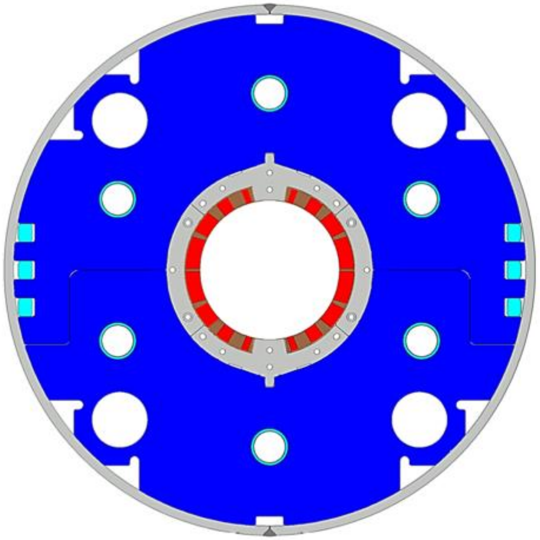
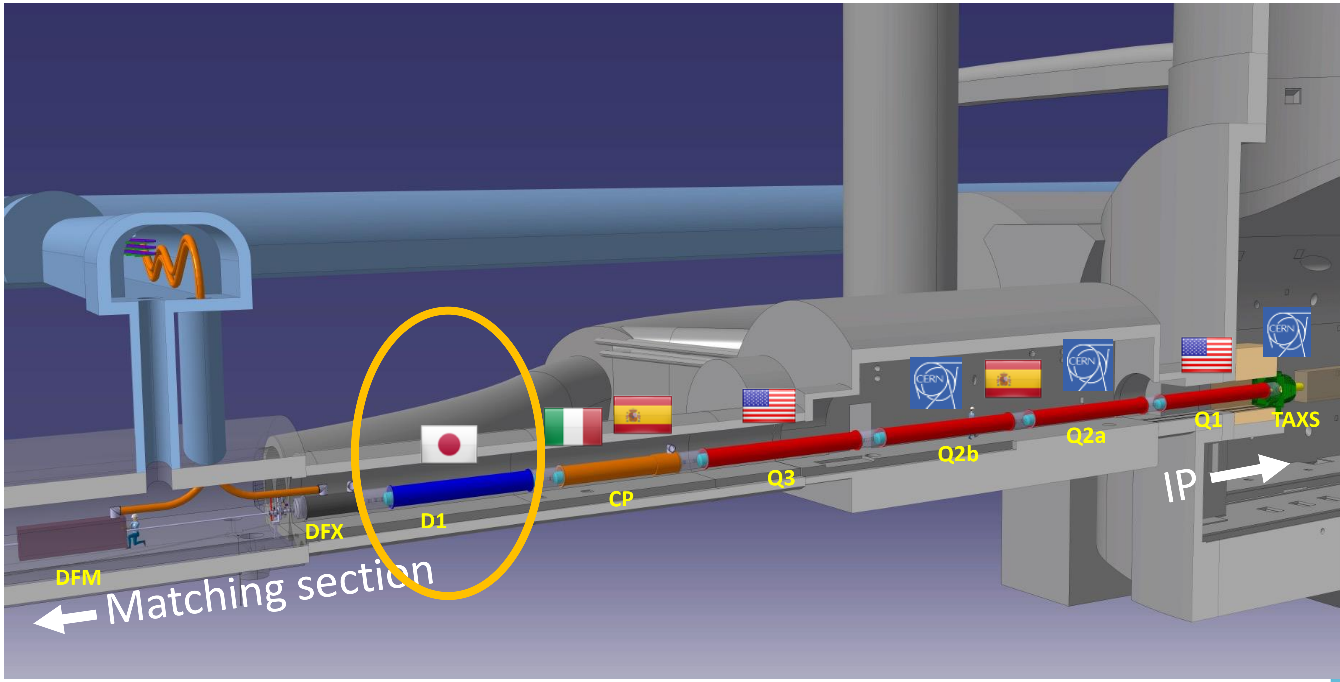
D1 Cold Mass Design and Plans for the Series

Tatsushi NAKAMOTO (KEK)
KEK
On behalf of CERN-KEK Collaboration for D1 Development for HL-LHC

International review on D1 and D2 superconducting magnets for HL-LHC,
CERN, 11-13 March, 2019

Japanese Contribution to HL-LHC: D1 magnets





- Beam separation dipole (D1) by KEK
  - Design study of D1 for HL-LHC within the framework of the CERN-KEK collaboration since 2011.
  - 150 mm single aperture, 35 Tm (5.6 T x 6.3 m), Nb-Ti technology.
  - Development 2-m long model magnets (3 units) at KEK
- Deliverables for HL-LHC
  - *1 full-scale prototype cold mass (MBXFP)*
  - *6 series cold masses (MBXF1-6)*

7 units x 7-m long cold masses

MOU's

- MOU's were signed on July 6, 2018 at MEXT, Tokyo, in presence of Dr. Isogai, Director General of Research Promotion Bureau, MEXT.

EDMS 17655515 V1.0

MEMORANDUM OF UNDERSTANDING
FOR COLLABORATION IN THE HIGH LUMINOSITY LHC PROJECT
AT CERN

BETWEEN: THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH ("CERN"), an Intergovernmental Organization having its seat at Geneva, Switzerland, as the Host Organization of the High Luminosity LHC project ("HL-LHC Project");

AND: THE INSTITUTES, LABORATORIES, UNIVERSITIES AND THEIR FUNDING AGENCIES AND OTHER SIGNATORIES OF THIS MEMORANDUM OF UNDERSTANDING,

KN4074/TE/HL-LHC

ADDENDUM

to

THE MEMORANDUM OF UNDERSTANDING FOR COLLABORATION IN THE HIGH LUMINOSITY LHC PROJECT AT CERN

between

THE INTER-UNIVERSITY RESEARCH INSTITUTE CORPORATION,

HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION (KEK)

and

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

concerning

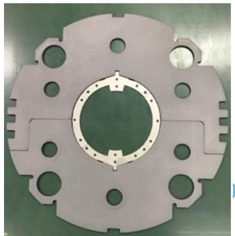
Collaboration in the construction of the superconducting separation dipole magnet D1 in the framework of the High Luminosity upgrade for the LHC at CERN

2018

Overview of Production of D1 Prototype and Series

- In-house development of 2-m model magnets so far.
  - Design, drawings, fabrication processes are available. Preparation for 7-m long magnets has started.
    - ✓ Fine tuning of cross section will be applied to the prototype.
  - Asset for 7-m magnets:
    - ✓ 7m long coil winding machine NEW!
    - ✓ 2 x 3.6m long hydraulic press
    - ✓ Fine-blanking dies for collar and yoke
    - ✓ 50% of stainless steel (NSSC130S) for the whole project
- Production of 7-m cold masses (prototype and series) by a manufacturer.
  - Involvement of Japanese firms already in model magnet development:

    >> smooth technical transfer, accurate (lower) cost estimate.

Overview of Production of D1 Prototype and Series

- **Very tight time frame for the prototype cold mass: delivery by Dec. 2020.**
  - Already 6 weeks delay for bidding process from the original schedule.

- Raw materials procured by KEK: timely provision to the manufacturer.
  - Due to some financial reasons, most of raw-materials for the magnet and the cold mass will be procured and provided by KEK.
    - Low cobalt iron and stainless steel, radiation resistant GFRP.

- Supplies from CERN:
  - insulated SC cables,
  - base laminates of QPH
  - HX tubes
  - insulated beam tubes
  - end-covers
  - Extremity parts such as flare flanges (under discussion).

Agreement of money transfer using Mixed Flow Budget Code in preparation.

Open Tender

- **Initial contract: multi-year contract covering prototype and 4 series cold masses.**

  * See schedule in *page 8*.

- **Bidding schedule**

  Feb. 26: Call for tender

  Mar. 1: Explanatory meeting for tender

  April 19: Deadline of bidding

  Technical Review

  *CERN HSE will cover QMS for PV.

  May 24: Bid opening

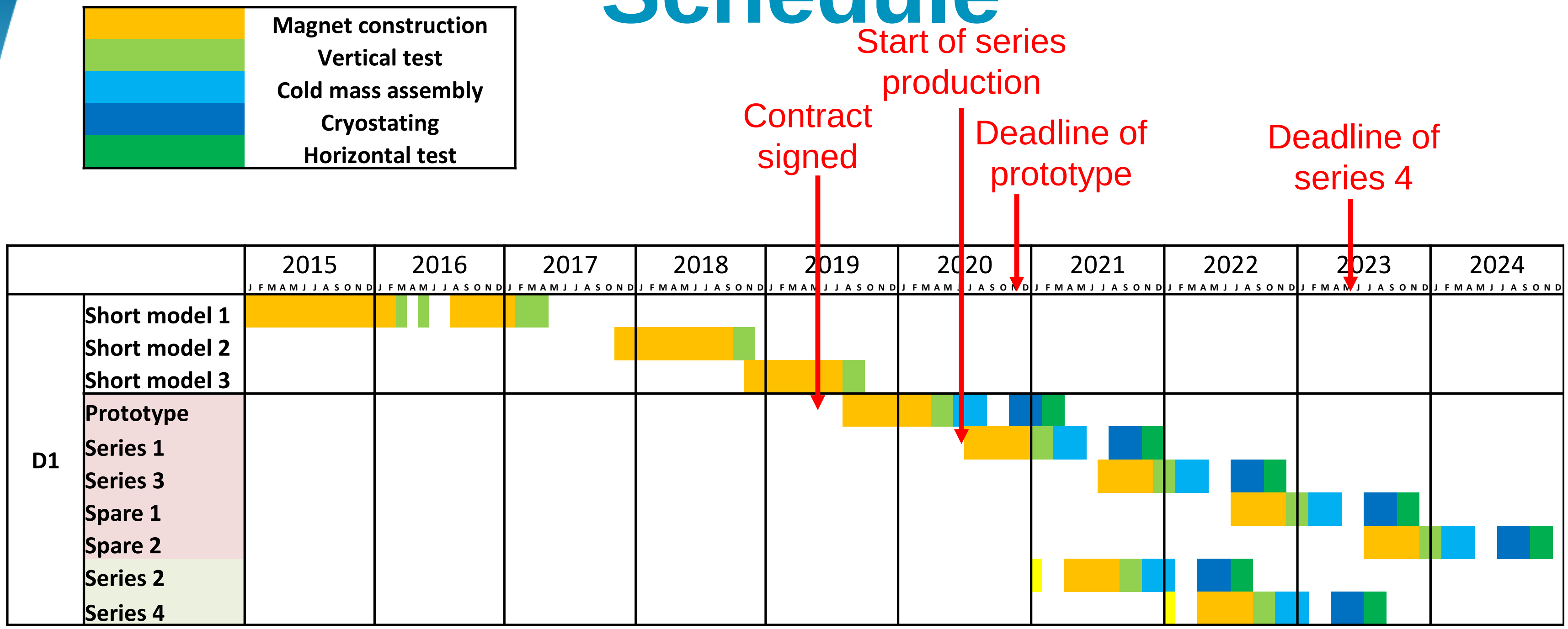
- **Next contracts for last 2 series cold masses are expected in JFY 2021 and 2022.**

Items of Technical Review for Open Tender

1. Bidder's own Technical Specification based on the Technical Specification provided by KEK
2. Proof of technical capability to produce cos-θ type superconducting accelerator magnets with Rutherford cable.
3. Proof of technical capability to produce large-scale superconducting magnets with a stored energy of 1MJ or larger and with coil internal stress of 100MPa or larger.
4. Proof of technical capability to produce superconducting magnets with sufficient accuracy in fabrication and assembly processes.
5. *Proof of technical capability to produce low temperature pressure vessels.
   - The bidder has to submit proof documents of technical capability to produce the helium pressure vessel (design pressure 2.0MPa_Abs, operating temperature 1.9K) specified in the Technical Specification provided by KEK in compliance with 2014/68/EU Pressure Equipment Directive (PED) with harmonized EN-13445:2014 code or nearly similar construction standard of ASME Boiler and Pressure Vessel Code Section VIII Division 2 with compensatory measures.
6. *Quality Management System for production of superconducting magnet cold masses specified by this Technical Specification
   - The bidder has to submit Quality Management System based on ISO 9001 or more strict standard, and preliminary Quality Plan specified in this Technical Specification. In case of subcontractors involved, the bidder also has to submit the documents describing subcontractor's name, technical capability, task and responsibility in the production.

