Engineering Specifications and Guidelines for Compliance with CERN Safety Rules

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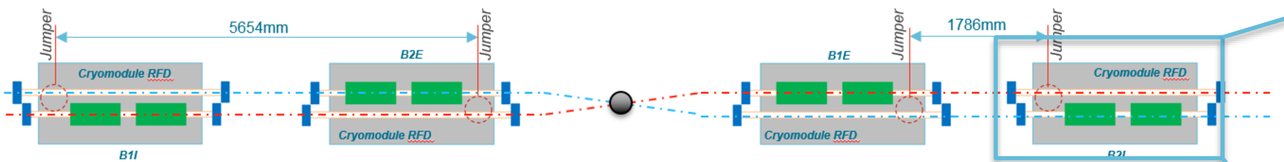
International Review of the Crab Cavity system design and production plan for the HL-LHC
June, 19th -21st 2019 (CERN)

Outline

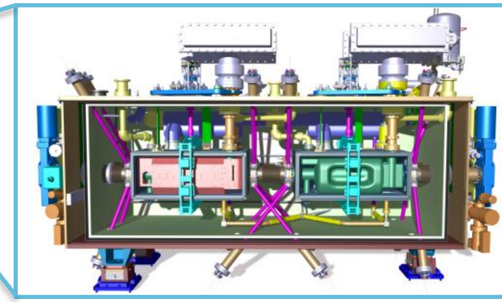
- Overall context: the cryomodule
- CERN rules for pressure/cryogenic equipment
- HiLumi structure for compliance with CERN Rules
- GSI-M-4/PED key words
  - Essential Safety Requirements (ESRs)
  - Technical documentation
- Strategy for cryomodule
  - Engineering specifications
  - Guidelines for compliance with CERN Safety Rules
- Jacketed cavity

Overall context: the cryomodule

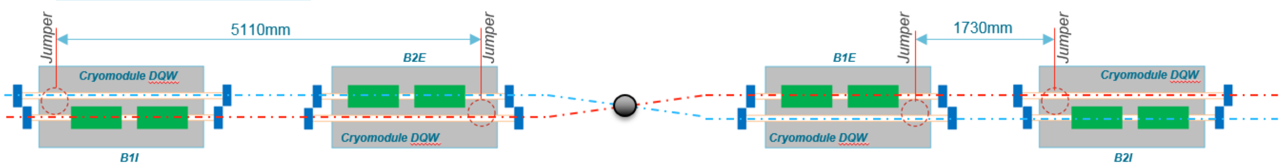
RFD at P1



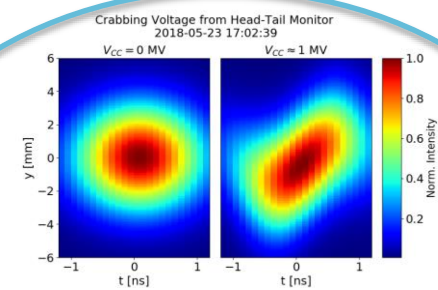
the installation in the LHC machine is out of the scope of this talk



DQW at P5



Actors:
- CERN
  - internal
  - outsourcing (industry)
- Canada contribution
  - internal
  - outsourcing (industry)
- UK contribution
  - internal
  - outsourcing (industry)
- US-AUP contribution
  - internal
  - outsourcing (industry)
- …



Functional, scientific, technical requirements

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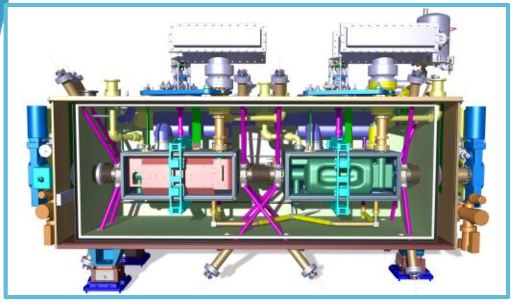
Compliance with CERN rules

Detailed system architecture for LHC



- RF systems and crab cavities (WP4)
  - RF superconducting crab cavities
    - LHC Cavities (ACF)
      - Cryomodule (ACFGA)
        - Cryomodule Assembly (ACF_A)
        - Cryomodule components (ACFCC)
          - Cryogenic circuits (ACFQC)
          - Thermal shield & MLI (ACFTS)
          - Vacuum Vessel (ACFVT)
          - Warm Magnetic shield (ACFWM)
          - Alignment Monitoring System (ACFAM)
          - Support and Alignment System (ACFAH)
          - RF internal lines (ACFRL)
        - Dressed cavities (ACFDC)
          - Bare cavities (ACFCA)
          - Helium vessel (ACFHT)
          - Tuning system (ACFTU)
          - HOM couplers (ACFHC)
          - Cold magnetic shield (ACFCM)
          - Pick-up antenna (ACFPU)
        - Instrumentation (ACFIS)
        - *Beam Axis (XYZ)*
          - Vacuum valves (VVG)
          - Cold –Warm Transitions (ACFVW)
          - Inter Cavity Chamber (ACFVC)
          - Beam Screen (ACFVS)
      - External supports (HACF)
      - General Tooling (ACF_T)
        - Forming Tooling (ACFFT)
        - Machining Tooling (ACFMT)
        - Welding Tooling (ACFWT)
        - Clean Room Tooling (ACFCT)
      - RF services (ACFSV)
        - LLRF & Fast Controls (ALL)
        - RF racks (AY)
        - Slow controls (AS)
        - Transmission lines (ACFWG)
        - Main coupler - FPC (ACFMC)
        - RF Pick-ups (APW)
        - Amplifiers (ACFA)
          - Amplifier Tetrode (ACFAA)
          - Amplifier IOT (ACFAB)
          - Amplifier Solid State (ACFAC)
          - Amplifier 2nd Generation IOT (ACFAD)
          - Amplifier 2nd Generation SSPA (ACFAE)

CERN Safety rules for mech. equip. applicable

- LHC
  - Harmonic system
    - 200 MHz
    - 800 MHz
  - Wide-band feedback system

Protecting devices

CERN rules for pressure/cryogenic equipment

SR-M Mechanical equipment

GSI-M-2 Standard pressure equipment → SSI-M-2-5 - Vacuum chambers and beam pipes

GSI-M-4 Cryogenic equipment

CE marking required, HSE could grant exception for "Cryogenic equipment liable to have major Safety implications:"

European law: Directive 2014/68/EU (PED)

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Applicable European harmonized standards →

Standard	Title
EN 764-5	Pressure equipment – Part 5: compliance and inspection documentation of materials
EN 764-7	Pressure equipment – Part 7: safety systems for unfired pressure vessels
EN 1251	Cryogenic vessels – Transportable vacuum insulated vessels of not more than 1000 litres volume
EN 1252	Cryogenic vessels – Materials
EN 1626	Cryogenic vessels – Valves for cryogenic service
EN 1797	Cryogenic vessels – Gas/material compatibility
EN 12213	Cryogenic vessels – Methods for performance evaluation of thermal insulation
EN 12300	Cryogenic vessels – Cleanliness for cryogenic service
EN 12434	Cryogenic vessels – Cryogenic flexible hoses
EN 13371	Cryogenic vessels – Couplings for cryogenic service
EN 13445	Unfired pressure vessels
EN 13458	Cryogenic vessels – Static vacuum insulated vessels
EN 13480	Metallic industrial piping
EN 13530	Cryogenic vessels – Large transportable vacuum insulated vessels
EN 13648	Cryogenic vessels – Safety devices for protection against excessive pressure
EN 14197	Cryogenic vessels – Static non-vacuum insulated vessels
EN 14398	Cryogenic vessels – Large transportable non-vacuum insulated vessels
EN 14917	Metal bellows expansion joints for pressure applications
EN ISO 4126	Safety devices for protection against excessive pressure

Compliance shall be granted

HiLumi structure for compliance with CERN Rules for Crab cryomodule

HiLumi Project

- Launch Safety Agreement (conventional aspects) EDMS 1827925
  → **General list** of Rules and Standards at project level:
  - CERN Rules and standards
  - European Rules and standards
- WP4 Crab cavities & RF
  - LLRF system
  - High-Power RF system
  - cryomodule — PS=2.1 bara (1.1 barg) — V=171 l /181 l
    - SSA System Safety Assessment for LHC cryomodule, EDMS 2010001
      →
      - List of risks (i.e. pressure, xray,…) **specific to cryomodule**
      - List of assumptions (i.e. MSI) **specific to cryomodule**
    - EDMS 2089140 Safety Request Form - Classification of DQW and RFD crab cryomodules in accordance with PED categories
      →
      - Cat I according to PED (Notified body not required)
      - exempt from CE-marking
      - liable to have Major Safety Implications (MSI)
      - the equipment shall meet the Essential Safety Requirements (ESRs) stated in PED 2014/68/EU
    - Memorandum on Safety checks expected for HSE-OHS Safety clearance

PED key words (valid also for GSI-M-4)

Directive PED 2014/68/EU
*"'**manufacturer**' : any natural or legal person who manufactures pressure equipment or an assembly or has such equipment or assembly designed or manufactured, and …uses it for his own purposes;"*
Article 6 *Obligations of manufacturers* *1… manufacturers shall ensure that (their pressure equipment or assemblies) have been designed and manufactured in accordance with the **essential safety requirements** set out in Annex I.*
Annex III Conformity assessment procedures *…* *1. Module A: (Internal production control)* *…* *2. Technical documentation* *The manufacturer shall establish the technical documentation. The **technical documentation** shall make it possible to assess the conformity of the pressure equipment to the relevant requirements, …*

CERN WP4 is manufacturer of the cryomodule

The cryomodule shall be designed and manufactured in accordance with the essential safety requirements.

