYPES SUCCESSFULLY TESTED

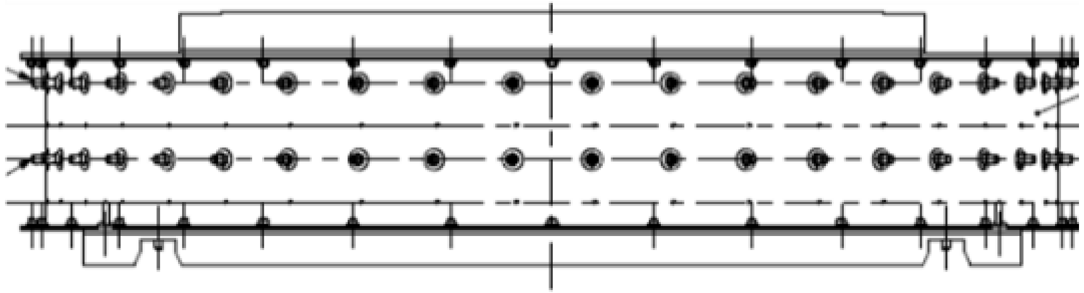


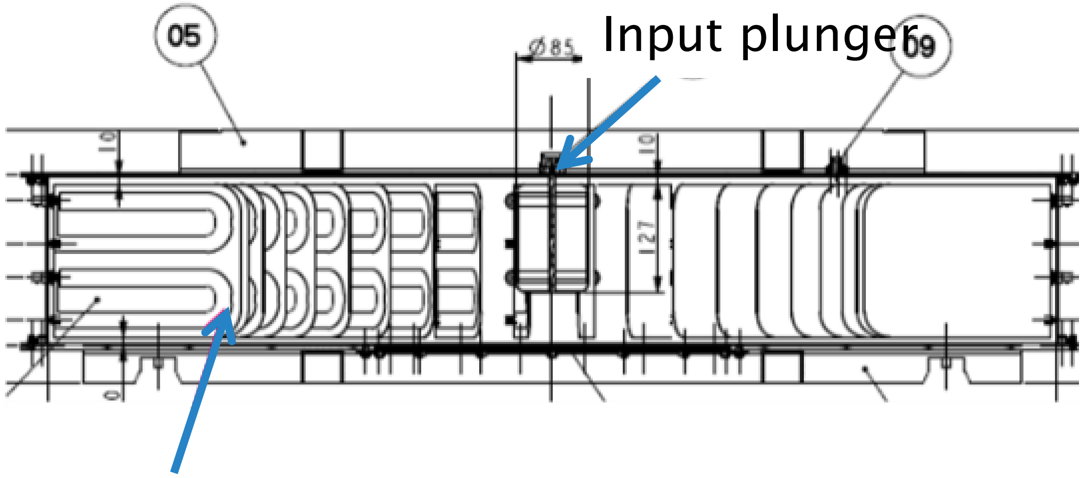
19/10/2016, SPS Cycle test Thales, on loads, 10 hours duration with no trip
Successfully repeated with 8 units

CAVITY SPLITTER 80:1



Input plunger

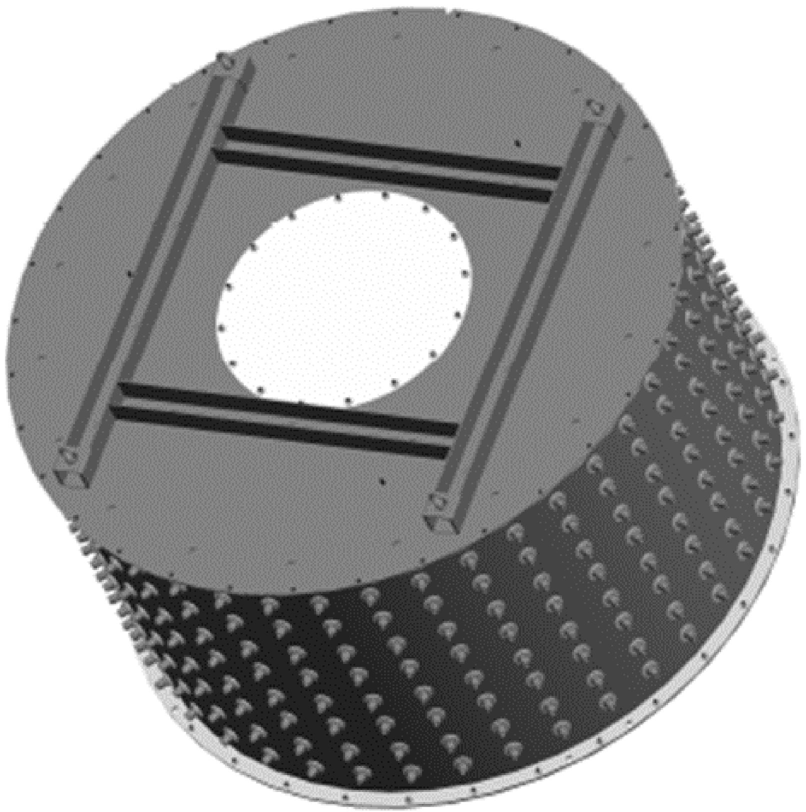


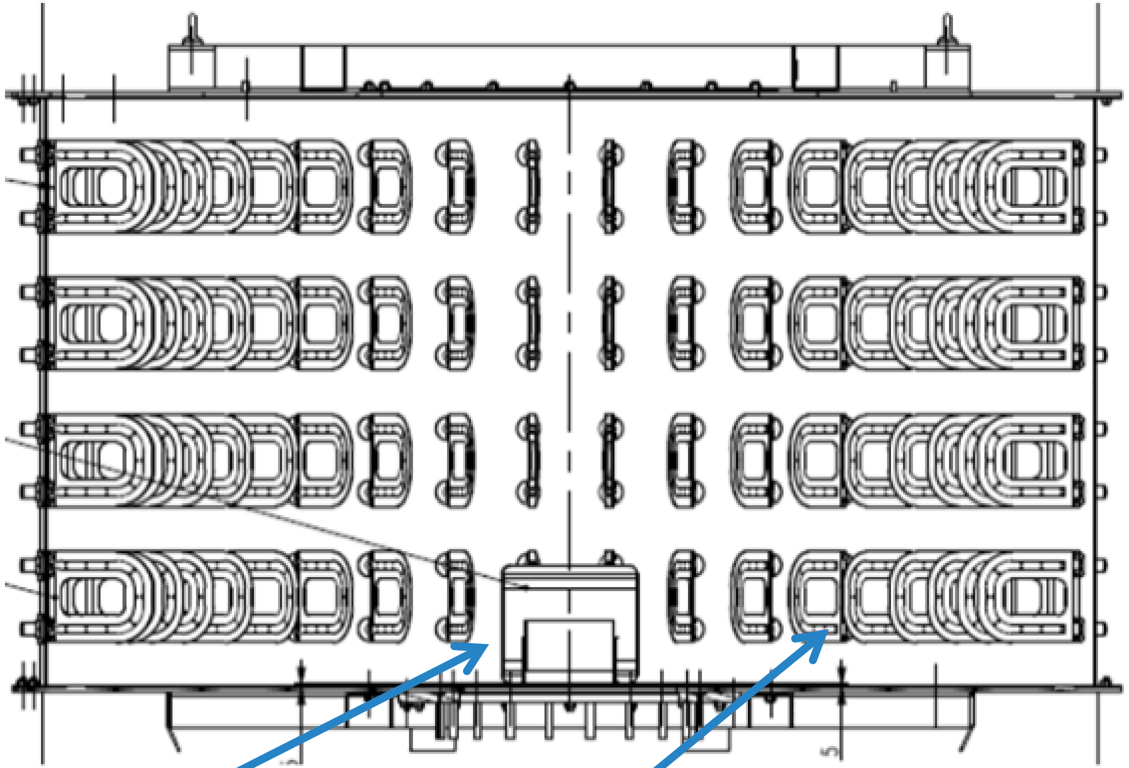


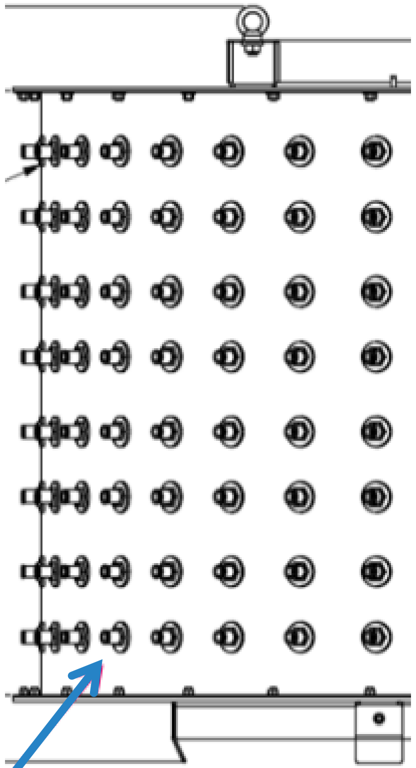
Input plunger

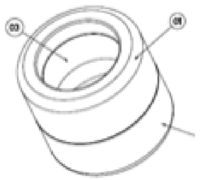
PCB with two coupling loops

CAVITY COMBINER 320:1







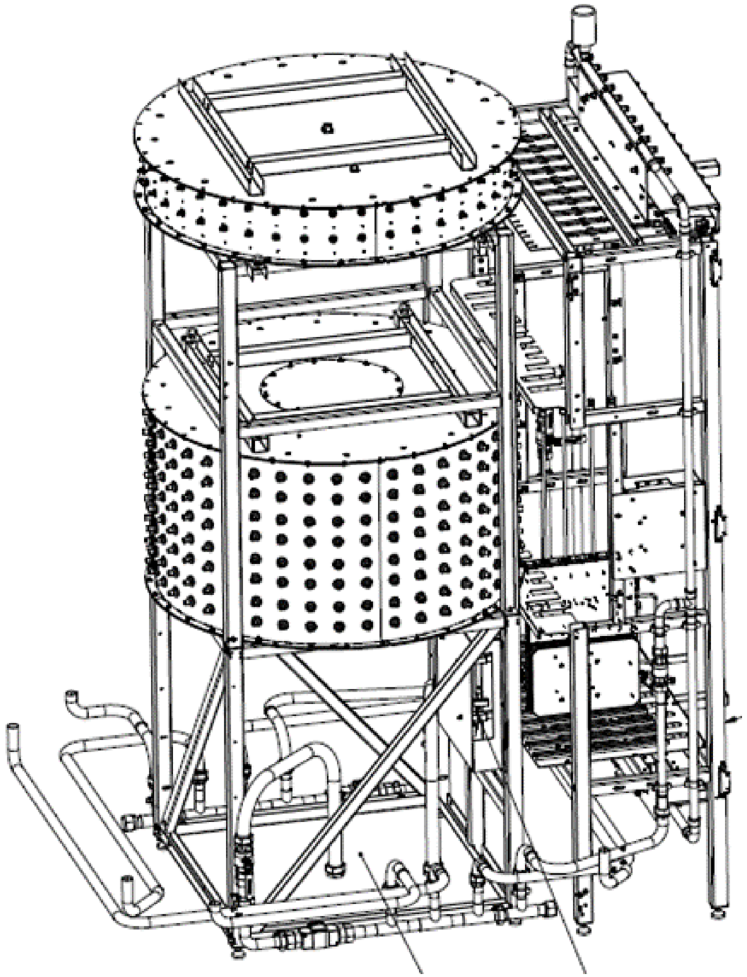


Output plunger

Coupling with PCB

C connector
(like N, but ¼ turn connection)
(really useful with 10240 in the system)

TOWER



A tower is composed of

- One frame
- Four bays
- One cavity splitter
- One cavity combiner
- Electrical distribution
- Water distribution

A color code has been defined not to mix the RF connections

Indeed, modules are all the same, but mounted top and bottom affect the RF connections

In addition, the frame has been made such that all cable lengths are identical, needed for the cavity combiner

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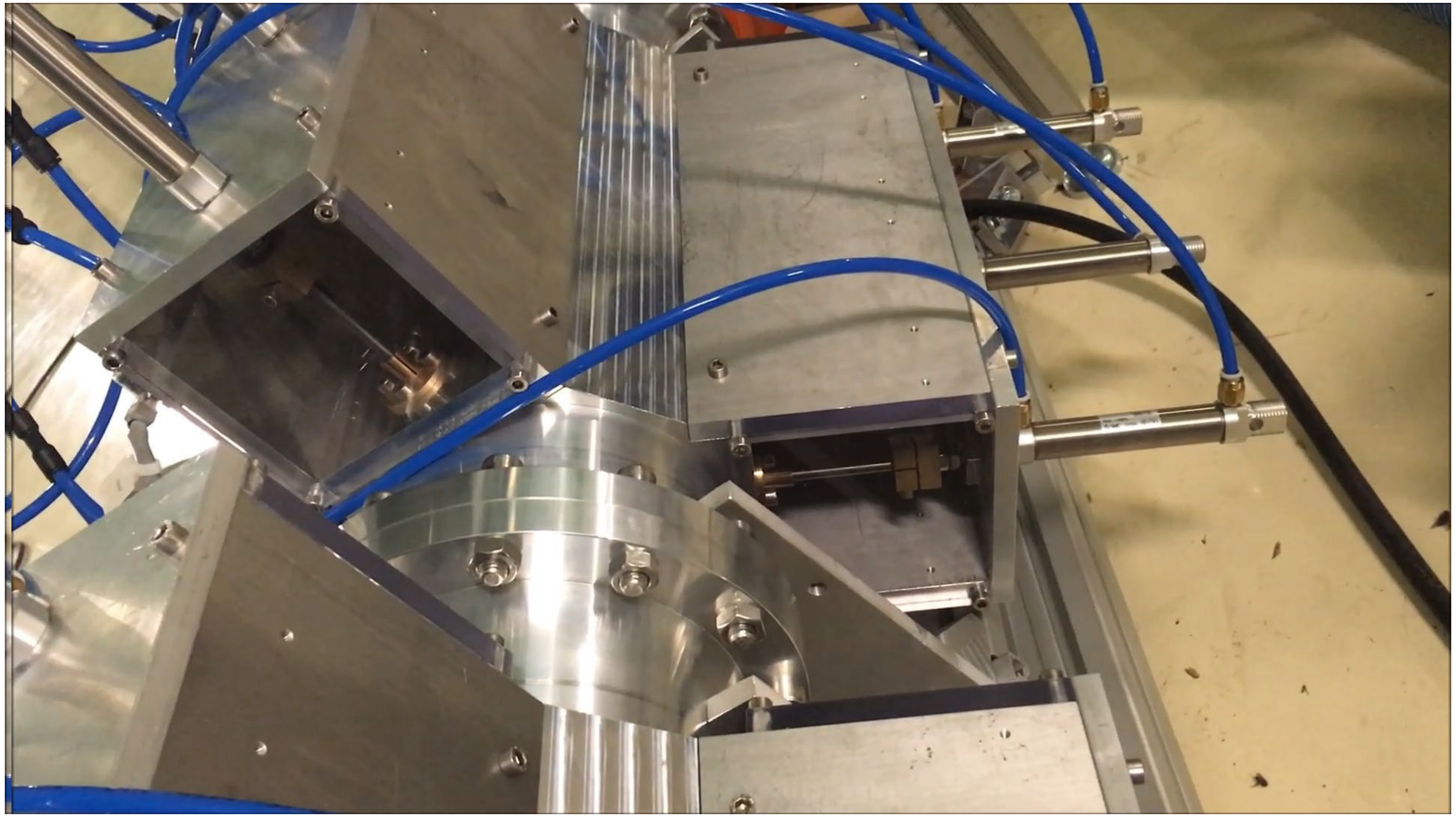
FIRST DEMONSTRATOR PROTOTYPE

A first demonstrator prototype tower was delivered
As we already had the drivers (Tti Norte)
We were ready for tests

SHORT CIRCUIT TEST



We started with the short circuit test

We constructed a 6-1/8 line with 6 planes having each 3 fingers

We repeated the short circuits during one hour every 5 seconds under various phase and various power conditions

RF switch was off 100 ms after reverse was detected, in operation, it will be 1 ms maximum

Not having a circulator was THE challenge (I thought…)

It was fully successful, not a single module failed, the test was **ok**

FIRST DIFFICULTIES

Despite a lot of simulations have been carefully made, transients induced during the short circuit cycles were much more demanding than expected

