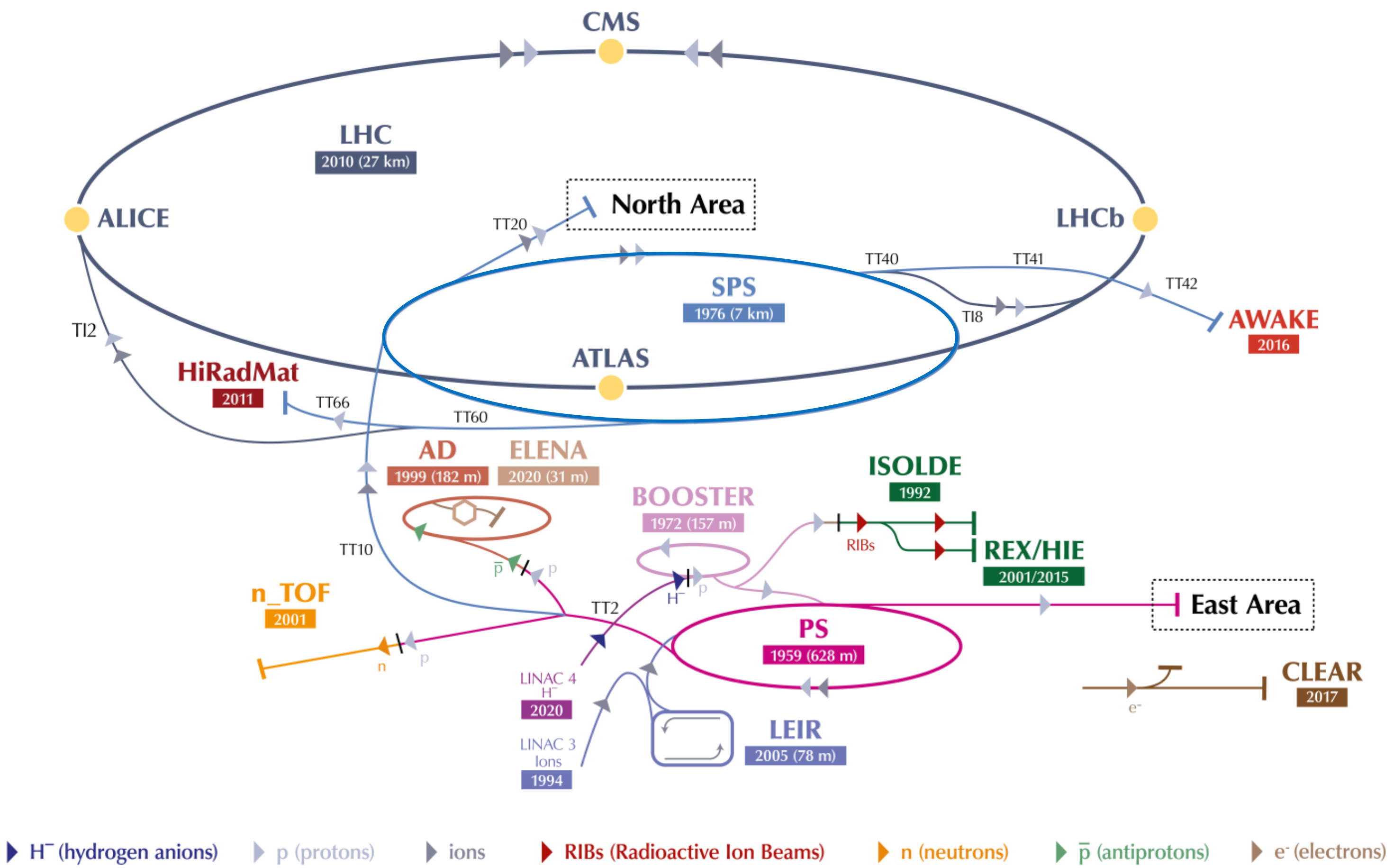
CERN SPS SSPA HIGH EFFICIENT SYSTEM AT THE END

Workshop on efficient RF sources
04-06 July 2022, CERN, Chateau de Bossey, Switzerland

eric.montesinos@cern.ch
On behalf of hundreds of colleagues who made it possible

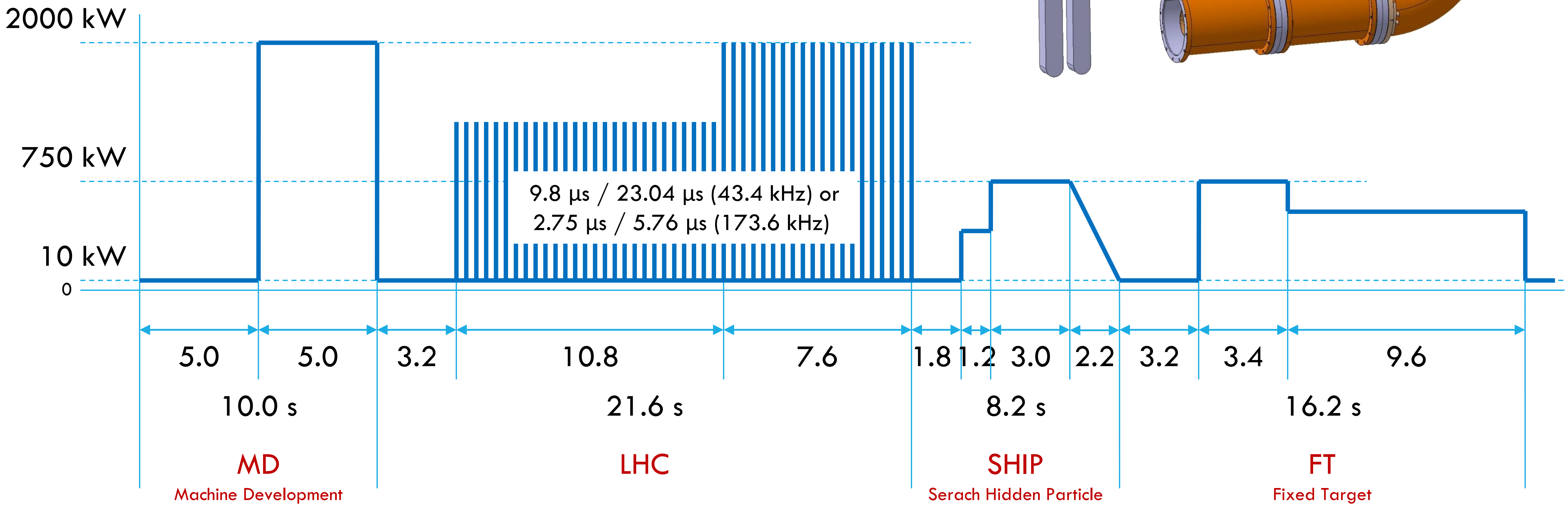
The CERN accelerator complex
Complexe des accélérateurs du CERN

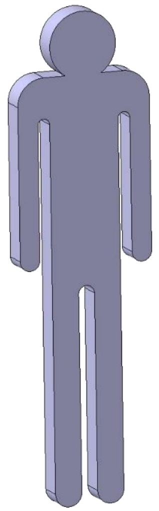


LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

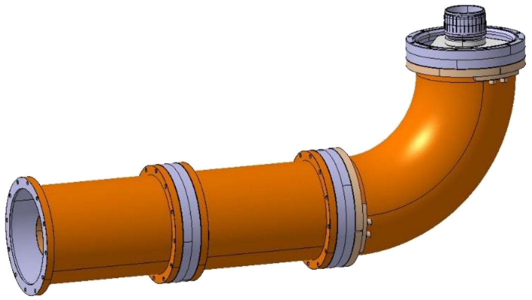
SPS SUPERCYCLE

Terrible cycle for all RF power stations!





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



eric.montesinos@cern.ch

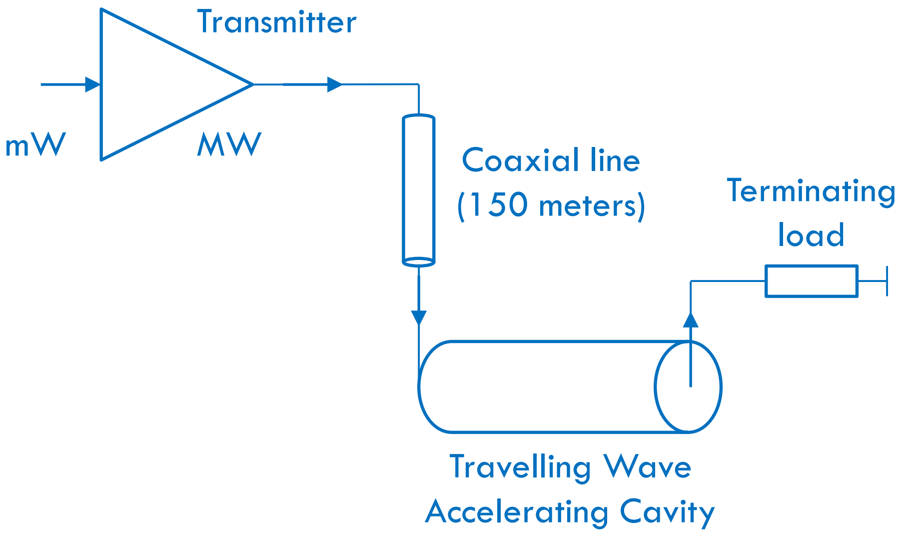
HISTORY OF THE RF IN THE SPS

The SPS RF started in 1976 with 2 x 650 kW RF power stations for main acceleration

Few years later, additional 2 x 650 kW RF power stations were added for main acceleration

Again few years later additional 2 x 250 kW RF power stations were added for Landau damping

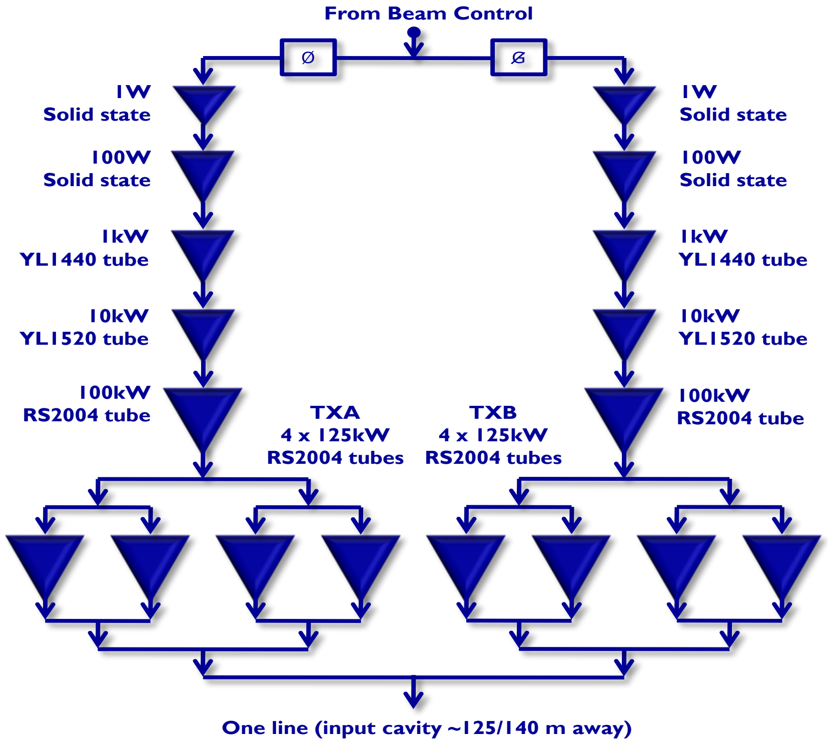
Configuration of one of the four 200 MHz power stations



eric.montesinos@cern.ch

HISTORY OF THE RF IN THE SPS

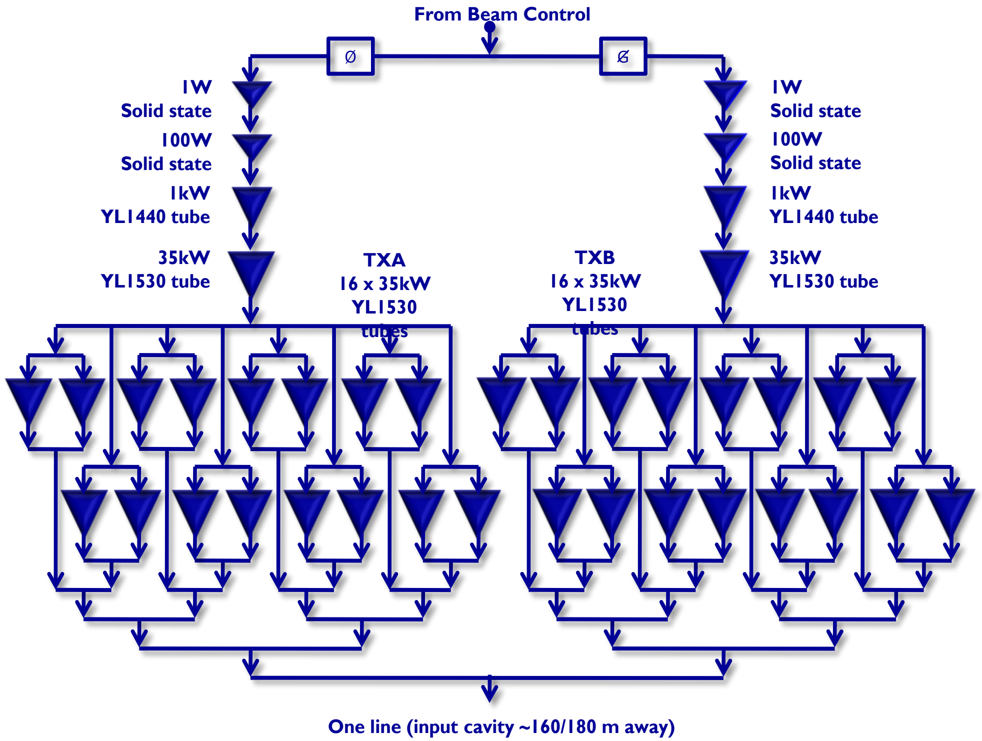
Each of the first two RF stations were composed of 8 x 137.5 kWp RS2004 Siemens tetrode, upgraded to RS2004 Thales tetrodes