CERN shall establish the technical documentation

GSI-M-4/PED key words - encore

Essential Safety Requirements (ESRs)

ESRs: a mix of
- Design requirements
- Manufacturing requirements
- Inspection requirements
- Operational requirements

often interconnected

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- CERN specificities (i.e. LHC installation)
- Crab project specificities (i.e. unconventional materials and joining technics)

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- CERN-WP4 drives the detailed design of the cryomodule
- CERN-WP4 establishes the actions needed to comply with the ESRs

Technical documentation for Crab cryomodules

Manufacturer shall demonstrate compliance →

Technical documentation / SAFETY FILE
- Risk analysis
- Technical file
- Instruction manual
- Tests report
- Acceptance report
- Declaration of commissioning
- Periodic inspection schedule and reports
- Maintenance operation schedule and reports
- Documentation related to repairs
- Dismantling instructions
- Identity of the owning organic unit

Technical file ←
- CERN-WP4
- Collaborating Entities
- Subcontractors (CERN or Collaborating Entities)

Acceptance report / Declaration of commissioning ← CERN HSE

Periodic inspection … Identity of the owning organic unit ← CERN WP4

EDMS and MTF are mandatory

So…

- Functional requirements
- CERN rules
- Technical requirements
- ESRs (Safety requirements)
- LHC compatibility
- Safety file (technical documentation for compliance)
- CERN Procedures
- Different actors
- Acceptance criteria
- Quality
- Traceability
- Manufacturer is the responsible for safety
- …

Strategy for Crab Cryomodule

CONTENT:
- Refers. to the corresponding Engineering Specification
- Demonstration of compliance, ESR by ESR

Intended for CERN internal use and for HSE, available for consultation

AUTHOR:
CERN-WP4

2 **main** documents for the cryomodule
- engineering specification
- guideline for compliance with CERN safety rule

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2 **main** documents per relevant component:
- engineering specification
- guideline for compliance with CERN safety rule

Respect of engineering specification
=
compliance with CERN safety Rules

CONTENT
- to catch the HL-LHC needs (functional and technical requirements)
- to comply with ESRs
- List of required documentation

AUTHOR:
CERN-WP4 involving Collaborating Entities

Ad-hoc agreements with Collaborating Entities based on described strategy / documentation can be discussed

Crab cryomodules

Cryomodule:

- EDMS 2043014 Engineering specification

- EDMS 2043016 Guideline for compliance with CERN safety rule

Name	ID code	Engineering Specification [EDMS number]	Guideline for compliance with CERN Safety Requirements [EDMS number]
Dressed cavities, including HOMs (ACFHC), Pick-up antennas (ACFPU), Cold magnetic shield (ACFCM)	ACFDC, including ACFHC, ACFPU, ACFCM	1389669	2058183
Cryogenic circuits	ACFQC	2093032	2101920
Thermal shield	ACFTS	2101922	2101923
MLI	ACFTS	2144140	Not needed
Vacuum vessel	ACFVT	2101924	2101925
Warm Magnetic shield	ACFWM	2101926	Not present
Alignment monitoring system	ACFAM	Not present	Not present
Support and alignment system	ACFAH	Not present	Not present
RF internal lines	ACFRL	Not present	Not present
Instrumentation	ACFIS	2145054	Not present
Vacuum Valves (beam line)	VVG (????)	2101929	2101930
Cold-Warm transition (beam line) + Intercavity Chamber	ACFVW + ACFVC	2101931	2101932
Fundamental Power Coupler	ACFMC	2101934	2101936
Tuning system	ACFTU	2101938	2101939
Safety protecting devices	????	2101940	2101943
Beam screen	ACFVS	2101950	2101951

Example for Engineering Specification

For the dressed cavities

4.2.7.2 *Qualifications (prior to production)*

4.2.7.3 *Electron beam welds: acceptance criteria for non-destructive tests*

4.2.7.4 *Electron beam welds: special requirements for acceptance criteria for joints on RF surfaces*

The following requirements are valid for qualification tests and for tests during production.

4.2.7.5 *Extent of non-destructive tests of electron beam welds (qualification)*

4.3.3 *Non-destructive tests of Nb and Nb55Ti welded joints during production*

The same requirements apply for Nb and Nb55Ti welded joints.

Production procedure:

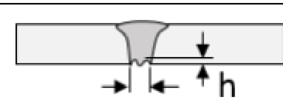
- As per qualified joints

Production tests:

- Visual Testing (VT): a 100 % visual inspection of welds is required (external surfaces and internal surfaces wherever possible):
  - Before welding: surface inspection is intended to detect any possible defects, ensuring that the plates do not have burrs or are unevenly cut (thus interfering with the welding process), verifying the tack welds, checking that the joint design complies with the applicable drawing and specifications.
  - After welding: the visual inspection shall be carried out prior to any other non-destructive test and any defect found will be repaired in compliance with the specified acceptance criteria.
- Radiographic Testing (RT): X-ray inspection of 25% of the total "circumferential" seams and 100% of the total "longitudinal" seams, according to §4.2.7. Note that corner joints and areas of high bending stress shall be treated as longitudinal seams.[3]
- 100% Helium leak test according to Section 4.3.5.

Acceptance criteria during production as specified in §4.2.7.

Repair of defective welds shall be discussed and agreed between all parties.

515	concavity		mm
5013	Shrinkage groove		Not acceptable

Acceptance Criteria included!

Example for Guideline

For the dressed cavities

List of Essential safety requirements from GSI-M-4 and PED

EDMS NO.	REV.	VALIDITY
2058183	0.2	DRAFT

REFERENCE : xxxxx

<table>
<tr><th>Sect.</th><th>Sub Sect.</th><th>GSI-M-4 Safety Requirement</th><th>Applicable document(s)/sections</th><th>Comments/Observations</th><th>Safety file document(s)</th></tr>
<tr><td></td><td></td><td>An item of cryogenic equipment shall not be operated beyond the values specified in the instruction manual, nor if a malfunction is detected, nor if the date of the next periodic inspection or of the requalification test has passed.</td><td></td><td></td><td></td></tr>
<tr><td></td><td>2.7</td><td>Periodic inspections
All items of pressurised cryogenic equipment, as well as safety accessories, shall be periodically inspected and
requalified as follows:
<table>
<tr><th colspan="2">Safety accessories</th><th colspan="3">Periodic inspections</th></tr>
<tr><th></th><th></th><th>Types of test</th><th>Periodicity</th><th>Performed by</th></tr>
<tr><td rowspan="2">Safety valves</td><td>Safety valves for inert fluids, excluding oxidising fluid</td><td rowspan="2">Functional test :
Test-bench verification of :
• set pressure;
• leak tightness.</td><td>5 years.</td><td rowspan="2">The HSE Unit at the request of the owning organic unit.</td></tr>
<tr><td>Other cases:
• valves whose function can be changed by internal / external influences;
• valves operating with flammable or oxidising cryogenic fluids;
• valves protecting cryogenic equipment liable to have major Safety implications;
• pilot-operated valves.</td><td>3 years.</td></tr>
<tr><td colspan="2">Rupture discs</td><td colspan="2">No periodic inspection required, but rupture disc must be replaced at intervals defined by the manufacturer or when it shows signs of damage, and after 10 years at the latest.</td><td>The owning organic unit.</td></tr>
</table>
<table>
<tr><th rowspan="2">Pressurised cryogenic equipment</th><th colspan="3">Periodic inspections</th><th colspan="3">Requalification</th></tr>
<tr><th>Types of inspections</th><th>At intervals of</th><th>Performed by</th><th>Types of test</th><th>At intervals of</th><th>Performed by</th></tr>
<tr><td>Fixed</td><td rowspan="3">External visual inspection, including safety accessories.</td><td rowspan="2">5 years.</td><td rowspan="3">The HSE Unit at the request of the owning organic unit.</td><td colspan="3">Not applicable.</td></tr>
<tr><td>Transportable</td><td>Pressure and leak tightness test at 90% of the maximum allowable pressure PS.</td><td>10 years.</td><td>Notified body appointed by the HSE Unit.</td></tr>
<tr><td>Liable to have major Safety implications</td><td>3 years.</td><td colspan="3">Not applicable.</td></tr>
</table>
The visual inspection consists of a general check of the installation conditions and a check that the item of pressured cryogenic equipment is in an identical state to that defined by the manufacturer for all</td><td></td><td>The owner organic unit will be responsible for the maintenance.

Periodic inspection can be performed only at the cryomodule level.
It is impossible to inspect all the external surface of the pressure vessel (no access to the beam vacuum).</td><td>Cryomodule documentation</td></tr>
</table>

Template EDMS No.: 1311288

Jacketed cavity

Actions for compliance / Specs / Develop. strategies

Material
- Certificate 3.1 + PMA from Desy
- Extensive test campaign (effect of forming, effect of heat treatment, tests at cold, Charpy tests planned)
- Extensive verification of the supplied material

Design
- Elastic – plastic calculation (most advanced available tool according to Eu harmonized standards)

Manufacturing
- Forming simulation matching very well the real cavity (knowledge of hardened areas)
- Extensive test campaign on e-beam joints, brazed joints Nb-st.steel, brazed joints Ti-st.steel, bolted joints
- Qualification according to specification (with detailed report on mechanical properties) / Notified Body required for series
- Extensive metrology analyses on prototypes

Inspection and testing
- Extension of NDTs well defined (25% minimum)
- Selection of most stressed joints to test

Proof test
- Baseline: proof test maintained at 1.25xPS for DQW and RFD (difference form SPS tests)

Difficulties encountered

Materials
- Definition of Yield strength: evolution and unexpected surprises, during series production
- Huge amount of tests required (not planned)

Design
- Elastic – plastic calculation (some plasticity allowed for Standards, plasticity to reduce for frequency performances)
- Not enormous margin (thin walls, complex shape)
- Analyses with frequency shift difficult to benchmark

Manufacturing
- Qualifications of joints in parallel with the design and manufacturing for prototype
- Difficult interactions with subcontractors (all the steps of manufacturing shall be accounted for in the qualification)
- Thickness reduction on real cavity (tolerances on specification drawing)

Inspection and testing
- Not 100% for the series

Proof test
- RFD is still in development

Conclusions

- Crab cryomodule: CAT 1 equipment according to PED, exempted form CE marking, “equipment liable to have major safety implications”

- CERN WP4 is manufacturer (PED meaning) of the cryomodule: CERN WP4 is responsible for compliance of the cryomodule with CERN rules and with PED ESRs

- Functional + technical + safety requirements

  => Strategy: 2 driving documents: “Engineering Specification” + “Guideline for compliance with CERN safety rules”

  for cryomodule and for relevant components

- Presumption of compliance with CERN rules if strategy is followed (= if engineering specification is respected)

- Jacketed cavity: nice object, with a lot of technics (and some difficulties…) behind!

