ESS cryomodules

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(with input from CNRS-IPNO and CEA-IRFU)

ESS Engineering Lecture

Lund University
February 12, 2016

Outline

- Cryomodule characteristics
- Cryomodule components
- Cryomodule assembly
- How to operate a cryomodule

Acknowledgements & references

➔ Acknowledgement to P. Duthil and P. Bosland

ESS SRF Linac Collaborative Space:
http://ess-ics.atlassian.net/wiki/display/CRYOM/Cryomodules+Collaboration+space

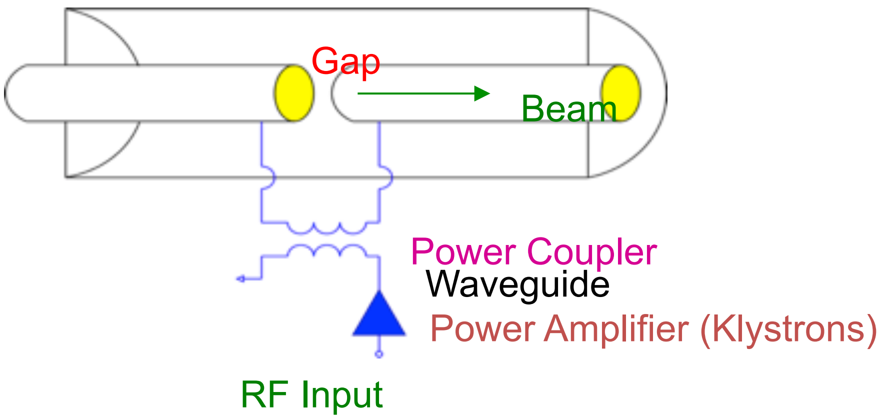
- US-Particle Accelerator School, http://uspas.fnal.gov/materials/materials-table.shtml
- CERN Accelerator School, http://cas.web.cern.ch/cas
- JUAS, https://espace.cern.ch/juas/SitePages/Home.aspx

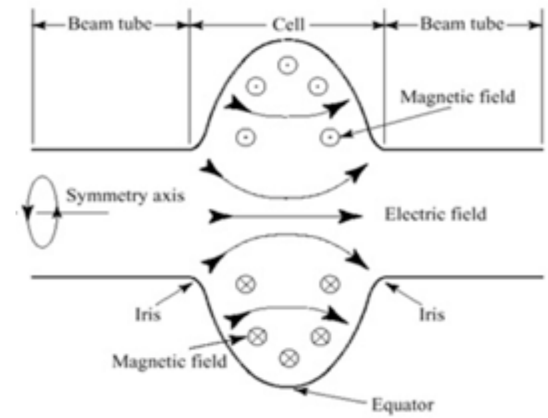
Few books

- RF Linear Accelerators, T.P. Wangler, Wiley, 2008
- RF Superconductivity for Accelerator, H. Padamsee, J. Knobloch, T. Hays, Wiley, 2011
- An introduction to particle accelerators, E.J.N. Wilson, Oxford Univ. Press, 2001
- An introduction to the physics of high-energy accelerators, D.A. Edwards & M.J. Syphers, Wiley, 1993

Particle Accelerators need SRF Cavity

EUROPEAN SPALLATION SOURCE



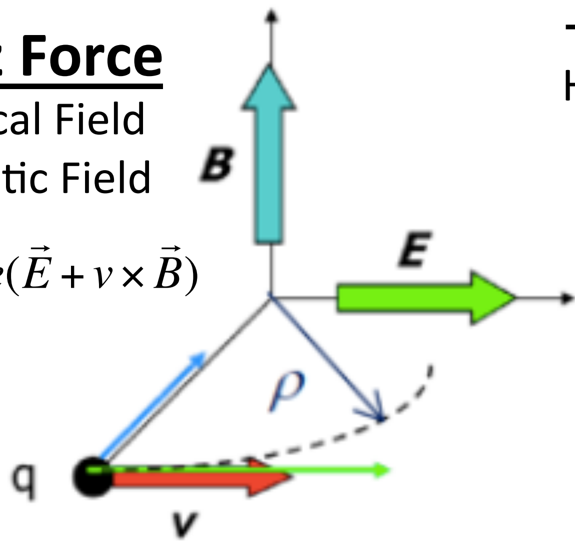


Lorentz Force

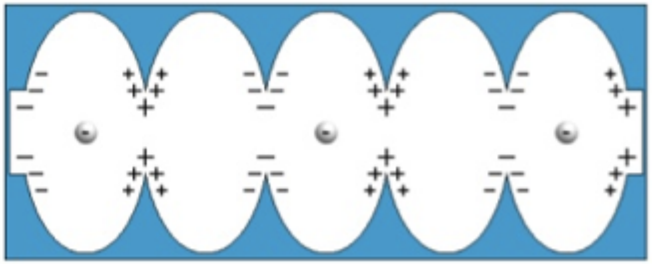
→ Electrical Field

→ Magnetic Field

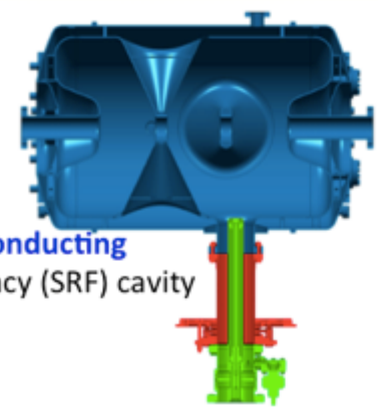
$$\vec{F} = \frac{d\vec{p}}{dt} = e(\vec{E} + v \times \vec{B})$$



→ Elliptical cavity
High β

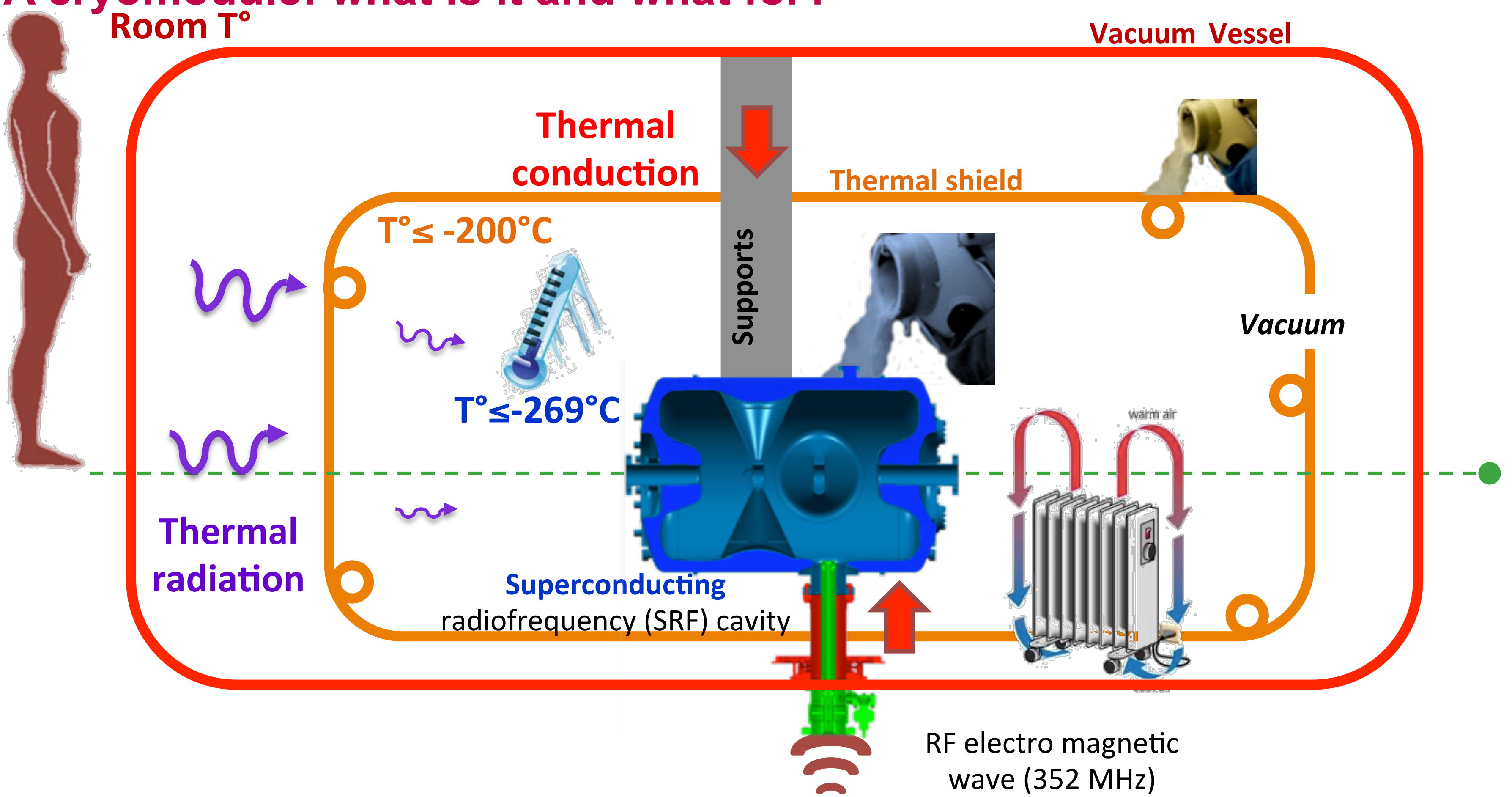


→ Spoke cavity
Low β



Superconducting
radiofrequency (SRF) cavity

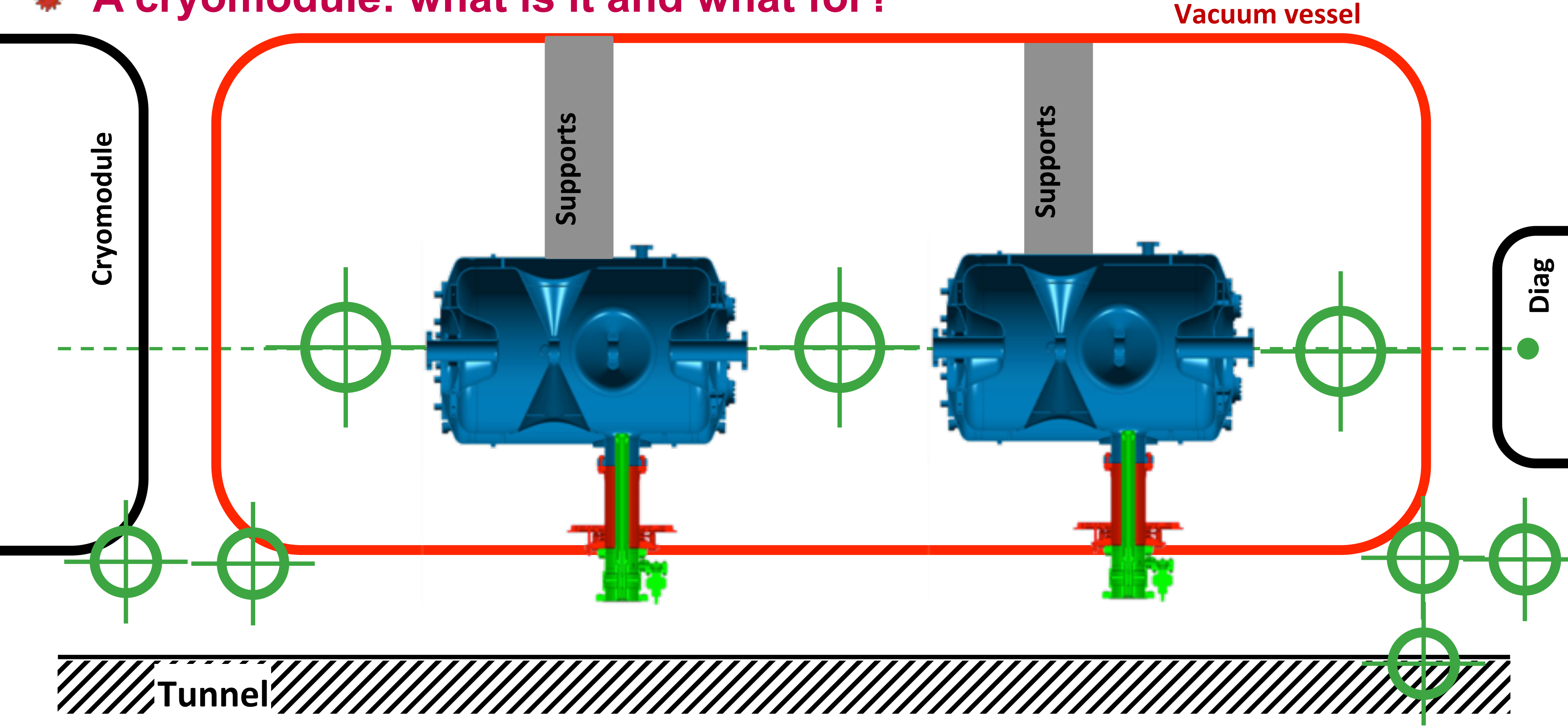
A cryomodule: what is it and what for?



1/ To provide a cryogenic environment to the cold mass (cavity) = cryostat:

- **distributing the cryofluids to cool-down and maintain at cold T° (LHe, LN_2)**
- **limiting the heat transfers**

A cryomodule: what is it and what for?

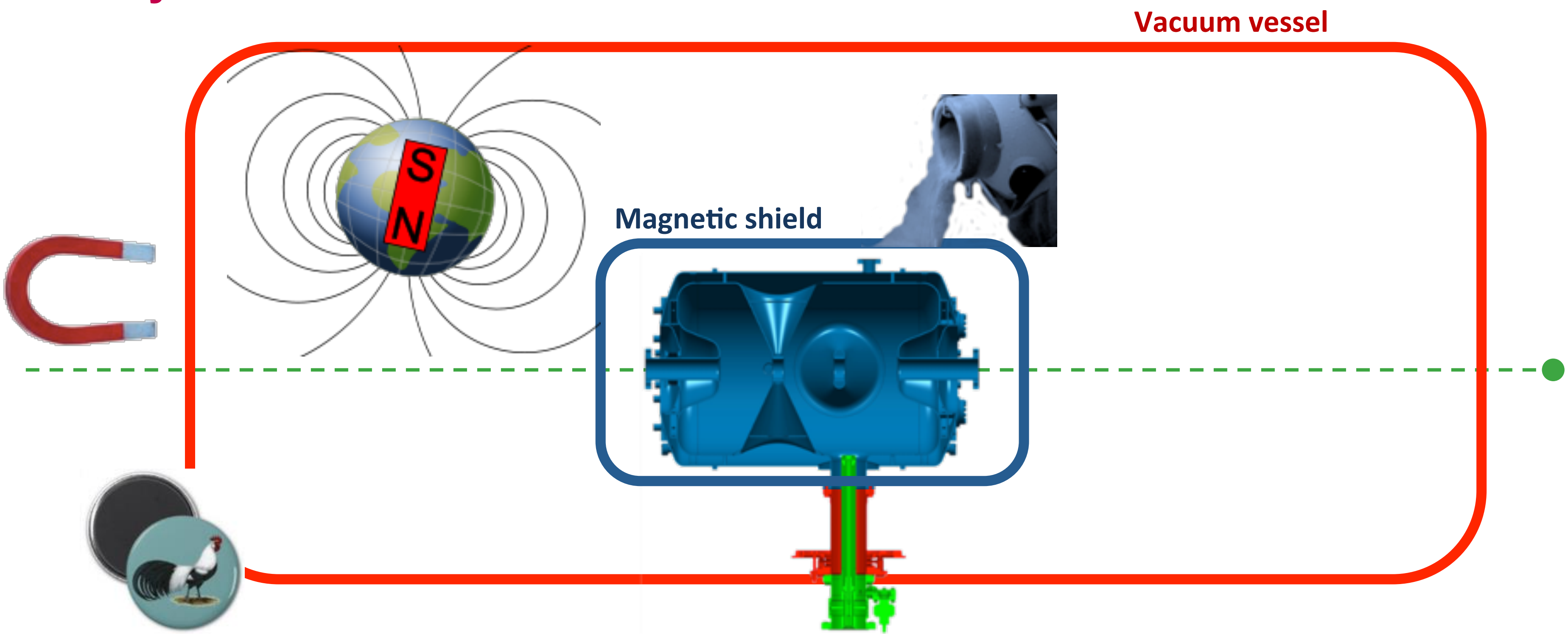


2/ To support the cavities and perform accurate alignment

- **with respect to the beam axis**
- **with respect to other linac components (cryomodules, diagnostics, tunnel)**

NB: alignment must be preserved during thermal and pressure cycles

A cryomodule: what is it and what for?

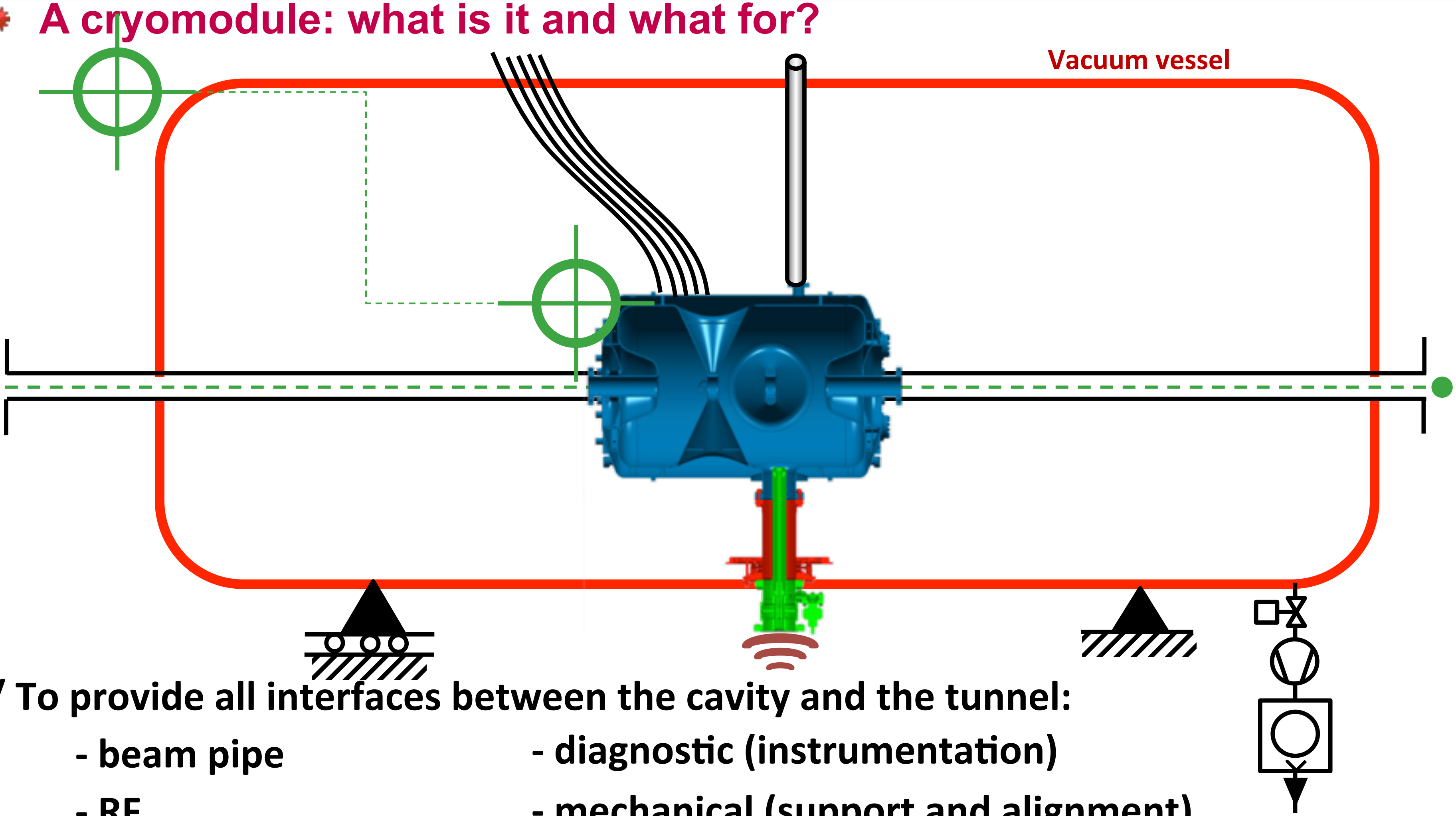


3/ To offer magnetic shielding

- **from the local magnetic sources**
- **from the earth magnetic shield**

NB: the magnetic shield might be cooled (for better performances)

A cryomodule: what is it and what for?

