

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 Upgrade SSPA Amplifiers

CWRF workshop 2016

21-24 June

ESRF Grenoble

Eric.Montesinos@cern.ch

Thanks to all CERN BE-RF-PM team members, with special thanks to

Charles Julie, Simon Rains, Gino Cipolla,

Ester Sancho Cabrera, Pilar Parrado Caballero, Philip Hofer, Antoine Boucherie, Sebastien Calvo, FSU-BE03



OUTLOOK

- Brief description of the RF power upgrade project
- RF cycles in the SPS
- New systems
- Purchasing strategy
- BAF3 – New RF building
- IT-3842, Drivers
- IT-3841, Finals
- Transistor power ratings – personal view of future perspective
- Cavity combiners
- IT-3841, Progress report
- Schedule
- Very High Power Cavity Combiner
- Present system upgrade
- Exciting years to come
- See you next CWRF



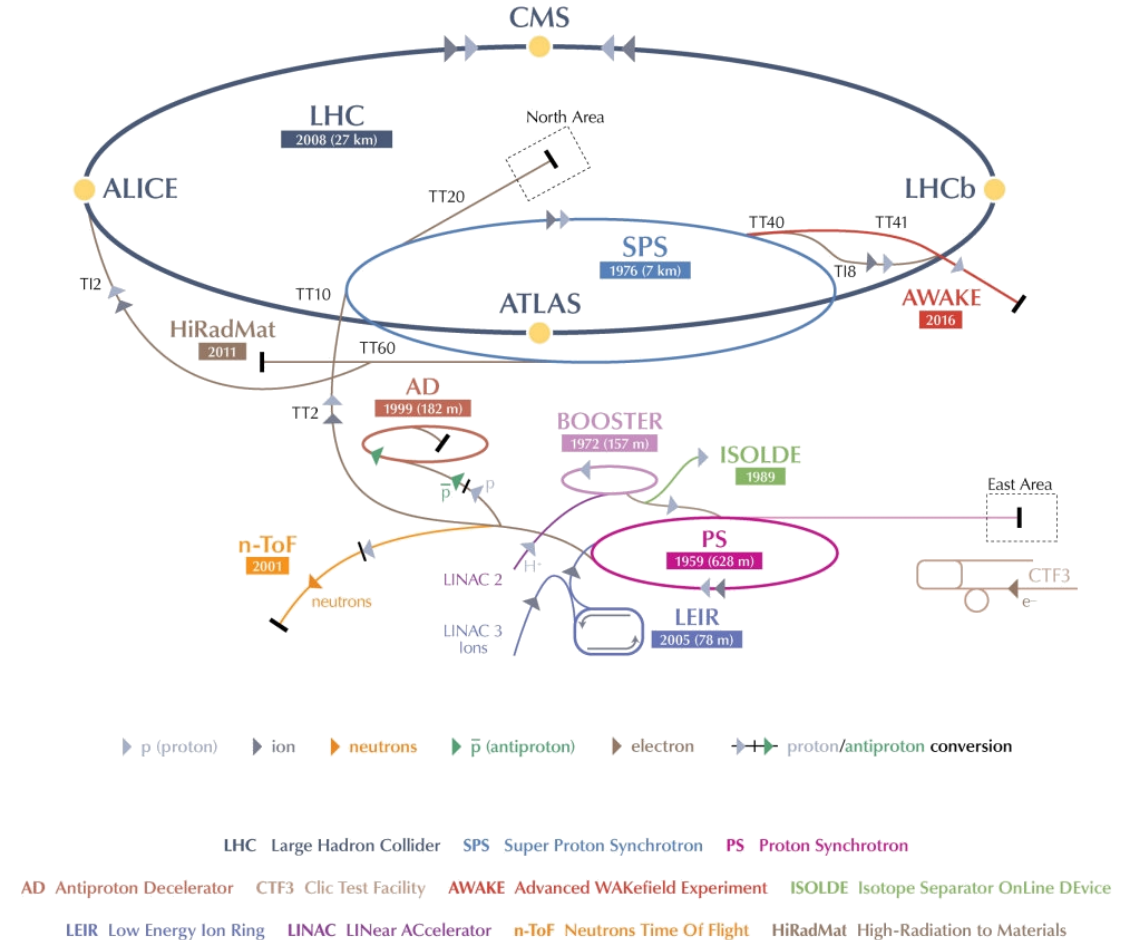
CERN SPS LIU PROJECT

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

CERN's Accelerator Complex

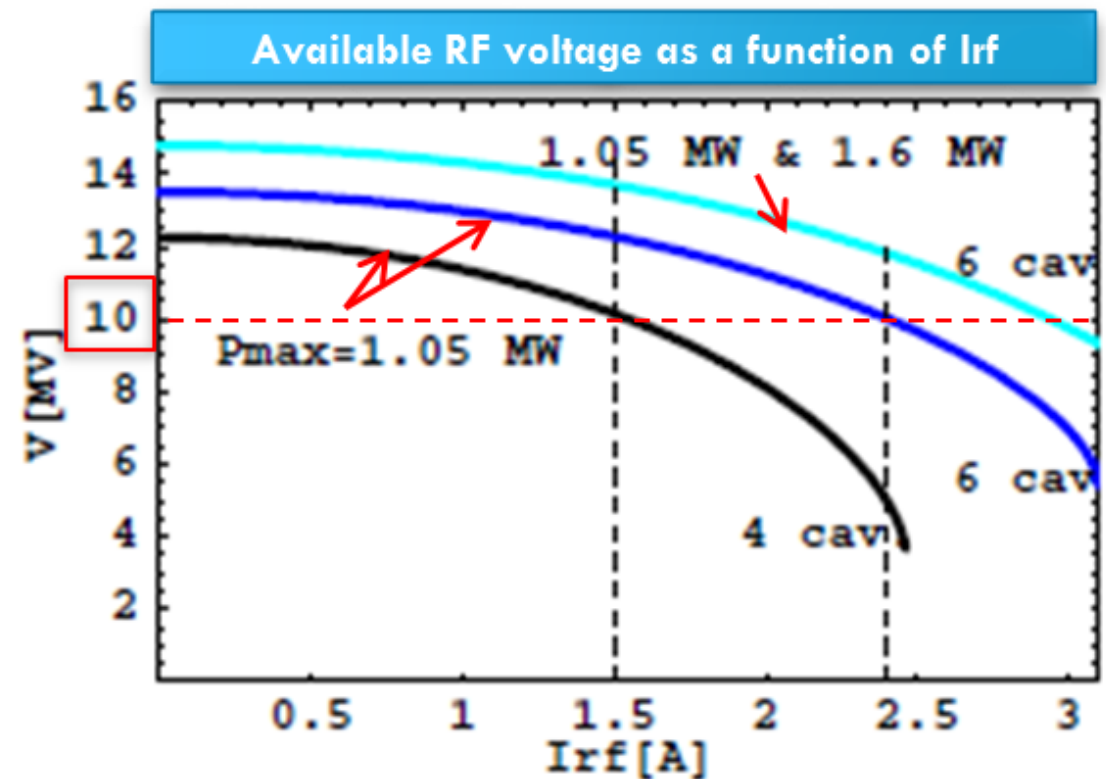


DESCRIPTION OF THE RF POWER UPGRADE PROJECT

Courtesy Elena Chapochnikova

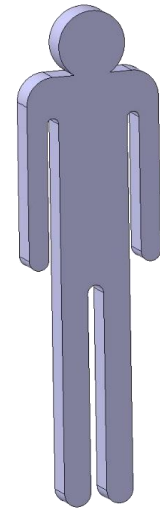
First definition of the project (2011)

- 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

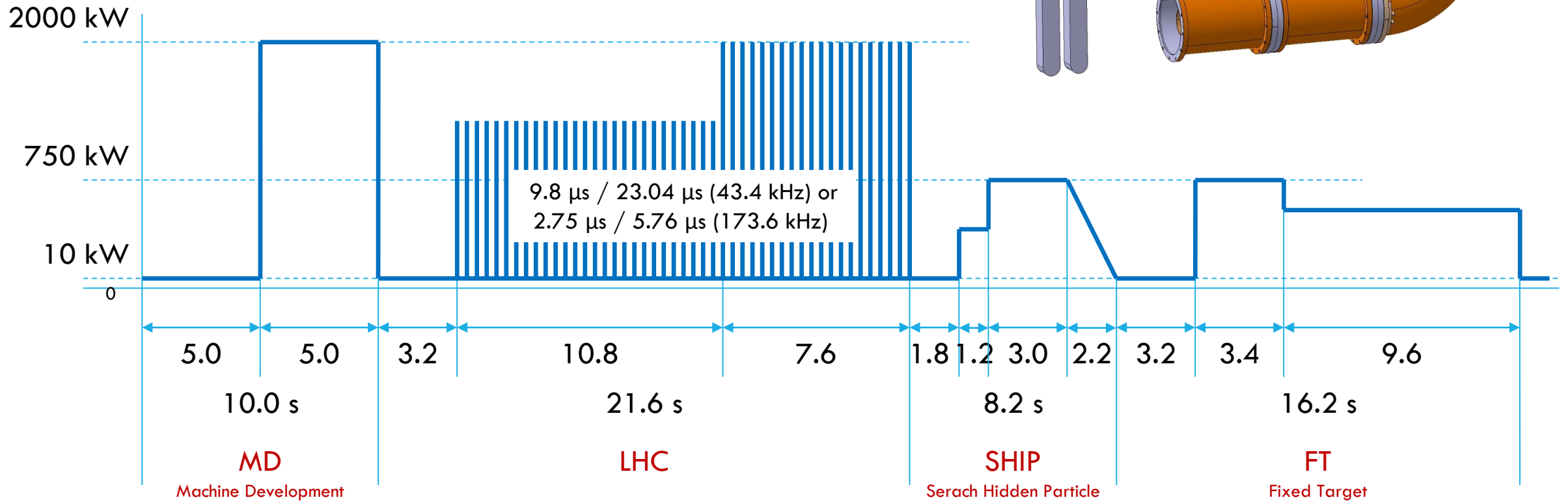
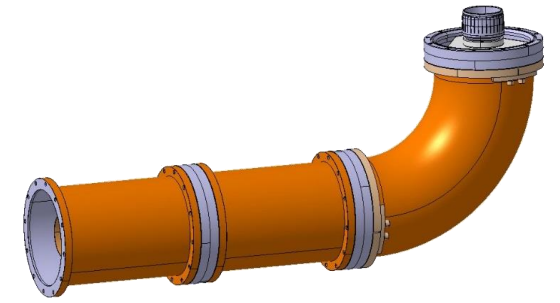




RF CYCLES IN THE SPS



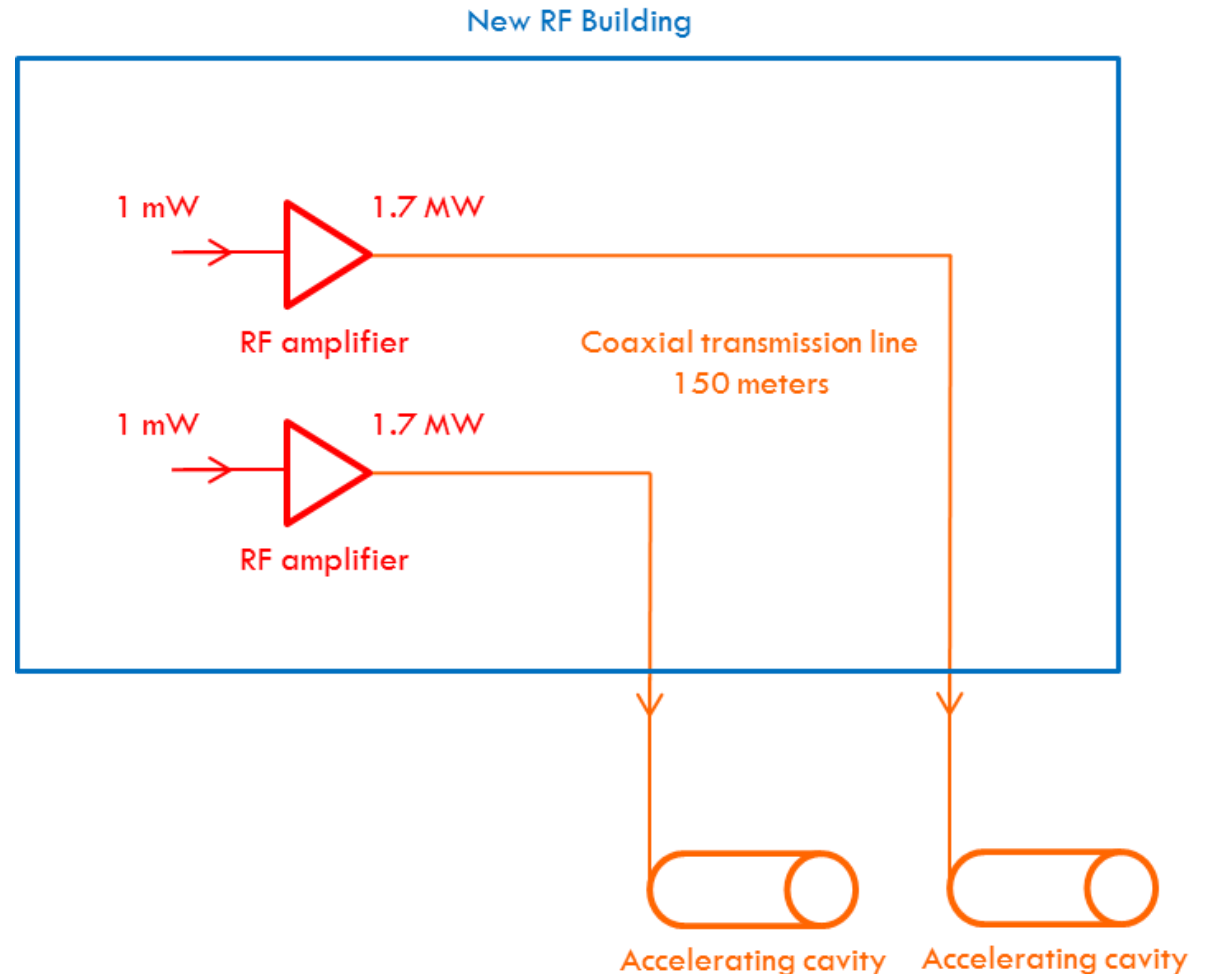
Average power limited to 750 kW due to 350 mm coaxial lines



