RF power for crab cavities & challenges

eric.montesinos@cern.ch reporting on behalf of many colleagues that have worked out the topic

Credits to Sebastien Calvo, Luciano Ciampo, Frederic Killing, Gino Cipolla, Nuria Valverde for all the illustrations of this talk

14th HL-LHC Collaboration Meeting, Genoa (Italy), 7-10 October 2024

Mandate for the talk of this meeting

Hi Eric, I write down some bullet points that come to my mind - not fully a mandate and I let you how to structure it

It is not essential that you cover all the point neither - what you feel would be useful for an audience

Couplers

- Experience with FPCs for the SPS-DQW, SPS-RFD & series production including RF conditioning - this doesn't have to be detailed by some kind of recap of choices, issues during the last years
- Issues related to HOMC & FA including RF lines, adapters, pins - more like an RF lessons learned on what could go wrong for future CMs

High Power RF stations

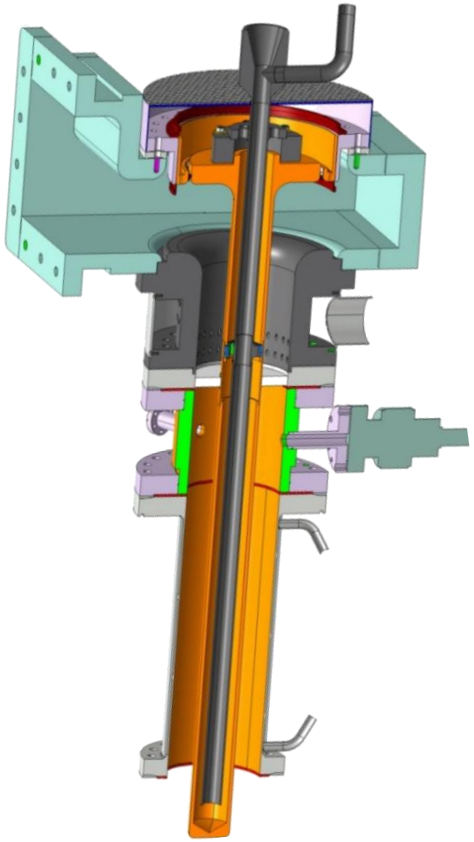
- HPRF - context of using the IOT, some experience from SPS-DQW and improvements for the series design
- Recent experience from RFD module and what to expect from conditioning for the future series including what/when we are going to send to Canada (SSPA, IOT ?)
- Series production with industry - next steps, POC, acceptance tests, ...
- Finally, is there a future for SSPA at 400 MHz?

Many thanks and I know the above is way too much to ask but I know you can give us a snapshot for the future

Rama

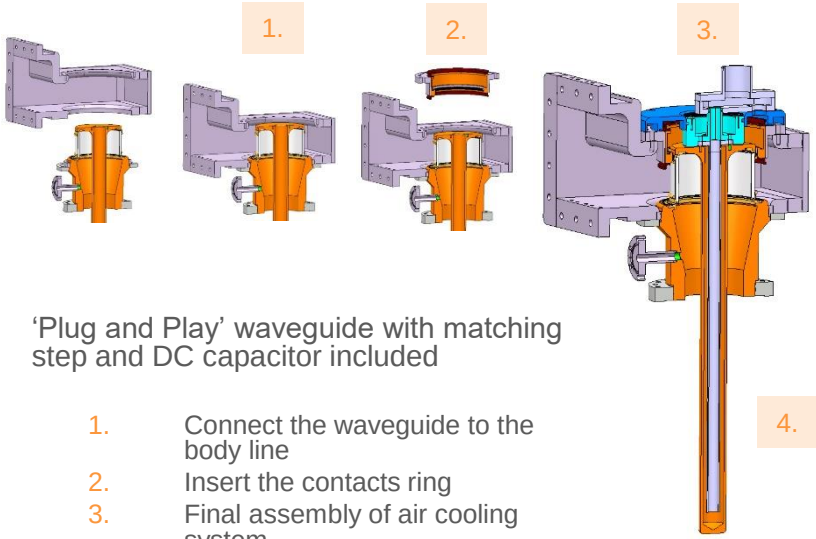
Experience with FPCs (including RF conditioning)

- Fundamental Power couplers are coupling the RF from the RF power source to the cavity
- The window, in case of high average RF power, that is usually an AL_2O_3 ceramic, ensures the vacuum integrity of the cavity
- It is often Titanium sputtered on the vacuum side to avoid electrostatic discharge and to reduce Secondary Emission Yield to reduce the sensibility to multipacting
- With the Crab project, we took advantage of the SPL coupler design, and we matched it to Crab requirements
- This helped us to start quicker the production phase
- We applied the SPL plug and play WG concept that enables RF matching and reduced mechanical stress to the ceramic



Experience with FPCs (including RF conditioning)

- Fundamental Power couplers are coupling the RF from the RF power source to the cavity
- The window, in case of high average RF power, that is usually an AL_2O_3 ceramic, ensures the vacuum integrity of the cavity
- It is often Titanium sputtered on the vacuum side to avoid electrostatic discharge and to reduce Secondary Emission Yield to reduce the sensibility to multipacting
- With the Crab project, we took advantage of the SPL coupler design, and we matched it to Crab requirements
- This helped us to start quicker the production phase
- We applied the SPL plug and play WG concept that enables RF matching and reduced mechanical stress to the ceramic



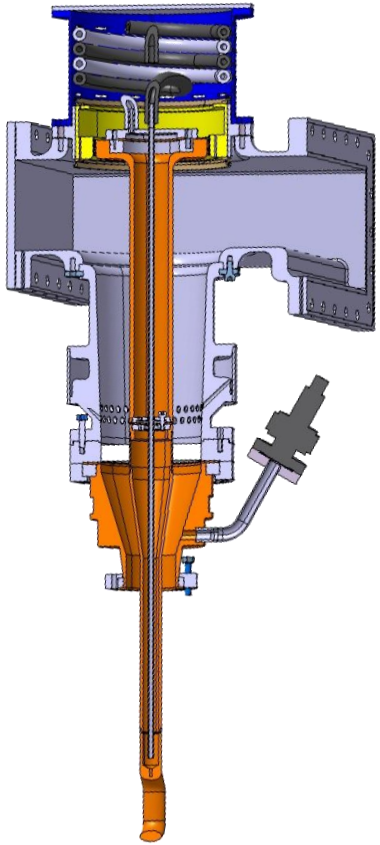
'Plug and Play' waveguide with matching step and DC capacitor included

1. Connect the waveguide to the body line
2. Insert the contacts ring
3. Final assembly of air cooling system
4. No doorknob, reduced height, with no mechanical stress to the ceramic

Experience with FPCs (including RF conditioning)

Except the coupling elements, all other devices are identical

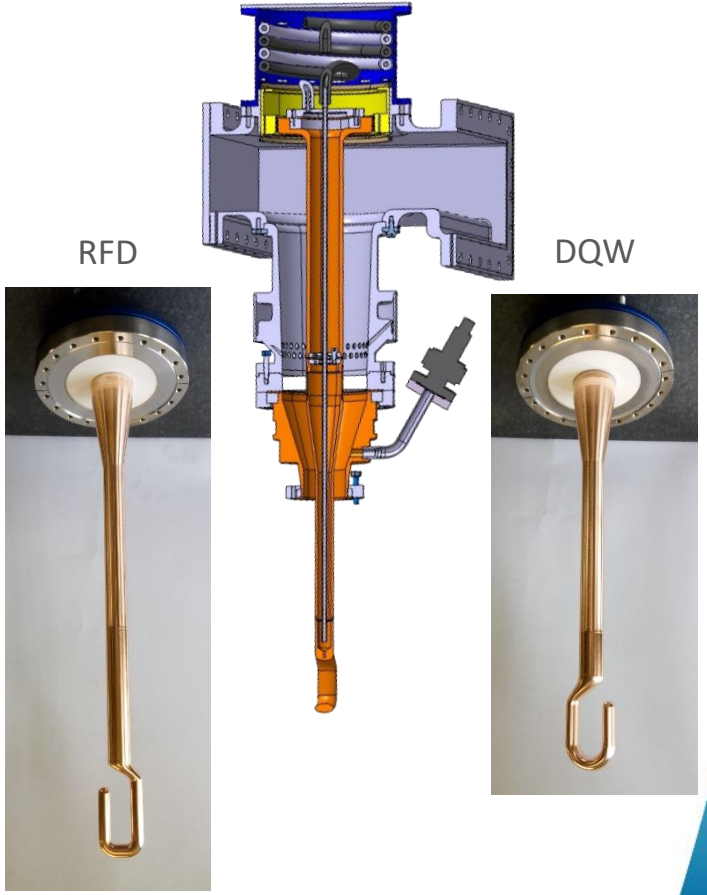
- Only bulk material for all vacuum side items
- Body with conical line for high power capability (calculated up to 1 MW)
- AL_2O_3, 99.6 % purity, 25 mm thickness disk ceramic, antenna from bulk copper, outer flange Titanium
- Air outer line with cyclotronic© air cooling system to avoid arcing
- Coaxial to WG without doorknob
- DC polarization to block multipacting
- Water cooled antenna as the hook has been calculated critical (very small geometry with respect to the requested CW power)
- Only the two coupling elements are different, everything else is identical



Experience with FPCs (including RF conditioning)

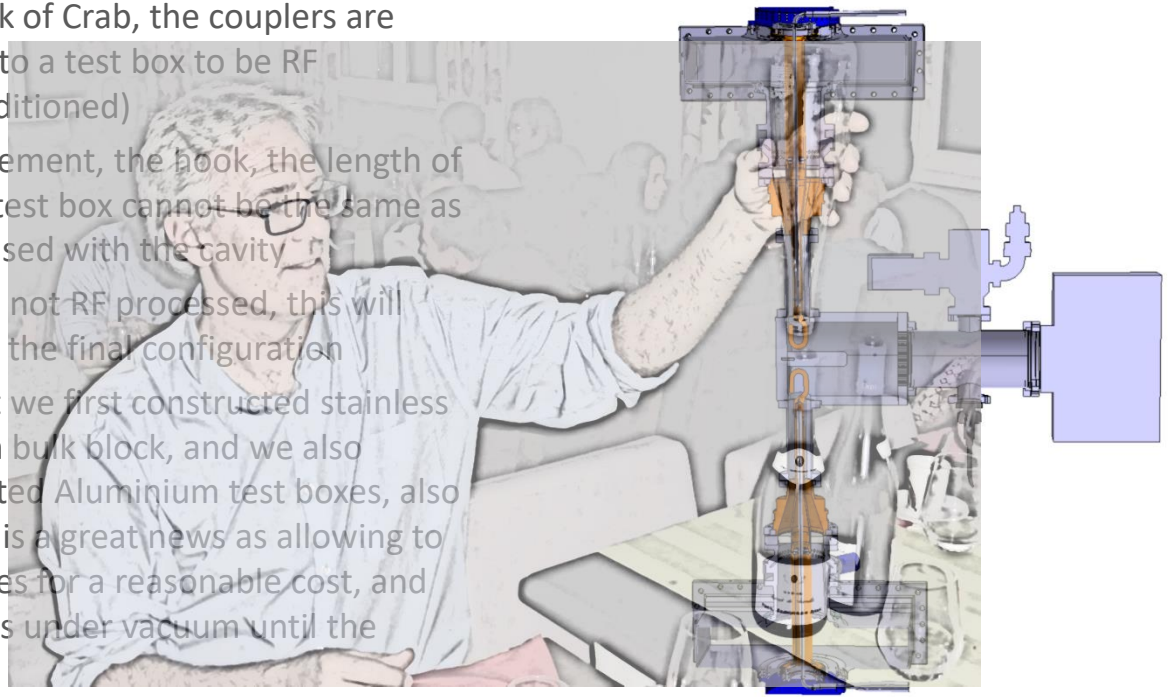
Except the coupling elements, all other devices are identical

- Only bulk material for all vacuum side items
- Body with conical line for high power capability (calculated up to 1 MW)
- AL_2O_3, 99.6 % purity, 25 mm thickness disk ceramic, antenna from bulk copper, outer flange Titanium
- Air outer line with cyclotronic© air cooling system to avoid arcing
- Coaxial to WG without doorknob
- DC polarization to block multipacting
- Water cooled antenna as the hook has been calculated critical (very small geometry with respect to the requested CW power)
- Only the two coupling elements are different, everything else is identical



