ESS Cryomodules

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

ESS Engineering Lecture

Lund University
September 14, 2017

Outline

- Cryomodule Functions
- Cryomodule Components
- Cryomodule Assembly
- How to operate a cryomodule

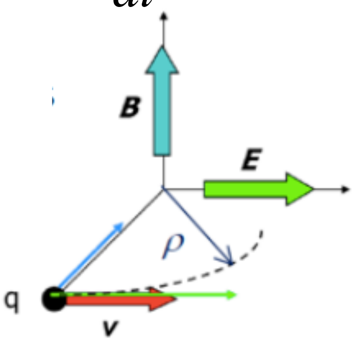
Main function: to house SRF cavities

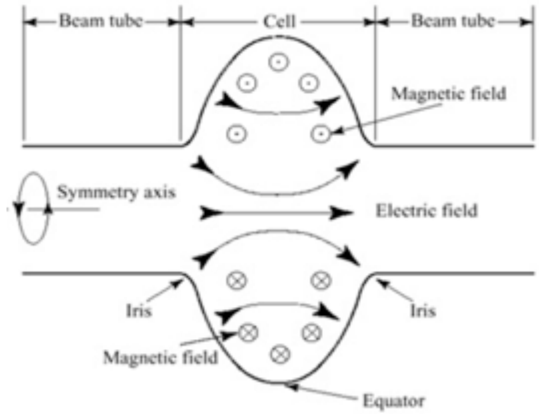
Lorentz Force

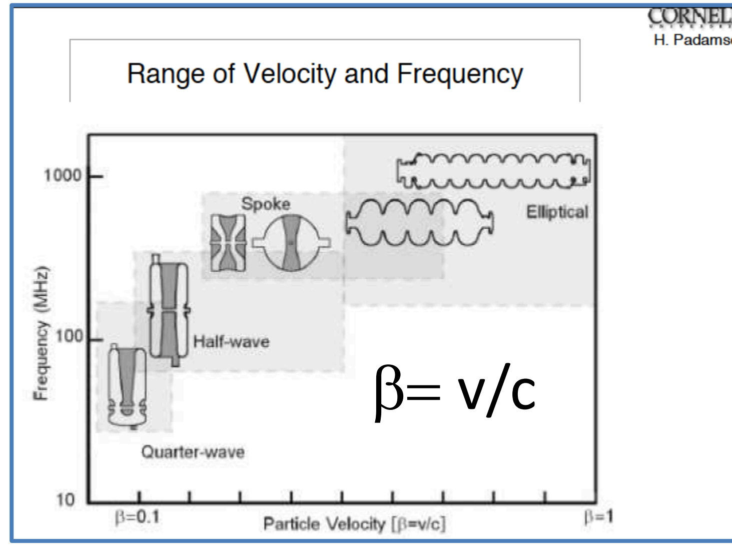
→ Electrical Field

→ Magnetic Field

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

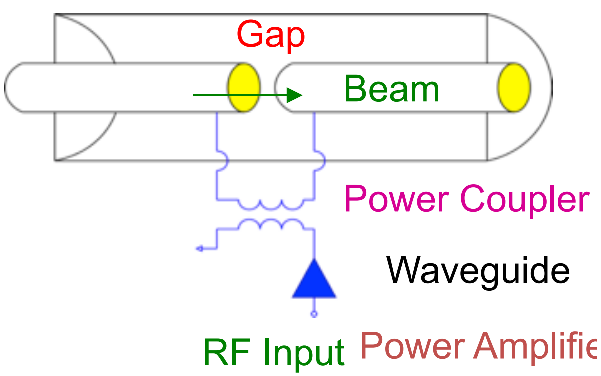


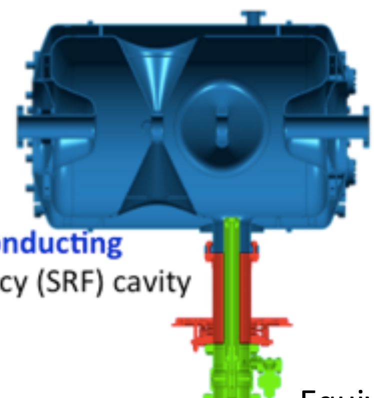




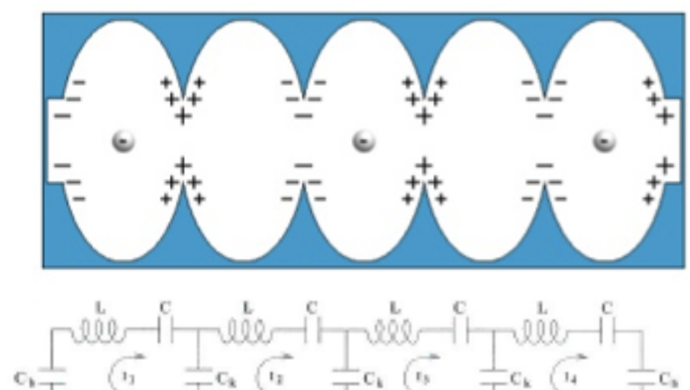
→ Low β – Spoke cavity

→ High β – Elliptical cavity



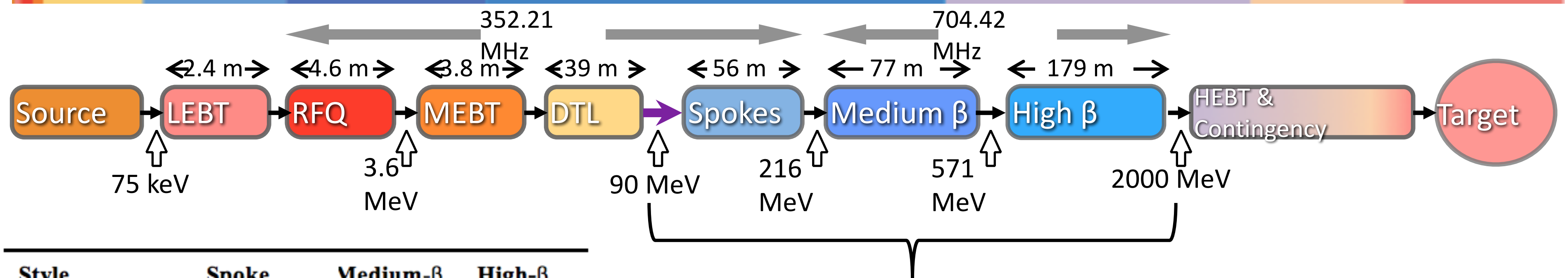


Superconducting radiofrequency (SRF) cavity

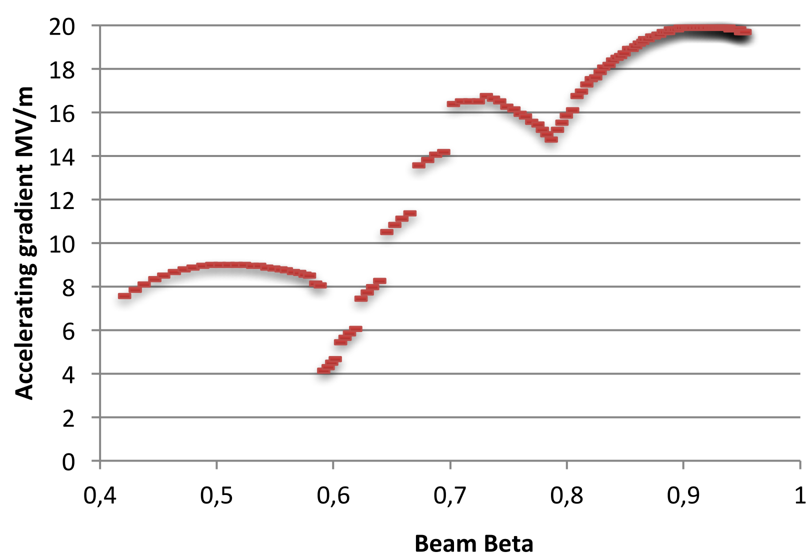


Equivalent circuit for a 4 cell cavity with beam pipe

ESS Linear Accelerator 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



➔ ESS needs high gradient SRF cavities

ESS Requirements and RF Parameters

EUROPEAN SPALLATION SOURCE

Spoke cavities

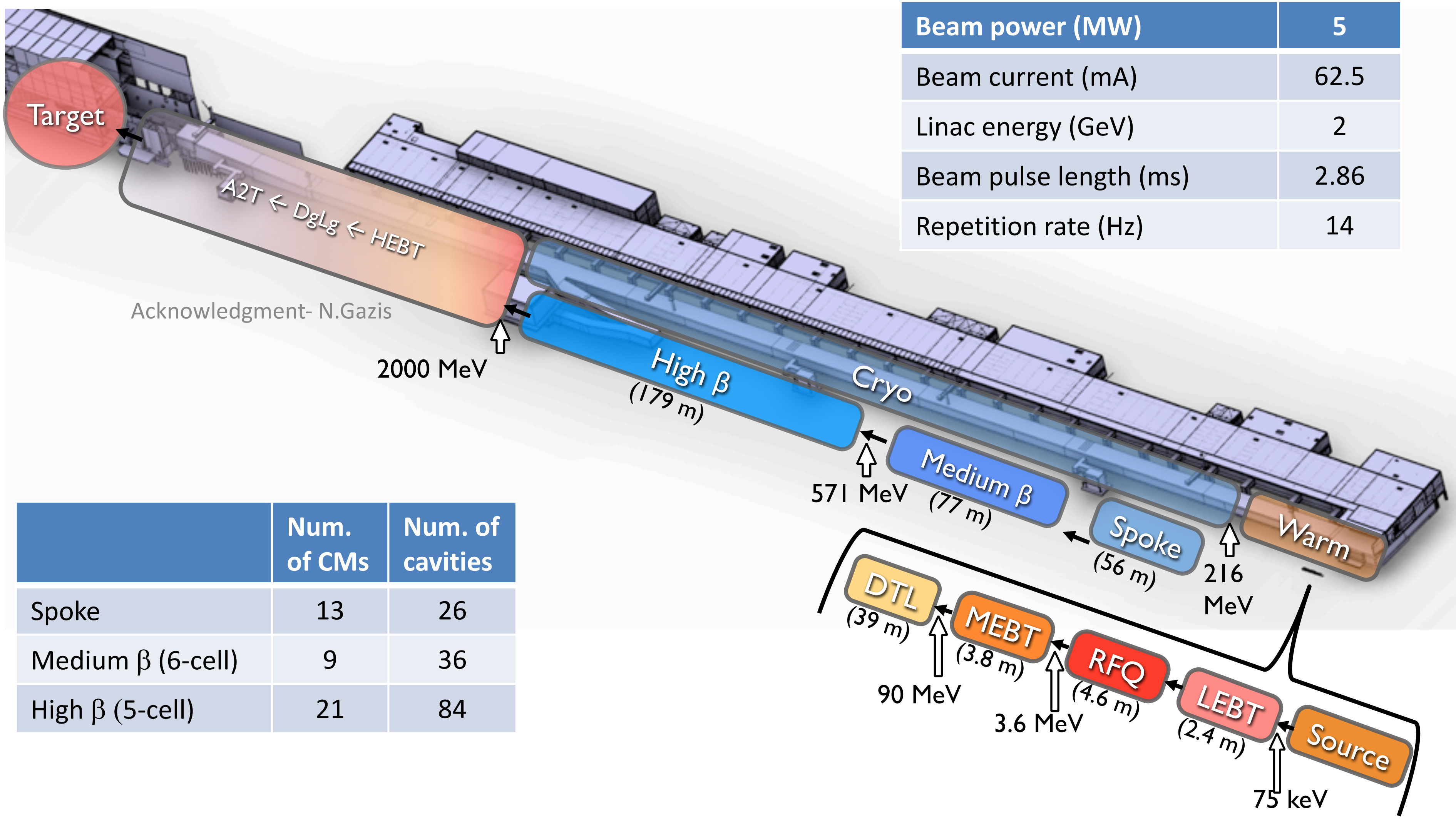
Geometric beta	0,50
Frequency (MHz)	352,2
Nominal Accelerating gradient (MV/m)	9
Lacc (βopt.x nb gaps x λ/2) (m)	0,639
Bpk (mT)	79 (max)
Epk (MV/m)	39 (max)
Bpk/Eacc (mT/MV/m)	<8,75
Epk/Eacc	<4,38
Beam tube diameter (mm)	50
RF peak power (kW)	335
G (Ω)	130
Max R/Q (W)	427
Qext	$2{,}85\ 10^5$
Q0 at nominal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

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

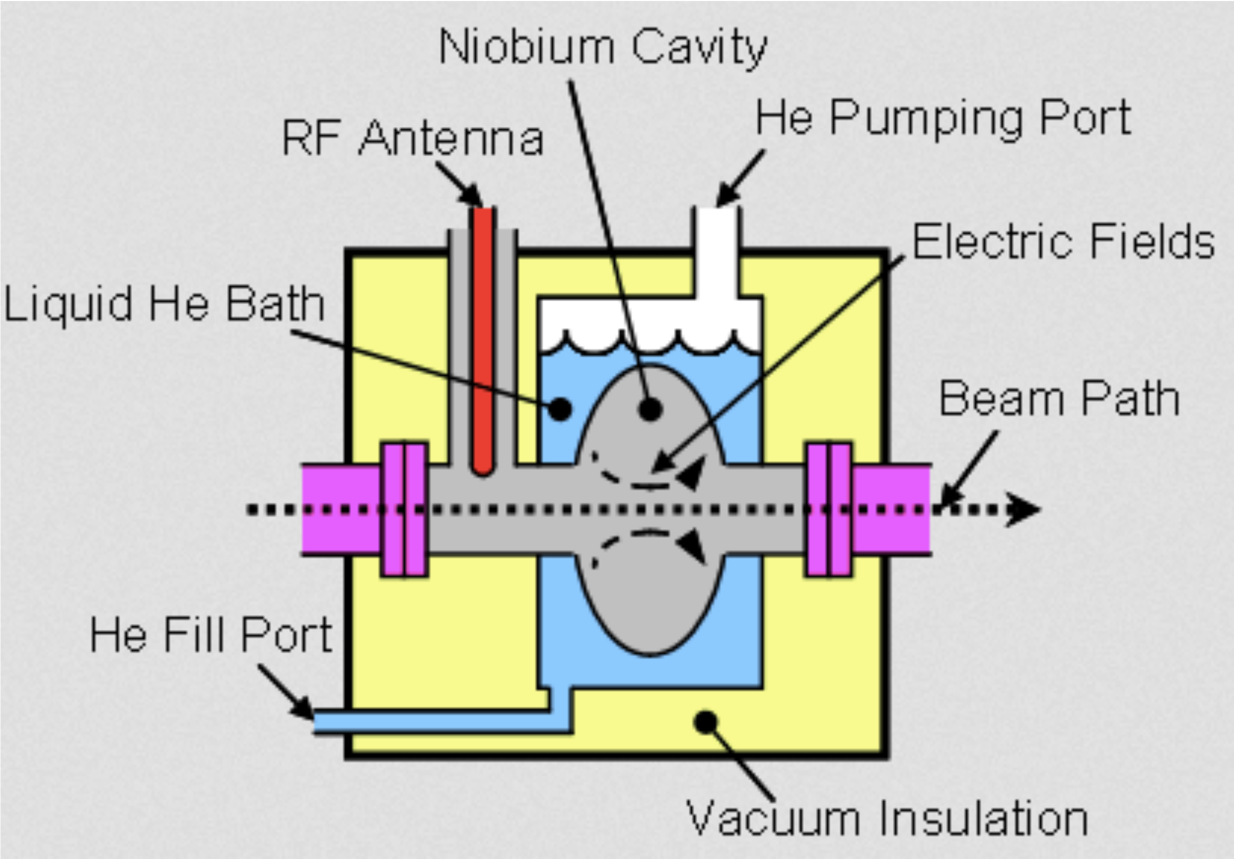


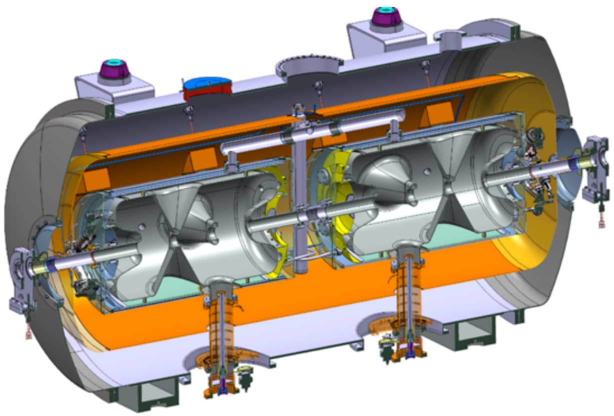
	Num. of CMs	Num. of cavities
Spoke	13	26
Medium β (6-cell)	9	36
High β (5-cell)	21	84

Cryomodules Function

A Cryomodule permits to operate SRF cavities in a cryogenics atmosphere.

For ESS, the Spoke and Elliptical cavities operate in a saturated superfluid helium bath





Environment - Superfluidity Helium

and Supraconductivity (see Steve Molloy's presentation)

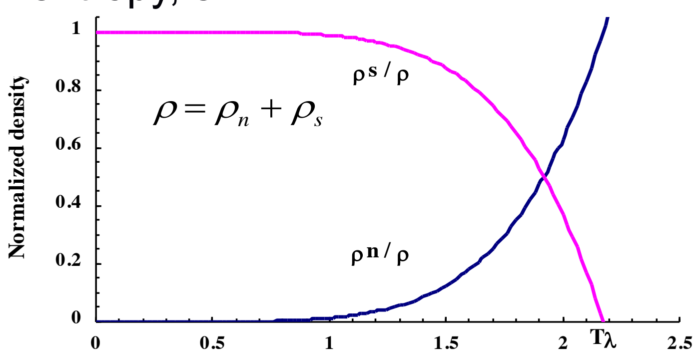
- Helium (25 %) is the most common element in Universe after Hydrogen (73 %)
- Two isotopes: ^3He (fermion) & ^4He (boson)

Normal-fluid fraction:

- excited states atom (phonons & rotons)

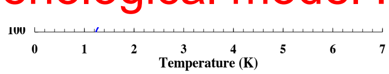
➔ like a conventional viscous fluid

- finite density , r_n
- finite viscosity, η
- entropy, *s*



Macroscopic quantum physic system simplification

The two-fluid model is only a phenomenological model !



Superfluid fraction:

- atoms that have undergone BEC

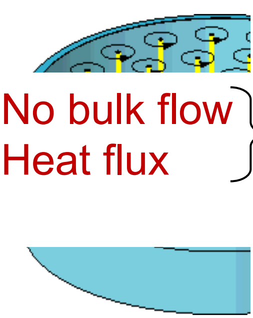
➔ like an ideal inviscid liquid resulting in the absence of classical turbulence.