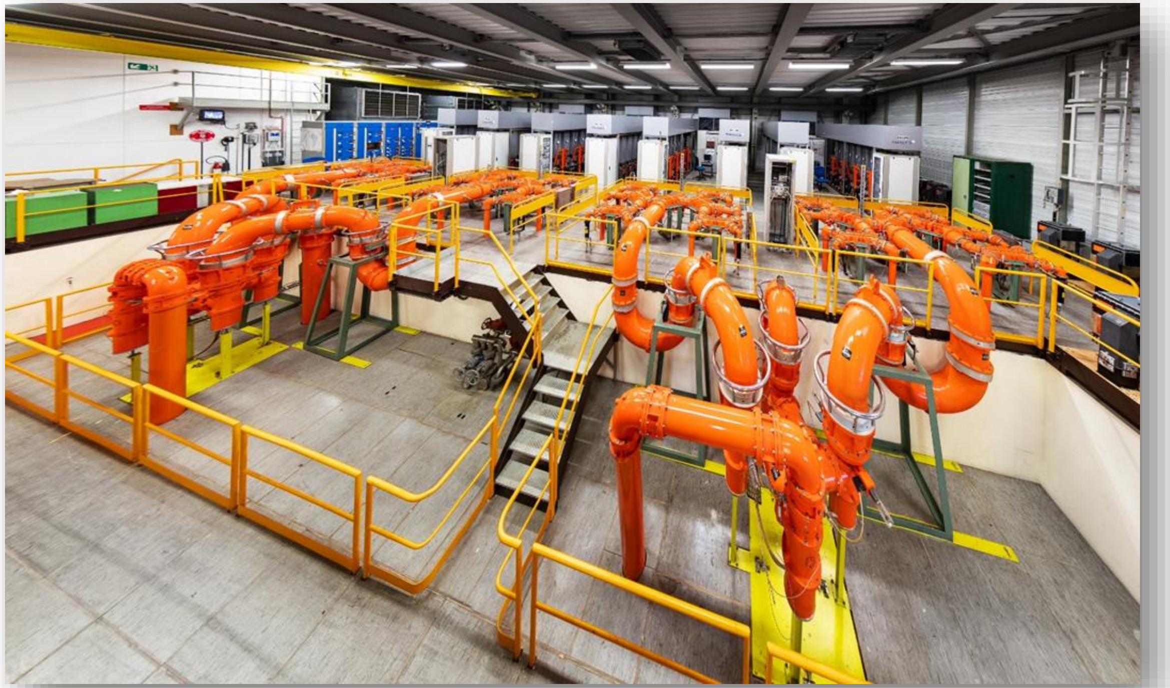


eric.montesinos@cern.ch

HISTORY OF THE RF IN THE SPS

Each of the next two RF stations were composed of 32 x 37.5 kWp YL1530 Philips tetrode upgraded to TH335SC Thales

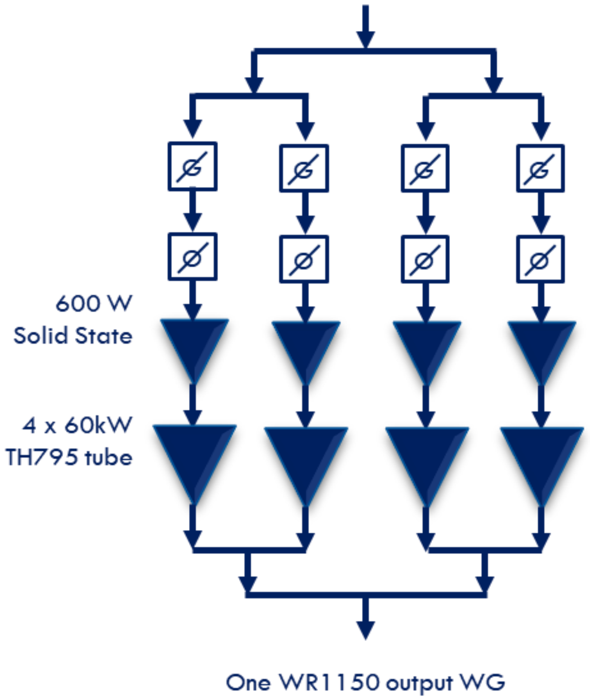




eric.montesinos@cern.ch

HISTORY OF THE RF IN THE SPS

Two additional RF stations were added for two Landau cavities, each is composed of 4 x 60 kW YK1198 Valvo klystrons upgraded to TH795 Thales IOT



eric.montesinos@cern.ch

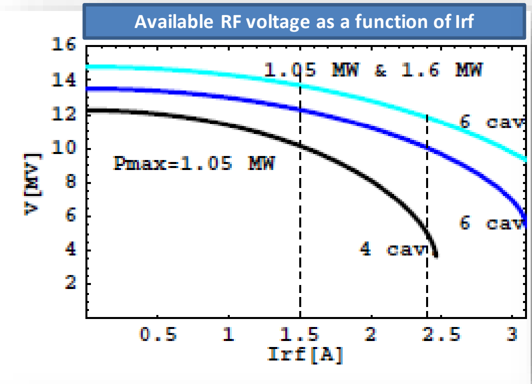
SPS RF POWER UPGRADE

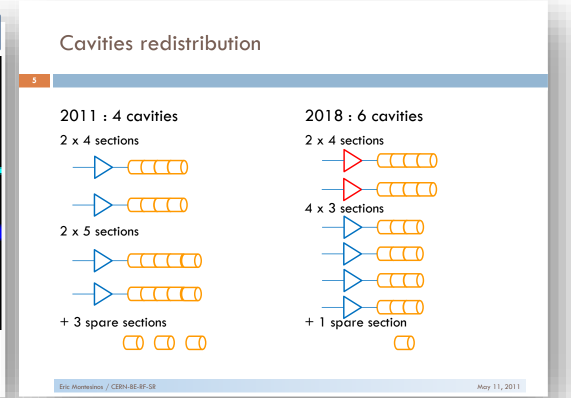
With the 4 cavities configuration we will have difficulties at high intensity LHC beam in the SPS : [IPAC11, Upgrade of the 200 MHz RF system in the CERN SPS]()

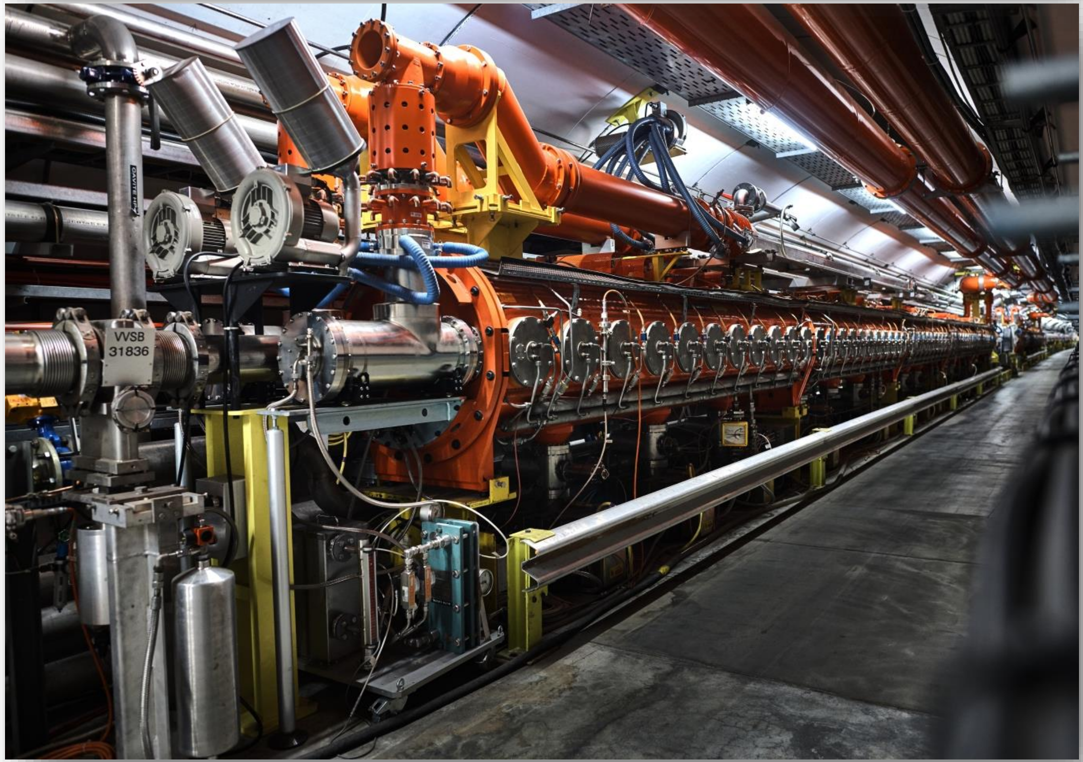
Increasing number of shorter cavities with two extra power plants should significantly improve the RF performance for higher LHC intensities

The best new compromise is 6 cavities

- 4 x 3 sections cavities with 1.0 MWp
- 2 x 4 sections cavities with 1.4 MWp (became 1.6 MWp)







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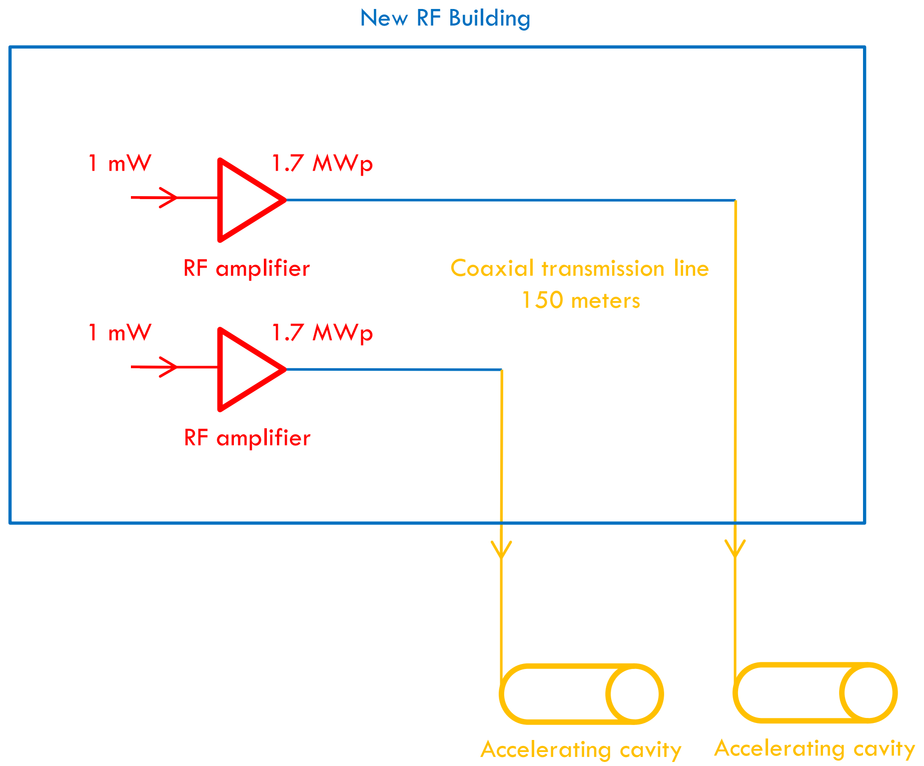
SPS RF POWER UPGRADE

Existing Amplifiers upgrade

New RF Amplifiers

New RF Building

LSS3 Tunnel integration



eric.montesinos@cern.ch

TEAMS INVOLVED (MORE THAN 350 PERSONS THANKS TO ALL OF THEM)

Dep-Group	Persons
BE-RF	Eric Montesinos, Charles Julie, Frederic Killing, Sébastien Calvo, Gino Cipolla, Antoine Boucherie, Simon Rains, James Bibby, Christophe Renaud, Cedrick Grandbois, Pilar Parrado Caballero, Irene Alonso Romero, Francisco Sauba Esteban, Morgan Wigham, Julien Novello, Sebastien Mutuel, Patrice Girod, Michel Ferrone, Jean-Marie Angonin, Romuald Terry, Sidi Chikhi, David Bastard, Lancelot Brechignac-Denis, Thomas Henry, Elena Shaposhnikova, Thomas Bohl, Christine Vollinger, Nasrin Nasresfahani, Patrick Kramer, Rama Calaga, James Mitchell, Wolfgang Höfle, Philippe Baudrenghien, Gregoire Hagmann, Luca Arnaudon, Carlos Oliveira, Diego Barrientos Turrion, Emile Grospelier, Thomas Kaltenbacher, Ester Sancho Cabrera, Débora Aguilera, Jose Enrique Varela Campelo, Paola Mazzotta, Toon Roggen, Urs Wehrle, Philip Hofer
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
BE-OP	James Ridewood
DG-LS	Florence Jacobs
HSE-SEE	Olivier Tison, Cécile Pinto, Jonathan Gulley, Laurent Colly, Guillaume Fontana
IPT-PI	Thierry Lagrange, Anders Unnervik, Ivo Lobmaier, Bjorn Jenssen, Fatima Najeh, Dante Gregorio, Laszlo Abel, Sandrine Magnan, Nordine Azizi, Alexandre Tabary, Sandra Benoit-Godet, Boi-Lan Nguyen-Lemoine
IT-CS	Stephane Casenove
EN-ACE	Katy Foraz, David McFarlane, Emmanuel Paulat, Patrick Bestmann, Julie Coupard, Sonia Bartolome Jimenez, Bertrand Nicquevert, Simon Cherault, Tobias Dobers, Yannick Beraud
EN-CV	Mauro Nonis, Serge Deleval, Michele Battistin, Alexandre Broche, Mathieu Archambau, Bill Bannister, Glen Mason, Aurelio Berjillos Barranco, Michel Obrecht
EN-EL	Nicolas Bellegarde, Guillaume Gros, Nuno Dos Santos, Thierry Bourrel, Jean-Claude Guillaume, Stefano Bertolazi, Georgy Georgiev, Gerardo Velasquez Gutierrez, Joel Lahaye, Denis Ribiollet, Simon Baird, Gérard Cumer, Davide Bozzini, Jérôme Pierlot, Juan Gomez, Thierry Octave, Christophe Crombez, François Duval, Jean-Pierre Sferruzza
EN-HE	Caterina Bertone, Jean-Baptiste Bonnamy, Pascal Brunero, Serge Pelletier, Yann Seraphin, Patrick Vallet, Gilles Roche, Helder Lorenco, Roberto Rinaldesi, Jean-Pierre Grandchelli, Jean-Louis Grenard
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, René Claret, Thierry Tardy, Pierre Moyret, Laurent Prever-Loiri, Jean-Marie Geiser
SMB-SE	Luz-Anastasia Lopez-Hernandez, Christophe Biot, Laurent Faisandel, Mathieu Fontaine
TE-EPC	Jean-Paul Burnet, Gilles LeGodec, Davide Aguglia, Karsten Kahle, Christophe Coupat, Clément Bovet
TE-MSC	Jérémie Bauche
TE-VSC	Paolo Chiggiato, Antonio Mongelluzzo, Sergio Calatroni, Wilhelmus Vollenberg, Ciara Pasquino, Jose Ferreira Somoza, Antonio Mongelluzzo