Thank you…

- Back-up slides: LHC crab cryomodules

Few technical considerations

- Very low risk components: each component is treated independently
- Assessment of the assembly according to PED (*ANNEX 1: 2.3. , 2.8. , 2.9.)*
- **<u>Notified body not required</u>**

Table 4 – main components of the cryogenic lines

Component		Maximum Allowable Pressure (PS)		Volume		Biggest diameter		Fluid	PED cat.
				DQW[1]	RFD (LHC)	DQW[2]	RFD		
		[bara]	[barg]	[l]	[l]	[mm]	[mm]		
Dressed cavity	(ACFDC)	2.1	1.1	2x59 (2nd pick-up added)	2x66	NA		Liquid He (1.9 K)	
Upper cryo. line	(ACFQC)	2.1	1.1	31 => 35	35 to 45	103 mm		Liquid He (1.9 K)	
Bottom cryo. line	(ACFQC)	2.1	1.1	5	4	28 mm		Liquid He (1.9 K)	
HOM cooling line	(ACFHC)	2.1	1.1	Included in the bottom c. l.	Included in the bottom c. l.	28 mm		Liquid He (1.9 K)	
*TOTAL 1.9K**		*2.1*	*1.1*	*154*	*171/181*			*Liquid He (1.9 K)*	*1*
Beam screen c. l.	(ACFVS)	20	19			As per RFD	8 mm (jumper) 4.76 pipe	Gas He (20K)	SEP
FPC c. l.	(ACFMC)	7	6			40 mm	As per DQW	Water (300 K)	SEP
Thermal shield line	(ACFTS)	25	24			15.2 mm	15.2	Gas He (30/40 K inlet + 60 K outlet maxi)	SEP
Cold-warm transition	(ACFVW)	NA, passive cooling	NA, passive cooling						NA
Vacuum vessel	(ACFVT)	1.5	0.5	Not rel.	Not rel.	NA	NA	Insulation vacuum	NA

*the 2 K volume until the jumper is considered as unique volume for the definition of the category according to PED [5].

LHC doc: status and tentative deadlines

	Status	Deadline
SSA System Safety Assessment	Draft (EDMS 2010001), circulated for feedback	

	Status of the End Spec	Status of the Guidelines for Safety	Deadline
Cryomodule	Draft in work, shared with Canada and UK	Draft	
Dressed cavities	**Approved by management, not yet Released in EDMS**	Engineering check	
Cryogenic lines	Draft	Not started	
Warm magnetic shield	Advanced draft, shared with Canada and UK	Not neded	
Thermal Shield	Waiting for decision	Not started	
Vacuum vessel	Advanced draft, shared with Canada and UK	Not started	
Main coupler	Not started	Not started	

	Status	Deadline
Protection device	Started (calculation on-going)	

Strength assessment (LHC) - 1

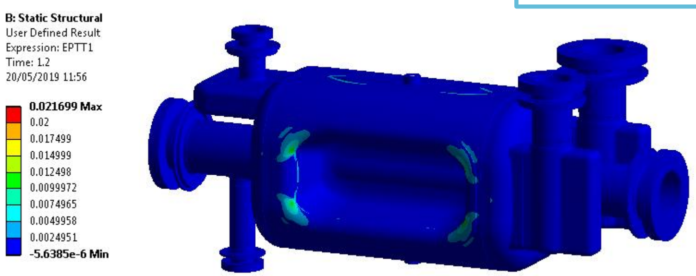
- According to EN 13445-3 Direct Route
- Material model as described in the standard: elastic-perfectly plastic
- Design checks:
  - Gross plastic deformation
  - Progressive plastic deformation
  - Instability

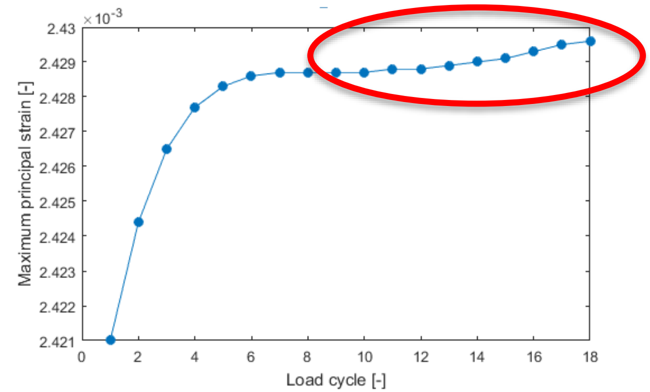
Assessment	Material Model	Loads	Others	Acceptability
Gross Plastic Deformation EN-13445-3, B.8.2 [2]	Elastic perfectly plastic $RM = R_{p0.2}$ $RM_d = \frac{RM}{\mathbf{1.5}}\frac{\sqrt{3}}{2}$	$\gamma_R = 1.2$ P = 2.16 bar a = 1.2 g	Large deflection OFF	Maximum principal strain below 5 %
Progressive Plastic Deformation (Ratcheting) EN-13445-3, B.8.3 [2]	Elastic perfectly plastic $RM = R_{p0.2}$ $RM_d = \frac{RM}{\mathbf{1.5}}$	$\gamma_R = 1$ P = 1.8 bar $a = g$	Large deflection OFF (First order theory, B.8.3.1)	1. Principal strain below 5 % after number of cycles specified for the load case or 2. Shakedown to elastic behaviour
Instability (Buckling) EN-13445-3, B.8.4 [2]	Elastic perfectly plastic $RM = R_{p0.2}$ $RM_d = RM$ (as per B.8.4.4b)	$\gamma_R = 1.2$ (safety factor of actions as per B.8.4.4a) $\gamma_R = 1.5$ (partial safety factor as per B.8.4.4c) Thus: $\gamma_R = 1.2 * 1.5 = 1.8$ (Minimum total load multiplier)	Large deflection ON in the non-linear buckling	Convergence reached with a load multiplier of, at least, 1.8 and maximum principal strain below 5 %

Strength assessment (LHC) - 2

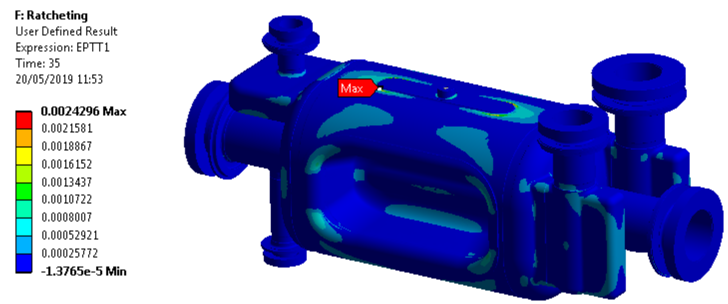
EN 13445-3 – Design by Analysis / Direct Route

