

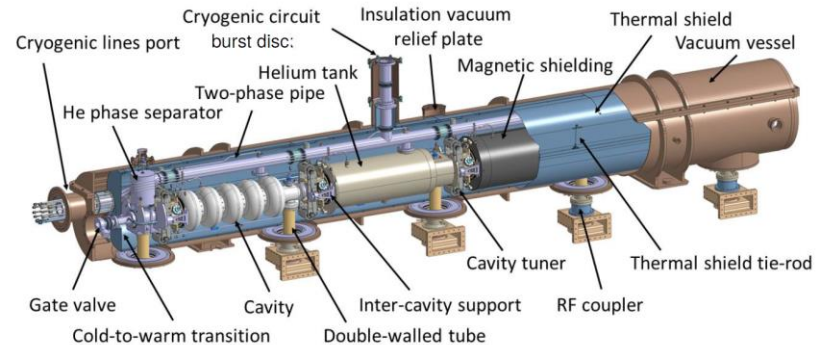
The Design of the 704 MHz Cryomodule

Luca Dassa

Outline

- History: from SPL cryomodule to HG cryomodule
- HG cryomodule: few hints
- Design status
- Cost evaluation
- Documentation
- Compliance with standards
- Towards PERLE

SPL (Superconducting Proton Linac) Short Cryomodule foreseen as a low power injector into PS2 (that would have replaced PS)



CEA – Saclay (F)

- Design of **$\beta=1$ cavities**
- Design & construction of **4 helium vessels for $\beta=1$ cavities**
- Supply of **4 tuners**
- Testing of RF couplers

CNRS – IPN – Orsay (F)

- Design of **prototype cryo-module cryostat**
- Construction of the vacuum vessel
- Design of **cryostat assembly tools**

CERN

- 4 $\beta=1$ cavities in industry + 1 in-house
- 4 RF couplers
- Test bench for studying the support strategy



**SPL (Superconducting Proton
Linac) Short Cryomodule**

SPL team
(CERN, CEA –
Saclay, CNRS –
IPN – Orsay)



Superconducting Proton Linac is
cancelled



**HG (High Gradient)
Cryomodule**

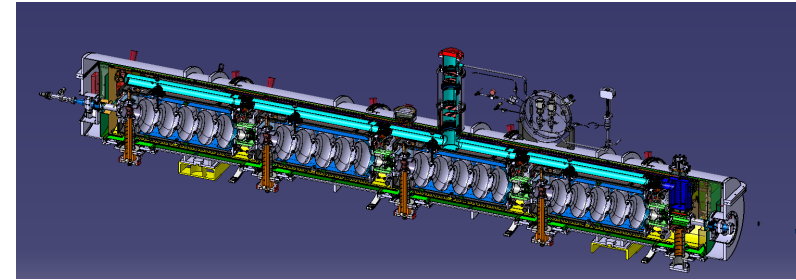
HG team (new
CERN team)

RF-related goals :

- RF tests on a multi-cavity assembly driven by a single RF source.
- Demonstration of reachable accelerating gradients and Q-values for 704 MHz, multi-cell, $\beta=1$ cavities. Establishment of state of the art bulk-Nb technology at CERN.
- RF testing of cavities in horizontal position, housed in their helium tanks, tuned, and powered by machine-type RF couplers
- Test critical components like RF couplers, tuners, HOM couplers in their real operating environment

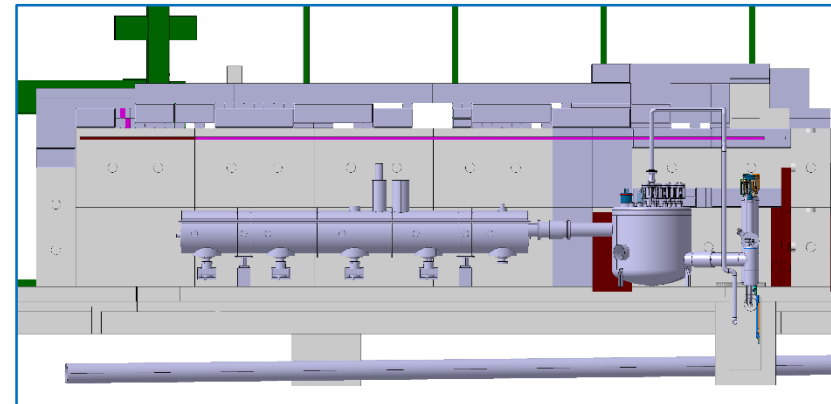
Cryomodule-related goals :

- Validation of design for innovative supporting of cavities via the RF couplers
- Learning of the critical assembly phases:
 - handling of long string of cavities with complete RF coupler
 - alignment/assembly in the cryostat
- Validation through operational experience:
 - Cool-down/warm-up transients and thermal mechanics
 - Gas-cooled RF coupler double-wall tube (active cooling effect on cavity alignment)
 - Alignment/position stability of cavities
 - Cryogenic operation (He filling, level control, etc.)

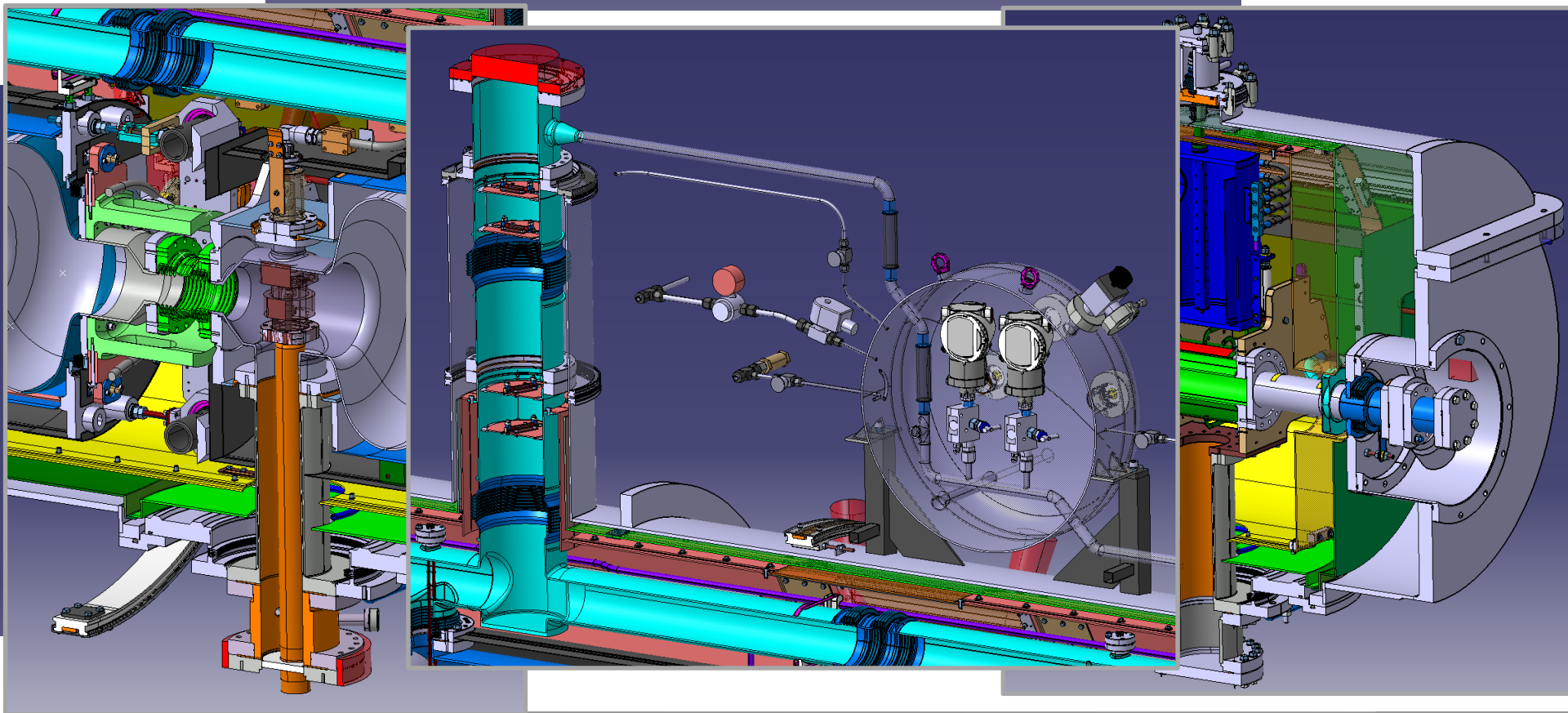
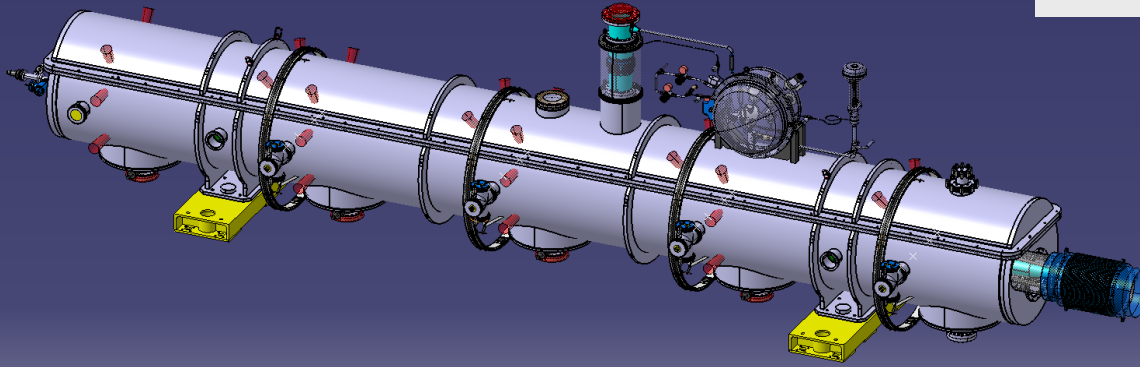


