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SOURCE

The ESS cryomodules: from design to fabrication

Industry-Academia Matching Event on Superconductivity

Madrid
2013 May, 27th

Christine Darve

704 MHz SRF LINAC Lead Engineer
and
WP5 (elliptical cryomodule) ESS liaison

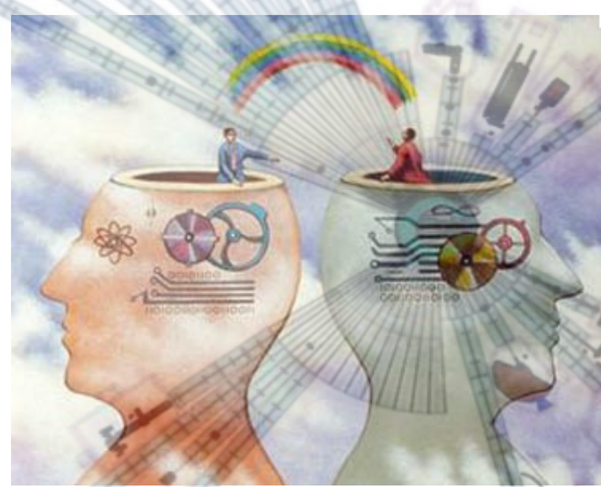
Outline

ESS High-Story: From dreams to reality

- ESS spirit
- Main parameters
- Expression of Interest

ESS cryomodules

- Functions and constraints
- Spoke cavities technologies
- Elliptical cavities technologies
- Technology Demonstrators



The fractality and entanglement ...

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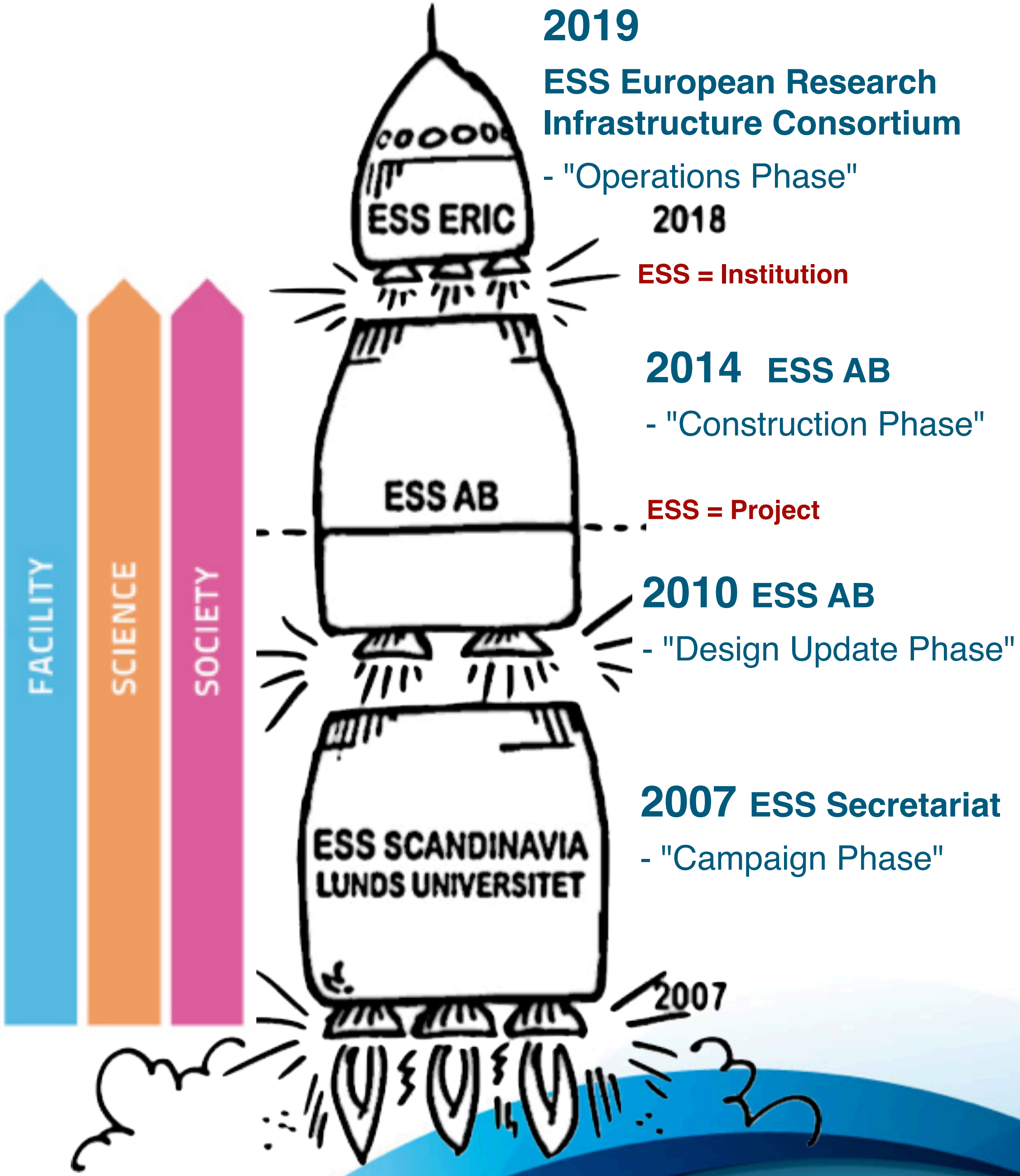
ESS High-Story: From dreams to reality

ESS Phases

Different phases have different needs

That requires different "organizations"

Each builds on the previous and prepares for the next



An unique program – ESS and Partners

Sweden, Denmark and Norway
50% of construction costs – 1479 M€ (2008)
20% of operation cost

+ 17 Partners
Today

The remaining 50%: Spain, France, Germany, Italy, Switzerland, Hungary, Czech Republic, Poland, Netherlands, Estonia, Latvia, Lithuania, Iceland & UK

Collaborative projects

Courtesy of Mats Lindroos
Head of Accelerator div. @ ESS

- ESS is an emerging research laboratory with (still) very limited capacity in-house
- Two possibilities:
  - Limit the scope of the project so that it can be done with in-house resources
  - Work in a collaboration where the scope of the project can be set by the total capacity (distributed) of the partners
- The accelerator part of the project well suited for this as this community has a strong tradition of open collaboration (XFEL, FAIR, European commission framework programs and design studies, LHC,...)
- To keep cost down and to optimize schedule this requires that investments in required infrastructure is done at the partner with best capacity to deliver

In-kind Process for Construction Begins

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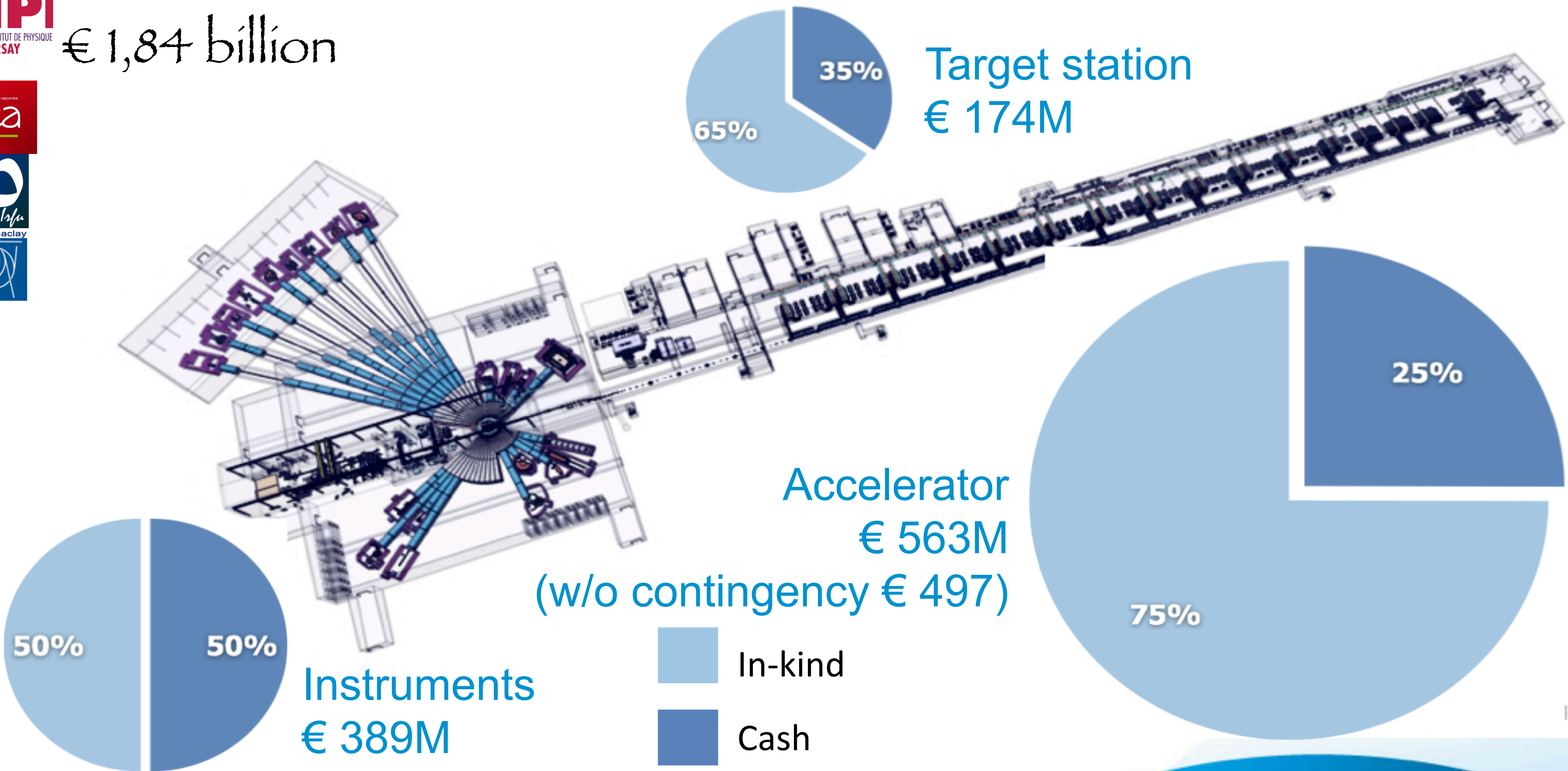
Courtesy of Allen Weeks
Head of Communications @ ESS