A redesign of the PCB coupling loop was needed

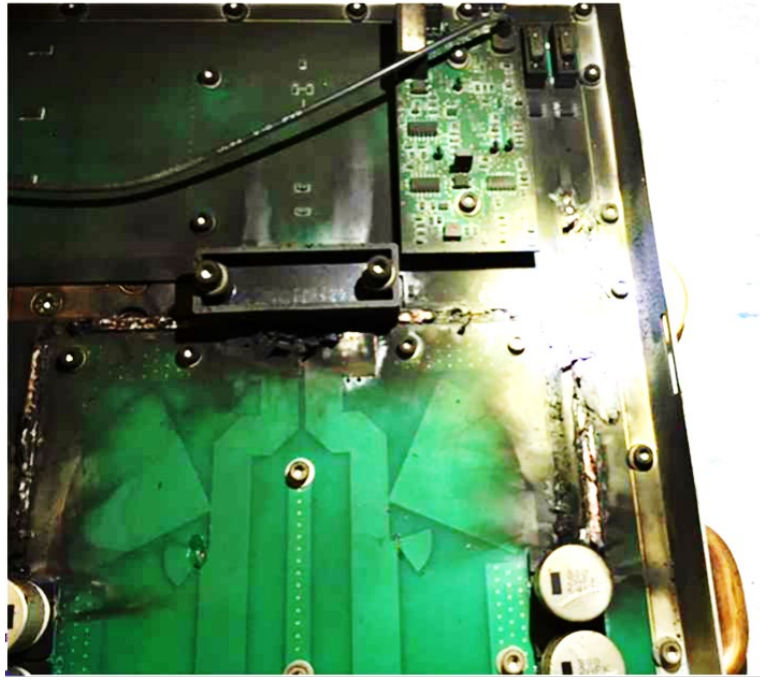
First alarm that Devil is in details…

TROUBLES WITH TRANSISTORS

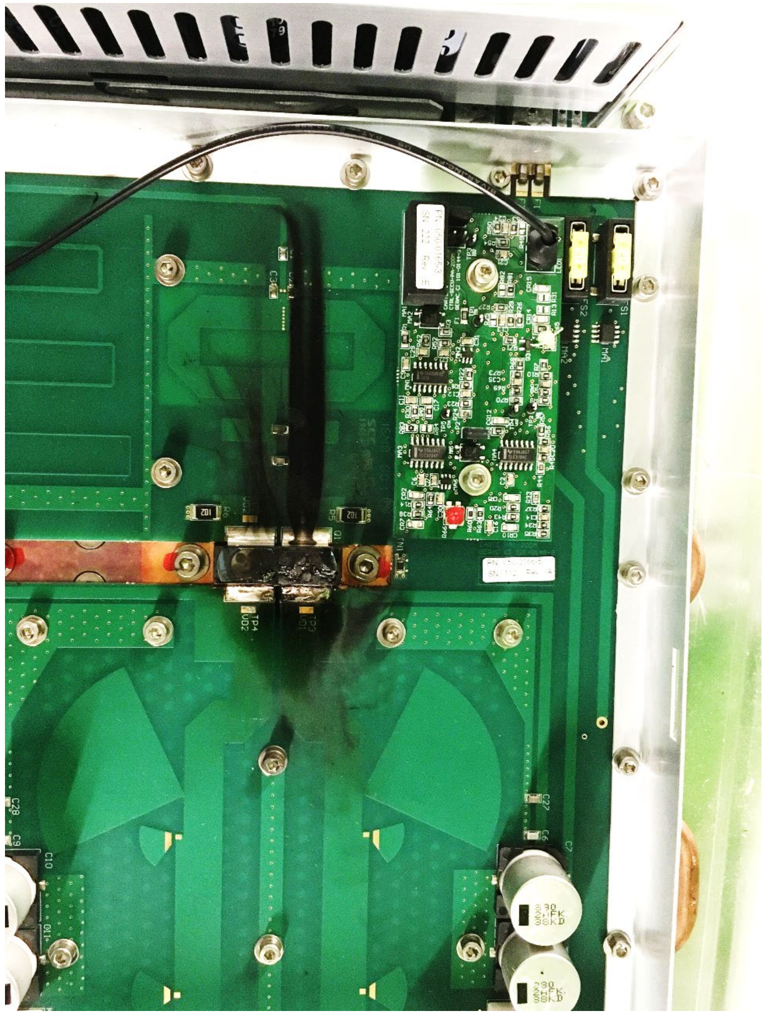
We then launched the long duration test

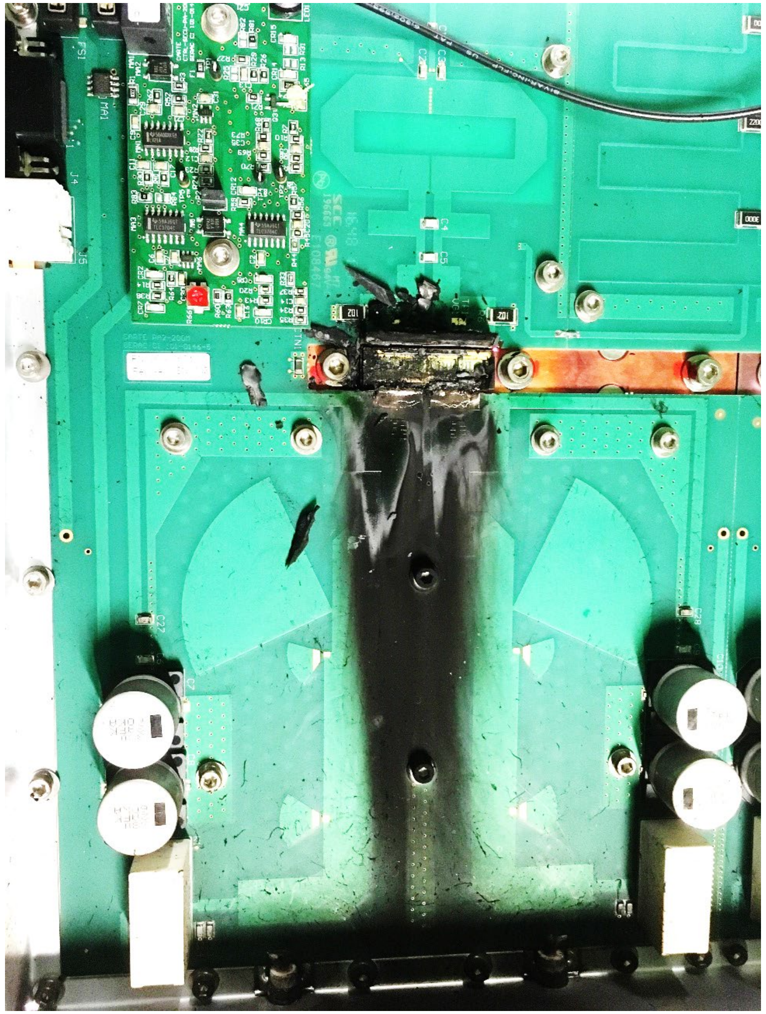
1000 hours was requested in the Technical Specifications (you will understand why I am always recommending to do so…)

During the first 700 hours, not a single trouble, then transistors started to brake one by one every 24 hours



TROUBLES WITH TRANSISTORS

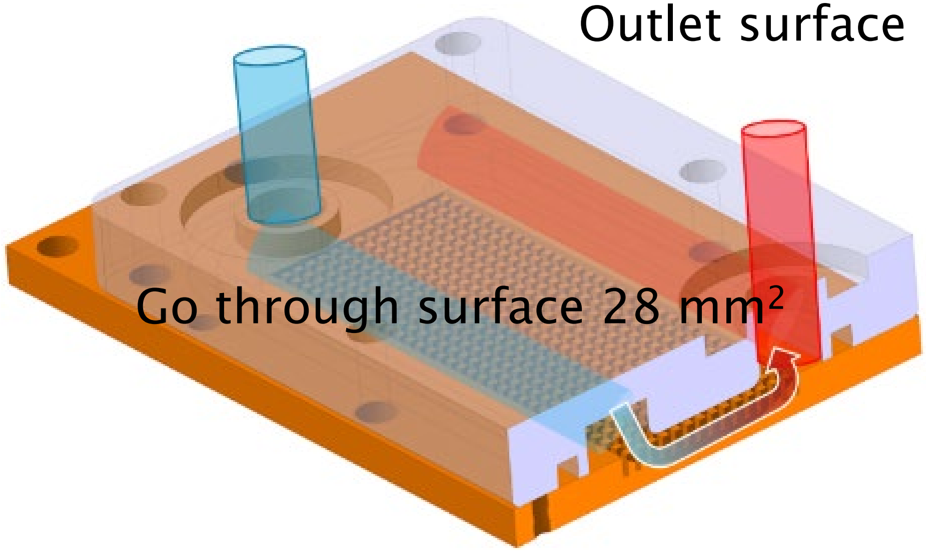




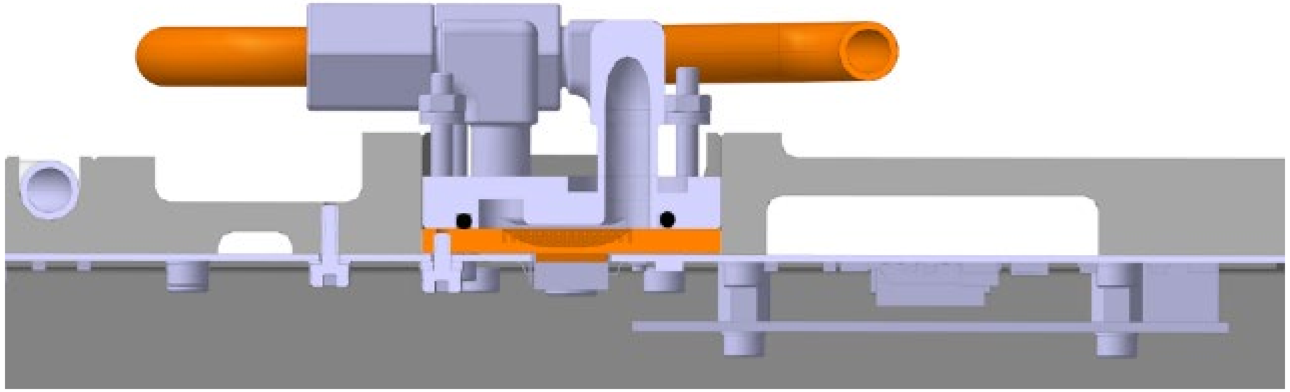
HEAT TRANSFER

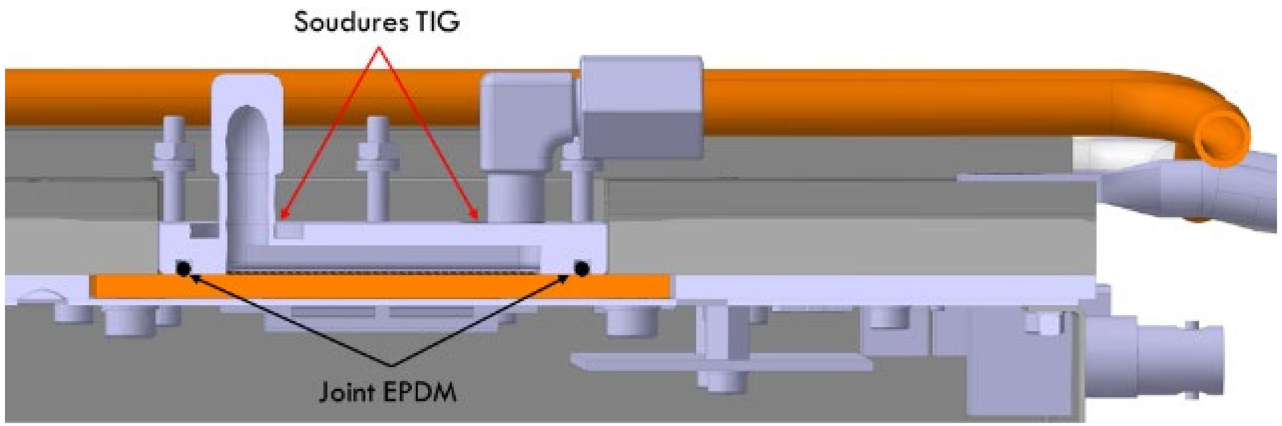
Inlet surface 28 mm²

Outlet surface 28 mm²



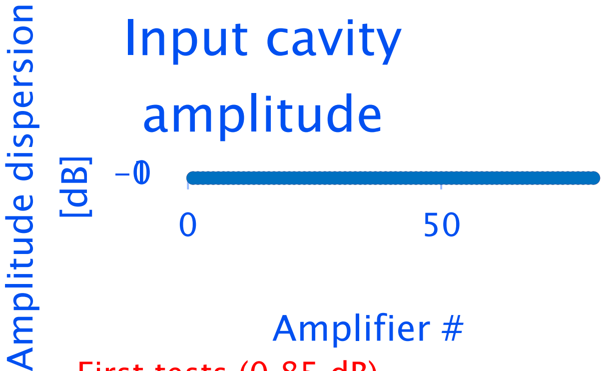
Go through surface 28 mm²



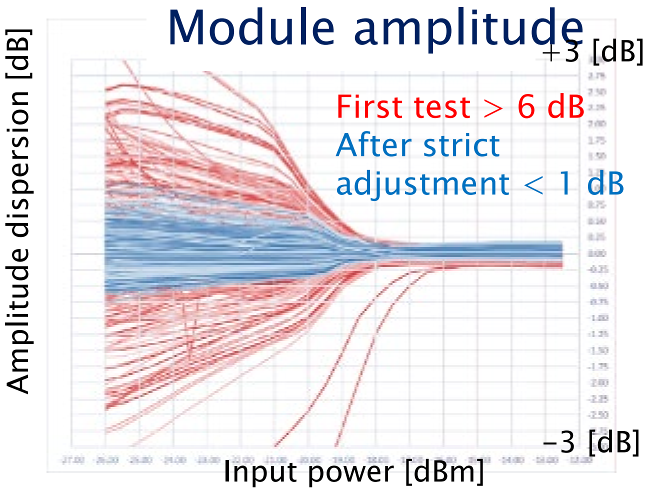


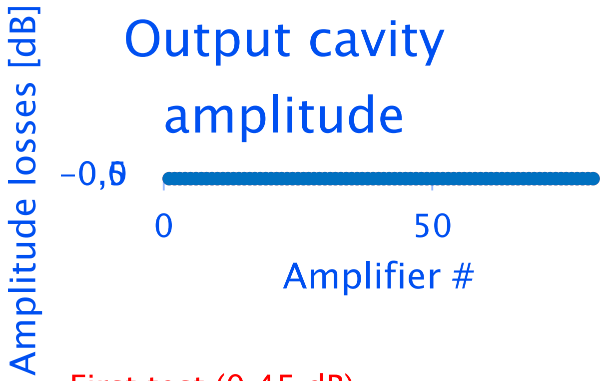
RF DISPERSION

First test	total amplitude	7.2 [dB]	total phase	51 [deg
After strict adjustment	total amplitude	1.7 [dB]	total phase	15

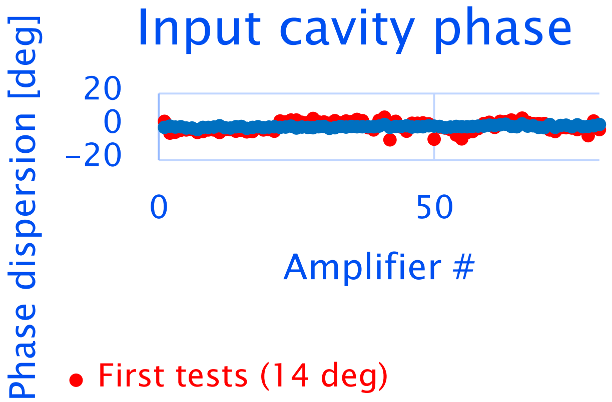


- First tests (0.85 dB)
- After strict adjustment (0.37 dB)

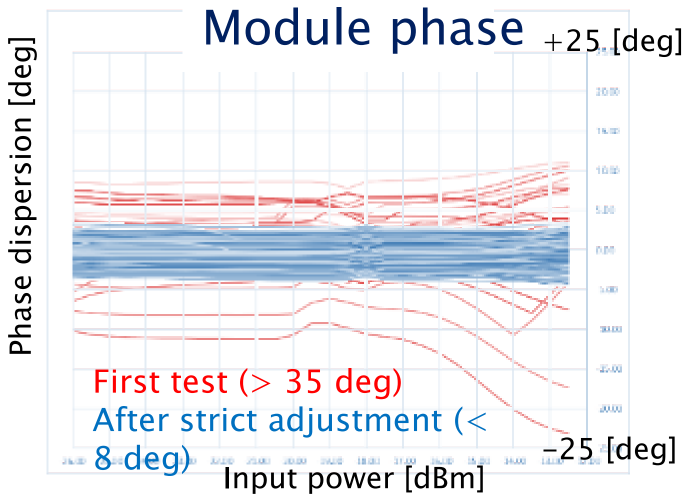


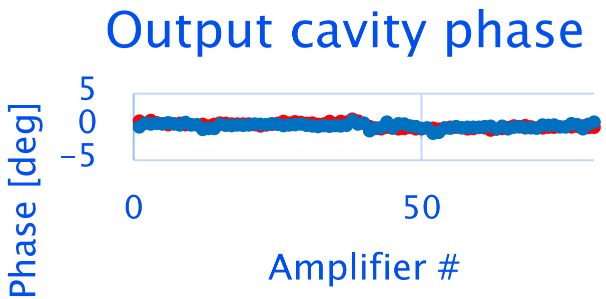


- First test (0.45 dB)
- After strict adjustment (0.33 dB)



- First tests (14 deg)
- After strict adjustment (4 deg)





- First test (2 deg)
- After strict adjustment (3 deg)

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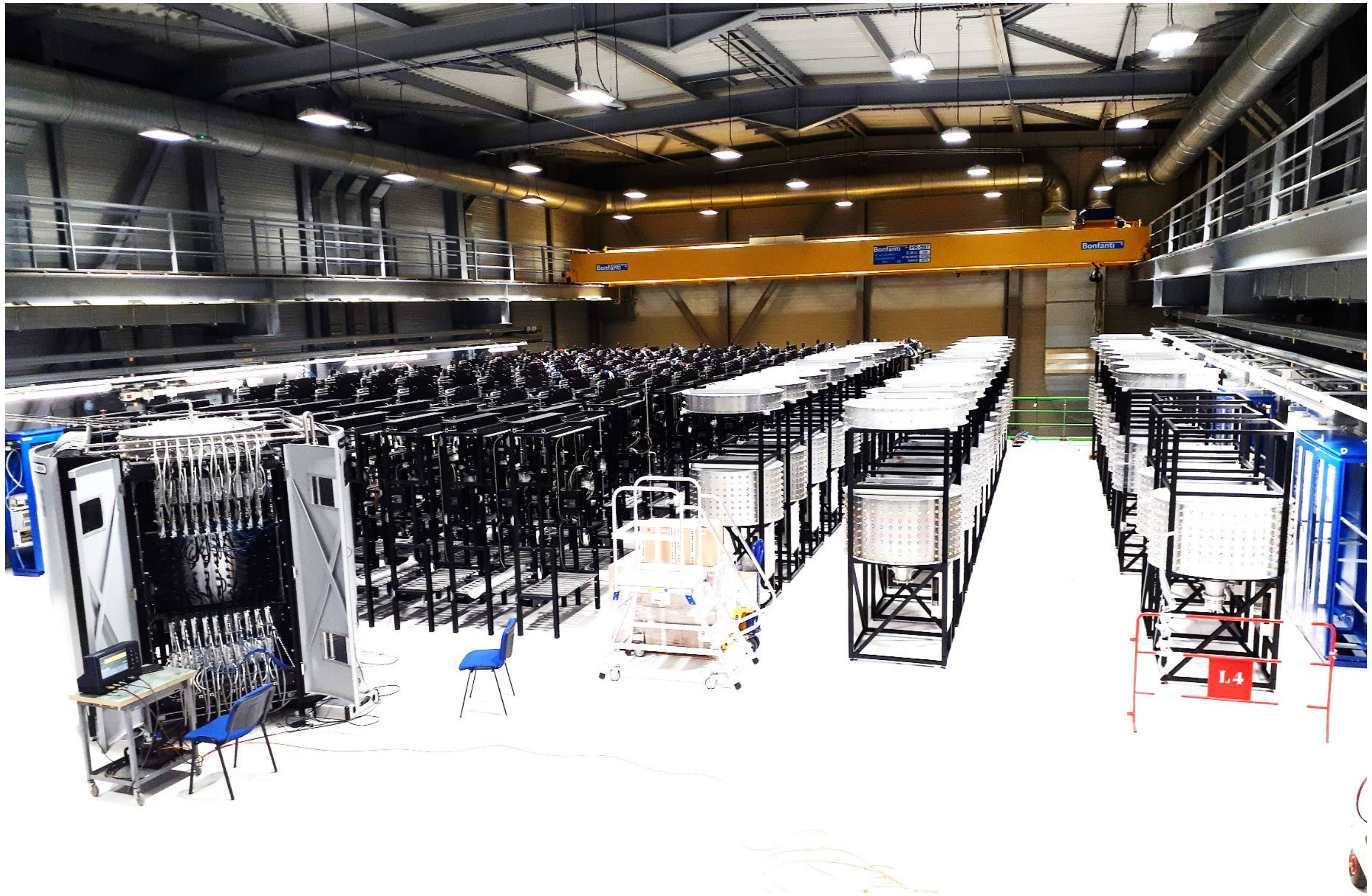
CERN & THALES NOT READY TO GIVE UP