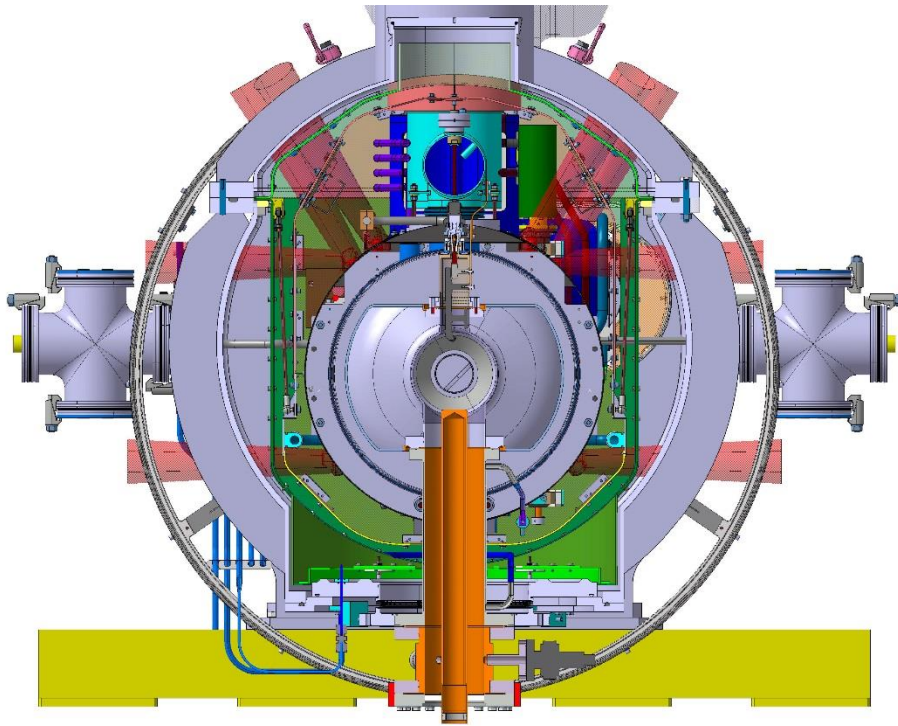
CERN

- Finalization of drawings
- Clean room tools
- Procurement of remaining components
- ...

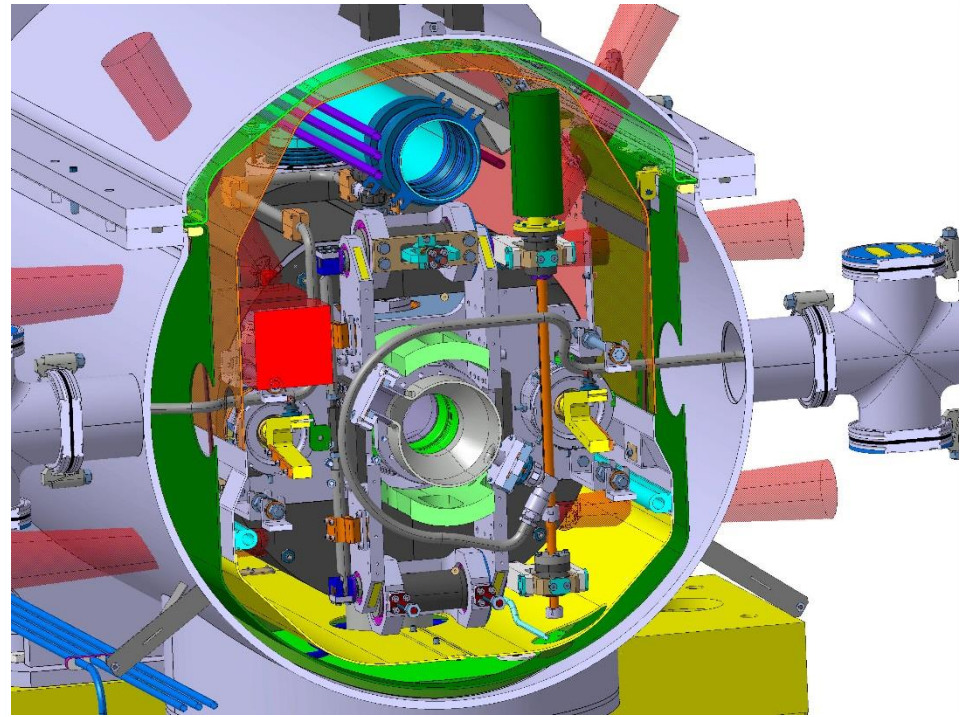


Test on RF bunker (lateral view)

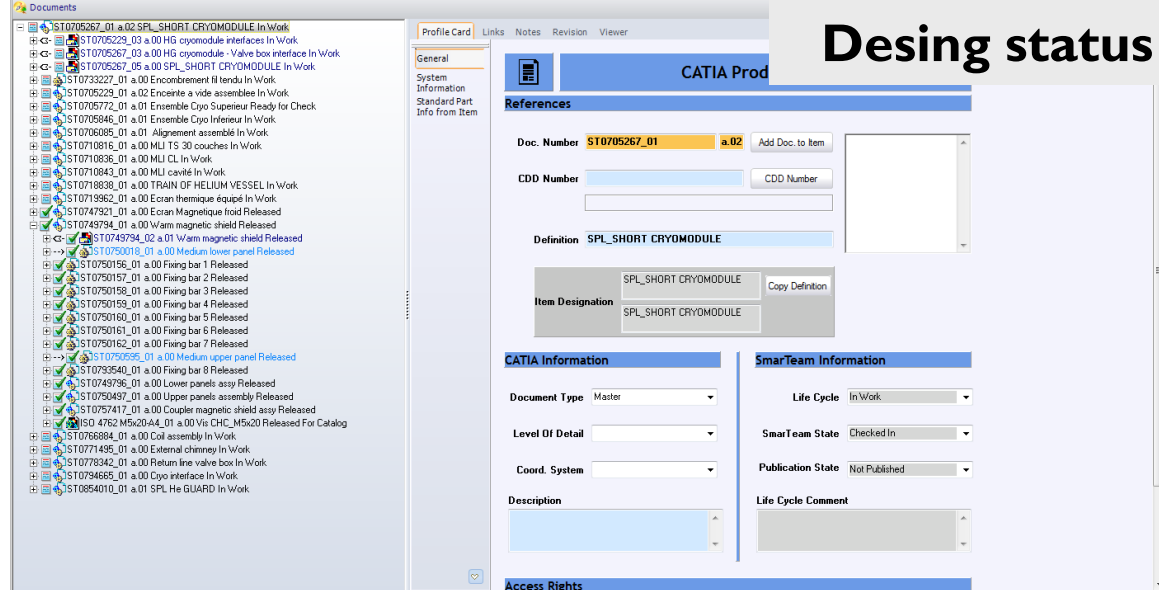




Cross section on the coupler axis



Cross section in the intercavity region



Design activities completed

- For the cryomodule: 3D + 2D in Catia V5, stored in SmarTeam are available.
- Not all the 2D are valid for execution (intercavity bars, mod on tuners, ext cryog components)