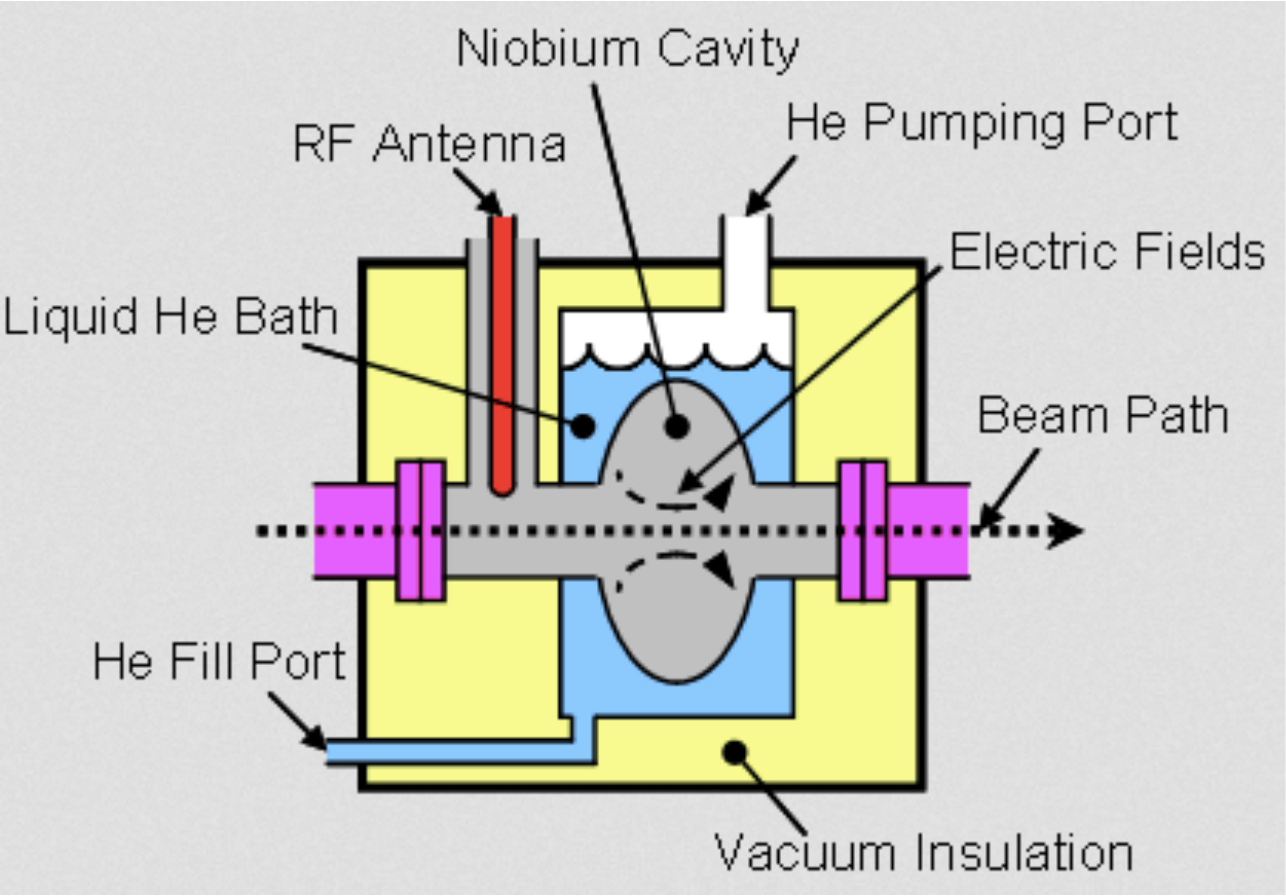


4/ To provide all interfaces between the cavity and the tunnel:

- beam pipe
- RF
- cryogenic
- vacuum
- diagnostic (instrumentation)
- mechanical (support and alignment)

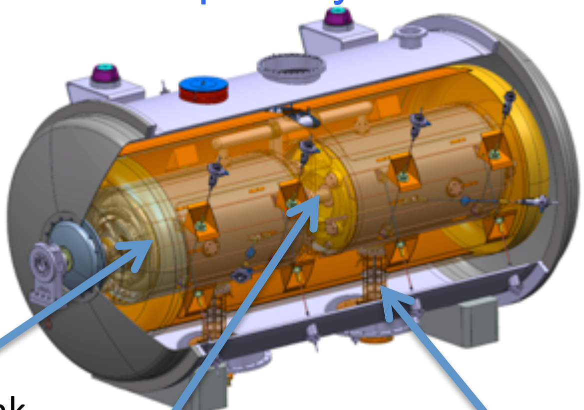
Cavities and Cryomodules

RF cavities housed in cryomodules, which keep the RF cavities working in a superconducting state, without losing energy to electrical resistance

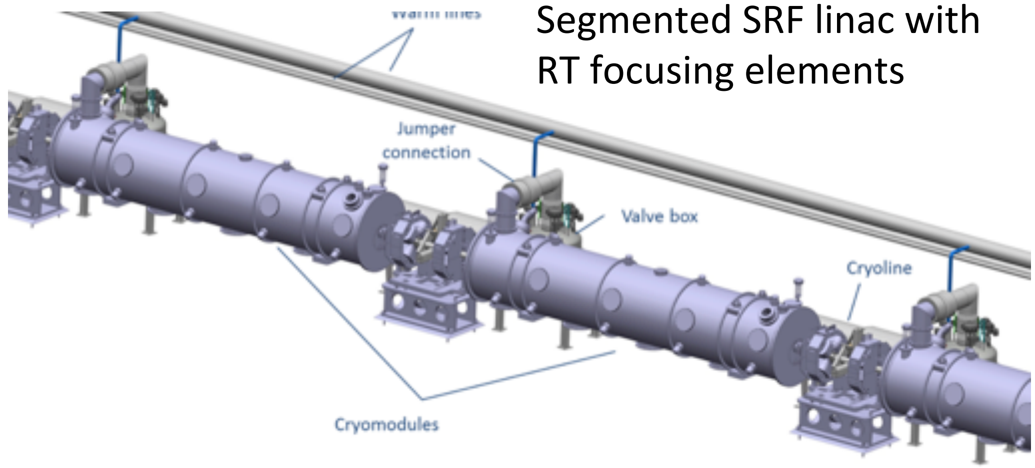


ESS SRF cavities and cryomodules

2 Spoke Cavities per Cryomodule



Segmented SRF linac with RT focusing elements

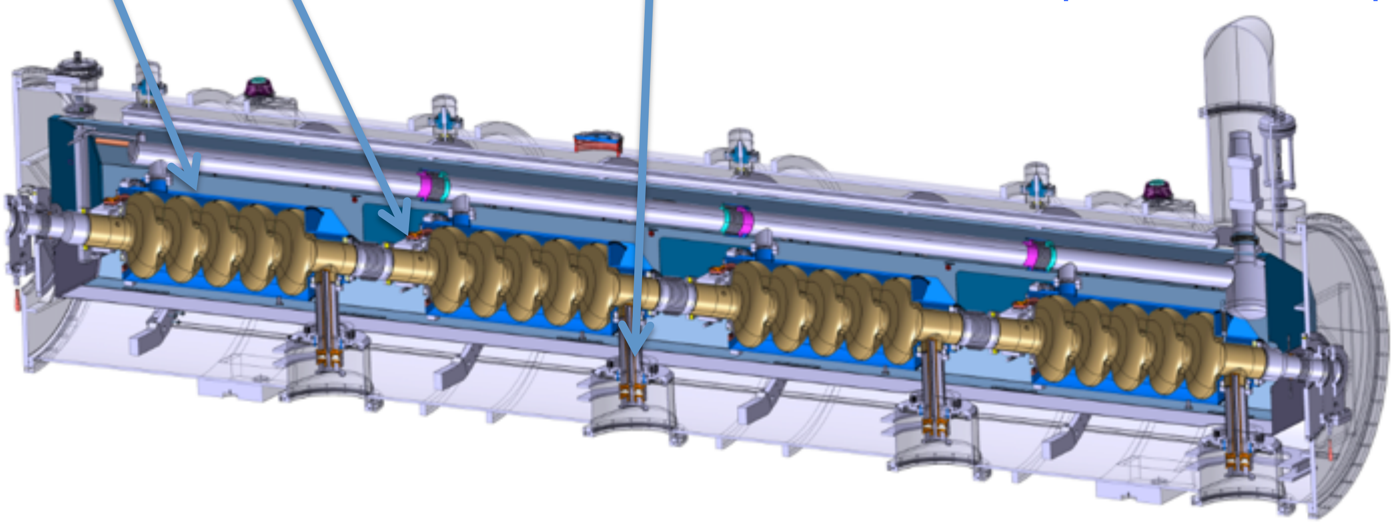


Ti. Helium tank

Cold tuning System

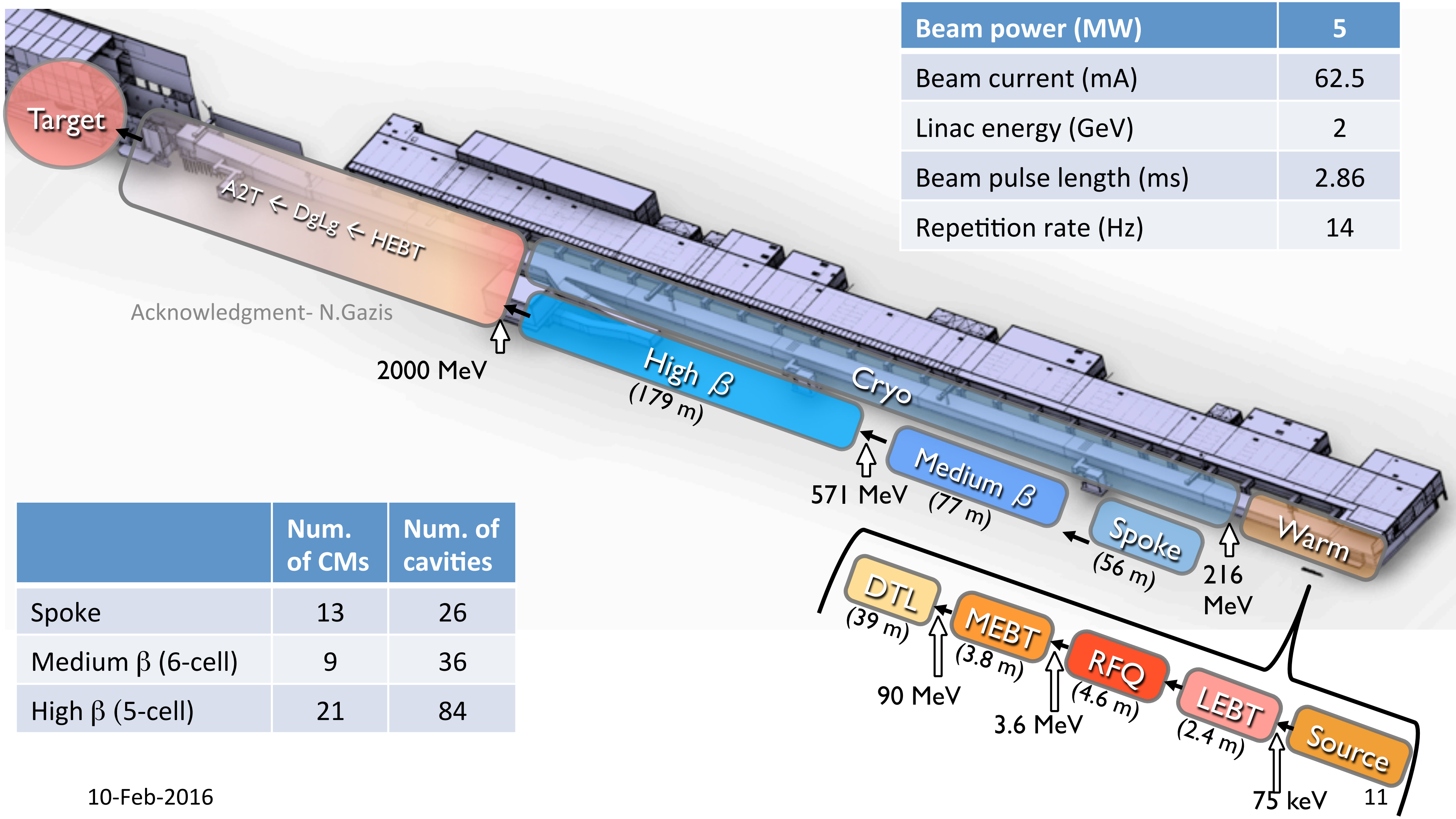
Power coupler

4 Elliptical Cavities per Cryomodule



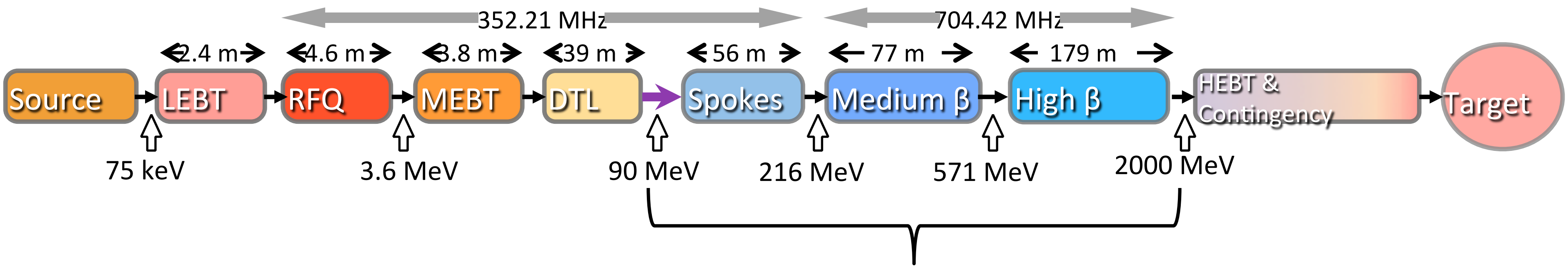
ESS Linac Layout

Beam power (MW)	5
Beam current (mA)	62.5
Linac energy (GeV)	2
Beam pulse length (ms)	2.86
Repetition rate (Hz)	14



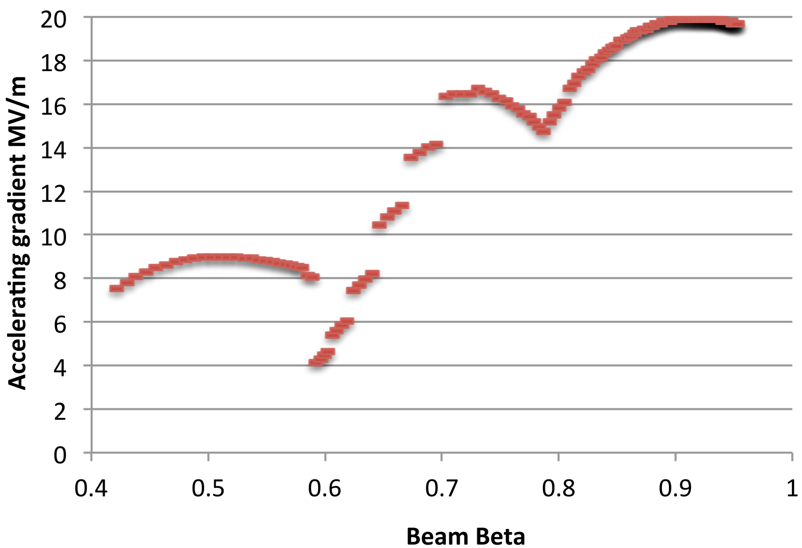
	Num. of CMs	Num. of cavities
Spoke	13	26
Medium β (6-cell)	9	36
High β (5-cell)	21	84

ESS Linac Layout



Style	Spoke	Medium-β	High-β
Freq. (MHz)	352.21	704.42	704.42
Cavity #	26	36	84
Velocity range	0.42 to 0.58	0.58 to 0.78	0.78 to 0.95
Nom. Acc. Voltage (MV)	5.74	14.3	18.2
Loaded quality factor	2.85×10^5	8×10^5	7.6×10^5

$$Qo = \frac{EnergyStored}{PowerLoss}$$



➔ ESS needs high gradient SRF cavities

ESS Requirements and RF Parameters

Spoke cavities

Frequency (MHz)	352,2
Optimum beta	0,50
Operating temperature (K)	2
Nominal Accelerating gradient (MV/m)	9
Lacc (βopt.x nb gaps x λ/2) (m)	0,639
Bpk (mT)	79 (max)
Epk (MV/m)	39 (max)
Bpk/Eacc (mT/MV/m)	<8,75
Epk/Eacc	<4,38
Beam tube diameter (mm)	50
RF peak power (kW)	335
G (Ω)	130
Max R/Q (W)	427
Qext	$2,85\ 10^5$
Q0 at nominal gradient	$1,5\ 10^9$

Elliptical cavities

	Medium	High
Geometrical beta	0.67	0.86
Frequency (MHz)	704.42	
Number of cells	6	5
Operating temperature (K)	2	
Epk max (MV/m)	45	45
Nominal Accelerating gradient (MV/m)	16.7	19.9
Q_0 at nominal gradient	> 5e9	
Q_{ext}	$7.5\ 10^5$	$7.6\ 10^5$
Iris diameter (mm)	94	120
Cell to cell coupling k (%)	1.22	1.8
p,5p/6 (or 4p/5) mode sep. (MHz)	0.54	1.2
Epk/Eacc	2.36	2.2
Bpk/Eacc (mT/(MV/m))	4.79	4.3
Maximum. r/Q (W)	394	477
Optimum β	0.705	0.92
G (Ω)	196.63	241
RF peak power (kW)	1100	

Outline

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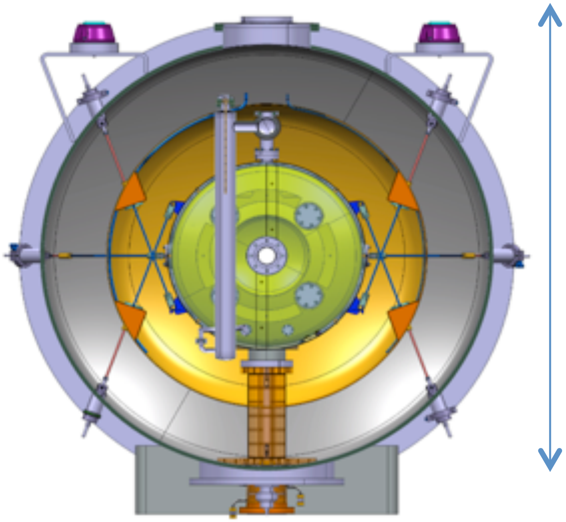
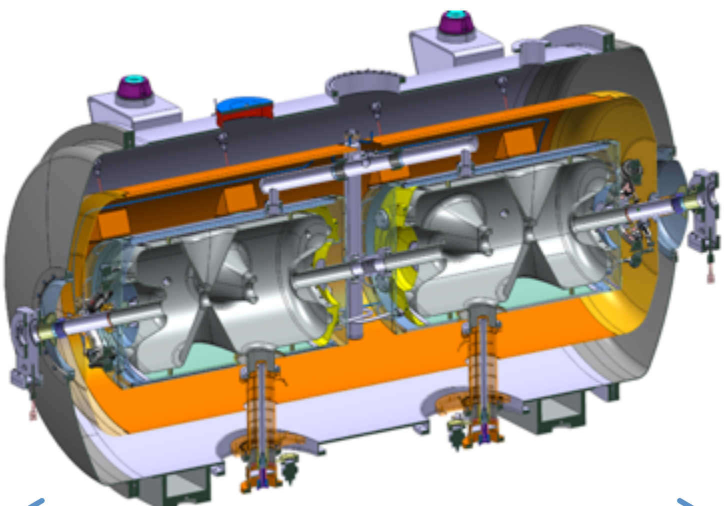
- How to operate a cryomodule

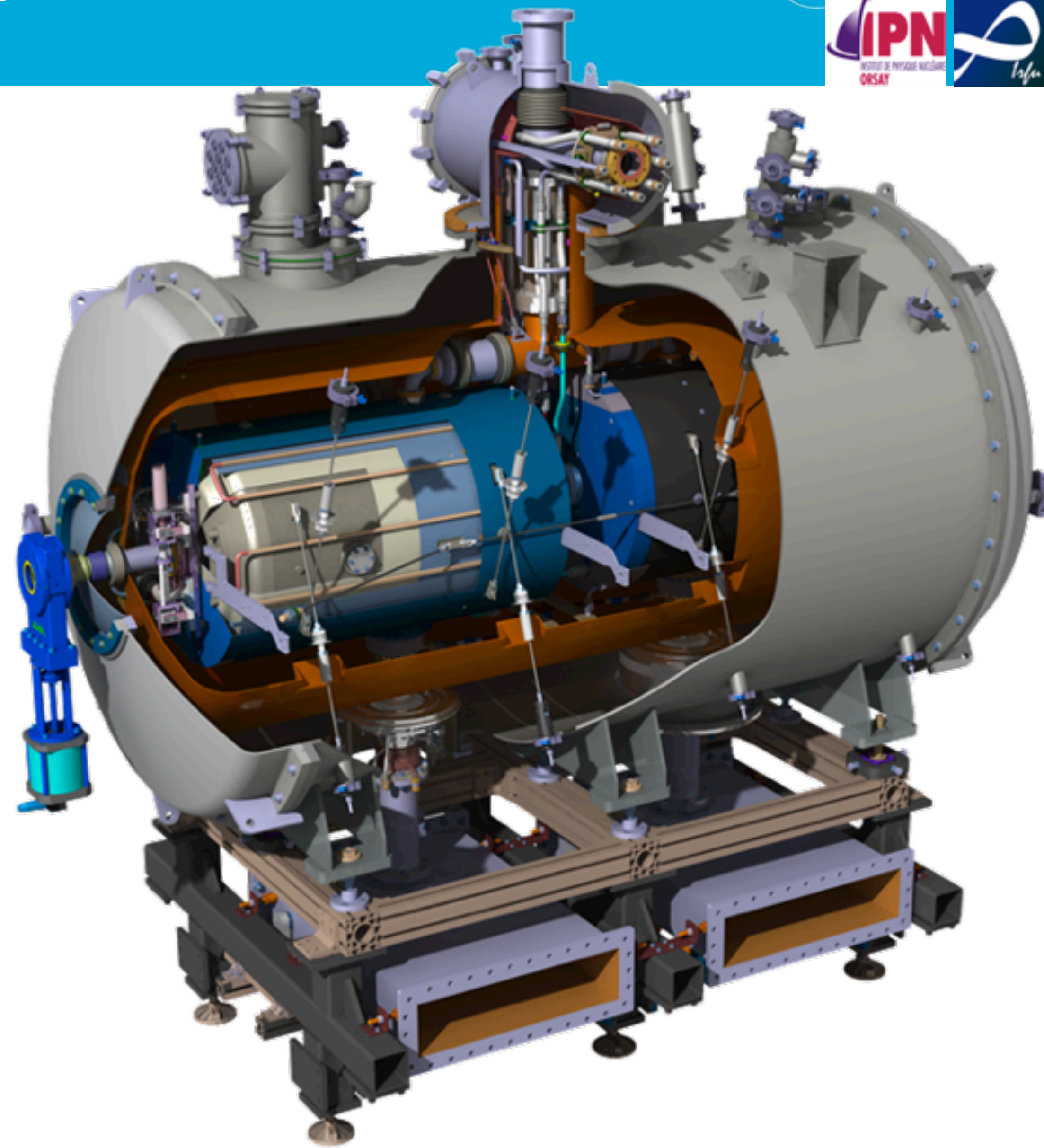
Spoke cryomodule



Diameter 1350 mm



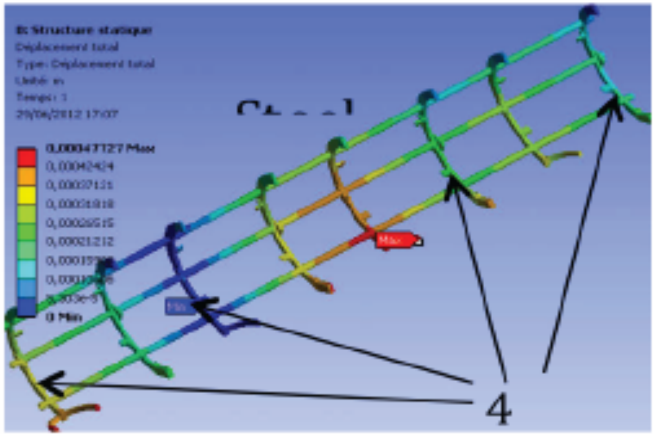
2900 mm



Elliptical Cryomodule Components
Design

The cryomodule design and calculation:

