Safety for cryogenic equipment and Crab cryomodule: lessons learned with the prototype and future application in LHC

Luca Dassa on behalf of the engineering team

8th HL-LHC Collaboration Meeting – October, 15th -18th 2018 (CERN)

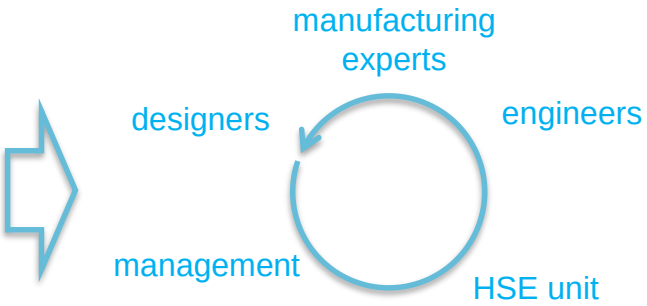
- SPS test stand
  - The SPS cryomodule
  - Documentation
- LHC installation
  - CERN rules
  - Cryomodule breakdown
  - PED key words / CERN rules specificity
  - Approach to grant compliance with CERN rules
  - Conclusions

- SPS test stand

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



Valid only for SPS cryomodule

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.

- Hydrostatic proof test will be replaced by alternative methods

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

Documentation

- 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

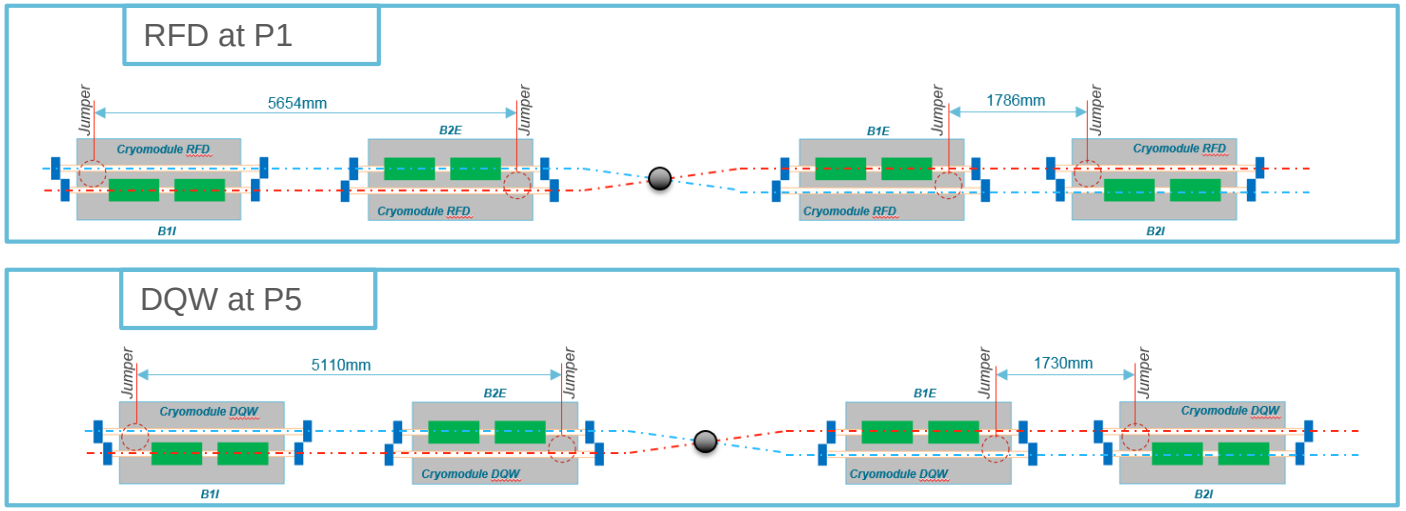
- Fabrication, Assembly and Verification drafts & notes
  - DQW Crab Cavities Cryomodule (SPS)
    - DQW Cryomodule Assembly
    - DQW Cryomodule Components
    - DQW Dressed Cavities
      - DQW Dressed Cavities Assembly
      - DQW Bare cavities
        - Manufacturing drawings
          - 1509802 (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

And similar for other components…

- LHC cryomodules

Overall context



Actors:

- CERN
  - internal
  - outsourcing
- Canada contribution
  - internal
  - outsourcing
- UK contribution
  - internal
  - outsourcing
- US-AUP contribution
  - internal
  - Outsourcing
- …

Compliance with CERN rules

Approach valid for every case

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)