***Items reviewed by KEK & CERN-HSE**

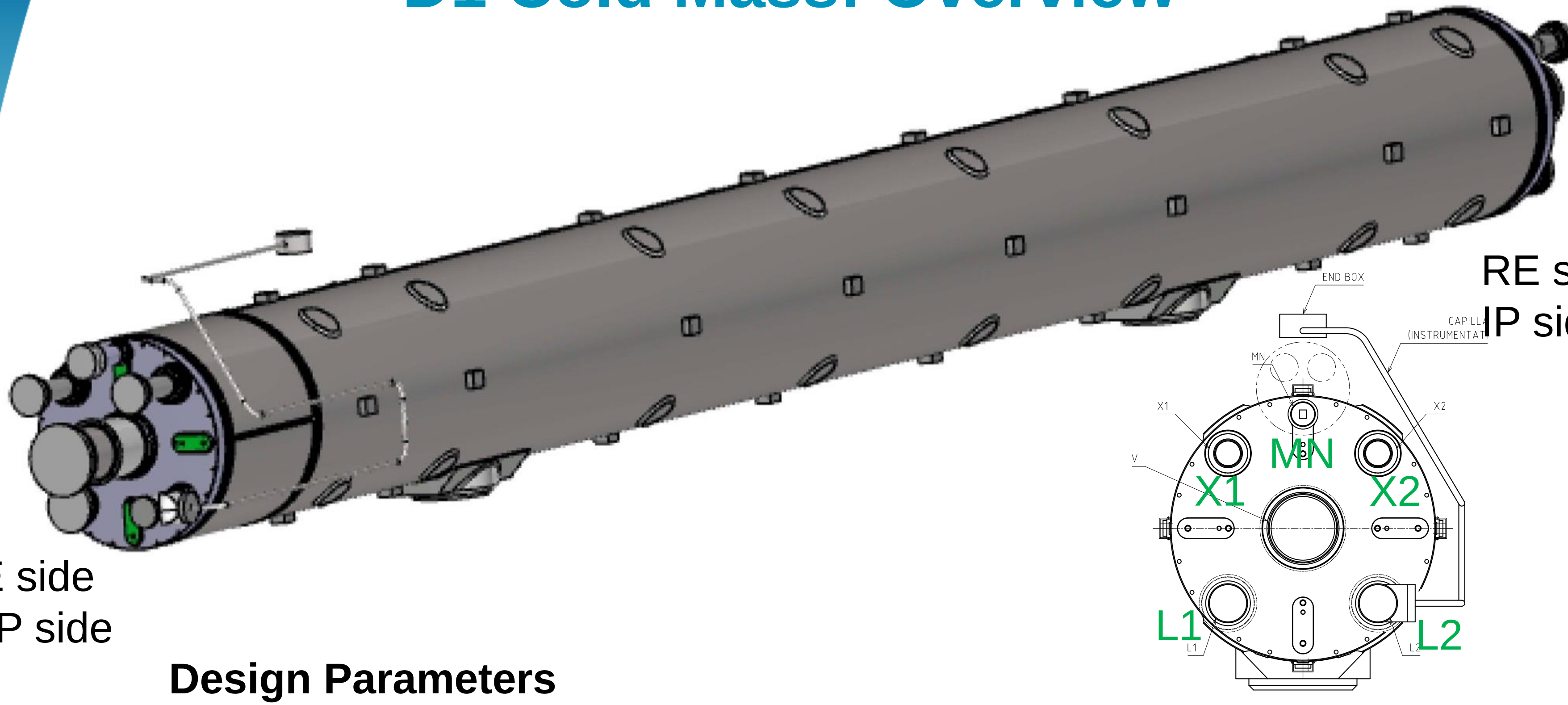
Schedule



- Prototype fabrication has to start before cold test of 3rd Model at Sep. 2019.
- Production of Series 1 will start after the vertical test of Prototype.
- Foreseen milestones: delivery date of cold masses (re-baselined after open-tender)
  - MBXFP (for string test): Nov. 2020.
  - MBXF1-4 (for the HL-LHC machine): April 2023.
  - MBXF1-6 (all): June 2024.

***Practical schedule will be fixed after discussion with successful bidder.**

D1 Cold Mass: Overview



RE side
IP side

LE side
NIP side

Design Parameters

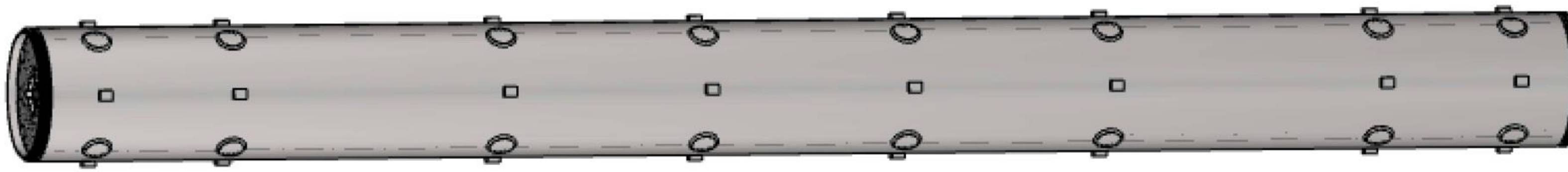
- Design pressure and operating temperature: 2.0 MPa, 1.9 K
- Pressure test at 2.5 MPa
- He leak rate below 1 x 10^{-10} Pa m^3/s
- Cold mass length and distance between saddles: 7370 mm and 3900 mm
- Outer diameter: < 630 mm ➡ Shell OD: 570 mm + markers
- The detail of extremities designed by CERN
  - ➢ Two HeII HX pipes in line with MQXF (X1, X2)
  - ➢ Two HeII conduction lines (L1, L2)
  - ➢ Bus bars interconnection line (MN)

Flow of D1 Cold Mass Production

PV: Pressure Vessel

5 installation of tubes (BT, HXT)

D1 magnet after process ”4” for vertical cold test at KEK



Manufacturer

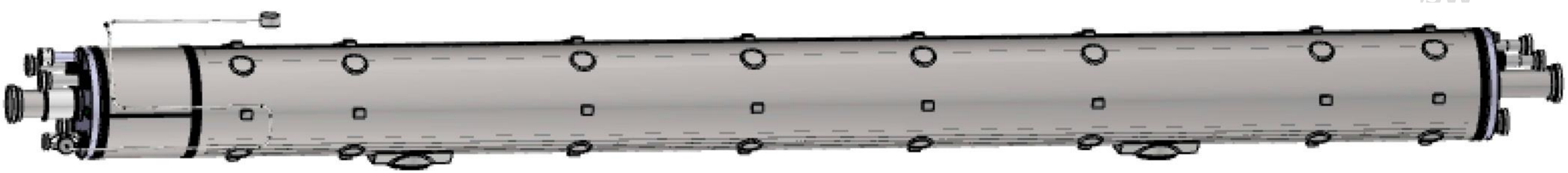
3 yoking

4 shell & end-ring welding, end-plate, splice

inspection incl. pressure test (@ 2.5 MPa)

Delivery

D1 cold mass after process ”5” for shipping to CERN



KEK

vertical cold test

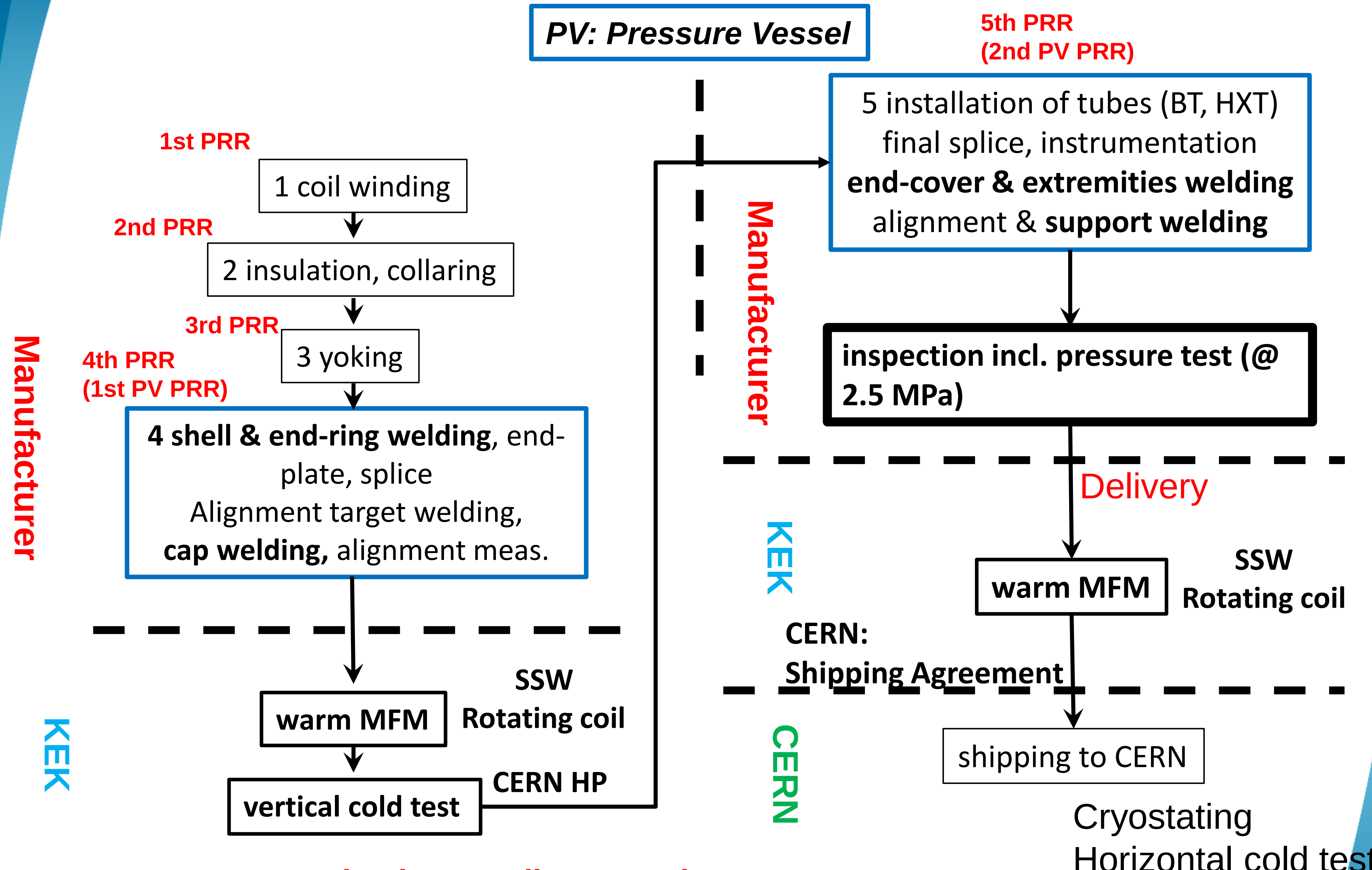
CERN HP

CERN

shipping to CERN

Cryostating
Horizontal cold test

Flow of D1 Cold Mass Production



PRR: Production Readiness Review

Subdivision of PRR is proposed to accommodate very tight schedule.

D1 Cold Mass: Pressure Vessel

Main Body design by KEK (in process "4")

- Two halves of Shell (t10, JIS SUS304L), longitudinal welding w/ insert ring
- End-rings (JIS F SUS304L), circumferential welding
- Shell-cap (JIS SUS304L), circumferential welding
- End-dome (t10, JIS SUS304L), longitudinal welding w/ insert ring

Pipes, End-cover, Extremity design by CERN. Cold mass completed by process "5"

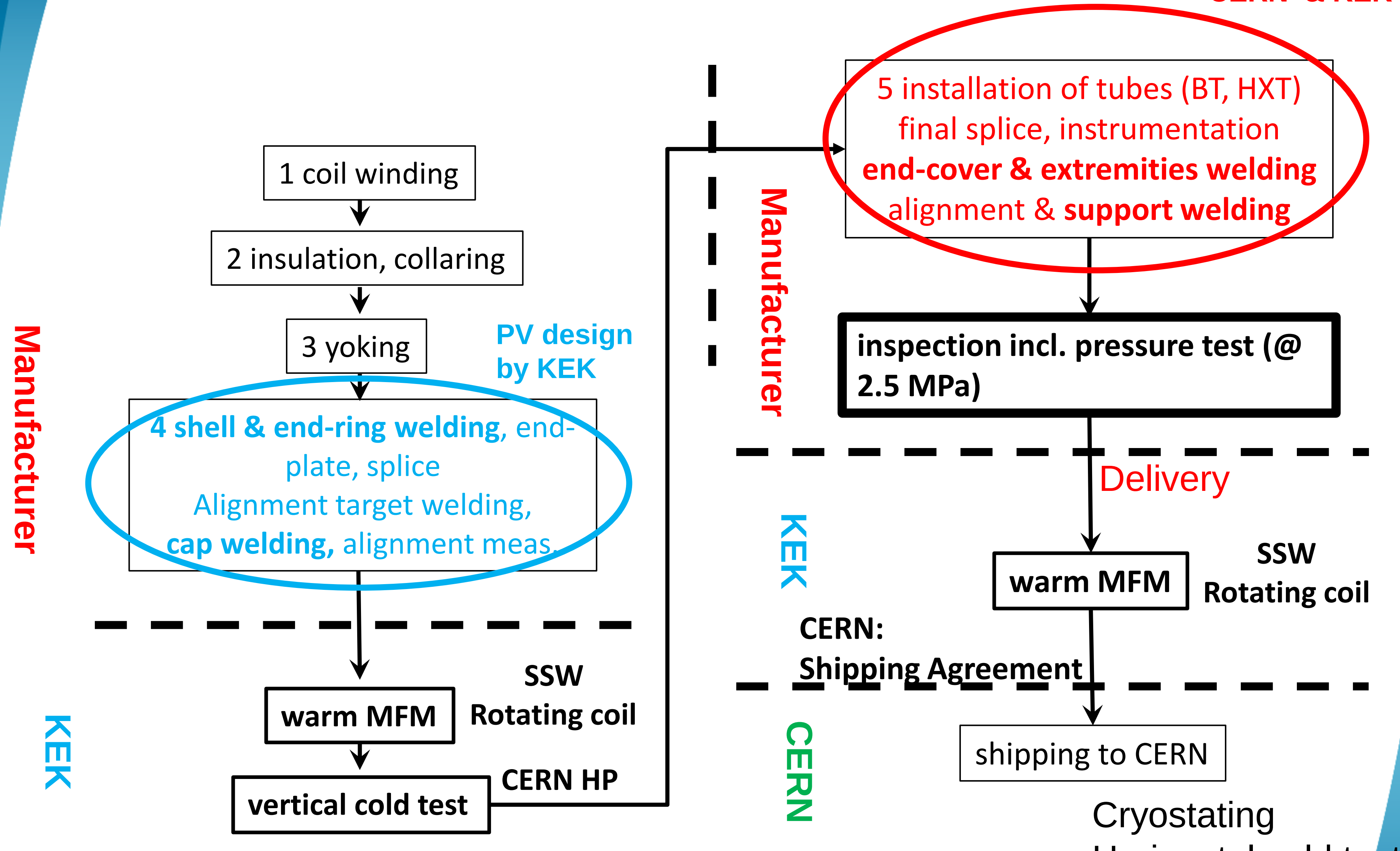
- End cover: Forging EN1.4429, machined.
- Cold bore: EN1.4429
- HeII HX pipes: OFC, 316L
- Capillary pipe for instrumentation wires: 316L
- Flare flanges
- Support saddles

Design work underway!!

