The ESS superconducting radio-frequency linac activities and implementation

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Deputy WP leader SRF accelerator

CATHI Final Review

Barcelona, September 25, 2014

www.europeanspallationsource.se

Outline

- The ESS Project
- SRF cavities and cryomodules
- SRF fabrication and testing

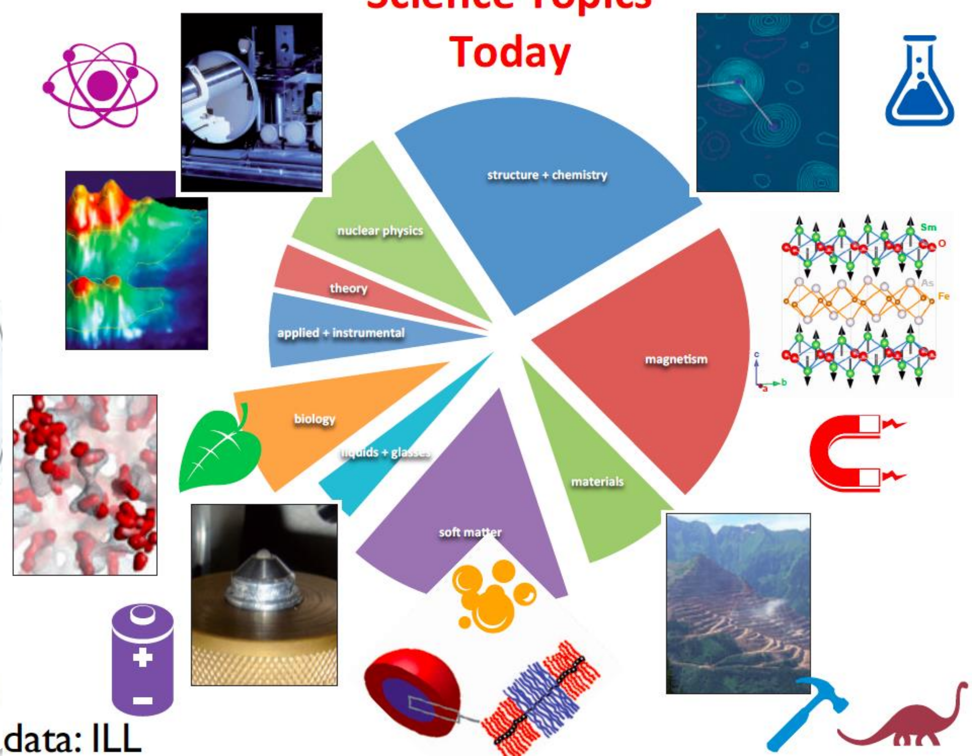
Materials, Life Science and Society

EU Horizon 2020 – strategy

The structure which the EC proposed consists of three basic priorities:

1. **Excellent Science**
2. **Industrial Leadership**
3. **Societal Challenges**

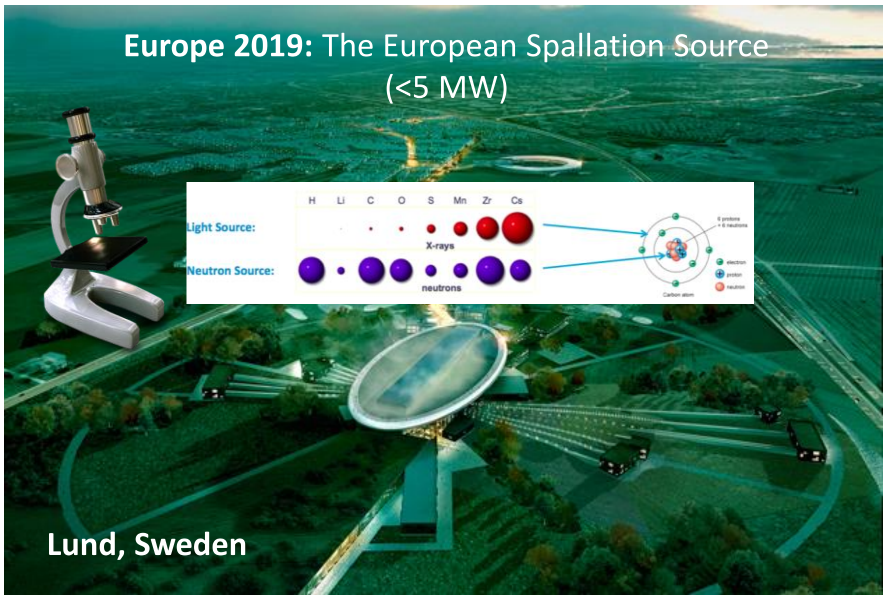
Science Topics Today

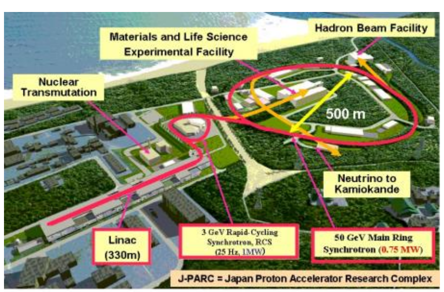


data: ILL

Spallation Sources

Philosophie de "Pré-vert": Greenfield





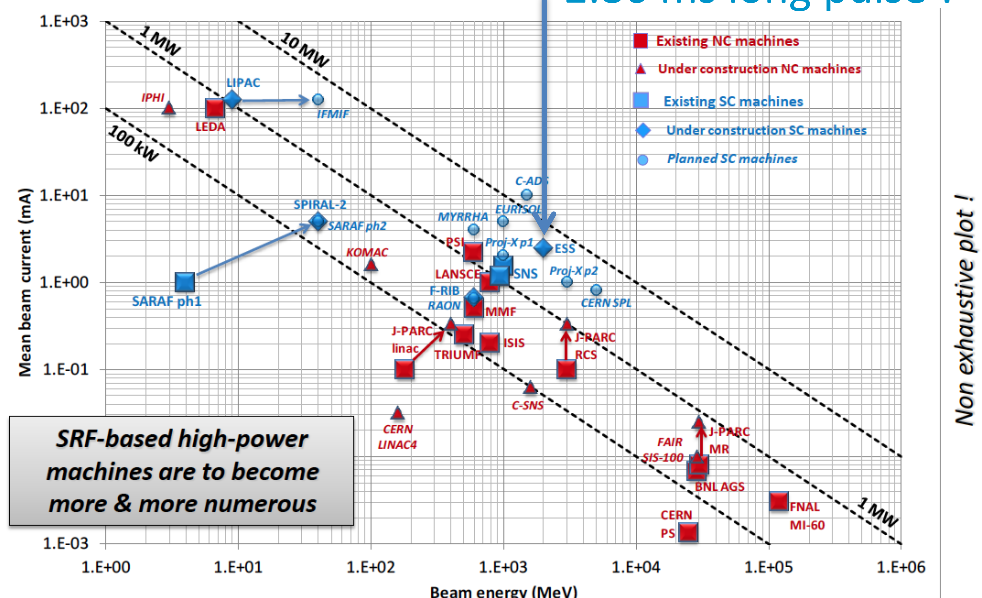
Japan 2008:
JPARC (<1MW)

USA 2006:
SNS (<1.4 MW)
1 GeV, 26 mA in linac, 627 ns long pulse, 60 Hz

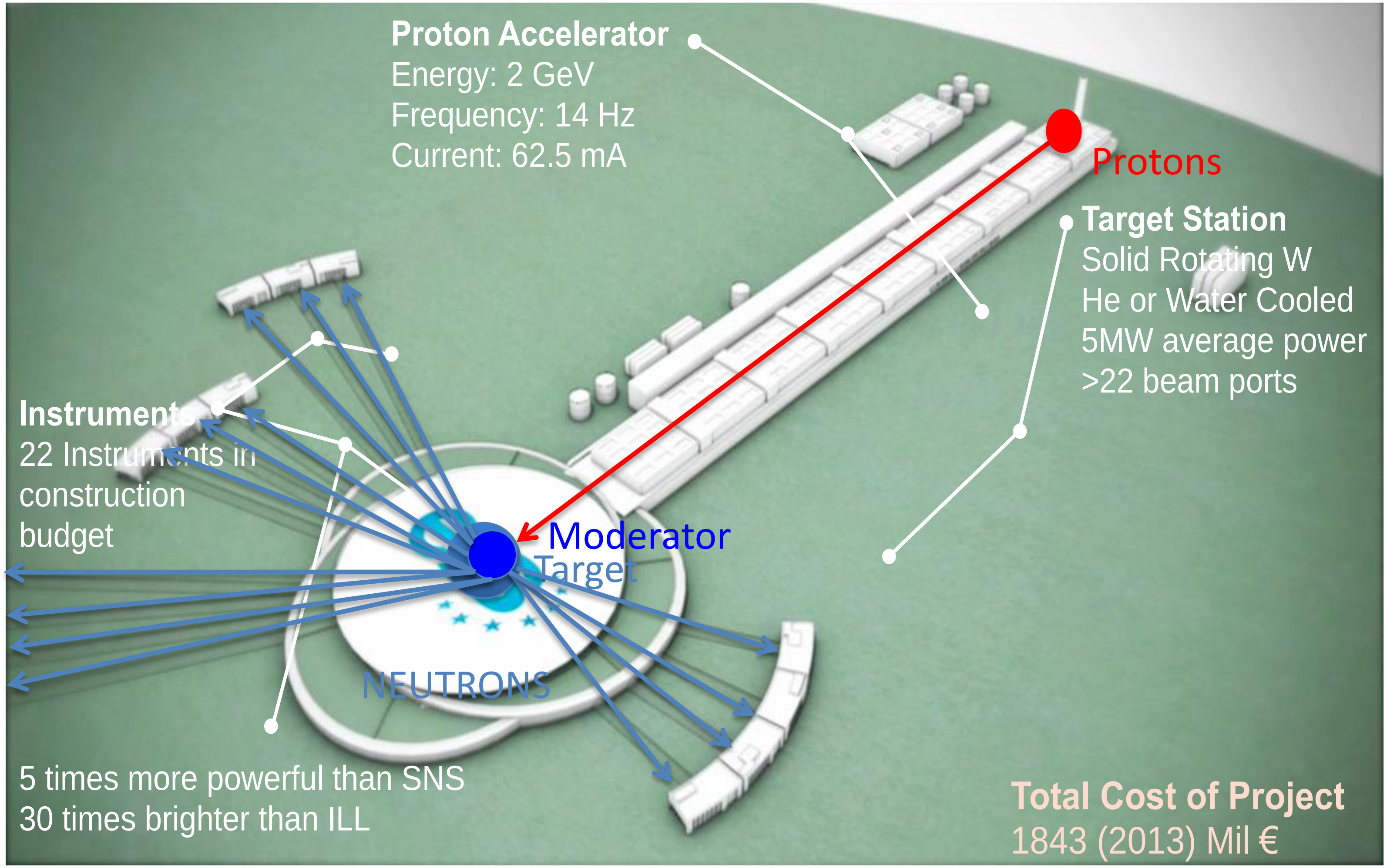
- Will bring new insights to the grand challenges of science and innovation
- Collaborative project: more than 17 countries
- 2014: Start of construction phase of the world's most powerful linear proton accelerator
- 2019: Provide the world's most advanced tools for studying materials with neutrons

(~ 450 employees; > 2500 users / year)

2.86 ms long pulse !

