Technical and logistical challenges for IFMIF-LIPAC cryomodule construction

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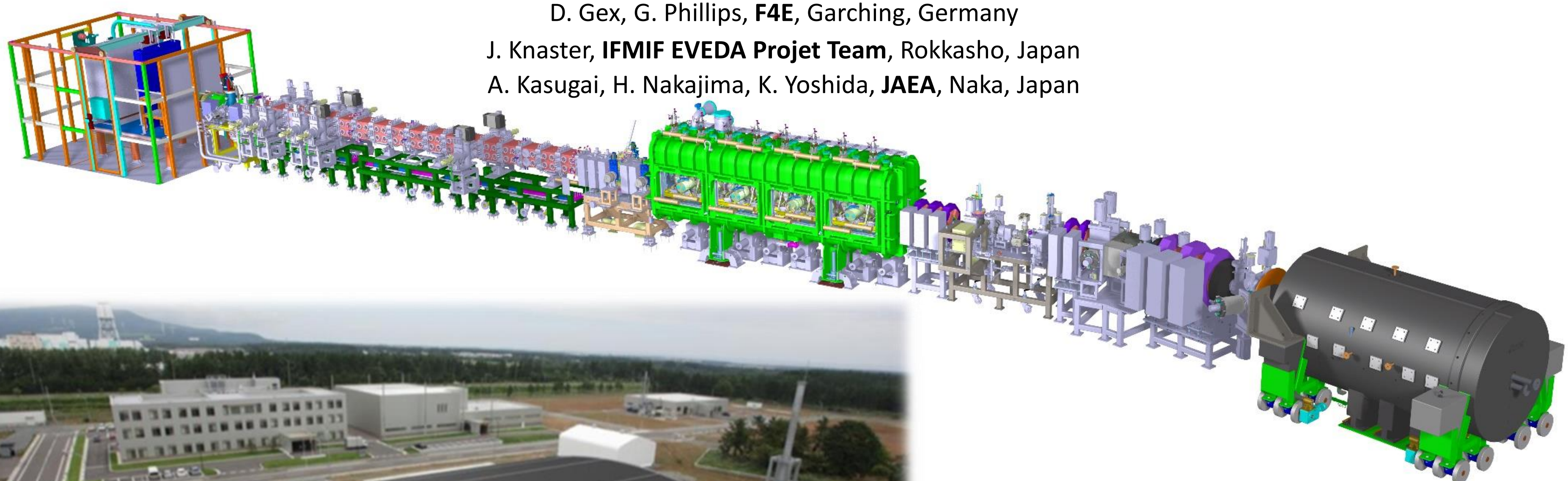
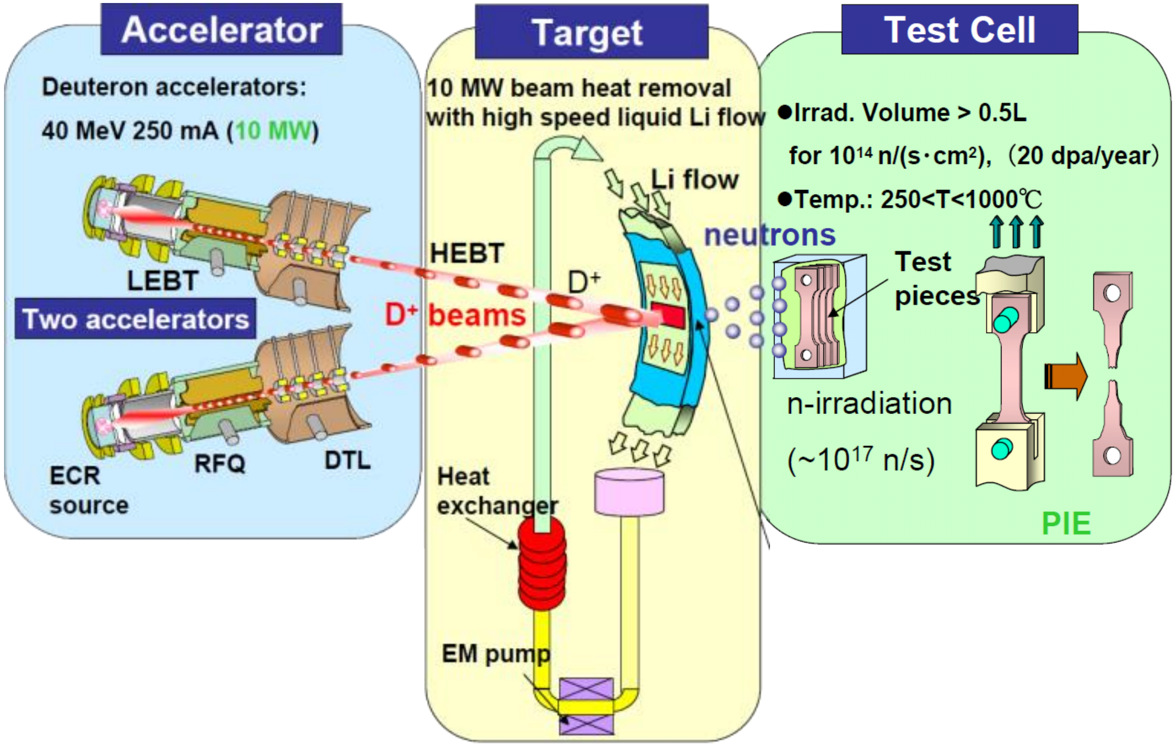


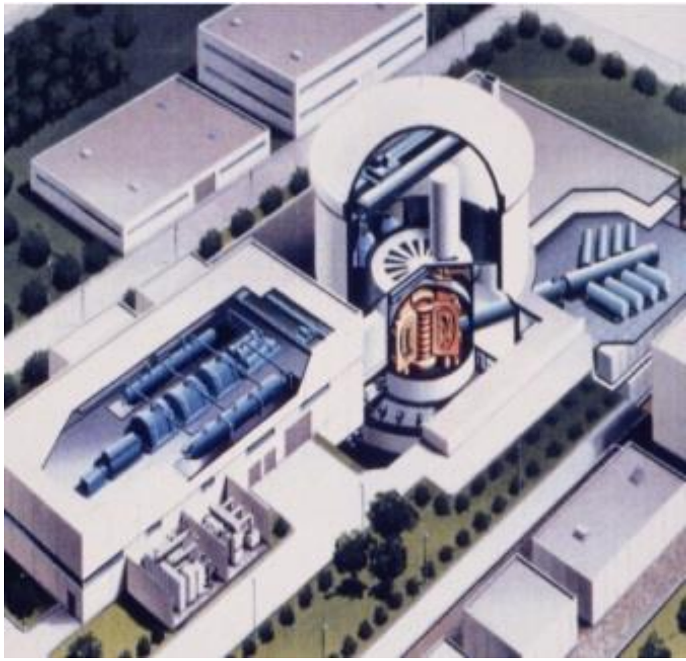
Outline

- Overview of the IFMIF LIPAc project
- Cryomodule Design
  - IFMIF cryomodule specifications
  - Constraints
  - Concept
- Risk mitigation and design optimization
  - Main risks identified
  - Magnetization
  - Seismic
  - Cool-down and thermal-hydraulic behavior
  - Tests before cryomodule assembly
  - Assembly site/transportation
  - Licensing
- Licensing
- Cryomodule manufacturing status
  - HWR cavities
  - Main cryomodule components
- Conclusion

IFMIF concept



Objective of the **I**nternational **F**usion **M**aterial **I**rradiation **F**acility (IFMIF): characterization of materials with intense neutrons flux (10^{17} n/s) for the future Fusion Reactor DEMO (~150 dpa)



2 identical Linacs each accelerating a continuous-wave 125-mA D^+ beam at 40 MeV (10 MW)

IFMIF/EVEDA – IFMIF LIPAc: scope of the work

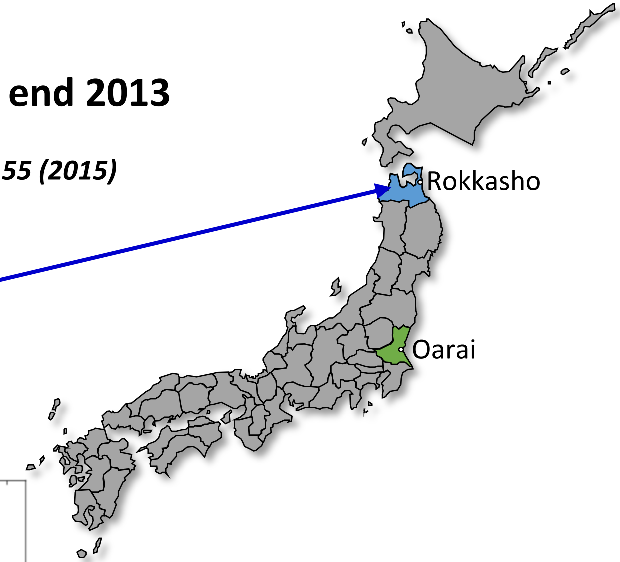
The Engineering Validation and Engineering Design Activities (EVEDA), conducted in the framework of the Broader Approach aim at:

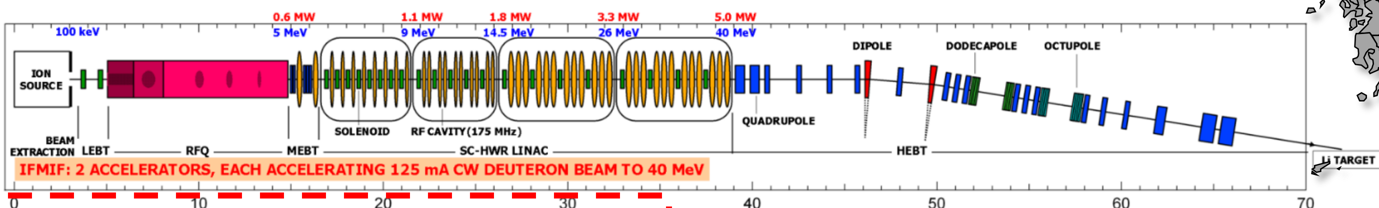
– **<u>Providing the Engineering Design of IFMIF</u> ➔ IIEDR released by end 2013**

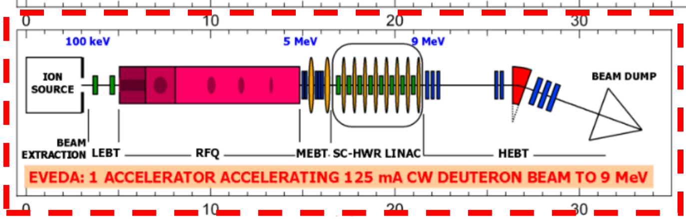
Cf. J. Knaster et al, "The accomplishment of the Engineering Design Activities of IFMIF/EVEDA: The European–Japanese project towards a Li(d,xn) fusion relevant neutron source", Nucl. Fusion 55 (2015)

– **<u>Validating the key technologies (high priority)</u>**

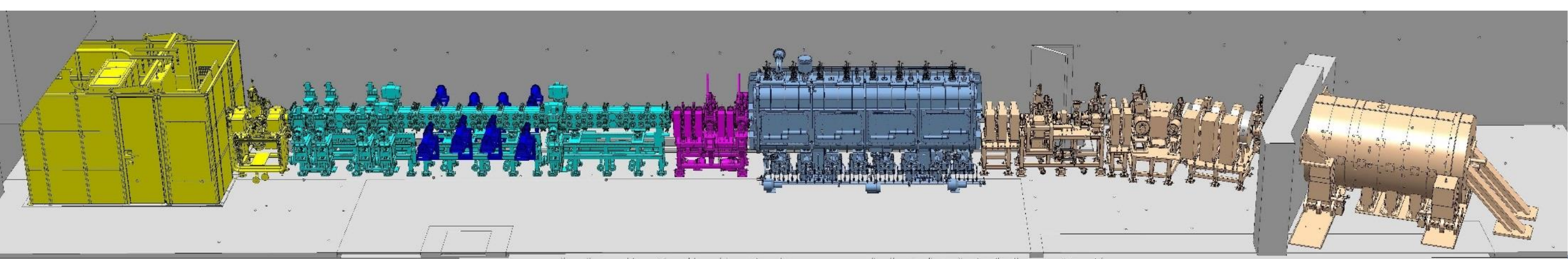
- The lithium target facility
- The high flux modules
- The low energy part of accelerator