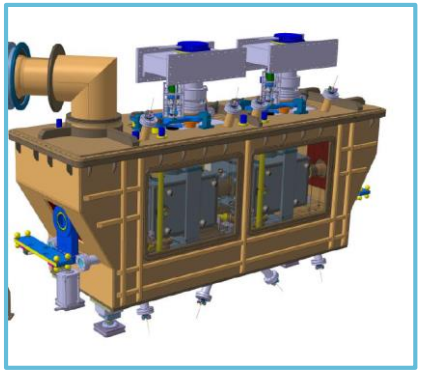
Applicable harmonized standards →

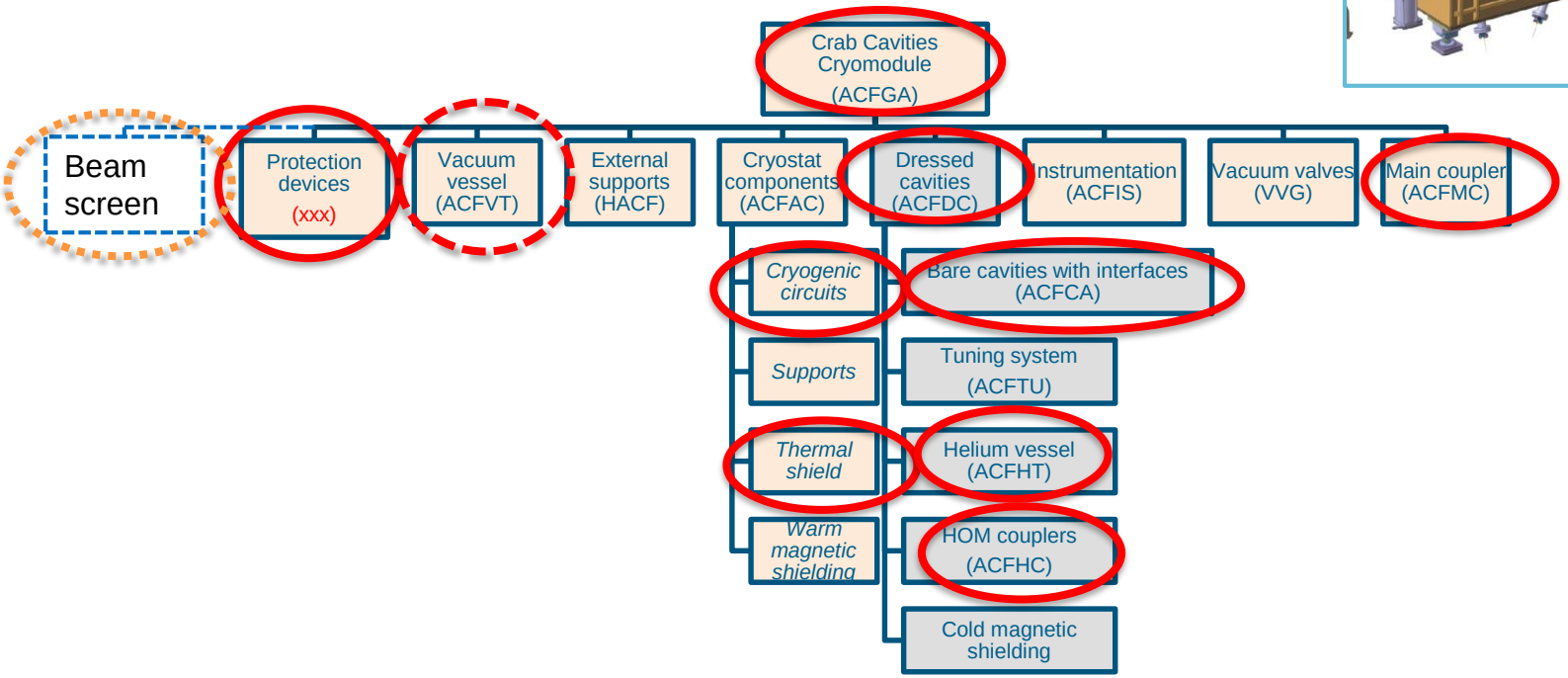
Standard	Title
EN 764-5	Pressure equipment – Part 5: compliance and inspection documentation of materials
EN 764-7	Pressure equipment – Part 7: safety systems for unfired pressure vessels
EN 1251	Cryogenic vessels – Transportable vacuum insulated vessels of not more than 1000 litres volume
EN 1252	Cryogenic 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

Cryomodule breakdown

The basic unit: the cryomodule up to the jumper for connection with supply lines





CERN rules for standard pressure / cryogenic equipment!