Still the results were not correct

Despite all these difficulties, Thales top management agreed to continue to invest in the project (up to maximum twice the amount of the possible penalties)

To demonstrate it, they delivered all other items than the modules

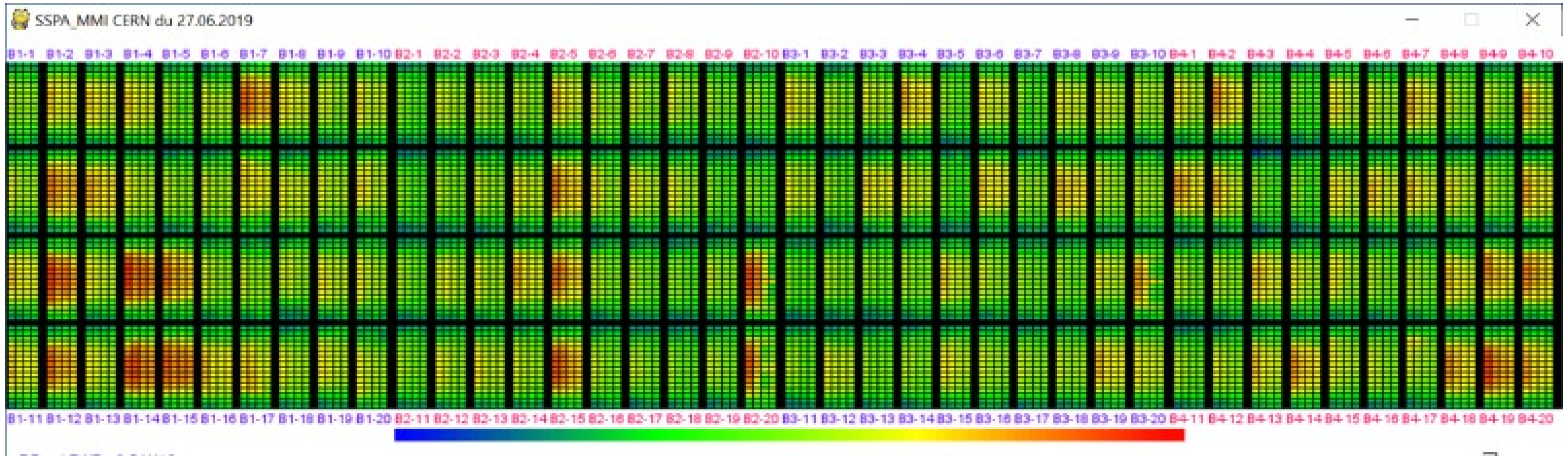
This was impressive, even for us

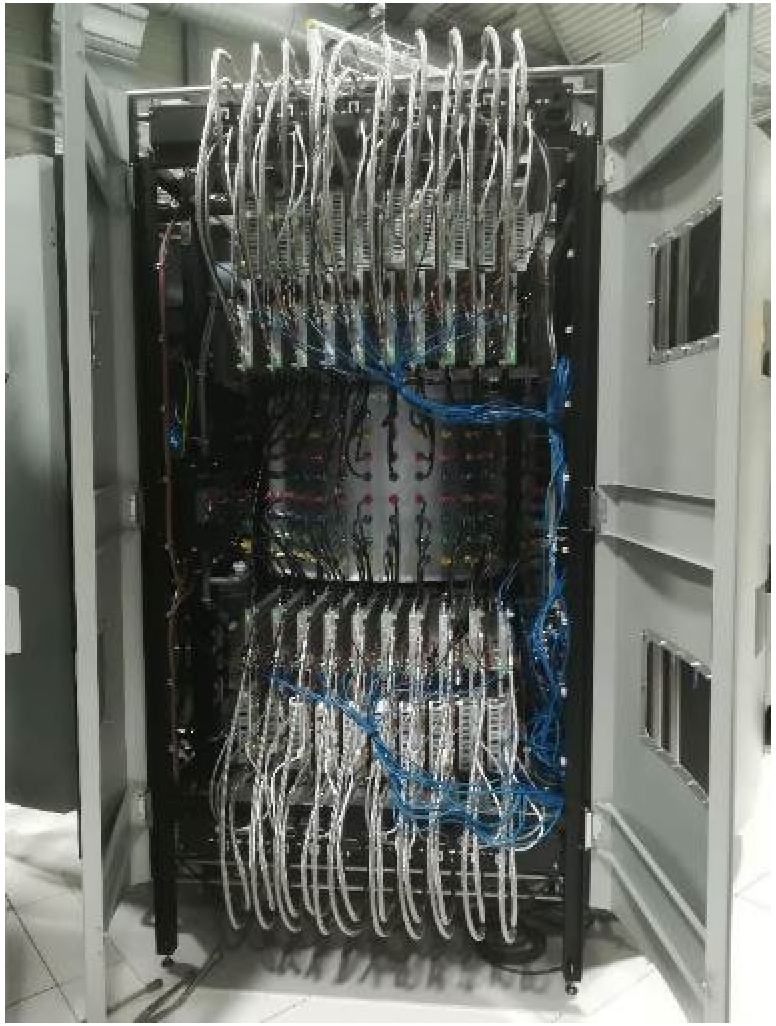


THERMAL CAMERAS ON TRANSISTORS

Patrick Goguillon from Thales had the brilliant idea to equip all covers with two thermal cameras each in order to observe the behavior of all the transistors

We were very surprised to discover a huge discrepancy in the way transistors were heating

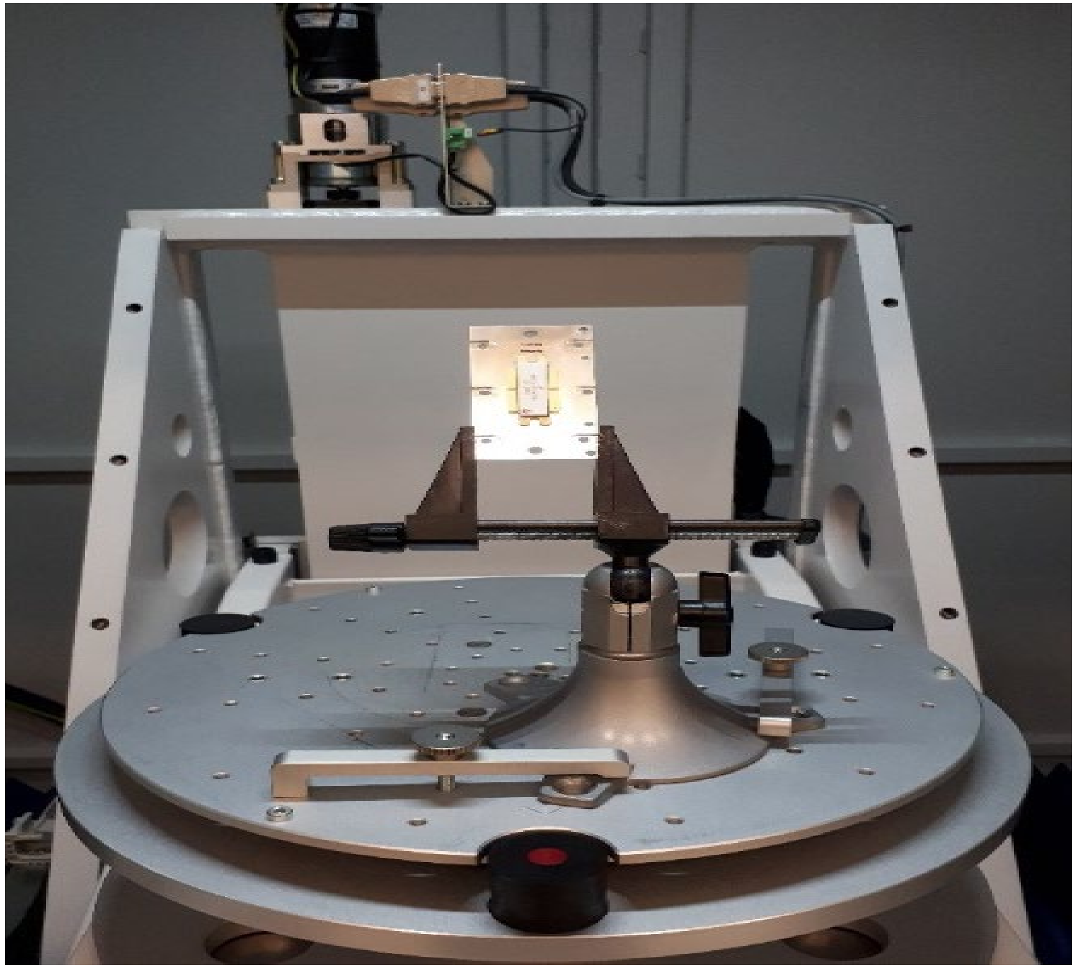




TOMOGRAPHY AT CERN

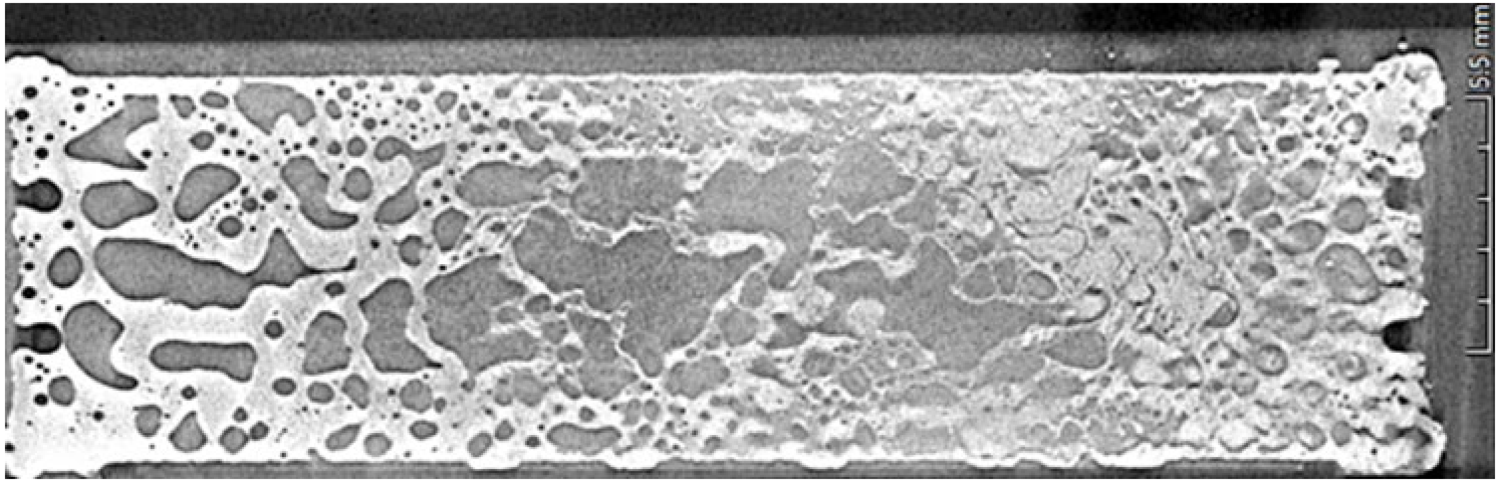
In order to understand the various default we had, we used micro tomography that metrology service at CERN uses for other purposes

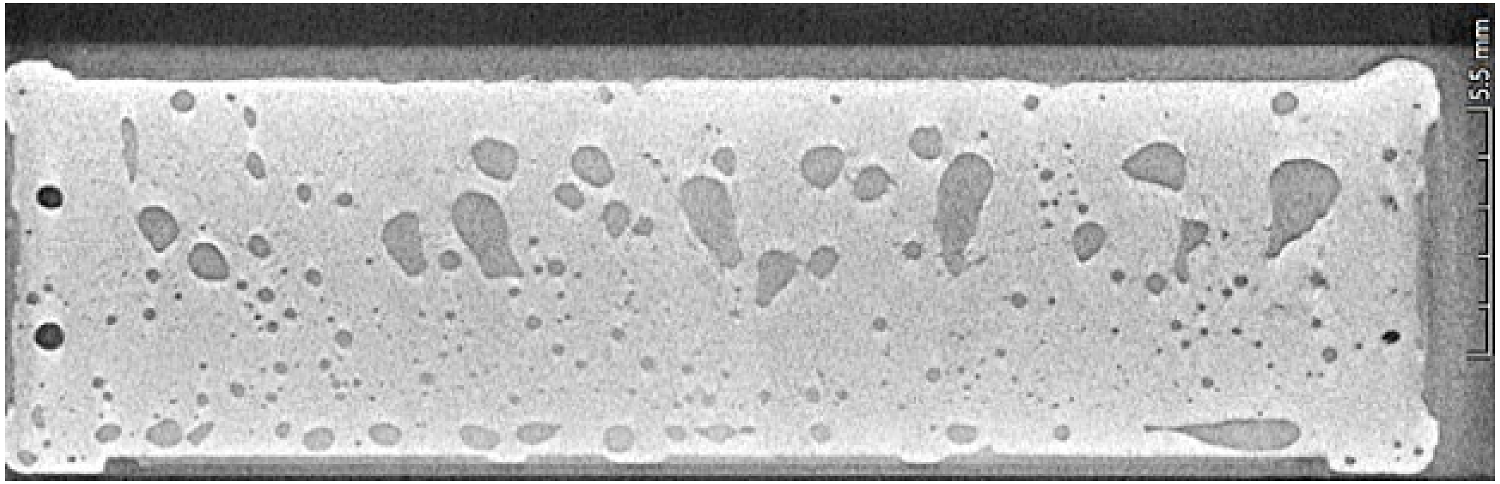
This was very useful in order to verify the way the transistors were brazed, and more over to define the best way to braze



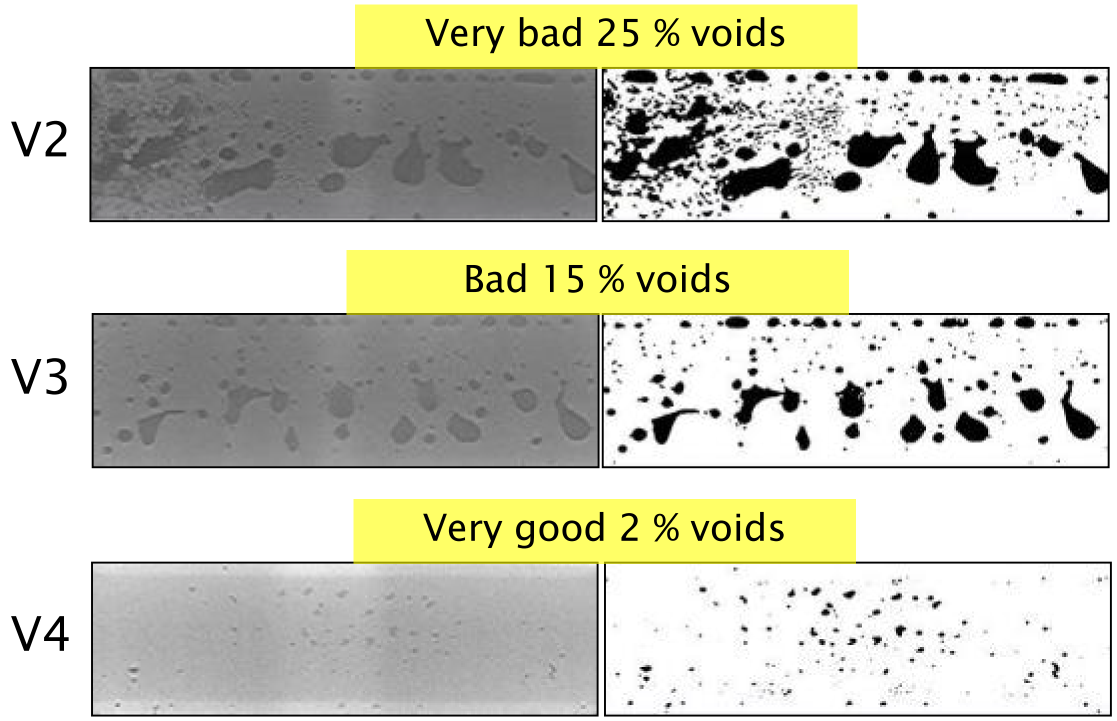
VOIDS

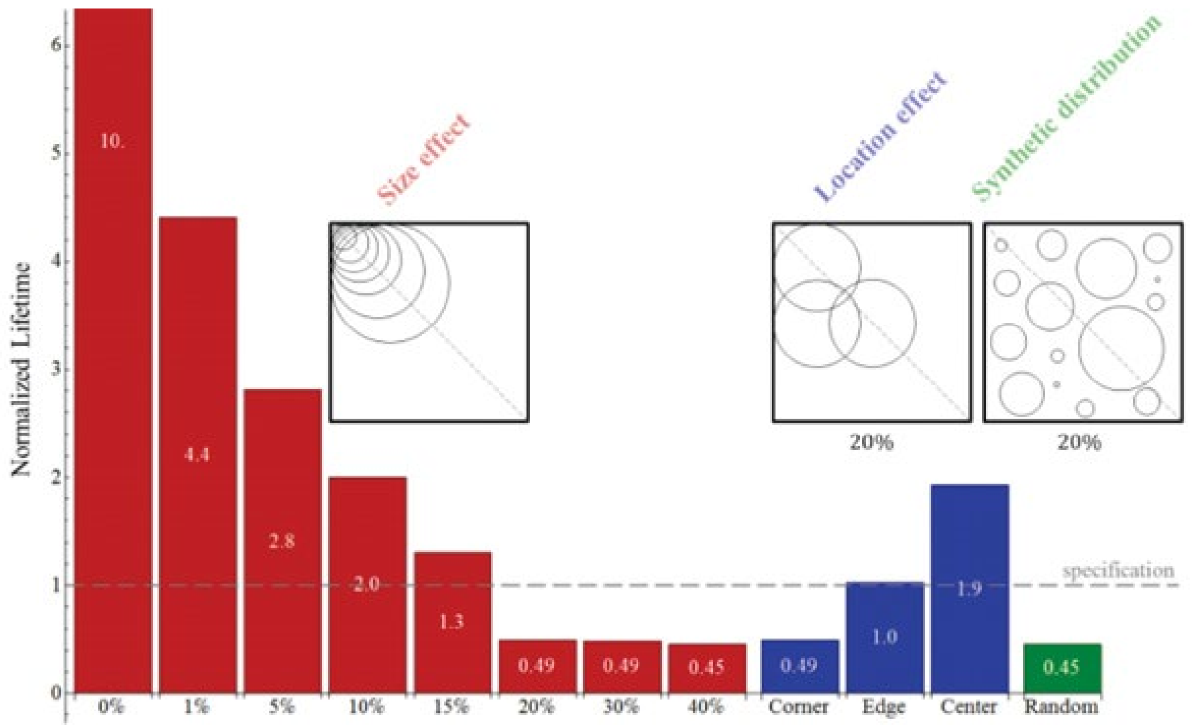
After quite some analysis, we were finally able to link that thermal effect to the way the transistors were brazed to their cold plate