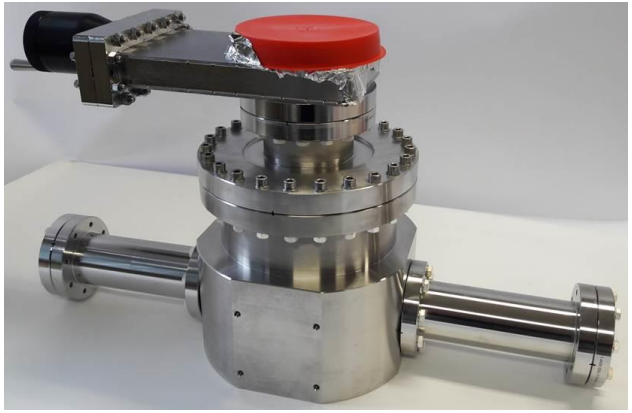
Experience with FPCs (including RF conditioning)

- Within the framework of Crab, the couplers are always assembled onto a test box to be RF processed (or RF conditioned)
- Due to its coupling element, the hook, the length of the outer line of the test box cannot be the same as the one that will be used with the cavity
- The outer line is then not RF processed, this will have to be done with the final configuration
- With the crab project we first constructed stainless steel test boxes, from bulk block, and we also successfully constructed Aluminium test boxes, also from bulk block, that is a great news as allowing to have several test boxes for a reasonable cost, and then keeping the FPCs under vacuum until the assembly on cavity



Experience with FPCs (including RF conditioning)

- Within the framework of Crab, the couplers are always assembled onto a test box to be RF processed (or RF conditioned)
- Due to its coupling element, the hook, the length of the outer line of the test box cannot be the same as the one that will be used with the cavity
- The outer line is then not RF processed, this will have to be done with the final configuration
- With the crab project we first constructed stainless steel test boxes, from bulk block, and we also successfully constructed Aluminium test boxes, also from bulk block, that is a great news as allowing to have several test boxes for a reasonable cost, and then keeping the FPCs under vacuum until the assembly on cavity

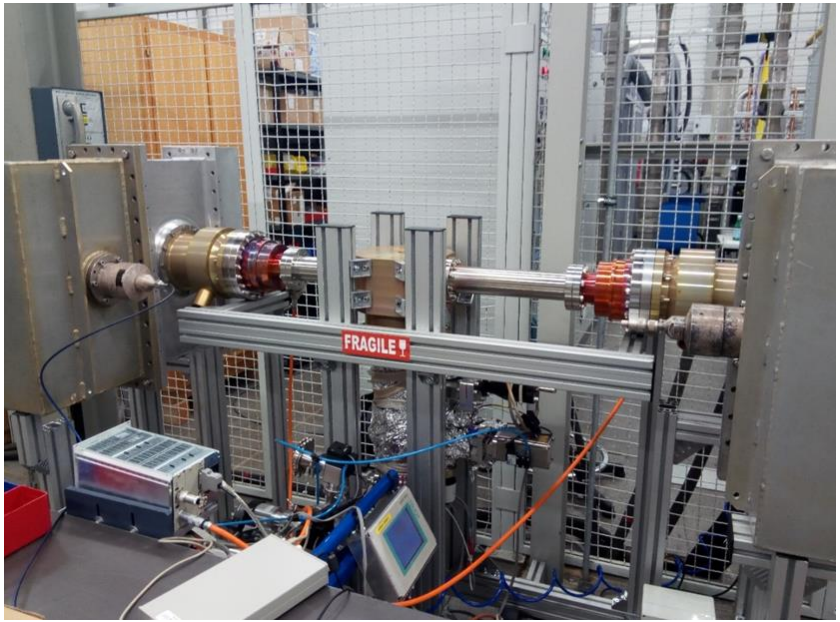


Experience with FPCs (including RF conditioning)

- Within the framework of Crab, the couplers are always assembled onto a test box to be RF processed (or RF conditioned)
- Due to its coupling element, the hook, the length of the outer line of the test box cannot be the same as the one that will be used with the cavity
- The outer line is then not RF processed, this will have to be done with the final configuration
- With the crab project we first constructed stainless steel test boxes, from bulk block, and we also successfully constructed Aluminium test boxes, also from bulk block, that is a great news as allowing to have several test boxes for a reasonable cost, and then keeping the FPCs under vacuum until the assembly on cavity

Experience with FPCs (including RF conditioning)

- Within the framework of Crab, the couplers are always assembled onto a test box to be RF processed (or RF conditioned)
- Due to its coupling element, the hook, the length of the outer line of the test box cannot be the same as the one that will be used with the cavity
- The outer line is then not RF processed, this will have to be done with the final configuration
- With the crab project we first constructed stainless steel test boxes, from bulk block, and we also successfully constructed Aluminium test boxes, also from bulk block, that is a great news as allowing to have several test boxes for a reasonable cost, and then keeping the FPCs under vacuum until the assembly on cavity



Experience with FPCs (including RF conditioning)

- Within the framework of Crab, the couplers are always assembled onto a test box to be RF processed (or RF conditioned)
- Due to its coupling element, the hook, the length of the outer line of the test box cannot be the same as the one that will be used with the cavity
- The outer line is then not RF processed, this will have to be done with the final configuration
- With the crab project we first constructed stainless steel test boxes, from bulk block, and we also successfully constructed Aluminium test boxes, also from bulk block, that is a great news as allowing to have several test boxes for a reasonable cost, and then keeping the FPCs under vacuum until the assembly on cavity

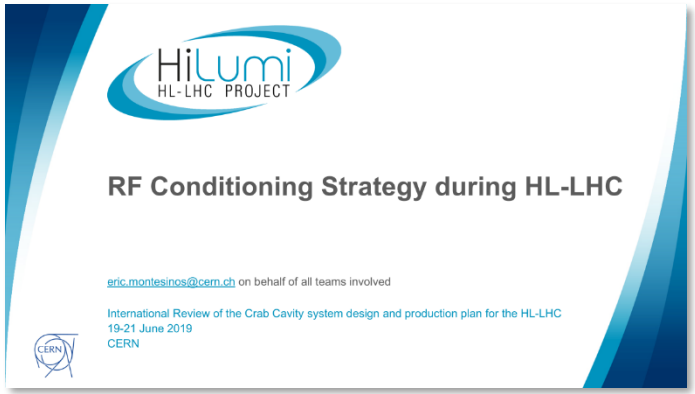
Experience with FPCs (including RF conditioning)

The RF process is the one successfully experienced since 1998 with all CERN's FPCs

- Always start with short pulses
- Increase the power level under vacuum control
- Repeat until CW

It is the same process and electronics we already deployed all over the world

- CERN, SOLEIL, ESRF, APS, BNL, LAL, KEK
- Always a long process and we have to be cautious
- With this approach, we have not broken any CERN coupler since 1998...

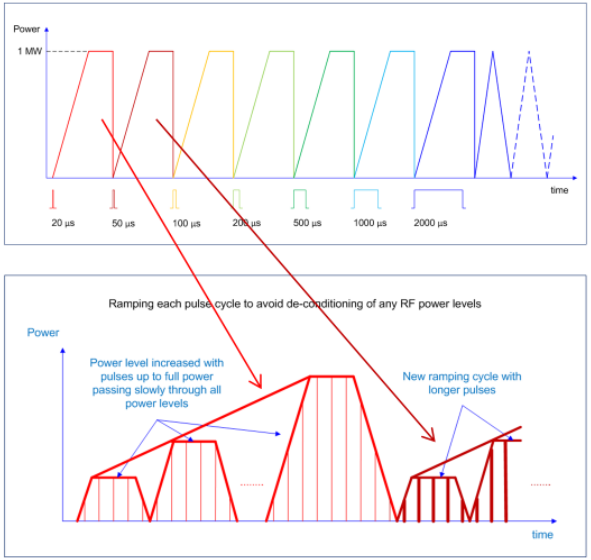


International Review of the Crab Cavity system design and production plan for the HL-LHC
RF Conditioning Strategy during HL-LHC
19-21 June 2019
CERN

Experience with FPCs (including RF conditioning)

RF Processing method

- What we also noticed is that making a ‘straight ramping’ could be dangerous
- Indeed, a higher power level can ‘de-condition’ a lower power level previously processed
- So inside one envelope, we ramp up and we ramp down to guaranty that ALL power levels have been processed with the shorter pulses
- This process ensures that the lowest energy is deposited into an arc if it should occur

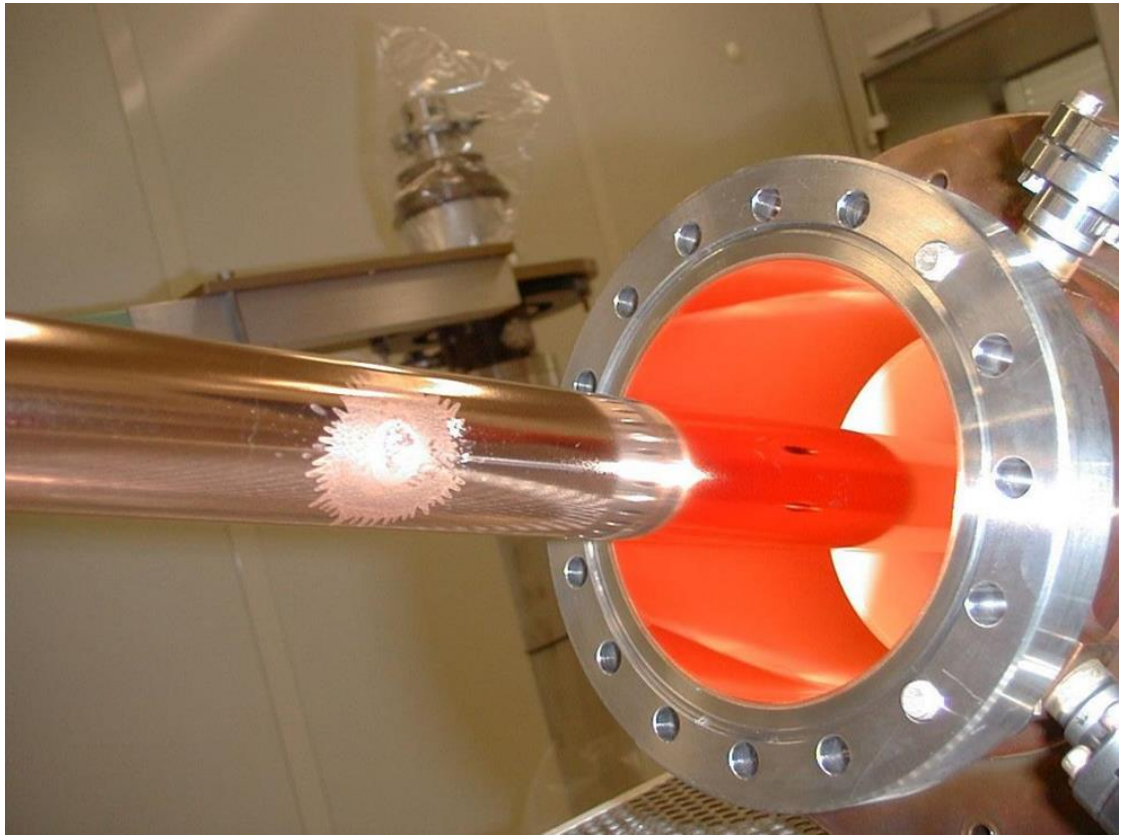


Always ramping the power level up and down to ensure that ALL power levels have been processed with the shorter pulses, i.e. minimum energy

Experience with FPCs (including RF conditioning)

When we tried to be quicker (with previous project – LHC coupler)
Thanks to the fact that we are always using bulk material we were able to continue to operate that coupler, otherwise it would have been catastrophic

