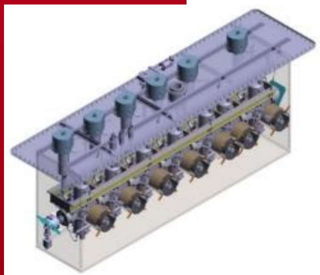
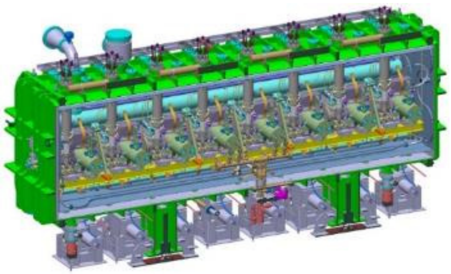
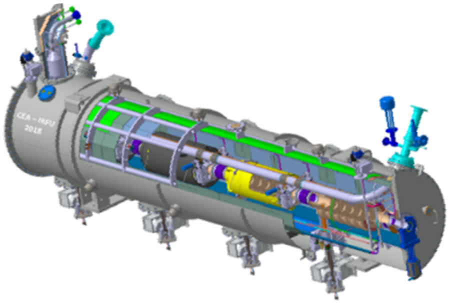
DE LA RECHERCHE À L'INDUSTRIE

Challenges in superconducting accelerating modules design and construction for proton accelerators







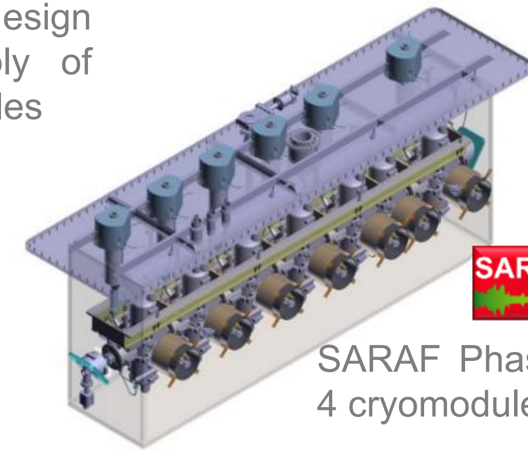
C. MADEC

September 18th, 2018

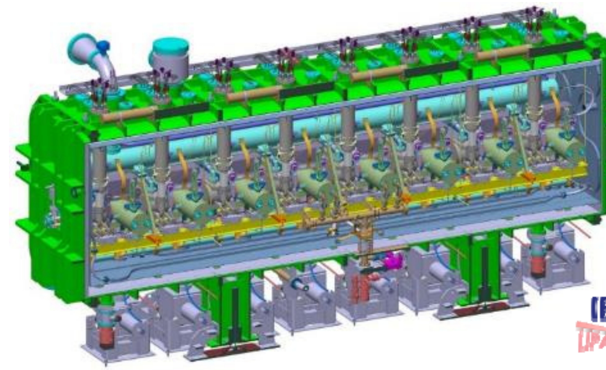
CEA EXPERIENCE ON SUPERCONDCUTING LINAC

Booster → MACSE → SOLEIL TTF → SPIRAL2 XFEL → IFMIF LIPAc → ESS, SARAF

SPIRAL2: design and assembly of 12 cryomodules



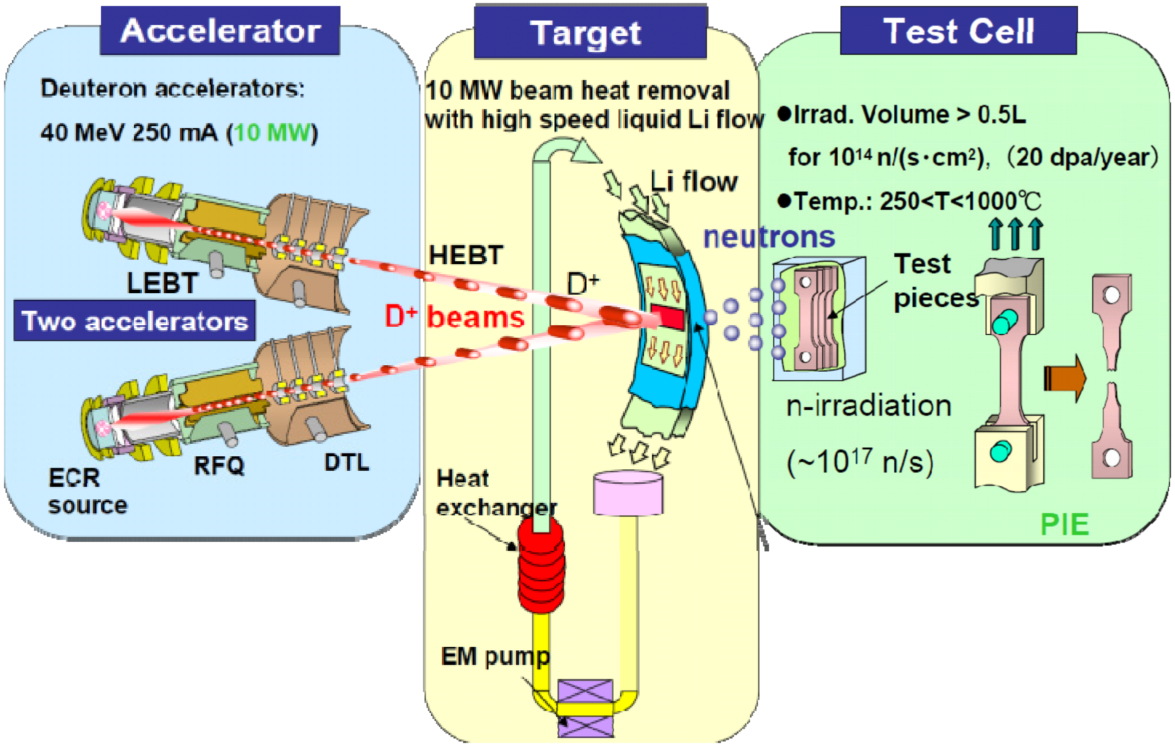
SARAF Phase2: 4 cryomodules



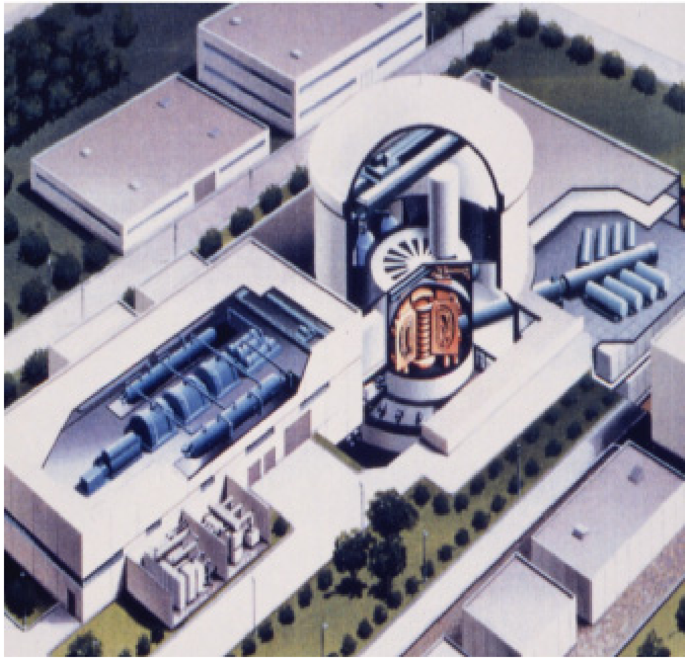
LIPAc: 1 cryomodule

XFEL: assembly of 103 cryomodules (1 CM/wk)

ESS: cavity and coupler design, procurement of all components but cavities, integration of 32 cryomodules



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



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

TU2A04 by M. Sugimoto

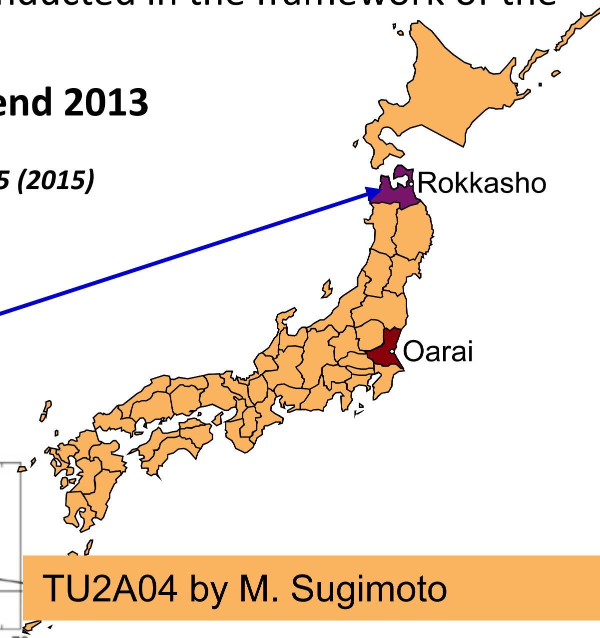
IFMIF LIPAc

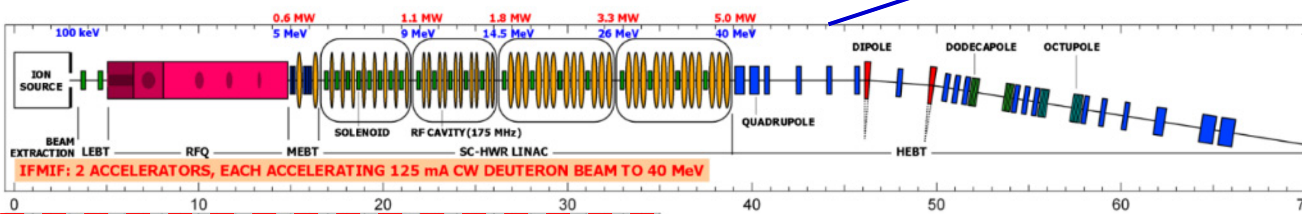
The Engineering Validation and Engineering Design Activities (EVEDA), conducted in the framework of the Broader Approach aim at:

- **Providing the Engineering Design of IFMIF ➔ IIEDR released by end 2013**

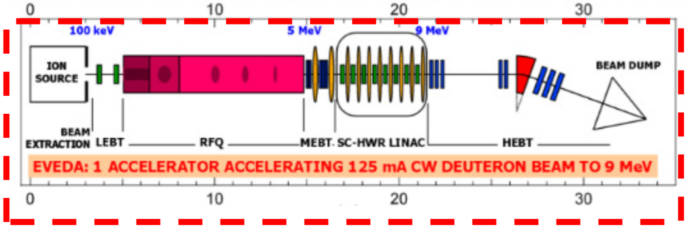
  Cf. J. Knaster et al, "The accomplishment of the Engineering Design Activities of IFMIF/EVEDA: The European–Japanese project towards a Li(d,xn) fusion relevant neutron source", Nucl. Fusion 55 (2015)

- **Validating the key technologies (high priority)**
  - The lithium target facility
  - The high flux modules
  - The low energy part of accelerator