- Thermo-mechanical studies
- Magnetic studies (CST)
- Hydraulic studies
- Safety analysis to size all components
- Reliability analysis, FMEA



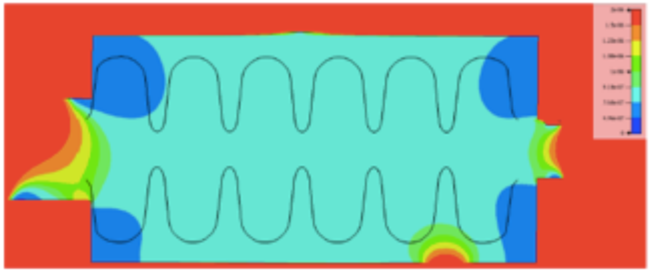
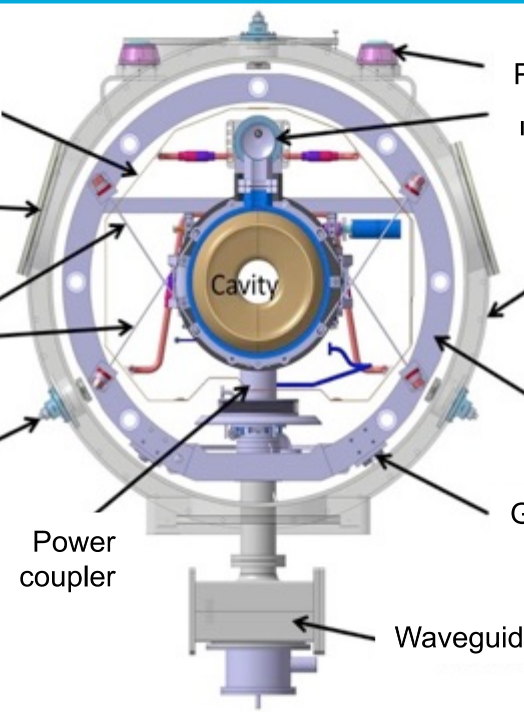
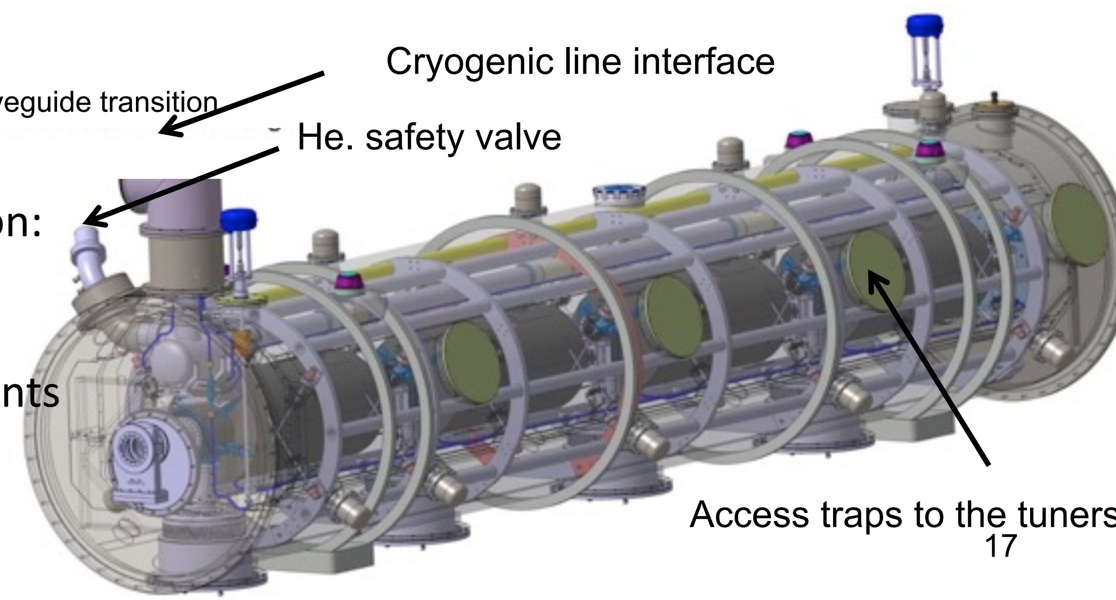


Figure 9: Magnetic field inside the shield for Hx = 23.5 A/m and Hy = 32 A/m.

Elliptical Cryomodule Components





The cryomodule design and calculation:

- Thermo-mechanical studies
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- Safety analysis to size all components
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Elliptical Cryomodule

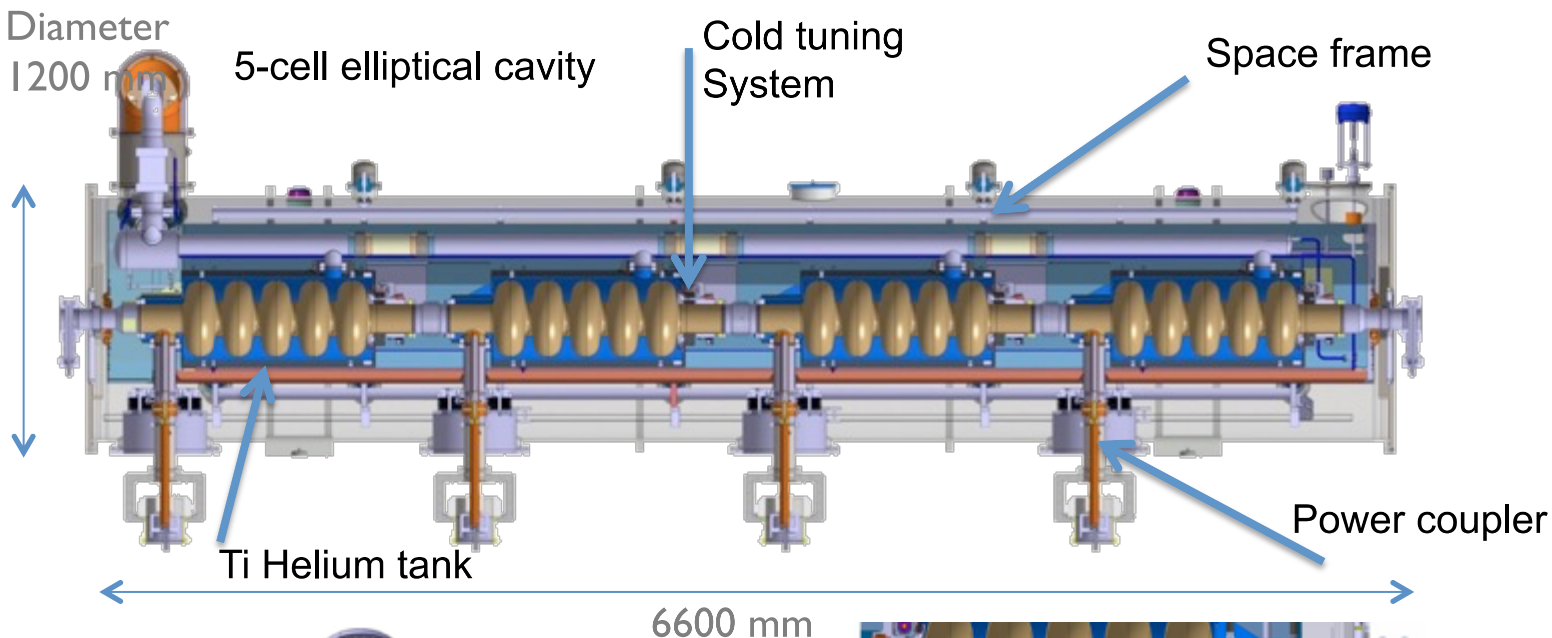
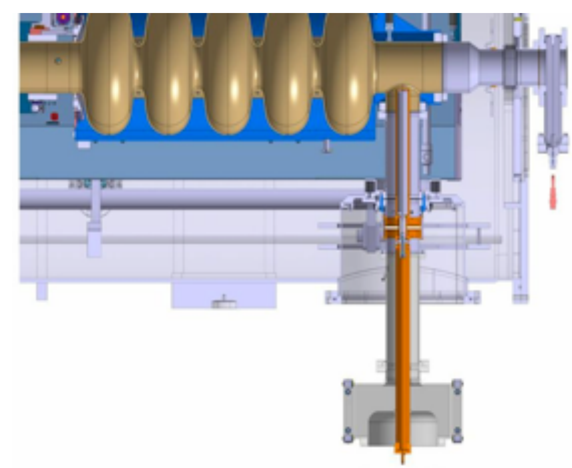


Figure 4.120: Helium vessel with hanging rod



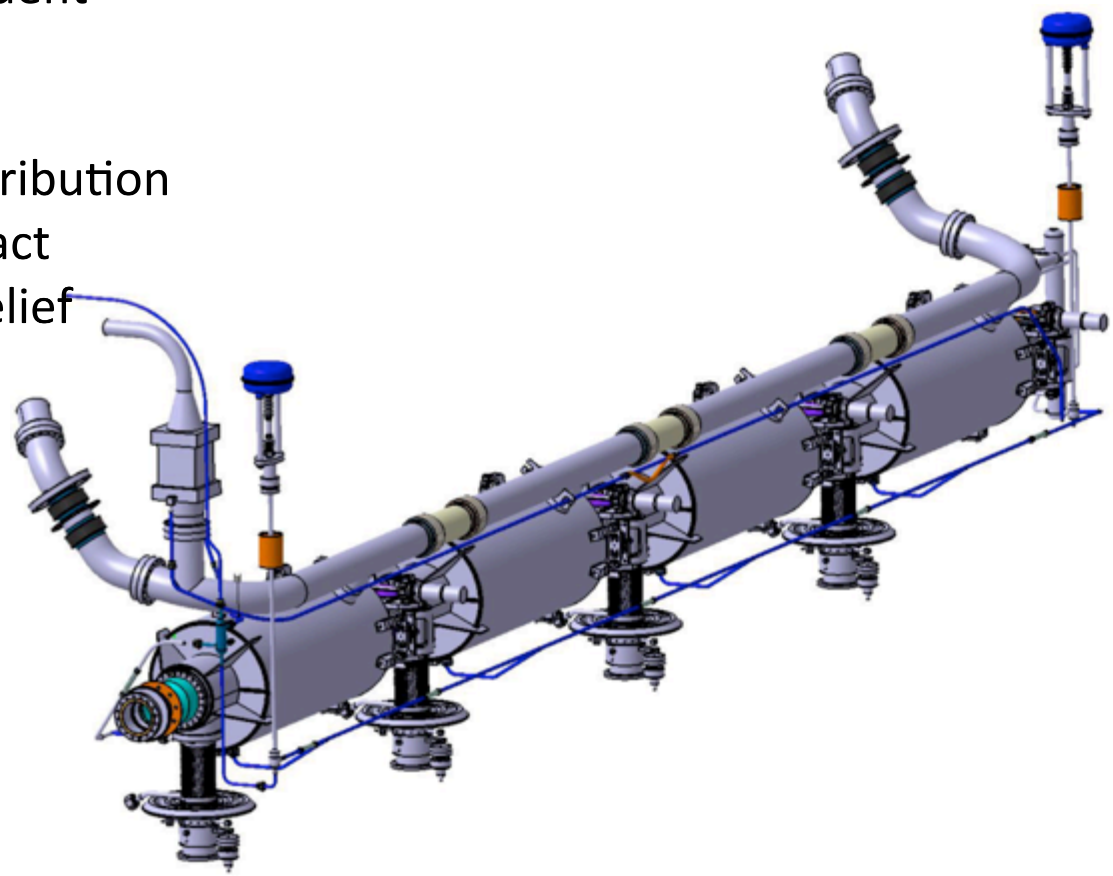
Safety relief devices

- Identify: Hydraulic circuits
  volume and pressure
  fluid
  most credible incident

$$\dot{m} = \frac{\dot{Q}}{L_V} \frac{\rho_L - \rho_V}{\rho_L}$$

- Assess/calculate:
  Pressure drop distribution
  Mass-flow to extract
  Diameter of the relief
  Type of device

- Mitigate/design ➔



SRF Cavities Development

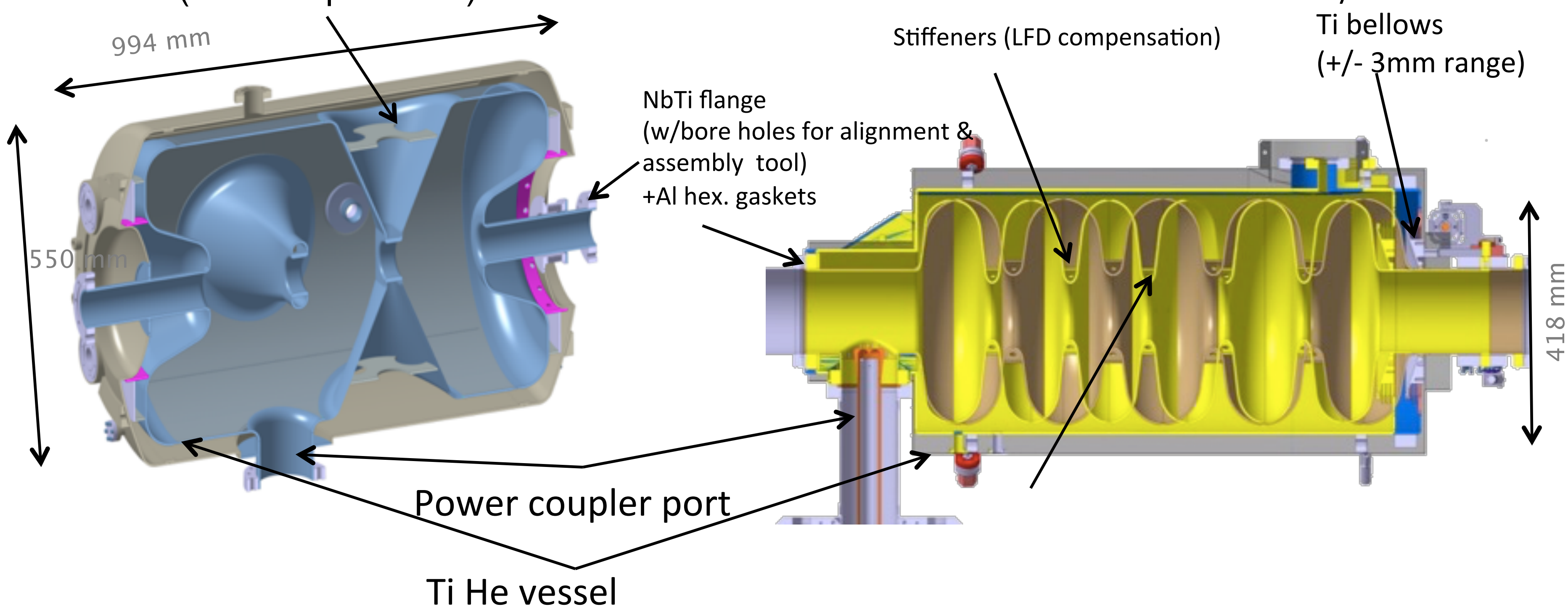
EUROPEAN SPALLATION SOURCE

Spoke cavity

→ Stiffeners on the Spoke bars (vacuum pressure)

Elliptical cavities

→ No HOM power couplers



Medium beta:

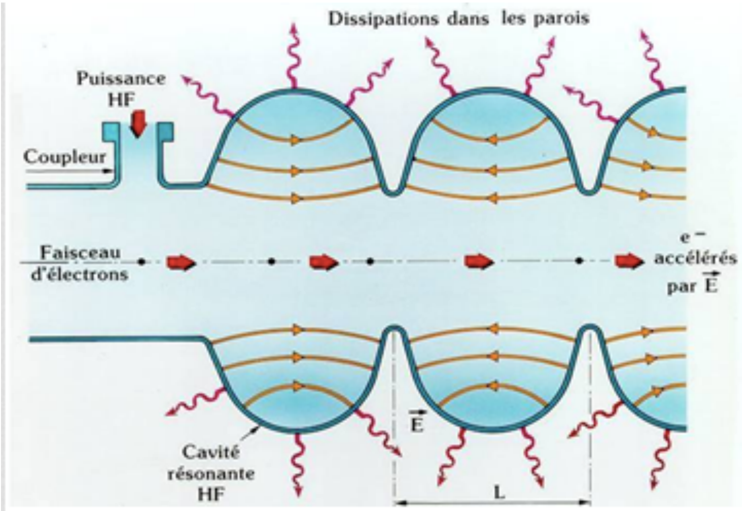
- **6 cells – beta=0.67**
- **Length 1259,40mm**

High beta:

- **5 cells – beta=0.86**
- **Length 1316,91mm**

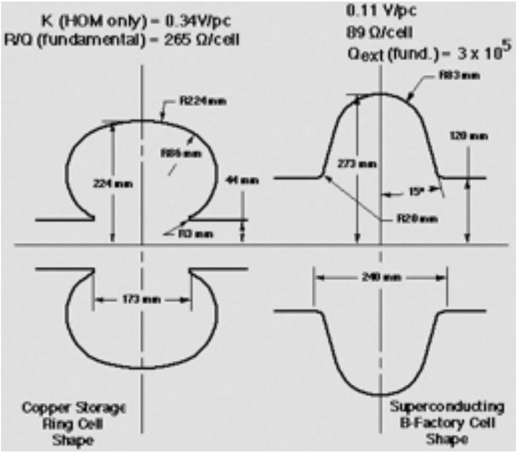
SRF Cavities Performances

- Accelerating gradient
- Peak Surface fields
- Power Dissipation
- Cavity Quality
- Shunt Impedance



Few limitations of performance:
- Thermal Breakdown, alias quench
- Field Emission: Electron induced by an electrostatic field
- Multipacting: electron avalanche

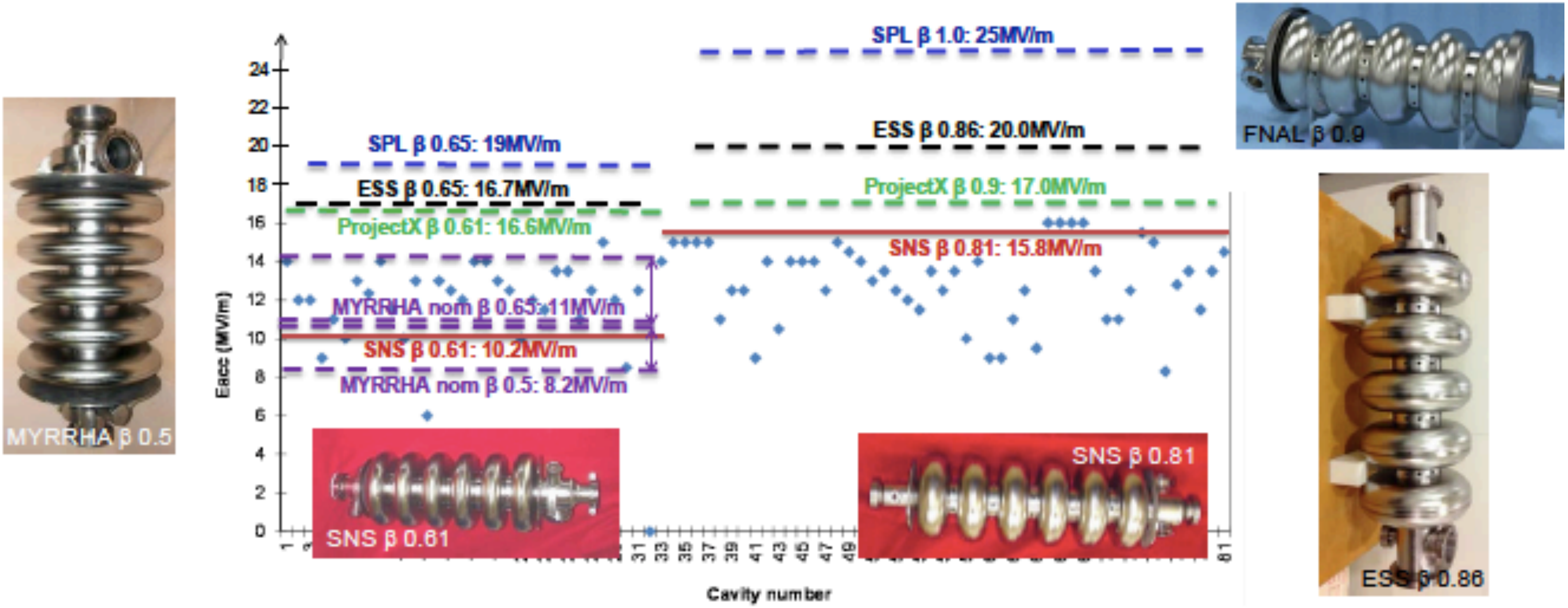
Limit power loss in the cavity wall:
- By using low-resistant material or superconductors
- By rounding the shape to optimize the field distribution
- Limit shape edge to prevent field emission
- Good vacuum to limit breakdown



