Design and Fabrication of the FRESCA2 Cryostat

High Field Vertical Magnet Test Facility (HFVMTF): First Workshop on User Interfaces (FNAL, LBNL)

A. Dallocchio – CERN (EN-MME) with contributions from A. Vande Craen (TE-MSC)

https://indico.fnal.gov/event/57027/

2022-11-21

Outline

NOTE: this talk will focus on the mechanical design, fabrication and assembling of the FRESCA2 cryostat. Some details about cryogenic design and operation will be given. Sample holder, instrumentation and measurement specifications are not in the scope…

- **FRESCA2 Facility: Main Functional Specification**
- **FRESCA2 Cryostat: Mechanical Design Solution**
- **Project Challenges and Organization**
- **Engineering, Calculations and QA-QC**
- **Mechanical Design & Assembly Procedures**
- **Fabrication, Assembly and Installation**
- **Lesson Learnt**

FRESCA2 Magnet – Functional Specification

Nb_3Sn block coil

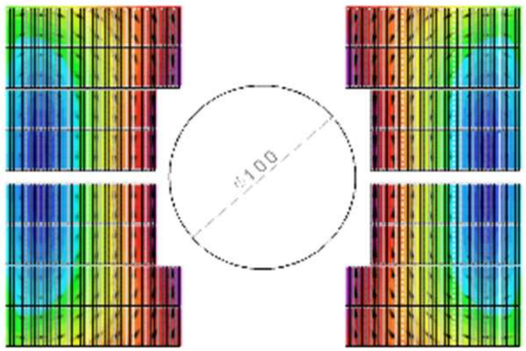
- PIT 192, 1 mm, 63 mH inductance
- 1.03 m ext. Ø, 2.23 m height, mass of 9 t

13 T nominal field

- 1500 mm field length (97 %)
- 100 mm aperture
- 10.9 kA, 4.6 MJ stored energy

CEA – CERN collaboration

Reached 14.6 T



Courtesy of C. Barth and A. Vande Craen
TE-MSC

FRESCA2 Cryostat – Functional Specification

I_c measurements of superconducting cables:

Characterization of Nb_3Sn, NbTi, MgB_2 and HTS cables

- I_c(B, T), splice resistance, NZPV, min. quench energy, T_{cs}
- 13 T / 14 T dipole, 70 kA, 1.9K – 50 K, 80 mm usable Ø
- in-field measurements of large Ø cables
- cable performance at operating conditions of future high field magnets
- T_{cs} measurements after cyclic EM loading ('Sultan'-type tests)

13 T / 14 T (ultimate)

Anti-cryostat (80 mm Ø)

- independent cryo operation
- 4.2 K / 1.9 K / 5 – 50 K
- Double-nested Cryostat

Sample anti-rotation device

- up to 5 kN E.M. torque
- limit rotation to 2° w.r.t. magnetic axis in operation

LHC HTS current leads

- < 0.4 g/s standby
- 1.0 g/s @ 13 kA

Courtesy of C. Barth and A. Vande Craen
TE-MSC

FRESCA2 Cryostat – Cryogenic design

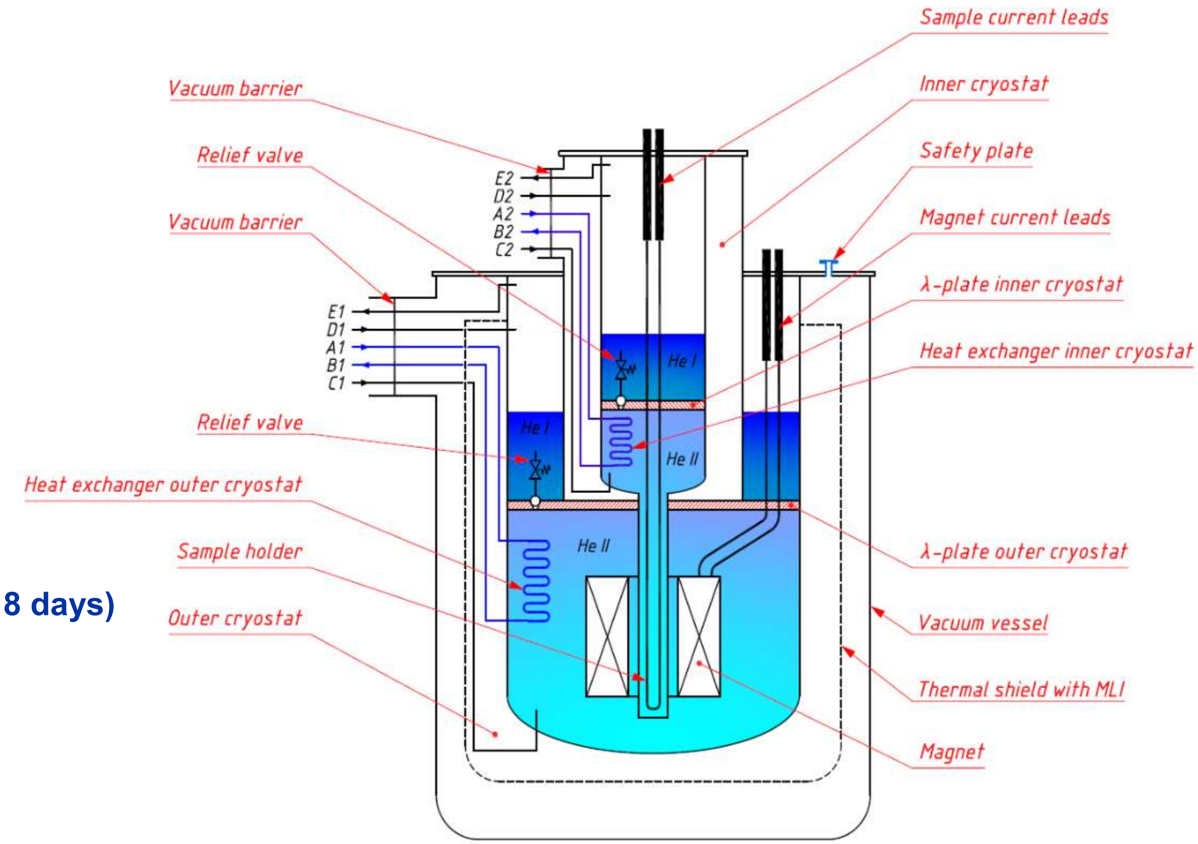
Test station composed of two nested cryostats:

Inner cryostat for sample to characterize

- Operation: 1.9 – 4.3K
- Pressurized helium (1.3 bar)
- **Warm-up, cool-down 1-2 times a week**

Outer cryostat for magnet

- Operation: 1.9 – 4.3 K
- Pressurized helium (1.3 bar)
- **Stays cold all year long (cool-down time 300 K → 4.5 K ~ 8 days)**



Courtesy of A. Vande Craen TE-MSC

FRESCA2 Cryostat – Cryogenic specification

Cool-down time

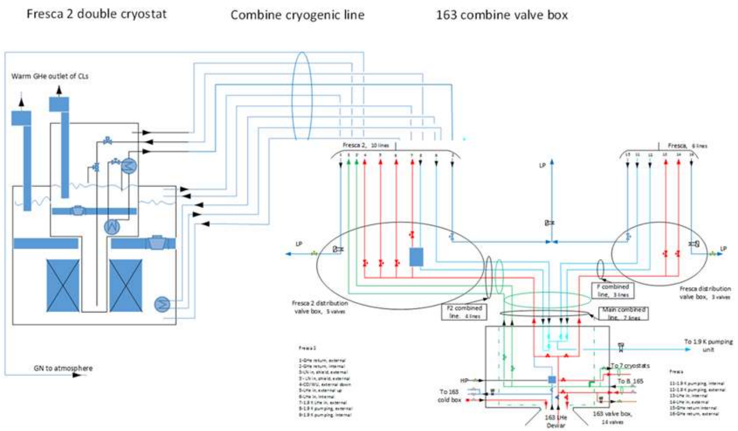
	Magnet	Sample
300 to 4.5 K	8 days (with limitation on magnet T° gradient)	8 h
4.5 to 1.9 K	10 h	2 h

Heat load budget

T° level	Outer cryostat	Inner cryostat
4.5 K (including current leads)	35 W	85 W
1.9 K	Shall allow cooling time and operation with upgraded pumping unit (2 g/s @ 1.8 K)	

Courtesy of A. Vande Craen TE-MSC

FRESCA2 Cryostat – Specific cryogenic features



Dedicated valve box for the test station, connection between the valve box and cryostat through a combined vacuum insulated cryogenic line.