Design activities partially completed

- Cryostating tools

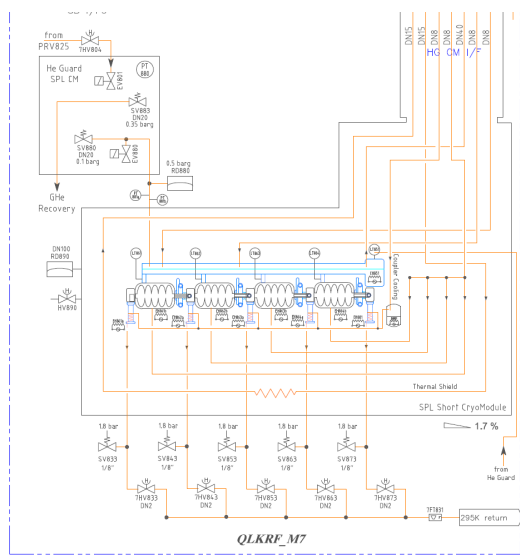
Design activities to do

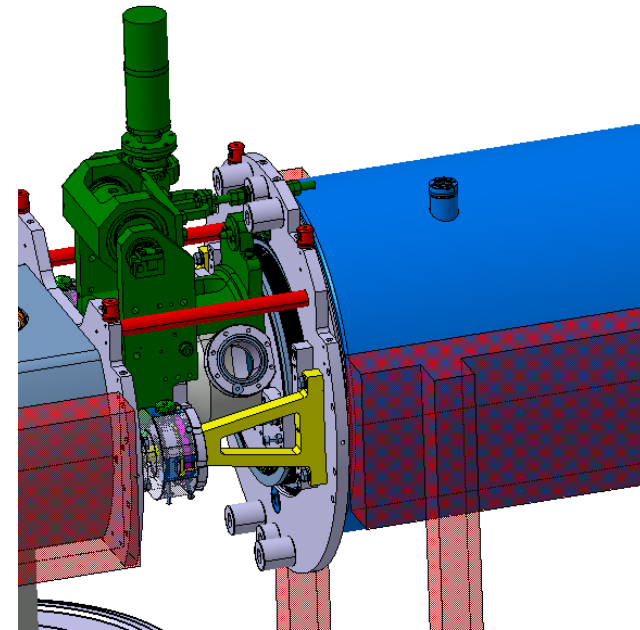
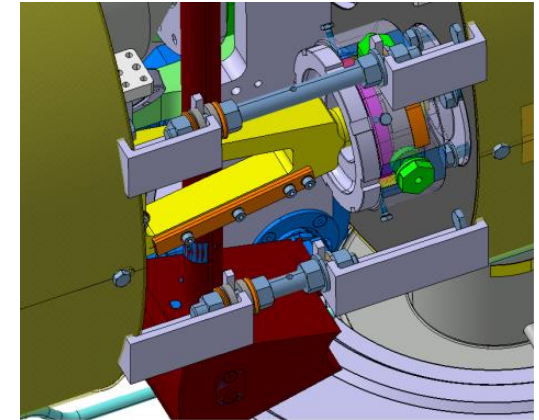
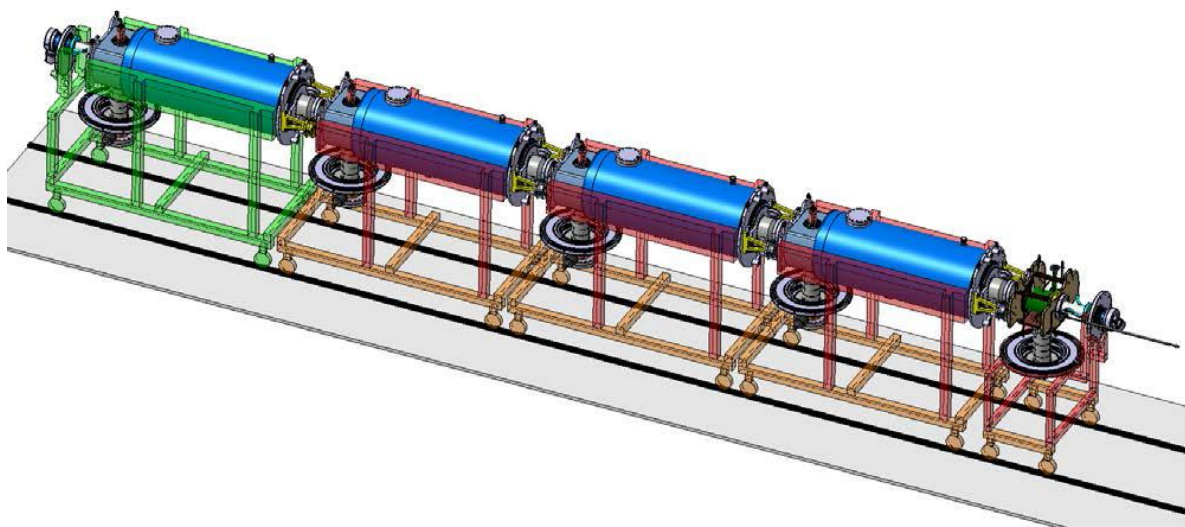
- Tools for clean room assembly

Engineering activities: collection of documentation related to calculation, schemas, procedures, ...

Engineering activities to do

- Safety devices finalization of sizing (linked to the pressure for the cavity (0.5 barg max today))
- Alignment of cavities (procedure)
- Clean room and cryostating procedures (to finalize)
- Follow-up of cavity displacement during transitory: wire system not studied / possibility to integrate laser system

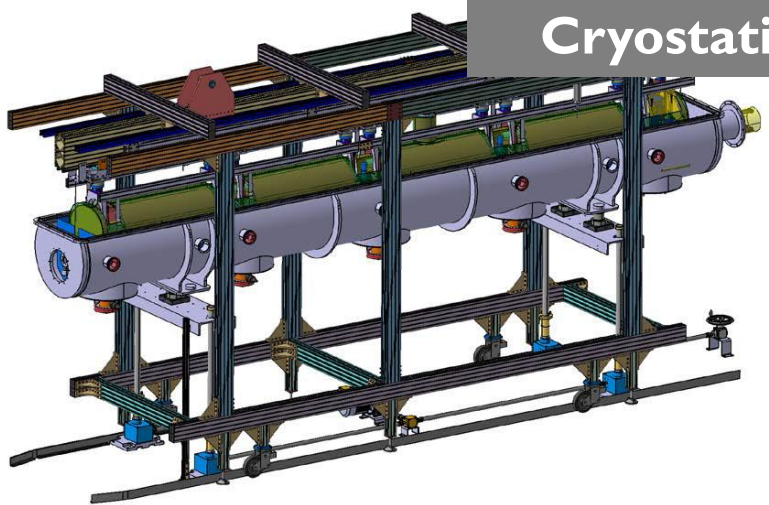
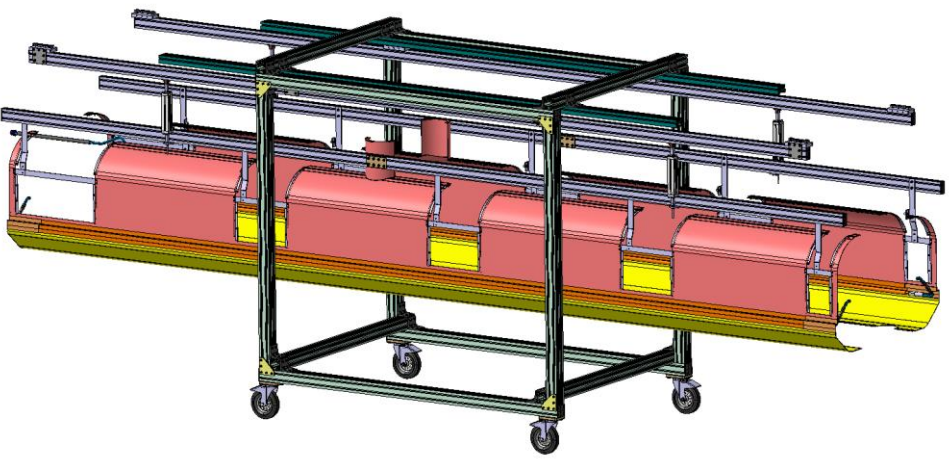




- Low lateral flexibility for the coupler bellows
- Torsion to be avoided on intercavity bellows
- Limited space for assembly in the intercavity region