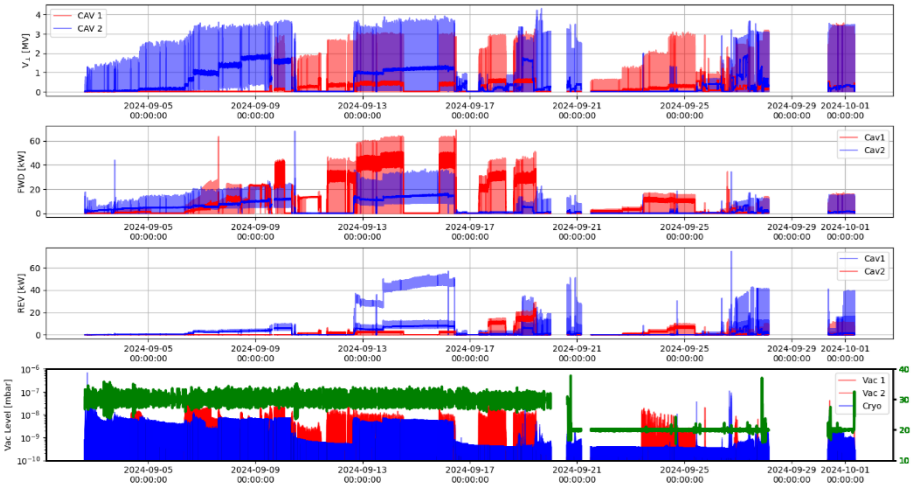
A new modern automated system is being prepared by LLRF team keeping the same strategy



Experience with FPCs (including RF conditioning)

- It took us quite some time to process the couplers, between two to four weeks
- We start off tune, to process the coupler alone, and we move on tune to process the coupler and the cavity
- With RFD #1, we discovered that a circulator was mandatory, without it, we had a resonance between the cavity of the tube and the crab cavity itself
- Fortunately (for transmission lines reasons explained last year – coax versus WG with respect to full reflection) we have it in the final scheme of the HL-LHC
- Despite FPCs have been misaligned, the field have been achieved, which is also a very important outcome of the RFD test

Courtesy Rama Calaga

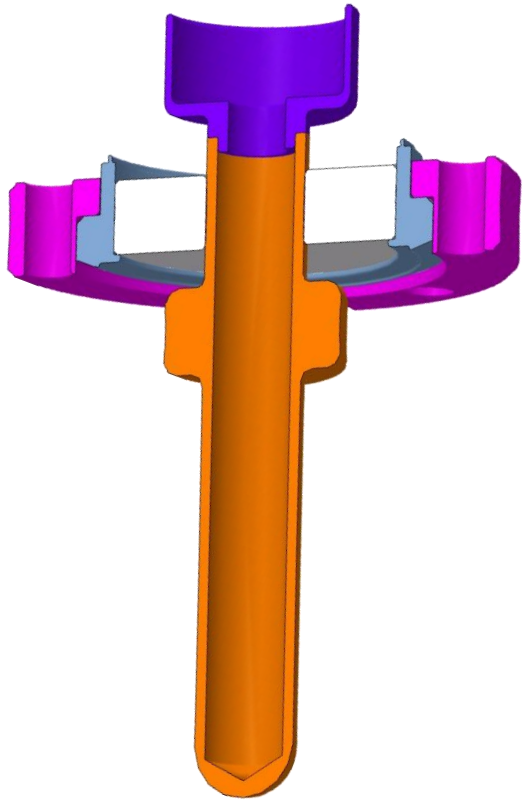


- Cavity #2 recovered very quickly, this is a very good news to learn that cavities have a very good memory of the RF processing!
- The fantastic news is that FPC #1 was able to take multiple x 10 kW (keep in mind the thickness of the ceramic that is key for the robustness of the FPC…)

Issues related to HOMC…

…more like a lessons learned on what could go wrong for future CMs

- It has been a very long and difficult item to design
- We had several versions (4) before having a robust enough item that enables to make the 2K vertical test
- Finally, it seems that apart from some production difficulties and cleanliness issues during construction, all HOM couplers and field antennas by themselves are doing ok



Issues related to HOMC…

…more like a lessons learned on what could go wrong for future CMs

- It has been a very long and difficult item to design
- We had several versions (4) before having a robust enough item that enables to make the 2K vertical test
- Finally, it seems that apart from some production difficulties and cleanliness issues during construction, all HOM couplers and field antennas by themselves are doing ok

Issues related to HOMC…

…more like a lessons learned on what could go wrong for future CMs

- Not yet really a lesson learnt, more a work in progress to improve the processing and anti-dust preparation of RF ancillaries, as well as standardize
- Issues are presence of oxides, drying stains, BCP residues, welded/brazed joints emitting large amounts of particles
- Actions taken are adding degreasing step after BCP to avoid BCP residues, modification of the BCP tooling to avoid acids in contact with the brazed joint, modification of the rinsing and drying procedure in cleanroom to avoid oxidation of copper antennas

Issues related to HOMC…

…more like a lessons learned on what could go wrong for future CMs

- Not yet really a lesson learnt, more a work in progress to improve the processing and anti-dust preparation of RF ancillaries, as well as standardize
- Issues are presence of oxides, drying stains, BCP residues, welded/brazed joints emitting large amounts of particles
- Actions taken are adding degreasing step after BCP to avoid BCP residues, modification of the BCP tooling to avoid acids in contact with the brazed joint, modification of the rinsing and drying procedure in cleanroom to avoid oxidation of copper antennas

Issues related to HOMC…

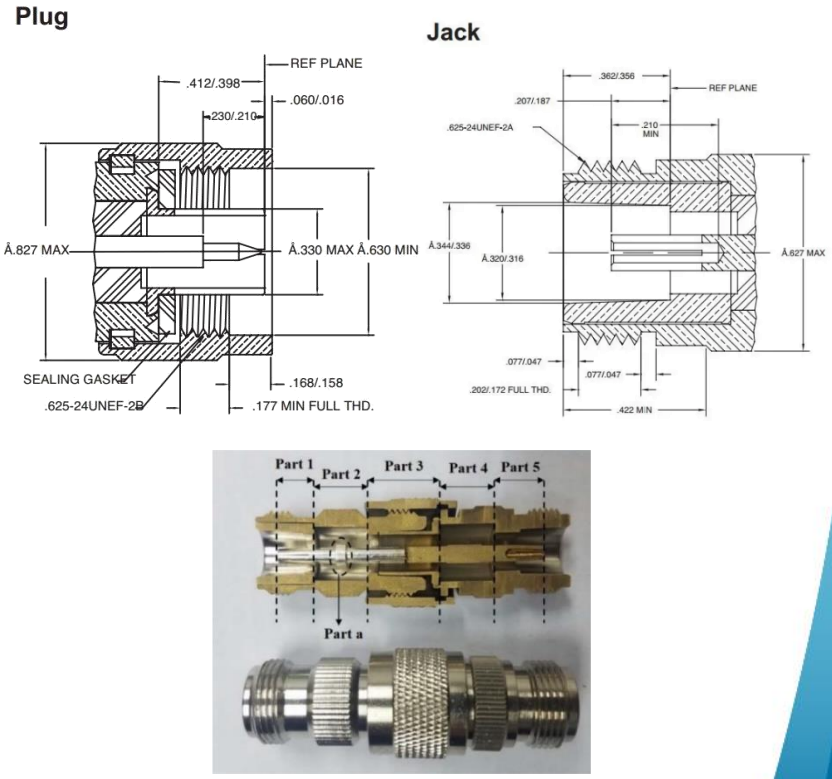
…more like a lessons learned on what could go wrong for future CMs

- Not yet really a lesson learnt, more a work in progress to improve the processing and anti-dust preparation of RF ancillaries, as well as standardize
- Issues are presence of oxides, drying stains, BCP residues, welded/brazed joints emitting large amounts of particles
- Actions taken are adding degreasing step after BCP to avoid BCP residues, modification of the BCP tooling to avoid acids in contact with the brazed joint, modification of the rinsing and drying procedure in cleanroom to avoid oxidation of copper antennas

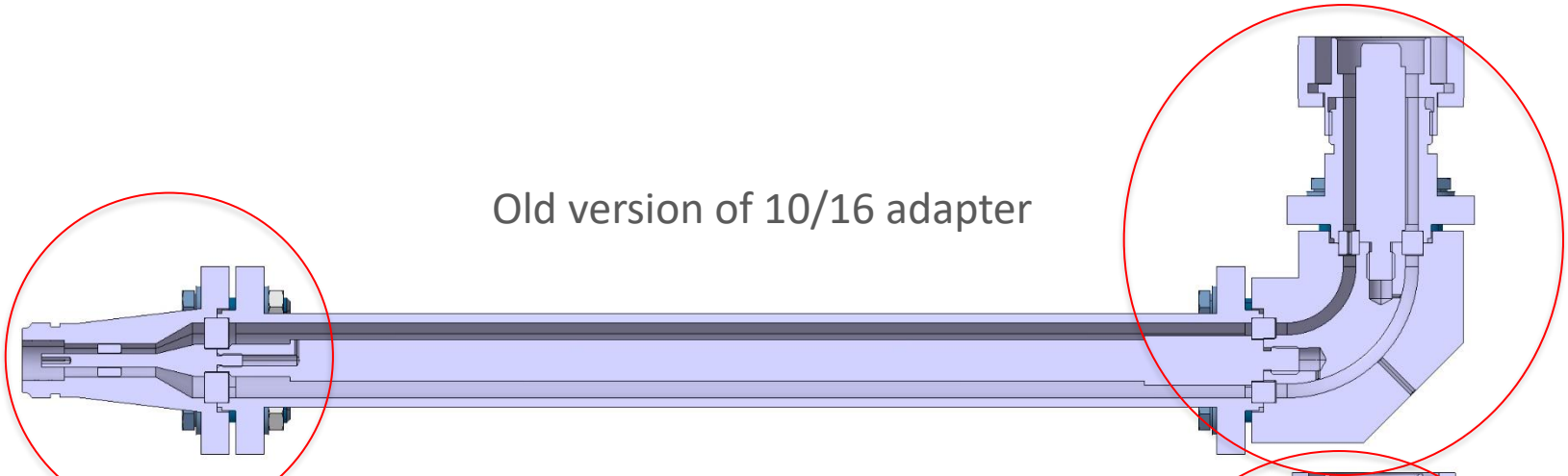
Issues related to HOMC…

…more like a lessons learned on what could go wrong for future CMs

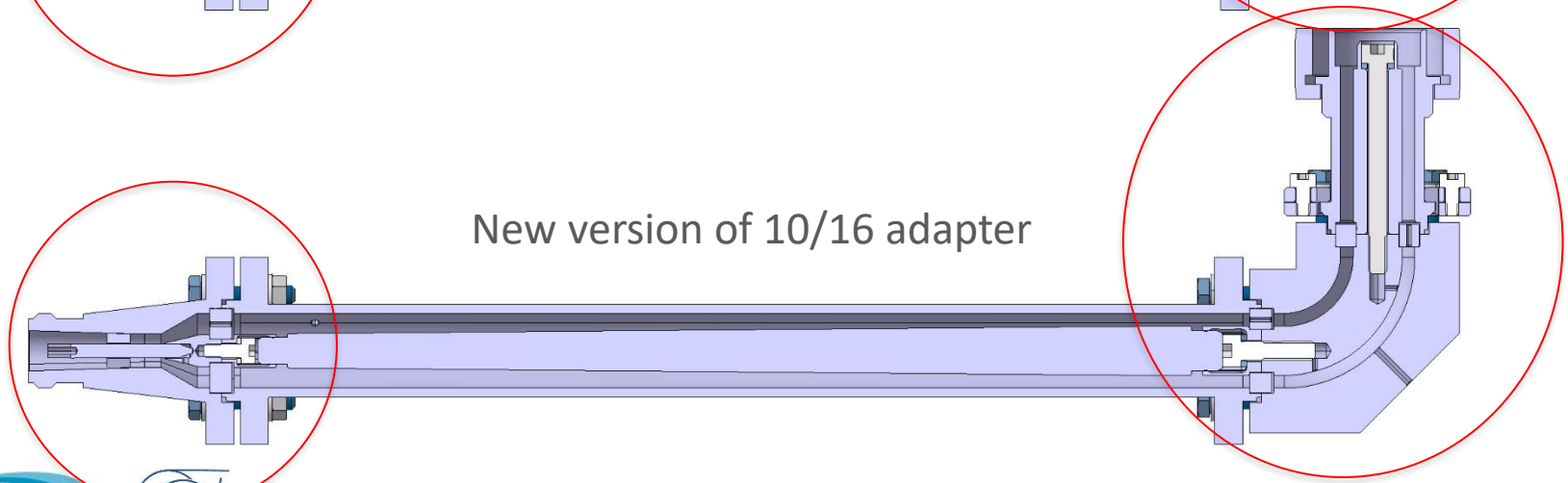
- The lines and adapters were more of a concern, and more specifically the RF contacts of the lines and adapters
- We identified several places with an RF contact in rotation
- This is an incorrect design by definition, but it is even worse in the case of a cold system
- The outcome is that we overtighten the connector thinking that we improve the RF contact
- This is wrong, we damage the connector that even if it is ok for the first test, will be bad later
- Only sliding contacts are now being implemented in our lines and adapters to cure the problem

