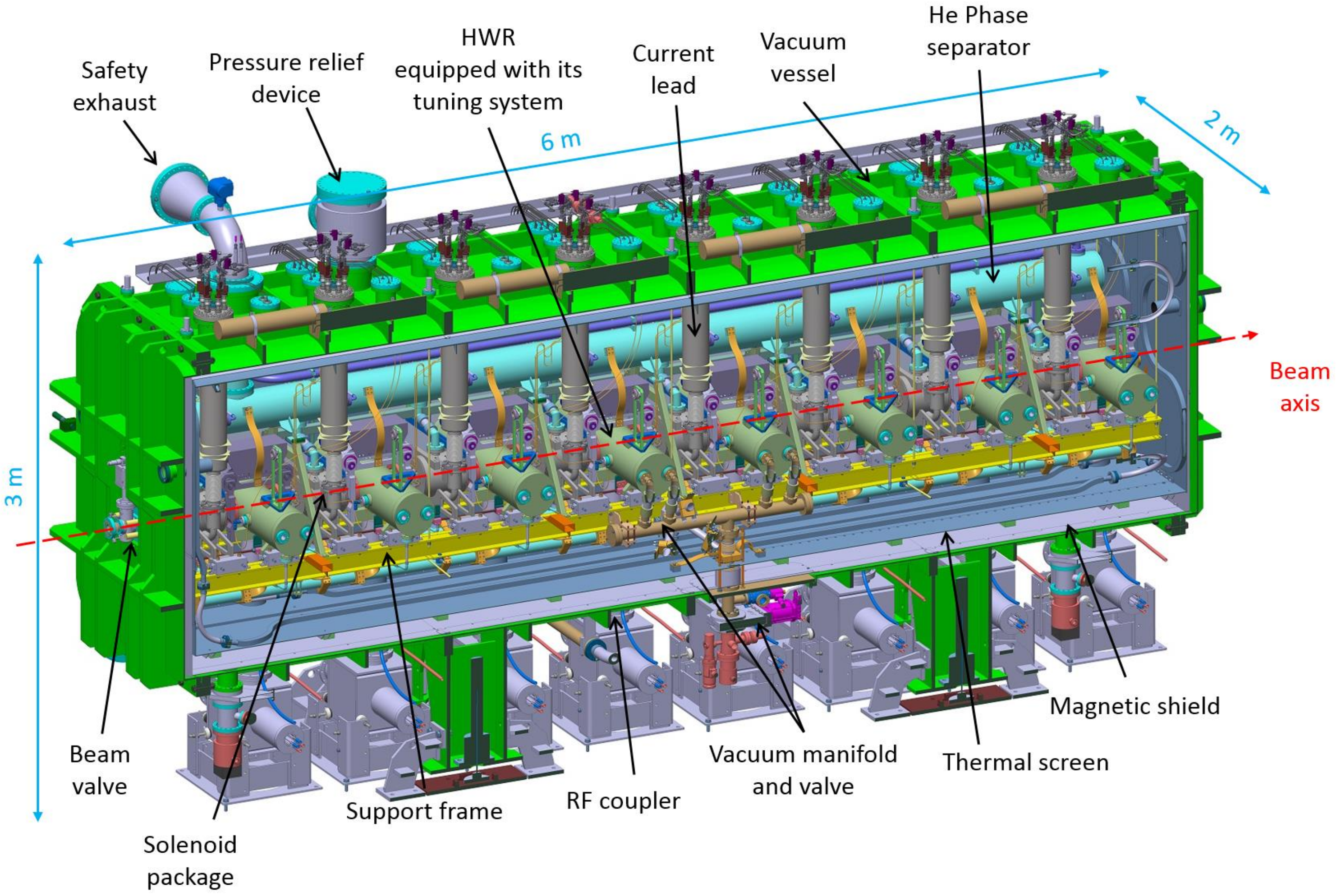
DE LA RECHERCHE À L'INDUSTRIE

Licensing of pressurized cryomodule components manufactured in Europe and installed in Japan: example of the IFMIF/EVEDA cryomodule