Indium

Vacuum grease

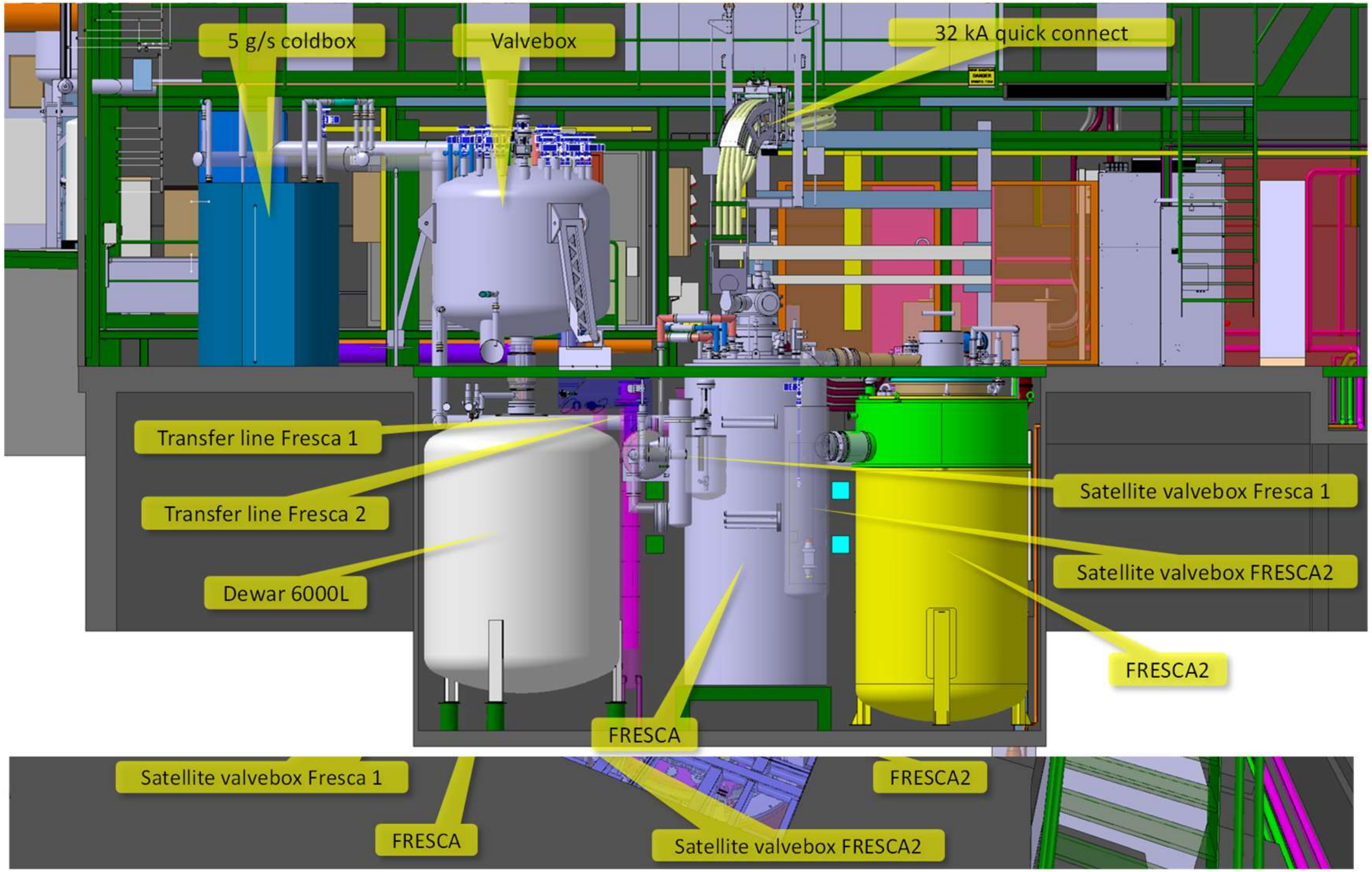
Leak tightness between 4.5 K and 1.9 K complex to achieve on large cryostat with high mechanical force transmission between the components:

- Indium seal where large compression force available
- Vacuum grease where limited compression force available
- Specific feedthrough design

Large heat exchanger to limit cool-down time from 4.5 K to 1.9 K

Courtesy of A. Vande Craen TE-MSC

FRESCA2 Facility @ B163 Superconducting Lab



Courtesy of EN-ACE

FRESCA2 Cryostat: Design Solution

FRESCA-2 cryostat:

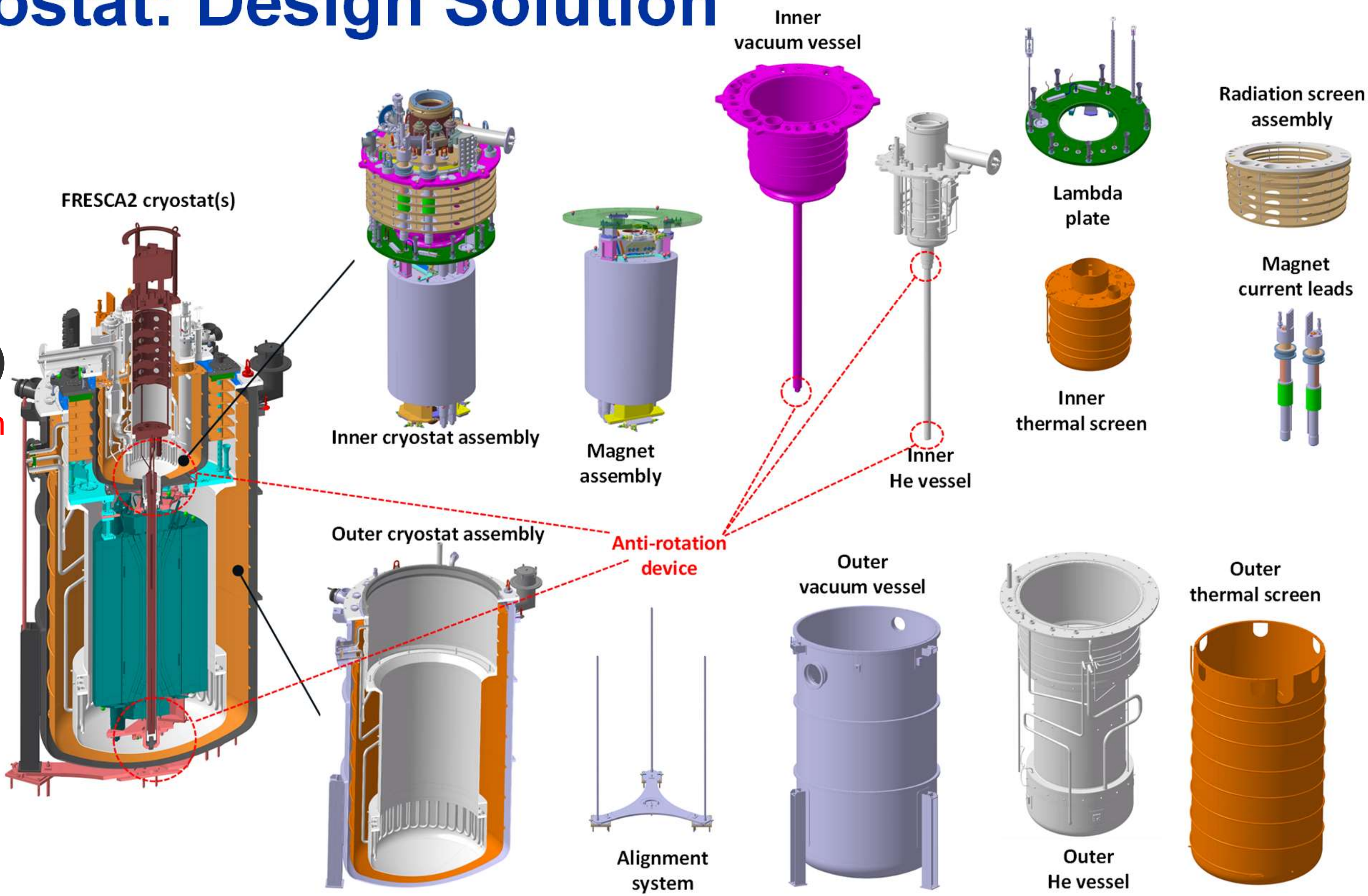
- ~5m height
- ~2m diameter
- >16T weight

Anti-cryostat (Ø 80mm)

- independent cryo operation
- 4.2°K / 1.9°K / 5 ÷ 50°K
- Double-nested Cryostat

Sample anti-rotation device

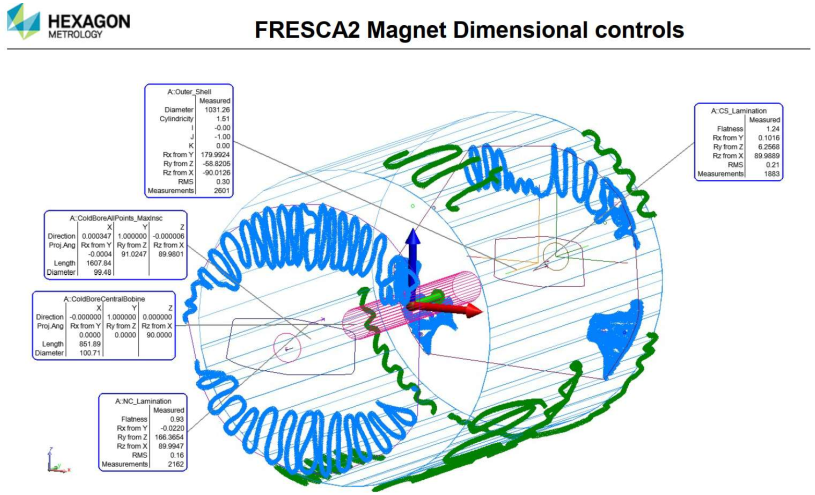
- up to 5 kNm EM torque
- limit rotation to 2° w.r.t. magnetic axis