- finite density, r_s
- NO viscosity
- carry NO entropy

→ irrotational behavior for an inviscid fluid

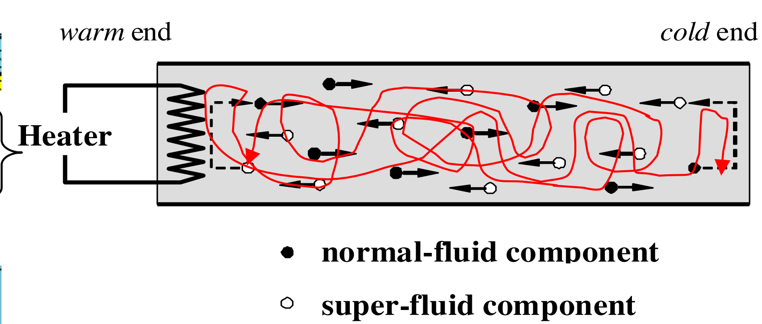
$$\nabla \times \mathbf{v}_s = \mathbf{0}$$

→ but vortices can be generated in the superfluid component

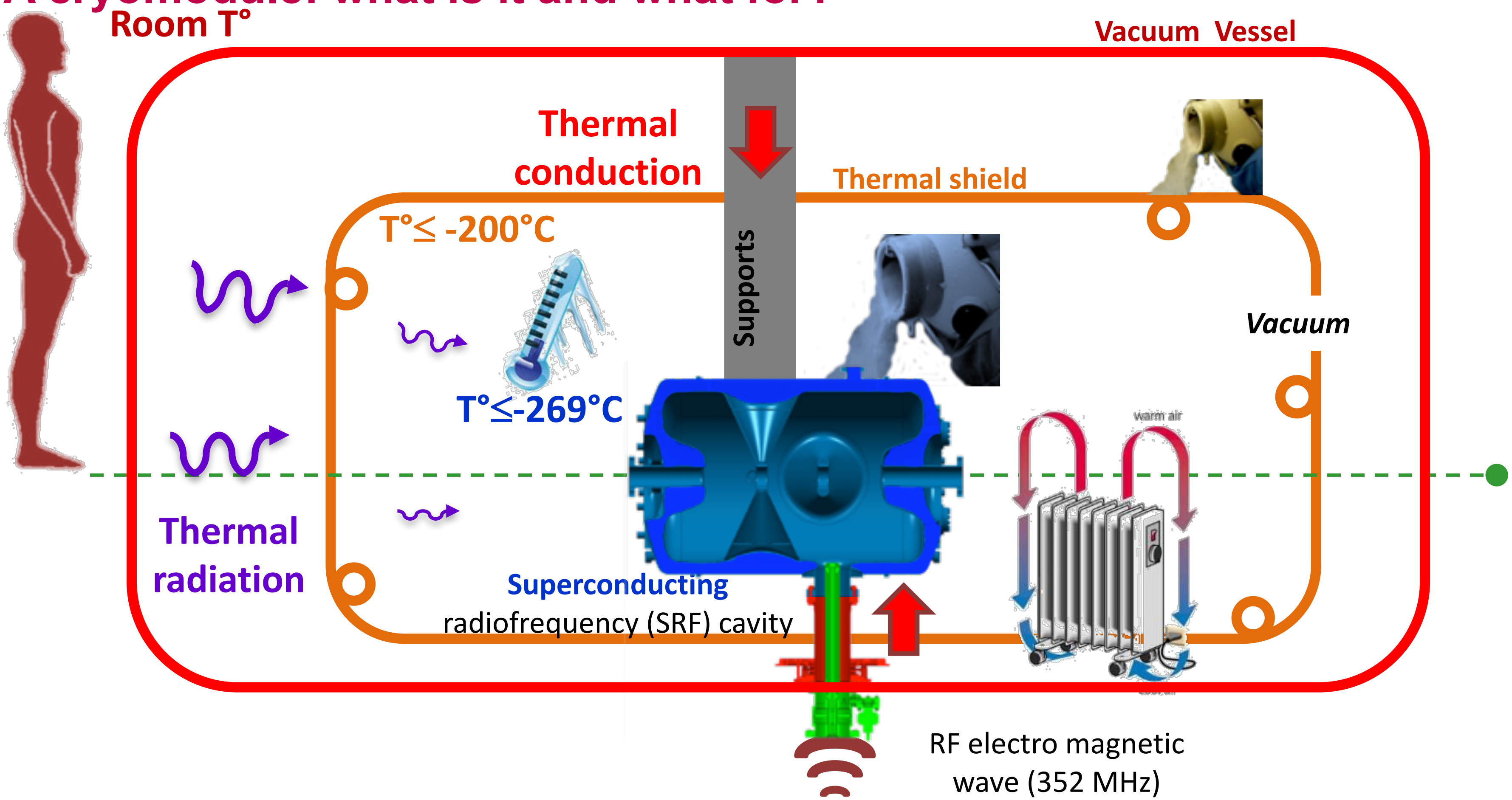


No bulk flow

Heat flux



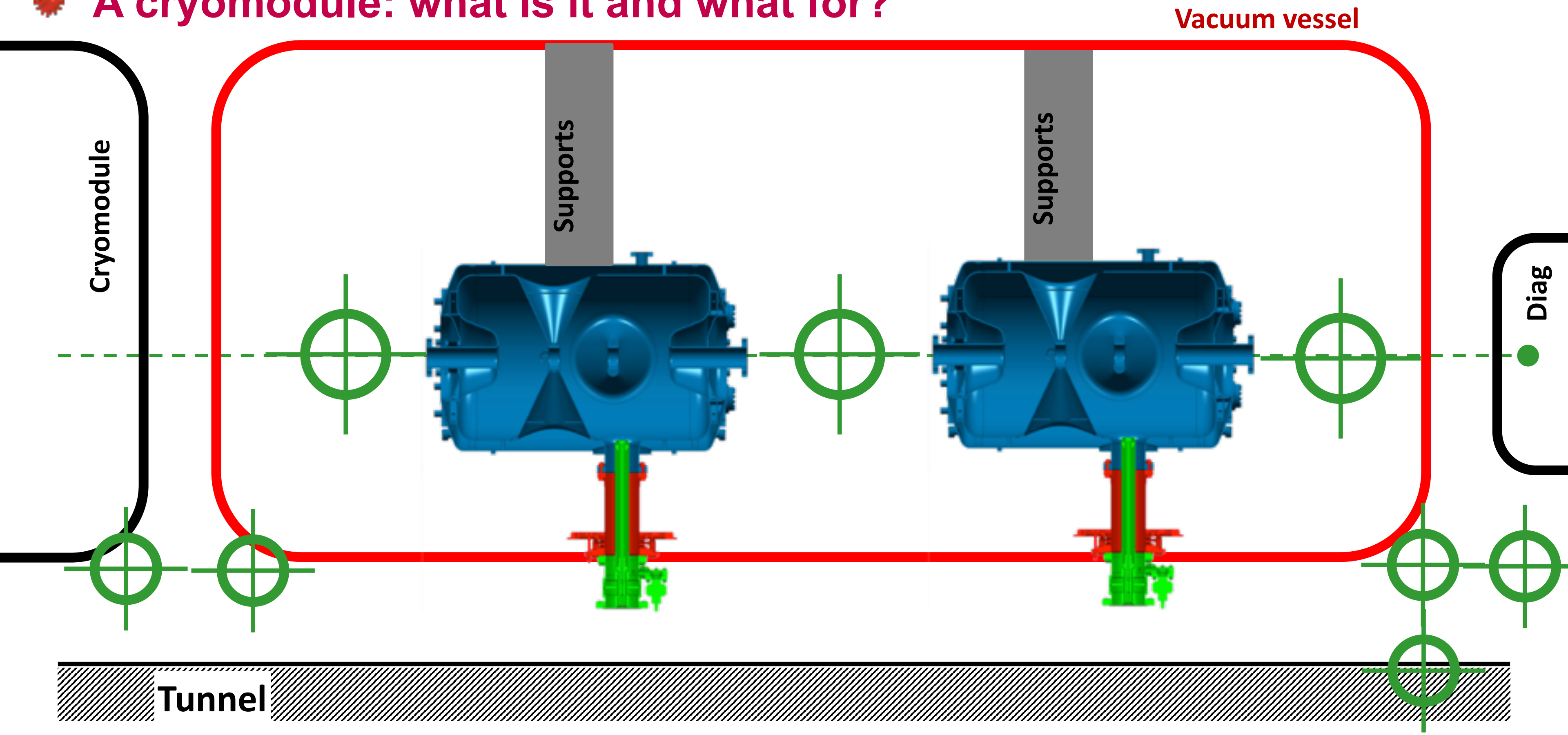
A cryomodule: what is it and what for?



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?

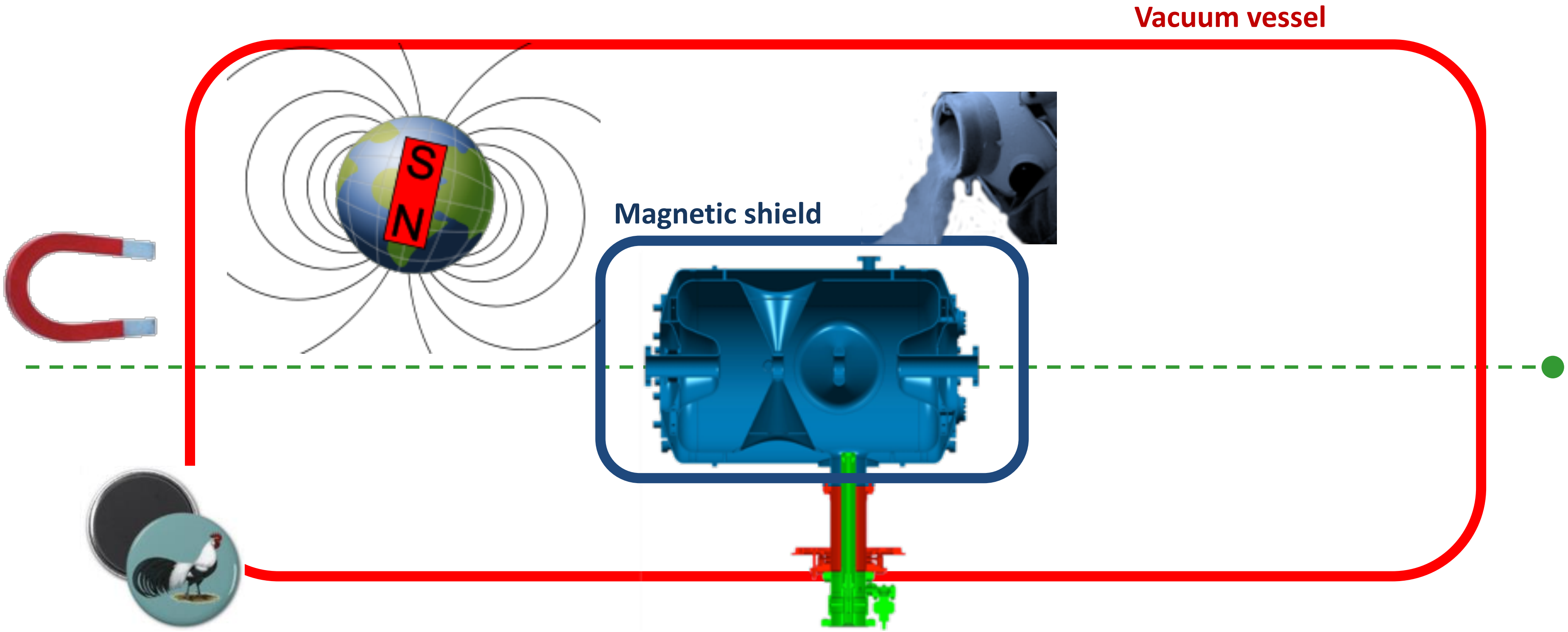


2/ To support the cavities and perform accurate alignment

- **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?

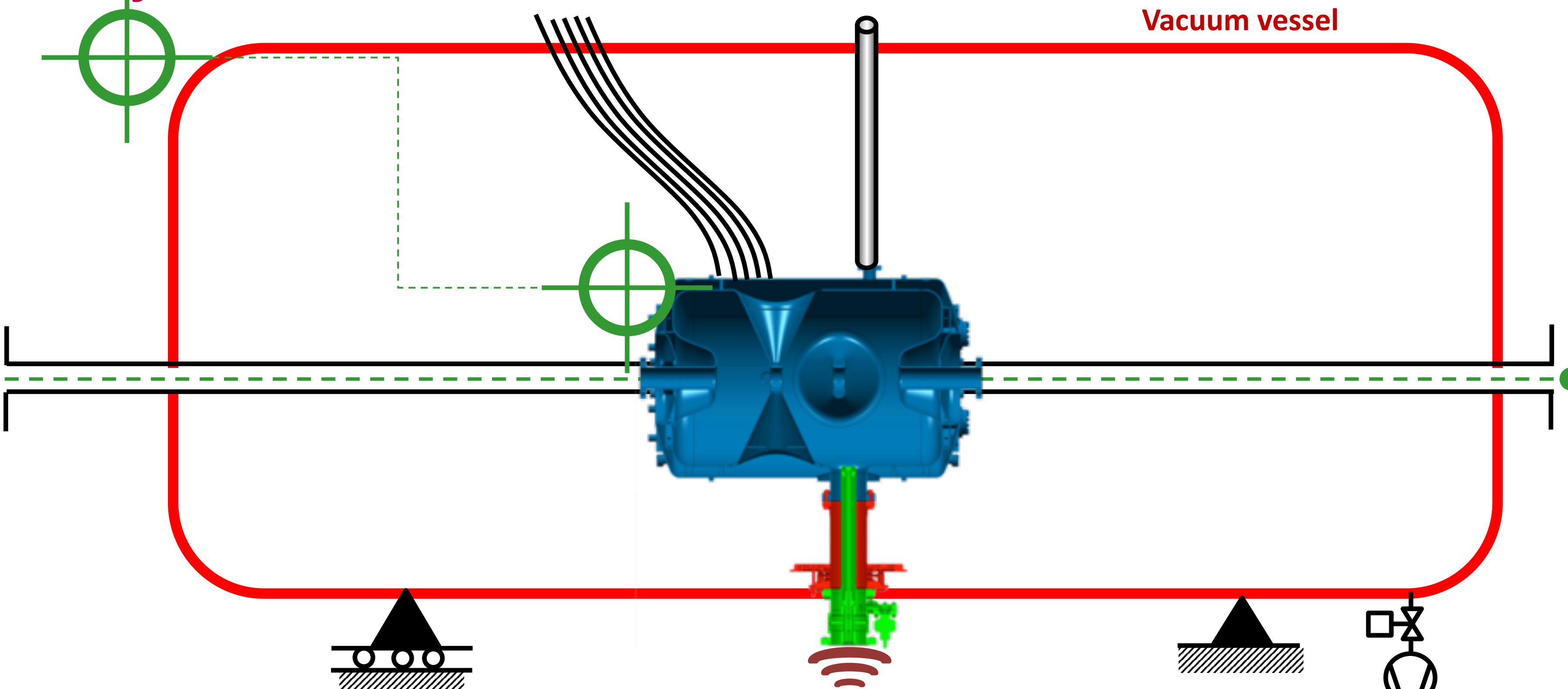


3/ To offer magnetic shielding

- **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)

Outline

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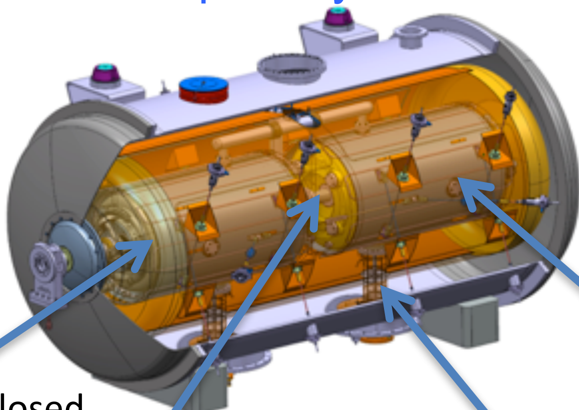
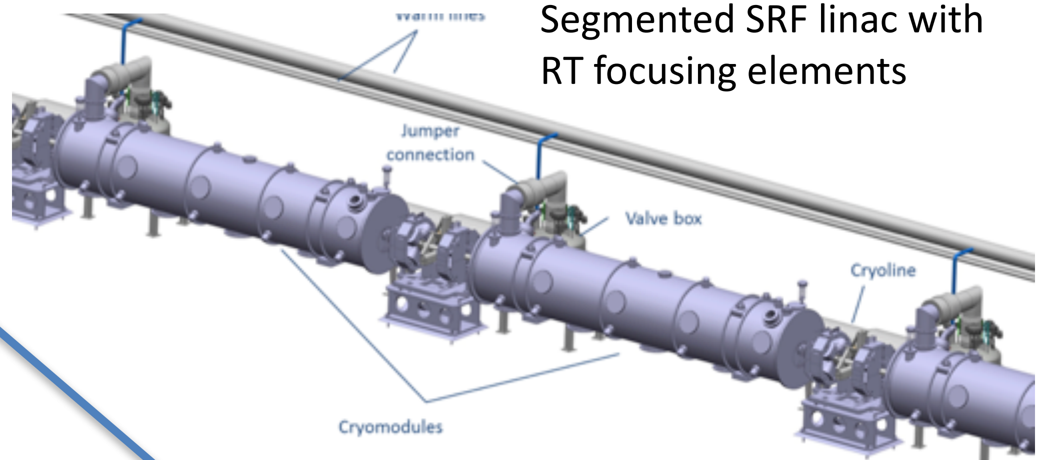
ESS SRF cavities and cryomodules