PED key words

Directive 2014/68/EU

"'**manufacturer**' means 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. When … using ... (their pressure equipment or assemblies) for their own purposes, manufacturers shall ensure that they have been designed and manufactured in accordance with the **essential safety requirements set out in Annex I**.

CERN is manufacturer of the cryomodule

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

CERN rules specificity

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

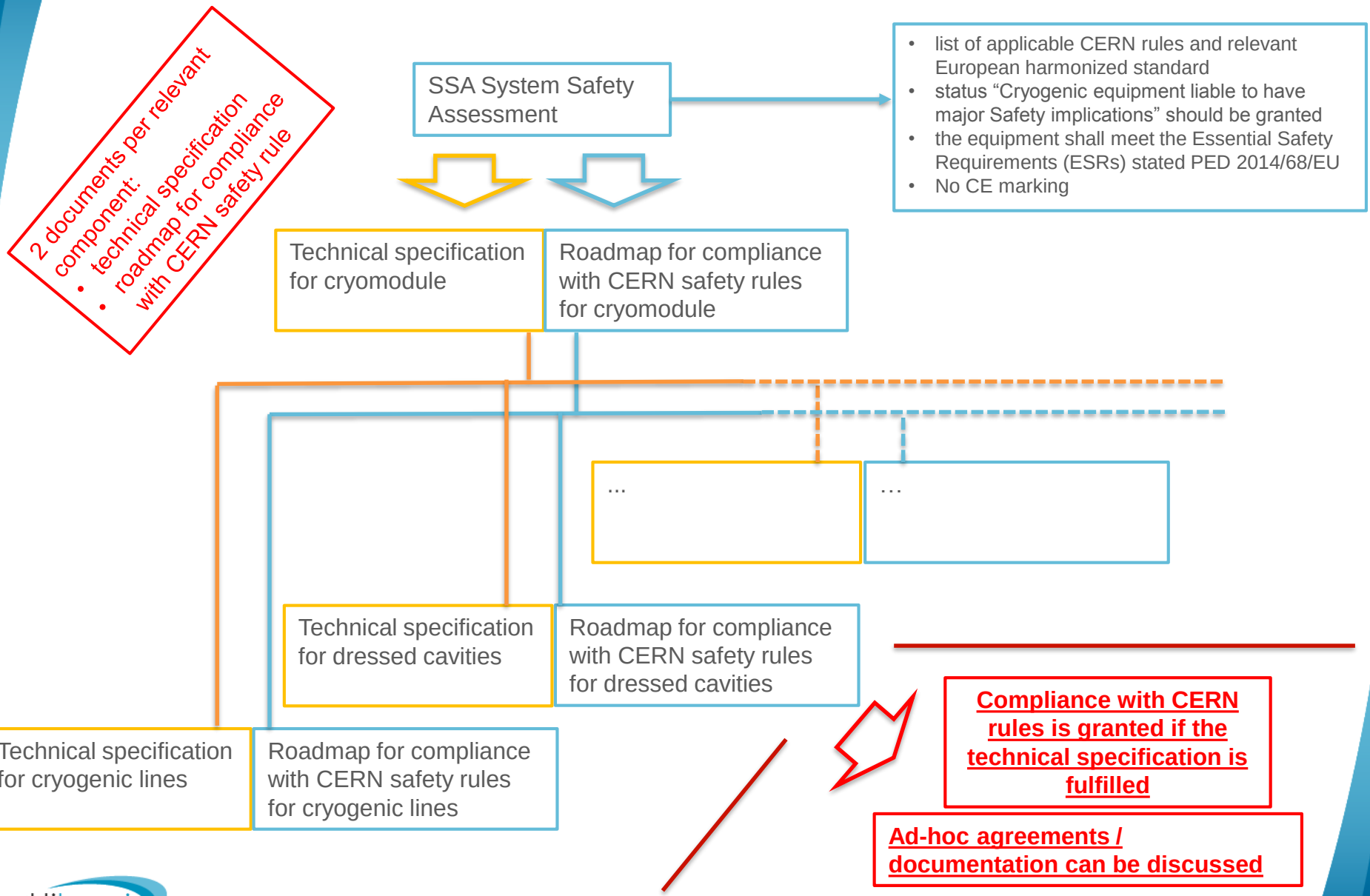
GSI-M-4 Cryogenic equipment

Cryogenic equipment liable to have major Safety implications

"… the approval of the HSE Unit is required for each stage in the life cycle of an item of cryogenic equipment liable to have major Safety implications."