NEW 1.7 MWp AMPLIFIER, I.E 1.4 MWp CAVITY

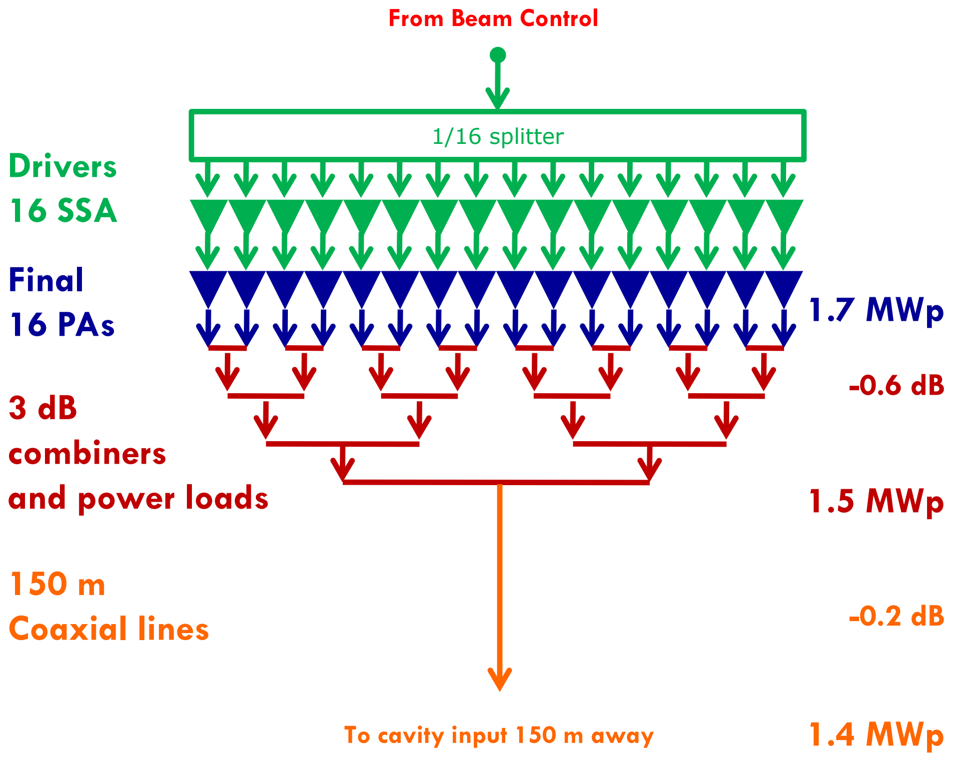
Operating frequency 200 MHz
Pulse mode 1.7 MWp max (10 µs / 43 kHz)
Average 850 kW (thermal limitations in coaxial lines)

A major improvement to existing systems will be to have ***individual SSA drivers*** per Final

Combiners and lines will be the same as with existing systems

Four contracts

- ❖Drivers (SSA)
- ❖Finals (Tetrodes, klystrons, IOT, SSPA, …)
- ❖Combiners (3 dB above 100 kW)
- ❖Transmission lines (coaxial, 345 mm outer)



FINAL OPENED TO ALL TECHNOLOGIES

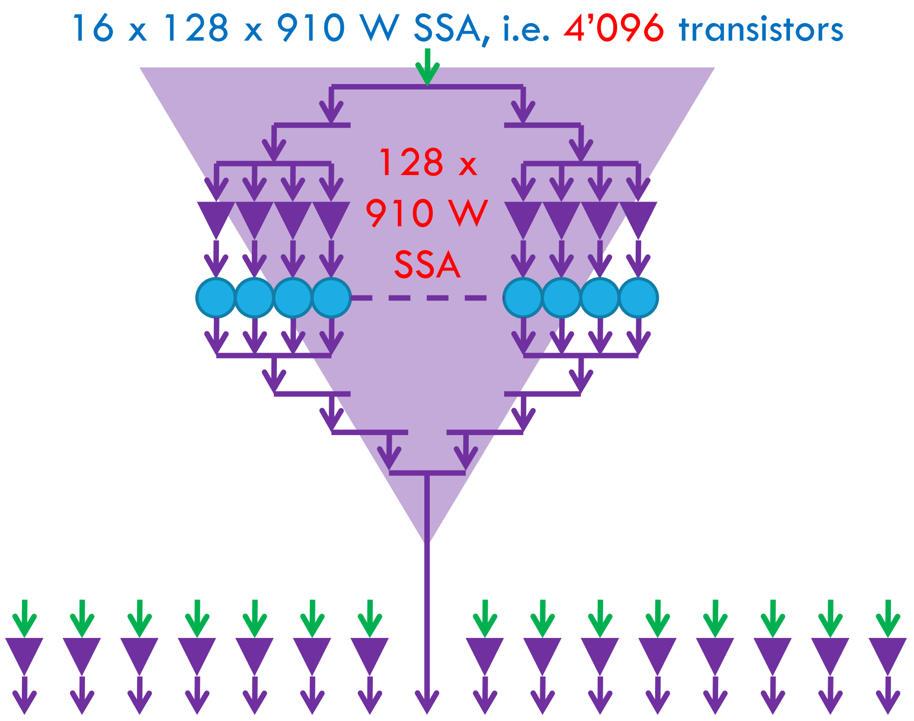
Qualified solution must have demonstrated to be reliable under scientific operation (not only broadcast operation)

Reliability and overall efficiency will be part of the adjudication

Main objective is **Availability**, and our target is 99,99 % availability for beams, this has driven the architectures of the possible systems

Each power station could have been

- 16 x 106 kW tetrodes
- 8 x 225 kW tetrodes
- 16 x 106 kW IOT
- 8 x 225 kW IOT
- 4 x 450 kW Diacrodes
- 2 x 1.7 MW klystrons
- 2'048 x 910 W Solid State Amplifiers



eric.montesinos@cern.ch

TRANSISTOR POWER RATINGS – PERSONAL VIEW OF FUTURE PERSPECTIVE (CWRF 2016 + IFAST 2022)

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

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

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 (CWRF 2016+ IFAST 2022)

Transistor supplier main business
will not be higher power per transistor

1482 Million Smartphones in 2015
6.1 Millions Micro cell stations 2009
5.9 Millions Macro cell stations 2009
Freescale + NXP Semiconductors revenue in 2015: $10'000 Millions

Coming soon, power transistors for Microwave ovens, almost doubling the revenue of transistor suppliers

Assumption (with a lot of simplifications)

Machine	# RF stations	Power	# 500 W LDMOS
FCC	100	1 MW	200'000

Cost of a LDMOS ~ $100
Revenue for transistors manufacturers $20 Millions
Over minimum 5 years $4 Millions per year

RF for the biggest RF accelerator could then be 0.04 % of main suppliers revenue per year

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

eric.montesinos@cern.ch

COMBINATION

$$\text{Pout} = \frac{\text{PA1} + \text{PA2}}{2} + \sqrt{\text{PA1 PA2}}$$

$$\text{Pload} = \frac{\text{PA1} + \text{PA2}}{2} - \sqrt{\text{PA1 PA2}}$$

3 dB combiner is very common for RF power combination at these frequencies since the 70’s

