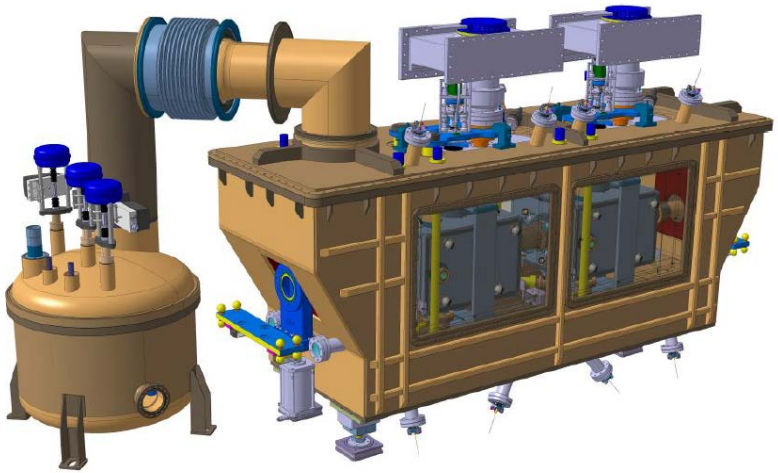
Crab cavity project: mechanical design and safety

- The Crab cavity project
- Safety rules at CERN
- Dressed RF cavity
- Materials
- Calculations
- Welded joints
- Pressure test
- Open points
- Conclusions

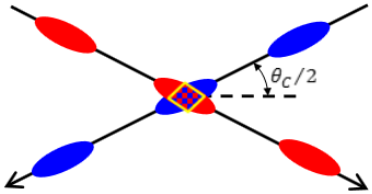
today…
inspiration from the past…
with new standards!



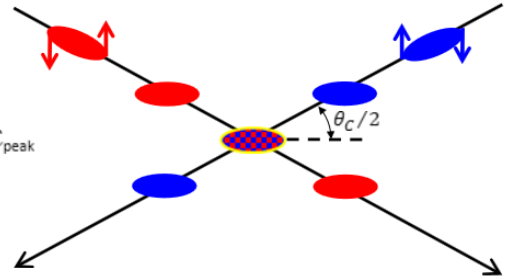
Framework - HL-LHC Crab cavities

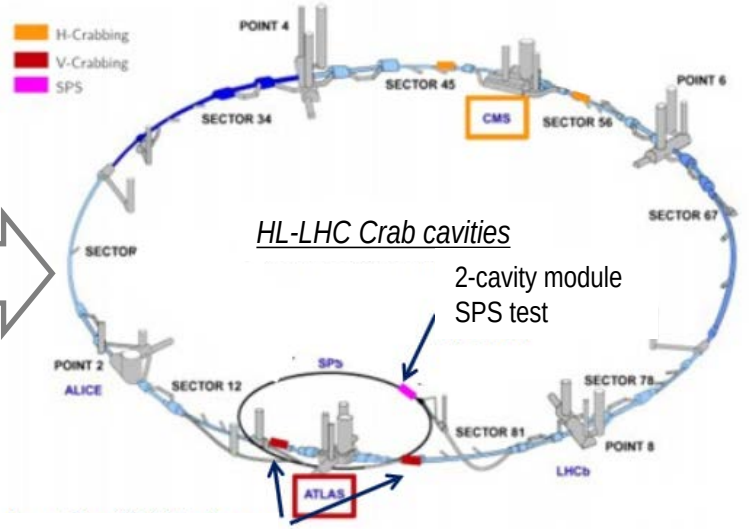
If head-on collisions, debris can interact with the machine

✓ Crossing angle
but decreased peak luminosity



✓ Crab crossing
reestablish head-on collision for maximal $\mathcal{L}_{peak}$

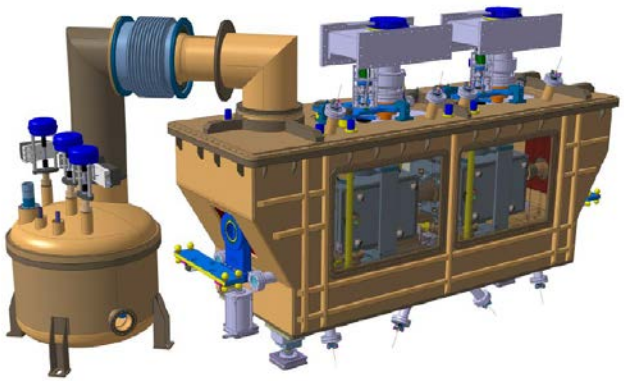




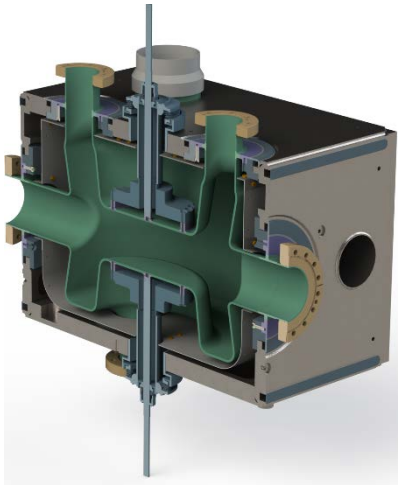
2 cavities / IP / side / beam
between D2 and Q4