N. BAZIN

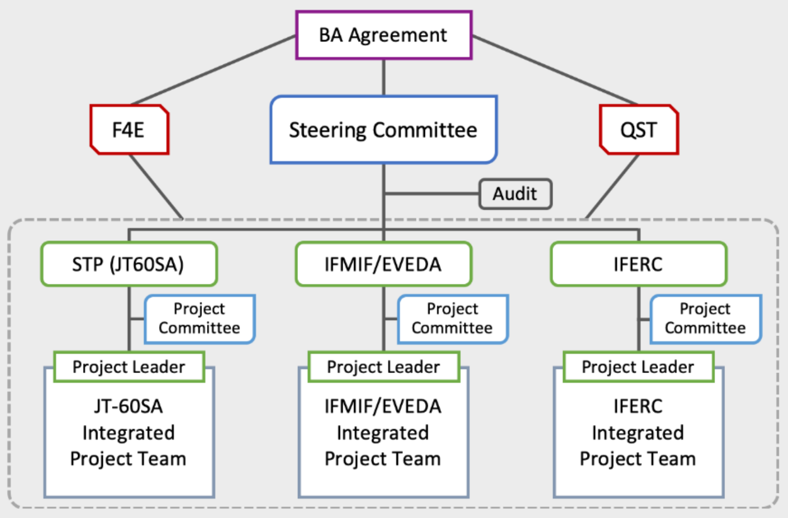
IFMIF/EVEDA Cryomodule: Overview



- Eight superconducting cavities and solenoids cooled with liquid helium
- Design pressure: 0.15 MPa (1.5 bar)
- Operating pressure: 0.125 MPa
- Operating temperature: 4.45 K
- Cryomodule designed by CEA (except superconducting solenoids under the responsibility of CIEMAT)
- Individual components manufactured and qualified in Europe
- Assembled and installed in Japan at QST Rokkasho Fusion Institute

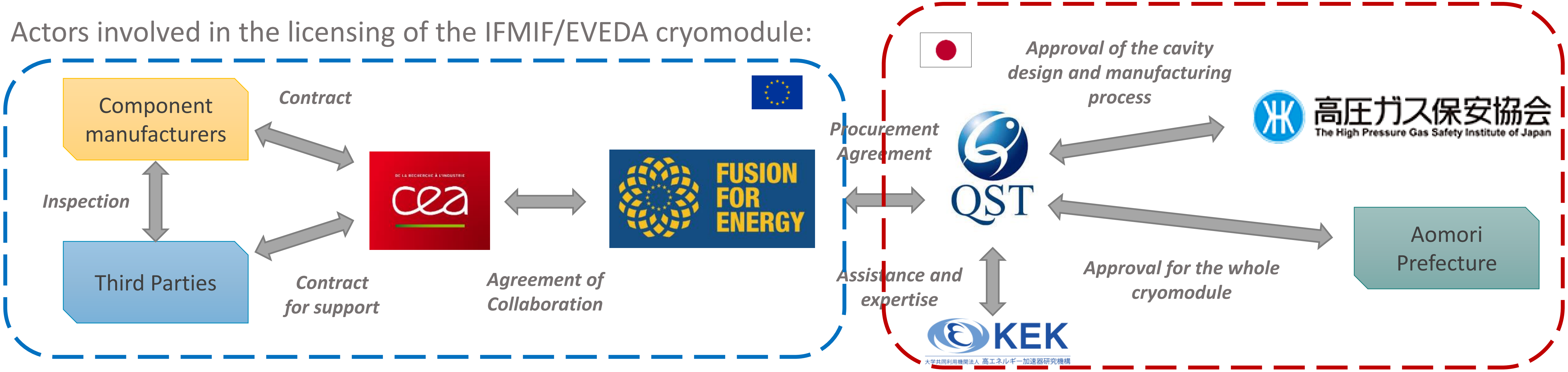
Organization

- The IFMIF/EVEDA Project is part of the ITER Broader Approach:



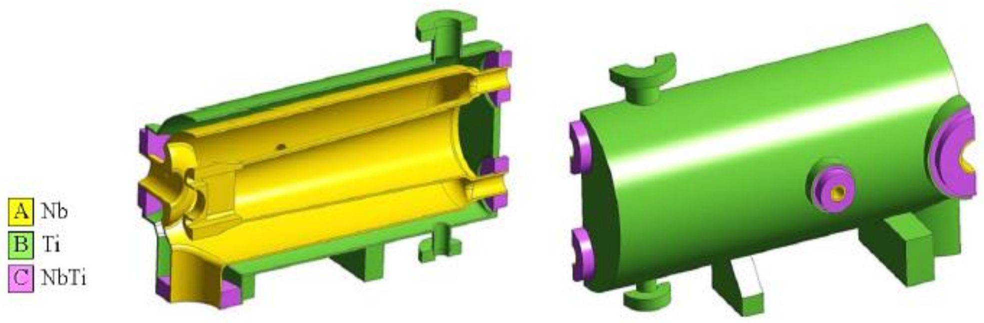
- F4E / QST = Implementing Agencies
- The Implementing Agencies are responsible for managing the European and Japanese contributions
- QST: Quantum and Radiological Science and Technology
- F4E: Fusion for Energy

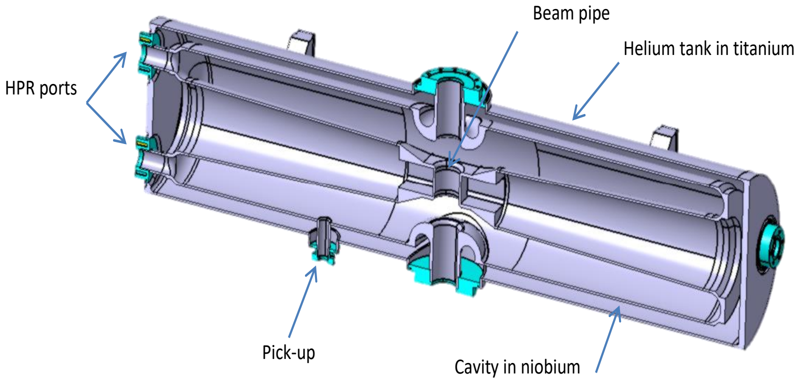
- Actors involved in the licensing of the IFMIF/EVEDA cryomodule:

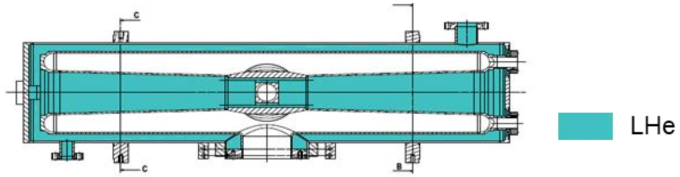


Licensing Strategy

- Cryogenic fluid inside the IFMIF cryomodule → the components must comply with High Pressure Gas Safety Law (HPGSL)
- All licensed components are subject to the approval of Aomori Prefecture before installation of the cryomodule in Rokkasho (application form submitted by QST)
- Strategy negotiated with the Japanese authorities: design, fabrication and tests of all the cryomodule components according to ASME BPVC (Boiler and Pressure Vessel Code) or B31.3
- Due to the use of non referenced ASME materials (Nb, NbTi) and complex geometry of the cavity, prior evaluation by the High Pressure Gas Safety Institute of Japan (KHK) was requested







Licensing of the Cavity

- The licensing procedure for the superconducting cavity started in December 2013 with the Japanese Authorities
- 7 meetings with KHK were necessary prior to the official submission in June 2015 to agree on requirements for the items non-compliant with the Specified Criteria of the Refrigeration Safety Rules:

5. Pressure Test
6. Air Tightness Test
19. Design Pressure
20. Materials for Refrigerant Facility
21. Ultrasonic Test for materials
22. Weld Efficiency
23. Strength of vessels and pipes
24. Welding
25. Stress Removal
26. Structure and Process of vessels
27. Mechanical Test for Welded Parts
28. Nondestructive Test for Welded Parts

List taken from: "Pressure Vessel Code for IFMIF", A. Kasugai, presentation at TTC meeting, 2016

Licensing of the Cavity

- Because of the non referenced materials, mechanical tests were required on Nb-Nb, Nb-NbTi, NbTi-Ti, Ti-Ti weld samples

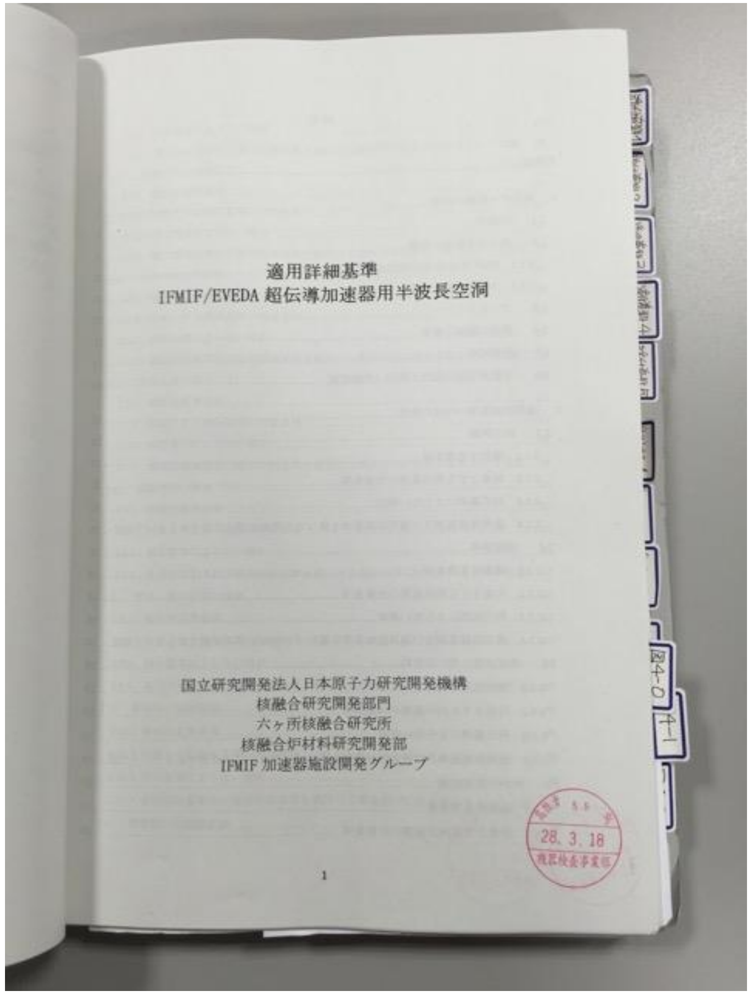
- QST performed tensile strength tests and Charpy impact tests at warm and cold temperatures to validate the use of niobium, niobium titanium alloy and titanium for the superconducting cavity