2 Spoke Cavities per Cryomodule



Segmented SRF linac with RT focusing elements



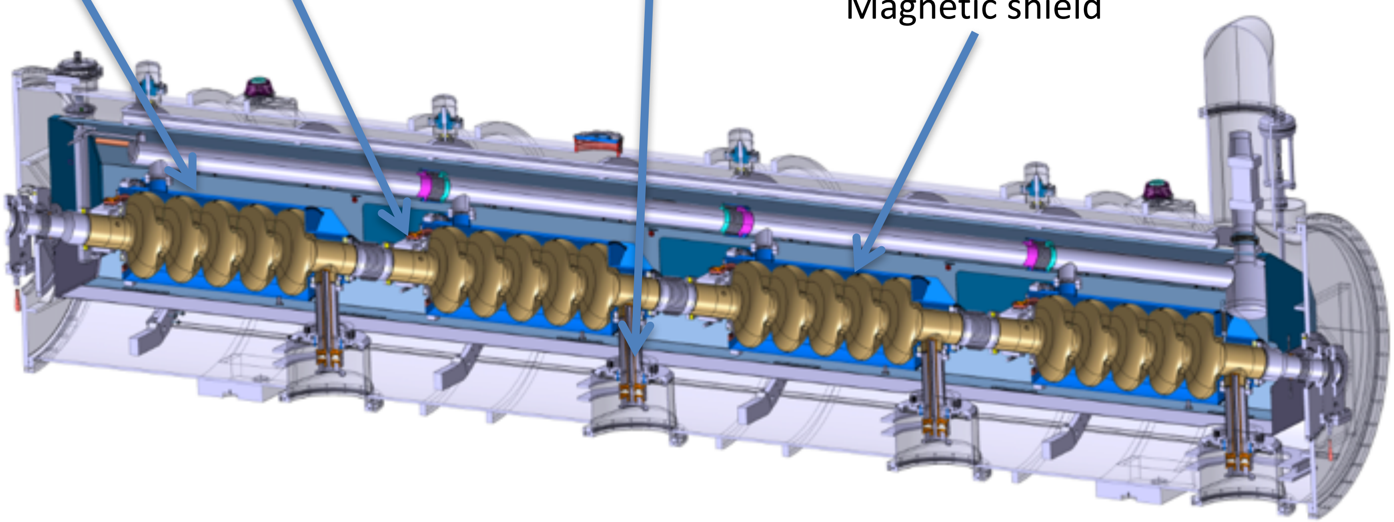
Nb cavity enclosed in Ti Helium tank

Cold tuning System

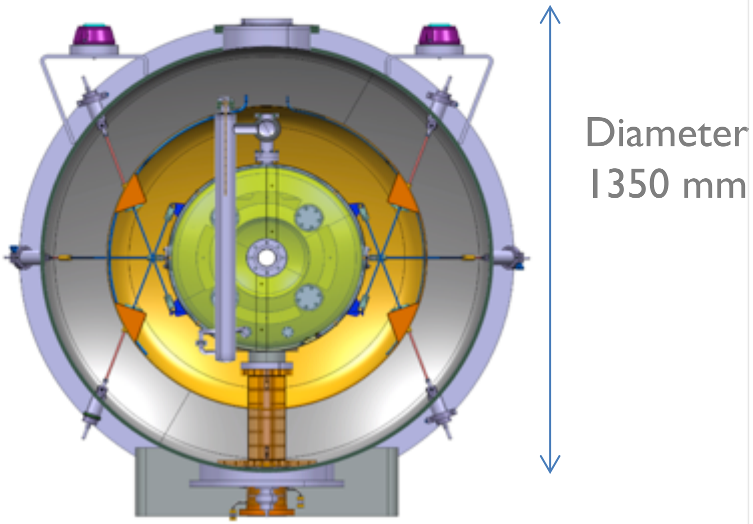
Power coupler

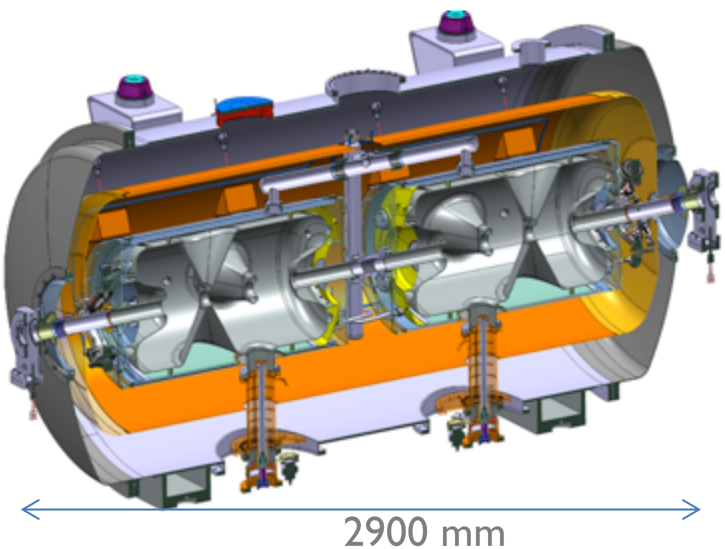
Magnetic shield

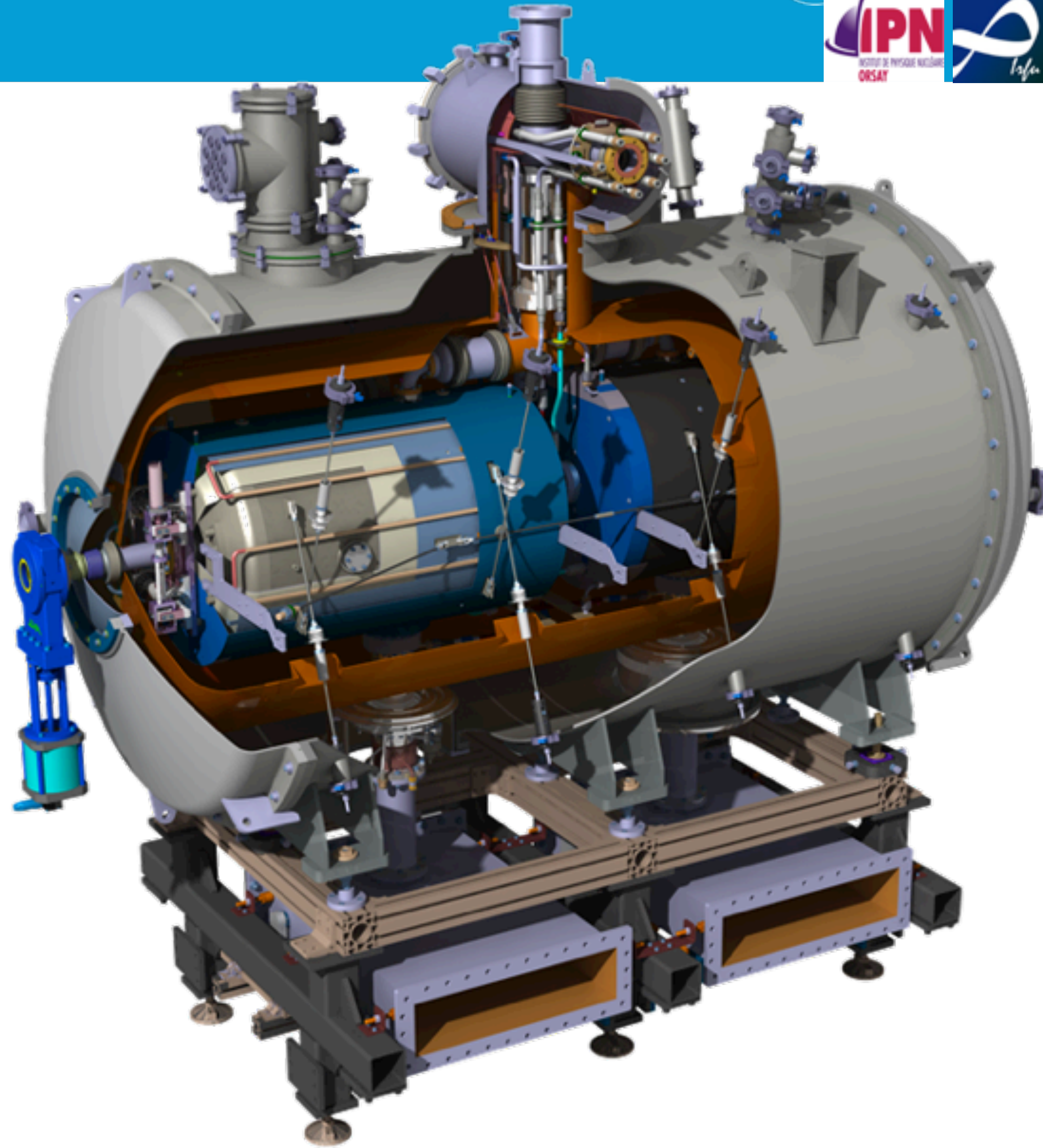
4 Elliptical Cavities per Cryomodule



Spoke cryomodule

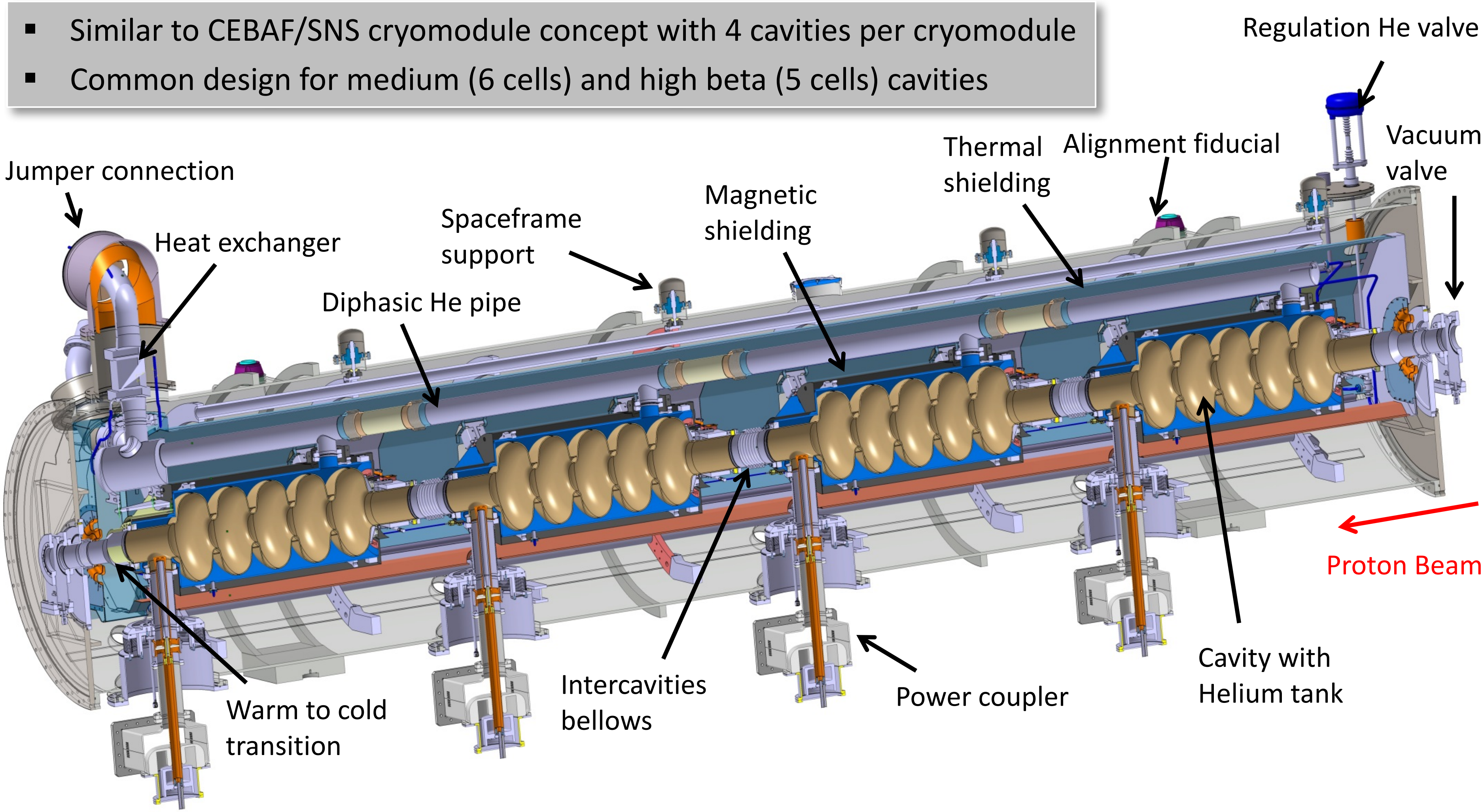






Elliptical cryomodule

- Similar to CEBAF/SNS cryomodule concept with 4 cavities per cryomodule
- Common design for medium (6 cells) and high beta (5 cells) cavities



Elliptical Cryomodule Components

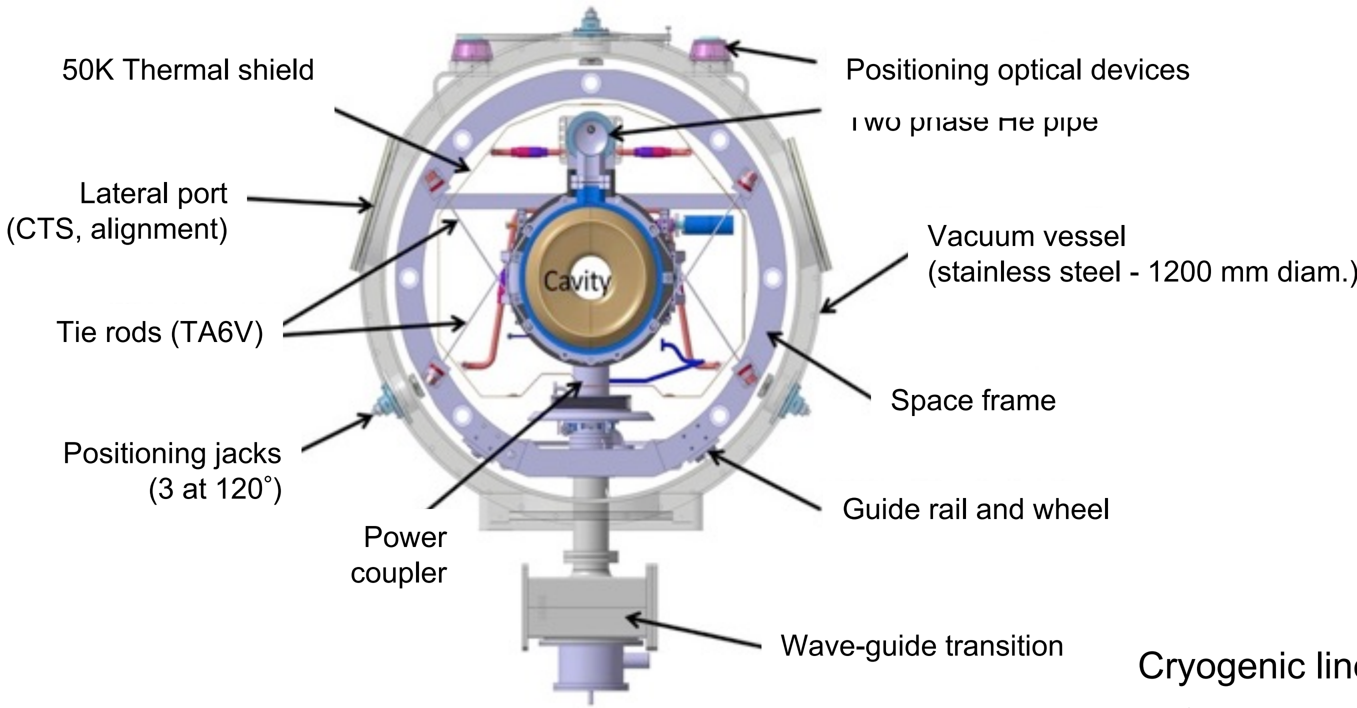
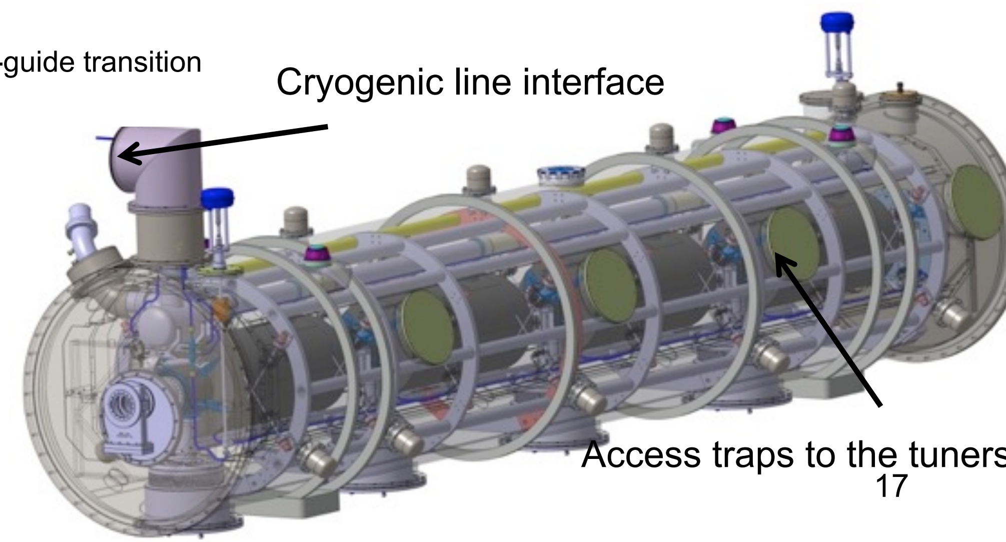


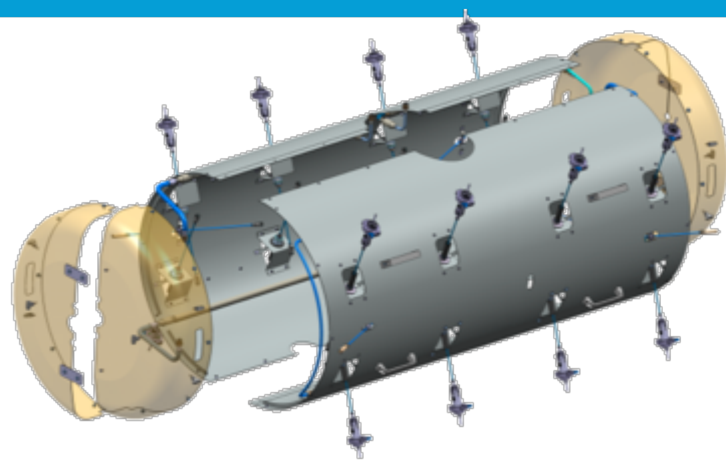
Figure 4.120: Helium vessel with hanging rod

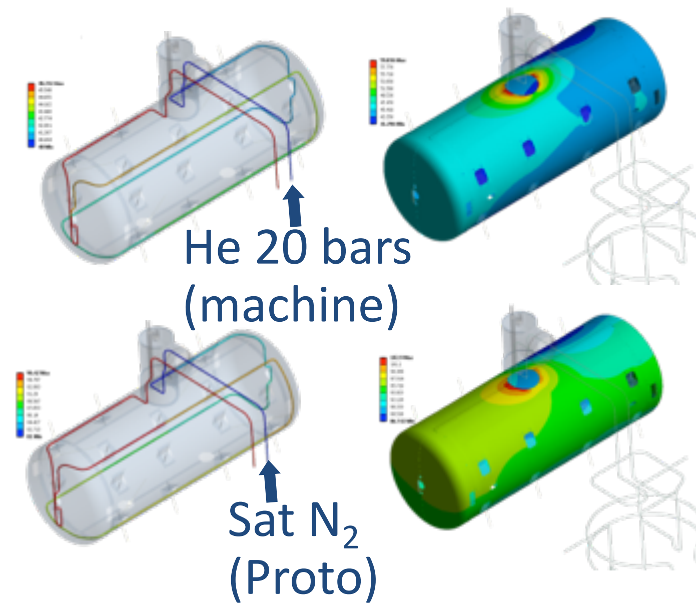


The cryomodule design and calculation:

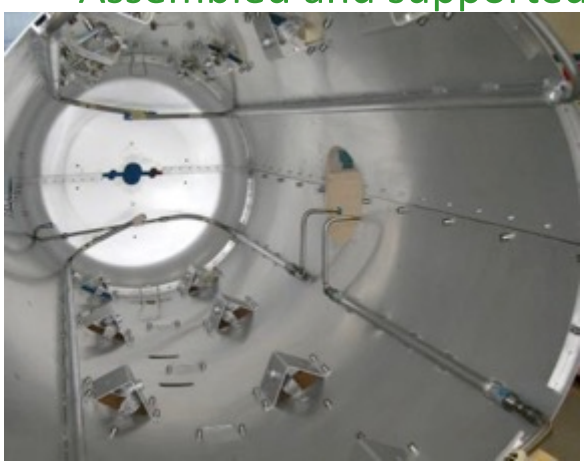
- Thermo-mechanical studies
- Magnetic studies
- Safety analysis to size all components
- Reliability analysis, FMEA

Thermal shield for Spoke cryomodule





- ✓ Material: Al6062
- ✓ Thickness: 2 mm
- ✓ Assembled and supported (rods)



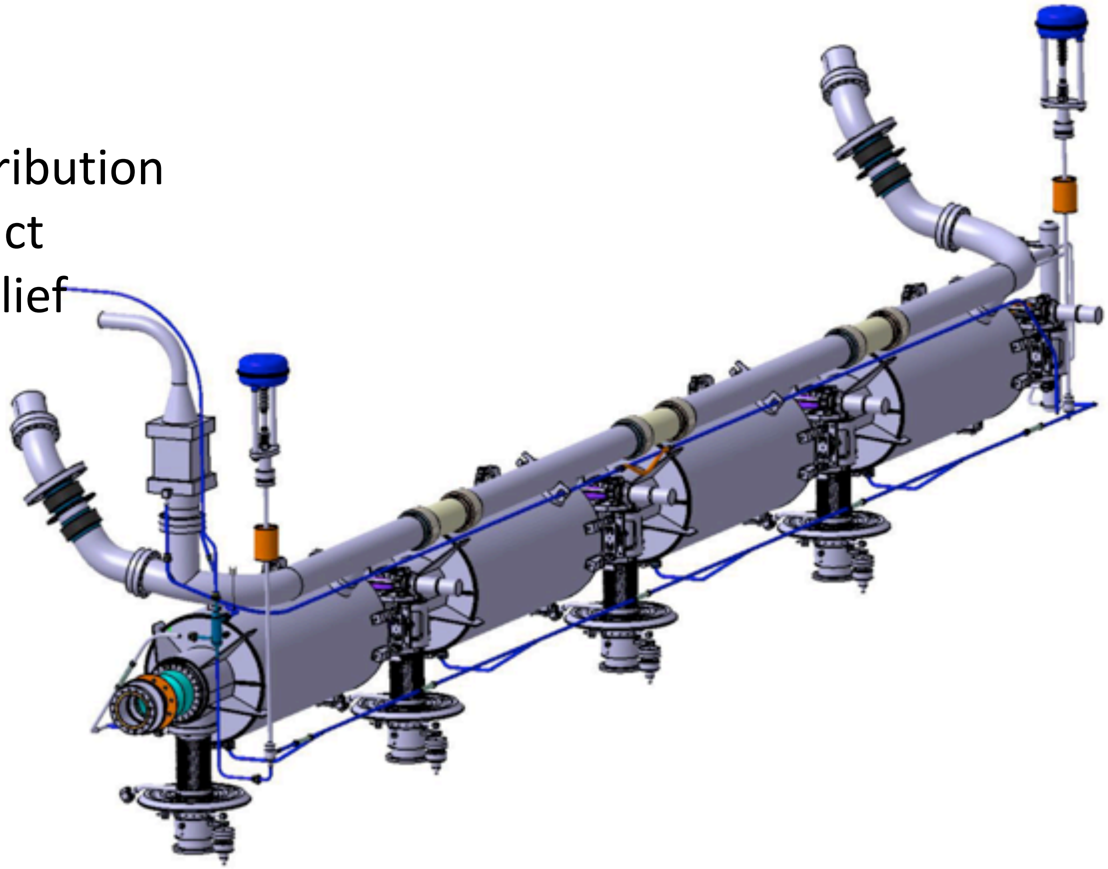
Safety relief devices

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

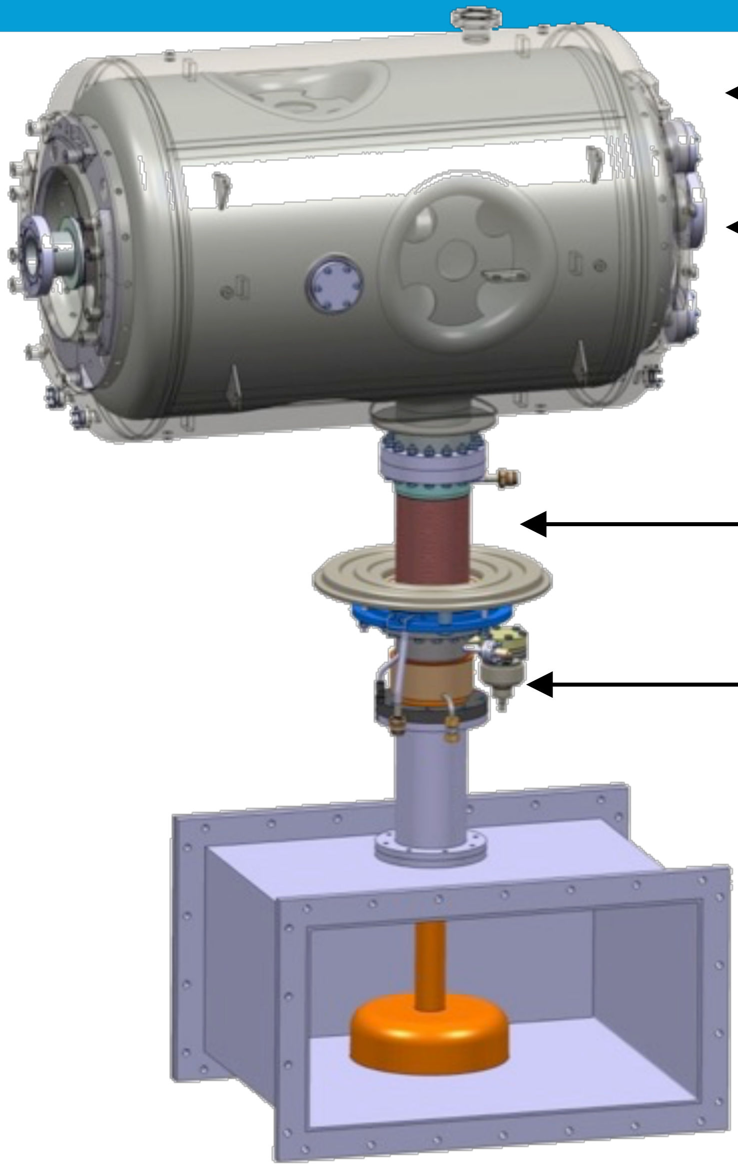
$$\dot{m} = \frac{\dot{Q}}{L_V}\frac{\rho_L - \rho_V}{\rho_L}$$

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

- Mitigate/design ➔



Cavity package



Double Spoke Cavity

Cold Tuning System

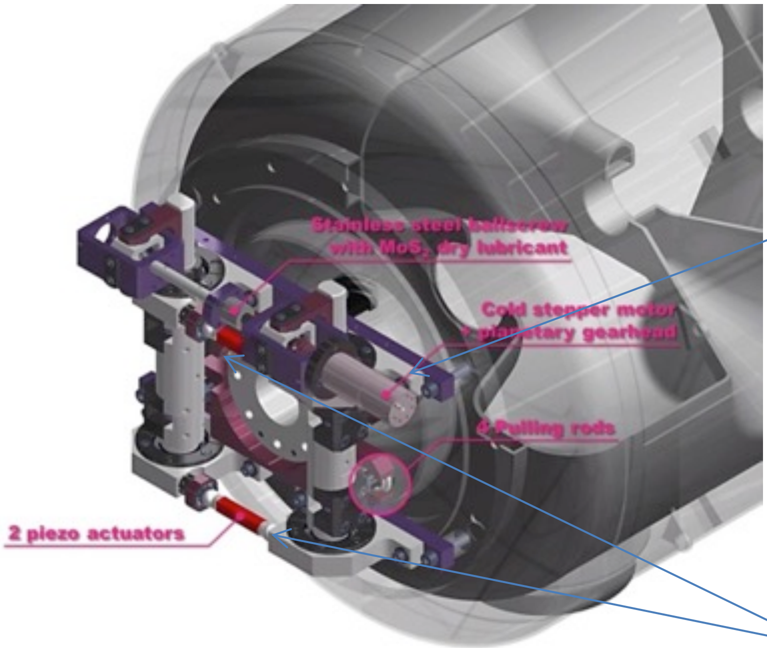
Heat exchanger necessary to make the transition from 300 K to 2 K
Integrating a mechanical system to compensate efforts

RF Power Coupler

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

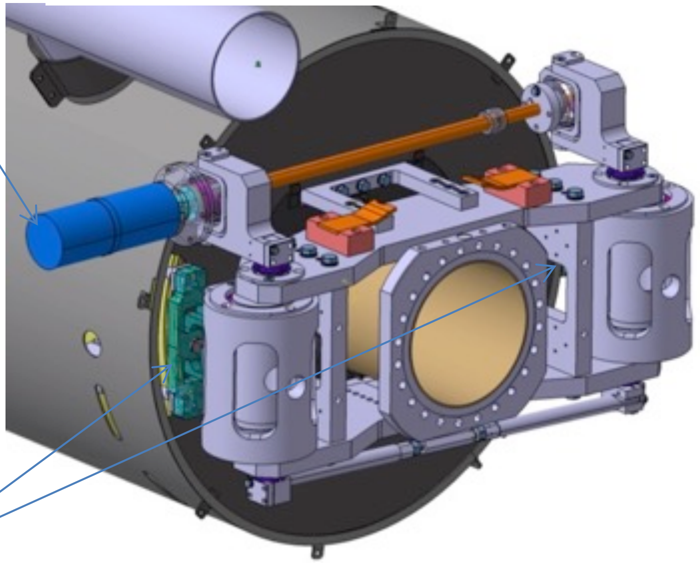
Cold Tuning System

Spoke CTS



Elliptical CTS

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



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

2 piezo stacks

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

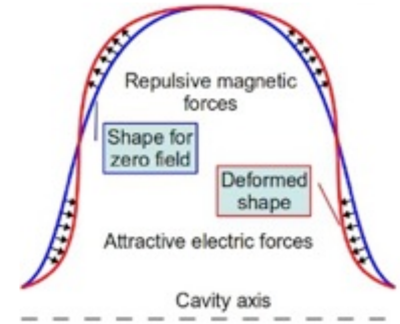
Cavities tuning: Lorentz De-tuning

ESS and long pulse: 2.86 ms

- Because of the enormous gradients in superconducting cavities,
  - the radiation pressure deforms the cavities

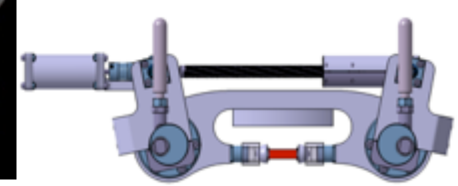
- We expect over 400 Hz of detuning in the ESS cavities
  - Unloaded cavity bandwidth = 0.07 Hz
  - Loaded cavity bandwidth = 1 kHz

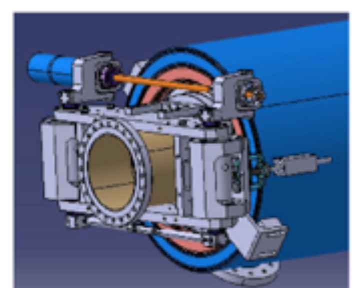
- The mechanical time constant of the cavities is about 1 ms compared to the pulse length of 3 ms
  - Static pre-detuning as done in SNS will not be sufficient
  - Dynamic de-tuning compensation using piezo-electric tuners is a must!
  - Or else pay for the extra RF power required



$$P_s=\frac{1}{4}(\mu|\vec{H}|^2-\varepsilon_0|\vec{E}|^2)$$

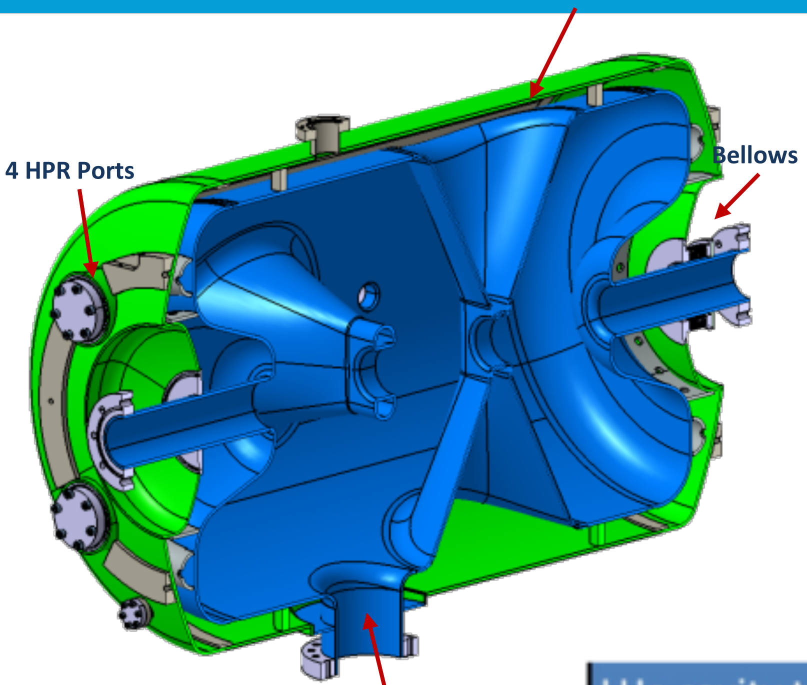
$$\Delta f_0=(f_0)_2-(f_0)_1=-K E_{acc}^2$$

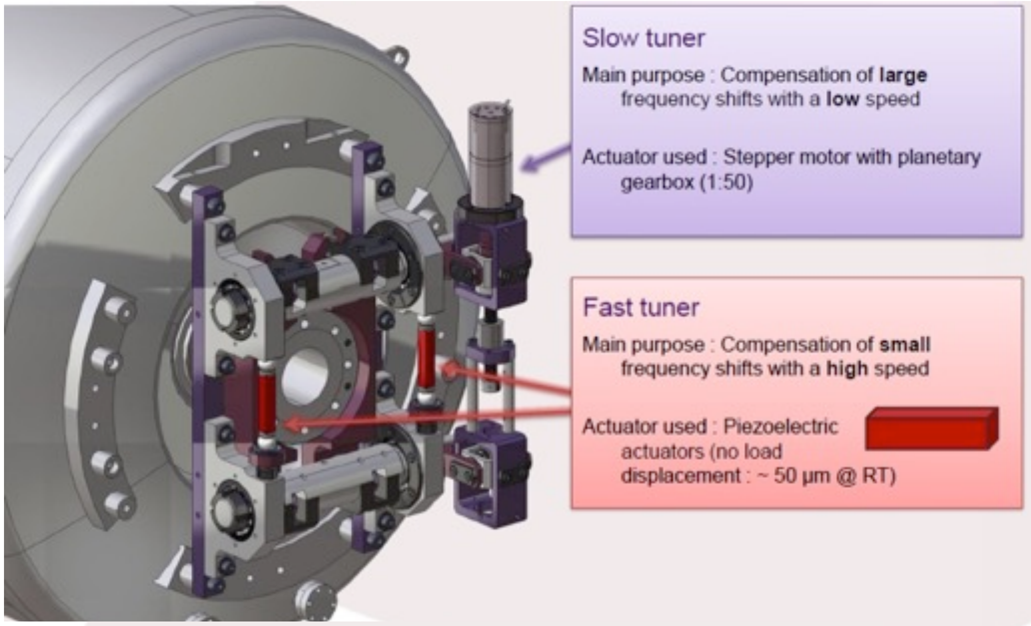


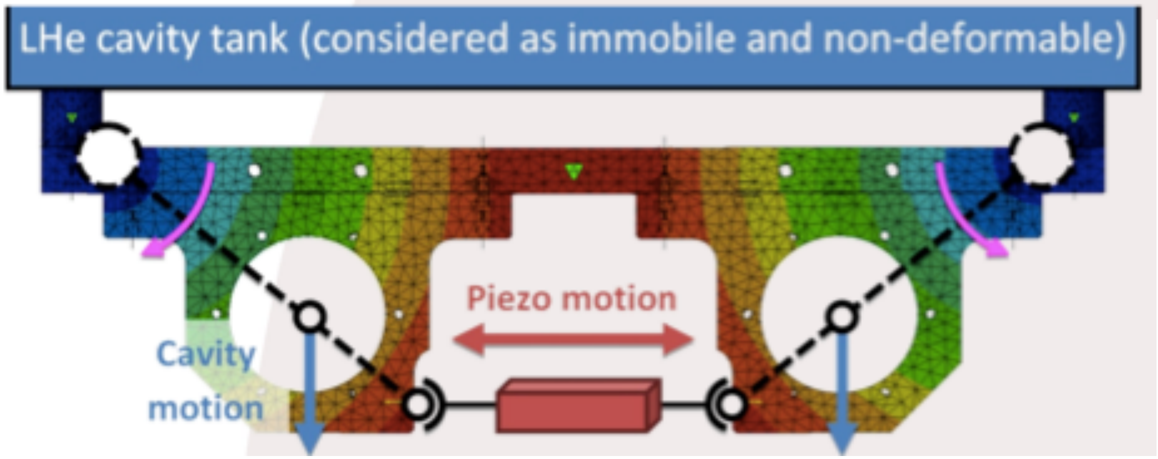


Saclay-V tuner concept adapted to the ESS cavity
Fast/slow tuner (with piezo)

