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

CERN LIU-SPS 200 MHZ RF SSPA FROM DESIGN TO OPERATION

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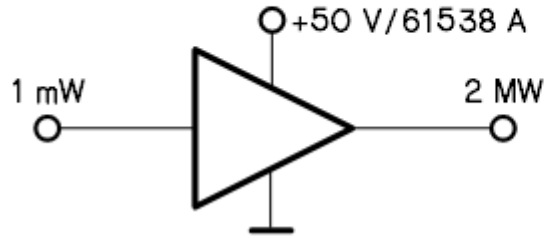
Twelfth Continuous Wave and High Average Power RF Workshop



12.-14.9.2022
CERN
Geneva, Switzerland
http://cern.ch/CWRF22

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. Specificities of the purchasing rules at CERN
3. Technical choices (and difficulties)
4. Operation since beginning 2021

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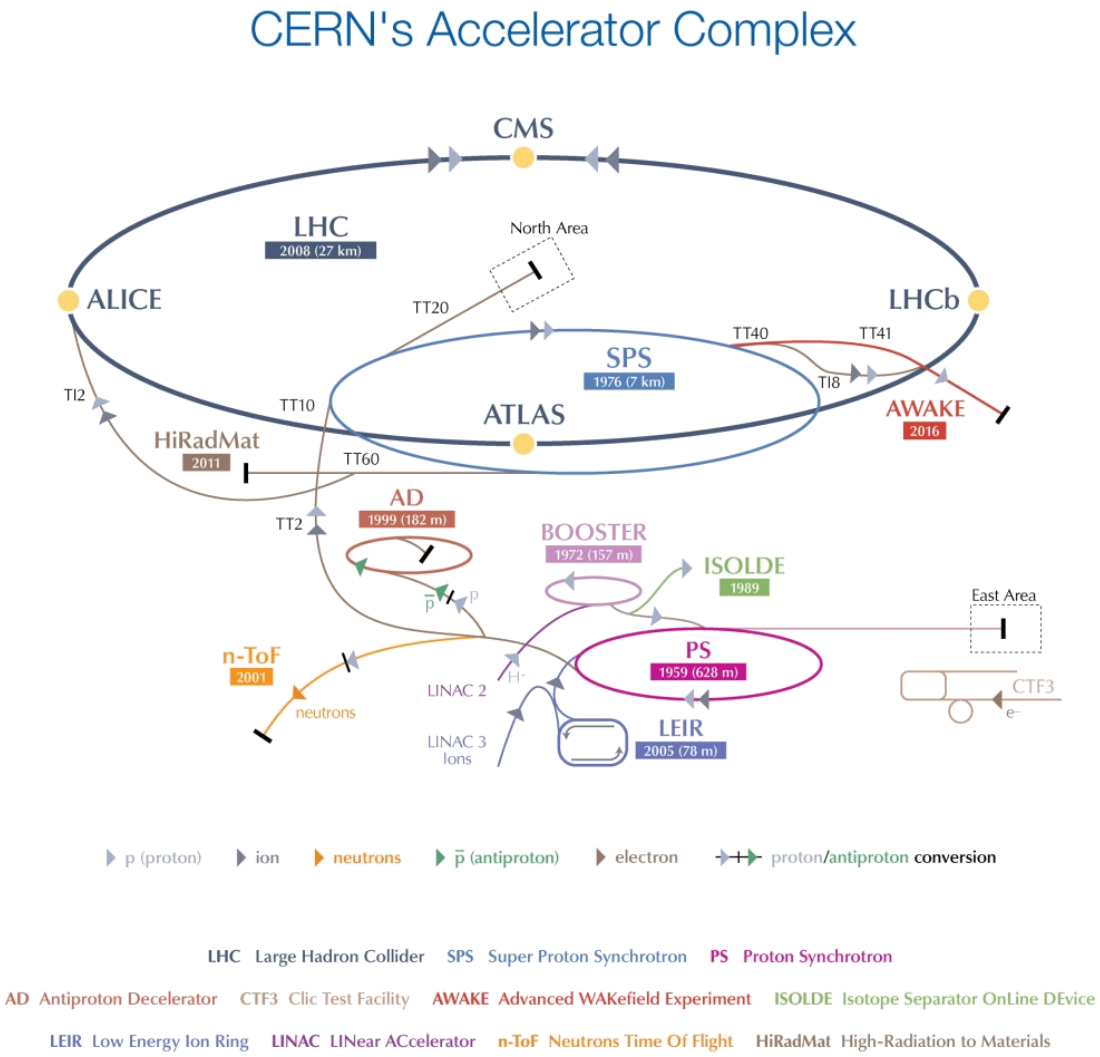
CERN SPS LIU PROJECT

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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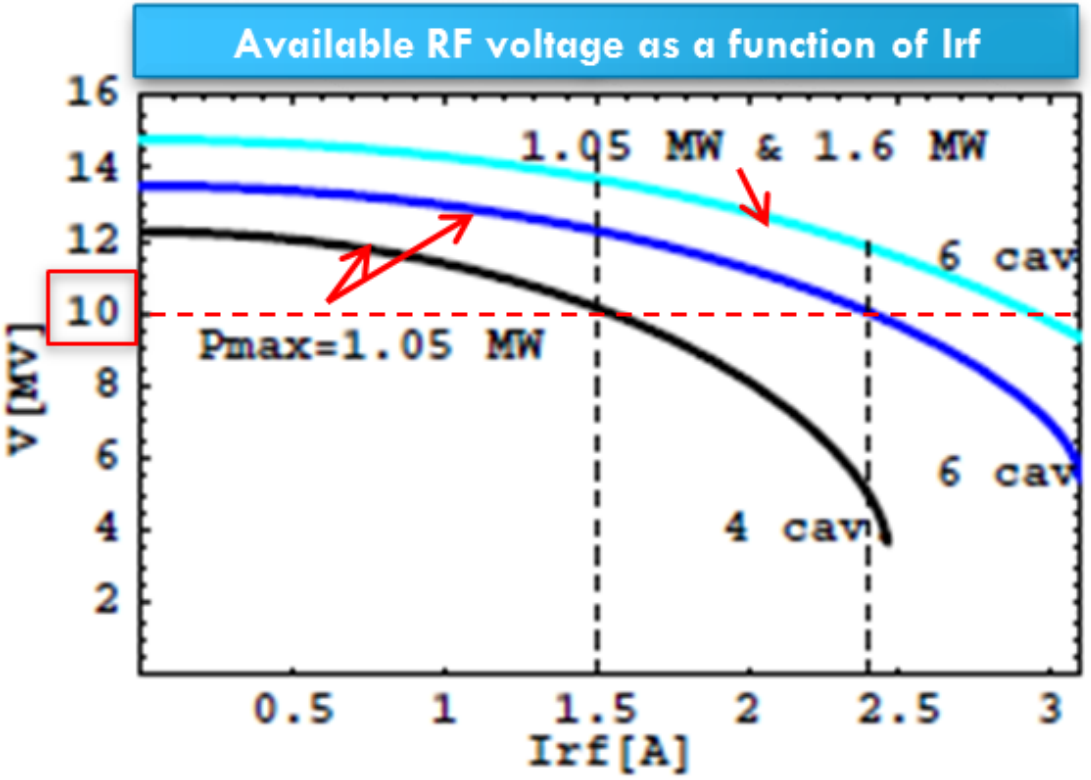
DESCRIPTION OF THE RF POWER UPGRADE PROJECT

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



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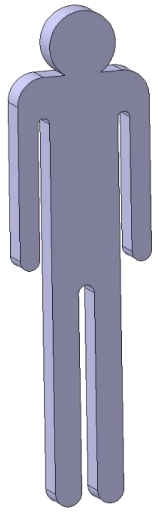
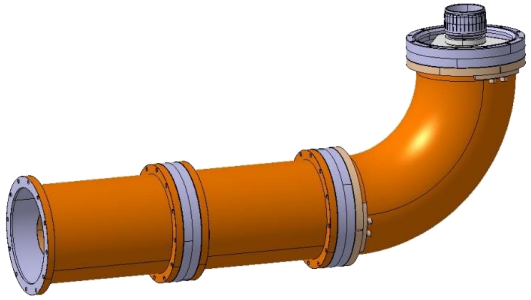
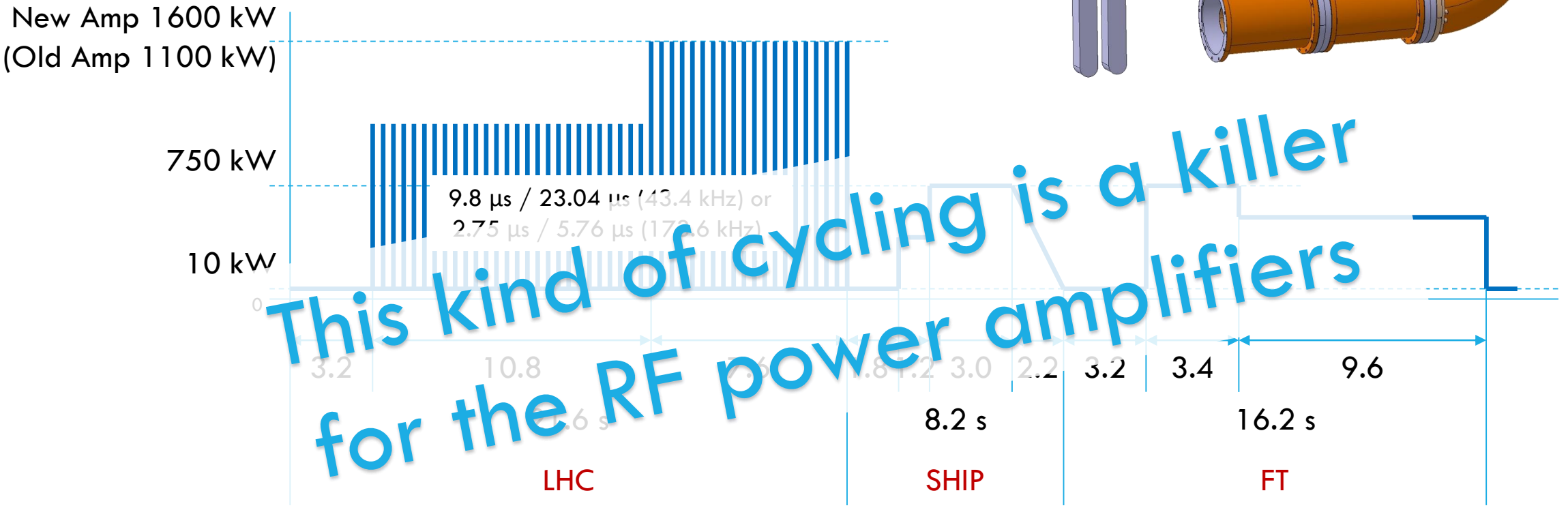
RF CYCLES IN THE SPS



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





This kind of cycling is a killer for the RF power amplifiers

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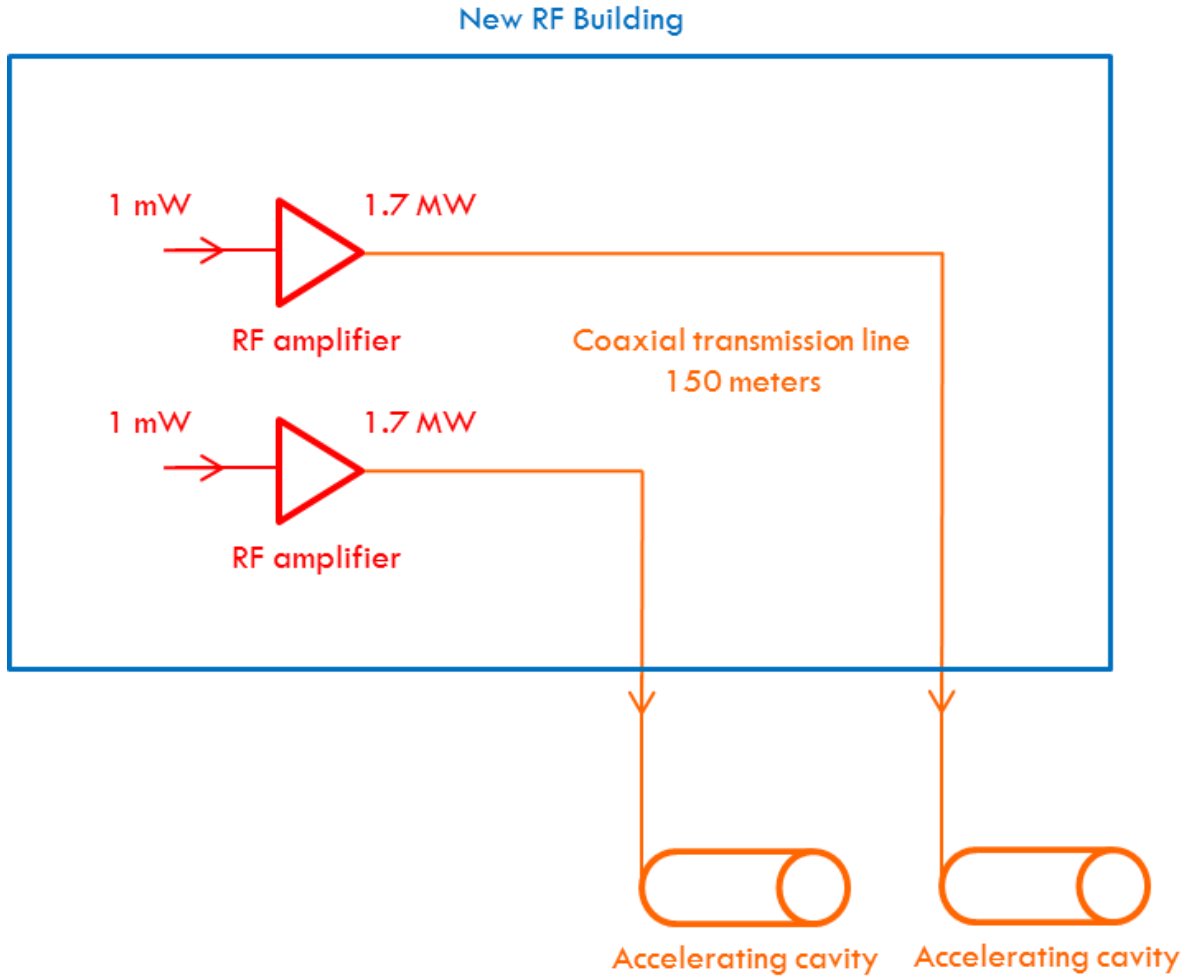
DESCRIPTION OF THE RF POWER UPGRADE PROJECT

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



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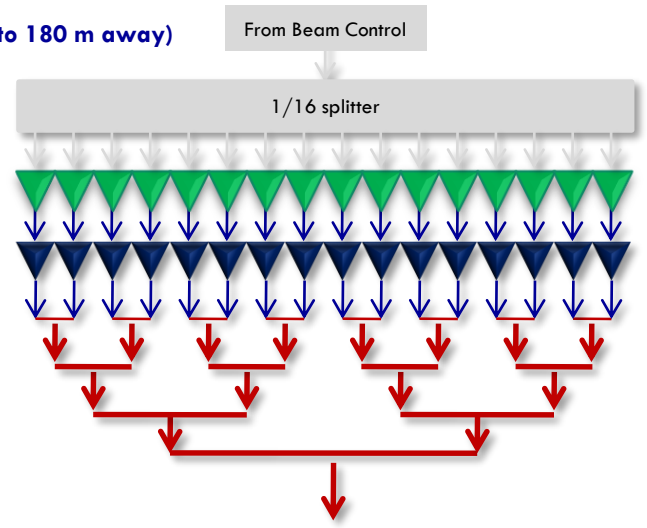
NEW SYSTEMS 2 x 1.7 MW @ 200 MHZ

2 x

One line
(input cavity ~120 to 180 m away)



1.4 MW at cavity input

4 stages of 3 dB combiners = - 0.6 dB
120 to 180 m Coaxial lines = - 0.2 dB
Final Amplifier output = 1.6 MW + 0.8 dB = 1.7 MW / 16 = **110 kW**

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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PURCHASING STRATEGY

Thanks to CERN purchasers, with special thanks to Anders Unnervik, Dante Gregorio, Jérôme Pierlot, Lazslo Abel, Boi-Lan Nguyen Lemoine, Bjorn Jenssen

Two contracts

- IT-3842 Drivers
- IT-3841 Finals

A first contract for the Drivers (IT-3842)

- SSPA only (best technology for a few kW amplifier)
- Will be a first input for a predefined cost for the Finals

Combining systems

- Done in house
- Will be a second input for a predefined cost for the Finals

Once Drivers contract adjudicated, a second contract for the Finals

Drivers IT-3842 cost
\+ Combiner cost (defined by CERN)
\+ Finals IT-3841 offer

IT-3841 adjudication to the lowest compliant

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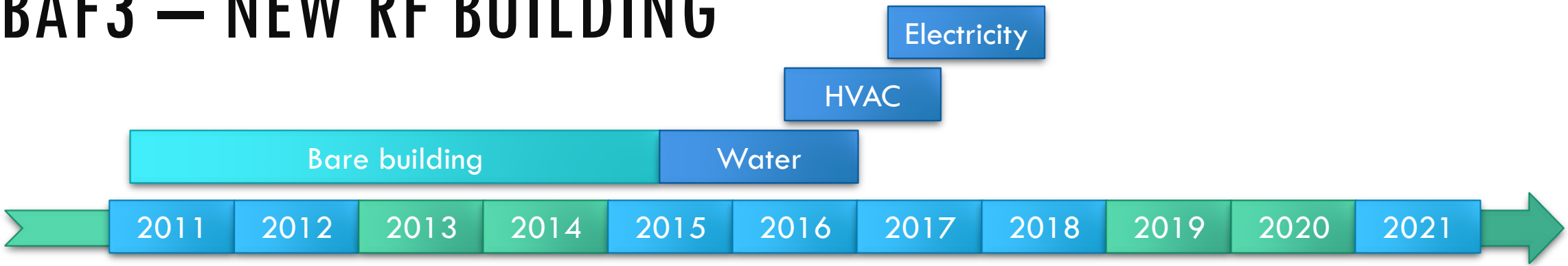
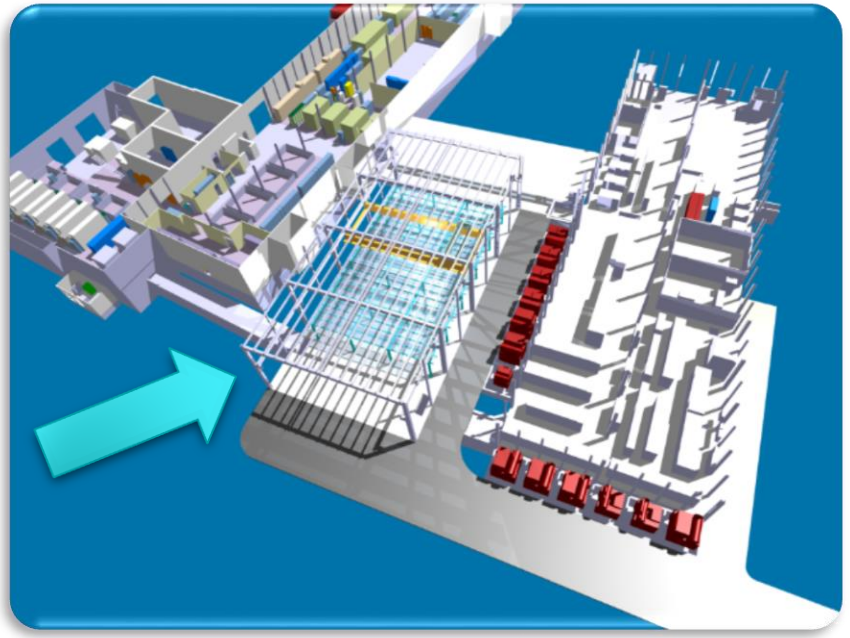
BAF3 – NEW RF BUILDING



Design completed by end of October 2011 to allow Civil engineering studies and authorisation requests to be launched

Goal to have the bare building completed by 2015

Even if we did not know what amplifier technology will be selected!



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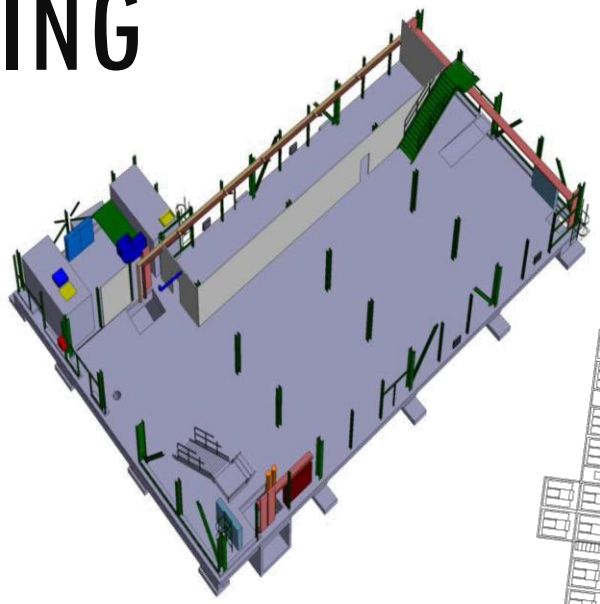
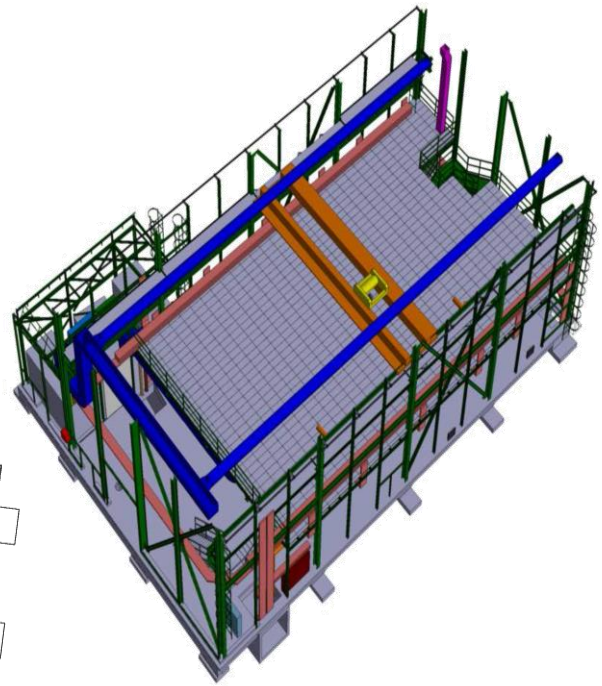
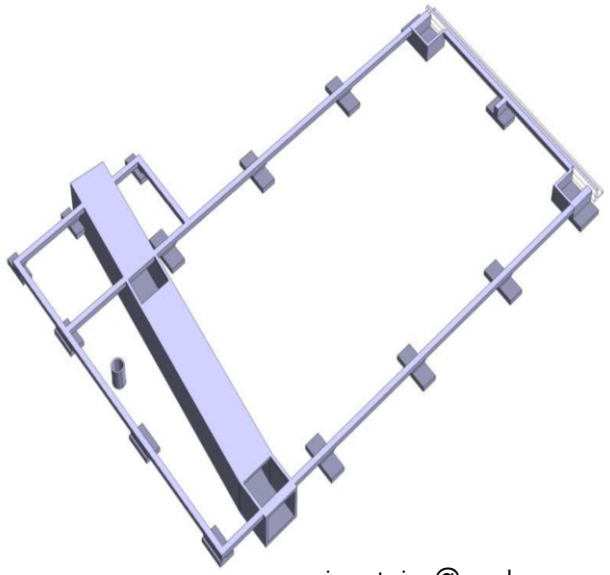
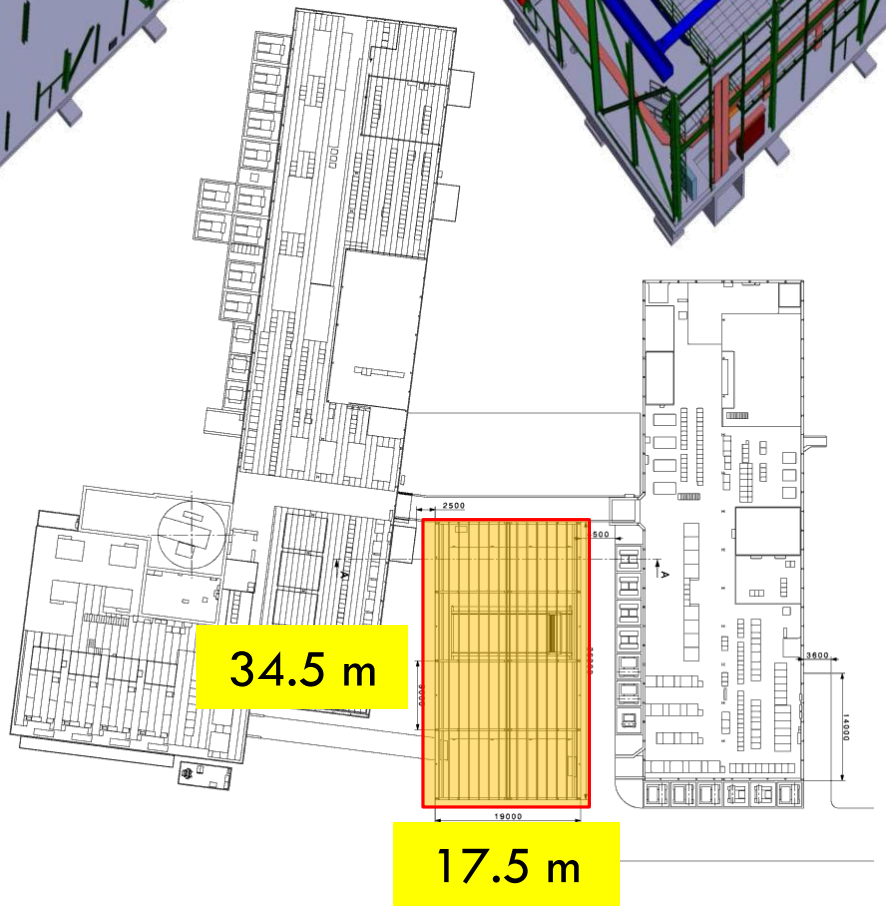
BAF3 – NEW RF BUILDING

Maximum size is restricted by the available land around CERN premises









Total surfaces

- Basement : 17.5 m x 34.5 m = 600 m^2
- Mezzanine : 450 m^2
- Total = 1050 m^2

Total for RF amplifiers

- Basement = 350 m^2
- Mezzanine = 350 m^2
- Total = 700 m^2

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BAF3 – NEW RF BUILDING

BAF3 for RF = 700 m²

Amplifier tendering process opened to several technologies

- 2 x 16 tetrodes (well known)
- 2 x 2048 SSPA (Solid State Power Amplifiers)
- 4 x Diacrodes (new tube)
- 4 x IOT (Inductive Output Tube)

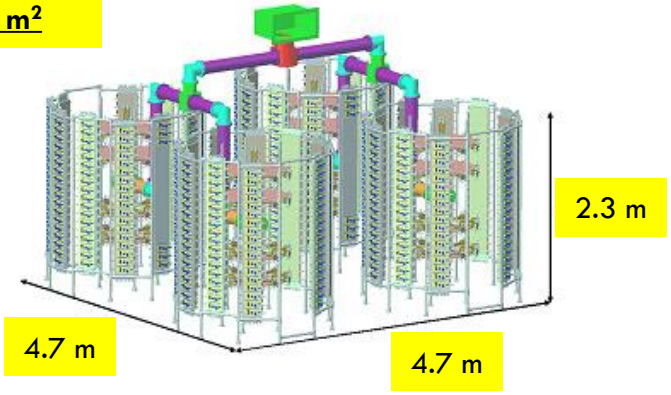
1 tube (160 kW) = 4 m²
HVPS = 192 m²
Total 32 tubes = **320 m²**

Combiners for 32 = **200 m²**

2 towers (320 kW) = 15 m²
LVPS = 72 m²
total 64 towers = **550 m²**

Hybrid combiners and coaxial lines will be similar to the ones in use with present systems

Courtesy
Patrick Marchand
(SOLEIL)



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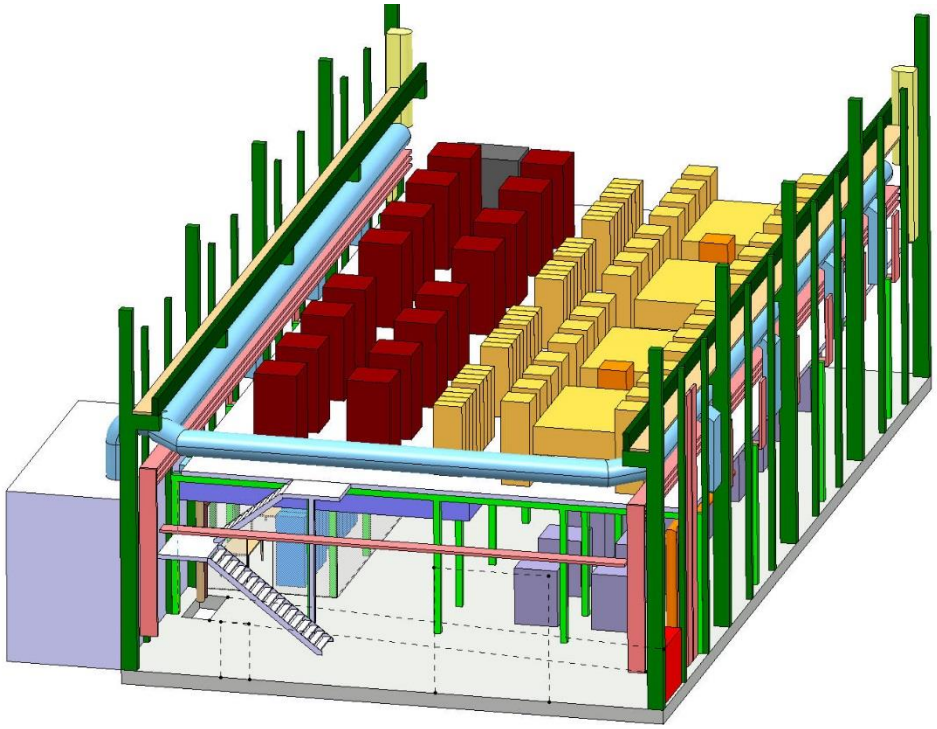
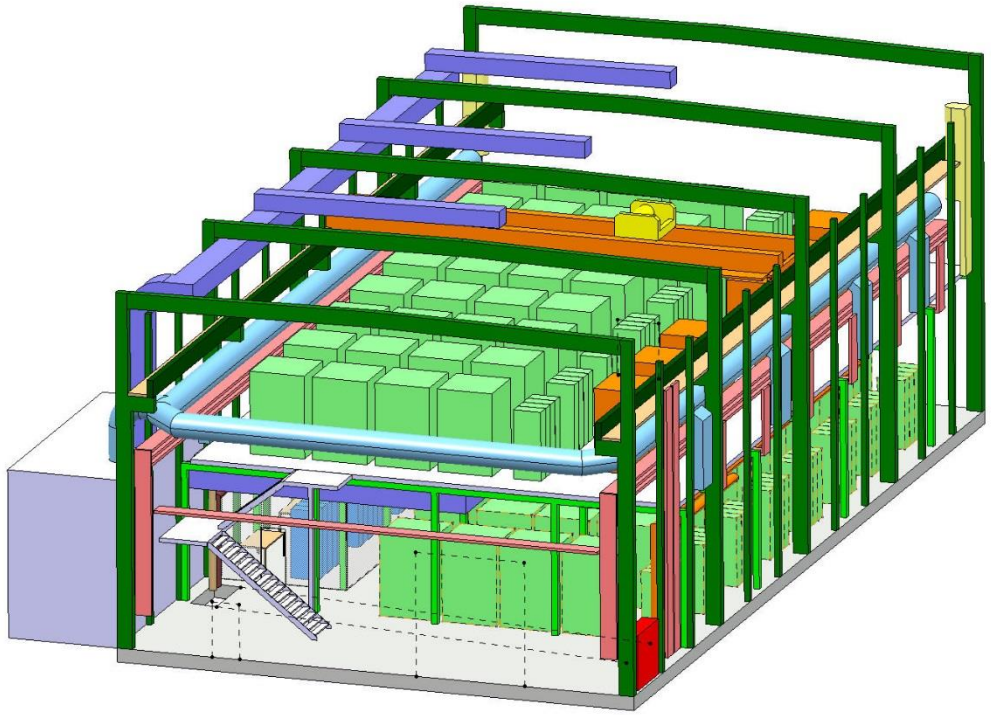
BAF3 – NEW RF BUILDING