Cavity gradients

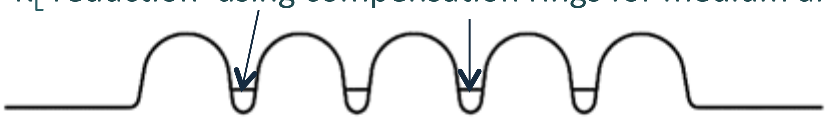
- **Cavity gradient is directly related to cost** -> tendency to push the gradients
- **SNS experiences a huge gradient variability -> needs for margins & operational flexibility !!**
  - ✓ Almost every SNS run, a few cavities have problems, resulting in lower E_{acc} or turn-off -> linac retuning
  - ✓ Achievable gradients are mainly limited by heating by electron activity at high duty factor (especially by induced collective limits)

Ex. CM13 individual limits; 19.5, 15, 17, 14.5 MV/m
Ex. CM13 collective limits; 14.5, 15, 15, 10.5 MV/m

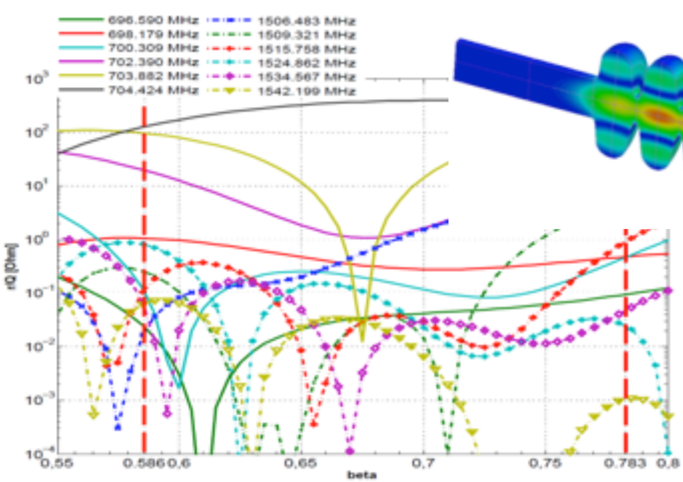


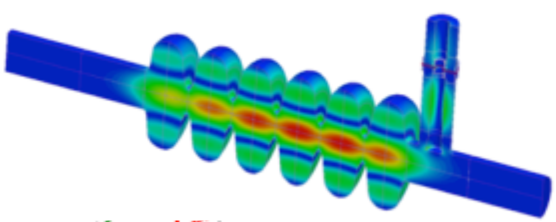
Cavities tuning

K_L reduction using compensation rings for medium and high-beta



Nominal wall thickness [mm]	3.6
Cavity stiffness Kcav [kN/mm]	2.59
Tuning sensitivity Df/Dz [kHz/mm]	197
K_L with fixed ends [Hz/(MV/m)²]	-0.36
K_L with free ends [Hz/(MV/m)²]	-8.9
Pressure sensitivity K_P [Hz/mbar] (fixed ends)	4.85



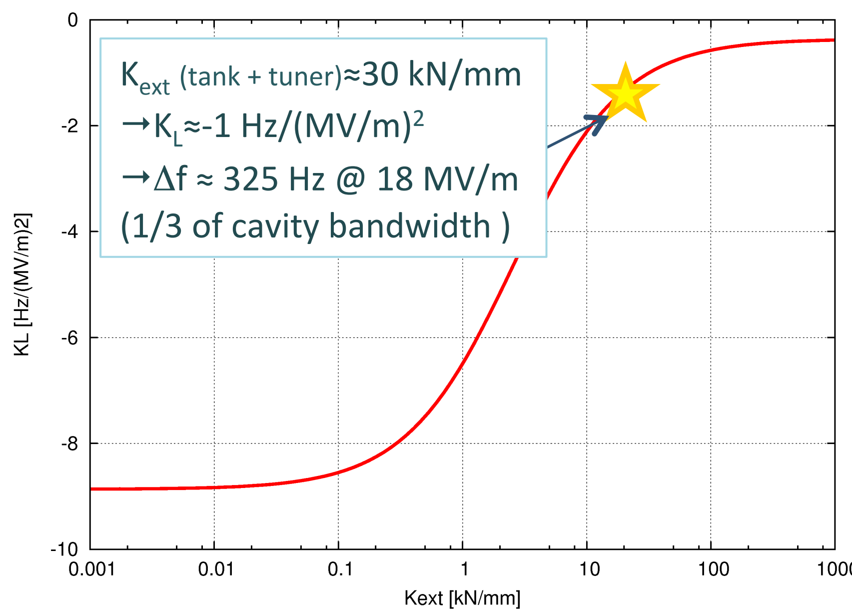


RF/mechanical design

Lorentz detuning

$$K_L = \Delta f / E_{acc}^{\;2}$$

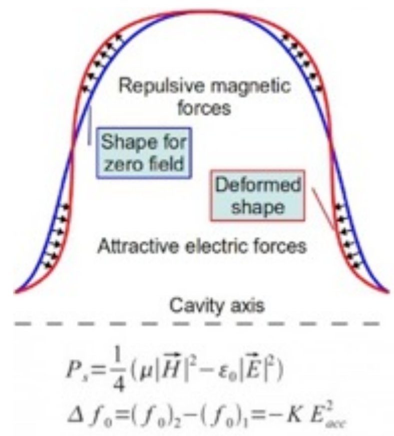
$$K_L = K_{L\infty} + \frac{\Delta f}{\Delta z} \frac{\overrightarrow{F_\infty} . \overrightarrow{u_z} / E_{acc}^{\;2}}{K_{ext} + K_{cav}}$$

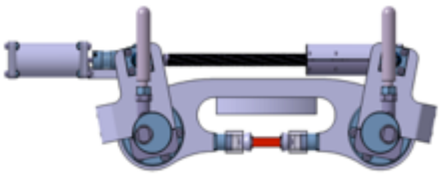


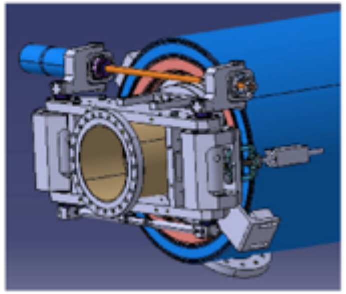
Cavities tuning: Lorentz De-tuning

ESS and long pulse: 2.86 ms

- Because of the enormous gradients in superconducting cavities,
  - the radiation pressure deforms the cavities
- We expect over 400 Hz of detuning in the ESS cavities
  - Unloaded cavity bandwidth = 0.07 Hz
  - Loaded cavity bandwidth = 1 kHz
- The mechanical time constant of the cavities is about 1 ms compared to the pulse length of 3 ms
  - Static pre-detuning as done in SNS will not be sufficient
  - Dynamic de-tuning compensation using piezo-electric tuners is a must!
  - Or else pay for the extra RF power required





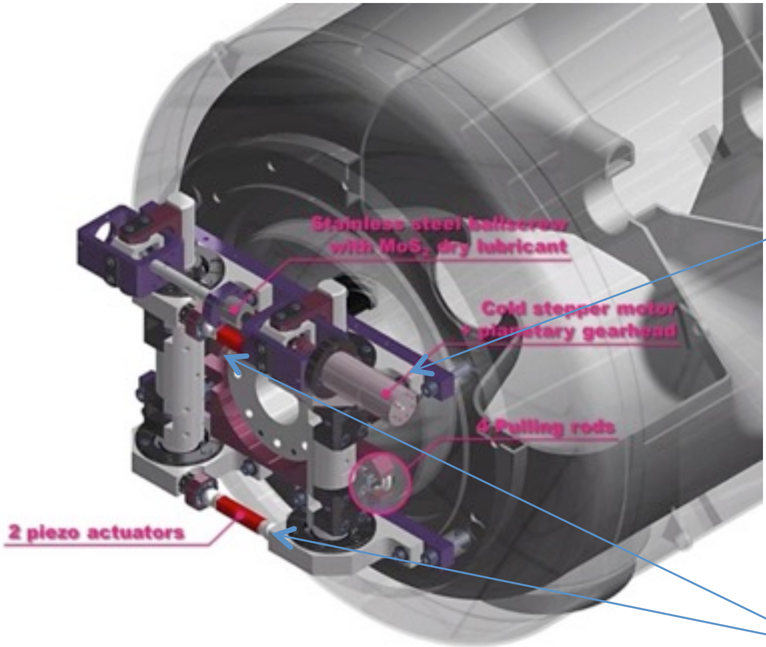


Saclay-V tuner concept adapted to the ESS cavity
Fast/slow tuner (with piezo)

Cold Tuning System

EUROPEAN SPALLATION SOURCE

Spoke CTS

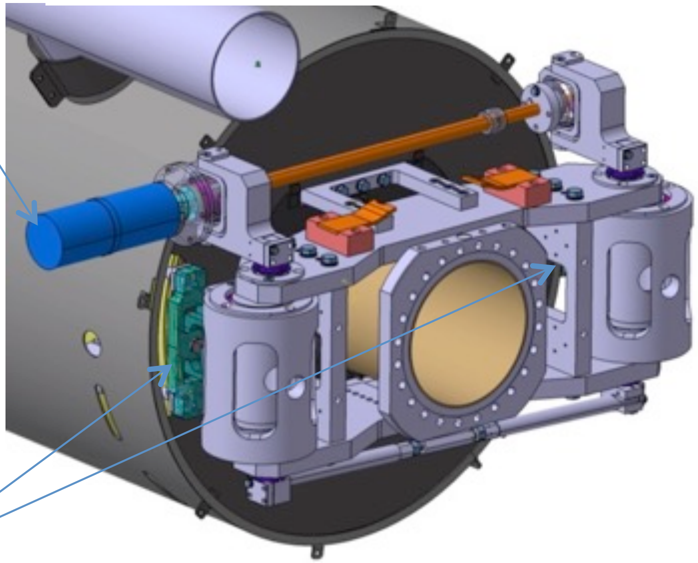


Stepper motor and planetary gearbox (1/100e) at cold and in vacuum

2 piezo stacks

Elliptical CTS

Type V ; 5-cell prototype
+/- 3 mm range on cavity



Slow tuner

Main purpose : Compensation of large frequency shifts with a low speed

Actuator used : Stepper motor

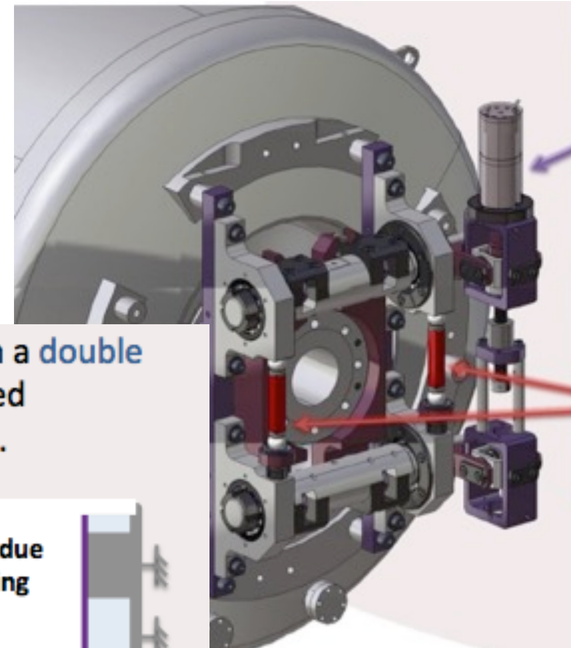
&

Fast tuner

Main purpose : Compensation of small frequency shifts with a high speed

Actuator used : Piezoelectric actuators

The Spokes Cryomodule



Slow tuner

Main purpose : Compensation of **large** frequency shifts with a **low** speed

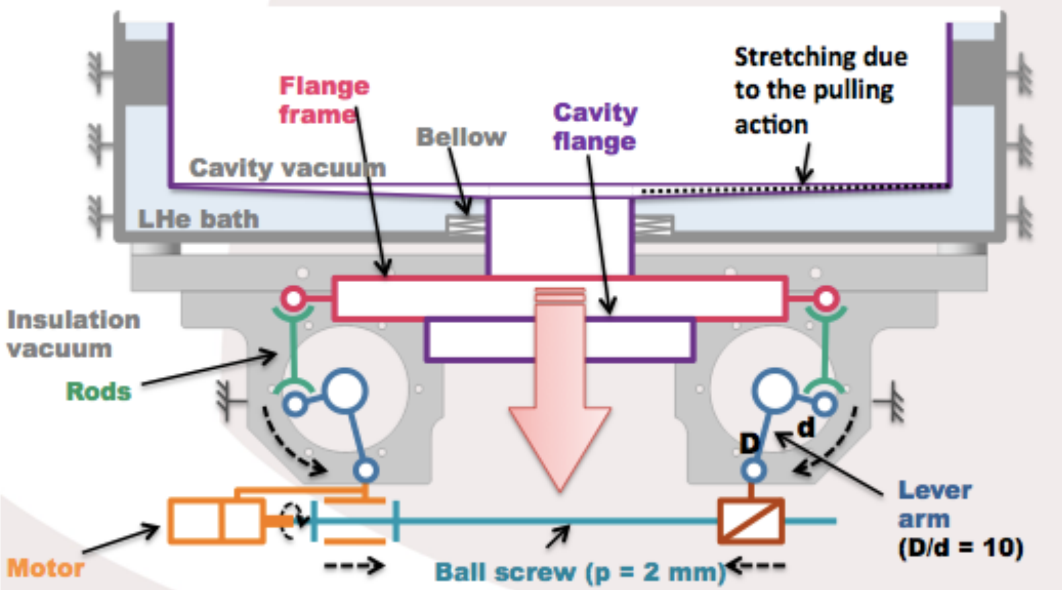
Actuator used : Stepper motor with planetary gearbox (1:50)

Fast tuner

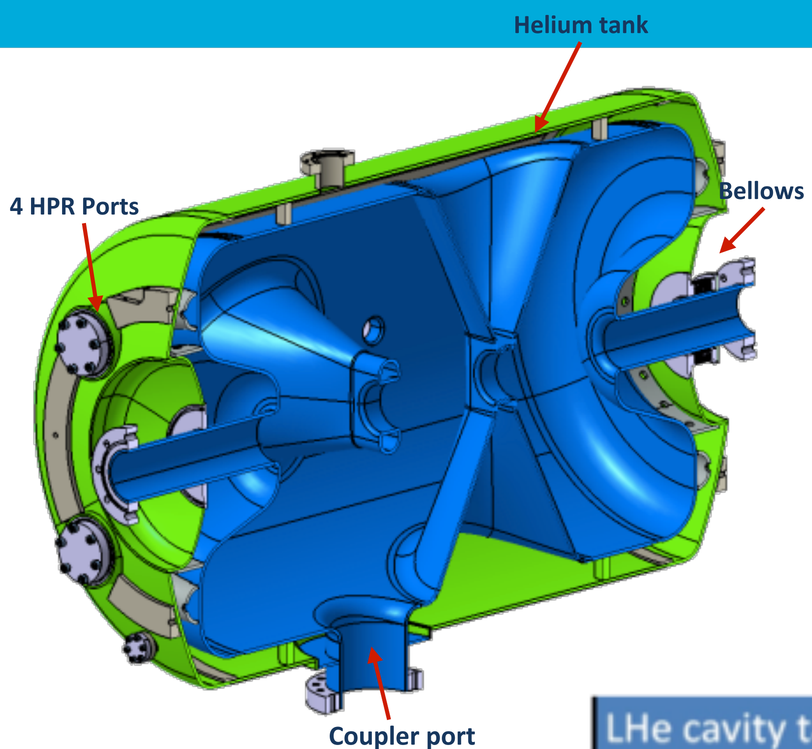
Main purpose : Compensation of **small** frequency shifts with a **high** speed

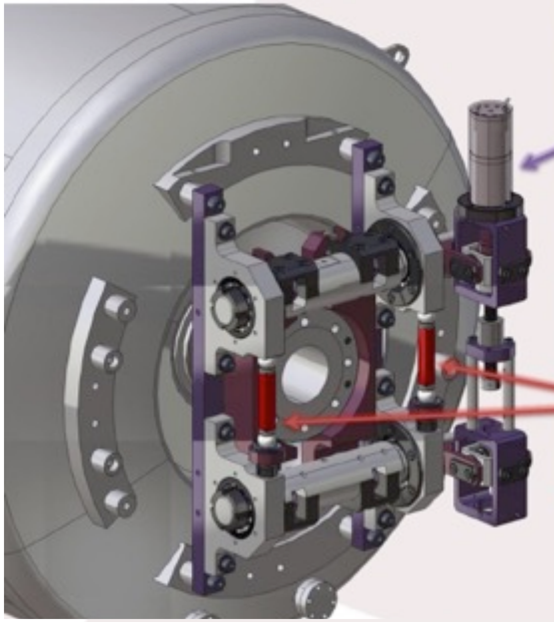
Actuator used : Piezoelectric actuators (no load displacement : ~ 50 µm @ RT)

A ball screw system driven by a stepper motor acts on a double lever arm mechanism to provide a significantly reduced displacement of the cavity flange along the beam axis.



The Spokes Cryomodule





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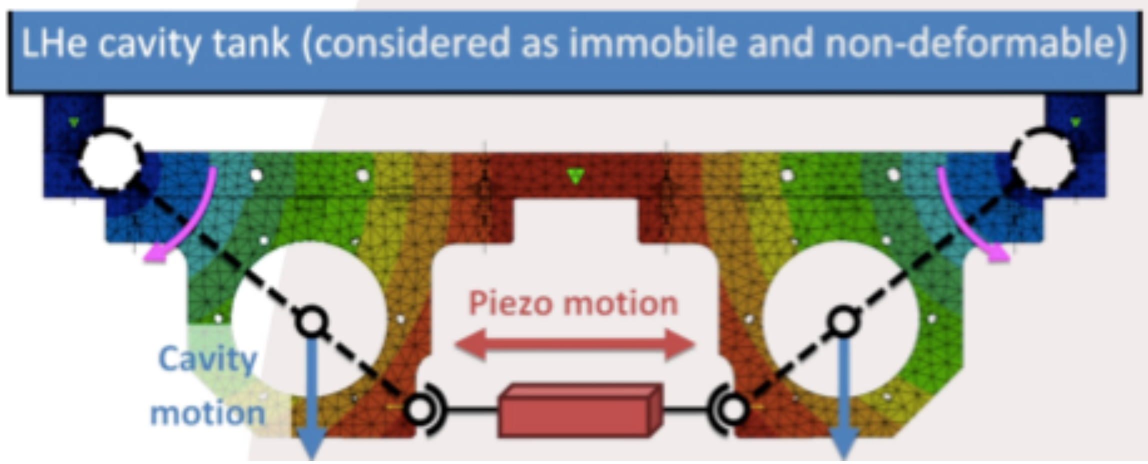
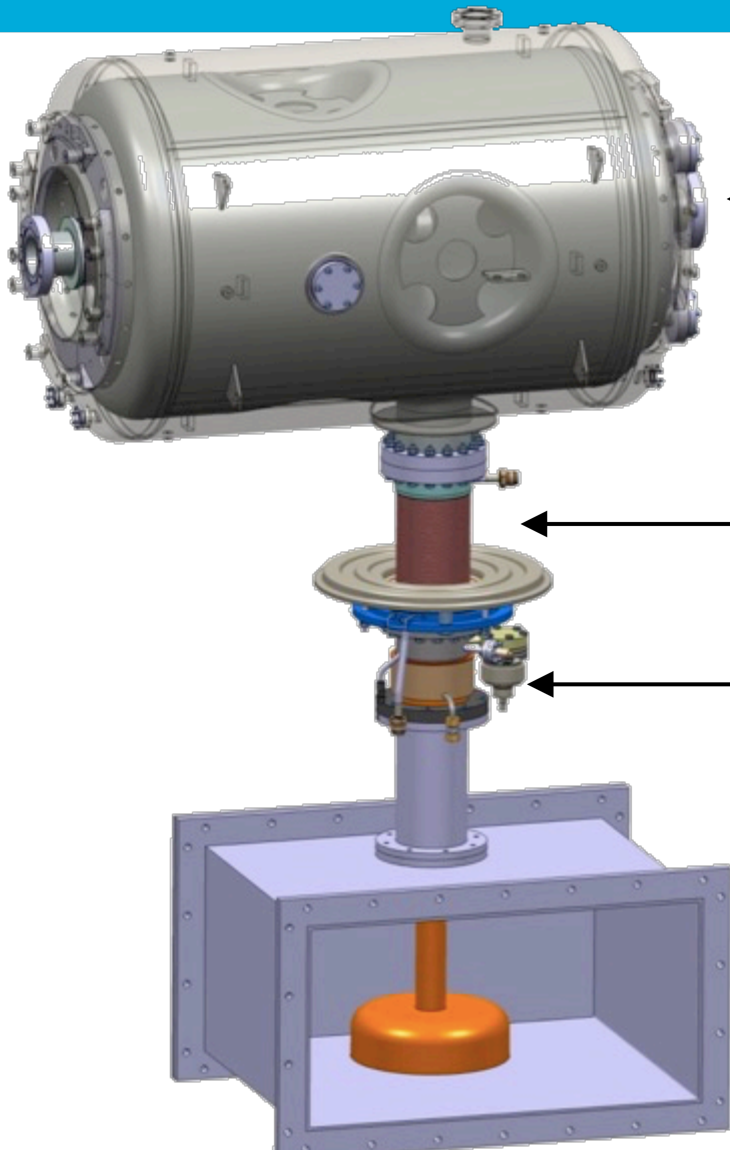