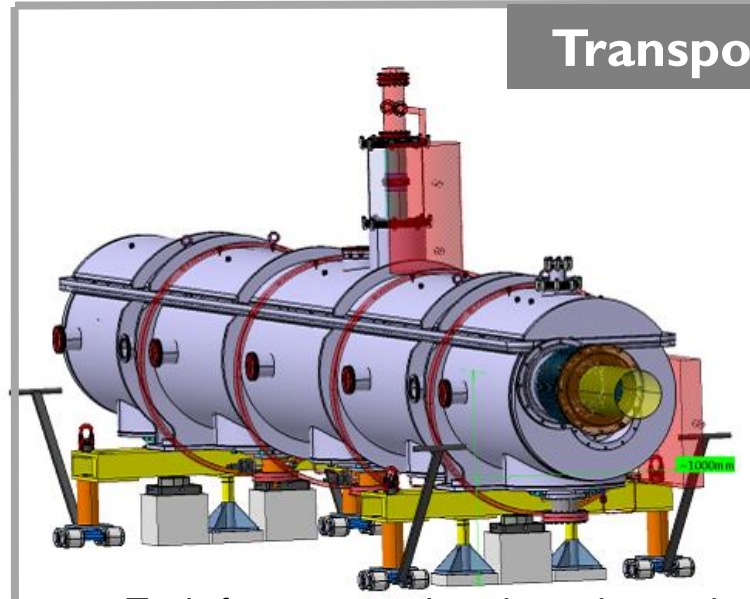


- Modification on the tuner frame validated
- Preliminary procedure available but not validated
- Coupler assembly direction to validate
- Tools for clean room assembly to design



Tools to be modified (modification on cryo lines, on thermal shield, on intercavity supports)

Cryostating procedure to update with the new shielding (and, in addition, door knobs assembly from bottom, as close as possible to the test bunker)



Tools for transport have been designed

	CRYOMODULE		
	total	achieved	to be planned
	[kChF]	[kChF]	[kChF]
Couplers + pick-ups	360	360	0
HOM (proto, material, 8 HOMs, design office)	561	40	521
in kind contribution for cryomodule (SPL design, vacuum vessel, tuners)	320	320	0
Design office (cryomodule revision + tools for clean room + tools for cryostating)	190	100	90
Cryogenic system	220	180	40
Cold magnetic shielding, Warm magnetic shield, Thermal shield	325	0	325
Management support (fellow) + Quality Assurance	274	274	0
Various	640	250	390
Tooling for Clean Room assembly and cryostating + manpower	560	60	500
total without cavities	3450	1584	1866

	CAVITIES		
	total	achieved	to be planned
	[kChF]	[kChF]	[kChF]
R&D + tools for manufacturing and testing	1194	1194	0
material (Nb)	420	420	0
4 cavities produced by RI + 1 mono-cell	375	375	0
1 CERN cavity	175	175	0
cavities	2164	2164	0



	TOTAL		
	total	achieved	to be planned
	[kChF]	[kChF]	[kChF]
cavities	2164	2164	0
total without cavities	3450	1584	1866
total with cavities	5614	3748	1866

	CRYOMODULE [kChF]
Couplers + pick-ups	260
HOM (8 HOMs)	432
vacuum vessel, tuners	240
Design office	50
Cryogenic system	220
Cold magnetic shielding, Warm magnetic shield, Thermal shield	325
Management support (fellow) + Quality Assurance	141
Various	640
Clean Room assembly and cryostating: manpower	100
total without cavities	2408

	CAVITIES [kChF]
material (Nb)	420
4 cavities produced by RI + 1 mono-cell	375
cavities	795



	TOTAL [kChF]
cavities	795
total without cavities	2408
total with cavities	3203



Cost 1st cryomodule – cost 2nd cryomodule = 2411 kChF

- High Gradient cavities
 - High Gradient cryo-module
 - Project management
 - Minutes
 - Planning
 - Presentations
 - 1539688 (v.1) 02/09/2015 - Status of the SPL Short cryomodule project
 - 1867351 (v.1) High Gradient cryomodule: status and future
 - 1872464 (v.1) High Gradient Study: Status Report
 - Cryo-module
 - Dressed cavity with tuner
 - Interactivity connection
 - Cavity train
 - Drawings
 - RF components
 - Thermal shield
 - Magnetic shield
 - Cryogenics
 - Instrumentation
 - Vacuum vessel, vacuum system and related components
 - Support jacks
 - Cryo-module assembly
 - Safety
 - General services
 - Installation
 - Survey and alignment
 - Inspection and tests
 - test
 - 1703854 (v.1) Interface code list for High Gradient cryomodule
 - Pictures
 - 1747708 (v.1) Pictures
 - Flange allocation for the High Gradient cryomodule
 - 1585133 (v.5)

- Drawings
 - 1561320 (v.1) Flanges coupler SPL
 - 1573279 (v.1) Upper cryoline drawings
 - 1573281 (v.1) Lower cryoline drawings
 - 1573292 (v.1) Vaporisator drawings
 - 1573293 (v.1) Cold-Warm transitions drawings
 - 1611601 (v.1) Inter-cavity bars
 - 1702280 (v.1) Interfaces
 - 1704632 (v.1) Warm magnetic shield gabarit
 - 1704642 (v.1) Thermal shield
 - 1704645 (v.1) Warm magnetic shield
 - 1715252 (v.1) Vacuum vessel tests drawing folder
 - 1585600 (v.1) Bellows
 - 1716283 (v.1) Cold magnetic shield drawings
 - 1722276 (v.2) Inter-cavities connection drawing folder
 - 1740796 (v.1) Cryostating toolings
 - 1750684 (v.1) Tuner supports
 - 1756492 (v.1) Outside valve panel
 - 1756513 (v.1) Warm magnetic shield toolings
 - 1756487 (v.1) Magnetic shield samples
 - 1800904 (v.1) Helium guard drawings
 - 1801248 (v.1) Chimney drawings
 - 1802245 (v.1) Cryomodule main drawings
 - 1809692 (v.1) Supporting frames
 - 1811356 (v.1) Heaters
 - 1835724 (v.1) Spherical bearing prototype
 - 1853276 (v.1) Flexible hoses drawings
 - Drawings (IN2P3 - CNRS definitive version)
 - 1516418 (v.1) SPL Short cryomodule - Drawings for the whole cryomodule
 - 1516420 (v.1) SPL Short cryomodule - Drawings for cryomodule components
 - 1542864 (v.2) SPL Short Cryomodule - Drawings for Cryostating tools
 - 1547971 (v.1) Ensemble palier support dossier IN2P3 21B1010

Documentation is available in EDMS (CERN storage system for document)

Main assumption for SPL and HG cryomodules: Maximum Allowable Pressure to be out of the scope of the Directive 68/2014 (PED)

- $PS \leq 0.5 \text{ barg} \Rightarrow$ out of the scope of the Directive 68/2014 (PED)
- $V \approx 340 \text{ l}$

Cryogenic lines can accept higher Maximum Allowable Pressure but there is no calculation of the maximum.

Manufacturing follow-up: welding book is included (NDT considered, based on reasonable assumptions, i.e. 10% on butt welded joints), no Notified Body involved

Only one burst disc (set pressure 0.5 barg) is installed : preliminary sizing is not compliant with standards but acceptable from a safety point of view

Main assumptions: new cavities, new HOMs (2 x cavity) actively cooled, beam presence, power couplers to be reused

- New cavities, smaller than the actual ones => positive impacts
- Higher heat loads (250 W for Perle / 200 W for HG) => seems not to be a problem
- 2 HOMs per cavity => modification to thermal shields, cold magnetic shields, cryogenic lines (minor) / volume reserved for wire system could be not anymore available

Advantages of re-using the SPL/HG design:

- Well-advanced development
- Detailed 3D environment available
- Available components (≈ 600 kChF)
- Possibility to test some interesting technical solution (i.e. supporting via main coupler)

Disadvantages of re-using the SPL/HG design:

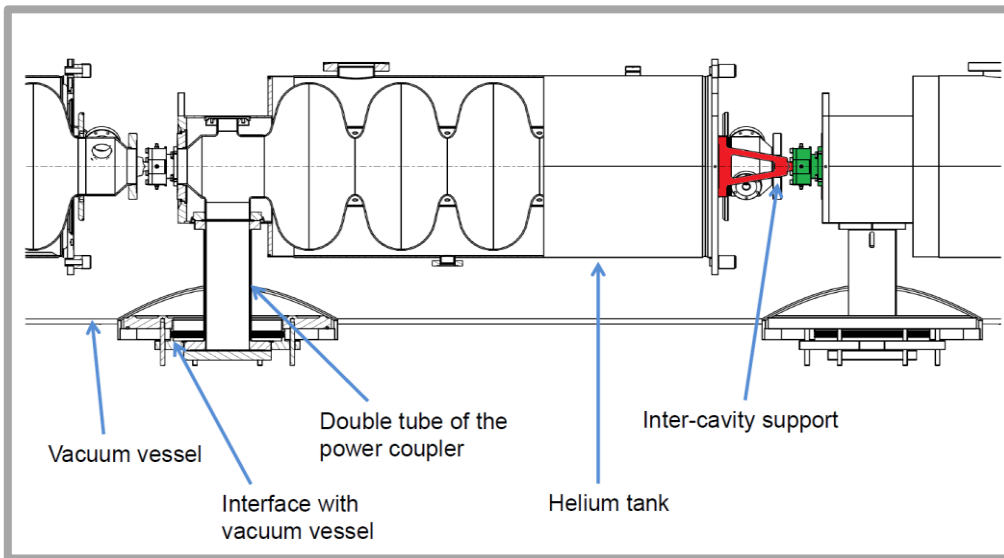
- Constraints from old technical choices (vertical cryostating, ...)
- Existing components (i.e. tuner, main power couplers)
- Actively cooled HOMs require some compromise and modifications to cryo lines, being now manufactured

Thank you...

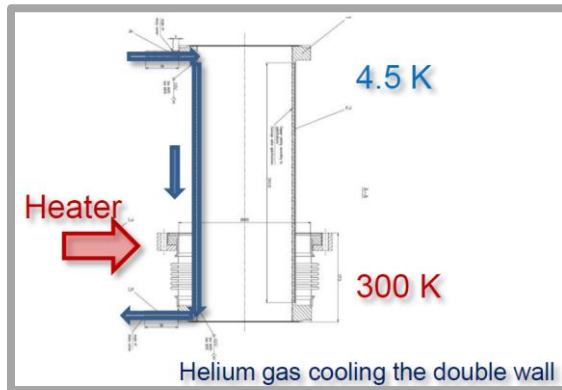


Back-up slides

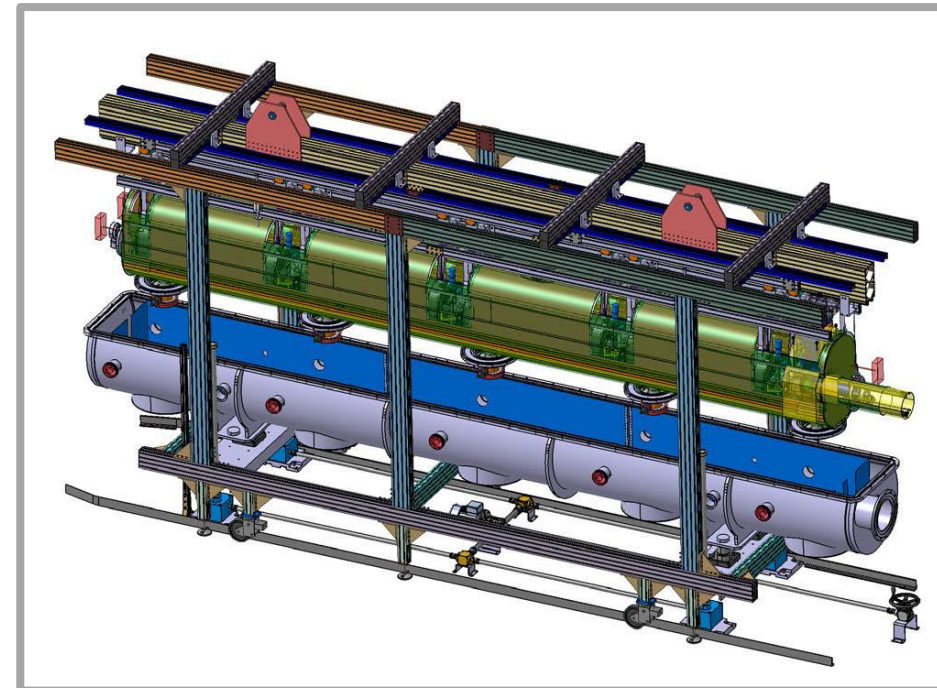
HG cryomodule: few hints



Requirement	Value
β	1
Frequency	704.4 MHz
Q_0	$>5 \times 10^9$
Gradient	25 MV/m
Operat.T	2 K



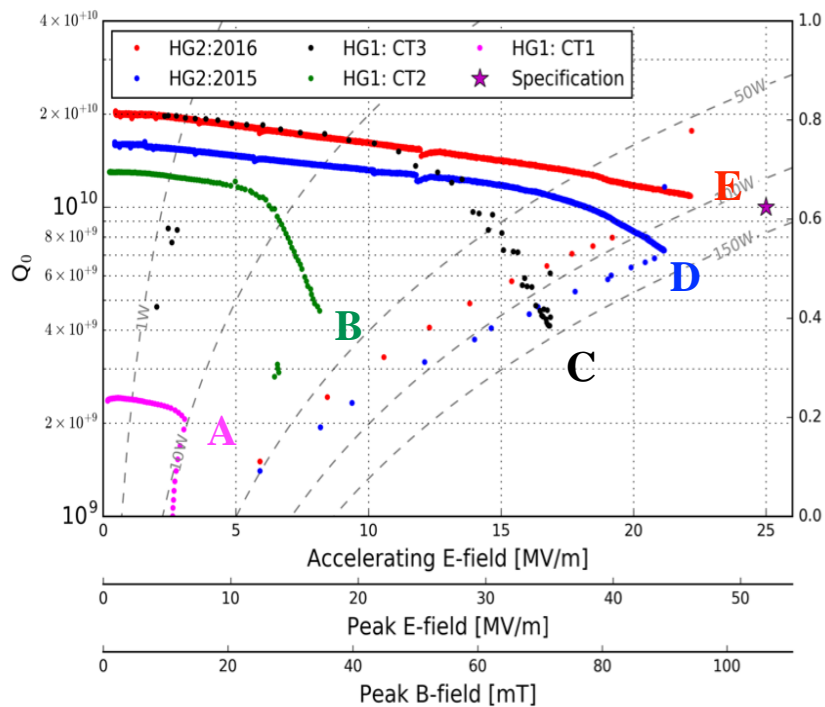
- Innovative supporting condition (coupler)
- Innovative coupler cooling (double walled tube)
- Vertical cryostating



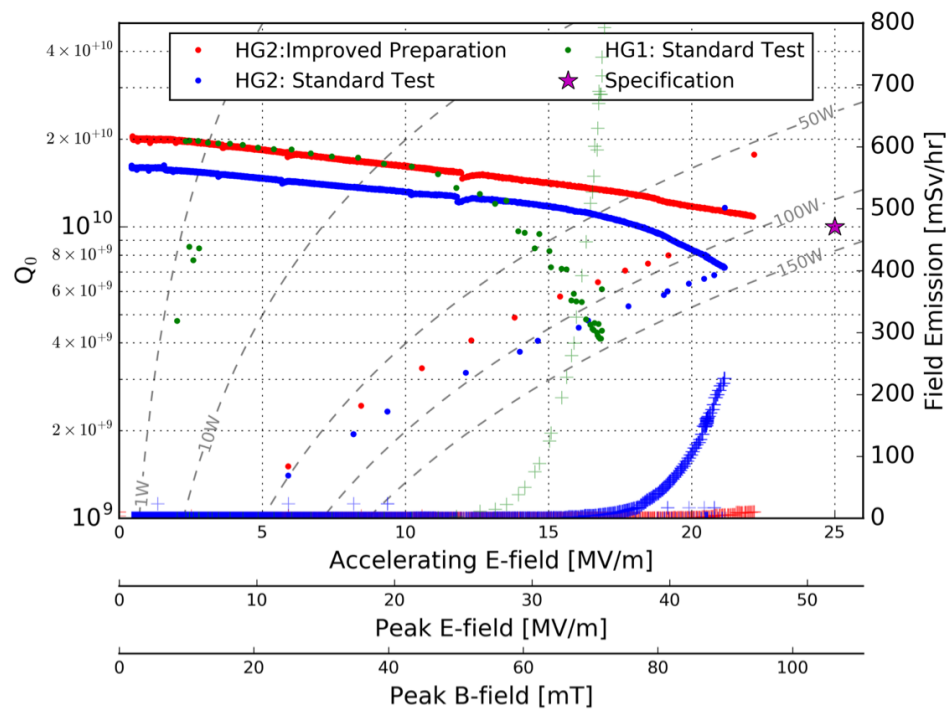
Cold Test	A	B	C	D	E
Cavity	HG1	HG1	HG1	HG2	HG2
Standard HPR	✗	✗	✓	✓	✓
120°C Bakeout	✓	✓	✗	✗	✗
Thermal Gradient Control at T_c	✓	✓	✓	✓	✓
Ambient B-field (<30nT)	✗	✓	✓	✓	✓
Improved Pre-HPR Preparation	✗	✗	✗	✗	✓