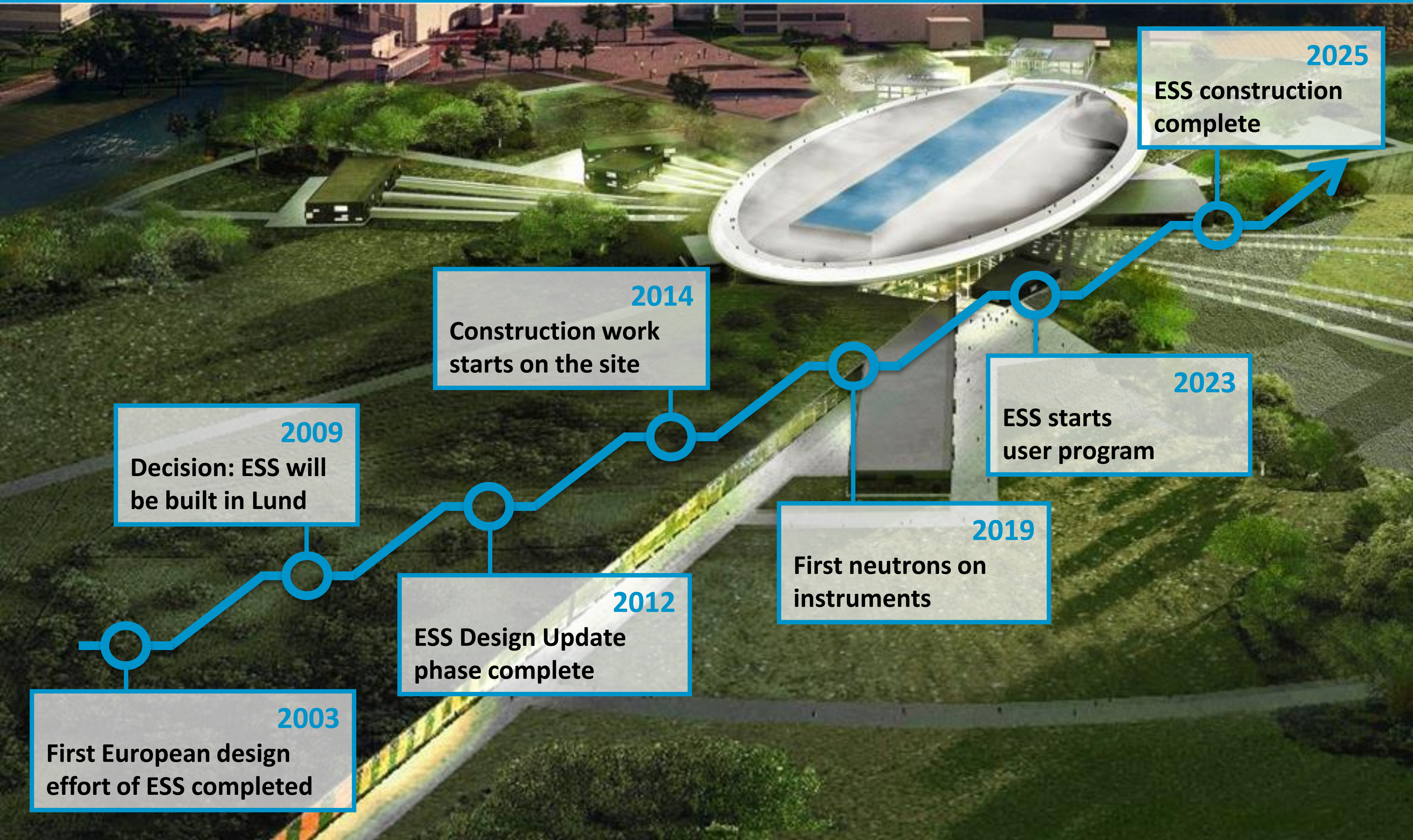


Helicopter view of ESS



Road to realizing the world's leading facility for research using neutrons

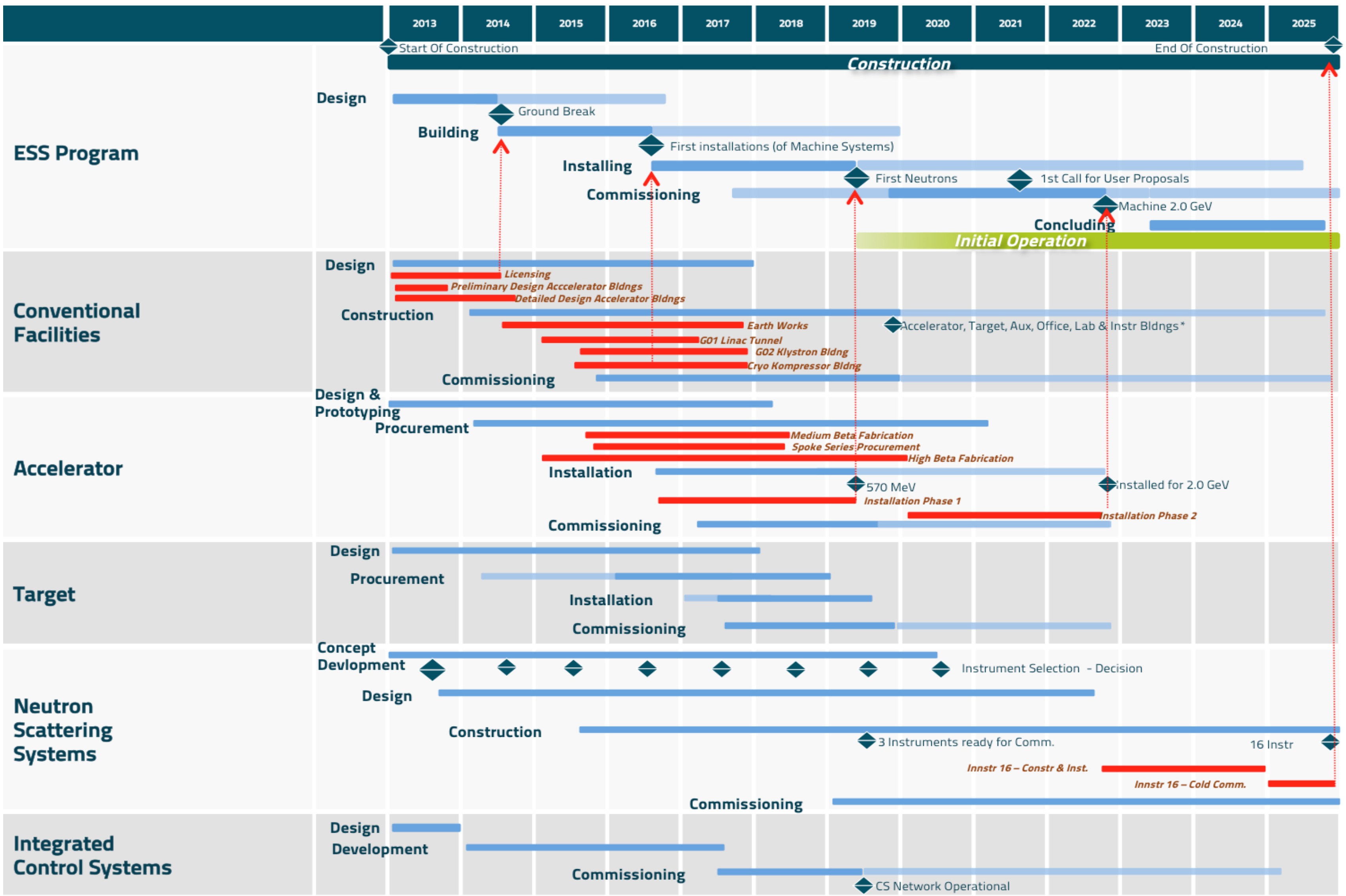
EUROPEAN SPALLATION SOURCE



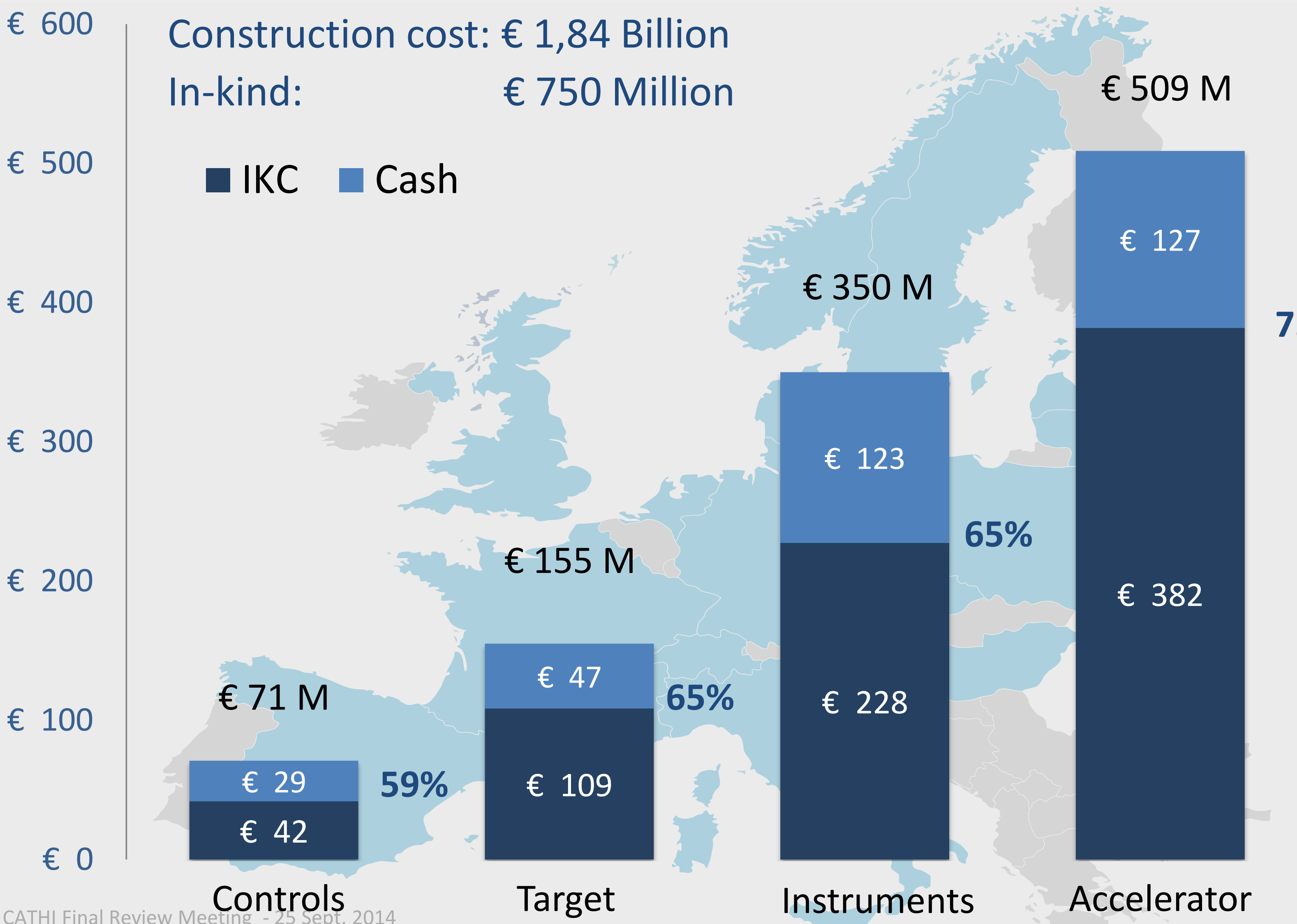
ESS ground Breaking

Jan Björklund (Swedish Research minister), Sofie Carsten Nielsen (Danish Research minister)
2014 September 2

Top-Level ESS Project Schedule



ESS In-kind Goals



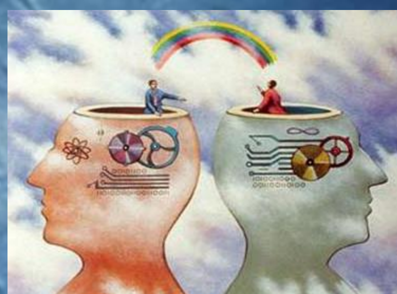
Collaborative projects

- 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

New Collaborations to Empower ?