BAF3 with Tetrodes



BAF3 with SSPA

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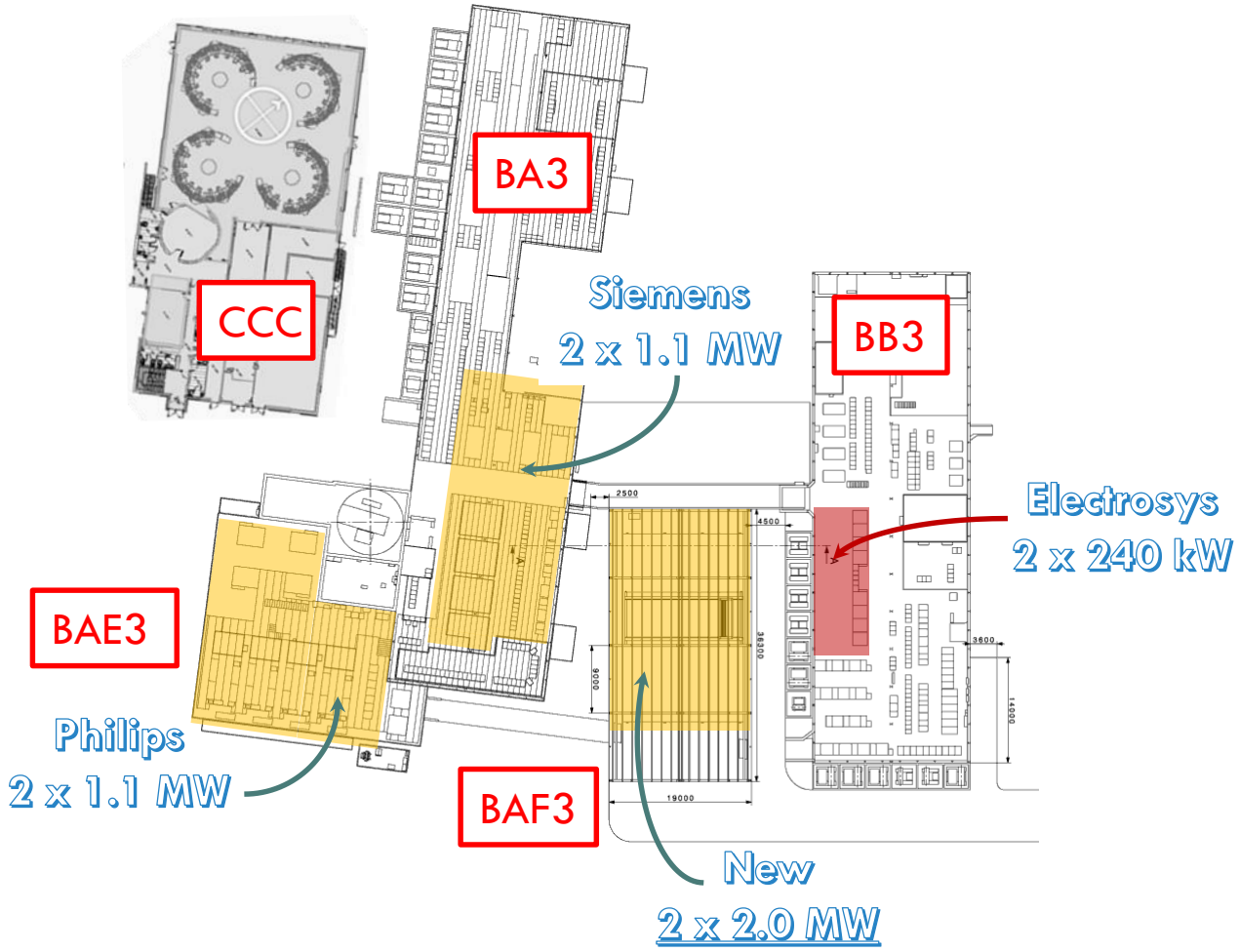
FUTURE POWER SYSTEMS IN THE SPS



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CONSTRUCTION OF THE NEW BUILDING

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IT-3842, DRIVERS

OK for Finals

72 companies consulted

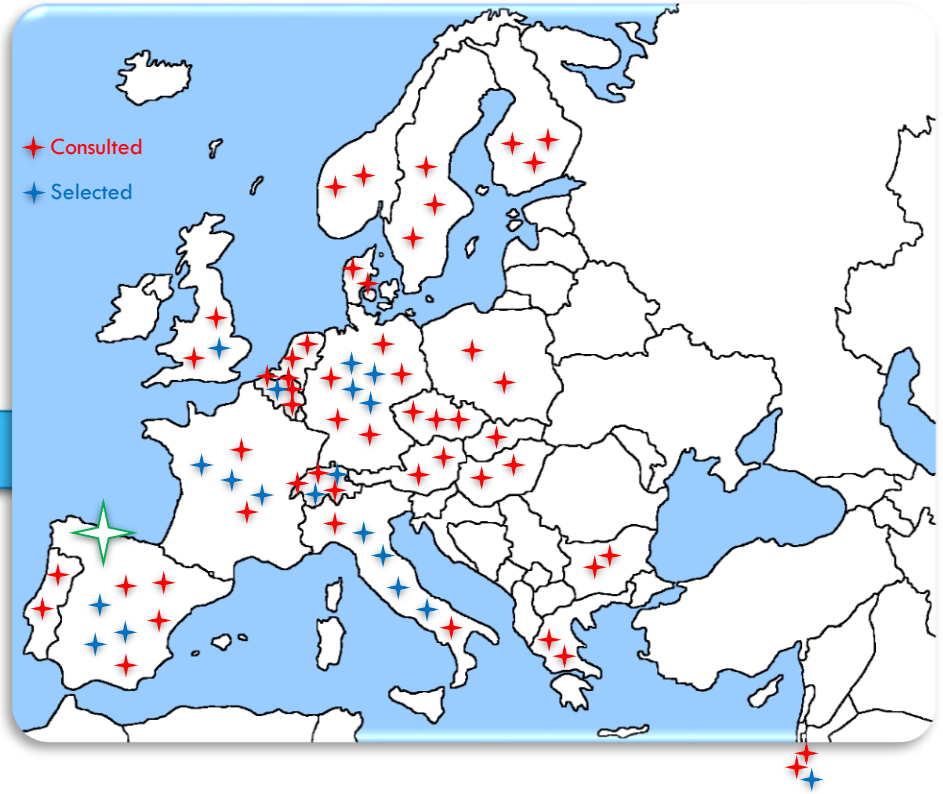
20 selected

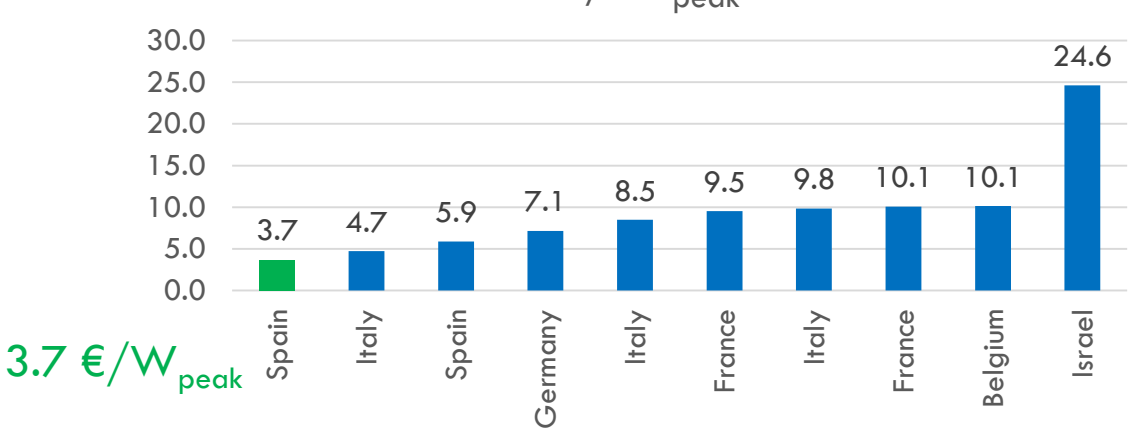
10 offers

Defined a 1.25 kW unit

- Compatible with all Finals technologies
  - 32 for SSPA & IOTS, 256 for Tetrodes, 192 for Diacrodes
- 12 pre-series for qualification (end of contract clause in case of any failure without any payment)
- One to six batches of 50 (total 62 to 312) regarding result of future Finals IT-3841

TTI Norte, Spain, awarded the contract (3.7 €/W)





3.7 €/W peak

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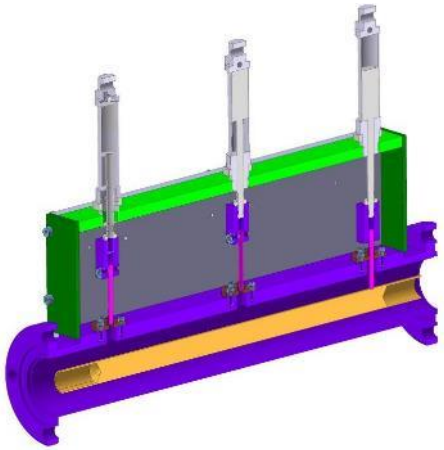
IT-3842, DRIVERS

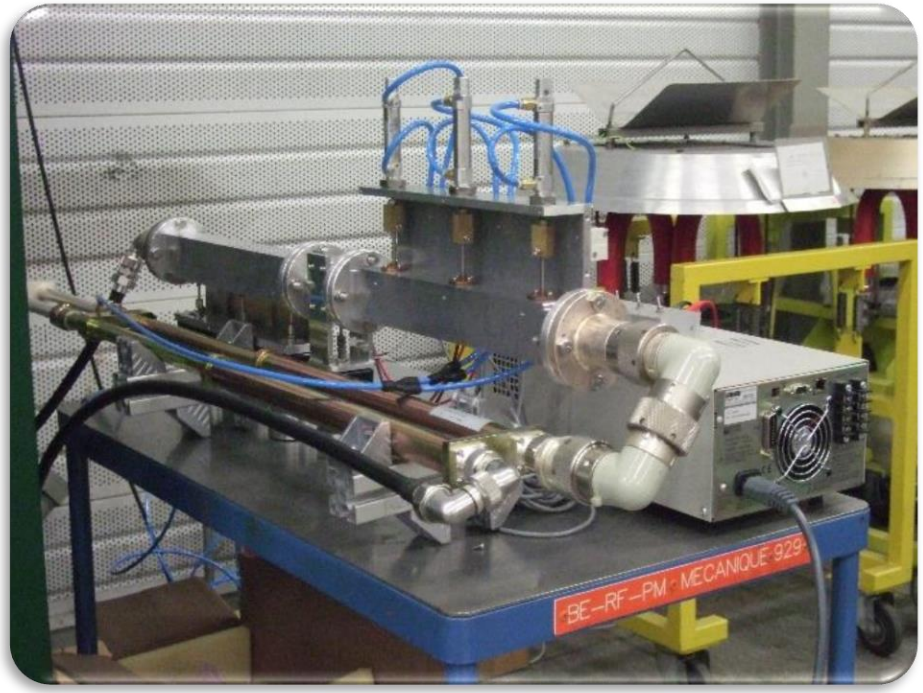


November 2011

Series production ok June 2016

The 12 pre-series have been qualified

- RF design is impressively robust
- Double circulators!
- Sustained the CERN Fast Short-Circuit test! Tungsten fingers at three phases spaced by λ/6
- Successfully completed the 1000 hours test with 12 units



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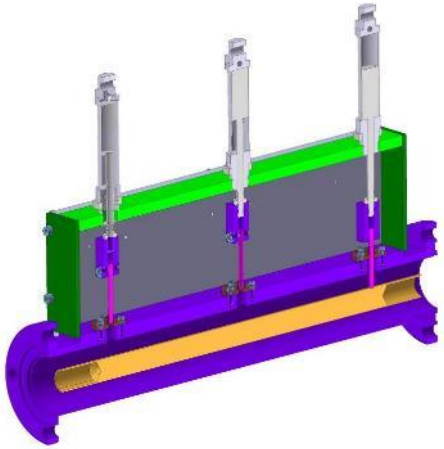
IT-3842, DRIVERS



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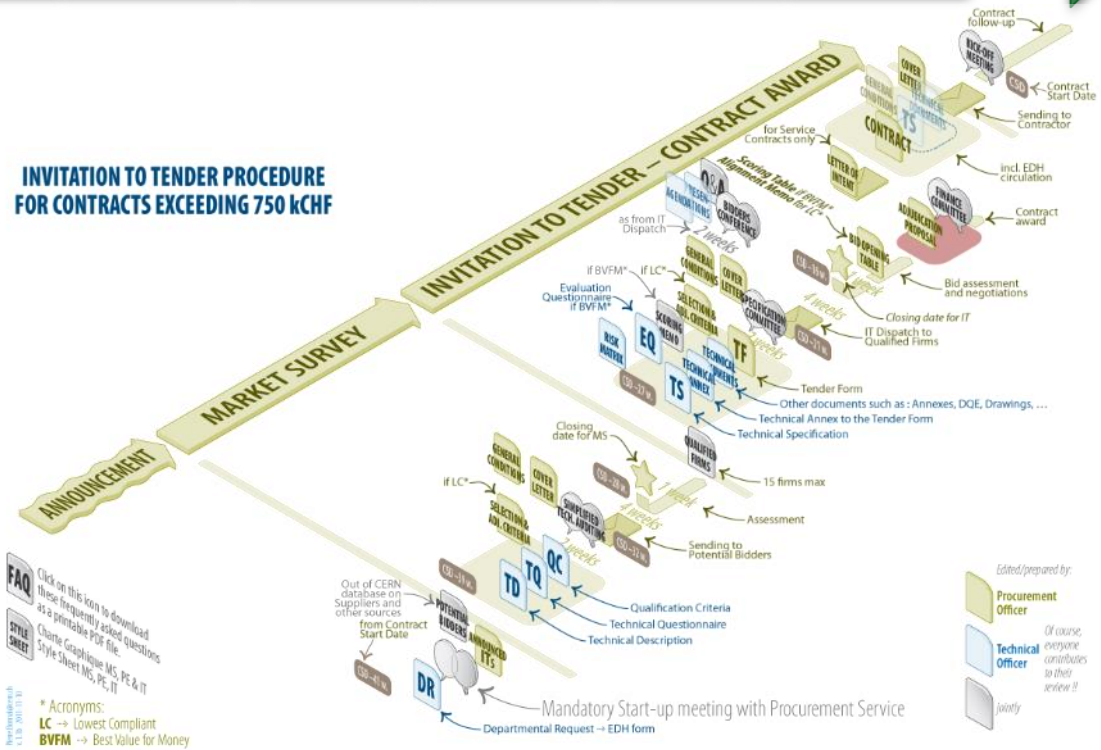
IT-3841, FINALS

Technical Specification with delay as to be finalized taking into account Drivers outcome



In the mean time power level request increased

- Cavity 1.4 to 1.6 MW
- **Amplifier from 1.6 to 2.0 MW!**

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IT-3841, FINALS ADDITIONAL COSTS

Drivers IT-3842 cost

- 5500 CHF per 1.25 kW unit
- SSPA & IOT 176 kCHF
- Tetrodes 1'408 kCHF
- Diacrodes 1'056 kCHF

Combiner cost (defined by CERN)

- SSPA & IOT 2'760 kCHF
- Tetrode 3'160 kCHF
- Diacrode 800 kCHF

Total additional cost per technology

- SSPA & IOT 2'936 kCHF
- Tetrode 4'568 kCHF
- Diacrode 1'856 kCHF

Input	Input Power	Output Power	Load	Directional coupler	Cost
6:1	1250 W	7.5 kW	0	14	10 kCHF
8:1	1250 W	10 kW	0	18	12.5 kCHF
2:1	7.5 kW	15 kW	1 x 50 kW	8	15 kCHF
2:1	15 kW	30 kW	1 x 50 kW	8	20 kCHF
2:1	30 kW	60 kW	1 x 50 kW	8	20 kCHF

Directional coupler + diode detector : 300 CHF

50 kW load: 6 kCHF

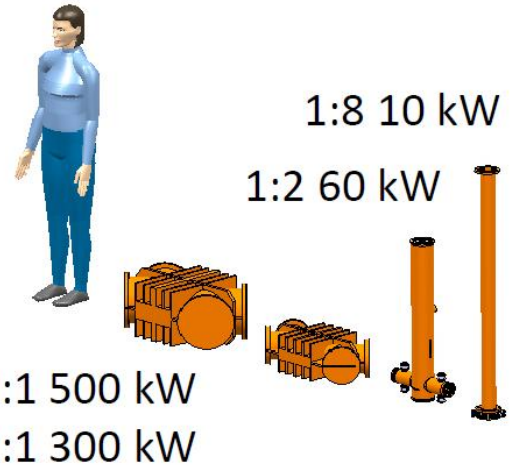
500 kW load: 60 kCHF

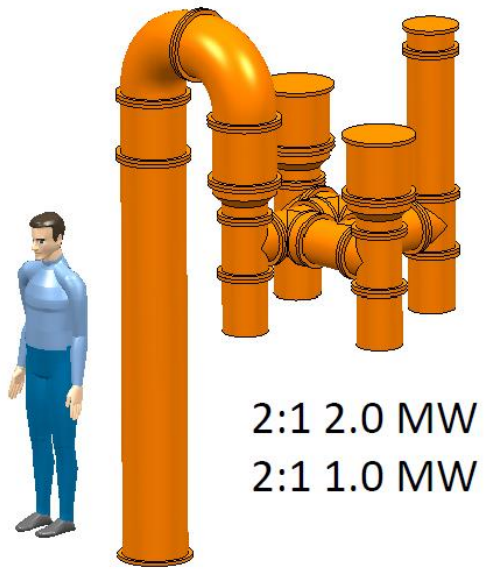
Important Note: Any price estimates in this document include direct and indirect costs (manpower, facilities, materials, ...)

Output	Input Power	Output Power	Load	Directional coupler	Cost
2:1	150 kW	300 kW	2 x 50 kW	8	60 kCHF
2:1	250 kW	500 kW	3 x 50 kW	8	75 kCHF
2:1	500 kW	1 MW	1 x 500 kW	8	200 kCHF
2:1	1 MW	2 MW	1 x 500 kW	8	200 kCHF

Input	P max	Unit cost	SSA	Tetrodes	IOTs	Diacrodes
6:1	7.5 kW	10 kCHF	-	-	-	8
8:1	10 kW	12.5 kCHF	-	16	-	-
2:1	15 kW	15 kCHF	-	-	-	4
2:1	30 kW	20 kCHF	-	-	-	2
2:1	60 kW	20 kCHF	-	-	-	1
Total per transmitter			0	200	0	200
Total kCHF			**0**	**400**	**0**	**400**

Output	P max	Unit cost	SSA	Tetrodes	IOTs	Diacrodes
2:1	300 kW	60 kCHF	8	8	8	-
2:1	500 kW	75 kCHF	4	4	4	-
2:1	1 MW	200 kCHF	2	2	2	-
2:1	2 MW	200 kCHF	1	1	1	1
Total per transmitter			1380	1380	1380	200
Total kCHF			**2760**	**2760**	**2760**	**400**





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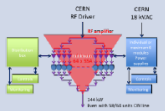
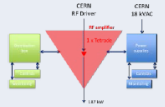
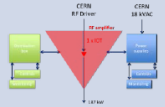
IT-3841, FINALS BIDDERS CONFERENCE

Defined the scope of the contract

- being as fair as possible regarding the technology
- Defining a quite costly Demonstrator in order to disqualify 'non serious' companies (we do not want to be R&D at low cost)
- Not a single CHF paid in case of failure of the demonstrator
- Taking into account tubes on an as long as possible period (over 5 years, CERN's rules)
- Including spares in order to operate during 20 years

Answered 102 questions from the suppliers

Technology	Demonstrator	Transmitters	Transmitter Spares	Consumables	Total
SSPA		32 x RF amplifiers (including all PS & controls)	1 RF amplifier 8 sets of main components 1 set of modules	-	33 RF amplifiers 1 demonstrator 8 sets of main components 1 set of modules
Tetrodes		32 x RF amplifiers (including all PS & controls)	4 RF amplifiers 8 sets of main components 8 Trolleys	Tubes to last 30,000 hours Plus 10 tetrodes	36 RF amplifiers 1 demonstrator 8 sets of main components 8 Trolleys 10 Tubes
IOTs		32 x RF amplifiers (including all PS & controls)	4 RF amplifiers 8 sets of main components 8 Trolleys	Tubes to last 30,000 hours Plus 10 IOTs	36 RF amplifiers 1 demonstrator 8 sets of main components 8 Trolleys 10 Tubes
Diacrodes		4 x RF amplifiers (including all PS & controls)	1 RF amplifier 1 set of main components	Tubes to last 30,000 hours 2 diacrodes	5 RF amplifiers 1 demonstrator 1 set of main components 2 diacrodes

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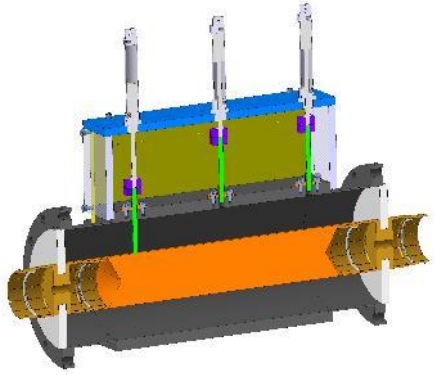
IT-3841, REQUIREMENTS

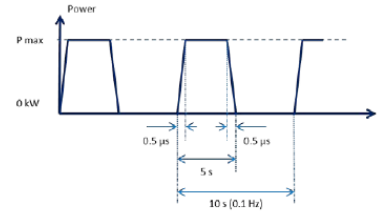
Requirements

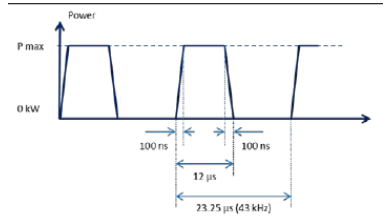
- Integration within the given building
- Repetition rate 0.1 Hz to 500 kHz (require a CW and a pulsed amplifier)
- Full reflection all phases 100 ms (equivalent to 4 time the power level along the lines)
- Non conventional way to measure the BW (required by LLRF and TWC)
- Very good linearity

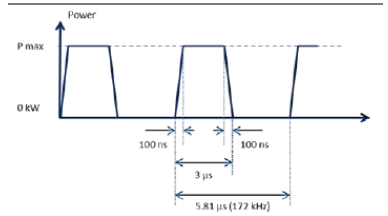
A lot of tests to qualify the Finals

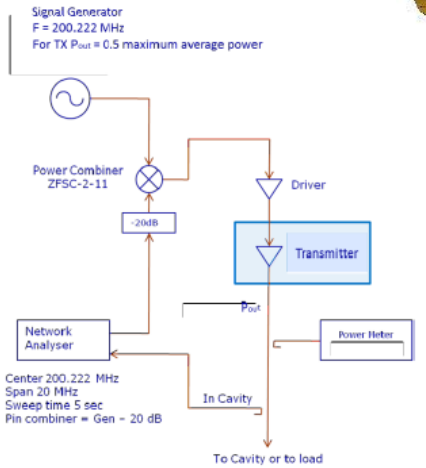
- Supercycle test, short circuit test, BW, linearity, …
- Short duration tests to qualify an Amplifier within one week
- Long duration tests to check reliability over 1000 hours

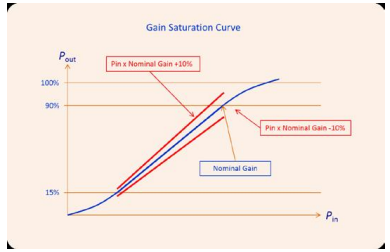


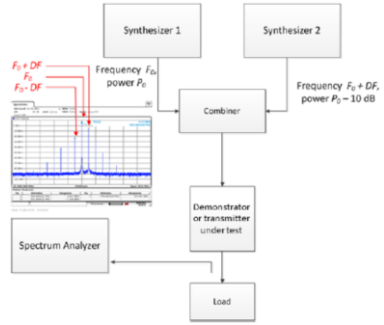


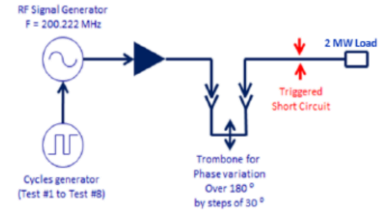


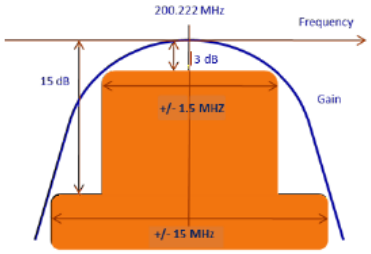












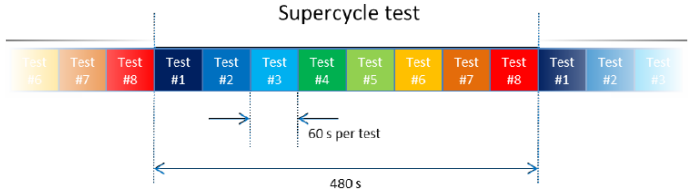


Figure 7: Supercycle test

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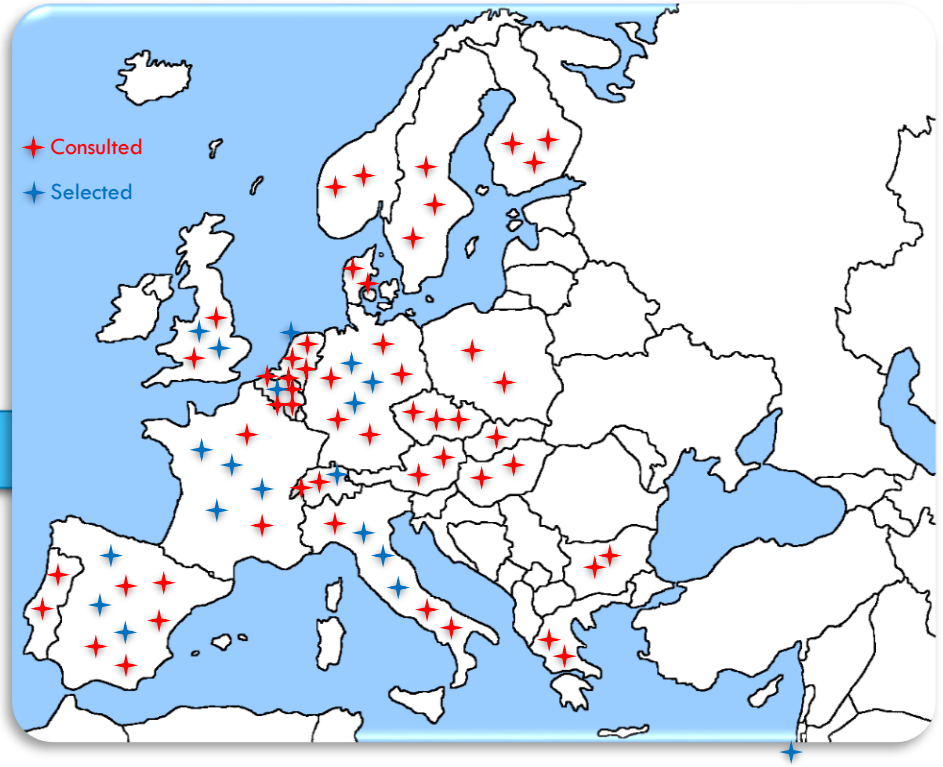
IT-3841

13 March 2015, bids opening



74 companies consulted

19 selected

8 declined

7 offered

No discussion about the Drivers neither the combiners costs

Unable to submit a competitive bid due to quantity being beyond our production capacity and we could not provide installation support

Dear all, We are sorry but we are not able to finish every documents within deadline. So we must decline to participate with our offer. Thank you for your opportunity. Best regards

We are not on time with the documents required

We believe that the chances are too low to get the contract by bidding Solid State Amplifier solutions. Additionally, the known dumping price structure of competitors in the field of Solid State Amplifiers, which get development provided free of costs by public institutes (already known due to the preceding call for tender for preamplifiers of the same frequency) also makes the chance to win the bid too small for the required work load for bid preparation

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IT-3841

17 September 2015, FC approval

13 March 2015, bids opening

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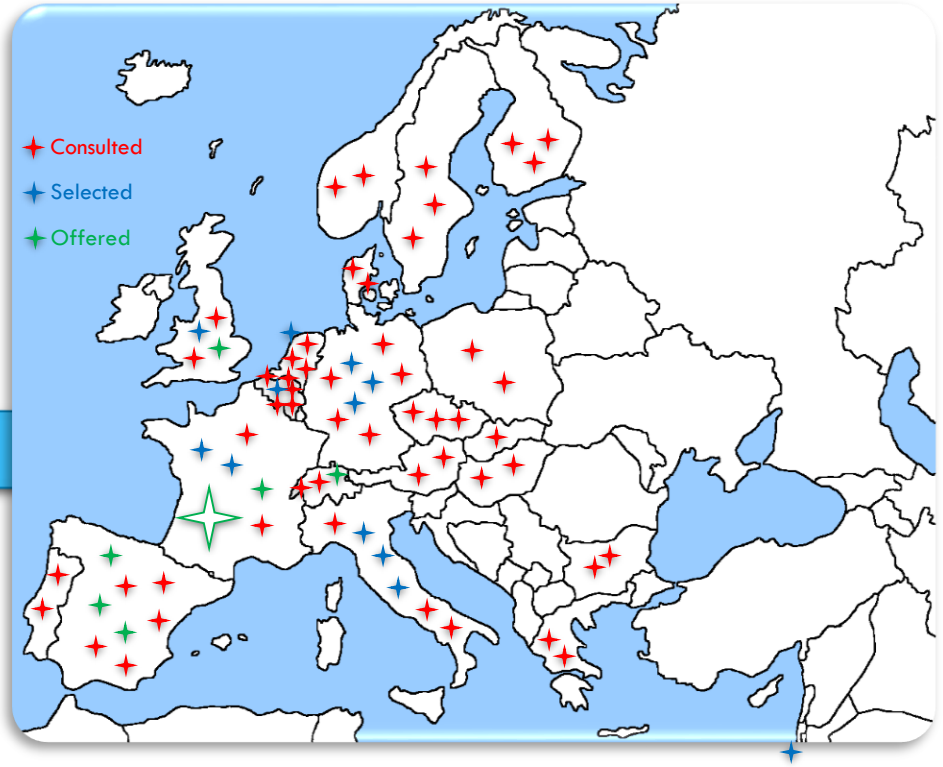
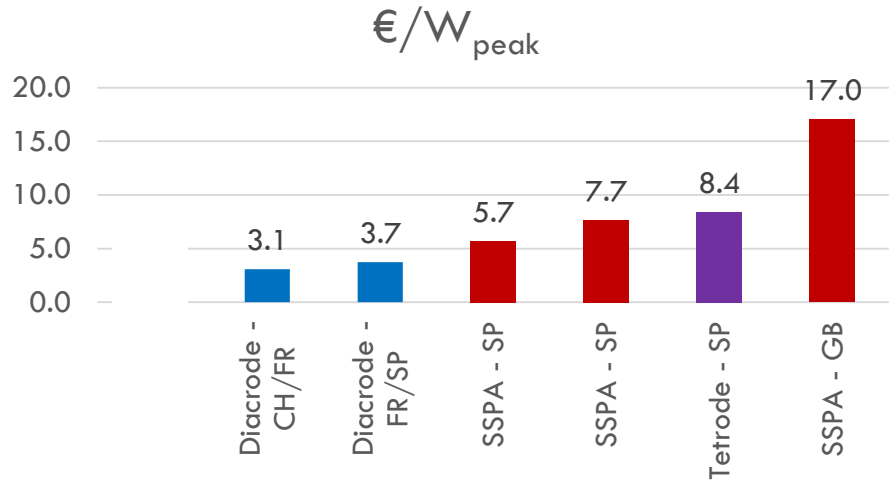
19 selected

8 declined

7 offers





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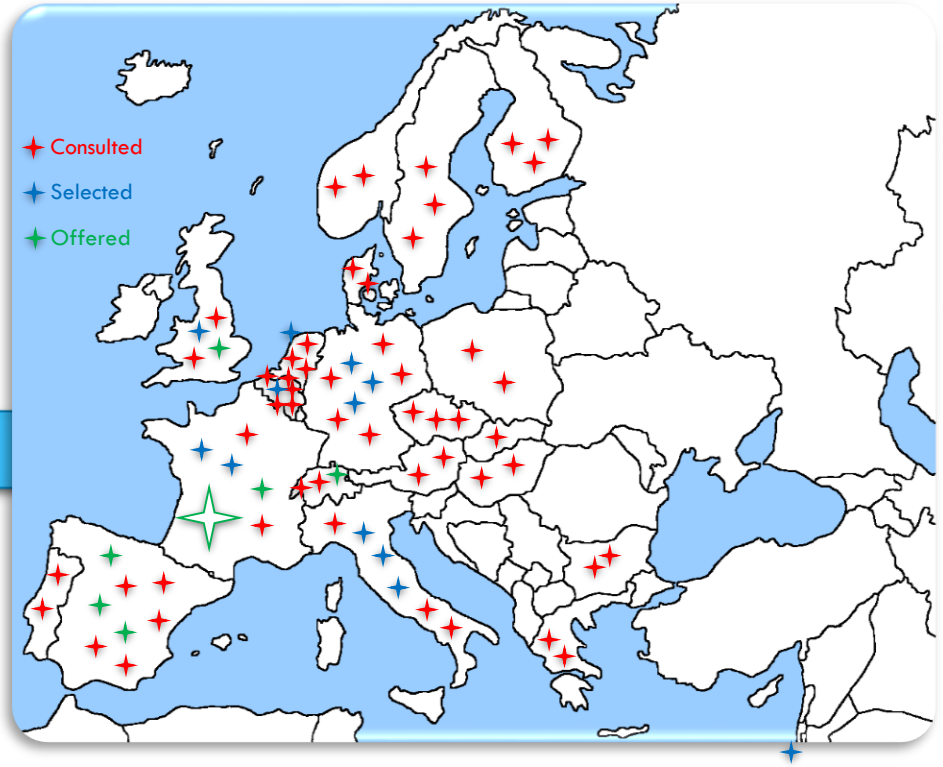


74 companies consulted

19 selected

8 declined

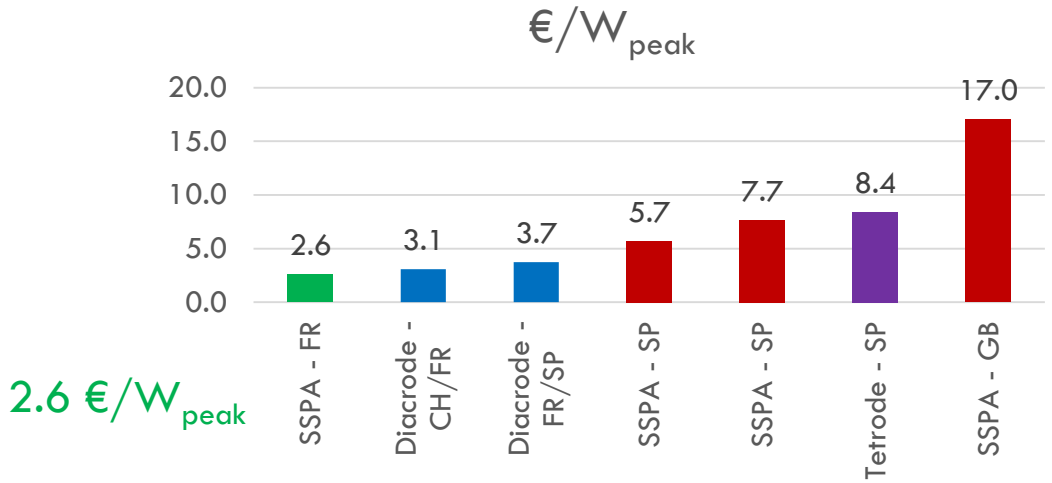
7 offers

March 2015 lowest bid was Thales Communication & Security

Very careful verification of the offer

(I am (was) a tube guy!)