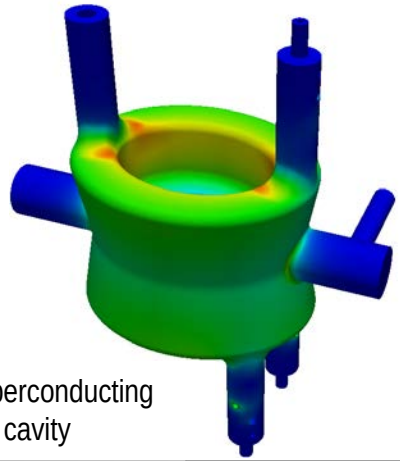
-> need 16 Crab cavities

dresses cavity



SPS cryomodule for
preliminary tests





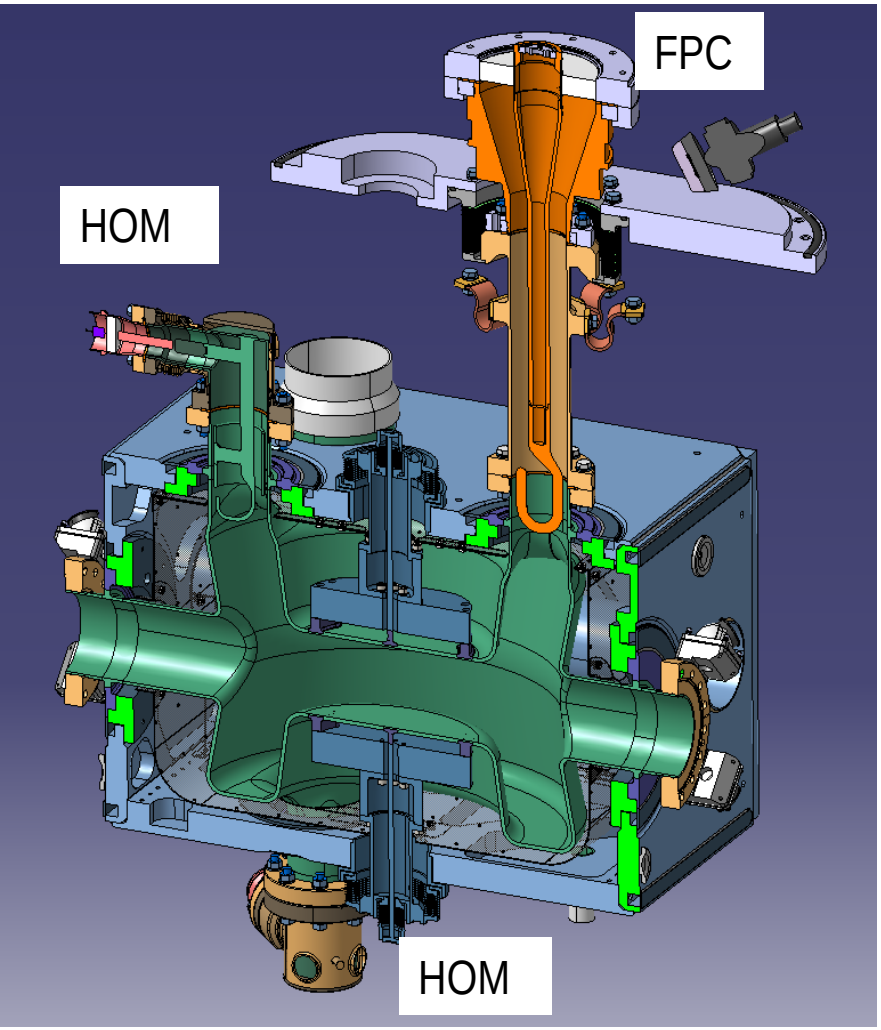
superconducting
RF cavity

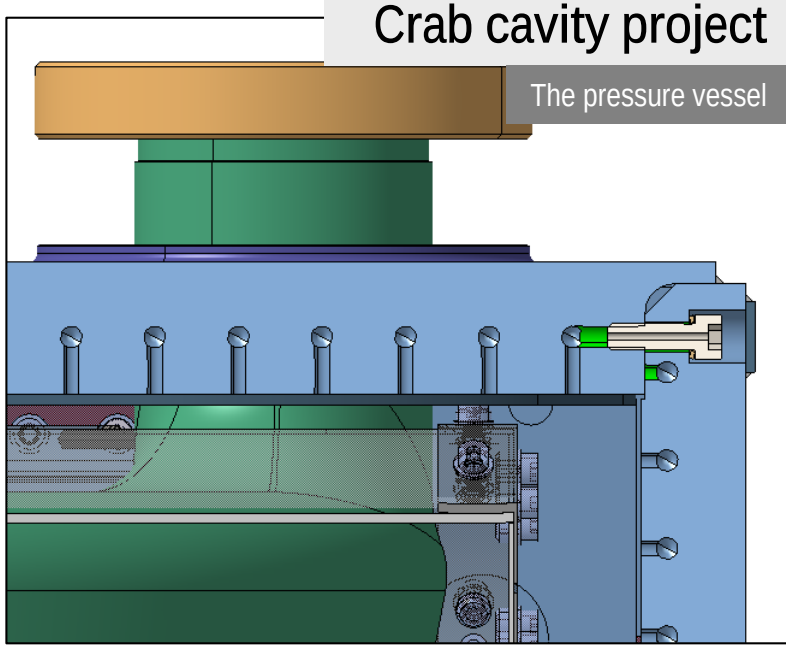
The pressure vessel

Dressed cavity:
- Cavity: Nb
- Transition NbTi
- Vessel: Ti Grade 2
- Bolts: Ti Grade 5 (Ti6Al4V)

Bolted pressure vessel: dressed cavity

Welded pressure vessels: actively cooled HOMs

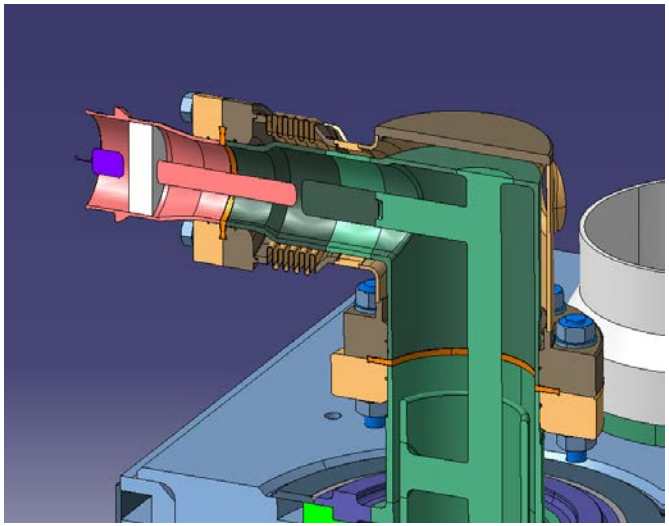




Bolts for He vessel

Leak tightness: welded joint (not pressure bearing joints!)