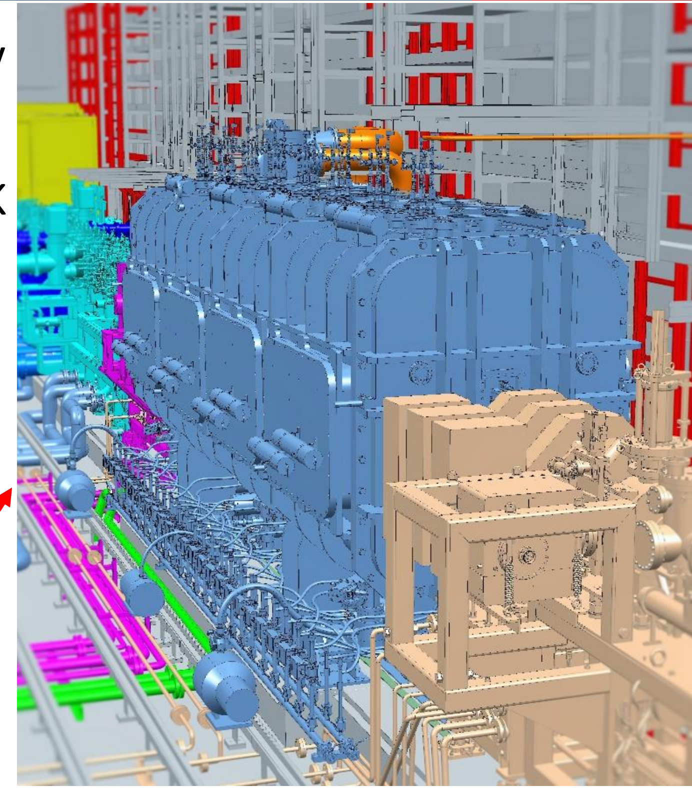


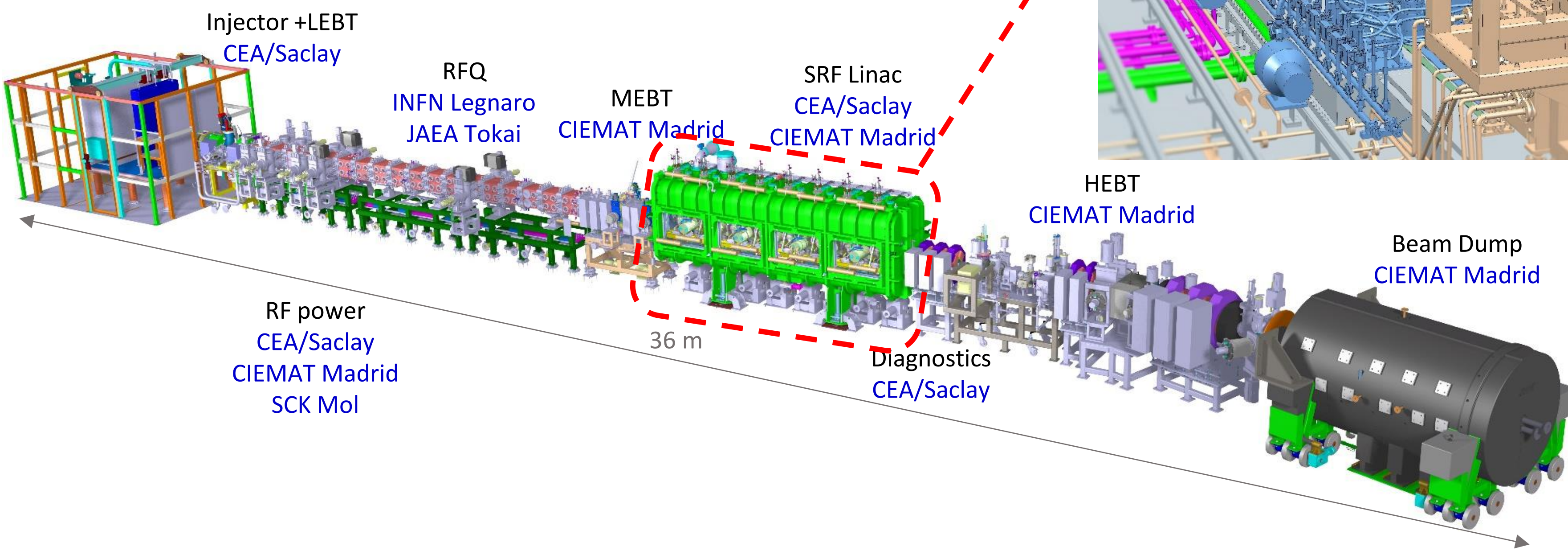
Accelerator's technological feasibility tested through design, manufacturing, installation, commissioning and testing activities of a 1:1-scale prototype accelerator from the injector to the first cryomodule (9 MeV, 125 mA D^+ beam CW): LIPAc (**L**inear **I**FMIF **P**rototype **Ac**celerator)



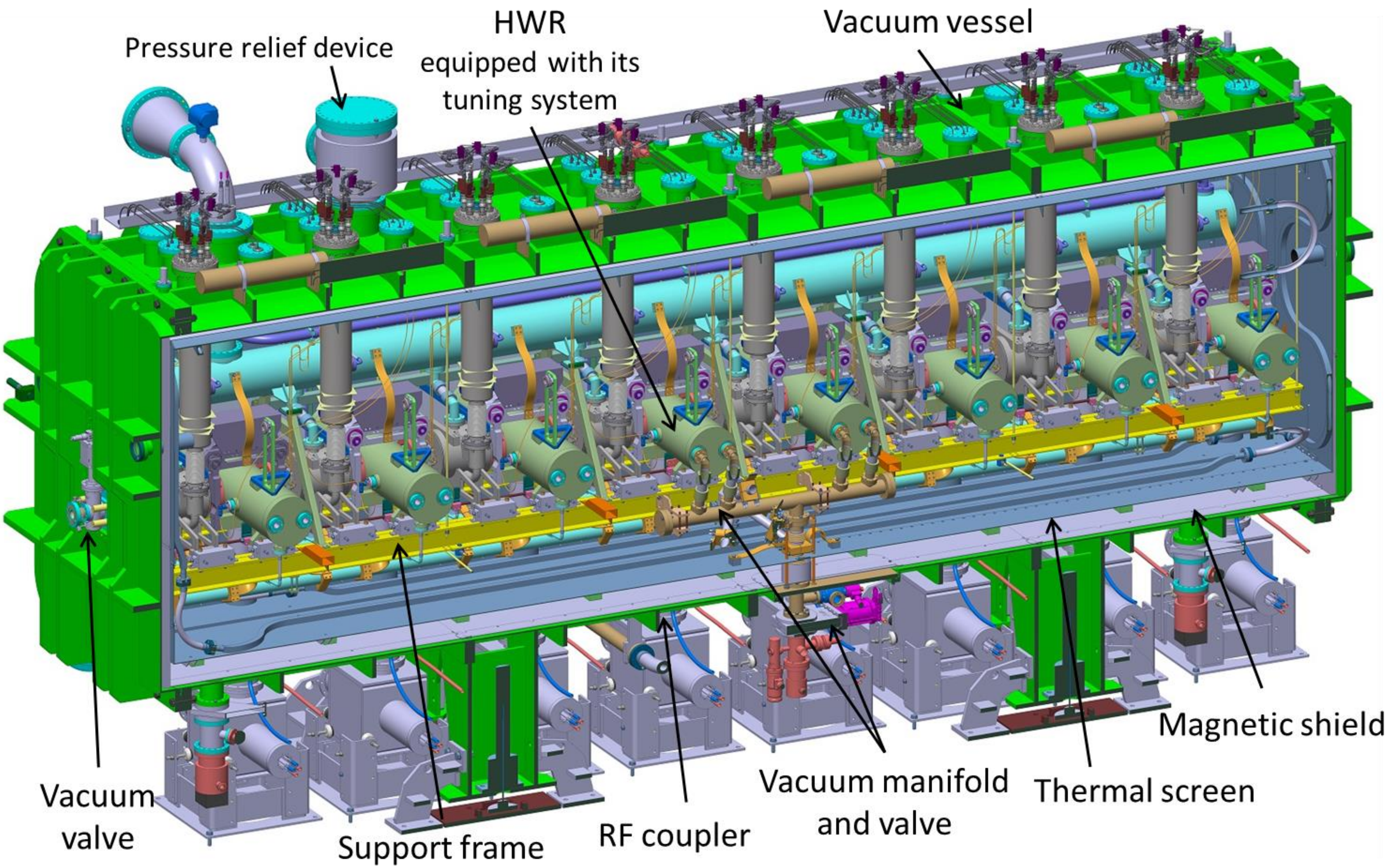
IFMIF LIPAc Cryomodule

- Transport and accelerate D^+ beam from 5 MeV up to 9 MeV
- 6 m long, 3 m high and 2.0 m wide, 12.5 tons
- 8 superconducting HWRs working at 175 MHz and at 4.45 K
  β=0.094, E_a=4.5 MV/m, $Q_0 \geq 5 \times 10^8$, $Q_{ext} 5 \times 6.5 \times 10^4$
  Tuning range [kHz]=50 kHz, Loaded bandwidth=2.7 kHz
- 8 Power Couplers (70 kW CW)
- 8 Solenoid Packages as focusing elements
- Reference for the realization of the IFMIF cryomodules





Cryomodule Design

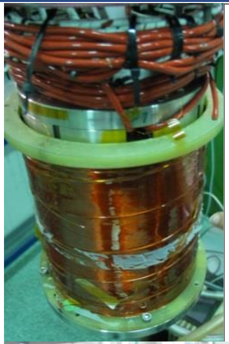


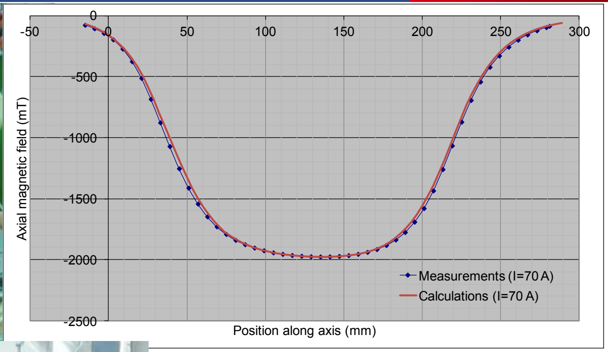
Overview of the development plan

- **Prototyping of the critical components in design phase**
  - **One solenoid prototype** was successfully tested;

    Magnet design (restricted space and low fringe field requirement)

S. Sanz et al "Fabrication and testing of the first Magnet Package Prototype for the IFMIF project", IPAC 2011





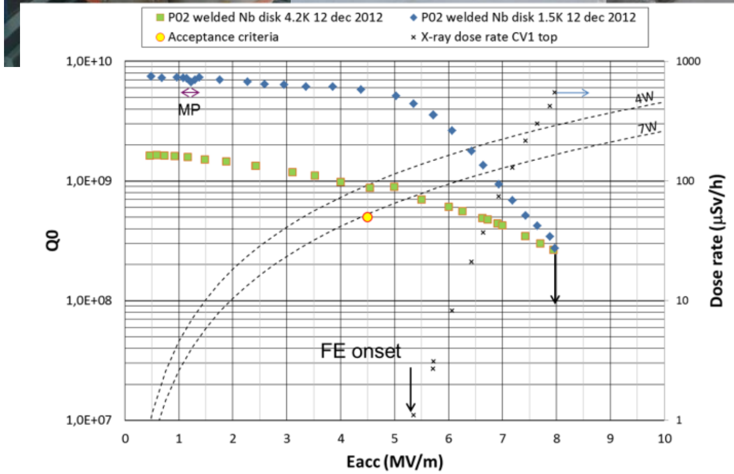
  - **2 Coupler prototypes** designed by CEA, fabricated by CPI Company and conditioned at room temperature by CIEMAT in April 2014, qualified their design and fabrication.