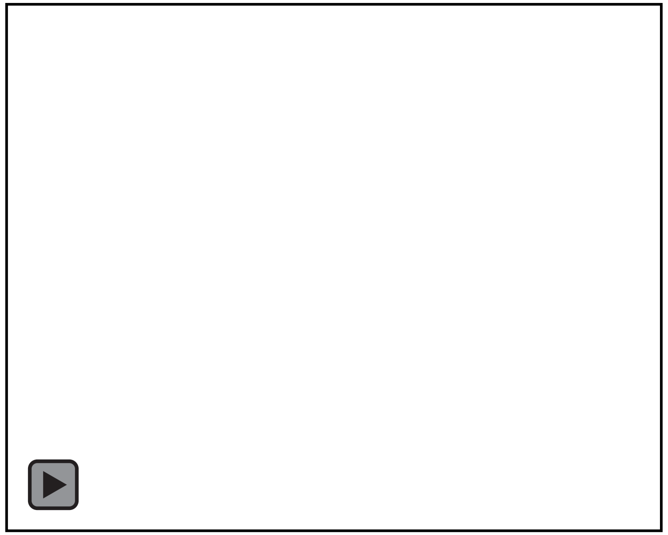
VERSION #4



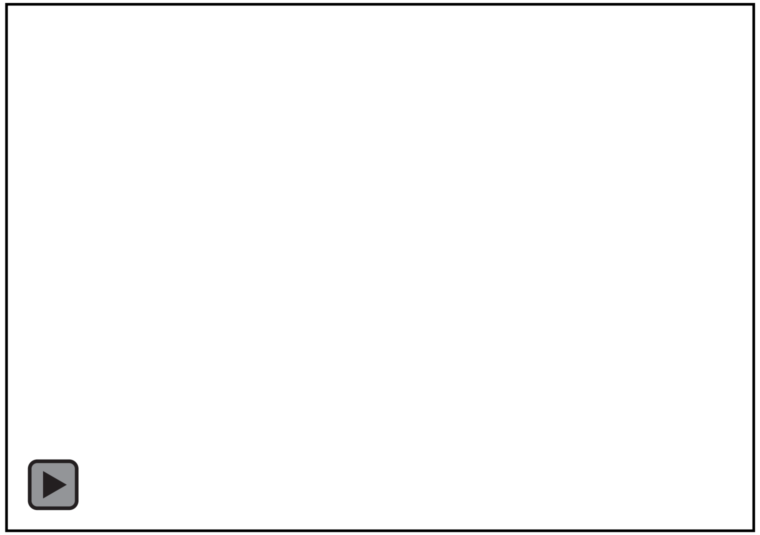


Thales developed a very specific way to proceed with the brazing, under vacuum, with a special deposition of the brazing pate, and a specific thermal ramp up and ramp down

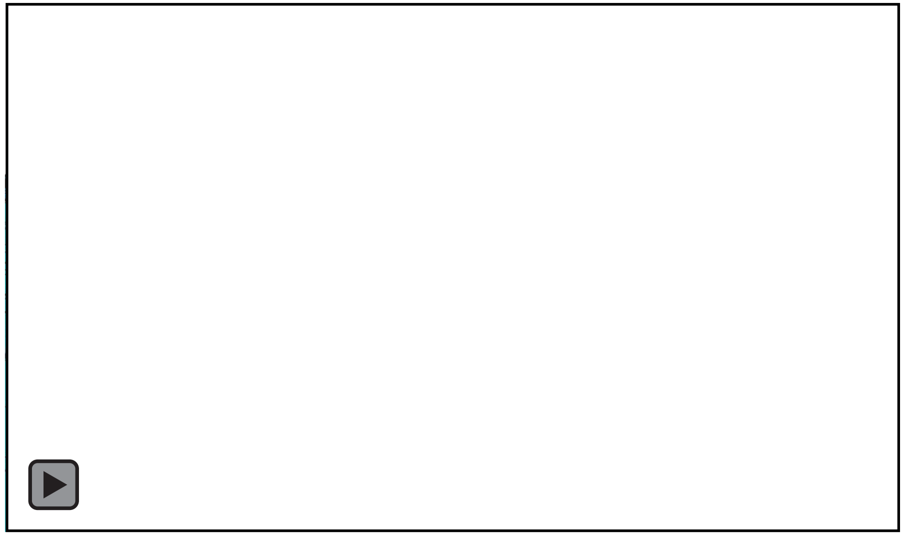
STRESS OF SPS CYCLE ON PCB & TRANSISTORS



V2



V3



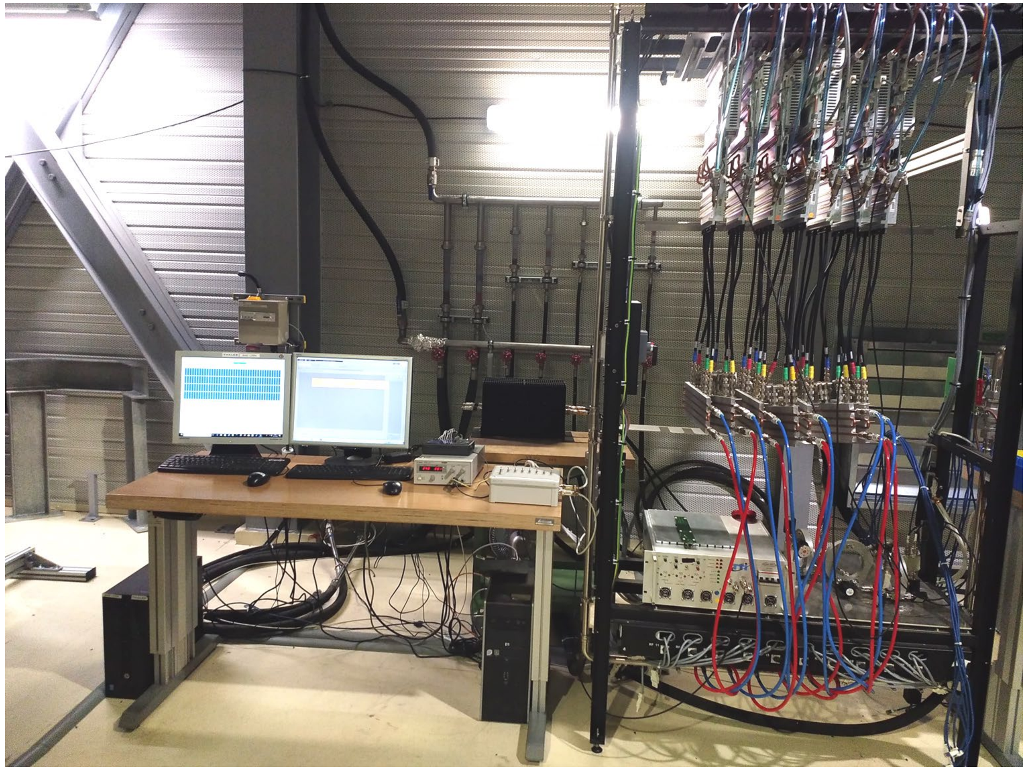
V4

AGEING ACCELERATING TEST BENCH

In order to verify our theories, we constructed a test bench with which we overstressed half of the modules, up to destruction and deduced lifetime of the transistors

It fitted perfectly with all our previous end of life of version V1/V2/V3

We then deduced the lifetime of V4



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LIFETIME THERMAL IMPROVEMENT

5 seconds ON / 5 seconds OFF cycle

V2+ (with 83 modules)

Nb cycles = 4E14*36^(-5) = 6.6E6

Tcase = 66

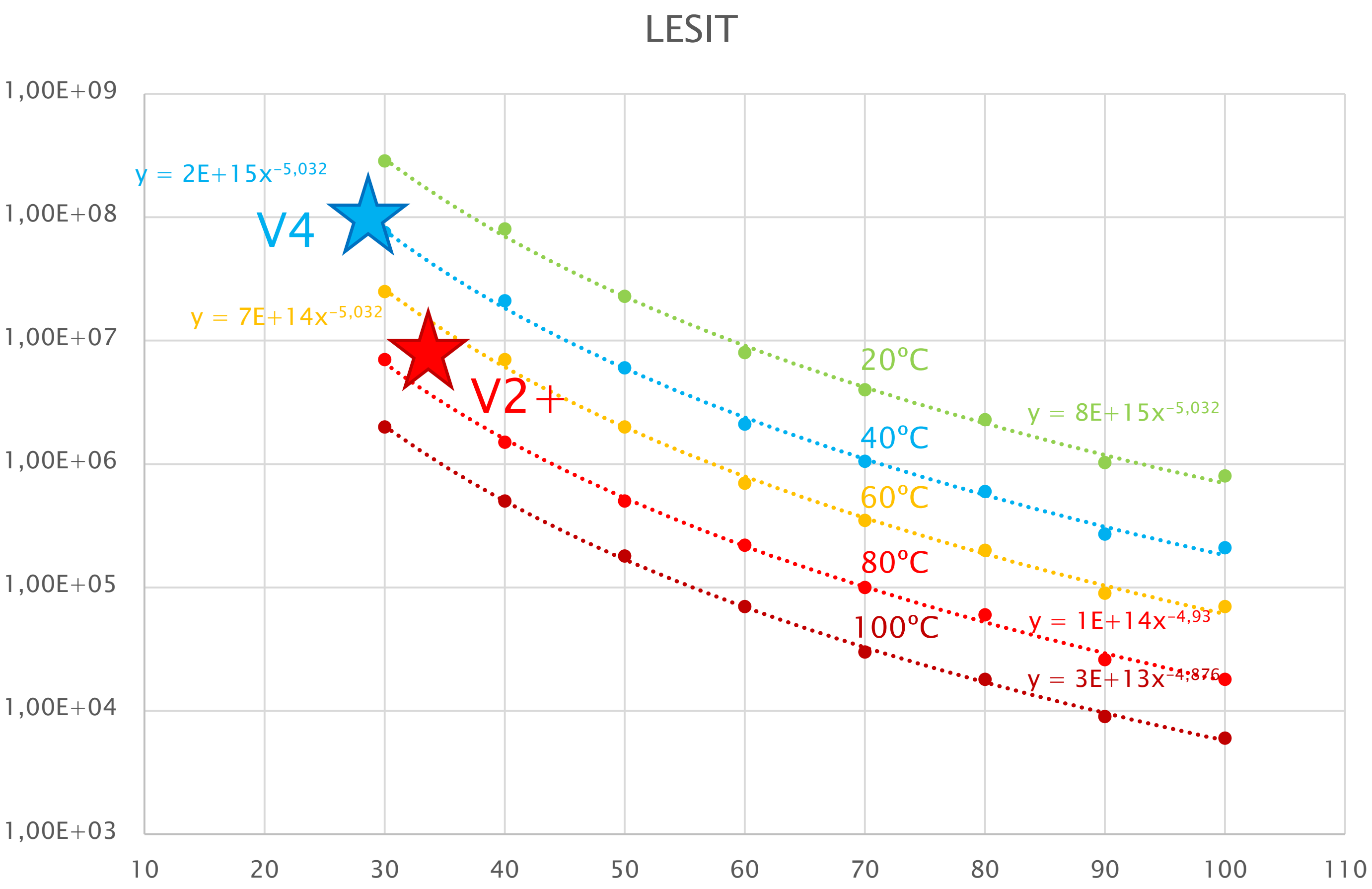
Delta T = 36

V4 (with 67 modules)