3 HOMs per cavity
- Hook + internal wall: Nb
- External wall: stainless steel



THE CERN SAFETY POLICY: Organization's policy concerning all aspects of Safety
SR-M: Safety Regulation for mechanical equipment
GSI-M2: General Safety Instruction for Standard Pressure Equipment (+ related SSI-M-2-Xs)
GSI-M4: Cryogenic Equipment

GSI-M4
- Definitions
- Supplementary rules (wrt SR-M)
- MINIMUM SAFETY REQUIREMENTS
- Safety file content

CERN Safety Rules
+
PED 97/23/EC (now replaced with 2014/68/EU)
+
European Harmonized Standards

total compliance with pressure vessel codes not always possible
derogation BUT proof of compliance with ESRs

Cryogenic **equipment (T≤ 123.15 K)** liable to have major Safety implications:
- not compliant with the applicable European directives, or
- of a highly complex design, or
- using reduced safety factors, or
- requiring special conditions of use, or
- using unconventional materials or manufacturing technologies, or
- presenting a high-level hazard

Review and discussion with HSE unit

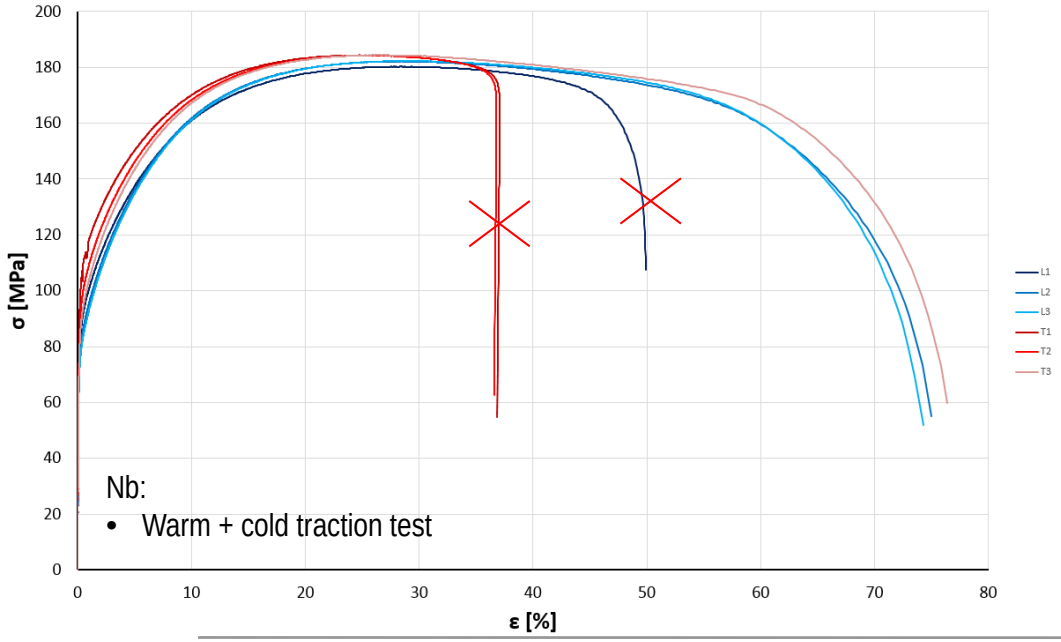
Crab SPS prototype cryomodule
- equipment liable to have major Safety implications
- exempted from CE-marking
- the equipment shall meet the Essential Safety Requirements (ESRs) stated PED 97/23/EC.
- European harmonized standards used whenever possible
- If not possible, ASME Section VIII Div. 2 + compensatory measures in view of compliance with the ESRs of the PED.
- Hydrostatic proof test will be replaced by alternative methods

Materials:
- Ti Gr. 2, Ti Gr. 5 high purity Nb and NbTi 55Ti-45Nb not considered in the Harmonised Standards
- manufacturer is in charge of the proof of conformity with the ESRs
- compliance with PED would require PMA

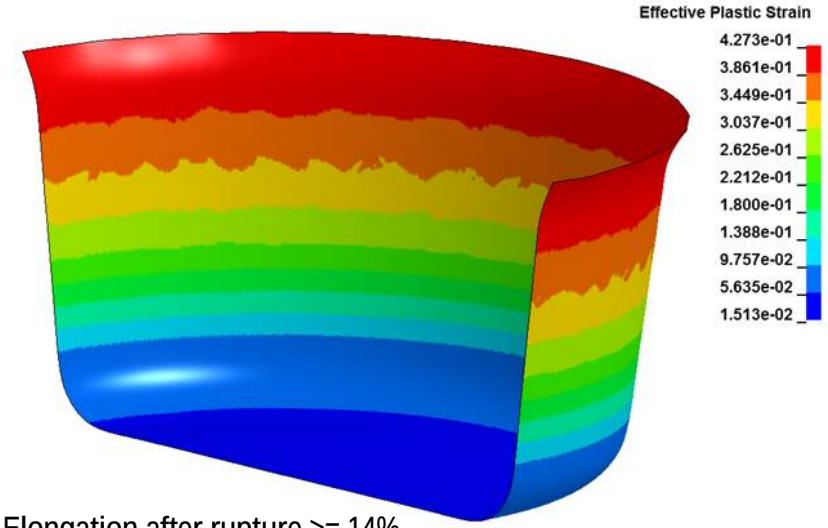
Crab cavity materials
- For Ti -> PMA provided by DESY XFEL -> material provided according to same standards
- For Nb and NbTi
  - PMA on similar material (DESY XFEL)
  - provided according to a Technical Specification developed internally at CERN
  - material certificate + internal tests