September 2015 CERN FC approval



2.6 €/W peak

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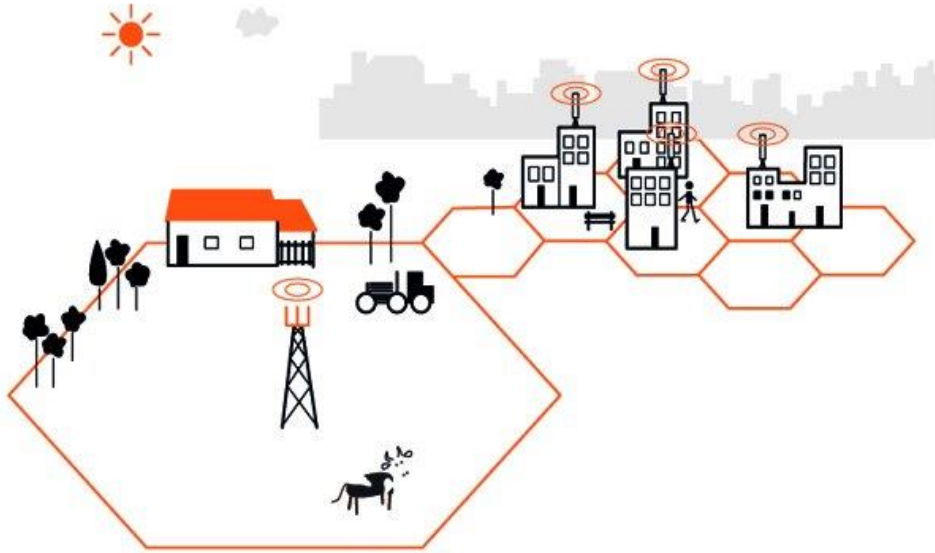
OUTLOOK

1. Brief description of the RF power upgrade project
2. Specificities of the purchasing rules at CERN
3. Technical choices (and difficulties)
4. Operation since beginning 2021

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

Voltage limits		
	2002	2006
900 MHz	41 V/m	3 V/m
1800 MHz	58 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

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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

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CAVITY COMBINERS

CRISP (Sept 2010)

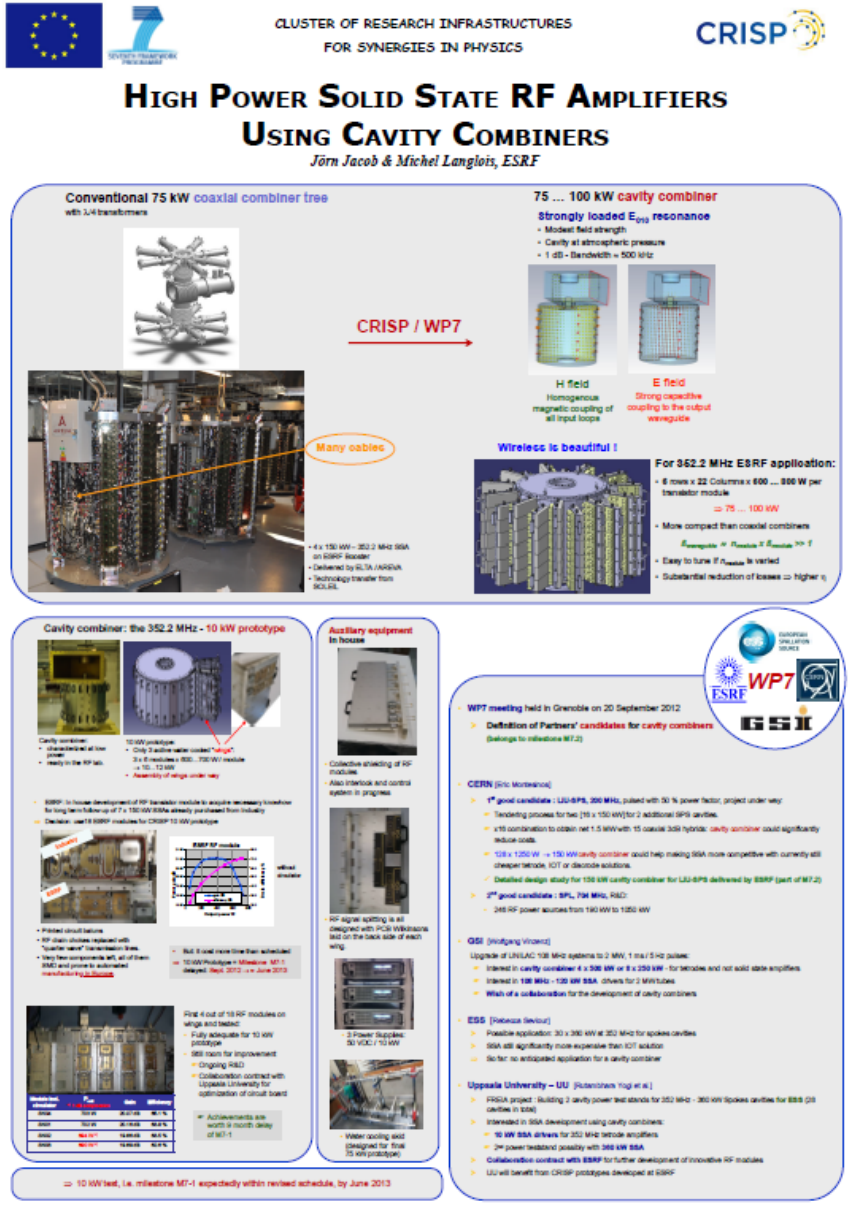
- Jörn Jacob (ESRF) asked for support to the development of cavity combiners receiving funding from the EU as work package WP7 in the framework of the FP7/ESFRI/CRISP program
- CERN immediately supported it

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



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CAVITY COMBINERS

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


EUROPEAN SYNCHROTRON RADIATION FACILITY

ESRF

Accelerator & Source

Technical Note

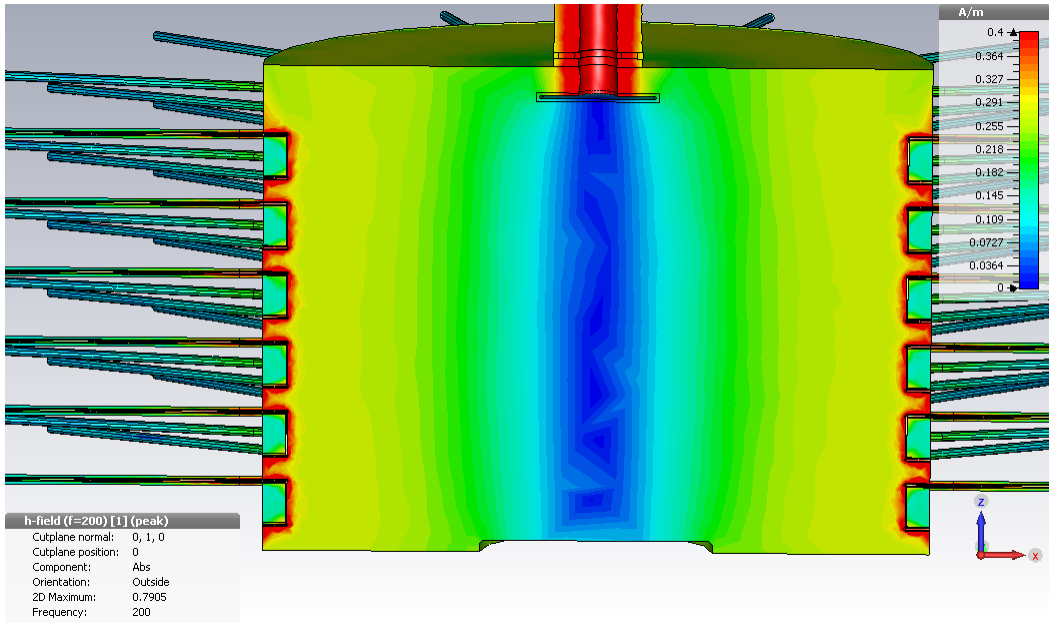
01-13/RF

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

Author(s): Michel LANGLOIS

Date: February11th, 2013

Distribution: Jörn JACOB, Eric MONTESINOS



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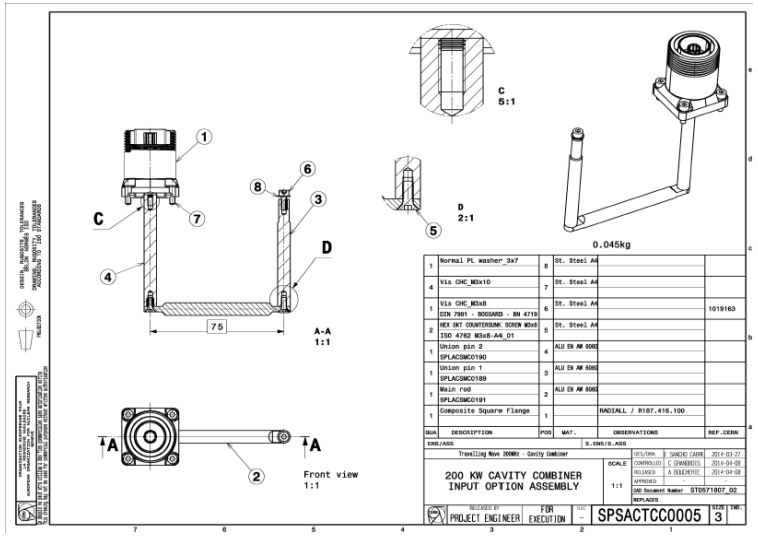

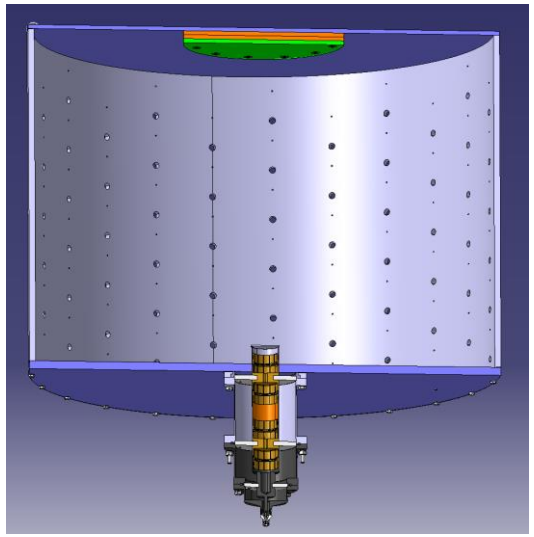

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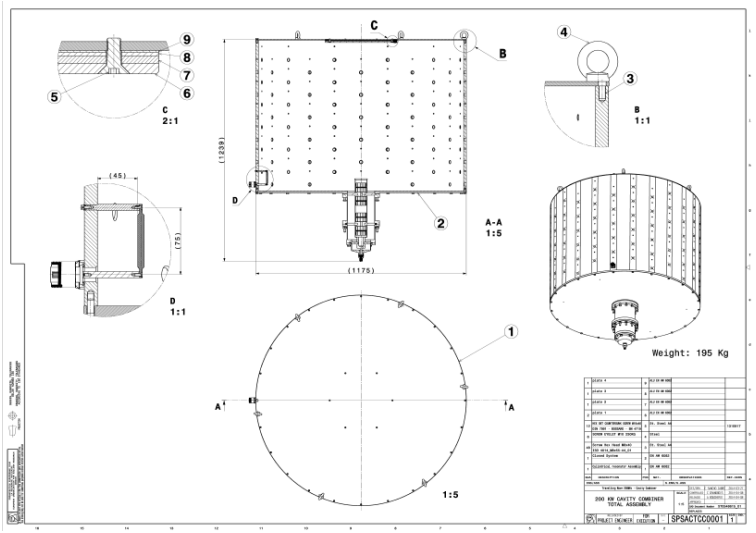

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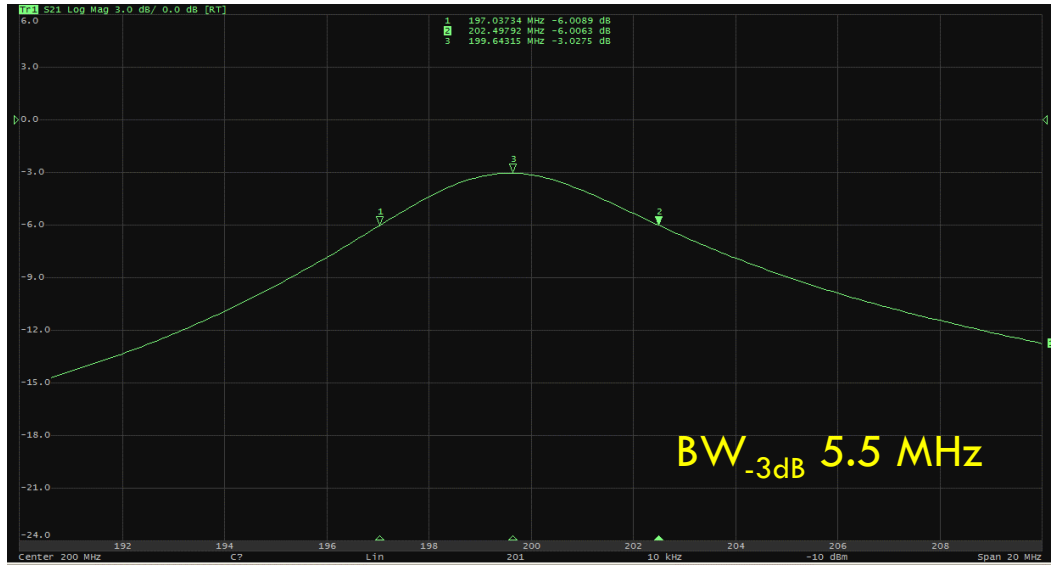

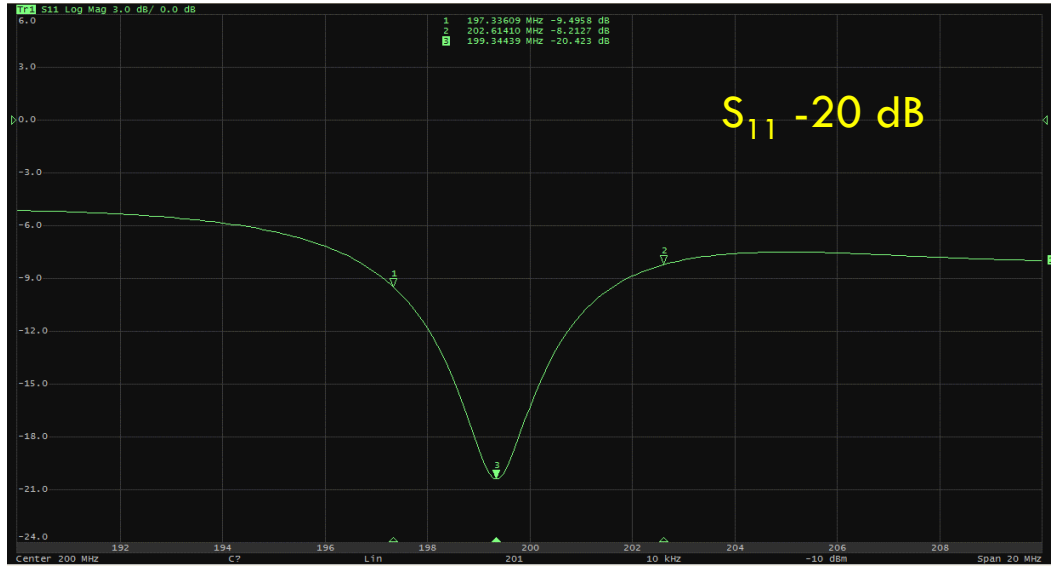

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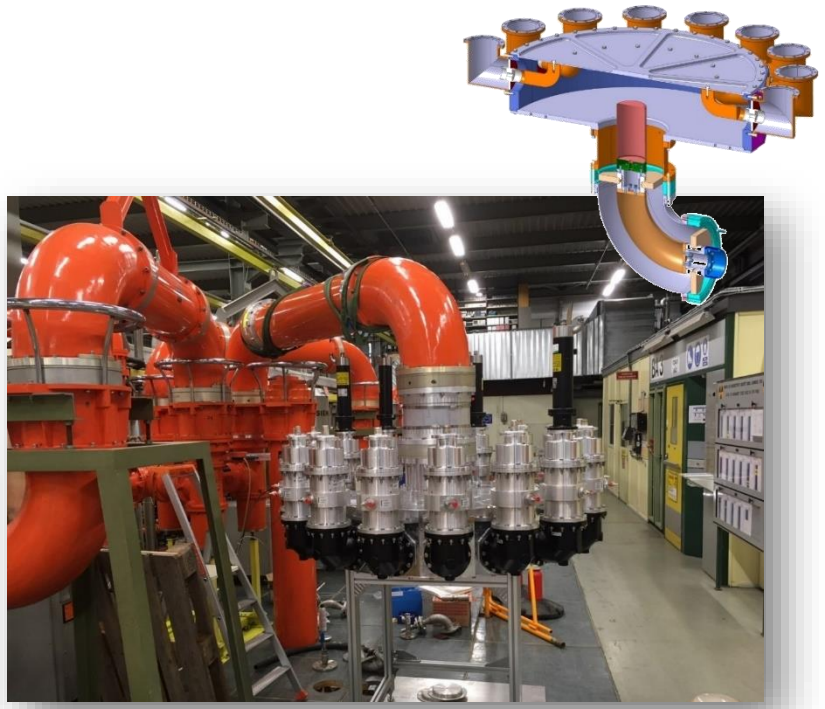
SUPER CAVITY COMBINER

3 dB combiner
32 x 35 kW to 1 x 1 MW
(~ 50 m^2)

CC (Cavity Combiner)
144 x 1 kW to 1 x 144 kW



VHPCC (Very High Power Cavity Combiner)
16 x 70 kW to 1 x 1 MW
(~ 3 m^2)

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IT-3841, FINALS

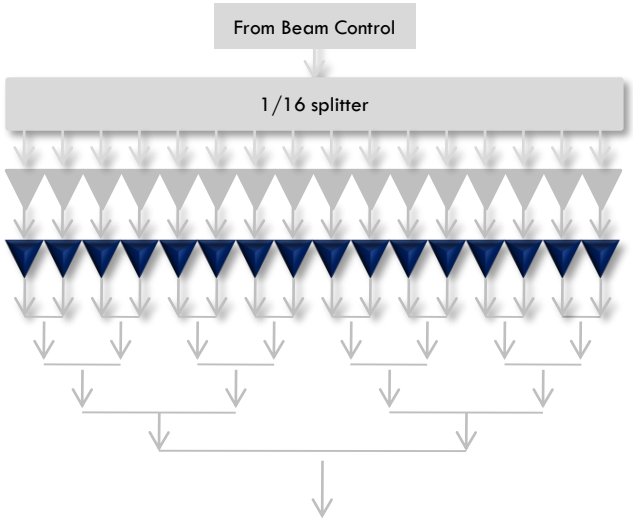
One Transmitter will be composed of
- 16 x 144 kW RF amplifiers

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 amplifiers
- 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

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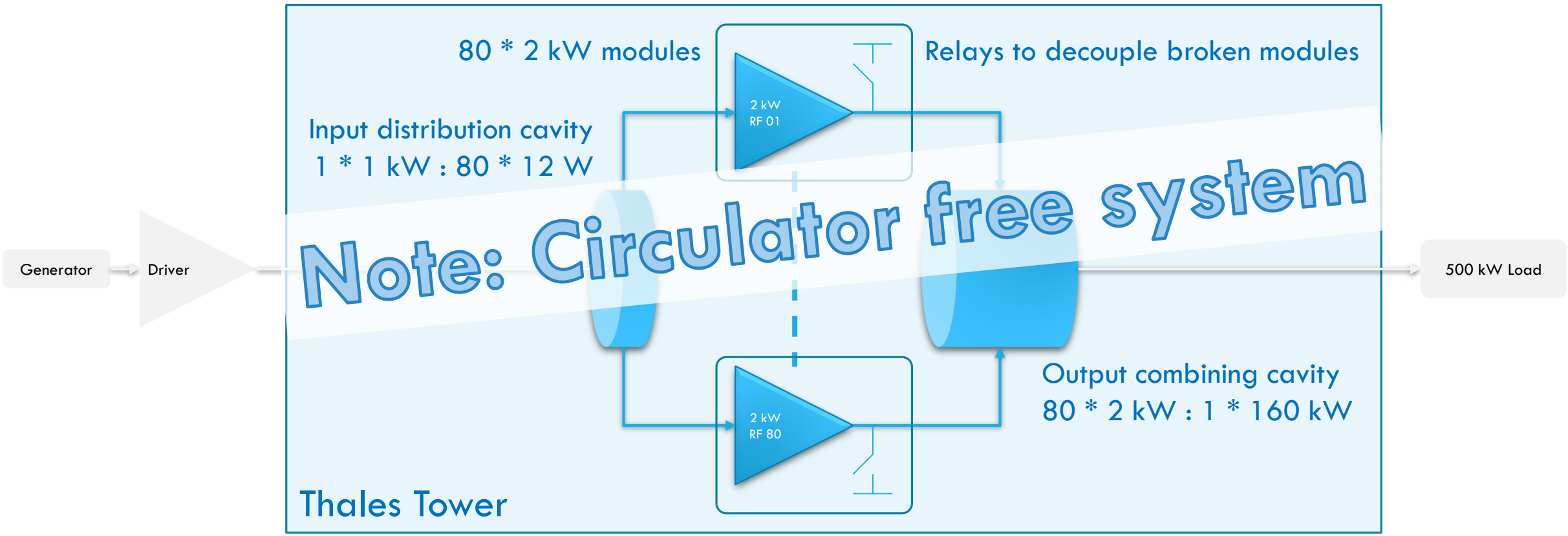
THALES SYSTEM ARCHITECTURE



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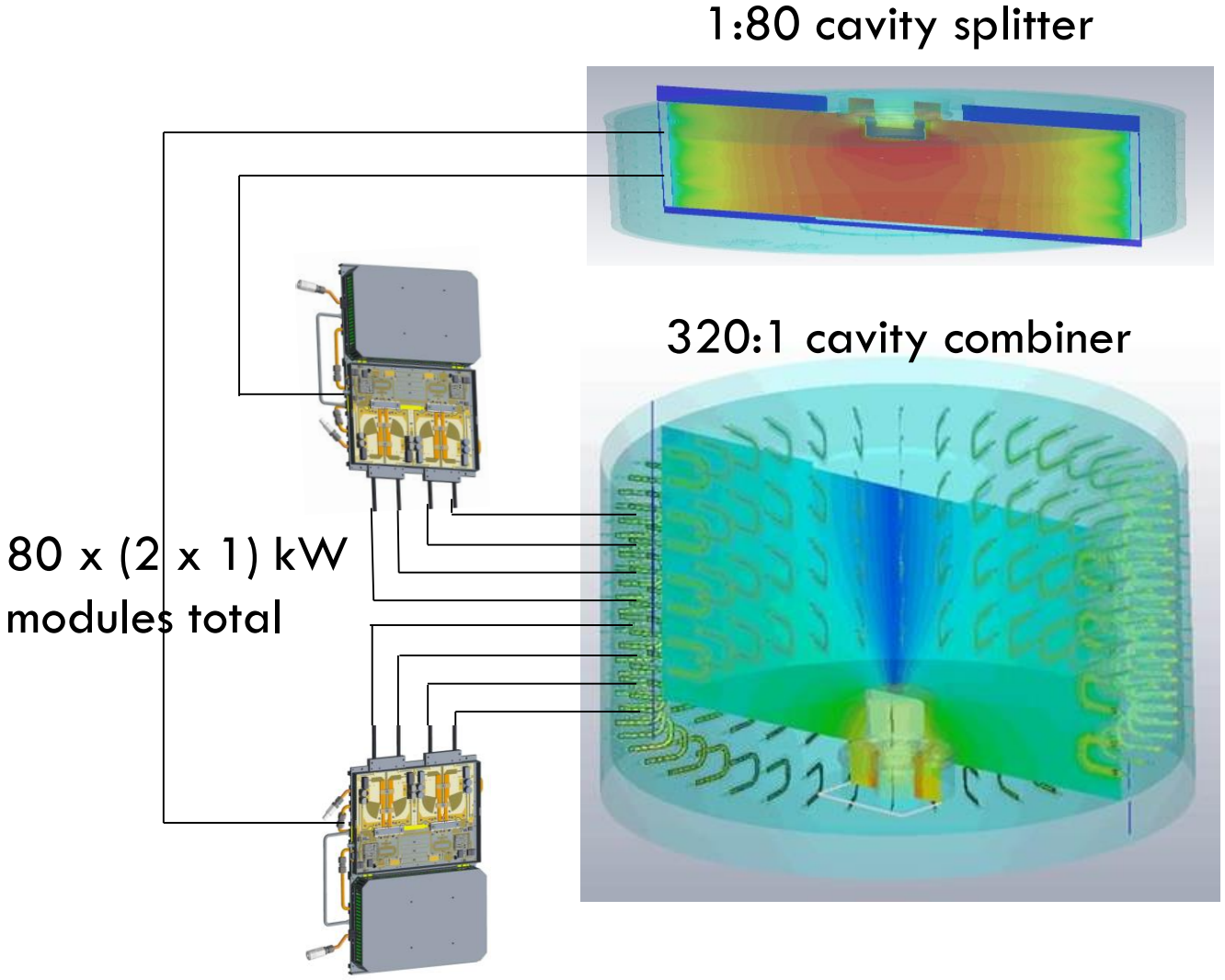
THALES SYSTEM ARCHITECTURE



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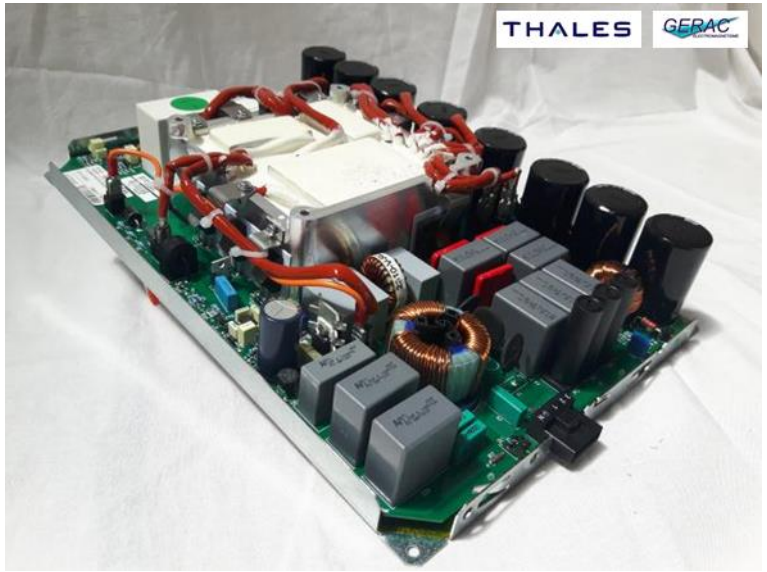
THALES V1



50 VDC power supply

Central frame of the tower
On top the cavity splitter
In the middle cavity combiner

2 kW RF module composed of
50 VDC power supply
Cold plate
RF board with 2 transistors
Output relays

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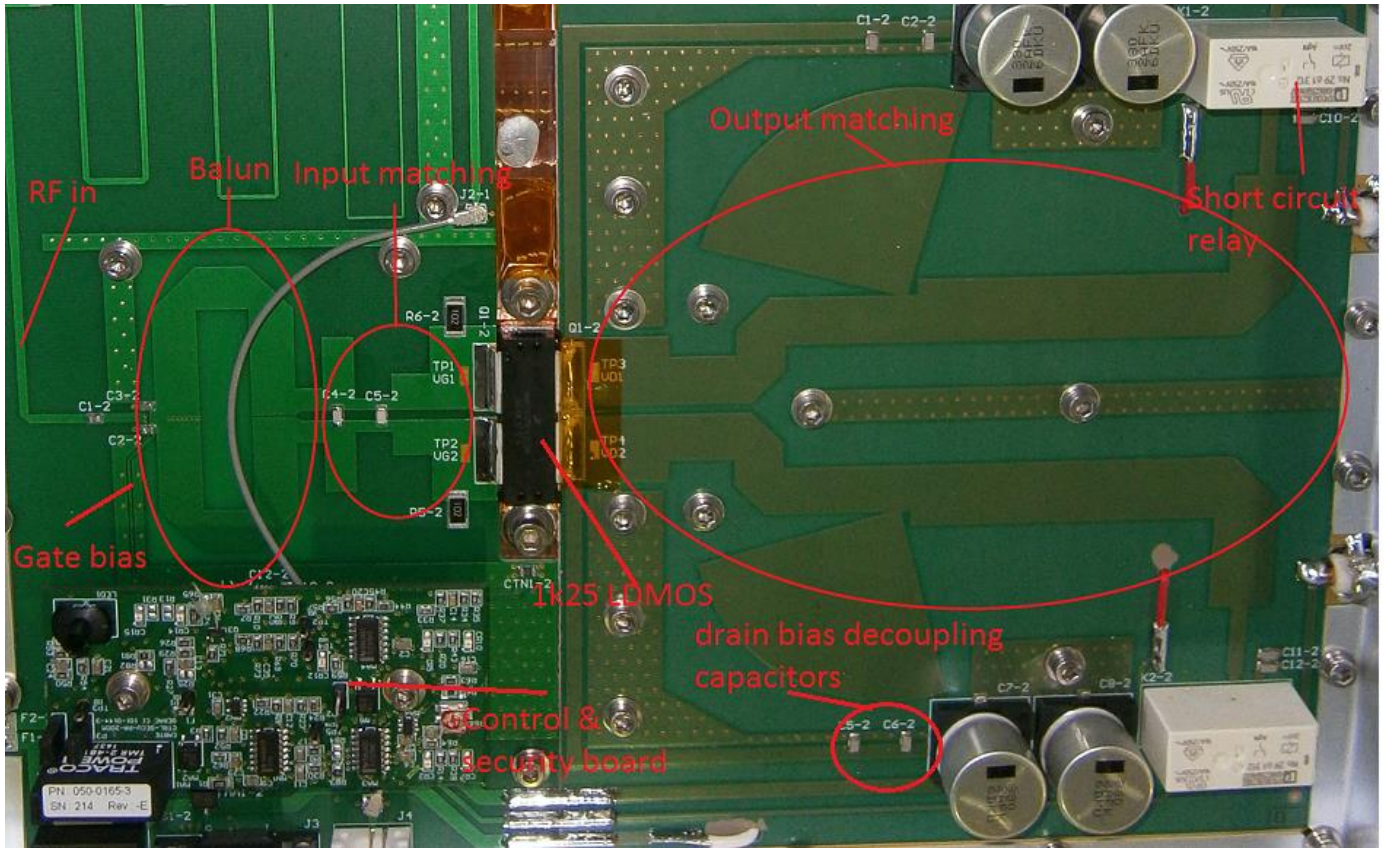
THALES V1



Class AB

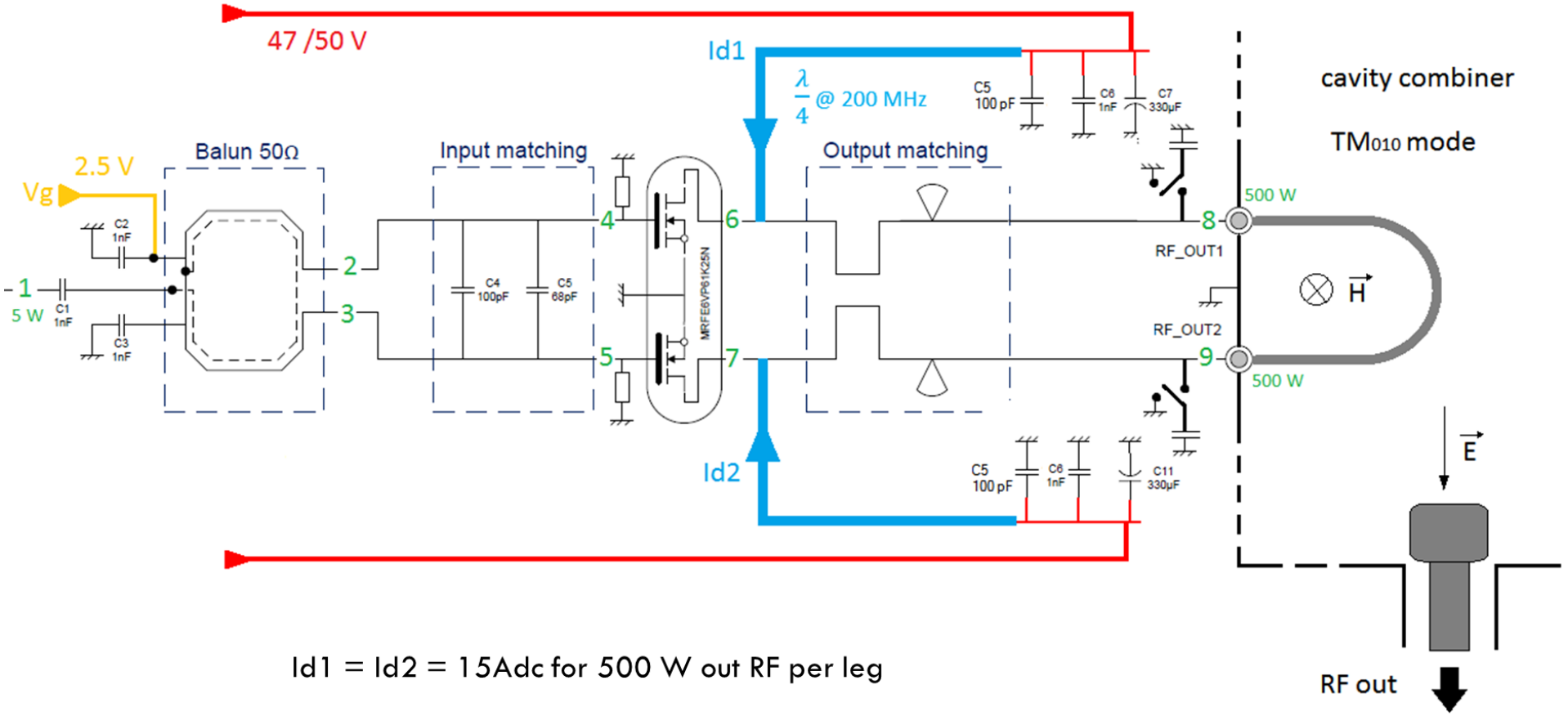
23 dB gain

Push pull configuration

180° out of phase output with the very clever proposal of having the output Balun closed inside the cavity combiner