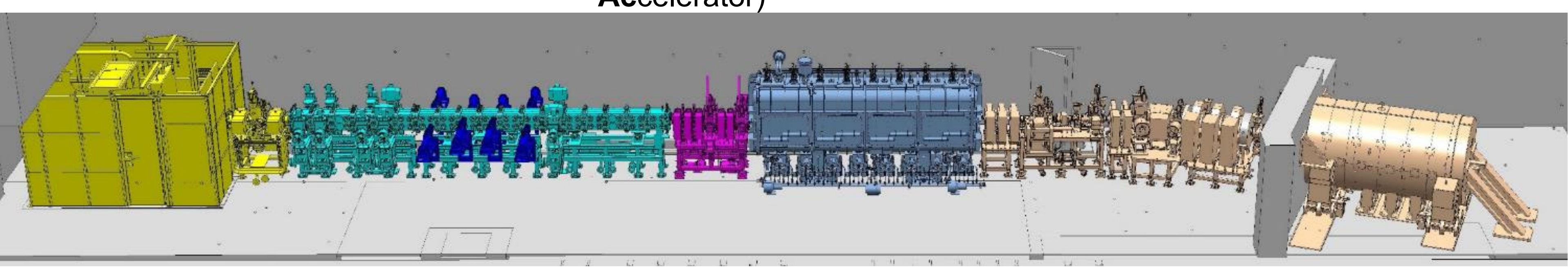




TU2A04 by M. Sugimoto

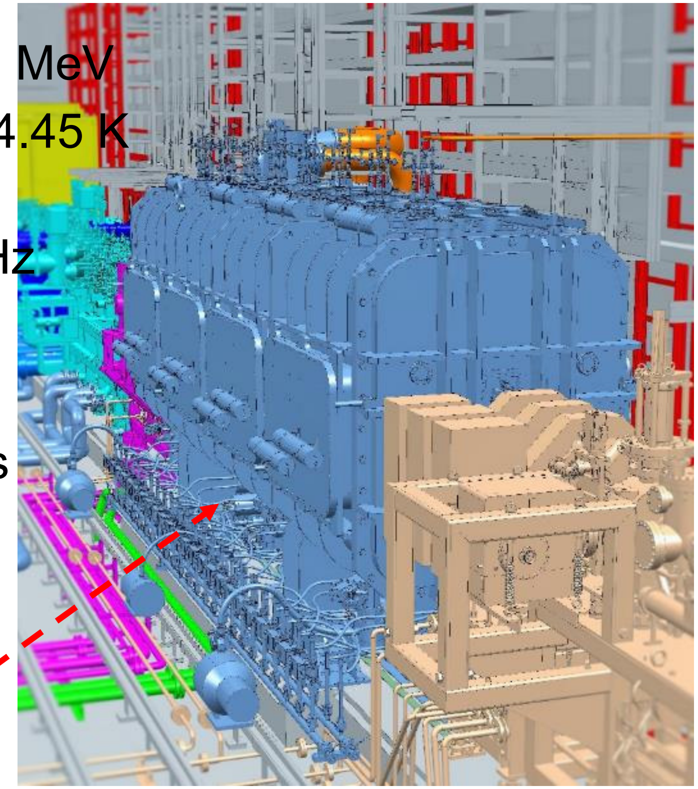


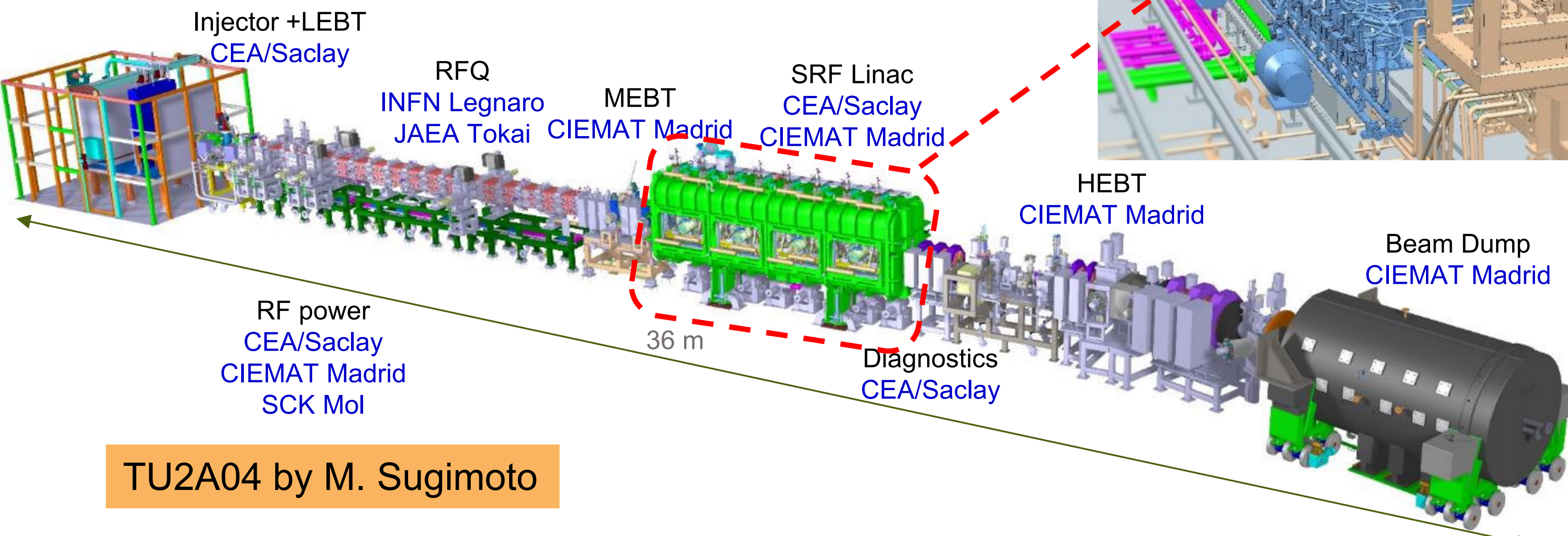
Accelerator's technological feasibility tested through design, manufacturing, installation, commissioning and testing activities of a 1:1-scale prototype accelerator from the injector to the first cryomodule (9 MeV, 125 mA D^+ beam CW): LIPAc (**L**inear **I**FMIF **P**rototype **Ac**celerator)



IFMIF LIPAc Cryomodule

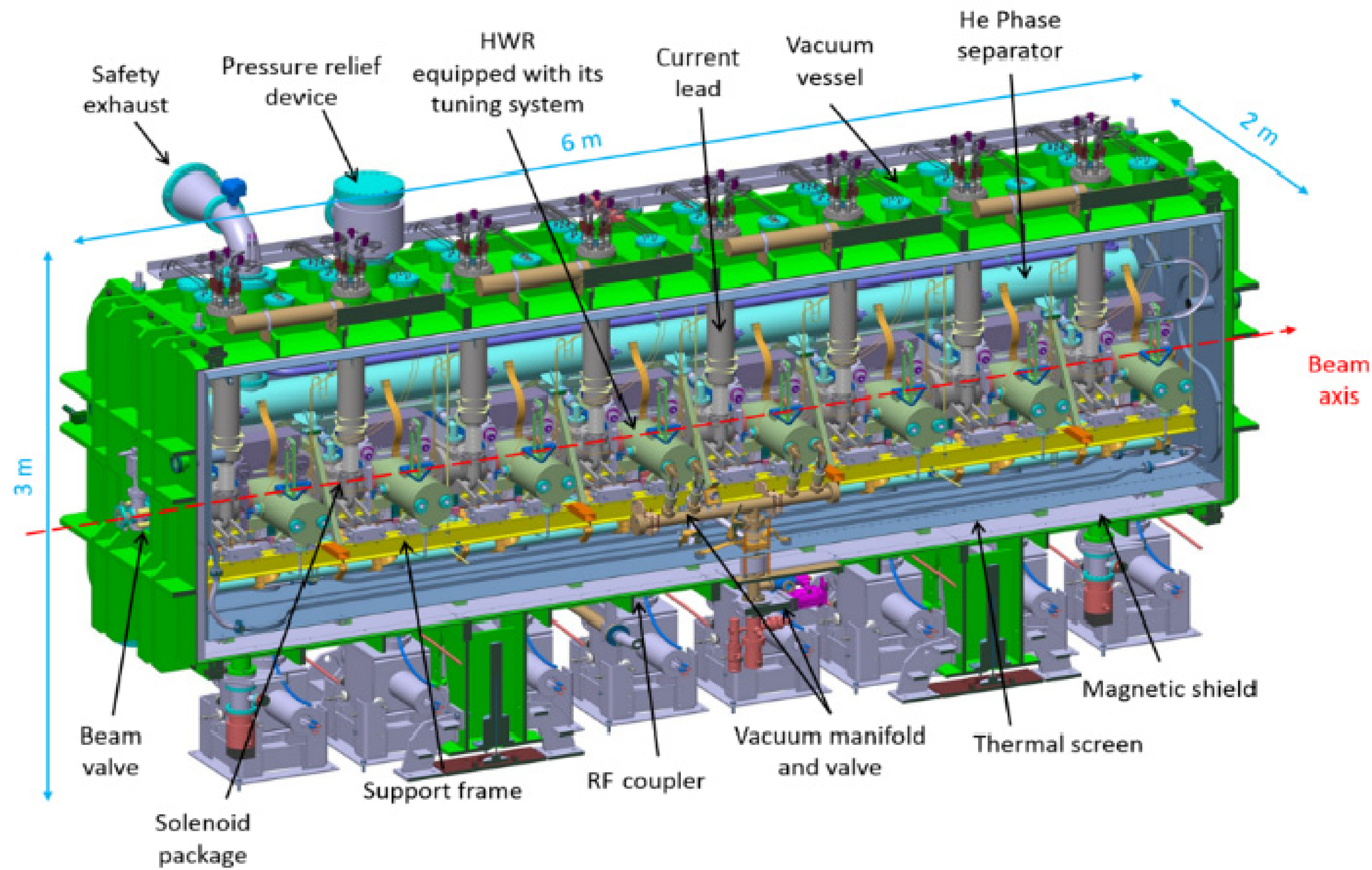
- Transport and accelerate D^+ beam from 5 MeV up to 9 MeV
- 8 superconducting HWRs working at 175 MHz and at 4.45 K
  β=0.094, E_a=4.5 MV/m, $Q_0 \geq 5\times10^8$, $Q_{ext} 5\times6.5\times10^4$
  Tuning range [kHz]=50 kHz, Loaded bandwidth=2.7 kHz
- 8 Power Couplers (70 kW CW)
- 8 Solenoid Packages as focusing elements
- Reference for the realization of the IFMIF cryomodules