Experience from other labs:
- DESY PMAs
- Fermilab technical report
- literature

No impact toughness test so far
DESY PMA: *"The evidence of ductility at lowest... temperature is not approved through Charpy tests. The applicability of the materials owing to the fact that there are long time running devices in testing facilities, the design of the facility and tests done under -**196 ˚C**"*



Nb:
- Warm + cold traction test



Elongation after rupture >= 14%

Standard: EN 13445-3:2014

Design by Formula approach not possible
So Design by Analysis -> 2 options

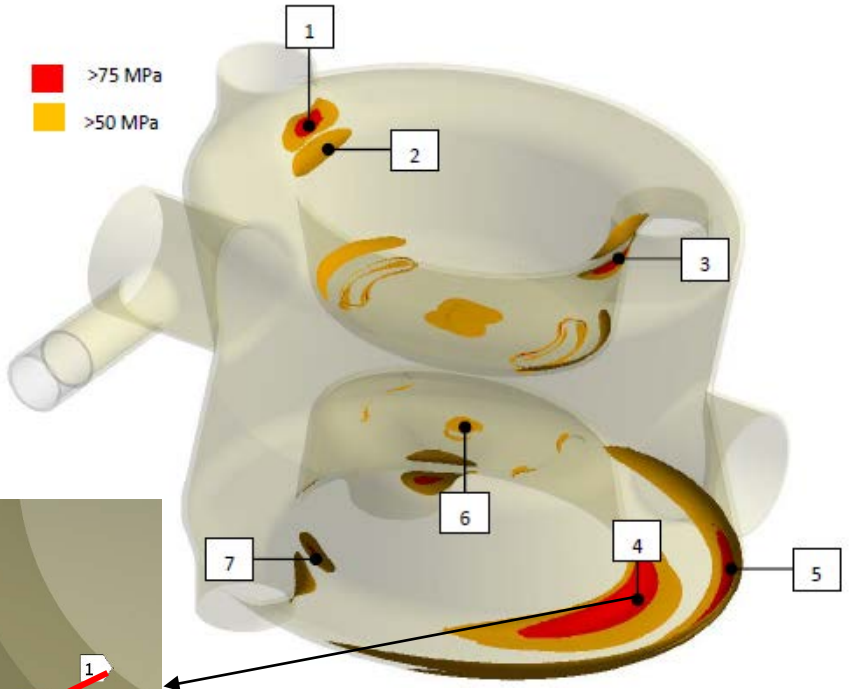
1) Method based on stress categories
- Linear analysis
- Interpretation of the results required
  - Selection of the supporting lines
  - Primary and Secondary Stress
  - Local and General Stress
  - Ambiguous
  - Welded joints difficult to treat

2) Direct Route
- Nonlinear analyses
- Some aspects not really clarified (see Progressive Plastic Deformation and Shakedown)

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

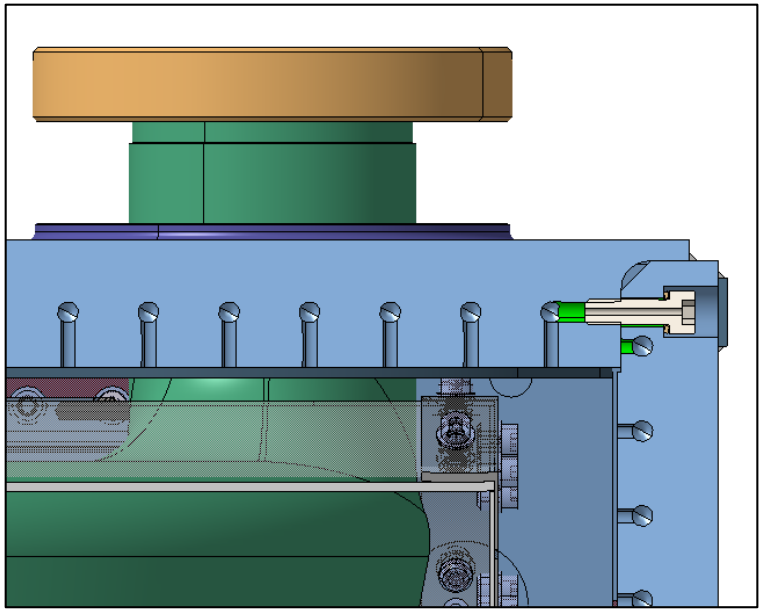
Loads not considered:
- Tuning (only at cold)