DESCRIPTION OF THE RF POWER UPGRADE PROJECT

Three main sub-tasks

- 1) New RF Building project
- 2) Cavities re-arrangement project
 - LSS3
 - Coaxial lines
 - Cavities
 - Fundamental Power Couplers
- 3) RF Power Amplifiers project
 - Present amplifiers upgrade
 - **New amplifiers**

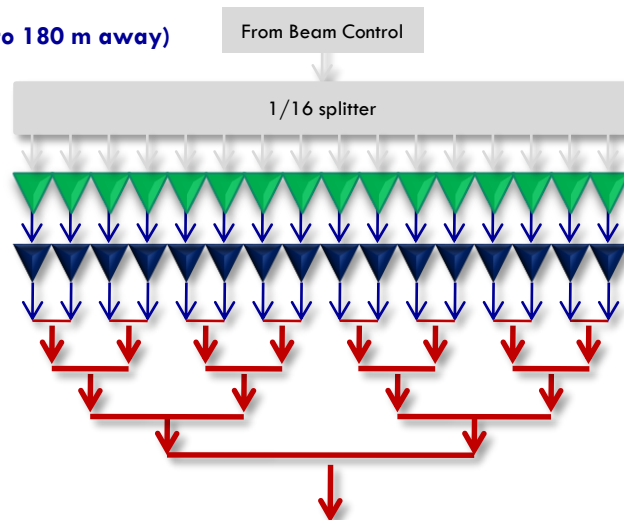




NEW SYSTEMS 2 x 1.7 MW @ 200 MHz

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 topics

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



PURCHASING STRATEGY

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**

Thanks to CERN purchasers, with special thanks to Anders Unnervik, Dante Gregorio, Lazslo Abel, Boi-Lan Nguyen Lemoine, Bertrand Nicquevert, Bjorn Jensen, Ivo Lobmaier

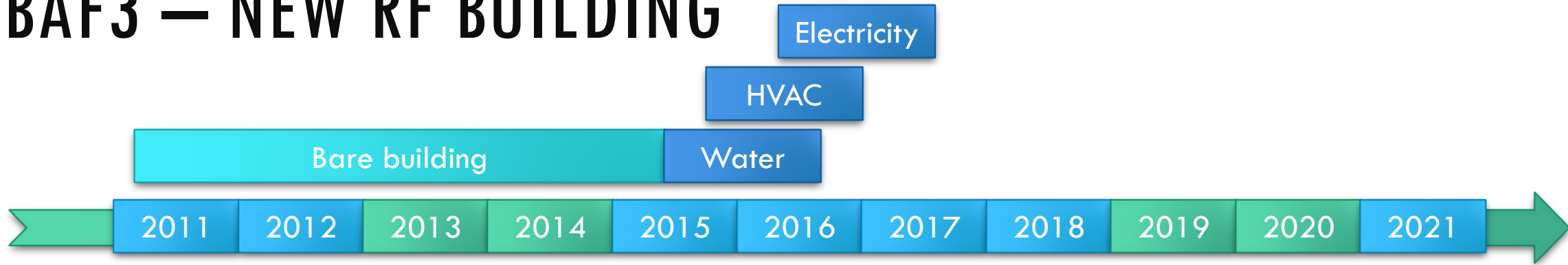
Drivers IT-3842 cost

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

IT-3841 adjudication to the lowest compliant



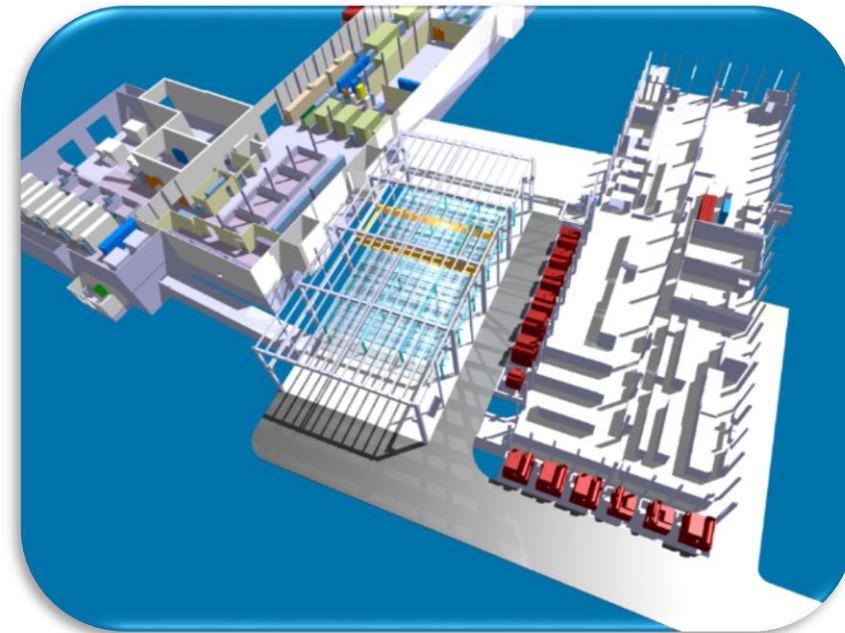
BAF3 – NEW RF BUILDING



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 (taking advantage of LS1 to minimize accident impacting SPS operation during construction)

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





BAF3 — NEW RF BUILDING

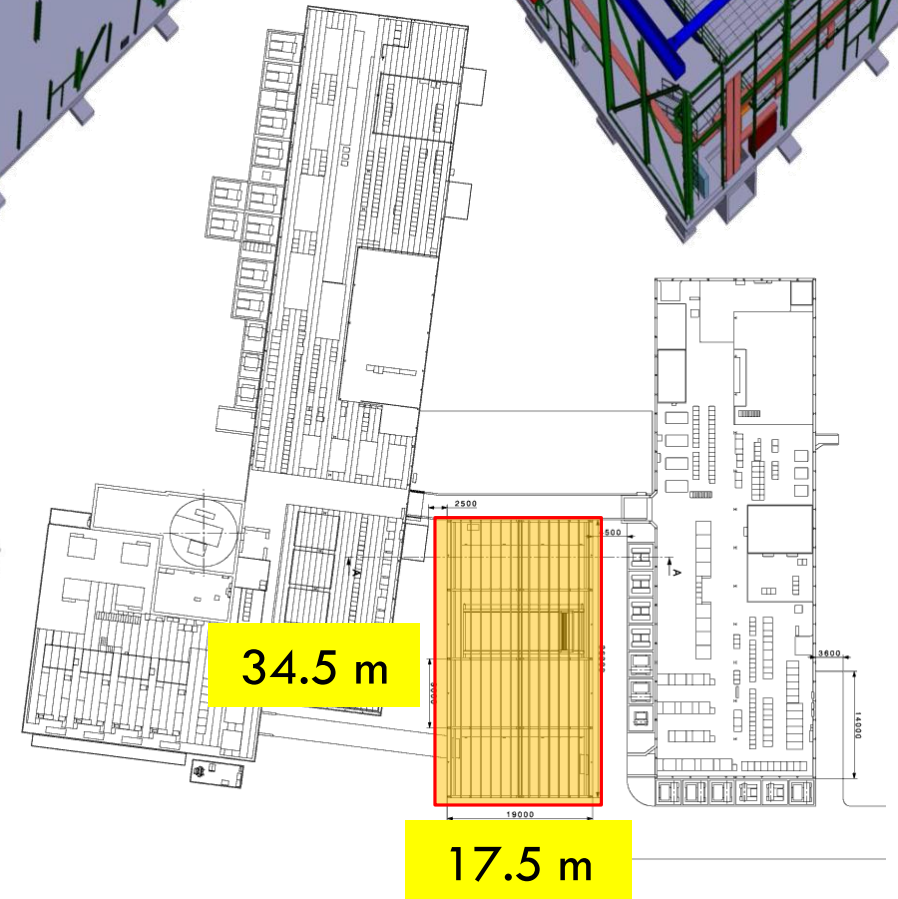
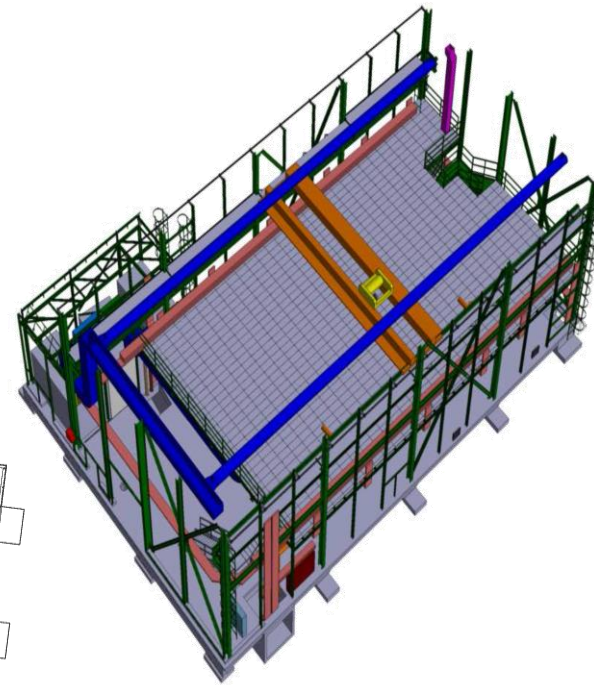
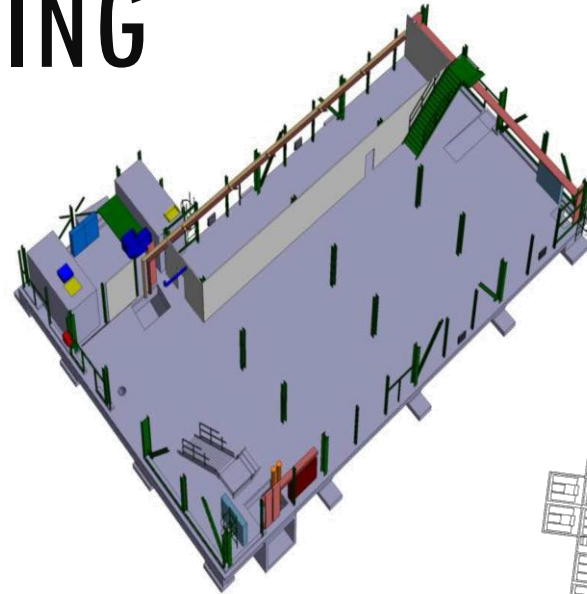
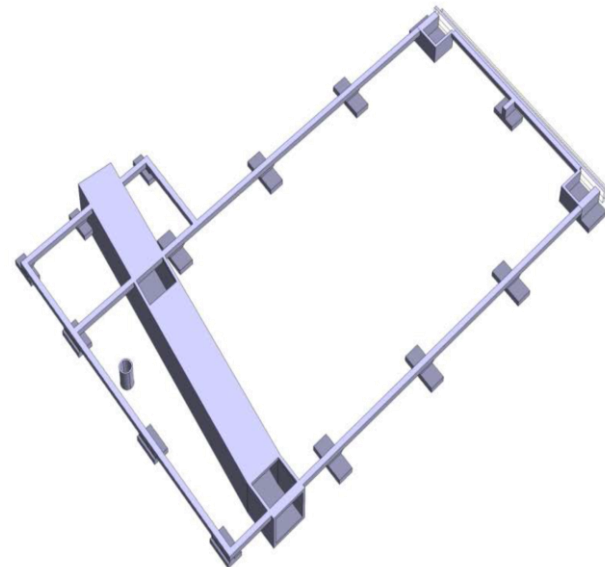
Maximum size is restricted by the available land around CERN premises

Total surfaces

- Basement : $17.5 \text{ m} \times 34.5 \text{ m} = 600 \text{ m}^2$
- Mezzanine : 450 m^2
- Total = 1050 m^2