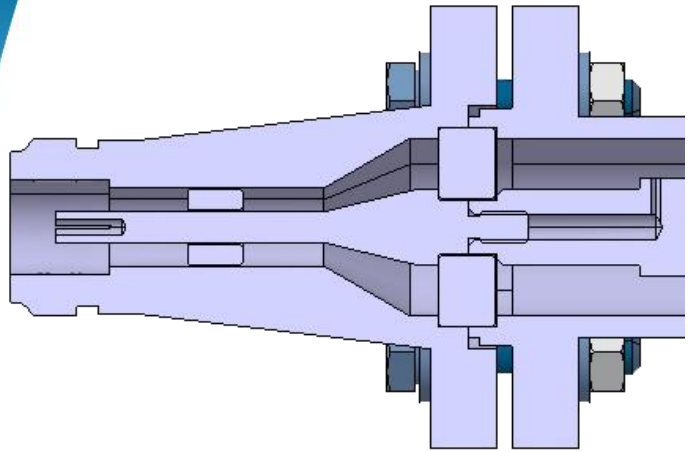


Old version of 10/16 adapter

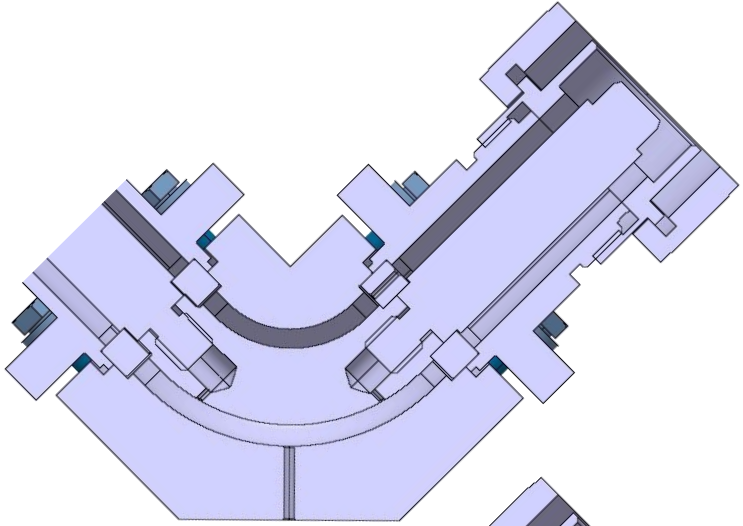


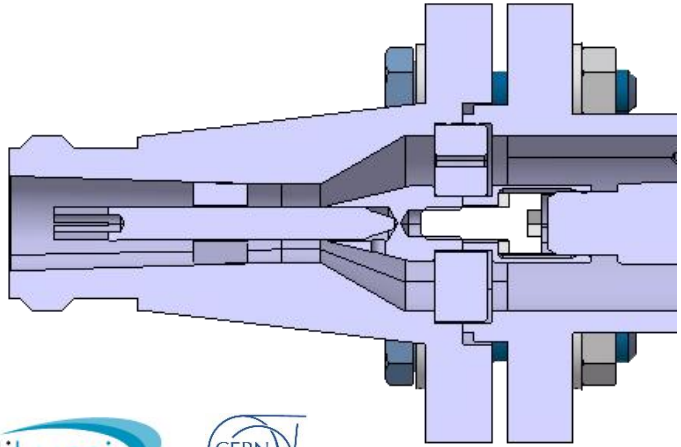
New version of 10/16 adapter



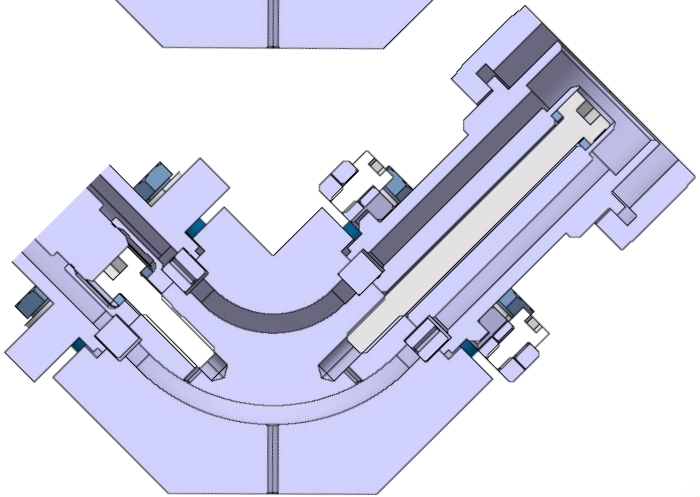


Old version of
10/16 adapter

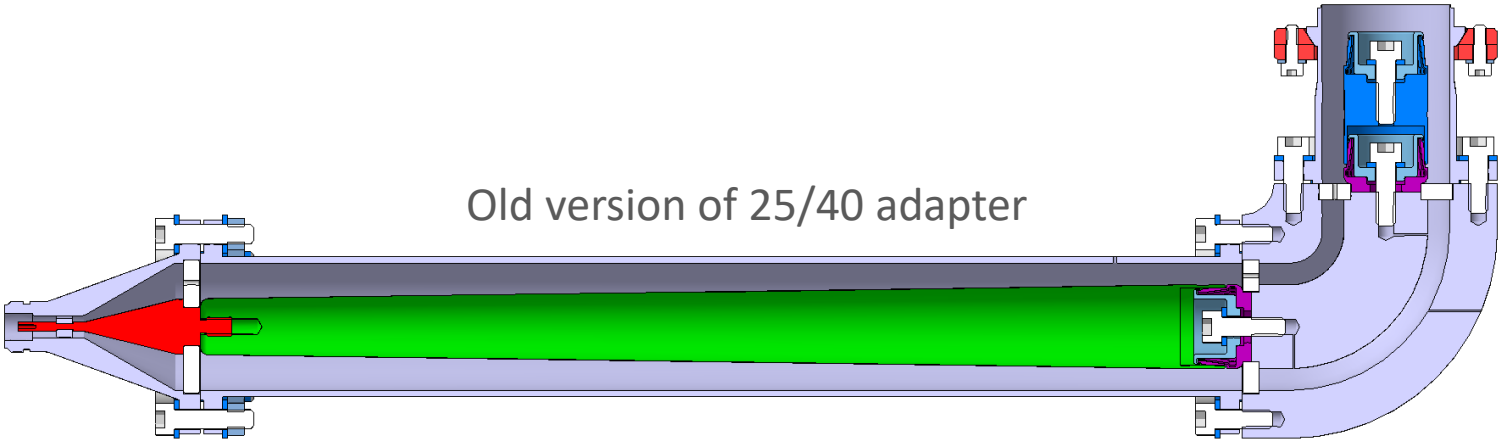




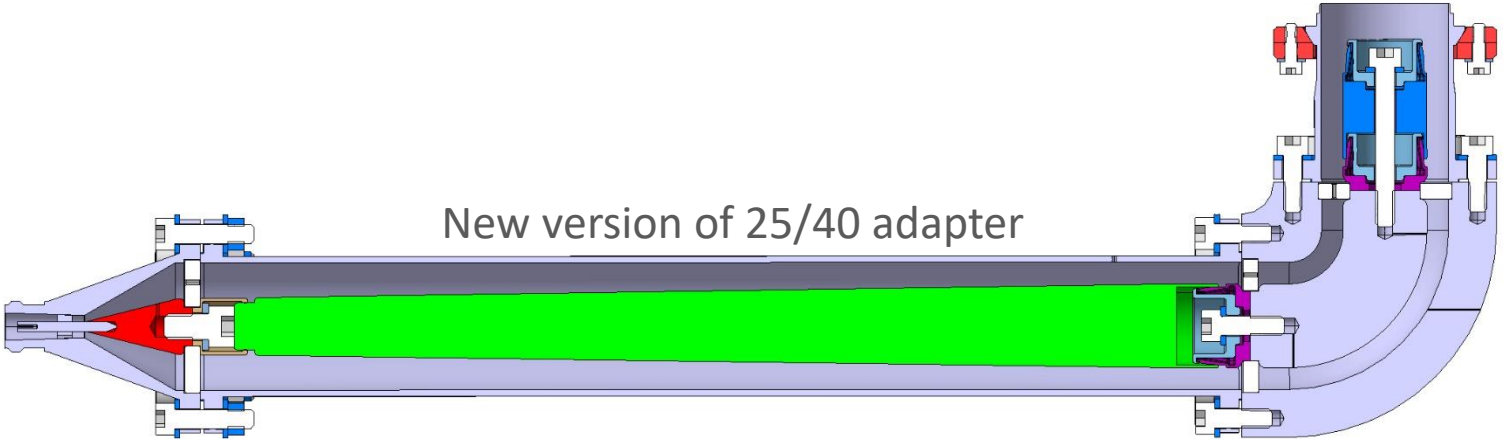
New version of
10/16 adapter



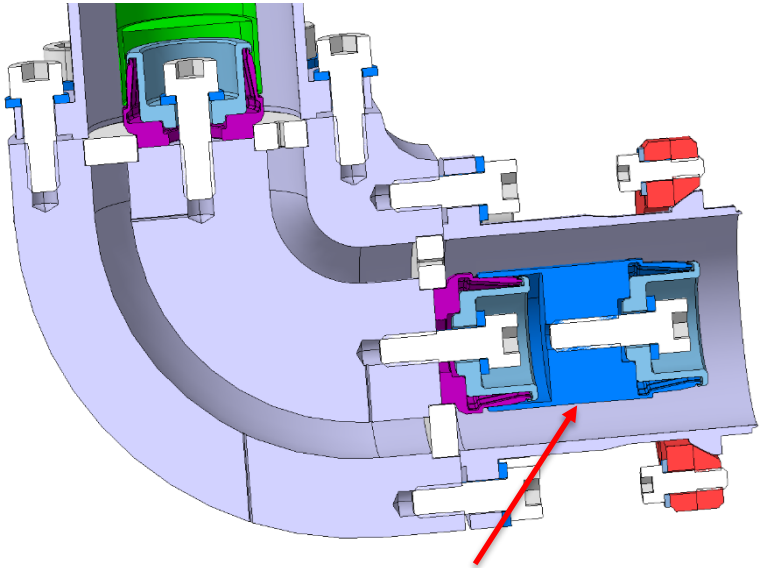
Old version of 25/40 adapter



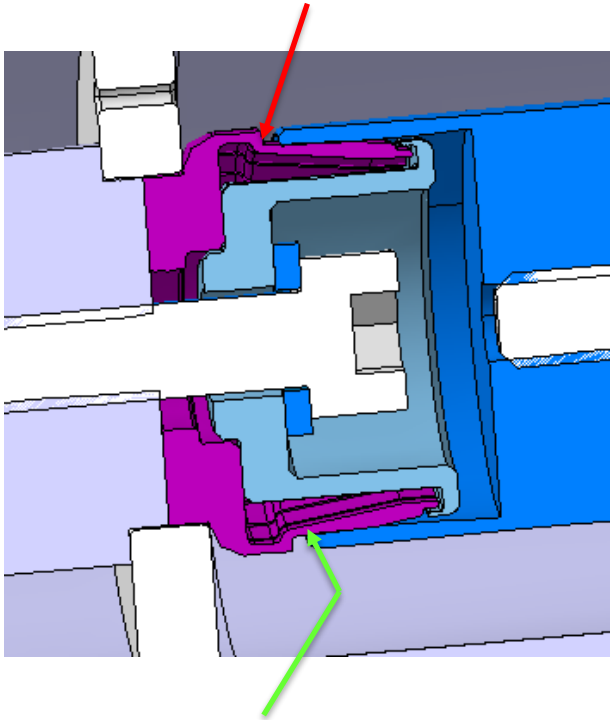
New version of 25/40 adapter



Issues related to HOMC…



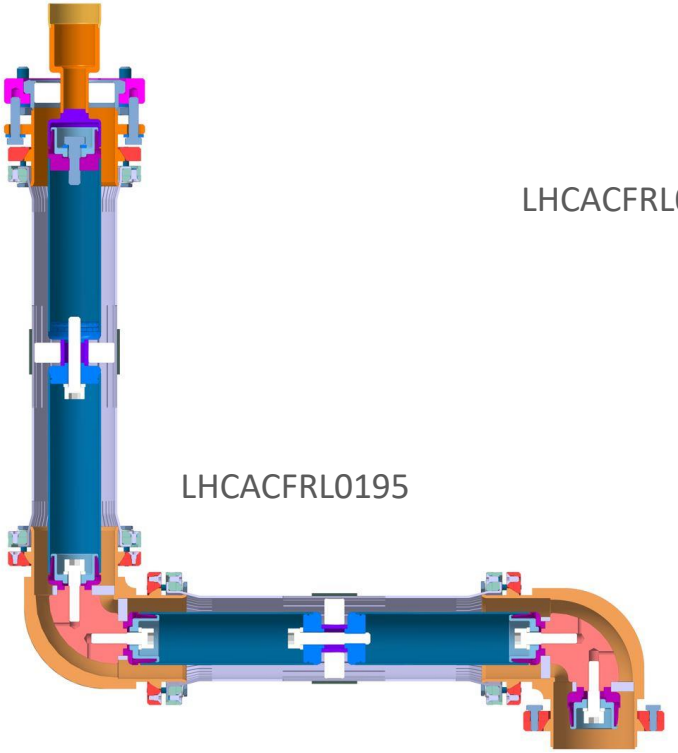
Wrong surface for RF contact



Correct location for RF contact

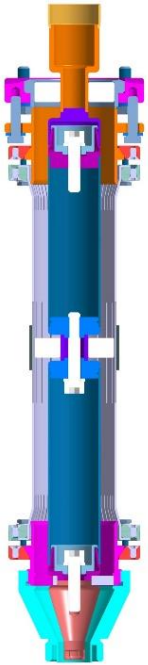
Because of a too long inner line, the RF contact was taking place on the wrong place

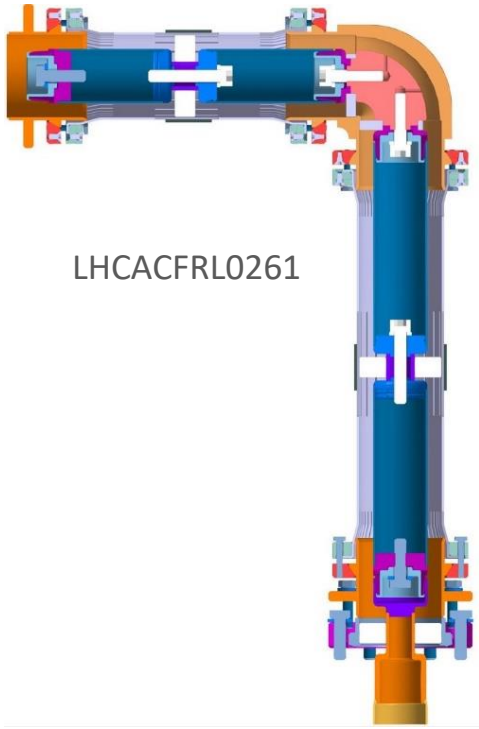
Overtightening gave the impression that all was ok, but in fact it was deforming the line inducing a bad contact during the next assembly or during the next warm up cool down cycle



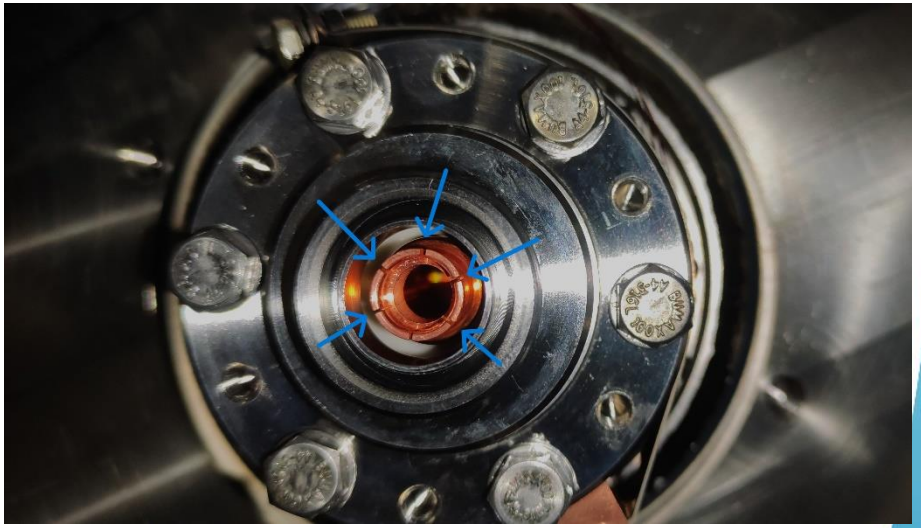
LHCACFRL0195

LHCACFRL0198

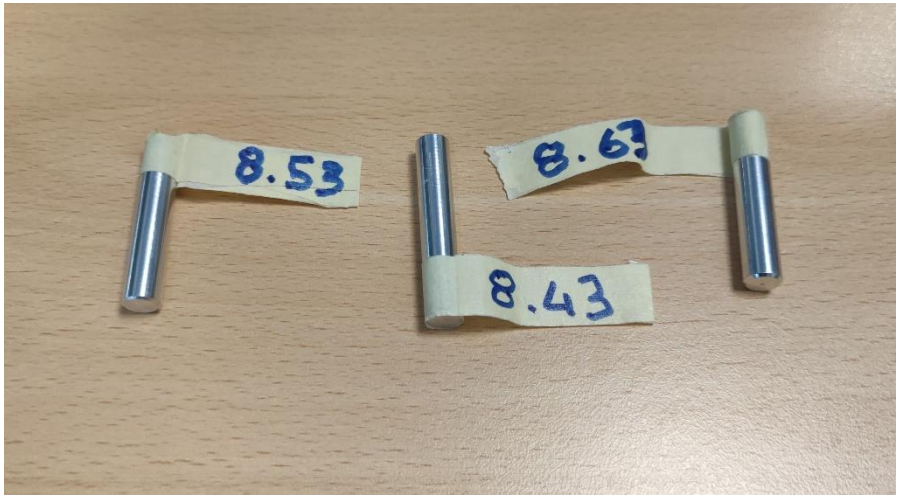




LHCACFRL0261



So please, never tighten an RF connector over the specified limit, even better, all our connectors could be tightened by hands only



The very good news here is that the feedthroughs have survived the massive overtightening we applied to them, demonstrating their robustness

Recent experience from RFD