Science institutions involved in the design & construction of ESS

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

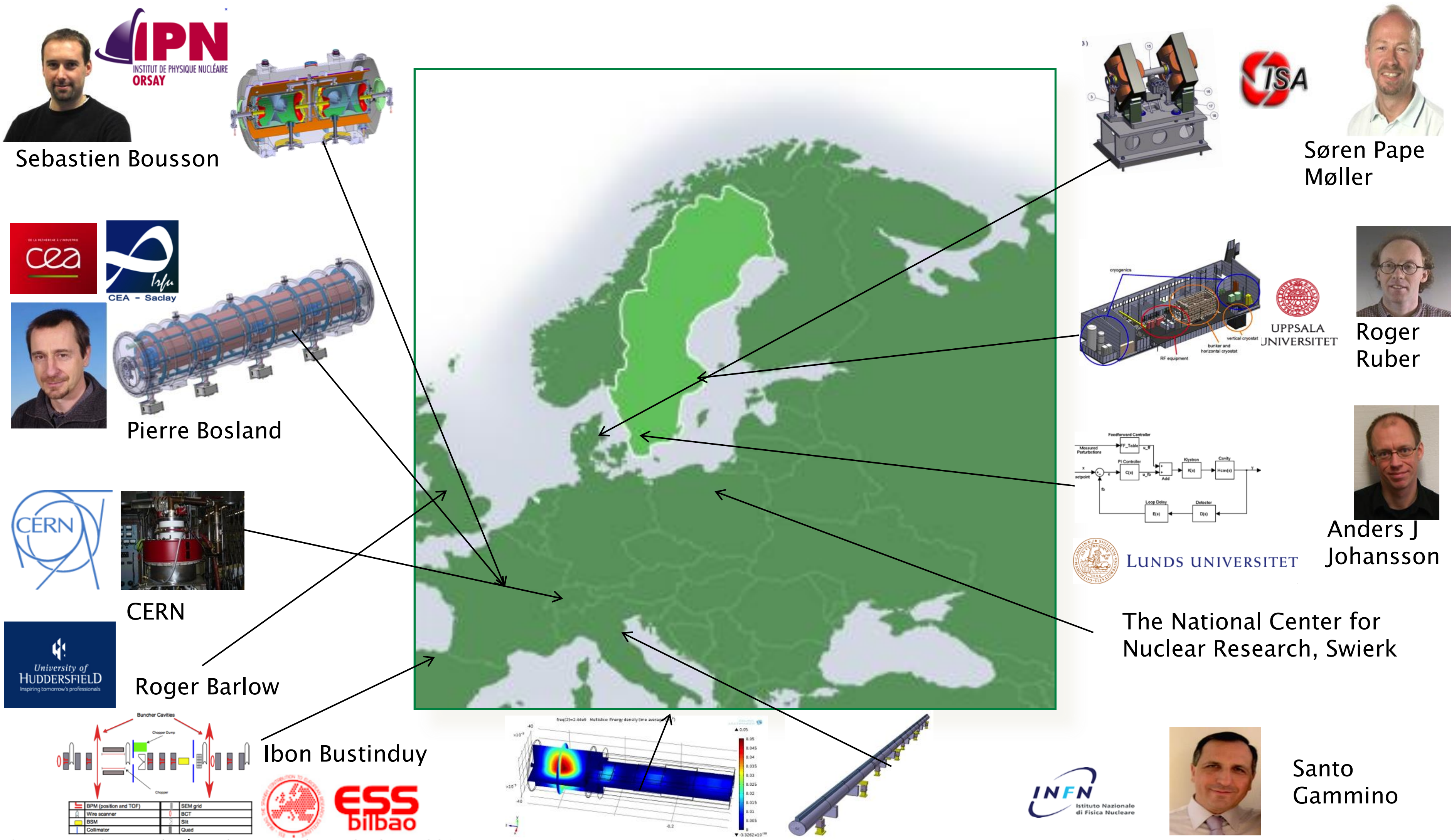


Fractality and entanglement

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

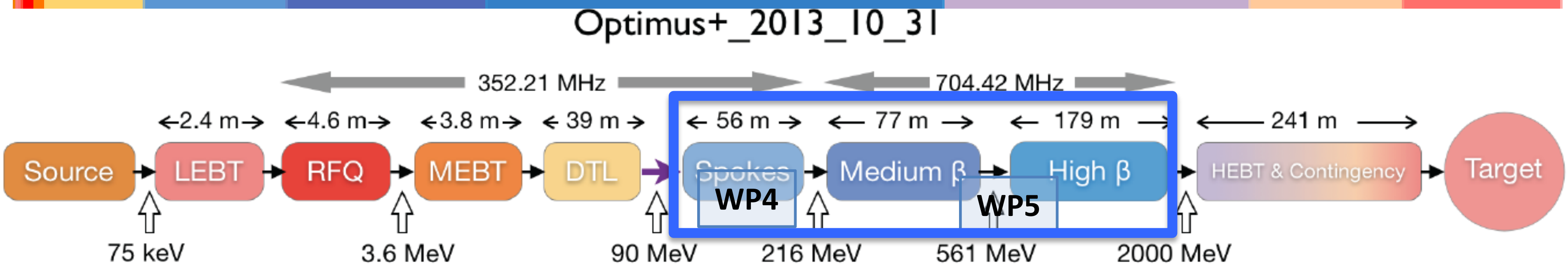
Accelerator project collaborations

EUROPEAN SPALLATION SOURCE

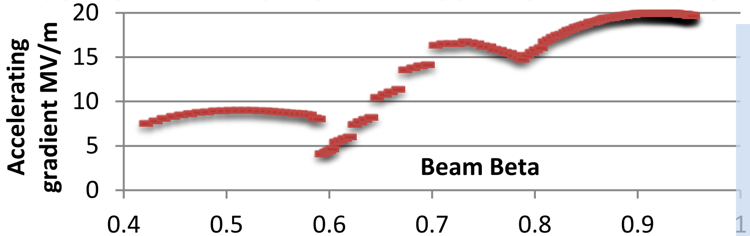


Linac redesign to meet ESS cost objective

EUROPEAN SPALLATION SOURCE



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

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

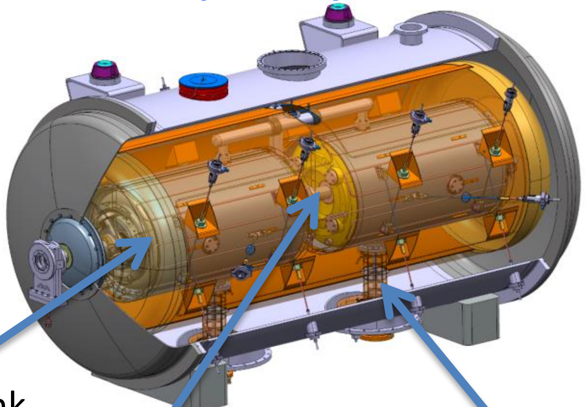
External WPs to:
- design,
- procure,
- fabricate,
- assemble,
- test and
- deliver

sections of the Linac

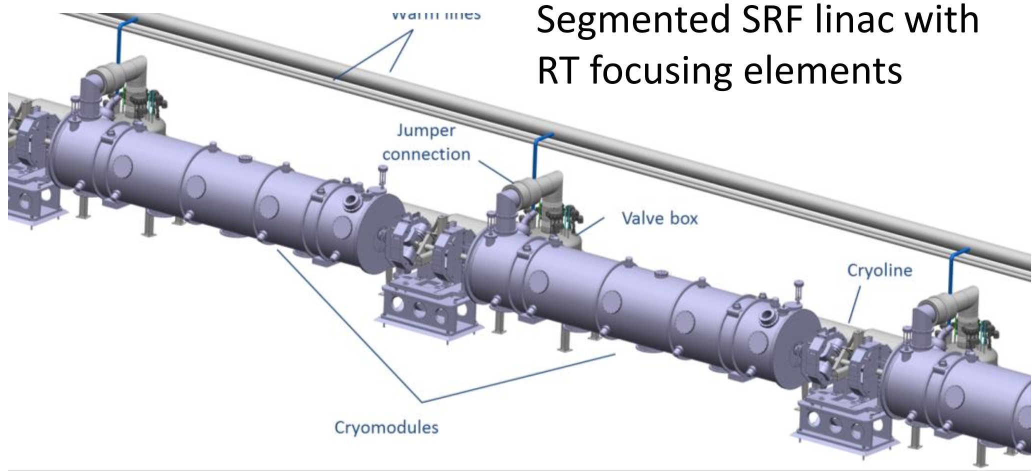
[SRF2013 – "The ESS Superconducting Linear Accelerator", C. Darve, M. Eshraqi, M. Lindroos, D. McGinnis, S. Molloy, P. Bosland and S. Bousson]

SRF Cavity Cryomodules for the ESS

2 Spoke Cavities per Cryomodule



Segmented SRF linac with RT focusing elements

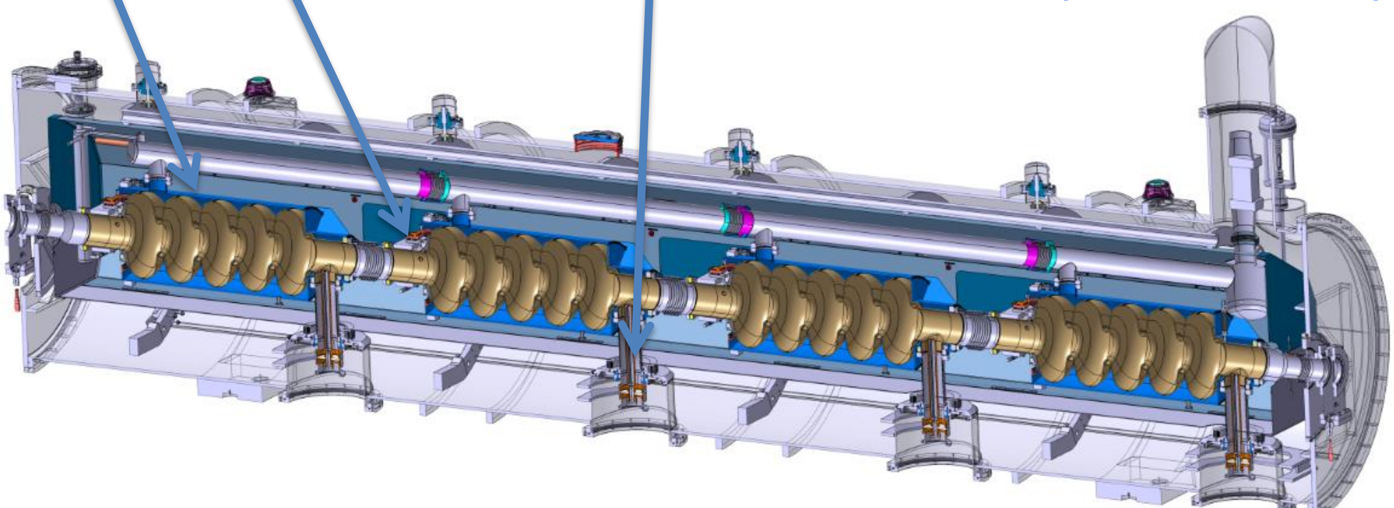


Ti. Helium tank

Cold tuning System

Power coupler

4 Elliptical Cavities per Cryomodule



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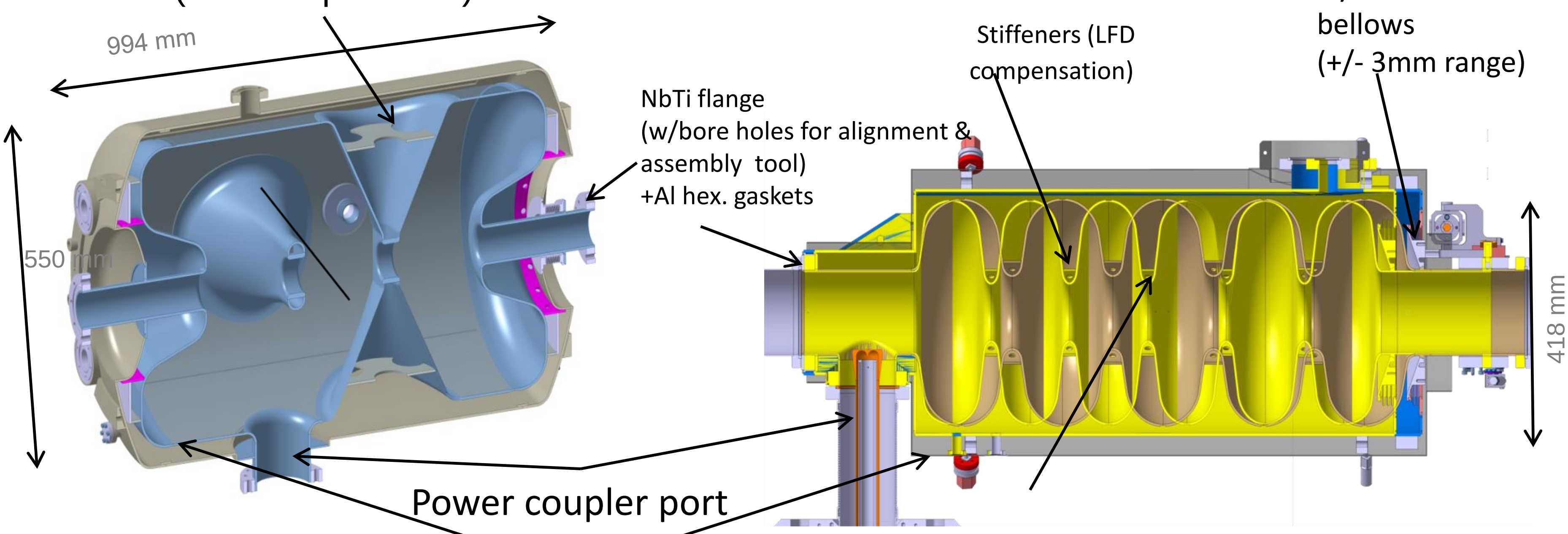
Cavities Development