Gross plastic deformation

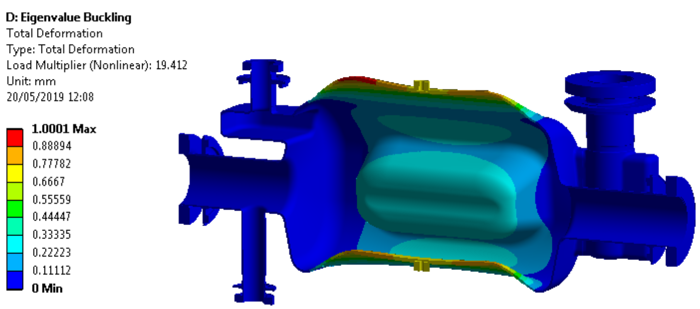


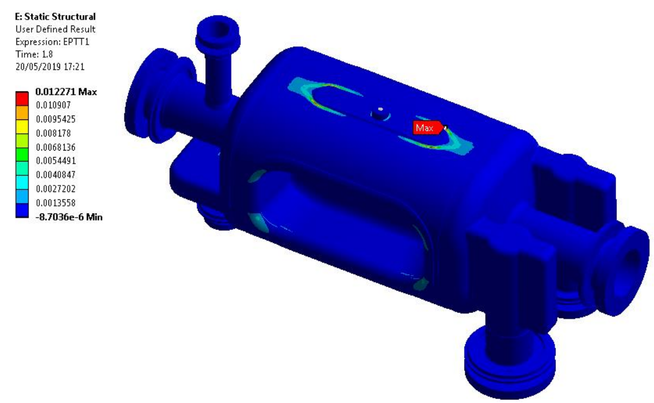


Progressive plastic deformation



Instability





HiLumi HL-LHC PROJECT

Risk analysis

EDMS 2142606 : work in progress

Based on EDMS 1758727, done for the SPS test prototype

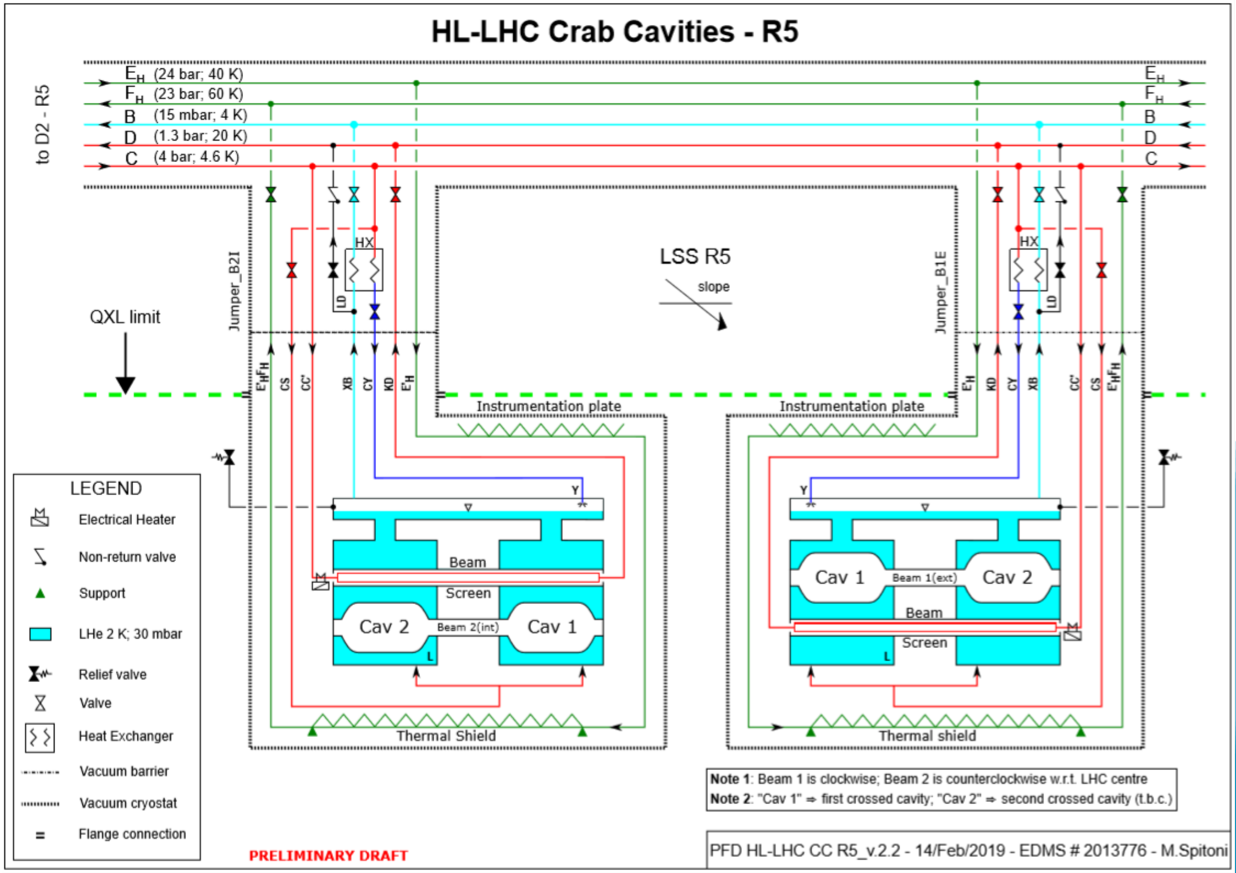
Cryogenic circuits and safety protection (LHC)

WORK IN PROGRESS

Individual safety devices for each cryomodule (sized according to according to ISO-4126):

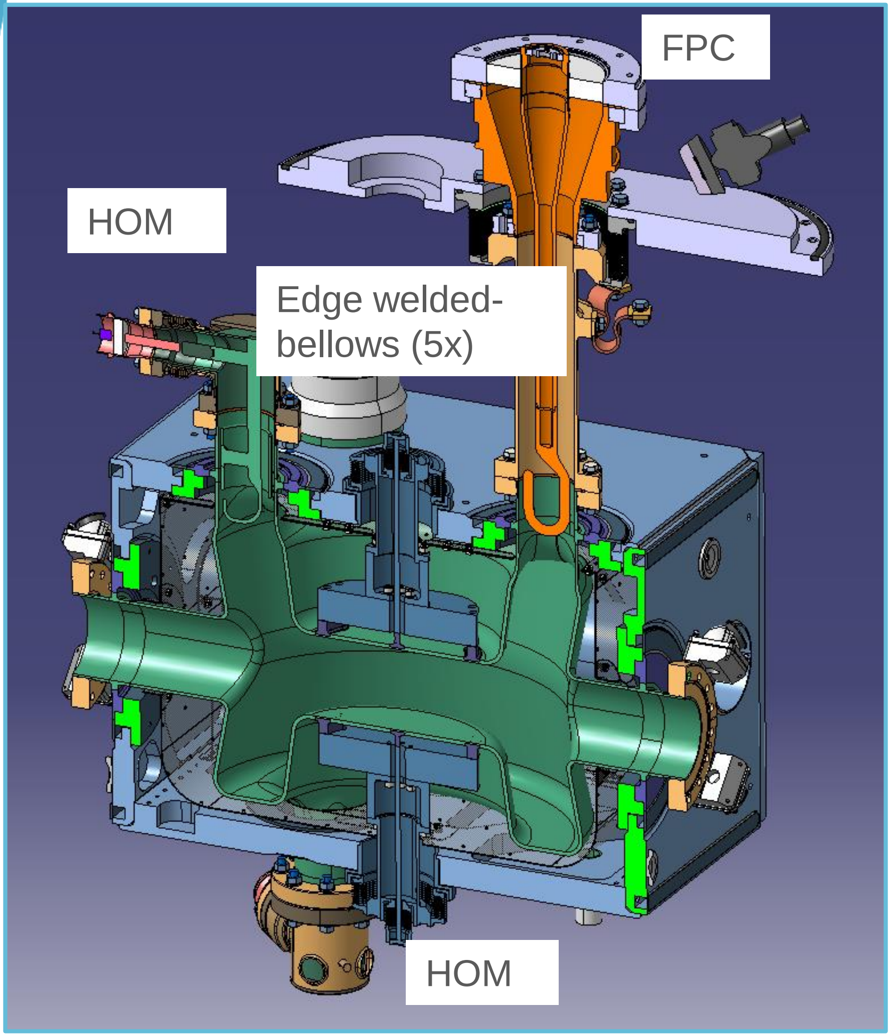
- Helium guarded operating valve at 1.8 bara
- Dedicated rupture disc at 2.1 bara, sized to cover beam vacuum break
- Vacuum vessel protection (vacuum barrier in the jumper) : disk at 1.05 bara

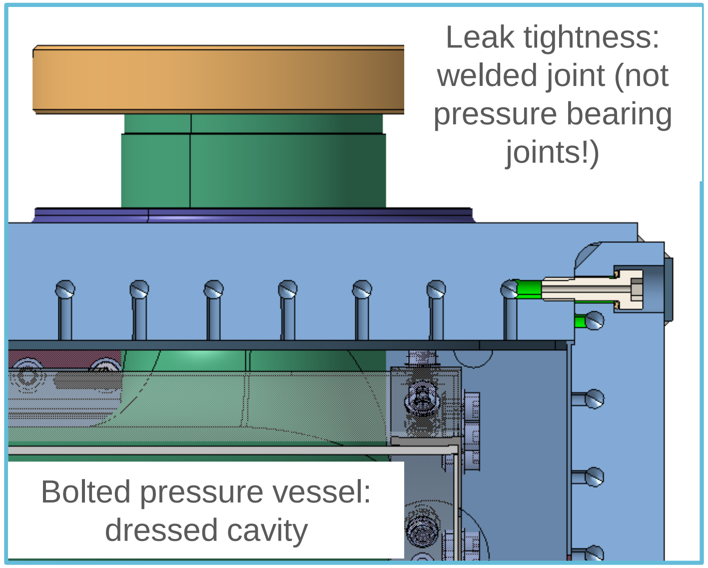
Beam screen circuits and thermal shield circuits protected OUTSIDE the cryomodule

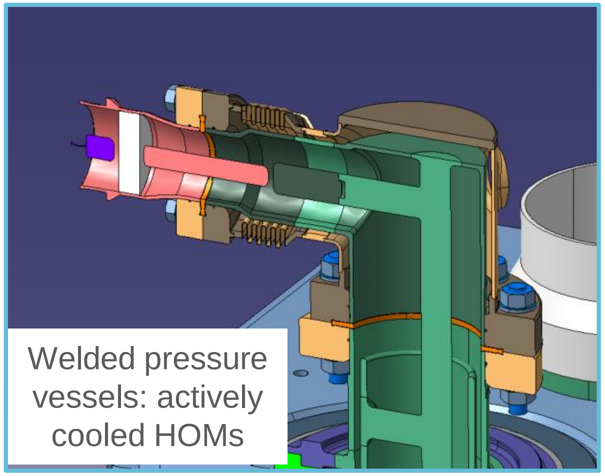


Courtesy of M. Sisti / M. Spitoni (IN WORK)

Pressure bearing components (DQW)







Material tests

Materials:

- Ti Gr. 2, Ti Gr. 5, high purity Nb and 55Ti-45Nb not considered in the Harmonised Standards
- conformity with the ESRs required
- compliance with PED would require PMA
  - For Ti -> PMA (DESY) + material certificate + internal tests (EDMS 1538192)
  - For Nb and NbTi -> PMA on similar material (DESY XFEL) -> material certificate + internal tests (EDMS 1722302 for Nb and EDMS 1493400 for NbTi)