Staged design assessment by HSE
for main body in process "4" & for the whole cold mass in "5"

Flow of D1 Cold Mass Production

PV design by CERN & KEK



PRR: Production Readiness Review
PV: Pressure Vessel

D1 Cold Mass: Structural Design Analysis

- **"HL-LHC Superconducting Magnets Compliance with Pressure Equipment Directive (PED 2014/68/EU) Essential Safety Requirements"** (EDMS 1891856, Rev. 4.1)
  - Baseline: 2014/68/EU Pressure Equipment Directive (PED) Essential Safety Requirements (ESR) and harmonized EN 13445 codes
  - Alternative: ***"ASME Boiler and Pressure Vessel Code Section VIII Division 2" in compliance with PED << KEK's baseline***
- Staged design assessment by HSE
  - **For "main body"**
    - ✓ Meeting w/ HSE for preliminary design assessment on Feb. 6, 2019.
      - https://edms.cern.ch/document/2085476/1 (see next pages)
    - ✓ ***Soundness of proposed design, choice of raw materials, welding design and procedure of inspection were confirmed.*** **Final design report is now in preparation.**
    - ✓ Suggestions for inspection of raw materials (***JIS SUS304L and welding consumables***)
      - **Particular Material Appraisal (PMA) with Charpy test at 77K & 4K, and UT**
  - **For "the whole cold mass" including extremities.**
    - ✓ "Pipes, End-cover and Extremity" design by CERN. To be released soon…
    - ✓ KEK will start the total design analysis after receiving the design outcome from CERN.
    - ✓ Need design assessment by September 2019 at latest.

HiLumi HL-LHC PROJECT

Policy of Structural Design of D1 Cold Mass: “Main Body”

A) D1 pressure vessel design is obeyed ASME Sec. VIII Div.2 and Compliance documents supplied by CERN.

B) Structural analysis for the cold mass skin is obeyed ”Elastic Stress Analysis Method” in “DBA” in ASME Section VIII Div.2 Part 5.

C) The shell cap design is proceeded with ”FEM Analysis” and “Experimental method per EN 13445-3:2014 Annex T” and “Hydrotest” under safety factor 5 with respect to service pressure”.

D) Welding design of the pressure vessel is obeyed “ASME Sec. VIII Div.2 Part 4”.

E) Material parameters are referred to “ASME Sec. II PART D (Metric)”.

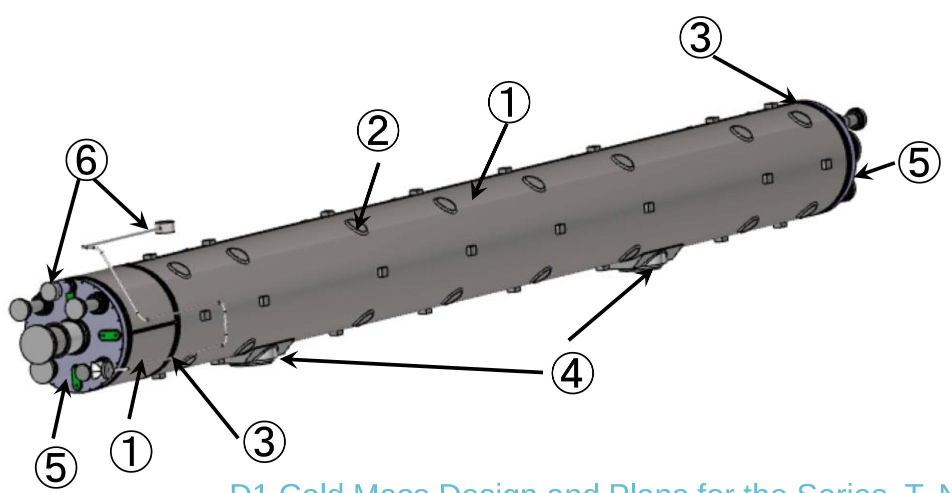
F) Welding rules such as WPS and WPQT are created and referred to “ASME Sec. IX Welding and Brazing and Fusing Qualifications”.

G) “Nondestructive Examination (NDT)” are obeyed “ASME Sec. V + Sec. VIII Div.2 Part 7+EN code”, but the qualification of inspectors are certified by ISO 9712, not certified by ASME.

See detail in Appendix

Applied Code for Structural Design: “Main Body”

PV Parts	ID	Code	Design Method	Remark 1	Remark 2
Shell End-dome	①	ASME BPVC Sec. VIII Div.2 Part 5	Design By Analysis	Welding tensile stress by FEM analysis	
Shell-cap	②	ASME BPVC Sec. VIII Div.2 Part 4		Peak stress on shell cap by FEM analysis	
				“Experimental method per EN 13445-3:2014 Annex T” and “Hydrotest” under safety factor 5 with respect to service pressure”	
End-ring	③	ASME BPVC Sec. VIII Div.2 Part 4			
Support saddle	④	**Design by CERN**		Design outcome and WPS will be provided by CERN.	
End-cover	⑤				
Cold bore, HX pipe and extremity	⑥				“Experimental method per EN 13445-3:2014 Annex T” and “Hydrotest” under safety factor 5 with respect to service pressure" for flare flange weld.
Capillary tube and end-box					



Results of Stress validation for LC1: “Main Body”

Load Case 1 (LC1): ***Design load (=Operation load)***
Design pressure : P = 2.0 MPa
Axial force to end-ring: $F = F_a + F_b$ =70 kN + 30 kN
Cold-mass weight : W =140 kN
Operation temperature : 1.9 K
With electric magnetic force : Full excitation

Stress validation for LC 1

Load case 1 (LC 1)						
	σ_{i-axis} (MPa)			σ_{eq} (MPa)		
	1 (r)	2(θ)	3(z)			
$P_m = P_m^{(1)}+P_m^{(2)}+P_m^{(3)}$	-2.0	56.0	38.1	51.4	$P_m < S$ (115MPa)	**Good**
P_L	0.0	0.0	5.9	5.9	$P_L < S_{PL}$ (172.5MPa)	**Good**
$P_L + P_b$	0.0	0.0	5.9	5.9	$P_L + P_b < S_{PL}$ (172.5MPa)	**Good**
$Q_m = Q_m^{(1)}+Q_m^{(2)}$	7.0	318	0.0	315	-	**-**
$P_L+P_b+Q_m$	7.0	318	5.9	312	$P_L+P_b+Q_m < S_{PS}$ (345MPa)	**Good**

Results of Stress validation for LC2: “Main Body”

Load Case 2 (LC2): ***Test load***

Test pressure : P = 2.5 MPa

Axial force to end-ring: $F = F_a$ =70 kN

Cold-mass weight : W =140 kN

Test temperature: Room temperature (300 K)

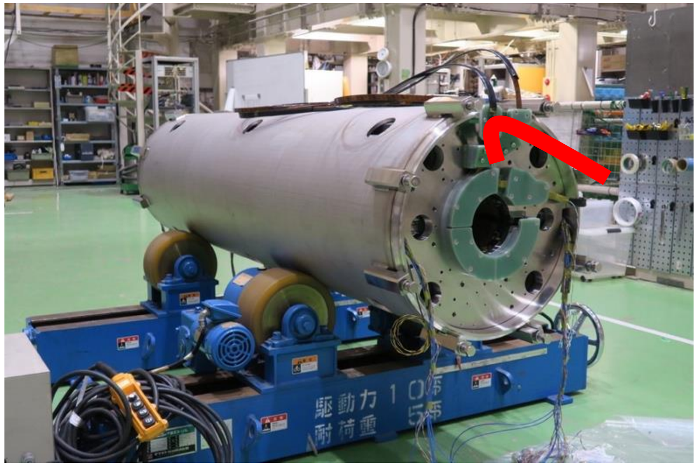
Without electric magnetic force

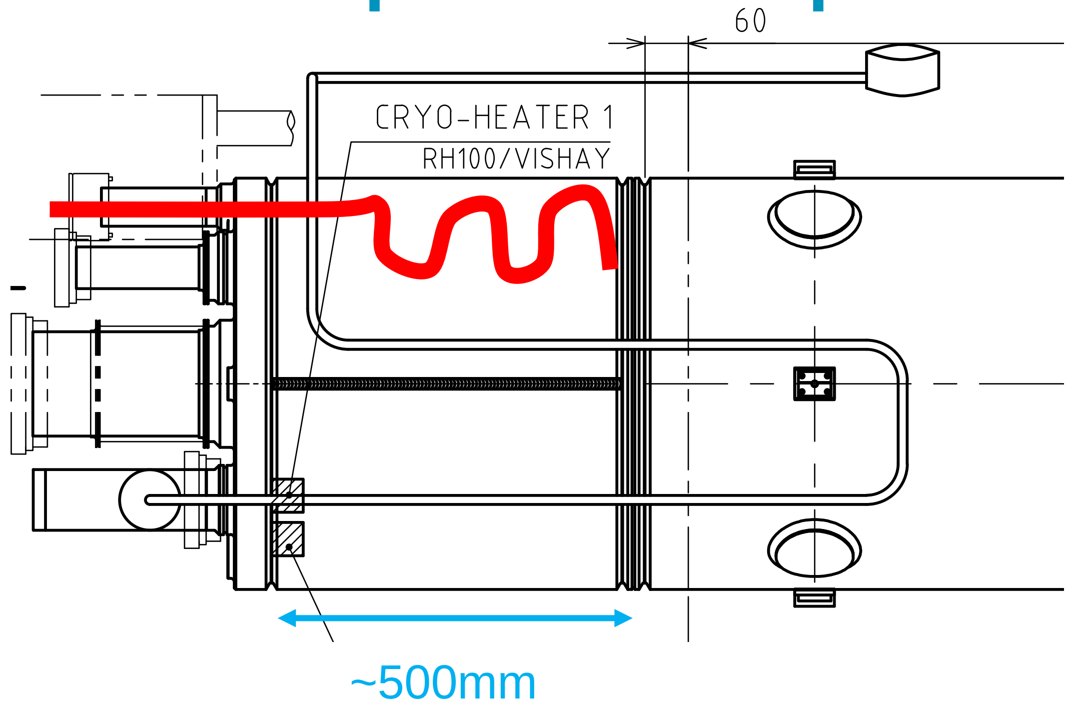
Stress validation for LC 2

Load case 2 (LC 2)						
	σ_{i-axis} (MPa)			σ_{eq} (MPa)		
	1 (r)	2(θ)	3(z)			
$P_m = P_m^{(1)}+P_m^{(2)}+P_m^{(3)}$	-2.5	70	44.6	63.7	$P_m < S$ (115MPa)	**Good**
P_L	0.0	0.0	5.9	5.9	$P_L < S_{PL}$ (172.5MPa)	**Good**
$P_L + P_b$	0.0	0.0	5.9	5.9	$P_L + P_b < S_{PL}$ (172.5MPa)	**Good**
$Q_m = Q_m^{(1)}+Q_m^{(2)}$	0.0	125	0.0	125	-	-
$P_L+P_b+Q_m$	0.0	125	5.9	122	$P_L+P_b+Q_m < S_{PS}$ (345MPa)	**Good**

Structural design of the ***Main Body*** of D1 cold mass was validated.