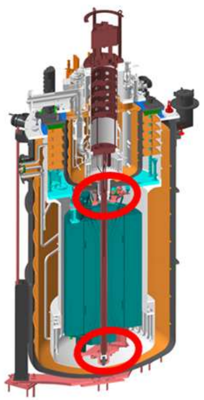


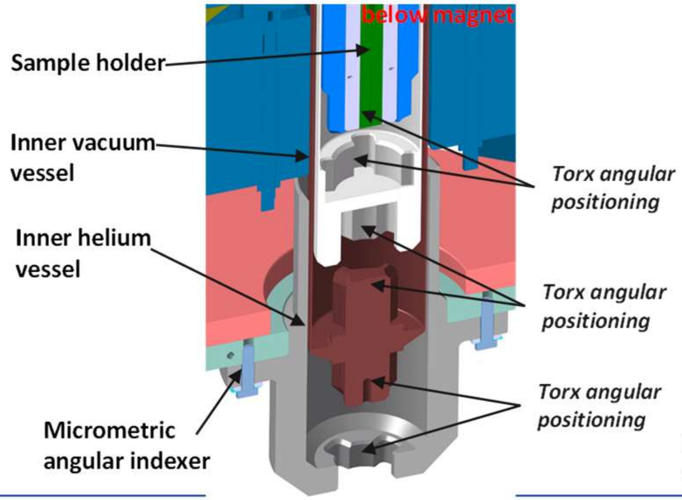
FRESCA2 Cryostat: Anti-Rotation System

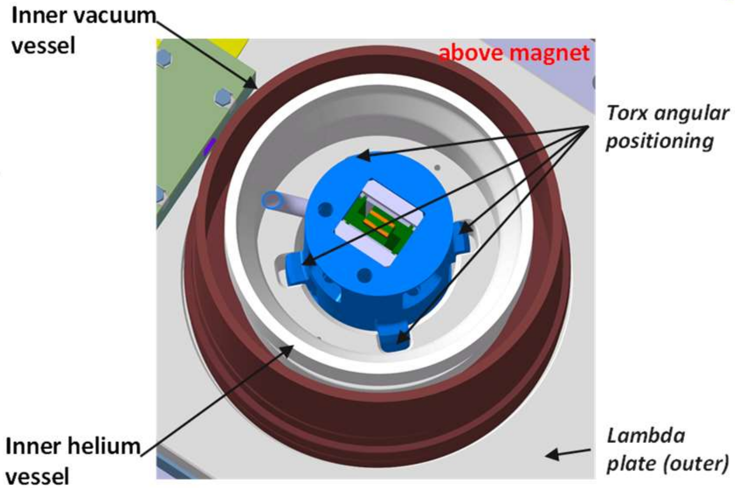
Measurements with different field-sample orientations

- 2 field directions (polarity selection switch: +B & -B)
- 4 sample directions (rotatable insert: 0°, 90°, 180°, 270°)
- up to 5 kNm E.M. torque, limit rotation to 2° w.r.t. magnetic axis
- sample holder rotation locked: below & above magnet
- TORX like system to optimize Hertz contact stress









Main Challenges of the Project

- **Pressure Vessels**
- **Cryogenics**
- **High forces and torques**
- **High precision alignment entailing tight tolerances**
- **Large Dimensions and Heavyweight**
- **Complex and precise assembling with heavy handling**
- **Critical Integration within limited space**

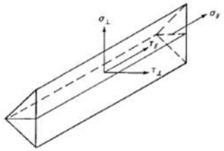
Project Organization

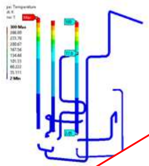
- **Make or Buy Strategy**
- **Pressure Equipment Directive (PED) to design and fabricate the vessels**
- **Identify the “Legal Framework” in agreement with HSE: Equipment Owner, Designer, Manufacturer, Notified Body**
- **Calculation Engineer responsible for a detailed Engineering File including more than 50 calculation reports**
- **Welding Engineer in charge of QA-QC to ensure complete traceability for fabrication following PED**
  - **Material certificates**
  - **Welding map including qualification of welders and of welding procedures (WPS, WPQR…)**
  - **Witness samples, NDTs, specific mechanical tests…**
  - **Traceability of Non-Conformities**
  - **Leak-Tests and Pressure tests**
- **Complete documentation traced on EDMS with pre-defined approval circuit approved by HSE (Welding Engineer managing dozens of documents!)**

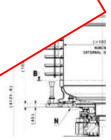
Engineering and Calculations

FRESCA2 Cryostat

- Strength assessment of the vessels — EN 13445-3:2014
- Welding connections — EN 1993 Eurocode 3, EN 13445-3:2014
- Piping — EN 13480-3:2014
- Torque distribution
- Handling transport
- …olted …ction — …ocode 3
- Pressure tests
- Outer and inner thermal screens

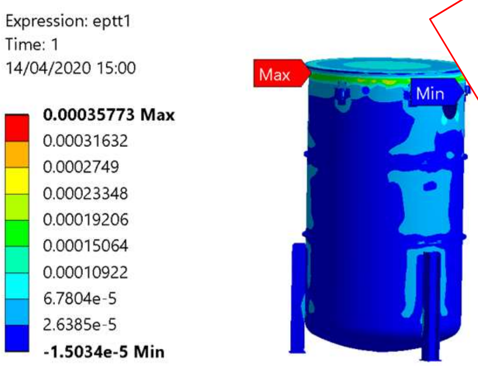


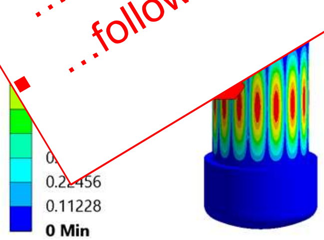


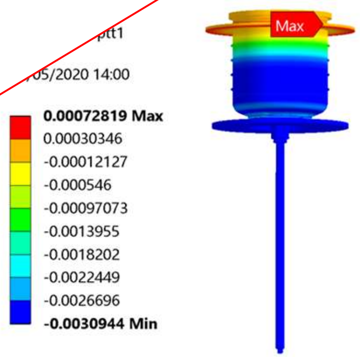


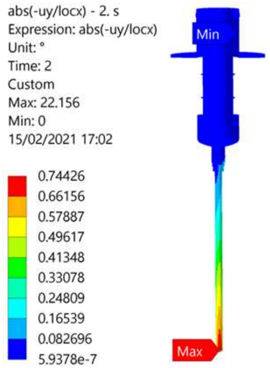
Assessment according to…

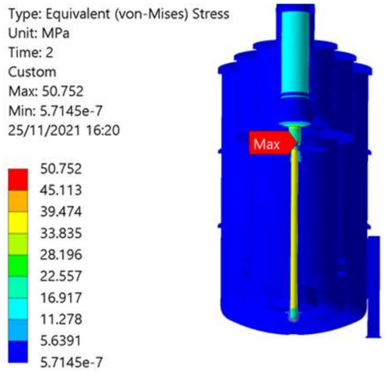
- Outer Vacuum Vessel
- …essel
- Inner Helium Vessel











- Detailed assessment of ALL critical components
- …in ALL relevant conditions
- …following relevant standards

QA-QC for Fabrication

EDMS | Home | Favo

Navigator

No active tags.

[...]

- Fresca 2
  - 2168870 (v.1) Meetings
  - 2168871 (v.1) Calculations
  - 2168872 (v.1) Documents, Spec
  - 2168873 (v.1) Fabrication
  - 2402502 (v.1) Main Assemblies
    - 2402504 (v.1) Outer Vacuun
    - 2402505 (v.1) Outer Helium
      - 2402544 (v.1) Design
      - 2402545 (v.1) Fabricatio
        - 2402839 (v.1) Fabric
        - 2402840 (v.1) Procu
        - 2402841 (v.1) Trace
        - 2402842 (v.1) Materi
        - 2402843 (v.1) Manuf
        - 2402844 (v.1) Formi
          - 2376919 (v.8) W
        - 2402845 (v.1) Non-c
        - 2402846 (v.1) Toolin
        - 2402847 (v.1) Misce
      - 2402546 (v.1) Inspectior
      - 2402547 (v.1) Instrumen
    - 2402506 (v.1) Inner Vacuum
    - 2402508 (v.1) Inner Helium
    - 2402509 (v.1) Outer and Inr
    - 2402512 (v.1) Magnet Asser
    - 2402539 (v.1) Other Compo

Engineering & Equipment Data M

WELDING BOOK / CAHIER DE SOUDAGE : | **FRESCA2 : TANK HELIUM EXTERNE** | REV.: 8 | DATE: 16-Jul-21 | EDMS: 2376919 | JOB: J3062169 | Issued/Réalise: Julien DEBEUX (I.W.E)