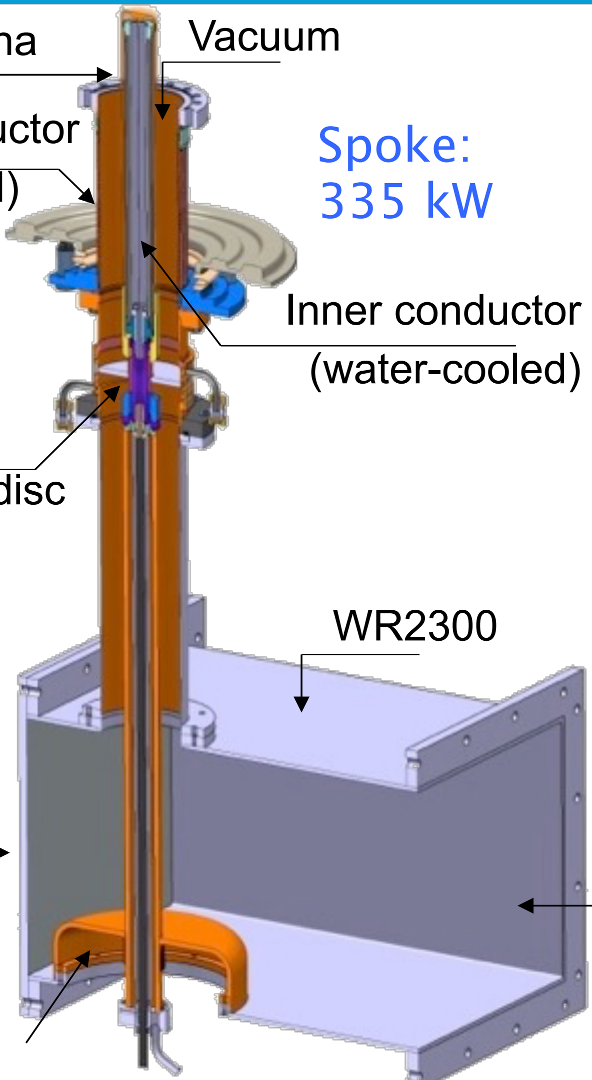
The Spokes Cryomodule



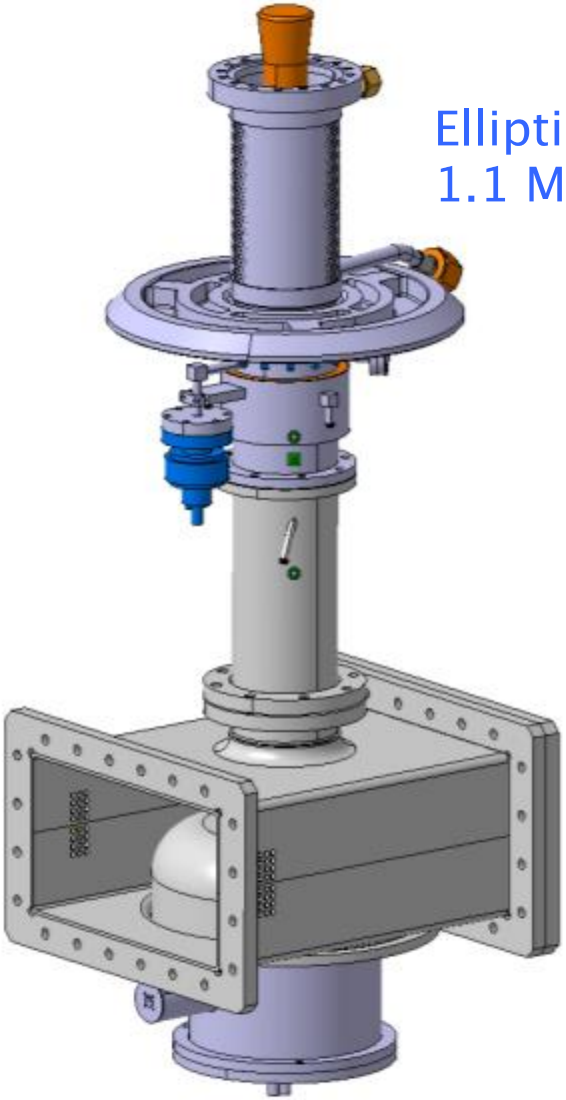




Fundamental Power Coupler



Spoke:
335 kW

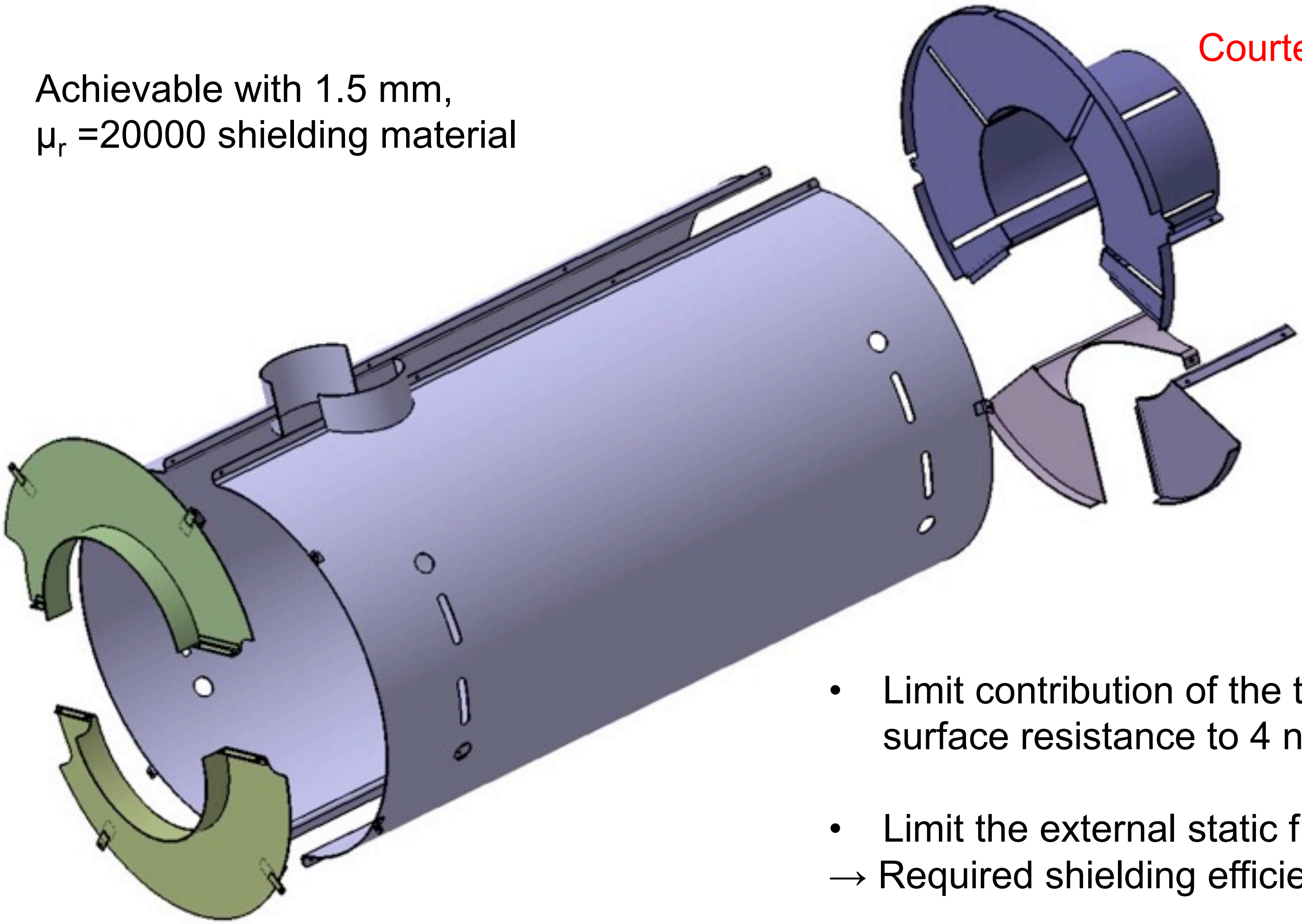


Elliptical:
1.1 MW

Magnetic shield for Elliptical Cavity

Courtesy of J. Plouin/ CEA

Achievable with 1.5 mm,
μ_r =20000 shielding material

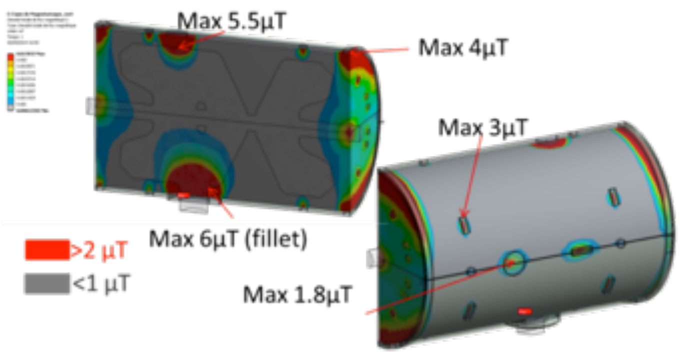


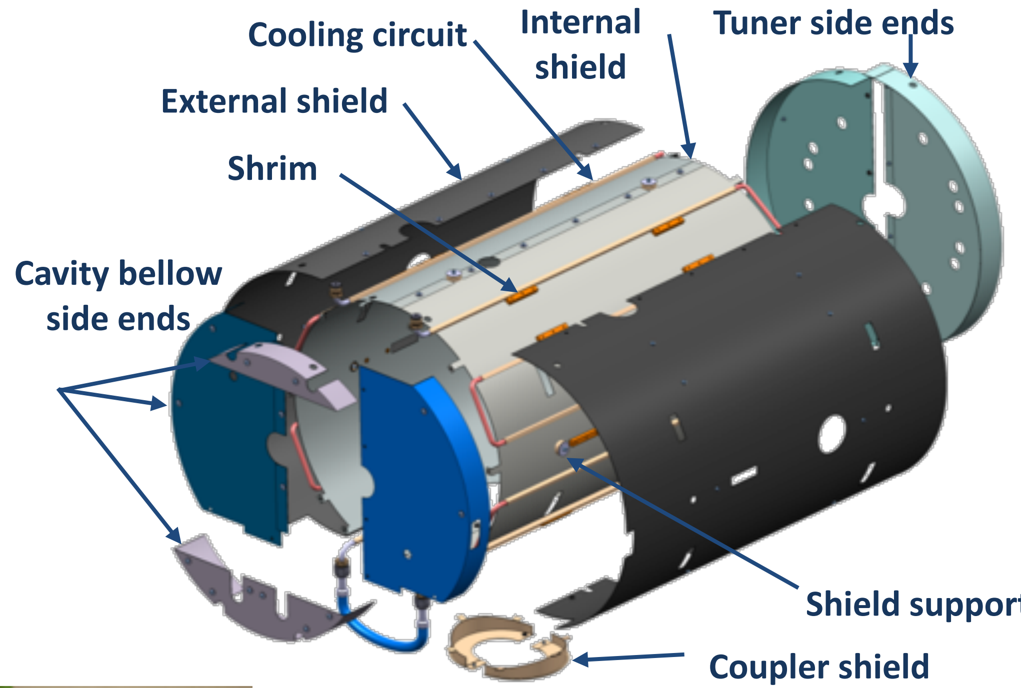
- Limit contribution of the trapped flux to the surface resistance to 4 nΩ

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

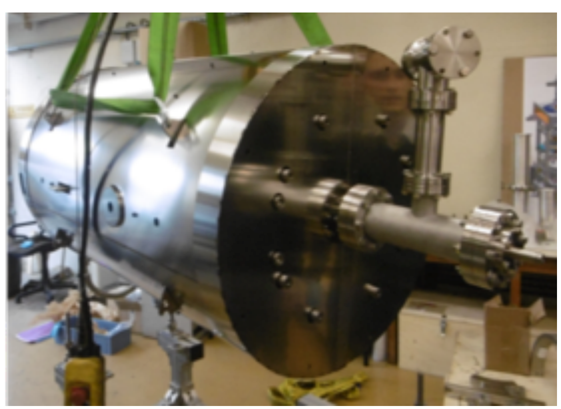
→ Required shielding efficiency equal to 35.

Magnetic shield for Spoke Cavity





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

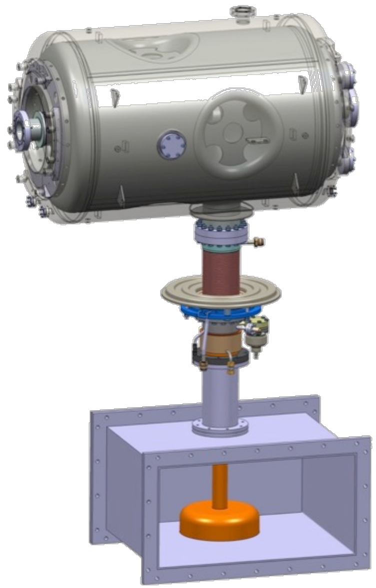


- ✓ Magnetic shields fabricated
- ✓ Assembly test performed
- ✓ To be tested within the cryomodule

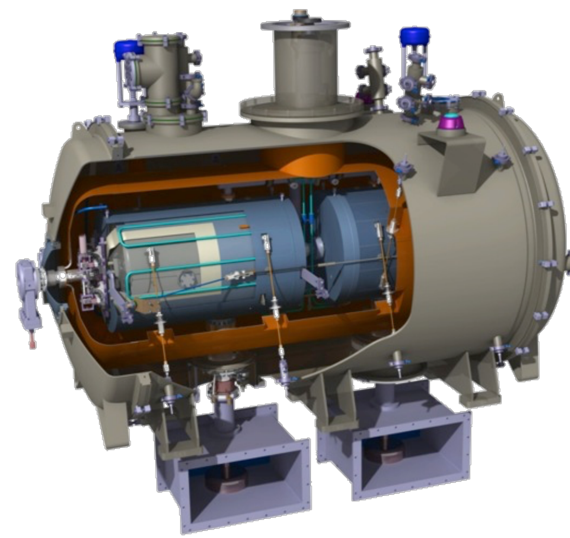
Validation of spoke cryomodule component performance

Step 1: Spoke cavity
@ IPNO
@ Uppsala University - HNOSS


Step 2: Spoke cavity packages
@ IPNO - Warm and 4 K
@ UU - HNOSS




Step 3: Cryomodule w/ prototype valve box
@ IPNO
@ UU - HNOSS



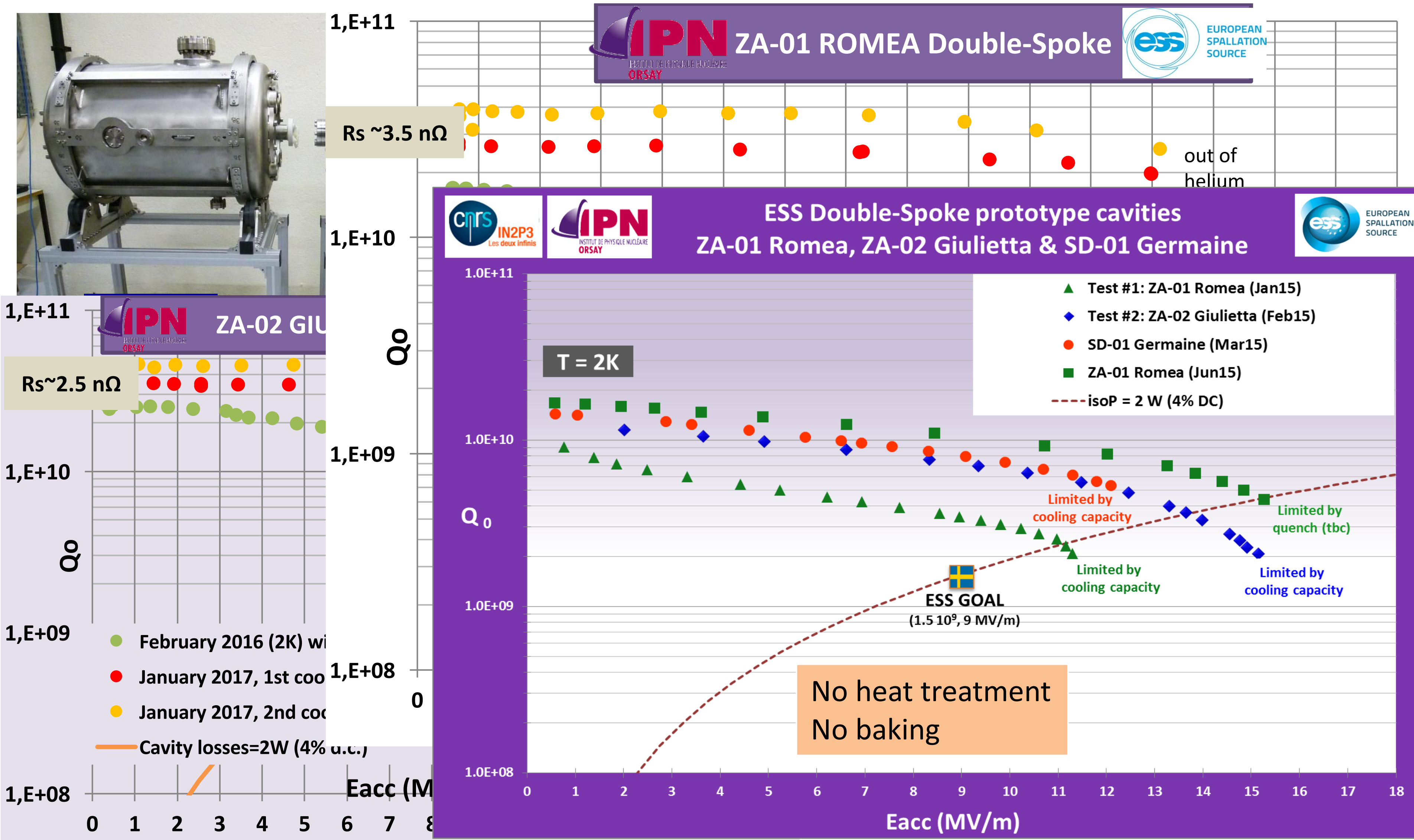
Double spoke cavity, 352.2 MHz, β=0.50

Goal: Eacc = 9 MV/m *[Bp= 62 mT; Ep = 39 MV/m]*

Lorentz detuning coeff.: ~-5.5Hz/(MV/m)^2

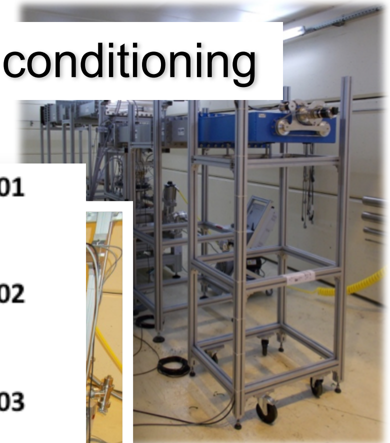
Tuning sensitivity $\Delta f/\Delta z$ = 130 kHz/mm