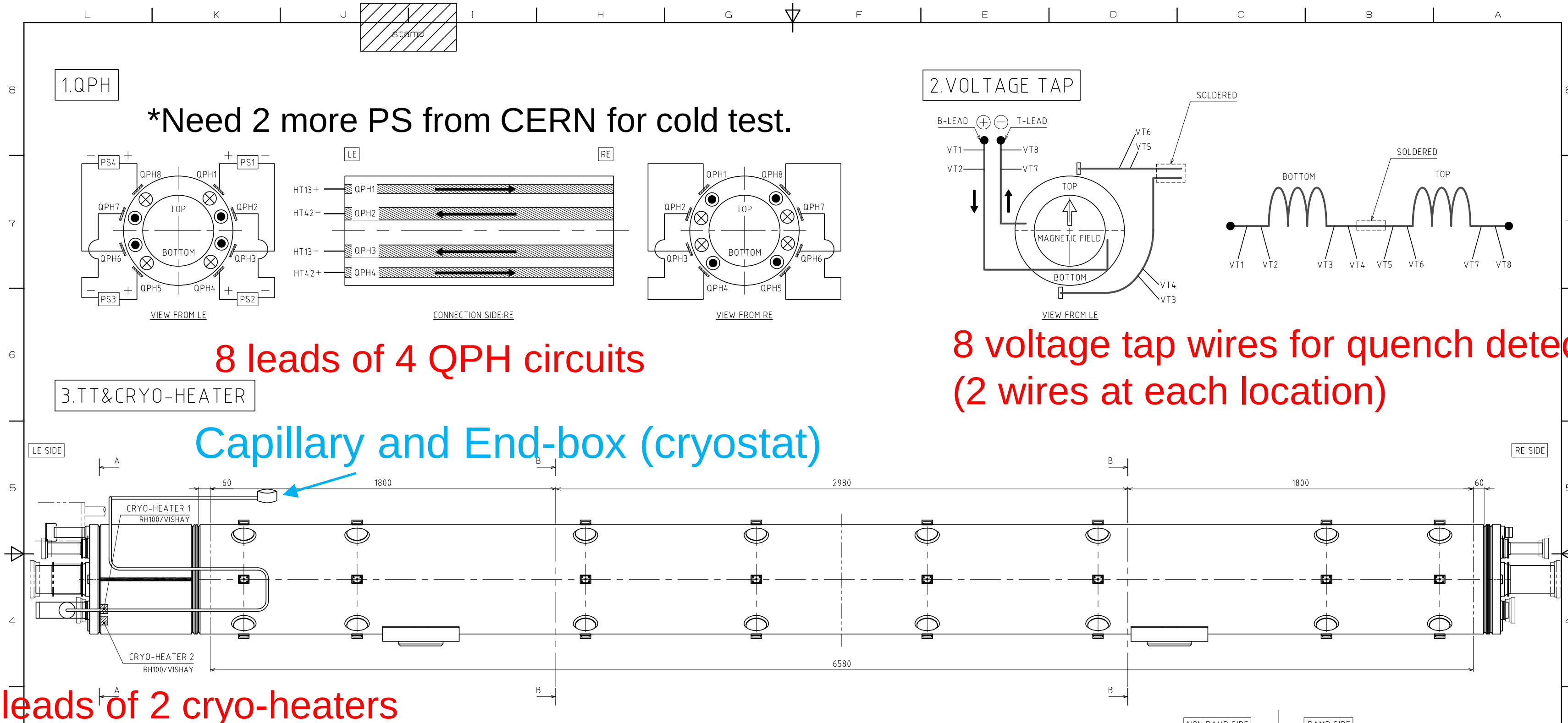
Main Busbar and Expansion Loop





- SC lead shunted with 1.5 × 15.1 mm^2 copper strip.
  - Quench performance of the superconducting busbar powering the HL-LHC D1 circuit (EDMS 2061856)
- "Expansion loop" to accommodate thermal shrinkage of D1 cold mass during cool-down
  - Displacement of 20 mm, allowable max. force of 200N
  - ***500 mm long end-dome providing sufficient space.***
  - Engineering study will start soon with making a mock-up.

Instrumentation



1.QPH

ID	REMARK	WIRE
HT13+	HEATER WIRE CONNECTED TO QPH1(INPUT)	HH1819-LH
HT13−	HEATER WIRE CONNECTED TO QPH3(RETURN)	HH1819-LH
HT42+	HEATER WIRE CONNECTED TO QPH4(INPUT)	HH1819-LH
HT42−	HEATER WIRE CONNECTED TO QPH2(RETURN)	HH1819-LH
HT57+	HEATER WIRE CONNECTED TO QPH5(INPUT)	HH1819-LH
HT57−	HEATER WIRE CONNECTED TO QPH7(RETURN)	HH1819-LH
HT86+	HEATER WIRE CONNECTED TO QPH8(INPUT)	HH1819-LH
HT86−	HEATER WIRE CONNECTED TO QPH6(RETURN)	HH1819-LH

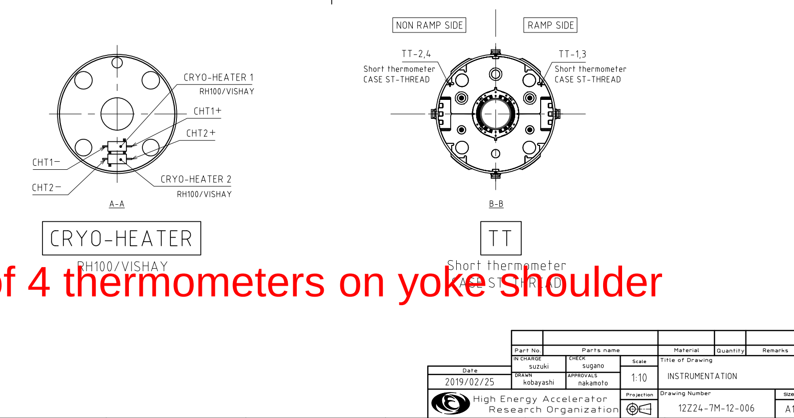
2.VOLTAGE TAP

ID	REMARK	WIRE
VT1	VOLTAGE TAP AT BOTTOM LEAD(PS SIDE)	HH2619-LH
VT2	VOLTAGE TAP AT BOTTOM LEAD(COIL SIDE)	HH2619-LH
VT3	VOLTAGE TAP AT JOINT(BOTTOM COIL SIDE)	HH2619-LH
VT4	VOLTAGE TAP AT JOINT(TOP COIL SIDE)	HH2619-LH
VT5	VOLTAGE TAP AT JOINT(BOTTOM COIL SIDE)	HH2619-LH
VT6	VOLTAGE TAP AT JOINT(TOP COIL SIDE)	HH2619-LH
VT7	VOLTAGE TAP AT TOP LEAD(COIL SIDE)	HH2619-LH
VT8	VOLTAGE TAP AT TOP LEAD(PS SIDE)	HH2619-LH

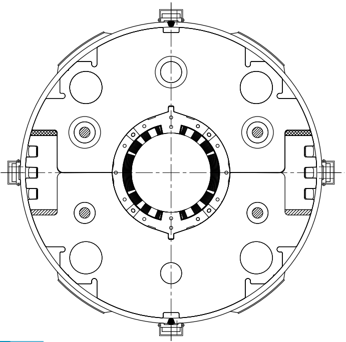
3.TT&CRYO-HEATER

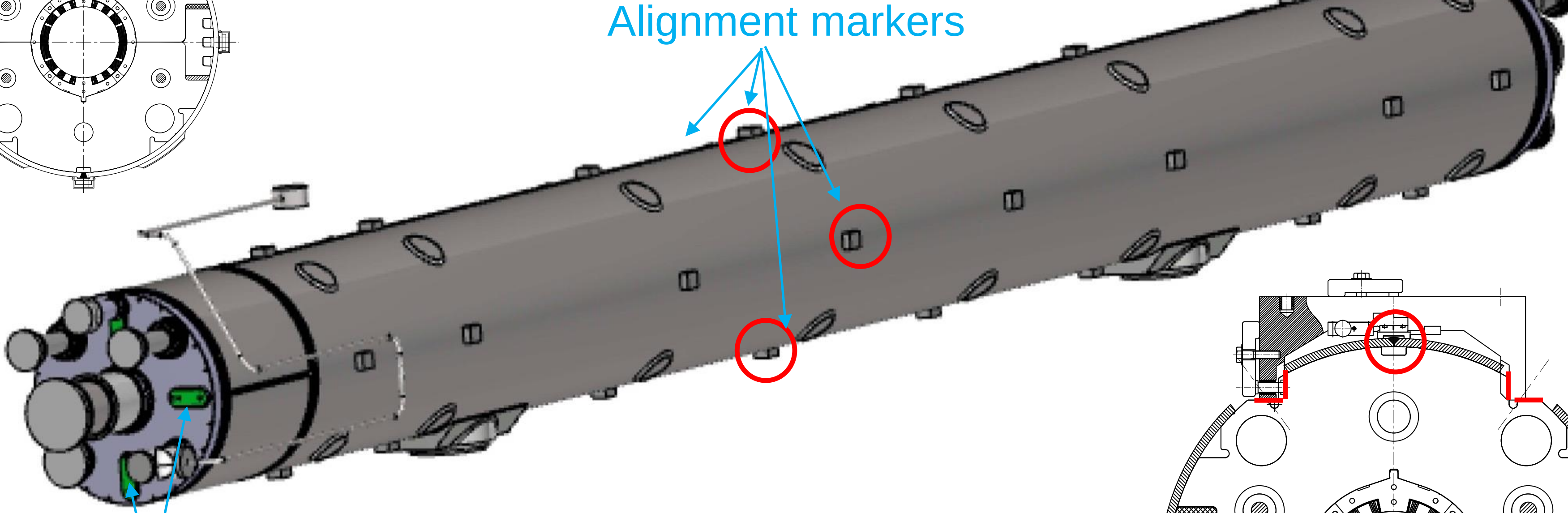
ID	REMARK	WIRE
TT1-I+	LE / RAMP SIDE	HT3007 H4-LH
TT1-I−	LE / RAMP SIDE	HT3007 H4-LH
TT1-V+	LE / RAMP SIDE	HT3007 H4-LH
TT1-V−	LE / RAMP SIDE	HT3007 H4-LH
TT2-I+	LE / NON RAMP SIDE	HT3007 H4-LH
TT2-I−	LE / NON RAMP SIDE	HT3007 H4-LH
TT2-V+	LE / NON RAMP SIDE	HT3007 H4-LH
TT2-V−	LE / NON RAMP SIDE	HT3007 H4-LH
TT3-I+	RE / RAMP SIDE	HT3007 H4-LH
TT3-I−	RE / RAMP SIDE	HT3007 H4-LH
TT3-V+	RE / RAMP SIDE	HT3007 H4-LH
TT3-V−	RE / RAMP SIDE	HT3007 H4-LH
TT4-I+	RE / NON RAMP SIDE	HT3007 H4-LH
TT4-I−	RE / NON RAMP SIDE	HT3007 H4-LH
TT4-V+	RE / NON RAMP SIDE	HT3007 H4-LH
TT4-V−	RE / NON RAMP SIDE	HT3007 H4-LH

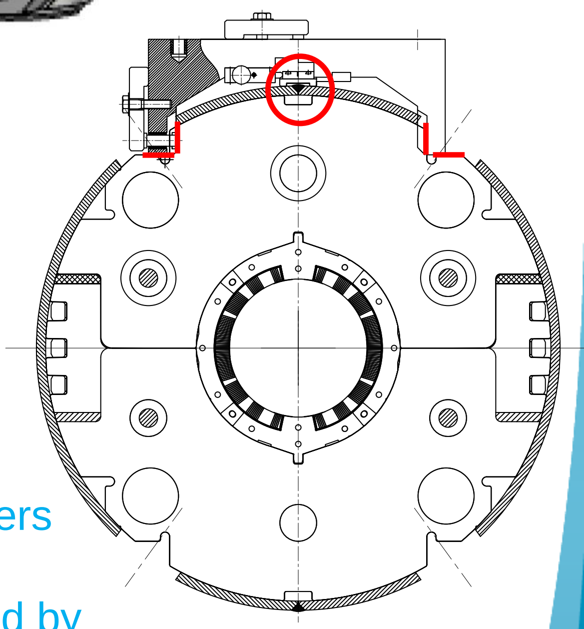
ID	REMARK	WIRE
CHT1+	HEATER WIRE CONNECTED TO CRYO-HEATER 1	HH1819-LH
CHT1−	HEATER WIRE CONNECTED TO CRYO-HEATER 1	HH1819-LH
CHT2+	HEATER WIRE CONNECTED TO CRYO-HEATER 2	HH1819-LH
CHT2−	HEATER WIRE CONNECTED TO CRYO-HEATER 2	HH1819-LH