Total for RF amplifiers

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





BAF3 – NEW RF BUILDING

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)

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



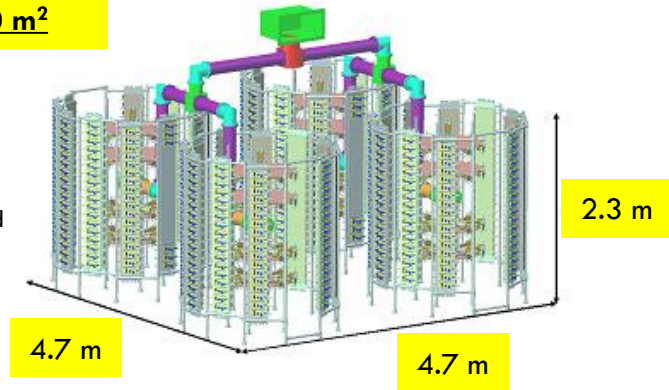
1 tube (160 kW) = 4 m²
Total HVPS = 192 m²
Total 32 tubes = **320 m²**

BAF3 for RF = 700 m²



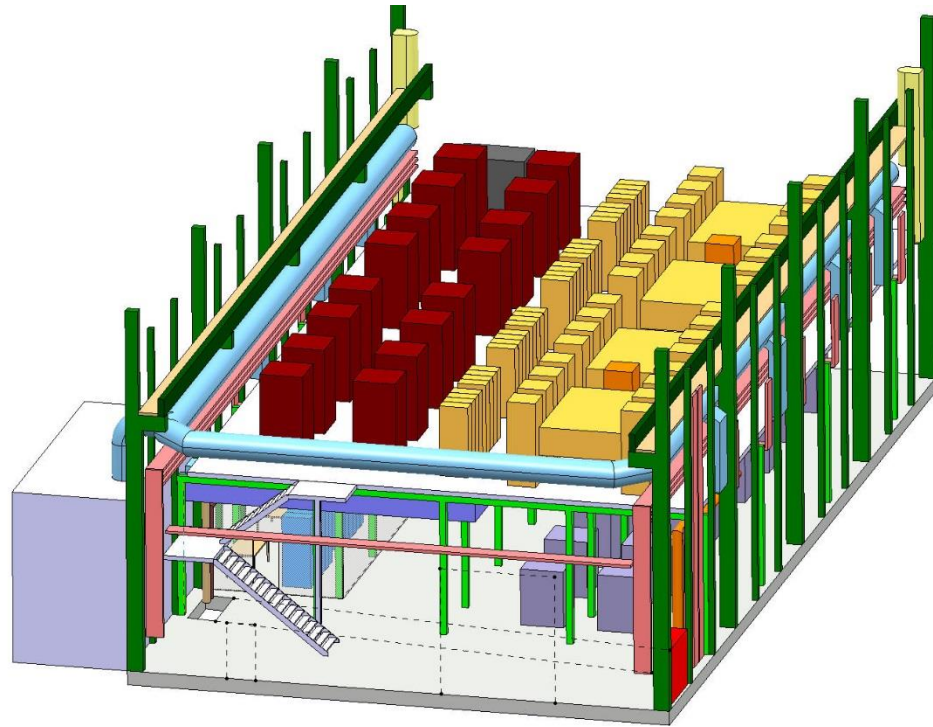
Combiners for 32 = **200 m²**

2 towers (160 kW) = 15 m²
Total LVPS = 72 m²
total 64 towers = **550 m²**

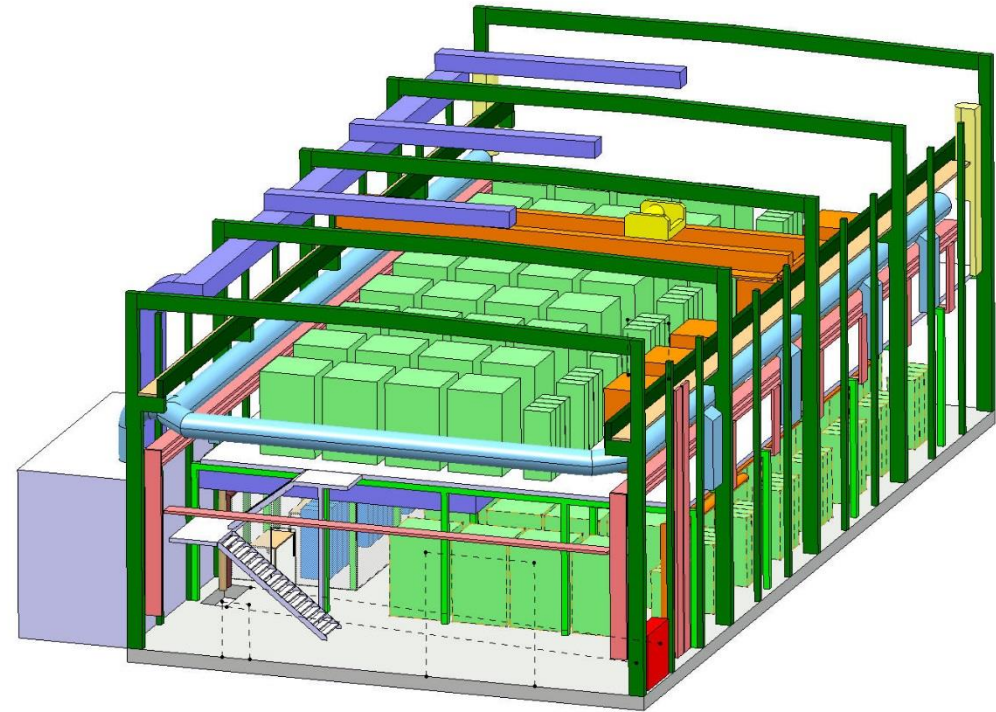


Courtesy
Patrick Marchand
(SOLEIL)

BAF3 — NEW RF BUILDING

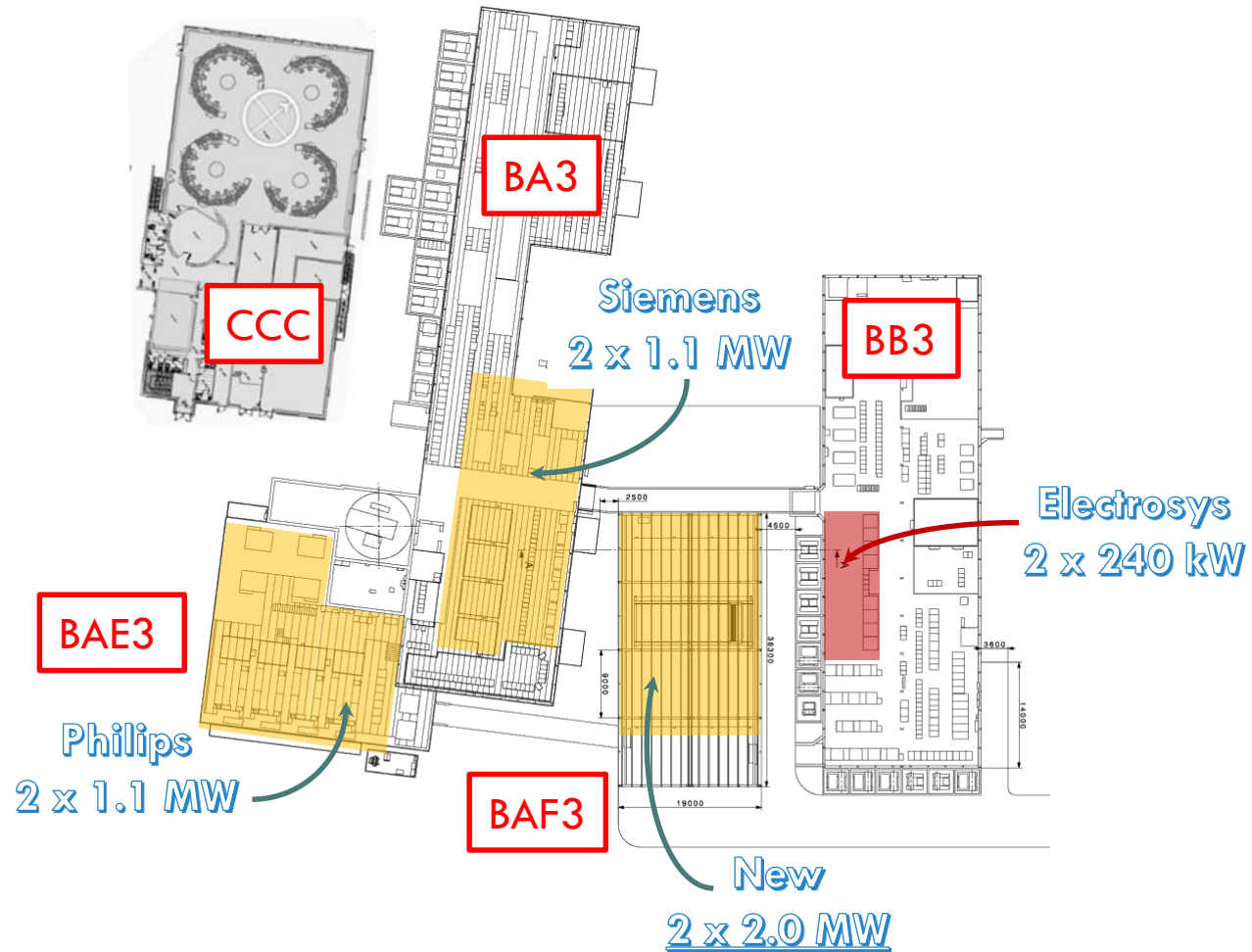


BAF3 with Tetrodes



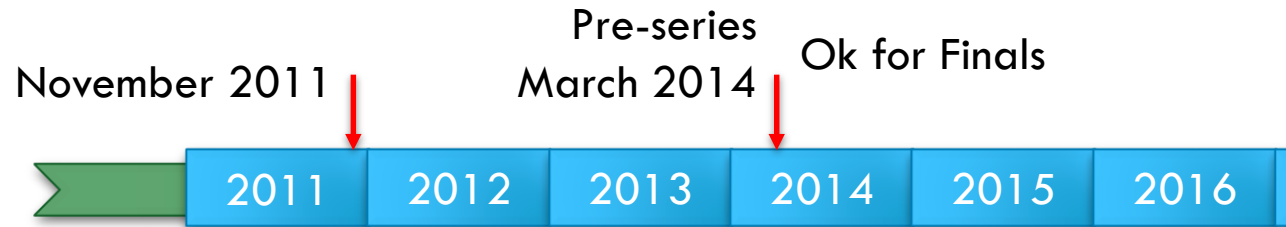
BAF3 with SSPA

FUTURE POWER SYSTEMS IN THE SPS





IT-3842, DRIVERS



72 companies consulted

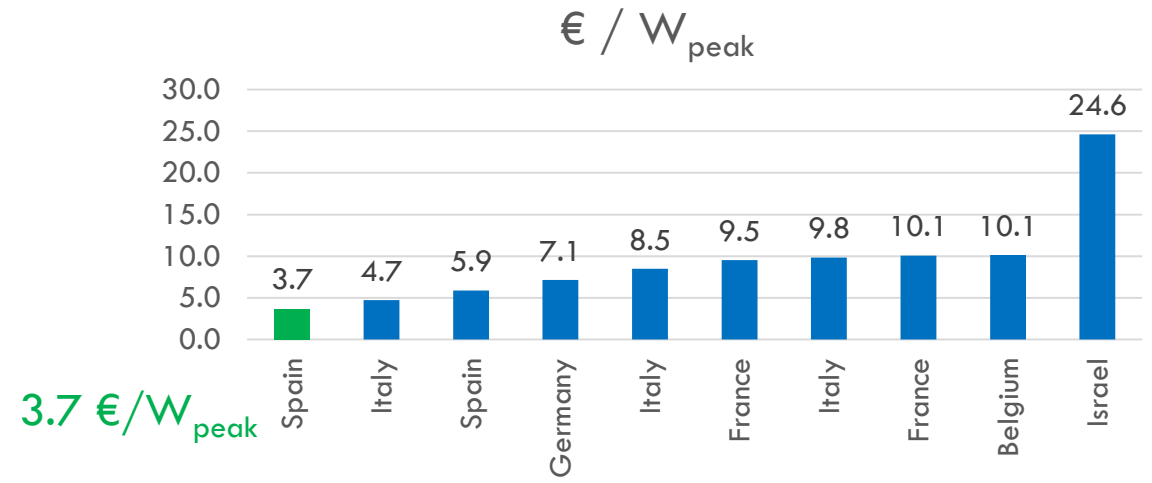
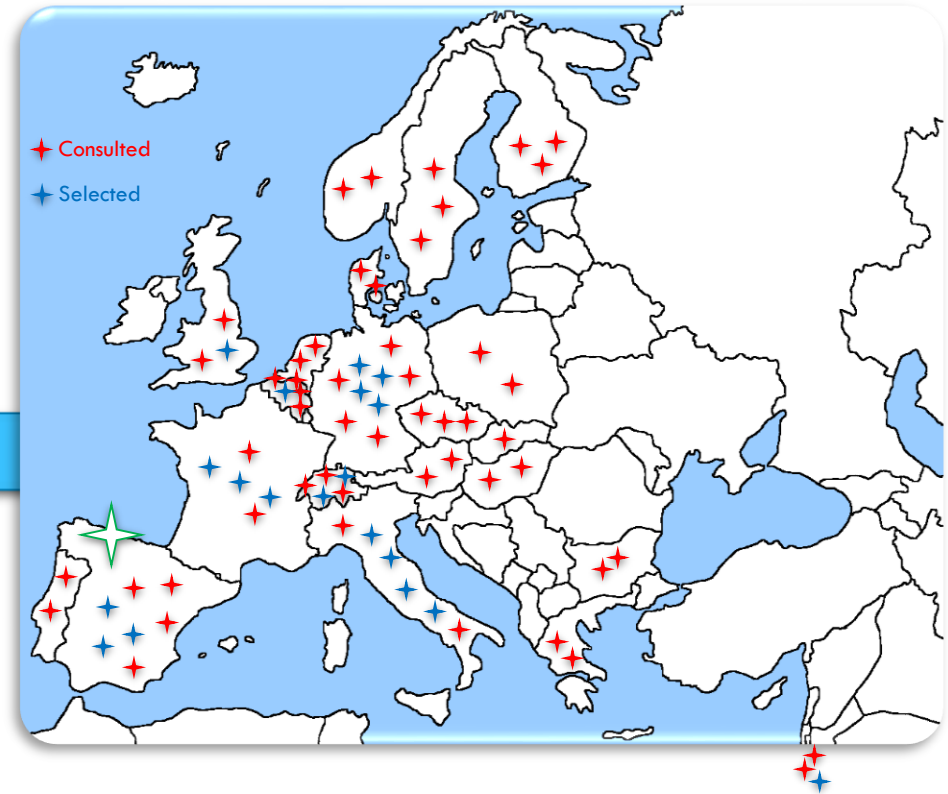
20 selected