Weld Nₒ / N° soudure	Dwg's reference / Références plans de détail	Joint Type / Type de joint	Dimension: Øext. [mm]	Dimension: Thickness [mm]	Dimension: Weld dim. [mm]	Dimension: Material	Process / Procédé	WPS / DMOS Descriptif de Mode Opératoire de Soudage	PQR / QMOS Qualification de Mode Opératoire de Soudage	Filler metal / Metal d'apport: Ø & Heat Nₒ / Ø et N° Coulee	Id N° / N° Soudeur: Signature & date	VT (Visual Test) Acceptance Criteria / Niveau d'acceptation: 100% ISO 5817 - Level B	RT (Radiographic testing) Acceptance Criteria / Niveau d'acceptation: ISO 17636-2 - Class B ISO 10675-1 - Level 1	Leak Test / Test d'étanchéité: Report Nₒ / N°Rapport, Signature & date	Pressure Test / Test de pression: Report Nₒ / N°Rapport, Signature & date	Observations
CRNQLKF2Q0006 - OUTER HELIUM VESSEL ASSEMBLY																
W01	CRNQLKF2Q0006	BW	1180	6	s6	EN 1.4306 (304 L) EN 1.4306 (304 L)	141 + 141 TM	2020-137-FW	EN-SA-21-0665	Ø 1.2 / 0.8 N°Coulee: 105597 / 100819	N°: 1329 Date: 21/06/2021	Ref.: J. DEBEUX Date: 23/05/2021	Ref.: 40%+Intersections EDMS 2575729 Date: W01 : 23/06/2021 (NOK) W01R1 : 01/07/2021 (OK)	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	Undercut on root side detected by radiographic testing on W01. W02R1 consists in back run by manual TIG on non acceptable areas
W02	CRNQLKF2Q0006	BW	1180	6	s6	EN 1.4306 (304 L) EN 1.4306 (304 L)	141 + 141 TM	2020-137-FW	EN-SA-21-0665	Ø 1.2 / 0.8 N°Coulee: 105597 / 100819	N°: 1329 Date: 21/06/2021	Ref.: J. DEBEUX Date: 23/06/2021	Ref.: 40%+Intersections EDMS 2575729 Date: W02 : 23/06/2021 (NOK) W02R1 : 01/07/2021 (OK)	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	Undercut on root side detected by radiographic testing on W01. W02R1 consists in back run by manual TIG on non acceptable areas
W03	CRNQLKF2Q0006	BW		6	s6	EN 1.4306 (304 L)	15 + 141 TM	2020-66-FW	EN-SA-20-0880 EN-SA-20-1078	Ø 0.8 N°Coulee: 100819	N°: 1329 Date: 30/10/2020	Ref.: J. DEBEUX Date: 04/12/2020	Ref.: 100% EDMS 2575729 Date: 07/12/2020	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W04	CRNQLKF2Q0006	BW		6	s6	EN 1.4306 (304 L)	15	2020-67-FW	EN-SA-20-0880	Ø N°Coulee:	N°: 1329 Date: 05/11/2020	Ref.: J. DEBEUX Date: 04/12/2020	Ref.: 100% EDMS 2575729 Date: 07/12/2020	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	1 production test done : EDMS 2402848 (see 2020-65-FW, the name of WPS changed)
W05	CRNQLKF2Q0006	BW	28	1.5	s1.5	EN1.4404 (316 L) EN 1.4429 (316LN)	141	2020-50-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1481 Date: 20/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: 25% Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W06	CRNQLKF2Q0006	BW	17.2	1.6	s1.6	EN1.4404 (316 L) EN 1.4404 (316L)	141	2020-50-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1481 Date: 13/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: 25% Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W07	CRNQLKF2Q0006	BW	42.4	2	s2	EN 1.4404 (316L) EN 1.4404 (316L)	141	2020-51-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 13/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: 25% Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W08	CRNQLKF2Q0006	BW	33.7	2	s2	EN1.4404 (316 L) EN 1.4404 (316L)	141	2020-51-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 20/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: 25% Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W09	CRNQLKF2Q0006	BW	33.7	2	s2	EN1.4404 (316 L) EN 1.4404 (316L)	141	2020-51-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 20/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: 25% Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W10	CRNQLKF2Q0006	BW	12	2	s2	EN1.4404 (316 L) EN1.4404 (316 L)	141	2020-51-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 14/07/2021	Ref.: J. DEBEUX Date: 15/07/2021	Ref.: 25% EDMS 2575729 Date: 19/07/2021	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W11	CRNQLKF2Q0006	BW	12	2	s2	EN1.4404 (316 L) EN1.4404 (316 L)	141	2020-51-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 14/07/2021	Ref.: J. DEBEUX Date: 15/07/2021	Ref.: 25% EDMS 2575729 Date: 19/07/2021	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W12	CRNQLKF2Q0006	FW (Set-in branch, lip weld) (Piquage emboîté, soudure sur lèvre)	12	2	z2	EN1.4404 (316 L) EN 1.4306 (304 L)	141	2020-52-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 20/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W13	CRNQLKF2Q0006	BW	12	2	s2	EN1.4404 (316 L) EN1.4404 (316 L)	141	2020-51-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 20/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: 25% Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W14	CRNQLKF2Q0006	BW	33.7	2	s2	EN1.4404 (316 L) EN1.4404 (316 L)	141	2020-51-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 20/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: 25% Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W15	CRNQLKF2Q0006	FW (Set-in branch, lip weld) (Piquage emboîté, soudure sur lèvre)	48.3	2	z2	EN 1.4306 (304 L) EN 1.4306 (304 L)	141	2020-52-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 20/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W16	CRNQLKF2Q0006	FW (Set-in branch, lip weld) (Piquage emboîté, soudure sur lèvre)	17.2	1.6	z1.6	EN1.4404 (316 L) EN 1.4306 (304 L)	141	2020-52-FW	EN-SA-20-0882	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 20/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	
W17 to W34	CRNQLKF2Q0006	FW	1180 20	6 7	a2	EN 1.4306 (304 L) EN 1.4307 (304 L)	141	2020-53-FW	EN-SA-20-0881	Ø 1.2 N°Coulee: 105597	N°: 1329 Date: 07/07/2021	Ref.: J. DEBEUX Date: 20/07/2021	Ref.: Date:	Ref.: 909-S30 EDMS 2655793 Date: 27/07/2021	Ref.: CRRP-05373 EDMS 2613188 Date: 29/07/2021	

Mechanical Design Strategy

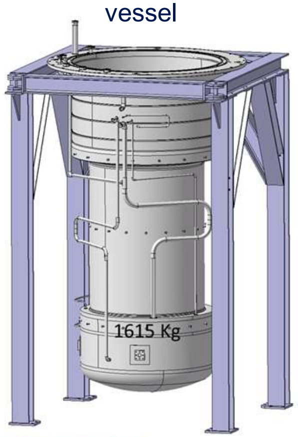
- **Design solution developed in parallel with assembly procedures…**
- **…as well as with assembly and handling tools (EN-HE)**
- **Early involvement of fabrication experts to guarantee feasibility of required tolerances**
- **Careful evaluation of the tolerance "budget" by considering**
  - Functional requirement: alignment of 2^{o} w.r.t. magnetic field
  - Structural deformations (cryo environment and EM forces) in operating conditions via detailed FEM…
  - Fabrication tolerances (sheet-metal forming with precise calibration + high-precision machining) ~50µm
  - Re-machining after welding to guarantee critical references
  - Large dimensions of components
  - Fits and clearances to allow precise assembly ~100µm