Nb cycles = 2E15*29^(-5) = 9.8E7

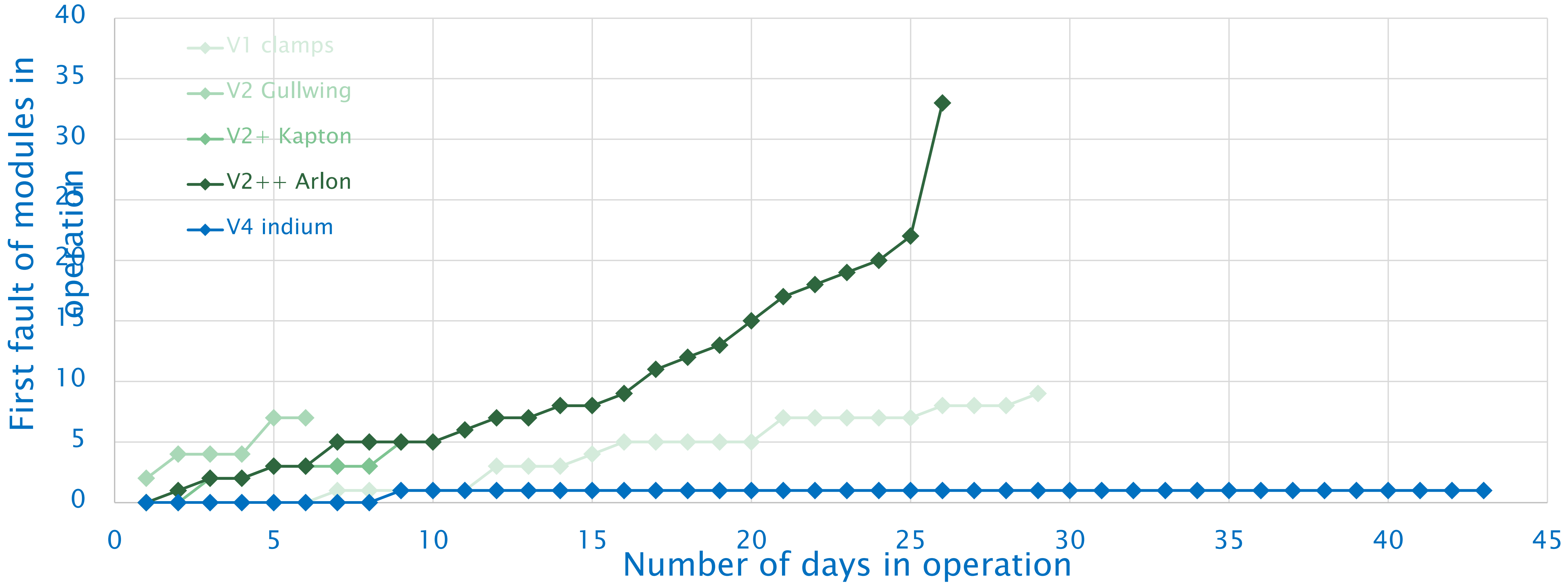
Tcase = 40

Delta T = 29

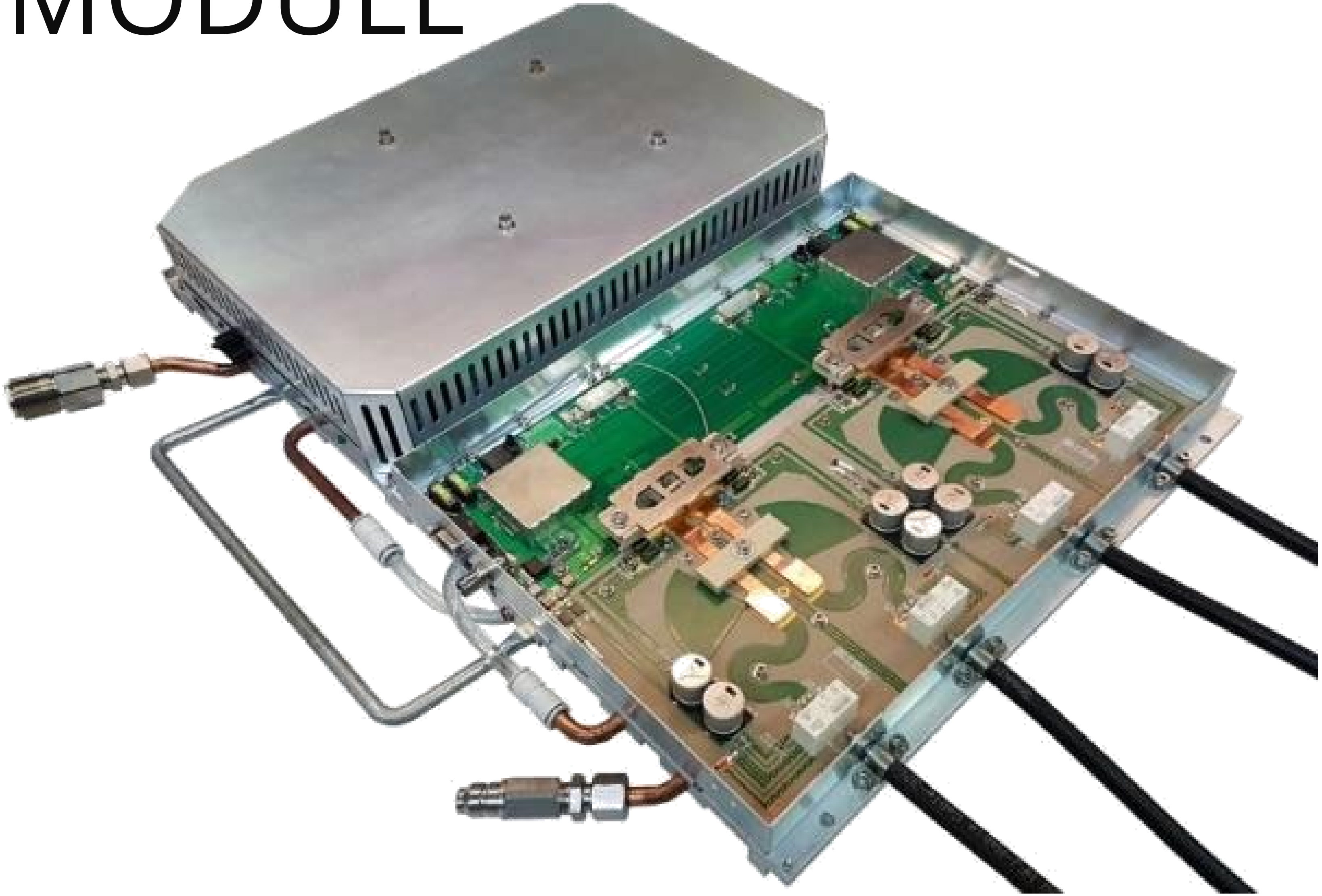


Improvement factor =8.2E7/7.5E6 = **15**

BROKEN MODULES DURING SUPERCYCLES ON DEMONSTRATOR



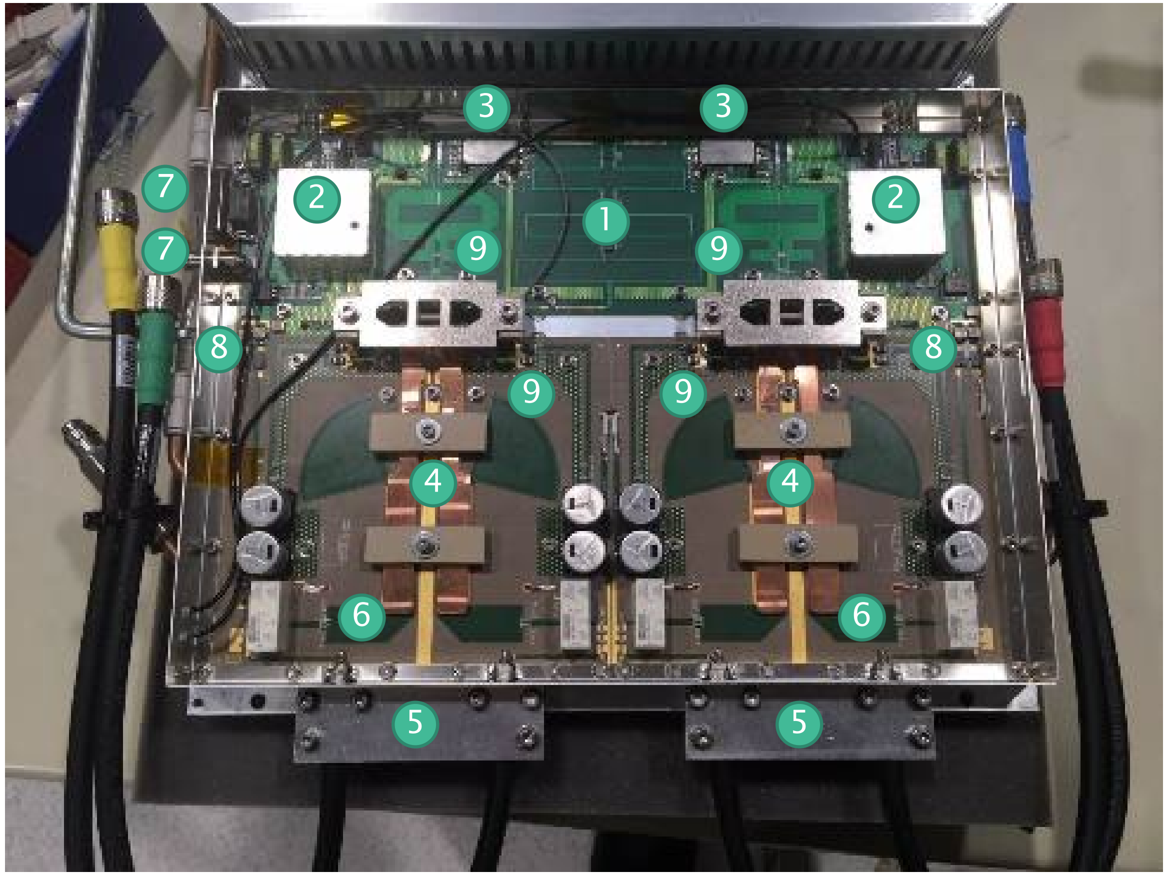
V4 MODULE



V4 MODULE IMPROVEMENTS

List of main improvements added to previous versions

1. New input divider with better balance
2. Control electronic in shielded box
3. Adjustment of gain and phase dispersion
4. Output tracks with thermal regulator
5. Mechanical support for output cables
6. Output DC blockers to allow circulators
7. Controls and RF connectors shielded
8. Drain voltage switched off in case of failure
9. Gate and Drain oscillation filtering with serial and parallel filters, and damping material
10. New water cooling system under the transistors
11. Brazing of transistors to their cold boxes



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SERIES PRODUCTION

Before Series production, we defined strict Acceptance Test Plans (ATP) and Acceptance Test Reports (ATR)

All tower devices have already been tested (3000 RF cables + 12'800 RF connectors + 190'000 contacts in controls connectors)

All input and output cavities are ok

Tower (x35)

- Input cavity
- Output cavity
- Bays (x4)
- Hydraulic
- Electrical distribution
- VBF (Vérification de bon fonctionnement)
- Temperature
- Bandwidth
- Linearity
- Harmonics
- Supercycle test 100 hours

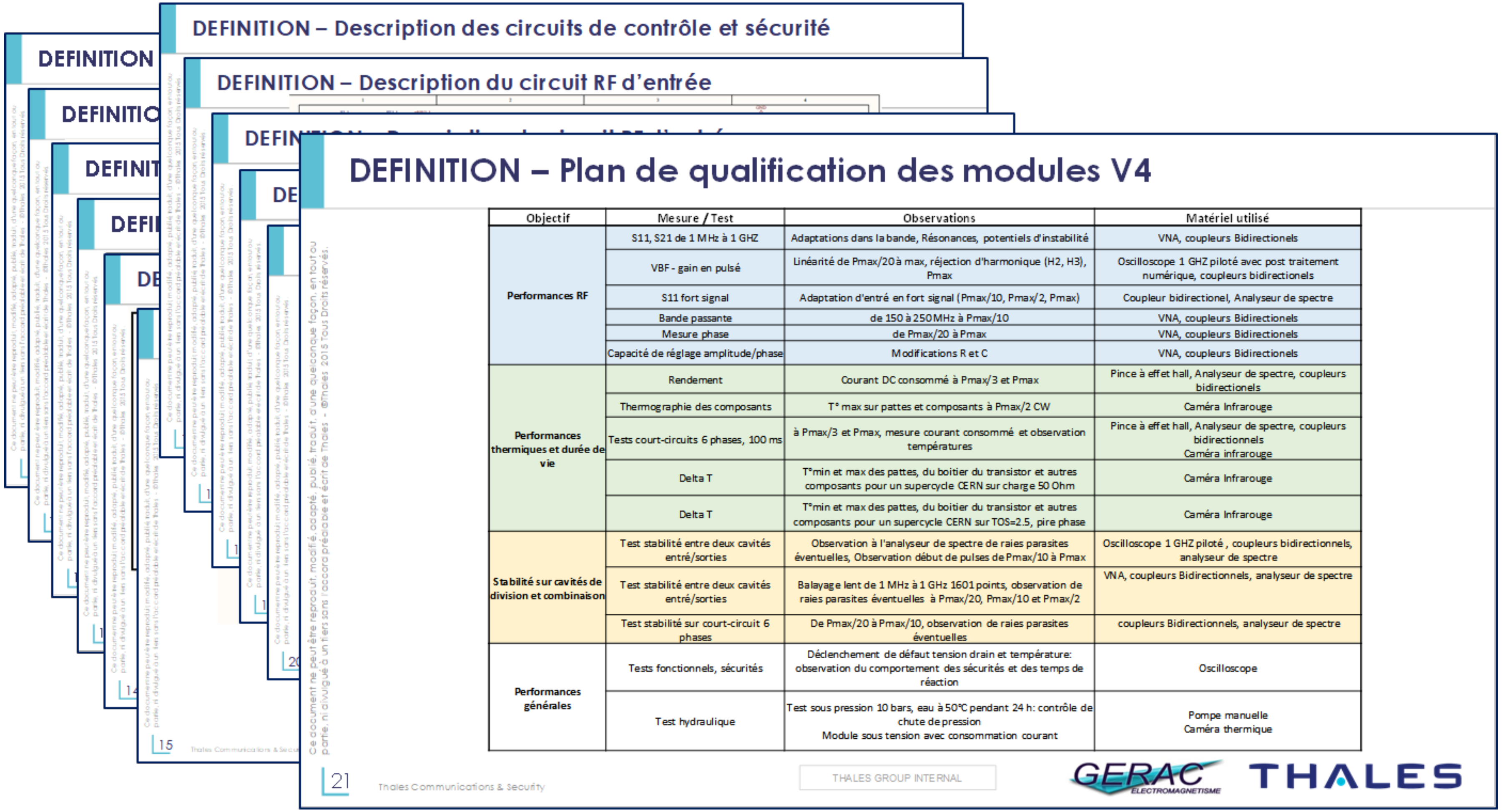
Module (3'000)

- Input Card
- Output Card
- Transistor on its heat sink (Ultra Sonic tomography sampling 100 % first batches than 2 %)
- Power supply
- Module
- Phase/Gain repeated at CERN (all checked by us, no sampling)

All modules had been tested one by one (by us) once delivered at CERN before being assembled in towers

In total this will be more than 15'000 test reports that had been produced

QUALITY CONTROL

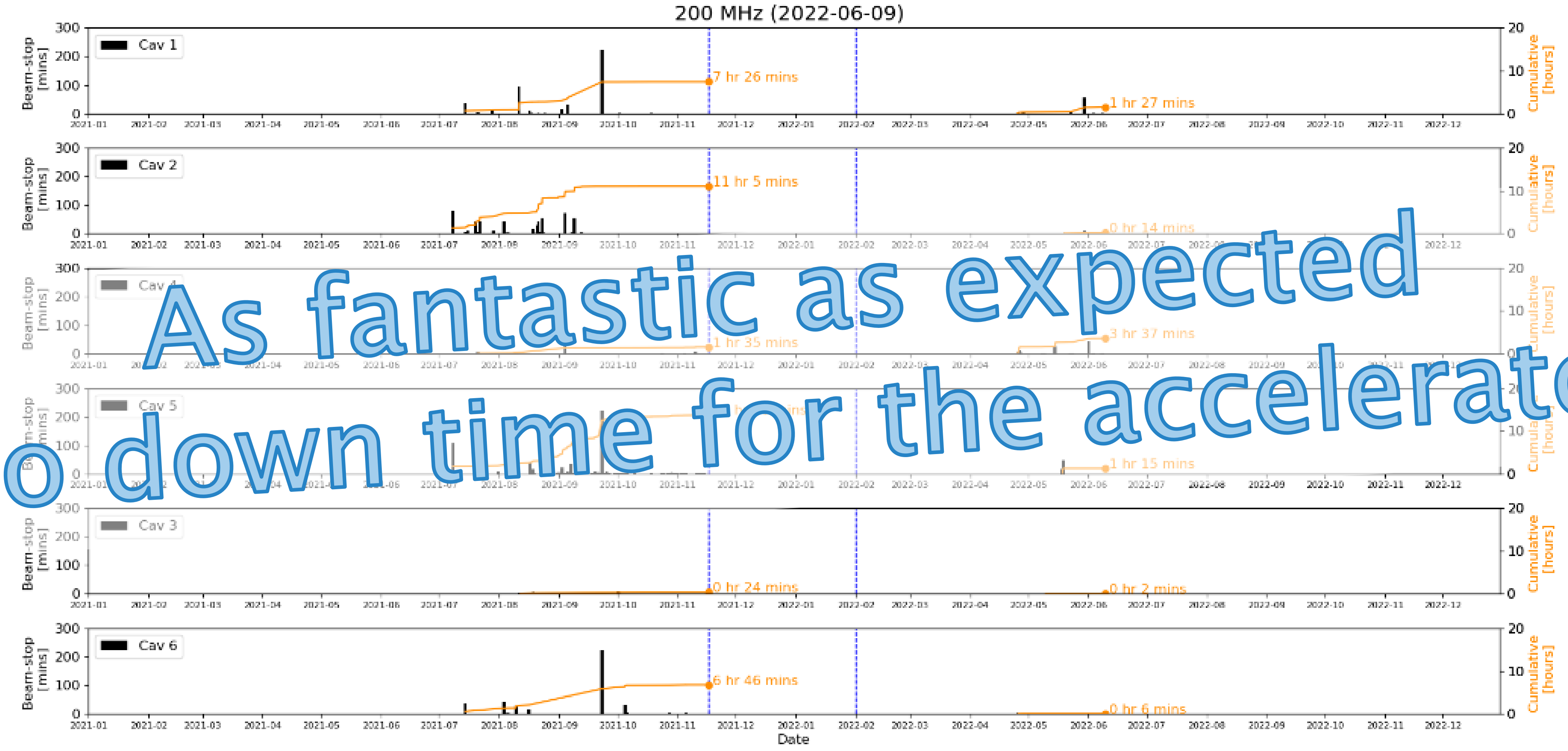


Objectif	Mesure / Test	Observations	Matériel utilisé
Performances RF	S11, S21 de 1 MHz à 1 GHZ	Adaptations dans la bande, Résonances, potentiels d'instabilité	VNA, coupleurs Bidirectionels
	VBF - gain en pulsé	Linéarité de Pmax/20 à max, réjection d'harmonique (H2, H3), Pmax	Oscilloscope 1 GHZ piloté avec post traitement numérique, coupleurs bidirectionels
	S11 fort signal	Adaptation d'entré en fort signal (Pmax/10, Pmax/2, Pmax)	Coupleur bidirectionel, Analyseur de spectre
	Bande passante	de 150 à 250 MHz à Pmax/10	VNA, coupleurs Bidirectionels
	Mesure phase	de Pmax/20 à Pmax	VNA, coupleurs Bidirectionels
	Capacité de réglage amplitude/phase	Modifications R et C	VNA, coupleurs Bidirectionels
Performances thermiques et durée de vie	Rendement	Courant DC consommé à Pmax/3 et Pmax	Pince à effet hall, Analyseur de spectre, coupleurs bidirectionels
	Thermographie des composants	T° max sur pattes et composants à Pmax/2 CW	Caméra Infrarouge
	Tests court-circuits 6 phases, 100 ms	à Pmax/3 et Pmax, mesure courant consommé et observation températures	Pince à effet hall, Analyseur de spectre, coupleurs bidirectionnels Caméra infrarouge
	Delta T	T°min et max des pattes, du boitier du transistor et autres composants pour un supercycle CERN sur charge 50 Ohm	Caméra Infrarouge
	Delta T	T°min et max des pattes, du boitier du transistor et autres composants pour un supercycle CERN sur TOS=2.5, pire phase	Caméra Infrarouge
Stabilité sur cavités de division et combinaison	Test stabilité entre deux cavités entré/sorties	Observation à l'analyseur de spectre de raies parasites éventuelles, Observation début de pulses de Pmax/10 à Pmax	Oscilloscope 1 GHZ piloté , coupleurs bidirectionnels, analyseur de spectre
	Test stabilité entre deux cavités entré/sorties	Balayage lent de 1 MHz à 1 GHz 1601 points, observation de raies parasites éventuelles à Pmax/20, Pmax/10 et Pmax/2	VNA, coupleurs Bidirectionnels, analyseur de spectre
	Test stabilité sur court-circuit 6 phases	De Pmax/20 à Pmax/10, observation de raies parasites éventuelles	coupleurs Bidirectionnels, analyseur de spectre
Performances générales	Tests fonctionnels, sécurités	Déclenchement de défaut tension drain et température: observation du comportement des sécurités et des temps de réaction	Oscilloscope
	Test hydraulique	Test sous pression 10 bars, eau à 50°C pendant 24 h: contrôle de chute de pression Module sous tension avec consommation courant	Pompe manuelle Caméra thermique