- Less power along the cables
- smaller cables
- Smaller connectors
- Loop inside the cavity made with a Printed Circuit Board

THALES V1



Id1 = Id2 = 15Adc for 500 W out RF per leg

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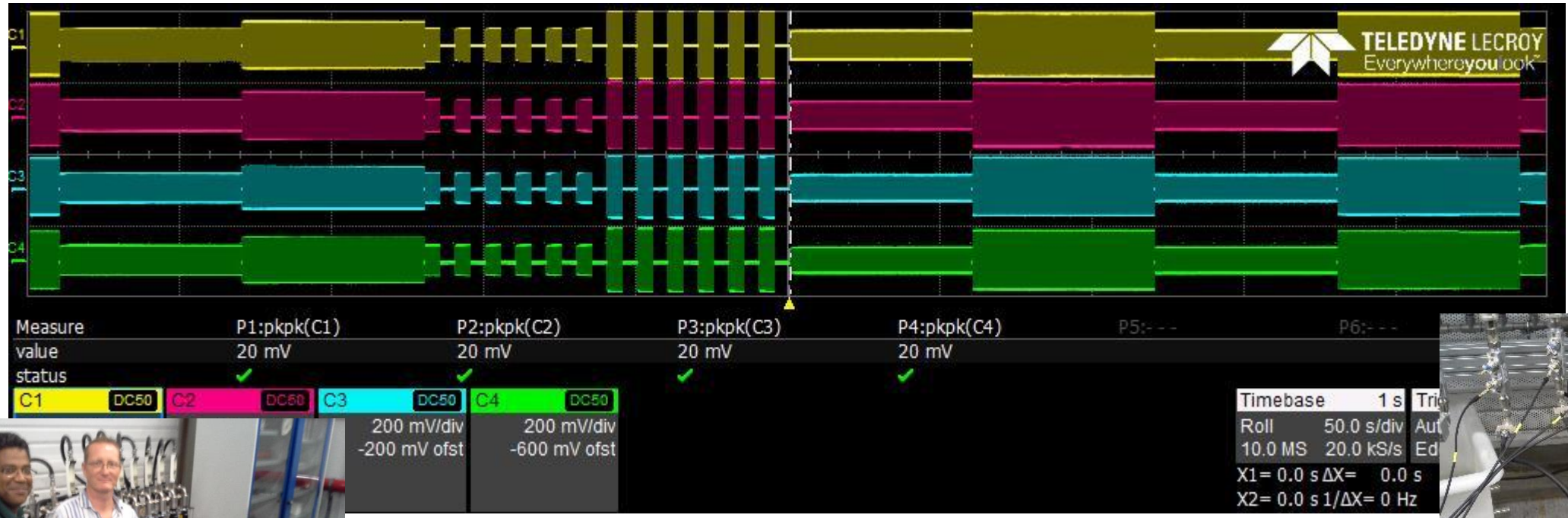
THALES V1 PROTOTYPES SUCCESSFULLY TESTED



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

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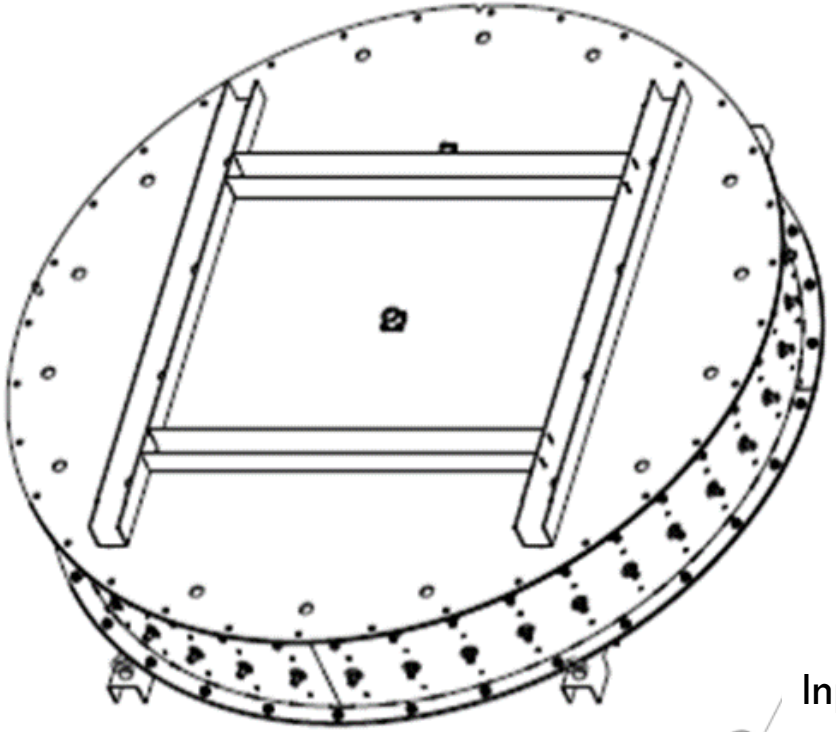
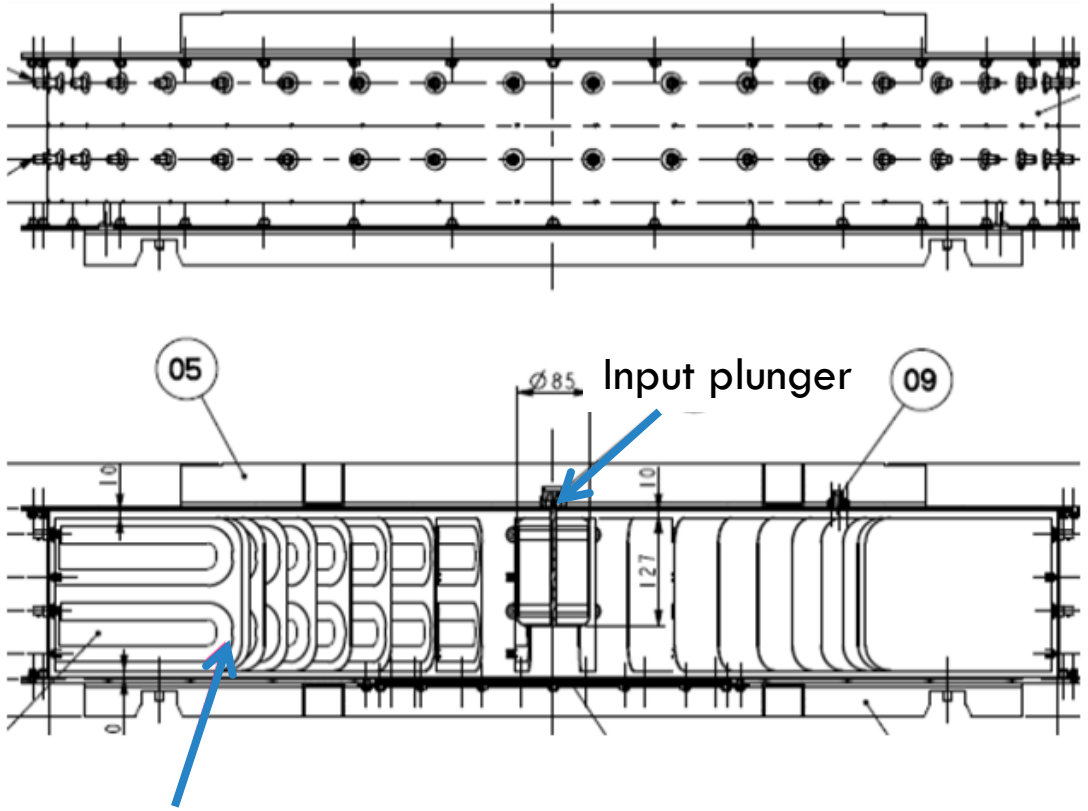
CAVITY SPLITTER 80:1





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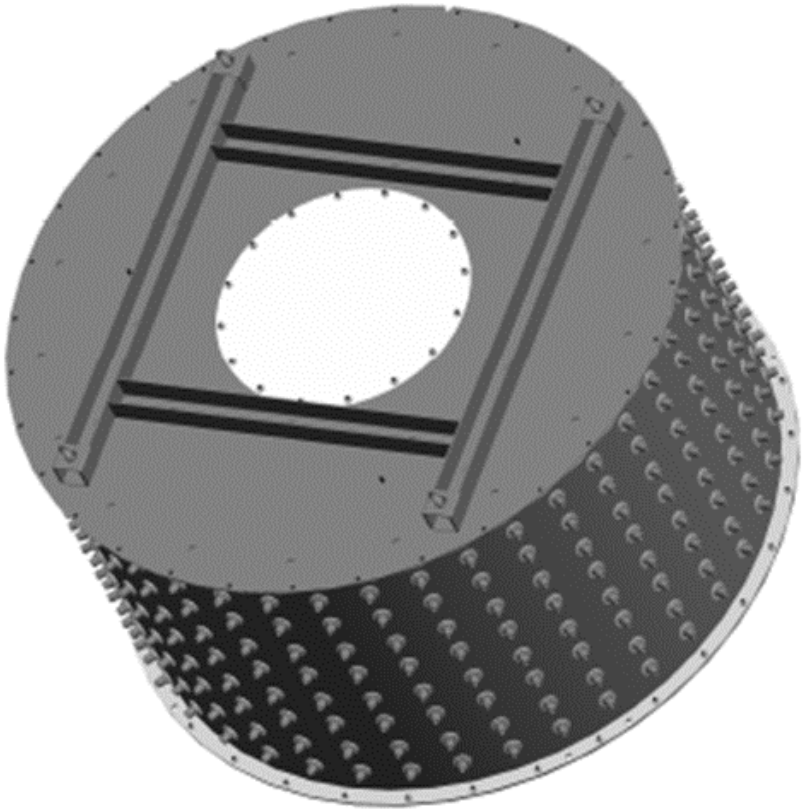
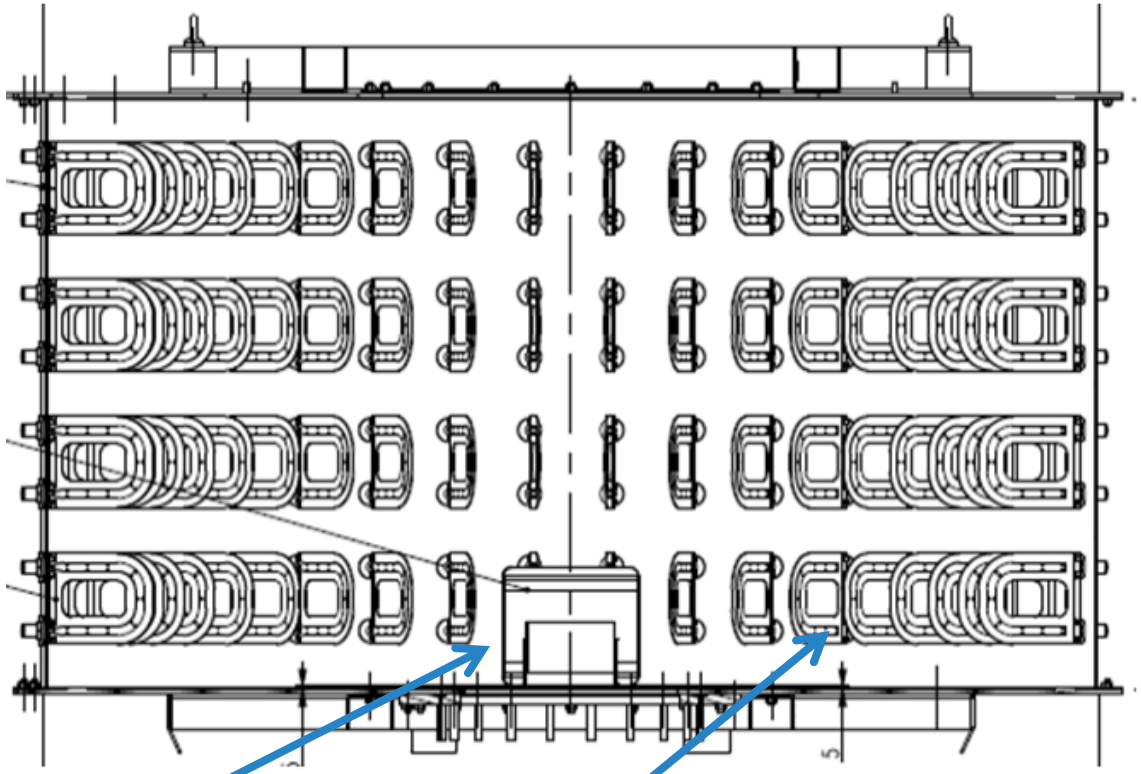
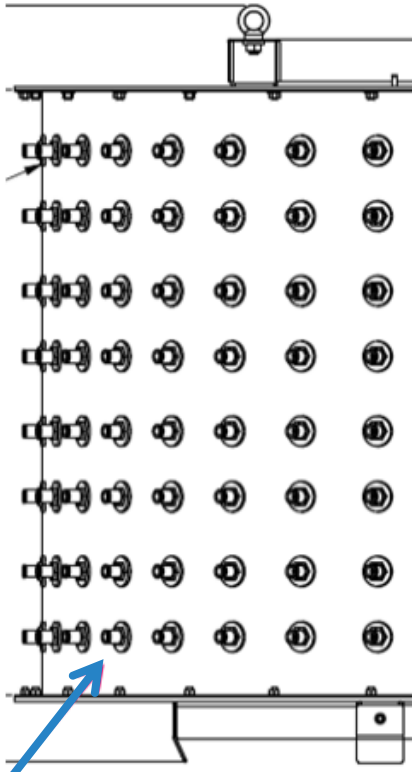
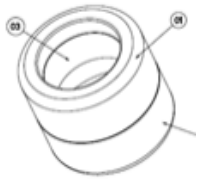
CAVITY COMBINER 320:1









Output plunger

Coupling with PCB

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

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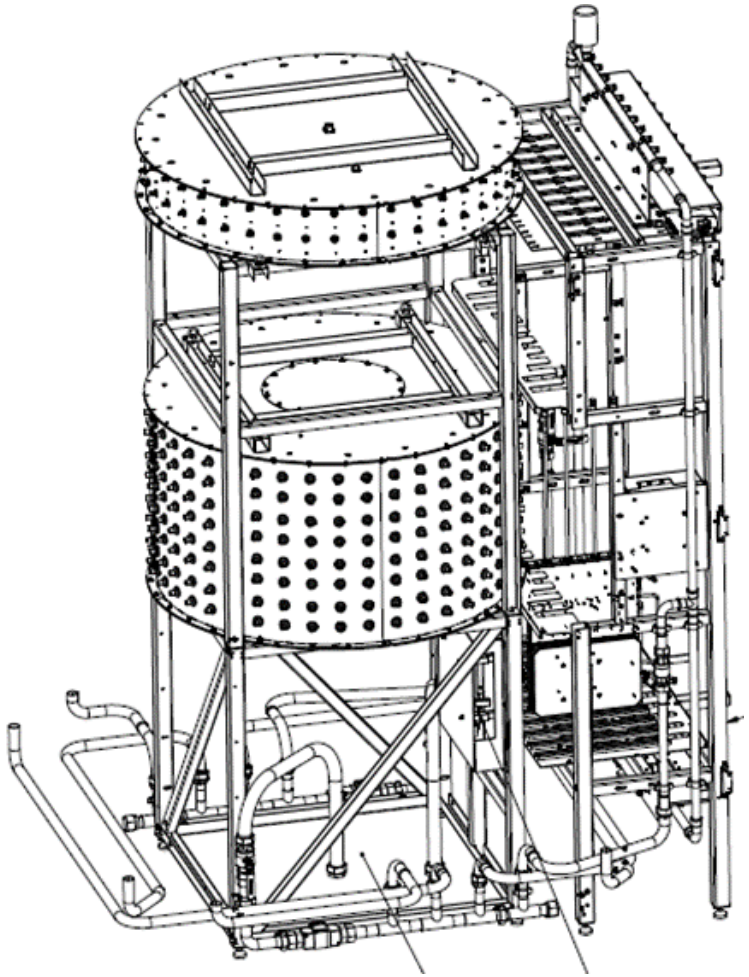
TOWER



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

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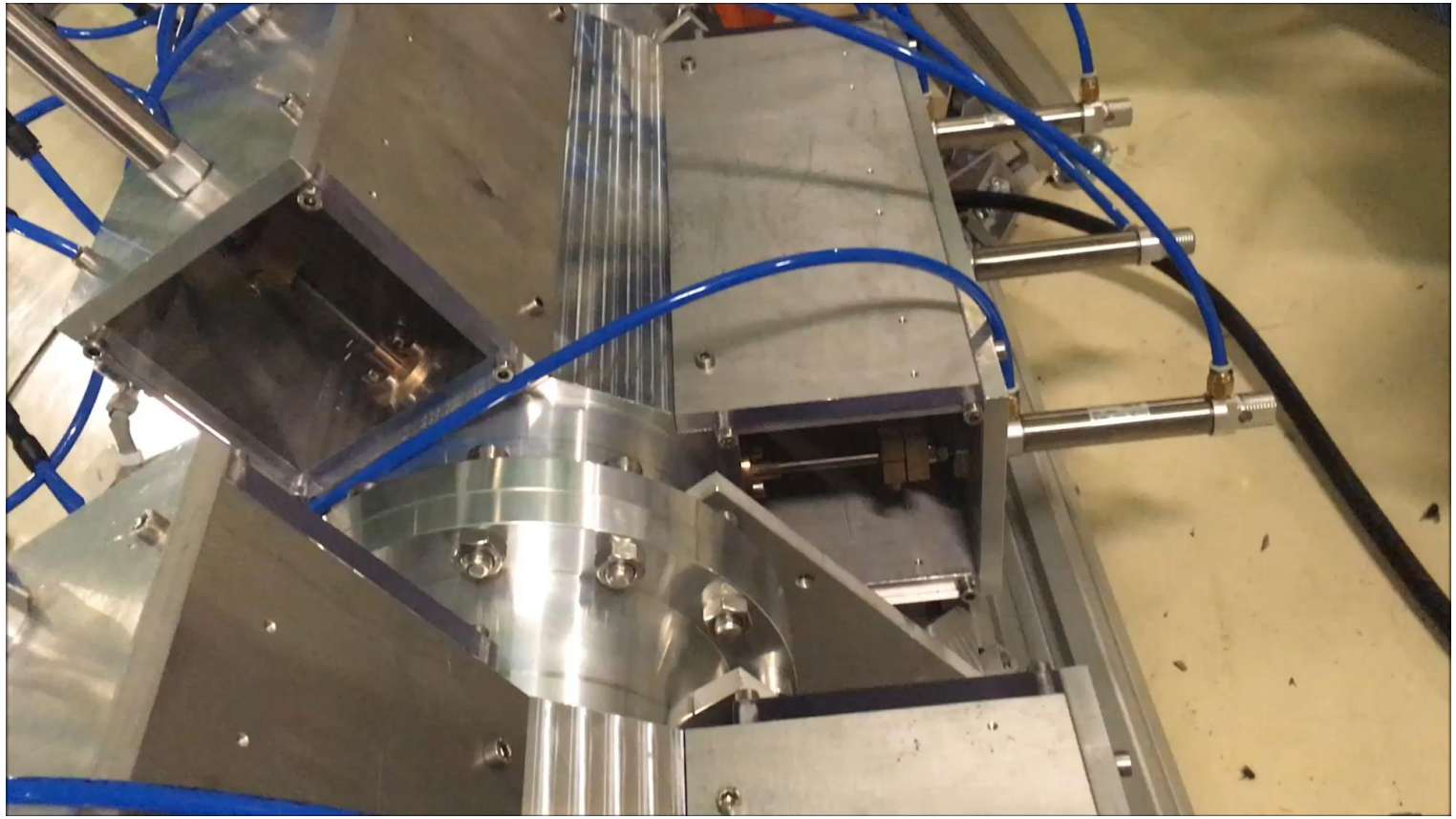
SHORT CIRCUIT TEST



We started with the short circuit test

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

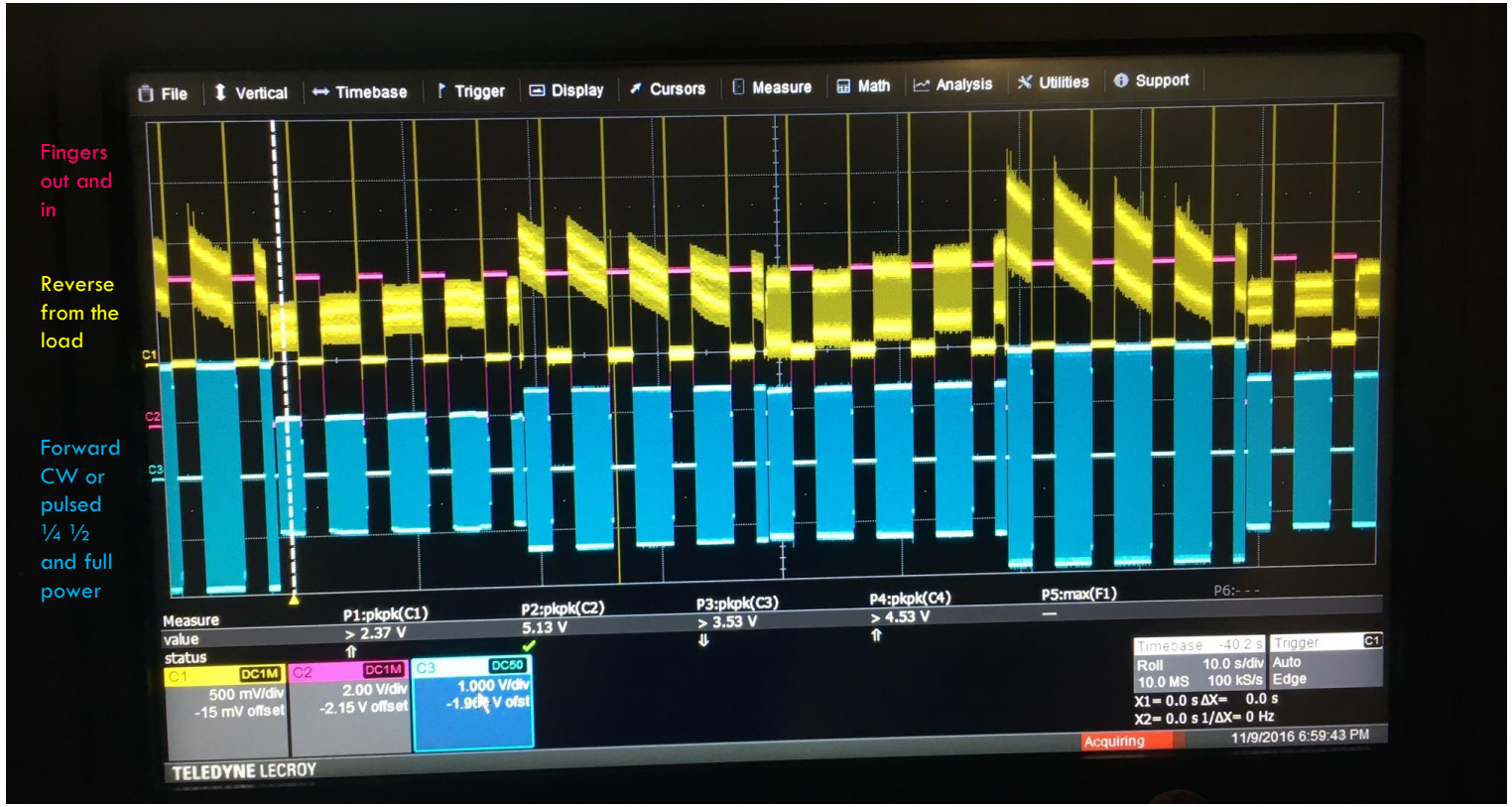
We repeated the short circuits during one hour every 5 seconds under various phase and various power conditions

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**

SHORT CIRCUIT TEST



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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…

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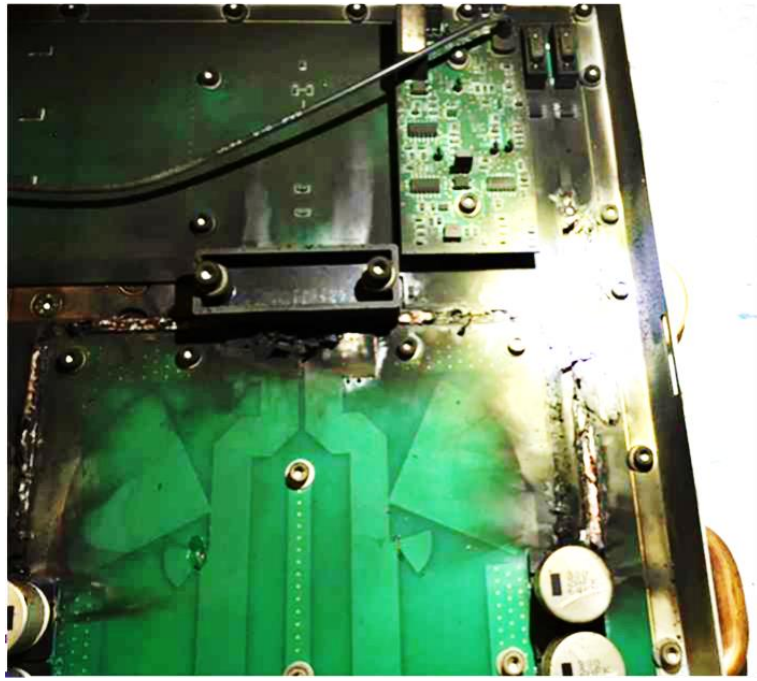
TROUBLES WITH TRANSISTORS

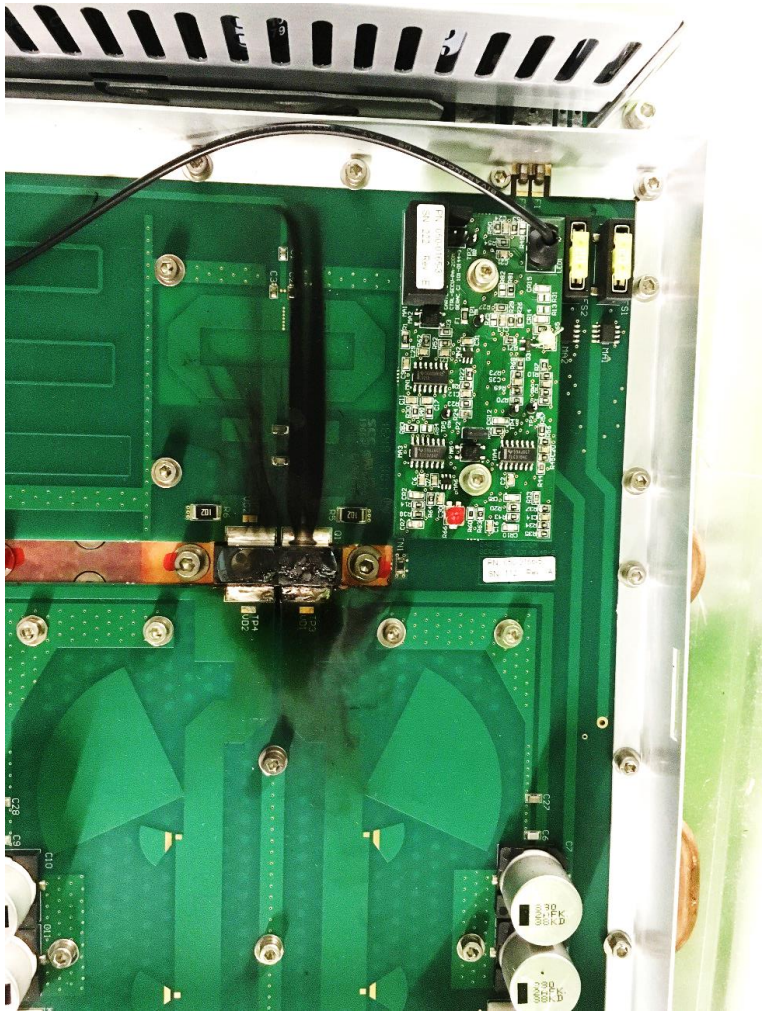
We then launched the long duration test

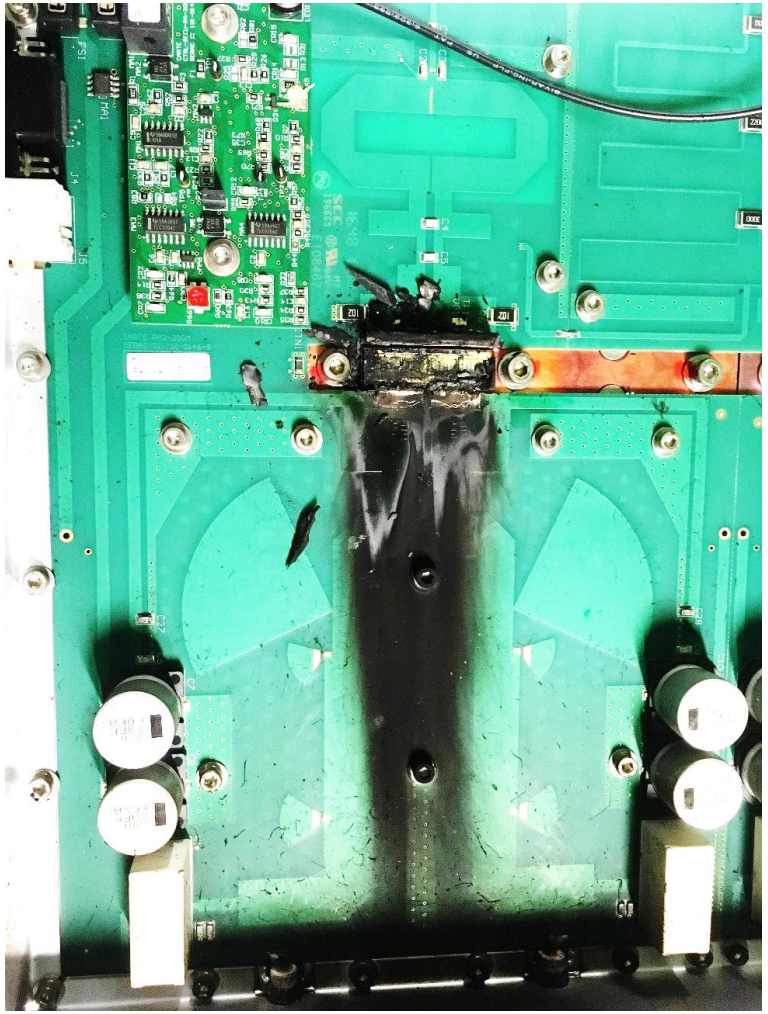
1000 hours was requested in the Technical Specifications (you will understand why I am always recommending to do so…)

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



TROUBLES WITH TRANSISTORS





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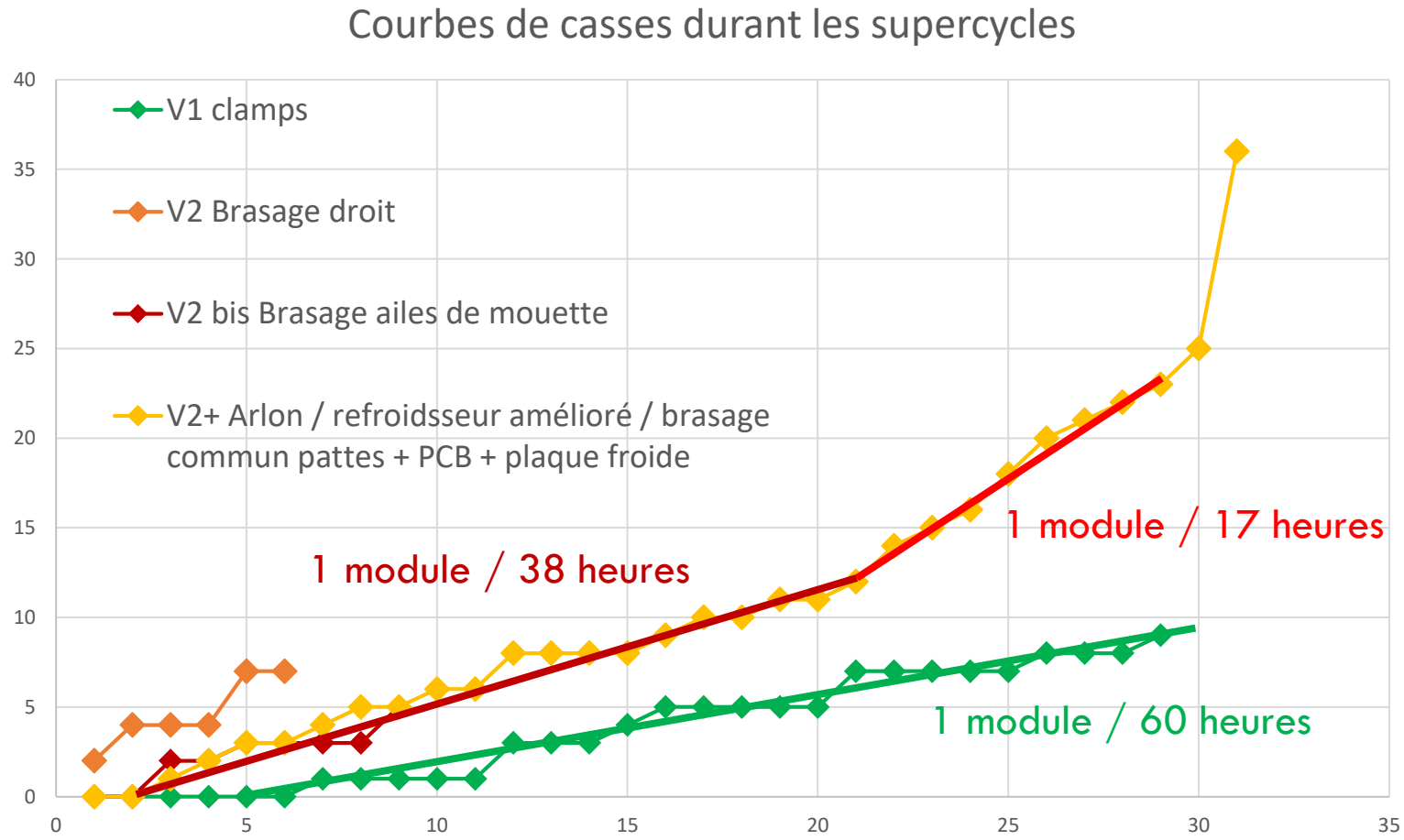
CLAMPED VERSUS BRAZED TRANSISTORS