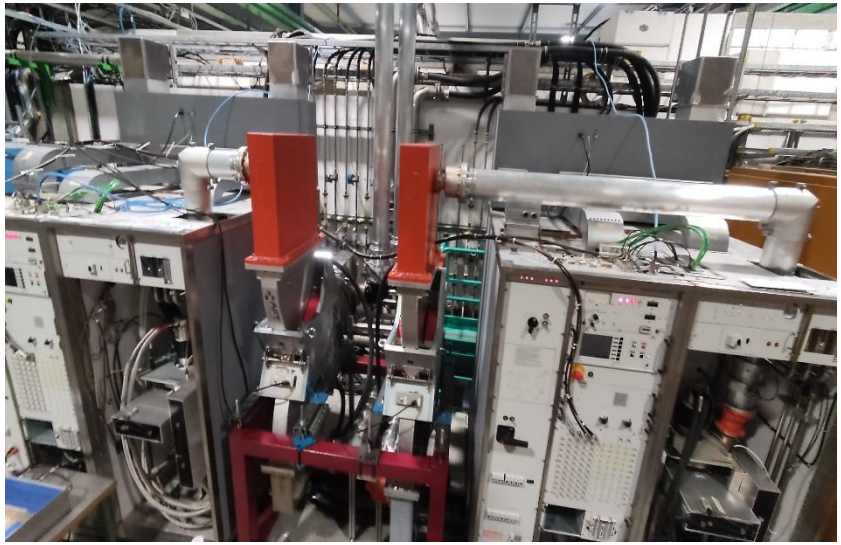
and what to expect from conditioning for the future series including what/when we are going to send to Canada (SSPA, IOT ?)

- We have three power stations at CERN available for the Crab project
- We are constructing a fourth one, a Proof Of Concept (POC) that will be the basis for the Invitation to Tender detailed Technical Specification
- By the end of 2024, we will then have four power stations
- Two will be operated in the SPS for the RFD test and for FPC processing
- One will be sent to Canada
- The POC will be moved to SM18 if needed

Recent experience from RFD

and what to expect from conditioning for the future series including what/when we are going to send to Canada (SSPA, IOT ?)

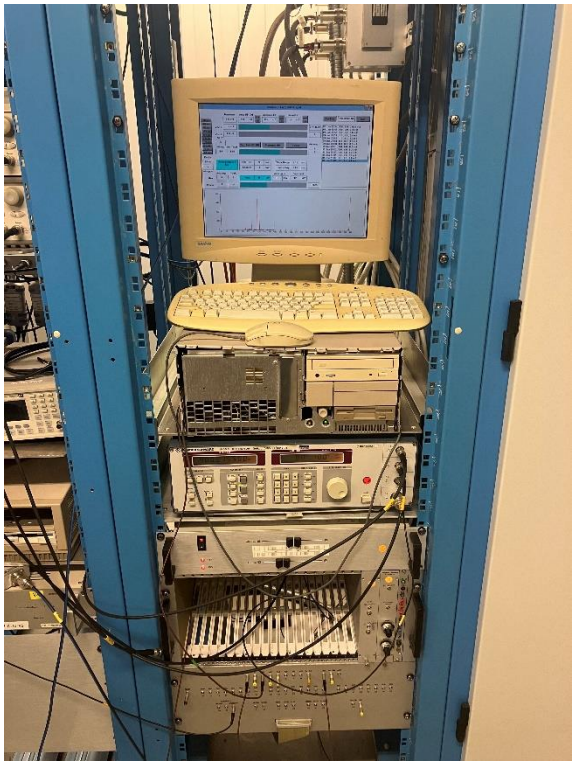
- What we recently discovered is that a circulator is needed between the power station and the cavity
- Circulators we installed in SM18 are for far oversized as being LHC spares with power ratings up to 350 kW
- As we will buy circulators for HL Crab, two prototypes will be ordered, one will be sent to Canada Q4 2025
- A new portable RF processing is also being finalized, and will be sent to Canada
- Still some details (but Devil is in the details) to be sorted out (240 VAC 50 Hz versus 110 VAC 60 Hz for example)



Recent experience from RFD

and what to expect from conditioning for the future series including what/when we are going to send to Canada (SSPA, IOT ?)