Cavity package



Double Spoke Cavity

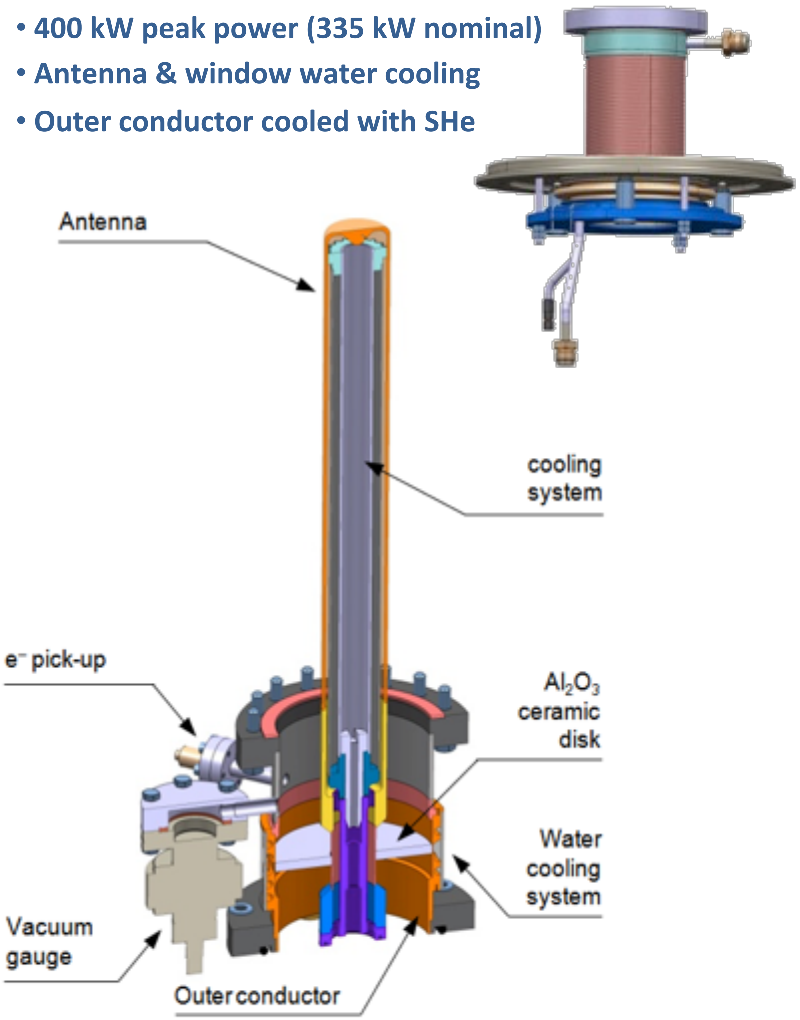
Heat exchanger necessary to make the transition from 300 K to 2 K
Integrating a mechanical system to compensate efforts

RF Power Coupler

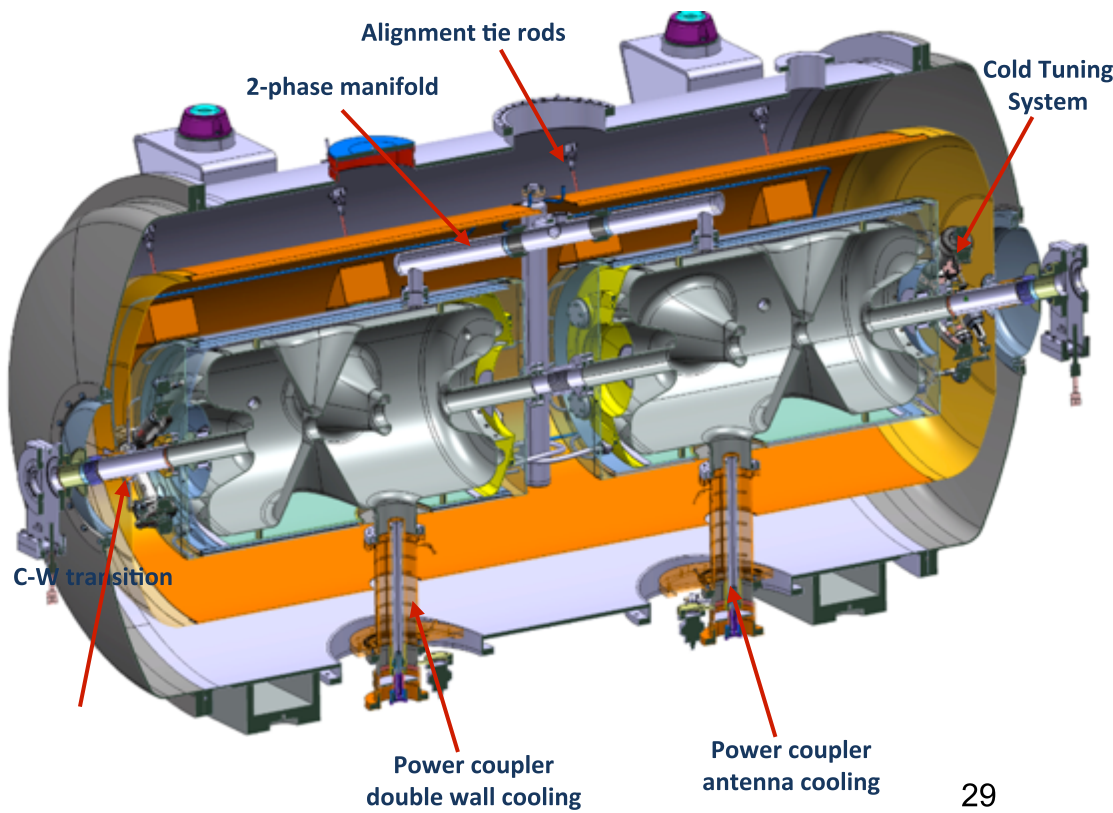
Doorknob – Transition between the coaxial power coupler and the WR2300 rectangular waveguide

The Spokes Cryomodule

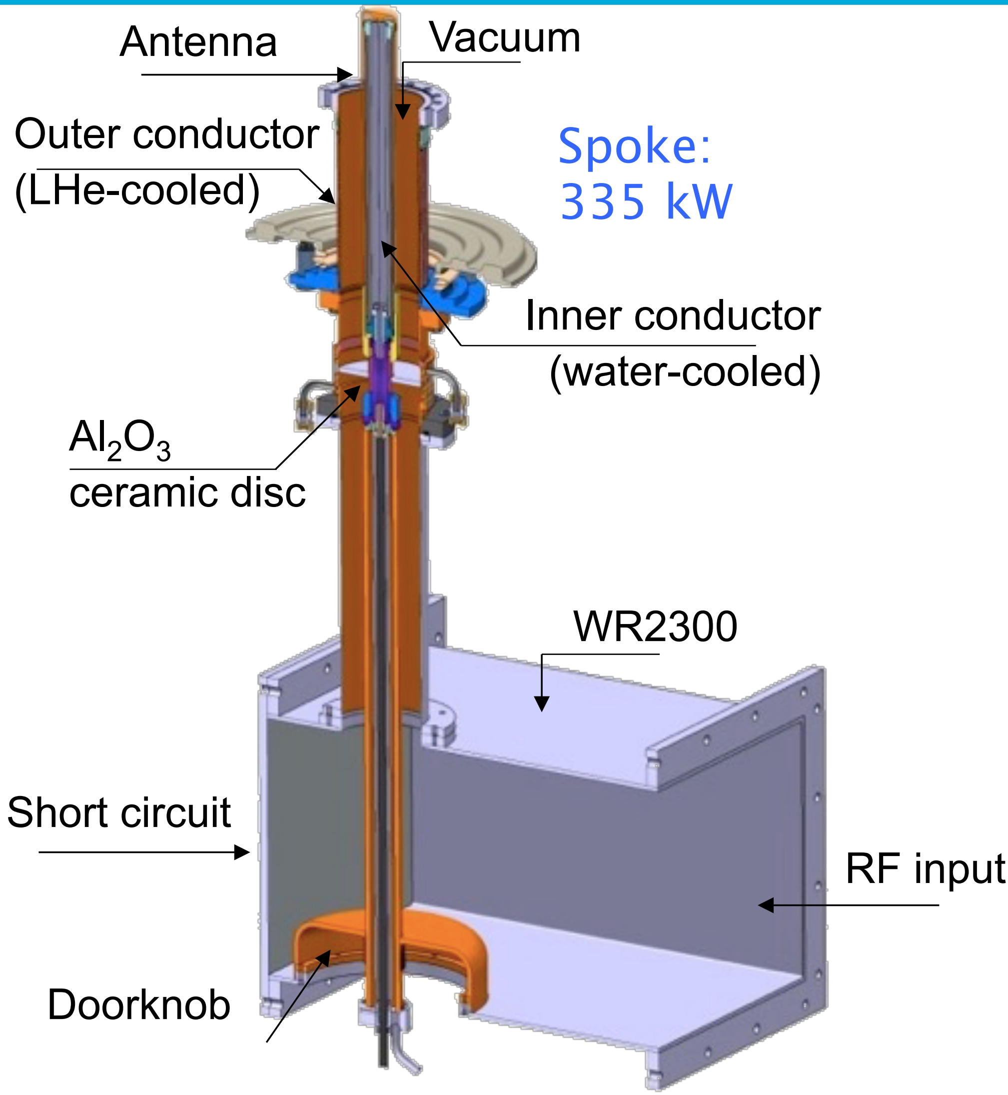
- Ceramic disk, 100 mm diameter
- 400 kW peak power (335 kW nominal)
- Antenna & window water cooling
- Outer conductor cooled with SHe

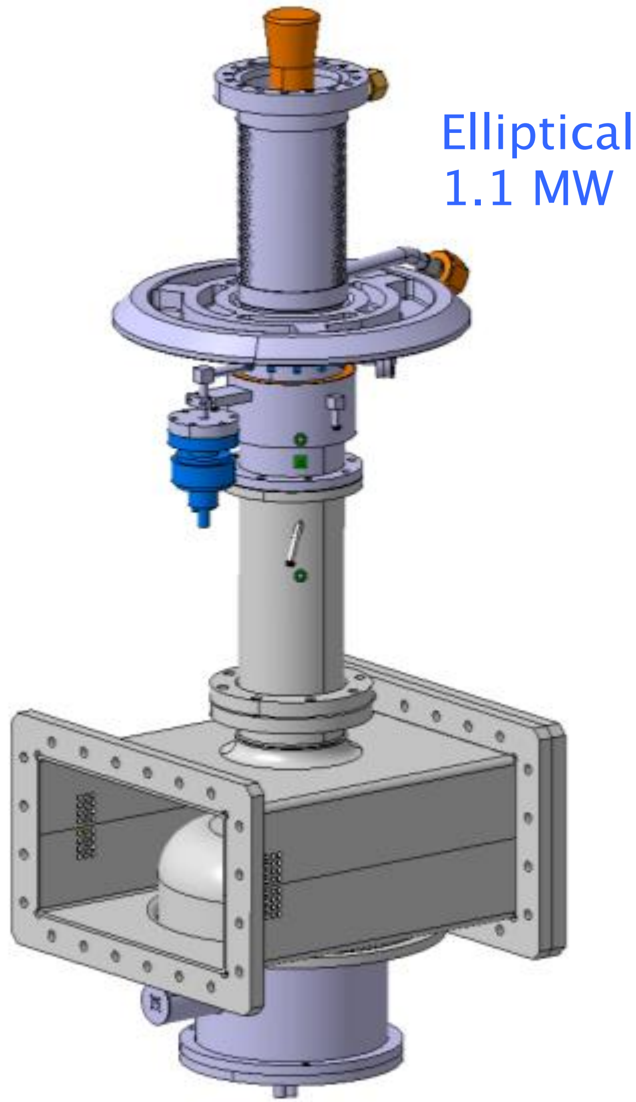


- Double spoke cavity (3-gaps), 352.2 MHz, β=0.50
- Goal: Eacc = 9 MV/m *[Bp= 62 mT ; Ep = 39 MV/m]*
- 4.2 mm (nominal) Niobium thickness
- Titanium Helium tank and stiffeners
- Lorentz detuning coeff. : ~-5.5 Hz/(MV/m)^2
- Tuning sentivity Δf/Δz = 130 kHz/mm



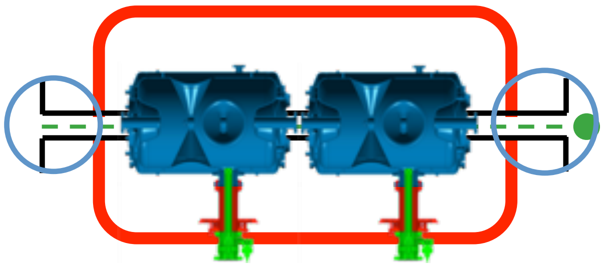
Fundamental Power Coupler



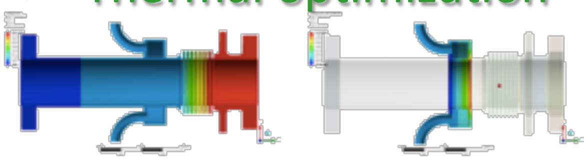


Other components (all are fabricated)

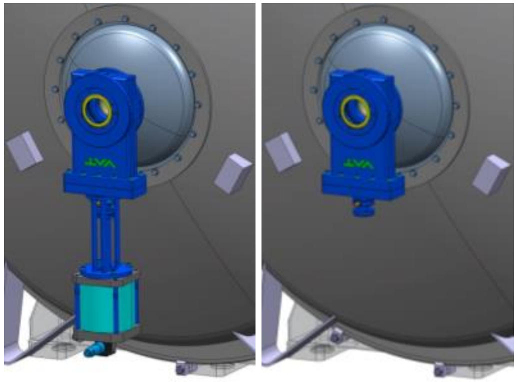
✓ Cold warm transitions



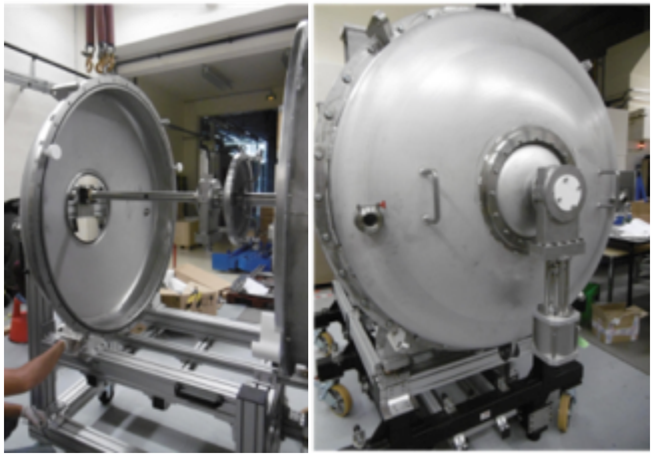
✓ Thermal optimization



✓ Gate valves



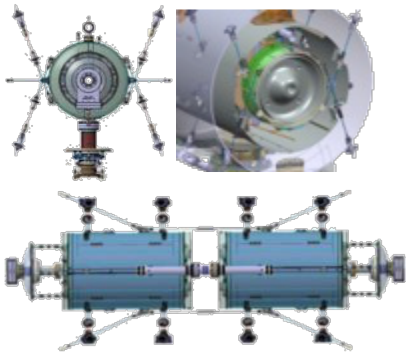
✓ Assembly tests



✓ Smaller/less parts inside the clean room

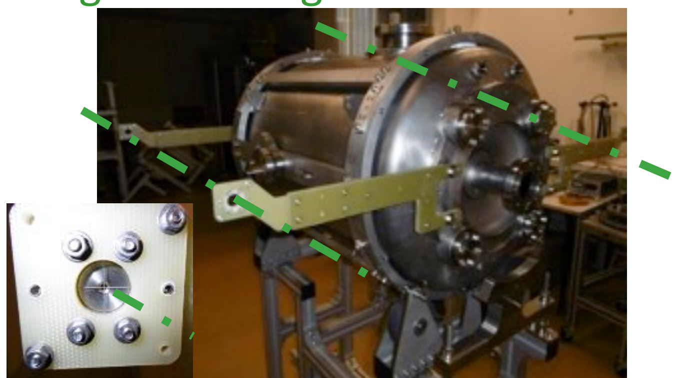
Other components (all are fabricated)

✓ Supporting system : rods based solution

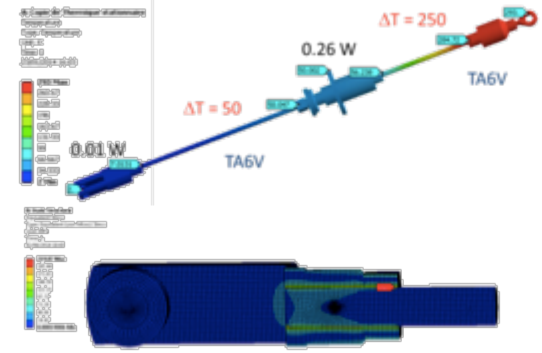


⇨ possibility of adjusting the alignment under vacuum and cryogenic working conditions

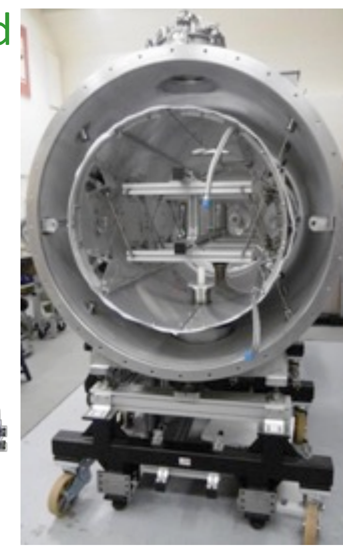
✓ Optical monitoring system for alignment diag. inside the cold CM



✓ Thermal and thermo-mechanical optimization

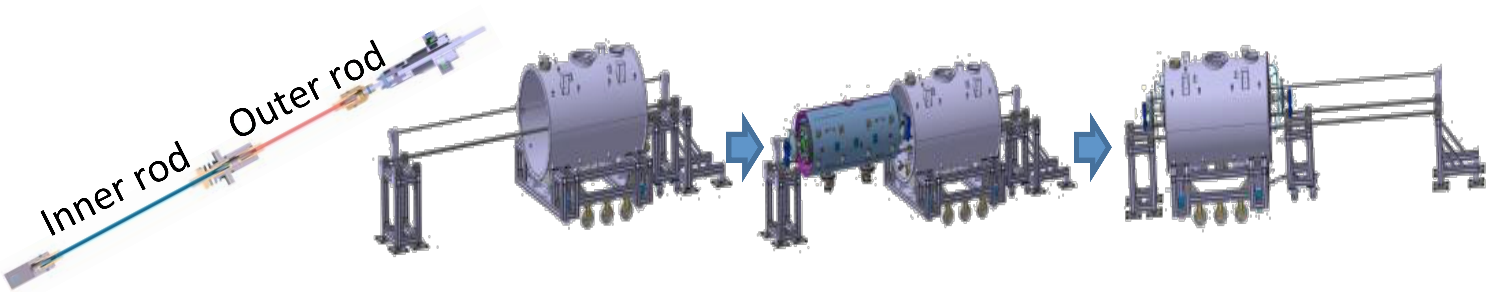


✓ Support rods fabricated
✓ Support tested



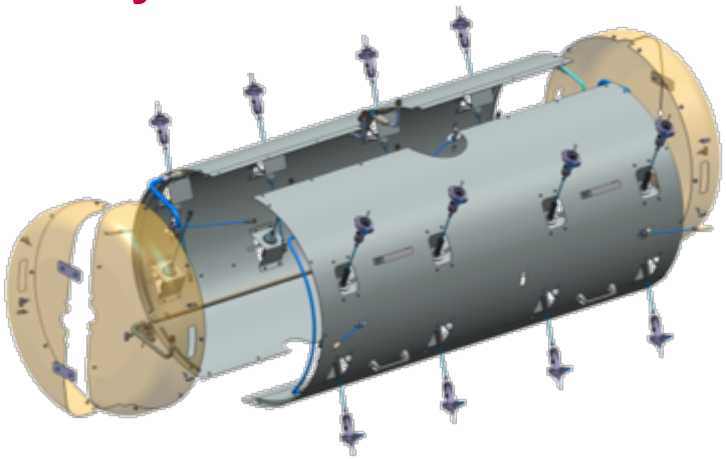
✓ Easier assembly (simpler tooling)