Other remarks
- Fatigue life: not applicable
- Pressure test: derogation

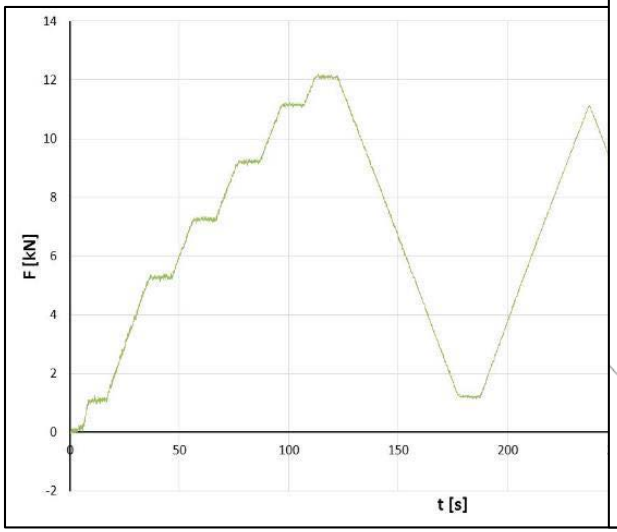


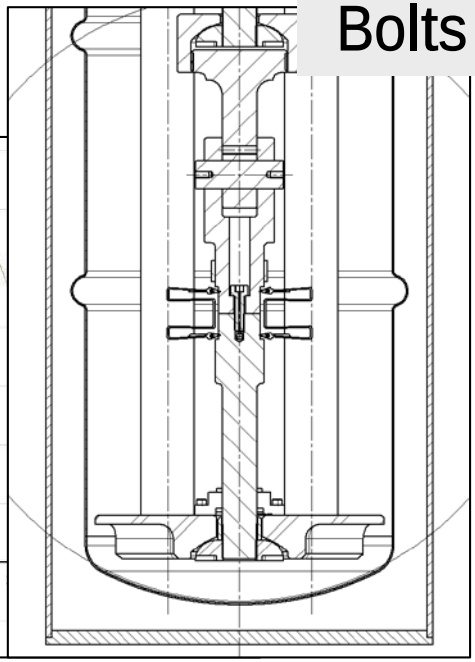
Ti Vessel

- Vessel stiffness has impact on cavity stress level
- Very low stress level for the vessel itself



Preloaded at 3.8 kN
Rupture at warm 15.9 kN
Tested at 4.5 K up to 12 kN





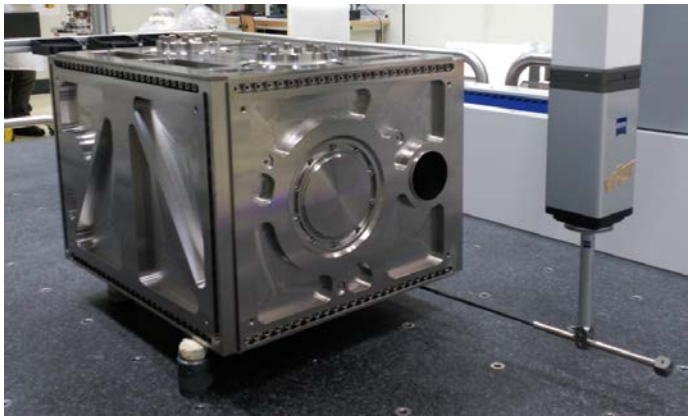
Bolted He vessel + welded joint for leak tightness

Bolted He vessel is unusual pressure vessel: in standards there are guideline for flanges

VDI2230:2014 has been adopted as guideline for bolt dimensioning

Ti bolts

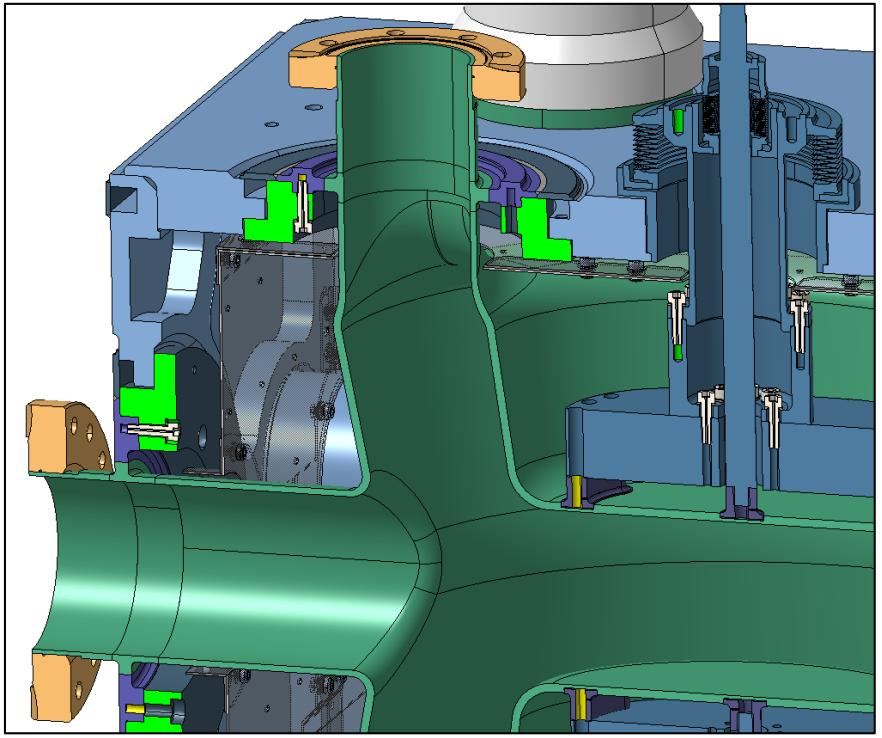
- High quality supplier
- Material certificate (not common for bolts)
- Specific tests on bolts at room T and at 4.5 K
- Dummy vessel tests
  - leak tests
  - thermal shocks
  - “conventional” pressure test (up to Δp=2.6 bar)



Welded joints

- some complex joint / not standard (not only for pressure)
- exotic materials
- allow manufacturer to follow ASME or EN standards

Vacuum brazing, electron-beam welding, TIG (GTAW) welding



Study of the ASME/EN standards:

- For brazing/welding qualifications: equivalence is stated
- For operator qualifications : equivalence is stated

Table 6: Standards applicable to electron-beam welding qualifications

DESCRIPTION	STANDARDS	
	AMERICAN	EUROPEAN
Welding Qualifications (WPQR&WPS)		
Electron beam	ASME BPVC Section IX PART-QW or AWS C7.3:1999R	EN ISO 15609-3- Welding procedures specification - Part 3: Electron beam welding; and EN ISO 15614-11- Welding procedure test - Part 11: Electron and laser beam welding.
Personnel Qualifications (WPQ)		
Operator of Electron beam	ASME BPVC Section IX PART-QW or AWS C7.3:1999R	EN ISO 14732: Welding personnel. Qualification testing of welding operators and weld setters for mechanized and automatic welding of metallic materials

For welding qualifications: ASME is less demanding than EN.

CERN reserves the right to ask for additional welding samples in order to perform test not listed in ASME but listed in EN

Study of the ASME/EN standards:
For Nb, NbTi, Ti (e-beam)

- For acceptance criteria on imperfections: EN requirements are retained, more stringent than ASME. Clearly stated
- Standards or part of standards related to Al alloy have been retained and own criteria have been derived from it, considering that Al is the material with the closest behaviour to Nb

For Ti (GTAW)

- equivalence is stated

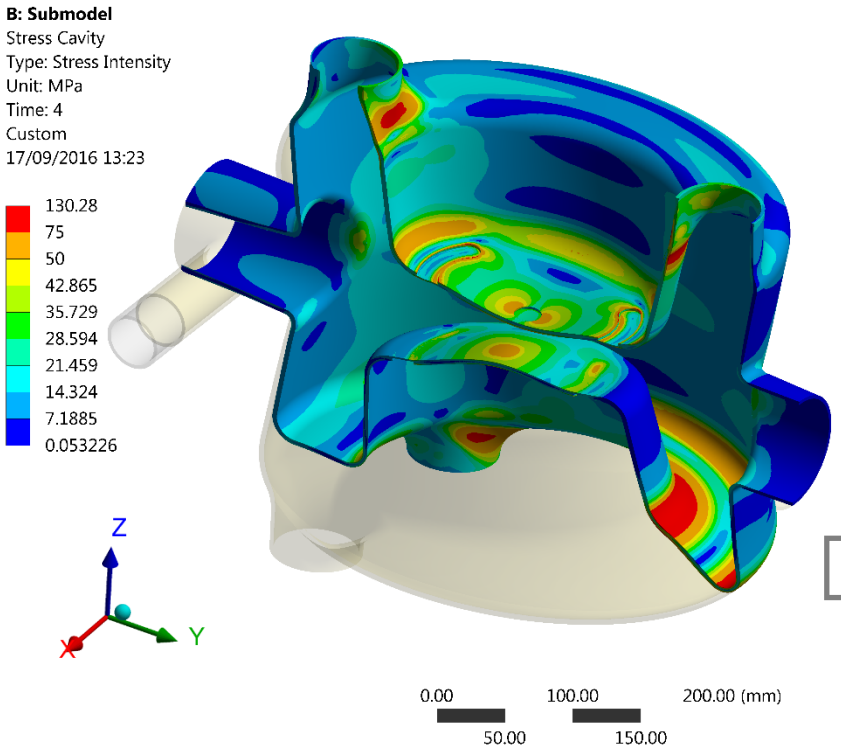
Concerning acceptance of defects, critical welded joints from a RF point of view have special requirements, independent from Safety aspects

Not possible to manufacture the entire dressed cavity according to ASME.

Table 8: Acceptance levels of other welded or brazed joints imperfections

Vacuum Brazing	Ultrasonic examination: Examination procedure according to ASTM E 1001 or EN 12799 combined with EN ISO 16827 • Channels: not acceptable • Combination of defects: the total projected area of defects shall not exceed 5% of the brazed area.	
Electron beam for titanium, niobium and niobium-titanium alloys.	EN ISO 13919-2. Acceptance criteria according to level B.	
GTAW	ASME BPVC Section VIII Div.2	EN ISO 5817 Level B
Qualifications of NDT personnel	Recommended Practice N° SNT-TC-1A Level II	EN ISO 9712 Level II

Results of preliminary analysis shows that an extended area would be interested by too high plasticization during pressure test.



De-tuning of the cavities at ambient temperature must be avoided

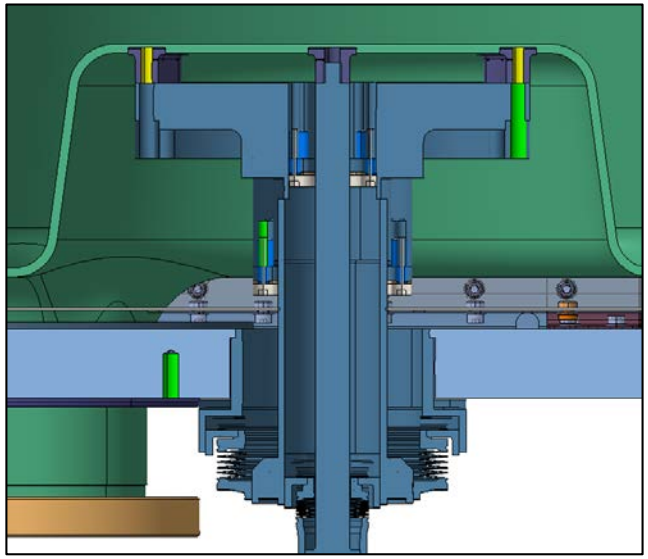
The mechanical properties of the material used for manufacture of the bare cavities will be verified by dedicated mechanical tests.