Initially, we agreed for a clamped transistor version

The advantage would have been the exchanged of broken transistors

We suspected that decision to be the root cause of our troubles, so Thales launched several brazed new versions

None were significantly better



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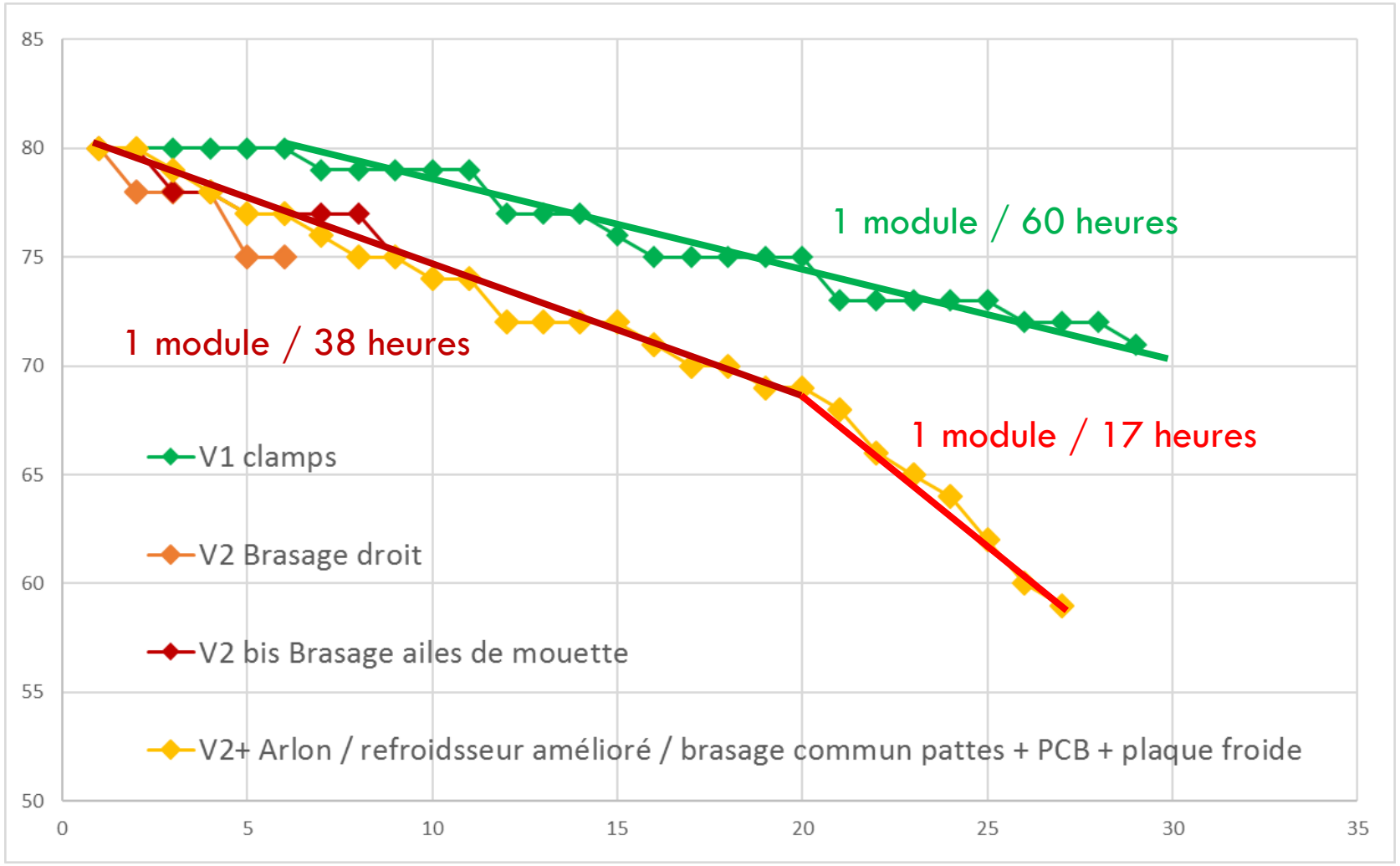
CLAMPED VERSUS BRAZED TRANSISTORS

We also modified the angle of brazing, not a success

We added Arlon instead of FR4, better on some aspects, but globally not a success

We improved the water cooling, helped but not a success



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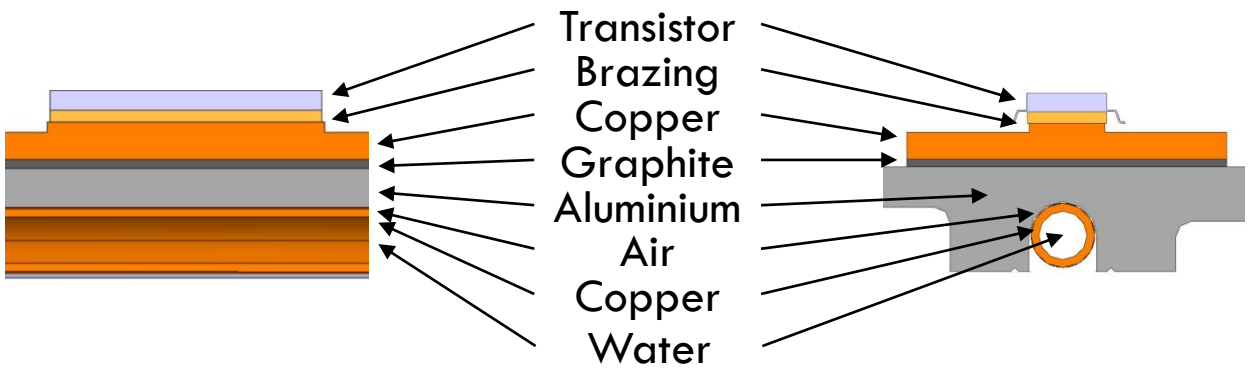
INITIAL VS NEW WATER COOLING DESIGN

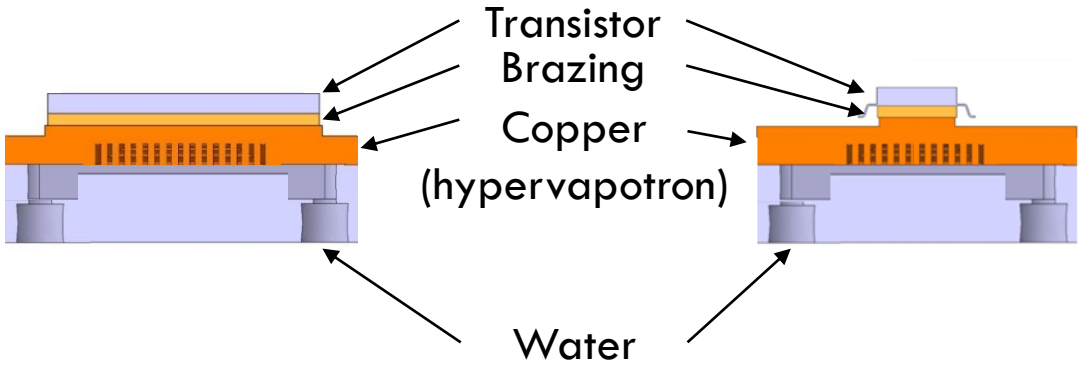
Initial design V1/V2

6 layers between water and die



New design V3/V4

2 layers between water and die



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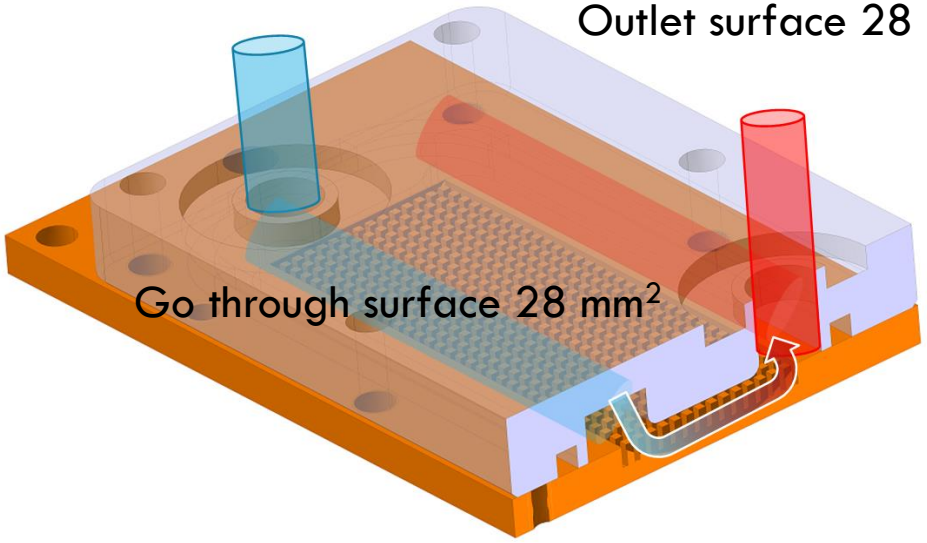
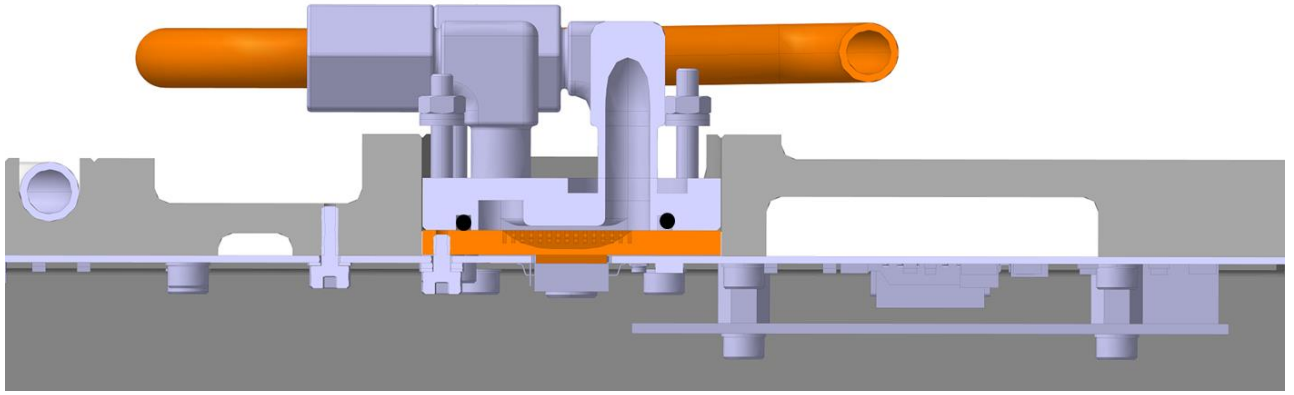
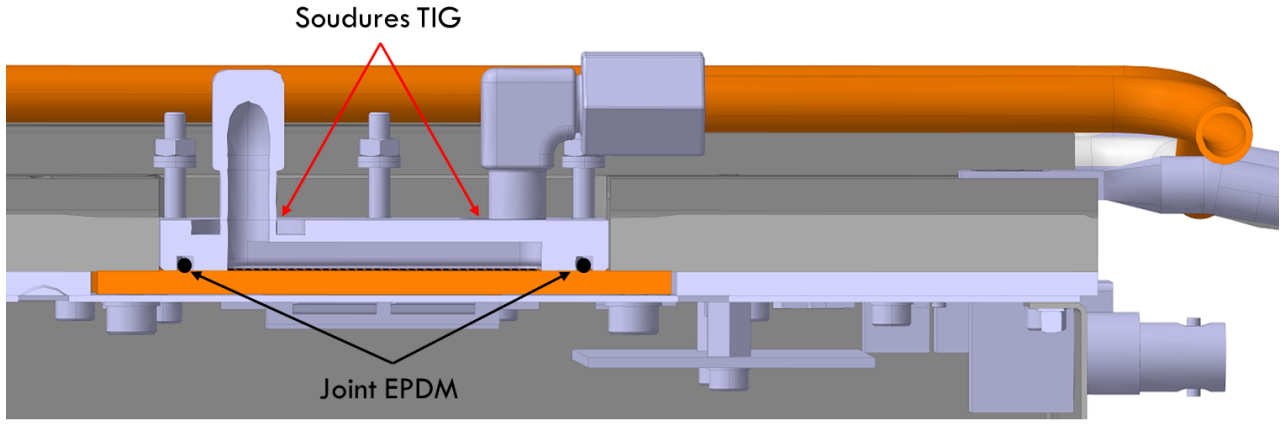
HEAT TRANSFER

Inlet surface 28 mm^2

Outlet surface 28 mm^2







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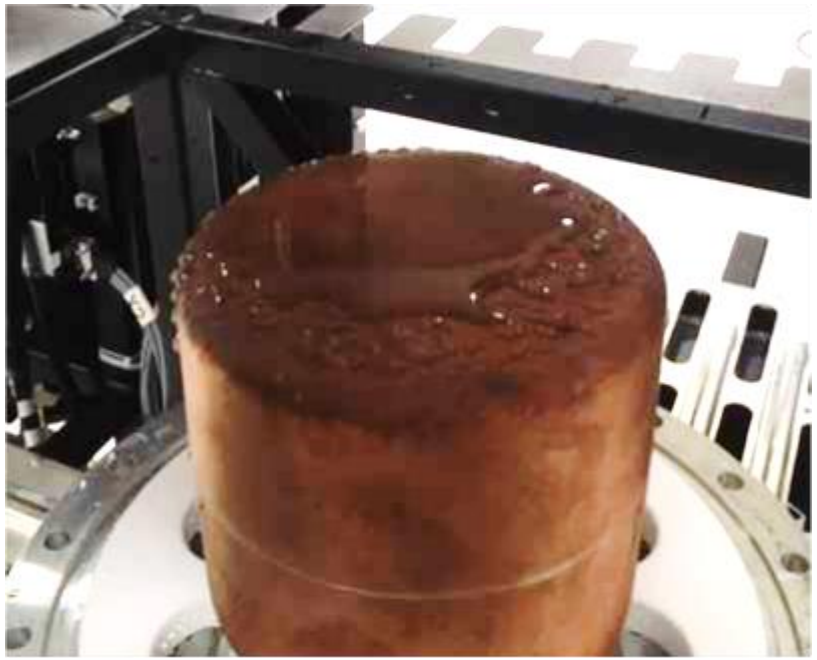
WATER COOLING

One piping failed and we had water flowing inside the combining cavity

It took us days to get rid of it

The good in it was that Thales immediately agreed to move from ‘plastic’ piping to stainless steel piping

It seems to be a detail, but a detail that cost them almost 1 MCHF



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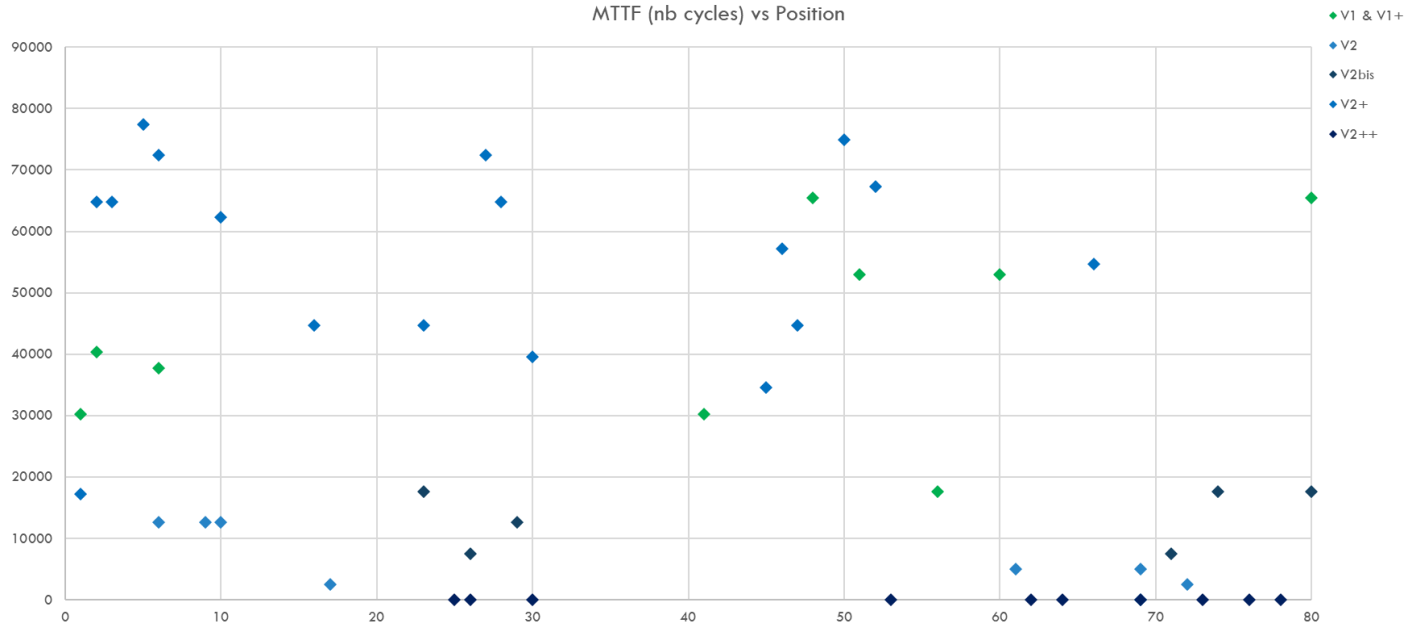
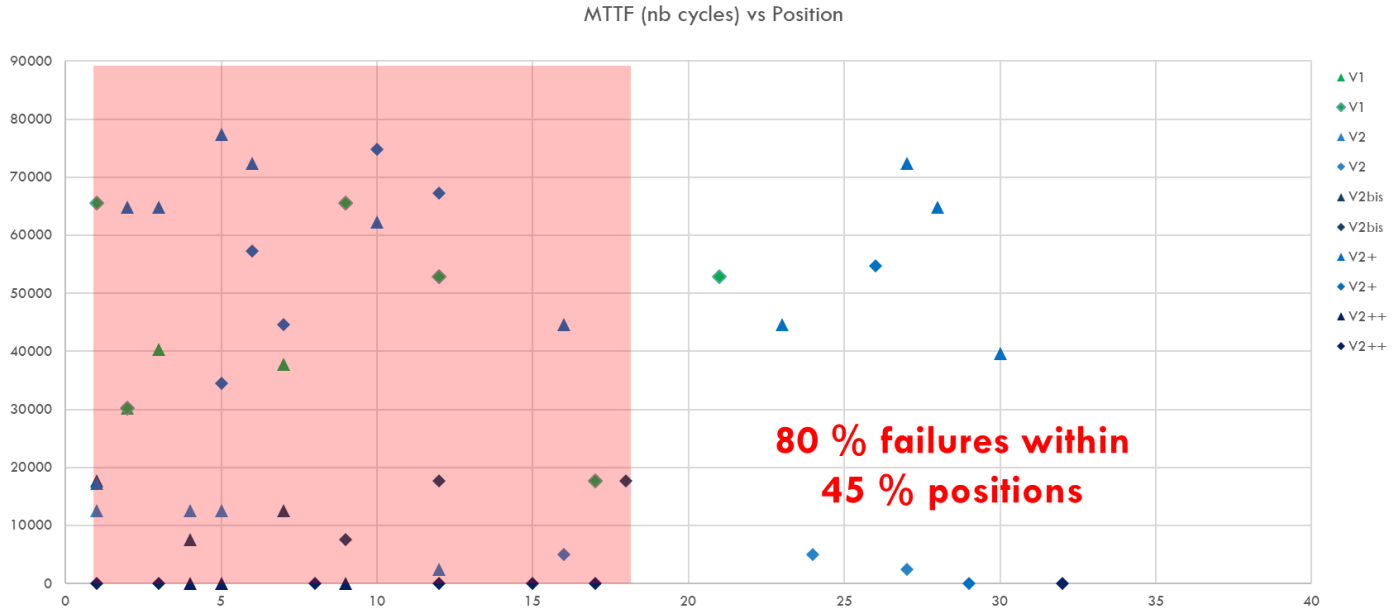
MTTF DATA

Failure seemed to be randomly distributed

However, playing with the data of the combining cavity, rotating it helped to show a dispersion effect





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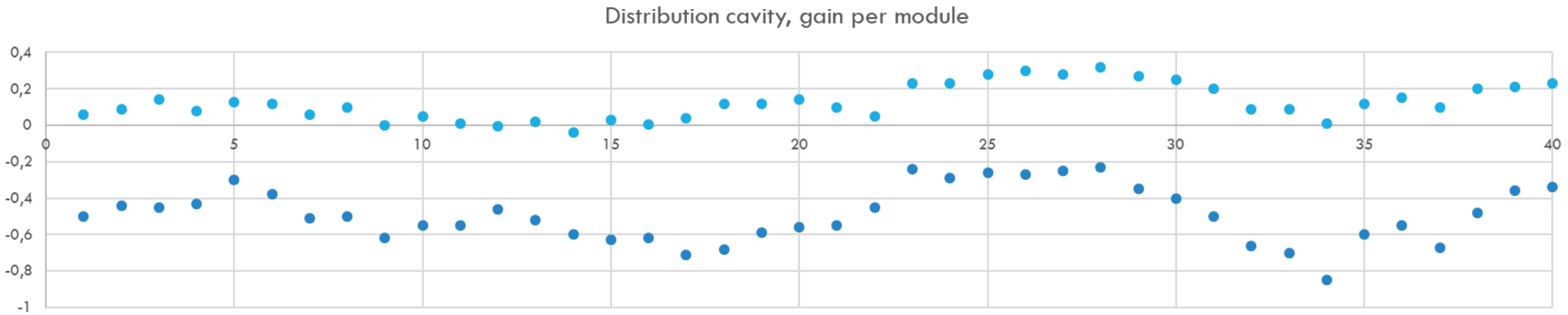
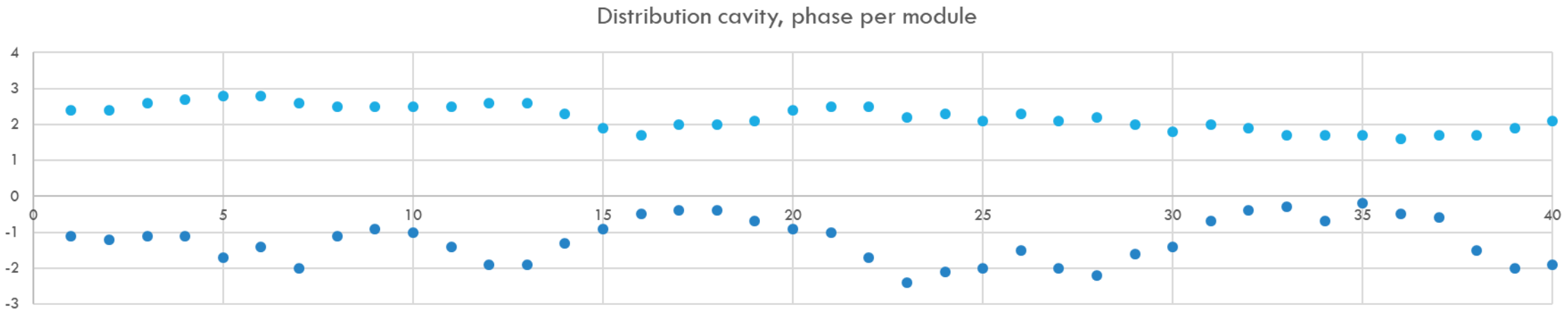
DISTRIBUTION CAVITY





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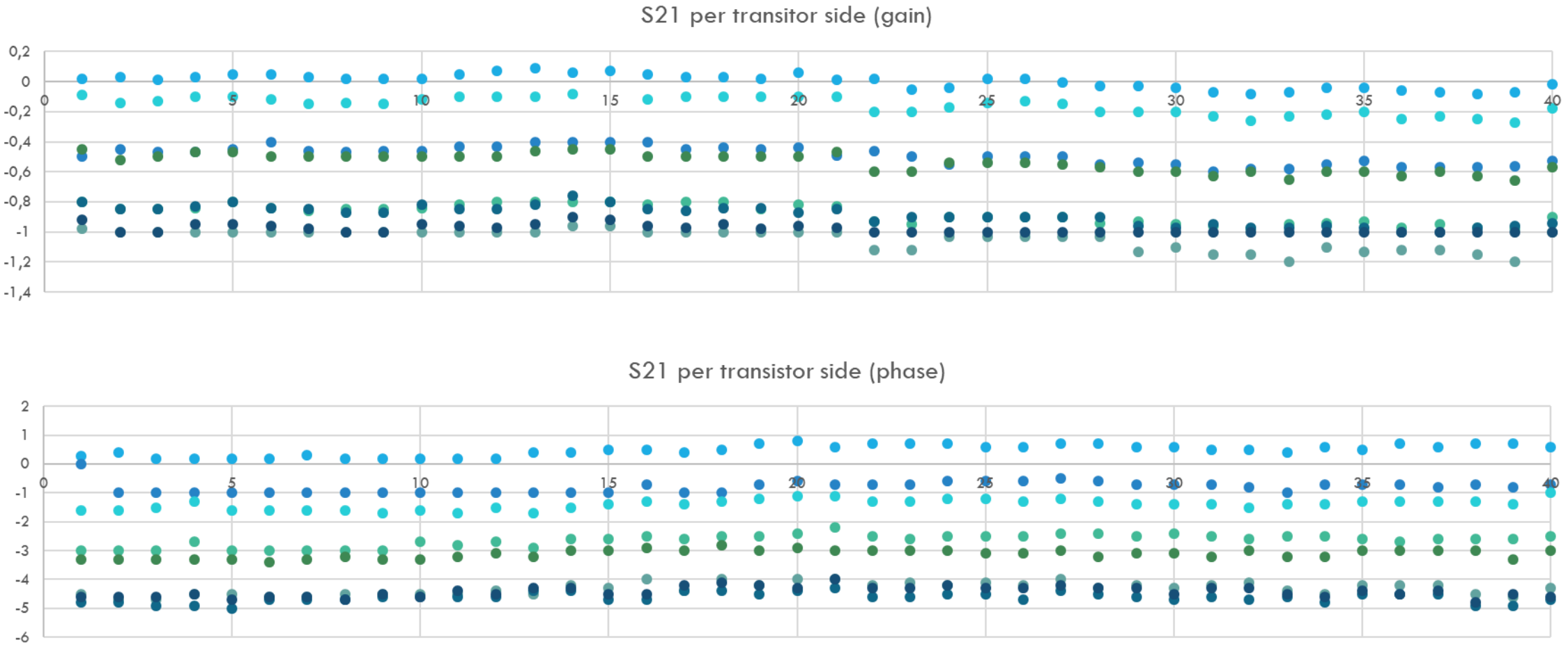
COMBINING CAVITY



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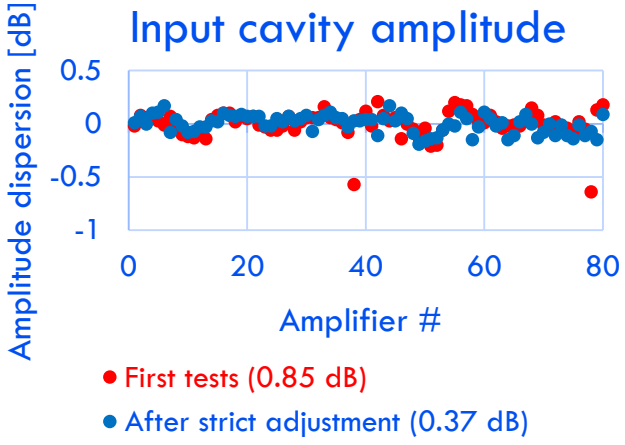
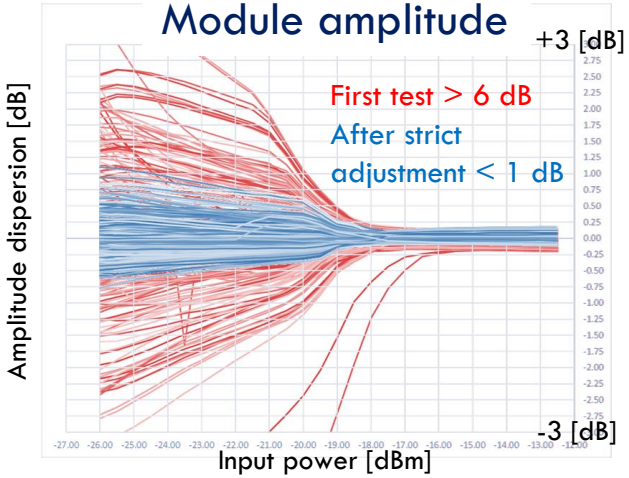
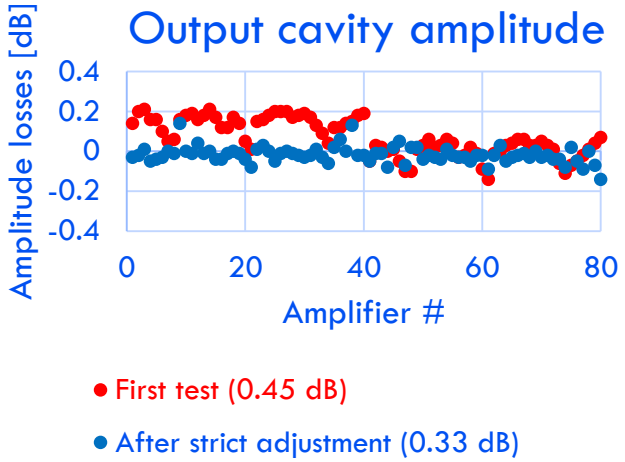
RF DISPERSION

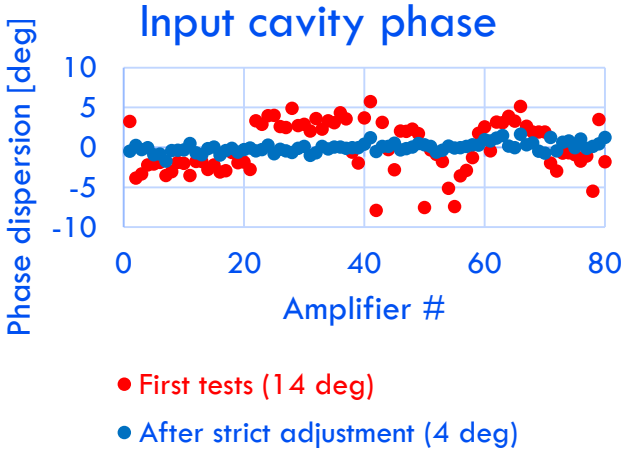
First test — total amplitude 7.2 [dB] — total phase 51 [deg]

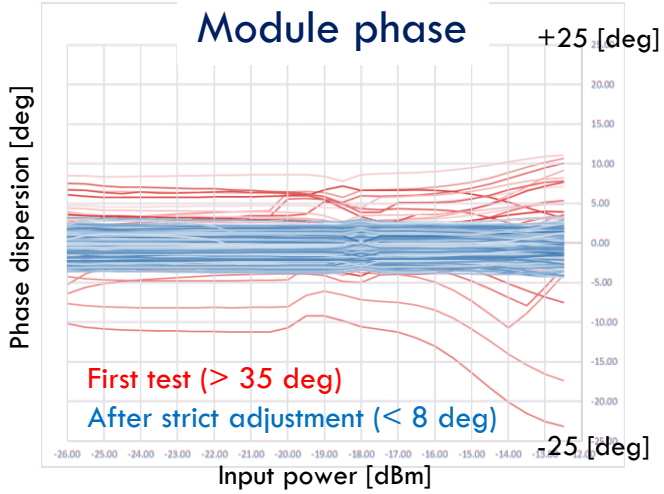
After strict adjustment — total amplitude 1.7 [dB] — total phase 15 [deg]