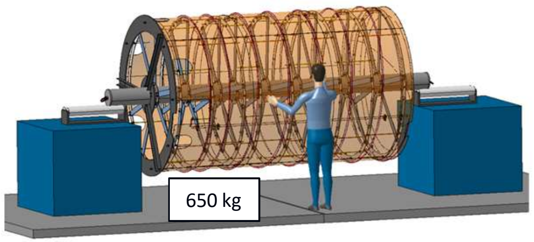
Outer Cryostat Assembly Procedure

1 Main components

Outer vacuum vessel

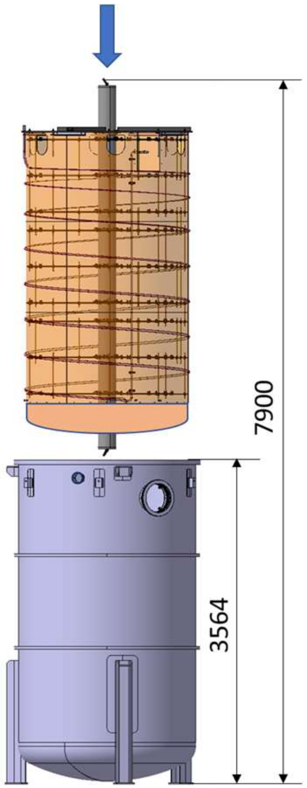
Outer helium vessel



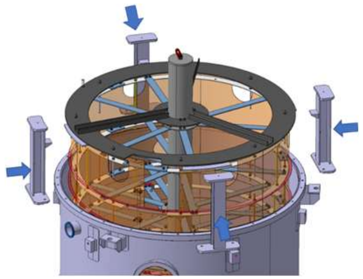


Outer thermal screen

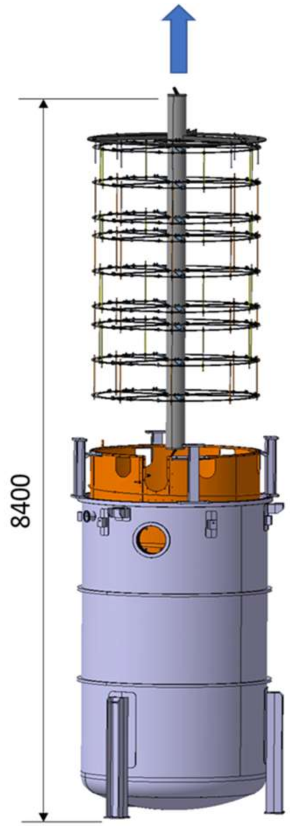
2 Insertion of the thermal screen



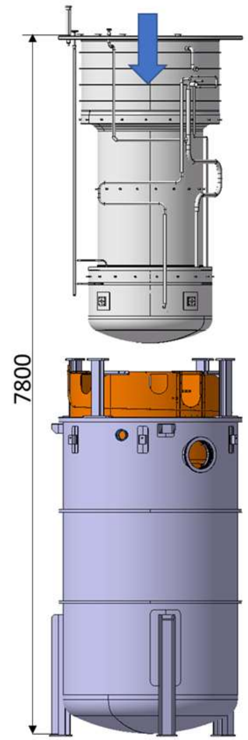
3 Pre-positioning of the thermal screen



4 Removal of the support frame

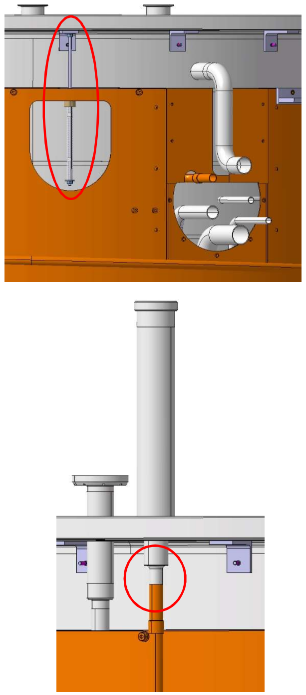


5 Insertion of the outer He vessel

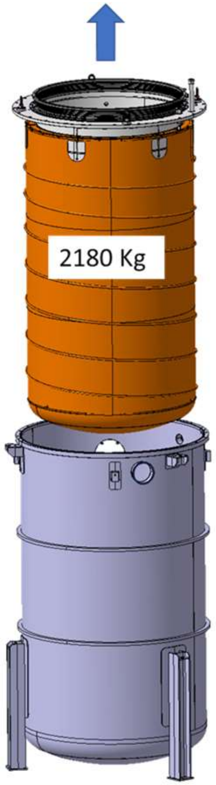


Outer Cryostat Assembly Procedure

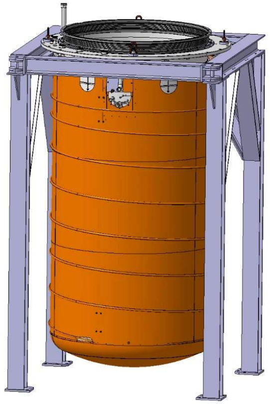
6 Thermal screen suspension system, LN2 welding & large bellow assembly



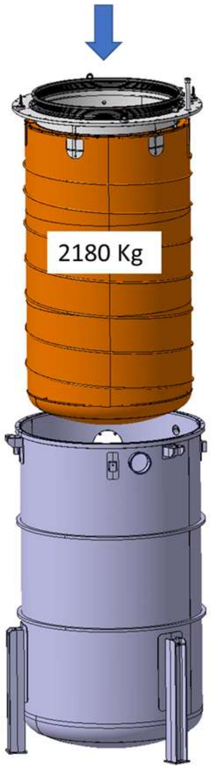
7 Removal of the inner helium vessel assembly



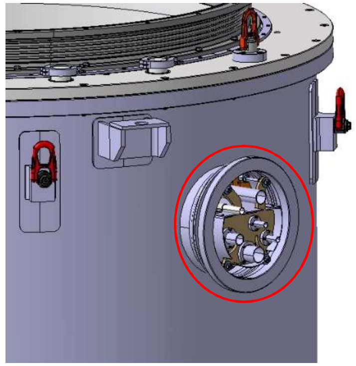
8 Fixation of the MLI



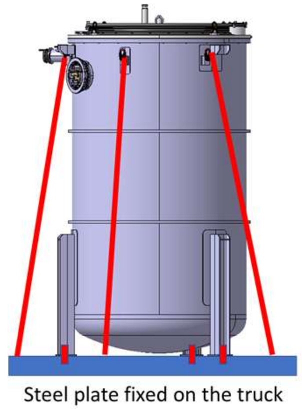
9 Re-insertion of the inner helium vessel assembly



10 Welding of extension tubes for the cryogenic connection & Assembly of the fixed point

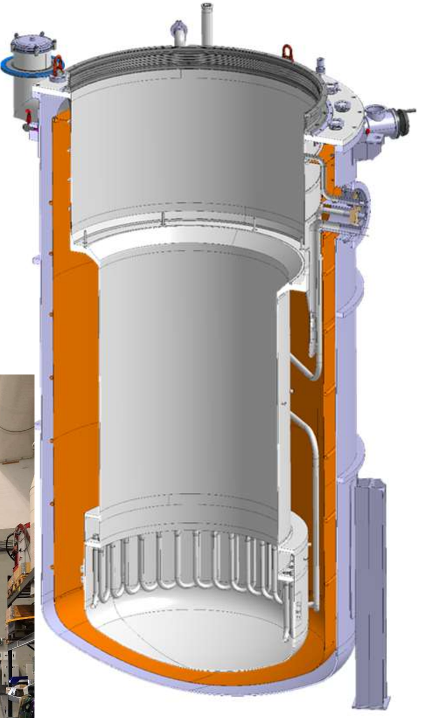


11 Outer cryostat ready for transport



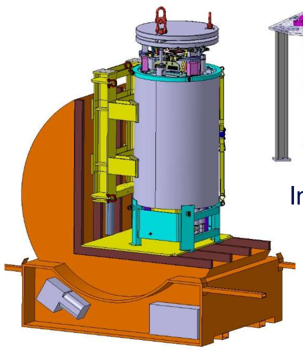
Fabrication of the Outer Cryostat

Fabrication of the Outer Cryostat

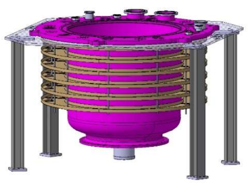


Inner Cryostat Assembly Procedure

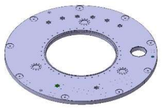
1 Main components



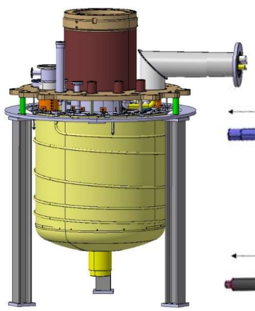
Magnet (9000 kg)



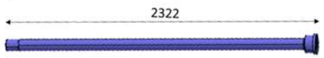
Inner vacuum vessel top part (750 kg)



Lambda plate (Ø1494 mm, 480 kg)



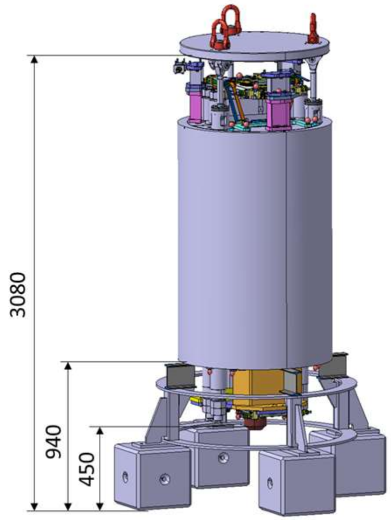
Inner He vessel assembly top part (700 kg)



Vacuum cane (14 kg)

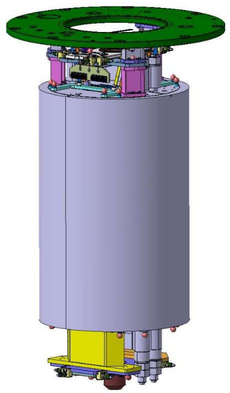
Helium cane (13 kg)

2 Positioning of the magnet on its supports (vertically)

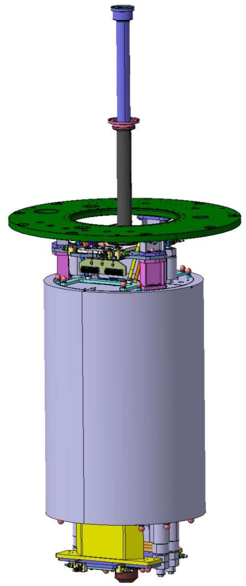


Magnet already equipped with the cane alignment system (centering + torx) at the correct position and angle

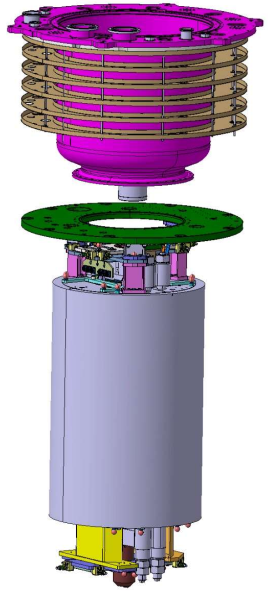
3 Assembly of the lambda plate (horizontal plane & rotation along z axis)