> Examples of Description of Content of Applicable Detailed Criteria
> (2) Materials
>
> Refrigeration Safety Rules
> The Half Wave Resonator in the Superconductive Accelerator will use Niobium, Niobium Titanium and ASTM specified Titanium. However, Niobium, Niobium Titanium and ASTM specified Titanium are not the materials specified in the Specified Criteria.
> (base metal & welding part)
>
> We carried out the tensile strength test and the fraction observation test at RT and -269 degC.
> We demonstrated the results of material safety.
> (Base metal of Niobium and Niobium Titanium) ex.
> - The lowest value of 0.2% proof stress measured after the heat treatment at RT is 59 N/mm2, which satisfies 40 N/mm2 of the guaranteed value. Also, 0.2 % proof stress increases at -269degC.
> - The lowest value of tensile strength measured at RT after the heat treatment is 171N/mm2, which satisfies 95N/mm2 of the guaranteed value. Also, tensile strength increases at -269degC.
> - The lowest value of elongation measured at -269 degC is 14.5 %.
> - From above, it is concluded that Niobium is can be used at LHe temperature.
>
> it was confirmed that the fracture surface was 100 % dimple and ductile fracture by the fraction observation conducted with SEM on a fractured tensile specimen tested at – 269 degC of the LHe temperature condition.

Slide taken from: "Pressure Vessel Code for IFMIF", A. Kasugai, presentation at TTC meeting, 2016

Licensing of the Cavity

- Several additional meetings with KHK were needed between the official submission in June 2015 and the formal approval of the Application Form on March 18th 2016



２８高機第５５号
平成２８年３月１８日

国立研究開発法人日本原子力研究開発機構
青森研究開発センター（国際核融合エネルギー研究センター）
所長　飯塚　幸治　殿

高圧ガス保安協会
会長　市川　祐三

詳細基準事前評価書

平成２７年６月４日付け原機（青管）０２０をもって申請がありました件については、「冷凍保安規則の機能性基準の運用について（平成 13・03・23 原院第 4 号）」に基づき事前評価を行いましたので、下記のとおり評価結果を通知します。

なお、留意事項欄に特別に記載した事項については、製造又は使用に当たり十分に留意してください。

記

１．高圧ガス設備等の製造者	名称	ETTORE ZANON S.p.A.
	所在地	36015 Schio VI-Italy-via Vicenza 113, Italy
２．高圧ガス設備等が設置される事業所	名称	国立研究開発法人日本原子力研究開発機構 青森研究開発センター（国際核融合エネルギー研究センター）
	所在地	青森県上北郡六ヶ所村大字尾駮字表舘 2 番地 166

３．適用すべき詳細な技術基準の内容

(1) 評価項目

	通達　冷凍保安規則の機能性基準の運用について（平成 13・03・23 原院第 4 号）別添「冷凍保安規則関係例示基準」の
耐圧試験	5.(1)ロに規定される耐圧試験以外の耐圧試験の採用
材料	20.1(5)及び 20.2 に規定される冷媒設備に用いる材料以外の冷媒設備に用いる材料の採用
許容引張応力	20.4(3)に規定される材料の許容引張応力以外の材料の許容引張応力の採用
縦弾性係数	20.9 に規定される材料の縦弾性係数以外の材料の縦弾性係数の採用
溶接効率	22.に規定される溶接効率以外の溶接効率の採用
強度計算	23.1.2 並びに 23.2, 23.4, 23.6 及び 23.10 に規定される容器及び配管の強度等以外の容器及び配管の強度等の採用
溶接	24.9(2)に規定される溶接以外の溶接の採用
機械試験	27.3(2),27.6(2)及び 27.7 に規定される溶接部の機械試験以外の溶接部の機械試験の採用
非破壊試験	28.1(4)並びに 28.2, 28.8, 28.9 及び 28.12 に規定される溶接部の非破壊試験以外の溶接部の非破壊試験の採用

(2) 設備の種類と概要

本申請対象である半波長空洞は、ビーム加速方向に 8 基並べられ、重陽子ビームを 5MeV から 9MeV まで加速させる超伝導加速器を構成する容器である。半波長空洞は、液体ヘリウムを貯めるチタン製の槽（以下「チタン槽」という。）、液体ヘリウム中に設置されるニオブ製の空洞（以下「ニオブ空洞」という。）及びニオブ空洞とチタン槽を接続するためのニオブチタン製のフランジから構成される。

種類	その他の圧力容器類「ＩＦＭＩＦ／ＥＶＥＤＡ　超伝導加速器用半波長空洞」　８基	
	チタン槽	ニオブ空洞
使用流体	毒性ガス又は可燃性ガス以外のガス（液体ヘリウム）	（真空）
処理容積(㎥/day 標準状態)	—	
貯蔵能力（ｔ）	—	
内容積（㎥）	０．０１８／基	

（１／３）

設計圧力（MPa）	０．０５＋０．１０１３	－０．０５－０．１０１３
設計温度（℃）	－２６９～＋３０	－２６９～＋３０
図面番号	JEAE-F4E-CEA.SRF0001 rev4　使用材料一覧及び設計仕様　(1/3)～(3/3) 3200.0.000.000 Rev.1　Half Wave Resonator-LIPAc SRF-Linac　Cavity with Helium Tank 3200.1.000.000 Rev.4　Half Wave Resonator-LIPAc SRF-Linac　Niobium Cavity 3200.2.000.000 Rev.0　Half Wave Resonator-LIPAc SRF-Linac　Helium tank - integration to cavity scheme	