HSE has verbally agree on Crab cryomodule as "Cryogenic equipment liable to have major Safety implications" and on exemption from CE Marking Finalization ongoing!

Approach to grant compliance with CERN rules



Example for Technical Specification

Choice between European and US standards is **sometimes** allowed.

Table 4. Codes for design and structural assessment

DESCRIPTION	STANDARDS	
	AMERICAN	EUROPEAN
Design by Analysis		
"Stres	ASME BPVC Sec VIII Div. 2, part 5,	EN 13445-3 Annex C (considered
Direct		

Acceptance criteria

The following requirements are valid for qualification tests a

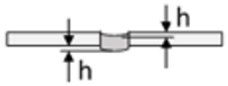
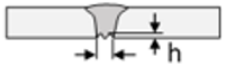
Table 10: Acceptance levels of other brazed joints acc

DESCRIPTION	
Vacuum Brazing	
Qualifications of N personnel	

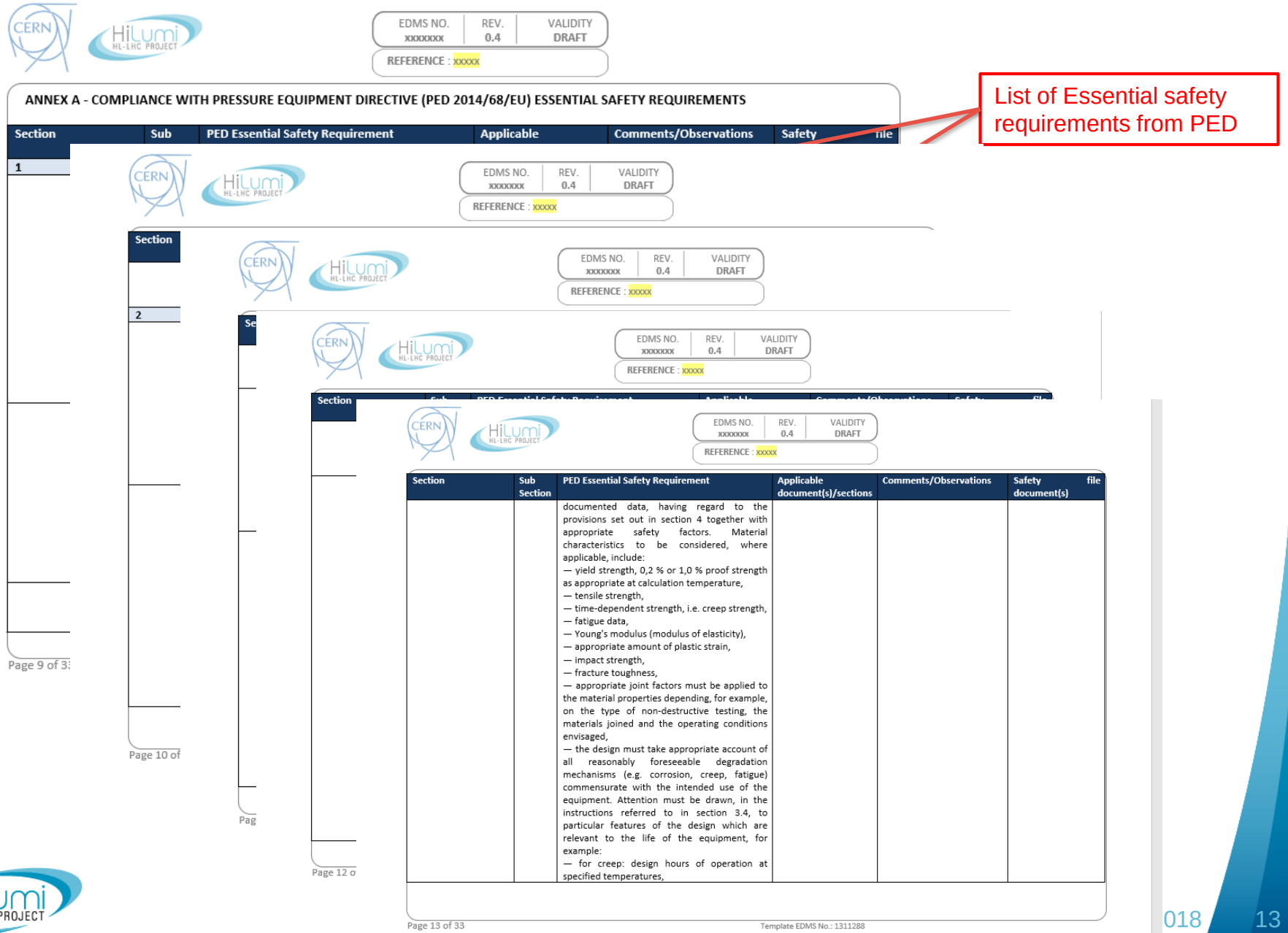
Table 9: Standards ap

DESCRIPTION	
Welding Qualifications (WPQR&WPS)	
Electron beam	AS QV
Personnel Qualifications (WPQ)	
Operator of Electron beam	AS QV

Table 13: Acceptance levels of niobium inner welded joints imperfections

EN ISO 6520-1 reference	Imperfection designation	Remarks	Limits for imperfections
5011 5012	Undercut		h max 0.05t mm
504	Excessive penetration		h max 0.4 mm
507	Linear misalignment		h max 0.05t mm
509	Sagging		h max 0.4 mm
511	Incompletely filled groove		h max 0.05t mm
515	Root concavity		h max 0.1t mm
5013	Shrinkage groove		Not acceptable

Example for Roadmap



Few technical considerations

- Very low risk components: each component is treated independently

Component	Pressure		Volume	Diameter	Fluid	PED risk category	Module for Conf. Asmnt.
	[bara]	[barg]	[l]	[mm]			
Dressed cavity (ACFDC)	1.8	0.8	80	NA	Liquid He (1.9 K)	1	A
HOM (ACFHC)	1.8	0.8	NA	28 mm	Liquid He (1.9 K)	SEP	NA
FPC	TBD	TBD	NA	TBD	Water (300 K)	TBD	NA
Upper cryogenic line (ACFQC)	1.8	0.8	NA	103 mm	Liquid He (1.9 K)	SEP	NA
Bottom cryogenic line (ACFQC)	1.8	0.8	NA	28 mm	Liquid He (1.9 K)	SEP	NA
Thermal shield line (ACFTS)	25	24	NA	16 mm	Gas He (50 K)	SEP	NA
Cold-warm transition (ACFVW)	25	24	NA	16 mm	Gas He (50 K)	SEP	NA
Vacuum vessel (ACFVT)	1.5	0.5	Not relevant	NA	Insulation vacuum	Out of scope	NA