4 Insertion of the canes



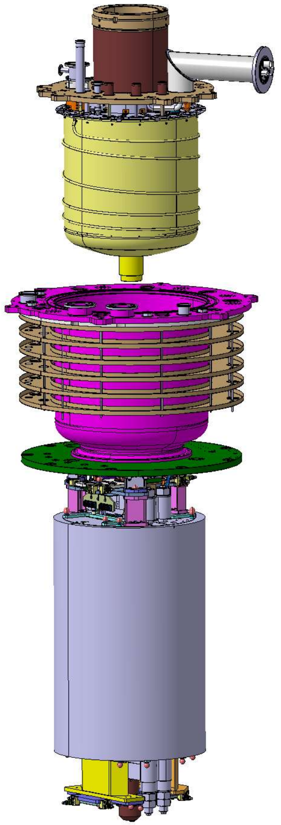
5 Assembly of the inner vacuum vessel



Inner Cryostat Assembly Procedure

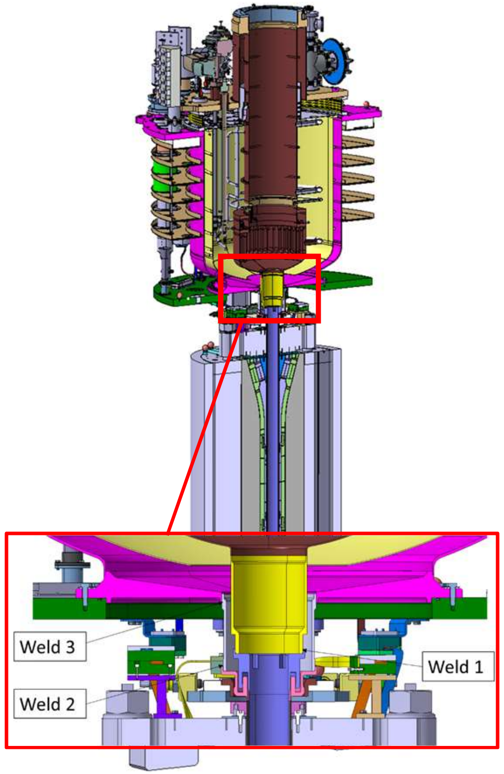
6

Assembly of the inner He vessel



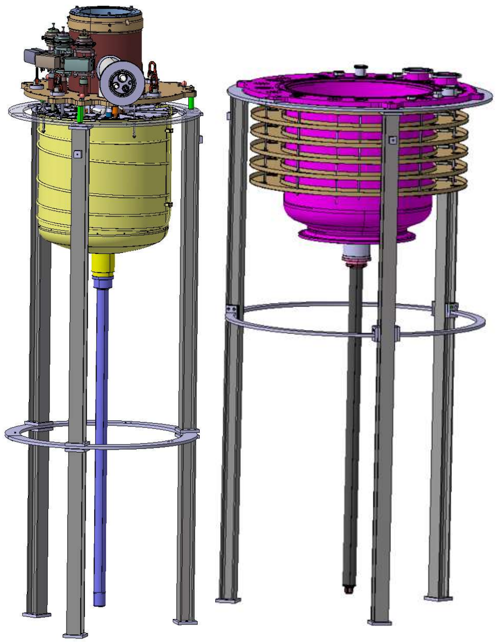
7

Preliminary welding of the canes on vessels



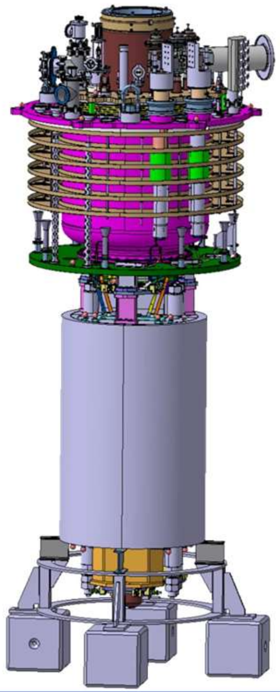
8

Removal of the vessels, final welding of the canes, geometrical check & fixation of the MLI



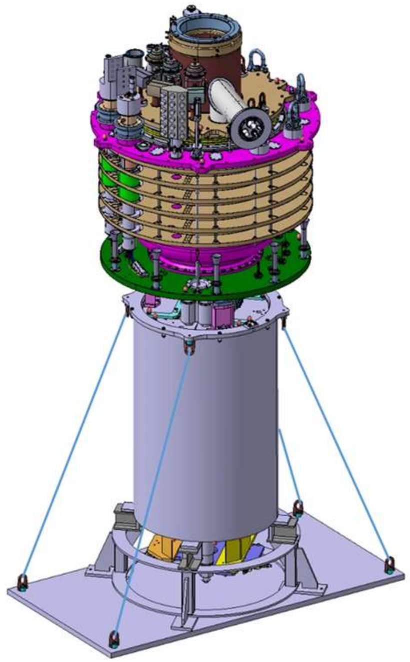
9

Assembly of all components incl. current leads, large bellows, safety devices & instrumentation



10

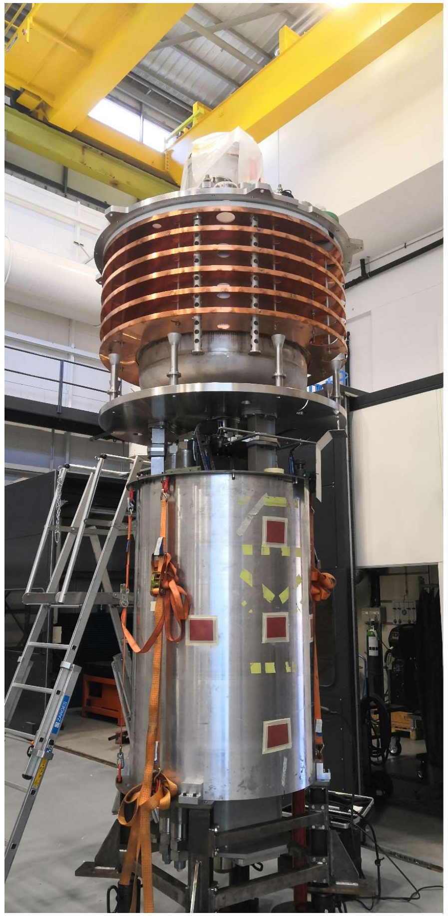
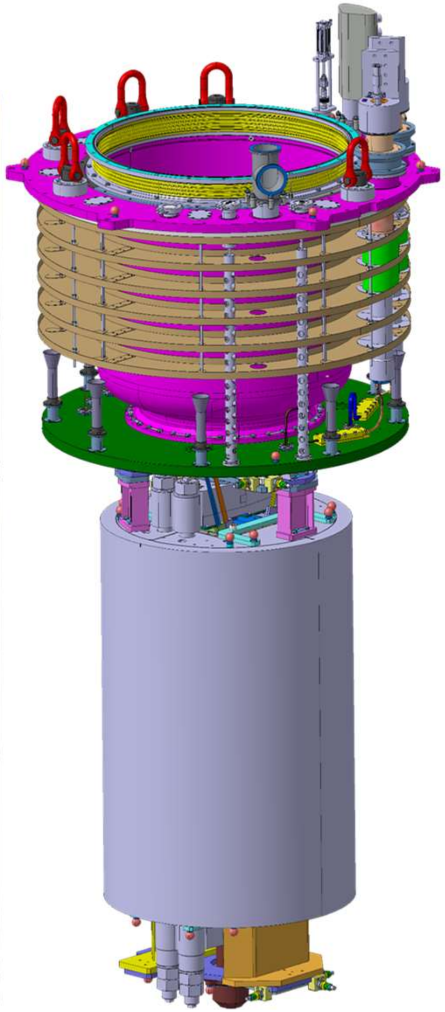
Inner cryostat insert assembly ready for transport



Steel plate fixed on the truck

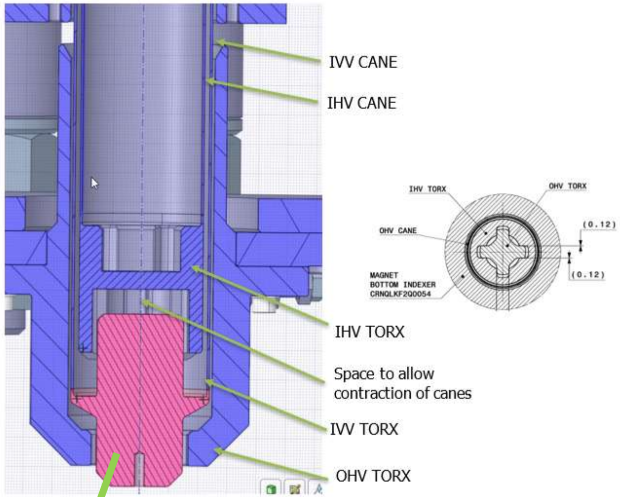
Fabrication of the Inner Cryostat

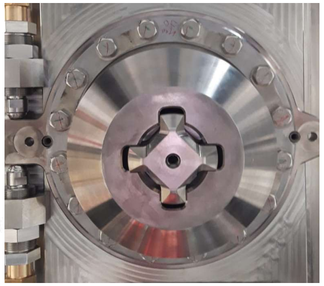


Fabrication of Canes

- **Sheet-metal forming with precise calibration**
- **High precision machining of TORX ends**
- **Surface treatment of TORX ends (Kolsterising ®)**
- **Intermediate re-machining**
- **Intermediate metrology**
- **Specific tool for pre-alignment**
- **Tack welding and EBW**
- **Final Metrology**
- **QA-QC (including NDTs and mechanical tests on mock-up)**
- **Tolerance range 25÷50÷100µm (over >2m)**