D1 Cold Mass: Alignment Feature

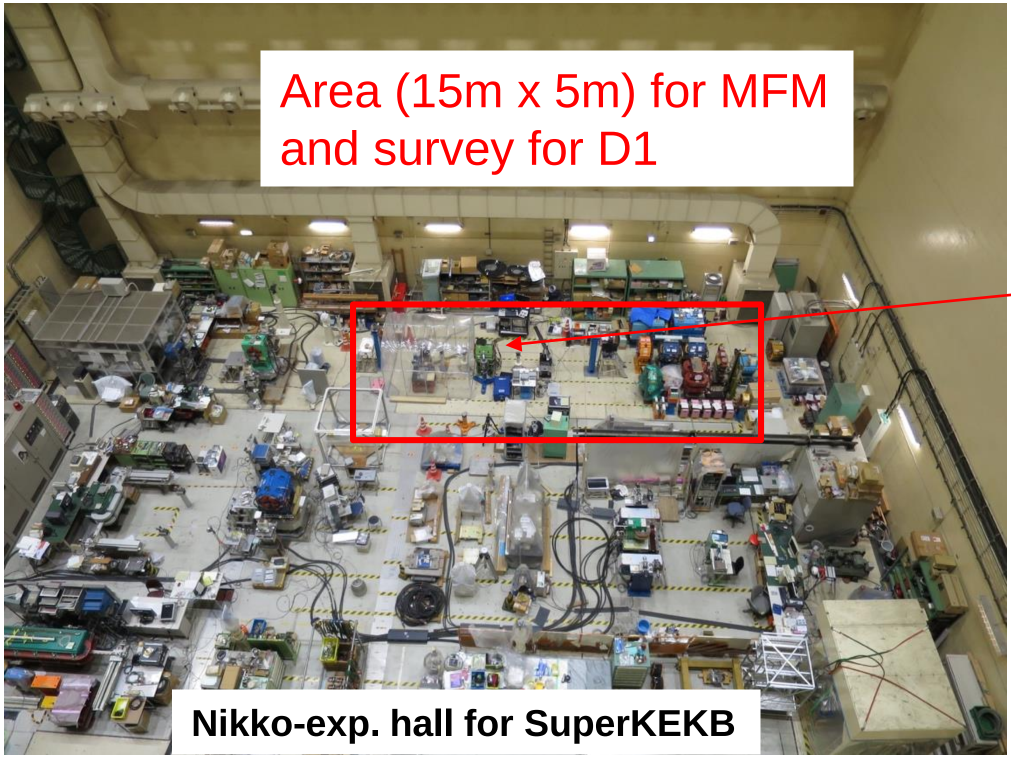


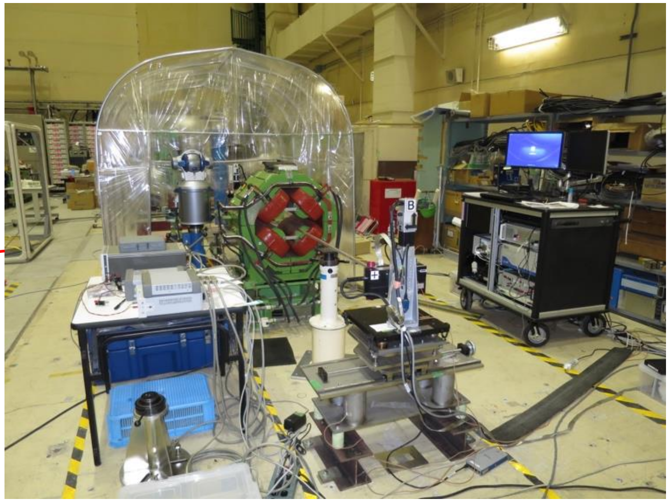




- Alignment feature on the shell: 8 x 4 holes for markers (like MQXA)
  - ➢ Local mechanical (magnetic) center determined by yoke shoulders.
  - ➢ 4 markers in cross section: top & bottom, left & right
  - ➢ 8 longitudinal positions
  - ➢ Straightness of the cold mass can be surveyed.
- Provision of mechanical reference for SSW measurement.
- Mechanical (magnetic) axis transferred to fiducials on end-covers.

SSW, MFM and Optical Survey for D1



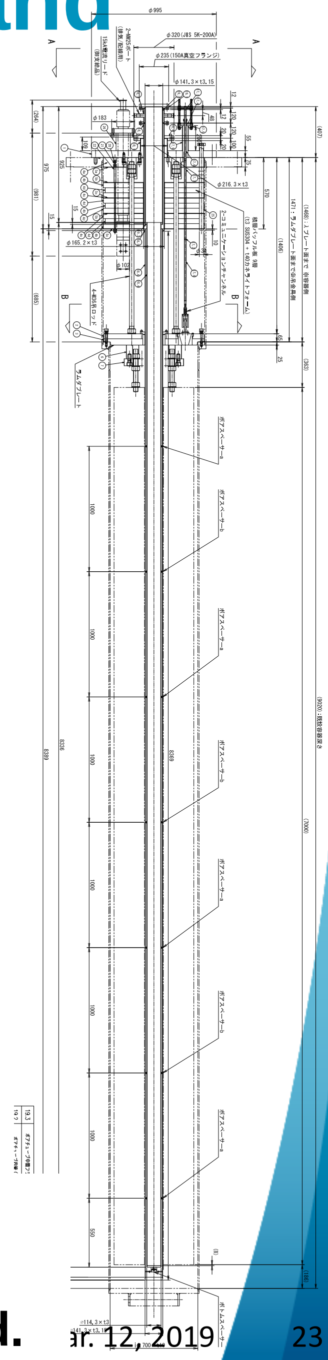


SSW system of QCS magnet for SuperKEKB

- Magnetic axis and field angle with respect to fiducials will be determined by MFM with SSW (Single Stretched Wire) and rotating coil in horizontal position.
- The measurement system was already developed for SuperKEKB QCS magnet and is now available for the D1.
  - The dedicated team joined the HL-LHC D1 project.
  - Preparation of measurement for the 7m long prototype cold mass is underway in Nikko-Exp. Hall at KEK.
- Laser-tracker will be used for the survey of the D1 cold mass.

Readiness of Vertical Cold Test Stand

- V-cryostat manufactured by Toshiba (2000)
  - 19 LHC-MQXA (7m) & 32 J-PARC SCFM (4m) tested.
- Operating Temp.: 4.4K to 1.9K
- Capacity
  - whole bath: 9020 mm deep.
  - 1.9 K bath: 7524 mm deep, 700 mm in a diameter.
- He Cryogenic Plants with HeII sub-cooler
  - Dedicated liquefier at 160 L/h (+ 350 L/h)
  - ΔT=30 mK at 80 W, 1.9 K. 4 parallel pump lines.
- 15 kA, 15 V Power Converter (1993)
  - Thyristor switch for prompt shutoff.
  - Dump resistor: 0, 12.5, 25, 50, 75 and 100 mΩ.
  - Quench detectors
    - 2 x V_balance + 2 x V_total
  - External 15 kA DCCT
- New header for the D1 (MBXF)
  - Manufactured in 2014
  - Anti-cryostat for field measurement: O.D. 141.3 mm
  - Quench antennas: 11 arrays for 7 m long magnet
  - Feedthrough: 48 poles x 10
  - HVWL: present limit 1.8 kV for QPH line. Improved up to 2.3kV
  - 15 kA Current Leads



Already operated for the cold tests of the 2m models

MFM system and DAQ are mostly ready.
Some improvement needs for Quench Antenna signals.
New rotating coils for 7m long magnet will be developed.

Summary

- KEK will deliver to HL-LHC with
  - *1 full-scale prototype cold mass (MBXFP)*
  - *6 series cold masses (MBXF1-6)*

- Open tender for production of D1 cold masses is underway and successful bidder will be determined at the 24th of May, 2019.

- Very tight schedule to deliver Prototype by Dec. 2020.

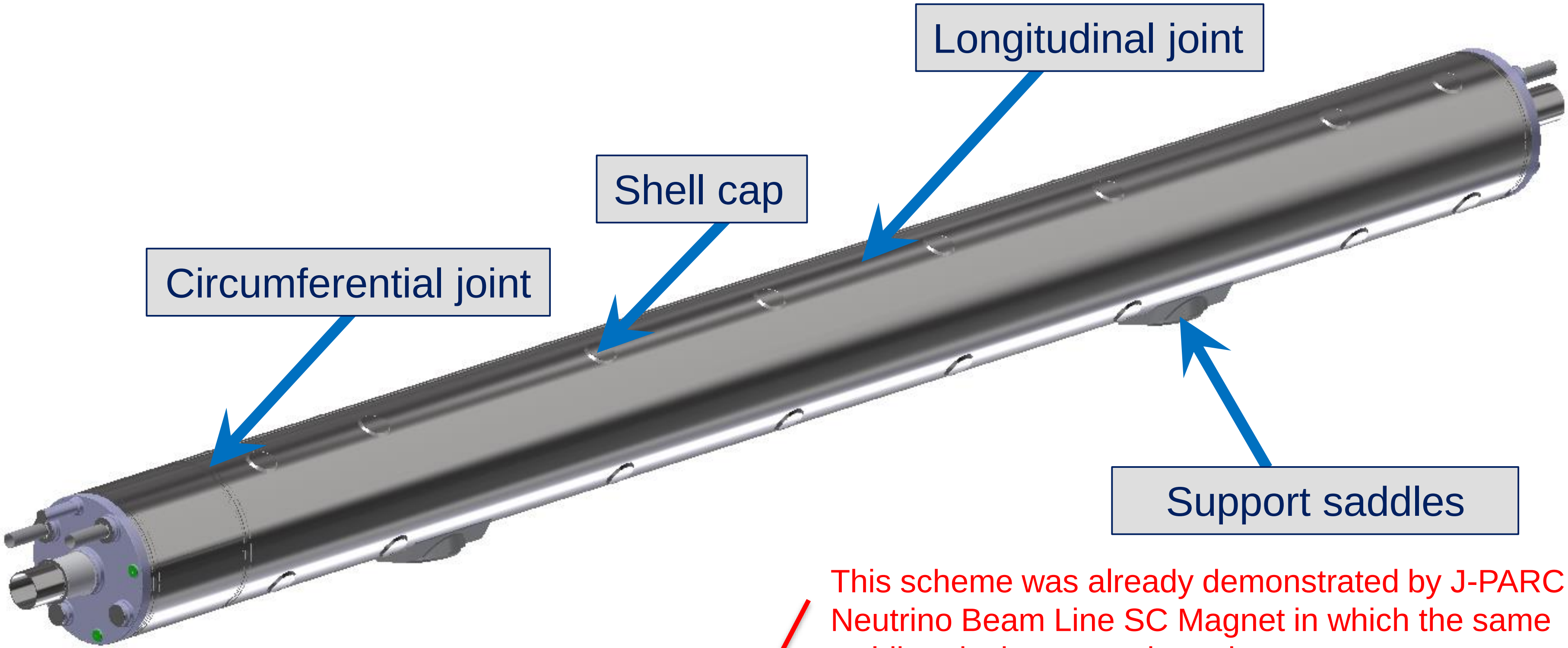
- Structural design analysis of "Main Body" of D1 cold mass was validated by CERN-HSE. Final report is in preparation.

- New horizontal MFM bench and vertical cold test stand are being arranged at KEK premise.

- Engineering for cold mass was started in collaboration with CERN.

Appendix

Outline of Weld joints and its Inspections



This scheme was already demonstrated by J-PARC Neutrino Beam Line SC Magnet in which the same welding design was adopted.

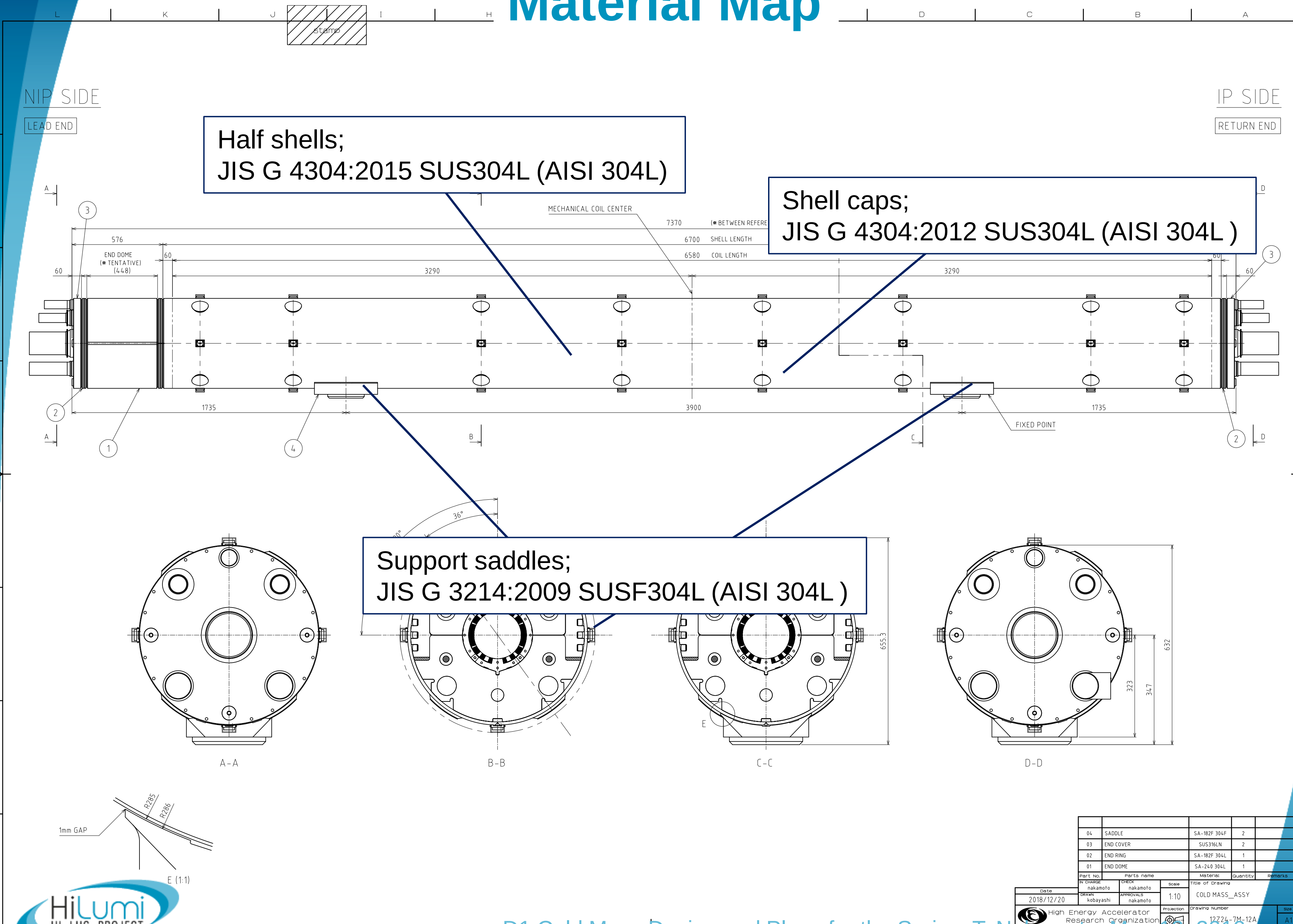
Part	Weld Joint efficiency	Inspection	Description
Longitudinal weld joint	1.0	100 % RT	Single welded butt joint with insert ring for full penetration weld
Circumferential weld joint	1.0	10 % UT	Single welded butt joint for full penetration weld
Shell cap	1.0	10 % UT	Groove weld
Support saddles	0.5	-	Fillet weld