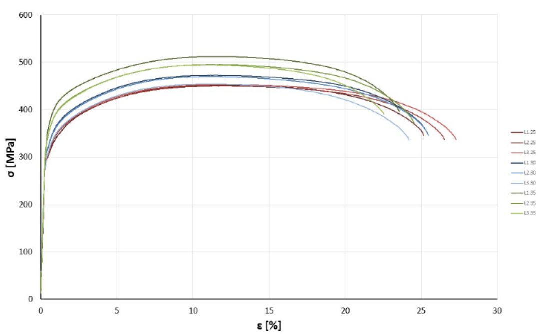


Figure 3: Stress-strain curves of titanium grade 2 at RT

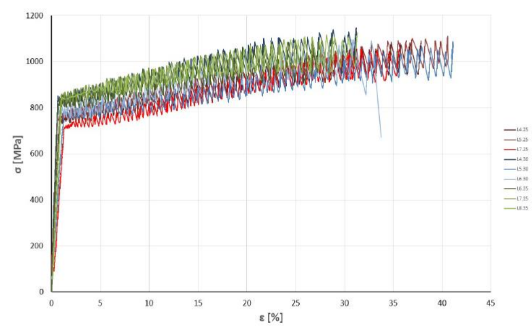


Figure 4: Stress-strain curves of titanium grade 2 at 4 K

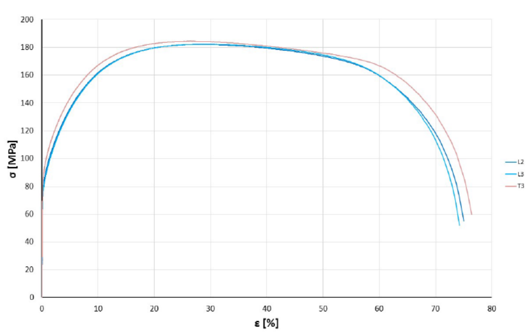


Figure 1: Stress-strain curves for RT tensile tests. Samples that broke outside of measured length are marked with an asterisk.

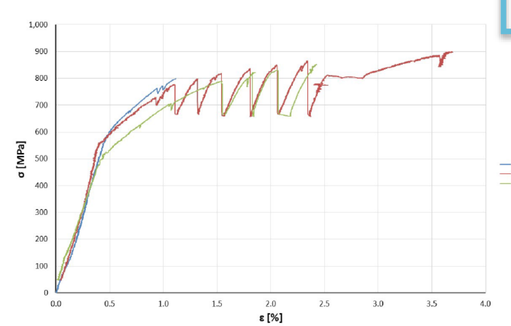
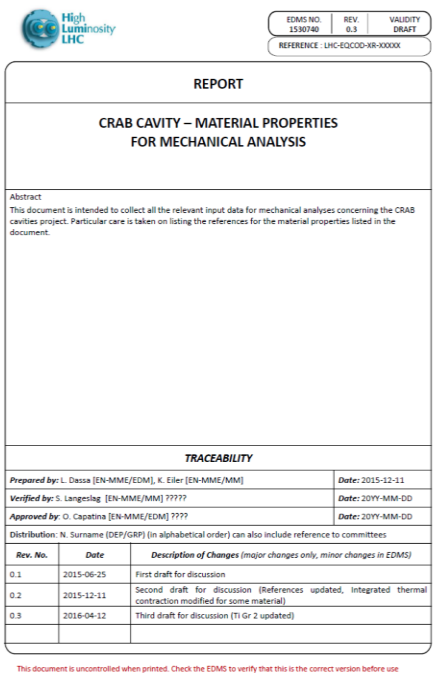


Figure 2: Stress-strain curves for tensile tests at 4 K



High Luminosity LHC

EDMS NO.	REV.	VALIDITY
1530740	0.3	DRAFT

REFERENCE : LHC-EQCOD-XR-XXXXX

REPORT

CRAB CAVITY – MATERIAL PROPERTIES FOR MECHANICAL ANALYSIS

Abstract

This document is intended to collect all the relevant input data for mechanical analyses concerning the CRAB cavities project. Particular care is taken on listing the references for the material properties listed in the document.

TRACEABILITY

Prepared by: L. Dassa [EN-MME/EDM], K. Eiler [EN-MME/MM]	***Date:*** 2015-12-11
Verified by: S. Langeslag [EN-MME/MM] ?????	***Date:*** 20YY-MM-DD
Approved by: O. Capatina [EN-MME/EDM] ????	***Date:*** 20YY-MM-DD
Distribution: N. Surname (DEP/GRP) (in alphabetical order) can also include reference to committees	

Rev. No.	***Date***	***Description of Changes** (major changes only, minor changes in EDMS)*
0.1	2015-06-25	First draft for discussion
0.2	2015-12-11	Second draft for discussion (References updated, Integrated thermal contraction modified for some material)
0.3	2016-04-12	Third draft for discussion (Ti Gr 2 updated)

This document is uncontrolled when printed. Check the EDMS to verify that this is the correct version before use

Material tests (2)

Tests:

- To verify compliance of the supplied material with CERN specification (i.e. Material for DQW production at RI): some problems have been encountered with the Nb supply from Ningxia for the pre-series cavity
- To evaluate the effect of the forming process on Nb properties
- To evaluate the effect of het treatment for hydrogen disease on Nb
- To evaluate the performances of joints
- To improve knowledge of material behavior at cryogenic properties (ductility)

Test on new brazed joints

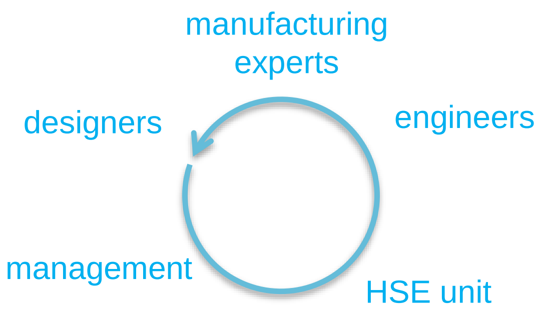
Ongoing tests to validate the utilization of brazed joint between titanium and stainless steel

- Back-up slides: SPS test cryomodules

The SPS cryomodule

- prototype approach
- in house manufacturing and assembly

- materials not considered in harmonised standards
- unconventional configuration (bolted vessel, edge-welded bellows…)
- proof test with high risk to impact on RF performances



Crab SPS prototype cryomodule

- According to PED Annex 2, the cryomodule belongs to risk category I
- equipment liable to have major Safety implications (GSI-M-4)
- exempted from EC-marking
- **the equipment shall meet the Essential Safety Requirements (ESRs) stated PED 97/23/EC.**

- EU harmonized standards used whenever possible
- If not possible, ASME Section VIII Div. 2 + compensatory measures in view of compliance with the ESRs of the PED.

- Difficulties in the definition of the PS (1.8 bara VS 2.1 bara) and in the sizing of the protecting devices
- Hydrostatic proof test will be replaced by alternative methods /

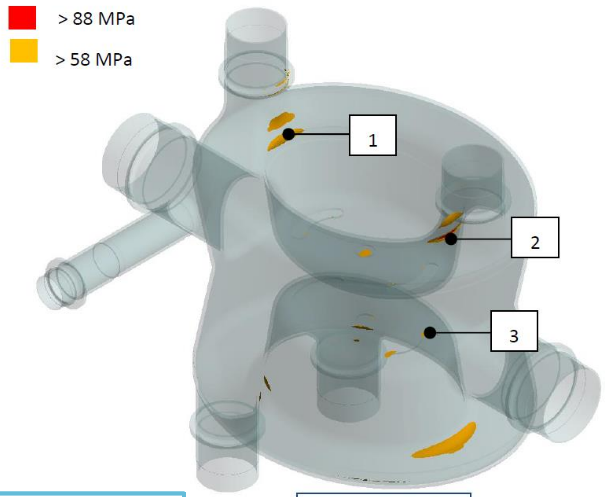
Review and discussion with HSE unit (EDMS 1494776 + EDMS 1541969)

Valid only for SPS cryomodule

Strength assessment (SPS tests) - 1

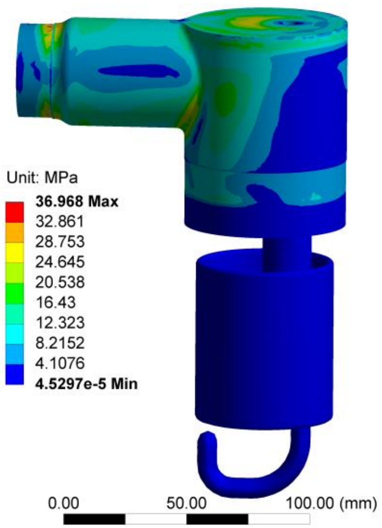
- Loads:
  - PS = 1.8 bar abs
  - T= 300 K
  - Static pre-tuning = 0.2 mm

    Loads not considered:
  - Dynamic fine tuning (only at cold)
- Other remarks
  - Fatigue life: not applicable (cycles < 500)
  - Pressure test: derogation

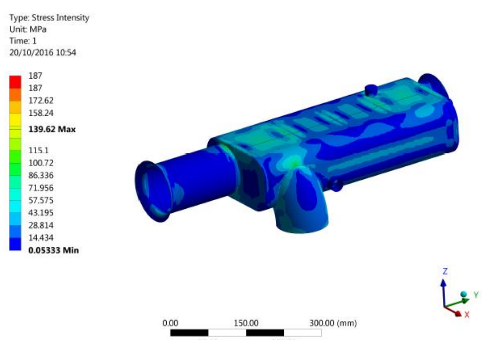


Pressure + tuning

EN 13445-3 – Design by Analysis / Method based on stress categories



- Cavity, bolts, weld assessment -> EDMS 1549819
- HOM assessment -> EDMS 1433086
- Vessel assessment -> EDMS 1712011
- Biphase line assessment -> EDMS 1727787