TU2A04 by M. Sugimoto

IFMIF CRYOMODULE



SARAF PHASE 2

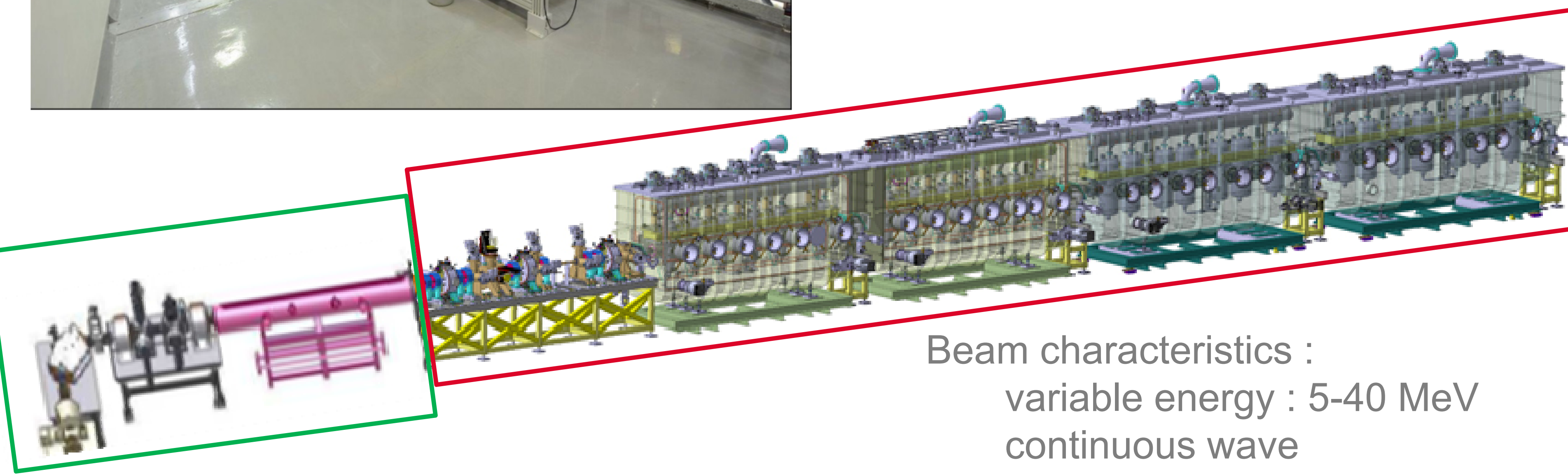
Radio Pharmaceuticals

Thermal neutron diffraction

Thermal neutron radiography

Nuclear Astrophysics

Radioactive beams

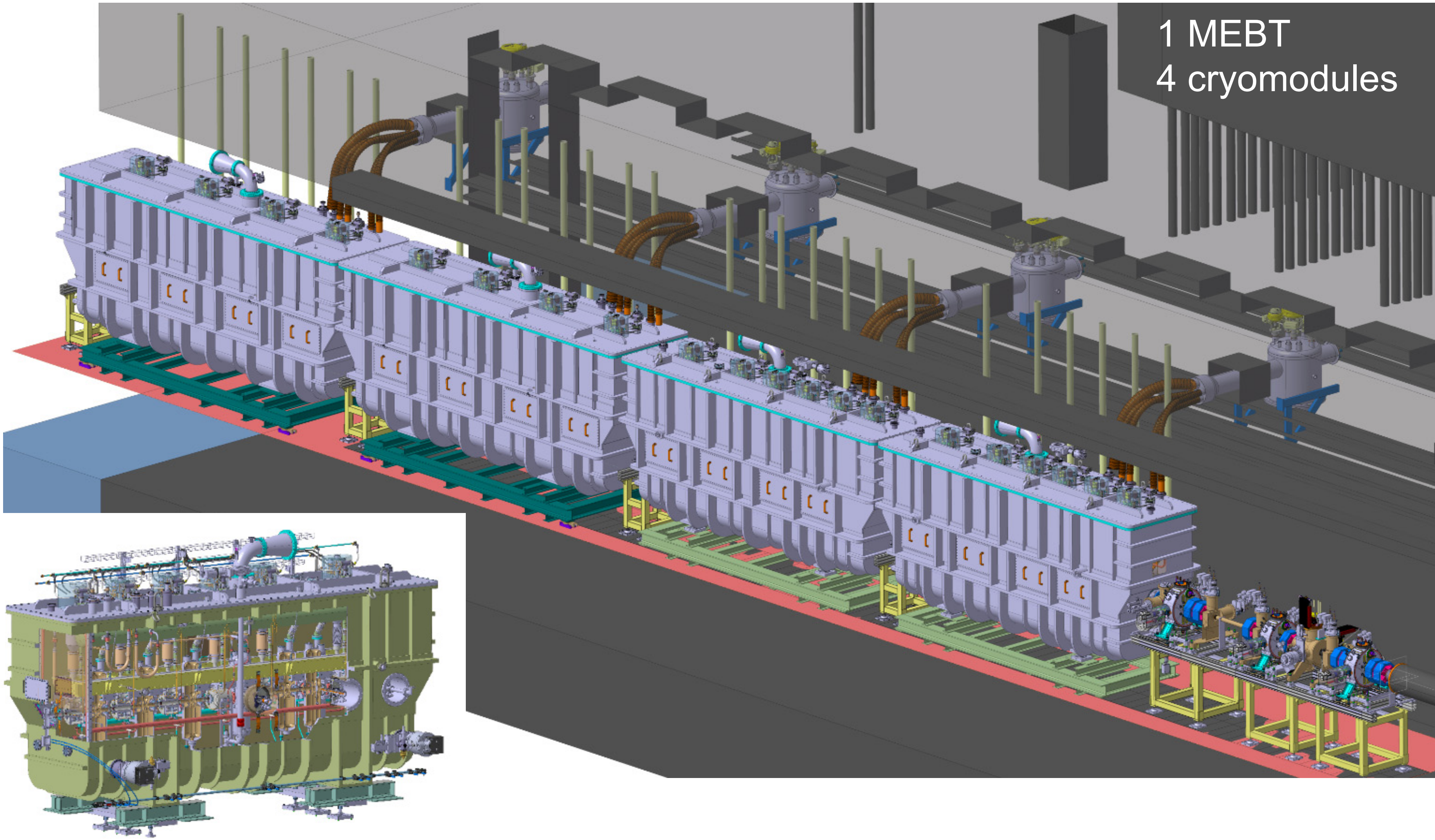


Beam characteristics :

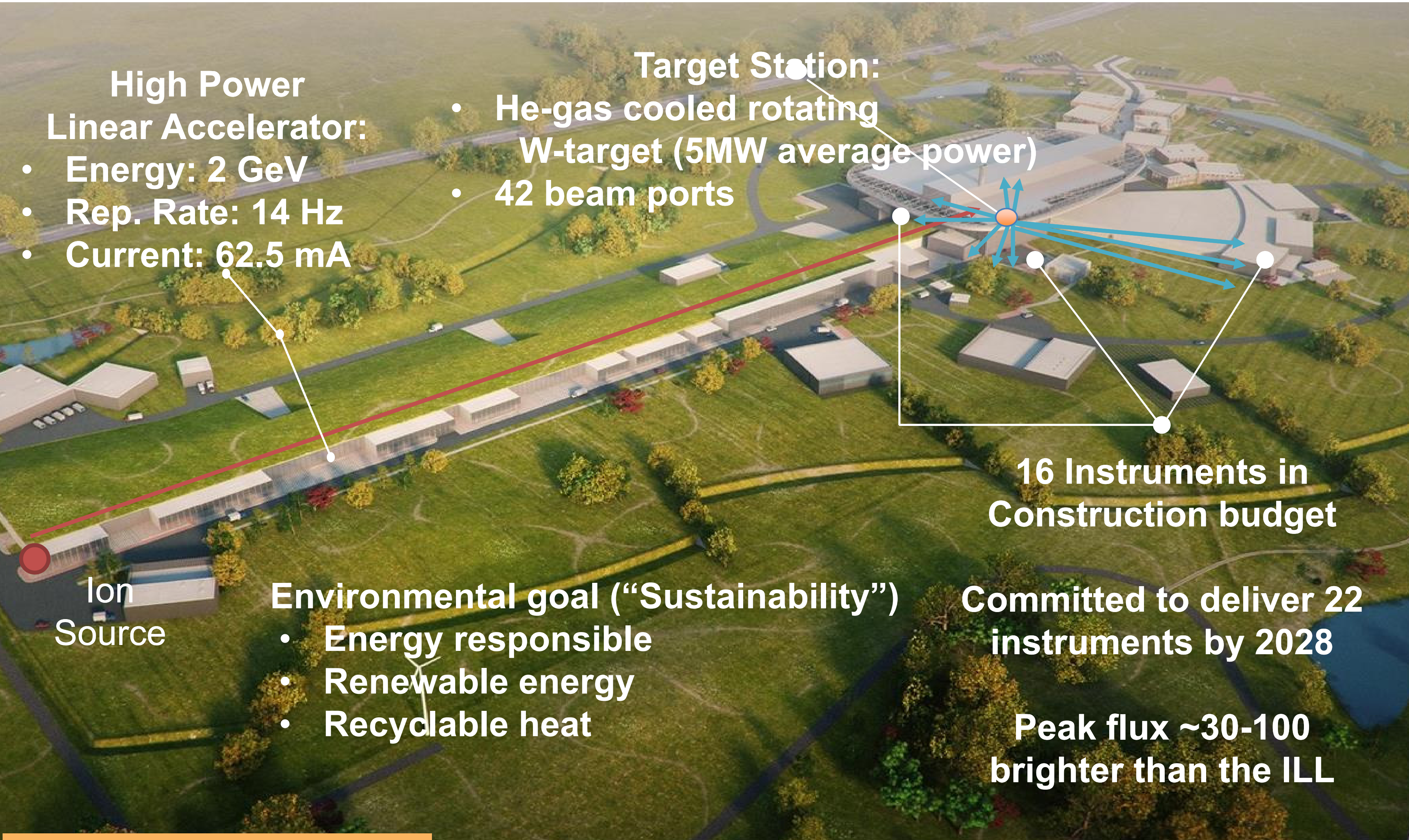
variable energy : 5-40 MeV
continuous wave
D/P current : 0.04-5 mA

WE2A04 by A. Perry

CEA MEBT AND SCL FOR SARAF PHASE 2



European Spallation Source



MO1P03 by A. Sunesson

ESS LINAC SPECIFICATIONS

Top-level requirements	
Pulse length (ms)	2.86
Energy (GeV)	2
Peak current (mA)	62.5
Pulse repetition frequency (Hz)	14
Average power (MW)	5
Peak power (MW)	125

95% of the energy gain with 146 SCRF cavities

2 types of cavities & 3 beta families

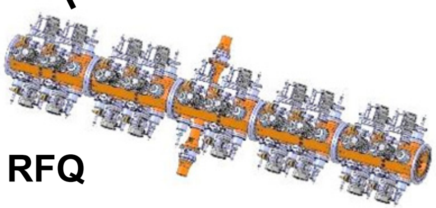
Beta 0.50 Spoke Cryomodules	
Cryomodule #	13
Double-Spoke cavity #	26
Eacc [MV/m]	9

Beta 0.67 Elliptical Cryomodules	
Cryomodule #	9
6-cell cavity #	36
Eacc [MV/m]	16.7

Beta 0.86 Elliptical Cryomodules	
Cryomodule #	21
5-cell cavity #	84
Eacc [MV/m]	19.9

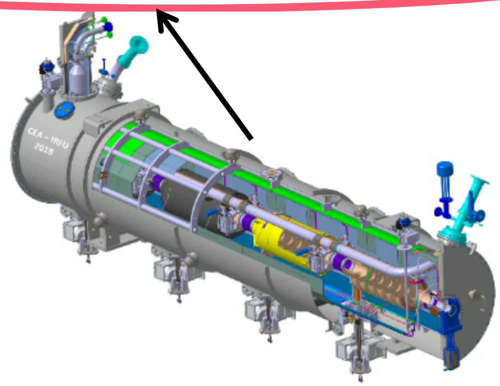
MO1P03 by A. Sunesson

CEA contribution to ESS Superconducting LINAC



RFQ

Diagnostics (EMU & Doppler sur la LEBT + NIPM + nBLM)
Parties du **Control System** (Source, LEBT, RFQ, nBLM)



2 cryomodules prototypes (one medium & one high beta including RF power testing)
30 Cryomodules (but the cavities)

Collaboration with IPN Orsay in charge of the design of the cryostat

2 Cryomodules demonstrators + 30 Cryomodules

- Delivery of 30 Cryomodules (but cavities) to ESS Lund including :
  - 120 power couplers conditionned up to 1.1MW
  - 120 Cold Tuning System
  - All the other components for 30 Cryomodules
- Assembly of 2 prototypes and 30 cryomodules
- Cryogenic and RF power tests of 2 prototypes, 3 Cryomodules medium b et 3 Cryomodules High b
- Technical assistance of ESS for the cavities fabrication follow-up (INFN & STFC)
- Technical assistance of ESS for installation and commissioning of the cryomodules at Lund

2013 : Redesign of IFMIF cavities, Conceptual design of ESS cryomodule, XFEL prototypes, Spiral2 CM testing

2014 : Redesign of IFMIF cavities, Conceptual design of ESS cryomodule, SARAF bridging phase, XFEL 20 CM

2015 : SARAF bridging phase, XFEL 82 CM, SPIRAL2 completed, ESS CM design, IFMIF 1st serie manufact.