Rod made of two parts for easier cryostating

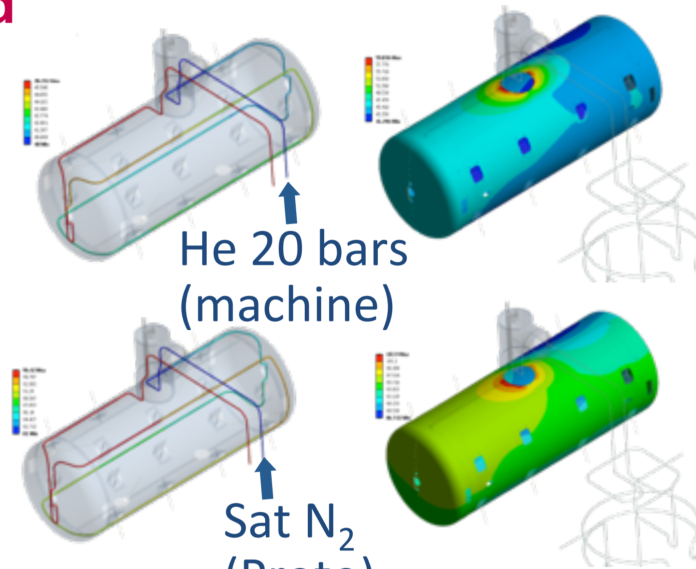


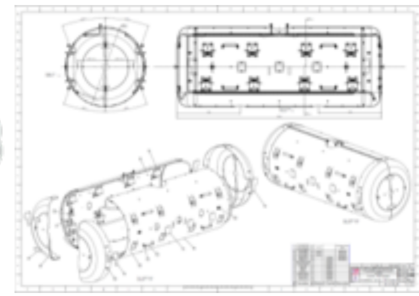
The Spoke cryomodule prototype

Cryomodule thermal shield

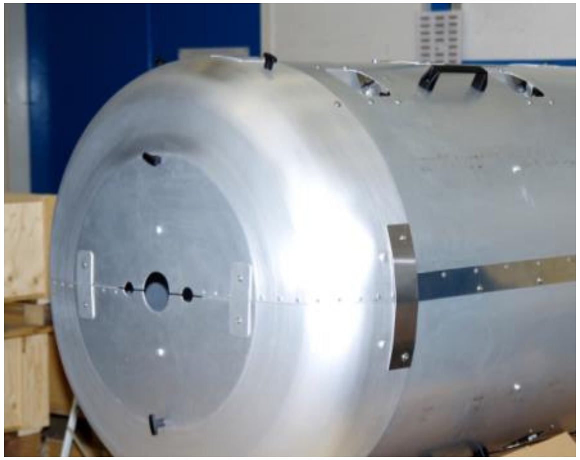


- ✓ Material: Al6062
- ✓ Thickness: 2 mm

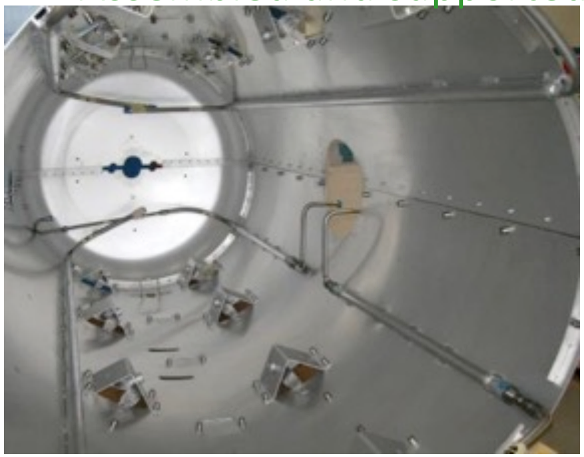




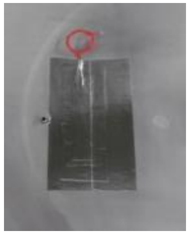
✓ Thermal shield fabricated



✓ Assembled and supported (rods)

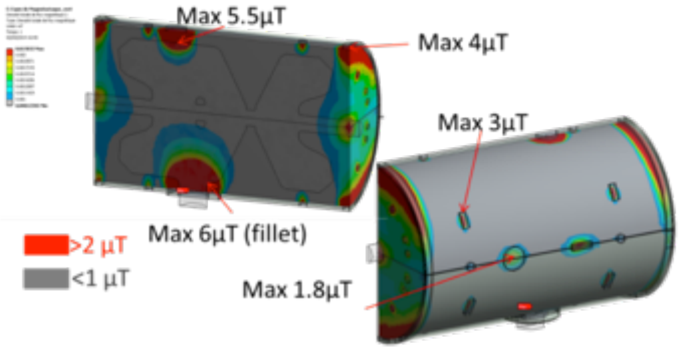


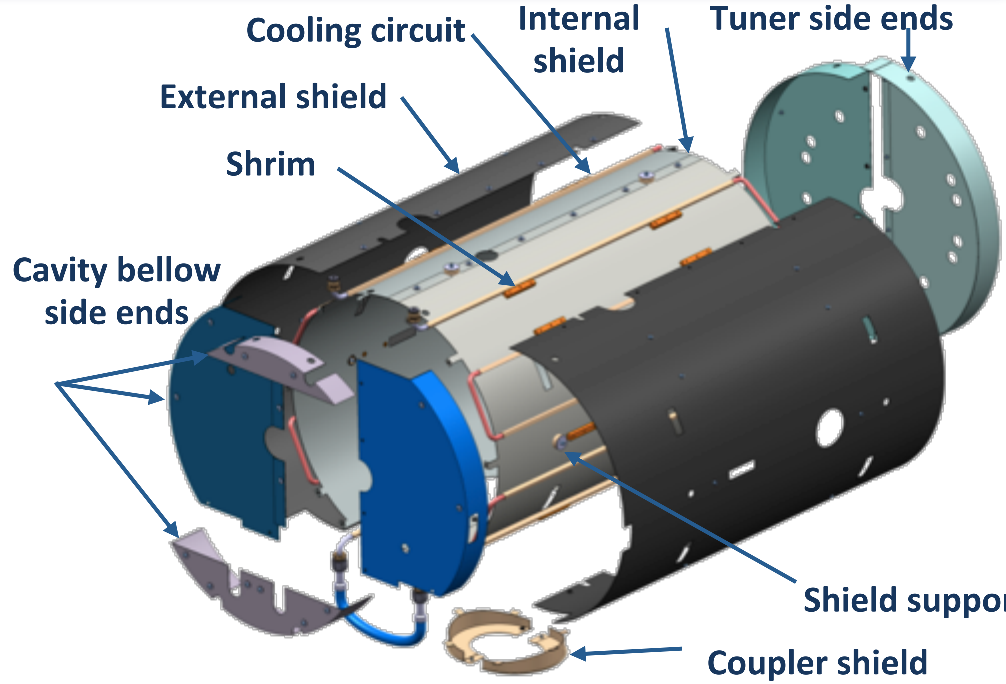
Instrum. and cool-down test



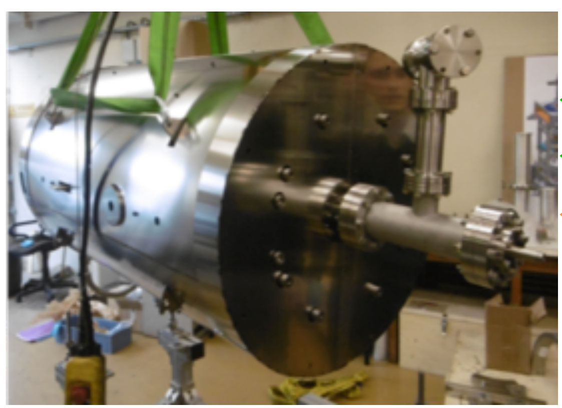
The Spoke cryomodule prototype

Cavities magnetic shield





- ✓ Material: Cryophy®
- ✓ Actively cooled (better performances)

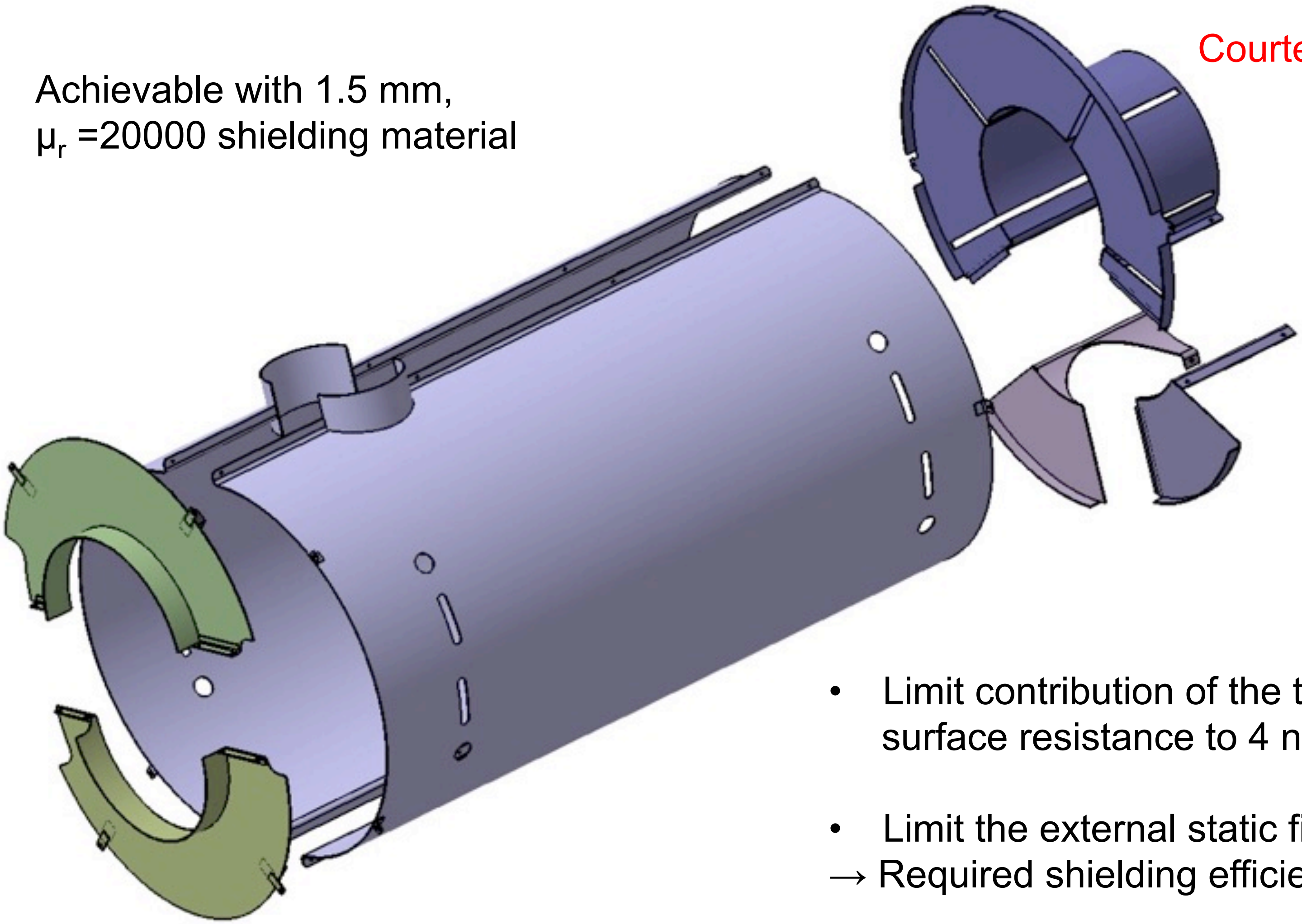


- ✓ Magnetic shields fabricated
- ✓ Assembly test performed
- ✓ To be tested within the cryomodule

Magnetic shield

Courtesy of J. Plouin/ CEA

Achievable with 1.5 mm,
μ_r =20000 shielding material

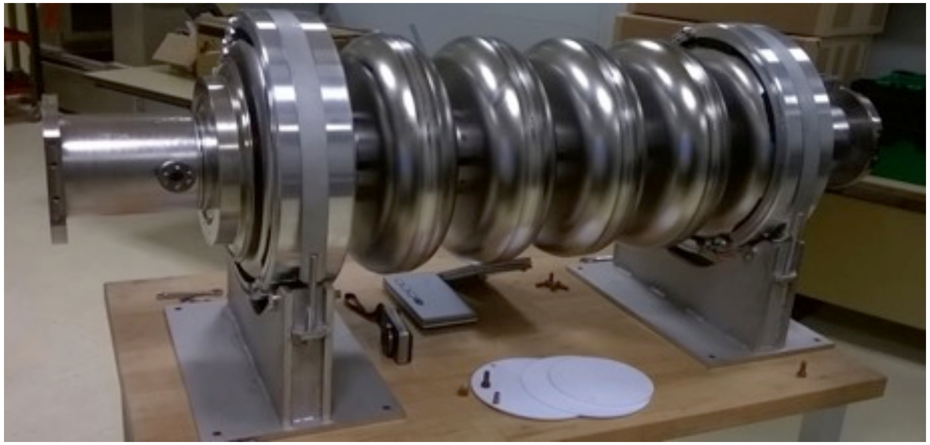


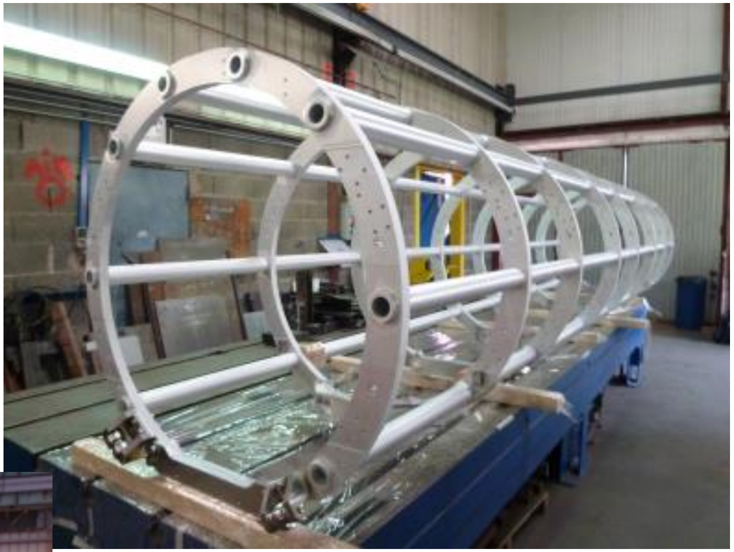
- Limit contribution of the trapped flux to the surface resistance to 4 nΩ

- Limit the external static field to Bext = 14 mG.

→ Required shielding efficiency equal to 35.

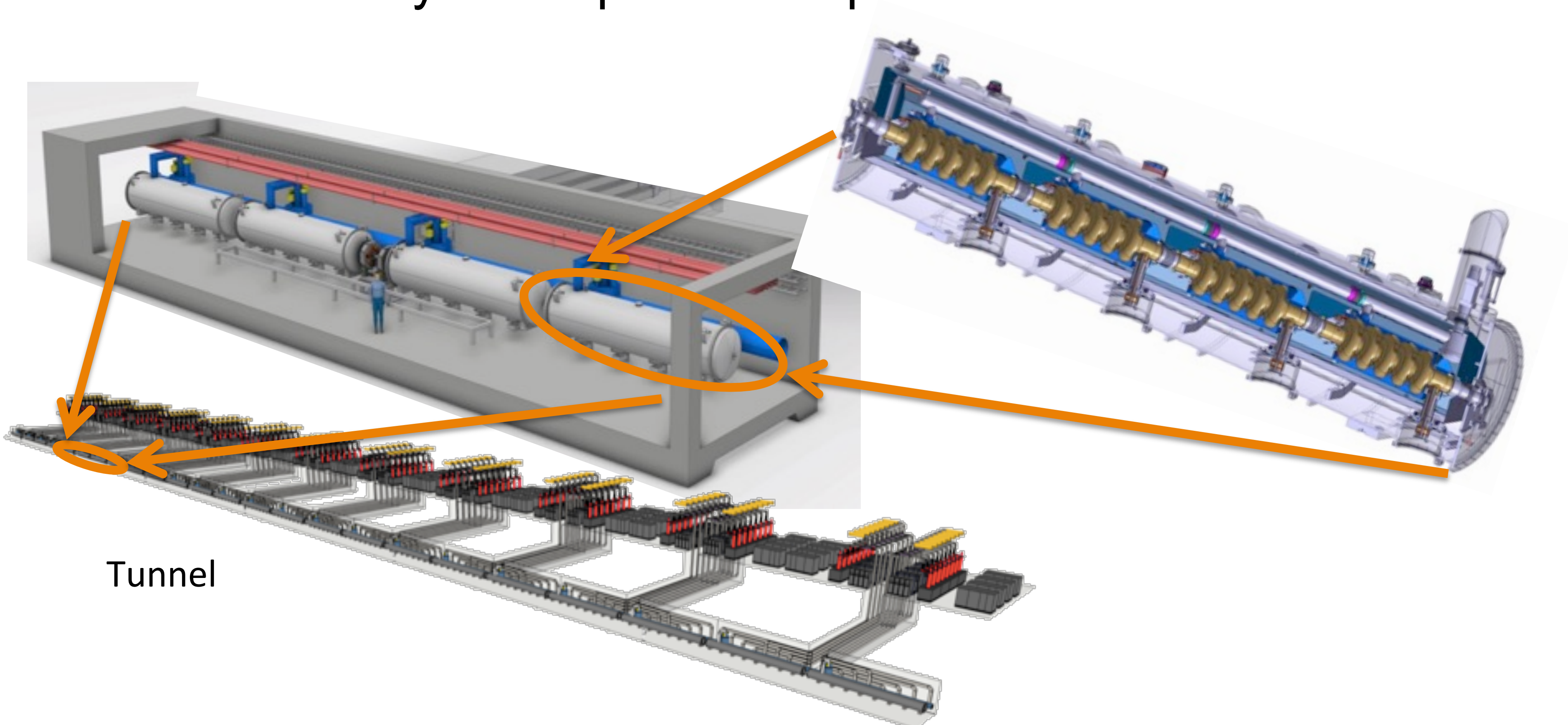
Elliptical Cryomodule



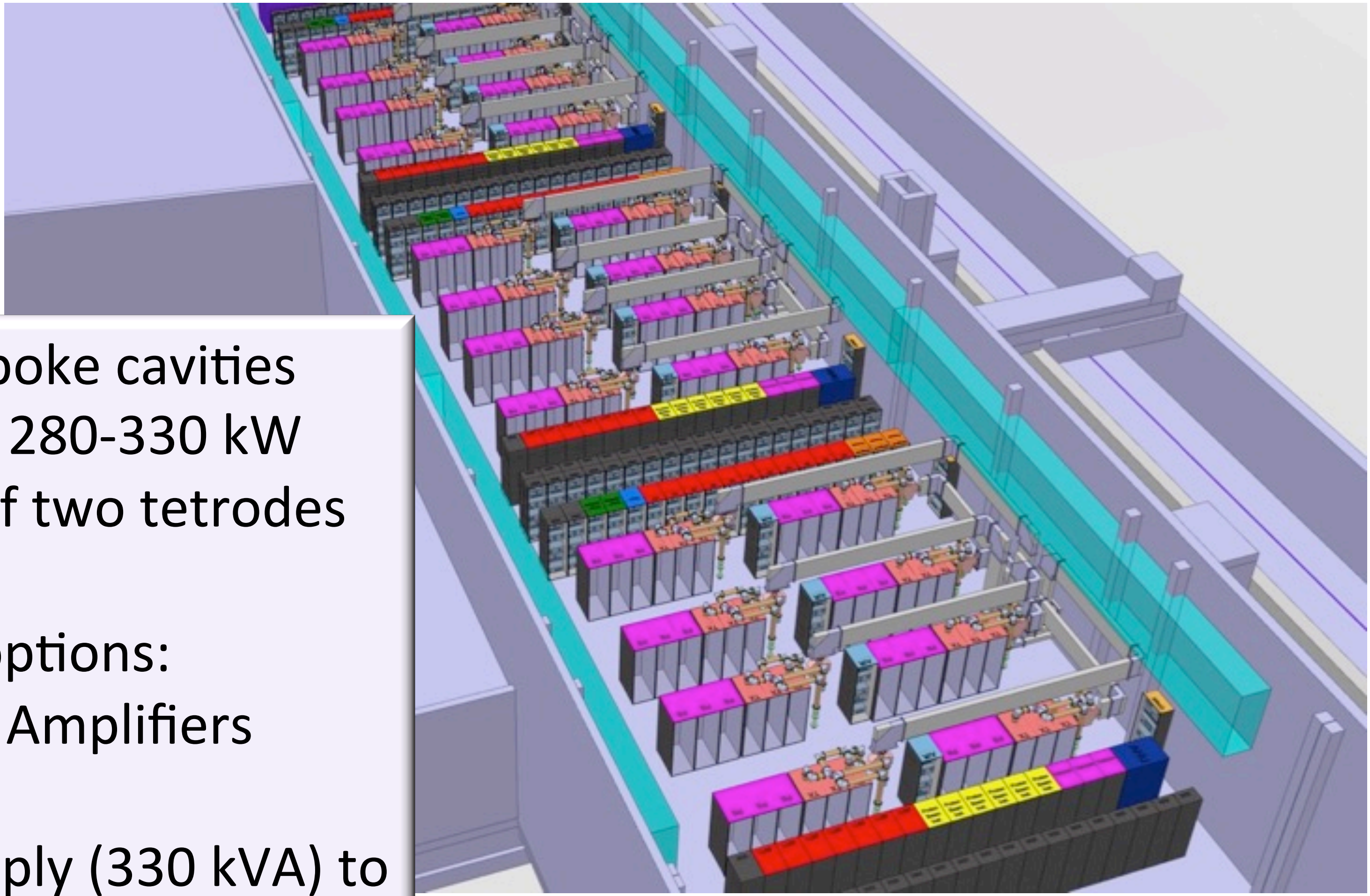


Elliptical (704 MHz) RF System Layout

- One cavity per klystron
- 4 klystrons per modulator
- 16 klystrons per tunnel penetration