Spoke cavities results @ IPNO

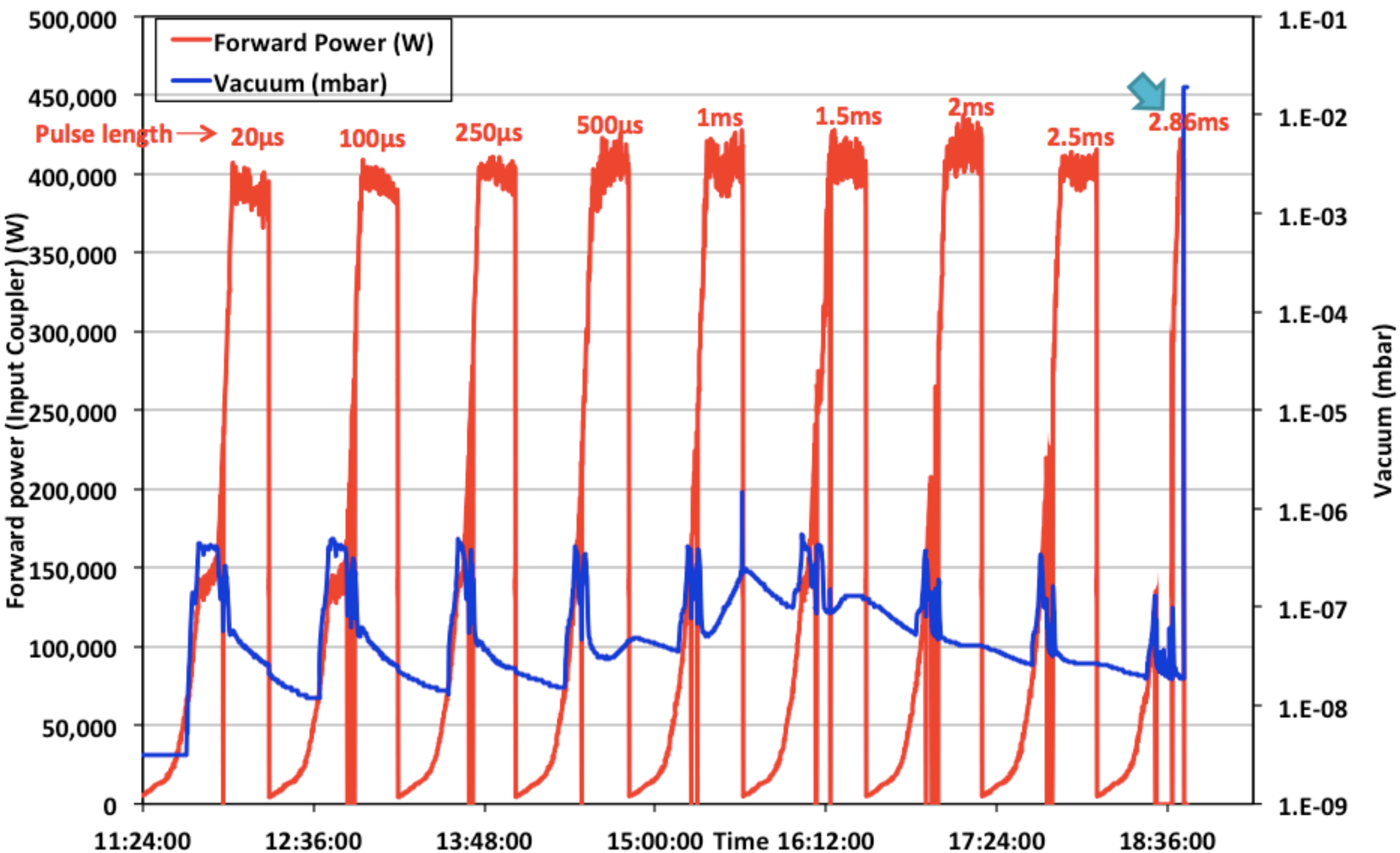


Test Stand and coupler conditioning @ IPNO

Power coupler conditioning



Control and security rack (with fast interlocks)



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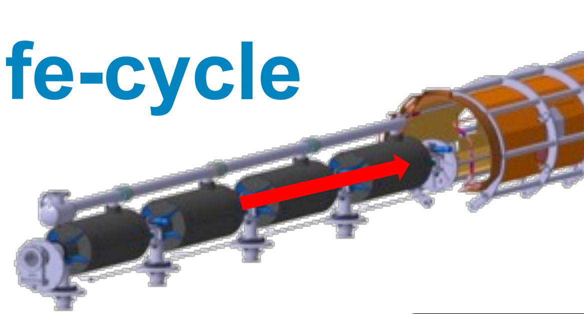
- How to operate a cryomodule

Cryomodule life-cycle



High pressure rinsing In clean room (ISO5 or ISO4)

Cavity fabrication

Chemical treatment

Validation test of the cavity in vertical cryostat

Cryomodule components fabrication

Qualified cavity storage

Cavity string assembling in clean room

Cryomodule assembling

Processed couplers storage

Tools fabrication

Coupler RF processing

Assembling in clean room

Power coupler fabrication

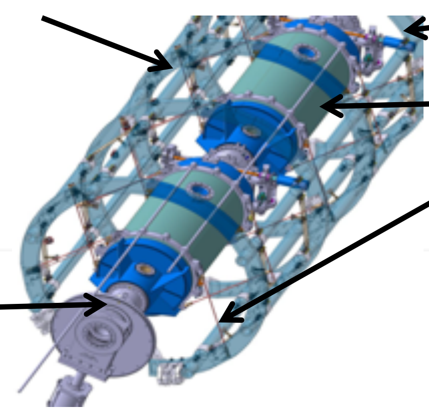
Transport

Cryomodule reception and storage

Validation test of the cryomodule

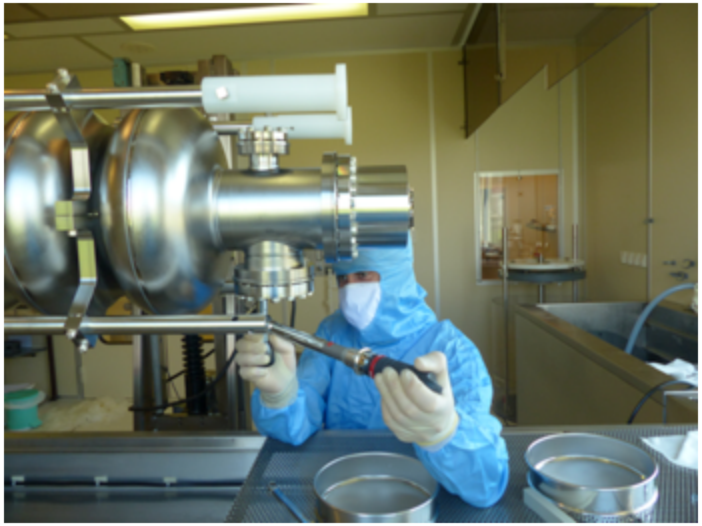
Cryomodule storage

Cryomodule on beam line



Elliptical Cavity Preparation

Elliptical beta cavity fabrication



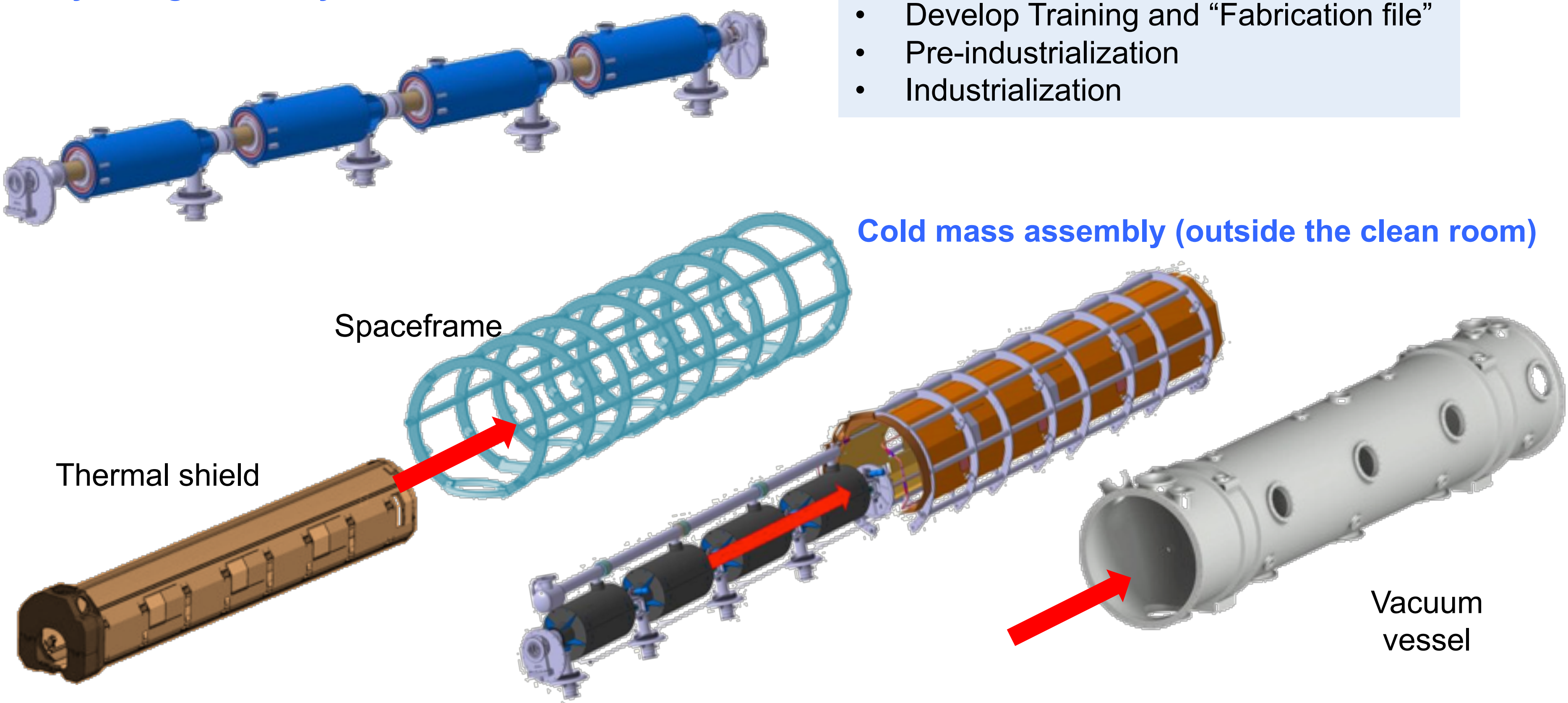
Vertical Electropolishing system@ CEA

Elliptical Assembly Procedure

Cavity string assembly in clean room

Build on existing knowledge (SNS, XFEL)
- Develop Training and "Fabrication file"
- Pre-industrialization
- Industrialization

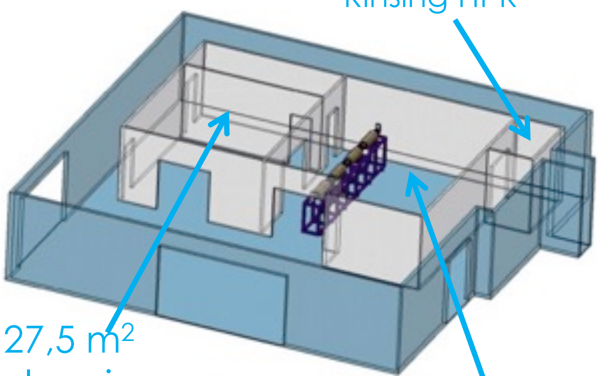
Cold mass assembly (outside the clean room)



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)

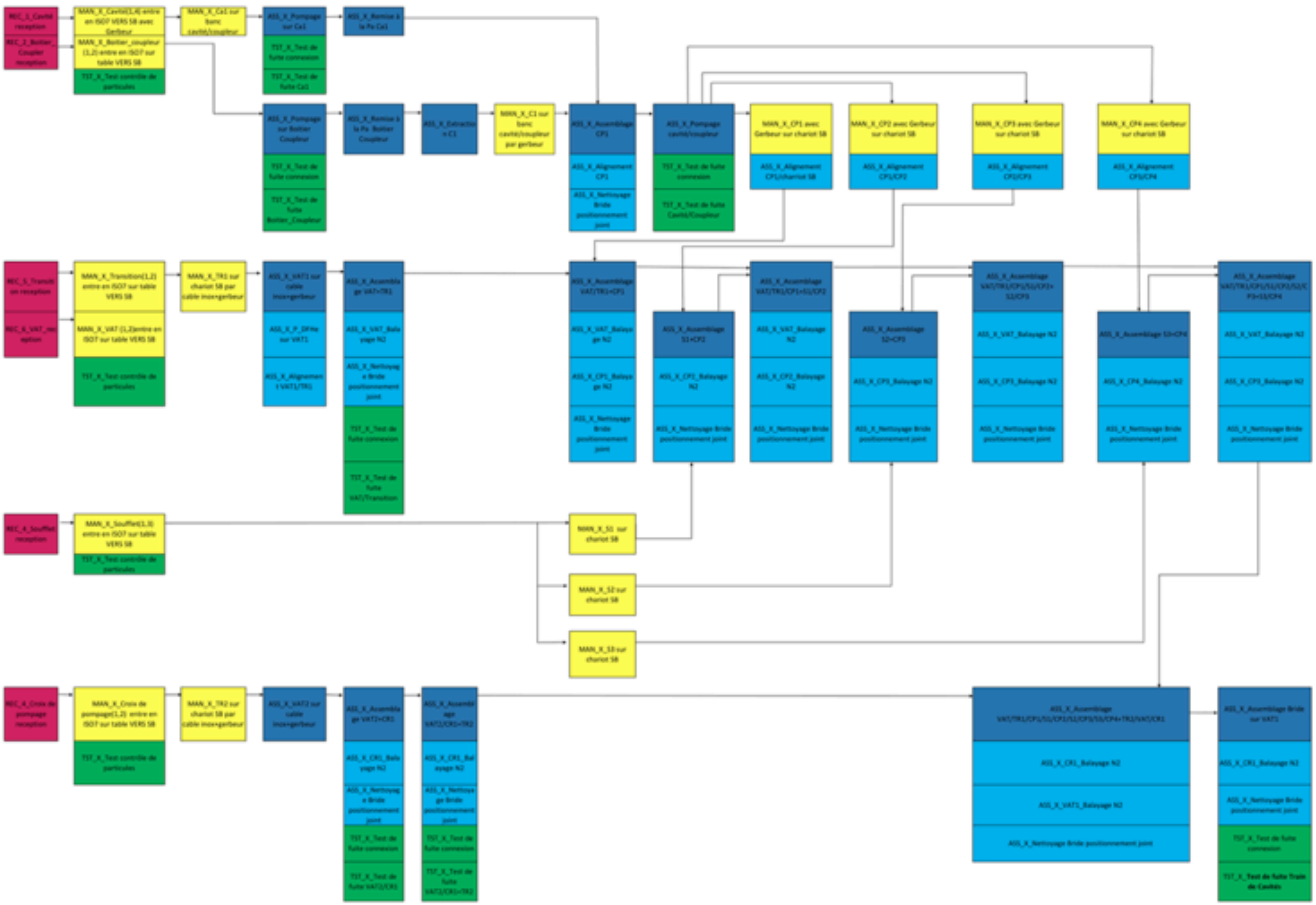


The clean room inauguration → May 13th 2014

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

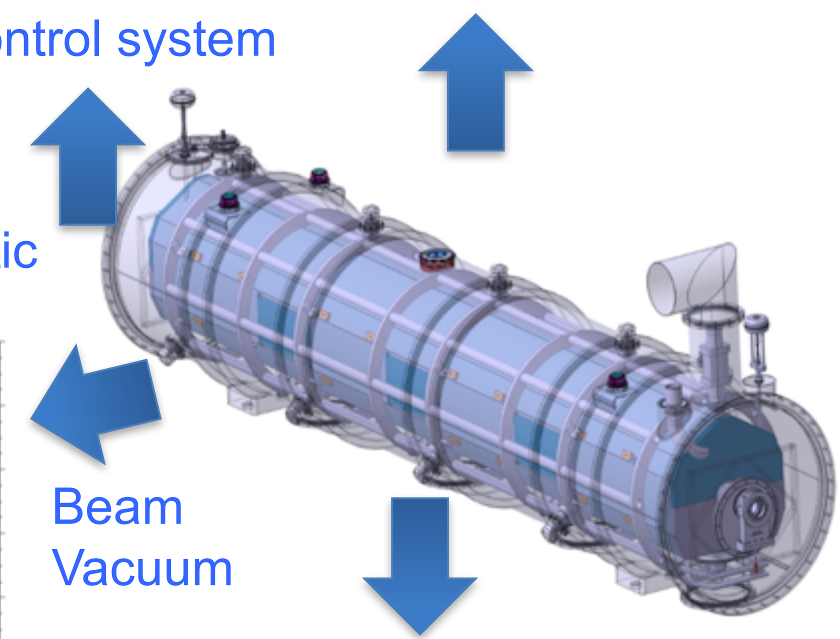


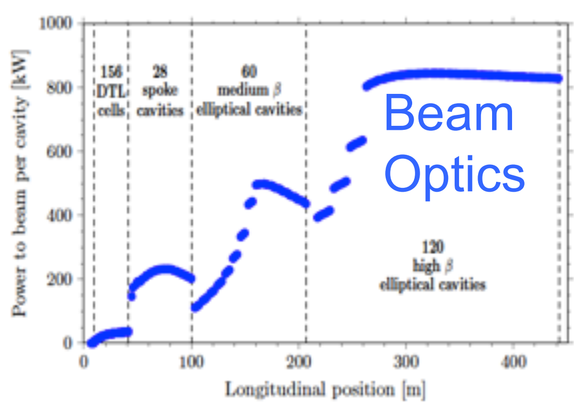
Outline

- Cryomodule Functions
- Cryomodule Components
- Cryomodule Assembly
- How to operate a cryomodule