D. Regidor et al, "LIPAc SRF linac couplers conditioning", Proc. of IPAC2014.

  - **One Superconducting HWR prototype** successfully qualified in Dec. 2012. The VT results were satisfactory with performance project specifications of 4.5 MV/m and Q_o of 5.10^8

F. Orsini et al, "Progress on the SRF Linac Developments for the IFMIF-LIPAC Project", IPAC 2013.

N. Bazin, Cavity Development for the linear IFMIF prototype accelerator SRF2013 THIOD03

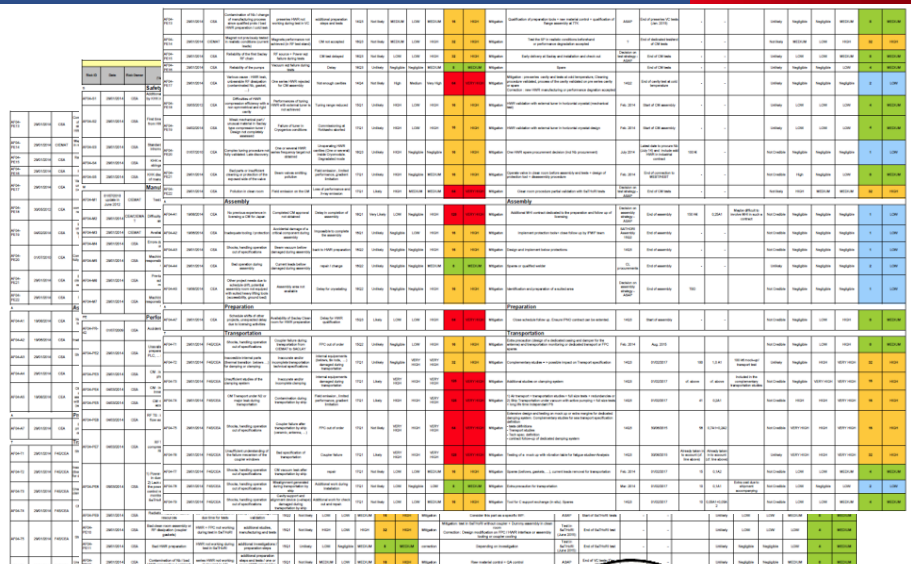


- **Design evaluation by a panel of international experts**
- **Detailed Risk analysis**
- **Mitigation plan**

Risk analysis

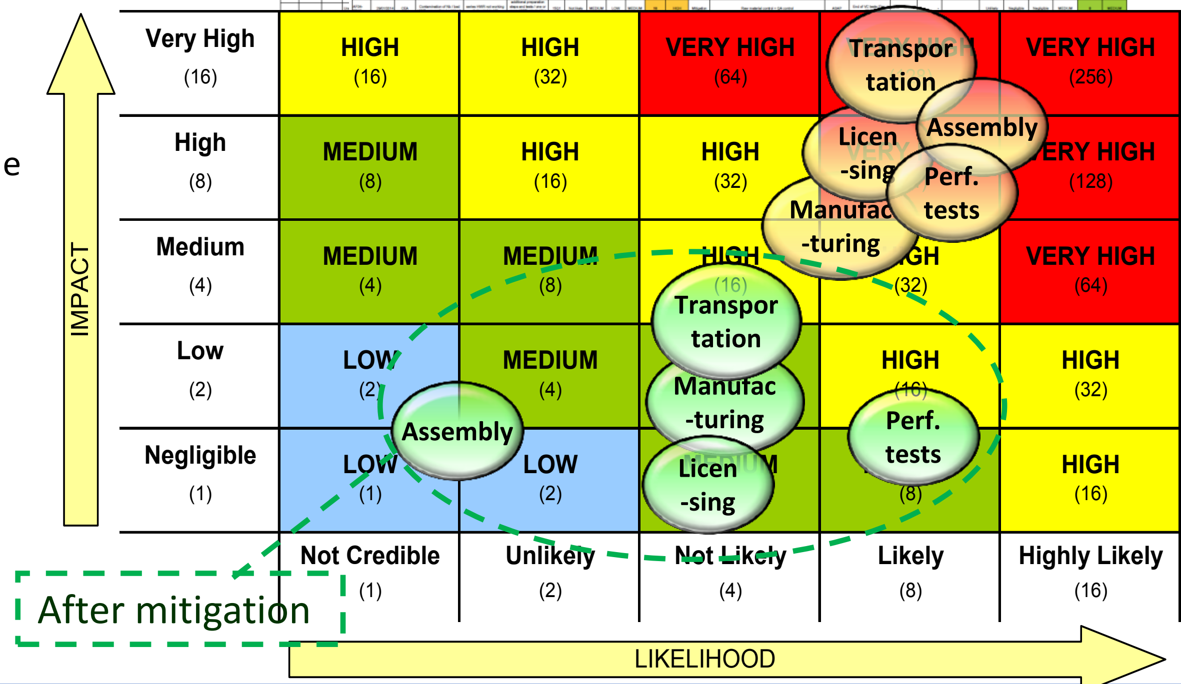
Detailed risk analysis (like FMECA)

- Detailed risk analysis taking into account the DDR remarks carried out.
- 63 risks identified
- 5 main hazard classes related to:
  - Safety and regulation (pressure equipment, licensing, seismic risk)
  - Manufacturing
  - Assembly
  - Transportation
  - Performance tests



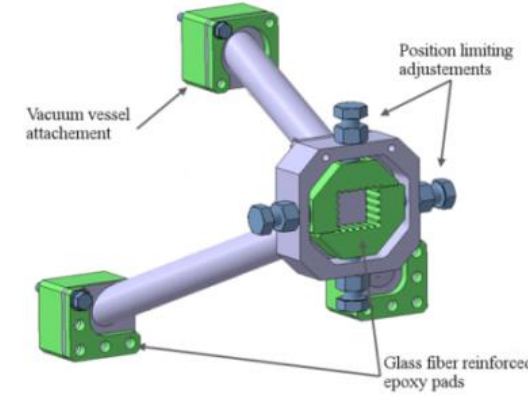
Mitigation actions to lower risk criticality

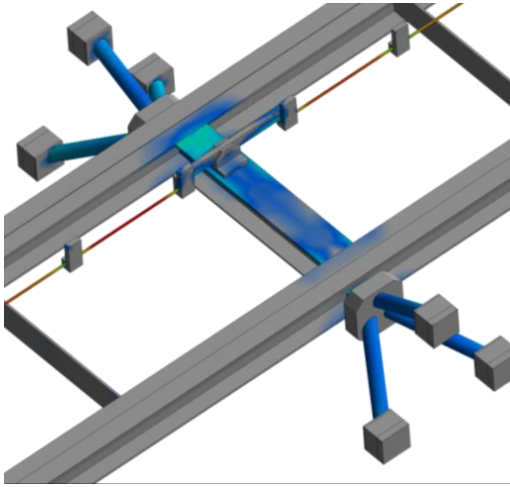
- Seismic analysis to check the cryomodule robustness to earthquakes,
- Mitigation of the risks due to magnetization,
- Numerical simulation in order to check the cryomodule cryogenic behavior.
- Additional tests before cryomodule assembly

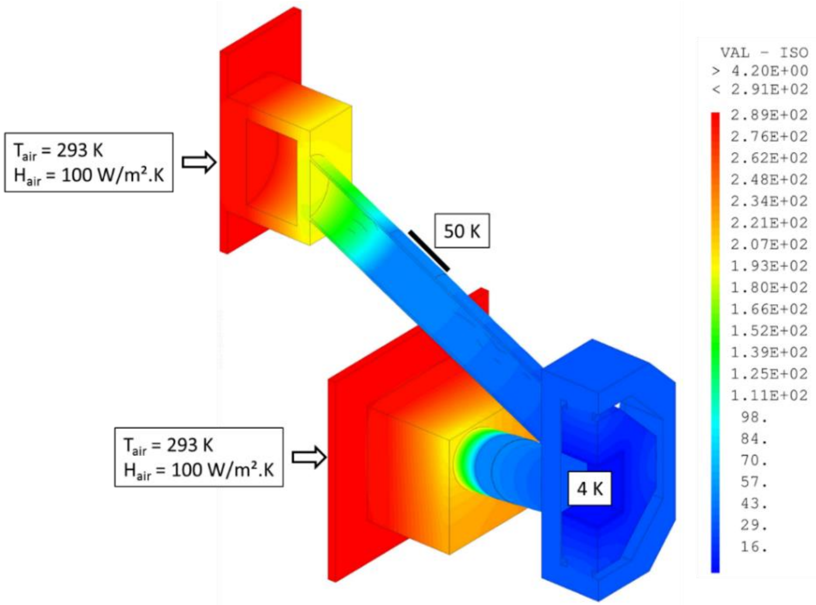


The Analyses highlighted some weaknesses of the cryomodule with regards to seism risks

- **First analysis on the design**
  - Major pb: cold mass swinging along the beam axis that could damage internal vacuum piping, bellows and lateral tie-rods for horizontal positioning of the support frame.
  - An additional mechanical structure, consisting of two tripods equipped with thermally insulated adjustable jaws, to anchor the frame along the beam axis.
  - The tripods are designed to sustain a 1.2 g acceleration of the 2.5 ton cold-mass without damage.
  - Thermal optimization. Total heat load on the 4K part due to the tripods is 1.3 W. Upper bound result since all the contacts are considered to be perfect.





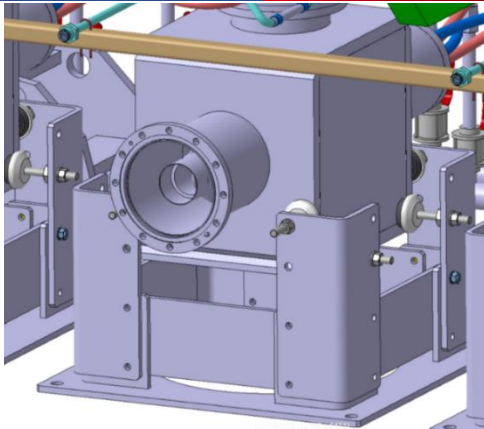


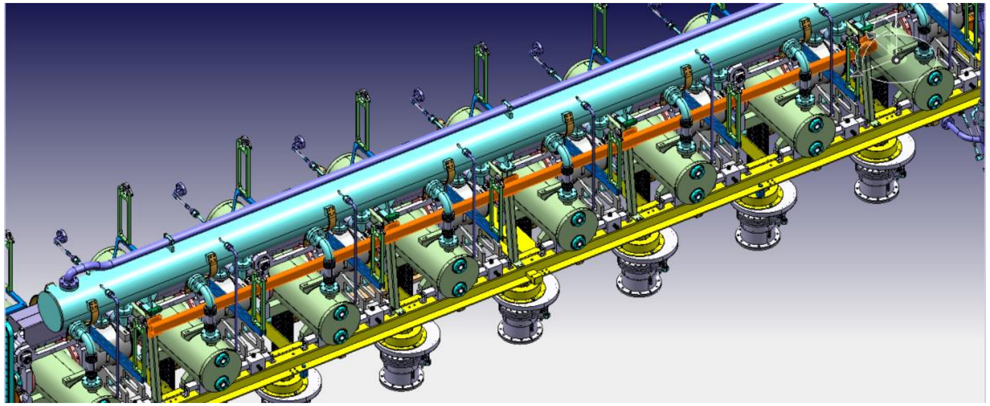
Seismic analysis – design improvements (cont'd)

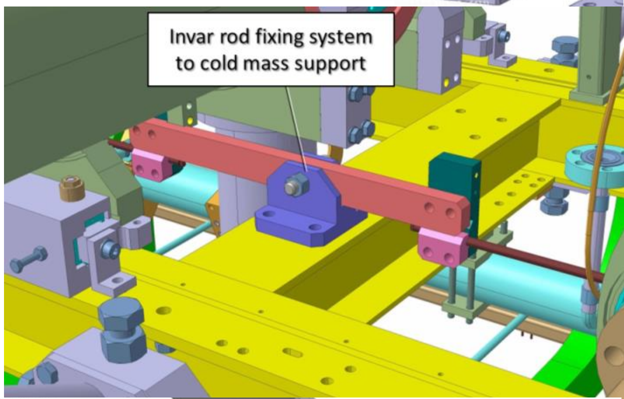
- Second analysis with anti-seismic tripods confirmed their efficiency but revealed new induced weaknesses

→ 4 major reinforcements:

1) Dampers for the coupler T-transitions were added to avoid power couplers swinging,
2) Phase separator supports reinforced with a longitudinal TA6V bar,

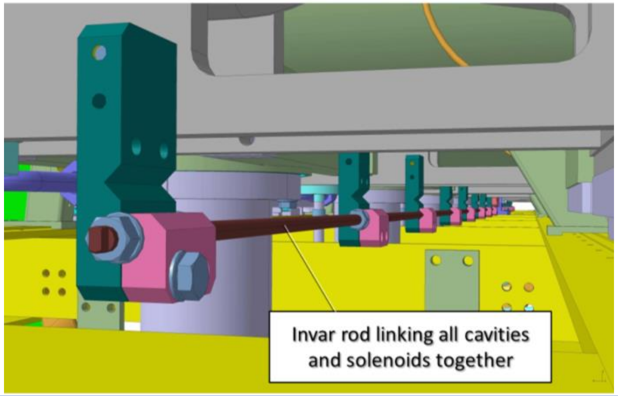


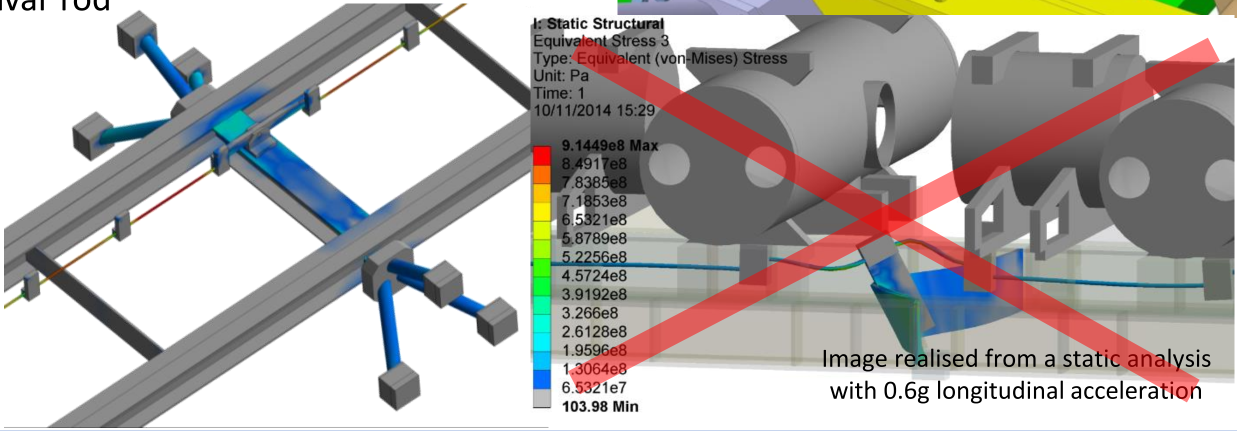




3) Plate in the middle of the support frame connected with invar rods stiffened,
4) invar rods diameter increased from 8 to 12 mm.