- Call for Expressions of Interest
- Based on TDR, Project Plan & Cost Book
- May contribute "component" or "work"
- Several calls; WPs will be released as they mature
- Slightly different for Accelerator, Target & Instruments
- Competence of the team(s) responding, references
- We expect there will be partnering on Work Packages
- An Institution or Laboratory, Company, or a Combination
- After EoI response, a detailed discussions for IKC begin

Reference Instrument Suite

ESS In-kind contributions potential

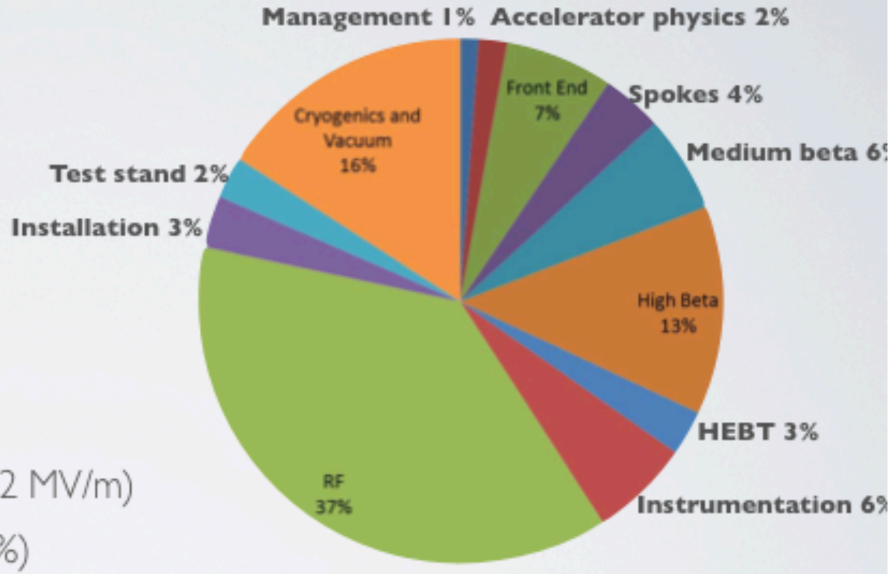
Total construction cost:
€ 1,84 billion



Courtesy of M. Eshraqi and D. McGinnis

2012 DESIGN

- Design features
  - 2.5 GeV, 50mA
  - 2.86 mS, 14 Hz
  - 97% superconducting
  - SC linac at 352 & 704 MHz
    - 1/3 current in 4 x the aperture
    - 14 cm bore compared to 7 cm
    - High gradient – 18 MV/m (vs 12 MV/m)
    - Dynamic heat load 65% (vs 25%)



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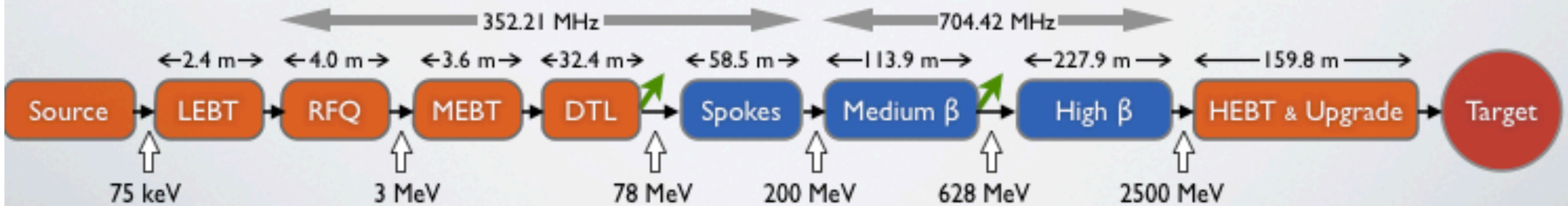
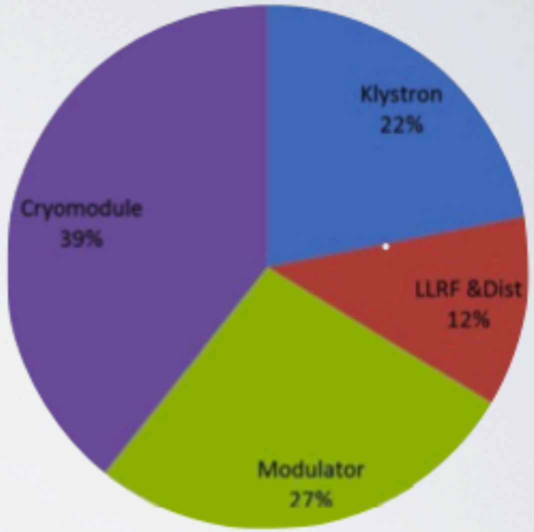


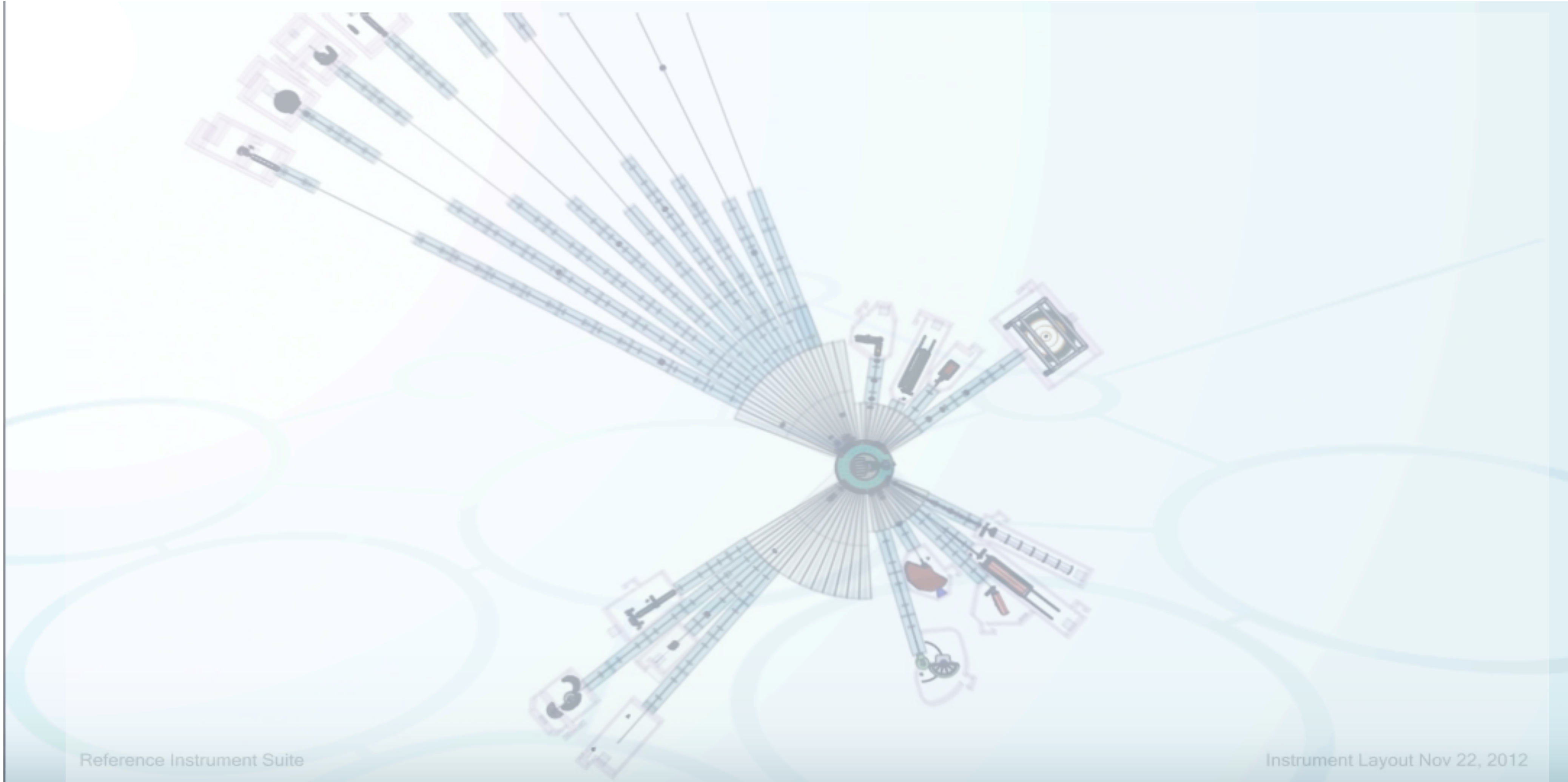
Courtesy of M. Eshraqi and D. McGinnis

COST DRIVERS

- Elliptical cryomodules occupy 19% of the cost
  - ✶ There are 45 elliptical cryomodules
  - ✶ The cryogenic plant absorbs 14% of the total cost
- RF systems comprise 37% of the cost
  - ✶ The RF costs are distributed over five major systems
  - ✶ The elliptical section comprises 82% of the RF system cost
- For the elliptical section
  - ✶ the klystrons and modulators comprise 80% of the RF system cost
  - ✶ **62% of the total cost of the linac**
  - ✶ 92% of the acceleration energy