If one correctly adjusts the phases and the amplitudes, equations show that

With PA1 = PA2 = PA3 = PA4 = P then

Pout = 4 P

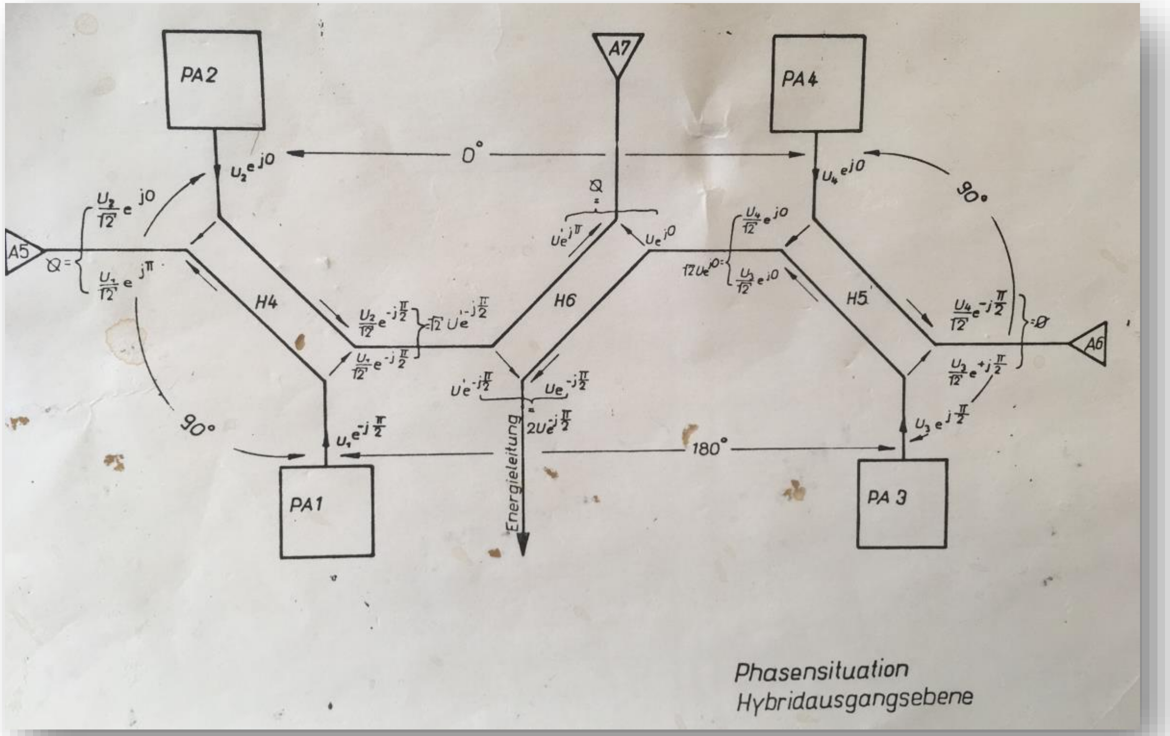
Load A5 = A6 = A7 = 0

In case **one** amplifier is **stopped** (PA1 for example), then

Pout = (9/16) 4P = **2,25 P**

Load A5 = 0,5 P

Load A7 = 0,25 P

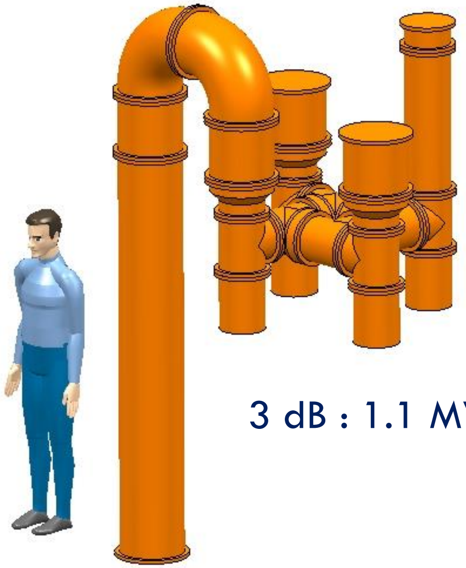


COMBINATION

CERN SPS 16:1 combiner @ 200 MHz

200 MHz CW combiners

3 dB : 550 kW
3 dB : 160 kW



3 dB : 1.1 MWp

eric.montesinos@cern.ch

CAVITY COMBINER

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

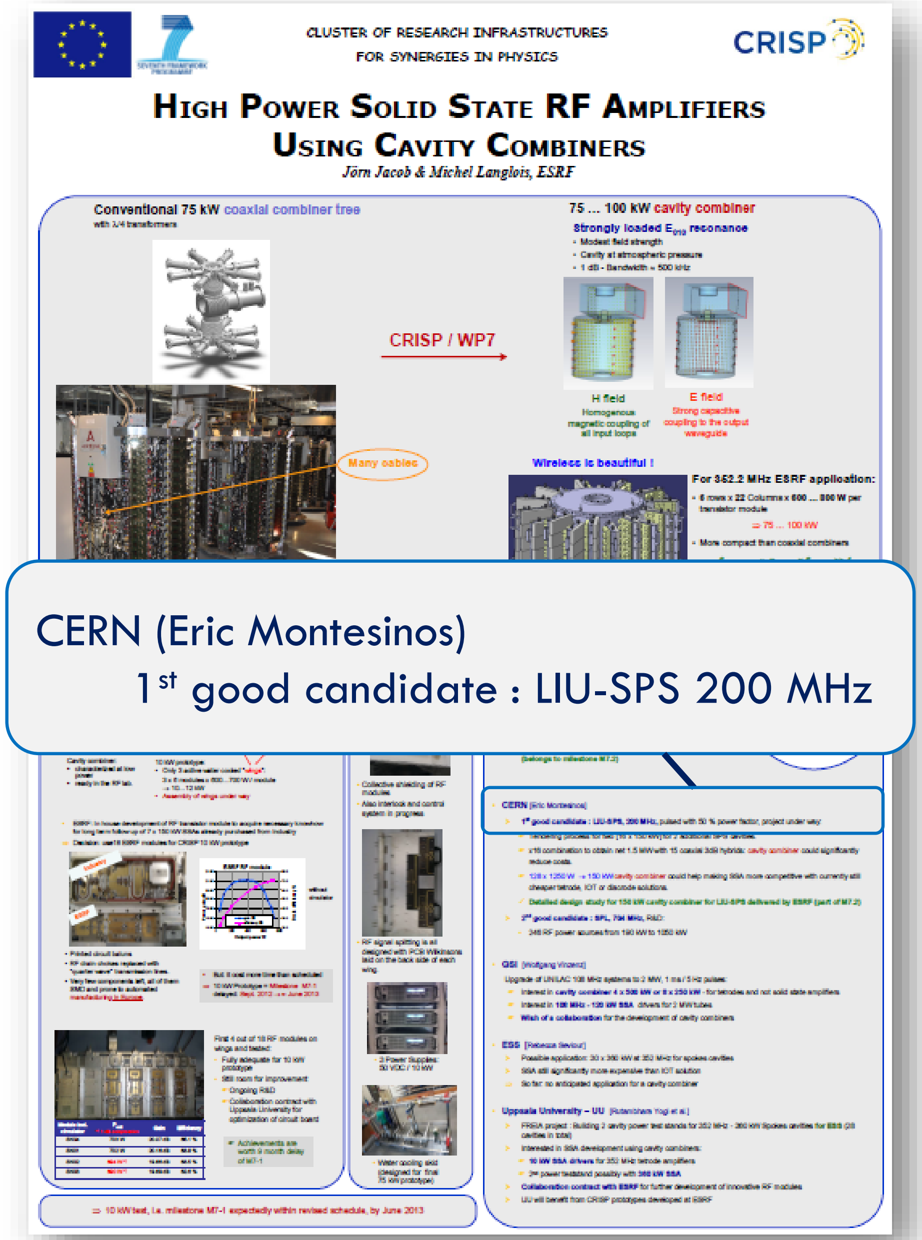
CERN immediately supported it

1st yearly meeting, Grenoble 20 September 2012

LIU-SPS 200 MHz

2nd yearly meeting, PSI 18-19 March 2013

144:1 Cavity combiner for CERN-LIU-SPS



CERN (Eric Montesinos)

1st good candidate : LIU-SPS 200 MHz

eric.montesinos@cern.ch

CAVITY COMBINER

Feb 2013, within the CRISP programme, we received a report from ESRF, describing how to build our LIU-SPS 200 MHz 144:1 cavity combiner

We completed the calculations and build a first prototype

We also completed the coupling loop design, the tuning design, and the output coupling element and we finally obtained at fantastic 144:1 cavity combiner with only 0,1 dB insertion loss, as calculated


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

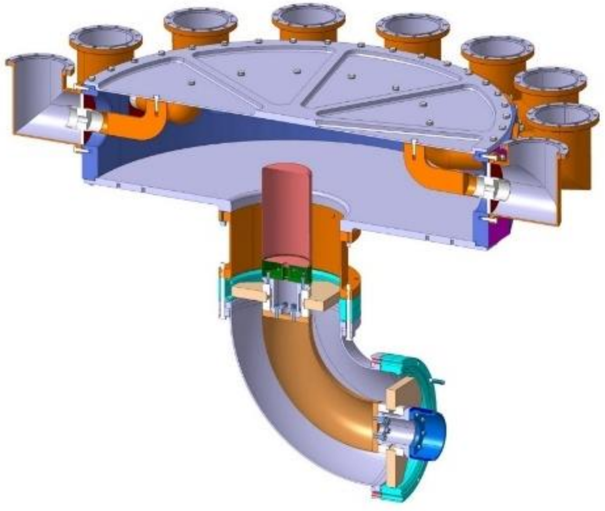
VHPCC (VERY HIGH POWER CAVITY COMBINER)

We also designed a VHPCC (Very High Power Cavity Combiner)

The goal was to have 16:1 combiner with inputs in the hundred of kW range and an output in the MW range

The 'cavity' has been machined from a single piece of metal

We tested it in reverse mode, as we had no hundred kW class amplifiers to test it in forward mode, and we checked that we had a perfect distribution between the test loads
With 1.26 MWp input, we obtained
78 kW +/- 1 kW
and the losses were less than 10 kW



eric.montesinos@cern.ch

BEAUTY OF CAVITY COMBINER

Cavity combiner is one of the best way to achieve power density with multiple sources

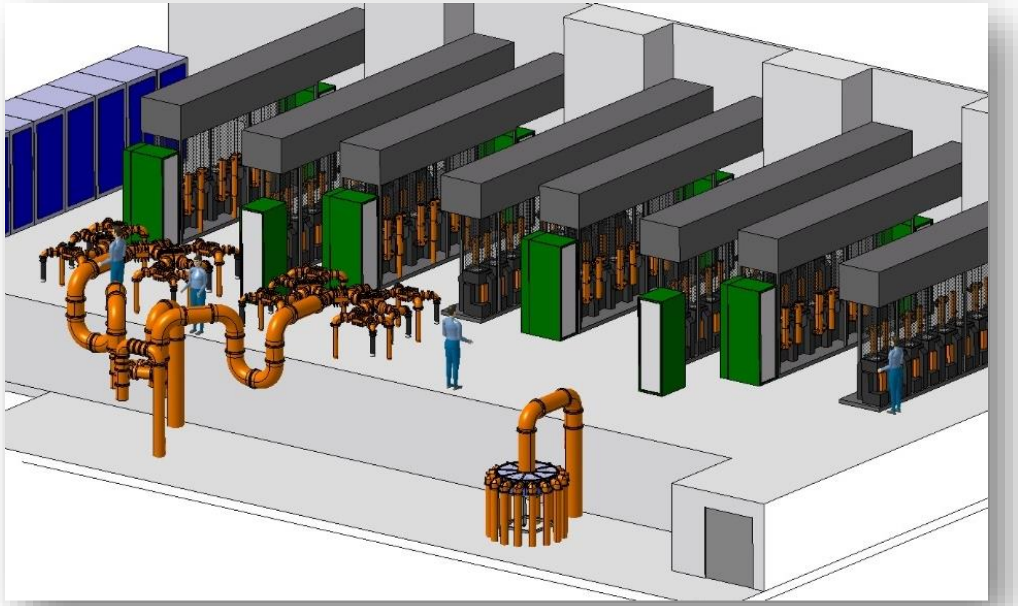
A fantastic intrinsic characteristic of a cavity combiner is that if you present a short circuit at a missing input, the output is the exact sum of all remaining inputs

16:1 combiner with	3 dB combiner Pout	Cavity combiner Pout
0 missing input	16 P	16 P
1 missing input	14 P	15 P
4 missing inputs	9 P	12 P

3 dB Combiner
(given the phases and amplitudes are correct)

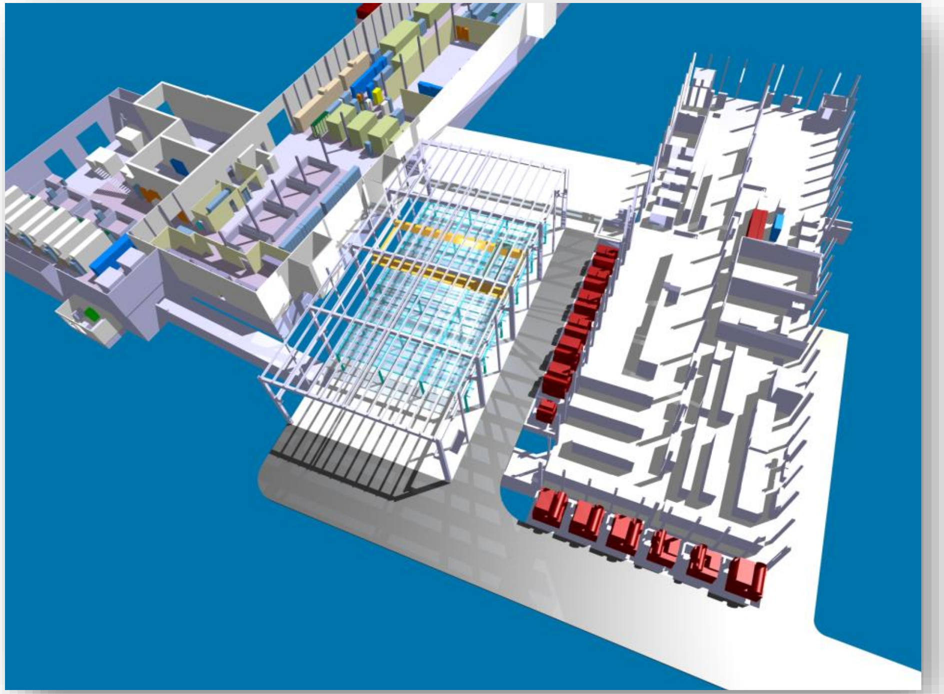
$$\text{Pout} = \frac{\text{PA1} + \text{PA2}}{2} + \sqrt{\text{PA1 PA2}}$$

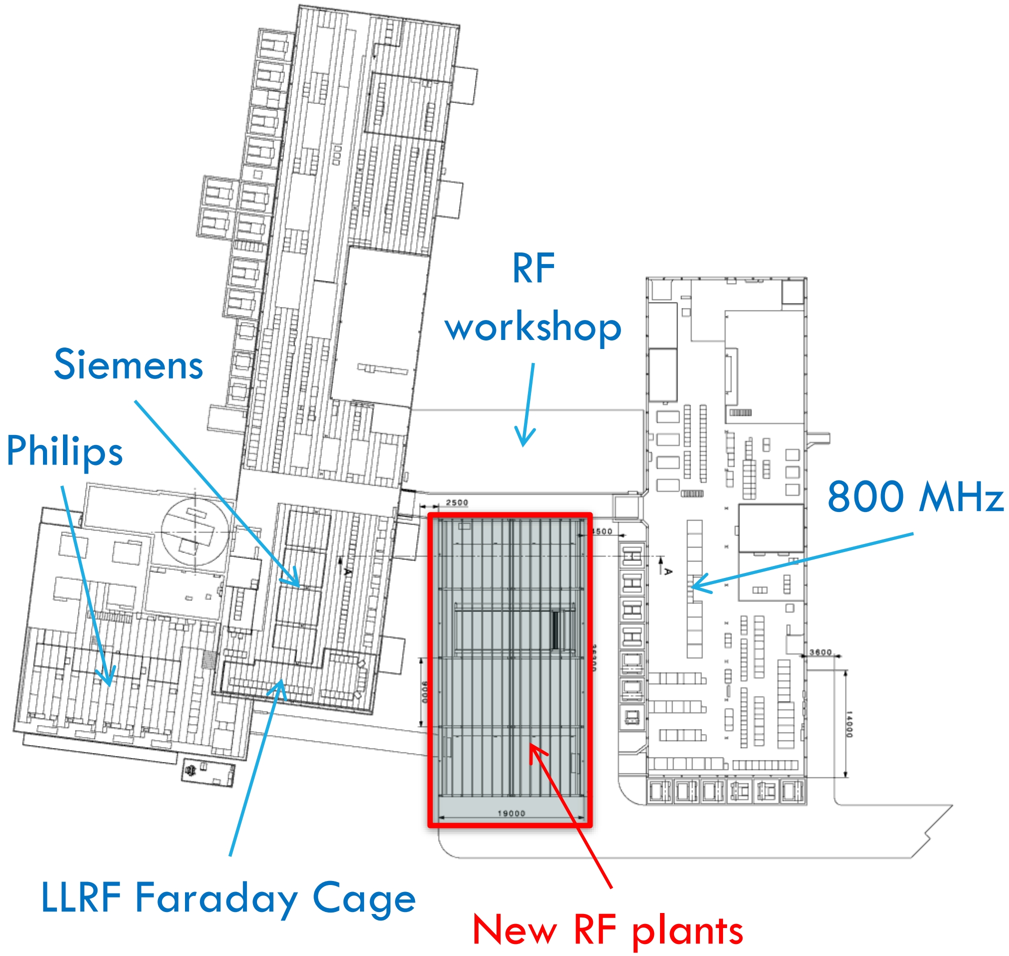
$$\text{Pload} = \frac{\text{PA1} + \text{PA2}}{2} - \sqrt{\text{PA1 PA2}}$$



NEW BUILDING

Whatever the solution, Tetrodes, Diacrode, IOT, Klystron, SSPA, the same building is offered
Best possible location allowed a maximum ‘RF’ foot print of 650 m2 + 500 m2





eric.montesinos@cern.ch

PROGRESS REPORT IN JUNE 2016 AT CWRF

THALES
GERAC ELECTROMAGNETISME

- ✓ Specific Power supplies validated
- ✓ First RF blocs tested up to 2 kW
- ✓ First Input cavity splitter and first Output cavity combiner constructed