Material Map

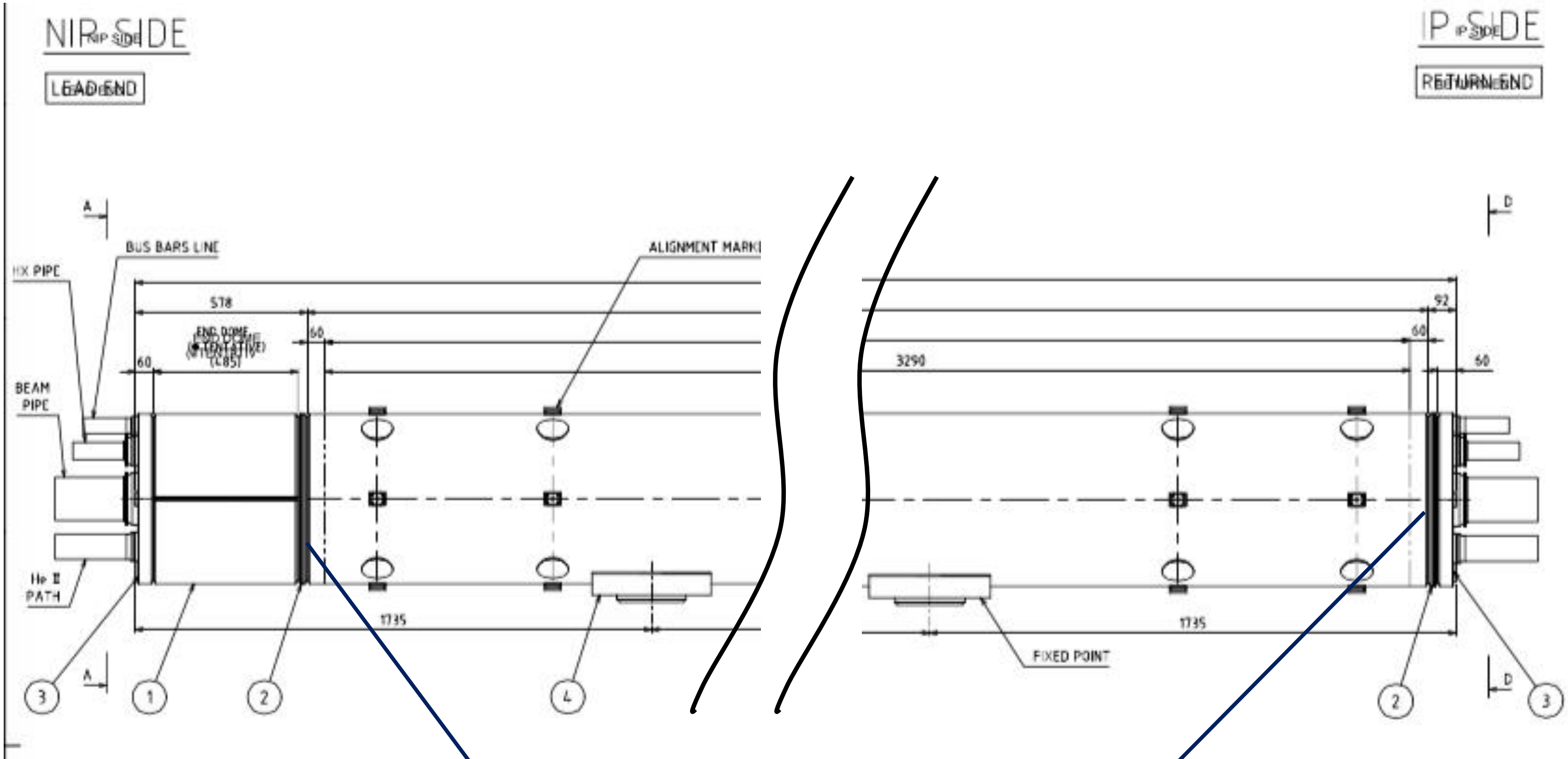
Half shells;
JIS G 4304:2015 SUS304L (AISI 304L)

Shell caps;
JIS G 4304:2012 SUS304L (AISI 304L)

Support saddles;
JIS G 3214:2009 SUSF304L (AISI 304L)



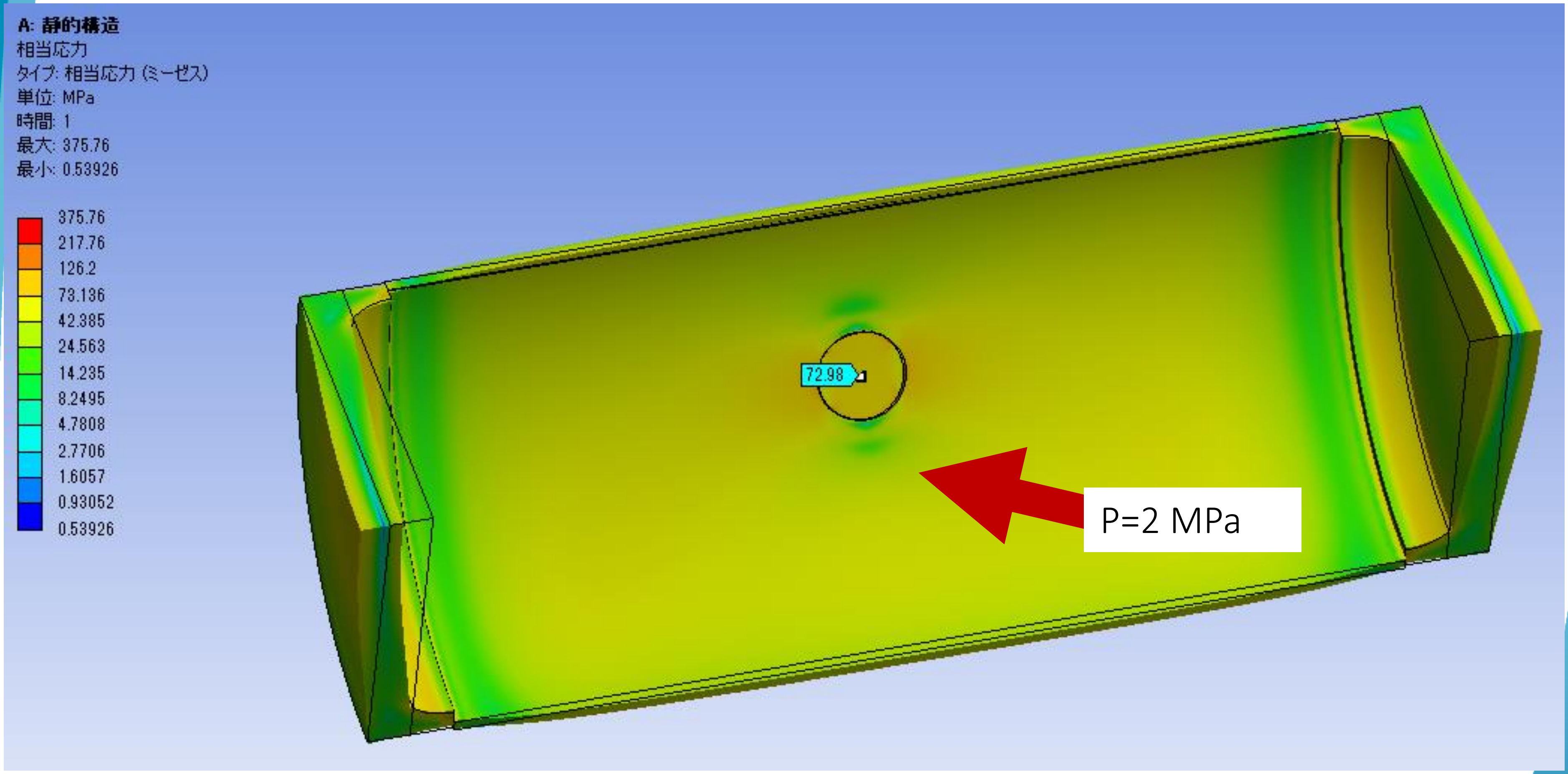
Material Map



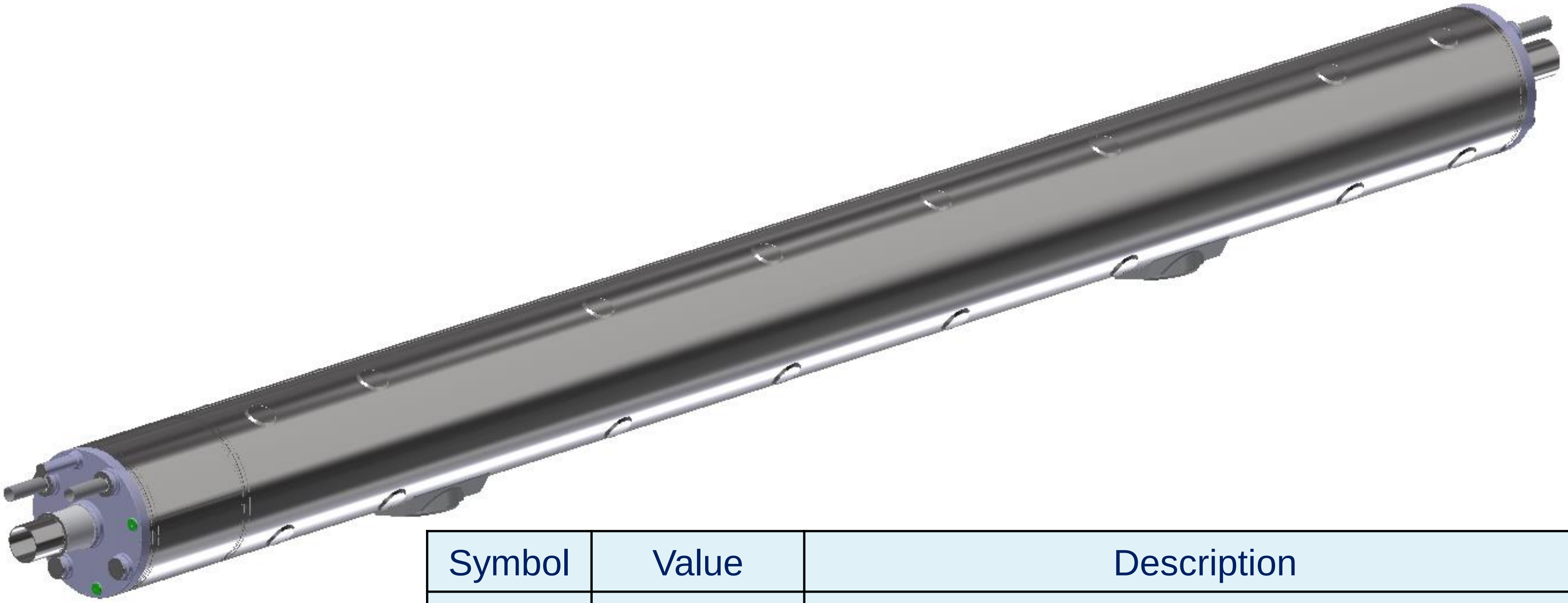
End ring;
JIS G 3214:2009 SUSF304L (AISI 304L)

Stress at Shell-Cap

Example of FEM analysis result for shell cap (3D model) under 2 MPa.
Equivalent stress of shell cap is around 73 MPa in the figure.
This value is lower than allowable stress, *S* =115 MPa.