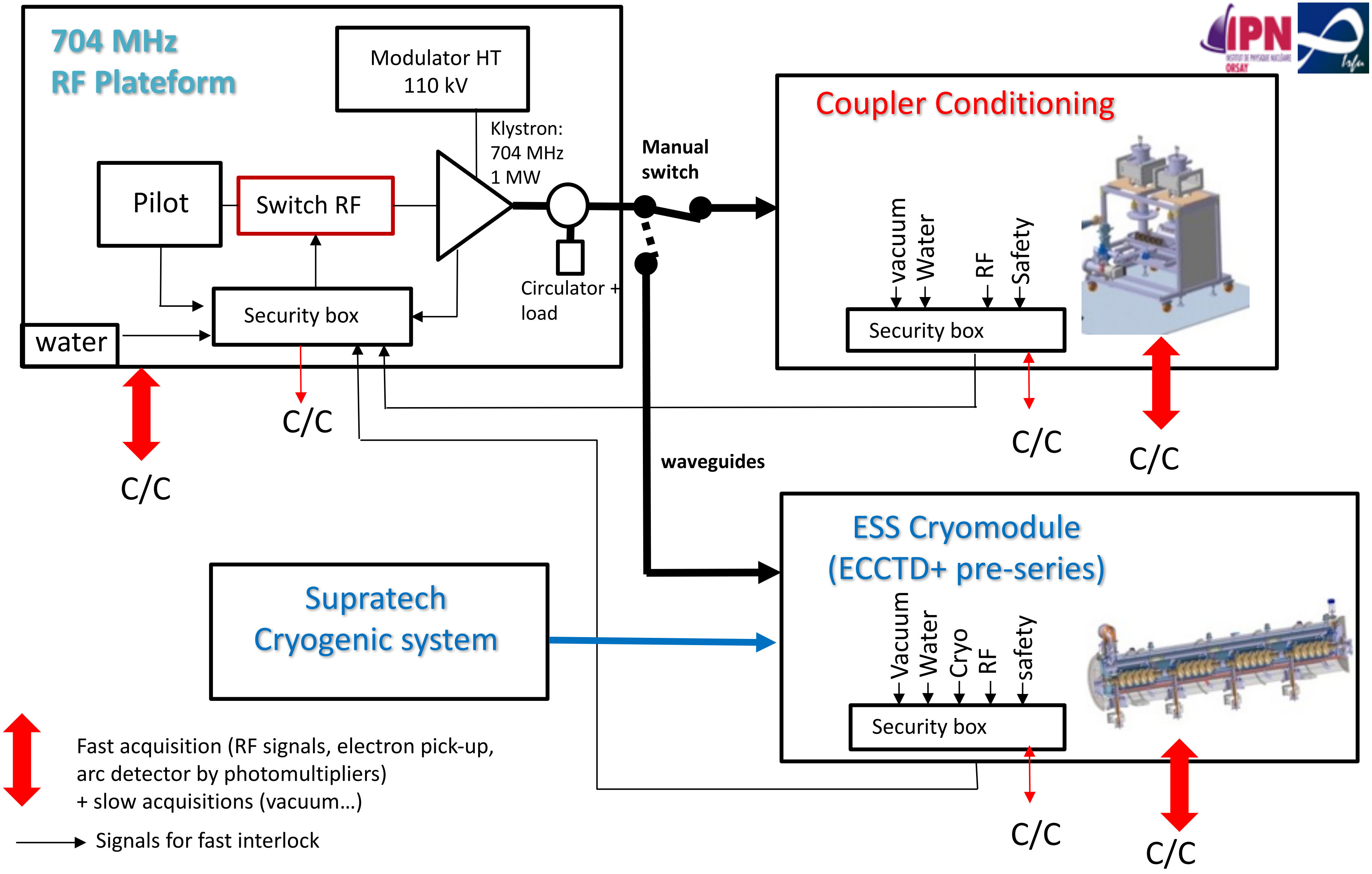
Cryomodule Interfaces

- 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)





RF power test stations at CEA Saclay



Test Stand @ Uppsala (FREIA)

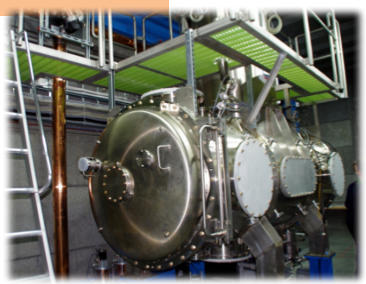
RF Power Source + LLRF

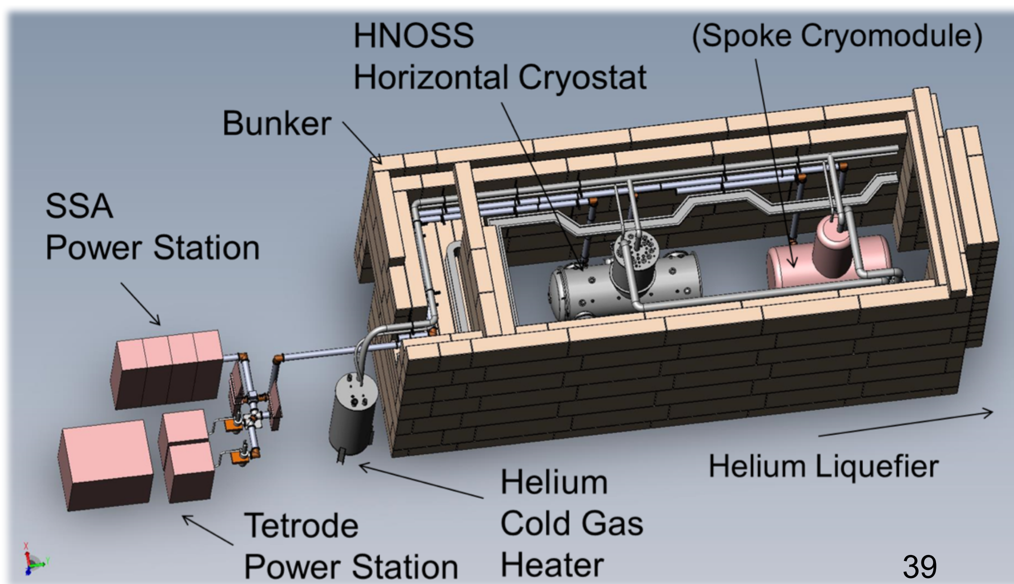
Control System & Interlock

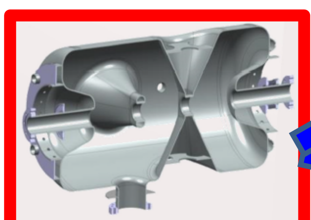
Cryogenics

Spoke & Elliptical cavity package

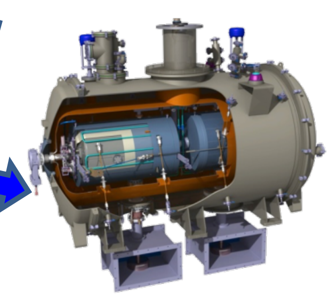
HNOSS







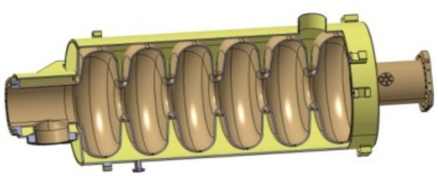
SRF cavity

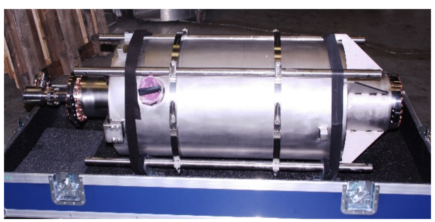


Validation of Elliptical Medium-β Technology Demonstrator

Step 1: Elliptical cavities

Medium-beta
@ Saclay
@ LASA

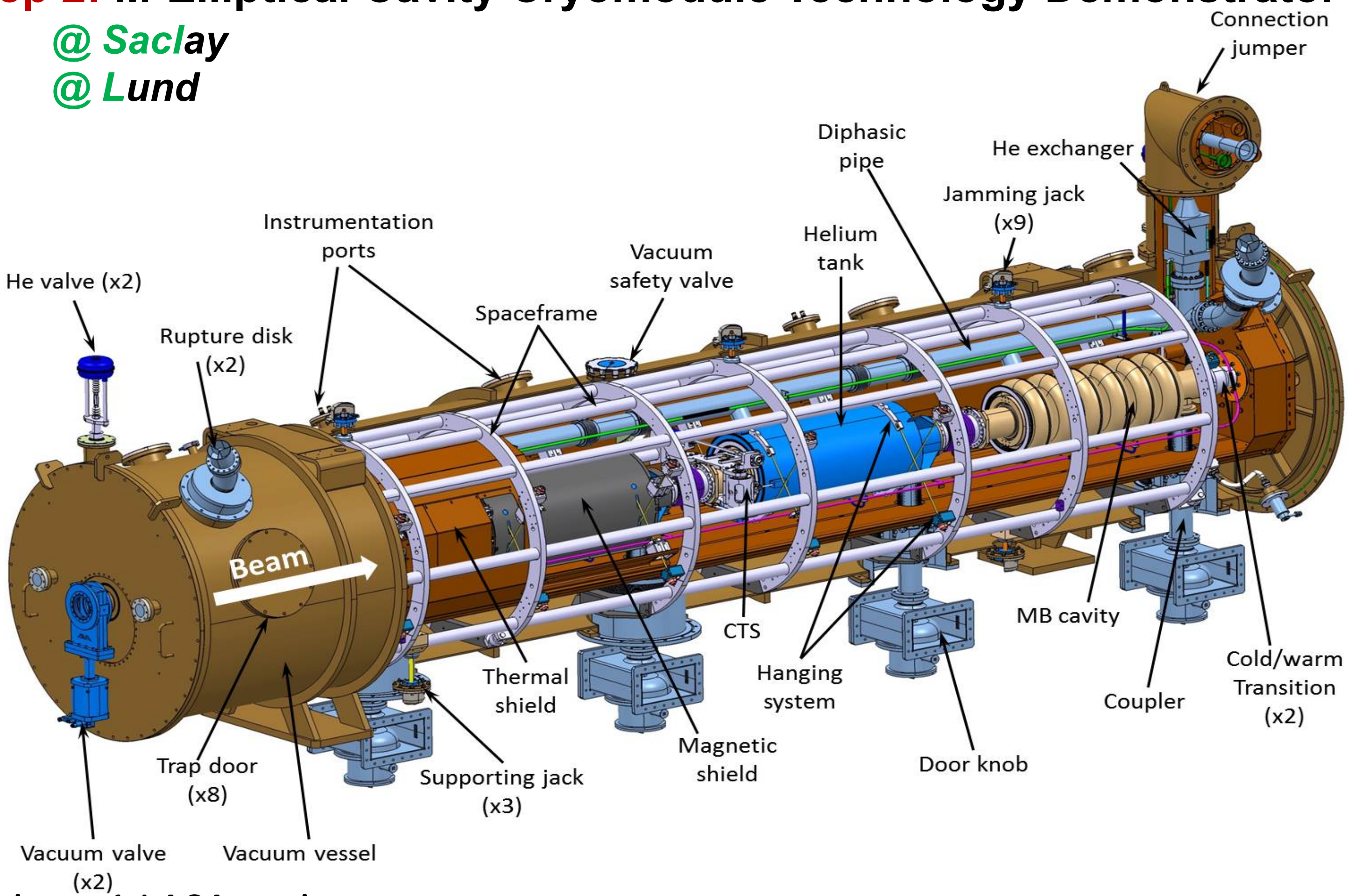




	LASA	CEA
Q_{ext}	7.7×10^5	7.5×10^5
k	1.55%	1.22%
sep. (MHz)	0.70	0.54
G (Ohm)	198.8	196.6
r/Q (Ohms)	374	394
E_{peak}/E_{acc}	2.55	2.36
E_{peak} (MV/m)	42.6	40
B_{peak}/E_{acc} (mT/MV/m)	4.95	4.79

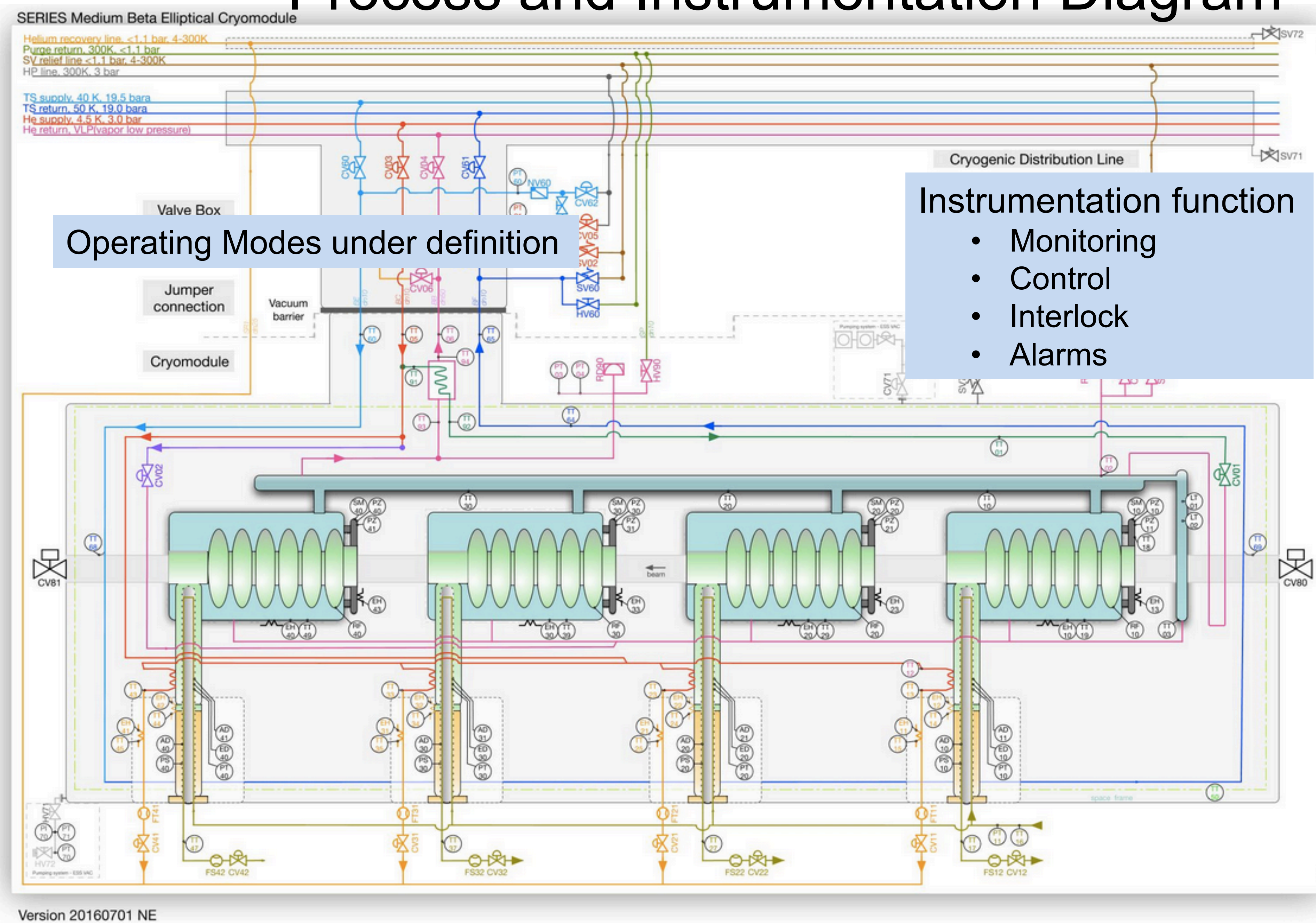
Step 2: M-Elliptical Cavity Cryomodule Technology Demonstrator