2016 : SARAF CDRs, XFEL 100 CM, ESS prototype cavities and cryostat components manufact. , IFMIF components manufact.

2017 : SARAF CDRs, ESS prototype cryomodule, IFMIF comp. shipping

2018 : SARAF CM design completed, ESS 2nd prototype cryomodule, IFMIF cavities

2019 : SARAF proto comp. acceptance, IFMIF assembly, ESS CM assy,

2020 : SARAF 1st CM assy, IFMIF commissiong, ESS CM assy & installation,

2021 : SARAF CM assy, ESS CM assy & installation,

2022 : SARAF installation & commissioning, ESS CM installation & commissioning

2023 : commissioning

Steps to meet the challenges

	SARAF	IFMIF	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	X	X
Assembly	X	x	X
CM test at CEA	X		X
Transport	X		

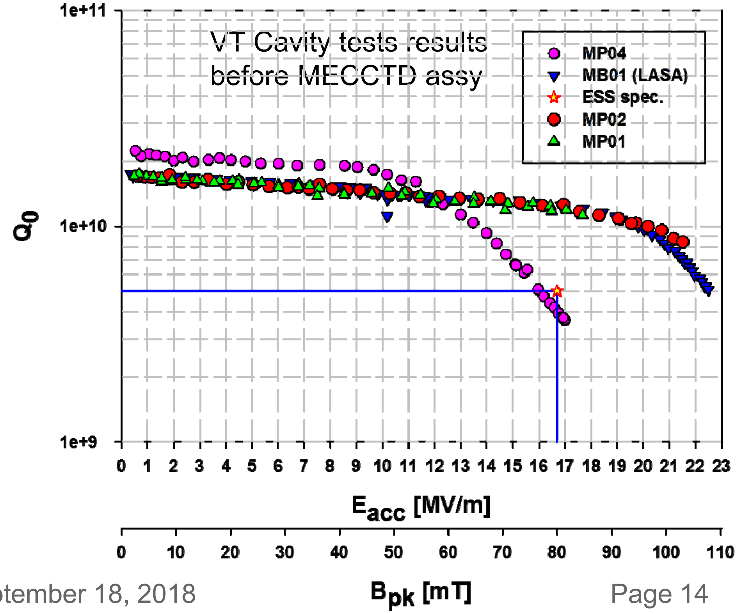
THE REQUIREMENTS

CEA is implementing standard engineering method for the requirements which are defined with the collaborators.

	ESS	SARAF	LIPAC
Particules	P+	P+/D+	D+
Energy [MeV]	2000	40/35	5 à 9
Frequency [MHz]	704	176	175
Operating temp.	2K	4.45K	4.45K
Beta value	**0.67/0.86**	**0.09/0.18**	**0.094**
Eacc [MV/m]	**16.7/19.9**	**7**	**4.5**
Epk [MV/m]	**45/45**	**34.6/35.9**	**21.6**
Bpk [mT]	80/85.6	65.6/65.3	49.5
Beam pipe ID (mm)	[illegible]4/120	40	40

From the beam dynamics requirements, CEA designed cavities to meet the accelerating field.

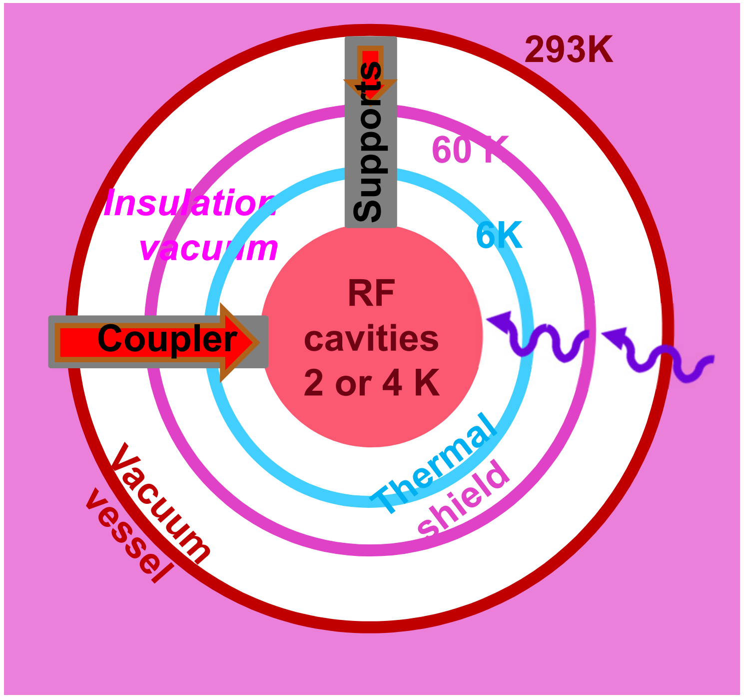
The peak electric field and thus magnetic field are rising and challenging for the high beta ESS cavities (65% of Hc1).

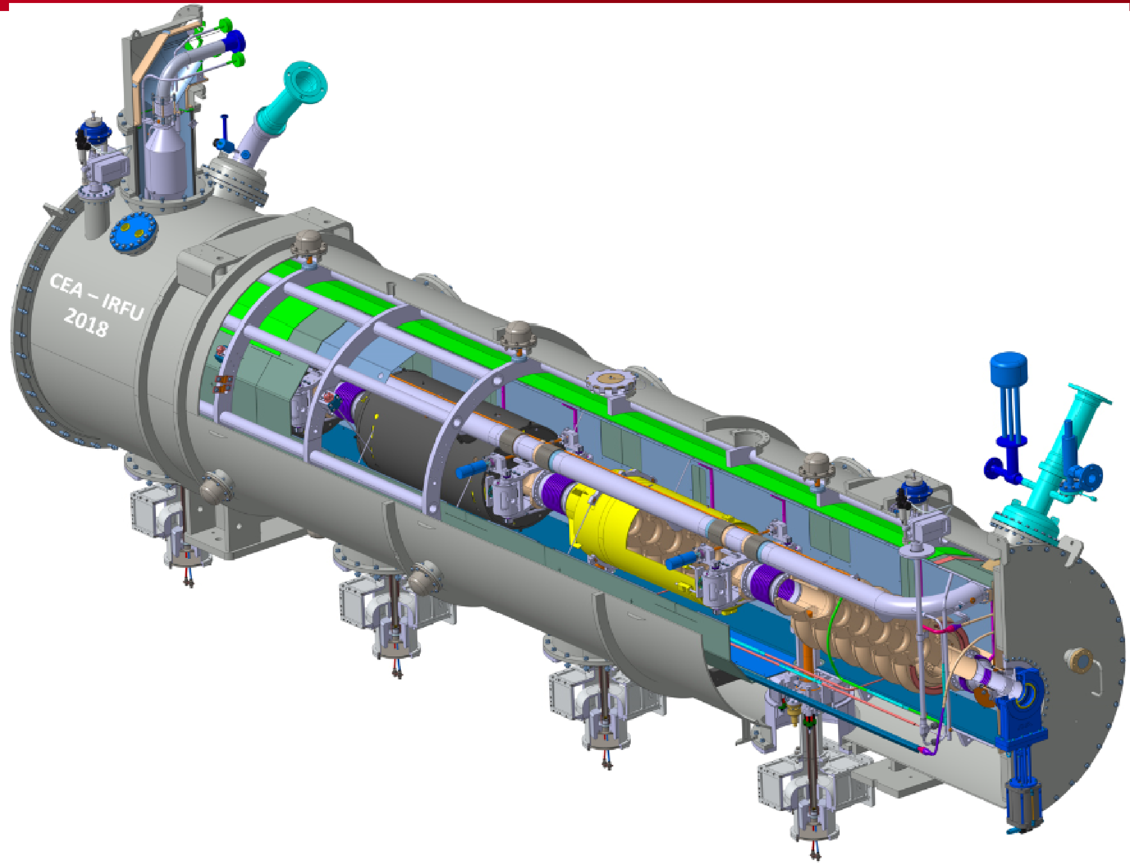


Steps to meet the challenges

	SARAF	IFMIF	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	X	X
Assembly	X	x	X
CM test at CEA	X		X
Transport	X		

THE DESIGN OF CRYOMODULES





A cryostat that :

- Keep the cavities at 2 or 4K
- Maintain the alignment so beam can go through
- Preserve cavities/solenoids performances

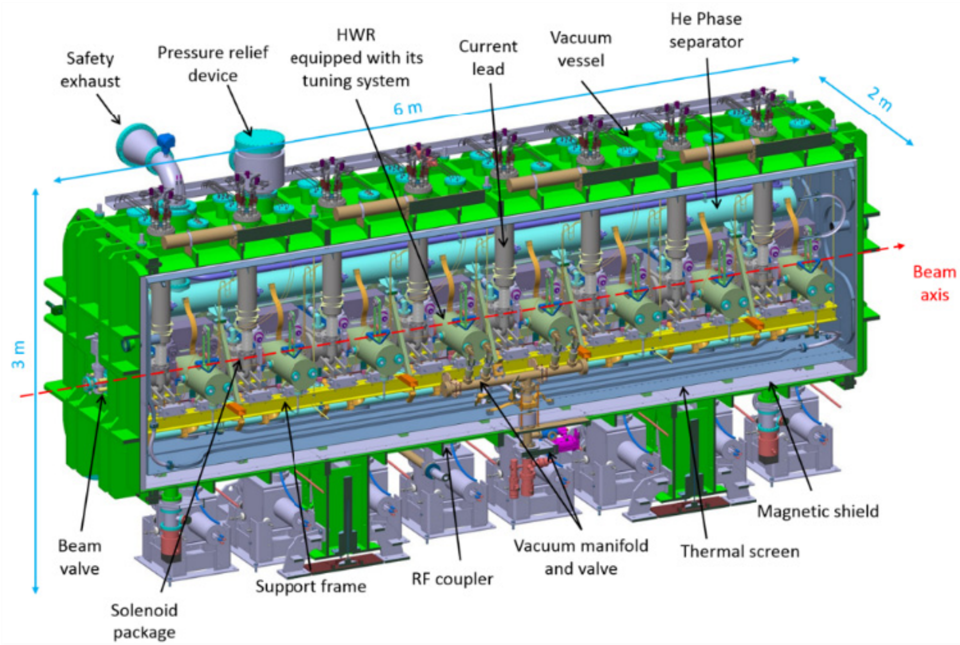
Design should :