GERAC ELECTROMAGNETISME THALES

DELIVERY OF MODULES

AVAILABILITY SINCE BEGINNING 2021



As fantastic as expected

No down time for the accelerator

DEMONSTRATED AVAILABILITY

We operated the system all along 2021

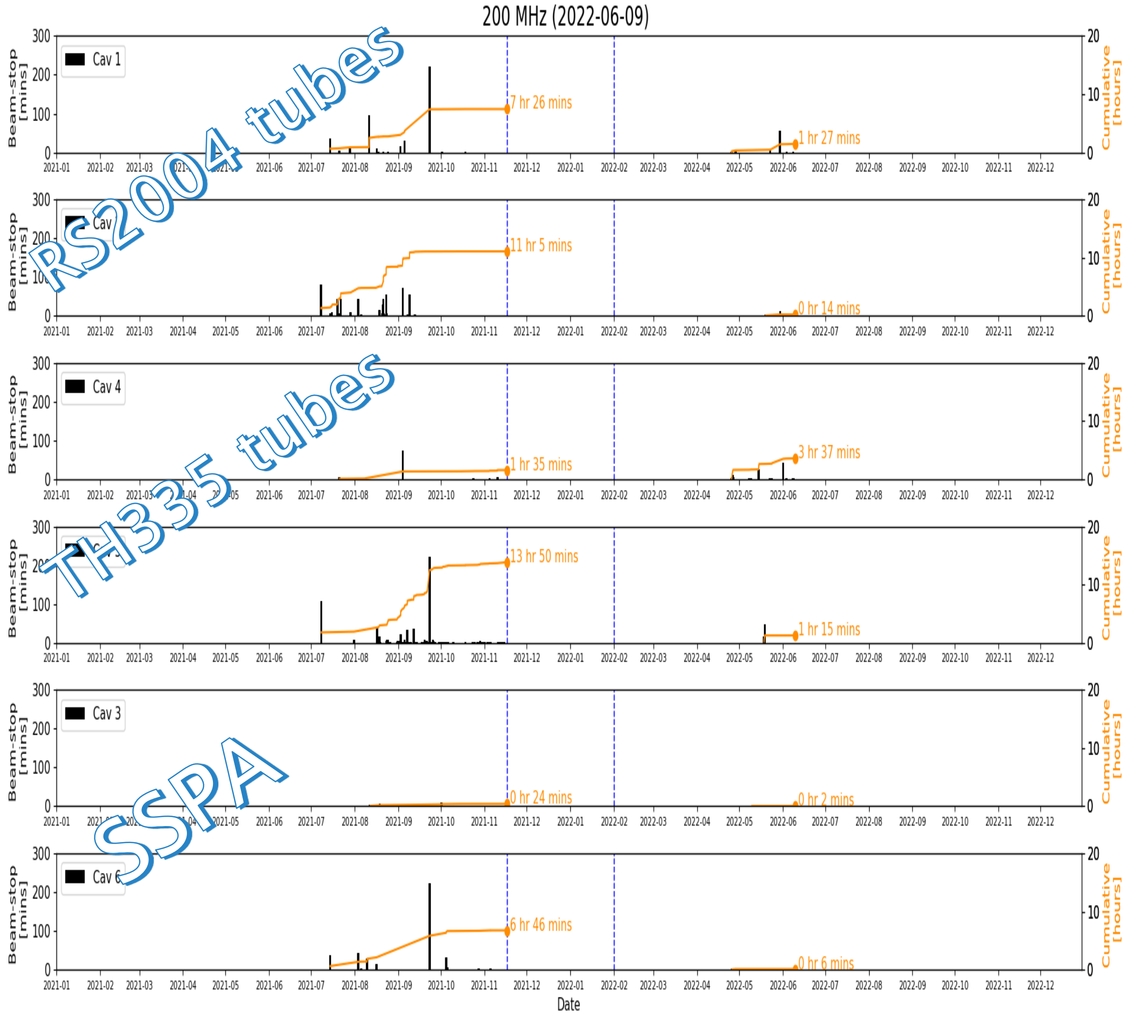
When tubes were the reason for beam interruption of

- 1.5 hours (99.98 % availability)
- 7.5 hours (99,9 % availability)
- 11 hours (99,84 % availability)
- 14 hours (99,8 % availability)

SSPA were stopping the beam for

- 0.5 hour (99,99 % availability)
- 6.5 hours (99,91 % availability)

This year, after we solved some initial youngness troubles, they seem to be 'invisible', and we are reaching our target of 99,99 % availability (8 minutes total / 2'000 hours)



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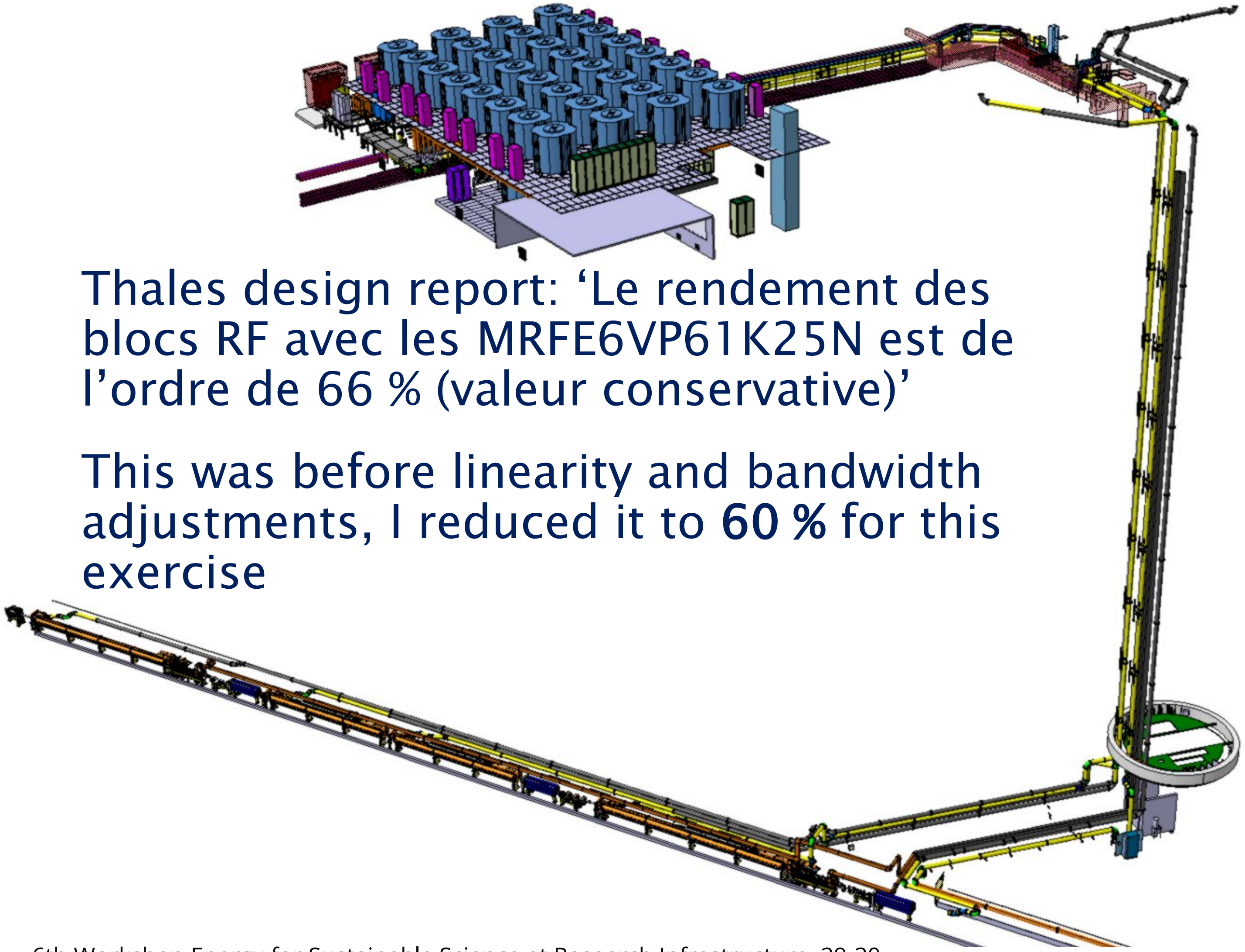
OUTLOOK

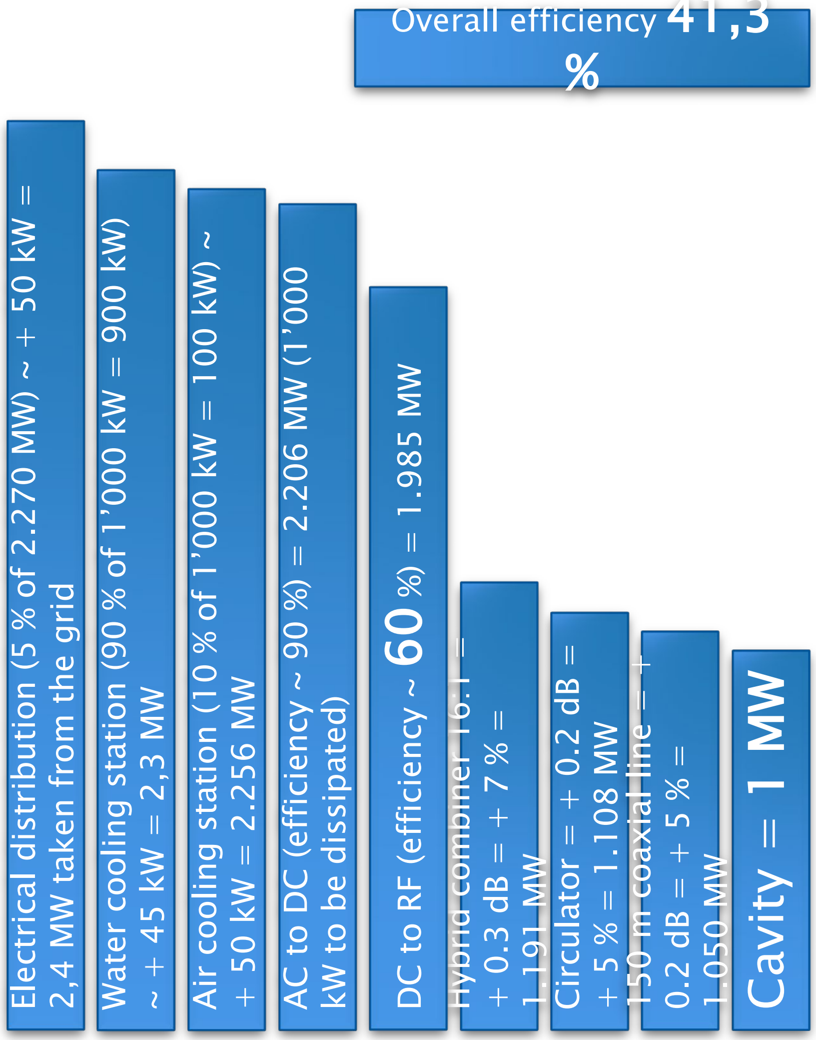
1. Brief description of the RF power upgrade project
2. Technical choices (and difficulties)
3. How to improve efficiency?

EFFICIENCY



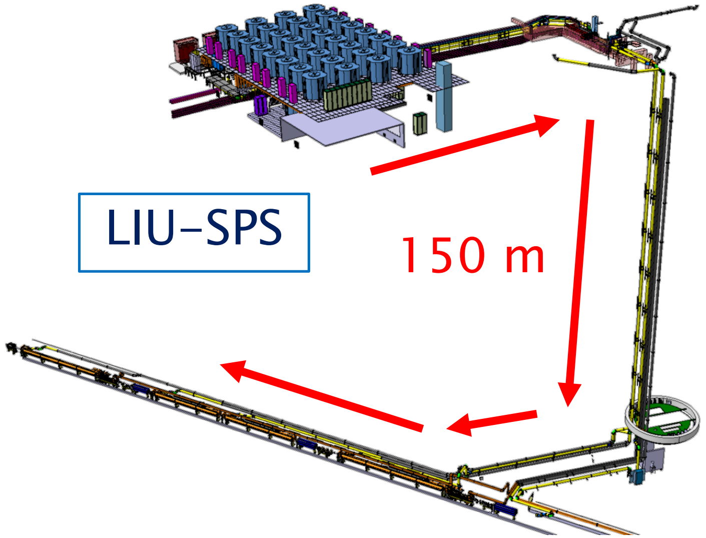
Thales design report: ‘Le rendement des blocs RF avec les MRFE6VP61K25N est de l’ordre de 66 % (valeur conservative)’

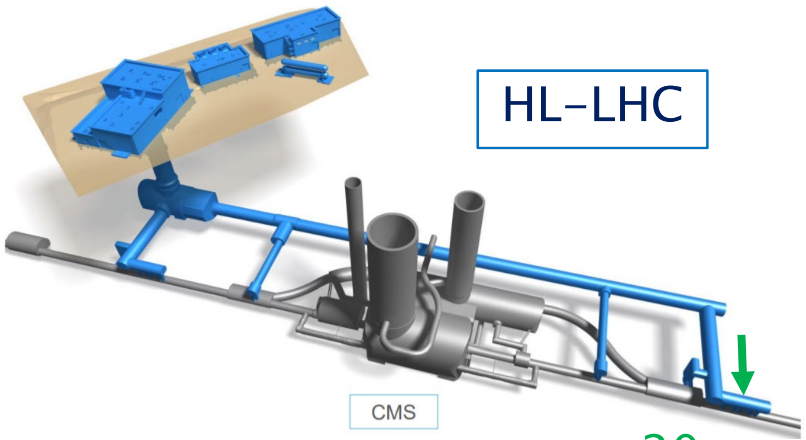
This was before linearity and bandwidth adjustments, I reduced it to **60 %** for this exercise

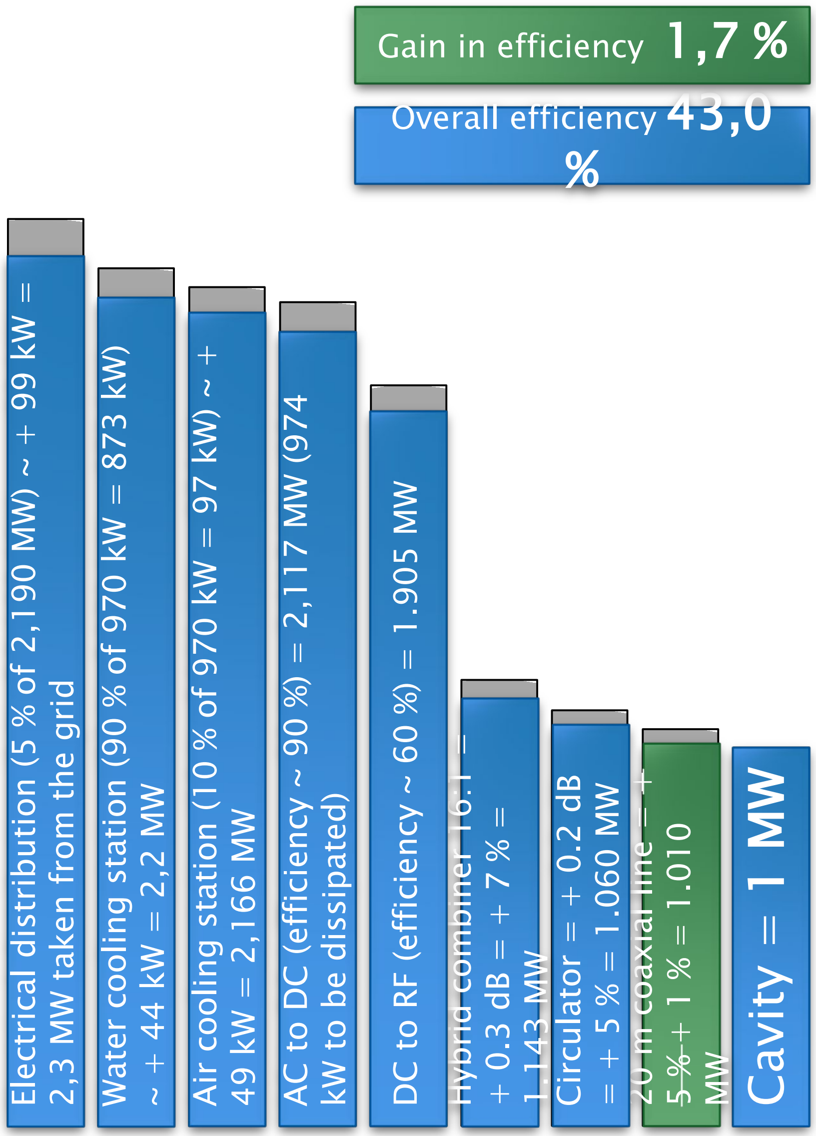


DISTANCE FROM AMPLIFIER TO CAVITY

Having the amplifiers very close to the cavity will reduce all other losses
A gallery is very expensive as an acquisition cost, but can help to reduce the acquisition cost of the transmission lines and to reduce the cost of operation