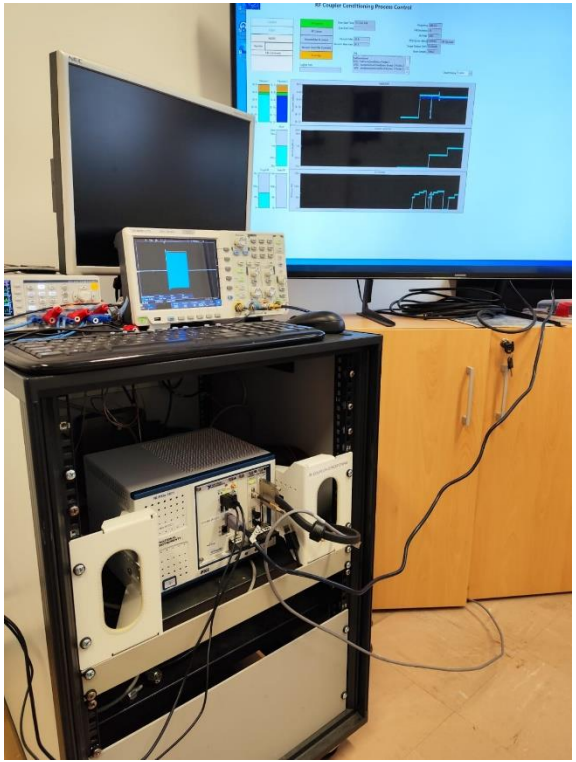
- What we recently discovered is that a circulator is needed between the power station and the cavity
- Circulators we installed in SM18 are for far oversized as being LHC spares with power ratings up to 350 kW
- As we will buy circulators for HL Crab, two prototypes will be ordered, one will be sent to Canada Q4 2025
- A new portable RF processing is also being finalized, and will be sent to Canada
- Still some details (but Devil is in the details) to be sorted out (240 VAC 50 Hz versus 110 VAC 60 Hz for example)



Recent experience from RFD

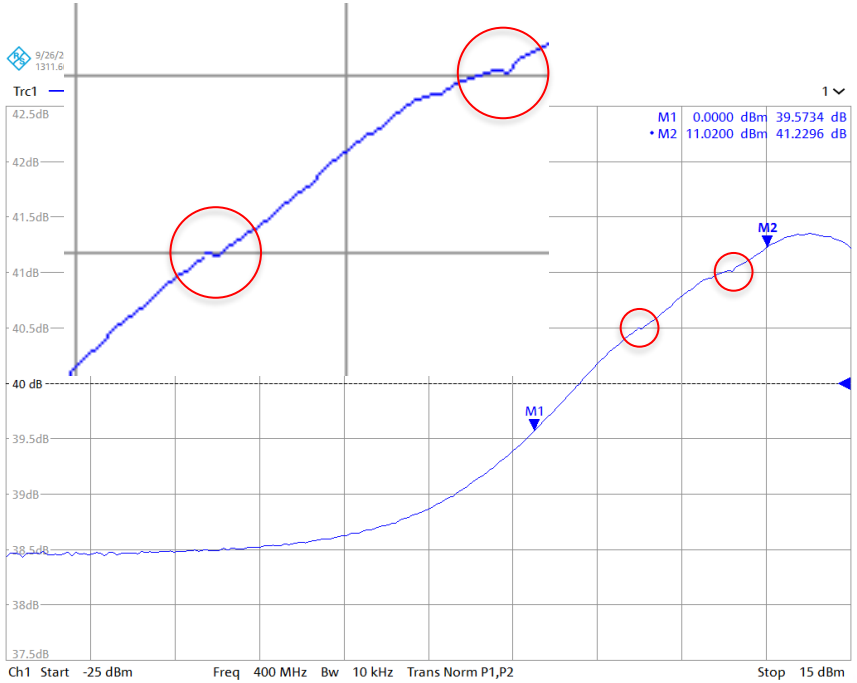
and what to expect from conditioning for the future series including what/when we are going to send to Canada (SSPA, IOT ?)

- What we recently discovered is that a circulator is needed between the power station and the cavity
- Circulators we installed in SM18 are for far oversized as being LHC spares with power ratings up to 350 kW
- As we will buy circulators for HL Crab, two prototypes will be ordered, one will be sent to Canada Q4 2025
- A new portable RF processing is also being finalized, and will be sent to Canada
- Still some details (but Devil is in the details) to be sorted out (240 VAC 50 Hz versus 110 VAC 60 Hz for example)



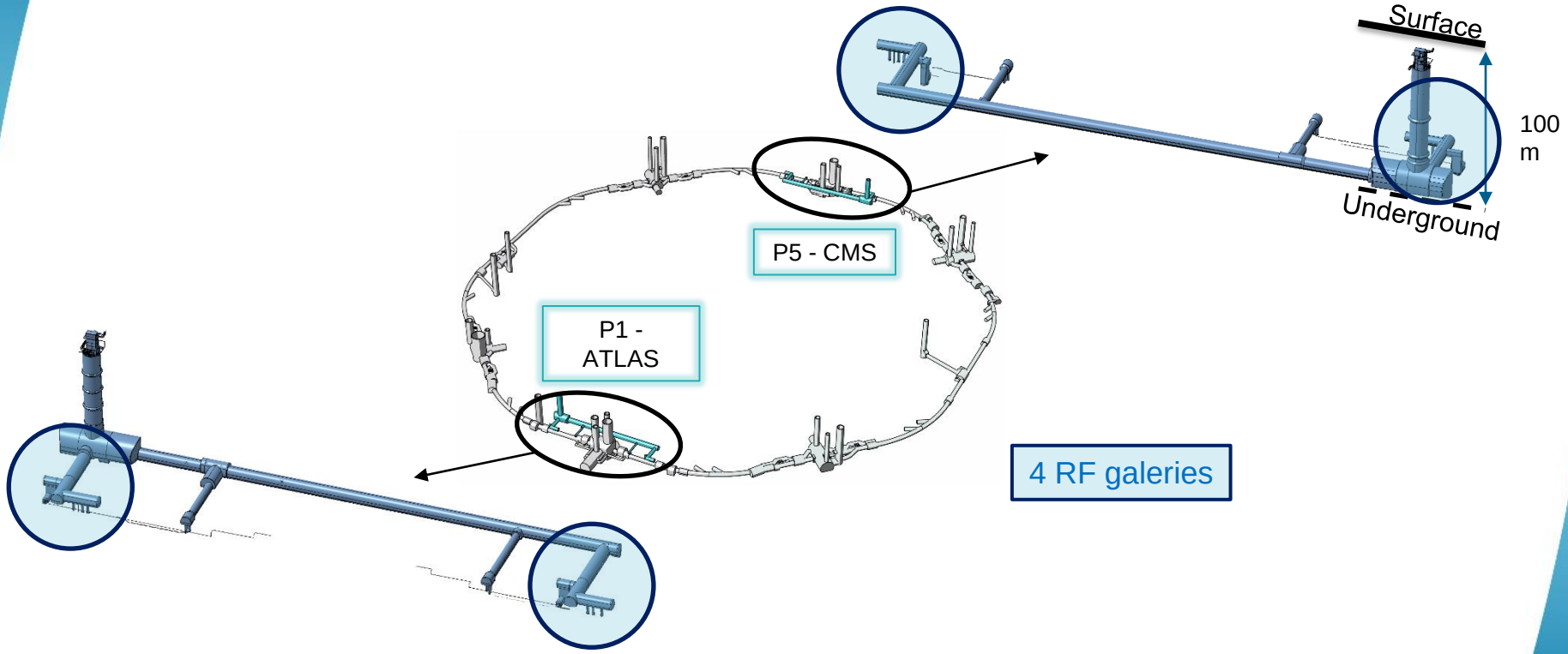
Monotonous Driver

- There is key parameter that we identified with the first SPS test that is the linearity and the monotonous behaviour of the transmitter
- We will not be able to do a lot with respect to the IOT
- The driver could be pre-adjusted to compensate the tube
- What we recently discovered with the RFD test is that the Driver was not having a monotonous behaviour
- From all this, we decided to make a separate purchase, with its own specific specification, under preparation