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**

ESS Requirements and RF Parameters

Spoke cavities

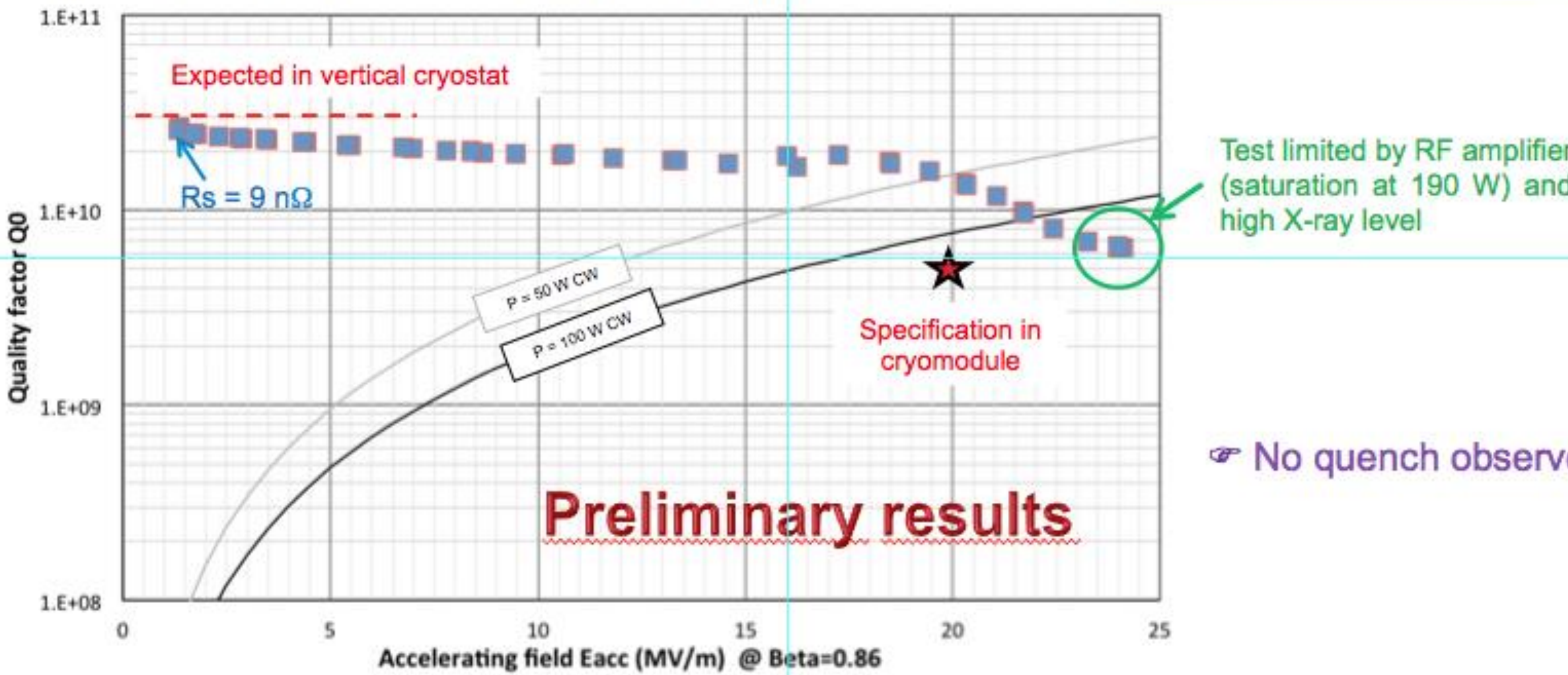
Frequency (MHz)	352,2
Optimum beta	0,50
Operating temperature (K)	2
Nominal Accelerating gradient (MV/m)	9
Lacc (βopt.x nb gaps x λ/2) (m)	0,639
Bpk (mT)	79 (max)
Epk (MV/m)	39 (max)
Bpk/Eacc (mT/MV/m)	<8,75
Epk/Eacc	<4,38
Beam tube diameter (mm)	50
RF peak power (kW)	335
G (Ω)	130
Max R/Q (W)	427
Qext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

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	

FIRST COLD TEST RESULT OF FIRST ESS HIGH BETA PROTOTYPE CAVITY

- Measurements done the 22th of May 2014 in **vertical cryostat** at CEA Saclay
- Testing conditions: CW mode
- Operating temperature: 2 K
- Resonant frequency of π mode (measured): 704.292788 MHz
- External coupling (measured) : $Q_i = 6.5^e9 \pm 1^e9$, $Q_t = 6.8^e12$
- Parameters used : G = 241, R/Q = 435.35 Ω (at β = 0.86), L_{acc} = 0.92 m

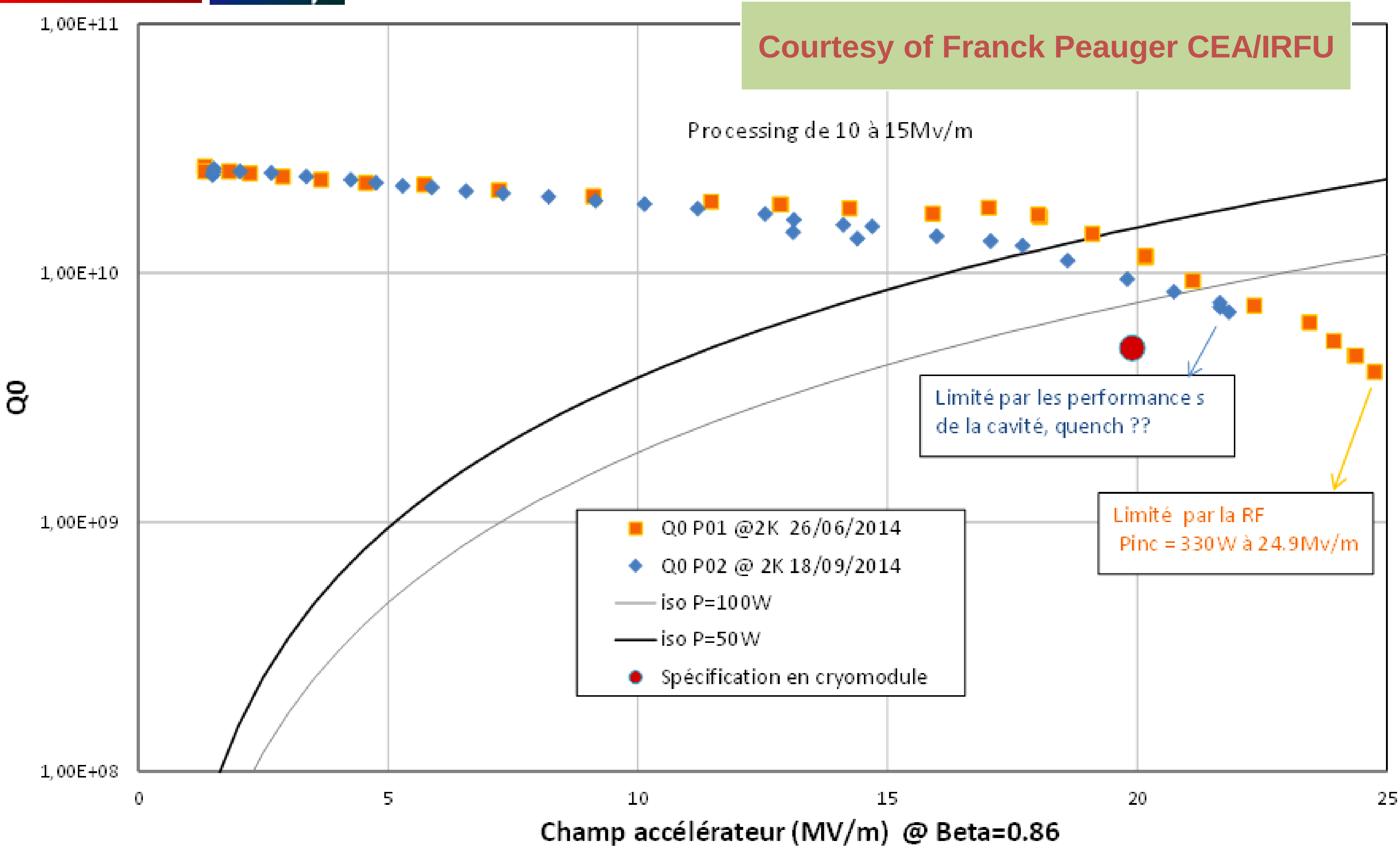


☞ No quench observed

Next plans:

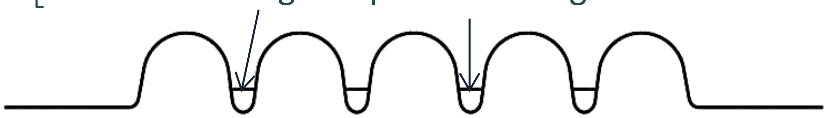
- Measurement of resonant frequency of 1st bandpass mode at 2K
- Measurement of resonant frequency of HOM at 2K
- If possible, increase accelerating field up to the quench limit
- Perform heat treatment at CERN at 650°C under vacuum