(3) 内容の評価

３．(1)に示す評価項目に対し、次の(a)～(i)に示す内容の確認等を行っており、妥当と評価する。

(a) 耐圧試験

耐圧試験を気体を用いる耐圧試験とする場合、次に示す非破壊試験が要求されるが、これらの非破壊試験を設計仕様での非破壊試験の検査割合に基づいて検査することに対して、次の①及び②の対応を講じるとしていること。

- 放射線透過試験を行うものとして設計された長手継手に係る突合せ溶接部の、全長についての放射線透過試験
- 周継手に係る溶接部及び放射線透過試験を行なわないものとして設計された溶接部についての浸透探傷試験

① 全長についての放射線透過試験に対して設計仕様の検査割合の適用について

設計仕様での検査割合が 20%部分放射線透過試験であるニオブ－ニオブ溶接部に対し、長手継手の全長について放射線透過試験が必要となるが、下記の対応を示していること。

- 例示基準では要求されていない溶接施工方法の確認試験を ASME Sec.IX(2010) Article II に準拠して実施し、溶接部の健全性を確認するとしている。
- 過去に類似形状に対する気体による耐圧試験の実績も十分にある。
- 試験時には安全対策を十分に講じるとしている。

② 周継手等に対する浸透探傷試験の省略について

設計仕様での検査割合で、放射線透過試験を行わないとしているニオブ及びニオブチタンに係る溶接部に対して浸透探傷試験が必要となるが、不純物の混入を防止する必要性から下記の対応を示していること。なお、チタン－チタン溶接部は、設計仕様の検査割合で全長について浸透探傷試験を実施するとしている。

- 当該溶接に引き続いて同一の条件で別個に溶接して製作する機械試験板の溶接部に対し、放射線透過試験及び浸透探傷試験を実施し、溶接部の健全性を確認するとしている。

また、JIS 規格に基づく放射線透過試験及び浸透探傷試験の試験方法に替えて ASME Sec.Ⅷ Div.1(2010)に規定される非破壊試験の方法を採用するとしているが、ASME Sec.Ⅷ Div.1(2010)は世界で広く利用されており、実績も十分にある検査方法であることより、問題はない。

(b) 材料

半波長空洞の使用材料一覧を表 1 に、各材料の機械的性質を表 2 に、化学成分を表 3 に示すが、当該材料を設計温度 -269 ～+30 ℃で使用することに問題のないことを、次の①～③により確認していること。

表 1　使用材料一覧

材料の種類	材料規格	材料の略称	使用部位
ニオブ	ASTM B393-09 Type 5 (UNS No.R04220) 相当材	ASTM B393 相当材	ニオブ空洞本体
	ASTM B391-03 Type 1 (UNS No.R04200) 相当材	ASTM B391 相当材	ニオブ空洞のパイプ部分
ニオブチタン	ASTM B348-10 Grade 36	ASTM B348 Gr36	フランジ
チタン	ASTM B265-10 Grade 2	ASTM B265	チタン槽
	ASTM B348-10 Grade 2	ASTM B348 Gr2.	

表 2　機械的性質（常温における規格値又は保証値）

	0.2%耐力 (N/mm²)	引張強さ (N/mm²)	伸び (%)
ASTM B393 相当材 及び ASTM B391 相当材	40 (注)	95	15 (注)
ASTM B348 Gr36	410	450	10
ASTM B265 及び ASTM B348 Gr2	275	345	20

(*) ASTM B393-09 Type 5 及び ASTM B391-03 Type 1 の 0.2%耐力及び伸びの規格値は、それぞれ 50N/mm², 30%であるが、ニオブ空洞の特性を達成するため不純物（ニオブ以外の成分）を極力抑えているため、保証値としている。

Impact of the licensing on the design

- The RF design of the cavity was validated in 2012 with the qualification of the prototype

  More details in "Cavity development for the linear IFMIF prototype accelerator", N. Bazin, presentation at the 16th International Conference on RF Superconductivity (SRF2013)

- The mechanical design of the niobium cavity, the niobium-titanium flanges and the titanium helium tank was redesigned according to ASME BPVC Section VIII and additional requirements from KHK:
  - FEM (Finite Element Method) Analysis taking into account many load cases, including the force induced by the frequency tuning system at cold.
  - Stress analysis reviewed by a Lloyd's register third part inspector.