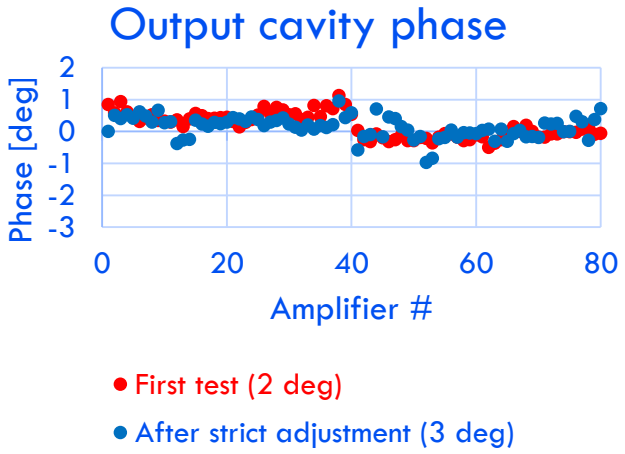












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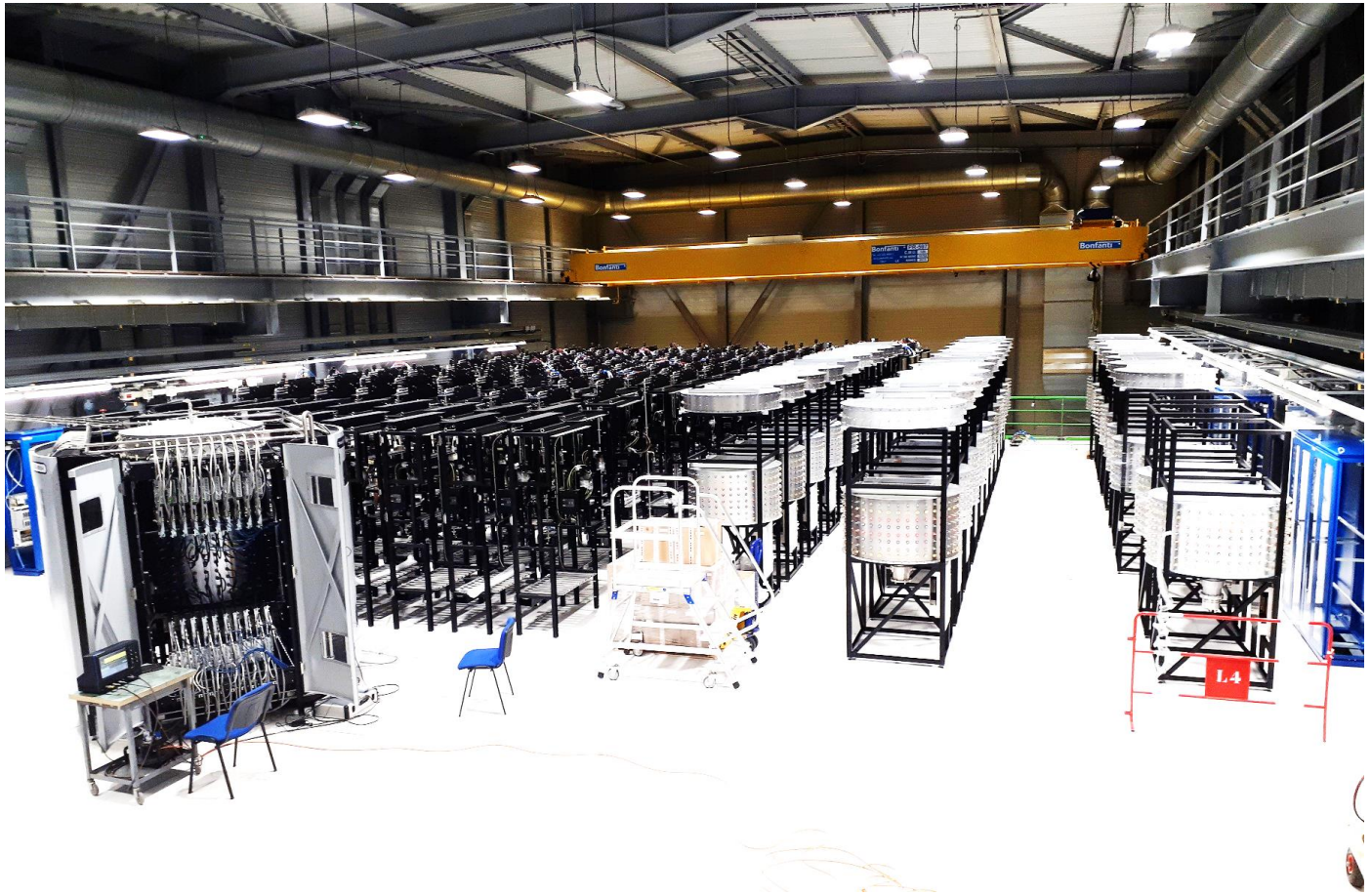
CERN & THALES NOT READY TO GIVE UP

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

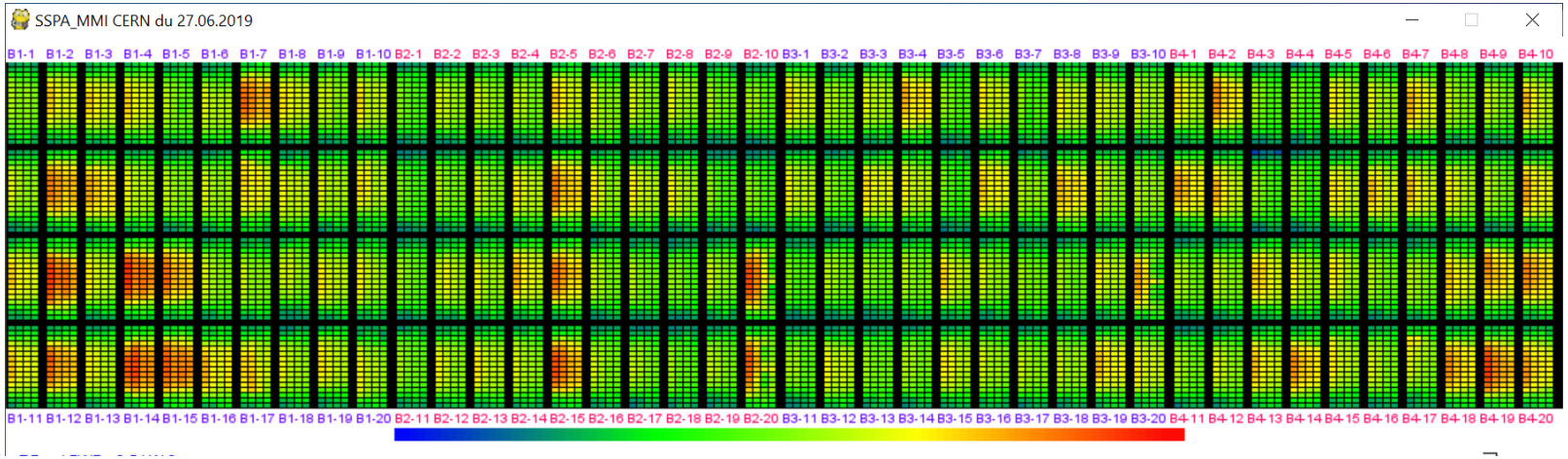
This was impressive, even for us

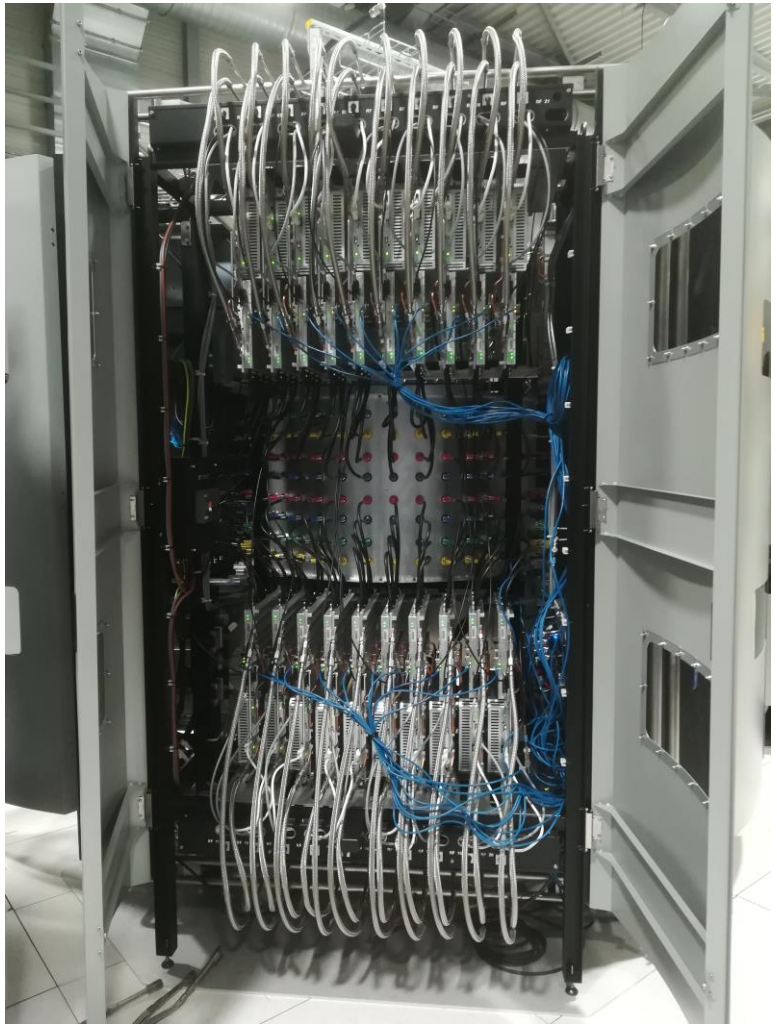


THERMAL CAMERAS ON TRANSISTORS

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





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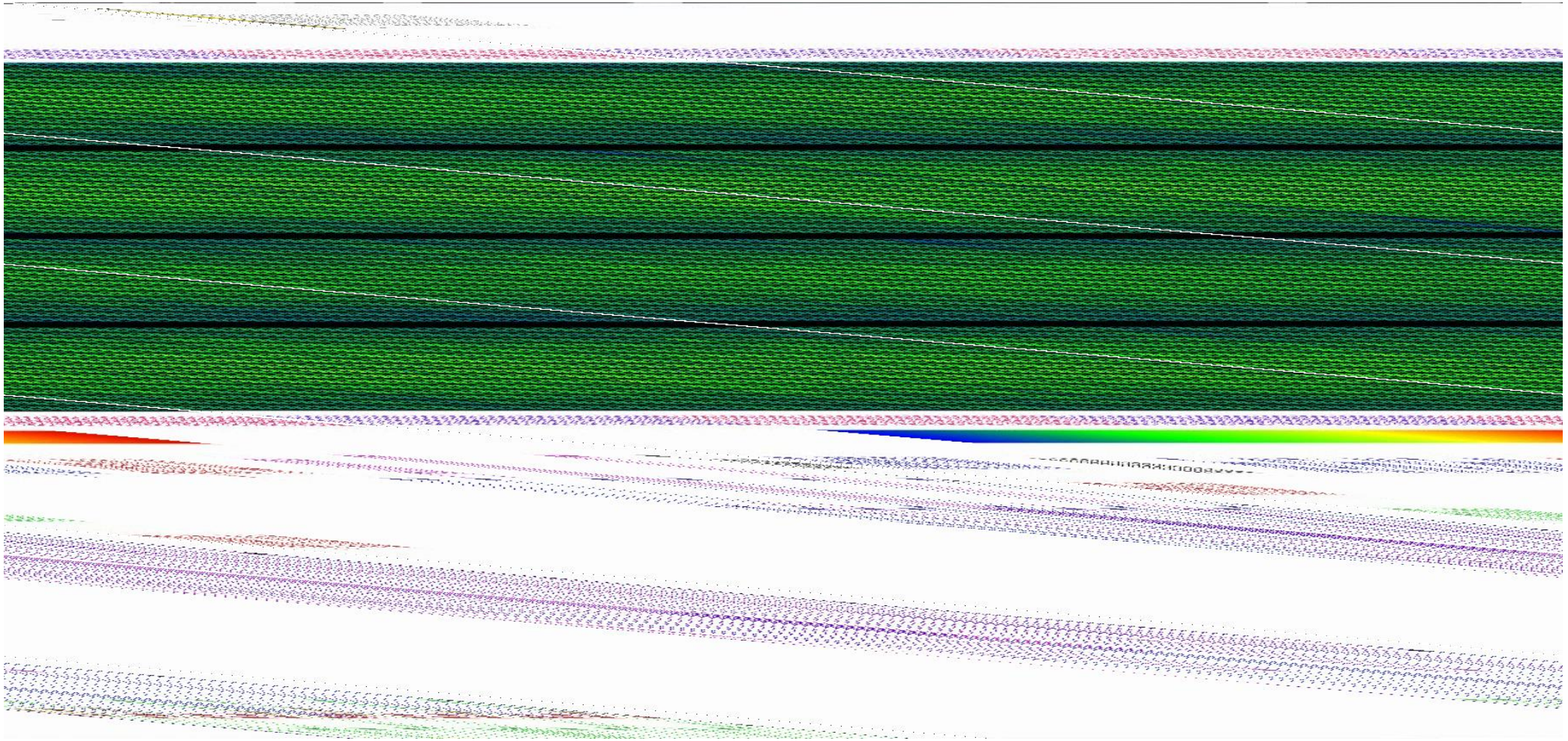
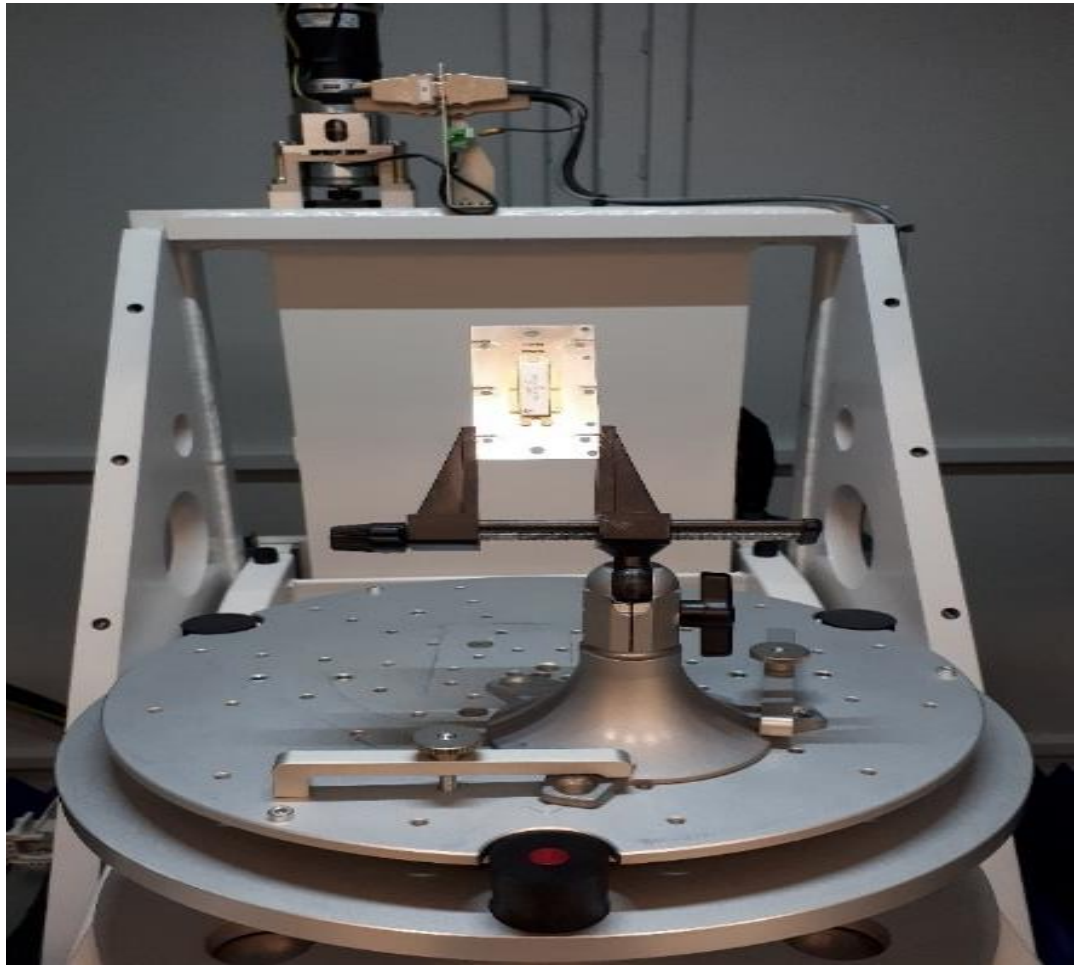
THERMAL CAMERAS ON TRANSISTORS



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



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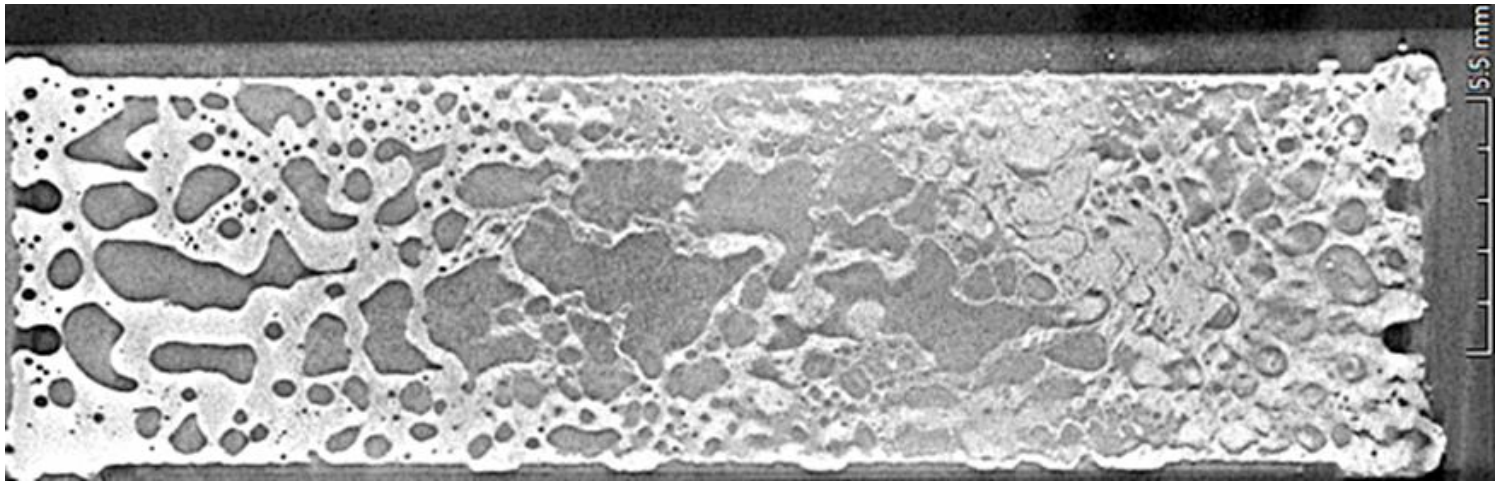
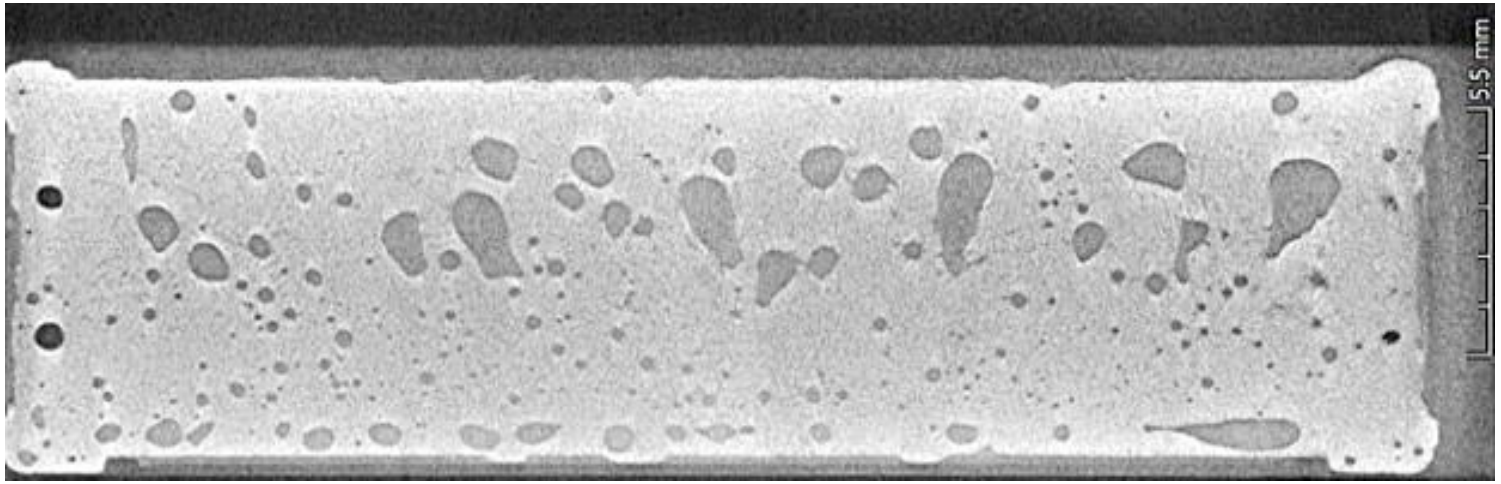
VOIDS

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





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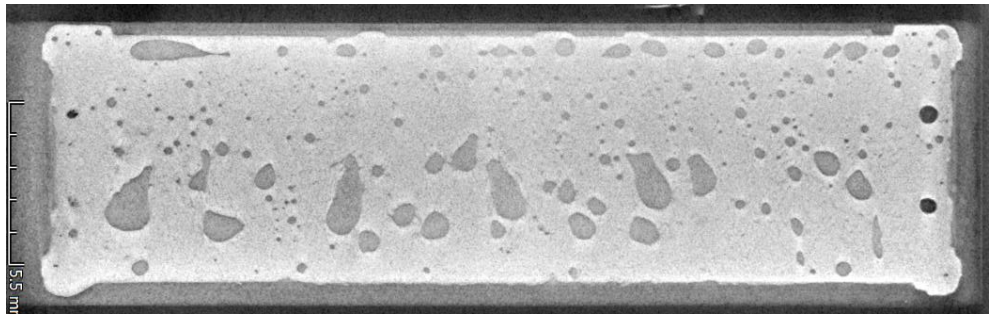
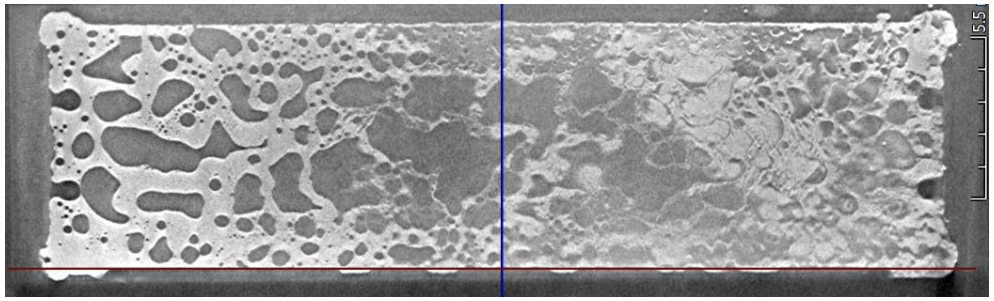
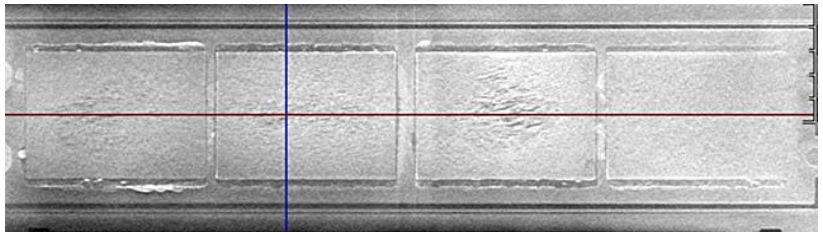
V2+ MODULE 268

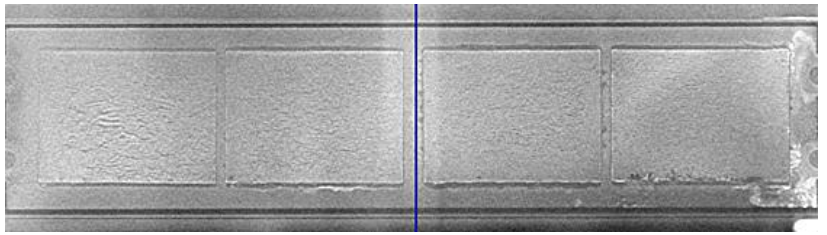
Bleu – Rouge

Vert – Jaune









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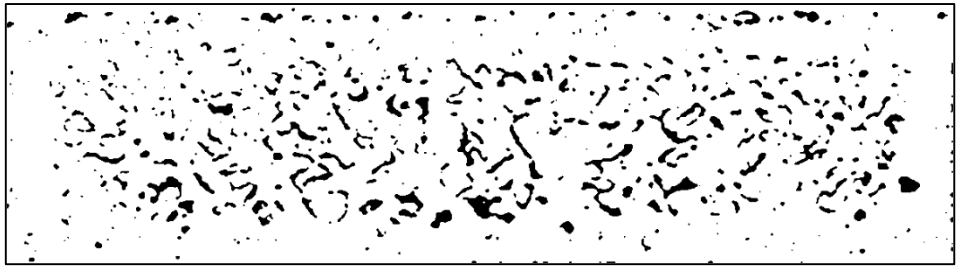
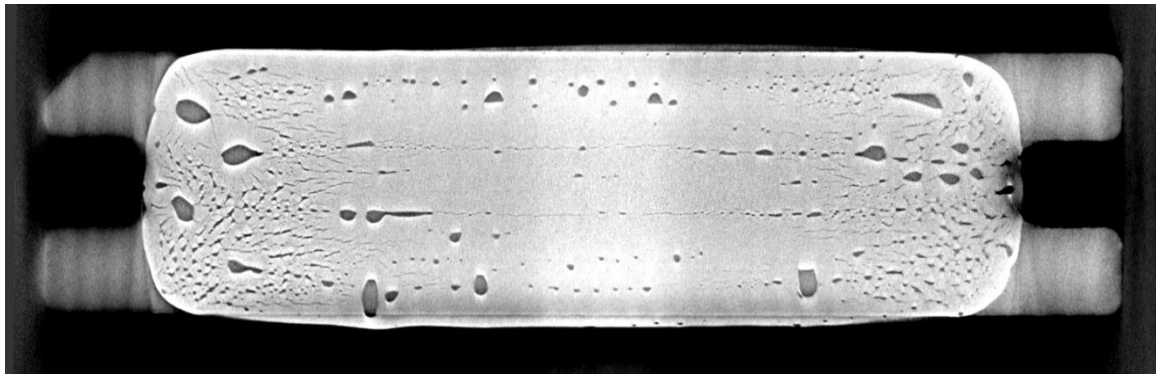
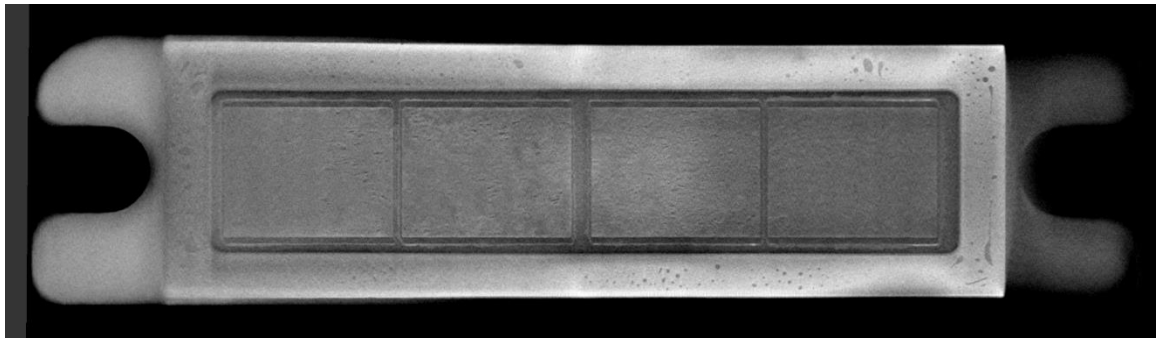
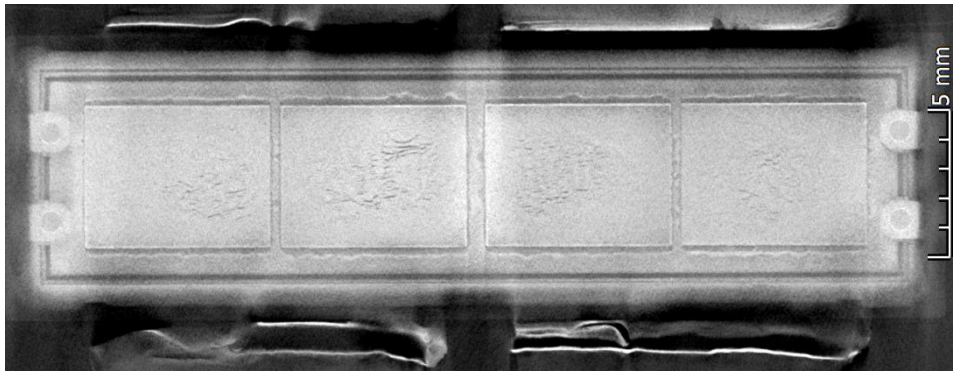
AG OR SAC 305

Porosity 8.3%









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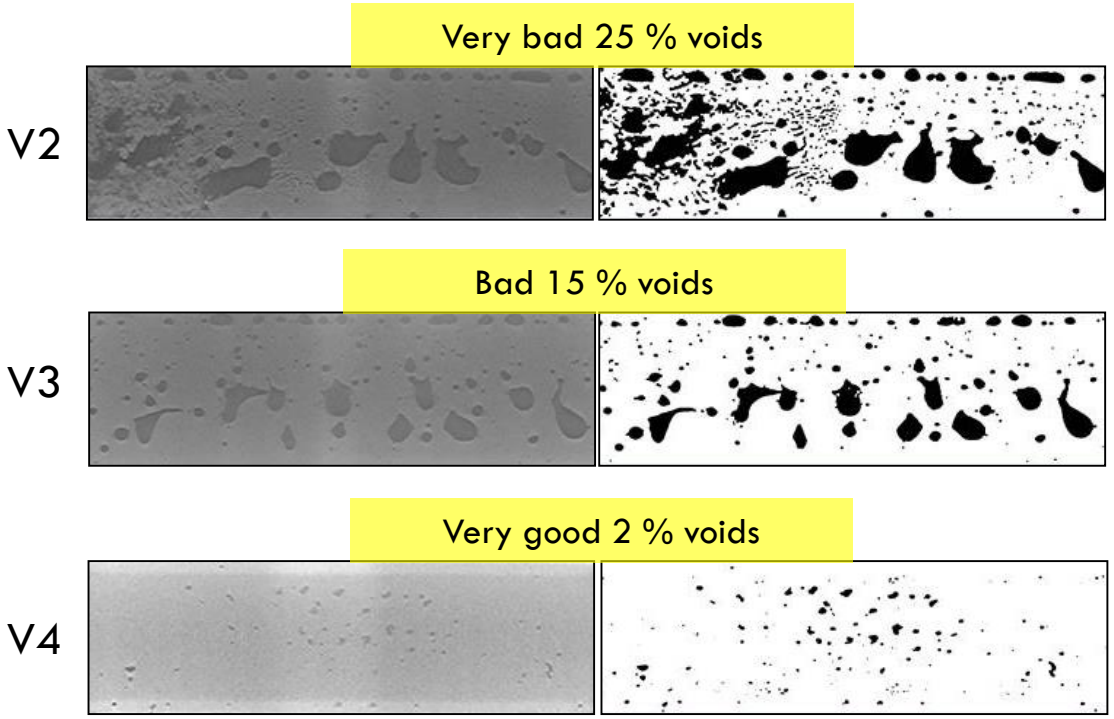
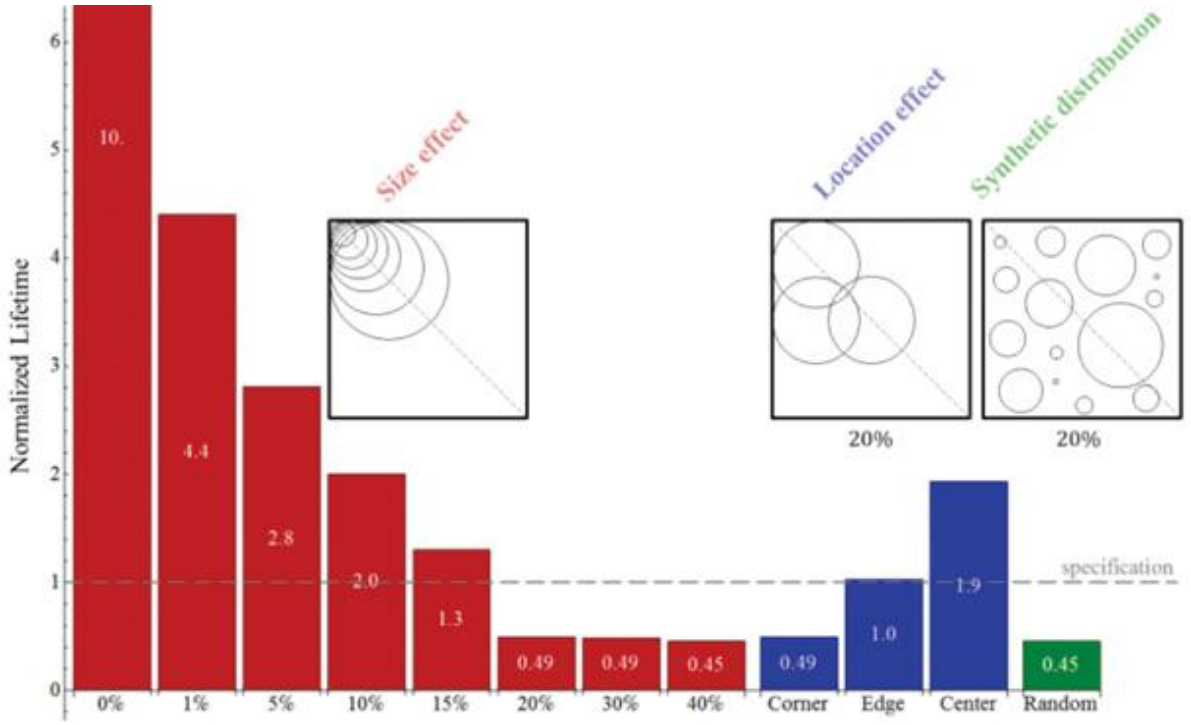
VERSION #4