Cavités ESS prototype β=0.86
P01 vs P02 @ 2K

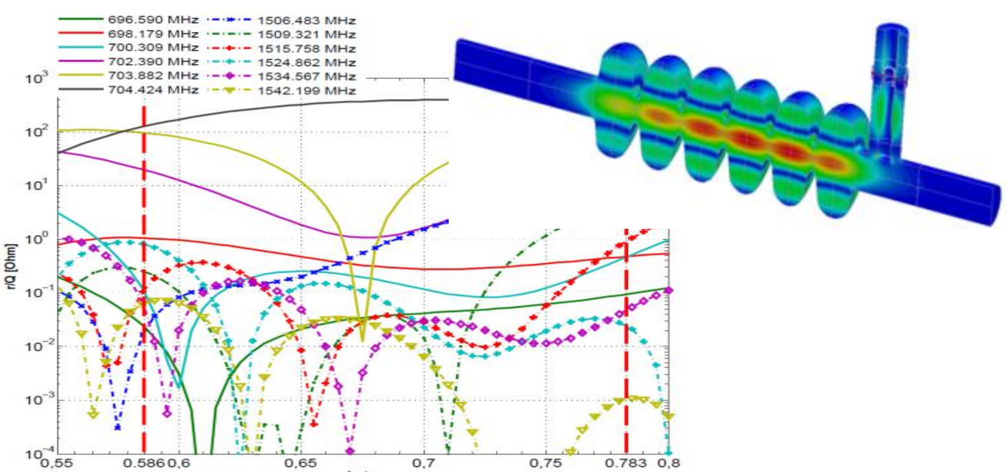


Medium-β Elliptical Cavities

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

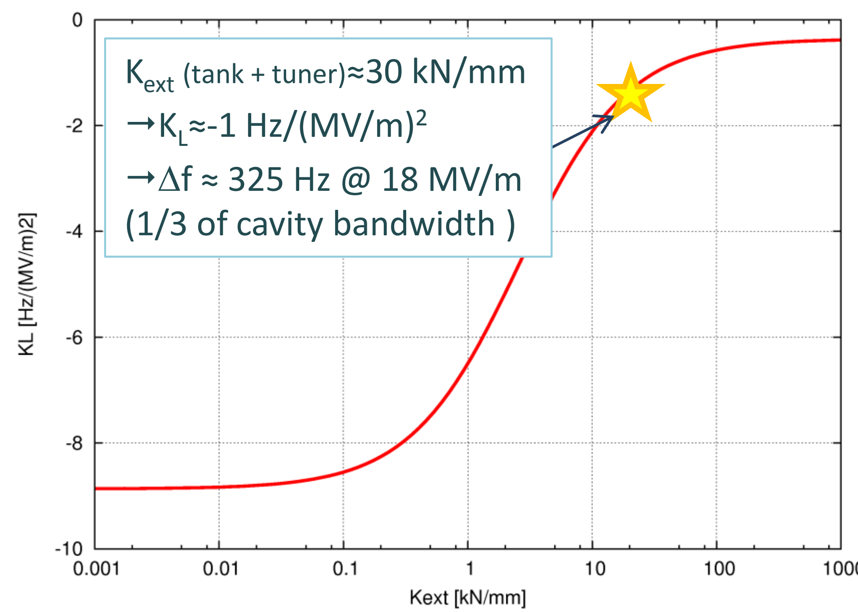


RF/mechanical design

Lorentz detuning

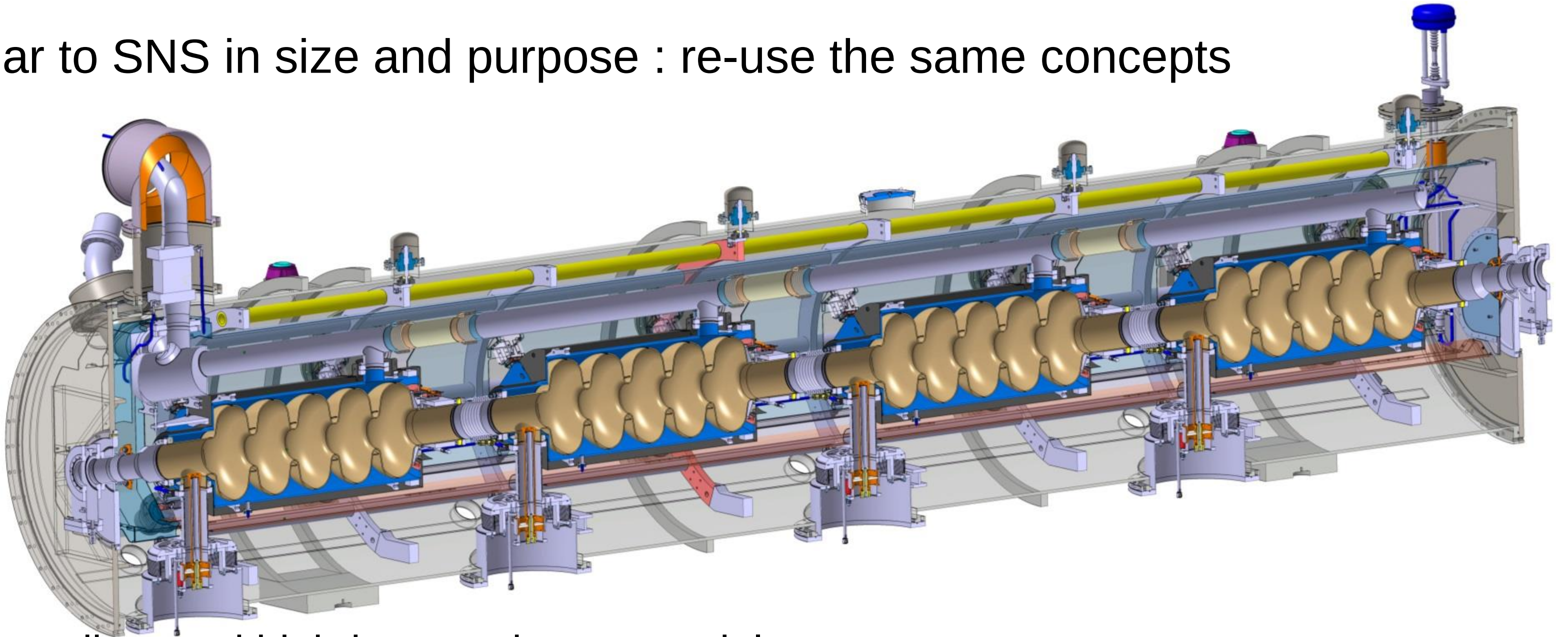
$$K_L = \Delta f / E_{acc}^2$$

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



Cavity Cryomodule - Generic

➢ Similar to SNS in size and purpose : re-use the same concepts



Similar medium and high-beta cavity cryomodules

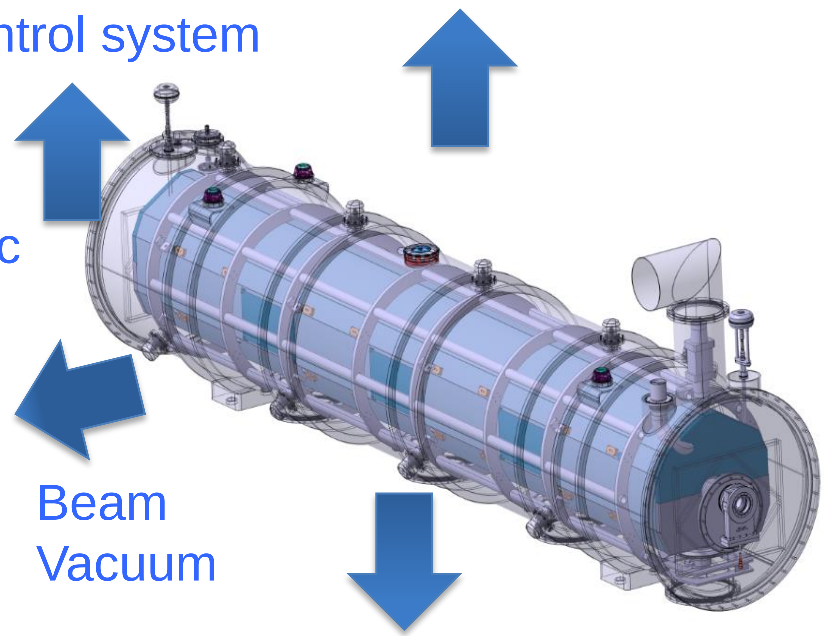
- Common design: Small length difference between medium and high-beta cavities
- Distance between power couplers
- Vacuum vessels, thermal shield, supports, alignment system.

Only minor differences:

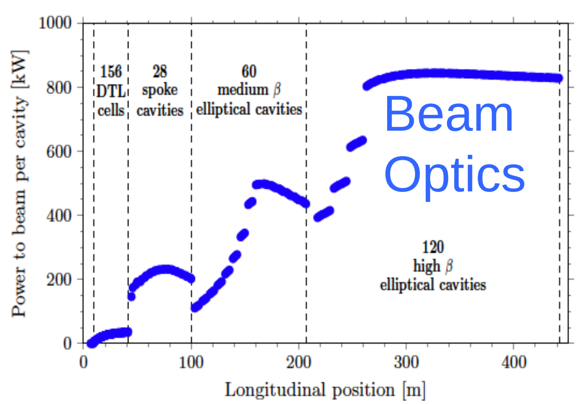
- Length of the inter-cavity bellows, details in cryo piping, beam pipe bellows
- Tuner piezo frames
- Penetration of the antenna for Q_{ext} adjustment

Cryomodule Interfaces

- Most AD internal Work Packages (beam optics, RF, cryo, vacuum, test stands, electrical, cooling, installation)
- External WPs cryomodule, cavity and designers and potential In-Kind collaborators
- Control command (Control Box, PLC, LLRF, MPS, EPICS)
- Data-logging ICS teams
- ESS ES&H
- Conventional Facility
- ESS system engineer, QA
- Survey experts
- Transport



Previous Linac version for comparison ➔



Elliptical Cryomodule Components

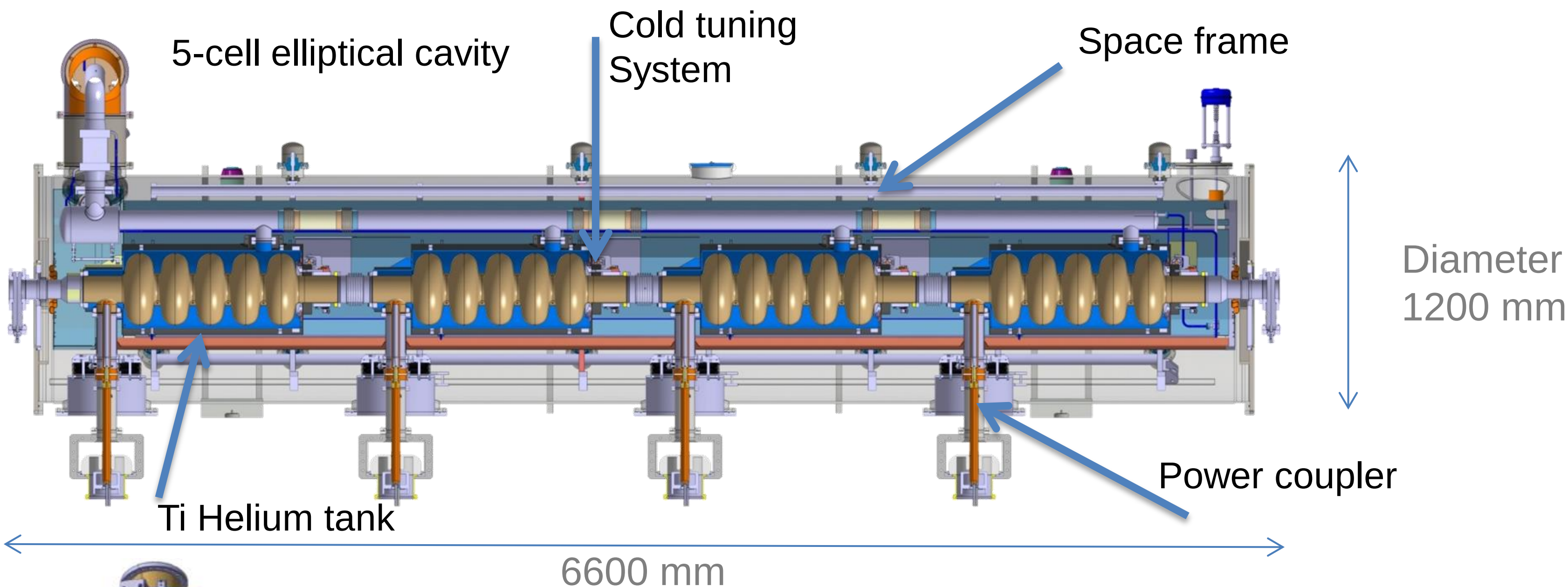
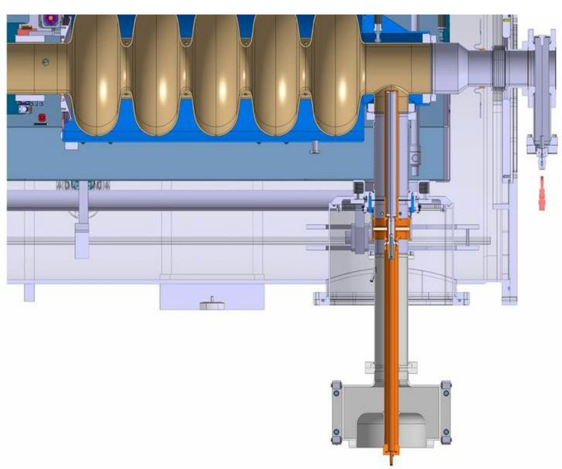
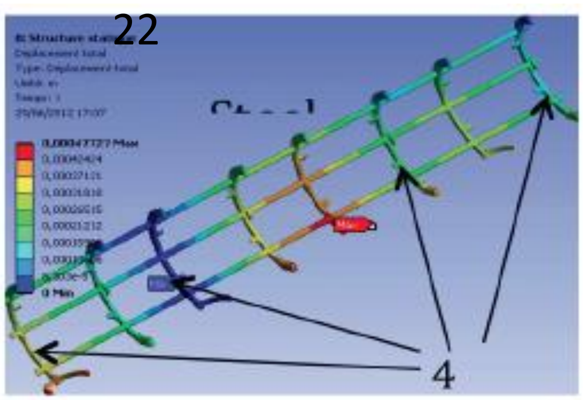
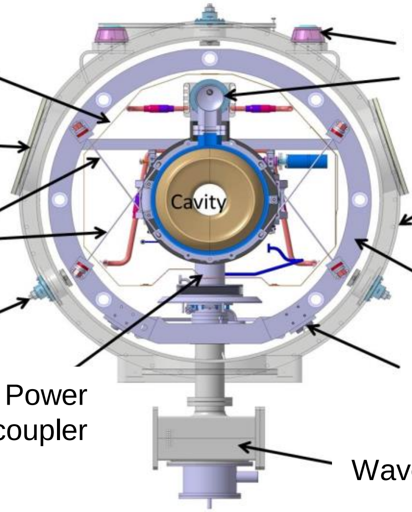