10 offers

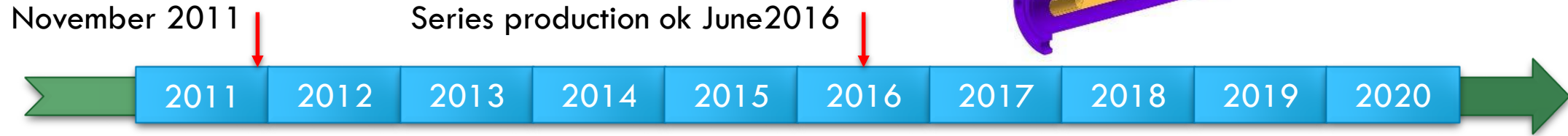
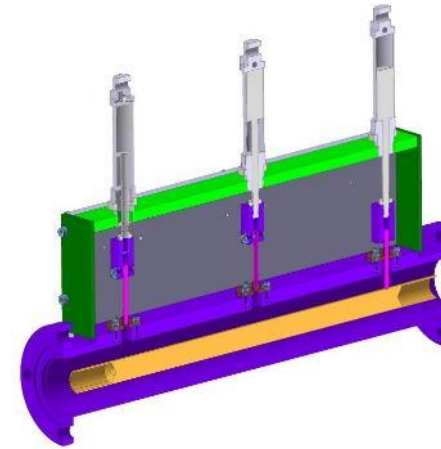
Defined a 1.25 kW unit

- Compatible with all Finals technologies
 - 32 for SSPA & IOTS, 256 for Tetrodes, 192 for Diacodes
- 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)



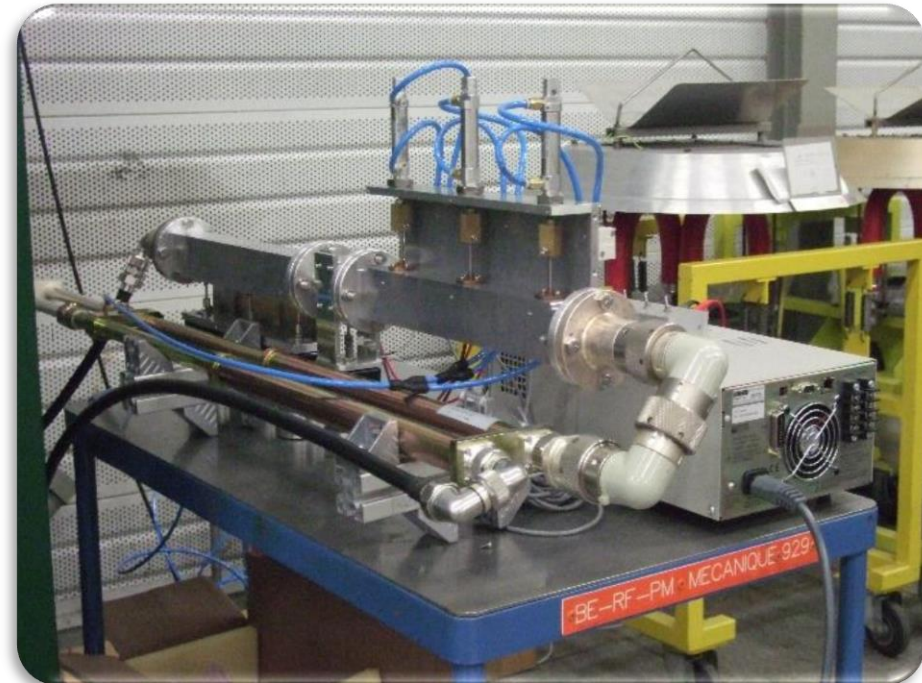
IT-3842, DRIVERS



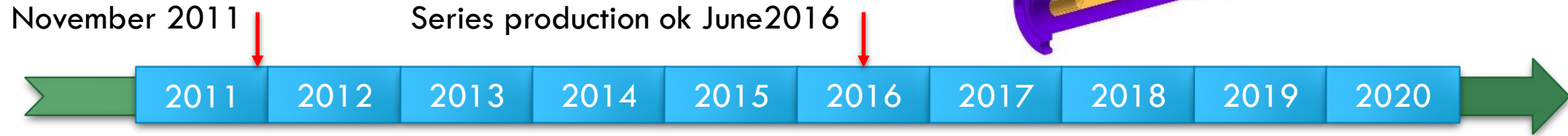
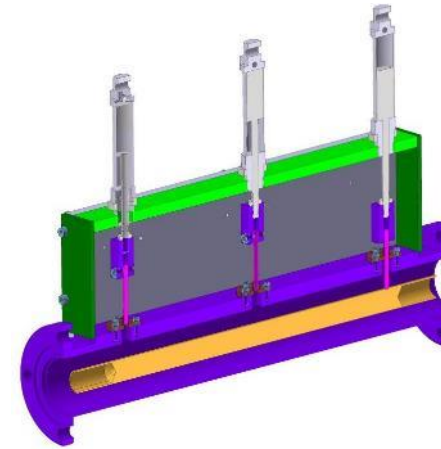
The 12 pre-series have been qualified

- RF design is impressively robust
 - Double circulators !
 - Sustained the CERN Fast Short-Circuit test !
- Successfully completed the 1000 hours test with 12 units
- Four units in operation since beginning of March without a single failure

First batch of 100 will be delivered before end 2016



IT-3842, DRIVERS



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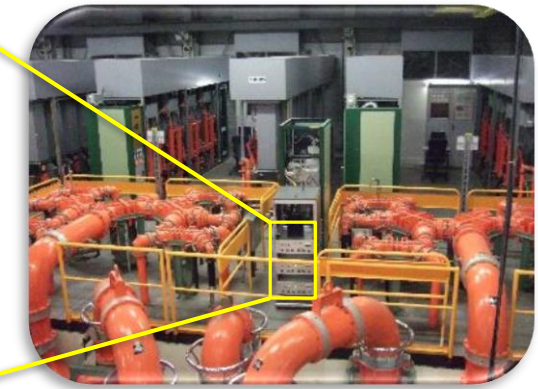
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IT-3842, DRIVERS

November 2011

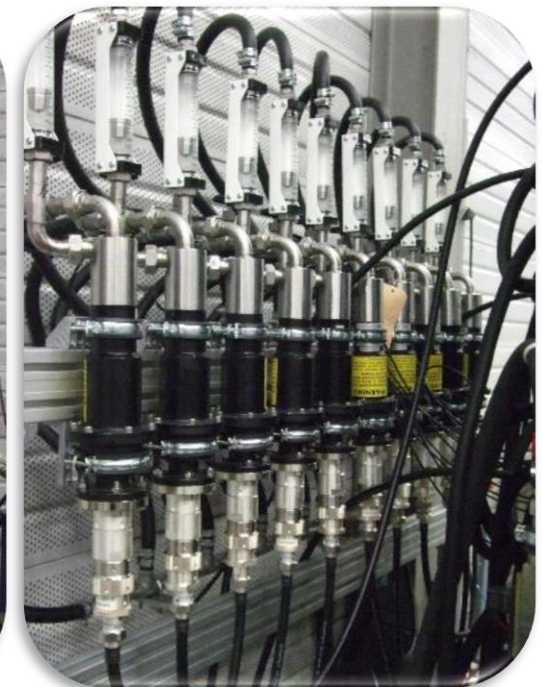
Series production ok June 2016



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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

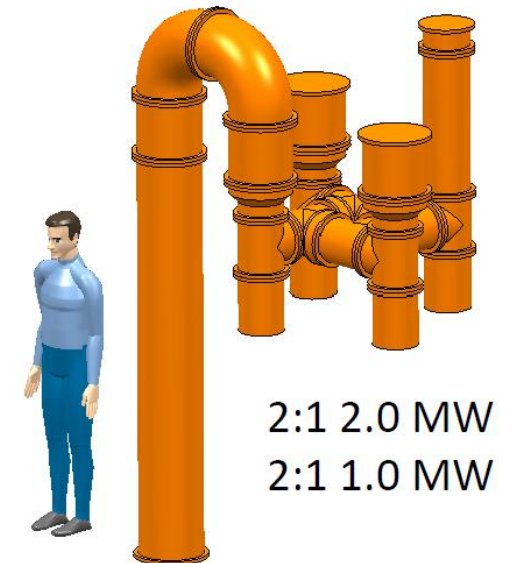
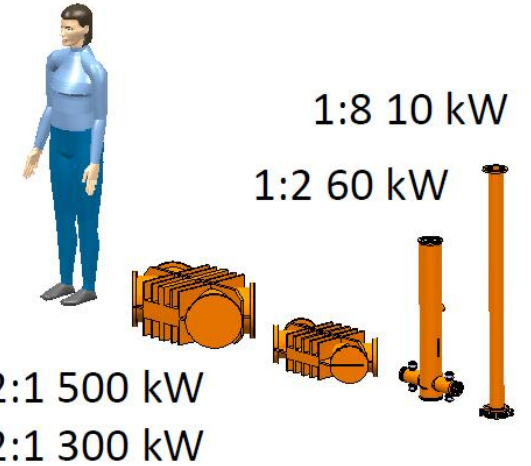
Directional coupler + diode detector : 300 CHF
 50 kW load: 6 kCHF
 500 kW load: 60 kCHF

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





IT-3841, FINALS BIDDERS CONFERENCE

20 January 2015



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

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
- Two tone at many power levels