Thales integrated two very clever ideas

- The way they make the coupling to the cavity
- The way they make possible to decouple one module

eric.montesinos@cern.ch

PROGRESS REPORT IN JUNE 2016 AT CWRF

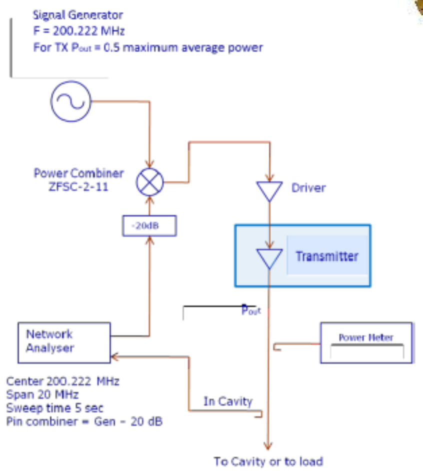
30 LONG MONTHS TO FIND A SOLUTION

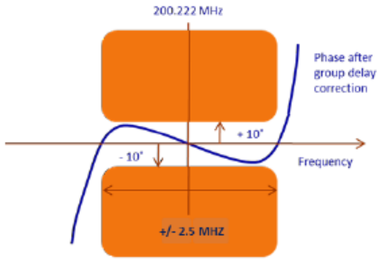
Technical specification with a lot of requirements

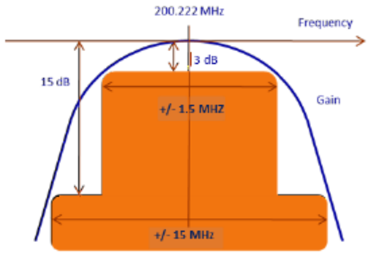
- Integration within the given building
- Repetition rate 0.1 Hz to 500 kHz (require a CW and a pulsed amplifier)
- Full reflection all phases 100 ms (equivalent to 4 time the power level along the lines)
- Non conventional way to measure the BW (required by LLRF and TWC)
- Very good linearity
- Two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

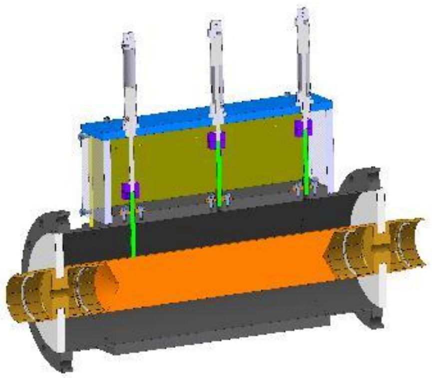
A lot of tests to qualify the amplifiers

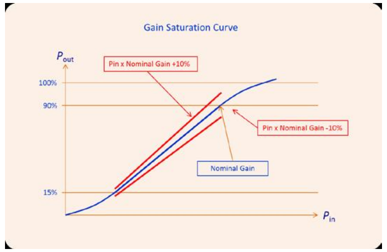
- Supercycle test, short circuit test, BW, linearity, …
- Short duration tests to qualify an Amplifier within one week
- Long duration tests to check reliability within one month

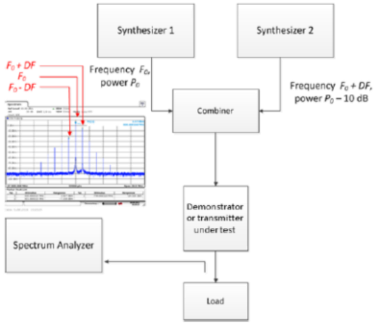


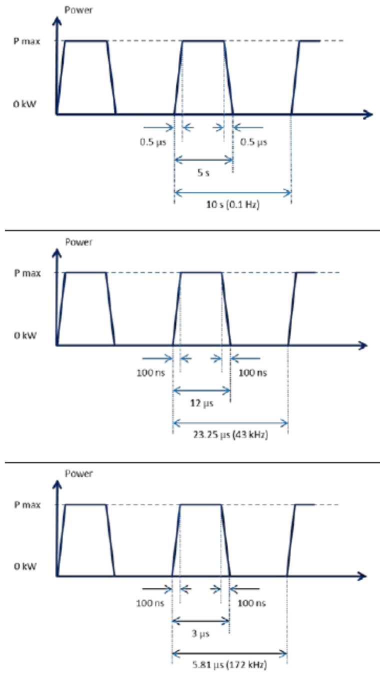


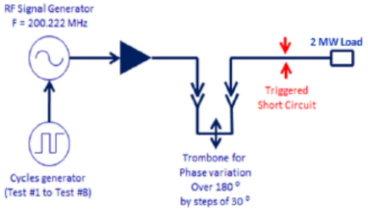












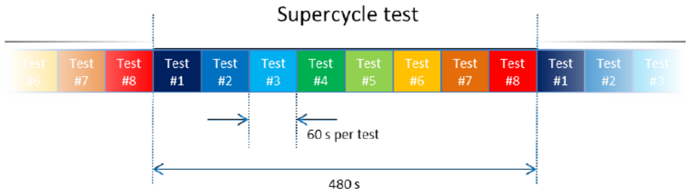


Figure 7: Supercycle test

30 LONG MONTHS TO FIND A SOLUTION

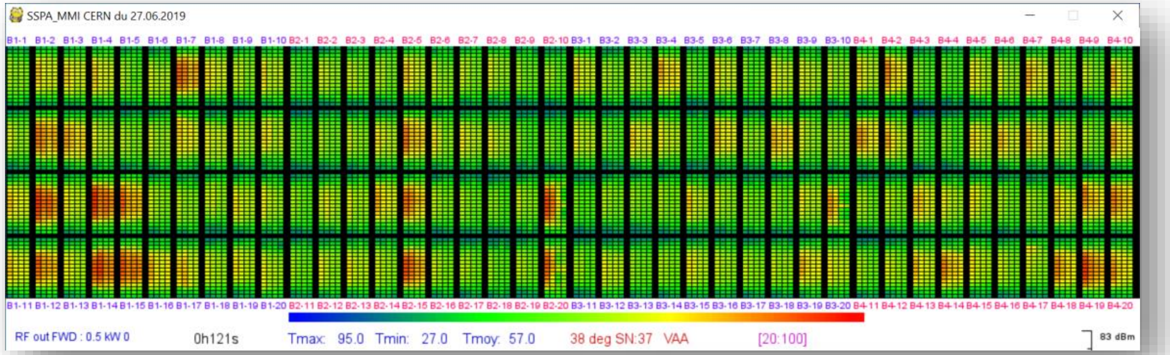
The first version successfully passed the qualification tests, including short circuit ones

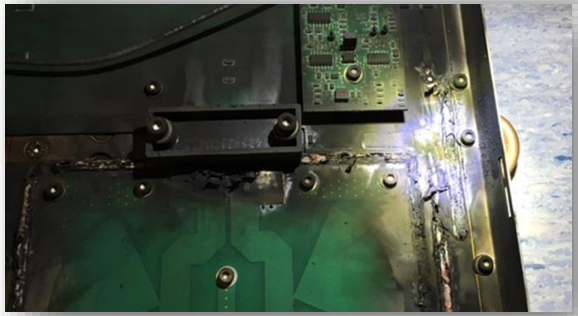
This was impressive as the solution is **without circulator**

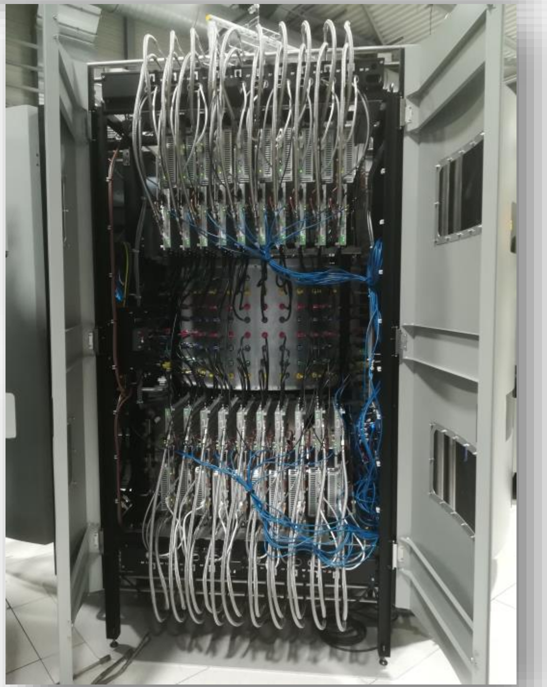
However, when doing the 1'000 hours long duration test, the transistors started to burn

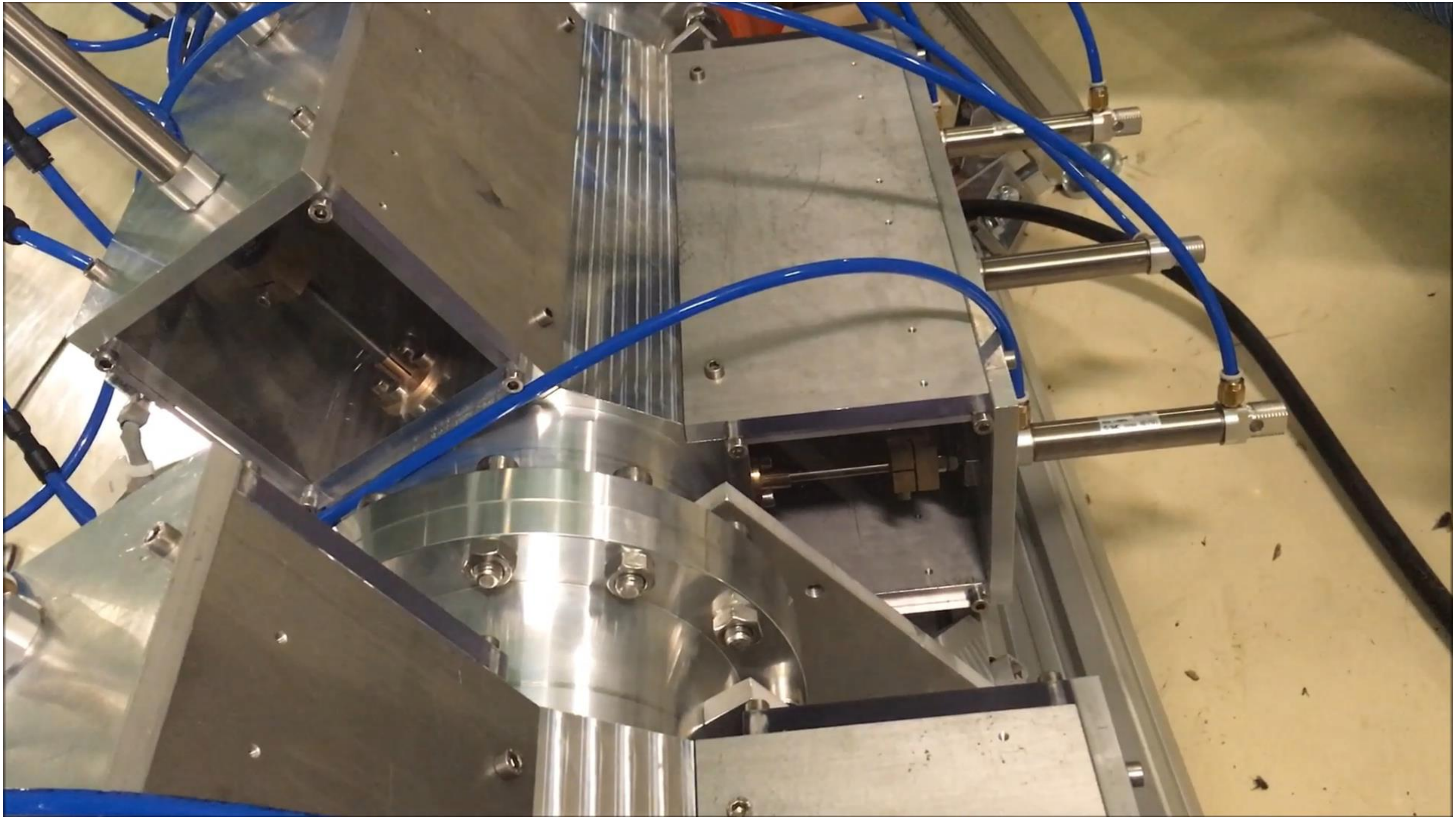
Thales implemented special thermal cameras to help to find out what were the troubles

We noticed that the overheating were randomly distributed amongst the cavity combiner



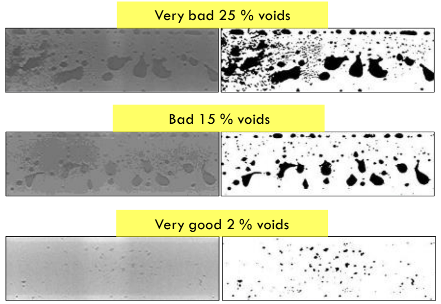




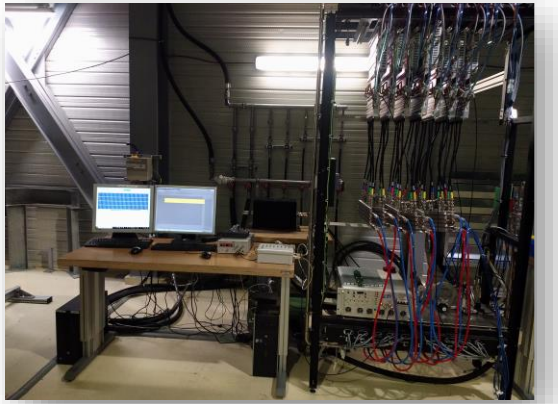


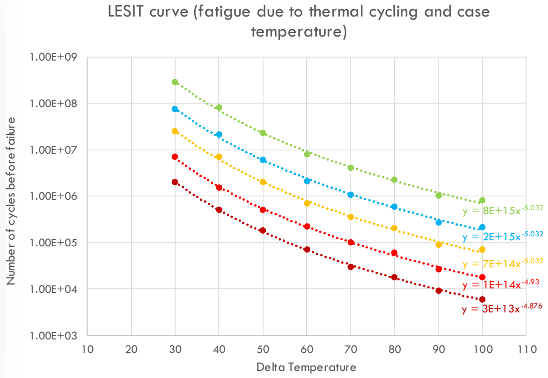
eric.montesinos@cern.ch

30 LONG MONTHS TO FIND A SOLUTION



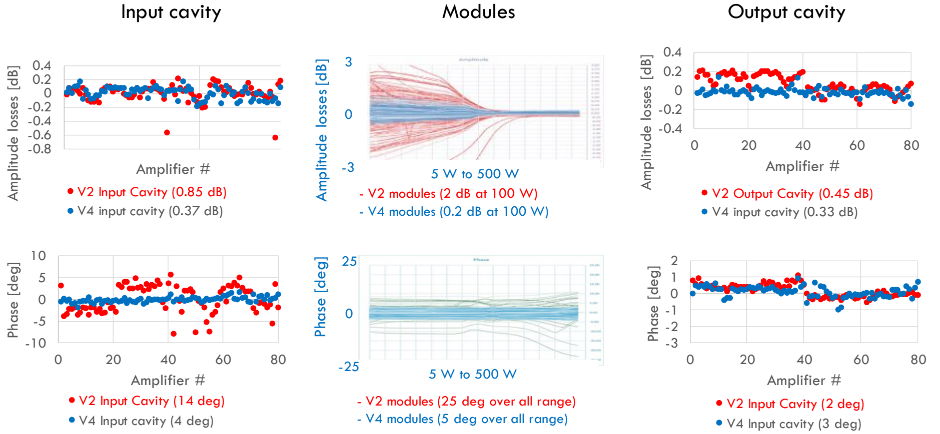
Thales built a second tower, with improved modules, but we still faced transistor destructions





In order to minimize the number of modules to be built, we built a test bench at CERN in order to do ageing fatigue tests with few modules (good to have modules connected to cavity combiners through cables!)