Spoke linac (352 MHz) RF System Layout



26 Double Spoke cavities
Power range 280-330 kW
Combination of two tetrodes

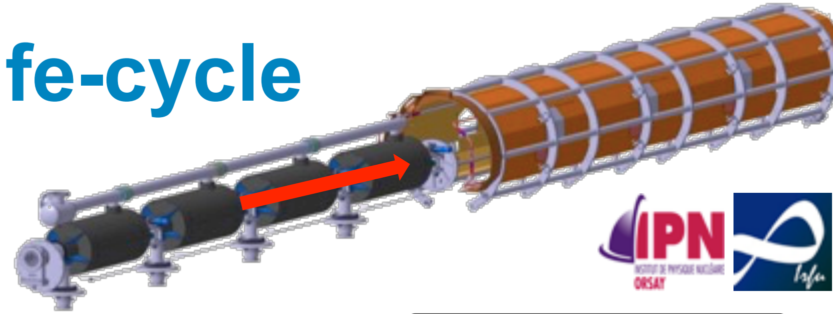
Other options:
Solid State Amplifiers

Large power supply (330 kVA) to supply 8 stations (16 tetrodes)

Outline

- Cryomodule characteristics
- Cryomodule components
- Cryomodule assembly
- How to operate a cryomodule

Cryomodule life-cycle



Cavity fabrication

Chemical treatment

High pressure rinsing
In clean room (ISO5 or ISO4)

Validation test of the cavity
in vertical cryostat

Qualified cavity storage

Processed couplers
storage

Coupler RF processing

Assembling in clean room

Power coupler
fabrication

Cryomodule
components
fabrication

Cavity string
assembling in
clean room

Cryomodule
assembling

Tools fabrication

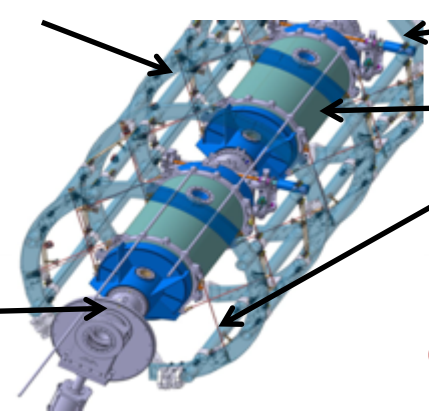
Transport

Cryomodule reception
and storage

Validation test of the
cryomodule

Cryomodule storage

Cryomodule on beam line



Courtesy of Pierre Bosland CEA/IRFU

Elliptical Cavity Preparation

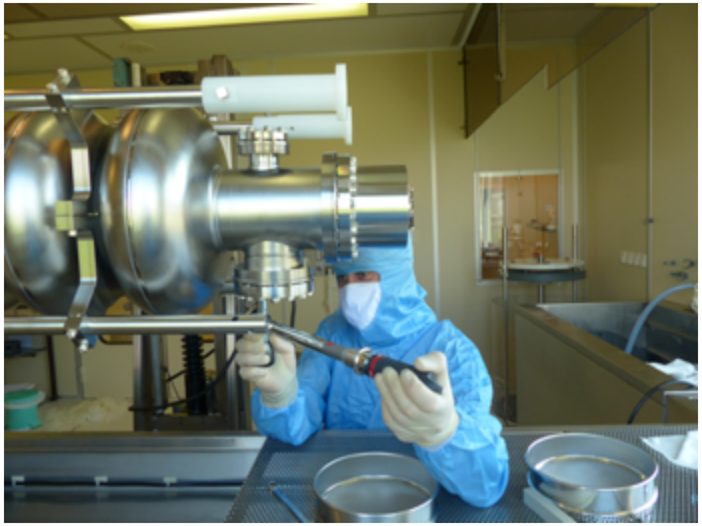
High beta cavity fabrication (Zanon and RI)

Study of the tooling in progress @ CEA

Example of the tooling for the assembling of the coupler on the cavity in clean room

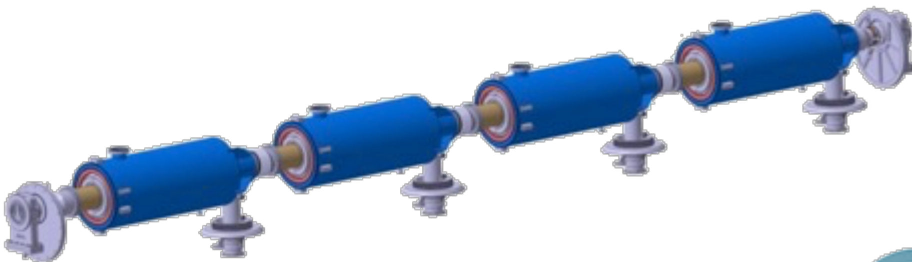
Vertical Electropolishing system@ CEA

High β Elliptical Cavity Activities in Clean Room



Elliptical Assembly Procedure

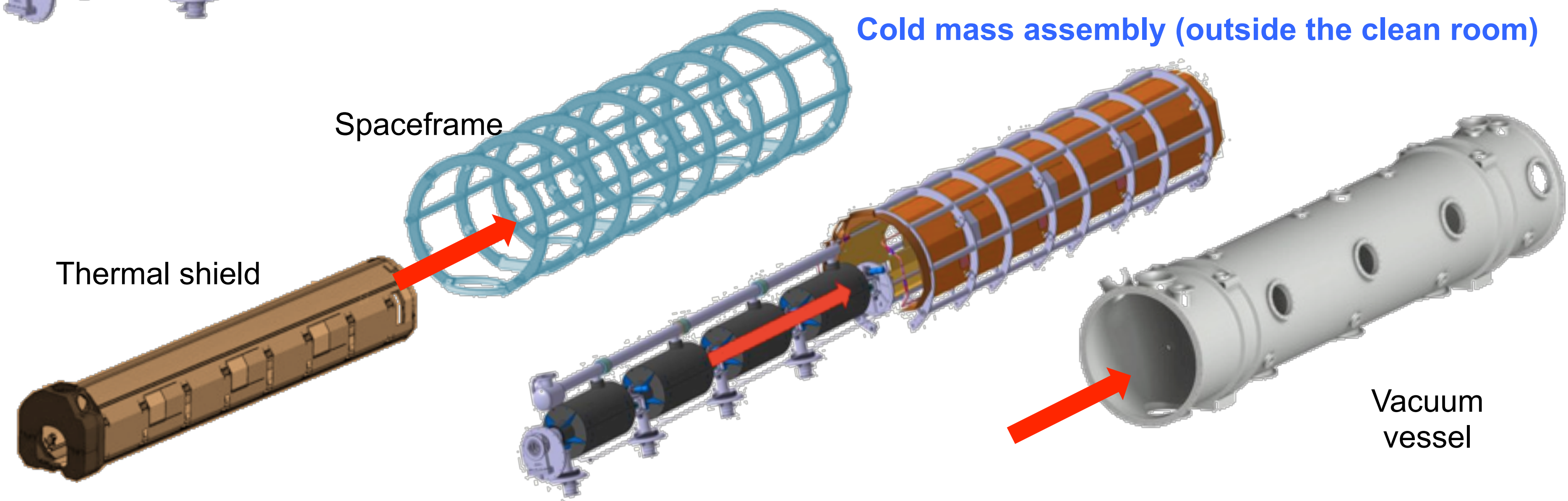
Cavity string assembly in clean room



Build on existing knowledge (SNS, XFEL)

- Develop Training and "Fabrication file"
- Pre-industrialization
- Industrialization

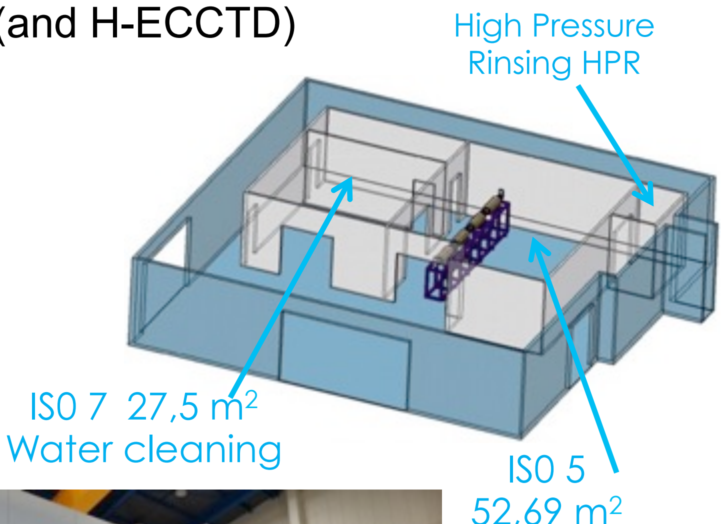
Cold mass assembly (outside the clean room)



Design concept of the tooling: most of parts will be used for both types of elliptical cryomodules

Infrastructure in Saclay

Clean room for the M-ECCTD (and H-ECCTD)

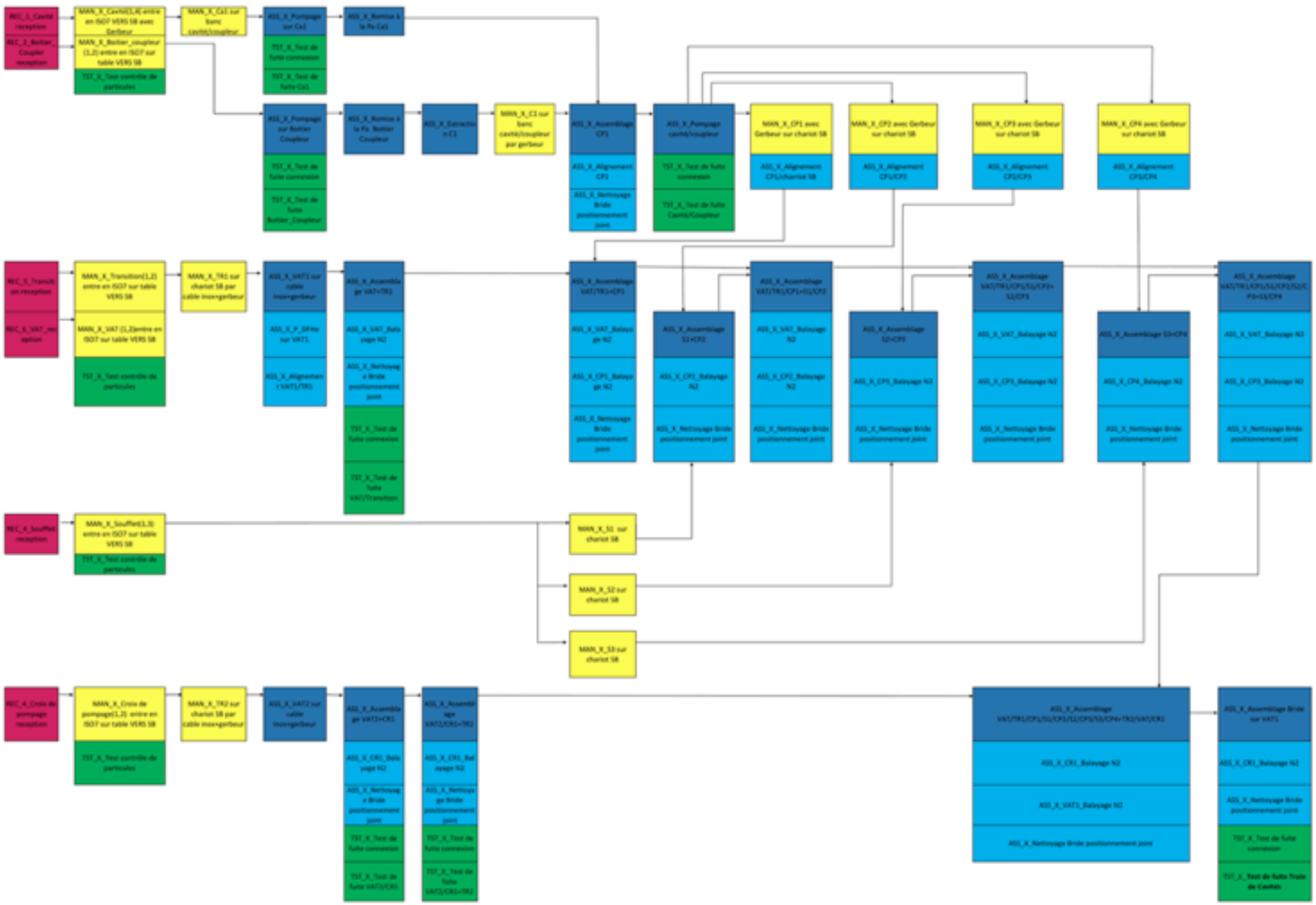


The clean room inauguration → May 13th 2014

Possible IKC for the assembly by industry at Saclay (XFEL cryomodules assembly)

- Uses the current infrastructure at Saclay
- Benefits from the experience of the XFEL cryomodule assembly (ALSYOM)

Assembly process inside the clean room



The bôth for the cryomodule assembly is almost ready

Assembly process outside the clean room

Sortie salle blanche

- Manutention train de cavité hors salle blanche 5001/6001
- transfert du train de cavité sur 6001
- Mise à niveau 5001 et 6001 par chandelles 6006 et pied carré 6001
- fixe chassis 6001 et chariot 5001

- Mesure laser tracker position des cavités

- Manutention train de cavité HALL 124 vers Bôth
- transfert du train de cavité sur remorque
- Soulève le chassis 6001 avec le palan
- Retrait des chandelles 6006
- Dépose sur remorque

Fixation du train de cavité au Spaceframe dans la Bôth

- Both: Mise à niveau chassis 6001 avec rail 6002

- Assemblage écran sur support écran 6002003
- Demi flan G
- Demi flan D
- MLI sur demi flan G et D

- Assemblage Spaceframe sur pied 6002012
- Place gabarit contrôle hauteur et coté 6002022*2 6002023*4

- Fixe l'écran sur Space frame
- Demonte 2 plaques 6002013
- Glisse le Space frame sur écran
- Fixe 16 équerres 6002020 et 6002021
- démonte 6002022, 6002023 et 6002003

- Réception train de cavité dans la Bôth
- Dépose 6001 sur 6002
- Mesure laser tracker contrôle transport/palan
- Caractérisation des bras de mires par rapport au référentiel de la Bôth

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- Soude les lignes dyphasiques
- Maintien ligne avec 6009

- Fixe 2 demi coquilles par cavités 0300003 0300004

- Fixe SAF
- Utilise outillage 6008
- Demonte équerres 0020001

- Fixe 4 demi anneaux par cavités
- Colle MLI sur tank hélium

- Fixe fût SAF sur 4 cavités
- 2 demi fond SAF 0300005 0300006
- 2 demi fût 0300001 et 0300002
- fond haut 0300007 et 2 colliers 0300008 0300009

- Ligne Cryogénique coupleur et cavité
- Soudure, bridage, et fixation des différents raccords et tubes

---

- Coulisse space frame sur train de cavité

- Place les tirants
- Visser dans les anneaux cavités
- Retire équerre 6002020 6002021

- Laser tracker contrainte liés aux tirants

- Ferme bas du Space frame

- Place outils reprise de charge 6003

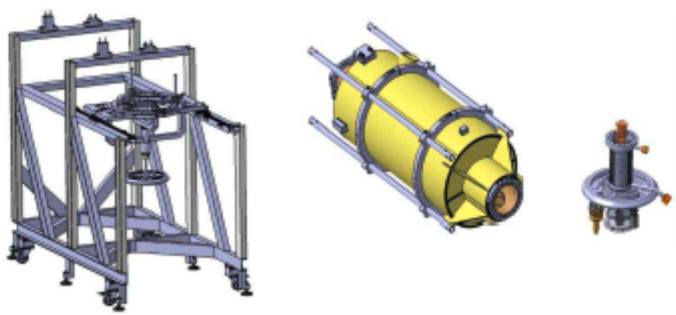
- Retire poteaux au milieu et sur les cotés et rigidificateur soufflet
- Laser tracker contrainte liés reprise de charge, rigidificateur

- Fixe longueur basse écran thermique
- Raccordement circuit hélium écran thermique
- fixe ligne de pompage des coupleurs

Example of assembling procedures in preparation

Irfu cea		
Assemblage banc cavité coupleur		

Procédure d'assemblage du coupleur sur la cavité



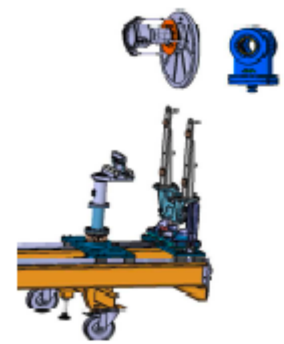
Cette Fiche d'Instructions définit les opérations d'alignement et d'assemblage d'une cavité avec son coupleur VAT1 sur la transition1.

Fiche d'Instructions Operationnelles					
	CEA				
	Rédigé par	Vérifié par	Autorisé par	Vérifié par	Approuvé par
Fonction					

Irfu cea		
Assemblage banc cavité coupleur		

Procédure d'assemblage de la vanne VAT 1 sur transition 1

Couverture 1



Cette Fiche d'Instructions définit les opérations d'alignement, d'assemblage et de test de fuite en ligne de la vanne VAT 1 sur la transition 1.

Fiche d'Instructions Operationnelles					
	CEA				
	Rédigé par	Vérifié par	Autorisé par	Vérifié par	Approuvé par
Fonction					

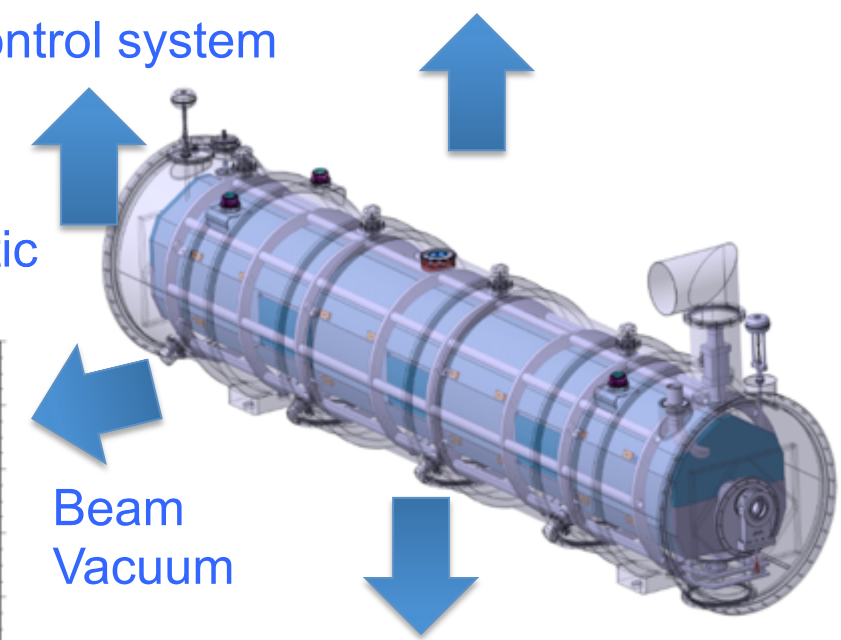
See the example of the coupler preparation in clean room for the RF processing: training with real components of geometry close to the final one

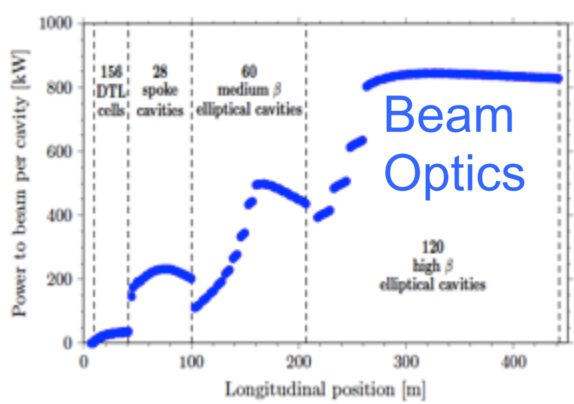
Outline

- Cryomodule characteristics
- Cryomodule components
- Cryomodule assembly
- How to operate a cryomodule