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

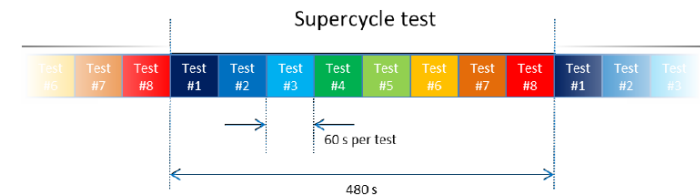
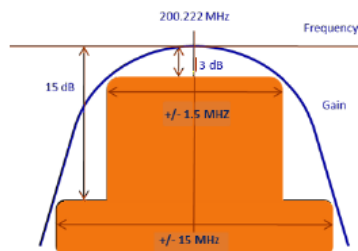
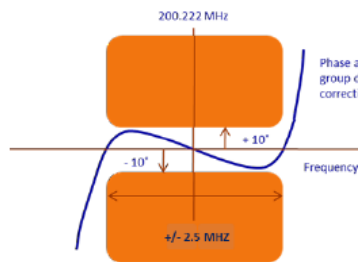
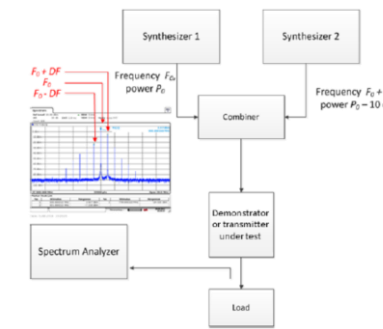
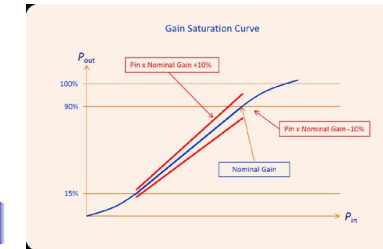
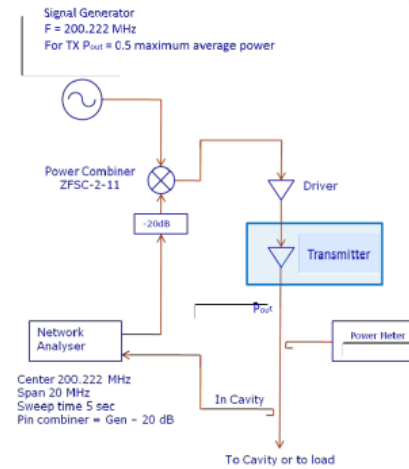
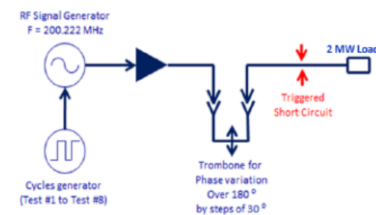
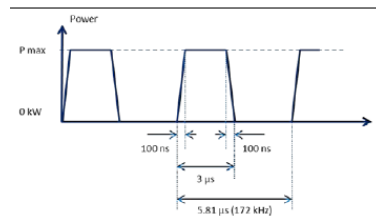
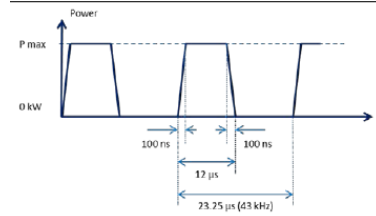
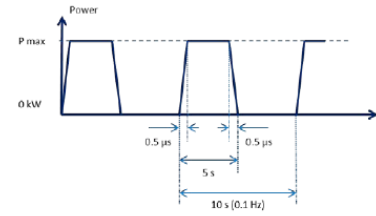
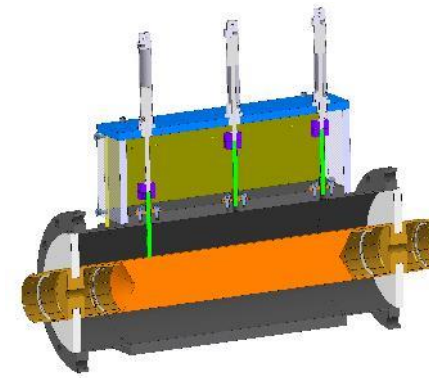


Figure 7: Supercycle test

IT-3841

13 March 2015, bids opening



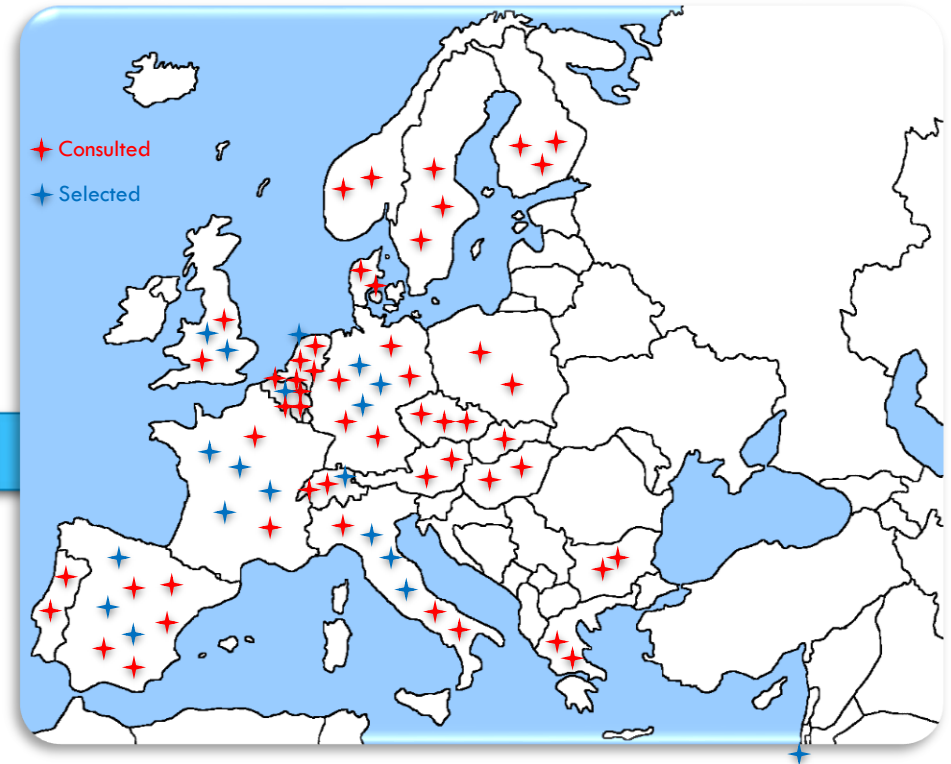
74 companies consulted

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



IT-3841

17 September 2015, FC approval

13 March 2015, bids opening

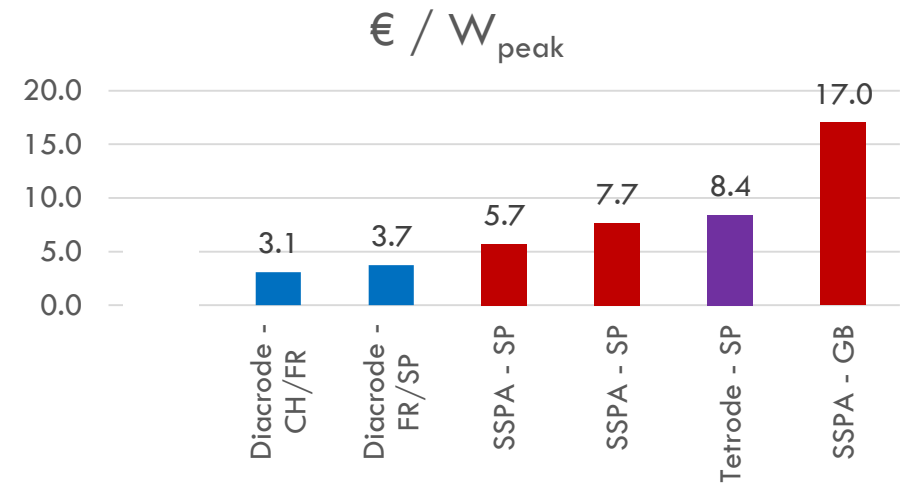
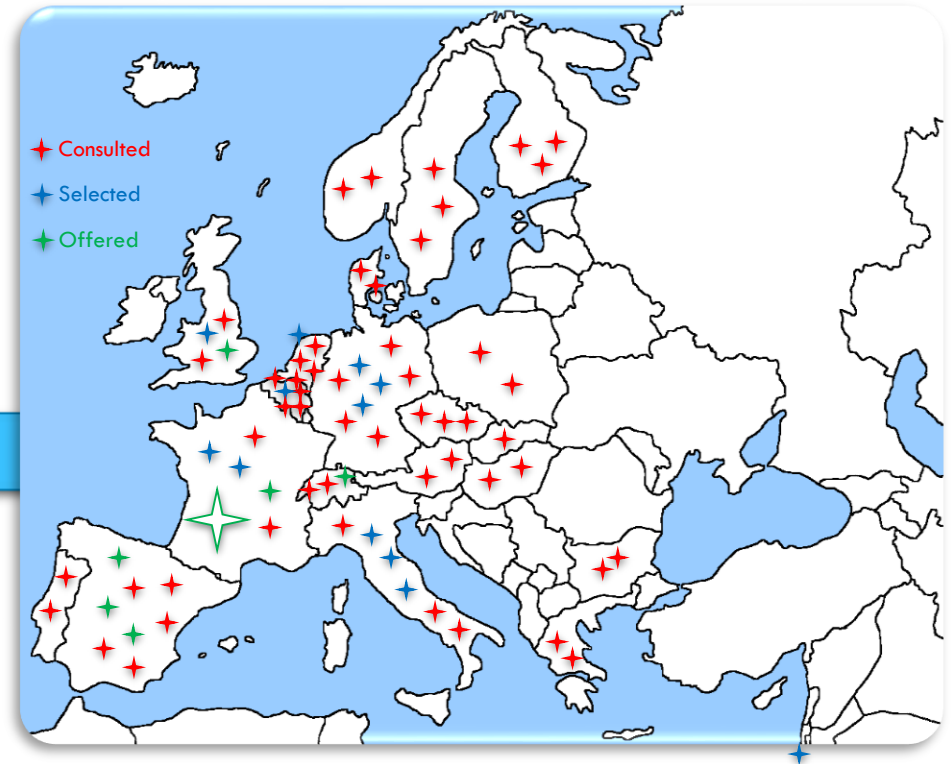


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IT-3841

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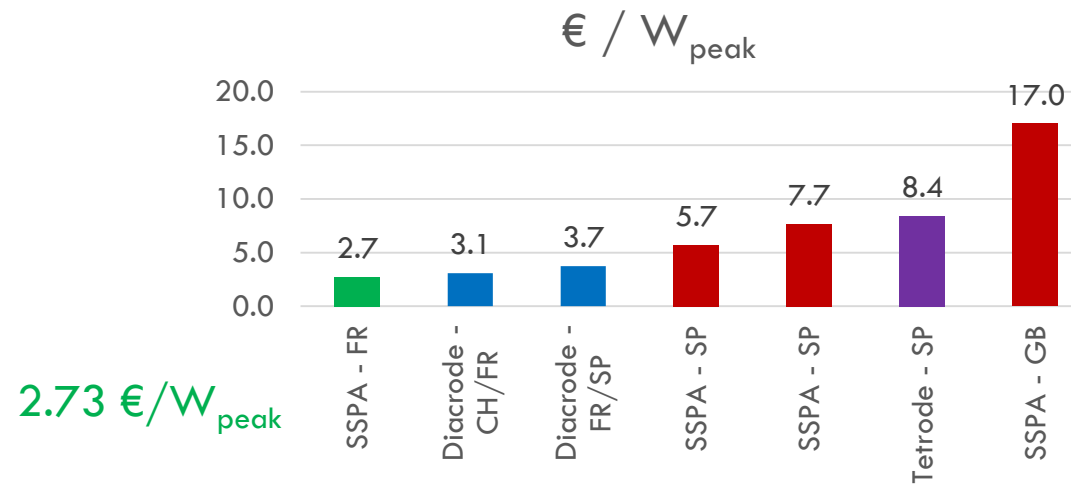
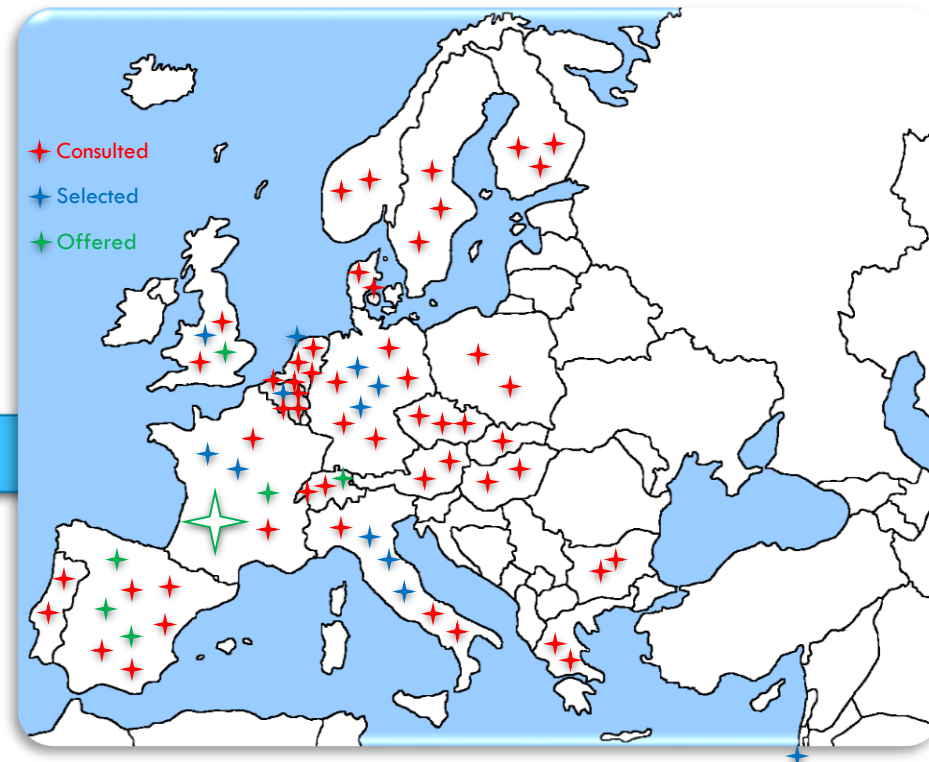
7 offers

March 2015 lowest bid is Thales
Communication & Security

Very careful verification of the offer

(I am (was) a tube guy !)