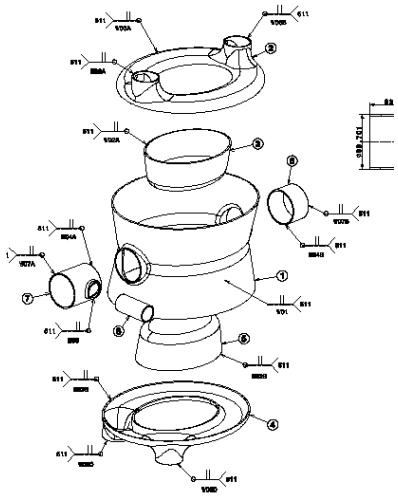
Alternative method proposed: pressure test at the maximum allowable pressure (0.8 barg) at ambient temperature.

Accepted by HSE CERN unit

Bellows (5 x cavity):
No standard is available for Ti edge-welded bellows -> a lot of welded joints, very difficult to control each of them
So proposal:

- high quality supplier (aerospace)
- documentation related to material / manufacturing (highly automated process)
- testing campaign at cold to perform





Conclusions

- CERN Safety Rules ask for compliance with PED but consider derogation for most complex cases -> Crab cavities are under the scope of the exception
- Materials not considered in Standards -> dedicated tests, experience from other labs
- Calculations: FE analyses mandatory, stress analysis complex
- Welded joints: ASME equivalence for manufacturing qualification but acceptance criteria only according to EN
- Pressure test: derogation accepted
- Open points: edge welded bellows compliance with ESRs not yet finalized

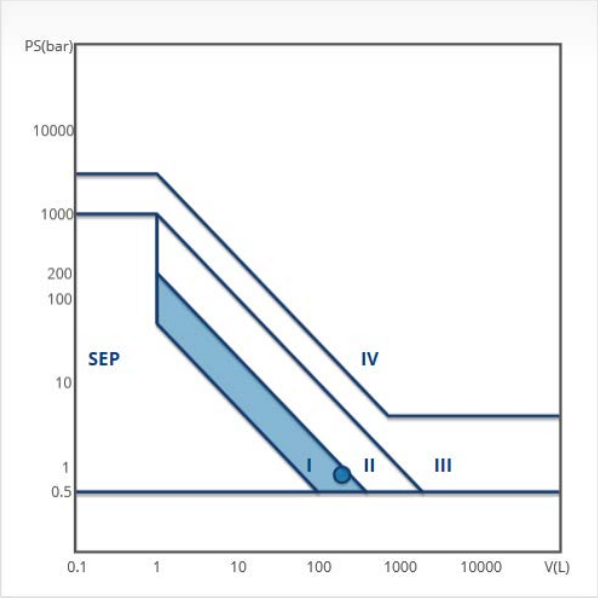
References

- Fermilab technical report - Guidelines for the Design, Fabrication, Testing and installation of SRF Nb Cavities (TD-09-005 in draft status?)
- CERN-ACC-NOTE-2013-003, Functional Specifications of the LHC Prototype Crab Cavity System
- EDMS 1494776, CRAB CAVITIES PROTOTYPE CRYOMODULE, A PROPOSAL FOR COMPLIANCE WITH CERN SAFETY REQUIREMENTS
- EDMS 1541969, Safety request form, Final safety requirements applicable to the Crab cavities cryomodules (HiLumi project) (ONLY FOR SPS MACHINE)
- EDMS 1549819 DQW dressed cavity strength assessment
- EDMS 1389669 Engineering Specification for the dressed bulk niobium Crab Cavities
- EDMS 1530740 Material properties for mechanical and thermal analysis
- EDMS 1581039, WELDING TESTS & QUALIFICATIONS - CRAB CAVITY

Aknolewdgements

C. Zanoni, P. Freijedo Menendez, N. Kuder, C. Parente, W. Singer (Desy)

Back-up slides



Working conditions (from project specification):