Thales built a third tower, with better results over the 1'000 hours tests, but then with destruction with short circuit tests



Tower

V2 : 3.3 dB (* 2.15)

V4 : 0.9 dB (* 1.23)

V2 : 41 deg

V4 : 12 deg

eric.montesinos@cern.ch

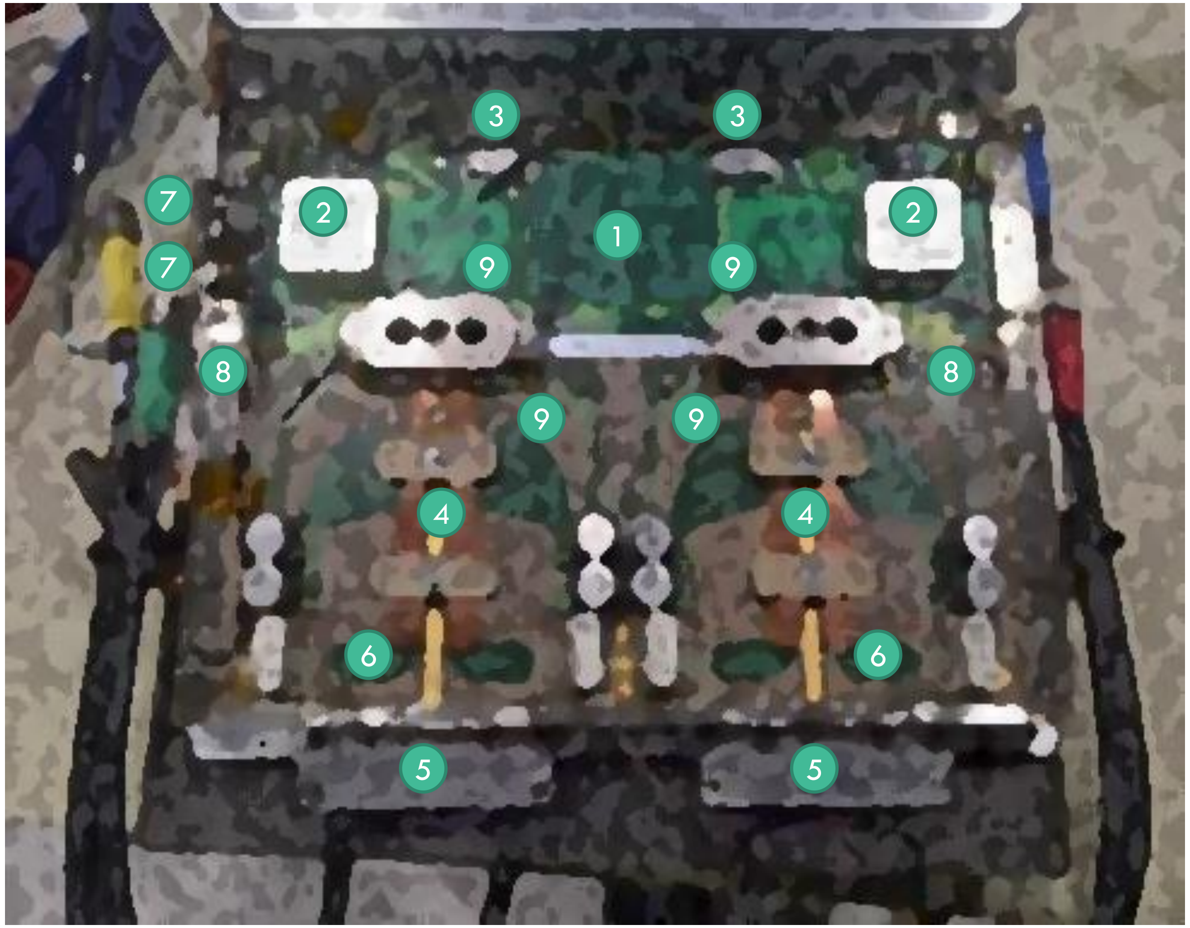
30 LONG MONTHS TO FIND A SOLUTION

Oscillations
- 9 Special oscillation filtering
- 2 Special control electronic
- 6 Output DC blockers to allow circulators
- 7 Special controls and RF connectors
- 8 Special switch off in case of failure

Dispersion
- 3 Adjustment of gain and phase dispersion of all modules
- 1 New input divider
- 12 Reduced RF dispersion of all sub-systems (input cavity + cables + modules + output cavity)

Thermal effects
- 10 New water cooling system
- 11 Special brazing of transistors
- 4 Special output tracks

Mechanical
- 5 Special output cables



eric.montesinos@cern.ch

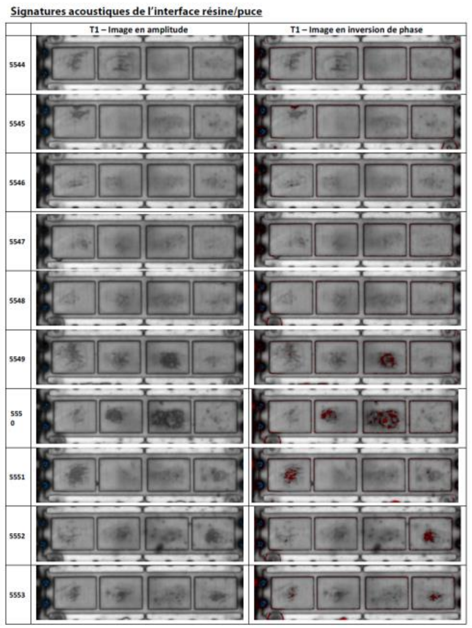
DEMONSTRATOR TO SERIES

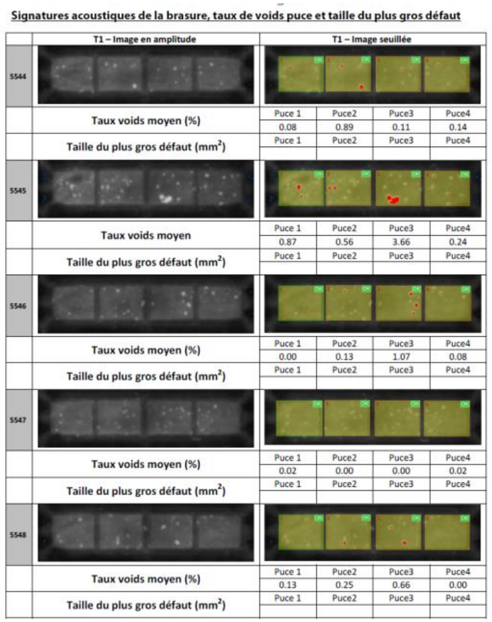
Before Series production, we defined strict Acceptance Test Plans (ATP) and Acceptance Test Reports (ATR)

Tower (x 35)
- Input cavity
- Output cavity
- Bays (x4)
- Hydraulic
- Electrical distribution
- VBF (Vérification de bon fonctionnement)
- Temperature
- Bandwidth
- Linearity
- Harmonics
- Supercycle 100 hours

Module (x 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 has been more than 15’000 test reports that have been produced





As an example of the quality plan, all brazed transistors are inspected (tomography) **no sampling** method is applied

eric.montesinos@cern.ch

DEMONSTRATOR TO SERIES

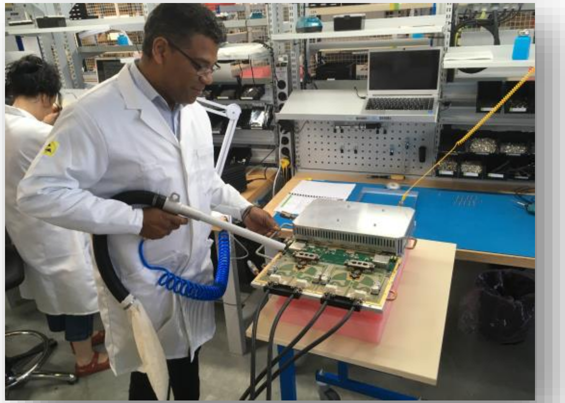
Gérac premises have been upgraded for industrialisation phase

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

Production capability is 120+ modules per week

First batch started to be delivered end of June 2019

Thales 'military' standards have been applied in order to satisfy the quality plan needed for our project



SERIES PRODUCTION

First Series tower qualified 10th July 2019

Qualification tests performed to qualify a tower, at a glance

1. 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
2. integration of the 80 modules in the tower with individual thermal camera per transistor
3. parameters checks; interlocks, bandwidth, linearity, harmonics, thermal behaviour with a SPS RF supercycle
4. 8 x 1 hour test at various predefined RF power levels and duty cycle
5. 100 hours long duration test with SPS RF supercycle, monitoring RF power and thermal behaviour
6. control that the parameters have not changed, repetition of bandwidth, linearity, harmonics and thermal behaviour

Despite the difficulties with the modules, Thales provided all the infrastructure for the 32 towers (even with no payment from CERN)

eric.montesinos@cern.ch

SERIES PRODUCTION

eric.montesinos@cern.ch

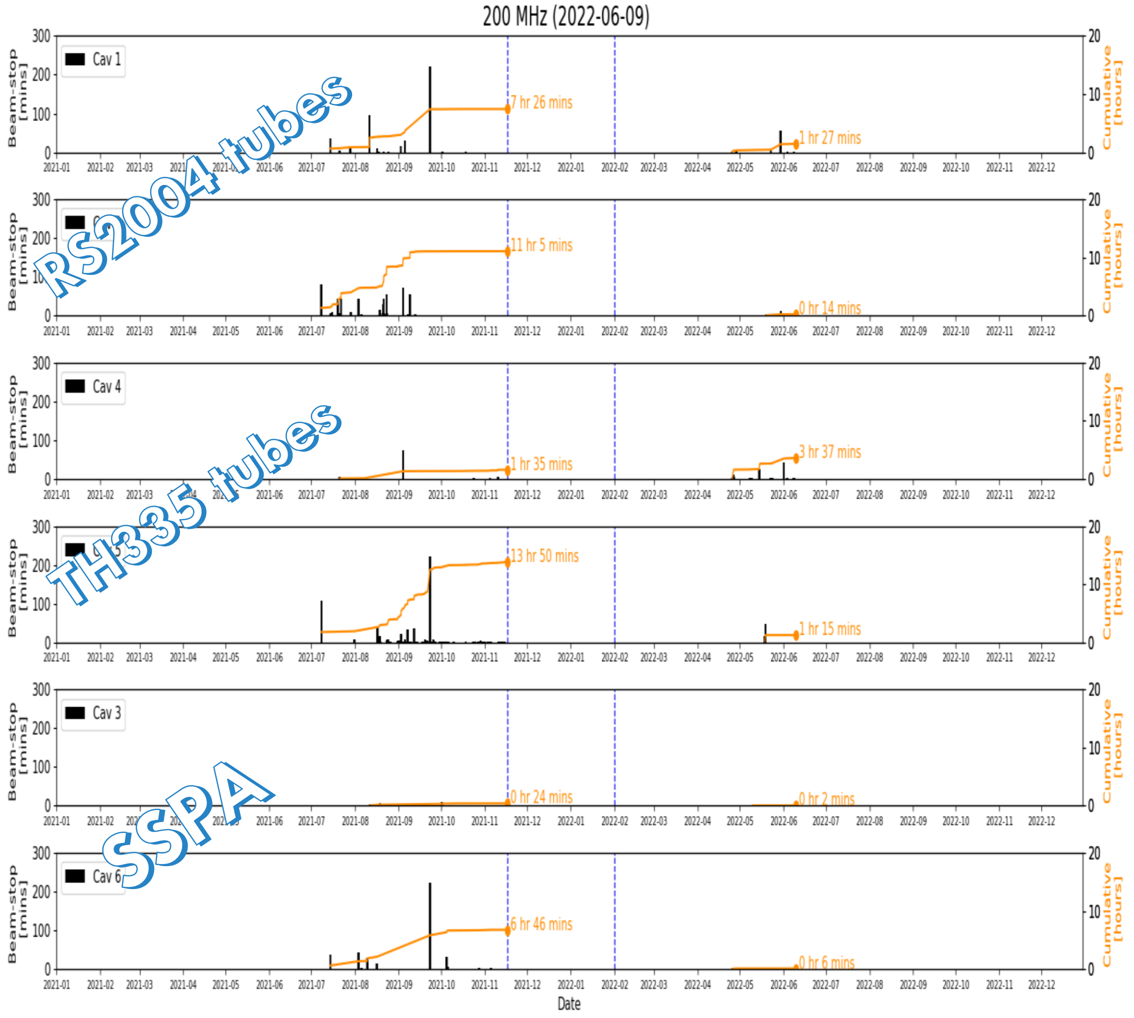
DEMONSTRATED AVAILABILITY

We operated the system all along 2021

Where 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)