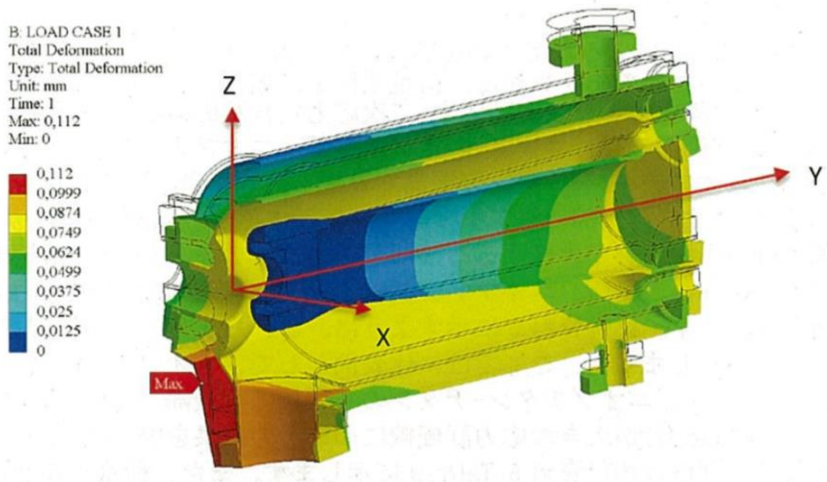


図 23 (a)　荷重条件 1 の場合の変位

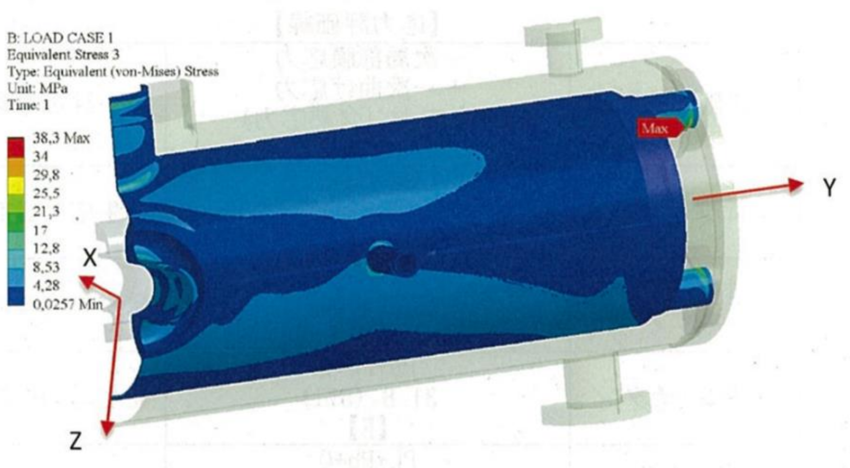


図 23 (b)　荷重条件 1 の場合の発生応力（ミーゼス等価応力）

Example of FEM analysis included in the Application Form

Impact of the licensing on the manufacturing

- The call for tenders for the manufacturing of the superconducting cavities was launched even if discussions with KHK were on-going and requirements not all fixed:
  - Because the manufacturing drawings with the location and types of the weld were needed for the Application Form as well as the control plan
  - To stick on the schedule of the project
- Contract signed end of 2014 with the cavity manufactured that procured in the following months some documentation:
  - Final cavity manufacturing drawings (with welding location and symbol with welding details)
  - Quality control plan with visual and dimensional test report and pressure test procedure
  - Welding book with WPS (Welding Procedure Specification) and PQR (Procedure Qualification Record)

➡ **This allowed to take a leap forward on the licensing with KHK**

Impact of the licensing on the manufacturing

- Thanks to the documentation provided by the manufacturer, it was possible to discuss with KHK on the tests to perform on each weld of the niobium cavity and helium tank. The list was agreed end of 2015.