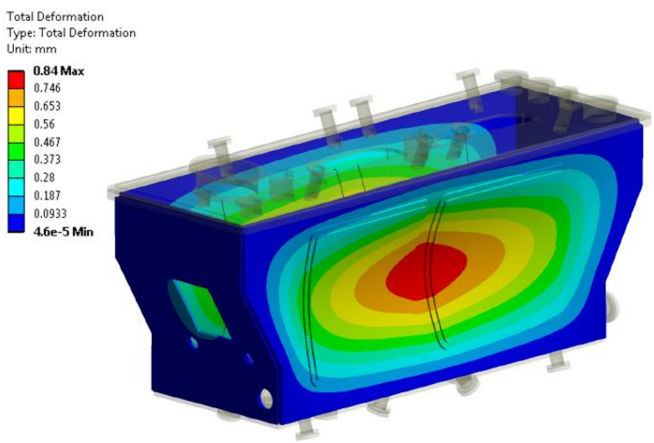
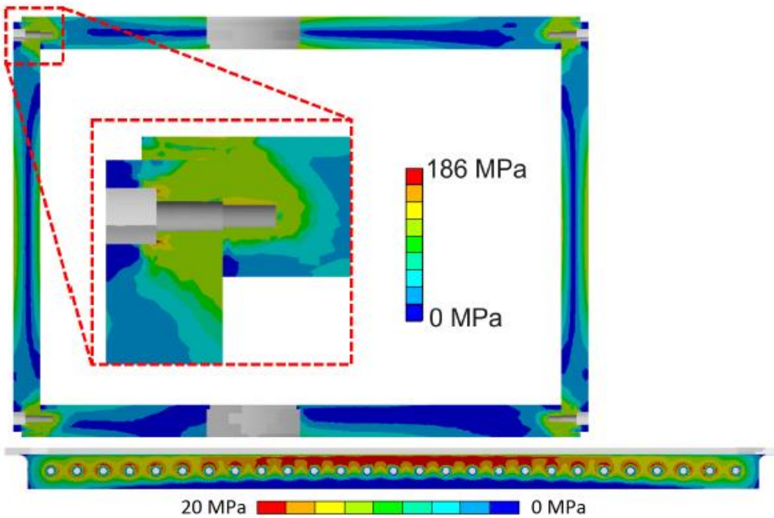


Figure 8 – Deformation of the vacuum vessel.

Strength assessment (SPS tests) - 2



Cavities:

- ANSYS stress intensity > 50 MPa
- analysis of linearized stress according to EN13445-3 ✓

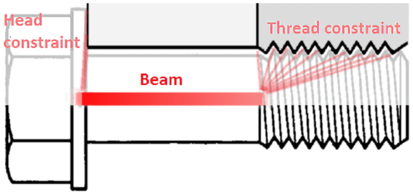
Courtesy of C. Zanoni, 11/11/2015 - SPS Cryo-module Engineering Review

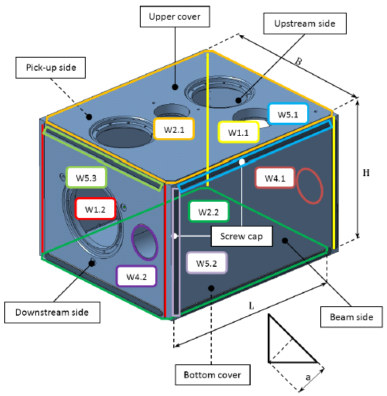
Strength assessment (SPS tests) - 3

Strength assessment: bolts and welds

Bolt model:

- beam
- extremities constrained
- cross section properties according to VDI 2230:2
- length = distance between head and first thread in the plate





Welds:

- no fatigue
- average stress on each weld assessed

assessment: results (bolts)

Name	Units	Bolts	Bolts + Welds
Preload	[N]	4500	4500
Max axial force	[N]	4650	4655
Max bending moment	[Nmm]	3430	1630
Max shear force	[N]	525	245
Equivalent stress	[MPa]	620	480
Proof stress	[MPa]	830	830
Safety factor	-	1.34	1.74

The friction between plates is not taken into account (very conservative assumption)

Courtesy of C. Zanoni, 11/11/2015 - SPS Cryo-module Engineering Review

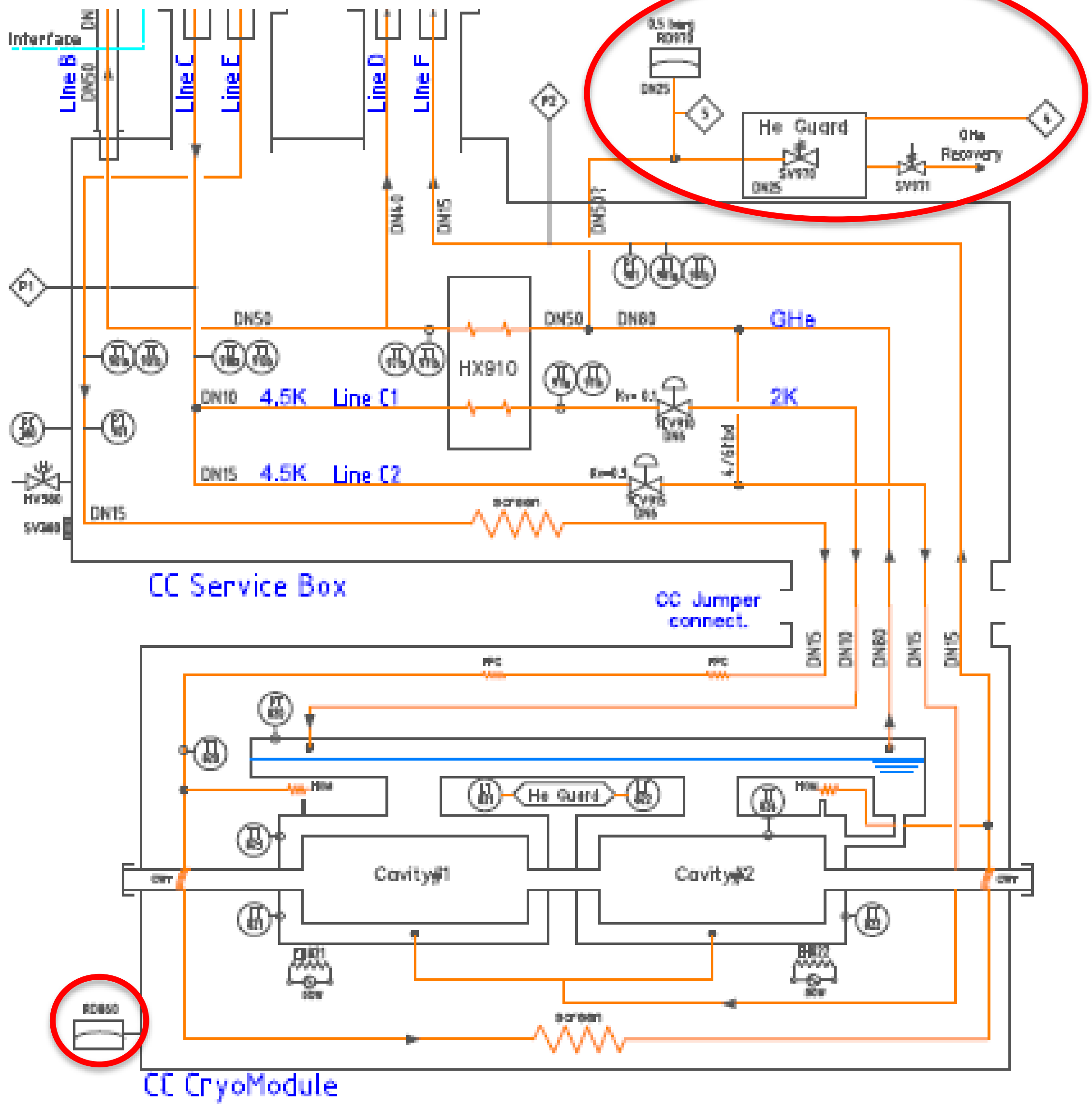
Strength assessment (SPS tests) - 4

Strength assessment: results (welds)

Weld	Material	$R_{p0.2}$ [MPa]	Stress [MPa]	Allowable stress (= $0.7 \cdot R_{p0.2}/1.5$) [MPa]	Safety factor
W1.1	Ti gr. 2	280	22.10	131	5.91
W1.2			26.74		4.89
W2.1			34.33		3.81
W2.2			14.89		8.78
W3.1.1			26.66		4.90
W3.1.2			24.17		5.41
W3.1.3			23.85		5.48
W3.1.4			26.57		4.92
W3.2.1			33.10		3.95
W3.2.2			33.89		3.86
W4.1			12.63		10.35
W4.2			11.90		10.98
W5.1			11.83		11.05
W5.2			10.60		12.33
W5.3			11.79		11.08
W6.1.1			15.33		8.55
W6.1.2			13.90		9.42
W6.1.3			13.94		9.39
W6.1.4			14.06		9.32
W6.2.1			14.37		9.12
W6.2.2			14.46		9.06

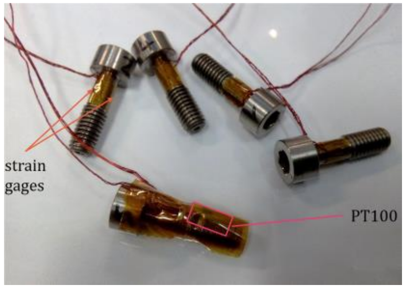
Courtesy of C. Zanoni, 11/11/2015 - SPS Cryo-module Engineering Review

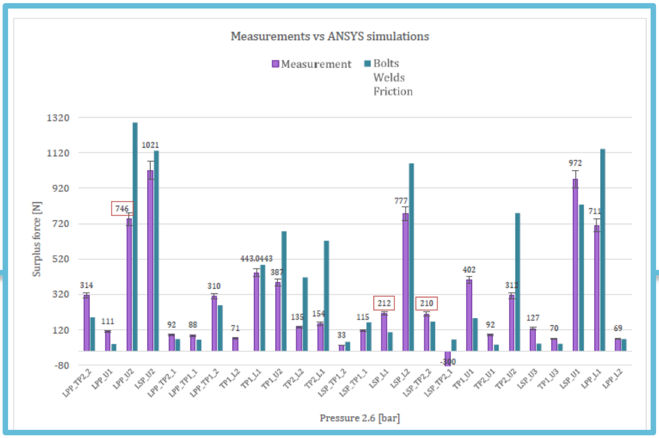
Cryog. circuits and safety protection (SPS tests)