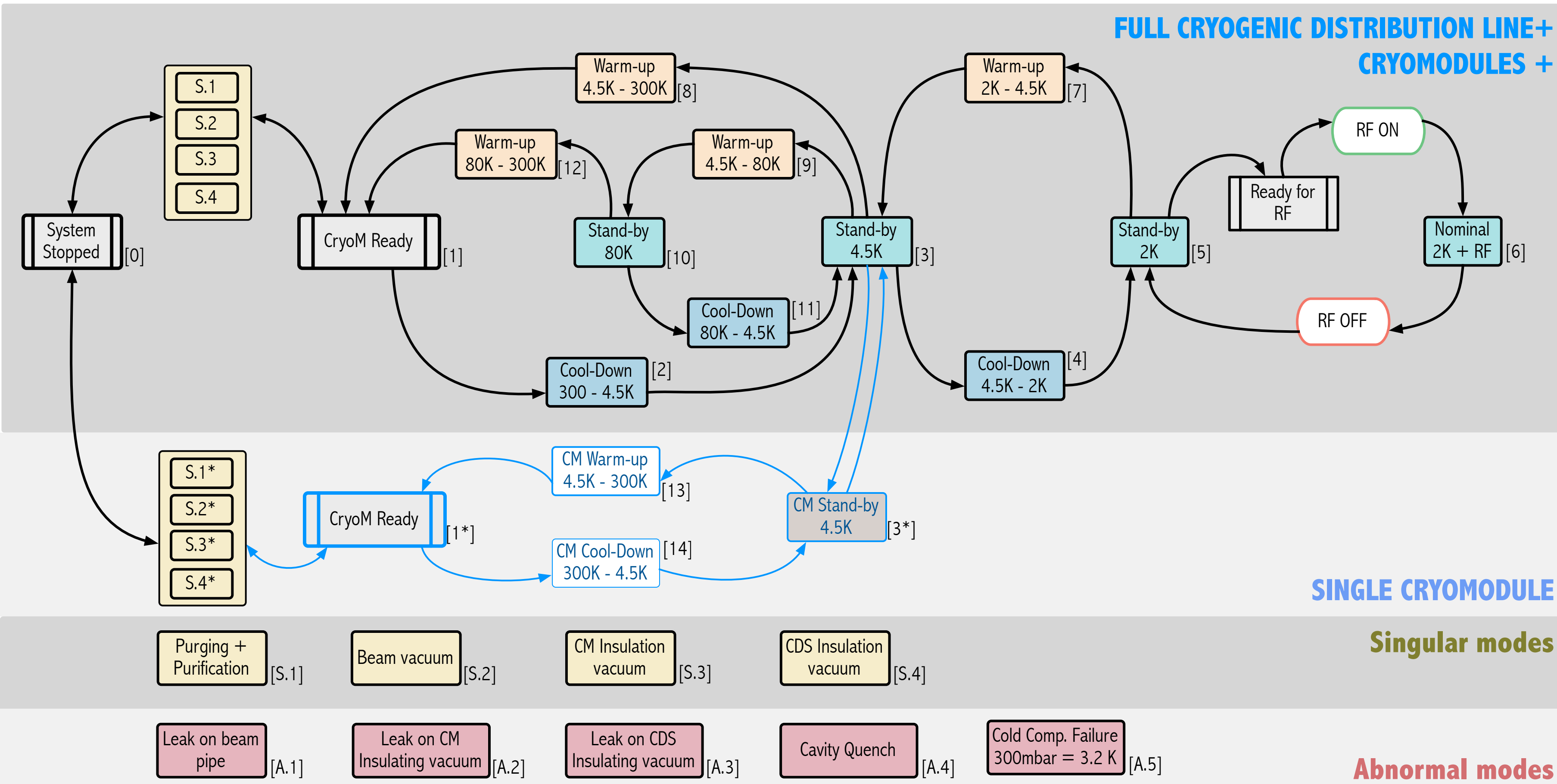
Cryomodule Interfaces

- Disciplines: beam optics, RF, cryogenics, vacuum, electrical, cooling
- Test stands
- Control command (Control Box, PLC, LLRF, MPS, EPICS)
- Quality Assurance
- Data-logging
- ES&H
- Conventional Facility
- Survey
- Logistics (Transport, storage)



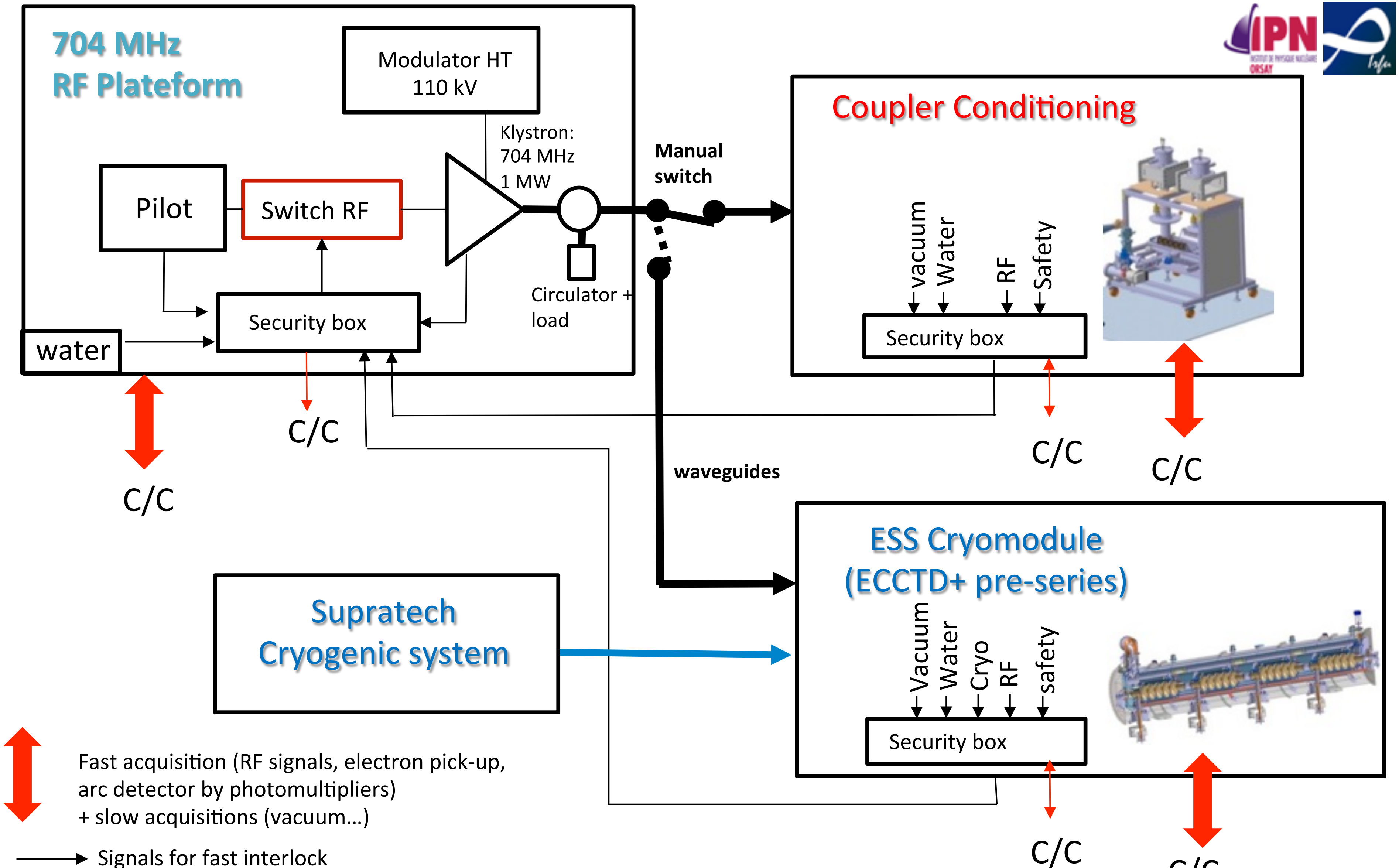


Cryogenic operating modes

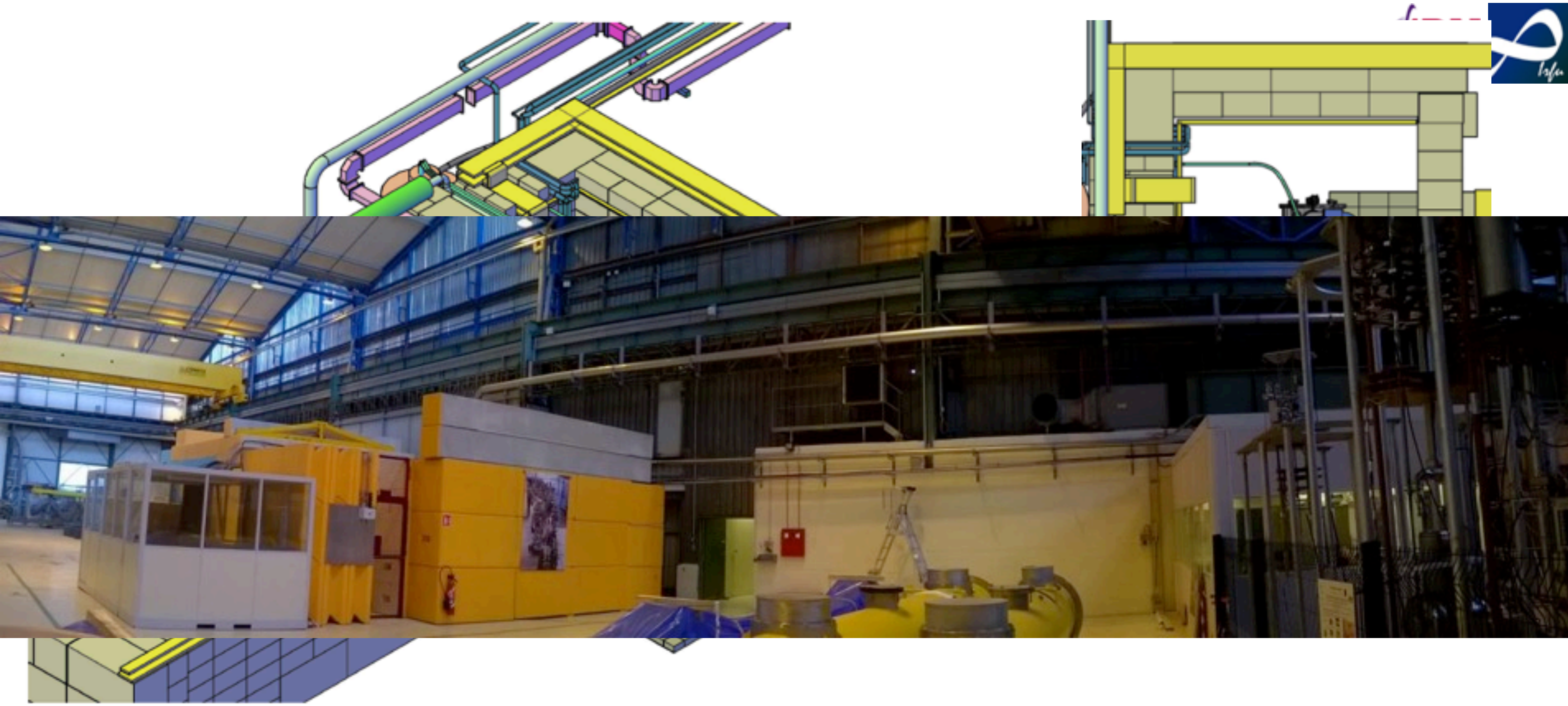


Acknowledgment : N Elias

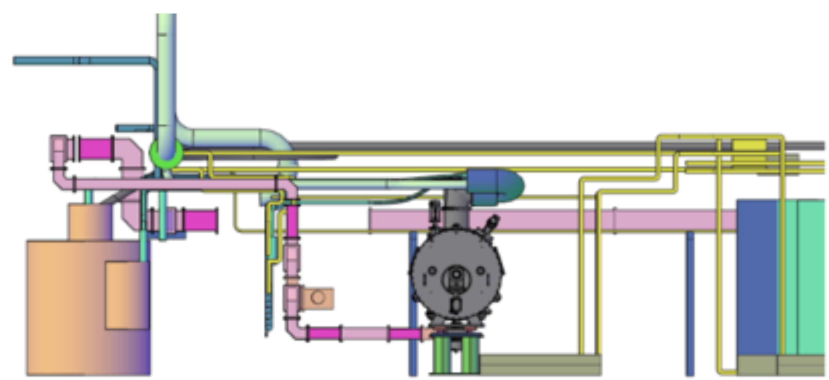
RF power test stations at CEA Saclay



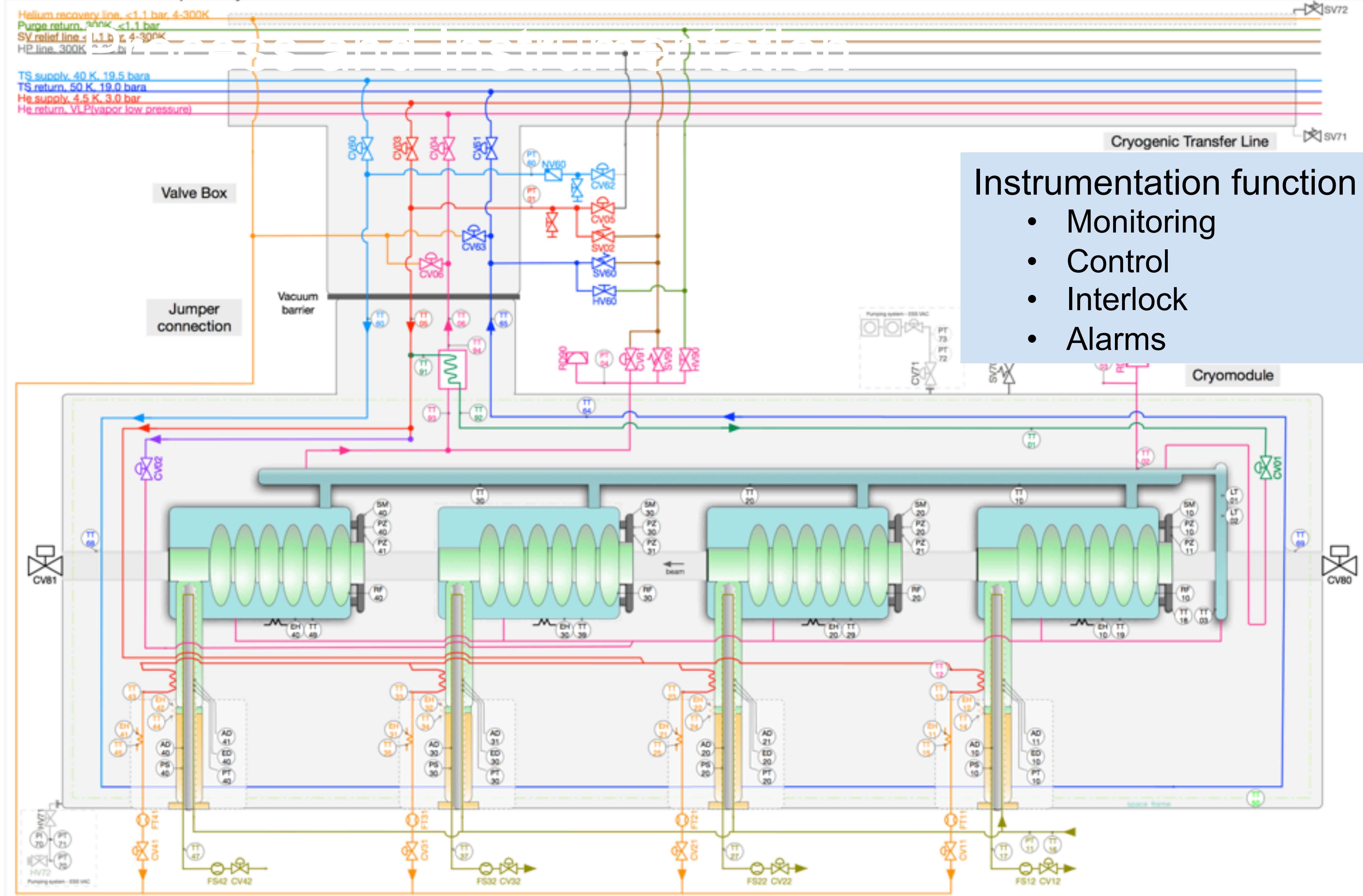
Tests station at Saclay



Parameters	ESS operation	ECCTD tests at CEA
Acc. gradient	16.7 and 19.9 MV/m	
Peak RF power	1.1 MW max	400 kW max
RF pulse length	2.86 ms	3 ms
RF pulse rate	14 Hz	16.7 Hz
Cavity cooling	LHe at 2K	
Coupler cooling	SHe at 4.5 K & 3 bara	GHe at about 4.64 K & 1.2 bara
Thermal shield temperature	GHe at 50 K & 19 bara	LN_2 at 77 K



SERIES Medium Beta Elliptical Cryomodule



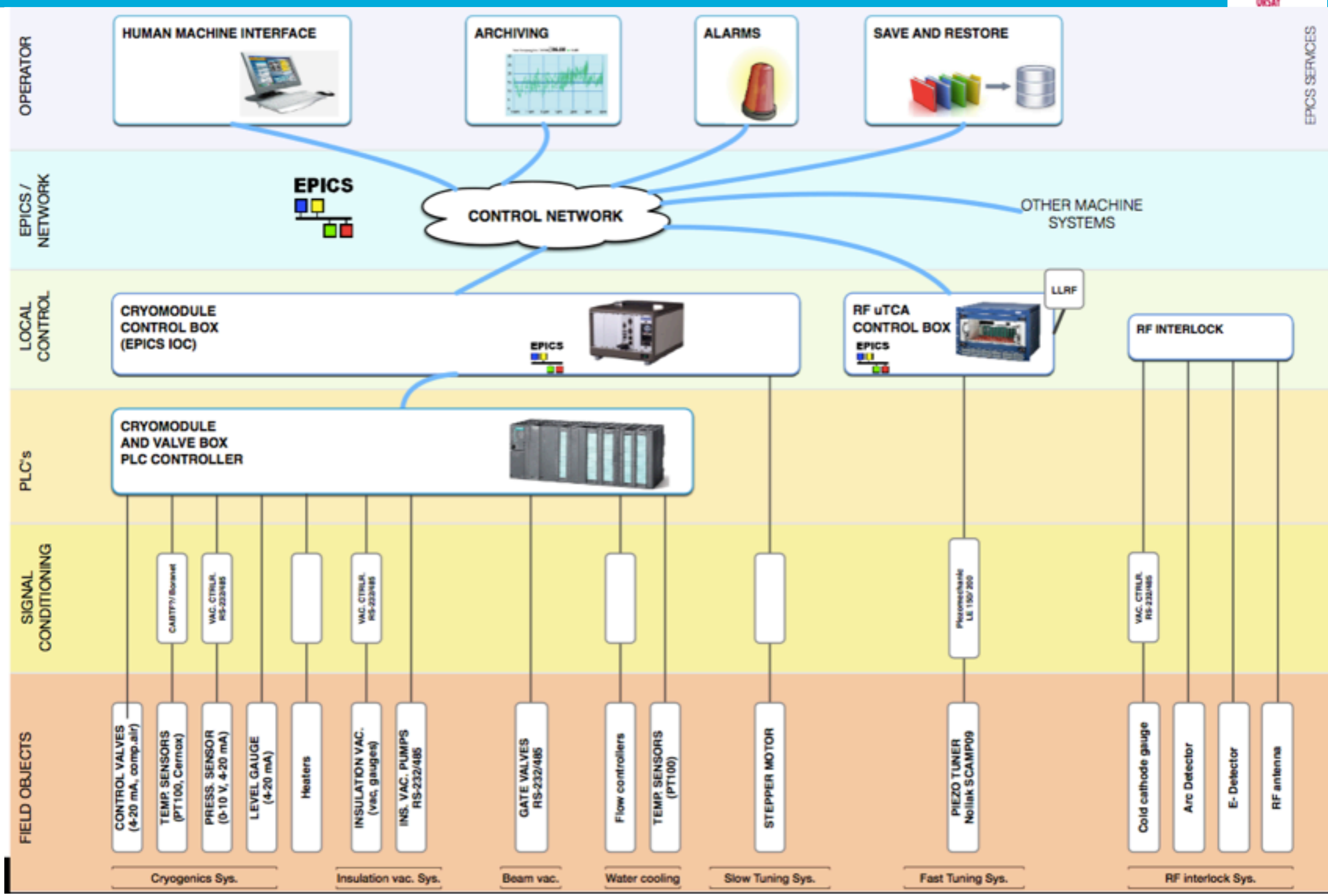
Instrumentation function

- Monitoring
- Control
- Interlock
- Alarms

Version 20151218 NE

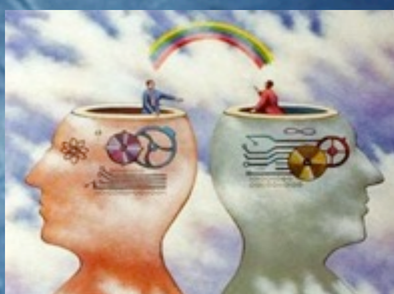
Control integration

EUROPEAN SPALLATION SOURCE



New Collaborations to Empower ?

Science institutions involved in the design & construction of ESS



Fractality and entanglement

Aarhus University
CEA Saclay, Paris
CNRS Orsay, Paris
ESS Bilbao
INFN, Catania
Lund University
Uppsala University
Accelerator Science and Technology Centre, Daresbury and Oxford
CERN, Geneva
Cockcroft Institute, Daresbury
DESY, Hamburg
ESS Bilbao
Fermi National Laboratory, Chicago

John Adams Institute for Accelerator Science, London and Oxford
Laval University, Canada
Maribor University, Slovenia
National Centre for Nuclear Research, Poland
Oslo University
Rostock University
Spallation Neutron Source, Oak Ridge
Stockholm University
Techical University of Darmstadt
Nuclear Physics Institute Of The Ascr
Czech Technical University, Prague
Aarhus University
University Of Copenhagen
University Of Southern Danmark
Technical University Of Danmark - Dtu
Institut Laue-Langevin - Ill
Llb (Laboratoire Léon Brillouin)
Helmholtz-Zentrum, Berlin
Helmholtz-Zentrum, Geesthacht
Technical University, Munich
Forschungszentrum, Jülich
Elettra-Sincrotrone Trieste
Università Di Perugia
Consiglio Nazionale Delle Ricerche
Delft University Of Technology
Institute For Energy Technology, Ife
Linköping University
Mid Sweden University
Epfl | École Polytechnique Fédérale De Lausanne
Paul Scherrer Institute, Psi