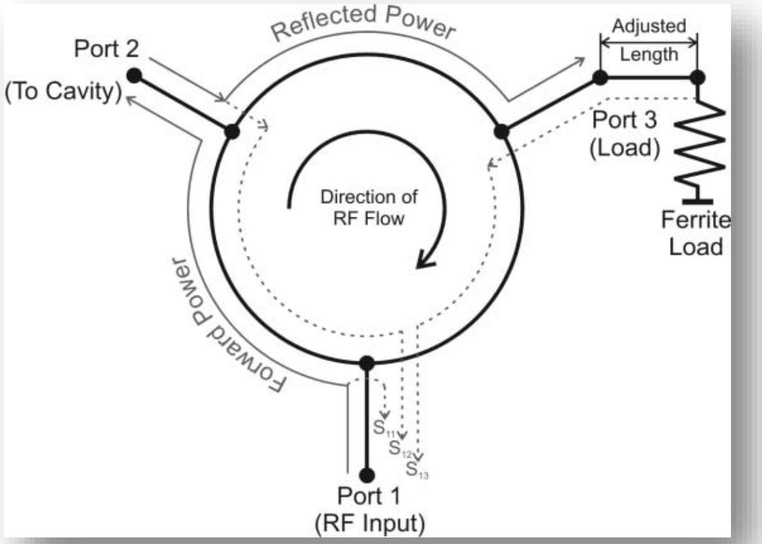


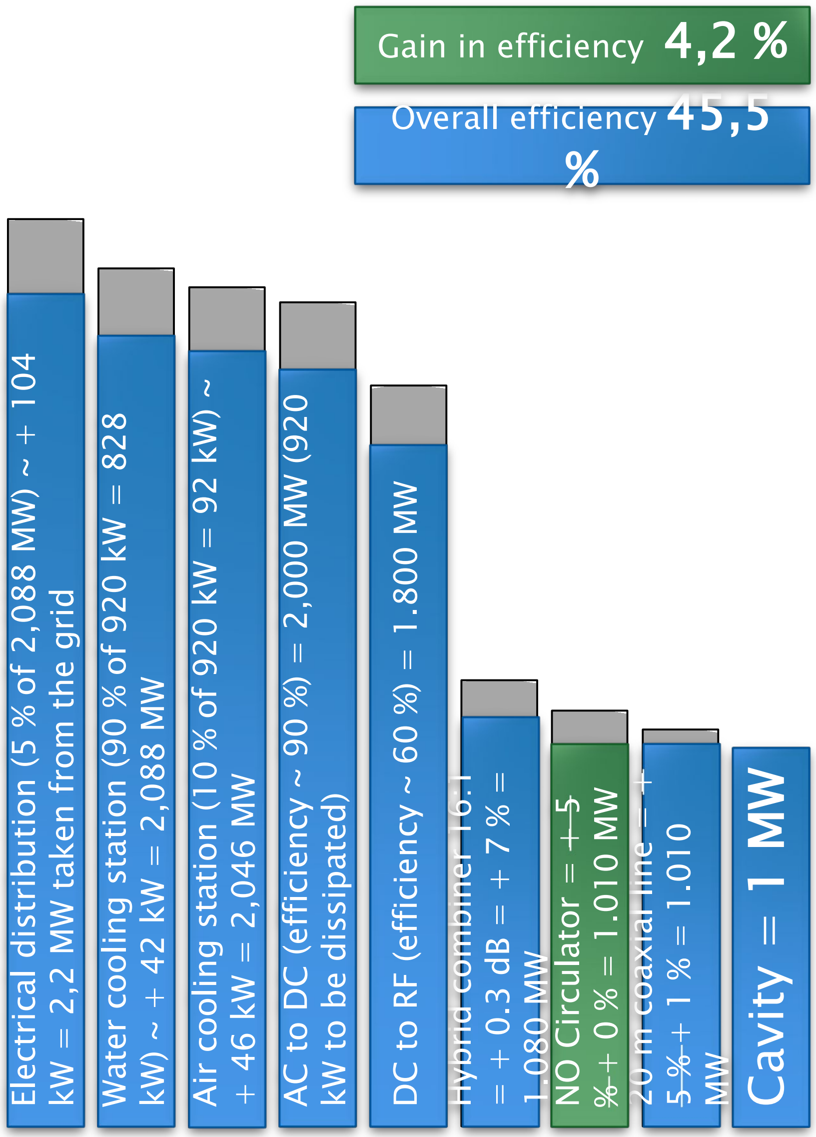




CIRCULATOR FREE

As we demonstrated it with the SPS project, we are now able to build SSPA **without** circulator (Tetrodes and IOT can also do it)
To do so, we need a very good protection system



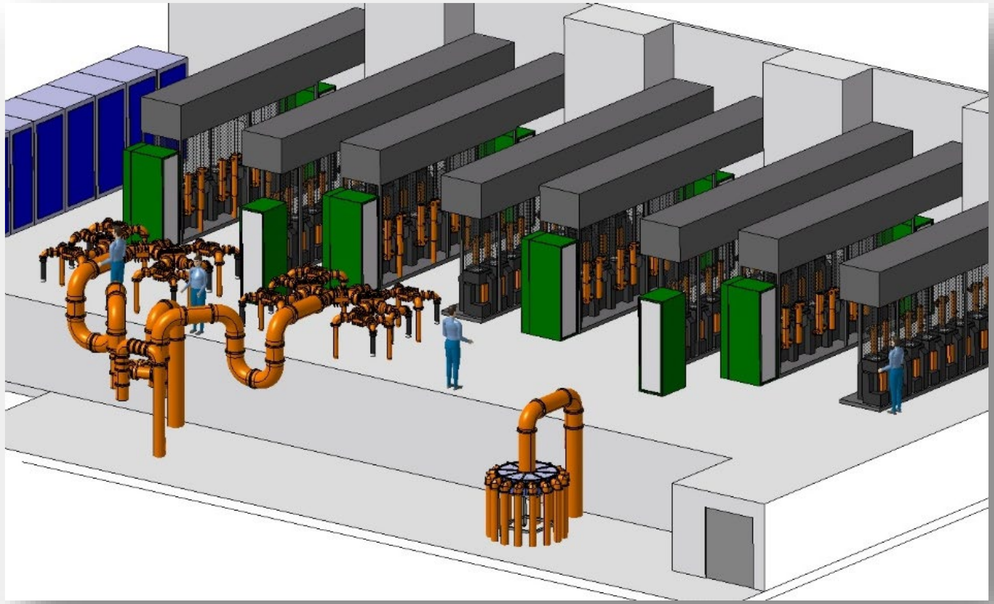


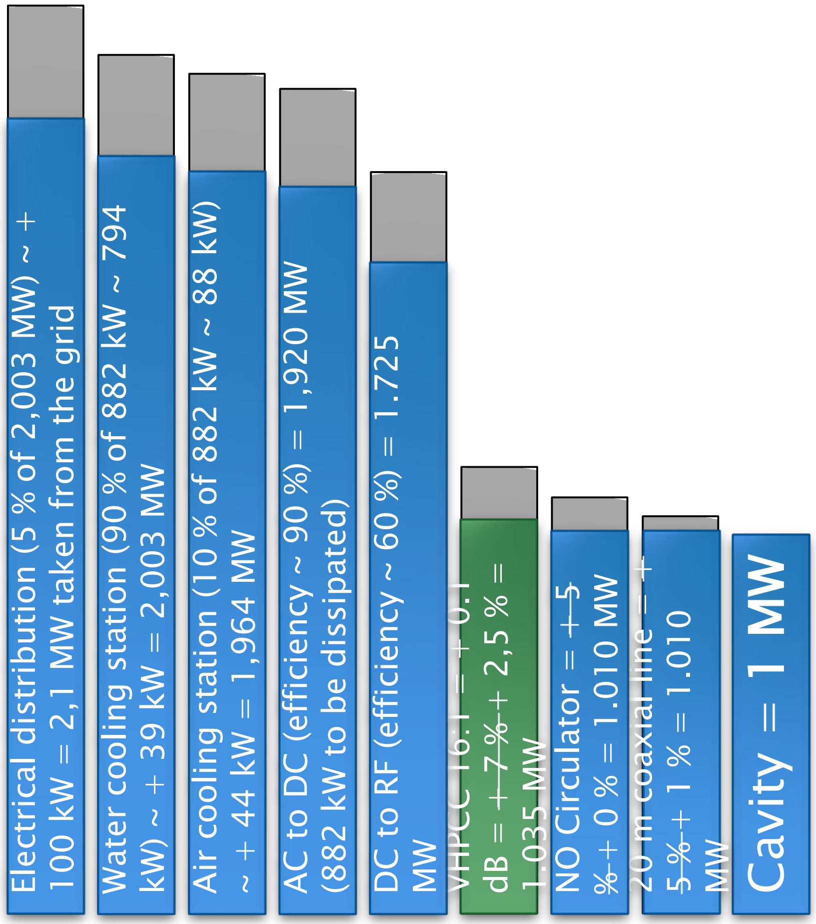
CAVITY COMBINER

Gain in efficiency **6,3 %**

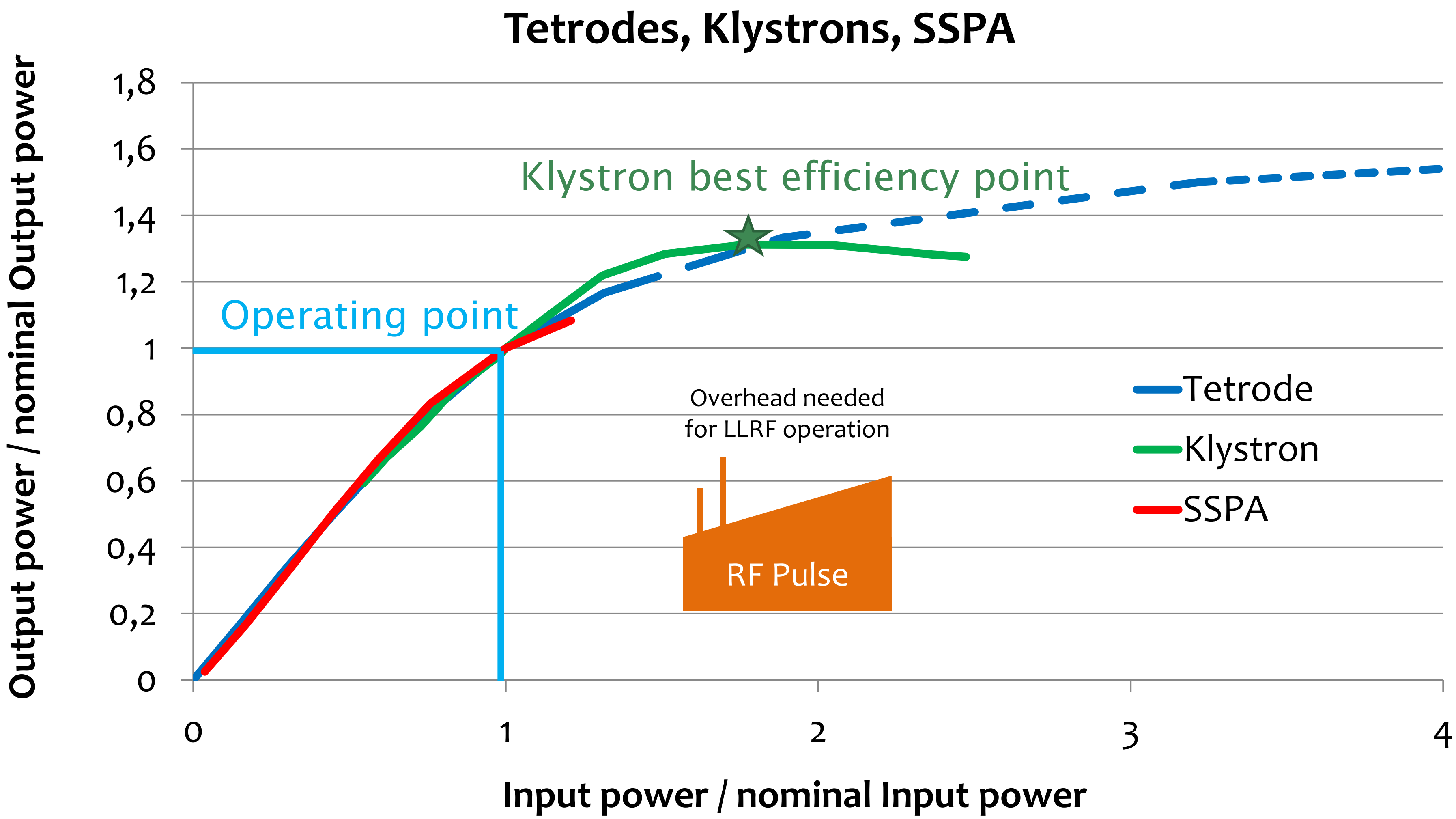
Overall efficiency **47,6 %**

Using cavity combiners instead of 3 dB combiners will also reduce maintenance cost as no more power loads to maintain

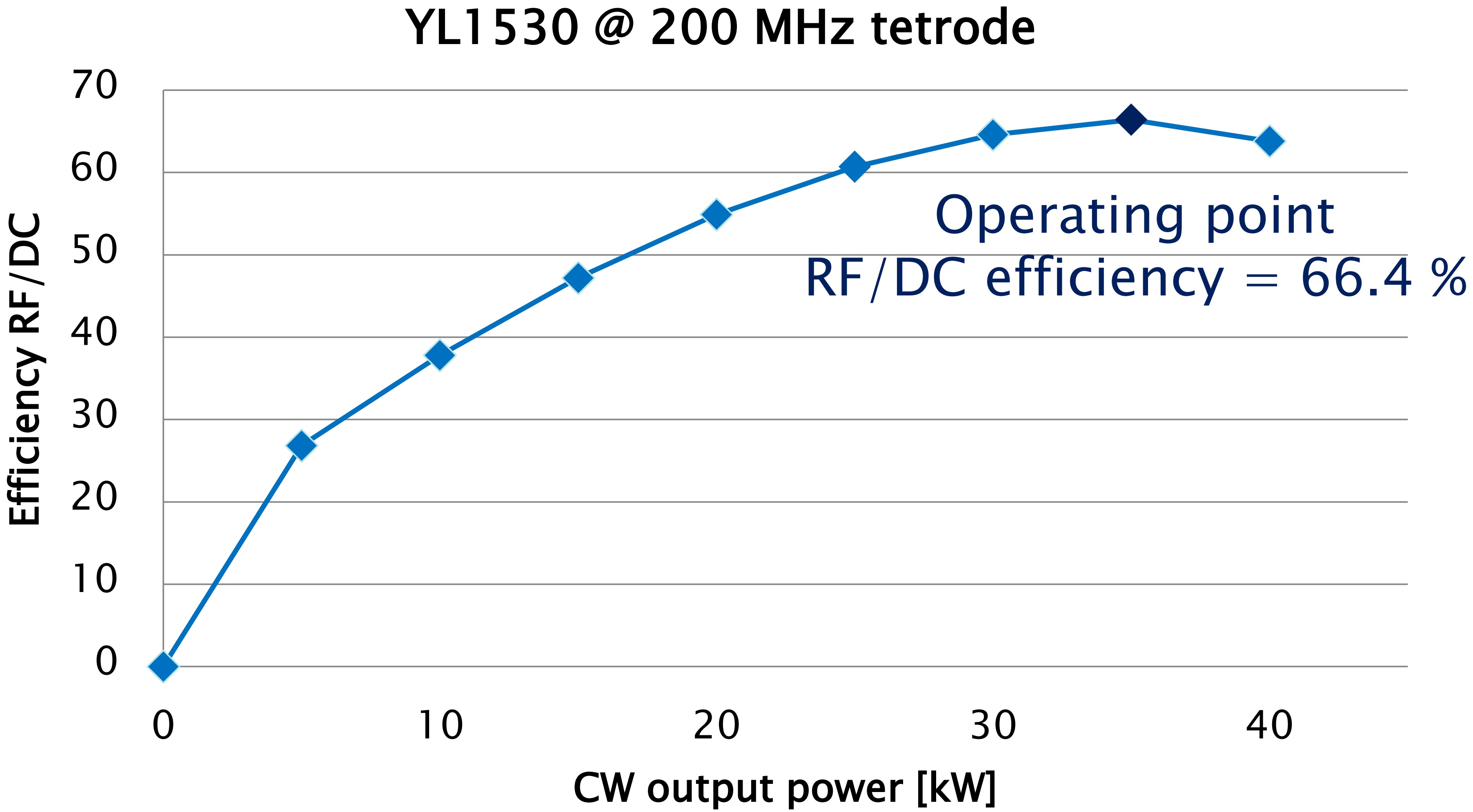




OPERATING POINT

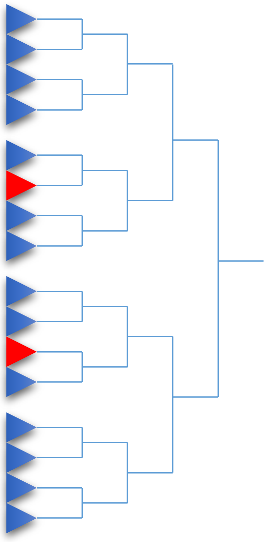


EFFICIENCY VERSUS POWER



COMBINING & EFFICIENCY

Assumption: guaranty 12 x Nominal power

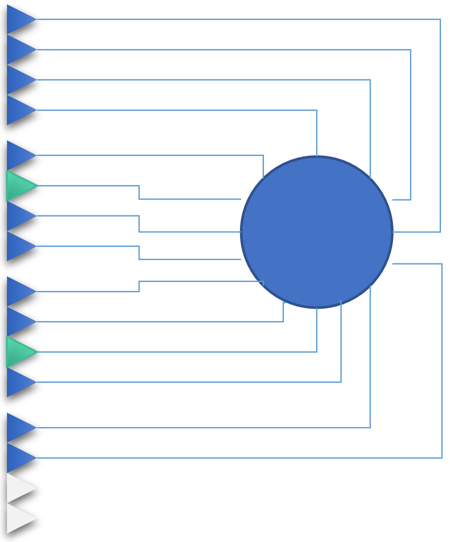


In order to guaranty availability of 12 x Nominal power at the output, with a conventional combiner, oversizing must be up to 16 tubes such that even with 14/16 tubes, the 12 x Nominal power is delivered at the output

Drawback for efficiency, is that if all Base units are operating ok, they will all operate at 12/16 Nominal power (75 % of nominal power), i.e. overall efficiency will be reduced by ~ 10 %

$$Pout = \frac{A1 + A2}{2} + \sqrt{A1 \,.\, A2}$$

In order to perform the same **12 x Base Unit**, with the same 2 Base unit tolerance, with a cavity combiner, you need only **14 x Base Unit instead of 16,** you can keep 2 units as hot spares, and most importantly, doing so, you can operate **all your 12 units at the best efficient point**