Courtesy of K. Brodzinski, Crab cavities SPS Test Stand Safety Review – CERN – 9 November 2016

Preliminary tests on components





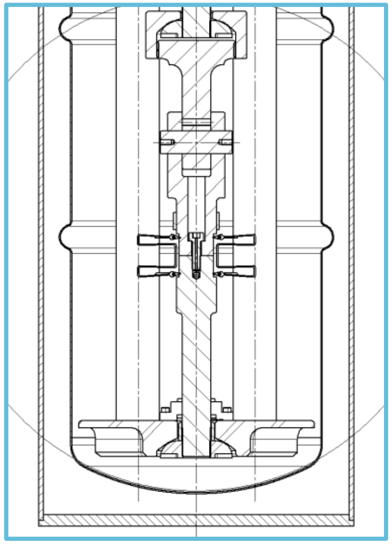
Prototype: goal

1. confirm the tank structural **resistance**
2. verify the **geometry** is good for assembling/welding
3. test the **assembly** procedure
4. test **welding** procedure and welds quality
5. verify **leak tightness** along a load cycle representative of real conditions
6. verify bolts do not loose **preload** during a load cycle
7. **validate FE** model with an estimate of the force on bolts, stress/strain and displacement on few tank locations

Report EDMS 1721359

Courtesy of C. Zanoni, 11/11/2015 - SPS Cryo-module Engineering Review

11 November 2015 13 / 20



Bolted He vessel = unusual pressure vessel

Report EDMS 1705731

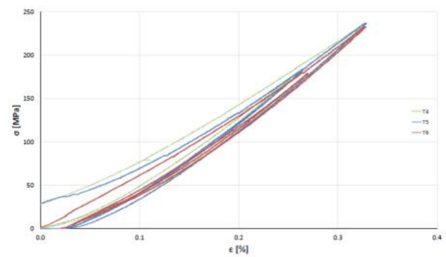


Figure 2: Stress-strain curves for RT tensile tests

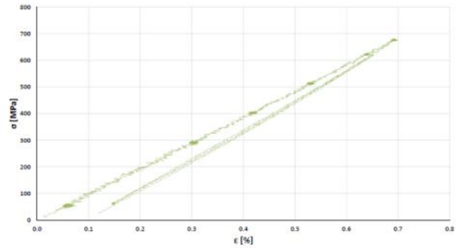
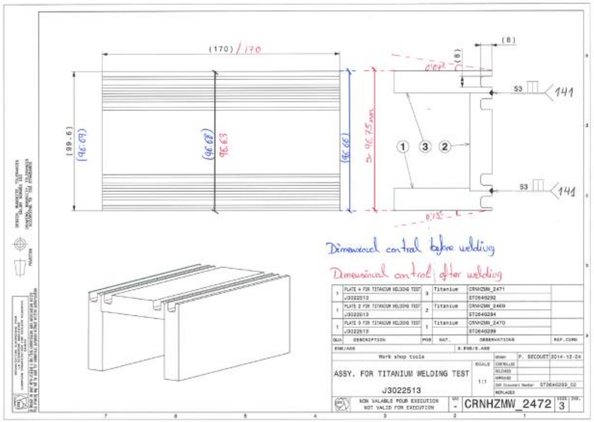


Figure 3: Representative stress-strain curve for a 4 K tensile test

Test on welded joints

- EDMS 1458356 Technical Report: Titanium Welding Test for Crab Cavities project.



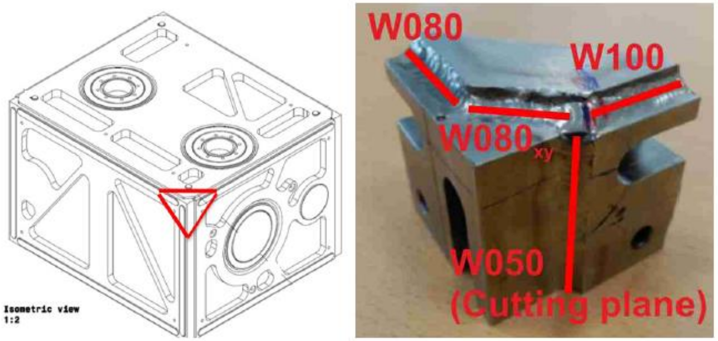
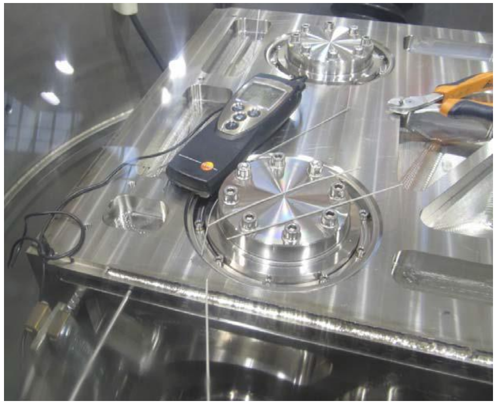


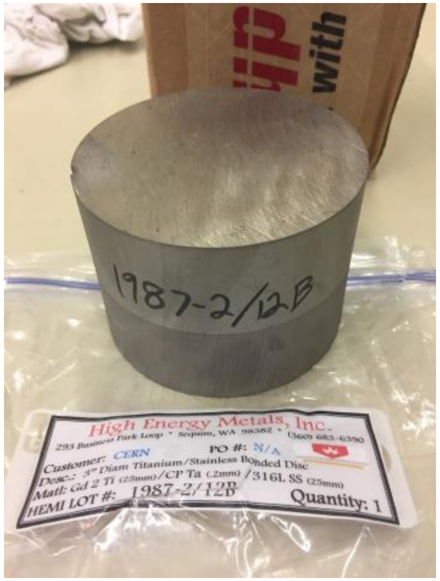
Figure 1: Location of the crossweld (left) and sample before cutting (right)

- EDMS 1716204 Metallographic Weld Analyses for Crab Cavity Helium Tank Prototype

- EDMS 1562825 WELDING HELIUM TANK PROTOTYPE CRAB CAVITY-DQW



Test on explosion bonding joints



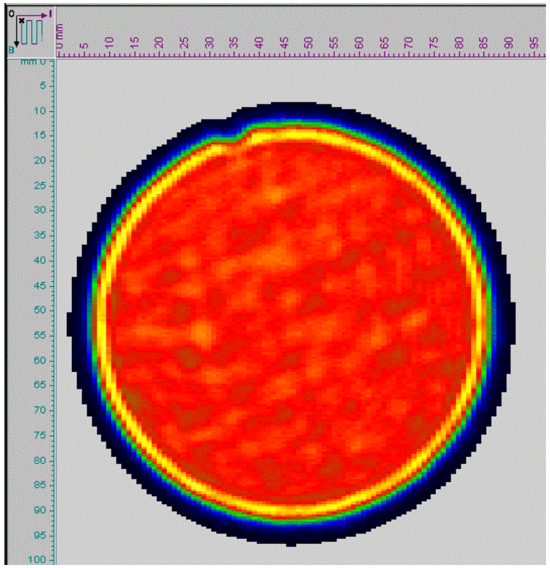
~~Explosion bonding (Nickel interlayer) -> EDMS 1705993~~

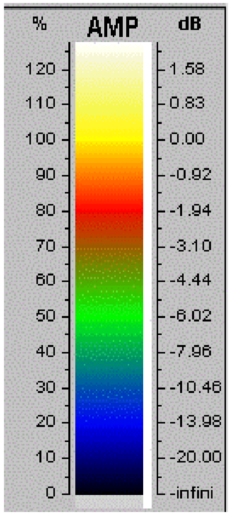
~~Explosion bonding (Copper interlayer) -> EDMS 1724598~~

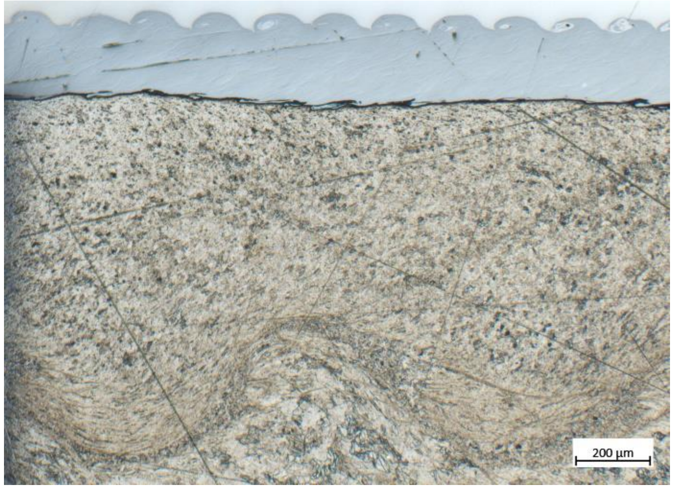
Explosion bonding (Tantalum interlayer) -> EDMS 1739621