@ Saclay
@ Lund



M-ECCTD = 3 CEA cavities + 1 LASA cavity

Process and Instrumentation Diagram

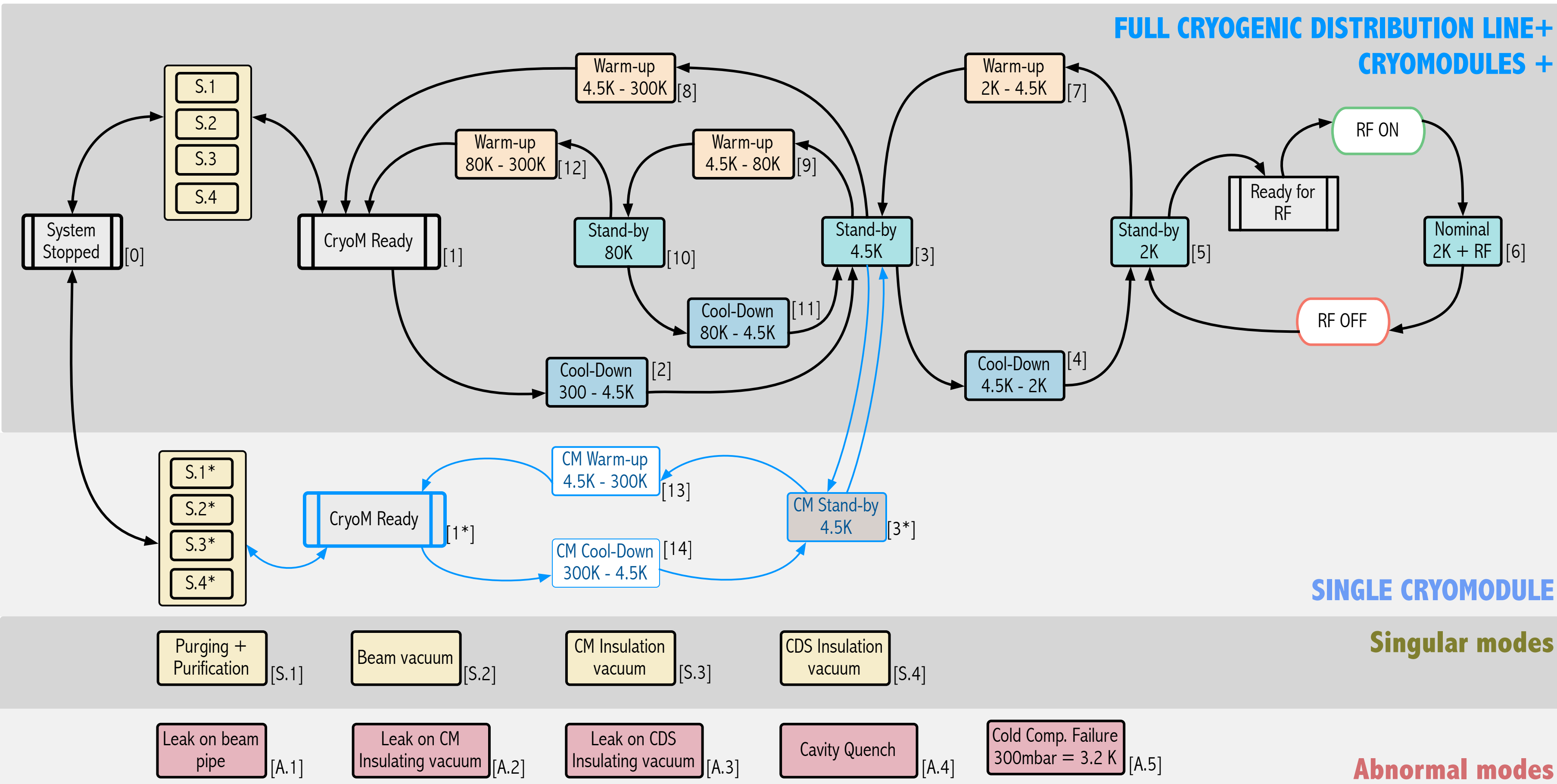


Operating Modes under definition

Instrumentation function

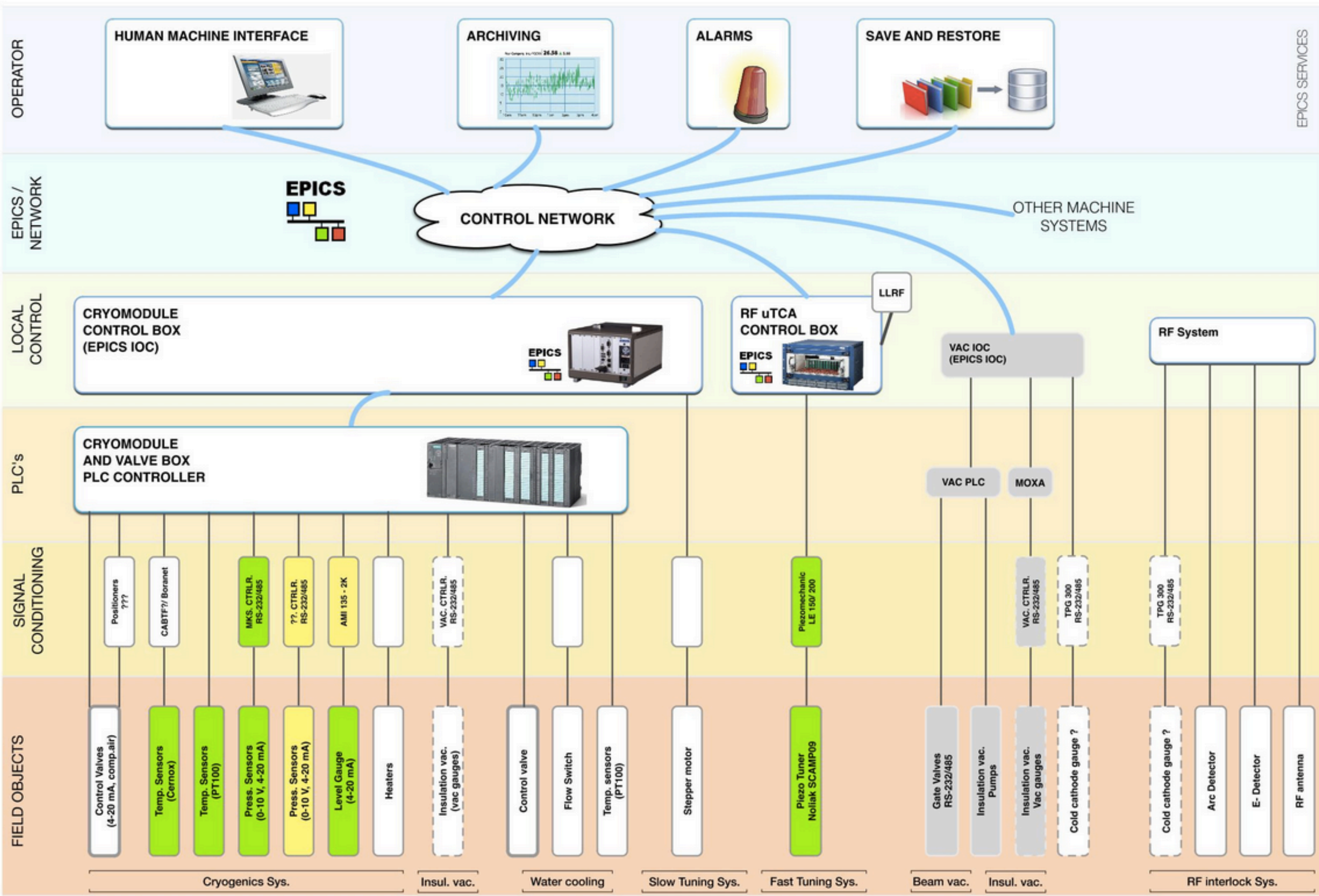
- Monitoring
- Control
- Interlock
- Alarms

Cryogenic operating modes

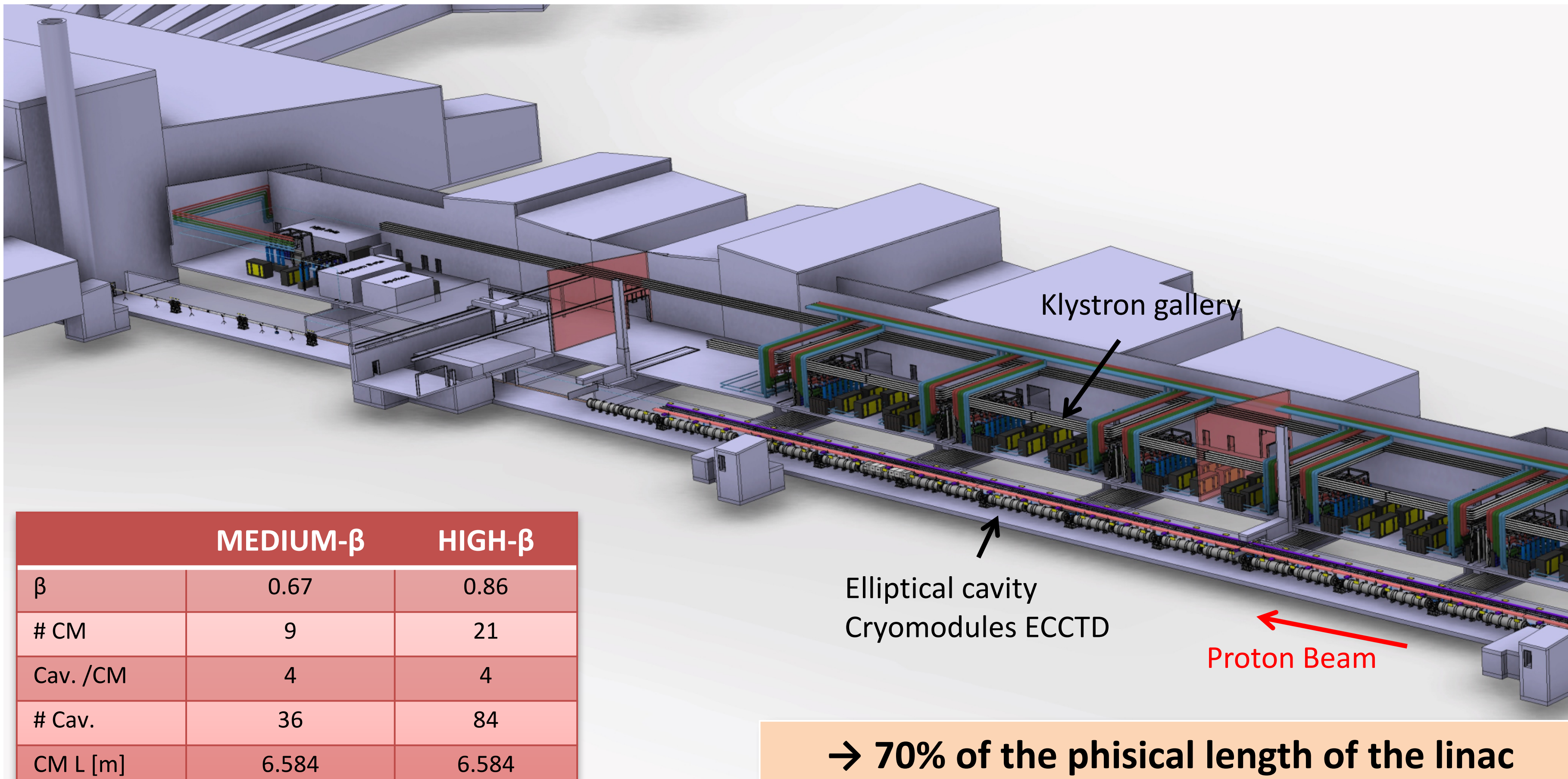


Acknowledgment : N Elias

Control integration



Superconducting linac

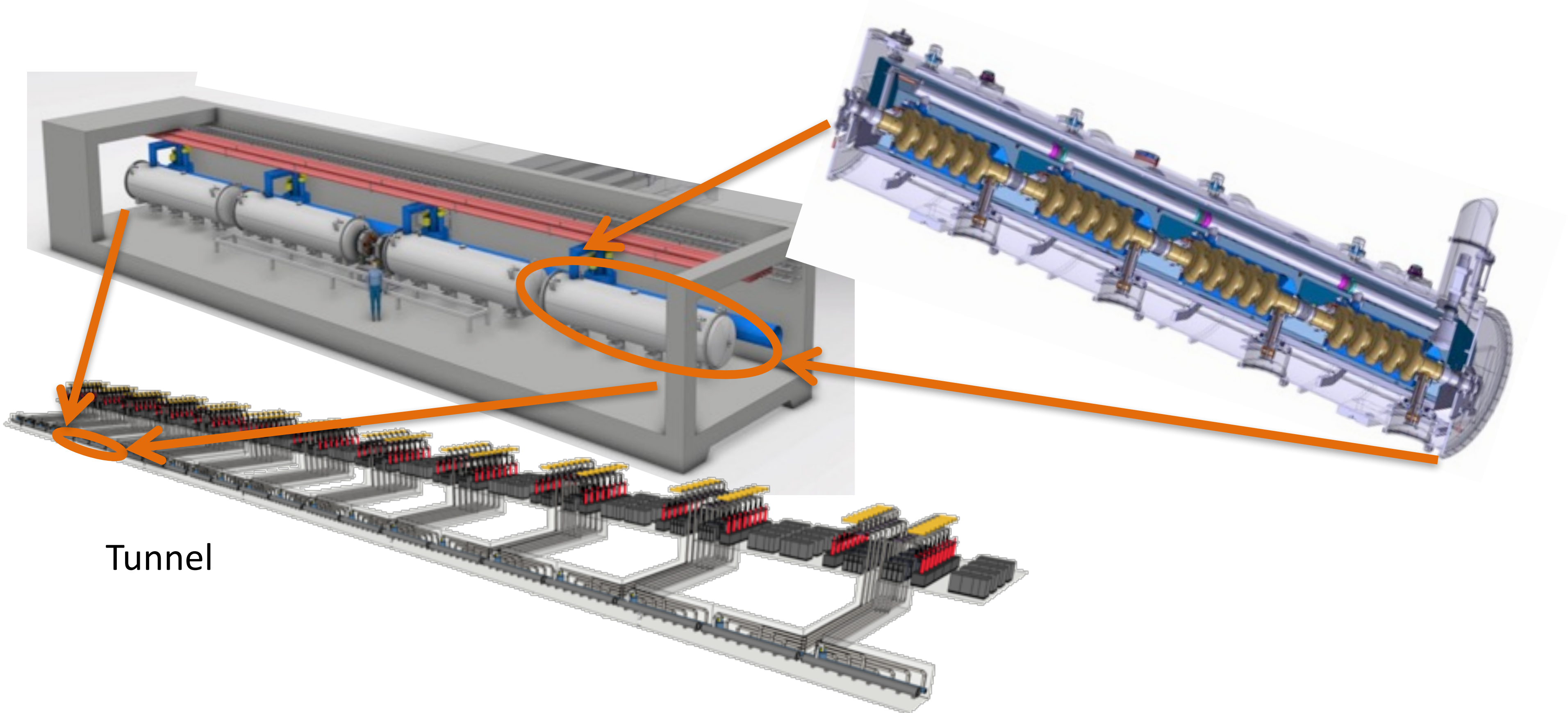


	MEDIUM-β	HIGH-β
β	0.67	0.86
# CM	9	21
Cav. /CM	4	4
# Cav.	36	84
CM L [m]	6.584	6.584
Sector L [m]	77	179

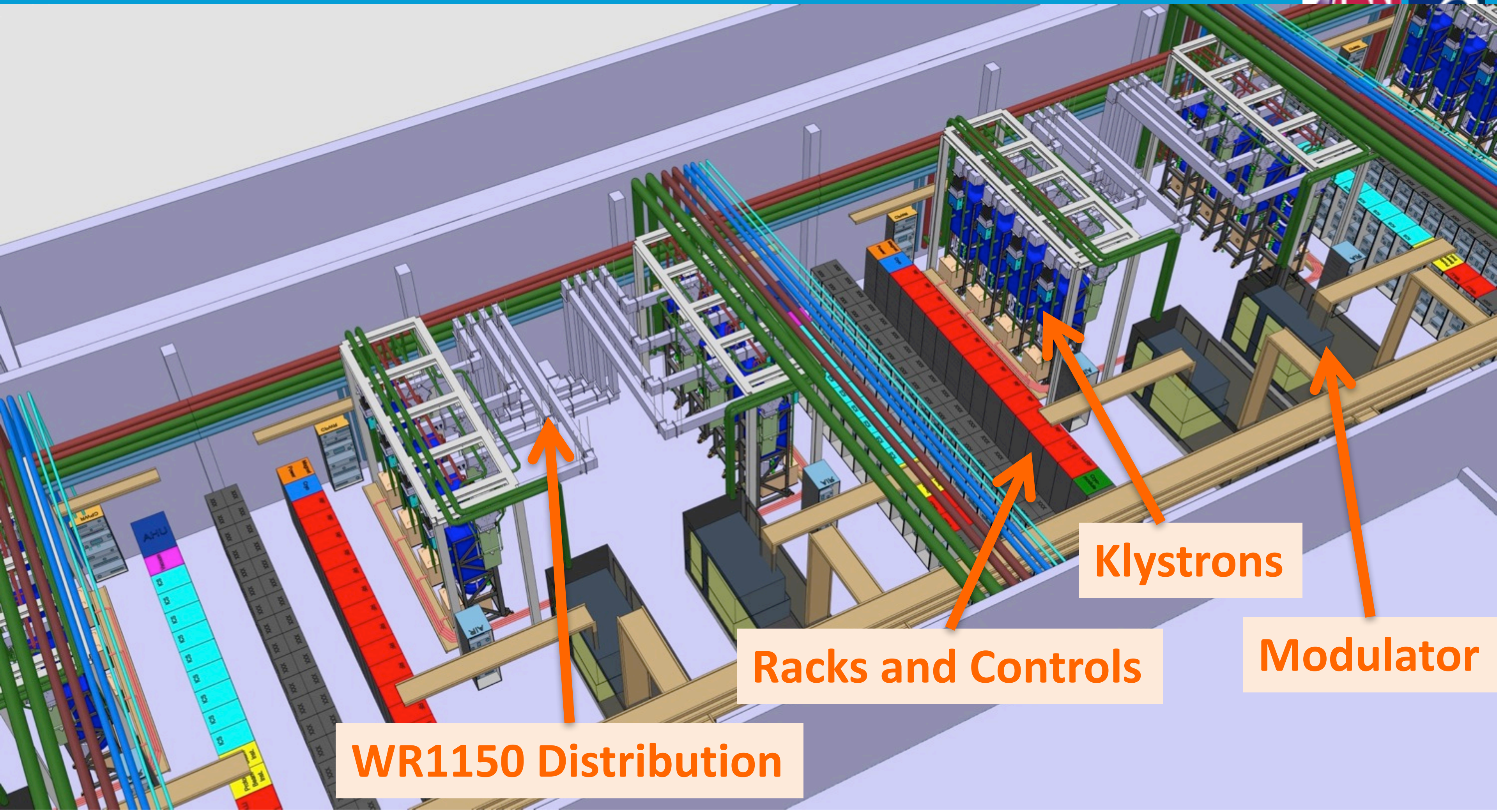
→ 70% of the phisical length of the linac
→ 95 % of the proton acceleration

Elliptical (704 MHz) RF System Layout

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



Elliptical (704 MHz) RF System Layout



4.5 Cells of 8 klystrons for Medium Beta

10,5 Cells of 8 klystrons (IOTs) for High Beta

Thank you for your attention!

Acknowledgements & References

ESS SRF Linac Collaborative Space: https://confluence.esss.lu.se/display/CRYOM

- 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
- NPAS, https://npap.eu/

Few books

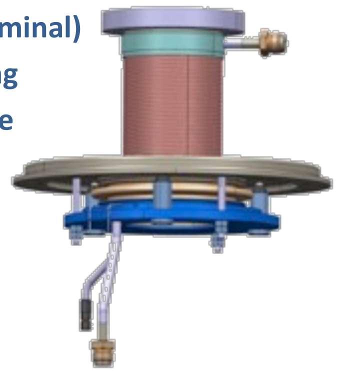
- RF Linear Accelerators, T.P. Wangler, Wiley, 2008
- RF Superconductivity for Accelerator, H. Padamsee, J. Knobloch, T. Hays, Wiley, 2011
- An introduction to particle accelerators, E.J.N. Wilson, Oxford Univ. Press, 2001
- An introduction to the physics of high-energy accelerators, D.A. Edwards & M.J.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

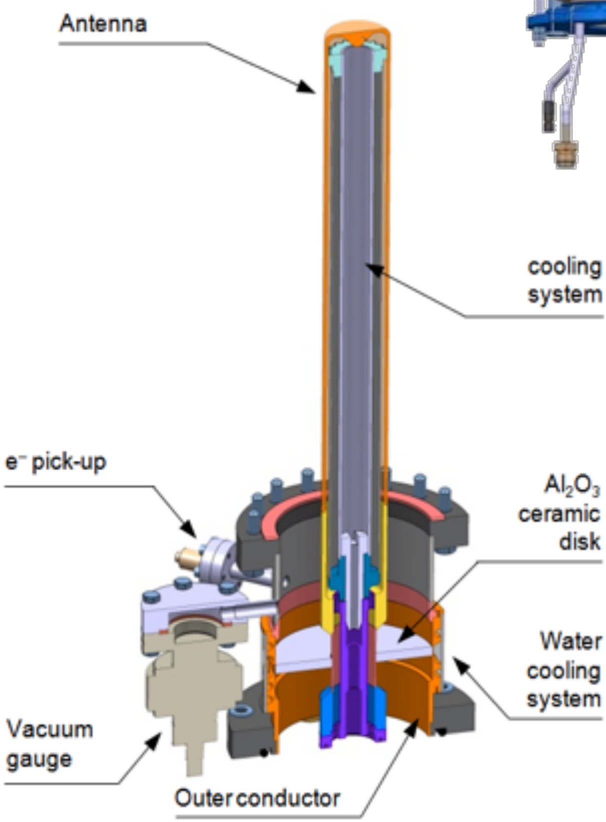
Extra slides

The Spokes Cryomodule

EUROPEAN SPALLATION SOURCE

- 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 $\Delta f/\Delta z$ = 130 kHz/mm