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

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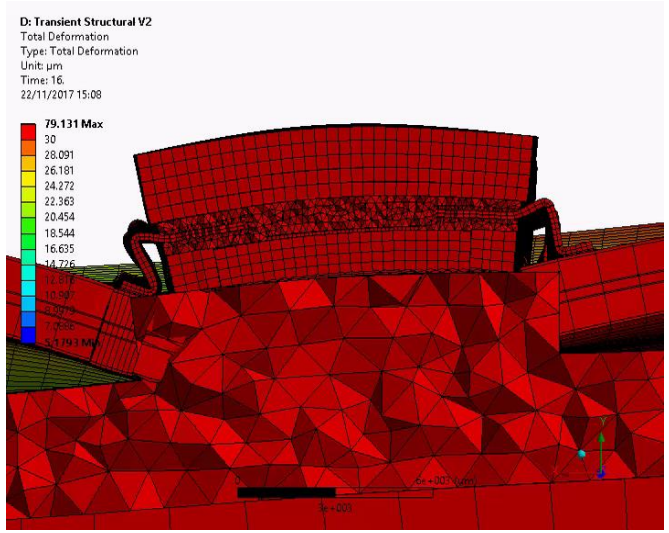
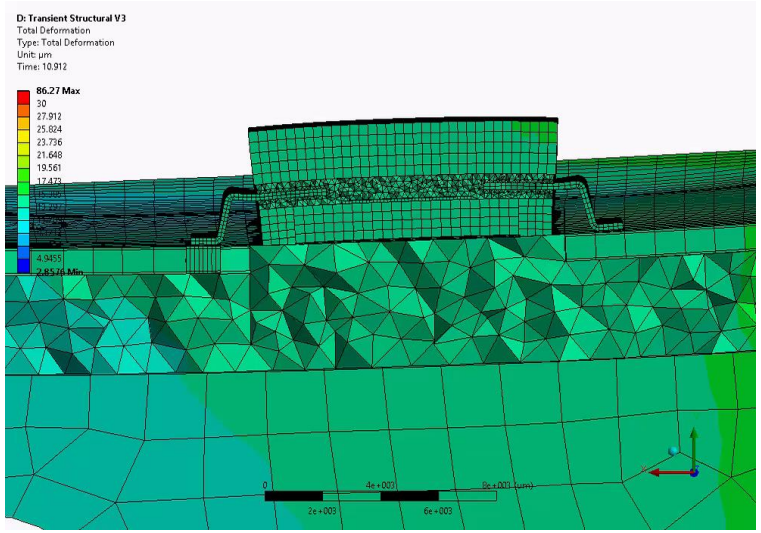
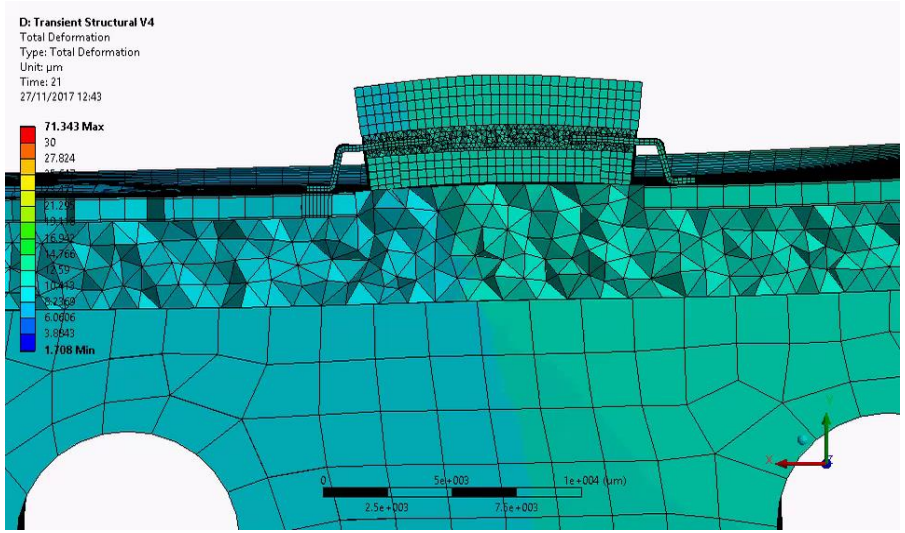
STRESS OF SPS CYCLE ON PCB & TRANSISTORS



V2



V3



V4

RECAP OF SOME VARIOUS VERSIONS

ORIGINE DES MODULES / DATE DE FABRICATION	V3	Proto V4 run1	Proto V4 run2	Proto V4 run3	Début juillet	Prod 30/06	Prod 30/06	Prod fin 20/07
Quantité à réaliser ou existante		1	1	6 -1 = 5	1	85	10	10
Affectation, Quantité	Banc sur table : 1		TOUR_V2 : 1	TOUR_V2 : 1 Spare : 4	TOUR_V2 : 1	TOUR_V4 : 80 Spare_V4 : 4 TOUR_V2 : 1	TOUR_V4 : - Spare_V4 : 9 TOUR_V2 : 1	TOUR_V4 : - Spare_V4 : 9 TOUR_V2 : 1
Désignation de la configuration	V3		A1	A2	A3	T1	T2	T3
Configuration PCB Entrée/PA1/PA2	V2+/V3	V4 run1	V4 run2	V4 run3	V4A	V4A	V4A	V4C
Brasure **source** Transistor	SAC305 AIR	SnPbAg AIR	Indium push	SnPbAg Vide	Ag Frittage	SAC305 Vide	SnAg Vide	SnAg Vide
Brasure **pattes** transistors	SAC305 AIR	Indium push	Indium push	Indium push	Indium push	Indium push	Indium push	SnAg Vide
Finition diffuseur	Cuivre	Cuivre	Or 0,08µm	Cuivre	Ag (6-10µm)	Or 0,08µm	Or 0,08µm	Or 0,08µm
Finition PCB	Or 0,08µm	Or 0,08µm	Or 0,08µm	Or 0,08µm	Or 0,08µm	Or 0,08µm	Or 0,08µm	Or 0,08µm
Brasure composants CMS	SAC305 AIR	SAC305 AIR	SAC305 AIR	SAC305 AIR	SAC305 AIR	SAC305 AIR	SAC305 AIR	SnAg Vide
Date-Code Transistor	2017	2015	2015	2015	2018	2018	2018	2018
Boitier transistor	Plastique	Plastique	Plastique	Plastique	Céramique	Plastique	Plastique	Plastique

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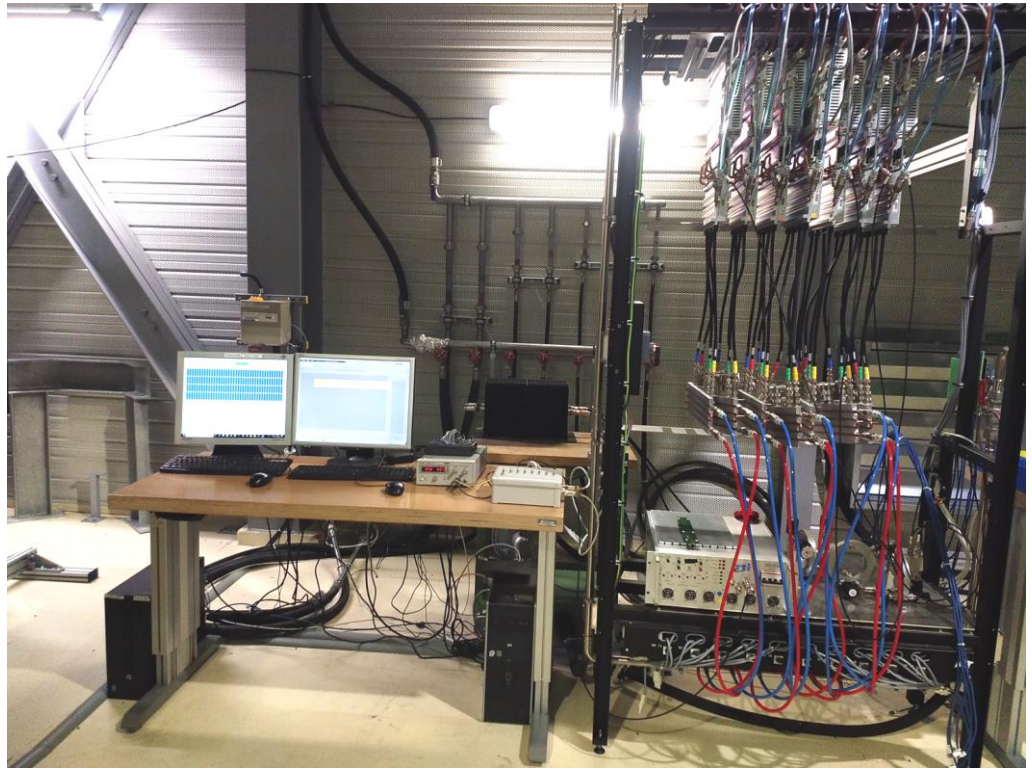
AGEING ACCELERATING TEST BENCH

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

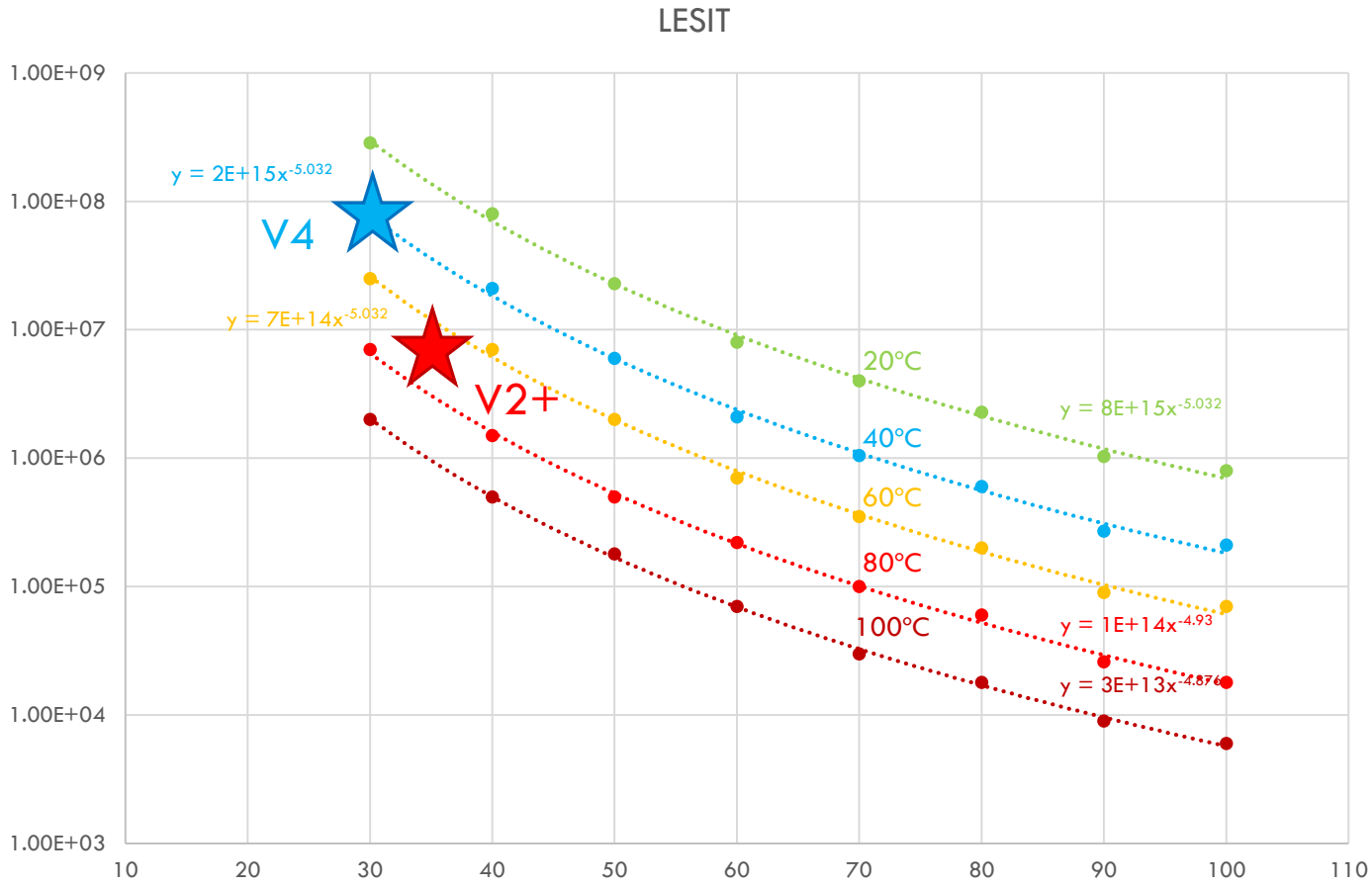
V4 (with 67 modules)

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

Tcase = 40

Delta T = 29

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



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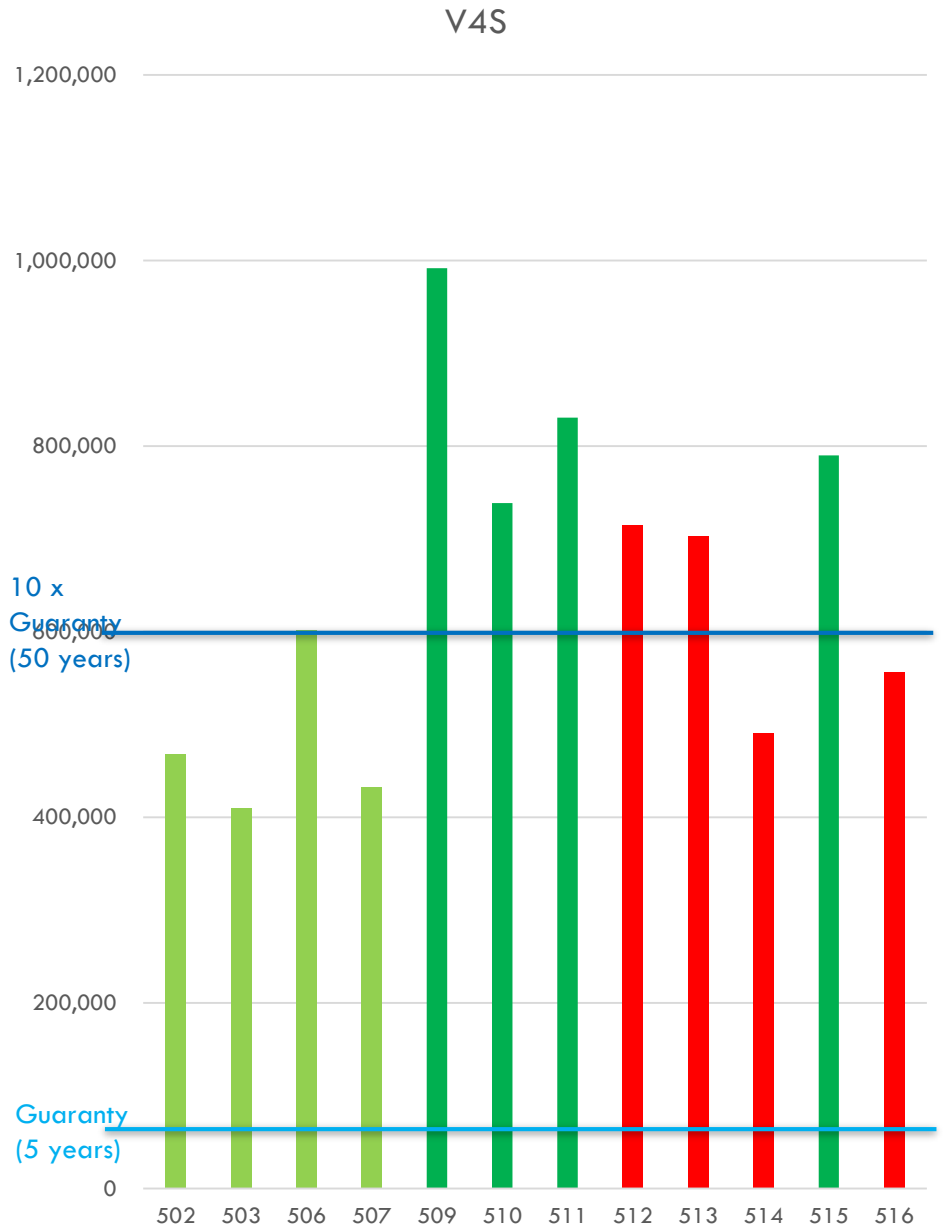
V4 LIFETIME

We then tested several V4 modules in order to verify that the solution was robust

Some transistors have failed with an extrapolated lifetime of more than 40 years of operation (in red), several were still alive but we had to stop the tests (in green)

We then built a new demonstrator (one tower fully equipped), and repeated all the tests, including short circuit tests



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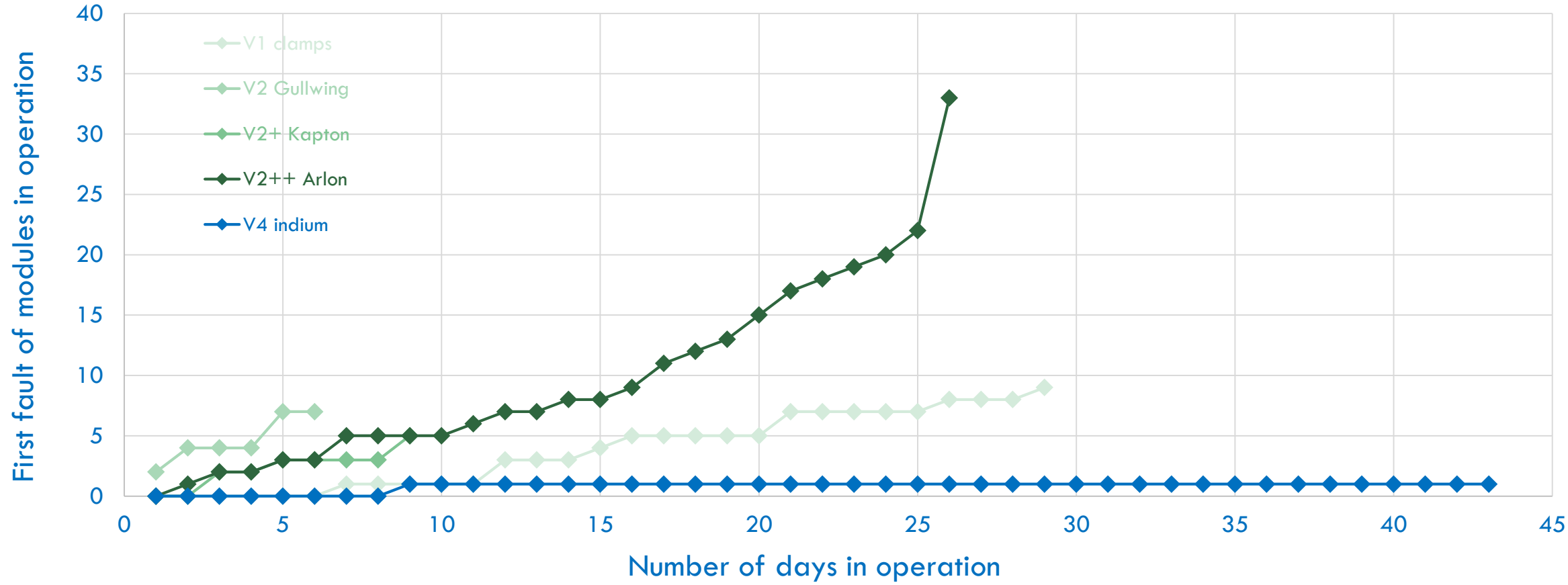
BROKEN MODULES DURING SUPERCYCLES ON DEMONSTRATOR



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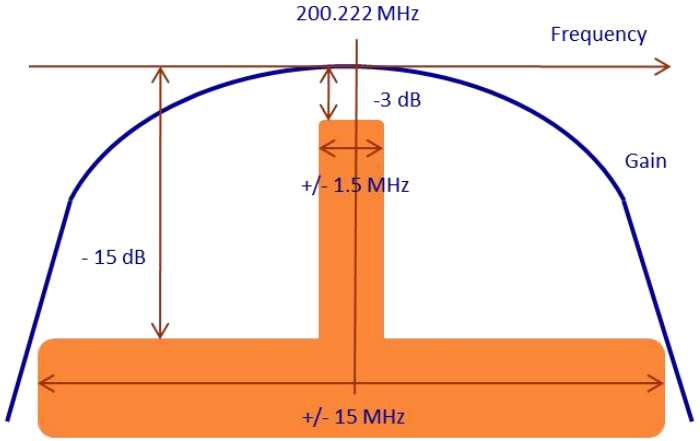
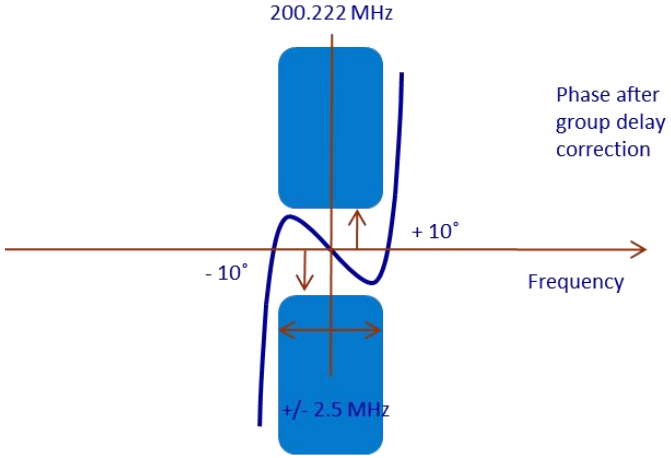
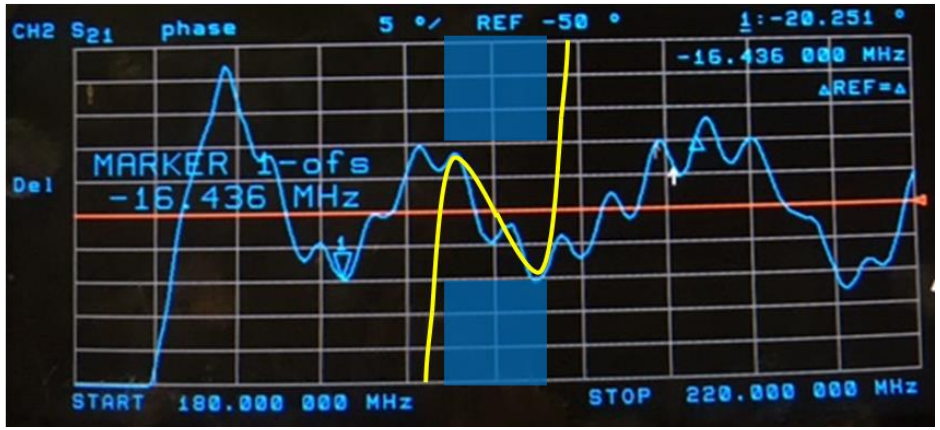
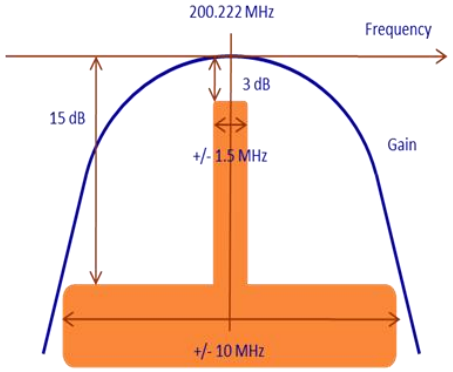
THALES BANDWIDTH & PHASE DISTORTION

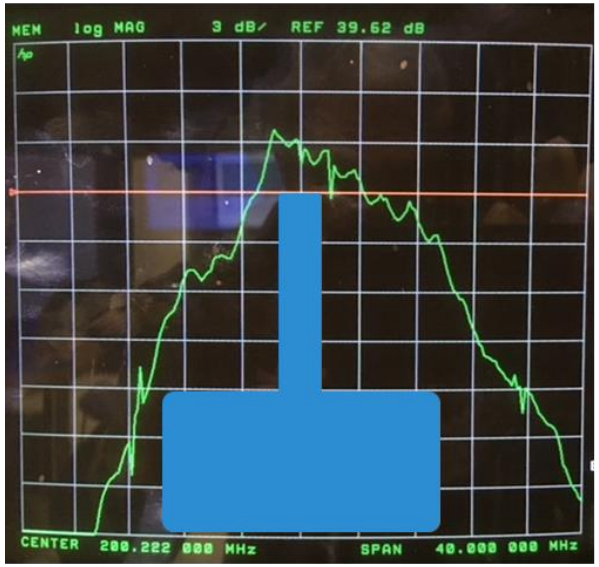




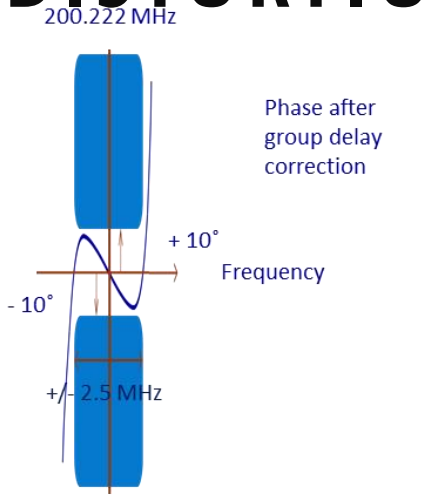


TTI + THALES BANDWIDTH & PHASE DISTORTION



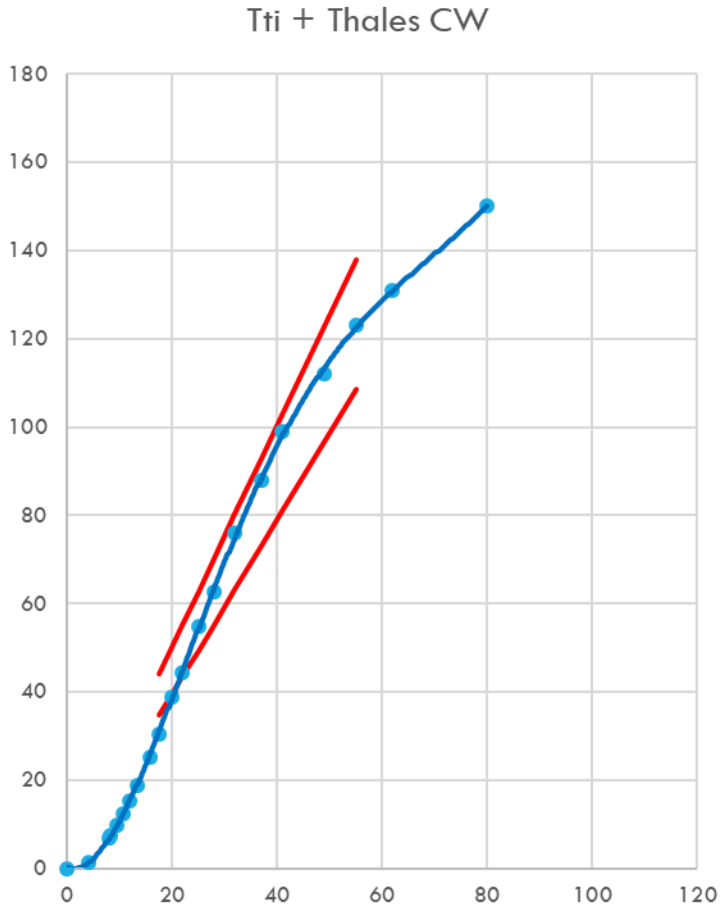


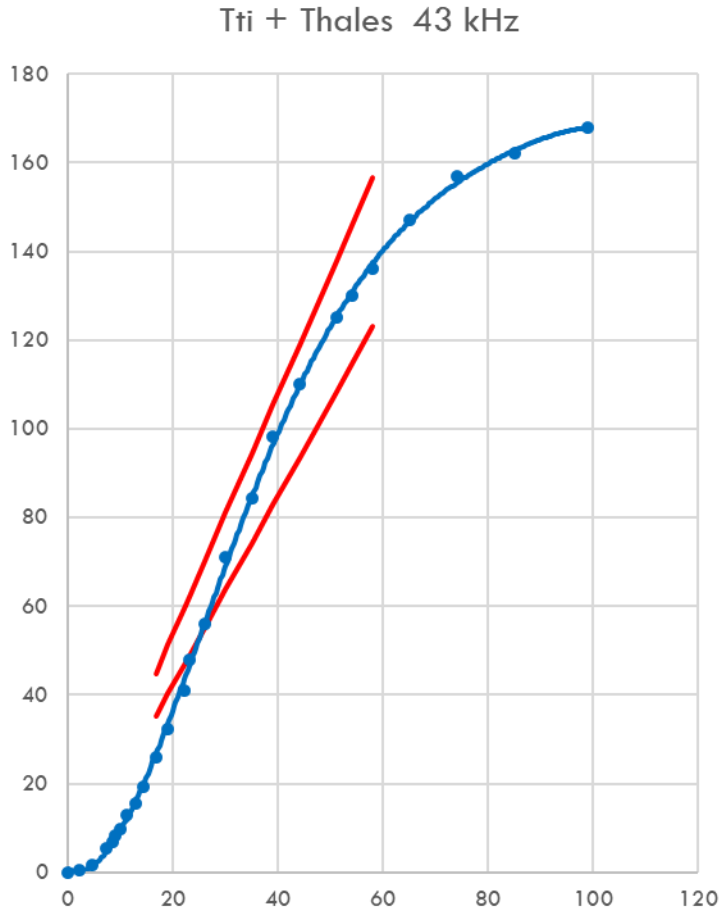
4 MHz/div
3 dB/div

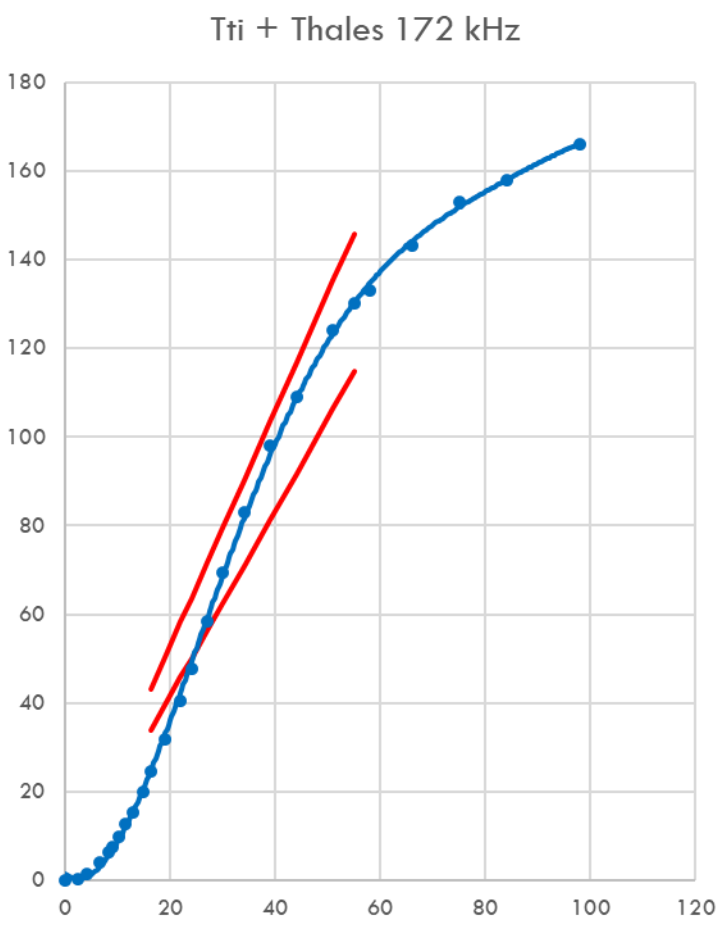


4 MHz/div
10 deg/div
Electrical delay 361 ns

TTI + THALES LINEARITY







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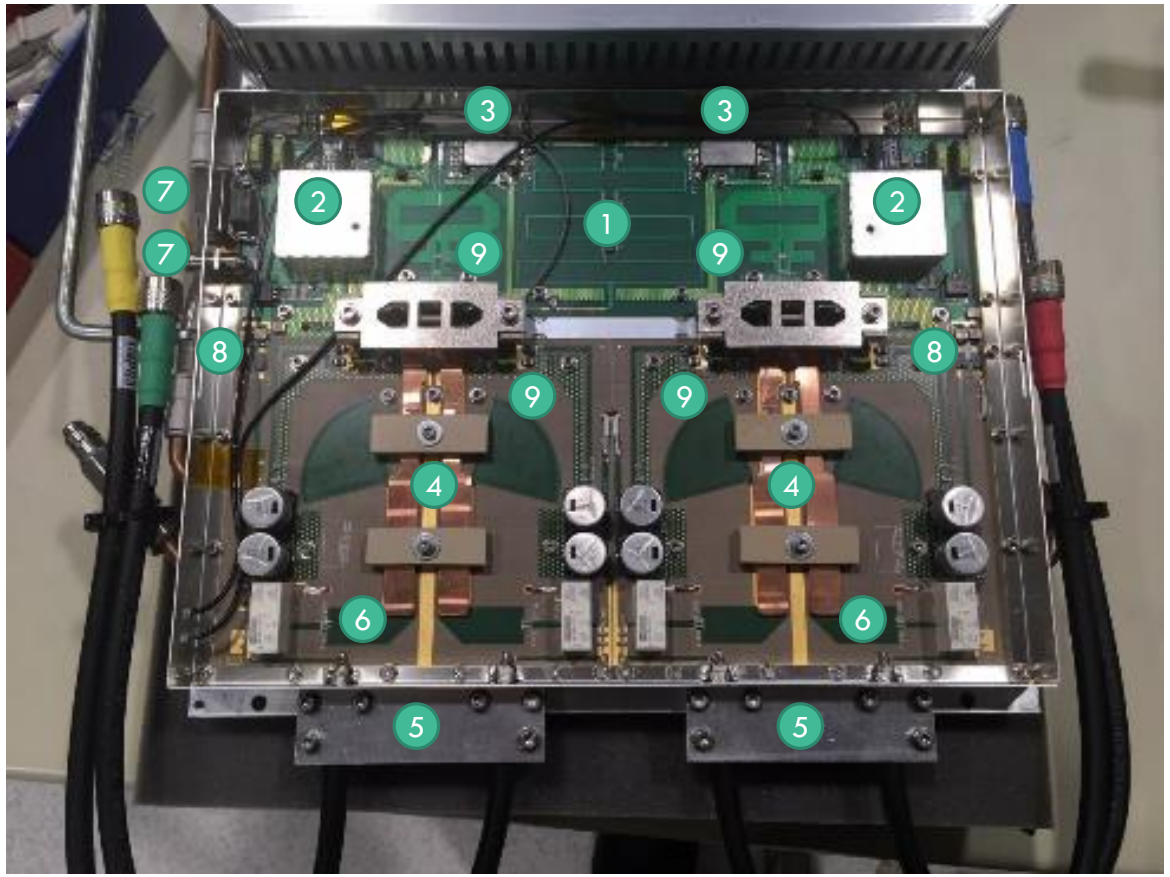
V4 MODULE IMPROVEMENTS