- PS = 1.8 bar abs
- Volume < 200 l
- Fluid group 2, gaseous state

Welded joints

Example of documentation

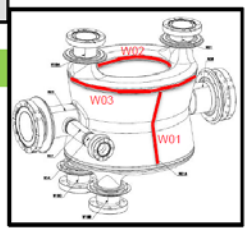
WELDING TESTS & QUALIFICATIONS - CRAB CAVITY										EDMS N°1581039 JOB N° 3027517	Created: Last update:		30 October,2015 2-Sep-16		WELDING MAP LHCACFCA0290	Issued/Réalise: P.Freijedo & T.Tardy
Weld N° / N° soudure & SEQUENCE	Joint identification	Joint configuration	Pass/Passe disposition	Dwg's reference / Références plans de détail	Joint Type / Type de joint	Dimension (Bot. drawing (mm))	Dimension (Exp. drawing (mm))	Dimension (Exp. to weld (mm))	Process / Procédé	Sample for Welding tests & Qualification (EN-15614-11) (Configuration & Dimensions)	Sample Welding Test Drawing N°	UNITS / ASSEMBLIES FOR QUALIFICATION	UNITS / ASSEMBLIES FOR TEST + WITNESS	Heat N° / Id. Sheet	PRIORITY	STATUS	pWPS /pDMOS	REMARKS
W01A/B			Par l'extérieur cavité: 1er pass: Soudage Usage pour l'interieur Welding by External side. Smooth pass by internal side	LHCACFCA0287 LHCACFCA0139	Longitudinal-BW with full penetration	-	4	4	511-EBW		LHCACF_T0002 LHCACF_T0003	1 ASSEMBLY	4 ASSEMBLIES	2015-11-24-940 160122 / Id. 471101	1°	RX satisfactory according ISO 13919-2 Samples tensiles & bending test ON-going	01-220616-Nb-CRAB-W01	Shrinkage (retraite): 0.45mm
W05	W05	Ext: (Vacuum) SOUDAGE (1) (Int RF)	Par l'extérieur cavité: Soudage Welding by External side	LHCACFCA0194 LHCACFCA0196	Circular-BW with full penetration	37,63	3	2	511-EBW		LHCACF_T0004 LHCACF_T0005	2 ASSEMBLIES	2 ASSEMBLIES	2015-11-24-940 160122 / Id. 471101	6°	SAMPLE WELDED RX satisfactory according ISO 13919-2	260716-W05/B-T	
W04A W04B	W04A W04B	Chafran 8° / Bevel 8°	Par l'extérieur cavité: Ser pass: Soudage avec talon. Usage local interieur si est possible Welding By External side with backing Internal pass if it's possible	LHCACFCA0185 LHCACFCA0196 LHCACFCA0194	Circular-BW with full penetration. Welde with backing (ring diameter int tube)	83,7	3	2,0/2,5	511-EBW		CRNHZMW_3919 CRNHZMW_3920 CRNHZMW_3921	1 ASSEMBLY	3 ASSEMBLIES	2015-11-24-940 160122 / Id. 471101	4°	SAMPLE WELDED RX satisfactory according ISO 13919-2	280716-W04-T	Welding with backing (Done from 2 rings in 4mm of thickness welded with Øint.tube + 1mm for machining after welding) Diam. Ext measured before longitudinal welding: 90mm. Measure after welding to check the shrinkage (retraite soudage)
W08	W08	Ext: (Vacuum) SOUDAGE (1) (Int RF)	Par l'extérieur cavité: Soudage Welding by External side	LHCACFCA0194 - LHCACFCA0196 LHCACFCA0182	Circular-BW with full penetration	37,63	3	2	511-EBW		LHCACF_T0004 LHCACF_T0005	QUALIFIED BY W05					260716-W05/B-T	
W30A (HOM) W30B (HOM) W30C (HOM) W31 (FCP)		Ext: (Vacuum) SOUDAGE (1) (Int RF) SOUDAGE/WELD 2 CLYCLES	Par l'exterieur cavité: soudage sans TALON Usage interieur By External side: Welding without backing By Internal Side: smooth pass	LHCACFCA0207 LHCACFCA0252 LHCACFCA0223 LHCACFCA0253	Circular-BW with full penetration	81	3	3	511-EBW		LHCACF_T0026 LHCACF_T0027	1 ASSEMBLY	2 ASSEMBLIES 1 ASSEMBLY	2015-11-24-940 160122 / Id. 471101 Id. 471101		SAMPLES WELDED RX satisfactory according ISO 13919-2	-	Welding without backing BEAM INCLINATION 25° 2 CYCLES
W06A (HOM) W06B (HOM) W05C (HOM) W24 (FPC)		Ext: (Vacuum) SOUDAGE (1) (Int RF)	Par l'exterieur cavité: Soudage AVEC TALON Welding by external side with backing	LHCACFCA0198 LHCACFCA0201 LHCACFCA0171 LHCACFCA0176	Circular-BW with full penetration. Welde with backing (ring diameter int tube)	61,67	3	2,0/2,5	511-EBW		LHCACF_T0006 LHCACF_T0007	1 ASSEMBLY	3 ASSEMBLIES	2015-11-24-940 160122 / Id. 471101	7°	SAMPLE WELDED. RX satisfactory according ISO 13919-2	280716-W06-T	Welding with backing (Øint. + 1mm Diam. Ext measured before
W07A W07B		Ext: (Vacuum) SOUDAGE (1) (Int RF)	Par l'exterieur cavité: Soudage AVEC TALON Welding by external side with backing	LHCACFCA0185 LHCACFCA0157 LHCACFCA0194 LHCACFCA0196	Circular-BW with full penetration. Welde with backing (ring diameter int tube)	83,7	3	3	511-EBW		LHCACF_T0026 LHCACF_T0027							
W09A W09B W09C W09D W10A W10B	W09A W09B W10A		Par l'exterieur cavité: Soudage Welding by external side	LHCACFCA0186	Nb-NbTi FW with partial penetration Nb-Nb FW with partial penetration		2	2	511-EBW		LHCACF_T0028 LHCACF_T0008 LHCACF_T0009 LHCACF_T0038	1 HARCOT	1 ASSEMBLY (3 HARCOTS)					

Dressed cavity in internal production at CERN: only EN standard

Internal qualification of each weld is performed

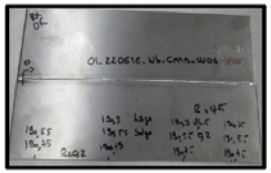
CAVITY-DQW: Samples to qualify the NIOBIUM welds

FINAL SAMPLES TO QUALIFY ACCORDING EN15614-11 WELDED



W01A/B Longitudinal "diabolo" welds :

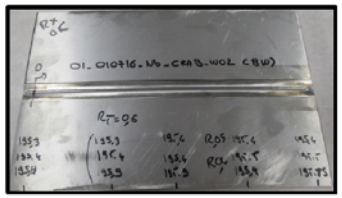
Linear welding test in 4mm of thickness performed by 2 sides with BW joint: External welding / Internal (RF)"lisage"

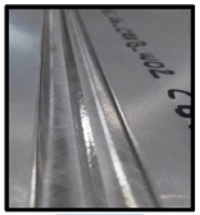


Average shrinkage measured (Retraite soudage):**0.45mm**

W02A/B Welds Bowl-Lunette":

Linear welding test in 3mm of thickness performed by 2 sides with BW joint: External (RF) welding+lisage
Internal welding





Average shrinkage measured (Retraite soudage):**0.5mm**