- **Maximum stress of 113 MPa** in the Invar rod



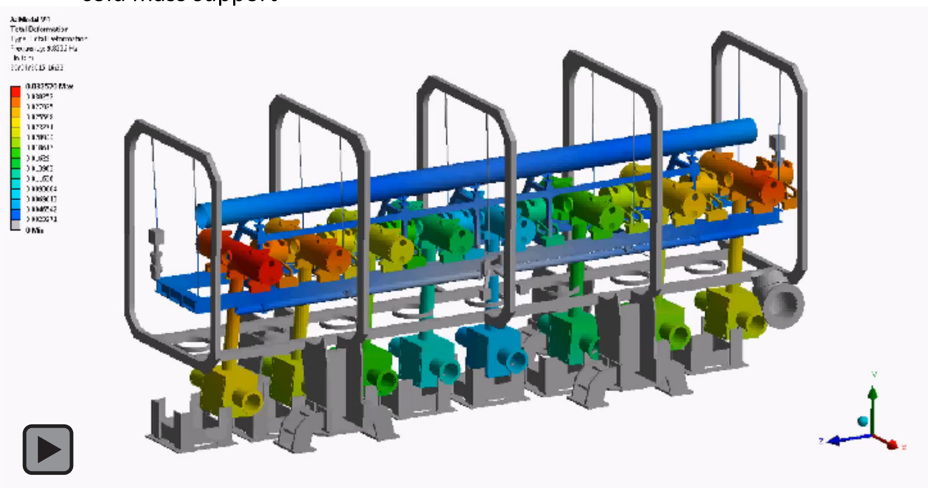


Seismic analysis – design improvement results

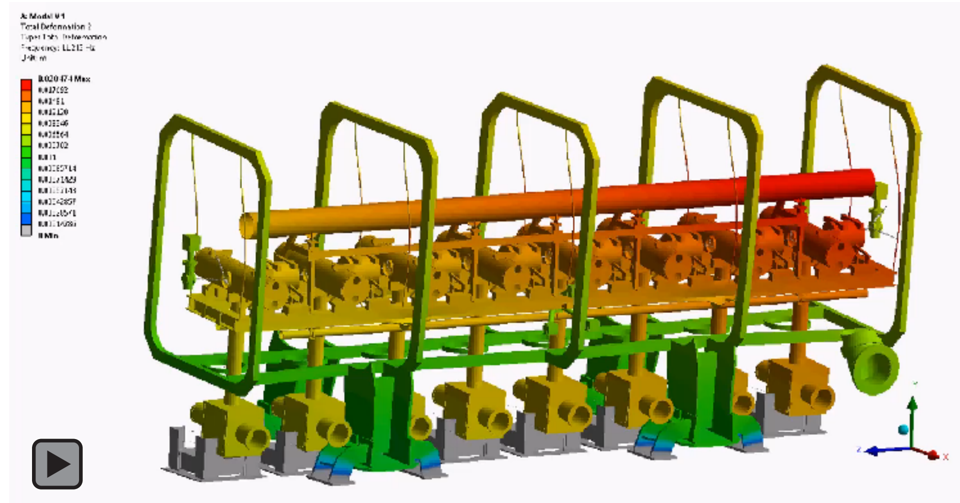
- **Third seismic analysis to validate the reinforcement measures**

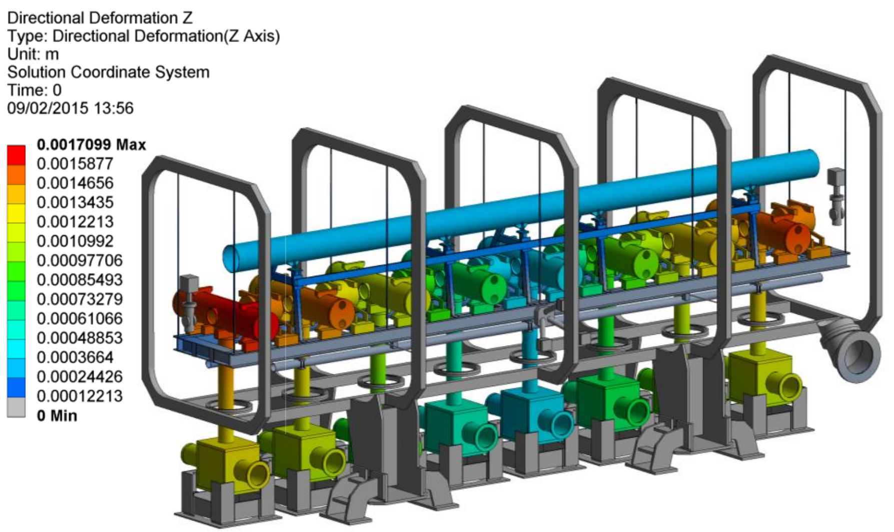
  Maximum **longitudinal displacement** of both end cavities of about 1.7 mm and a **transversal one** less than 1.2 mm.

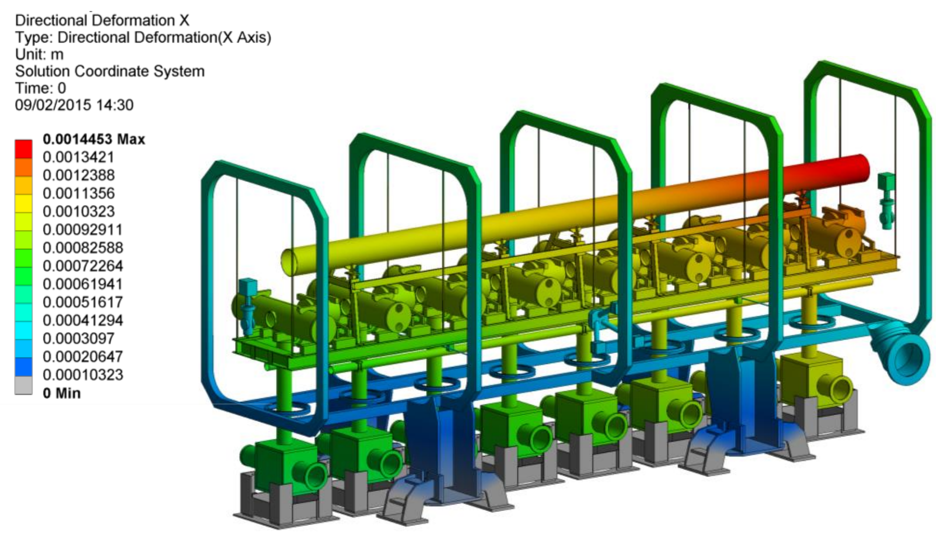
Natural mode 1: longitudinal displacement of solenoids and cavities on the cold mass support



Natural mode 2: transversal swinging of the cryomodule







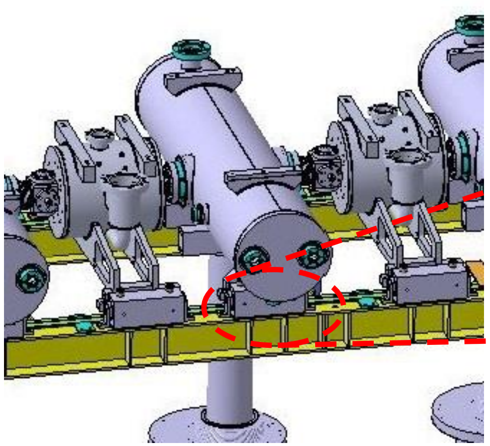
Mitigation to minimize magnetization issues

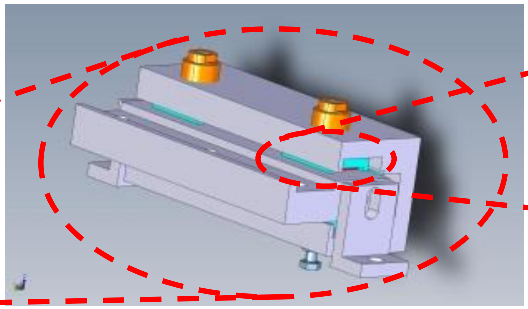
❑ Magnetization hazard

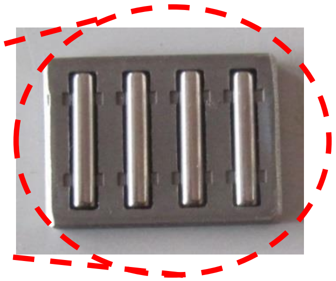
– Solenoid packages and cryogenic stepper motors inside the magnetic shield

➔ Risk of magnetization of some components by the fringe field of the solenoids during operation of the cryomodule