- Assessment of the assembly according to PED (*ANNEX 1: 2.3. , 2.8. , 2.9.)*
- **Notified body not required**

Status and tentative deadlines

	Status	Deadline
SSA System Safety Assessment	Draft (EDMS 2010001)	19/11/2018 for circulation

	Status of the Tech Spec	Status of the Roadmap for Safety	Deadline
Cryomodule	Draft in work	Not started	28/02/2018 for circulation
Dressed cavities	Well advanced draft	Well advanced draft	19/11/2018 for circulation
Cryogenic lines	Well advanced draft	Well advanced draft	
Thermal Shield	Waiting for decision about material	Not started	
Vacuum vessel	Well advanced draft	Not started	31/12/2018 for circulation
Main coupler	Not started	Not started	

	Status	Deadline
Protection device	Started (calculation on-going)	End of 2018

Conclusions

- CERN is manufacturer of the cryomodule
- Status of “cryogenic equipment liable to have major safety implications”
- Baseline approach “Technical specifications + Roadmap for compliance with CERN safety rules”
  - CERN is responsible for compliance with CERN rules of the cryomodule
  - Manufactures of components shall comply with technical specifications => **not blindly!**
- Choice between European and US standards is sometimes allowed

Thank you…

- Back-up slides

CERN rules specificity

GSI-M-4 Cryogenic equipment

Cryogenic equipment liable to have major Safety implications: cryogenic equipment:
- 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 for people, the environment or other installations in the event of failure.

Assessment of the cryomodule as “an assembly”

ANNEX 1

2.3. Provisions to ensure safe handling and operation

The method of operation specified for pressure equipment shall be such as to preclude any reasonably foreseeable risk in operation of the equipment. Particular attention shall be paid, where appropriate, to:

— closures and openings,

— dangerous discharge of pressure relief blow-off,

— devices to prevent physical access whilst pressure or a vacuum exists,

— surface temperature taking into consideration the intended use,

— decomposition of unstable fluids.