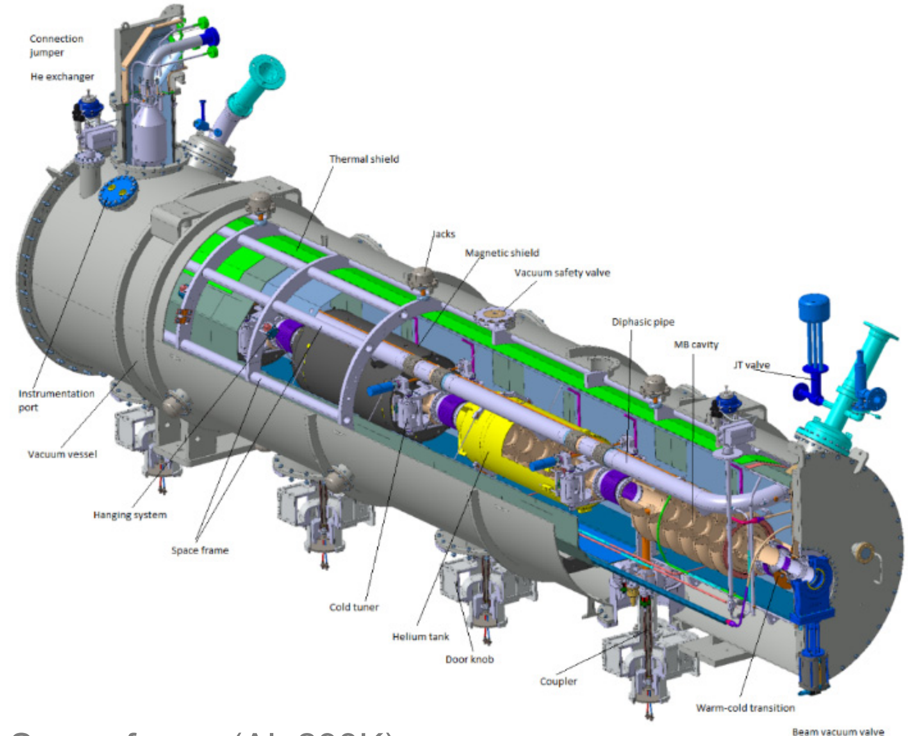
- Limit the losses by radiation
- Limit losses by conduction
- Limit losses by convection

All cryomodules feature a vacuum vessel, thermal shields, insulation vacuum, Helium supply, magnetic shield, support to hold the cavities on beam axis, couplers, tuners …

With doors for maintenance, frame for control during intermediate steps

ESS AND LIPAC CRYOMODULES





Support frame (Ti and ~ 5-10K)

Operating temperature : *4.45K*

Magnetic shield is *on the CM wall,*

Magnetic hygiene

8 cavities and solenoids

Ta6V

Space frame (Al, 293K)

2K

Magnetic shield *on individual cavities*

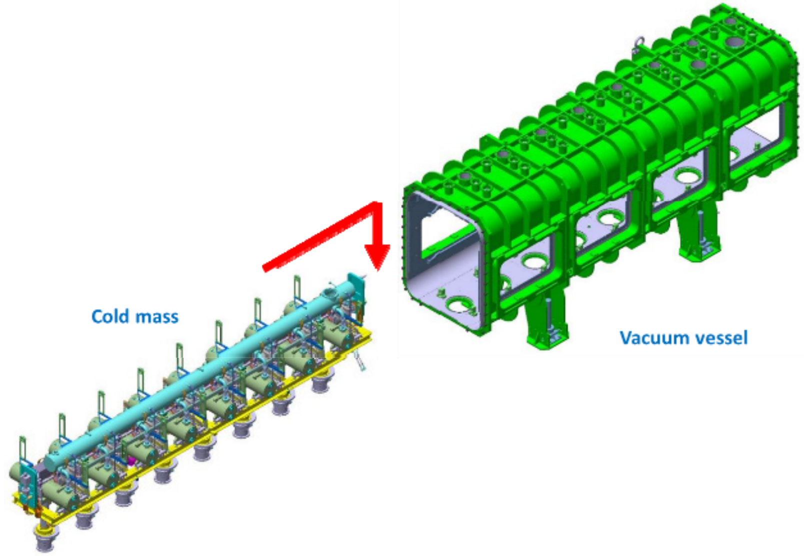
One type of vacuum vessel type for both beta

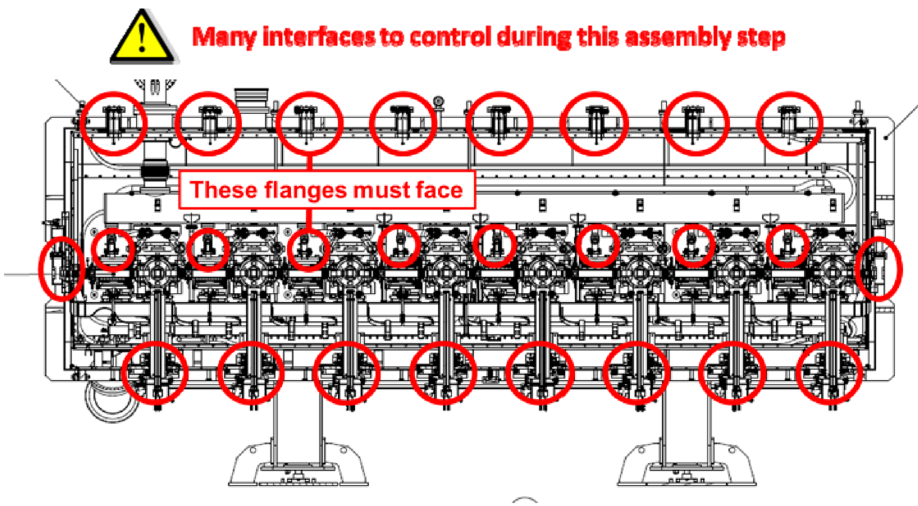
4 cavities

TA6V and hold the transport with additional clamping

LIPAC: SIDE LOADED CRYOMODULE LESSONS LEARNED

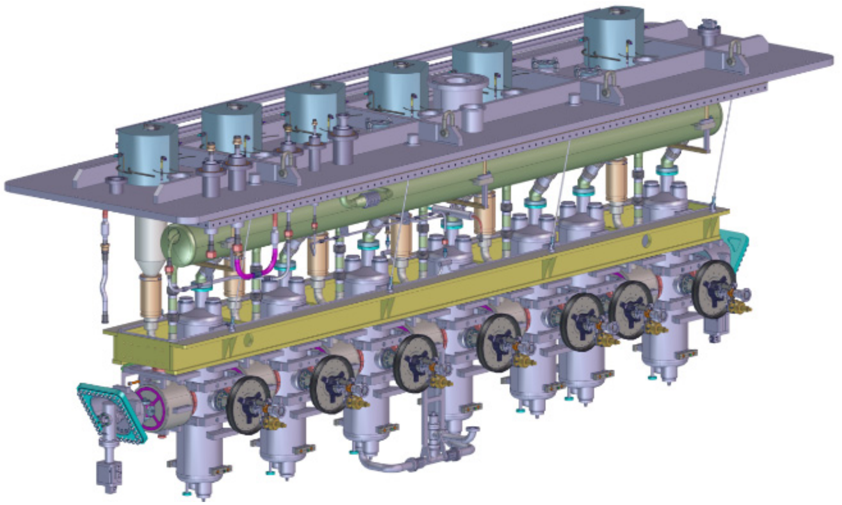
- Configuration set at the beginning of the design phase
- Due to the couplers, the cold mass must be inserted in the vacuum vessel in two steps:
  - Horizontal sliding of the frame which is higher than its final position. The frame should be set up so that the couplers are facing the flanges of the vacuum tank.
  - Vertical motion of the frame until the coupler flanges touch the vacuum tank flanges.
- During the insertion of the cold mass, the operators have to be sure that every interface flange of the power couplers properly mates with its corresponding flange (same for the flange of the pumping line).
- The operators have also to check that the interface flange between the solenoid and the current lead package faces its corresponding flange of the vacuum vessel, and that he interface flange of the beam valves faces its corresponding flange of the two doors.
- Tools used for the operation have to be removed without damaging the components of the cryomodule (small space).
- Many assembly steps have to be performed after the insertion of the cold in the vacuum vessel, with small access room for some operations (example: welding of the solenoid package wires to the current lead busbars).





SARAF AND DONES:
TOP LOADED CRYOMODULE

- As all the interfaces but the power couplers and the beam valves are with the top plate, the assembly process is simpler.
- Most of the work could be performed before the insertion in the vacuum vessel:
  - Completion of the helium circuitry with leak and pressure tests
  - Installation of the current leads
  - Cabling of the sensors and actuators
  - Installation of the multi layers insulation blankets
  - Installation of the thermal shield with leak and pressure tests



- SARAF tunnel width and the beam axis position are set by the already existing infrastructures.
- During installation and maintenance, two cryomodules should be rolled side by side.
  => cryomodule width can not exceed 1850 mmm.
- RF design of cavity has set its dimension to 1018 mm.
- Taking into account the vacuum vessel wall thickness, the magnetic and thermal shield thickness,
  => cavities have to stand vertically.

Steps to meet the challenges

	SARAF	IFMIF	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	X	X
Assembly	X	x	X
CM test at CEA	X		X
Transport	X		

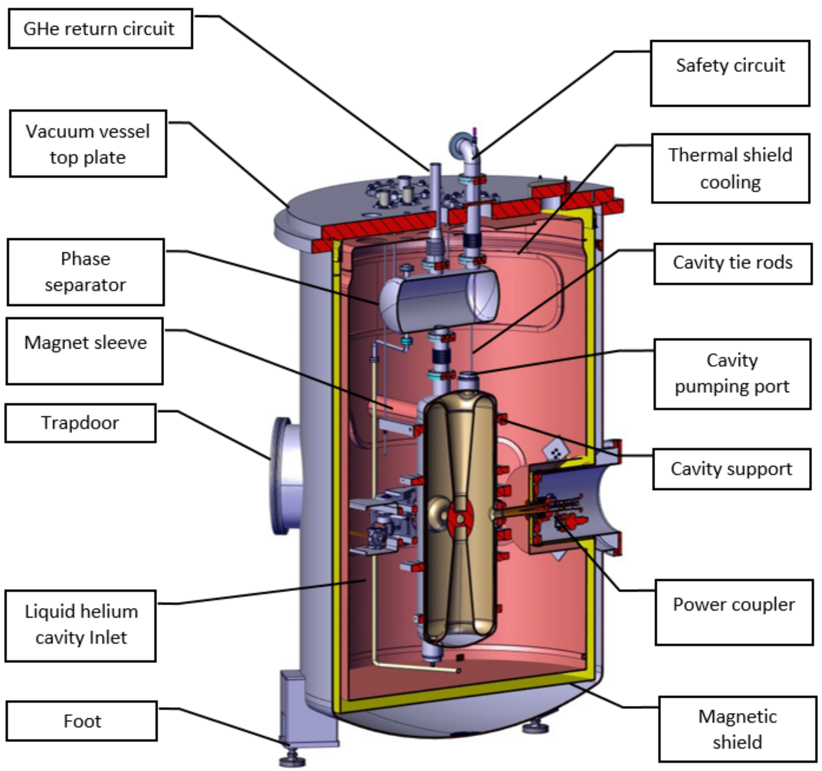
REVIEW AND MITIGATION PLAN

Cryomodule designs are submitted to a panel of international experts (Detailed Design Review for LIPAC cryomodule, EDR for SARAF and CDR for ESS).