										Inspection requirement to eliminate Product PT from KHK								
Weld ID	**Weld description**	**Materials**	**Weld penetration**	**Weld process**	**Joint category**	**Weld type**	**Joint efficiency ASME**	**Joint efficiency HPGSA**	**Joint efficiency Used**	**PQR RT**	**PQR PT, VT**	**PQR Tensile**	**PQR Bending**	**Production Sample RT**	**Production Sample PT, VT**	**Production Sample Tensile**	**Production Sample Bending**	**Product PT**
EB1	Longitudinal body	Nb – Nb	Full – 3 mm	EB	A	1	0,85	1	0,85	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Not required
EB3 EB4	Longitudinal cone	Nb – Nb	Full – 3 mm	EB	A	1	0,85	1	0,85									
EB5 EB6	Cone to central part	Nb – Nb	Full – 3 mm	EB	B	1	0,7	0,7	0,7									
EB7	Cone to torus	Nb – Nb	Full – 3mm	EB	B	1	0,7	0,7	0,7									
EB8	Body to torus	Nb – Nb	Full – 3mm	EB	B	1	0,7	0,7	0,7									
EB9 EB10	Body and cone to torus	Nb – Nb	Full – 3mm	EB	B	1	0,7	0,7	0,7									
EB12	Body to coupler flange	Nb – Nb	Full – 3mm	EB	B	1	0,7	0,7	0,7									
EB13	Longitudinal coupler flange	Nb – Nb	Full – 3mm	EB	A	1	0,85	1	0,85									
EB23	Body to pick-up	Nb – Nb	Full – 3 mm	EB	D	1	0,7	0,7	0,65									
EB25 EB26	Body to beam port	Nb – Nb	Full – 3 mm	EB	D	1	0,7	0,7	0,65									
EB14 EB15	HPR to torus	Nb – Nb	Full – 3 mm	EB	B	1	0,6	0,7	0,6	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Not required
EB16 EB17	HPR to torus	Nb – Nb	Full – 3 mm	EB	B	1	0,6	0,7	0,6									
EB25b EB26b	Beam port	Nb – Nb	Full – 5 mm	EB	B	1	0,7	0,7	0,7									
EB18 EB19 EB20 EB21	HPR to flange	Nb – NbTi	Full - 6 mm	EB	C	7	1	0,7	0,6	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Mandatory required	Not required
EB22	Coupler to flange	Nb – NbTi	Full - 6 mm	EB	C	7	0,85	0,95	0,85									
EB24	Pick-up to flange	Nb – NbTi	Full - 6 mm	EB	C	7	0,7	0,7	0,7									
EB27 EB28	Beam port to flange	Nb – NbTi	Full - 6 mm	EB	C	7	0,6	0,7	0,6									
L1 L2	Longitudinal body	Ti – Ti	Full – 3 mm	TIG	A	2	0,65	0,9	0,65	Non-Mandatory required	Non-Mandatory required	Mandatory required	Mandatory required	Non-Mandatory required	Non-Mandatory required	Mandatory required	Mandatory required	Mandatory required
C1 C2	Flat head	Ti – Ti	Full – 3 mm	TIG	C	2	0,7	0,7	0,7									
L3 L4 L5	Longitudinal port	Ti – Ti	Full – 3 mm	TIG	A	1	0,65	0,65	0,65	Non-Mandatory required	Non-Mandatory required	Mandatory required	Mandatory required	Non-Mandatory required	Non-Mandatory required	Mandatory required	Mandatory required	Mandatory required
C3 C6	Body to port	Ti – Ti	Full – 3 mm	TIG	D	7	1	0,7	0,7									
C4 C5	Body to port	Ti – Ti	Full – 3 mm	TIG	D	7	1	0,7	0,7									
C7	He in and out	Ti – Ti	Full – 3 mm	TIG	D	7	1	0,7	0,7									
C8	He in and out	Ti – Ti	Full – 3 mm	TIG	D	7	1	0,7	0,7									
C9 C10 C11 C12	HPR to flange	Ti – NbTi	2 mm	TIG	C	7	0,6	0,7	0,6	Non-Mandatory required	Non-Mandatory required	Mandatory required	Mandatory required	Non-Mandatory required	Non-Mandatory required	Mandatory required	Mandatory required	Mandatory required
C15 C16 C17 C18	Port to flange	Ti – NbTi	2 mm	TIG	C	7	0,6	0,7	0,6									

RT: radiographic control using X-rays

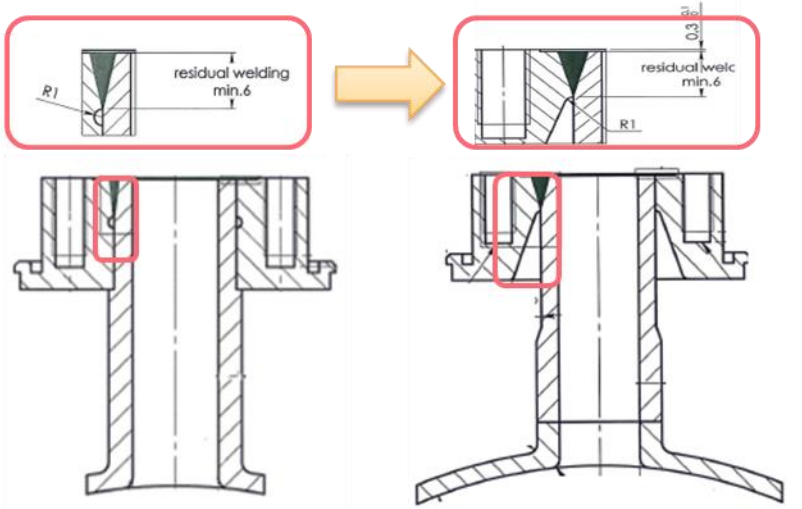
PT: dye penetrant test (using on welds of the helium tank)

Impact of the licensing on the manufacturing

- Qualification of the welds according to ASME (with a Lloyd's register third part inspector).

- Early 2016, an issue in the weld qualification of the NbTi flange on the niobium cavity led to design and manufacturing process changes. Additional niobium material was required, which delayed the production for several months.

Design change

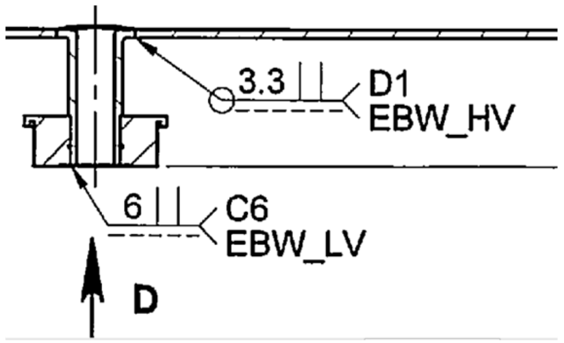


Weld from top of flange to a groove → does not fulfil KHK requirement of full penetration weld

The groove has been removed and the bottom of the flange cut out: full penetration OK