Cost breakdown for elliptical cryomodule system



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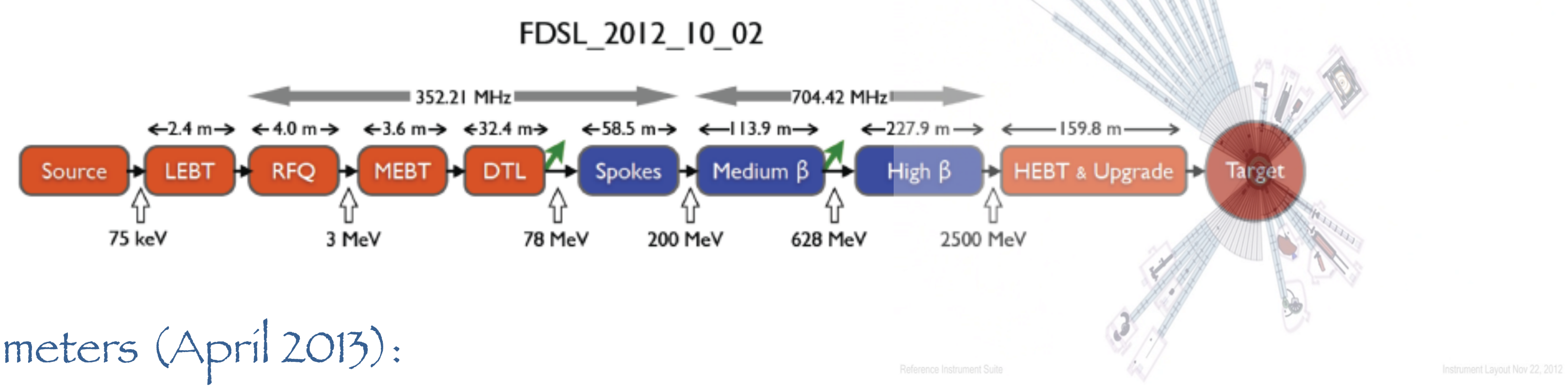
The ESS Accelerator

ESS accelerator – from TDR to cost target



Key parameters (April 2013):

-2.86 ms pulses

-2.0 GeV

-62.5 mA pulse current

-Repetition rate : 14 Hz

-Protons (H+)

-Low losses

-Low heat loss cryostats for minimum energy consumption

-Flexible design for future upgrades

Design Drivers:

High Average Beam Power 5 MW

High Peak Beam Power 125 MW

High Availability > 95%

Infrastructures used today – ESS Accelerator

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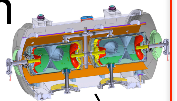
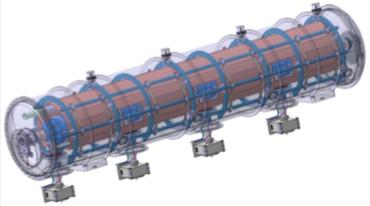
The National Center for Nuclear Research, Swierk

IPN Orsay Division Accélérateurs

Sebastien Bousson



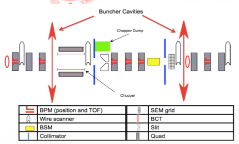


cea

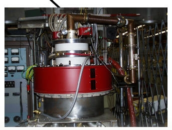
Pierre Bosland

Ibon Bustinduy

ESS bilbao



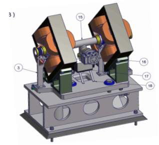
CERN



CERN

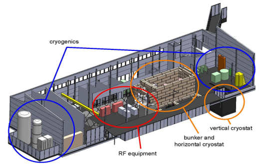
ISA

Søren Pape Møller



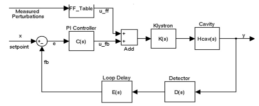
UPPSALA UNIVERSITET

Roger Ruber



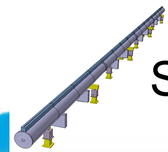
LUNDS UNIVERSITET

Anders J Johansson



INFN Istituto Nazionale di Fisica Nucleare

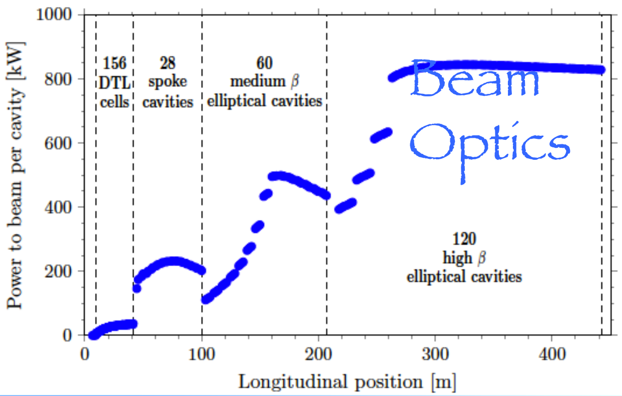
Santo Gammino

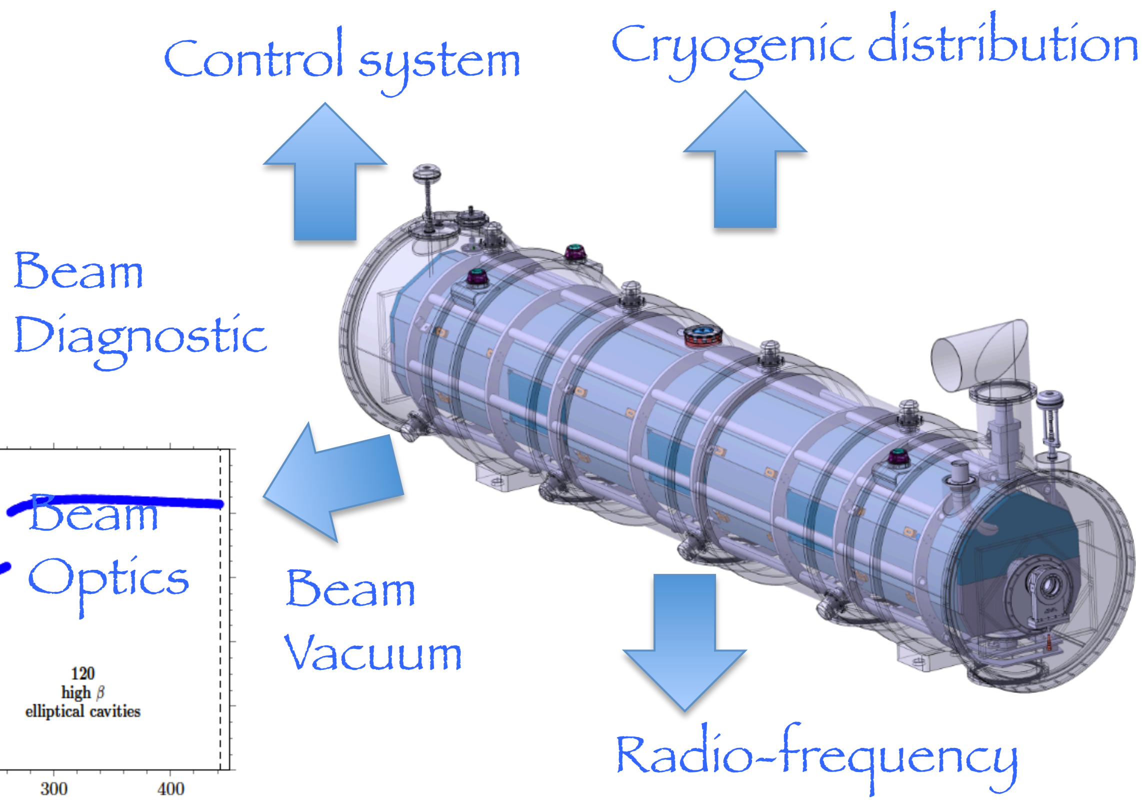


Cryomodule stakeholders - Interfaces

- ESS lead engineers and work-package leaders
- Cryomodule designers
- Cavity package designers
- Control command (Control Box, PLC, LLRF, MPS)
- Instrumentation teams
- Safety team
- RF team
- Component assembly teams
- ESS system engineer, QA
- Survey experts
- Test stand service
- Toolings
- Transport
- Conv. Fac.