Tests

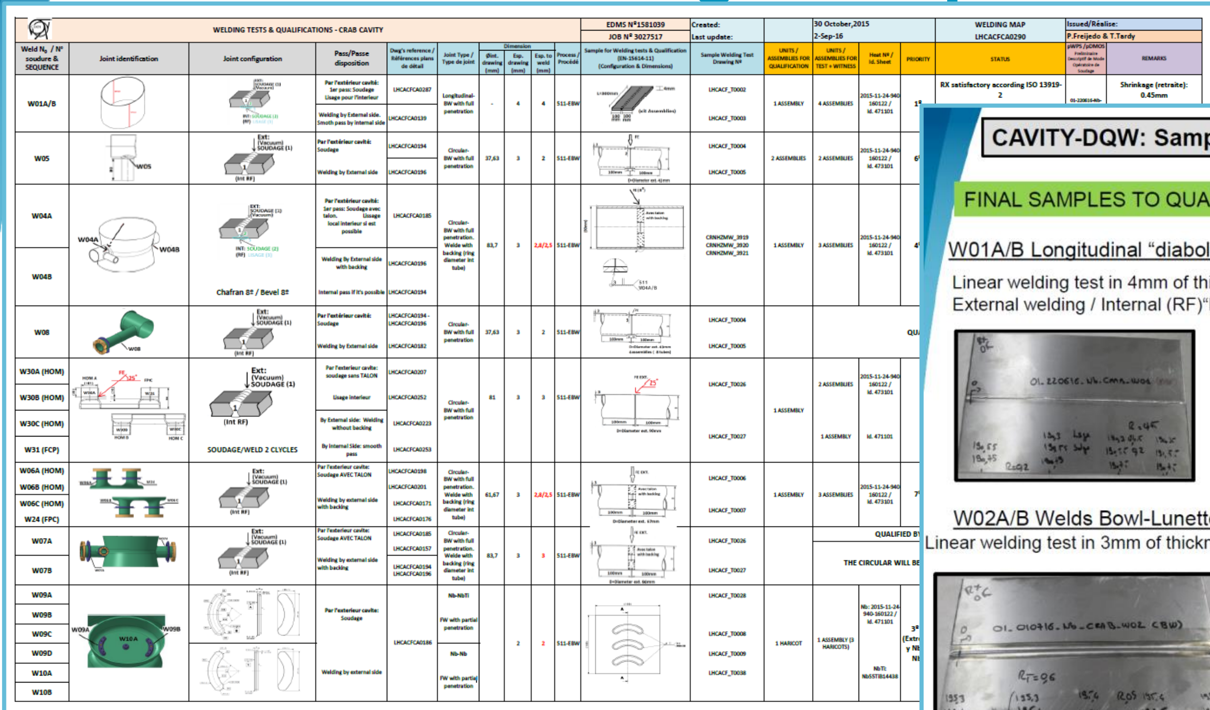
- Leak
- Traction
- Metallographic
- Ultrasonic
- *+ thermal cycles on the real component + leak test*

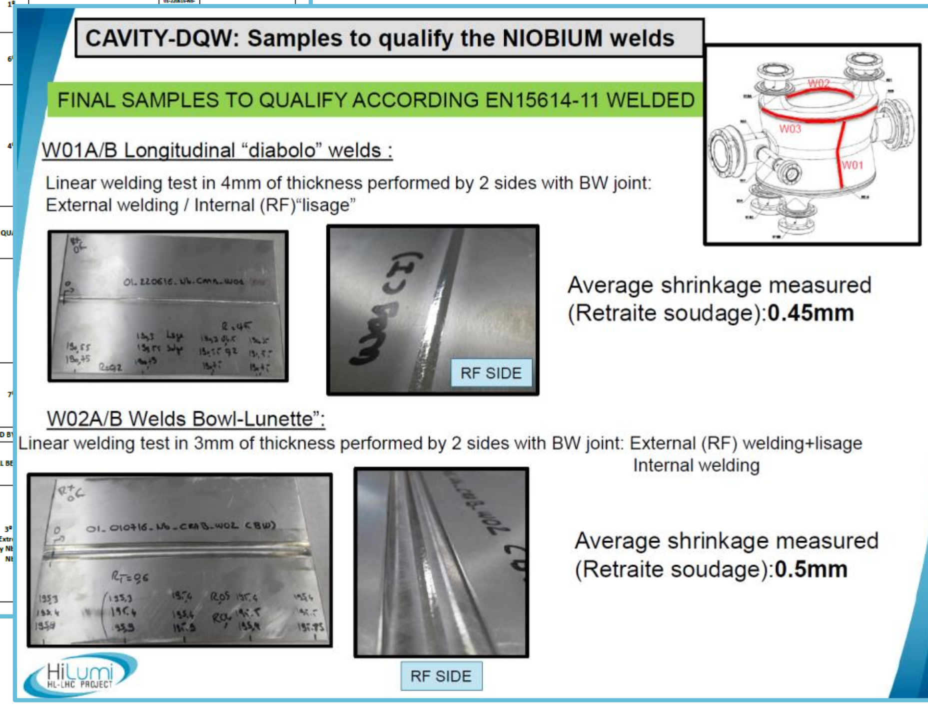






Manufacturing & Inspection (SPS tests)





Bare cavity

- EDMS 1581039 CERN documentation for welding qualification and tests
- EDMS 1685099 Welding Book Crab Cavity DQW. Extremities and Final assembly. : ASSETS HCACFCA004-CR000001 & CR000002.
- EDMS 1758810, WELDING DOCUMENT CRAB CAVITY DQW

Material traceability:

- EDMS 1549318 Summary of materials for Crab Cavity and He tank manufacturing at CERN

Ti vessel:

- welding book in progress

Documentation for SPS test proto

- Engineering drafts & notes
  - DQW Crab Cavities Cryomodule (SPS)
    - DQW Cryomodule Assembly
    - DQW Cryomodule Components
    - DQW Dressed Cavities
      - DQW Dressed Cavities Assembly
        - Specifications
          - 1389669 (v.2.1) Engineering Specification for the dressed bulk niobium Crab Cavities
        - Engineering calculations & tests
          - 1458356 (v.1) Technical Report: Titanium Welding Test for Crab Cavities project.
          - 1549819 (v.4) DQW dressed cavity strength assessment
          - 1576057 (v.2) Dressed CRAB cavity strength assessment guidelines according to ASME
        - Functional drawings & models
          - 1347072 (v.5) DQW CRAB Cavity + HOM + FPC Parametrized 3D Models
          - 1347072 (v.4) BNL CRAB Cavity + HOM Hooks + FPC Hooks
          - 1393174 (v.6) DQW cavity + magnetic shield + helium vessel

- design

- CERN-0000115183
- CERN-0000115182

- DQW Cryomodule Components
  - DQW Cryogenic circuits
  - DQW Thermal Shield & MLI
  - DQW Vacuum Vessel
    - Manufacturing drawings
      - 1710424 (v.1) Drawing folder - CRAB - DQW - Vacuum tank
    - Manufacturing procedures
      - 1716297 (v.1) CRAB Cavity Vacuum Vessel Technical Specification for Manufacturing
    - Inspection & test procedures
    - Qualifications
    - Manufacturing records
  - DQW Warm Magnetic Shield
  - DQW Alignment Monitoring System
  - DQW Support and Alignment System
  - DQW RF Internal Lines

- cryomodule components

And similar for other components…

- Fabrication, Assembly and Verification drafts & notes
  - DQW Crab Cavities Cryomodule (SPS)
    - DQW Cryomodule Assembly
    - DQW Cryomodule Components
    - DQW Dressed Cavities
      - DQW Dressed Cavities Assembly
      - DQW Bare cavities
        - Manufacturing drawings
          - 1509802 (v.1) Niowave Fabrication Drawings for DQW Cavity
          - 1455150 (v.2) Prototype Beam Tube Weld Map
        - Manufacturing procedures
          - 1606329 (v.1) Chemical polishing CRAB DQW
          - 1697915 (v.1) Niowave procedures
          - 1685099 (v.1) CERN WELDING BOOK DQW CRAB CAVITY HCACFCA004.
          - 1703145 (v.1) GAMME FABRICATION : MAIN BODY / CAP / BOWL / WELDING
          - 1707210 (v.1) CERN MANUFACTURING INSPECTION PLAN (M.I.P): CRAB CAVITY DC
          - 1721591 (v.1) Thermal treatment procedure for niobium cavities
        - Inspection & test procedures
          - 1472180 (v.1) Metallurgical qualification of EB welded Nb plate samples
          - 1493400 (v.1) Tensile tests of Nb samples
          - 1462732 (v.1) Niowave test procedures
          - 1556016 (v.1) Analysis of large grain size, low ductility niobium material
          - 1711164 (v.1) Analysis of Nb from Niowave
          - 1722302 (v.1) Tensile Tests of Niobium RRR 300 for Crab Cavity Production at Ambient a
          - 1712865 (v.1) Surface analysis of RRR 300 niobium sheets after different forming steps
          - 1687692 (v.1) Surface Pollution Study of RRR 300 Niobium sheets
          - 1727700 (v.1) Effect of water jet cutting on the surface state of RRR 300 niobium
          - 1728883 (v.1) Materials Analyses 9/2015
          - 1728884 (v.1) Analyses of Niobium Material 10/2015
          - 1728888 (v.1) Qualification of EB welds
          - 1728891 (v.1) Alumina pollution on Nb sheets ¿ history and current status 6/2016
          - 1729769 (v.1) Step-by-step list of Flanges
        - Qualifications
          - 1472180 (v.1) Metallurgical qualification of EB welded Nb plate samples
          - 1549318 (v.1) Summary materials for Crab Cavity manufacturing at CERN
          - 1493400 (v.1) Tensile tests of Nb samples
          - 1612289 (v.1) J-LAB documentation for welding qualification
          - 1615813 (v.1) NIOWAVE documentation for welding qualification
          - 1581039 (v.1) CERN documentation for welding qualification and tests
          - 1710978 (v.1) Surface pollution and chemical cleaning study of niobium sheets for RF cav
        - Manufacturing records
          - HCACFCA004-CR000001 - DQW Bare Cavity (variant #1)
          - HCACFCA004-CR000002 - DQW Bare Cavity (variant #1)
          - 1597118 (v.1) MATERIAL CERTIFICATES. FABRICATION AT CERN
        - DQWCC USLARP
        - 1669129 (v.0.1) Planning Manufacturing DQW Cavity

- only for bare cavity