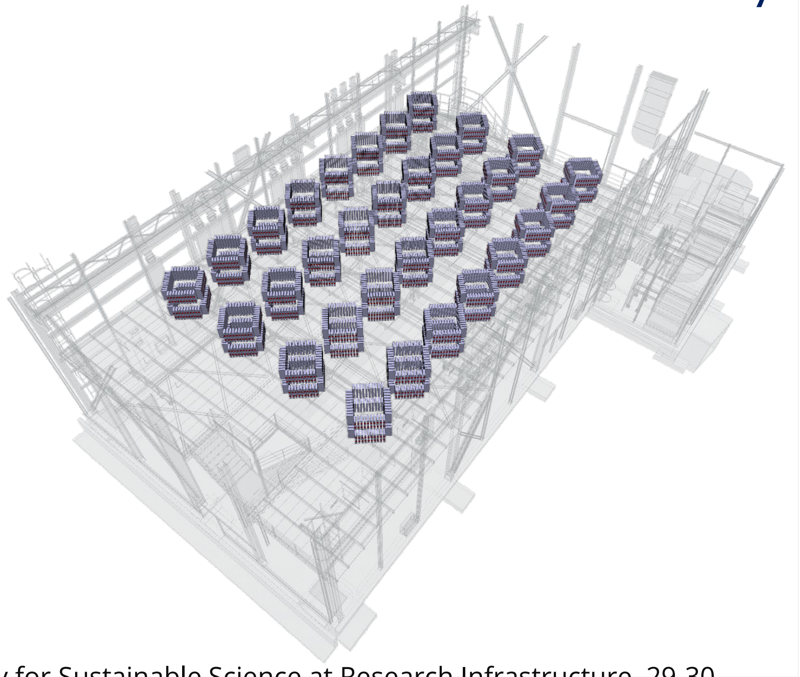


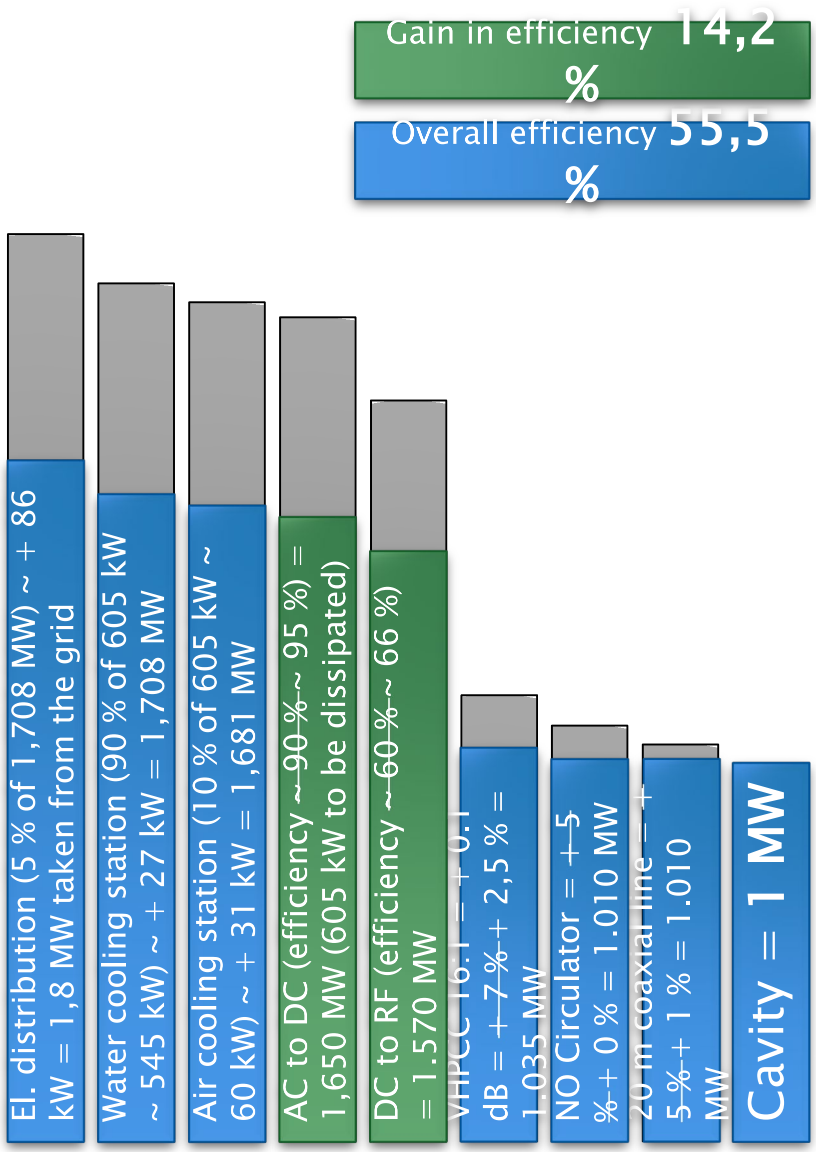
$$Pout = n\, A1$$

GRANULARITY & CAVITY COMBINER

Thanks to the cavity combiner, granularity of the SSPA solution also allows to switch ON the exact correct number of modules such that we operate as close as possible to the nominal point with the best DC to RF efficiency

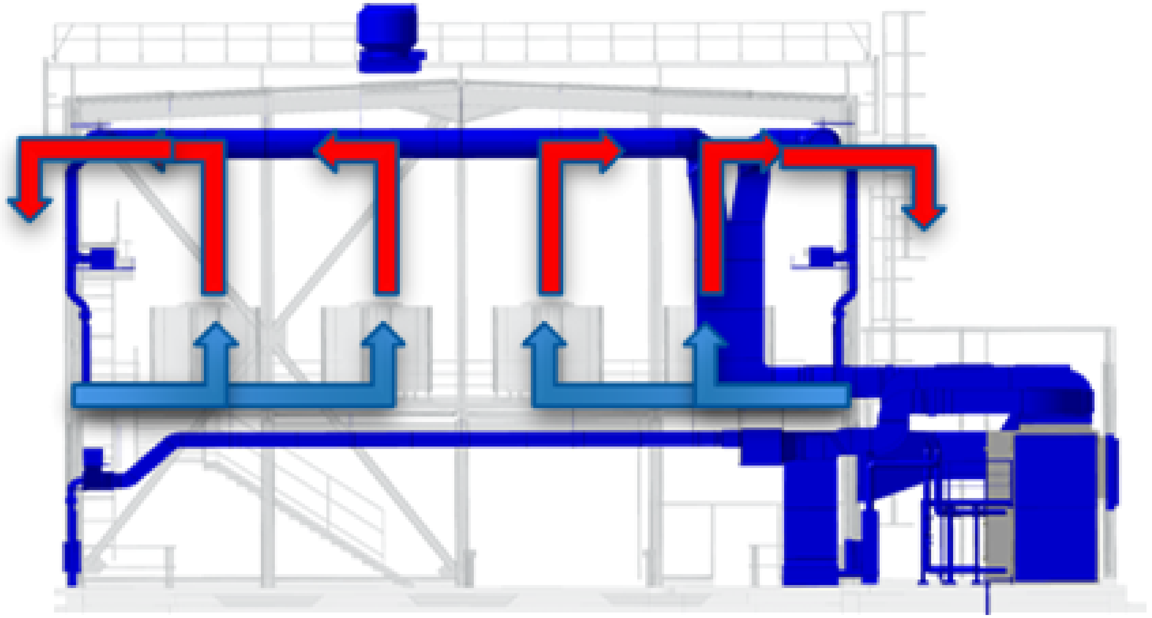
This also enable to have the best efficiency for the power suppliers

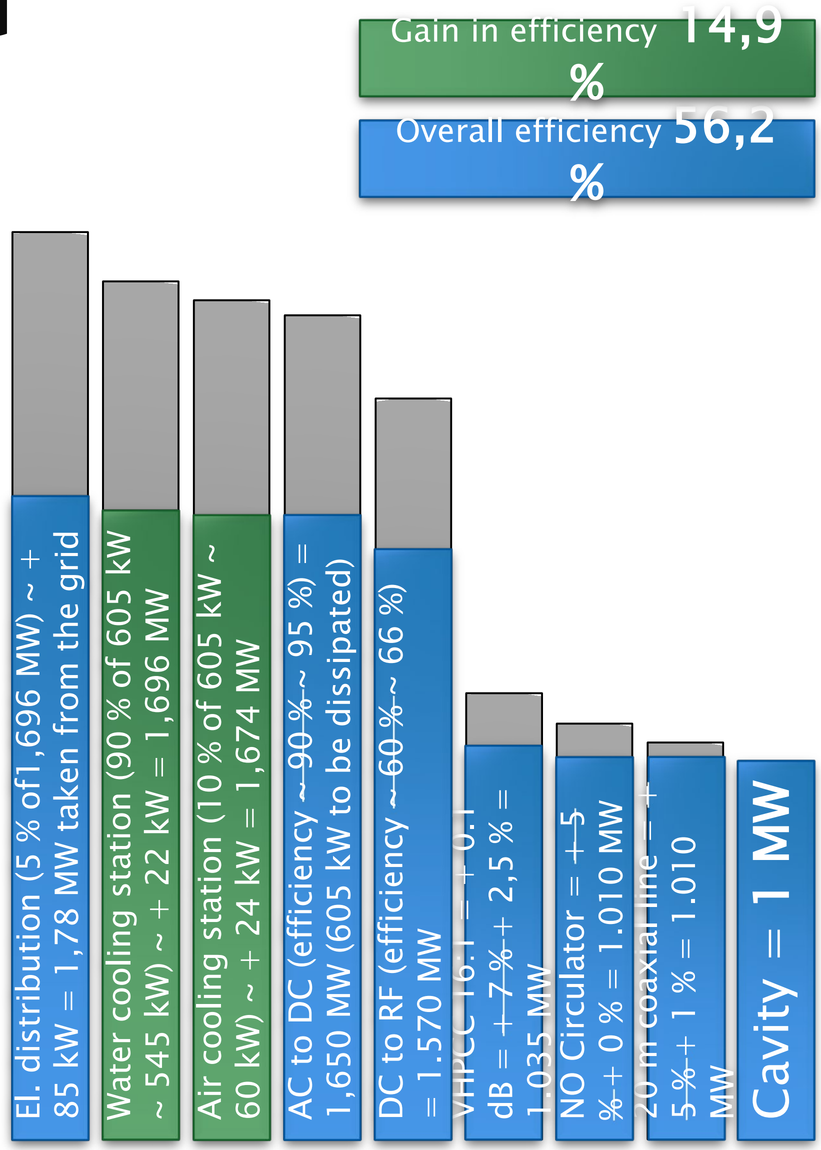




COOLING & CABLING

Taking advantage of the natural chimney effect of the tower, having a well defined water station (variable speed), helps reducing the remaining losses





COOLING & CABLING

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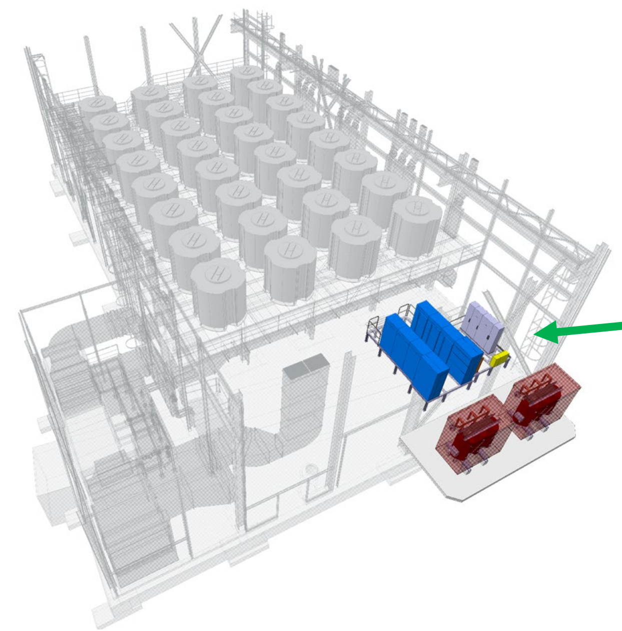
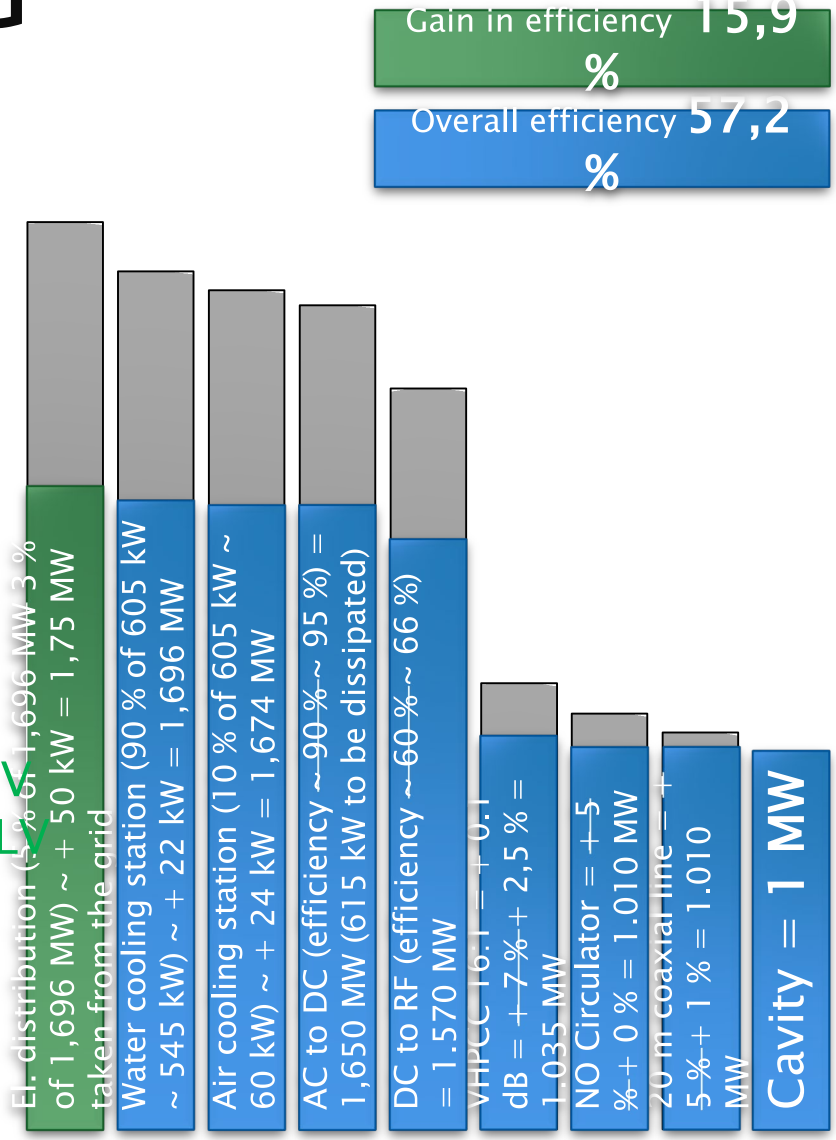


5 m from AC HV to AC MV
~ cm from AC MV to DC LV



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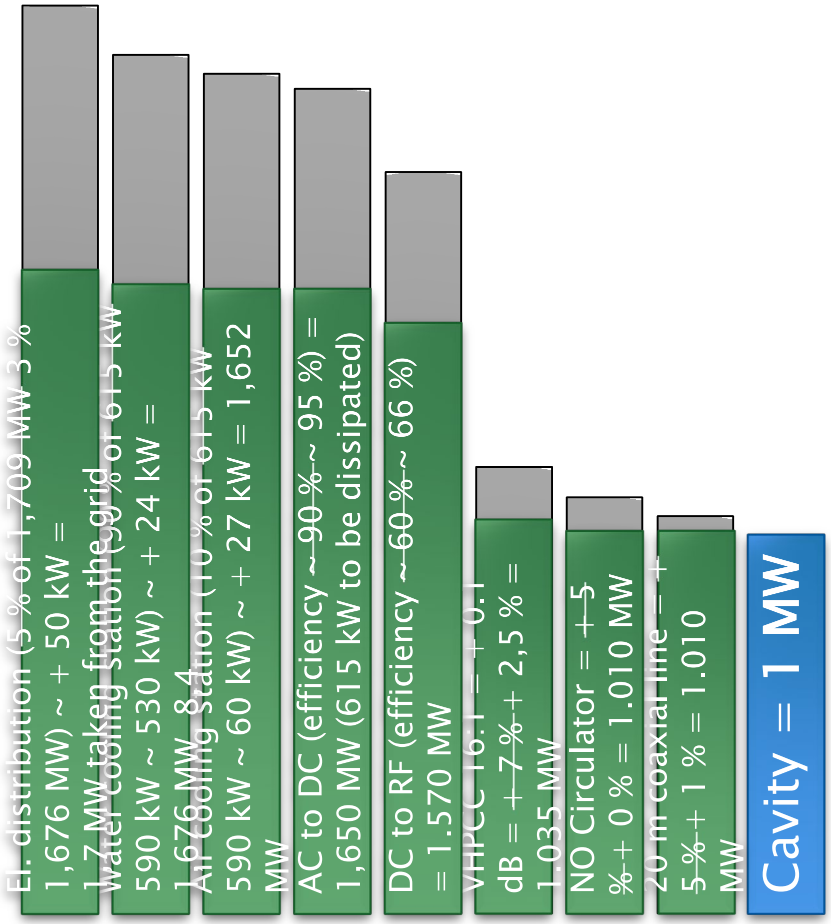
BETTER EFFICIENCY

Gain in efficiency 15,9 %

Overall efficiency 57,2 %

Improving the efficiency will of course be improving the DC to RF efficiency (High efficient klystrons for example)
It will also be applying all the principles that I listed, and some additional others that could even help to succeed to reach higher numbers and that we are now working out for SSPA

- Integrated modules without cables, was too early this time, but clearly an option to be looked at
- Seebeck modules with Shapal substract as cooler of the transistors and re-injecting the losses into the power supplies
- Embedded spares with no replacement neither maintenance
- Multi layers waveguide combiners
- Plenty of other ideas already in mind…



CONCLUSION (I/II)

A special thank to SOLEIL for being the pioneer in the field of SSPA taking a lot of risks in 2007 with moving to that technology

A special thank to ESRF for the cavity combiner development, a real advantage with such an architecture

2 MW SSPA, we did it and it operates with maximum availability

Such projects are always tailored made solutions, and 'Devil is in many details!'

One must have a very solid industrial partner

Large series are not necessarily less expensive (need of dedicated production line)

CONCLUSION (II/II)

Efficiency was not the main objective this time, but we already see a lot of possibilities to be (very) efficient with a SSPA solution

- Fantastically efficient cavity combiners
- Granularity allowing to operate very close to the best efficient point
- Granularity allowing for replacement not seen by operation
- Our availability target has been reached, is 99.99 %

In addition, we already work on several innovative ideas

- Integrated modules without cables, Seebeck / Shapal cooler, Embedded spares, new power combiners with higher power density…

SSPA experts are different experts, but difficulty is really important, and you still need (very good) RF experts

They did not know it was impossible, so they did it
(Mark Twain, 1835-1910)

Thank you very much!

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