October 2012
Baseline





ESS Cryomodule constraints and risks

Integrated hazards due to operating environment:

- Cryogenic temperature: 2 K (Helium II), cryogenic vessel, pressure vessel
- Sub atmospheric condition 31 mbar saturated, leak-tightness
- Magnetic environment (14 mGauss)
- Radiation environment (high intensity proton beam)

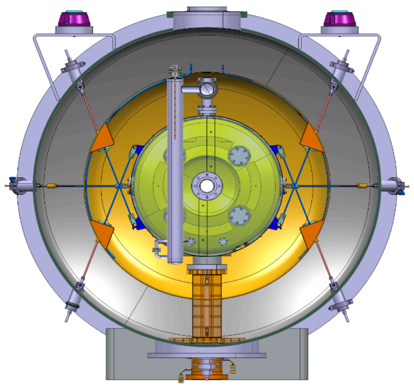
Main challenges:

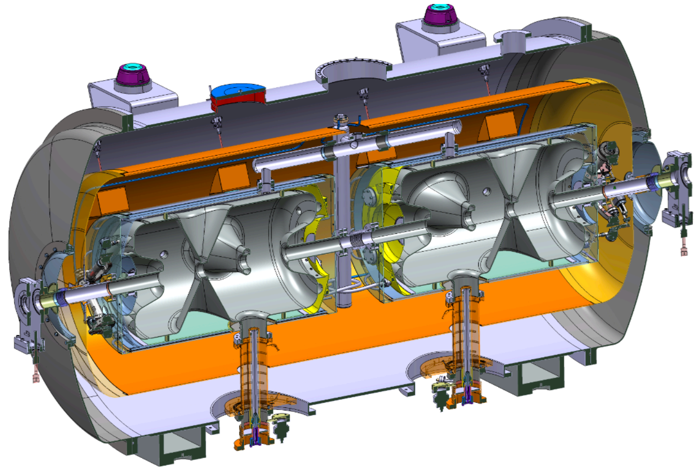
- Cost reduction and Quantity
- Quality: science and innovative using SRF cavities
- Short time project scale
- Transfer technology to industry for industrialization series production

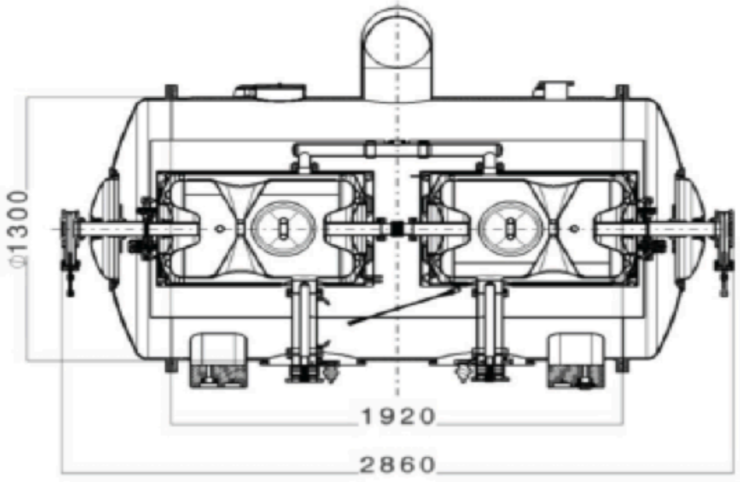
Spoke cryomodules – IPN Orsay/CNRS

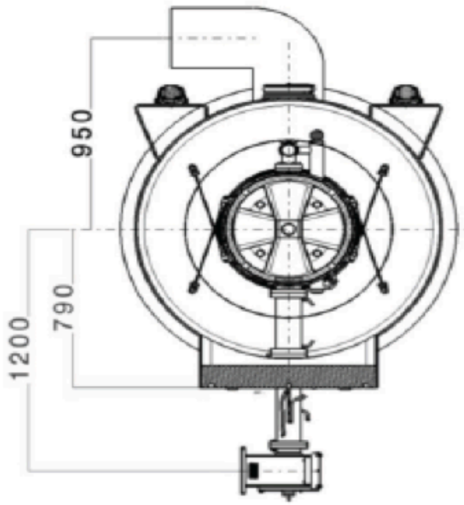
→ Cryomodule is mainly composed of:

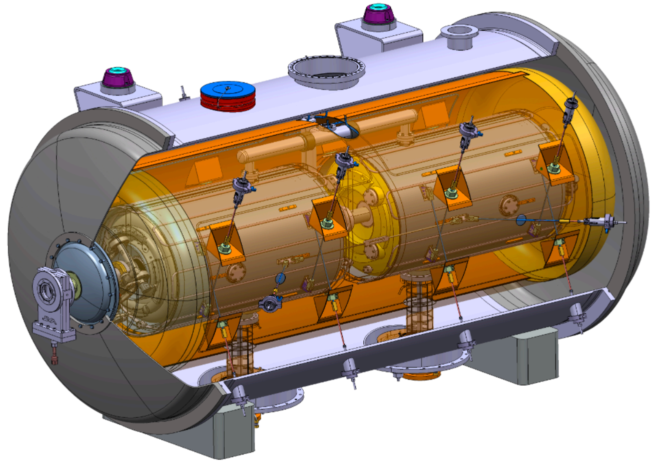
- 2 SRF spokes cavities
- 2 power couplers
- 2 cold tuning systems
- Supporting system
- Thermal shielding
- Magnetic shielding









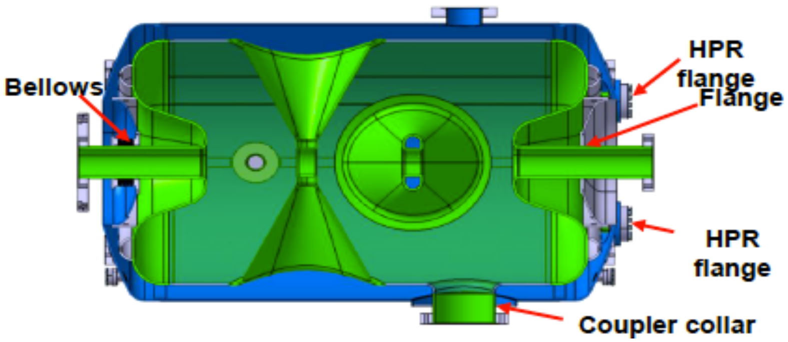


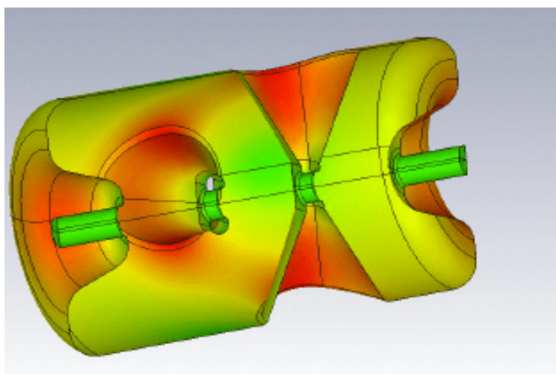
Spoke cryomodules – IPN Orsay/CNRS [TDR]

→ First accelerator to integrate spoke cavities

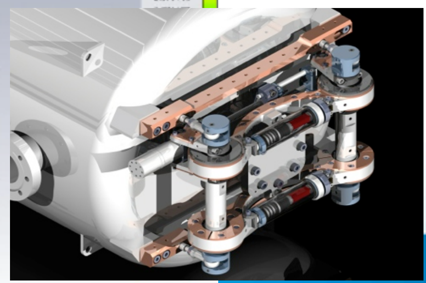
- Naturally stiff (less sensitive to mechanical perturbation such as vibrations)
- Exhibit high cell to cell coupling (no field flatness required, less sensitive to HOM or trapped modes)
- Not susceptible to dipole steering effect
- High longitudinal acceptance (accelerating efficiency over a wide range)

DOUBLE-SPOKE CAVITY SPECIFICATIONS	
Beam mode	Pulsed (4% duty cycle)
Frequency [MHz]	352.2
Beta_optimal	0.50
Temperature (K)	2
Bpk [mT]	70 (max)
Epk [MV/m]	35 (max)
Gradient Eacc [MV/m]	8
Lacc (=beta optimal x nb of gaps x λ /2) [m]	0.639
Bpk/Eacc [mT/MV/m]	< 8.75
Epk/Eacc	< 4.38
Beam tube diameter [mm]	50 (min)
P max [kW]	300 (max)