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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V4 MODULE

12TH SEPTEMBER 2019, RECOMMENDATION TO THE CERN MANAGEMENT

Demonstrator V4

- 1'000 hours test with 80 V4 modules ok
- 110 hours test with 72/80 modules at nominal values for operation ok
- Short circuit test at all phases ok

I propose that we validate the qualification of the Thales SSPA amplifier, and that we launch the Series definition and production phases

SERIES PRODUCTION

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

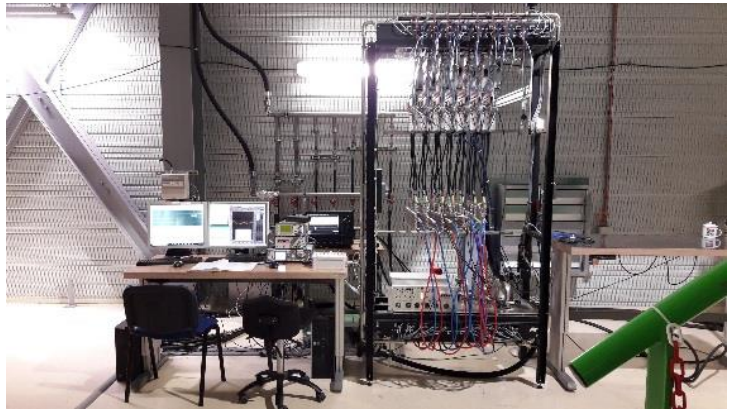
Before Series production, we defined strict Acceptance Test Plans (ATP) and Acceptance Test Reports (ATR)

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)

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

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



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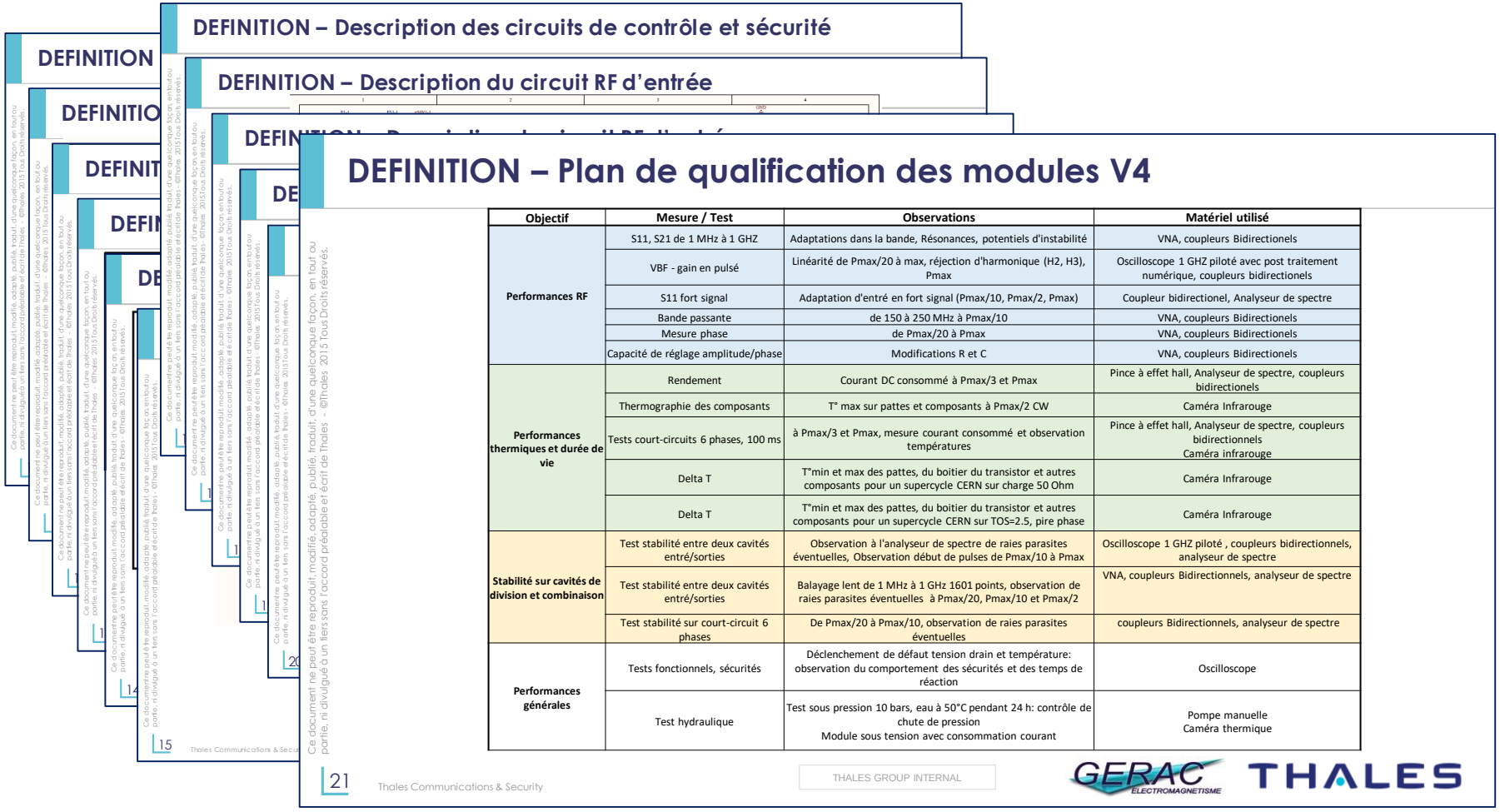
QUALITY CONTROL



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

SERIES PRODUCTION

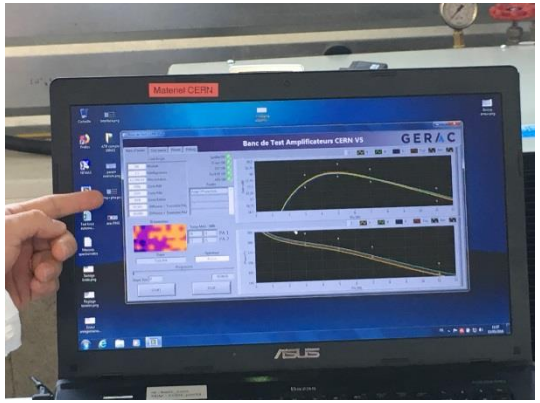
Gérac premises have been upgraded for industrialisation phase

- Two production lines
- Two test benches
- One test place for 'non conformities'
- Area within highest standards
- One storage area

Thales 'military' standards (Cholet-France) have been applied to Gérac (Bordeaux-France) in order to satisfy the quality plan needed for our project

Production capability was 120+ modules per week

First batch to be delivered starting end of 2019



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READY TO RECEIVE THE MODULES

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DELIVERY OF MODULES

FIRST SERIES OF 16 TOWERS

At a glance, for each tower

Verification of all the 80 modules received by Thales on our CERN's modules test bench, power sweep to verify amplitude and phase of all modules

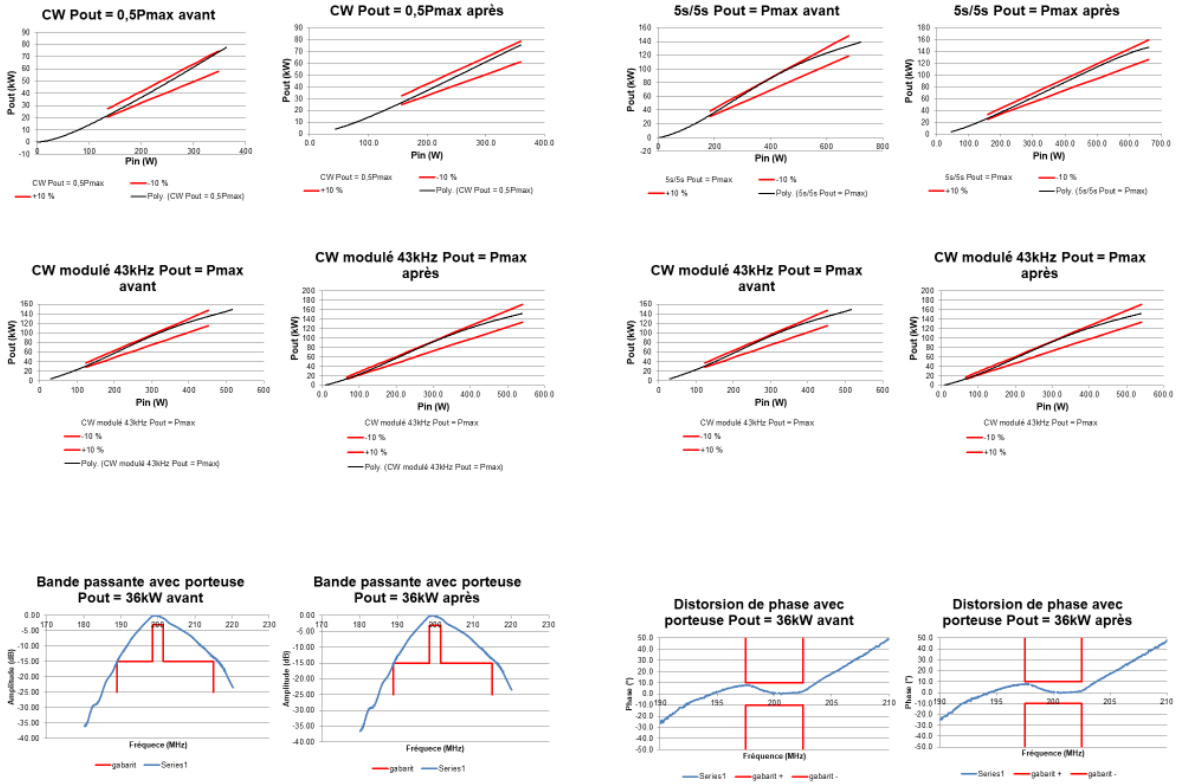
Integration of the 80 modules in the tower with individual thermal camera per transistor

Parameters checks; interlocks, bandwidth, linearity, harmonics, thermal behaviour with a SPS RF supercycle

8 x 1 hour test at various predefined RF power levels and duty cycle

100 hours long duration test with SPS RF supercycle, monitoring RF power and thermal behaviour

control that the parameters have not changed, repetition of bandwidth, linearity, harmonics and thermal behaviour



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SECOND SERIES TOWERS QUALIFIED 14TH MARCH 2020

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THANKS TO ALL COLLEAGUES INVOLVED

Dep-Group	Persons
BE-RF	Eric Montesinos, Charles Julie, Sebastien Calvo, Gino Cipolla, Antoine Boucherie, Simon Rains, Ellen Milne, Christophe Renaud, James Bibby, Flory Ten Broeke, Frederic Killing, Cedrick Grandbois, Serge Massot, James Mitchell, Nicolas Villanti, Lars Haarsma, Sonia Garcia Scheifler, Abigail Lee, Frida Eriksson, Morgan Wigham, Aashlesha Sharma, Maria Sanchez Barrueta, Julia Mirowska, Ester Sancho Cabrera, Débora Aguilera, Philip Hofer, Francisco Sauba Esteban, Paola Mazzotta, Pilar Parrado Caballero, Irene Alonso Romero, Miren Kevin Marques, Remi Socquet-Clerc, Julien Novello, Sebastien Mutuel, Michel Ferrone, David Bastard, Lancelot Brechignac-Denis, El Houssine El Gahrbi, Jesus Manuel Lopez Loureiro, Cedric Mendez Lopez, Stéphane Lavorel, Emerick Falenta, Patrice Girod, Jean-Marie Angonin, Romuald Terry, Sidi Chikhi, Thomas Henry, Emile Grospelier, Machdi Jendoubi, Elena Chapochnikova, Rama Calaga, Heiko Dammerau, Christine Vollinger, Nasrin Nasresfahani, Patrick Kramer, Wolfgang Höfle, Philippe Baudrenghien, Gregoire Hagmann, Daniel Valuch, Andy Butterworth, Luca Arnaudon, Carlos Oliveira, Diego Barrientos Turrion, Pierre Maesen, Florence Crochon, Kevin Marecaux, Alejandro Diaz Fontalva, Thomas Kaltenbacher, Jose Enrique Varela Campelo, Toon Roggen, Urs Wehrle, Frédéric Boulenger, Thomas Bohl, Aurelien Lahu
BE-ABP	Benoit Salvan, Hannes Bartosik, Ghislain Roy, Yannis Papaphilipou
BE-ASR	Marc Tavlet, Christelle Gaignant, Anne Funken, Lisa Kobzeva, Axelle Deleu, Paola Carvalho Correia
BE-BI	Christian Boccard, Patrick Ogier
BE-ICS	Denis Raffourt, Nino Rama, Pablo Gaviglio, Grégory Smith
BE-OP	James Ridewood
DG	Florence Jacobs, Claudia Passeri
HSE-SEE	Olivier Tison, Cécile Pinto, Jonathan Gulley, Laurent Colly, Guillaume [illegible]
IPT-PI	Thierry Lagrange, Anders Unnervik, [illegible] odet, Boi-Lan Nguyen-Lemoine
IT-CS	Stephane Casenove, Nils Barring
EN-ACE	Katy Foraz, David McFarlane, Emma [illegible] s, Yannick Beraud
EN-CV	Mauro Nonis, Serge Deleval, Michel [illegible] aux, Yannick Body, Rodrigo Sanches Pedro, Laurent Catin, Paul Cruz, Abdessamad El Fathi, Glen Mason, A [illegible]
EN-EL	Nicolas Bellegarde, Guillaume Gros, [illegible] sceglie, Gael Girardot, Pierre Broussart, Thomas Glaerum, Serge Chalaye, Thierry Charvet, James Devine, Frans [illegible] Simon Baird, Gérard Cumer, Davide Bozzini, Jérôme Pierlot, Juan Gomez, Thierry Octave, Christophe Crombez, François Duval, Jean-Pierre Sferruzza [illegible]
EN-HE	Caterina Bertone, Jean-Baptiste Bonnard, Pascal Bruñero, Serge Pelletier, Yann Seraphin, Patrick Vallet, Gilles Roche, Helder Lorenco, Roberto Rinaldesi, Jean-Pierre Grandchelli, Jean-Louis Grenard, Dominik Schaerer
EN-MEF	Yvon Muttoni, Frédéric Galleazzi, Scharif Mehanneche, Antoine Kosmicki
EN-MME	Gilles Favre, Stefano Sgoba, Alessandro Dallocchio, Jean-Marc Malzacker, Laurent Deparis, Alession D'Andrea, Fritz Motschmann, René Claret, Thierry Tardy, Pierre Moyret, Mariusz Jedrychowski, Laurent Prever-Loiri, Jean-Marie Geisser, Yann Farys, Piguiet Aline-Marie, Damien Foresy, Philippe Frichot, Alexandre Gerardin, Alain Stalder
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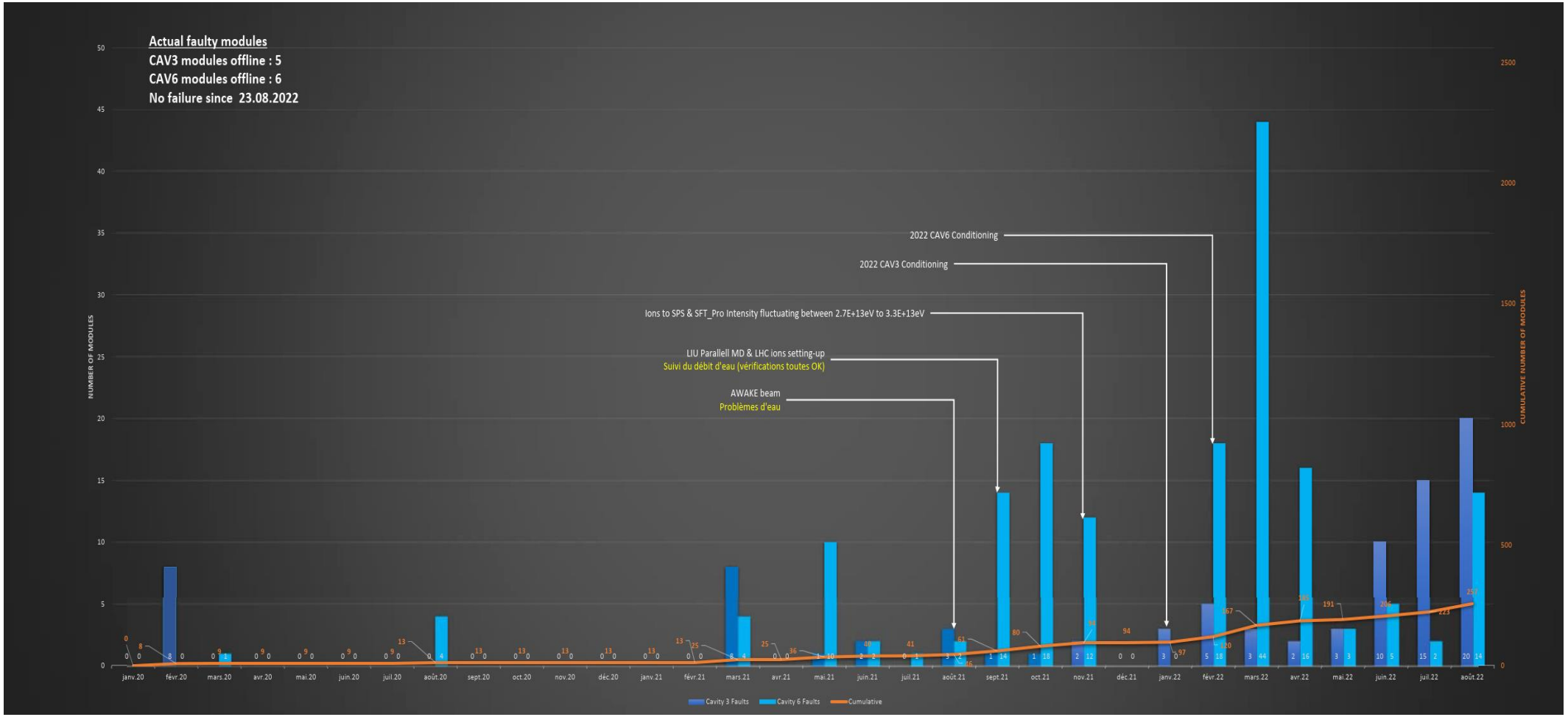
SMB	Luz-Anastasia Lopez-Hernandez, Christophe Biot, Laurent Faisandel, Eliseo Perez-Duenas, Patrice Sajous, Paula Barriere, Mathieu Fontaine, Martine Auerbach, Boris Cabaud, Remi Noel, Alessandro Domenino, Morgan Farre, Roland Arnoul, Adrien Billat, Damien Le Van, Damien Liegeart, Alejandro Martinez Selles, Daniel Parchet, Manuel Lopes Giesta
TE-EPC	Jean-Paul Burnet, Gilles LeGodec, Yves Thurel, Davide Aguglia, Karsten Kahle, Christophe Coupat, Clément Bovet
TE-MPE	Raphael Berberat
TE-MSC	Jérémie Bauche, Sébastien Clément, Daniele Gouyette
TE-VSC	Paolo Chiggiato, Antonio Mongelluzzo, Sergio Calatroni, Wilhelmus Vollenberg, Ciara Pasquino, Jose Ferreira Somoza, Wim Willemjan, Marc Thiebert, Alexandre Sinturel, Jan Helge Hansen, Benoit Teissandier, Frédéric Duprat, Franck Monnet, Grégory Pigny

Great thanks to all 250+ colleagues
Special mention to RF team
Special mention to the various Thales teams

OUTLOOK

1. Brief description of the RF power upgrade project
2. Specificities of the purchasing rules at CERN
3. Technical choices (and difficulties)
4. Operation since beginning 2021

FAILURE RATE TOO HIGH



Total number of modules

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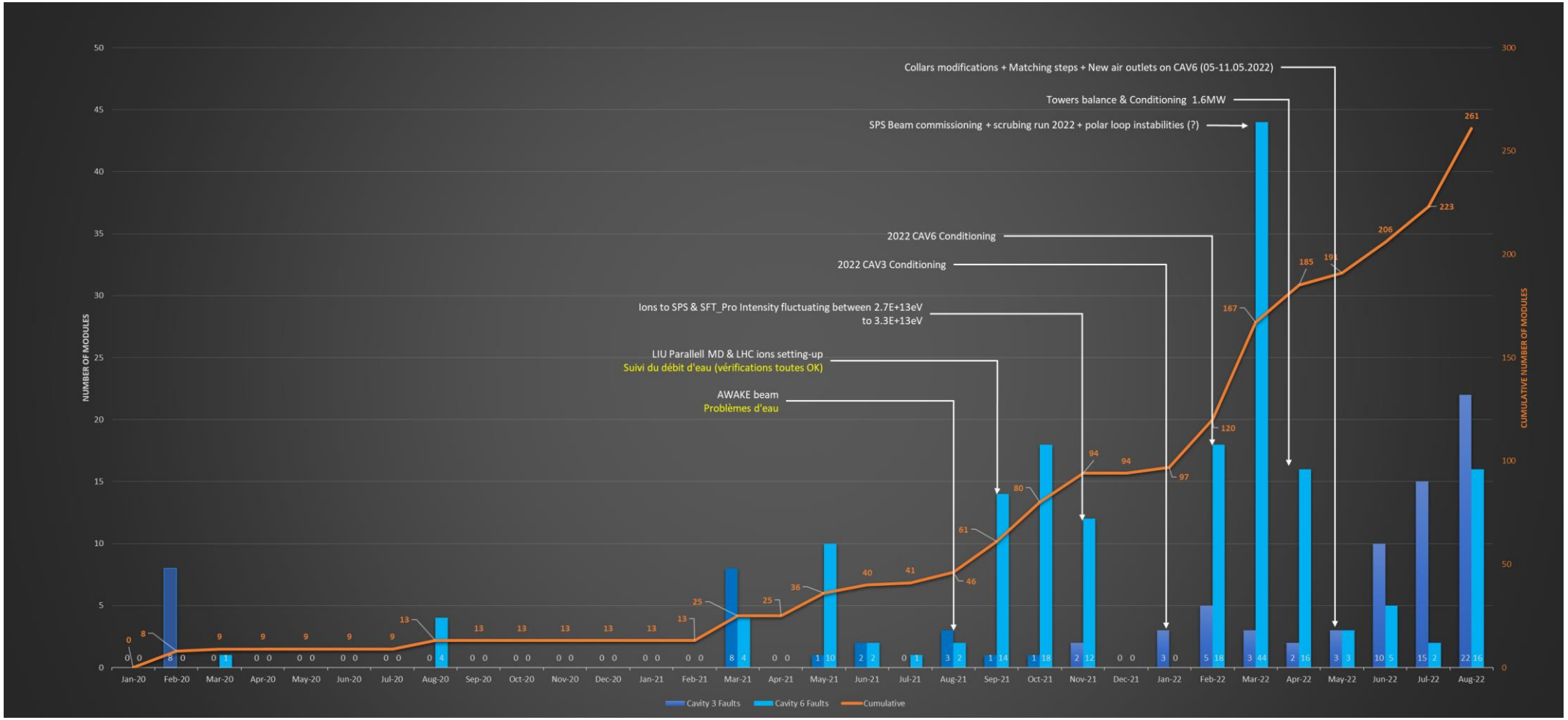
FAILURE RATE TOO HIGH (ZOOM)



10 % of Total number of modules

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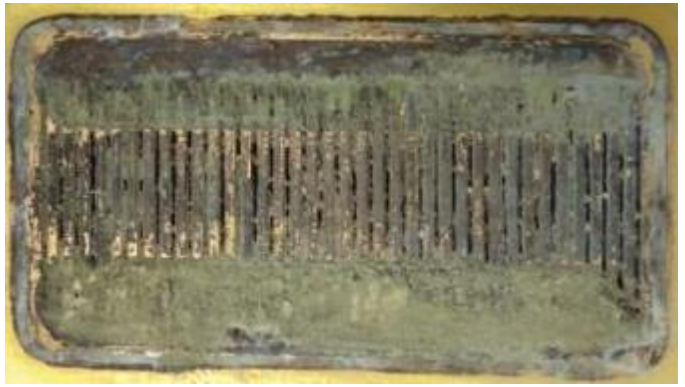
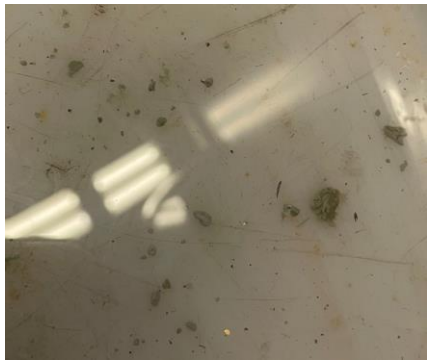
MISTAKE IN THE WATER COOLING SYSTEM

Despite we agreed with Thales that no pate neither filament should be used, their plumber did use it

We had to setup a crash program and cleaned the 3000 modules with a special process, 30 minutes rinsing the modules with changing the water flow sense every 5 minutes under a flow of 2,4 l/min, twice the nominal





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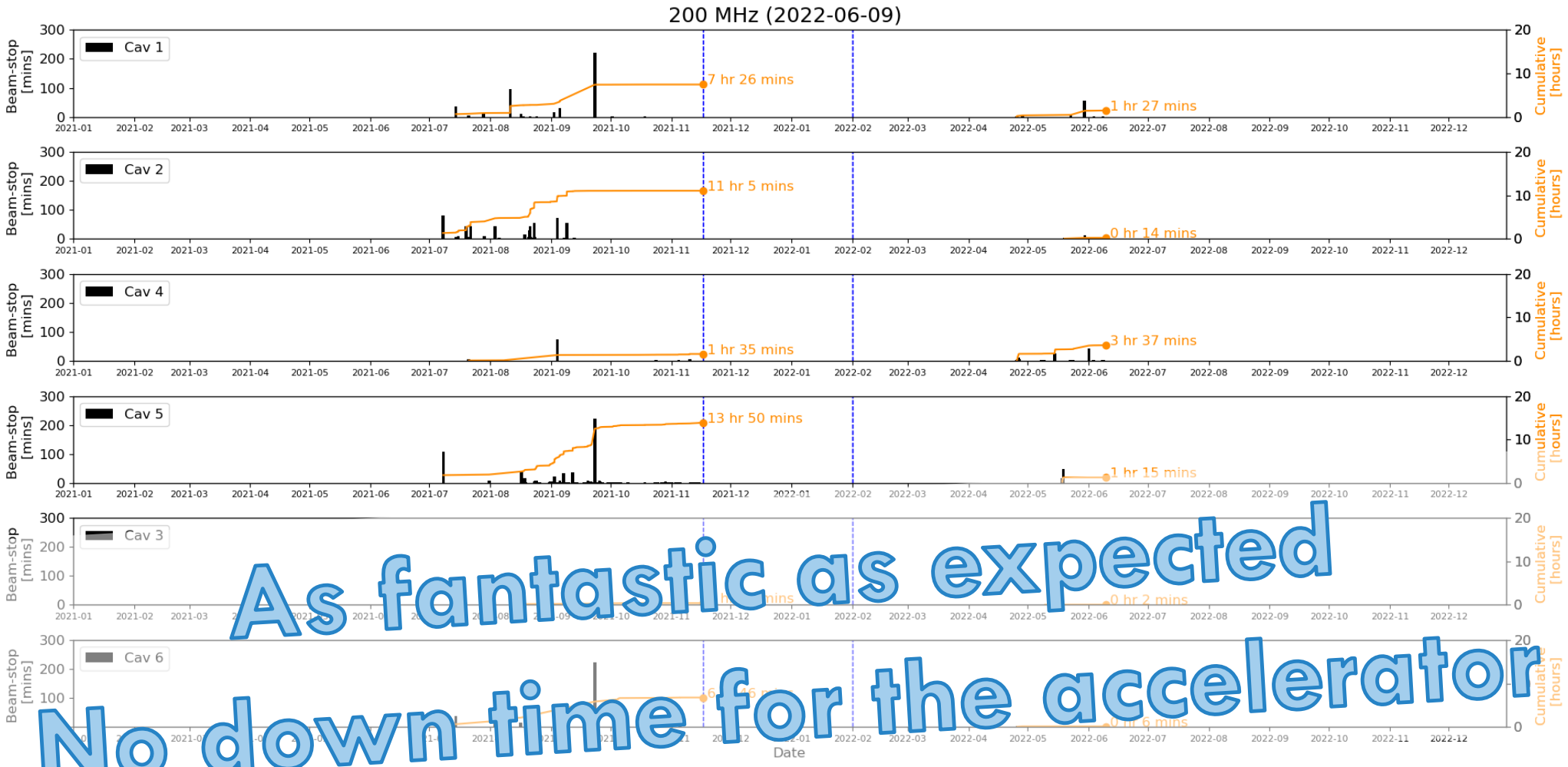
AVAILABILITY SINCE BEGINNING 2021



As fantastic as expected

No down time for the accelerator

OBSOLESCENCE

When we started the project in 2015, Thales selected the transistor based on recommendation from NXP

It was said that this transistor has no end of production expected

In January 2022, we received the information from NXP that we had 5 months to place a Last Buy Order

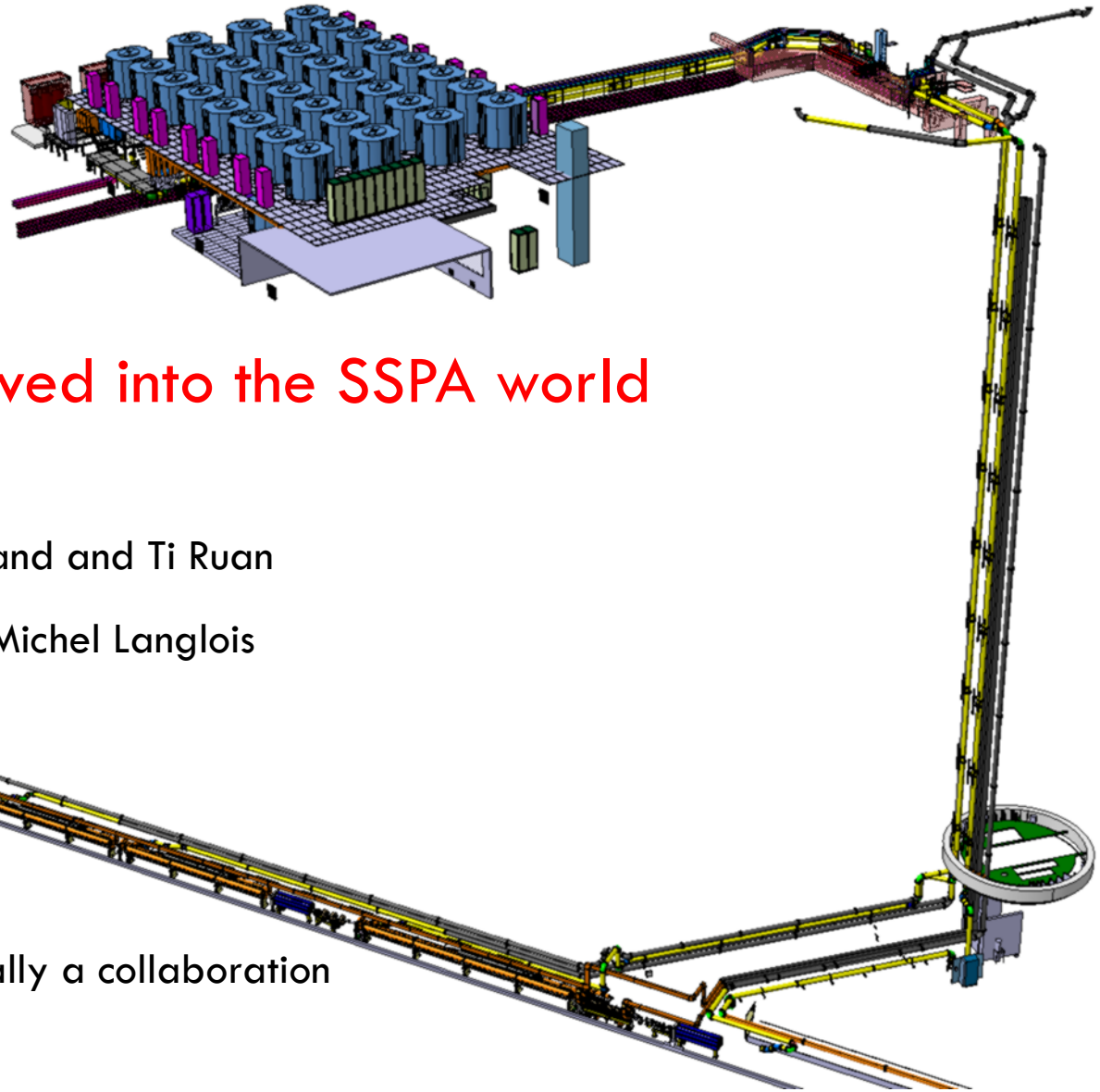
This is not possible within our internal CERN rules to take such a decision so quickly (given the quantity needed, the amount is around ½ MCHF)

We agreed with Thales that they will buy a large stock (in thousands)

I am participating in several reviews on SSPA, every time the same scenario occur, from time of design to end of production, transistors become obsolete

Even more difficult, the voltage has changed, so be careful, always consider your project including transistors quantity calculated by the MTBF over the entire lifetime of the SSPA

CONCLUSION



With this project CERN strongly moved into the SSPA world

Thanks to SOLEIL, with special thanks to Patrick Marchand and Ti Ruan

Thanks to ESRF, with special thanks to Jörn Jacob and Michel Langlois

Again, special thanks to all CERN colleagues involved

and a special thanks to Thales colleagues as it was really a collaboration

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Thank you very much for your attention

Visit of the equipment tomorrow, much more impressive in true life than a picture!