Ex: Off-the-shelf bearing originally intended to be used



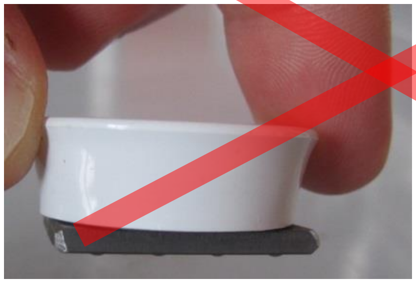




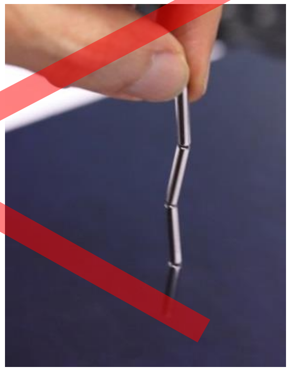
Off-the-shelf rollers

❑ Mitigation

– Use non ferromagnetic materials



Bearing cage

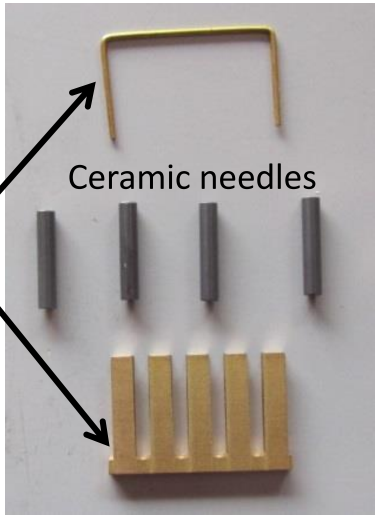


Needles magnetized

Mitigation ➔

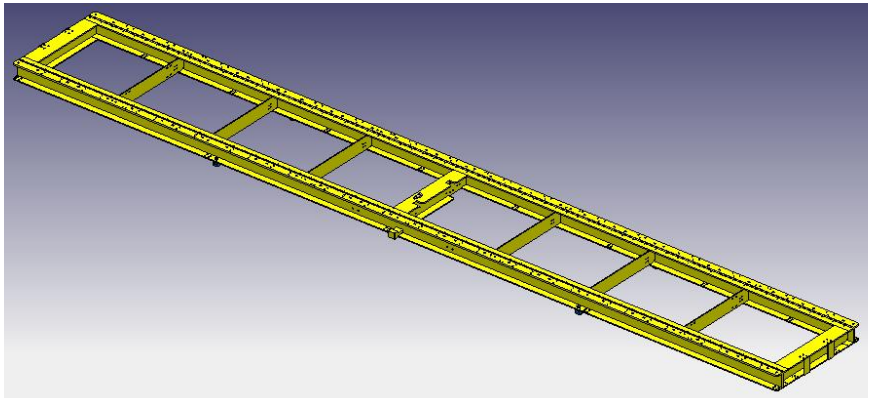
Homemade rollers

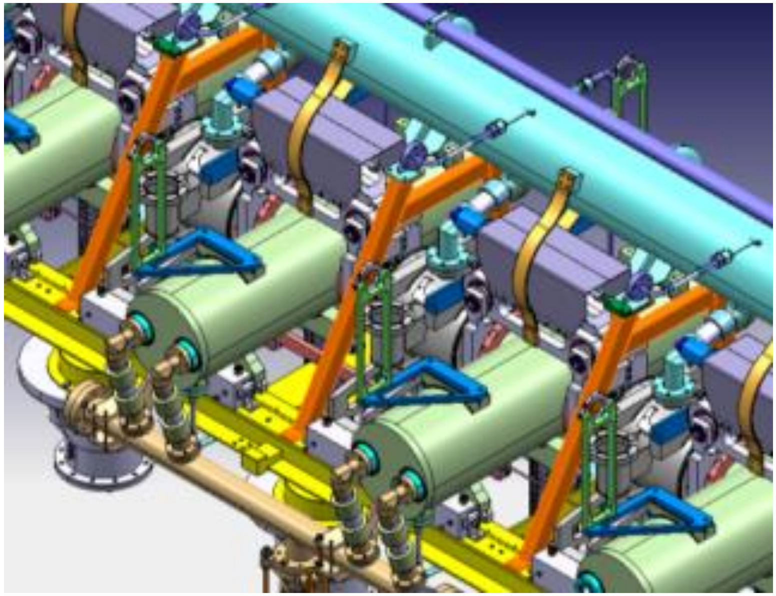
Brass cage



Mitigation to minimize magnetization issues

➔ New support frame in Ti40 instead of stainless steel 316L devised



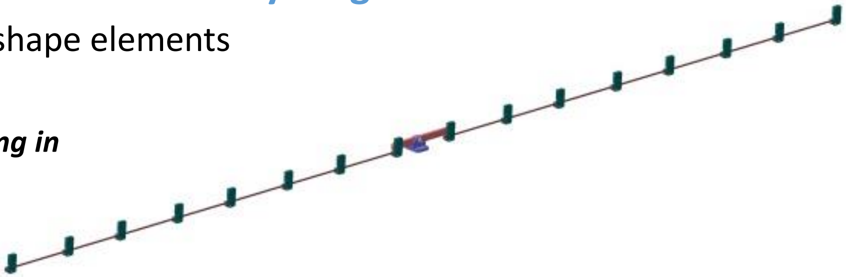


➔ No more pb with the welds
➔ Additional benefits: shrinkage lowered, cooling time divided by 3
➔ Supporting elements of the phase separator in Ti40

❑ Studies and measurements of all parts inside the magnetic shield of the cryomodule liable to be magnetized or naturally magnetized

Motors, rollers, circlips, Invar tie rod, rolling components and c-shape elements supporting the cavities, bearings of the tuning system, etc.

Cf. PLOUIN et al, "CEA experience and effort to limit magnetic flux trapping in superconducting cavities", SRF2015, TUPB100



❑ Procurement specifications and control procedures

Systematic checking of the components liable to be magnetized before cryomodule assembly

❑ Additional studies to be performed

Work out degaussing procedures to eliminate any magnetic pollution

cf. R. LAXDAL, Review of the Magnetic Shielding Design of Low-Beta Cryomodules, SRF2013, WEIOD01

Cool-down and thermal-hydraulic behavior

Crosscheck global cooling down already calculated and check thermal-hydraulic stability

- Use a code for the simulation of thermo-hydraulic processes in cryogenics systems.
- Highlight any potential imbalances in the cryogenic lines preventing the cryomodule from cooling down correctly with a reasonable time span taking into account the expected performance of the cryoplant to be built at Rokkasho.

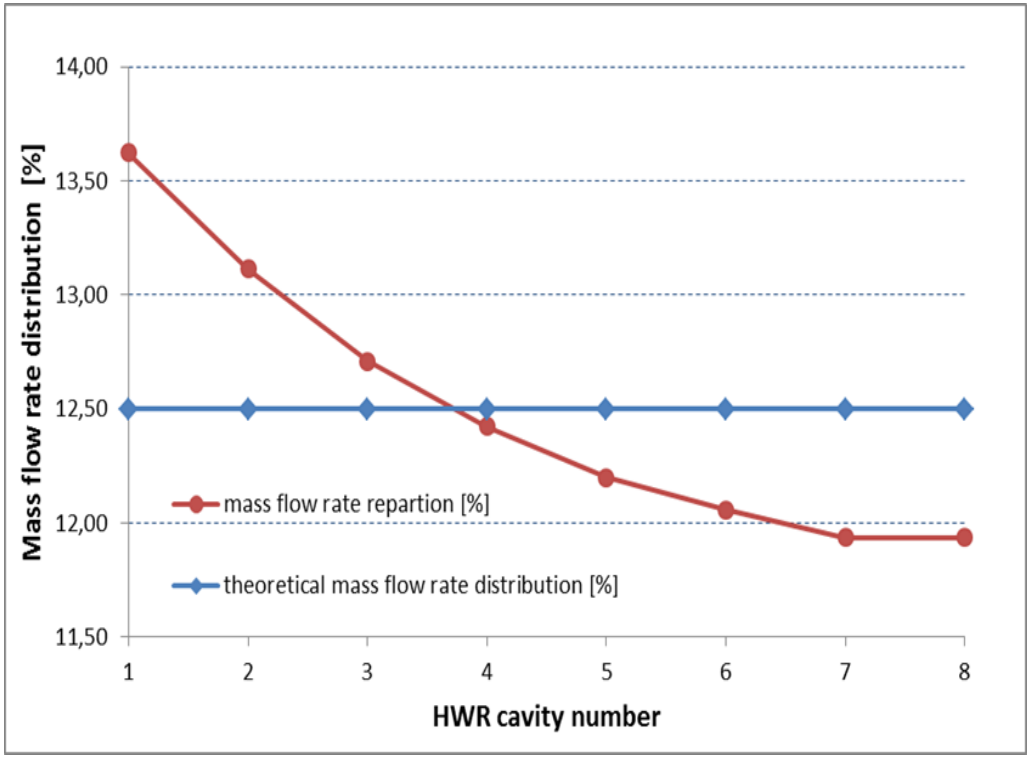
- **Results:**

➔ Confirmation of a global cooling down time expected to last about 80 h.

➔ No thermo-hydraulic imbalance in the cryogenic channels should preclude a satisfactory cooling down of the cavities.

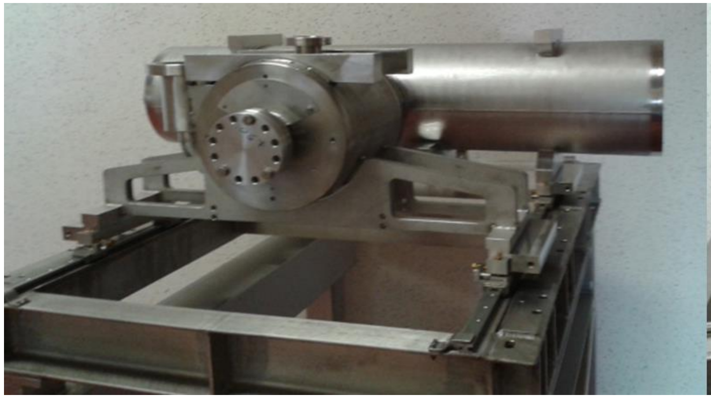
➔ Mass flow rate distribution between different channels remains balanced in acceptable values within plus or minus 10 % around the theoretical average

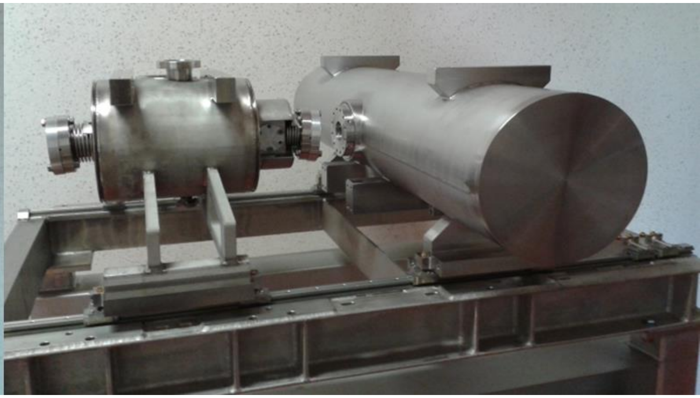
➔ Various temperature steps were tested to assess the thermo-hydraulic response of the system and confirm a satisfactory behavior.



Early testing before cryomodule assembly

- Important mitigation measure to prevent a critical event during the assembly of the cavity string.
- A dummy cavity, solenoid, coupler and part of the support frame manufactured and used to perform tests outside and inside the clean room to validate and optimize the assembly procedure and the tools.



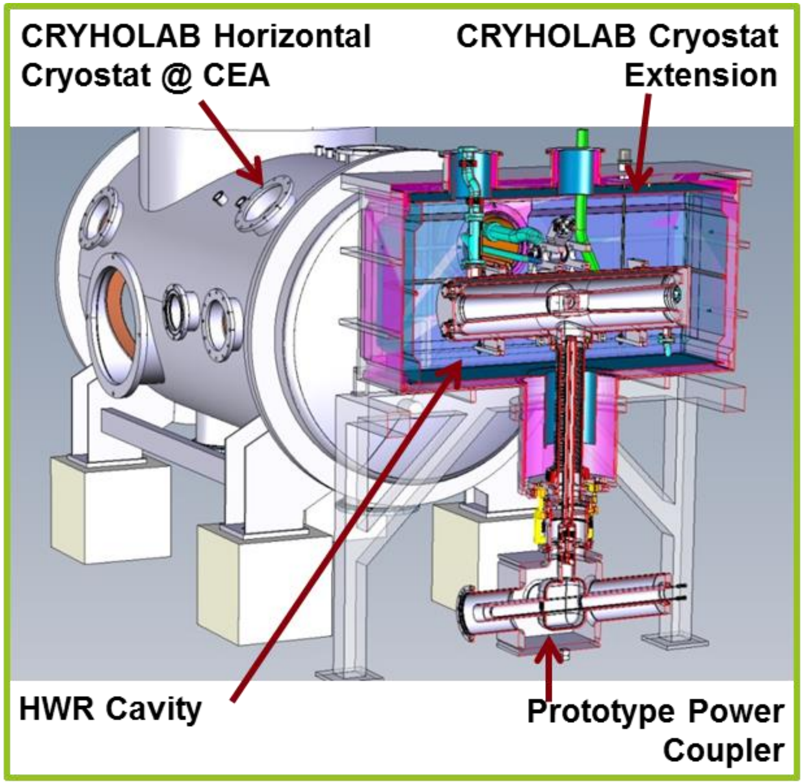


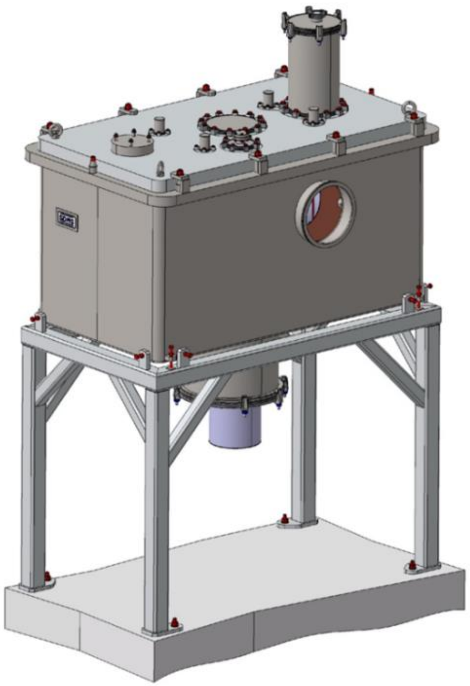
- Dummy element welds are leak tight ➔ check of the leak tightness of the gaskets between the dummy cavity, solenoid and coupler.
- Mock-ups intended to be used to train the operators for the assembly of the whole cavity string.