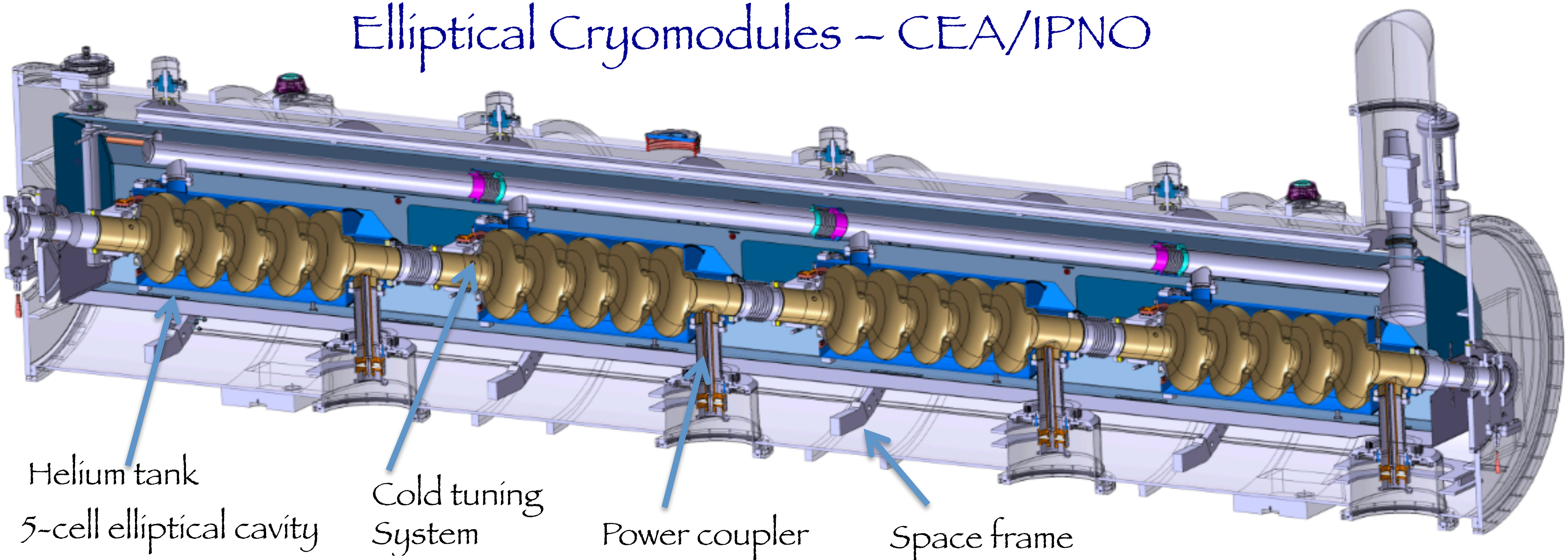




Eurisol coupler and cold tuning system



Elliptical Cryomodules – CEA/IPNO



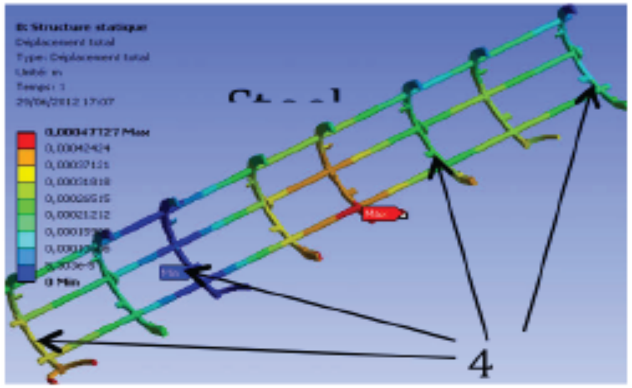
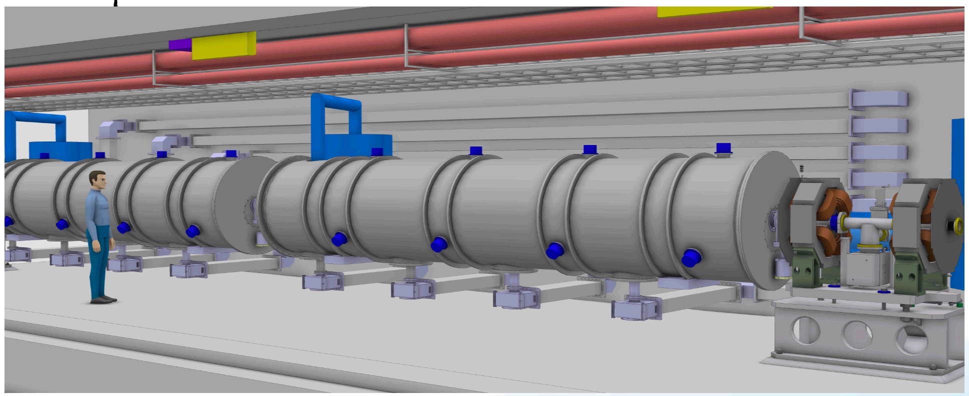
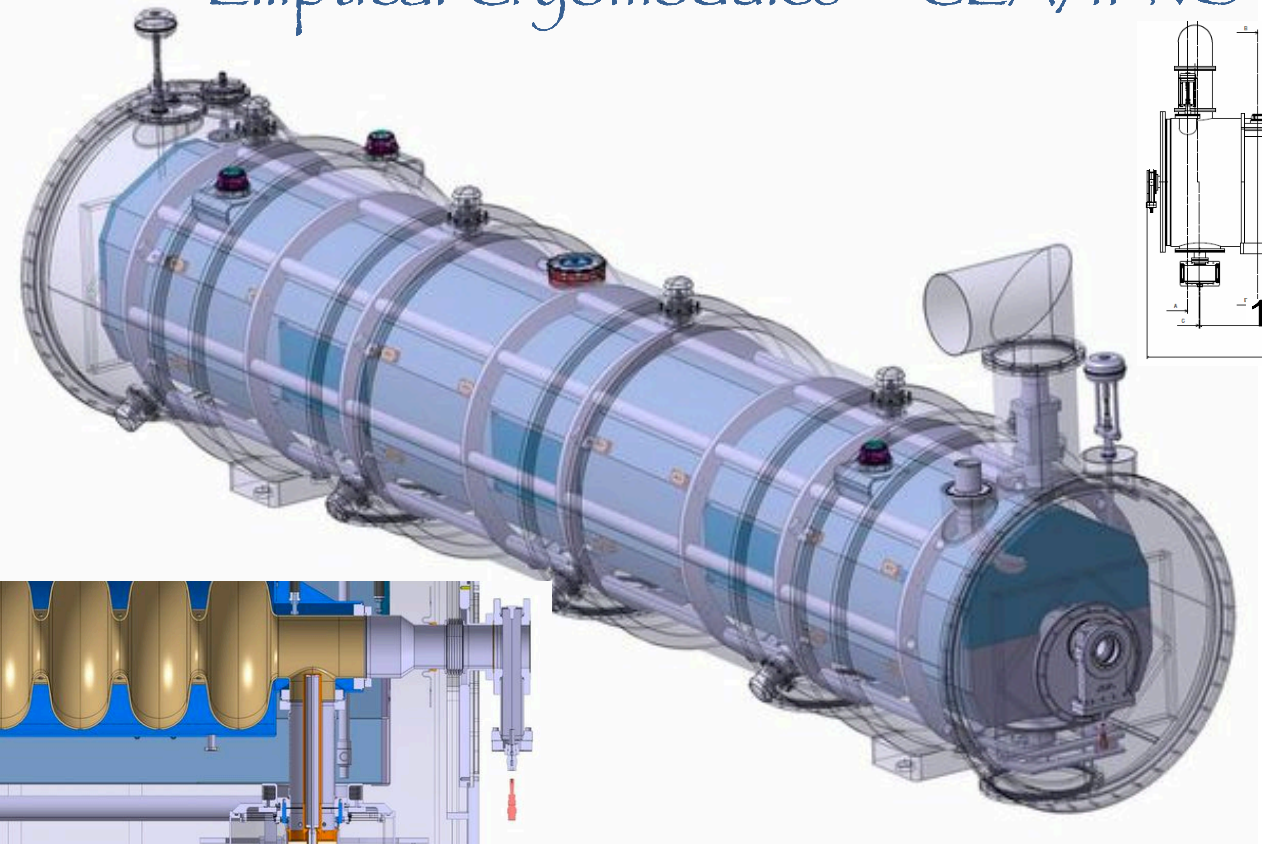


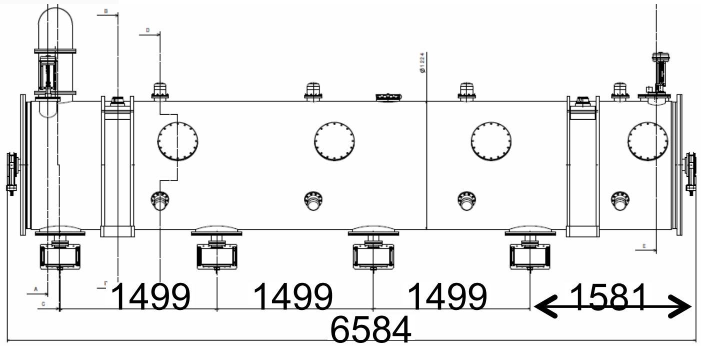
Figure 4.120: Helium vessel with hanging rod

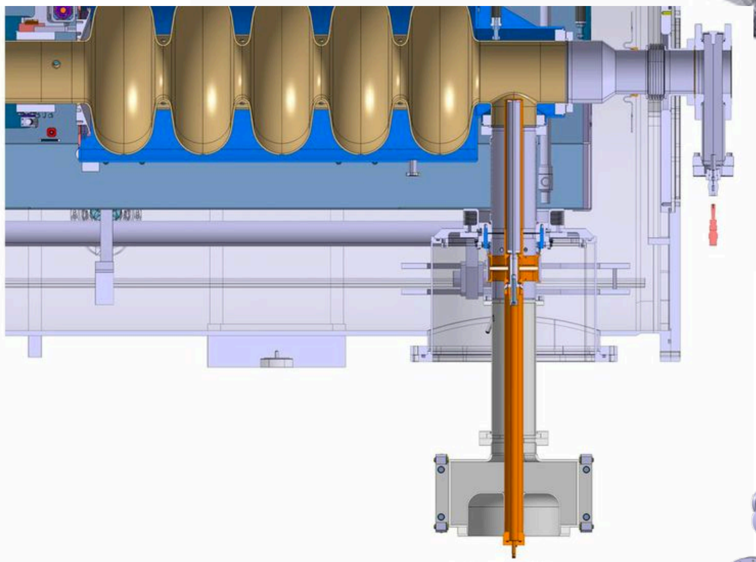


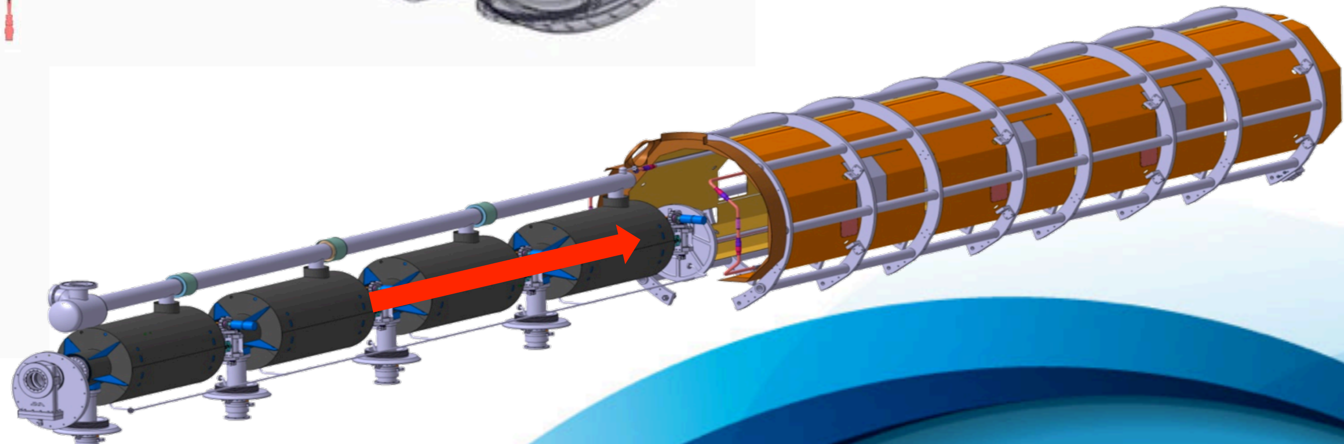
→ Elliptical Cavities Cryomodule Technology Demonstrator results by the end of 2015