=> Mitigation plans have been implemented

=> Design optimization conducted

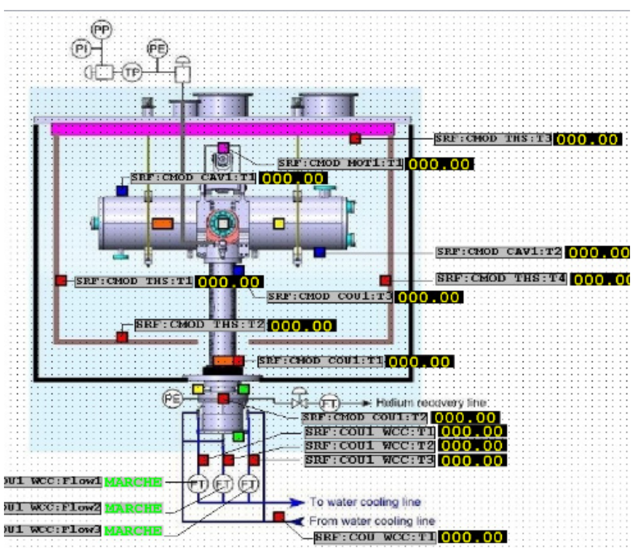
For the three projects, it was decided to perform early testing on dedicated test bench and mock-ups to check critical components and operations before the beginning of the cryomodule assembly. To detect potential issues during operation of such complete set of components:



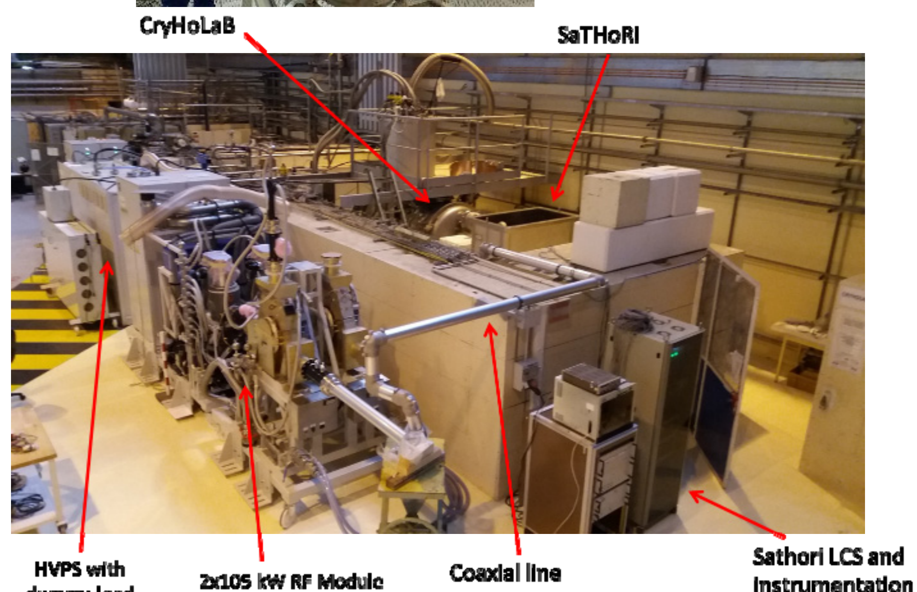
- ❑ SATHORI test stand has been built and was used to test LIPAc jacketed cavity with coupler and tuner.
- ❑ ECTS is built for SARAF
- ❑ Medium beta Elliptical Cavity Cryomodule Technical Demonstrator (MECCTD)

SATHORI : A EQUIPPED CAVITY TESTS STAND

- Dedicated cryostat
- Instrumentation and commande control
- RF power source from contributors
- Assembly in clean room with coupler-to-cavity tooling
  - => validation of tooling
- Assembly in hall under specific top plate tooling
  - => Confidence for top loading for other projects
- Transfer of the loaded top plate to cryostat



Instrumentation



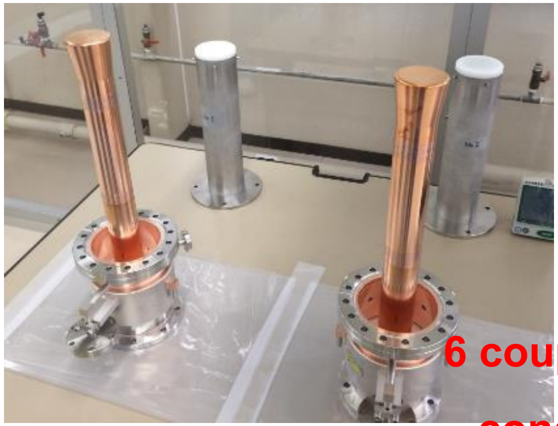
Steps to meet the challenges

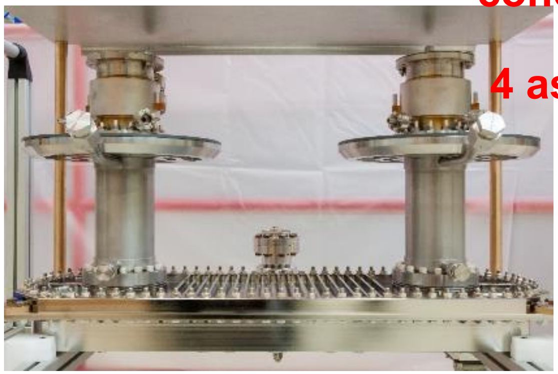
	SARAF	IFMIF	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	X	X
Assembly	X	x	X
CM test at CEA	X		X
Transport	X		

PROTYPES

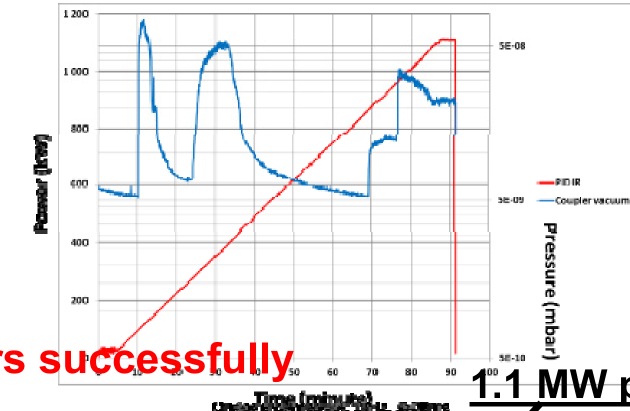
Meanwhile the cryomodule design is going on, the critical components namely solenoid, coupler, tuner and cavity are built in order to test and validate their design.

- LIPAC superconducting HWR prototype : Plunger -> tuner mechanically deforming the cavity
- ESS couplers prototypes ; validating the performances



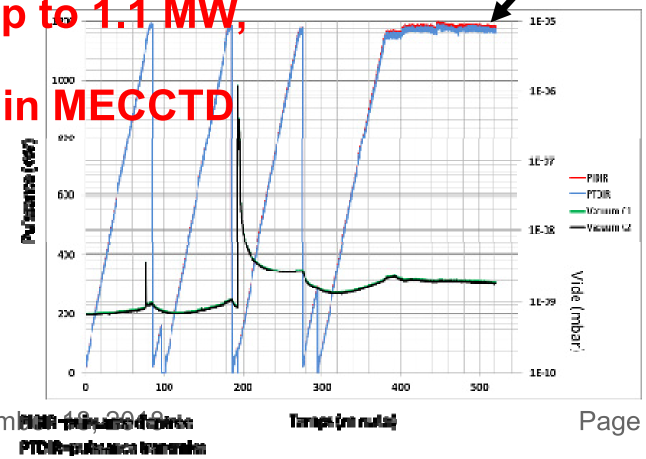


PIDIR: incident input power



6 couplers pairs successfully conditioned up to 1.1 MW, 4 assembled in MECCTD

1.1 MW pic

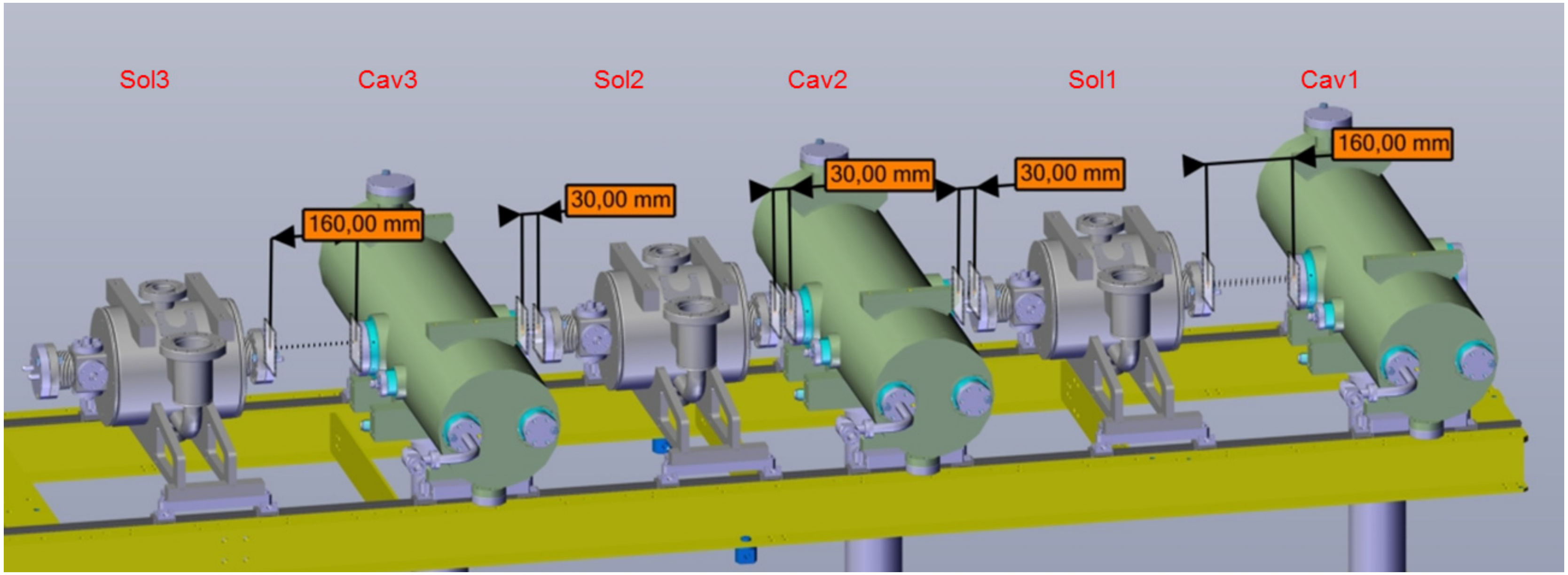


Steps to meet the challenges

	SARAF	IFMIF	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	X	X
Assembly	X	x	X
CM test at CEA	X		X
Transport	X		