Outline of Design Parameters of the pressure vessel



Symbol	Value	Description
D	0.57 m	Outer diameter of the pressure vessel
t	0.01 m	Thickness of half shell
L	7.13 m	Length of the pressure vessel
P	2.0 MPa	Design pressure (quench regime)
P_{test}	2.5 MPa	Test pressure
T	1.9 K	Operating temperature
W	140 KN	Weight of cold-mass

Parameters for DBA: "Main Body"

Symbol	Value	Unit	Description
r_1	0.275	m	Inner radius of the pressure vessel
r_2	0.285	m	Outer radius of the pressure vessel
r	0.275	m	$r=r_1$
t	0.01	m	Thickness of the pressure vessel
L	7.13	m	Length of the pressure vessel
P	2.0	MPa	Design pressure (quench regime)
P_{test}	2.5	MPa	Test pressure
T	1.9 K	K	Operating temperature
F_a	70	kN	Pre-axial loads on end ring (given by experiment)
F_b	30	kN	Electromagnetic axial loads on end ring (given by experiment)
W	140	kN	Weight of cold-mass
A_{shell}	0.0173	m^2	Cross-sectional area of shell
A_{saddle}	0.12	m^2	Cross-sectional area of support saddle
E_{ss}	193	GPa	Young's modulus at room temperature
$\alpha_{ss}\Delta T$	3×10^{-3}		Integrated thermal contraction of austenitic stainless steel - between room temperature and liquid helium 1.9 K
$\alpha_{lc}\Delta T$	2×10^{-3}		Integrated thermal contraction of low carbon steel-between room temperature and liquid helium 1.9 K
M	1.27×10^{7}	N·mm	Bending moment
Z	2.42×10^{6}	mm^3	Section modulus of shell as pipe shape

Material Properties: “Main Body”

Physical property numbers of S and S_y for SA-240/AISI304L are determined in “ASME BPVC Sec. VIII Div.2 Part 3&Part 5 :2017”

&

“ASME BPVC Sec. II D Table 5A Maximum Allowable Stress Values S for Ferrous Materials”

Mechanical properties of SA-240/AISI304L

Symbol	Value	Unit	Definition
S	115	MPa	$S = \frac{2}{3}S_y$
S_y	170	MPa	minimum specified yield strength
S_{PL}	172.5	MPa	$S_{PL} = 1.5S$
S_{Ps}	345	MPa	$S_{Ps} = 3S$
-	485	MPa	*minimum tensile strength*

Analysis method according to ASME Sec. VIII Div.2 Part 5

Elastic Stress Analysis Method was selected in ASME BPVC Sec. VIII Div. 2 Part 5 5.2.1.1 Design by analysis requirement as DBA.

A quantity known as equivalent stress, S_e, is computed at location in the component and compared to an allowable value of equivalent stress.

The equivalent stress is equal to the von Mises equivalent stress, σ_e, given by the following.

$$S_e = \sigma_e = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{0.5}$$

Stress categories and limitation of equivalent stresses

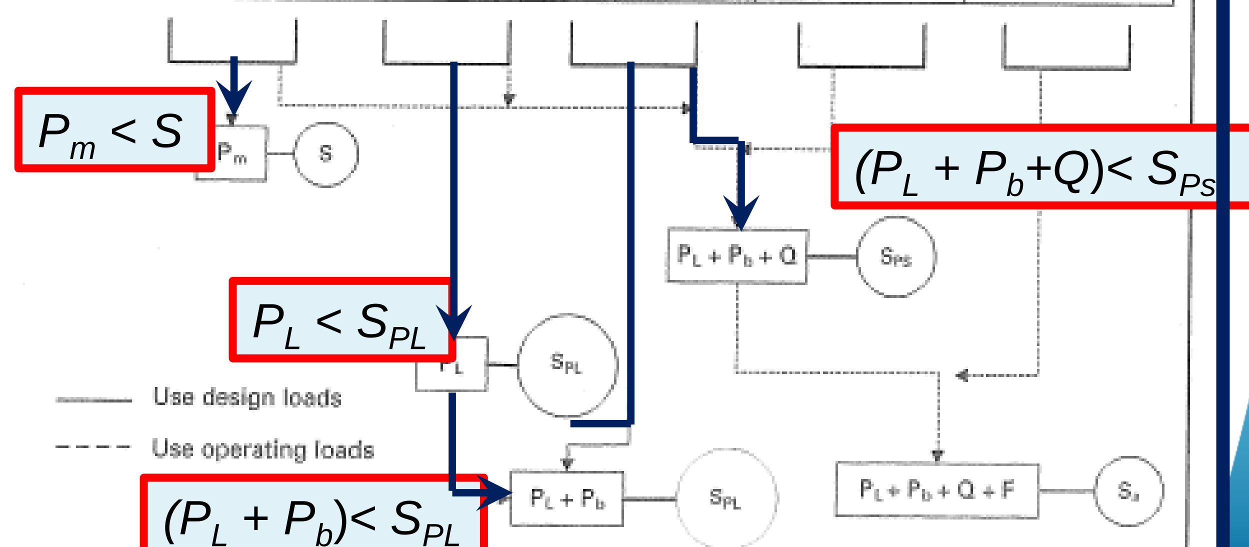
Symbol	Description	Symbol	Description
P_m	General primary membrane stress	$P_m^{(1)}$	Stress by the internal pressure
		$P_m^{(2)}$	Stress by the bending moment at support saddle
		$P_m^{(3)}$	Stress by the axial force to end-ring by pre-stress (+electric magnetic force) in the SC coil
P_L	Local primary membrane stress	$P_L^{(1)}$	$P_m^{(2)}$+ membrane stress from support saddle
P_b	Primary bending stress	P_b	Not applicable: $P_b = 0$
Q_m	Secondary membrane stress	$Q_m^{(1)}$	Stress by the thermal shrinkage
		$Q_m^{(2)}$	Stress by the welding shrinkage
σ_e	Equivalent stress range		

Limits of equivalent stress

5.15 FIGURES

Figure 5.1
Stress Categories and Limits of Equivalent Stress

Stress Category	Primary			Secondary Membrane plus Bending	Peak
	General Membrane	Local Membrane	Bending		
Description (For examples, see Table 5.2)	Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Average stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads.	Component of primary stress proportional to distance from centroid of solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations.	1. Increment added to primary or secondary stress by a concentration (notch). 2. Certain thermal stresses which may cause fatigue but not distortion of vessel shape.
Symbol	P_m	P_L	P_b	Q	F

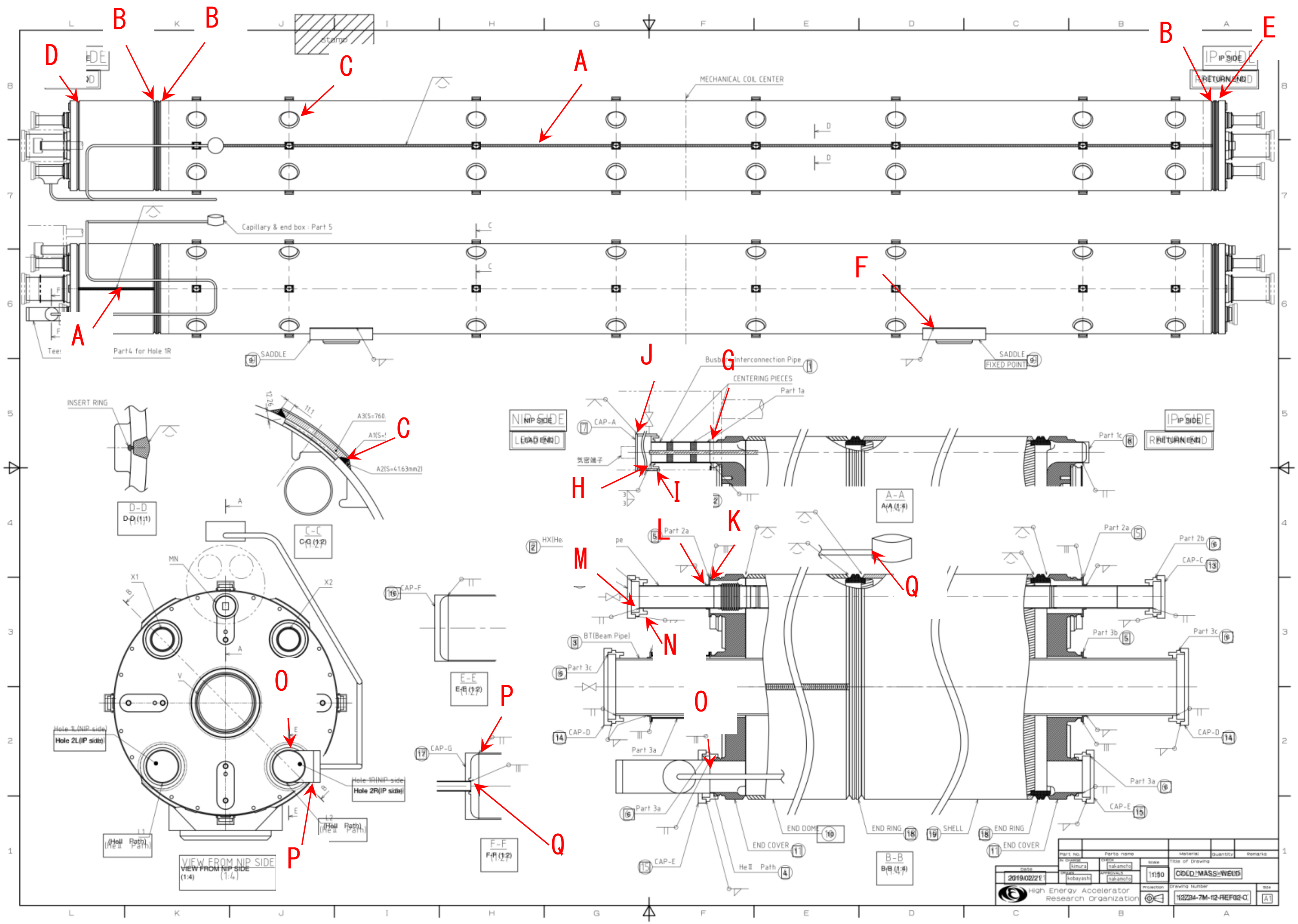


Applied Inspection for Materials: “Main Body”

PV Parts	Grade	Remark 1	Remark 2
Shell End-dome	JIS G 4304:2015 SUS304L	Material Certificate (EN 10204:2004 Type 3.1)	Chemical analysis, Yield strength 0.2Rp & 1.0Rp, Tensile Strength, Elongation, Hardness, Charpy test at 77K and 4.2K, UT.
		stencil	
		Co: < 0.1%	
Shell-cap		Material Certificate (EN 10204:2004 Type 3.1)	
		stencil	
		Co: < 0.1%	
End-ring	JIS G 3214:2009 SUSF304L	Material Certificate (EN 10204:2004 Type 3.1)	
		stencil	
		Co: < 0.1%	
End-cover	EN 1.4429 316LN	Material Certificate (EN 10204:2004 Type 3.1)	Material Certificate (EN 10204:2004 Type 3.1)
		stencil	
		Co: < 0.1%	
Support Saddle	JIS G 3214:2009 SUSF304L	Material Certificate (EN 10204:2004 Type 3.1)	Chemical analysis, Yield strength 0.2Rp & 1.0Rp, Tensile Strength, Elongation, Hardness, Charpy test at 77K and 4.2K, UT.
		stencil	
		Co: < 0.1%	
Cold bore, HX pipe and extremity	AISI316LN, 316L, OFC	HX Pipe	Material Certificate (EN 10204:2004 Type 3.1)
		Cold bore	
		pipe extension	
		Flare flange	
Capillary tube and end-box	AISI316L, 316LN	Capillary tube	Material Certificate (EN 10204:2004 Type 3.1)
		end-box	
Welding rod	ASME BPVC Sec. VIII Div.2 Part 3 ASME BPVC Sec. II-C ASME BPVC Sec. IX	Candidate: SFA 5.9/AWS A5.9:ER308L SFA 5.9/AWS A5.9:ER308L SFA 5.9/AWS A5.9:ER316LN	Material Certificate (EN 10204:2004 Type 2. 2). 3 < FN < 8.
Insert ring	ASME BPVC Sec. VIII Div.2 Part 3 ASME BPVC Sec. II-C ASME BPVC Sec. IX	Candidate: SFA 5.9/AWS A5.9:ER308L	Material Certificate (EN 10204:2004 Type 2. 2). 3 < FN < 8.