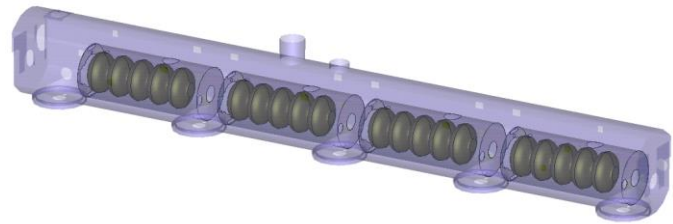
06/07/2016

Evolution of Cavity Performance



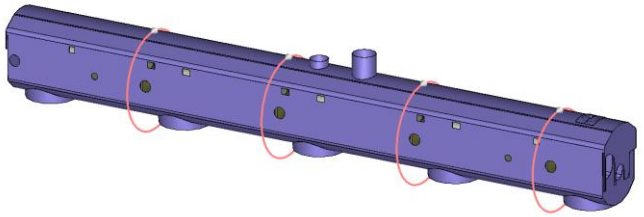
Comparison of HG I & HG2





Warm + cold magnetic shield + compensating coils

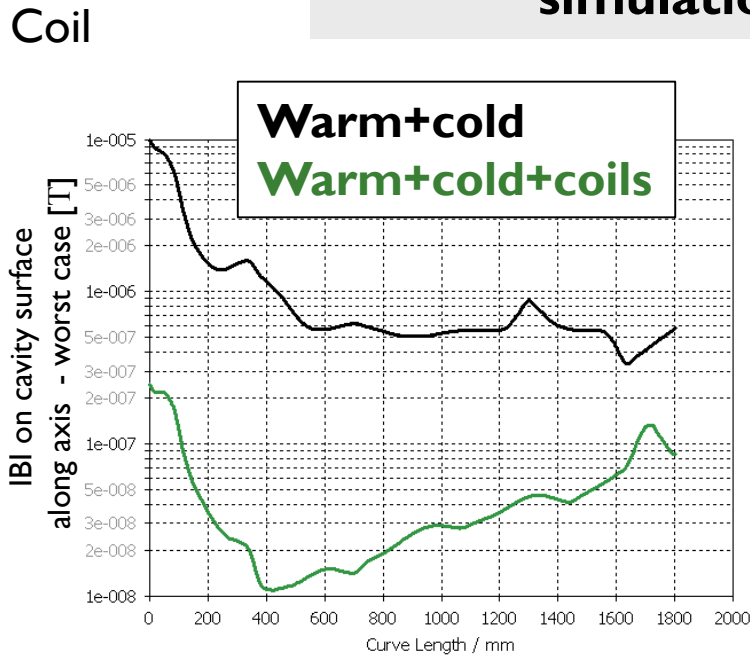
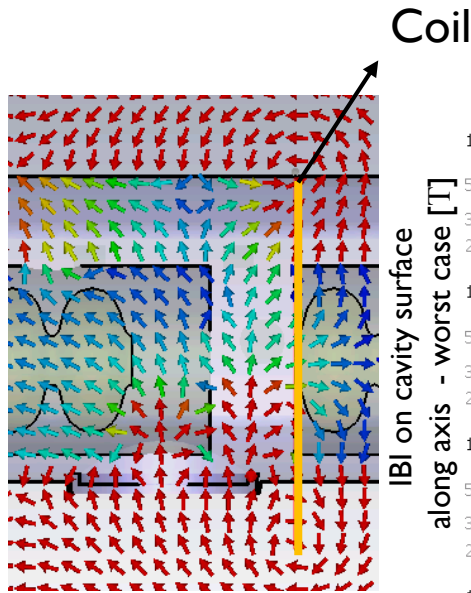
New warm magnetic shield: simulation



Considering also recent studies on quenching, Q deterioration and recovery: $B_{ext} < 0.1 \mu T$!

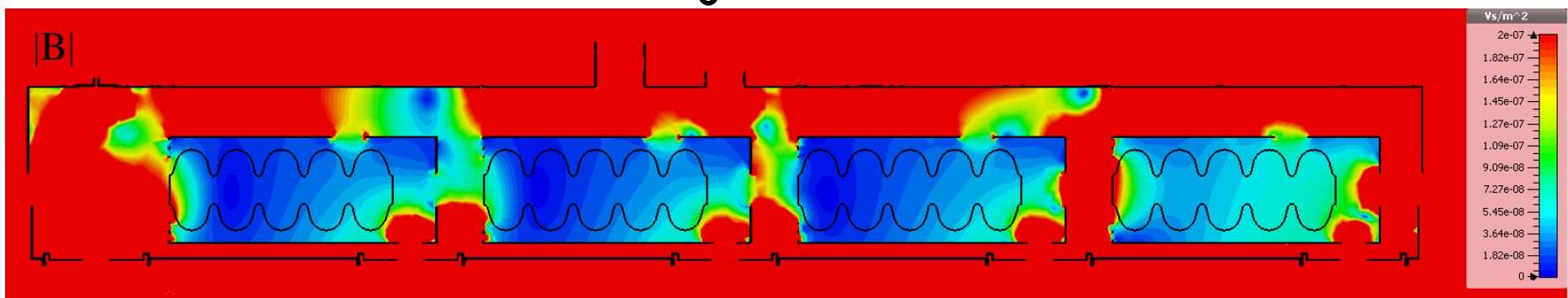
Early results further investigation needed.

3D Simulation results (CST)
2D plot – axial side view

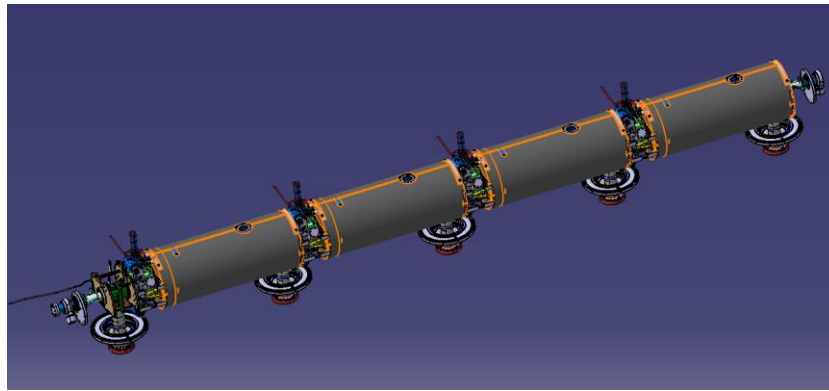


\odot | \ominus $B=50 \mu T$

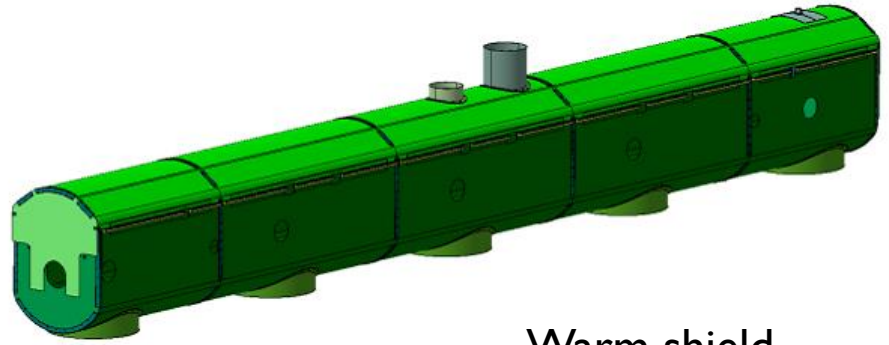
$0.2 \mu T$



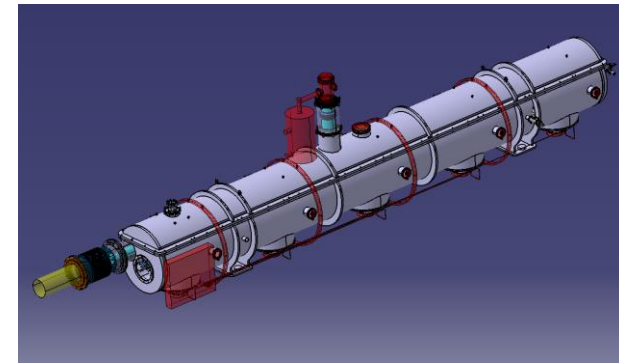
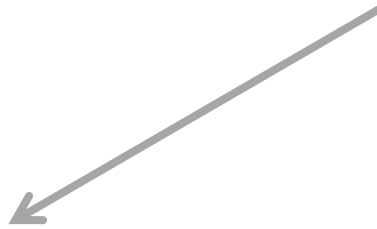
Simulations showed need of warm magnetic shield
Magnetic shielding: 3 levels of shielding strategy resumed -> need to introduce a warm magnetic shield in coupler region