September 2015 CERN FC approval



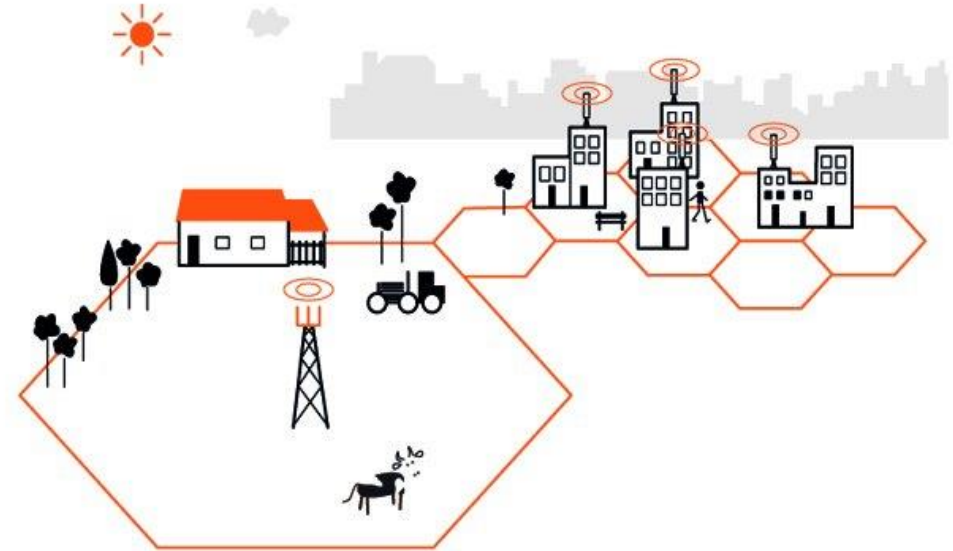
2.73 €/W_{peak}

TRANSISTOR POWER RATINGS – PERSONAL VIEW OF FUTURE PERSPECTIVE

Voltage limits

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

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



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



TRANSISTOR POWER RATINGS – PERSONAL VIEW OF FUTURE PERSPECTIVE

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

1 482 Million Smartphones in 2015

6.1 Millions Microcell stations 2009

5.9 Millions Macrocell stations 2009

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

Assumption (with a lot of simplifications)

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

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

RF for accelerators could be 0.1 % of main suppliers revenue

CAVITY COMBINERS

CRISP (Sept 2010)

- Jörn Jacob (ESRF) asked for support to the 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

HIGH POWER SOLID STATE RF AMPLIFIERS USING CAVITY COMBINERS

Jörn Jacob & Michel Langlois, ESRF

Conventional 75 kW coaxial combiner tree
with 1:4 transformers

CRISP / WP7

Many cables

4 x 150 W - 352.2 MHz SBA on ESRF booster
• Delivered to PSI, JARA/JA, and technology transfer from JARA/JA

75 ... 100 kW cavity combiner
Strongly loaded E_{110} resonance

- Modest field strength
- Cavity at atmospheric pressure
- 1 dB - Bandwidth = 500 kHz

H field Homogeneous magnetic coupling of all input loops

E field Strong capacitive coupling to the output waveguide

Wireless is beautiful!

For 352.2 MHz ESRF application:

- 6 rows x 22 Columns x 600 ... 800 W per translator module
- ⇒ 75 ... 100 kW
- More compact than coaxial combiners
- $Q_{\text{resonance}} = Q_{\text{cavity}} \cdot F_{\text{coupling}} \gg F$
- Easy to tune if $Q_{\text{resonance}}$ is verified
- Substantial reduction of losses ⇒ Higher η

Cavity combiner: the 352.2 MHz - 10 kW prototype

• 10 kW prototype
• Only 2 active water cooler "wings"
• 2x 4.5 kW/1000 W - 750 W module
• 10 ... 12 kW
• Assembly of single under way

ESRF in house development of RF translator module to acquire necessary booster for long term delivery of 7 x 100-200 kW/1000 W per channel from industry

• Delivered: use 18 ESRF modules for CRISP 10-100 prototype

ESRF RF modules

• Printed circuit boards
• RF drive circuitry related with "high power" translation lines
• New laser components are all from ESRF and given to subcontractor manufacturer [M&P](#)

• Red 2 coil wave line that will be used
• 10 kW Prototype - Milestone M7-1 (delivered: Sept. 2012 - in June 2013)

Ring 4 out of 18 RF modules on wings and bench
• Fully adequate for 10 kW prototype
• 800 team for improvement
• Ongoing R&D
• Collaboration contract with Uppsala University for optimization of circuit board

• Achievements are worth a round table
• M7-1

Water cooling and designed for final 15 kW prototype

⇒ 10 kW test, i.e. milestone M7-1 expected within revised schedule, by June 2013

Auxiliary equipment in house

• Collective stacking of RF modules
• Also in-house and control system in progress

RF power supply: is all designed with PCB Vibration 800 on the back side of each wing

• 3 Power Supplies: 50 VDC / 10 kW

Water cooling and designed for final 15 kW prototype

ESRF meeting held in Grenoble on 20 September 2012

Definition of Partners' candidates for cavity combiners
(belongs to milestone M7.2)

- CERN** (Eric Monteseinos)
 - 1st good candidate: LIU-SPS, 300 MHz, pulsed with 50 % power factor, project under way
 - Tendering process for two (15 x 150 kW) for 2 additional SPS cavities
 - 1/3 contribution to obtain net 1.5 MW with 15 cascade 300 hybrid cavity combiner could significantly reduce costs
 - 100 x 120 W → 150 kW cavity combiner could help making SBA more competitive with currently all cheaper MDS, ICT or diode solutions
 - Detailed design study for 150 kW cavity combiner for LIU-SPS delivered by ESRF (part of M7.2)
- 2nd good candidate: SPS, 700 MHz, R&D;
 - 240 RF power sources from 140 kW to 1200 kW

ESRF (Eric Monteseinos)

- Upgrade of CRISP: 30 x 300 kW at 352 MHz for SPS cavities
- In-house and not sold state amplifiers
- In-house 150 MHz - 120 kW SBA, drives for 2 MW tubes
- Wish of a collaboration for the development of cavity combiners

ESF (Eric Monteseinos)

- In-house and not sold state amplifiers
- SBA are significantly more expensive than ICT solution
- So far no anticipated application for a cavity combiner

Uppsala University - UU (Eric Monteseinos)

- ESRF project: building 2 cavity power test stands for 352 MHz - 300 kW SPS cavities for ESRF (20 cavities in total)
- In-house in SBA development using cavity combiners
- 10 kW SBA drives for 300 MHz SPS cavities
- RF power resonant cavity with 300 kW SBA
- Collaborative contract with ESRF for further development of innovative RF modules
- UU will benefit from CRISP prototypes developed at ESRF



CAVITY COMBINERS

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



Accelerator & Source

Technical Note

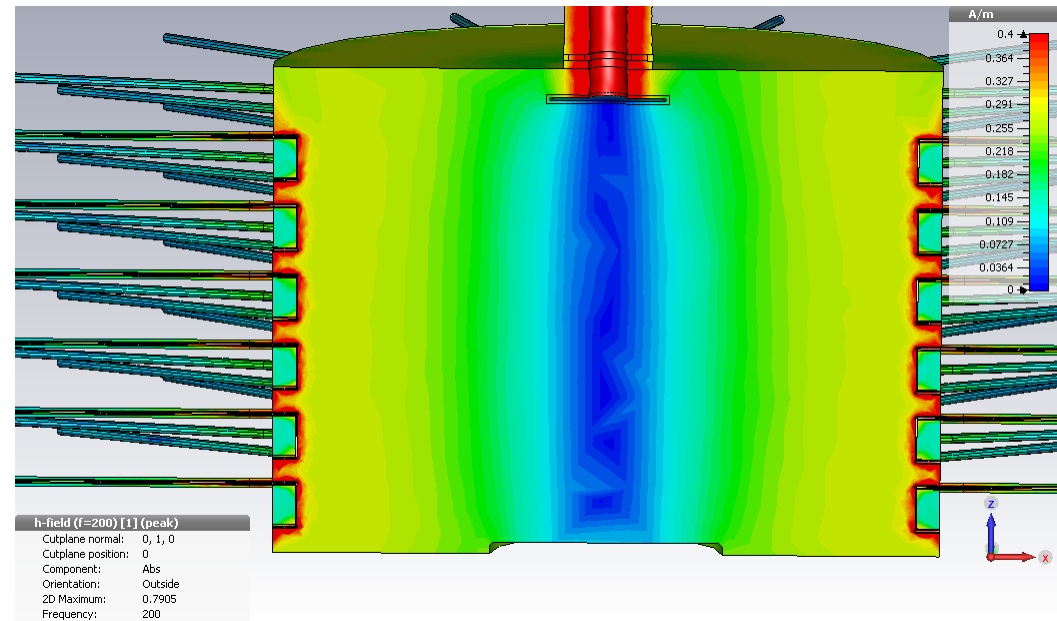
01-13/RF

150 kW Cavity combiner for CERN-LIU-SPS¹

Author(s): Michel LANGLOIS

Date: February 11th, 2013

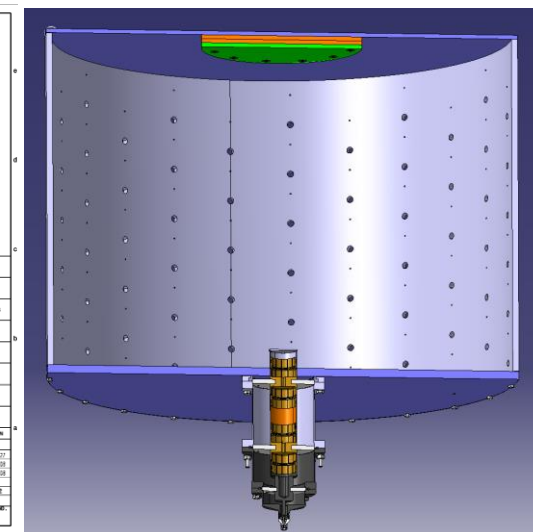
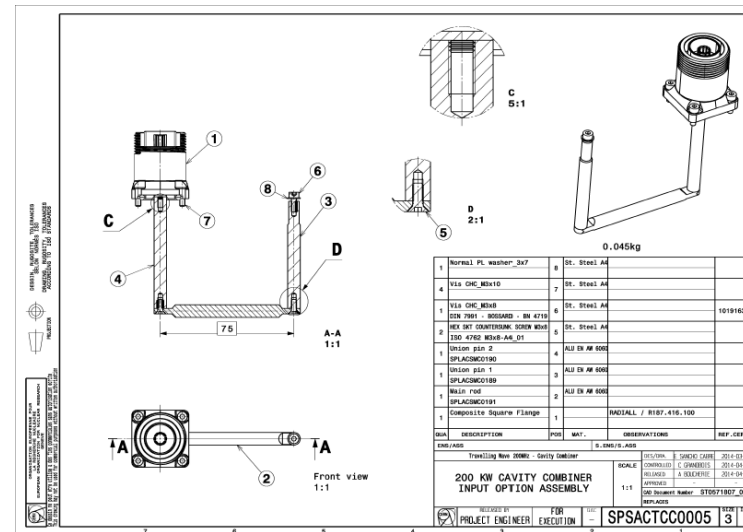
Distribution: Jörn JACOB, Eric MONTESINOS





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EUROPEAN SYNCHROTRON RADIATION FACILITY



Accelerator & Source

Technical Note

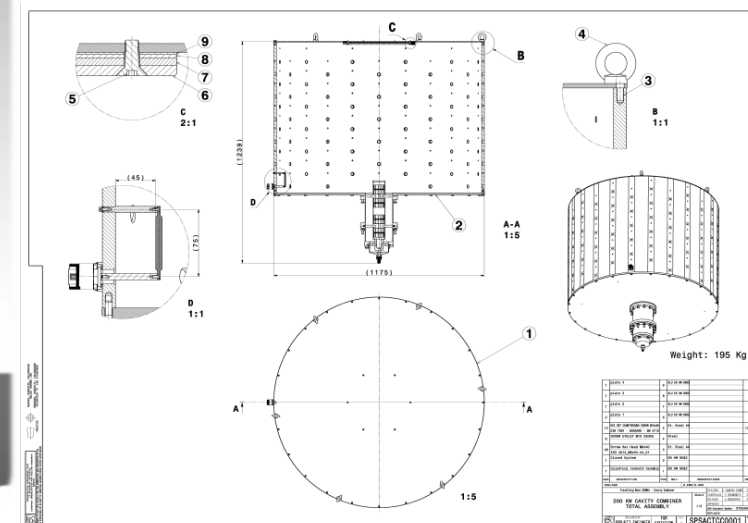
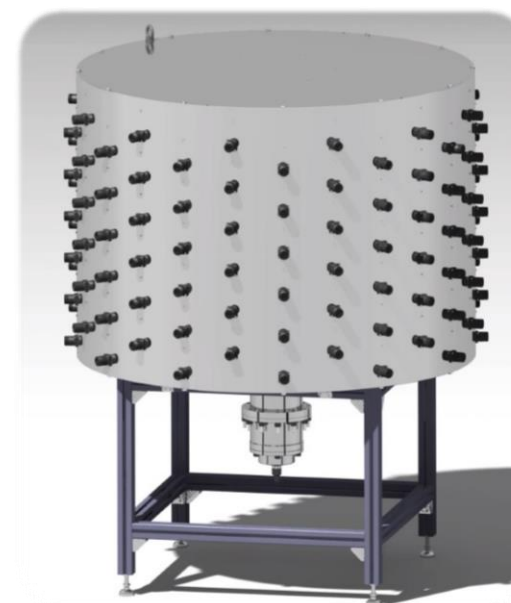
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Accelerator & Source