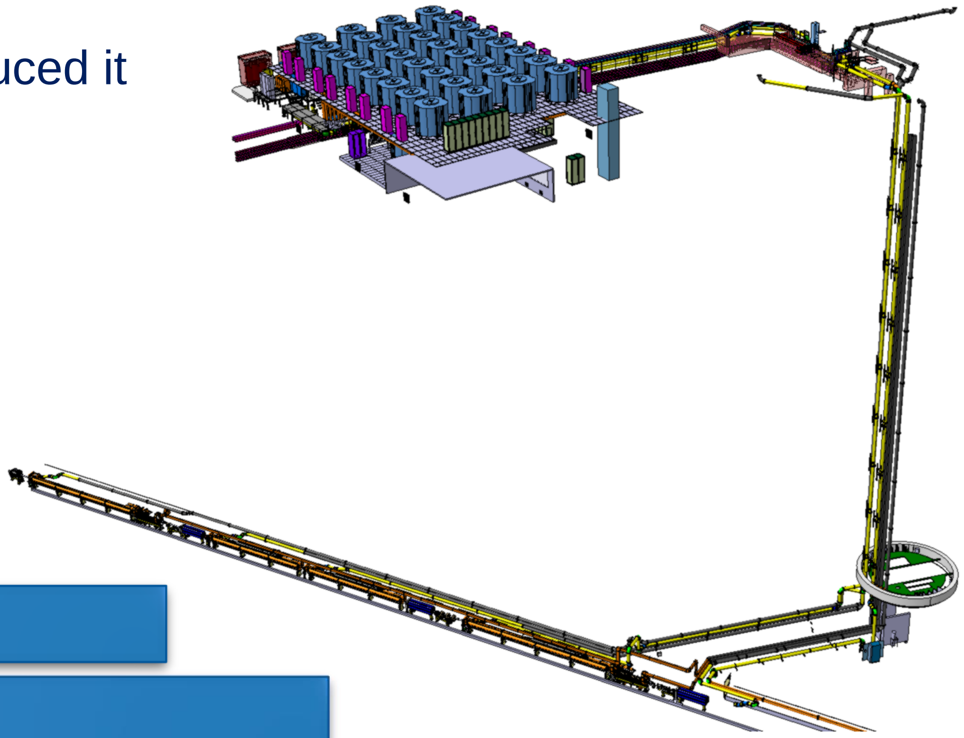


eric.montesinos@cern.ch

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



Cavity = 1 MW

150 m coaxial line = + 0.2 dB = + 5 % = 1.050 MW

Circulator = + 0.2 dB = + 5 % = 1.103 MW

Hybrid combiner 16:1 = + 0.3 dB = + 7 % = 1.175 MW

DC to RF (efficiency ~ **60** %) = 1.960 MW

AC to DC (efficiency ~ 90 %) = 2.175 MW (1'000 kW to be dissipated)

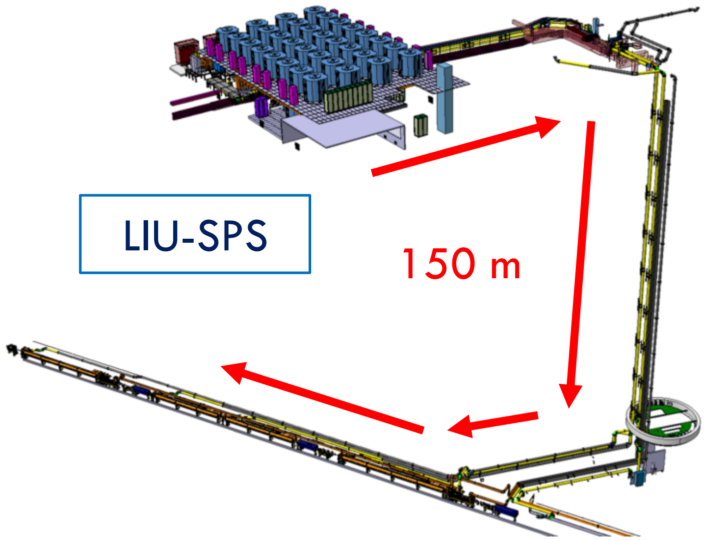
Air cooling station (10 % of 1'000 kW = 100 kW) ~ + 50 kW = 2.225 MW

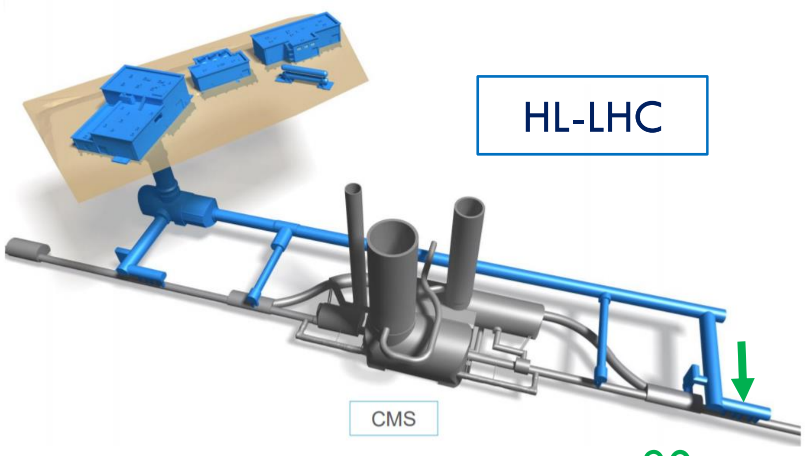
Water cooling station (90 % of 1'000 kW = 900 kW) ~ + 45 kW = 2,270 MW

Electrical distribution (5 % of 2.270 MW) ~ + 50 kW = **2,4 MW** taken from the grid

Overall efficiency **41,9 %**

EFFICIENCY





Cavity = 1 MW

20 m coaxial line = ~~+ 5 %~~ + 1 % = 1.010 MW

Circulator = + 0.2 dB = + 5 % = 1.060 MW

Hybrid combiner 16:1 = + 0.3 dB = + 7 % = 1.130 MW

DC to RF (efficiency ~ 60 %) = 1.890 MW

AC to DC (efficiency ~ 90 %) = 2,100 MW (970 kW to be dissipated)

Air cooling station (10 % of 970 kW = 97 kW) ~ + 49 kW = 2,149 MW

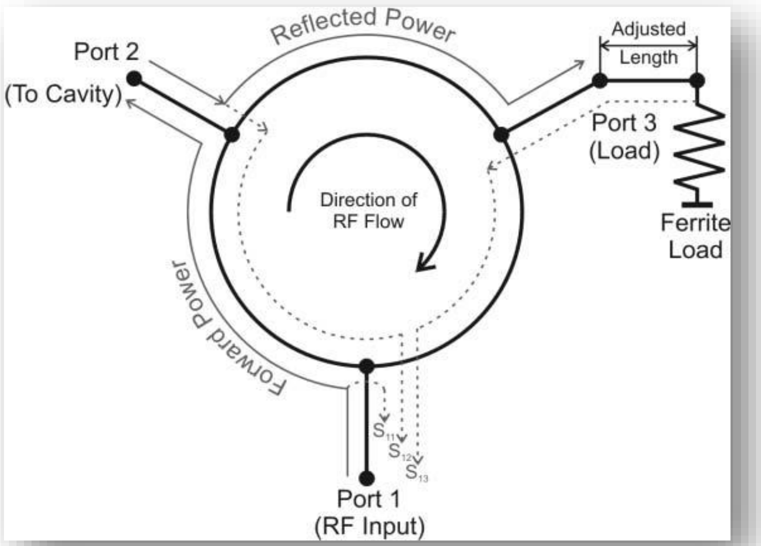
Water cooling station (90 % of 970 kW = 873 kW) ~ + 44 kW = 2,190 MW

Electrical distribution (5 % of 2,190 MW) ~ + 99 kW = **2,3 MW** taken from the grid

Overall efficiency **43,5 %** **41,9 %**

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 acquisition cost of transmission lines and to reduce cost of operation

EFFICIENCY



Cavity = **1 MW**

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = ~~+ 5 %~~ + 0 % = 1.010 MW

Hybrid combiner 16:1 = + 0.3 dB = + 7 % = 1.080 MW

DC to RF (efficiency ~ 60 %) = 1.800 MW

AC to DC (efficiency ~ 90 %) = 2,000 MW (920 kW to be dissipated)

Air cooling station (10 % of 920 kW = 92 kW) ~ + 46 kW = 2,046 MW

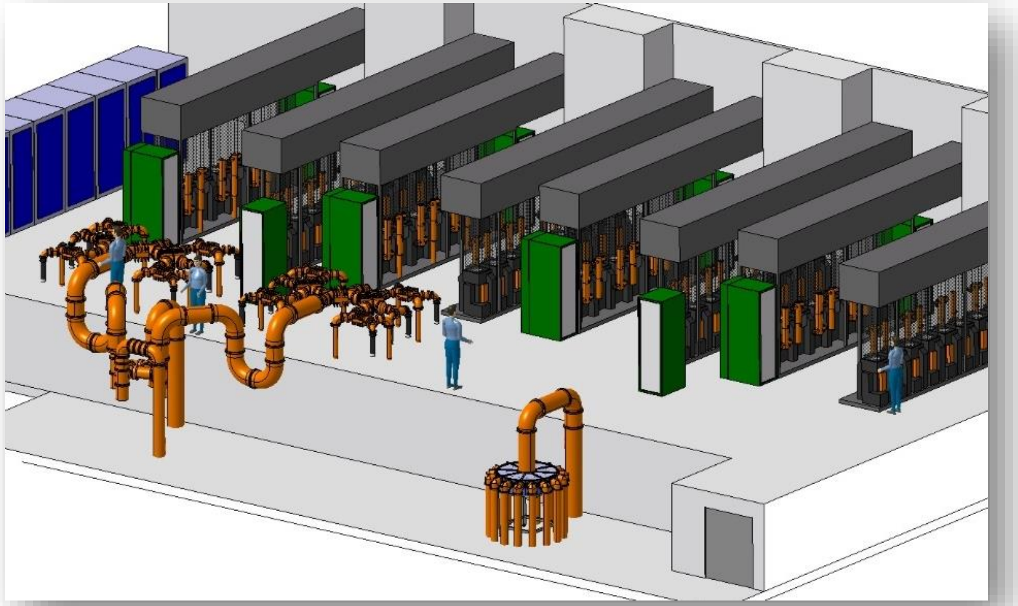
Water cooling station (90 % of 920 kW = 828 kW) ~ + 42 kW = 2,088 MW

Electrical distribution (5 % of 2,088 MW) ~ + 104 kW = **2,2 MW** taken from the grid

Overall efficiency **45,5 %** 41,9 %

As said, we are now able to build SSPA **without** circulator (Tetrodes and IOT can also do it)
The 'cost' is a (very) good protection system on the LLRF side

EFFICIENCY



Cavity = 1 MW

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = 1.010 MW

VHPCC 16:1 = + 0.1 dB = ~~+ 7 %~~ + 2,5 % = 1.035 MW

DC to RF (efficiency ~ 60 %) = 1.725 MW

AC to DC (efficiency ~ 90 %) = 1,920 MW (882 kW to be dissipated)

Air cooling station (10 % of 882 kW ~ 88 kW) ~ + 44 kW = 1,964 MW

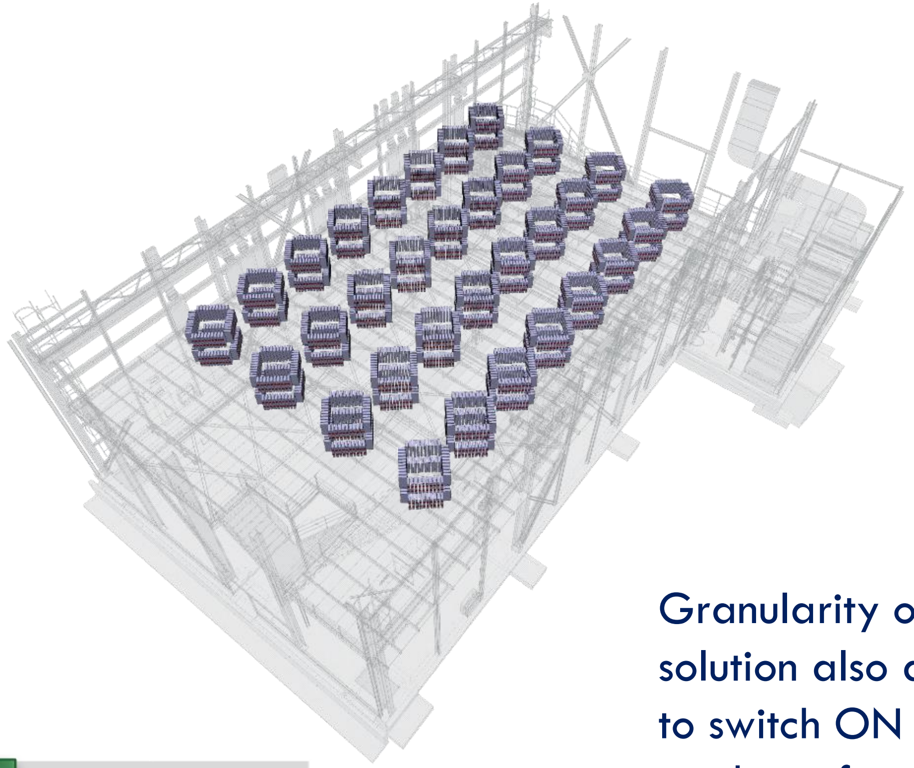
Water cooling station (90 % of 882 kW ~ 794 kW) ~ + 39 kW = 2,003 MW