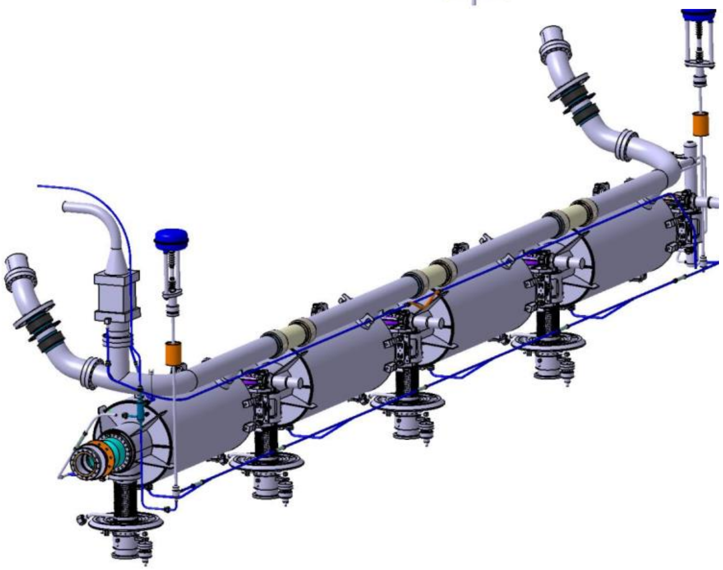

Figure 4.120: Helium vessel with hanging rod

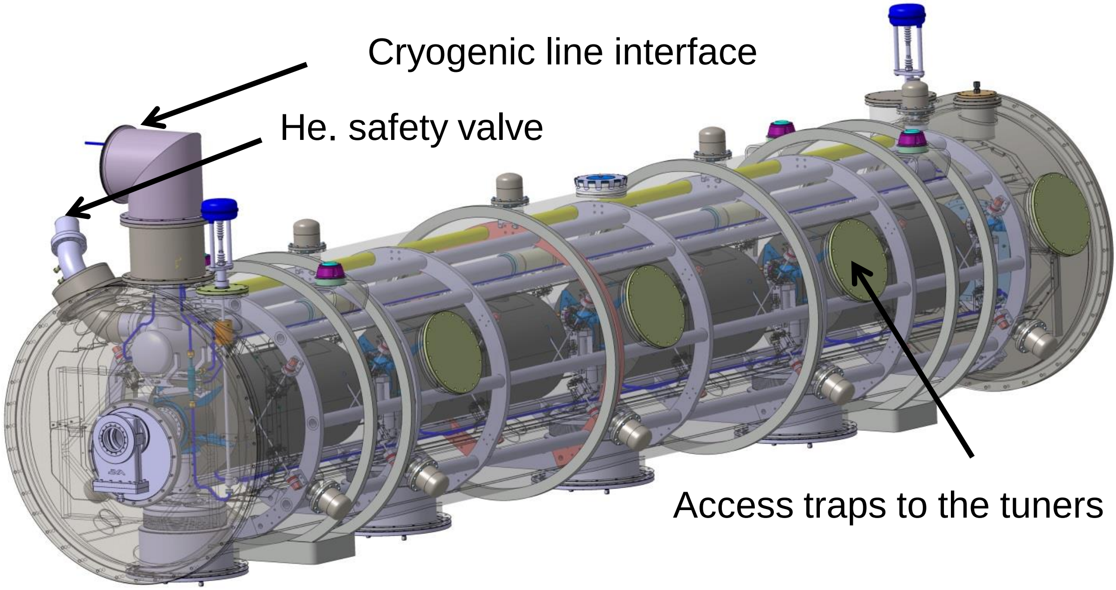




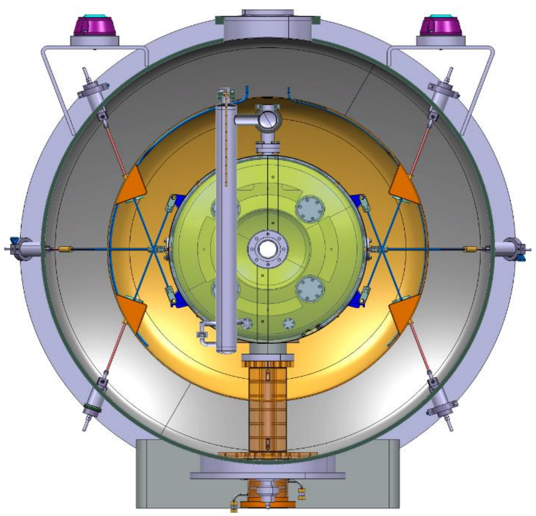
Elliptical Cryomodule Components



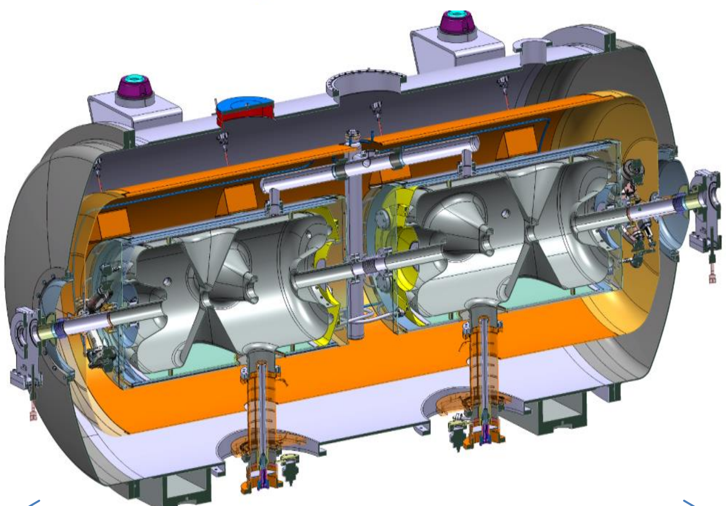




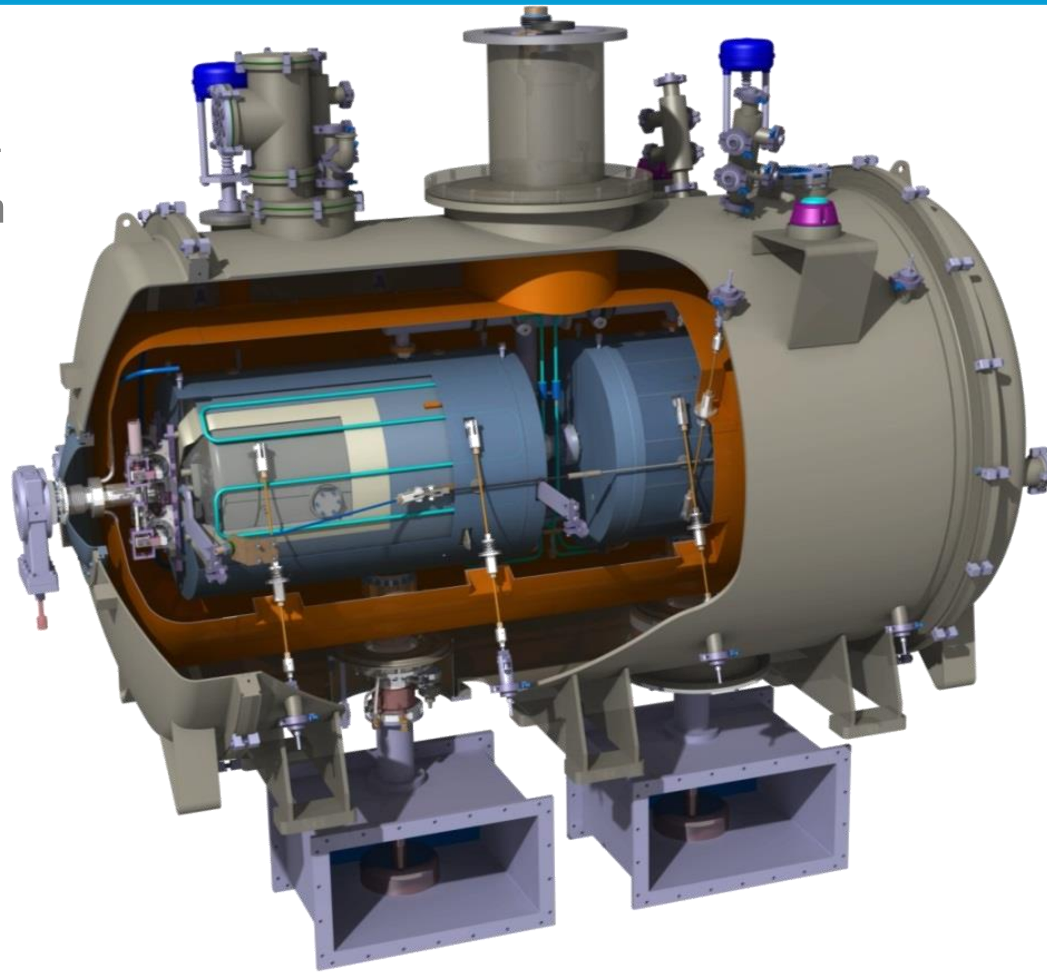
Spoke cavity string and cryomodule package



Diameter
1350 mm

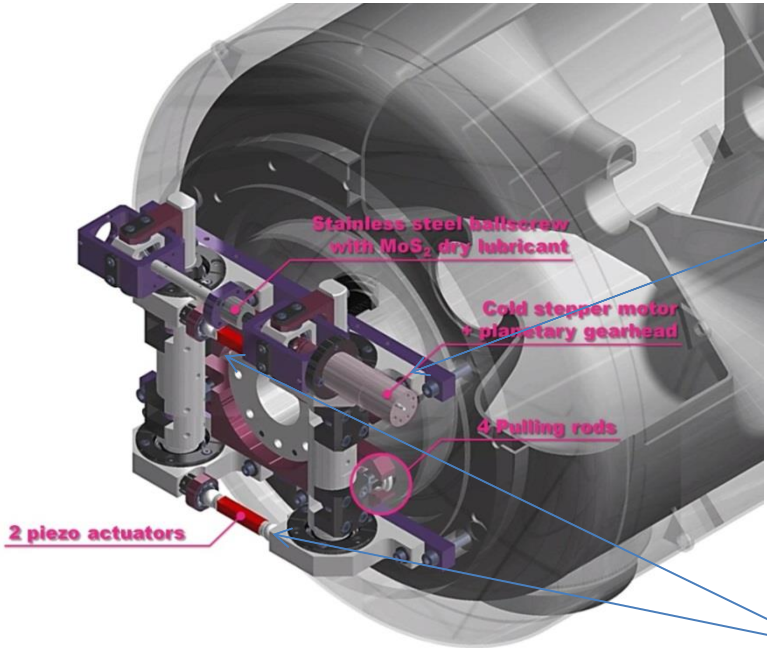


2900 mm

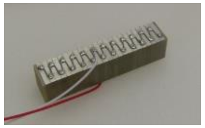


Cold Tuning System

Spoke CTS



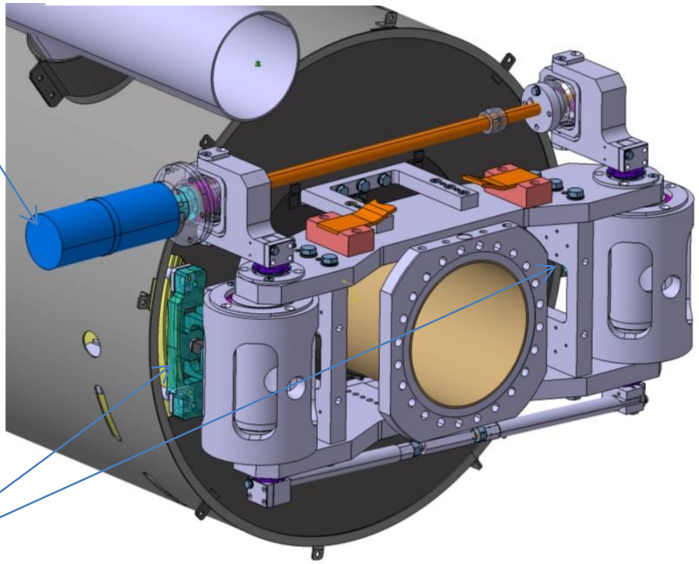
Stepper motor and planetary gearbox (1/100e) at cold and in vacuum