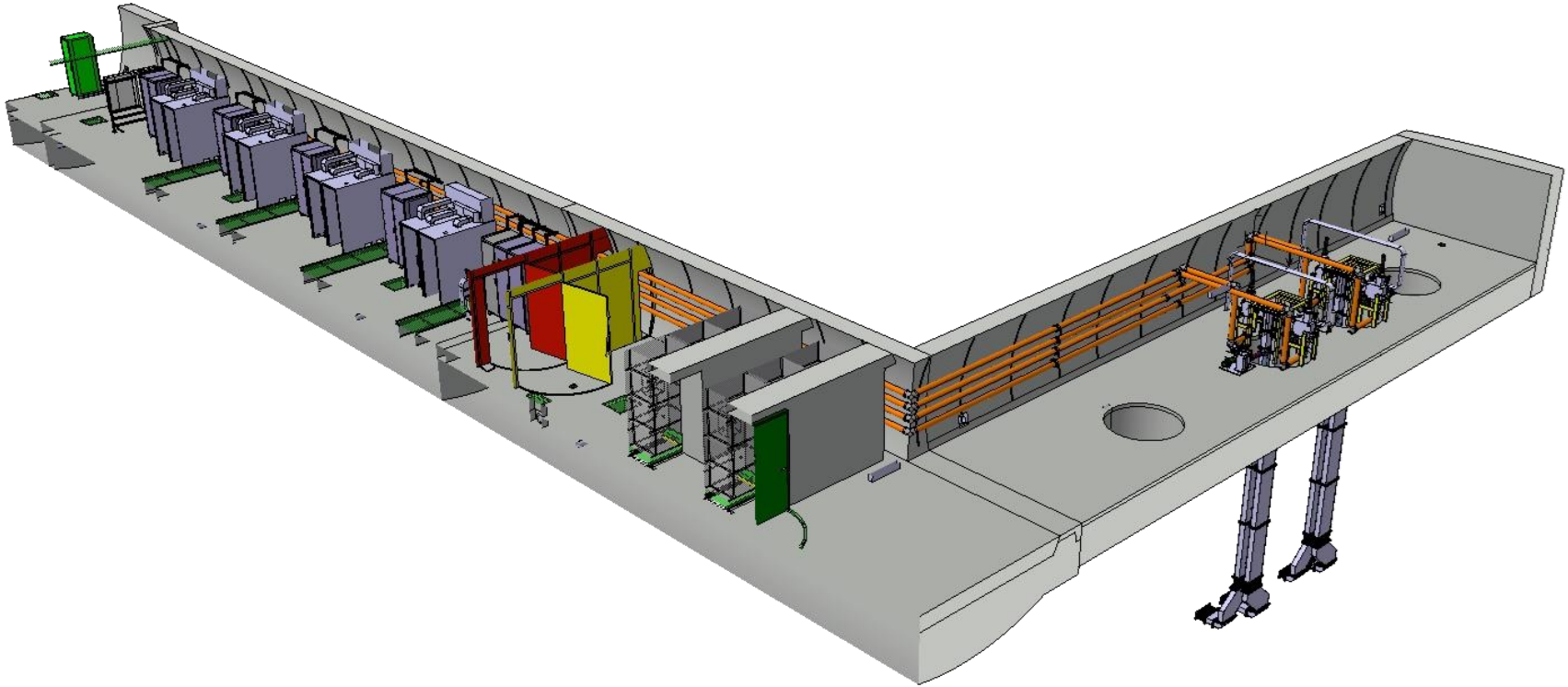


U-shape in RF power lines

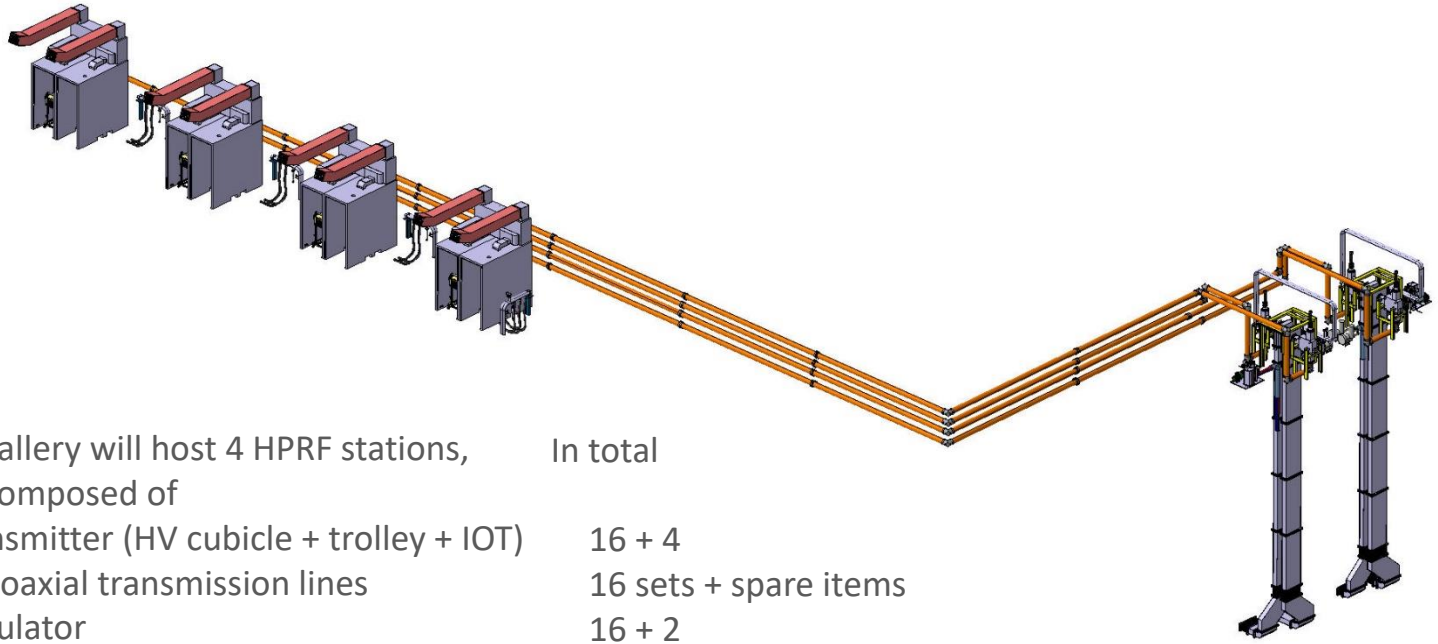
Series production with industry



Series production with industry



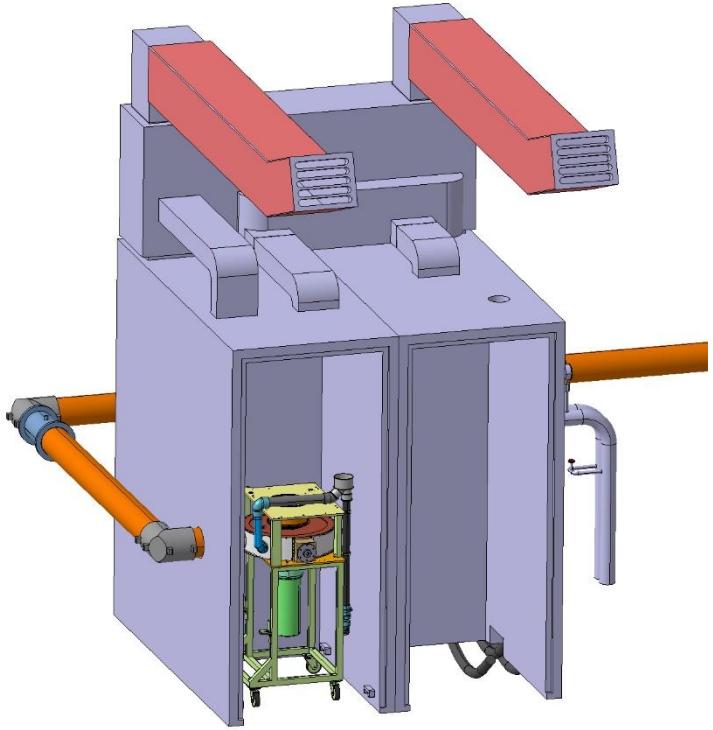
Series production with industry



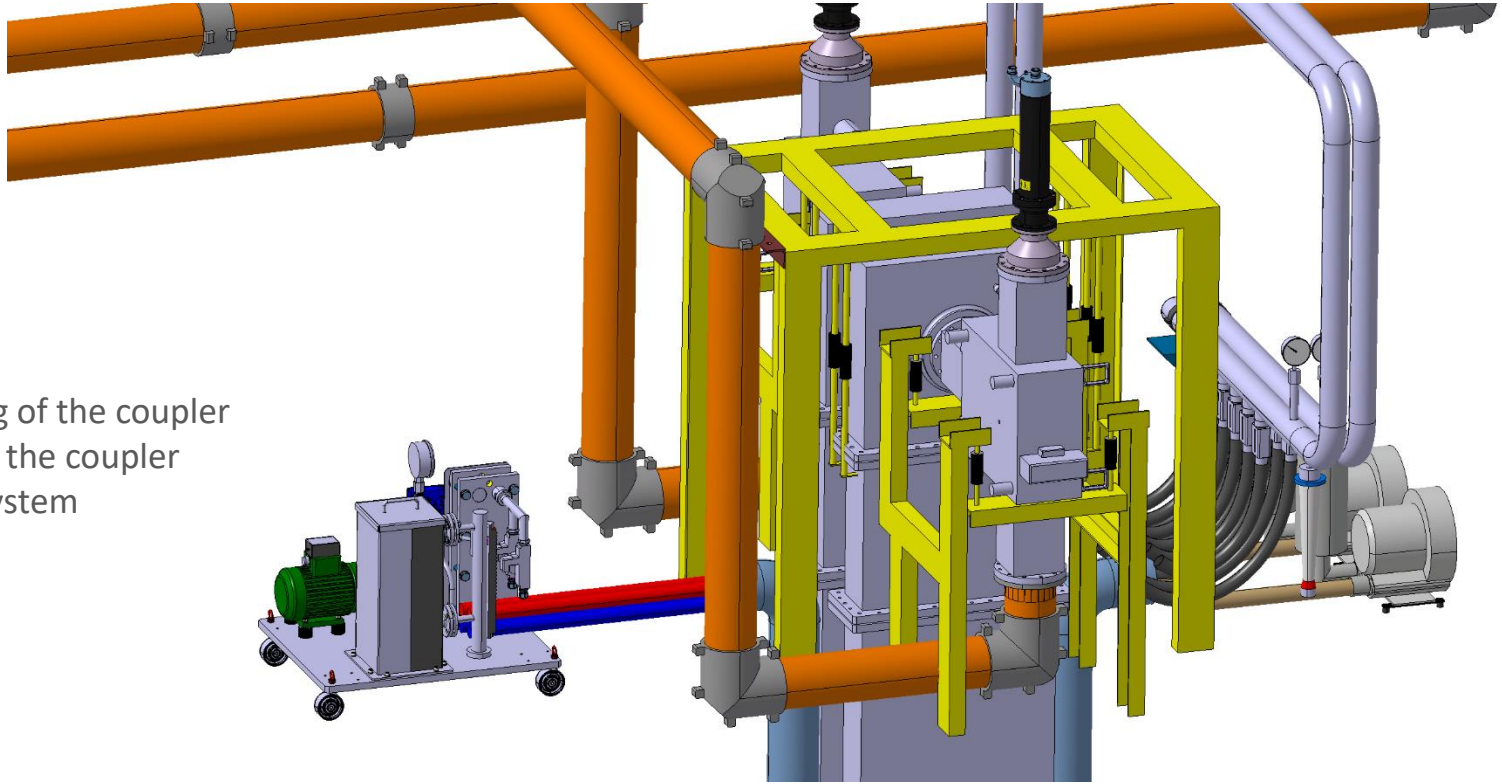
Each gallery will host 4 HPRF stations, each composed of	In total
Transmitter (HV cubicle + trolley + IOT)	16 + 4
RF coaxial transmission lines	16 sets + spare items
Circulator	16 + 2
Circulator’s dummy load	16 + 2
RF waveguides	16 sets + spare items

Series production with industry

Transmitter
- Driver
- IOT
- Trolley
- HV cubicle (including controls)



Circulator
Load
Water cooling of the coupler
Air cooling of the coupler
Supporting system



Series production with industry

next steps, POC, acceptance tests, ...

- Next step is, now that we acquire a lot of experience thanks to BA6 tests over the past years and SM18 tests this year, the preparation of the contracts
- Tubes and trolleys contract have been approved by last Finance Committee, this is a very important milestone
- Market Survey for Cubicle is being launched
- MS for circulators is being launched
- Request for quotes of all other items are in preparation (drivers, coaxial lines, waveguide, loads for circulators)

Series production with industry

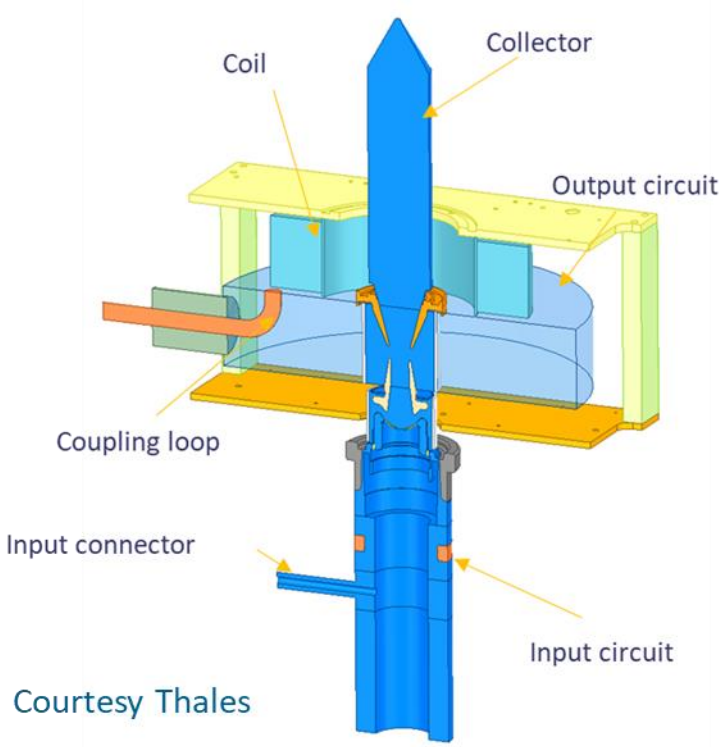
next steps, POC, acceptance tests, ...

- POC (Proof Of Concept) of a very simplified Cubicle, but correctly defined to our needs, is almost completed, tests should start before the end of the month
- This will allow for a very well defined detailed technical specification regarding the Cubicle
- In addition, we will test a new mono-cavity output circuit for the IOT, designed by Thales in the framework of a collaboration for the Crab IOT

Series production with industry

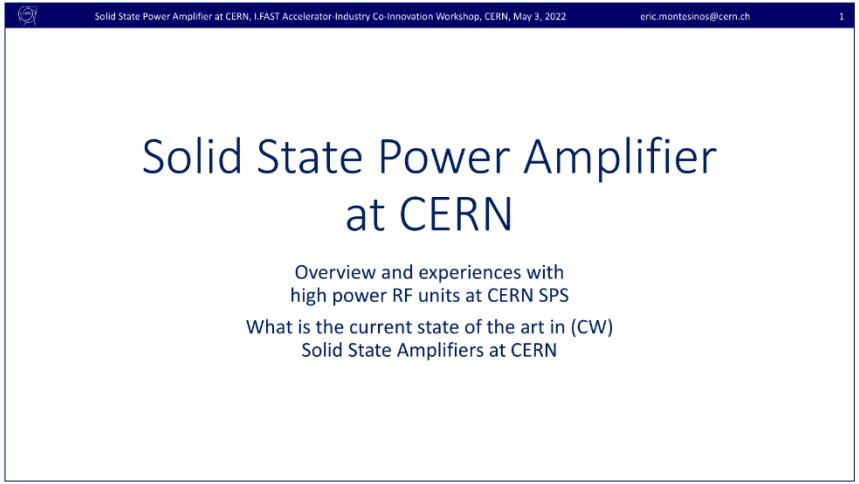
next steps, POC, acceptance tests, ...

- POC (Proof Of Concept) of a very simplified Cubicle, but correctly defined to our needs, is almost completed, tests should start before the end of the month
- This will allow for a very well defined detailed technical specification regarding the Cubicle
- In addition, we will test a new mono-cavity output circuit for the IOT, designed by Thales in the framework of a collaboration for the Crab IOT



Finally, is there a future for SSPA at 400 MHz?