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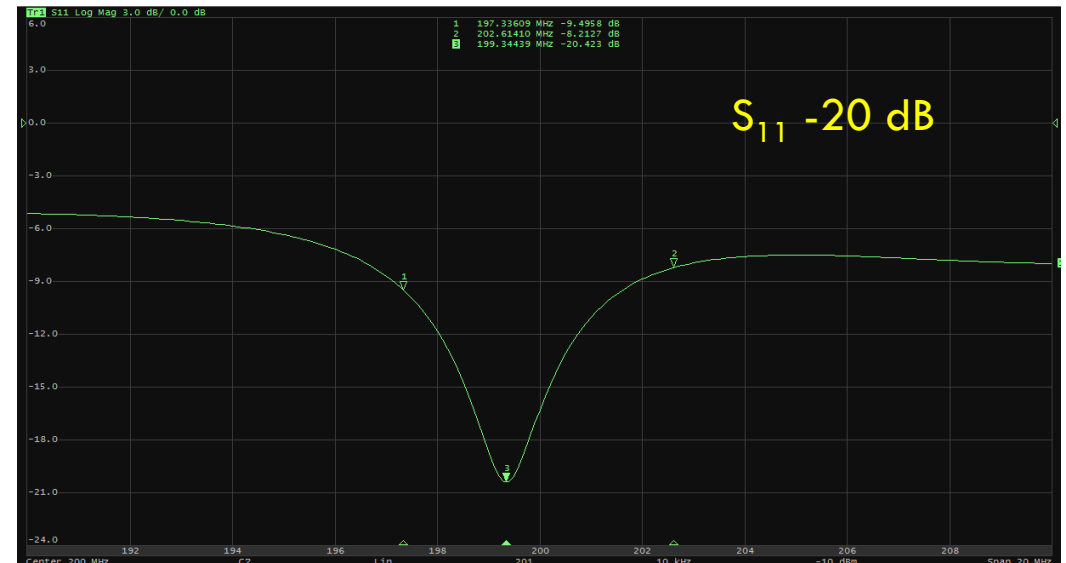
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IT-3841, FINALS

One Transmitter will be composed of

- 16 x 144 kW RF amplifiers

One RF amplifier will be composed of

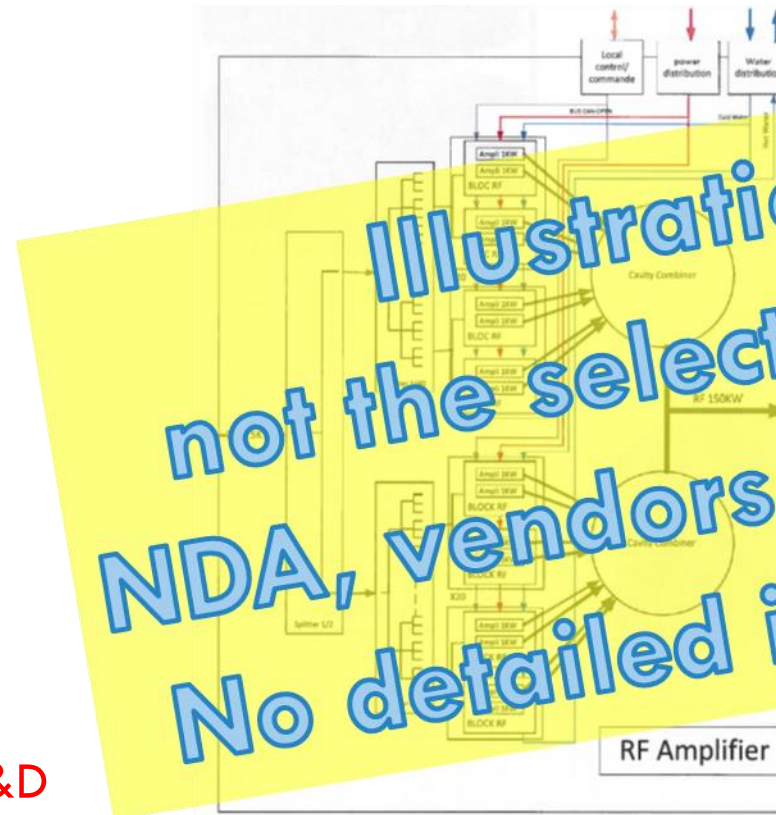
- 80:1 cavity combiner
- 80 x 2 kW RF blocs
- 160 transistors

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
- New very interesting features covered by a NDA



2 x 16 x 150 kW
RF Amplifiers

Illustration is not the selected option
NDA, vendors in the room
No detailed information



Figure 3 - Combiner à cavité 40 par 1

PROGRESS REPORT FROM LAST WEEK (JUNE 2016)

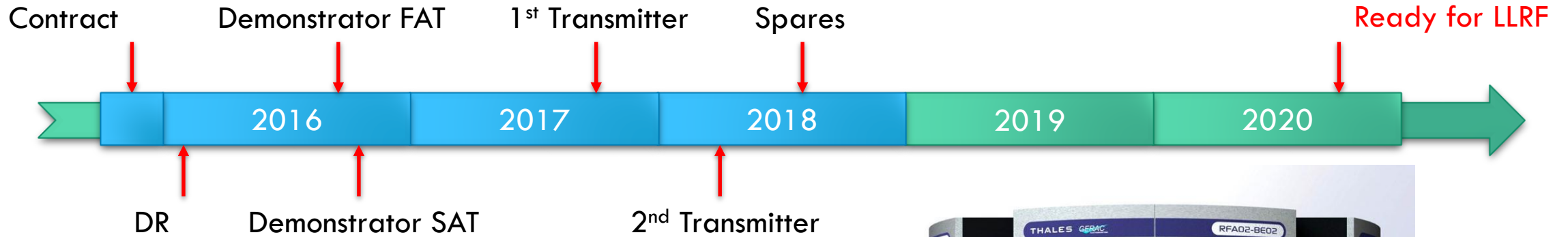


- ✓ Specific Power supplies validated
- ✓ First RF blocs tested up to 2 kW
- ✓ First Input cavity splitter and first Output cavity combiner constructed





IT-3841, SCHEDULE



End 15	Contract awarded
Autumn 16	Demonstrator
Autumn 17	First transmitter of 16 RF amplifiers
Spring 18	Second transmitter of 16 RF amplifiers
Summer 18	All spares delivered



144 kW RF amplifier

VERY HIGH POWER CAVITY COMBINER

VHPCC (Very High Power Cavity Combiner)

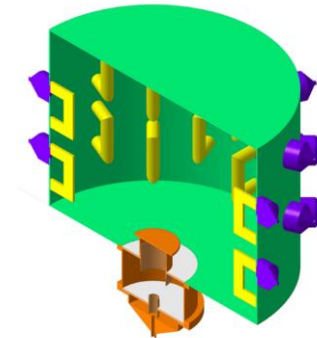
- 16:1
- 150 kW inputs
- 2.5 MW output

Each of our new transmitter will have

- one single VHPCC

or

- the classical 3 dB combiner as we already have in the Philips plant



Two pictures almost on same scale





PRESENT SYSTEMS UPGRADE TO 4 x 1.1 MW

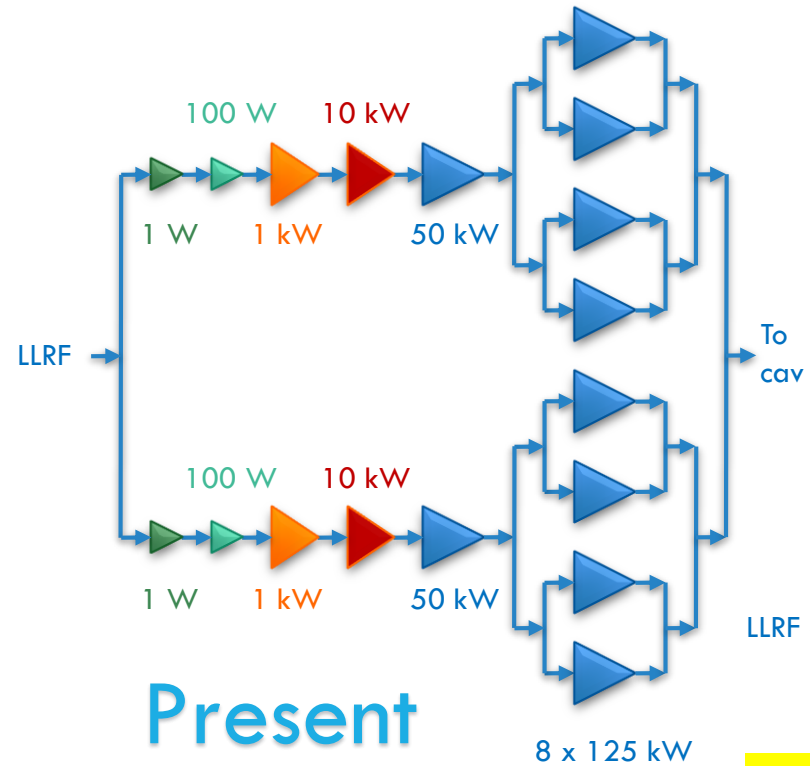
IT-3842 will also be used to upgrade Siemens and Philips plants

Thales	32	
Siemens	160	Will free 4 x RS 2004 trolleys
Philips	64	One Driver to one Final or special CC
Total	256	312 with IT-3842 contract

1 kW YL1440 tube & 10 kW YL 1520 tube do not exist anymore

Old relays and CMOS controls upgraded to new PLC controls

HVPS upgraded



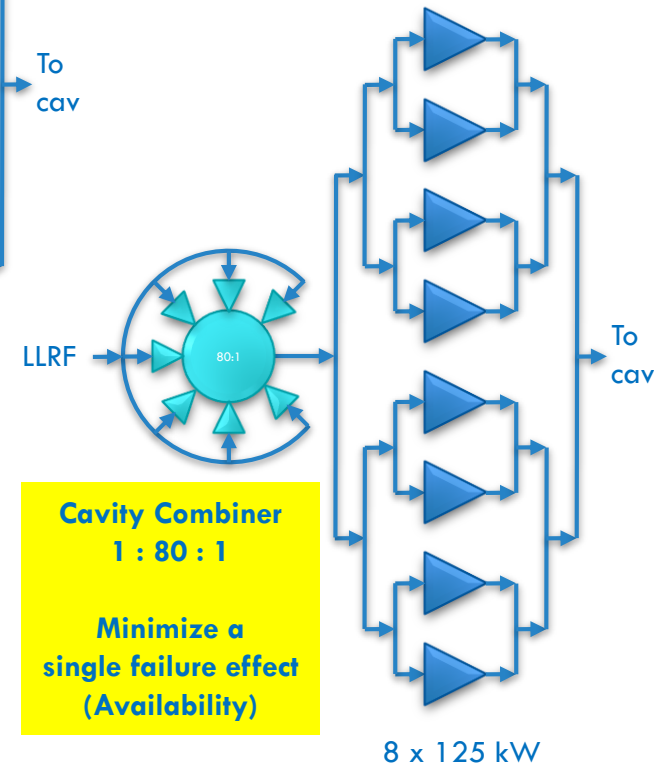
Present
'Siemens'

2 x 10 x RS 2004
2 spare trolleys

Future

'Siemens'

2 x 8 x RS 2004
6 spare trolleys
CC 80:1



Cavity Combiner
1 : 80 : 1
Minimize a
single failure effect
(Availability)