Manufacturing process change

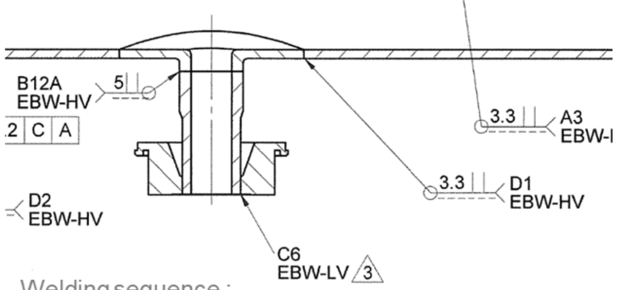
Initial configuration



Welding sequence :

- Welding of the Nb part of the PU to the cavity body (weld D1)
- Welding of the NbTi flange to the port (weld C6)

New configuration



Welding sequence :

- Welding of the NbTi flange to the port (weld C6)
- Welding of the 2 Nb parts of the PU (weld B12A)
- Welding of the port to the cavity (weld D1)

- Meanwhile, a pre-serie cavity was manufactured (without all the licensing requirements) and fully qualified second half of 2016.

Licensing of the cavity: summary

- The licensing of the superconducting cavity was not straightforward!
- The licensing frame was not well defined at the beginning of the project. It led to several design changes, some during the manufacturing of the components.
- The licensing activity has been an unexpectedly time and resource consuming activity to perform the numerical simulations, deal with the many questions raised by KHK, prepare and test the samples and complete the application form. It also induced hold points and delay in the cavity production that were difficult to anticipate.
- Thanks to the collaborative work between CEA, F4E and QST and the strong involvement of the cavity manufacturer, the Application Form was approved in March 2016.
- Once all the requirements have been well defined and the pre-series cavity fully qualified, no licensing issue occurred during the production of the eight series cavities. In addition to the tests presented earlier:
  - Production Test Coupons (PTC) for each WPS.
  - Pressure test witnessed by a Lloyd's register third part inspector.

Licensing of other components

- Because of the materials (stainless steel or aluminum) of the other components of the cryomodule, prior evaluation by the High Pressure Gas Safety Institute of Japan (KHK) was not needed and the licensing frame was well defined:

Component	Licensing procedure	Code
Phase Separator	YES – Pressure vessel	ASME BPVC Section VIII Div.1
Solenoid vessels (CIEMAT)	YES – Pressure vessel	
Current leads assembly (CIEMAT)	YES – Piping	ASME B 31.3
Cryo-piping, thermal shield piping	YES – Piping	
Power coupler (outer conductor only)	YES – Piping	
Vacuum vessel	**NO** – ΔP < 0,1 MPa	x

Pressure vessels as per ASME BPVC Sec. VIII Div.1 §U-1
Internal diameter > 6 in. (152 mm)

Piping as per ASME B 31.3
Internal diameter < 6 in.

- Additional requirements to be compliant with the Refrigeration Ordinance of HGPSL, but easy to overcome because standard: calculation notes, radiographic examination and dye penetrant test of welds, pressure test witnessed by a third party inspector, production test coupons …

- U-stamp not required.

- The manufacturing documentation and the test reports are part of the Application Form submitted to the Aomori Prefecture prior to the installation of the cryomodule.

Applicable Tests

- The list of applicable tests for every component was a compromise between the Japanese Industrial Standard (JIS) used in HGPSL and the use of the components in the cryomodule:
  - Indeed, to avoid liquid contamination of the cavity beam vacuum, it was negotiated not to perform dye penetrant test on the beam vacuum piping and to follow the non-destructive tests required in ASME Sec. VIII Div. 1 in addition to radiographic tests.
  - For the other components (components of the cryogenic circuits): radiographic tests and dye penetrant tests.
- Welding qualification according to ASME BPVC Section IX or ASME B31.3 (WPS, PQR, PTC…)
- All components were leak tested and pressure tested with test factor higher than the one required by ASME:
  - Hydrostatic test: **1.5** (ASME: min. 1.3) time the maximum allowable working pressure (MAWP).

$$P_{test} = 1.5 \times 0.15 = 0.225\ MPa$$

  - Pressure test: **1.25** (ASME: min. 1.1) time the MAWP if there is a reason to avoid water contamination.

$$P_{test} = 1.25 \times 0.15 = 0.187\ MPa$$

  - Hydrostatic test or pneumatic test witness by a *third party* inspector.
  - Leak test witnessed by an *in-shop* inspector.

Lessons Learnt

- In order to avoid delays and extra costs, it is mandatory to define the licensing frame with the requirements and the precise list of tests to be performed during all stages of the project.
- For the same reason, qualification procedures and tests must be anticipated in order to purchase the material in addition to the one needed for the production.
- For the cavities, it is mandatory to involve the manufacturer at the beginning of the discussions with the Japanese authorities. The hold points to wait for approval of licensing documents must also be known to be anticipated.
- Because of the back and forth communication between the designers, the manufacturer and the Japanese Authorities, collaborative work between the European and the Japanese teams is one of the keys of the success.