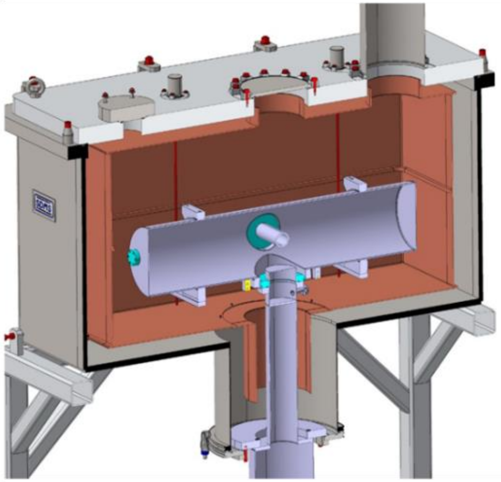
N. Bazin et al, "Development of a test bench to prepare the assembly of the IFMIF LIPAC cavity string", TUPB107, SRF2015

Early testing before cryomodule assembly (cont'd)

❑ **New dedicated test cryostat (SaTHoRI) for an intermediate characterization of a jacketed and fully dressed cavity with its coupler and tuner**





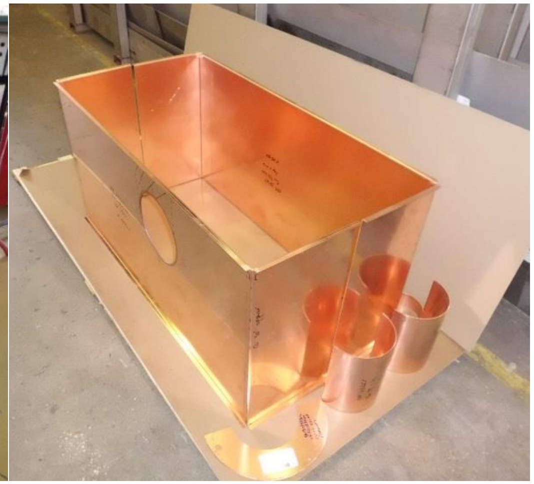


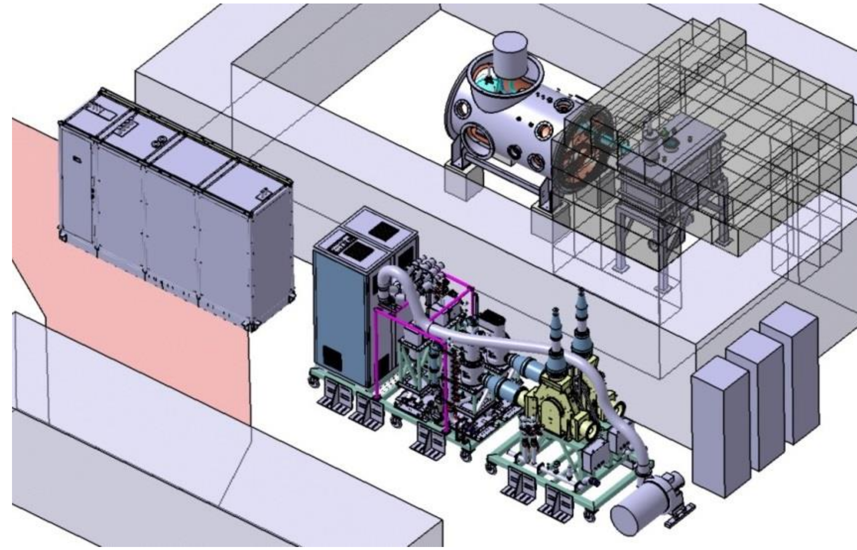
- Experts' recommendation made during the IFMIF cryomodule DDR
- Powerful mitigation mean for detecting potential issues during operation of a fully equipped cavity in realistic conditions before cryomodule assembly

Early testing before cryomodule assembly (cont'd)

SaTHoRI test bench status

- Construction started by early 2015
- First tests on the pre-series cavity expected in January 2016





Tests to be carried out with SaTHoRI test bench

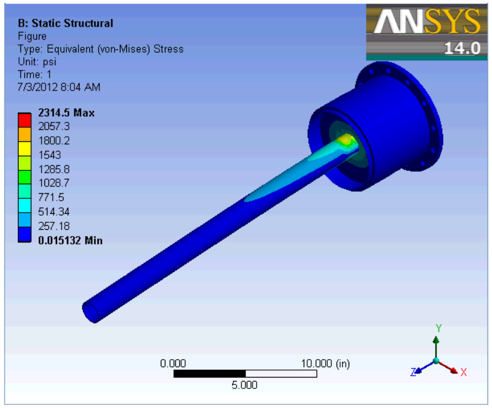
- Measurement of RF dissipation in the coupler flange and gasket
- Heat transferred and power radiated from the coupler to the cavity
- Q_{ext} of the coupler connected to the cavity
- LLRF performance assessment
- Power coupler conditioning with cold surface assessment
- Validation of the quality of the assembly in clean room by comparison with the tests of individual components

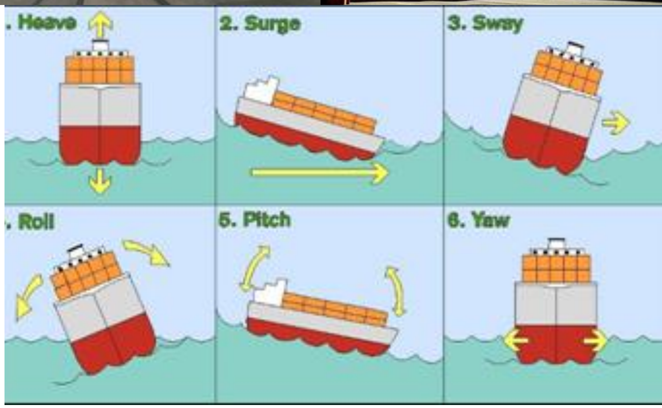
Transportation

❑ Original plan

– Transportation by sea. Cheapest solution but:
  - Several loadings/unloadings ➔ heavy shocks possible during transshipment
  - Coupler window failure or weakening due to fatigue (resulting from ocean swell)
  - Risk of contamination of the beam vacuum during shipment (long journey)
  - Additional transport studies

(fatigue, shock and vibration levels, frame, container, etc.)





❑ Mitigation

– Transportation by plane

– Assembly in Japan

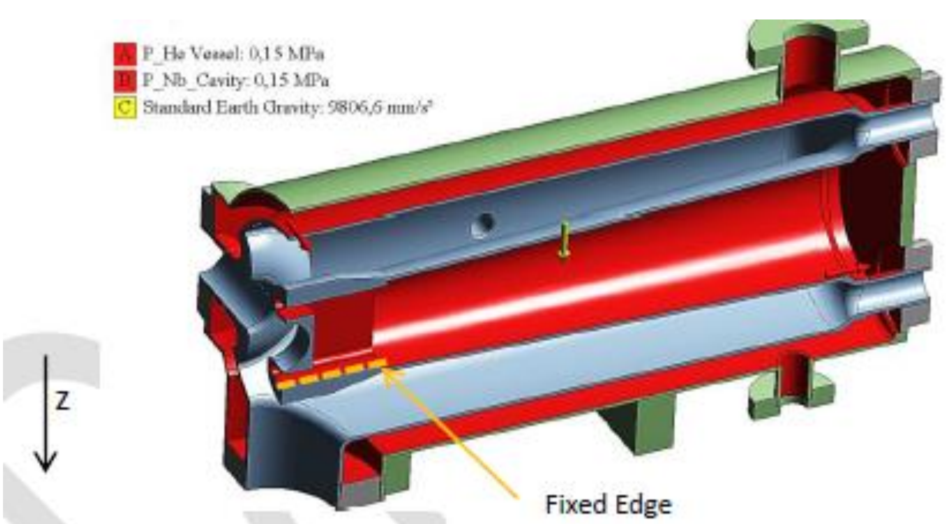
Licensing

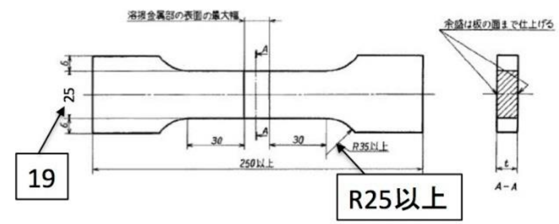
- Cryogenic fluid inside the IFMIF cryomodule ➔ Must comply with High Pressure Gas Safety Law
- Strategy negotiated with the Japanese authorities: design, fabrication and tests of all the cryomodule components according to ASME BPVC or B31.3
- HWR is the most complicated part to be licensed due to the use of non referenced materials (Nb, NbTi) and complicated geometry

➔ The licensing procedure with the Japanese Authorities started with this component in Dec 2013.

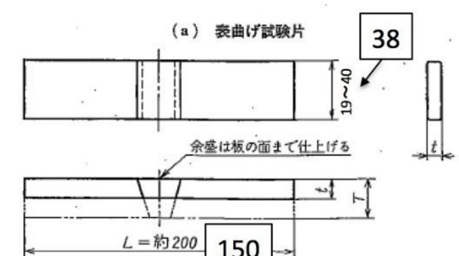
➔ 7 meetings with KHK were necessary prior to the official submission in June 2015.

➔ 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 (NbTi, Nb, NbTi-Ti, NbTi-Nb, Nb-Nb), and complete the application form.





JIS Z 3121 1A号試験片とASME Sec.IX QW462.1(a)の寸法の比較
（四角で囲った数字がASME Sec.IX QW462.1(a)）



Cavity Licensing

Design	Welding	Material	Manufacturing and testing
ASME BPVC, Section VIII, Division 1	ASME BPVC, Section IX	ASME BPVC, Section II	ASME rules & third party conformity assessment

Design approved

様式６別紙 1

適用詳細基準の内容の説明（1/13）

○申請者の名称 国立研究開発法人日本原子力研究開発機構
○申請者の所属部署 核融合研究開発部門
○申請者の氏名 大平 茂 TEL 0175-71-6612 FAX 0175-71-6602
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機能性基準条項	対象とする例示基準の対象条項	内容: 例示基準によらない理由	内容: 適用詳細基準及び適用詳細基準を裏付ける理由並びに安全であるという立証	備考

概要

日本原子力研究開発機構（以下「原子力機構」という）は、核融合分野における国際協力活動の一環として実施される国際核融合材料照射施設／工学実証工学設計活動（IFMIF/EVEDA）事業において、図１に示す原型加速器を用いて125mAの重陽子ビーム（以下、「ビーム」という）を9MeVまで加速する実証試験を行います。原型加速器は大きく分けて、125mA-100keVのビームを発生させる入射器、100keVから5MeVまで加速させる高周波四重極加速器、さらに5MeVから9MeVまで加速させる超伝導加速器、加速したビームを処理するビームダンプから構成されます。このうち超伝導加速器は、図２に示すように、８個の半波長空洞をビーム加速方向（以下、「ビーム軸」という）に沿って水平に並べた構造をしており、パワーカプラポートから入力される高周波電界をビームが通過することによりビーム軸方向に加速されます。

半波長空洞は、液体ヘリウムを貯めるチタン製の槽（図３緑色部、「チタン槽」）、液体ヘリウム中に設置されるニオブ製空洞（図３灰色部、「ニオブ空洞」）及びニオブ空洞とチタン槽を接続するための、ニオブチタンで作られたフランジ（図３青色部、「ニオブチタンフランジ」）から構成され、これらが溶接で一体化されることにより、図３に示す黄色の部分に液体ヘリウムを貯蔵する高圧ガス保安法・冷凍保安規則の冷凍能力が20トン以上の冷媒設備に係わる容器となり、本申請により適用詳細基準の事前評価をうける対象となります。また、圧力の他に、加速器としての性能を発揮させるため、ビーム軸方向（容器の径方向）にニオブ空洞を最大0.3mm変形させるための圧縮力が負荷されます。

半波長空洞は加速器としての性能を発揮する観点から設計・製作され、複雑な構造を有することから、設計・製作において冷凍保安規則の例示基準に従えない部分があります。これに加え、国際協力の観点から、プロジェクトとして、国際的に認知度が高く、かつ、信頼性のあるASME Sec. Ⅷ Div. 1（2010）に準拠して設計・製作することを基本的な合意としているため、欧州で設計・製作され、日本に輸入される半波長空洞では、試験検査の方法、基準等において冷凍保安規則の例示基準に従えない部分があります。このため、耐圧試験、冷媒設備に用いる材料、容器及び配管の強度等、容器の構造及び加工、溶接部の機械試験、及び溶接部の非破壊検査の６項目について事前評価を申請致します。

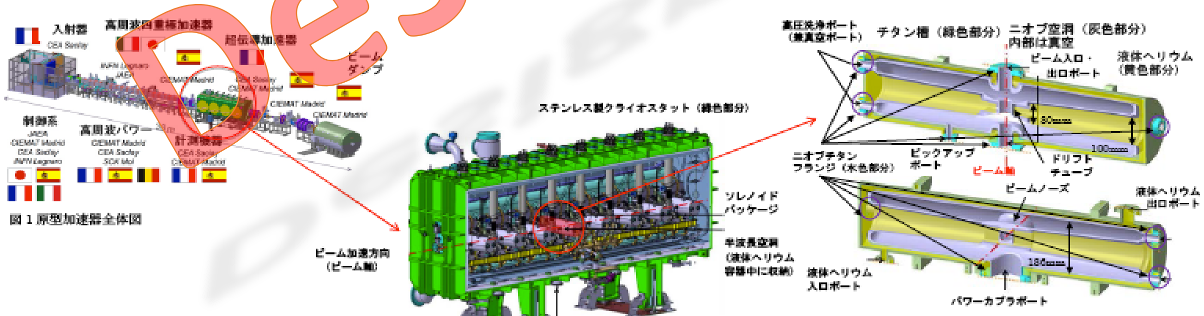

図１ 原型加速器全体図
図２ 超伝導加速器の内部構造
図３ 半波長空洞の断面図

1

Application form summary

様式６

詳細基準事前評価申請書
（冷凍保安規則関係）

原機（青管）020
平成27年 6月 4日

高圧ガス保安協会会長
作田 頴治 殿

申請者
住 所 青森県上北郡六ヶ所村大字尾駮字表舘2番地166
名 称 国立研究開発法人日本原子力研究開発機構
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代表者 所長 飯塚 幸治 印