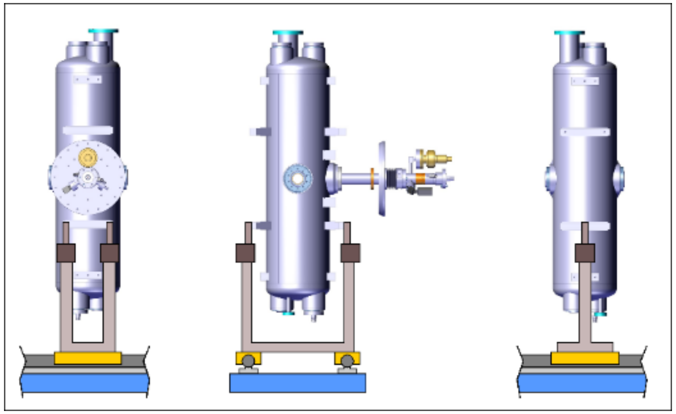
MOCK-UPS LESSONS LEARNED

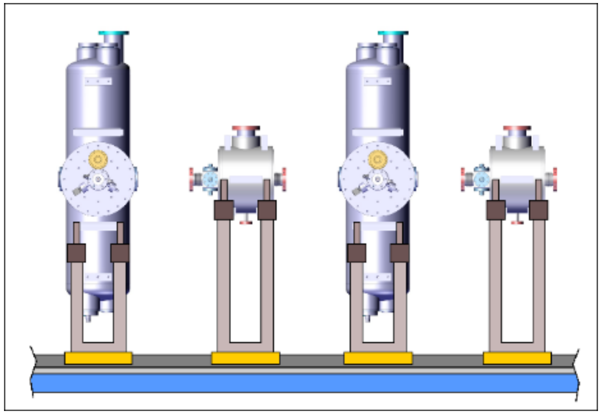
- LIPAc cryomodule: the titanium frame is used as support of the cavity string in clean room →severe requirements on the manufacturing:
  - For clean room reasons, all the surfaces of the I-beams are machined before welding
  - After welding, the top surface of the frame are precisely machined (flatness requirement: 0.1 mm/m)
- The minimum distance between the flanges of a solenoid and a cavity is 160 mm for a safe removal of the flanges used to position the components → constraints on the motion of the elements along the frame due to the vertical power couplers and the strengthening bars



IMPROVEMENT IN ASSY TOOLING

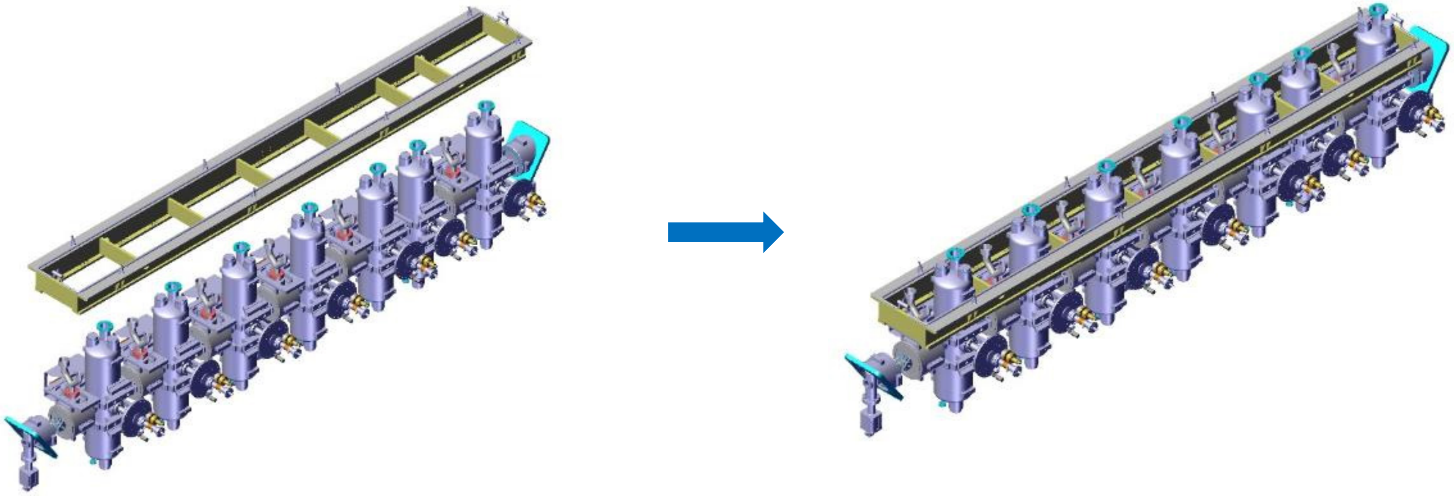
- SARAF cryomodule: The frame is not used in clean room, but a trolley with rails and positioning post (as for XFEL and ESS cryomodule)





Cavity string assembly support for ESS ECCTD

- Assembly of the cavity string to the support frame outside the clean room



Steps to meet the challenges

	SARAF	IFMIF	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	X	X
Assembly	X	x	X
CM test at CEA	X		X
Transport	X		

TRANSPORT

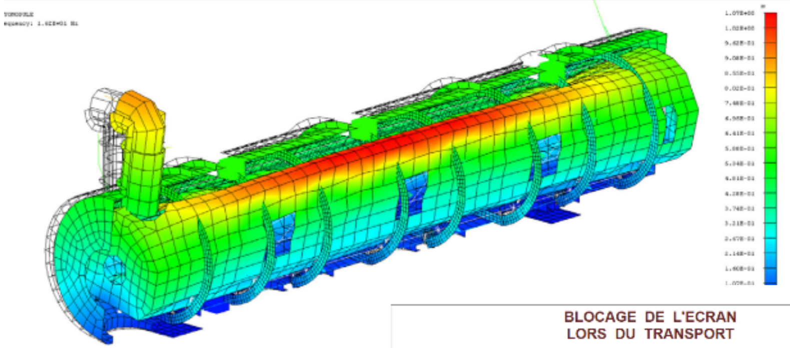
What makes CEA design unique : cryomomdules are assembled at CEA and then transported to the accelerator site in Sweden or Israel.

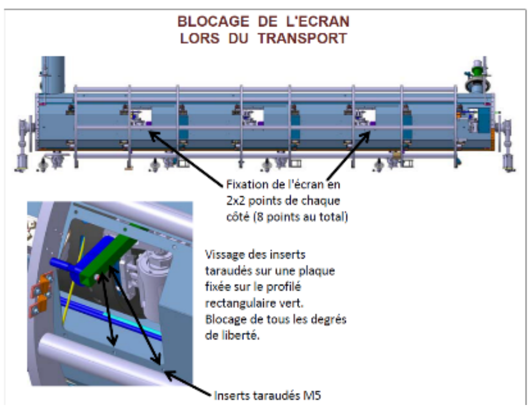
=> transport study and development of structure that can handle the road transport and maintain the alignment over more than one thousand kilometer or airplane transport.

ESS transport studies led to the clamping of the thermal shield and cavities on the space frame and the reinforcement of the feet of the cryomodule.

The mitigation of the transport risk for IFMIF has been to assemble the cryomodule on site at Rokkasho.

Figure 19 : Version 2 - Mode 3 - Ensemble - Axe Y - Fréquence =16.2Hz



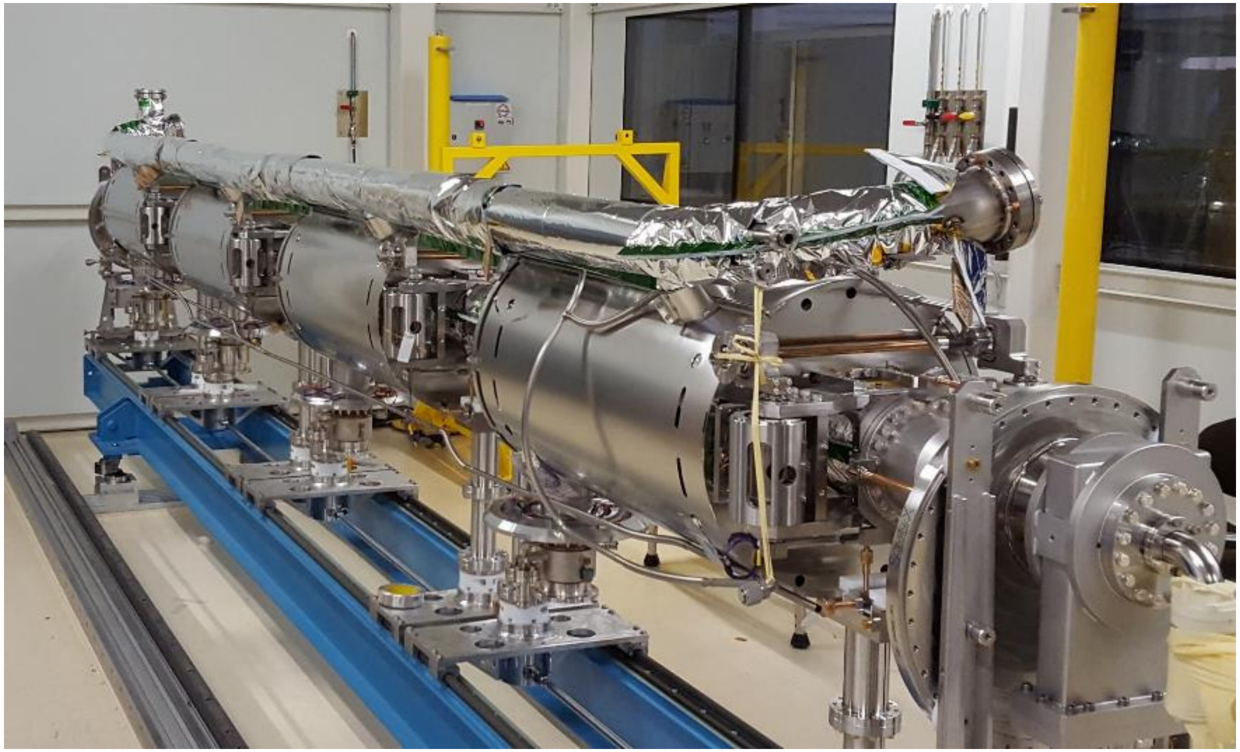


Steps to meet the challenges

	SARAF	IFMIF	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	X	X
Assembly	X	x	X
CM test at CEA	X		X
Transport	X		