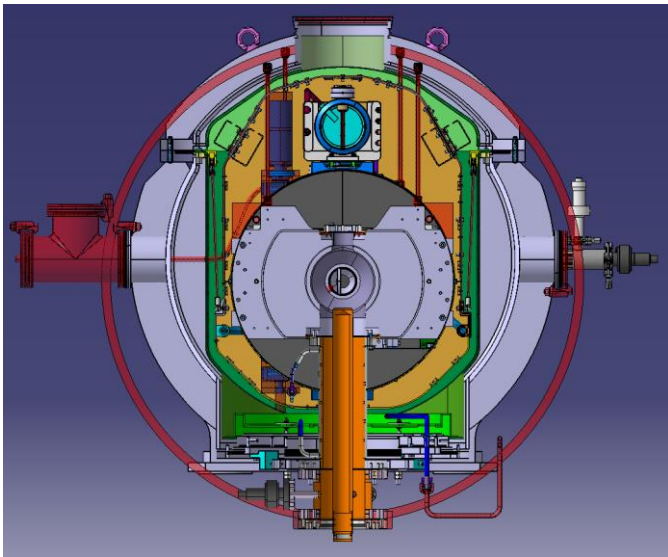
Cold shields



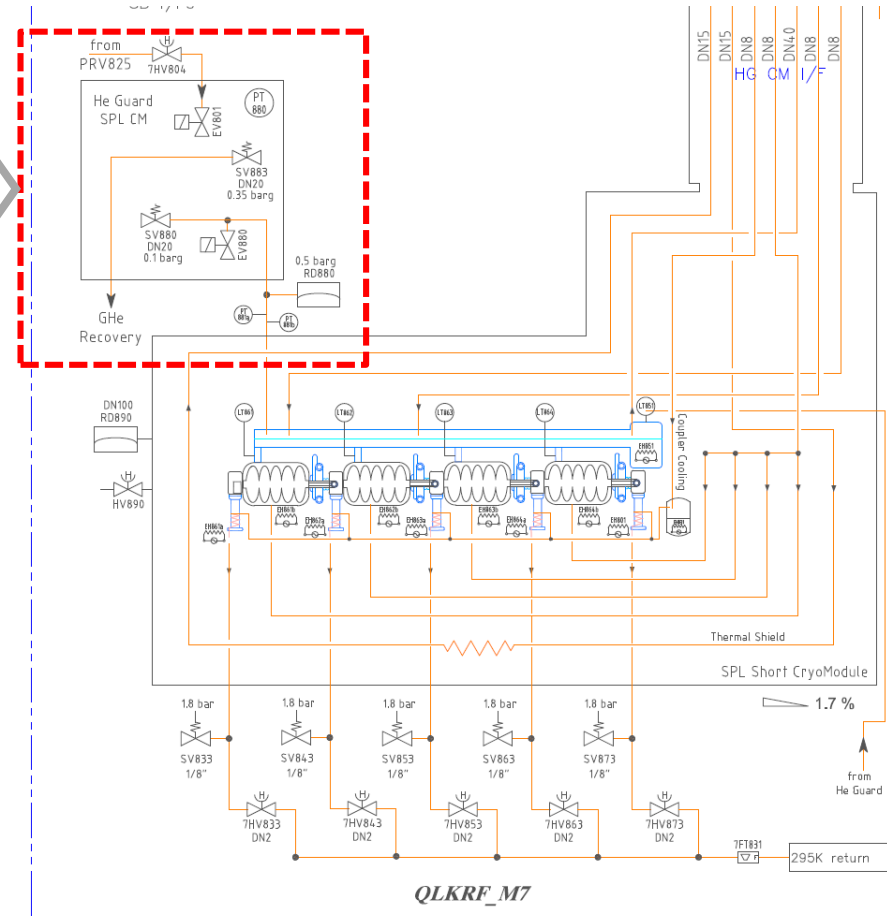
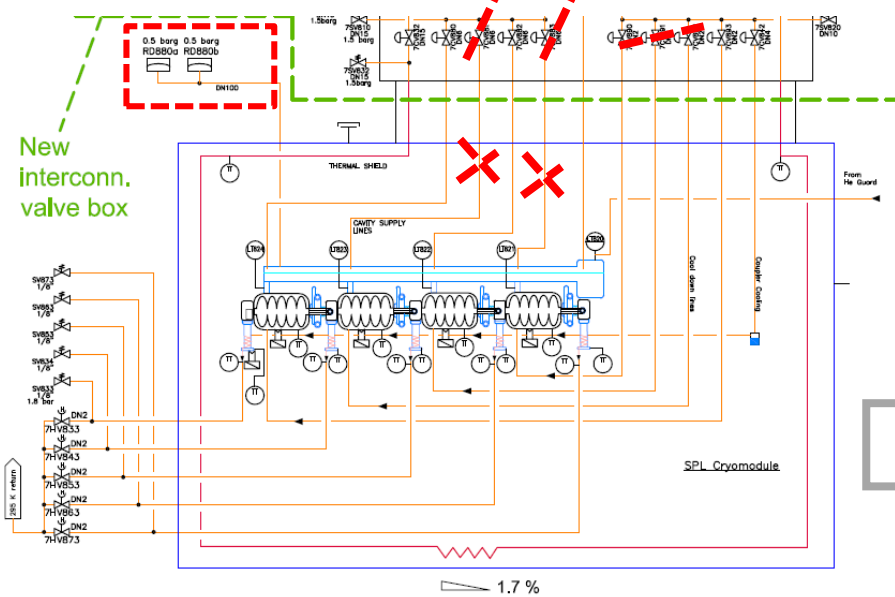
Warm shield



Correction coils



New interconn. valve box

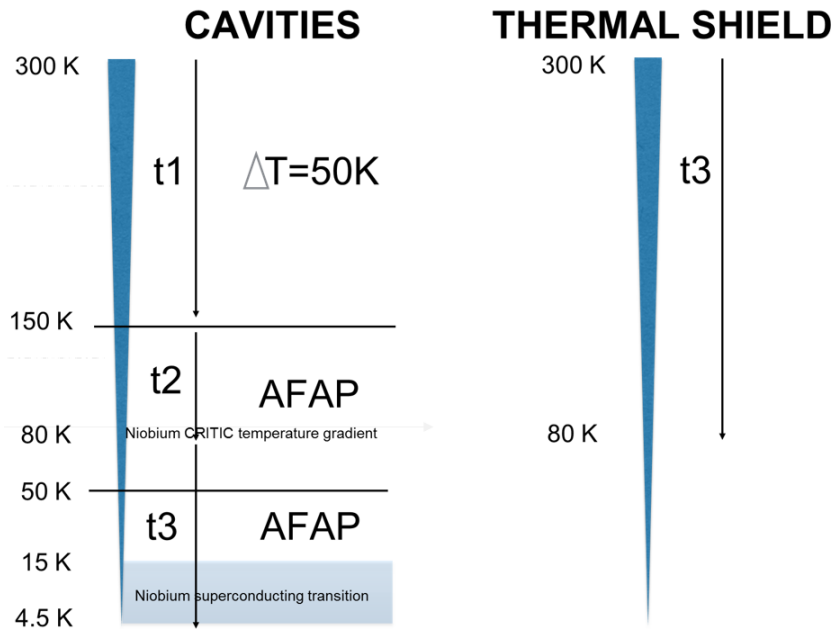


- Operating condition: $p < 0.5$ bar gauge
- Box with valves to reduce peaks during transient
- Redundant cryogenic reduced (but not eliminated)