Electrical distribution (5 % of 2,003 MW) ~ + 100 kW = **2,1 MW** taken from the grid

Overall efficiency **47,6 %** 41,9 %

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

EFFICIENCY



Cavity = 1 MW

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = 1.010 MW

VHPCC 16:1 = + 0.1 dB = + 2,5 % = 1.035 MW

DC to RF (efficiency ~~~ 60 %~~ ~ 66 %) = 1.570 MW

AC to DC (efficiency ~~~ 90 %~~ ~ 95 %) = 1,650 MW (615 kW to be dissipated)

Air cooling station (10 % of 615 kW ~ 62 kW) ~ + 31 kW = 1,681 MW

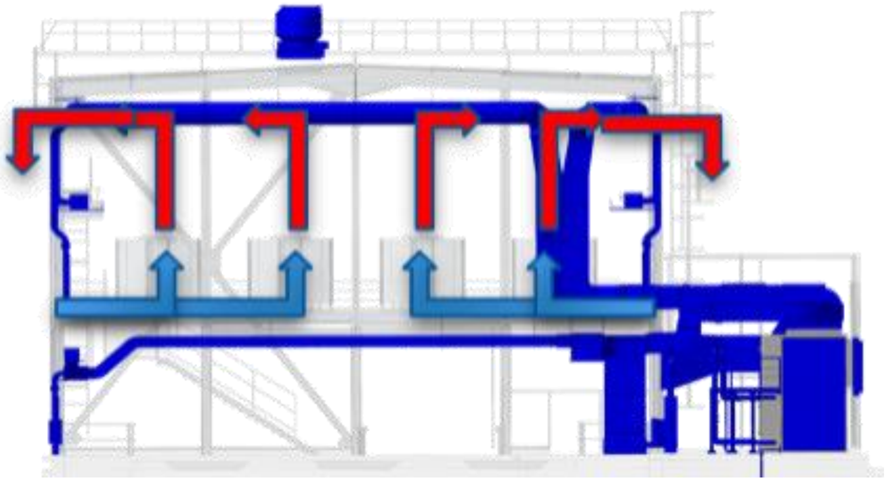
Water cooling station (90 % of 615 kW ~ 553 kW) ~ + 28 kW = 1,709 MW

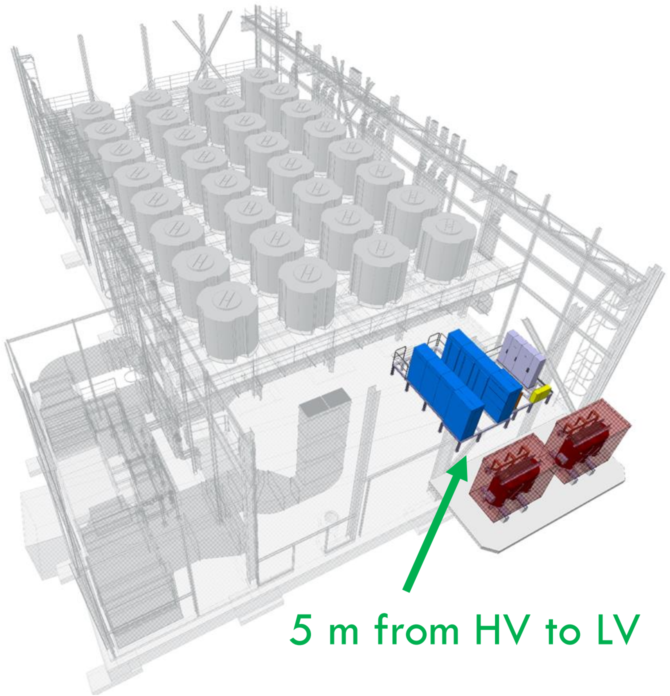
El. distribution (5 % of 1,709 MW) ~ + 86 kW = **1,8 MW** taken from the grid

Overall efficiency **55,5 %** 41,9 %

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

EFFICIENCY





Cavity = **1 MW**

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = 1.010 MW

VHPCC 16:1 = + 0.1 dB = + 2,5 % = 1.035 MW

DC to RF (efficiency ~ 66 %) = 1.590 MW

AC to DC (efficiency ~ 95 %) = 1,625 MW (590 kW to be dissipated)

Air cooling station (10 % of ~~615 kW~~ 590 kW ~ 60 kW) ~ + 27 kW = 1,652 MW

Water cooling station (90 % of ~~615 kW~~ 590 kW ~ 530 kW) ~ + 24 kW = 1,676 MW

El. distribution (~~5 % of 1,709 MW~~ 3 % 1,676 MW) ~ + 50 kW =
1,7 MW taken from the grid

Overall efficiency **58,8 %** **41,9 %**

Taking advantage of the natural chimney effect of the tower, having a well defined water station (variable speed), and shortening the LV cables will help reducing the remaining losses

CONCLUSION (I/II)

A special thank to SOLEIL for being the pioneer in the field

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

2 MWp SSPA per station? 750 kW SSPA per station?
We did it and it operates very reliably from Day1

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, being reached, is 99.99 %

FCC could very be with SSPA, we already work on it

- 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
- Vapour cooling
- Embedded spares with no replacement neither maintenance
- Plenty of other ideas already in mind…

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

The ultimate sophistication is simplification
(Leonardo Da Vinci, 1452-1519)

eric.montesinos@cern.ch

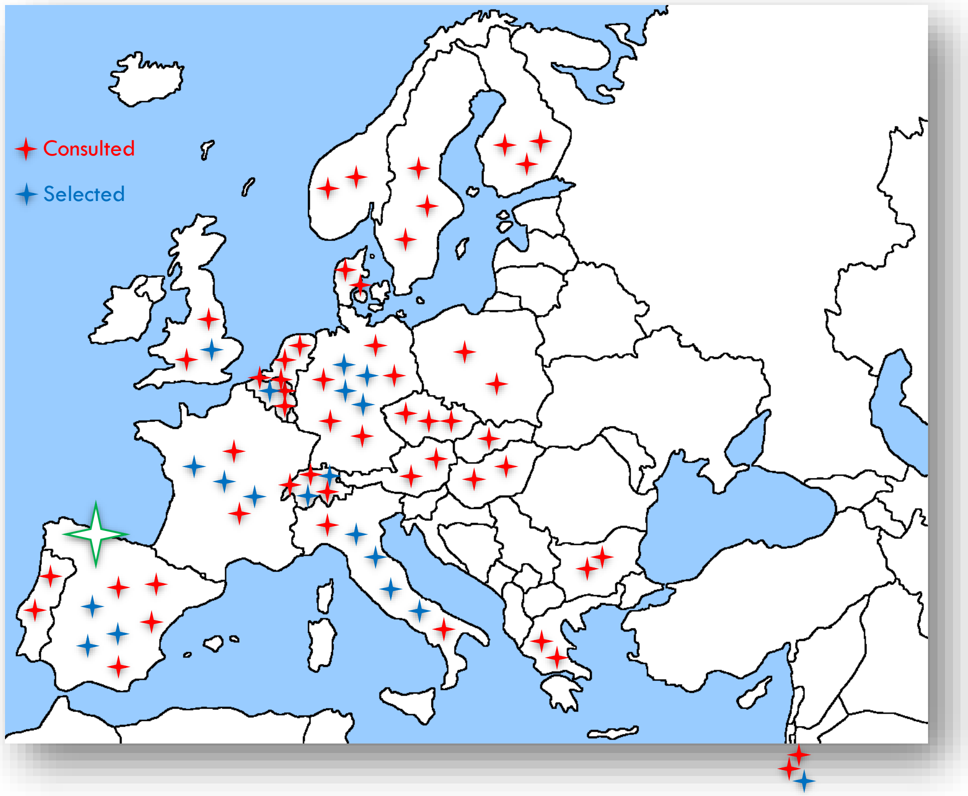
DRIVERS

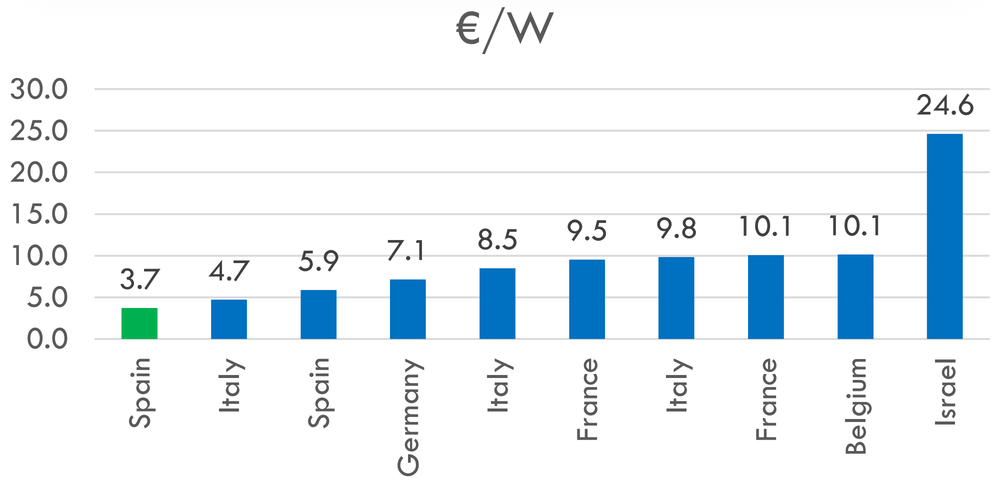
72 companies consulted
20 selected
10 offers

Defined a 1.25 kW unit

- Compatible with all Finals technologies
- One to six batches of 50 regarding result of future Finals contracts

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





eric.montesinos@cern.ch

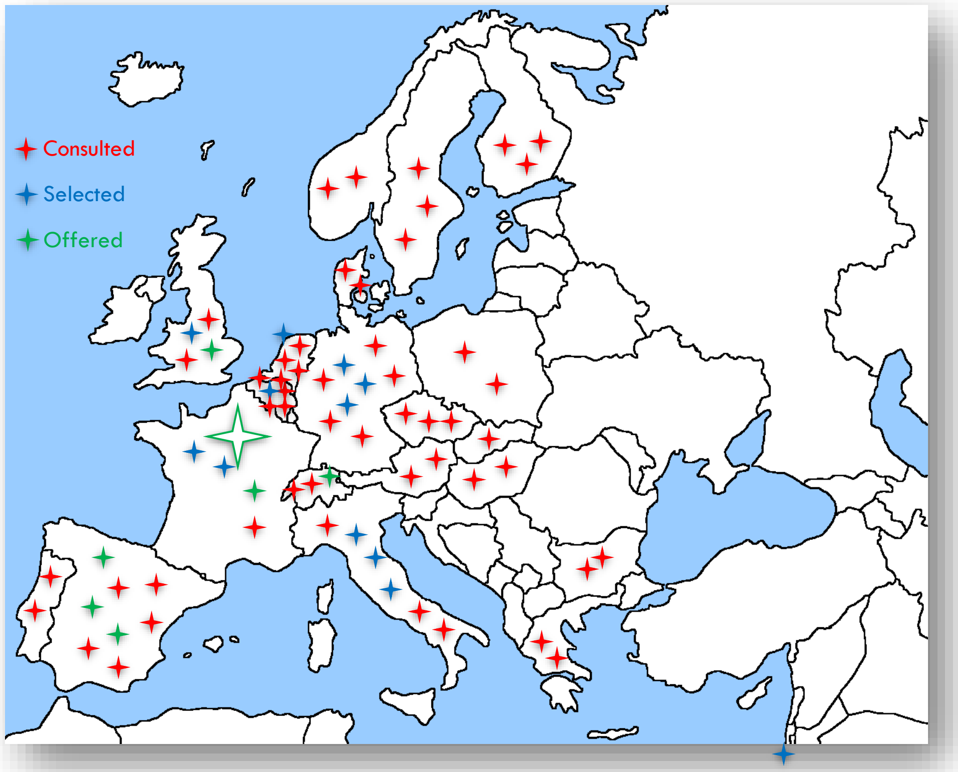
FINALS

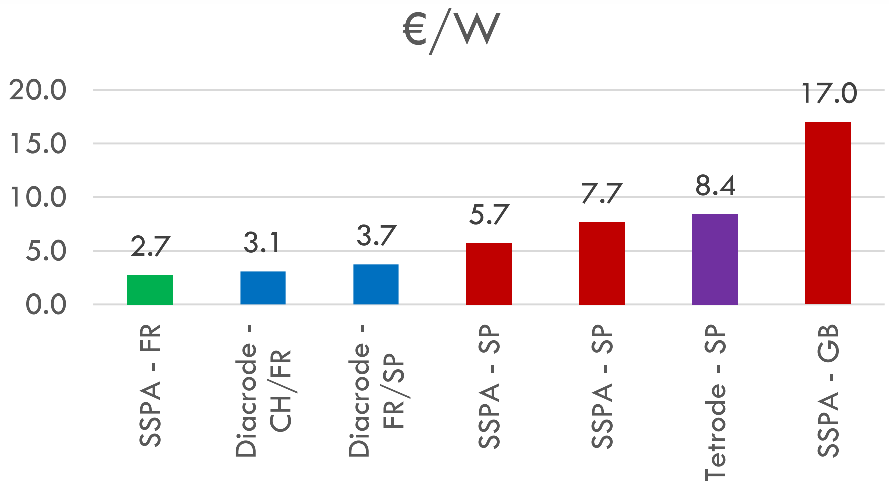
74 companies consulted
19 selected
8 declined
7 offers

March 2015 lowest bid was Thales Communication & Security

Very careful verification of the offer
(I am (was) a tube guy !)
I tried during 6 months to convinced Thales that this offer was not at a correct price
Thales ensured they will do it

December 2015, THALES, France, awarded the contract **(2.7 €/W)**





eric.montesinos@cern.ch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