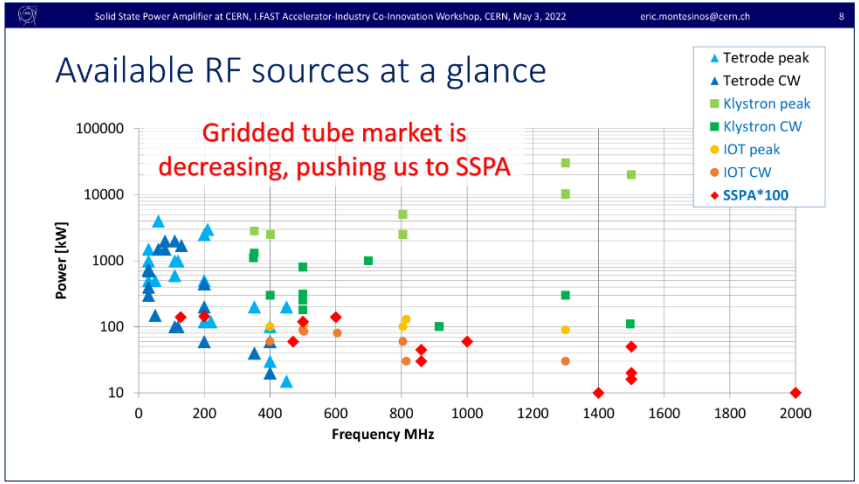
- The answer is yes of course, there is a future for SSPA at 400 MHz
- during the last CWRF2024 workshop, several colleagues have reported studies on GaN transistors, that will certainly replace LDMOS with a better power density and a better efficiency
- Combining systems have evolved over the last decade, allowing for a large number of inputs to one output in a single stage, that was a prerequisite for moving from SSA to SSPA
- So, for all about up to 100 kW, SSPA will certainly be an option to consider



Accelerator-Industry Co-Innovation workshop, CERN, May 2022, SSPA at CERN

Finally, is there a future for SSPA at 400 MHz?

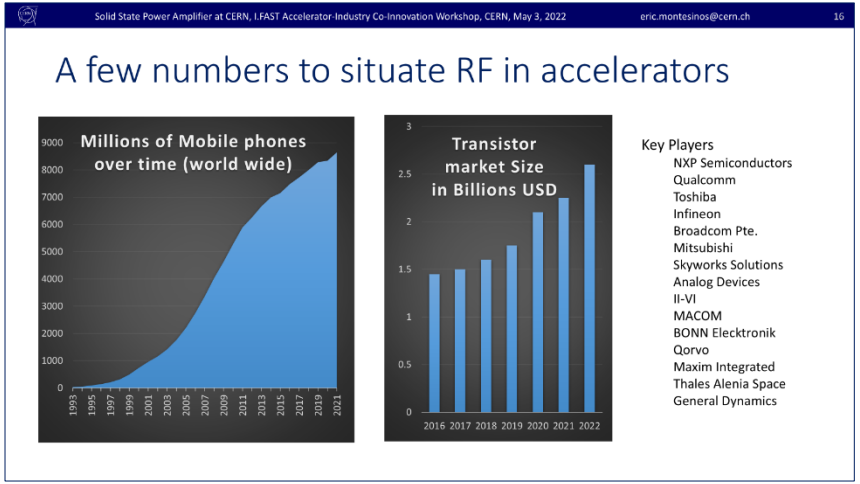
- The answer is yes of course, there is a future for SSPA at 400 MHz
- during the last CWRF2024 workshop, several colleagues have reported studies on GaN transistors, that will certainly replace LDMOS with a better power density and a better efficiency
- Combining systems have evolved over the last decade, allowing for a large number of inputs to one output in a single stage, that was a prerequisite for moving from SSA to SSPA
- So, for all about up to 100 kW, SSPA will certainly be an option to consider



Accelerator-Industry Co-Innovation workshop, CERN, May 2022, SSPA at CERN

Finally, is there a future for SSPA at 400 MHz?

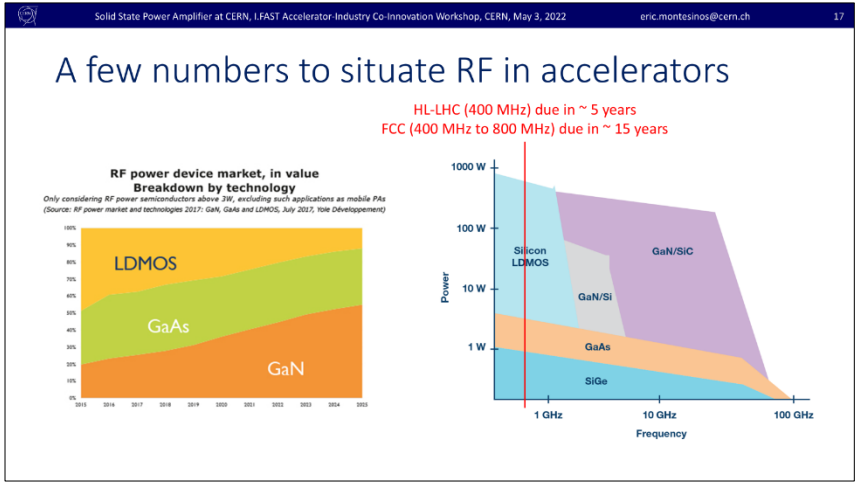
- The answer is yes of course, there is a future for SSPA at 400 MHz
- during the last CWRF2024 workshop, several colleagues have reported studies on GaN transistors, that will certainly replace LDMOS with a better power density and a better efficiency
- Combining systems have evolved over the last decade, allowing for a large number of inputs to one output in a single stage, that was a prerequisite for moving from SSA to SSPA
- So, for all about up to 100 kW, SSPA will certainly be an option to consider



Accelerator-Industry Co-Innovation workshop, CERN, May 2022, SSPA at CERN

Finally, is there a future for SSPA at 400 MHz?

- The answer is yes of course, there is a future for SSPA at 400 MHz
- during the last CWRF2024 workshop, several colleagues have reported studies on GaN transistors, that will certainly replace LDMOS with a better power density and a better efficiency
- Combining systems have evolved over the last decade, allowing for a large number of inputs to one output in a single stage, that was a prerequisite for moving from SSA to SSPA
- So, for all about up to 100 kW, SSPA will certainly be an option to consider



Accelerator-Industry Co-Innovation workshop, CERN, May 2022, SSPA at CERN

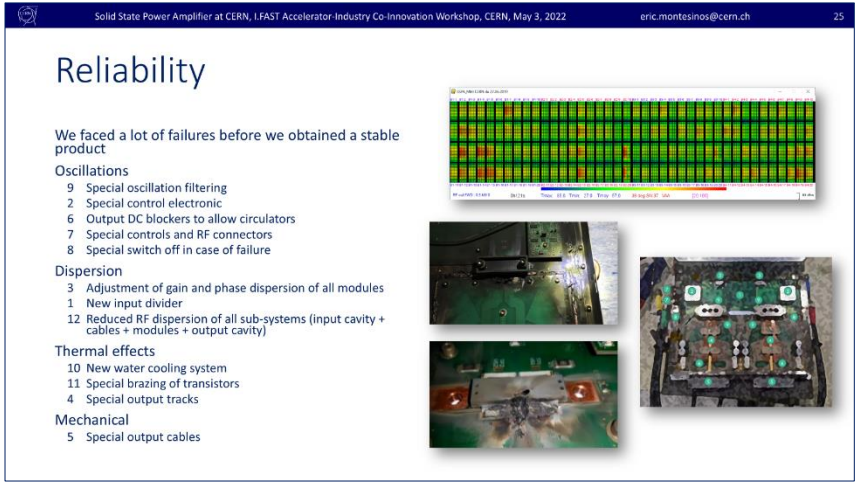
Finally, is there a future for SSPA at 400 MHz?

- The answer is yes of course, there is a future for SSPA at 400 MHz
- during the last CWRF2024 workshop, several colleagues have reported studies on GaN transistors, that will certainly replace LDMOS with a better power density and a better efficiency
- Combining systems have evolved over the last decade, allowing for a large number of inputs to one output in a single stage, that was a prerequisite for moving from SSA to SSPA
- So, for all about up to 100 kW, SSPA will certainly be an option to consider

Accelerator-Industry Co-Innovation workshop, CERN, May 2022, SSPA at CERN

Finally, is there a future for SSPA at 400 MHz?

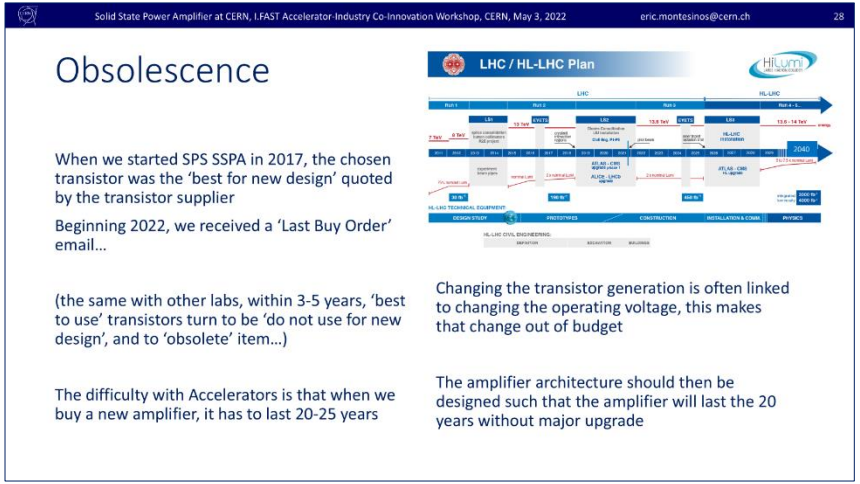
- But perhaps not yet there for all specific accelerator applications…
- Indeed, during the same last CWRF2024 workshop, several colleagues have reported breakages of transistors when fast transients occur
- This could also be one of the reasons of our failures with the SPS transistors system that we have
- If these transients are short enough, they could be damaging the transistors directly linked to the cavity, despite being protected with a circulator
- And there is a remaining question: obsolescence? Of course, one can think of buying a lot of transistors, but then, what about lifetime under storage?



Accelerator-Industry Co-Innovation workshop, CERN, May 2022, SSPA at CERN

Finally, is there a future for SSPA at 400 MHz?

- But perhaps not yet there for all specific accelerator applications
- Indeed, during the same last CWRF2024 workshop, several colleagues have reported breakages of transistors when fast transients occur
- This could also be one of the reasons of our failures with the SPS transistors system that we have
- If these transients are short enough, they could be damaging the transistors directly linked to the cavity, despite being protected with a circulator
- And there is a remaining question: obsolescence? Of course, one can think of buying a lot of transistors, but then, what about lifetime under storage?



[Accelerator-Industry Co-Innovation workshop, CERN, May 2022, SSPA at CERN]

Conclusion

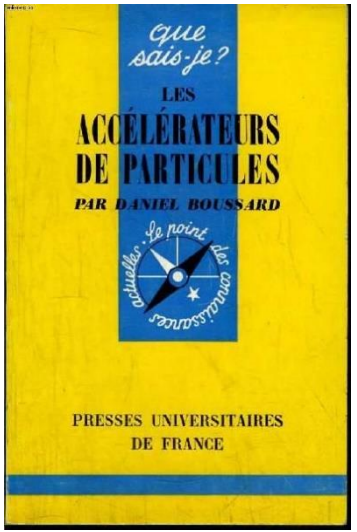
- The main lesson learnt is that real life tests are mandatory
- We are really very grateful to Rama and Ofelia that have defended the SPS tests and the SM18 tests
- These were so important for us to discover the many details that could make such a system failing

Not an exhaustive list

- feedthrough design
- spacers in 6-1/8 coaxial lines
- U-shape in coaxial lines
- need of circulators to avoid tube cavity and Crab cavity coupling effect
- conditioning process
- linearity of HPRF

Rama Calaga, a very special boss

- US Particule Accelerator School Prize, prestigious Prize
  - 1997, Daniel Boussard (Group Leader who hired me at CERN in 1992) that was saying (from how I remember it) ‘accelerators will be with superconducting cavities or will not be…’, incredibly visionary
  - (not in my line management, 2011, Jean Delayen)
  - 2022, Rama Calaga, with who I have the pleasure to work with! (on Crab… and on many other topics)



1968

My sincere thanks to

HL management, always positive, always supportive, never micromanaging, which was really appreciated, thank you very much to Oliver and Markus for instilling such a good spirit

All WP4 members and all CERN community that helped us with the many difficulties that occurred all along the last decade working on the Crab project

The members of my team that worked hard to fix the many troubles that occurred when moving from power point to real life

A special Thank You to Ofelia and Rama for their constant support

Simplicity is the ultimate sophistication

Leonardo Da Vinci (500+ years ago)

They did not know it was impossible, so they did it

Mark Twain