8 x 125 kW



PRESENT SYSTEMS UPGRADE TO 4 x 1.1 MW

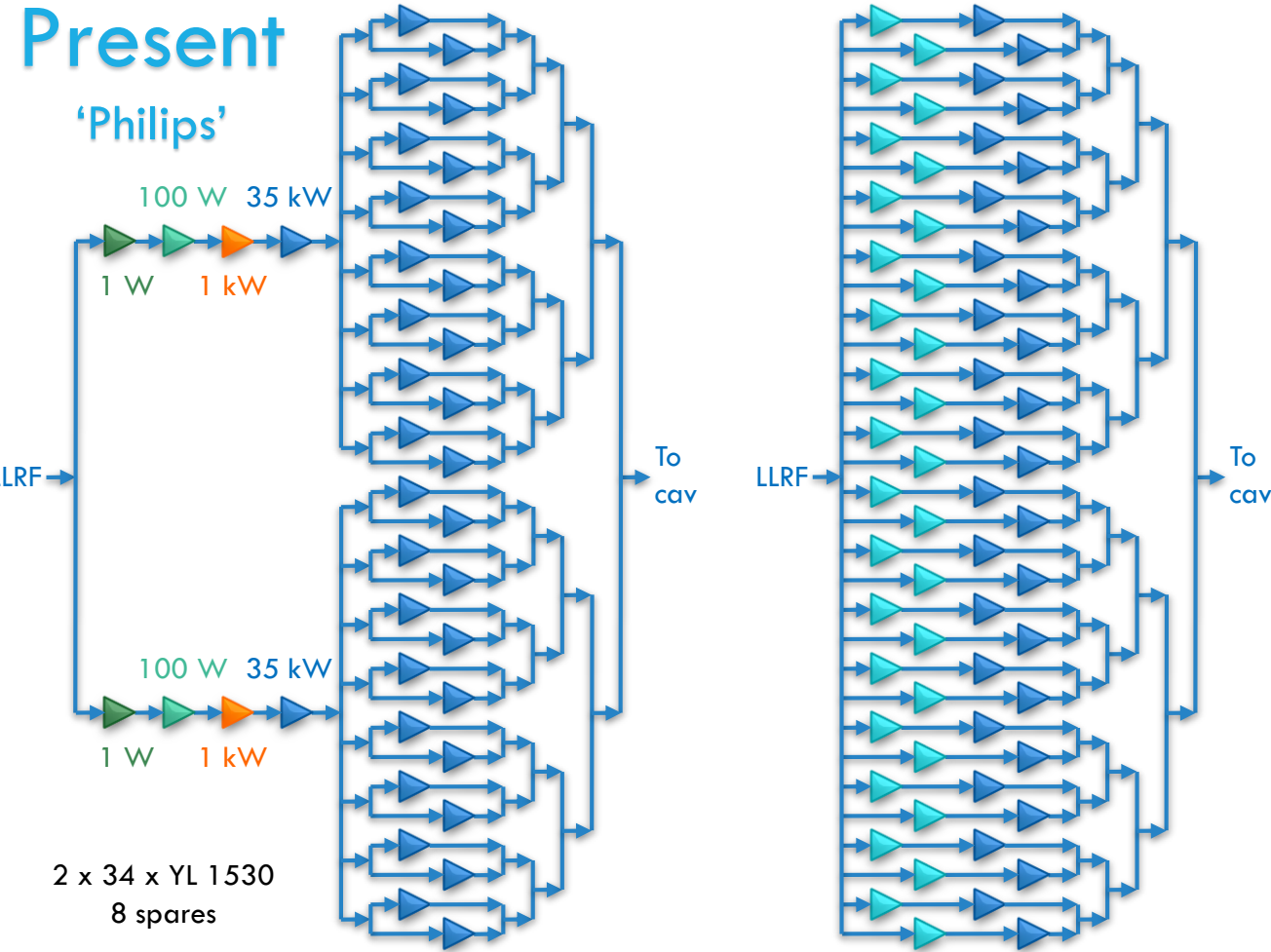
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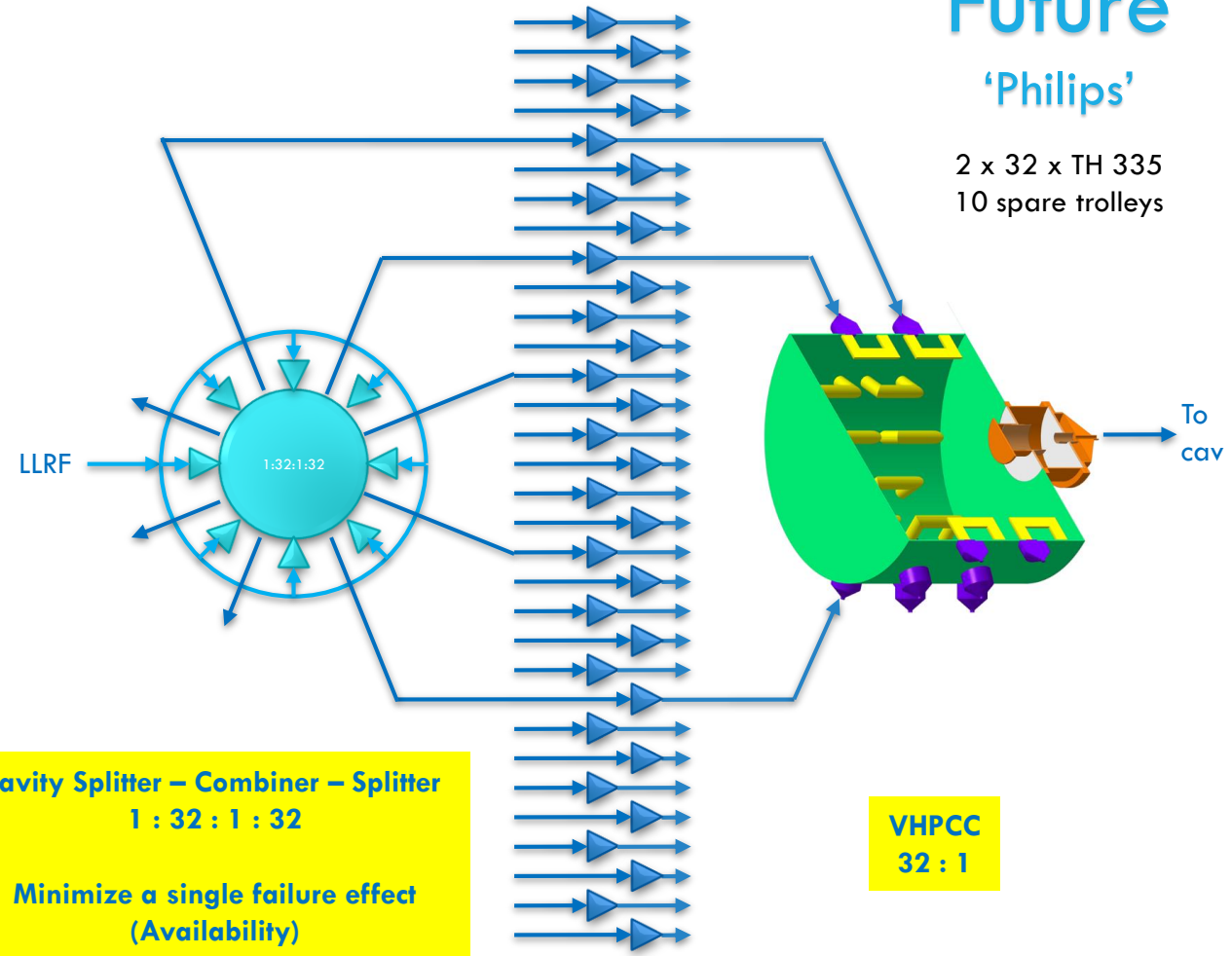
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Future 'Philips'

2 x 32 x TH 335
10 spare trolleys





PRESENT SYSTEMS UPGRADE TO 4 x 1.1 MW

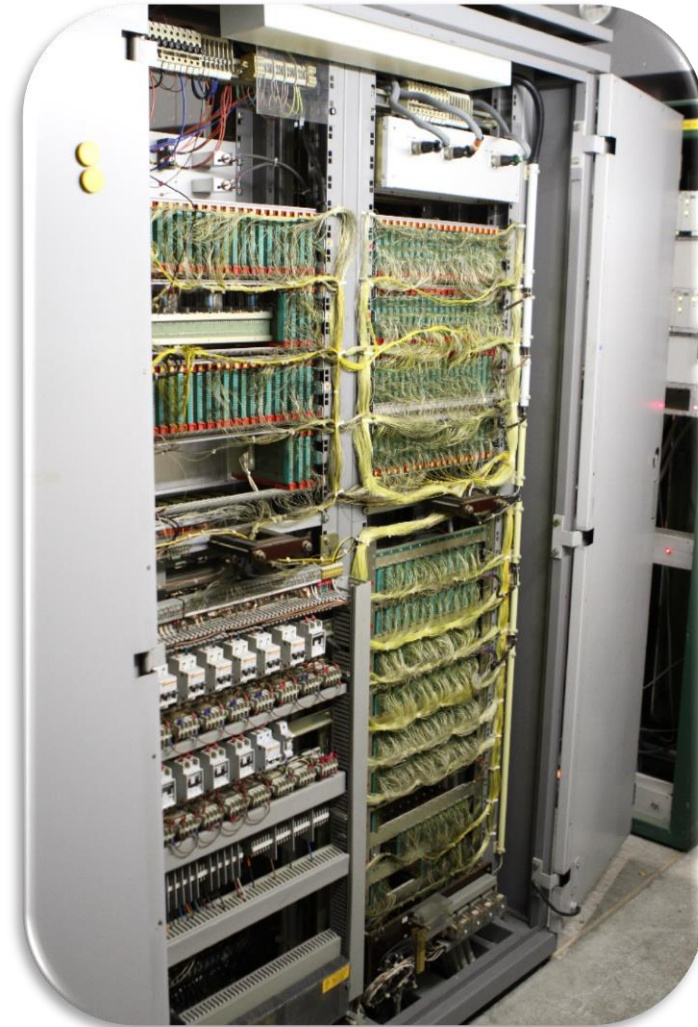
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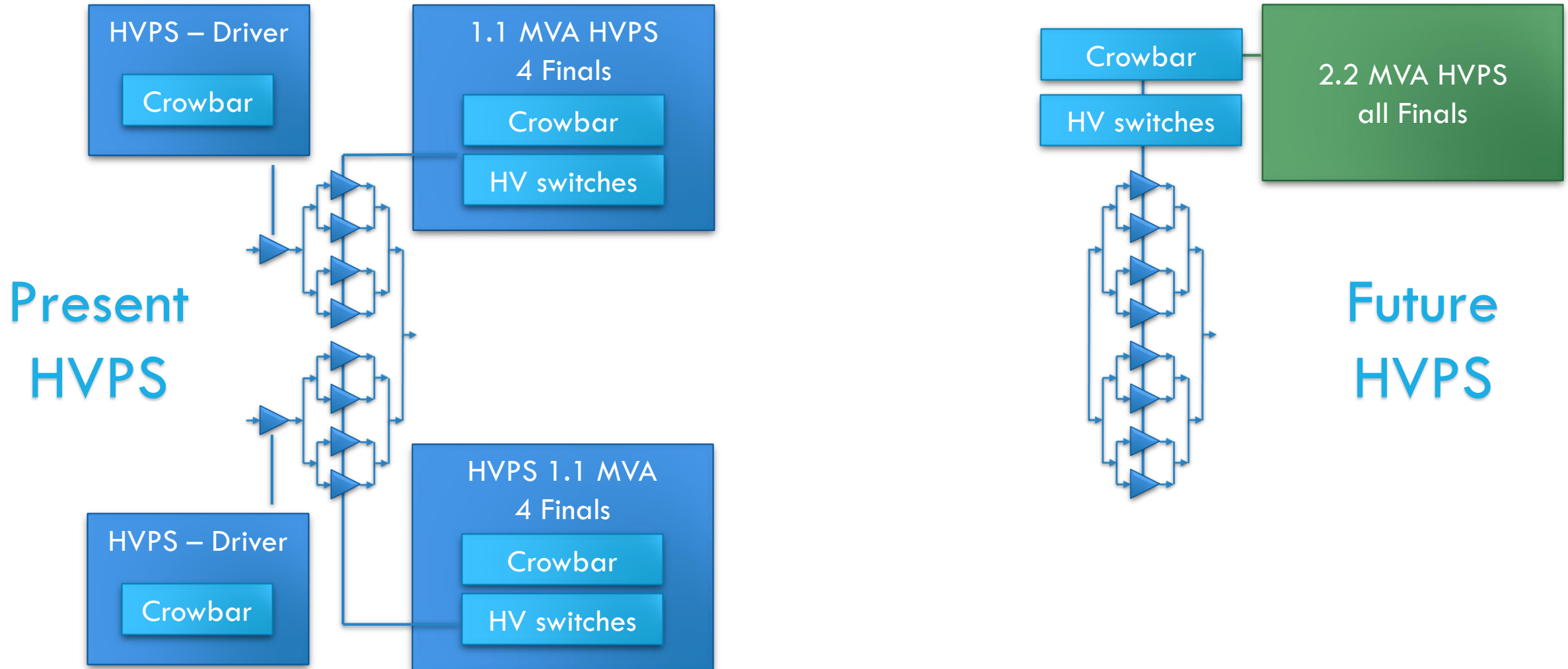
One of the four wire wrap control system of the 'Philips' power plant since 1980

Very reliable controls but wire insulators and connectors are brittle nowadays

Thousands of contacts to be reconnected



PRESENT SYSTEMS UPGRADE TO 4 x 1.1 MW





EXCITING YEARS TO COME

We spent quite some time on

- RF Building BFA3
- Amplifiers, Drivers and Finals
- **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

Now we will deeply focus on

- Cavity combiners
- HVPS
- Controls
- Coaxial lines
- Tunnel LSS3
- Cavities
- FPC (WWFPC#2 12-13 July at CERN, if you have any topic you would like us to address, please let me know)

**Thank you so
much for your
attention**

**See you in two years
to report the (hopefully) good results**