Elliptical Cryomodules – CEA/IPNO

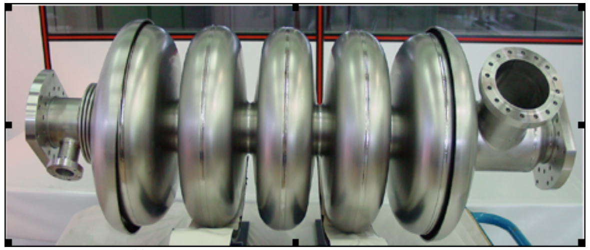




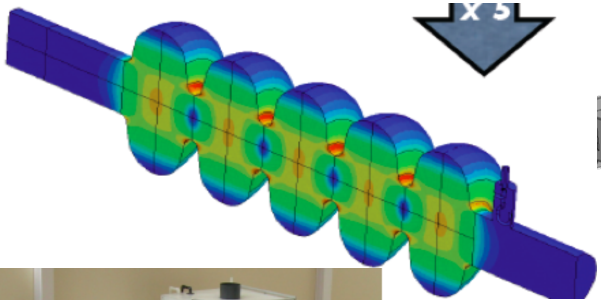


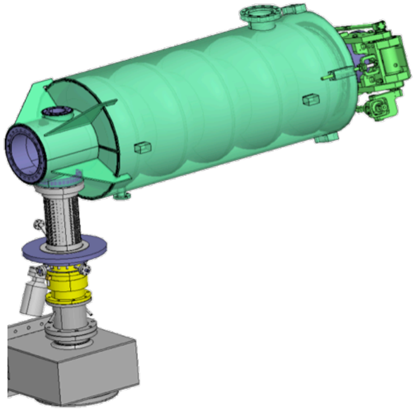


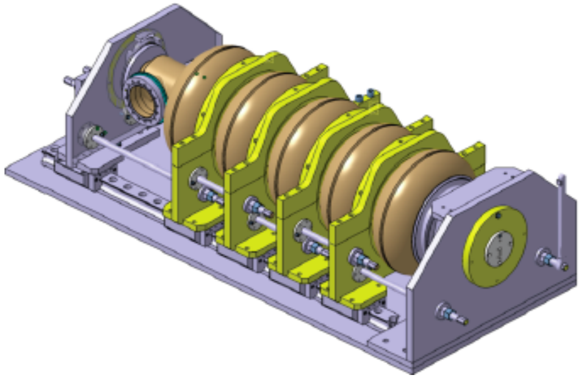
Elliptical Cryomodules – CEA [TDR]



SC 5 cell cavity for 704 MHz, CEA and CNRS







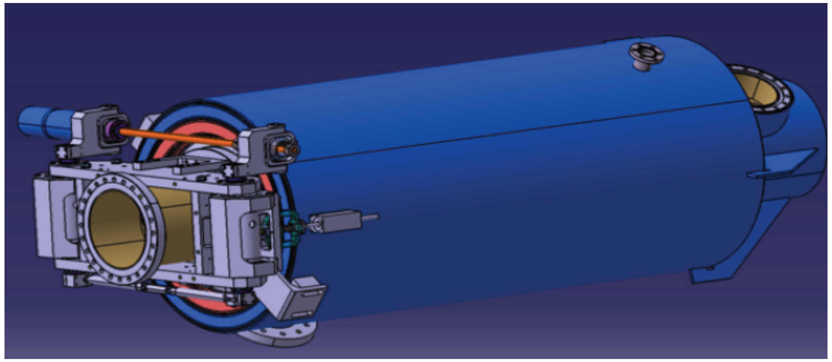
Parameter	Unit	Value
RF frequency	MHz	704.42
Temperature	K	2
MEDIUM-BETA		
Output energy	MeV	654
Number of cells per cavity		5
Geometric beta		0.67
Cavity length	m	1.145
Expected gradient, horizontal	MV/m	15
Expected gradient, vertical test	MV/m	17
Cavity Q_0		6×10^9
Fundamental mode Q_{ext}		6.8×10^5
Fundamental mode R/Q	W	340
Average heat load at nominal gradient	W	5.9
Power coupler power forward power	MW	1.2
Maximum Power transmitted to beam	MW	0.6
HIGH-BETA		
Output energy	MeV	2500
Number of cells per cavity		5
Geometric	beta	0.9
Cavity length	m	1.356
Nominal gradient in the linac	MV/m	18
Expected gradient, vertical test	MV/m	20
Geometric beta prototype		0.86
Optimum beta prototype		0.92
Cavity length prototype	m	1.315
Fundamental mode R/Q prototype	W	477
Fundamental mode Q_{ext} prototype		7.1×10^5
Cavity Q_0 at nominal gradient, prototype		6.0×10^9
Average heat load at nominal gradient, prototype	W	4.5
Power coupler power rating	MW	2
Power coupler forward power	MW	1.2
Maximum power transmitted to beam	MW	0.9
Cell to cell coupling	%	1.8
Epk/Eacc		2.2
Bpk/Eacc	mT/(MV/m)	4.3
Separation between π and $4\pi/5$ modes	MHz	1.2
Iris diameter	mm	120

Elliptical cavities for ESS

- P_{RF} max = 1.2 MW <= HIPPI power coupler
- Piezo tuner <= Saclay V tuner (HIPPI / SPL tuner)

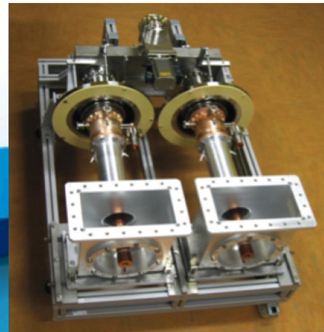
Adapted to ESS cavities

- Titanium helium vessel (Thickness: 5 mm), Flanges material: NbTi
- L_Pulse x rep rate = DC : 2.86 ms x 14 Hz = 4 %
- 5-cell high beta (0.86)
- 6-cell medium beta (0.67) [S. Molloy]



"Mustang"'s proposed parameters

- Power: 1 MW (2019), 5 MW (2025)
- Peak surface field → 45 MV/m
- Energy → 2 GeV ⇒ Current → 62.5 mA



Cavity Cryomodule Technology Demonstrator

One full scale cell of 704 MHz high- and medium-beta cavity cryomodule

A staged approach towards the ESS Linac tunnel installation

- Validate the cryomodule design: cavities, coupler, CTS, alignment
- Preparation of the industrialization process by validating component life-cycles (assembling process, QA)
- Validate the performances: RF, mechanical, thermal and vacuum
- Develop ESS 704 MHz SRF linac operating procedures
- Validate control command strategy (Control box, PLC, EPICS, LLRF)
- Test the ESS integration and interface with cryogenics, vacuum systems
- Train and collaboration building

→ Similar process for the spoke cryomodules

Standards and ESS Safety Culture

Engineering standards

- CEN, European Committee for standardization
- SIS, Swedish Standard Institute
- ISO, International Organization for standardization
  - → e.g. European Directive 97/23/EC, PED ; EN ISO 4126
  - → ESS guidelines for pressure vessel modeled after FNAL, European and CERN expertises

Radio-Protection and Rad-hard equipment

- As low as reasonable achievable (ALARA)
- Passive and active safety measures (safety barrier)
- Personnel Protection System, Machine Protection System (IEC61508)