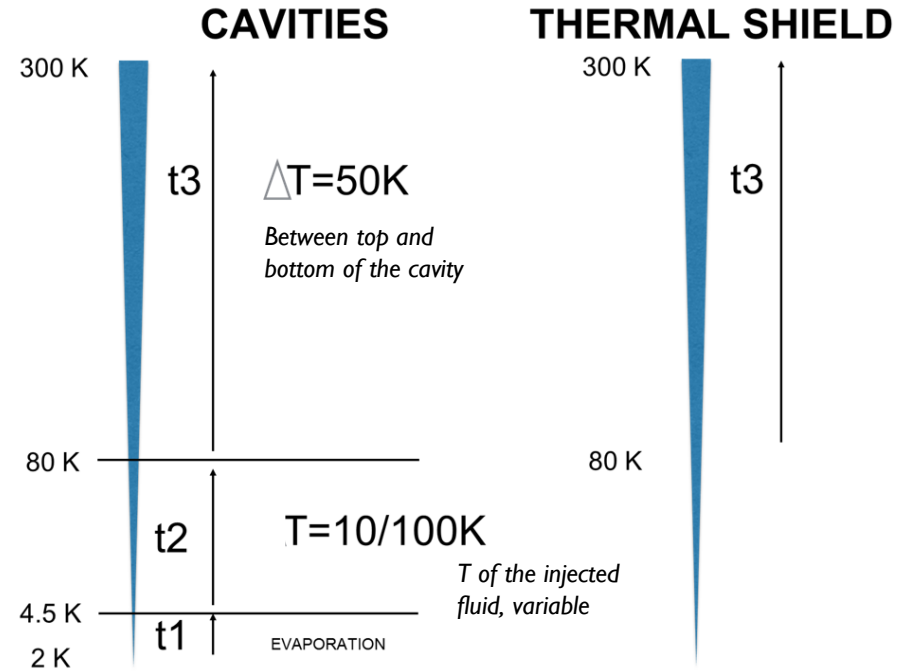
Circuit	Temp. in K	Pressure in bar	Heat load in W	Flow rate in g/s
Thermal radiation shield	50 – 75	1.4 - 1.15	240	1.85
Liquid supply (two cavity circuits)	2.2	1.2	200 dynamic	10 in total
Helium return	2	0.0031	-	10
Power couplers 4x	4.5 – 300	1.25 – 1.05	-	0.1

Proposal to adopt the same operating procedures for CRAB test cryomodule

CoolDown



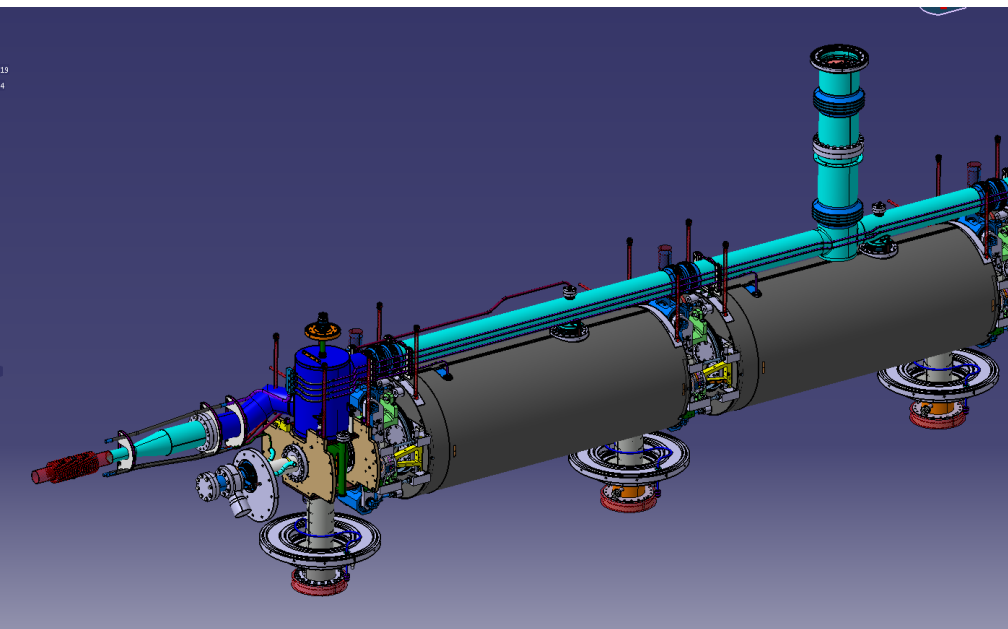
WarmUp



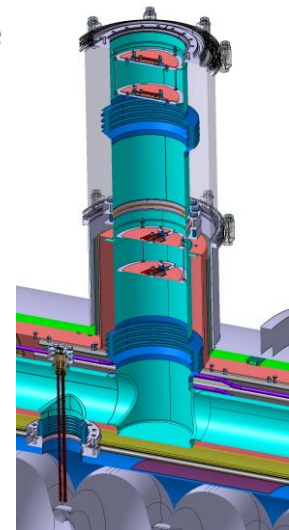
- T1 - Cavities 300 K \rightarrow 150 K (control of $\Delta T \sim 50 K$)
 - T2 - Cavities 150 K \rightarrow 80 K (AFAP)
 - T3 - Cavities 80 K \rightarrow 4.5 K (AFAP)
 - T3 - Thermal Shield 300 K \rightarrow 80 K
 - T4 - Cavities 4.5 K \rightarrow 2 K
- OPTION:
- T3 - Cavities 80 K \rightarrow 15 K (AFAP)
 - + stop at 15 K for thermalization
 - + cavities 15 K \rightarrow 4.5 K

- T1 - Cavities 2 K \rightarrow 4.5 K (Evaporation by heaters)
- T2 - Cavities 4.5 K \rightarrow 80 K (control of $T \sim 10-100 K$)
- T3 - Cavities 80 K \rightarrow 300 K (control of $\Delta T \sim 50 K$)
- T3 - Thermal Shield 80 K \rightarrow 300 K

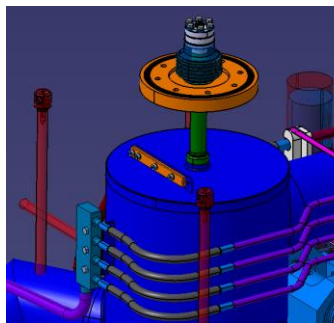
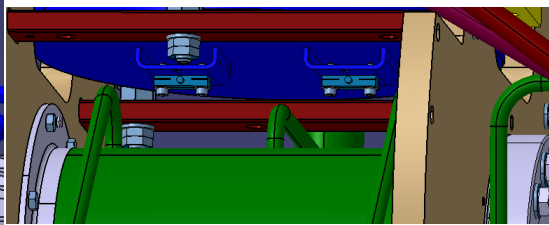
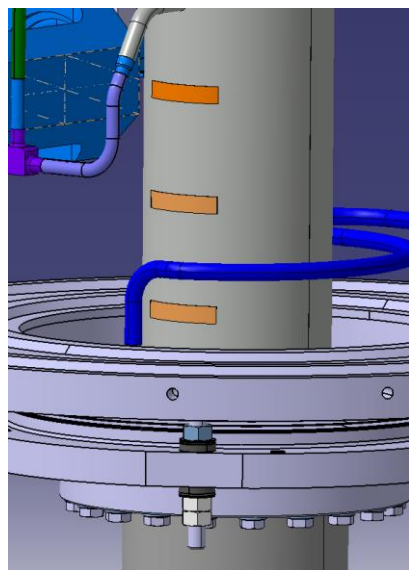




- New chimney with intermediate shields to reduce heat transfer on the biphase tube
- materials : I.4429 (316LN) is the best but not always possible
- Safety devices under dimensioning (past calculations are available but not definitive)
- Welded details compliant with European Standards



ID	Component Name	Location	Quantity	Material	Weight (kg)	Volume (cm³)	Notes
...	Thermometer	...	1	...	...	...	...
...	Heater	...	...	...	...	...	...
...	Level gauge	...	...	...	...	...	...
...	Cold magnetic shield	...	...	...	...	...	...
...	Warm magnetic shield	...	...	...	...	...	...
...	Thermal shield	...	...	...	...	...	...



- integration in drawings
- new magnetic sensors in the intercavity region and inside the He vessel (TBC)
- flow meter installed in the valve box

- Thermometer
- Heater
- Level gauge
- Cold magnetic shield
- Warm magnetic shield
- Thermal shield
- Step motor
- Piezo
- Potentiometer
- M- switch
- Magnetic sensor
- Head for optical wire position monitor
- Pressure sensor
- Pick-up