機器の製造に係る技術上の基準について詳細基準事前評価を受けたいので申請します。

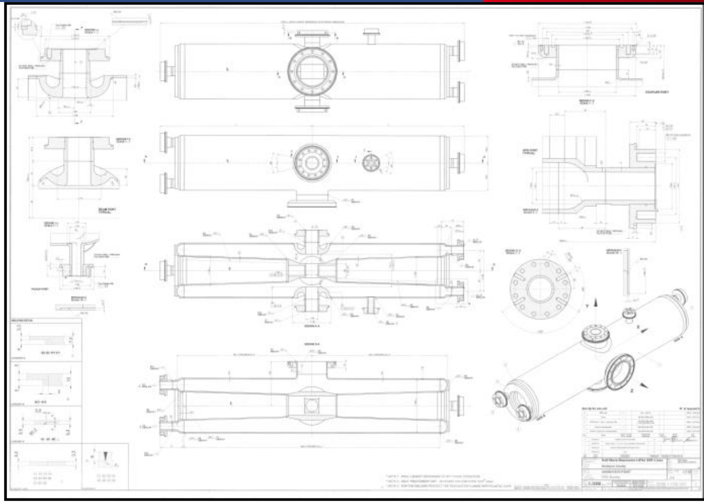
事前評価を受ける事業所	名称	国立研究開発法人日本原子力研究開発機構 青森研究開発センター （国際核融合エネルギー研究センター）
	所在地	青森県上北郡六ヶ所村大字尾駮字表舘2番地166
適用詳細基準の内容の説明		別紙のとおり

適応詳細基準
IFMIF/EVEDA 超伝導加速器用半波長空洞

国立研究開発法人日本原子力研究開発機構
核融合研究開発部門
六ヶ所核融合研究所
核融合炉材料研究開発部
IFMIF 加速器施設開発グループ

Application form

HWR cavity manufacturing status



- **Manufacturing phase ongoing**

– Contract launched in Dec. 2014

➔ Final cavity manufacturing drawings could be issued

(Welding location and symbol with welding details)

➔ Quality control plan, welding book, visual and dimensional test report, pressure test procedure issued by the manufacturer could be provided

– Qualification of the welds according to ASME BPVC ongoing (with a Lloyd's register third part inspector)

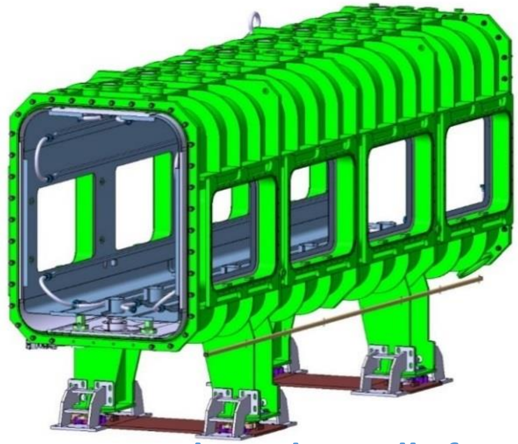
– Pre-serieries cavity to be delivered at Saclay in Oct. 2015 for chemical etching

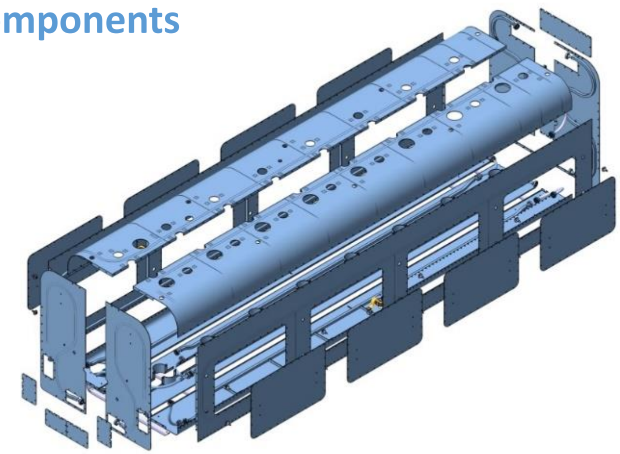
cf. G. Devanz et al, Progress in IFMIF half wave resonators manufacturing and test preparation, THPB045

– First test in SaTHoRI test bench by early 2016

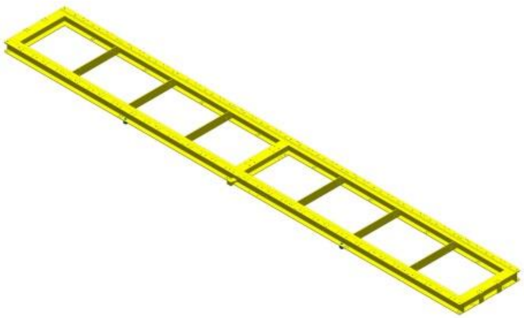
Manufacturing status of the other main Cryomodule components

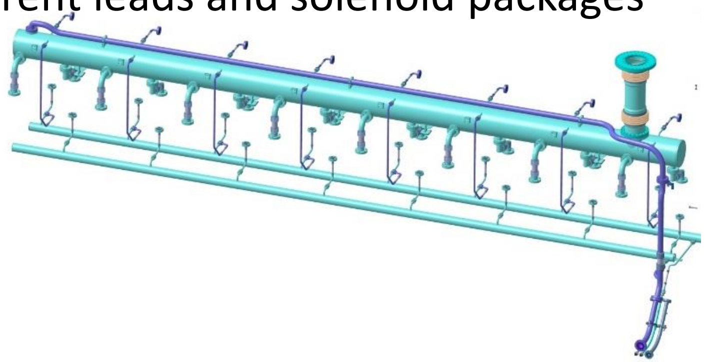
- **Ongoing fabrication of key cryomodule components**
  - Power couplers
  - Vacuum tank, thermal shield

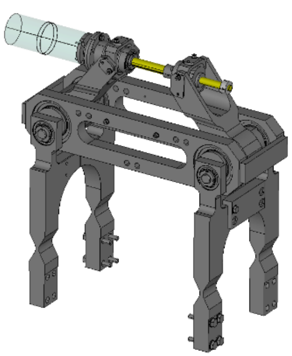


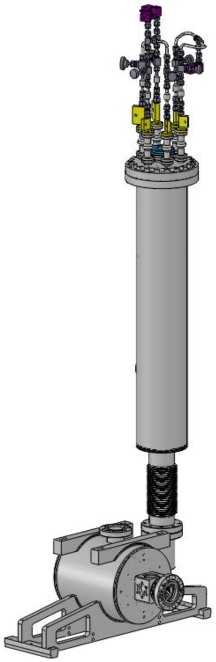


- **Manufacturers selected or calls for tender on going**
  - Phase separator, cryo and vacuum piping
  - Support frame, magnetic shield, tuning systems
- **Technical specifications being prepared (CIEMAT)**
  - Current leads and solenoid packages









Conclusion

- The main risks related to the fabrication and performance of the LIPAc cryomodule have been identified and mitigation strategies have been implemented
- The design of the IFMIF cavity has been approved by KHK
- The licensing is not anymore a show stopper. A lot of work is still to be done but licensing may no longer jeopardize the project
- The pre-series cavity is being manufactured and is expected at Saclay in October 2015 for chemical tuning and the first test (vertical cryostat)
- The first test of a fully equipped cavity in realistic conditions in a new dedicated test cryostat will start by early 2016
- The fabrication of the series cavities is on going and the fabrication phase of the critical components has started
- All the cryomodule components are expected to be delivered by the end of 2016 and qualified by March 2017

Job opportunities at CEA/Saclay in SRF

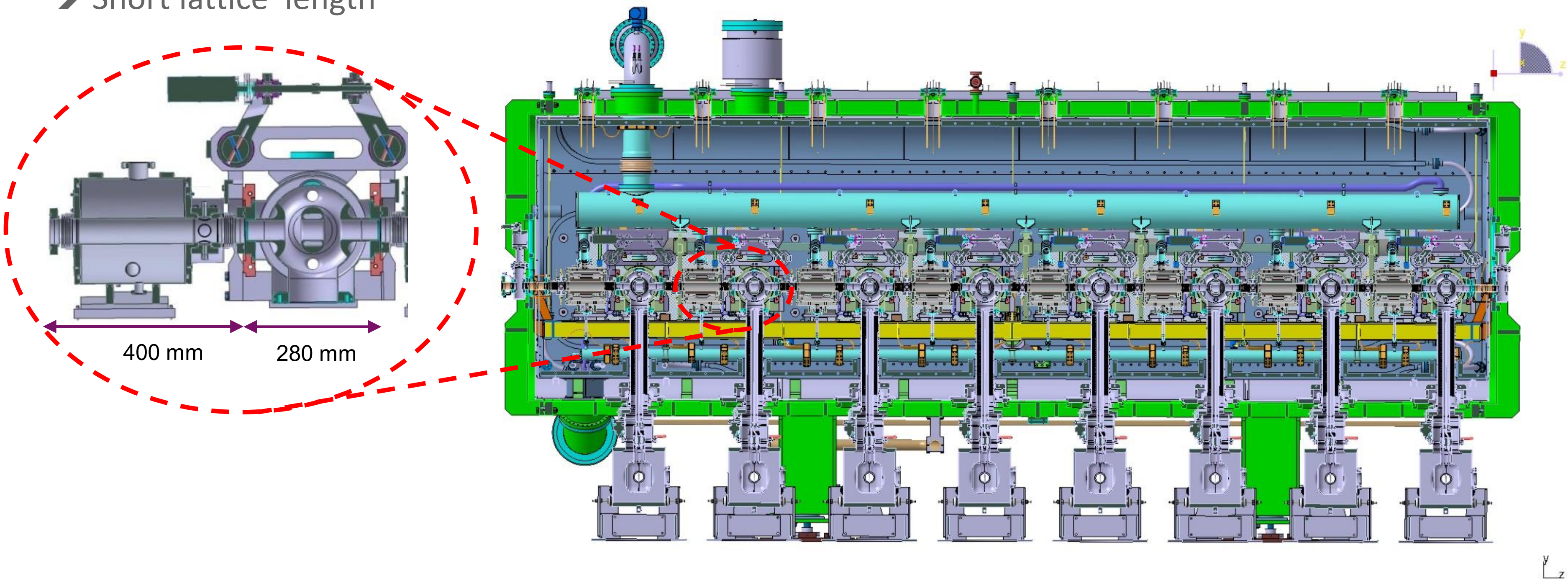
Please contact:

catherine.madec@cea.fr

Back-up slides

Main Design Constraints

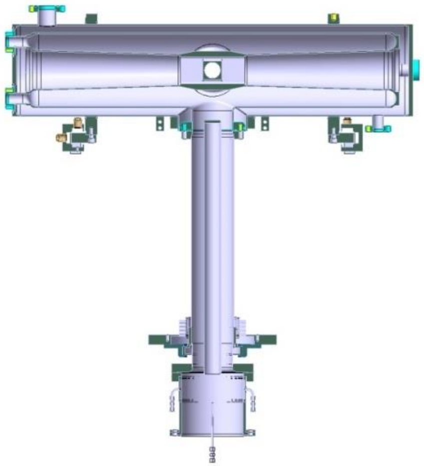
- **Beam dynamics**: many components in a restricted space (8 cavities and 8 solenoid packages)
  ➔ Short lattice length



- **Alignment requirement**:
  - ± 1 mm and ± 10 mrad around the beam axis for SP
  - ± 2 mm and ± 20 mrad around the beam axis for cavities
- **Safety and Licensing**
- **Transport and installation in Rokkasho**