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

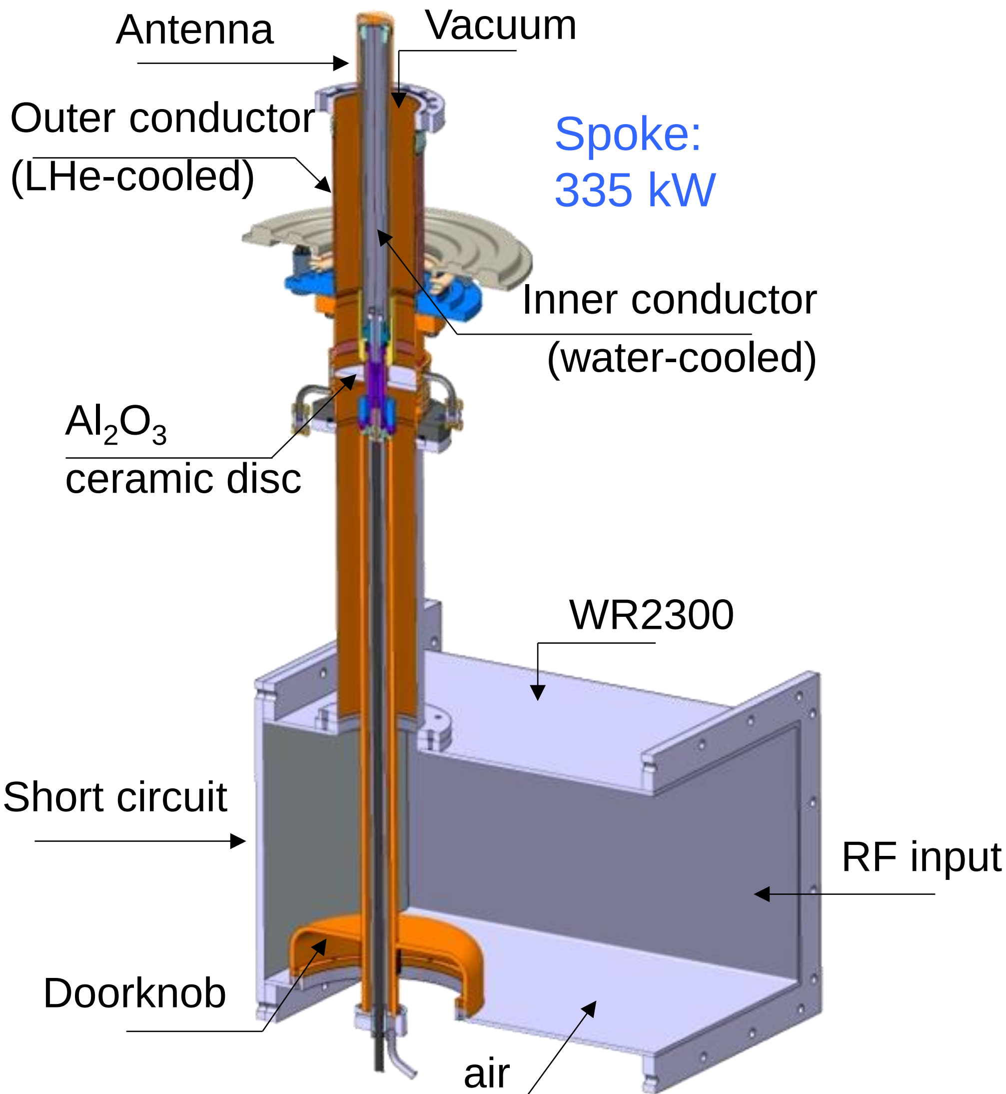
&

Fast tuner

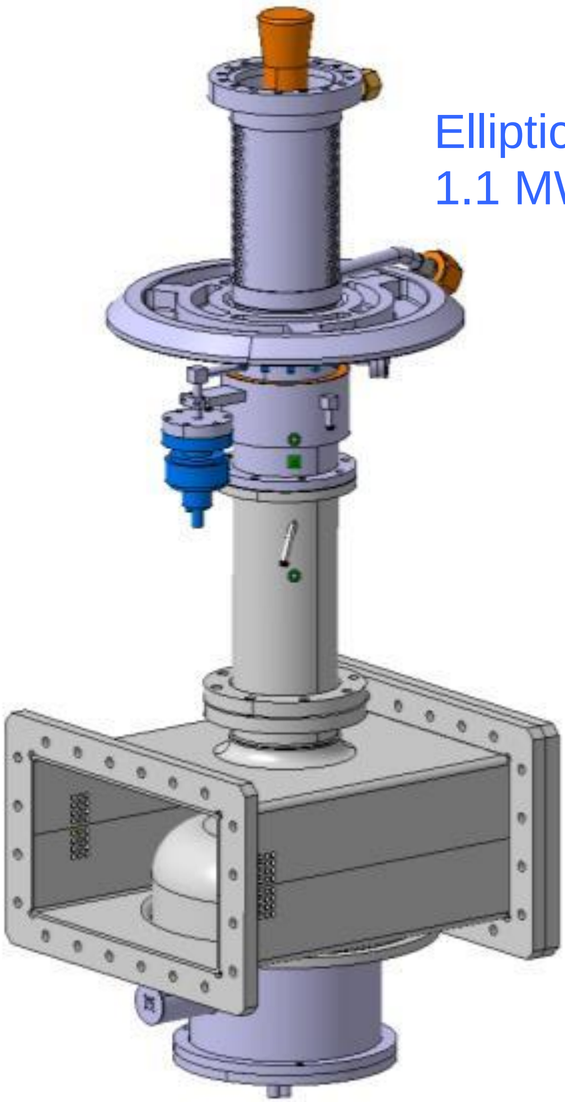
Main purpose : Compensation of small frequency shifts with a high speed

Actuator used : Piezoelectric actuators

Fundamental Power Coupler

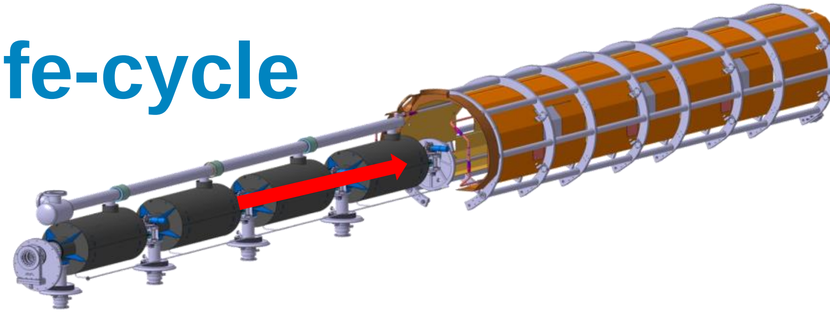


Spoke:
335 kW

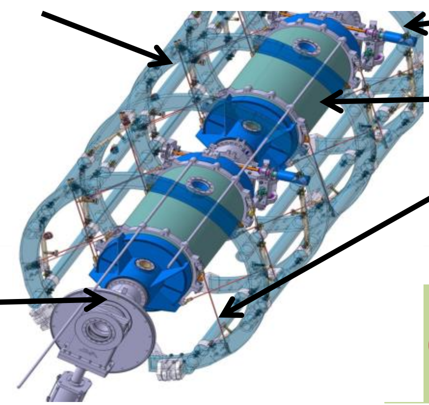


Elliptical:
1.1 MW

Cryomodule life-cycle



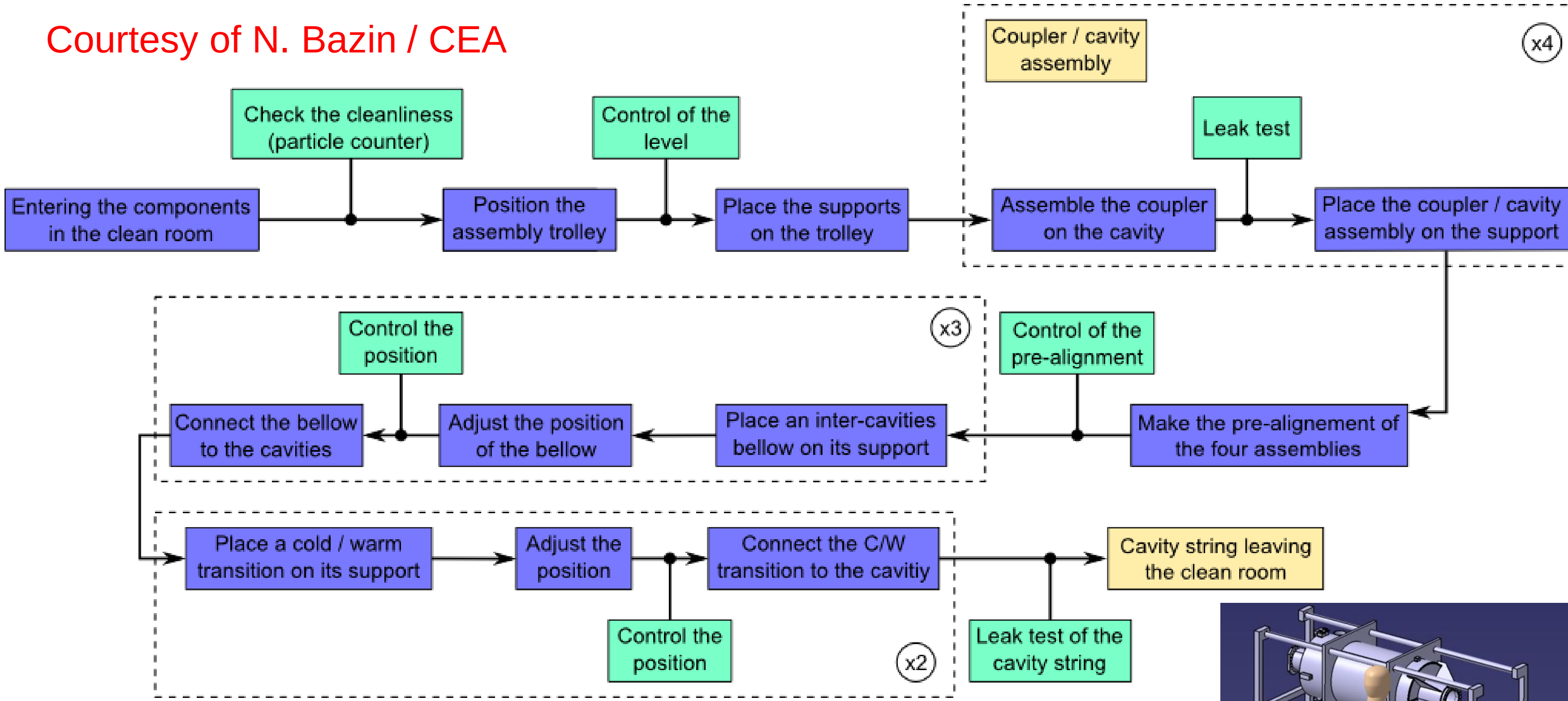
- Cavity fabrication
- Chemical treatment
- High pressure rinsing In clean room (ISO5 or ISO4)
- Validation test of the cavity in vertical cryostat
- Qualified cavity storage
- Power coupler fabrication
- Assembling in clean room
- Coupler RF processing
- Processed couplers storage
- Cryomodule components fabrication
- Tools fabrication
- Cavity string assembling in clean room
- Cryomodule assembling
- Transport
- Cryomodule reception and storage
- Validation test of the cryomodule
- Cryomodule storage
- Cryomodule on beam line