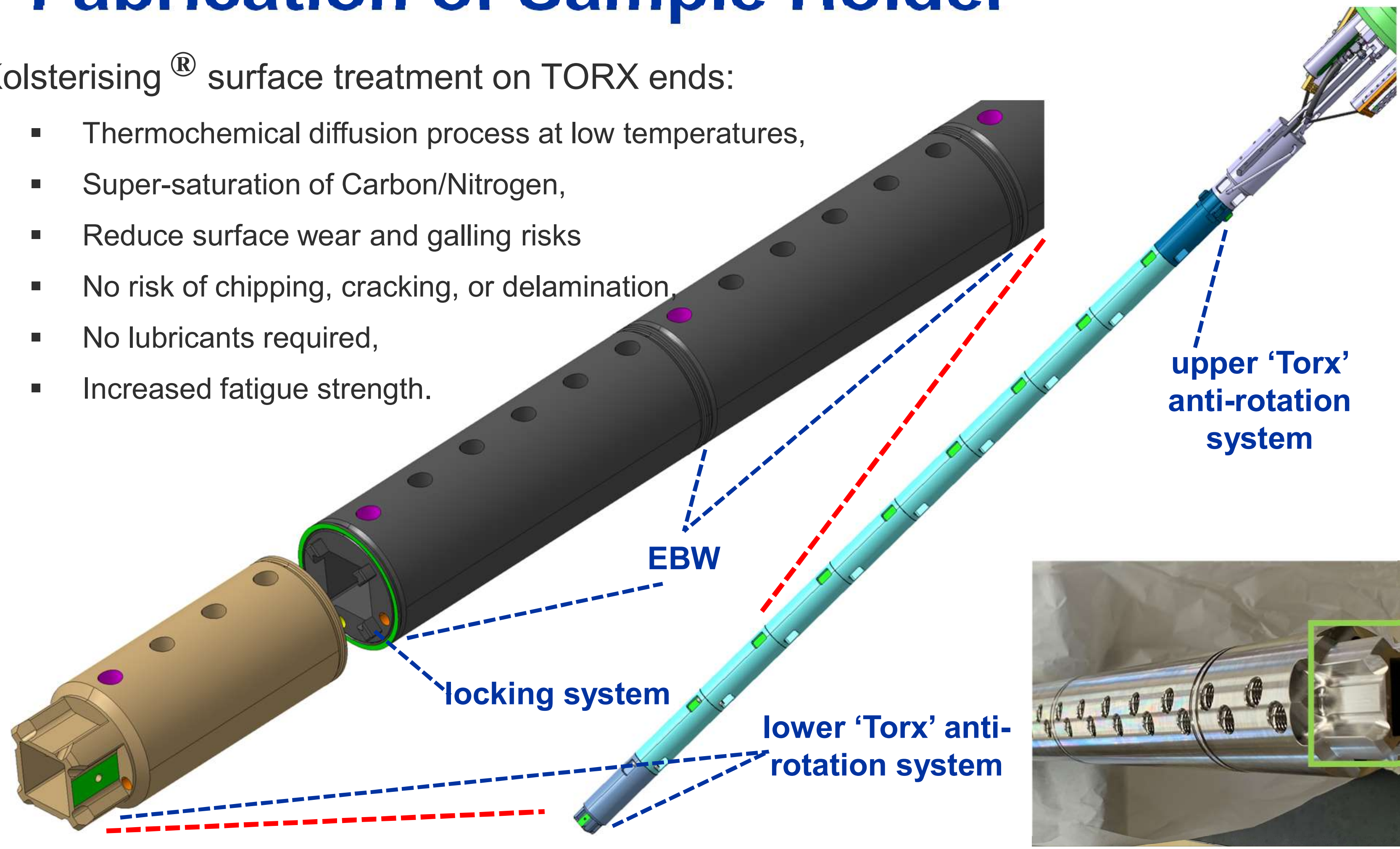


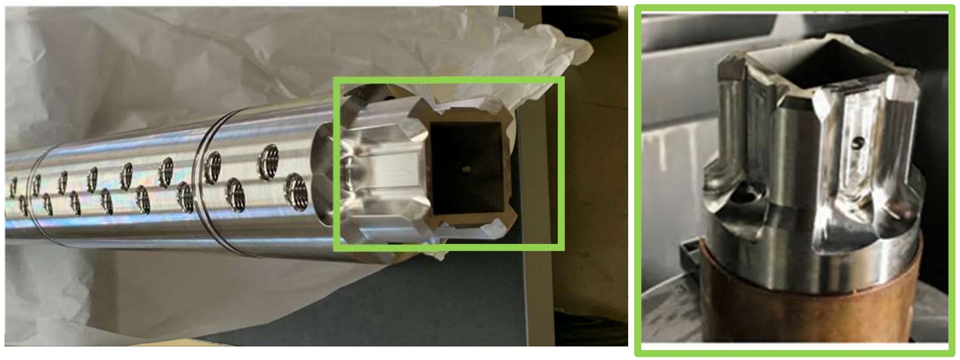
Anti rotation system seen from below

Fabrication of Sample Holder

Kolsterising ® surface treatment on TORX ends:

- Thermochemical diffusion process at low temperatures,
- Super-saturation of Carbon/Nitrogen,
- Reduce surface wear and galling risks
- No risk of chipping, cracking, or delamination,
- No lubricants required,
- Increased fatigue strength.