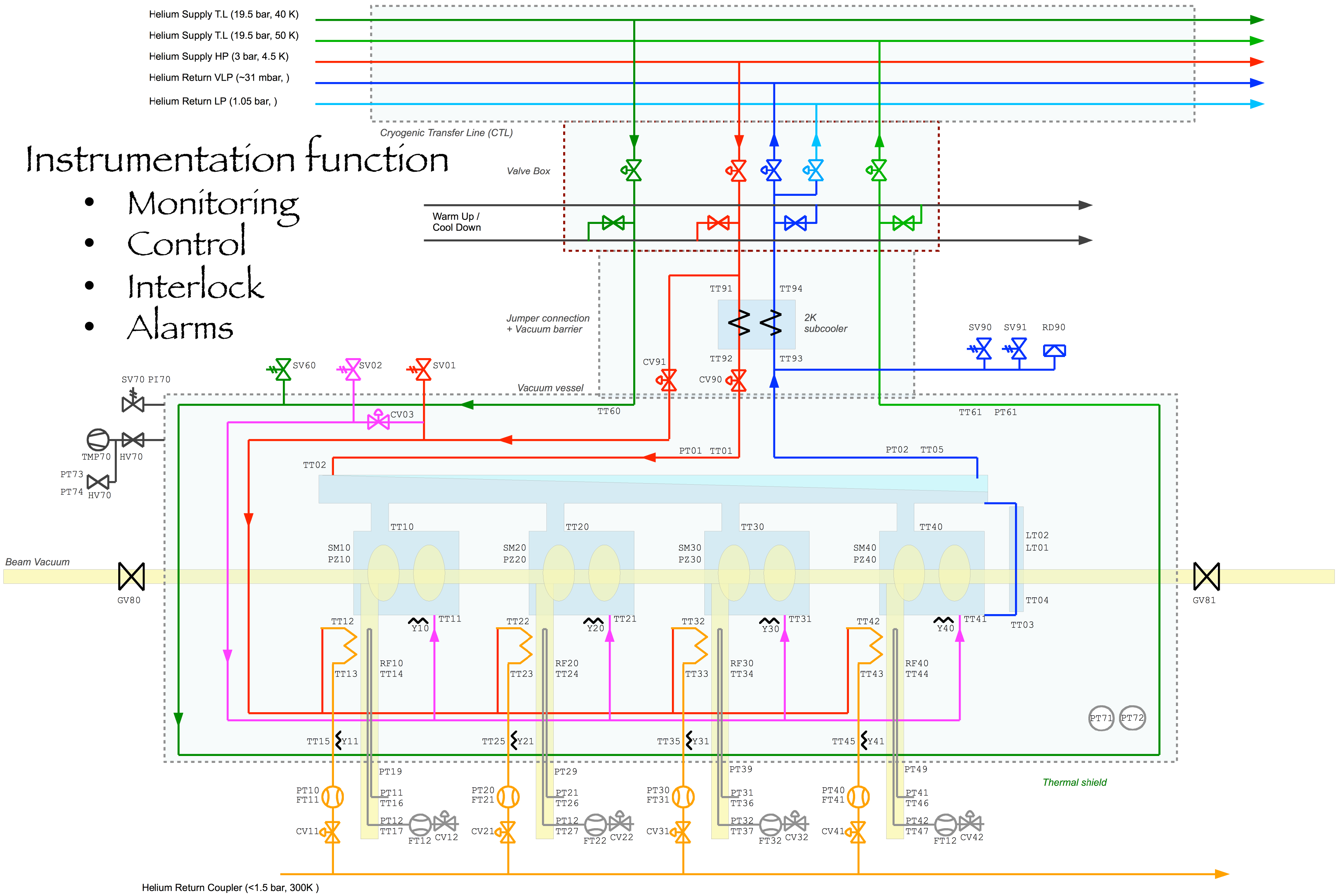
Risk analysis and reliability study

Safety reviews

Quality Assurance

Instrumentation function

- Monitoring
- Control
- Interlock
- Alarms



Cavities' fabrication scheme

Courtesy of Claire Antoine/CEA

Step	WHY	COMMENTS
Forming		
EB Welding	Clean welding	Nb = getter material. If RRR/ 10 @ welding => $Q_0/10$
Ti purification	RRR enhancement	RRR 300-400 now commercially available
Chemical etching 100-200 µm (BCP / EP)	Remove contamination and damage layer	Limitation : BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility
Annealing 800°C, 2h (or 600°C, 10h)	Get rid of hydrogen	Source of H: wet processes H segregates near surface in form of hydrides (= bad SC)
Chemical etching 5-20 µm	Remove diffusion layer (O, C, N)	Diffusion layer < ~1µm in bulk, a little higher at Grain Boundaries
Specific rinsing	e.g. remove S particles due to EP	Under evaluation HF, H_2O_2, ethanol, degreasing,…
High pressure rinsing (HPR)	Get rid of dust particles	Not always enough (recontamination during assembly)
Assembling	Ancillaries : antennas, couplers , vacuum ports…	***In clean room, but recontamination still possible***
Baking, 120°C, 48h	Decrease high field losses (Q-drop)	Unknown mechanism, first 10 nm of the surface in concern.
Post processing	Get rid of "re-contamination" ?	Under evaluation: dry ice cleaning, plasma
Test RF	Cavity's performance	First naked cavity in vertical cryostat, then dressed in horizontal cryostat/ accelerating facility
He processing, HPP	Decrease field emission	RF power with/ without He to destroy field emitters (dust particles) NB field emission : principal practical problem in accelerators