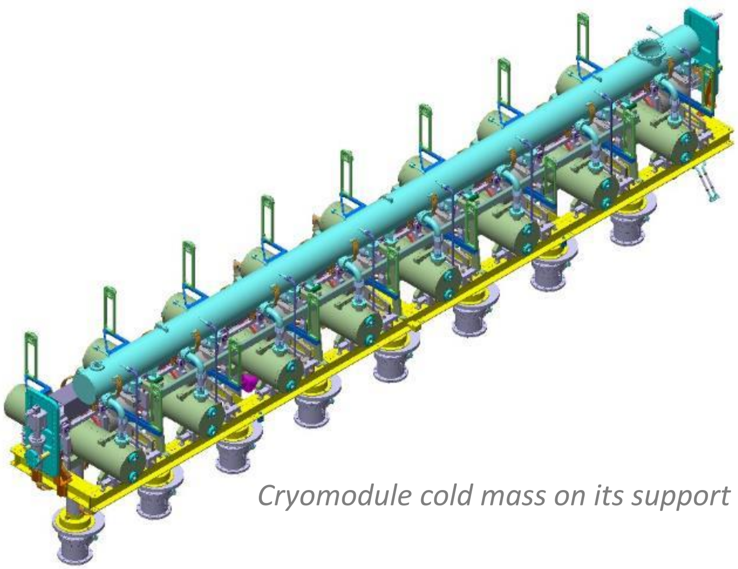
Design Concept

- **Component orientation**
  - Coupler design with a long antenna brazed on a ceramic
  - Safer to position the coupler vertically to avoid high stress on the ceramic

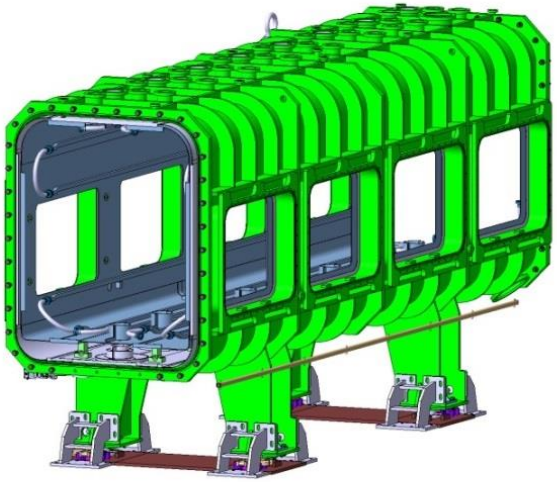


Cavity and coupler assembly

- **Common support for the whole cold mass**
  (including cavities, SP, couplers, cryogenics,…)
  - Base of the clean room assembly
  - To limit the cold mass handling (around 2500 kg)
  - Including alignment adjustments
  - Cold mass preassembly outside the vacuum tank
- **Two main sub-assemblies for integration**



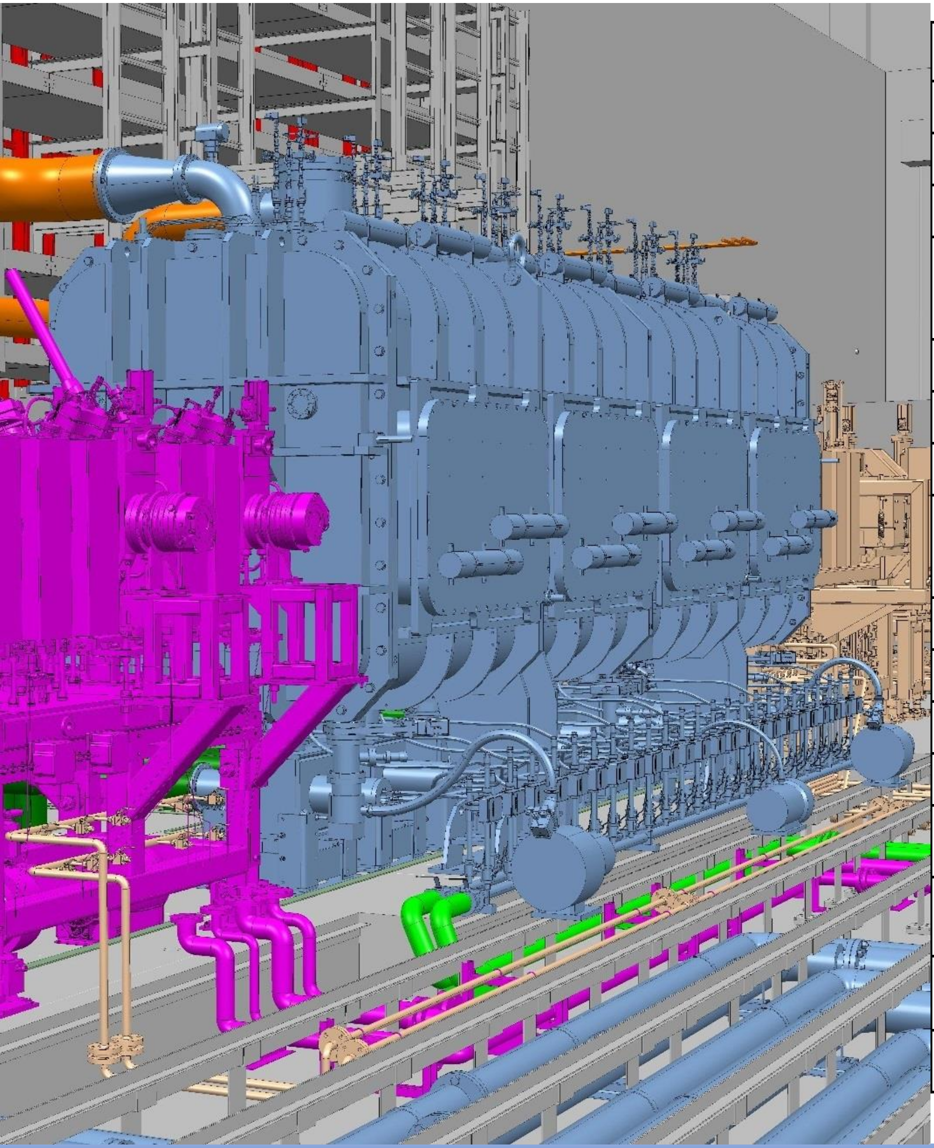
Cryomodule cold mass on its support



Vacuum tank with magnetic and thermal shield

SRF Linac: Specifications

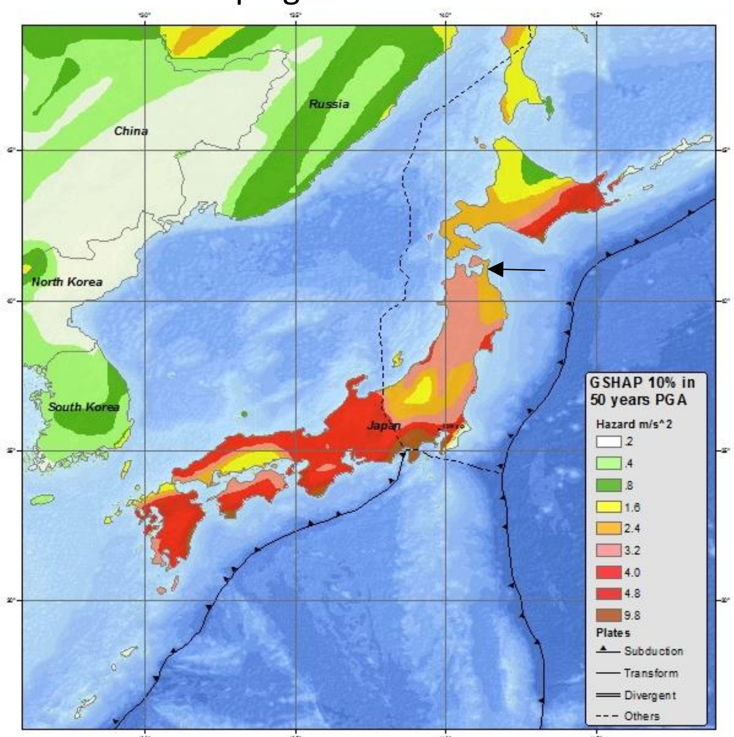
Objective: accelerate a 125 mA D^+ beam in CW operations from 5 to 9 MeV

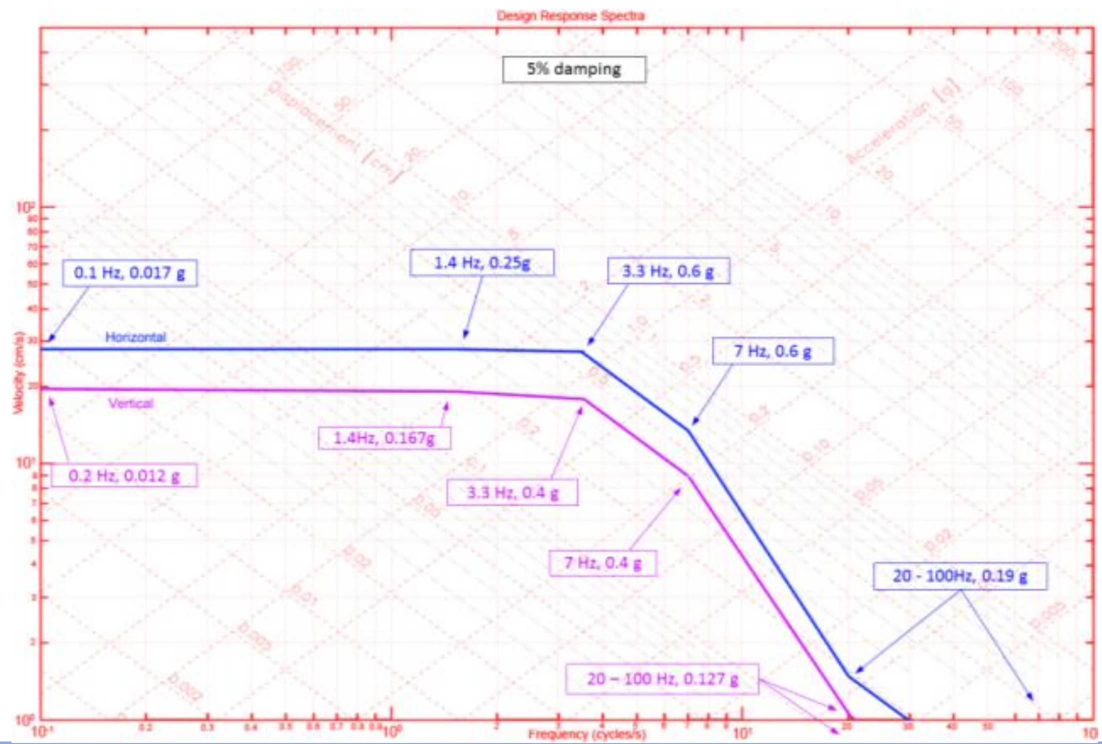


Target Values of complete Cryomodule	
Frequency	175 MHz
β value of the HWR	0.094
Accelerating field E_a	4.5 MV/m
Unloaded Quality factor Q_0 for R_s=20 nΩ at nominal field	1.4×10^9
Beam aperture HWR/SP	40 / 50 mm
Freq. range of HWR tuning syst	60 kHz
Freq. Resolution of tuners	200 Hz
Max. transmitted RF power by coupler in CW (for LIPAc)	70 kW
Max. reflected RF power in CW	20 kW
External quality factor Q_{ex}	6.3×10^4
Magnetic field B_z on axis max.	6 T
$\int$ B.dl on axis	1 T.m
Field at cavity flange	$\leq$ 20 mT
CBPM position meas. Accuracy	0.25 mm
CBPM phase meas. accuracy	2 deg
Total Static/Dynamic Heat losses	26 / 95 W

Seismic risk

- **Static + response spectrum analyses performed to check the cryomodule behavior in case of earthquake**
  - Design presented at the DDR, 1st structural reinforcement, final reinforced design
  - Check the effect of the reinforcement.
- **Seismic spectrum**:
  - Spectrum built according to criteria defined in ASME III, Appendix N, Analysis Methods
  - Peak ground acceleration map from the Global Seismic Hazard Assessment Program (GSHAP) was used to determine the ground accelerations at Rokkasho site (values with 10% probability of exceedance in 50 years).
  - 5% damping effect taken into account.





Structure of High Pressure Gas Safety Law

High Pressure Gas Safety Law

Ordinance of High Pressure Gas Safety Law

- General High Pressure Gas Safety Regulations
- Refrigeration Safety Regulations
- Container Safety Regulations

Guidelines constituted by METI (Ministry of Economy, Trade and Industry)

The High Pressure Gas Safety Institute of Japan (KHK)
- Management Principles, Code of Conduct, etc.

JAEA Internal Rules

- Safety Management Rules for General High Pressure Gases
- Safety Management Rules for Refrigerator
- Planning of Safety Training for High Pressure Gas

High Pressure Gas vs Refrigeration Safety Regulations

	High Pressure Gas Safety Reguration	Refrigeration Safety Reguration
Safety Management Structure	- Safety management structure is required. - Appointment of responsible persons for every watching shift	- Appointment of a responsible person for safety management - No safety management structure is required
Monitoring	- 24 hour monitoring is required.	- 24 hour monitoring is not required.
Facility Inspection	- Every year - Self inspection with disasembling	- Every three years
Licencing Application	- Whole factory, institute	- Each machine