In particular, pressure equipment fitted with an access door shall be equipped with an automatic or manual device enabling the user easily to ascertain that the opening will not present any risk. Furthermore, where the opening can be operated quickly, the pressure equipment shall be fitted with a device to prevent it being opened whenever the pressure or temperature of the fluid presents a risk.

2.8. Assemblies

Assemblies shall be so designed that:

— the components to be assembled together are suitable and reliable for their duty,

— all the components are properly integrated and assembled in an appropriate manner.

2.9. Provisions for filling and discharge

Where appropriate, the pressure equipment shall be so designed and provided with accessories, or provision made for their fitting, as to ensure safe filling and discharge in particular with respect to risks such as:

(a) on filling:

— overfilling or overpressurisation having regard in particular to the filling ratio and to vapour pressure at the reference temperature,

— instability of the pressure equipment;

(b) on discharge: the uncontrolled release of the pressurised fluid;

(c) on filling or discharge: unsafe connection and disconnection.

LHC crab cavities (1)

EDMS 1698982, S. Baird, head of the HSE Unit: Conformity approach for Pressure Equipment for the High Luminosity LHC Project (**June 10th, 2016**)

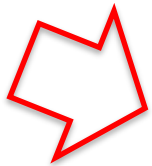
- SR-M, GSI-M-2, GSI-M-4 -> PED (2014/68/EU) -> Category? -> CE marking -> general approach
- Approach by exception -> per equipment basis -> unique in-house technical competency -> no Notified Body (it would not add any risk mitigation) -> HSE-SEE will act as de facto Notified body

Example: see WP3 and EDMS 1753780 (07/02/2017)

- Responsibility for design, manufacture, testing and quality insurance remains with HL-LHC Project team / technical justification shall be prepared by the equipment owner-work package leader

- Formal derogation not required if the HSE-SEE classes the equipment as being "liable to have major safety implications"

- Technical requirements
- Organizational and quality assurance requirements



Is the LHC crab cryomodule concerned???

EDMS 1698982, S. Baird, head of the HSE Unit: Conformity approach for Pressure Equipment for the High Luminosity LHC Project (June 10th, 2016)

4. Organisational and quality assurance aspects

In order to assure that the technical requirements described above are being met, this implies:

- HSE, Departments and HL-LHC Project team to collectively set and strictly respect prescriptions, milestones and deadlines for the equipment activities.
- Owner/work package leader to appoint a single point of contact within their team, with responsibility for quality assurance and preparation of the safety file and associated documentation, that HSE-SEE can regularly liaise with
  - Person should be sufficiently competent and conversant in the Essential Safety Requirements of the Pressure Equipment Directive.
- Owner/work package leader, their quality assurance person and HSE-SEE to jointly develop and agree to the Inspection and Test Plan.
- Agreement made between all relevant parties on dealing with non-conformities.
- Quality of engineering deliverables to be at an equivalent level as if the documents were being sent externally for formal approval by a Notified body, prior to requesting validation or endorsement.
- External partners (industry, other research institutes, in-kind contributions, etc.) shall supply on time the same technical documentation for design, manufacture, inspection and testing.
- Design to be validated by HSE-SEE prior to starting fabrication.

  - Including appropriate documentation of the 'effective equivalence' in all areas, e.g. materials selection, qualification of welders, NDT operator qualification, etc.
- Safety accessories – as standard products – shall fully comply, as applicable, with either:
  - GSI-M-2 Standard Pressure Equipment and SSI-M-2-3 Safety Accessories for Standard Pressure Equipment, or
  - GSI-M-4 Cryogenic Equipment.
- Safety accessories shall therefore be CE marked, including those used on equipment obtained as in-kind contributions from countries not subject to the European Pressure Equipment Directive.

3. Technical requirements for Pressure Equipment under the modified approach

The modified approach shall be based on the following requirements:

- Equipment shall fully meet the applicable Essential Safety Requirements (ESR) stated in Annex I of the European Pressure Equipment Directive.
  - Owner/work package leader shall demonstrate and document that they have achieved compliance to these Essential Safety Requirements.
  - Full traceability has to be assured, and auditable.
  - Equipment can be, however, exempted from CE marking.
- European harmonised standards shall be used whenever possible in the design, manufacture, inspection and testing of the equipment.
- When the use of harmonised standards is not fully achievable due to the specific features of the project (e.g. use of materials not covered by the harmonised European standards, in-kind contributions from non-EU countries, etc.) the use of ASME Section VIII Div. 2 can in general be applied, taking into account any necessary compensatory measures in view of compliance with the Essential Safety Requirements of the European Pressure Equipment Directive.