Cavities' fabrication scheme
vs surface and material properties

EUROPEAN SPALLATION SOURCE

Courtesy of Claire Antoine/CEA

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

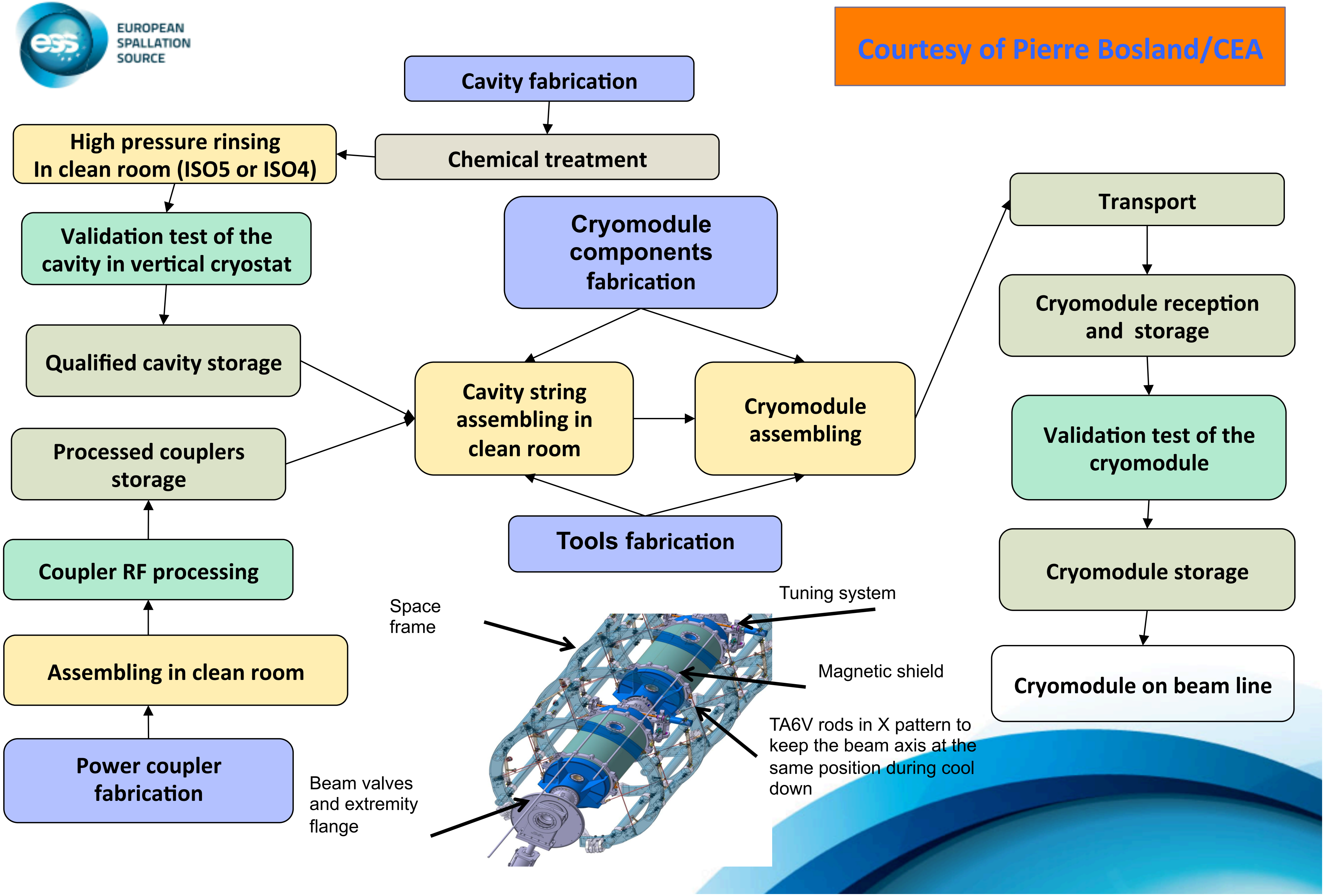
cea

Irfu CEA - Saclay

CERN

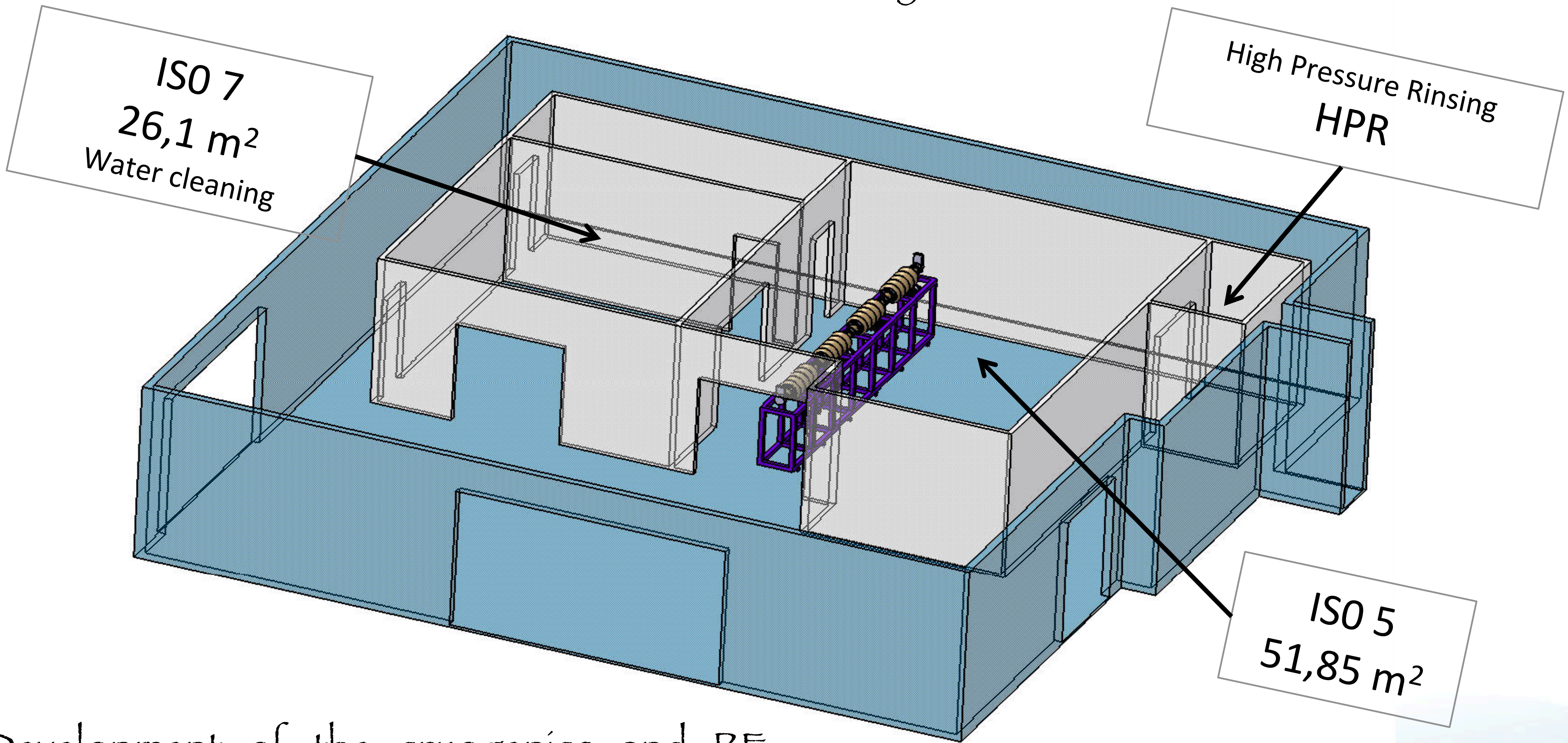
WHY

- Forming → **Mechanical properties, grain size, strain hardening…**
- EB Welding — Clean weldi…
- Ti purification — RRR enhance… → **Purity issues**
- Chemical etching 100-200 µm (BCP / EP) — Remove contaminatio… damage layer — : BCP ~ 30MV/m; EP => >40 mV/m; …f reproducibility → **Surface composition and surface morphology**
- Annealing 800°C, 2h (or 600°C, 10h) — Get rid of hydrogen → **Surface composition**
- Chemical etching 5-20 µm — Remove diffusio… — …sion layer < ~1µm in bulk, a little higher at Grain …ndaries
- Specific rinsing — e.g. remove S particles due… — Under evaluation → **Surface cleanliness**
- High pressure rinsing (HPR) — Get rid of dust particles — …ring assembly)
- Assembling — Ancillaries : antennas, couplers, vacuum ports… — *In clean room, but recontamination still possible*
- Baking, 120°C, 48h — Decrease high field losses (Q-drop) — Unknown mechanism, first 10 nm of the surface in …
- Post processing — Get rid of "re-contaminatio… — …ma → **Surface composition**
- Test RF — Cavity's performance — First naked cavity in vertical cryostat, then dressed in … …ty
- He processing, HPP — Decrease field emission — …y field — NB field emission : principal practical problem in accelerators → **Surface cleanliness**


EUROPEAN
SPALLATION
SOURCE
Courtesy of Pierre Bosland/CEA
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
Space frame
Tuning system
Magnetic shield
TA6V rods in X pattern to keep the beam axis at the same position during cool down
Beam valves and extremity flange

CEA ISO 5 new clean room

Availability of the clean room: June 2013



➔ Development of the cryogenics and RF bunker to test the final ECCTD @ CEA Saclay

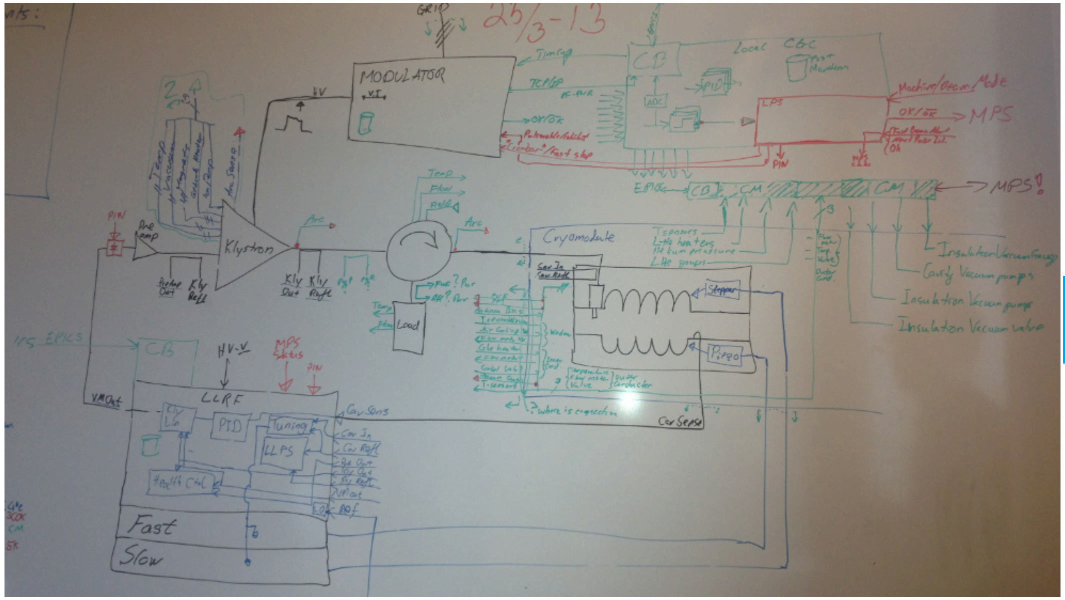
Additional implementation

- ESS tunnel valve box
- ESS tunnel control system

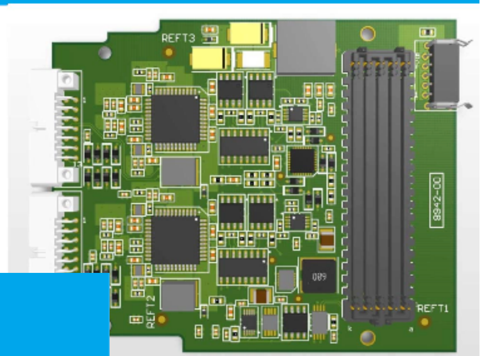
ESS Linac control system and PLCs

In the framework of the ECCTD project, a ESS general control system shall be developed between CEA, Desy and ESS expertise

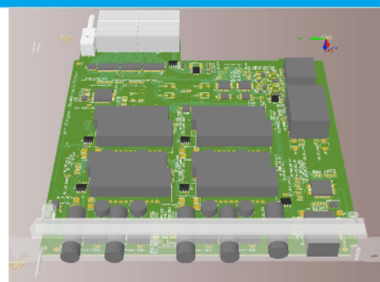
- Aim to extrapolate the same system to the ESS linac tunnel control system
- Propose a common architecture



stepper motor driver.



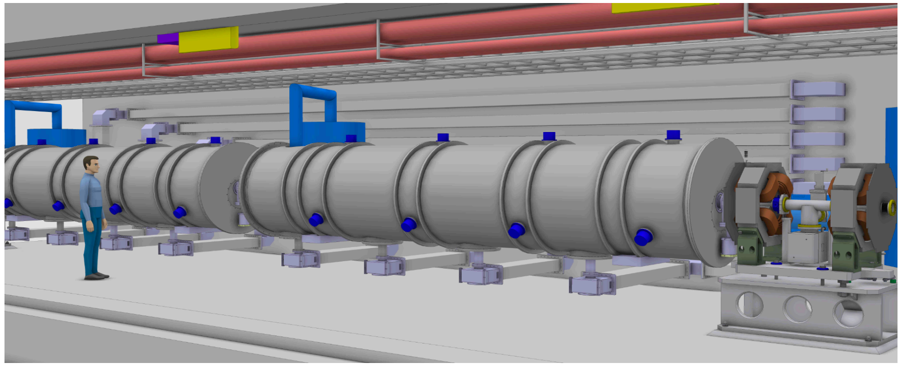
Piezo Driver.



Conclusion

A new Program for Spallation in Europe

- Validate the SRF cryomodule components
- Validate the industrialization process for cryomodule series production
- Activate a scientific worldwide partnership



EXTRA

ESS EoI & In-Kind Management Process

ESS Invites Expressions of Interest for the Construction Phase (see web page)

Courtesy of Allen Weeks