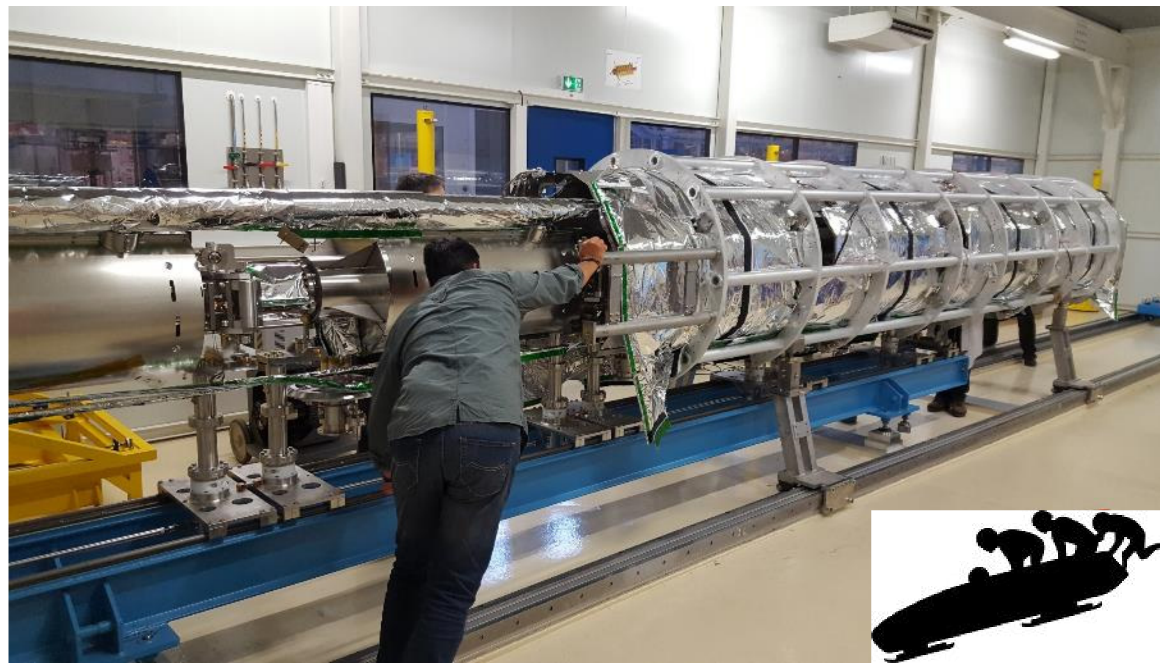
CRYOMODULE ASSEMBLY

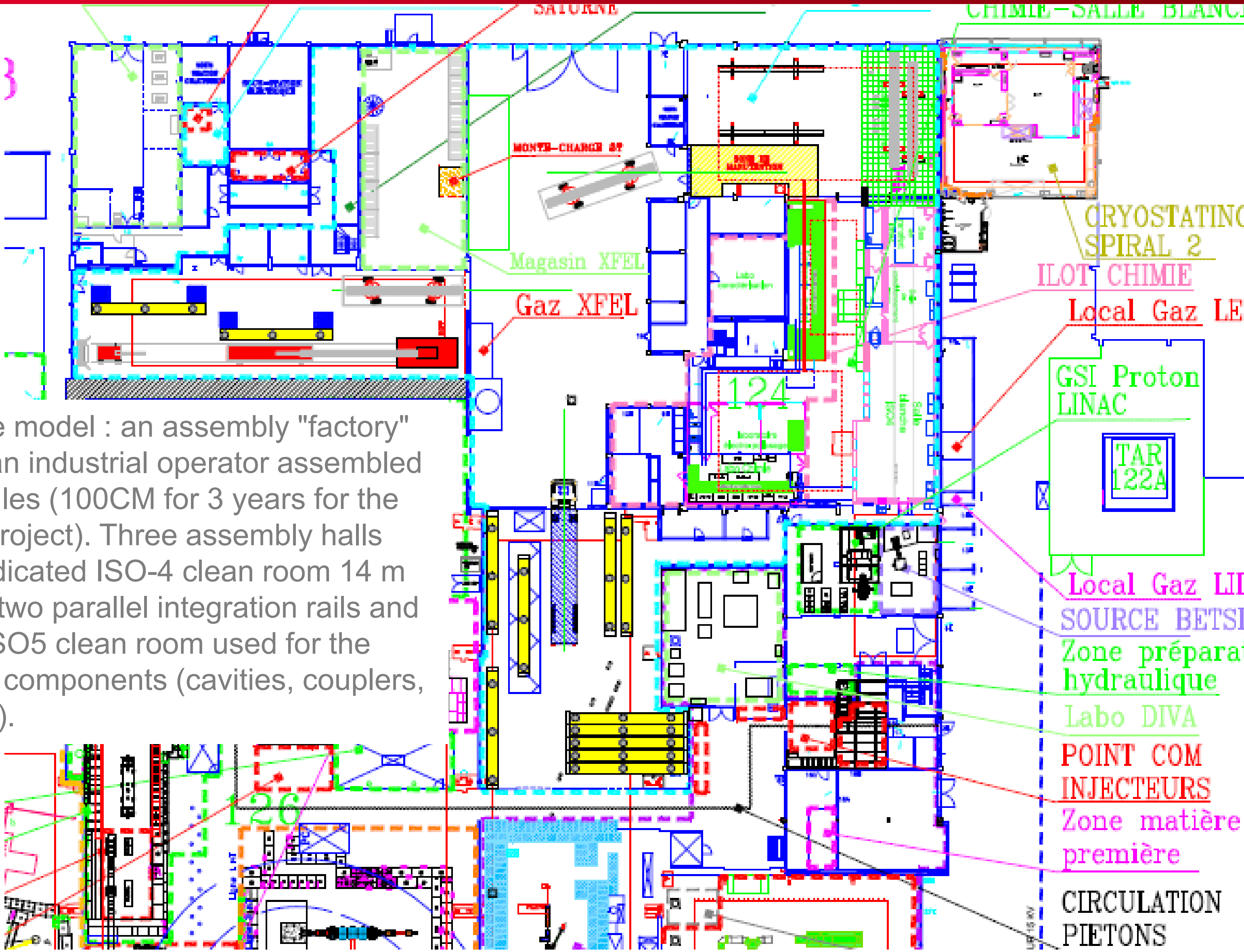
MECCTD Assembly in ISO4 clean room :
tests of tooling
tests of procedures
tests of welding



CRYOMODULE ASSEMBLY

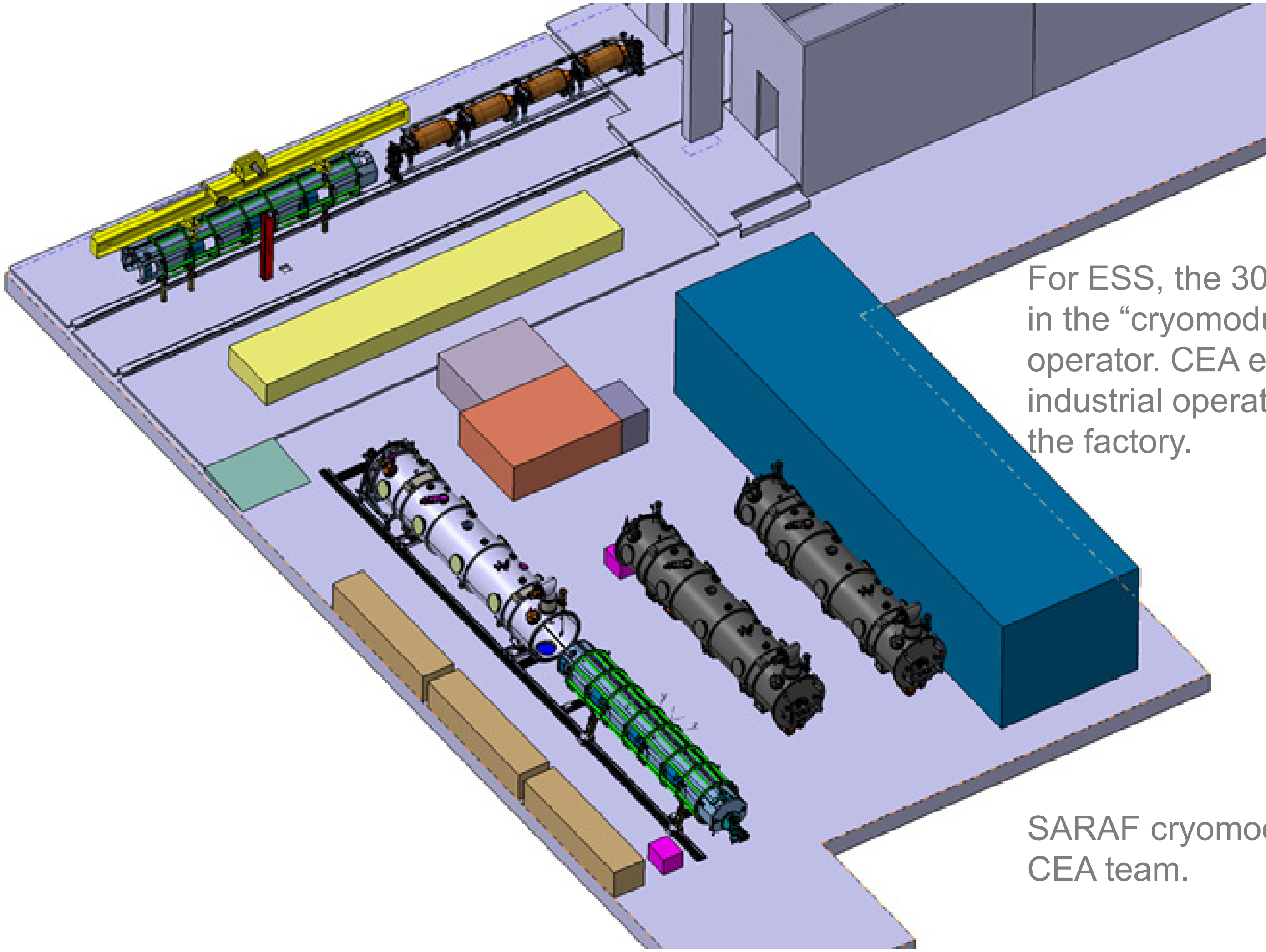
MECCTD Assembly : insertion in the space frame





An unique model : an assembly "factory" in which an industrial operator assembled cryomodules (100CM for 3 years for the E-XFEL project). Three assembly halls with a dedicated ISO-4 clean room 14 m long with two parallel integration rails and a 50m2 ISO5 clean room used for the individual components (cavities, couplers, solenoids).

CRYOMODULE ASSEMBLY FACTORY FOR ESS



For ESS, the 30 cryomodules will assembled in the “cryomodule” factory by an industrial operator. CEA ensures a close follow-up of the industrial operator with a CEA team always in the factory.

SARAF cryomodule will be assembled by a CEA team.

Steps to meet the challenges

	SARAF	IFMIF	ESS
Requirements definition	X	X	X
Design	X	X	X
Review	X	X	X
Risk analysis and mitigation plan	X	X	X
Prototypes	X	X	X
Tooling design and Mock-up tests	X	x	X
Transport studies and tests	X	x	x
Manufacturing	X	X	X
Assembly	X	x	X
CM test at CEA	X		X
Transport	X		

CM TESTS STAND

ESS CM in tests stand in August

A dedicated cryomodule test stand for all projects

Cryogenic fluid and RF power equipments

Command control and test equipment developed according to the projects needs and standardized allowing easy exchange of components

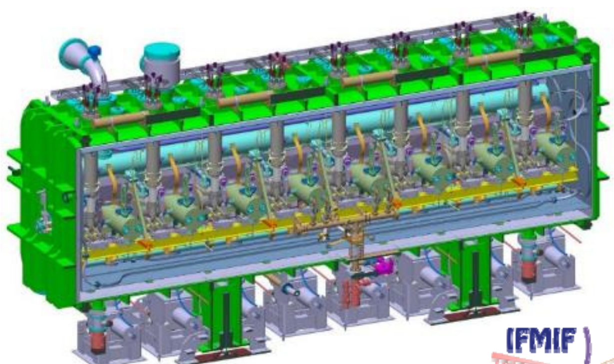
The test conditions are different from the operation conditions : the 4.5 K – 3 bars superfluid helium (SHe) supply is replaced by 4.64K -1.2 bara Gas helium supply and the 40 K – 19.5 bara helium cooling circuit of the thermal shield is fed with liquid nitrogen at 77K.

About a hundred people on Cryomodules activities

CEA EXPERIENCE ON SUPERCONDCUTING LINAC

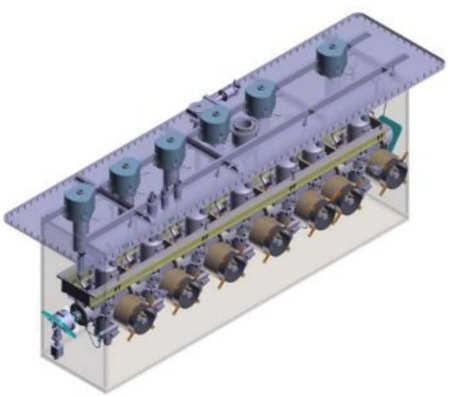
Booster → MACSE → SOLEIL TTF, SLS → SPIRAL2 XFEL → IFMIF LIPAc → ESS, SARAF → DONES Others → Future

SPIRAL2: design and assembly of 12 cryomodules



IFMIF LIPAc: 1 cryomodule

XFEL: assembly of 103 cryomodules (1 CM/wk)



SARAF Phase2: 4 cryomodules

ESS: cavity and coupler design, procurment of all bu cavities, integration of 32 cryomodules

Thank you
for your attention