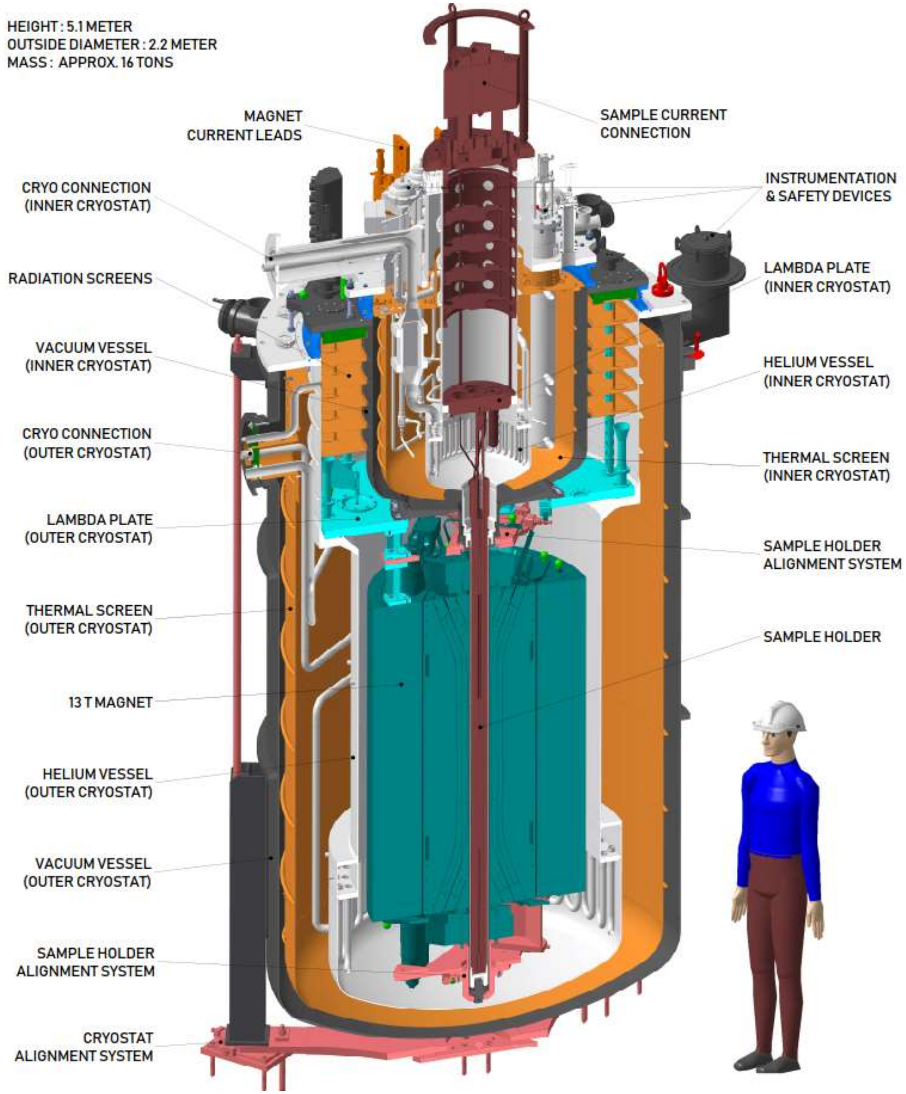


High Precision Machining

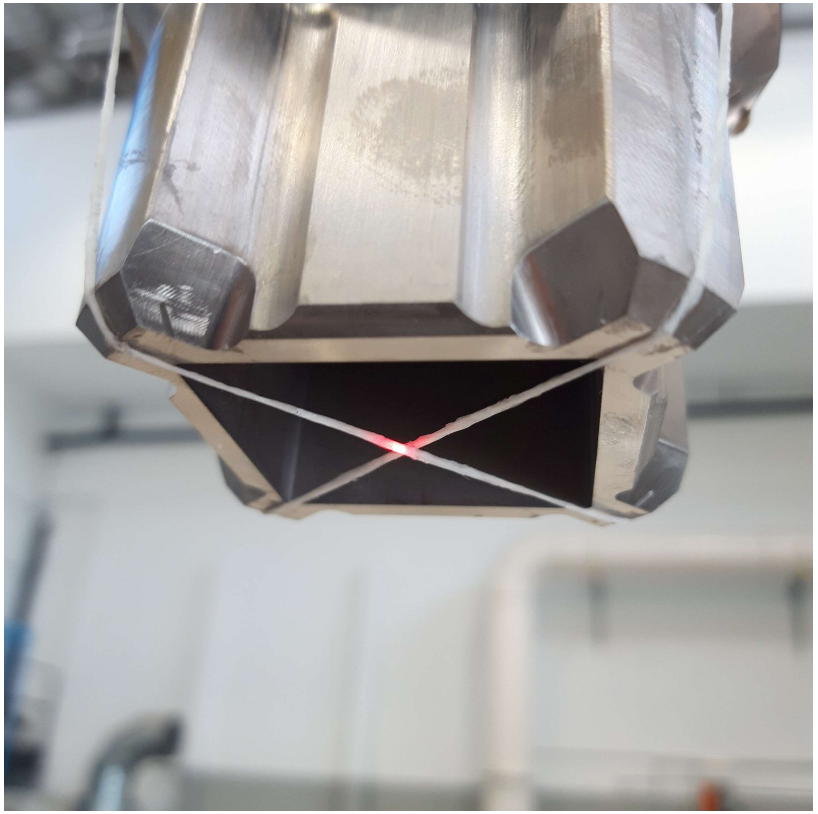
- Re-machining of large components (>2m)
- Development of specific tools
- Tolerance range 50÷100µm

Pressure Tests @ B181

Final Blank Assembly Test



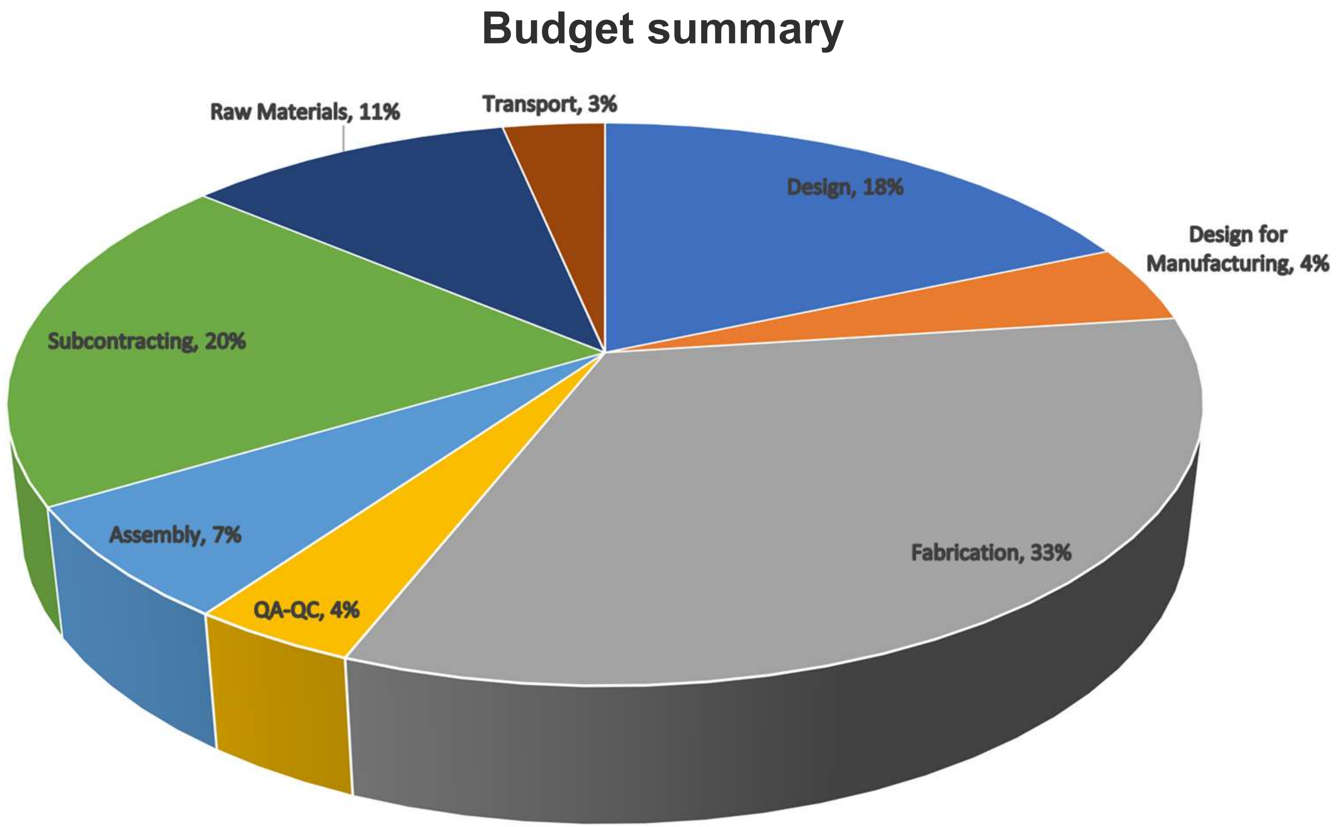
Sample Holder Assembly Test

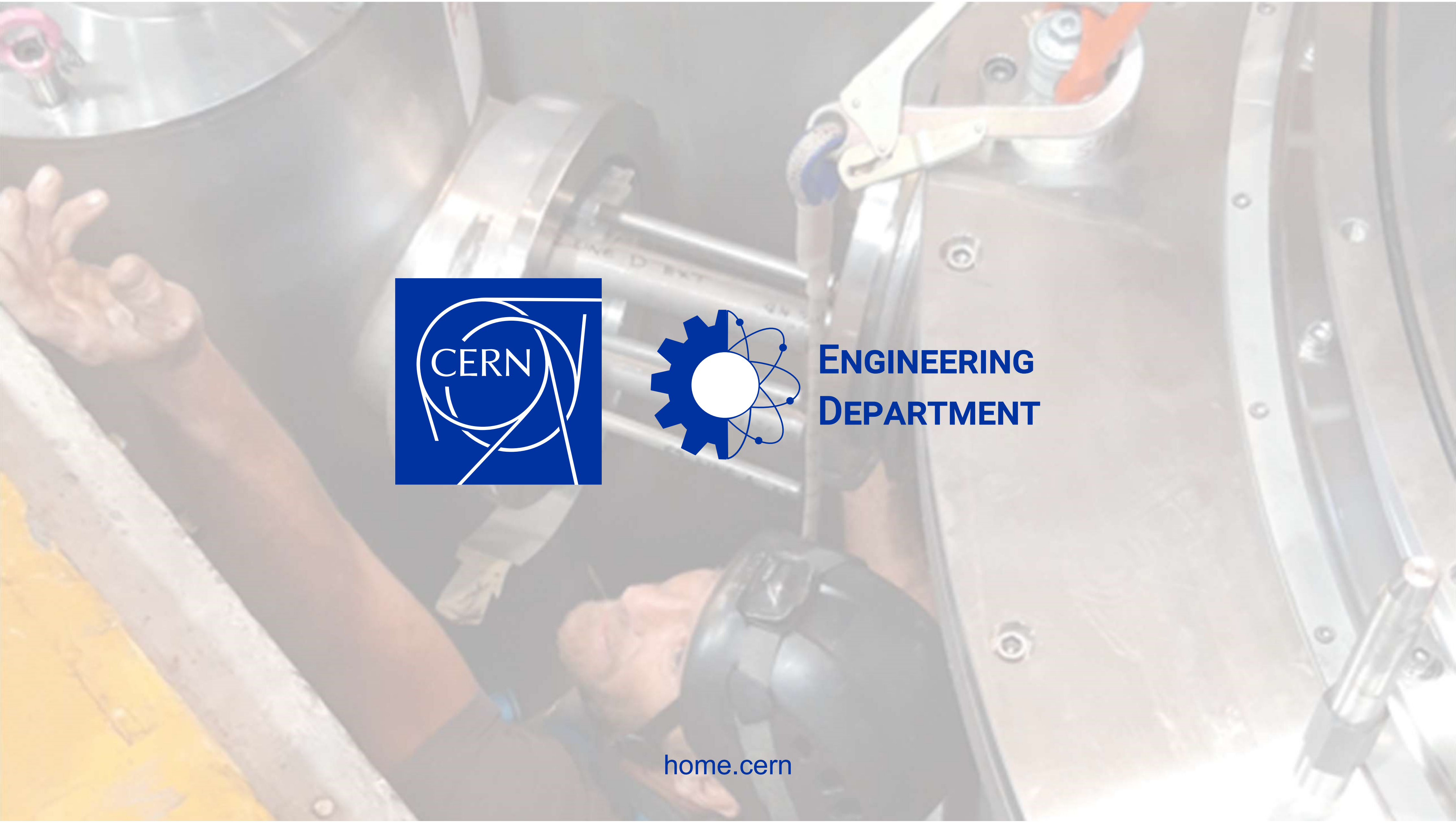


Transport and Final Installation @ B163

Lesson Learnt

- FRESCA2 Cryostat: designed, engineered, fabricated and assembled by EN-MME from May 2019 to November 2021
- Make or Buy strategy: cryostat or complex instrument?
- Early design of the interfaces between the magnet and the cryostat
- Integration between Design and Fabrication…
- Assembly procedures for large components…
- QA-QC and Legal Framework…

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