Supplied by CERN

Welding Map: “Main Body”



Applied Code for Welding: “Main Body”

welding part	welding part	ID	Code	Structure	Joint Type and Joint Category	Remark 1	Remark 2
Shell, End-dome SUS 304L	Shell, End-dome SUS 304L	A	ASME BPVC Sec.VIII Div.2 Part 4-4.2 ASME BPVC Sec.IX	longitudinal welding (single-V groove)	Joint Type:1 Joint Category:A	WPS, WPQT, Qualification of welder	full penetration welding with insert-ring
Shell, End-dome SUS 304L	End-ring SUS F304L	B		circumferential welding (single-V groove)	Joint Type:1 Joint Category:B		single side full penetration welding
Shell-cap SUS 304L	Shell SUS 304L	C		circumferential welding (groove)	Joint Type:9 Joint Category:D		single side full penetration welding
End-dome SUS 304L	End-cover 316LN	D		circumferential welding (single-V groove)	Joint Type:1 Joint Category:C		single side full penetration welding
End-ring SUS F304L	End-cover 316LN	E		circumferential welding (single-V groove)	Joint Type:1 Joint Category:C		single side full penetration welding
Shell SUS 304L	Support saddle SUS F304L	F		fillet welding	Joint Type:- Joint Category:E		
extension pipe (316LN or 316L)	End-cover 316LN	G	WPS provded by CERN	butt welding	Joint Type:1 Joint Category:D		
extension pipe (316LN or 316L)	Flare flange (316LN or 316L)	H		lip welding	Joint Type:- Joint Category:C		
sleeve (316LN or 316L)	Flare flange (316LN or 316L)	I		fillet welding	Joint Type:- Joint Category:C		
sleeve (316LN or 316L)	End-flange (316LN or 316L)	J		circumferential welding (single-V groove)	Joint Type:- Joint Category:C		
Flare flange (316LN or 316L)	End-cover 316LN	K		lip welding	Joint Type:- Joint Category:D		
Flare flange (316LN or 316L)	HX joint (316LN or 316L)	L		fillet welding	Joint Type:- Joint Category:C		
Flare flange (316LN or 316L)	End-flange (316LN or 316L)	M		socket, lip weld ing	Joint Type:- Joint Category:C		
Flare flange (316LN or 316L)	End-flange (316LN or 316L)	N		fillet welding	Joint Type:- Joint Category:C		
Tees (316LN or 316L)	End-cover 316LN	O		butt welding	Joint Type:1 Joint Category:D		
Tees, end-box (316LN or 316L)	End-flange (316LN or 316L)	P		butt welding	Joint Type:1 Joint Category:C		
Capilary tube 316L	End-flange, End-box (316LN or 316L)	Q		socket welding	Joint Type:- Joint Category: C		

Applied Inspection for Welding (1) : “Main Body”

ID	Structure	Code	Inspection condition	Remark 1	Remark 2
A	longitudinal welding (single-V groove)	ASME BPVC Sec. V ASME BPVC Sec. VIII Div.2 Part 7	NDT >> See (2)	Examination Group:1b Weld joint effciency:1.0 RT:100%	WPS, WPQT, Qualification of welder. DT >> See (1)
C	circumferential welding (groove)			Examination Group:1b Weld joint effciency:1.0 UT:10%	
B	circumferential welding (single-V groove)			Examination Group:1b Weld joint effciency:1.0 UT:10%	
D	circumferential welding (single-V groove)			Examination Group:1b Weld joint effciency:1.0 UT:10%	
E	circumferential welding (single-V groove)			Examination Group:1b Weld joint effciency:1.0 UT:10%	
F	fillet welding			Examination Group:1b Weld joint effciency:1.0 PT or UT:10 %	
G	butt welding			Examination Group:1b Weld joint effciency:1.0 RT:100%	WPS, WPQT, Qualification of welder. DT >> See (1)
H,K	lip welding				
I,L,N	fillet welding				
J	circumferential welding (single-V groove)				
M	socket, lip welding				
O	butt welding				
P	butt welding				
Q	socket welding				

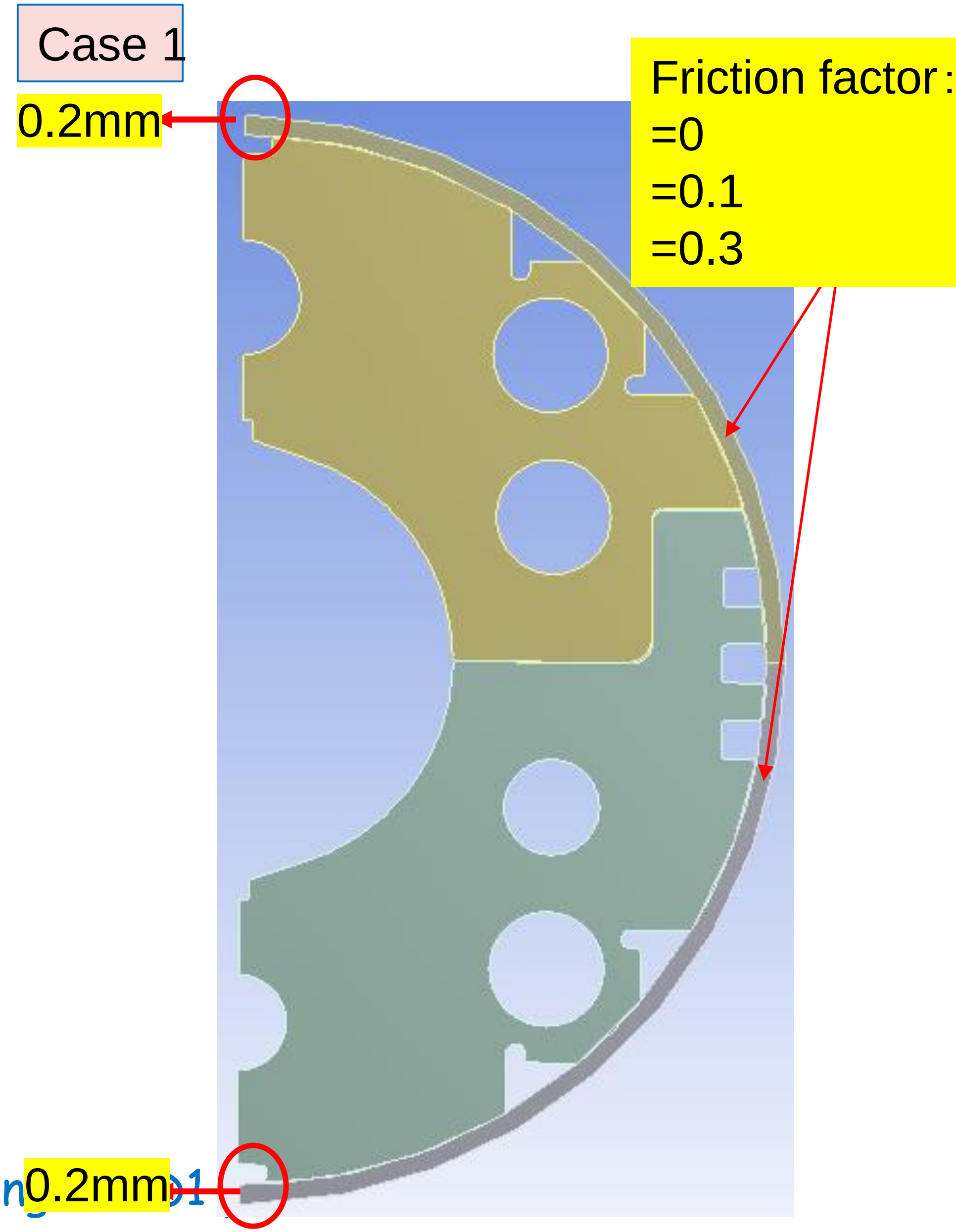
Applied Inspection for Welding (2) : "Main Body"

		Inspection	Code and Standard	Remark	Approval	Applied standard at CERN
(1)	Destructive test (DT)	Transverse tensile test	ASME sec. IX, QW-150	1 required	Review and approval by CERN HSE	EN 4136 EN10002-1
		Longitudinal tensile test within the weld bead	EN 5178	EN 5178 1 required		EN 5178
		Charpy V-Notch test	ASME sec. VIII Div.2,Part 3,3.11.7 Refer to SA-370 or JIS Z 2242 (ISO148-1)	4.2 K and 77 K,(3 required in heat affected zone, 3 required in weld material)		ISO 17638-1 EN ISO 148-1
		Bending Test	ASME sec. IX, QW-160	1:Normal,1:Root		EN910, ISO7438
		Macrography	ASME sec. IX, QW-184	1 required		EN 13639
		Macrograph	ASTM E3	1 required		EN 13639
		Magnetic permeability	ASTM A342 Method 5	1 required		ASTM A342 Method 5
		Fracture toughness	ASTM E1820 (or eq. ASME sec. VIII Div.2 Part 3)	RT,4.2K (both heat affected zone, weld material. 1 Long., 1 Trans. each at each temperature) Minimum 8 samples		ASTM E399 ASTM E813-89 ASTM E1820 (or eq. ASME sec. VIII Div.2 Part 3)

		Inspection	Code and Standard	Remark	Approval	Applied standard at CERN
(2)	Non-destructive test (NDT)	Qualification	ISO 9712		Review and approval by CERN HSE	EN-ISO 9712
		VT	EN-ISO 17637:2016, 5 Personal qualification, "an appropriate level in the relevant industry sector as a personal qualification"	100% of welded part		EN-ISO 17637
		RT	ASME BPVC Sec.V	100% of logntudinal welding		NA
		UT	ASME BPVC Sec.V	10% of circumferential welding		NA

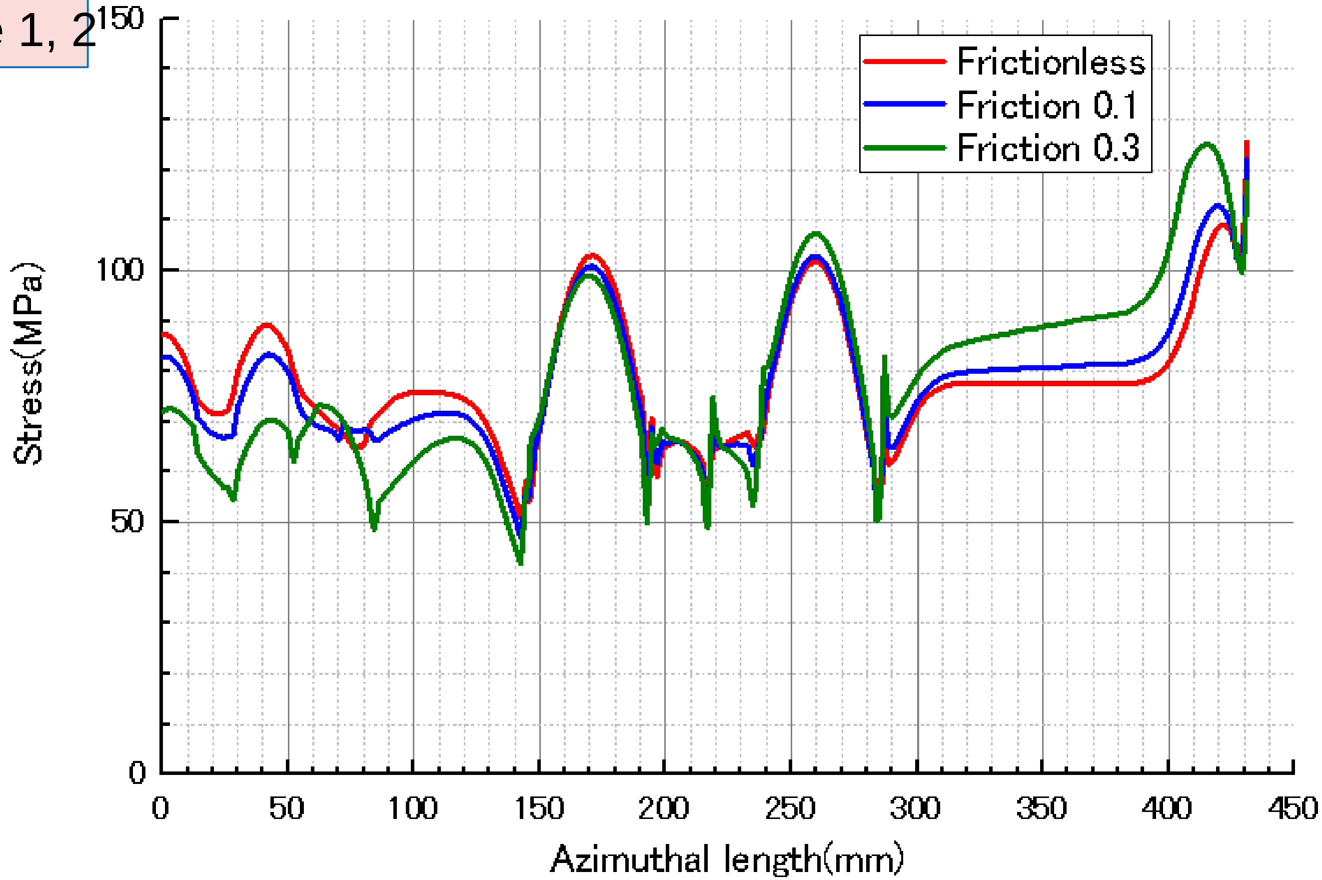
4.5 Stress by weld shrinkage

FEM analysis for weld shrinkage (2D model)



Result of FEM Analysis for Stress Distribution by weld shrinkage

Case 1, 2



Stress Component	Value (Case 1)	Value (Case 2)
Q_{m1} (2)	0.0 MPa	0.0 MPa
Q_{m2} (2)	125 MPa	125 MPa
Q_{m3} (2)	0.0 MPa	0.0 MPa