Courtesy of Pierre Bosland CEA/IRFU

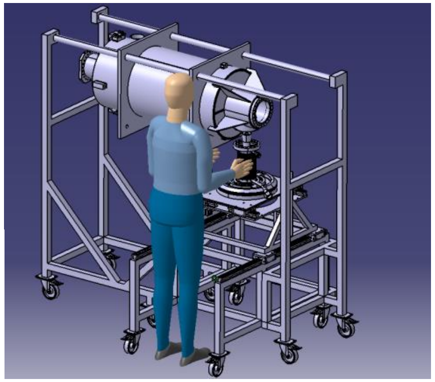
Assembly of elliptical cryomodules

Courtesy of N. Bazin / CEA



- Detailed procedures will be defined for every phases
  - Components and tools
  - Operations
  - Controls and tests

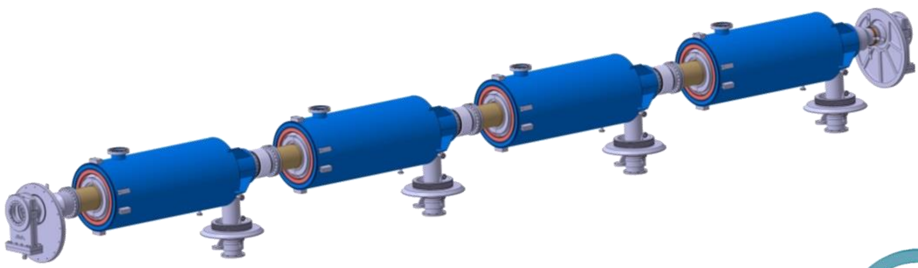
Tooling for elliptical cavities:



Elliptical Assembly Procedure

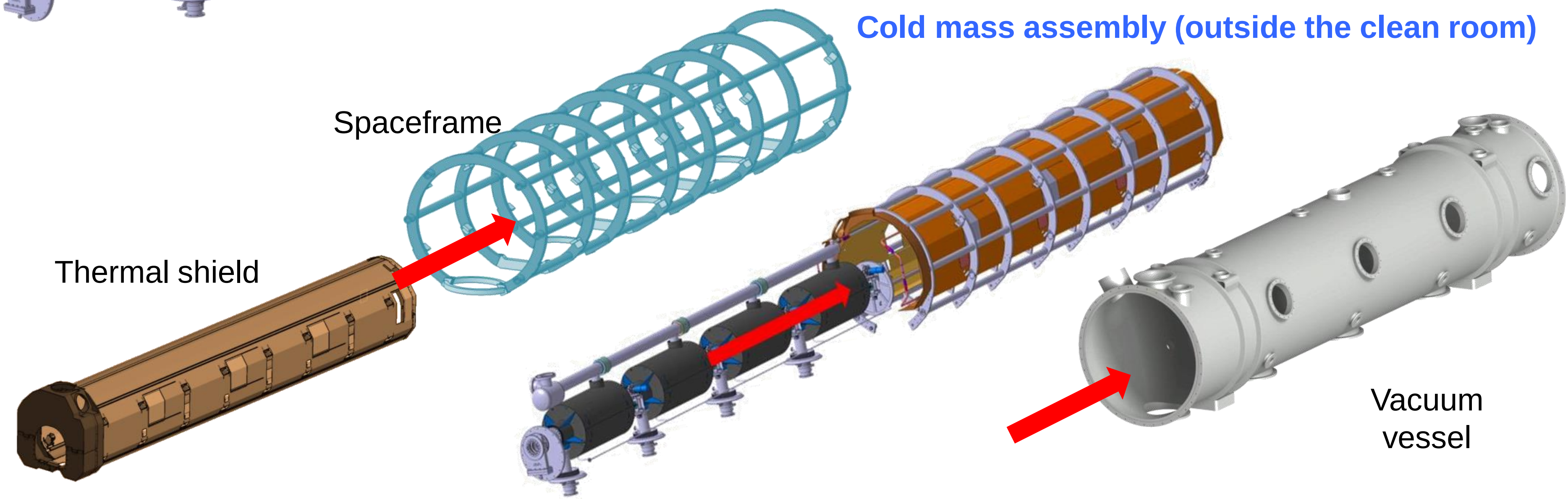
EUROPEAN SPALLATION SOURCE

Cavity string assembly in clean room



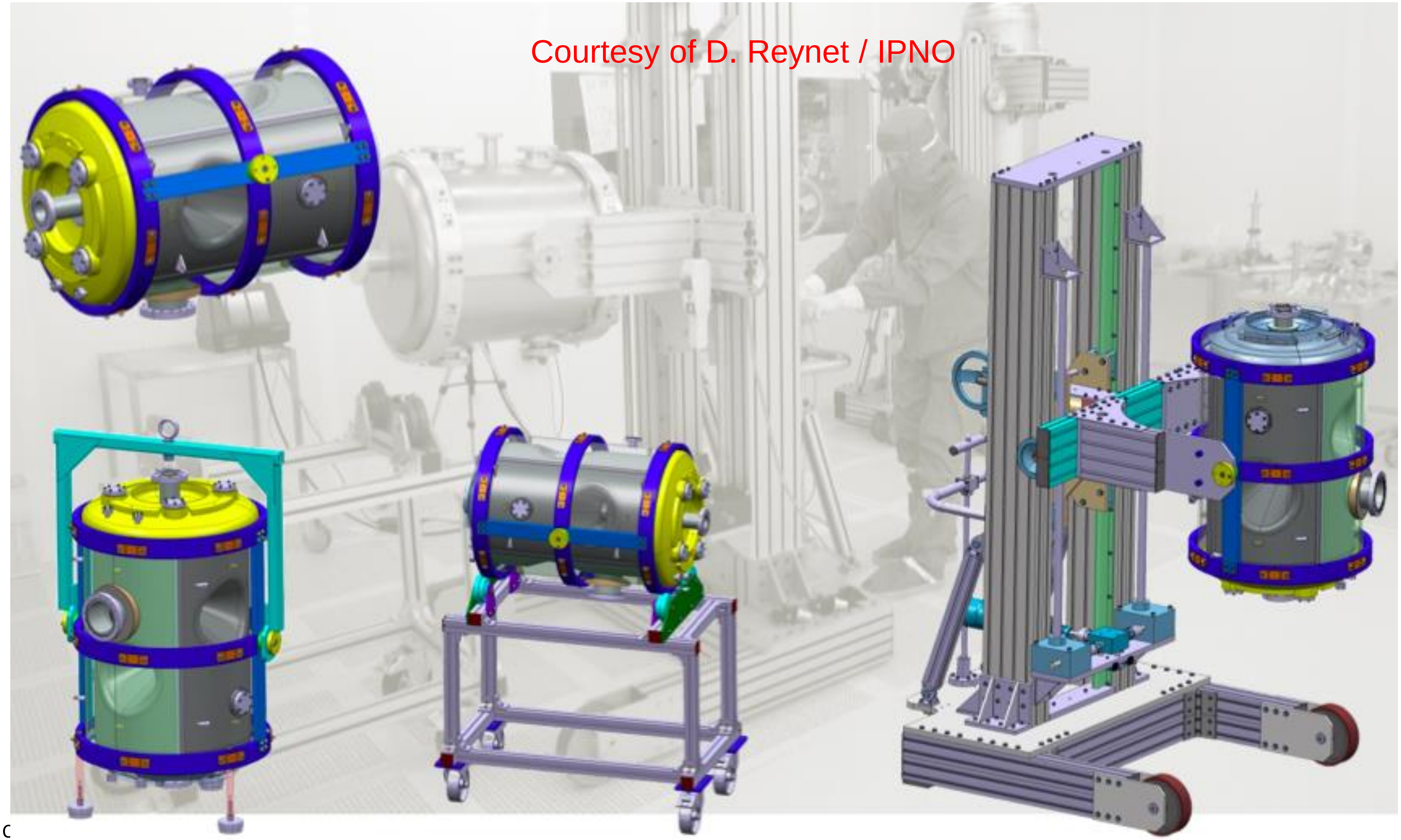
Build on existing knowledge (SNS, XFEL)
- Develop Training and “Fabrication file”
- Pre-industrialization
- Industrialization

Cold mass assembly (outside the clean room)



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

Spoke assembling in clean room/IPNO



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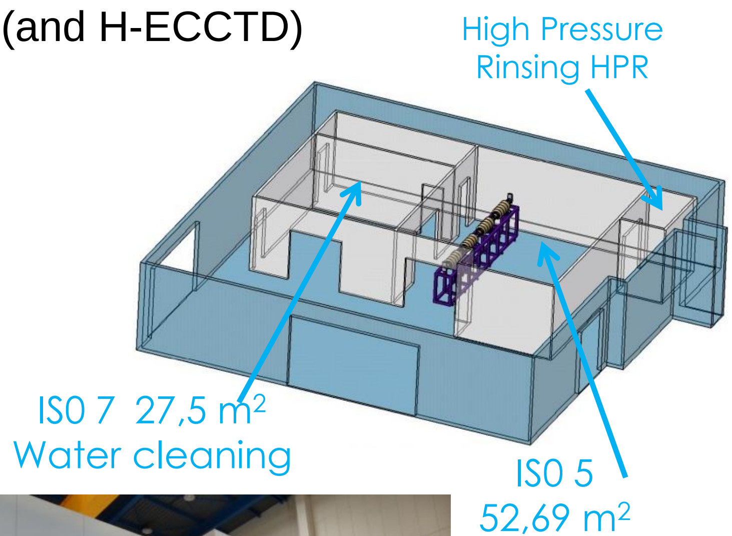
Infrastructure in Saclay

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)




Standards and ESS Safety Culture

Engineering standards

- Codes and standards: CEN, European Committee for standardization and SIS (Swedish Standard Institute)
- ISO, International Organization for standardization

→ Compliance with Pressure European Directive 97/23/EC; EN ISO 4126

→ Necessary procedures validated by "Notified body"

→ "ESS guidelines for design, manufacture, conformity assessment and operation of pressure equipment for cryomodules"

→ Standardization effort (e.g. naming convention, motion ctl)

Radio-Protection and Rad-hard equipment

- As low as reasonable achievable (ALARA)
- Passive and active safety measures (safety barrier)

Personnel **Protection System** and Machine Protection System (IEC61508)

Risk Analysis (Project and Technical risk assessment)

Reliability Study (Systematic over the ESS)

Safety Reviews (Preliminary DR, Critical DR, Annual Audit)

Quality Assurance

Cryomodule Technology Demonstrators

One full scale spoke, medium and high-beta cavity cryomodules tested by end of 2016 !
A staged approach towards the series industrialization and the ESS Linac tunnel installation

- Validate designs and construction capability of SRF components
- Prepare the industrialization process by validating component life-cycles (incl. assembling process, QA/QC)
- Validate component performances (incl. RF, mechanical, thermal)
- Develop ESS SRF linac operating procedures
- Validate control command strategy (Control box, PLC, EPICS, LLRF)
- Validate ESS interfaces with RF, cryogenics, vacuum and control systems
- Train people in ESS SRF Technology and build an ESS collaboration

Preparation of the stand for the RF power tests at 2 K

Development and installation of:

1. Cryogenic line (L > 50 m) + Dewar + ESS valves box + jumper line
2. C/C system
3. RF wave guide line at 704MHz
4. Modification of the klystron modulator to increase the pulse length up to the ESS requirements (2ms => 3ms)

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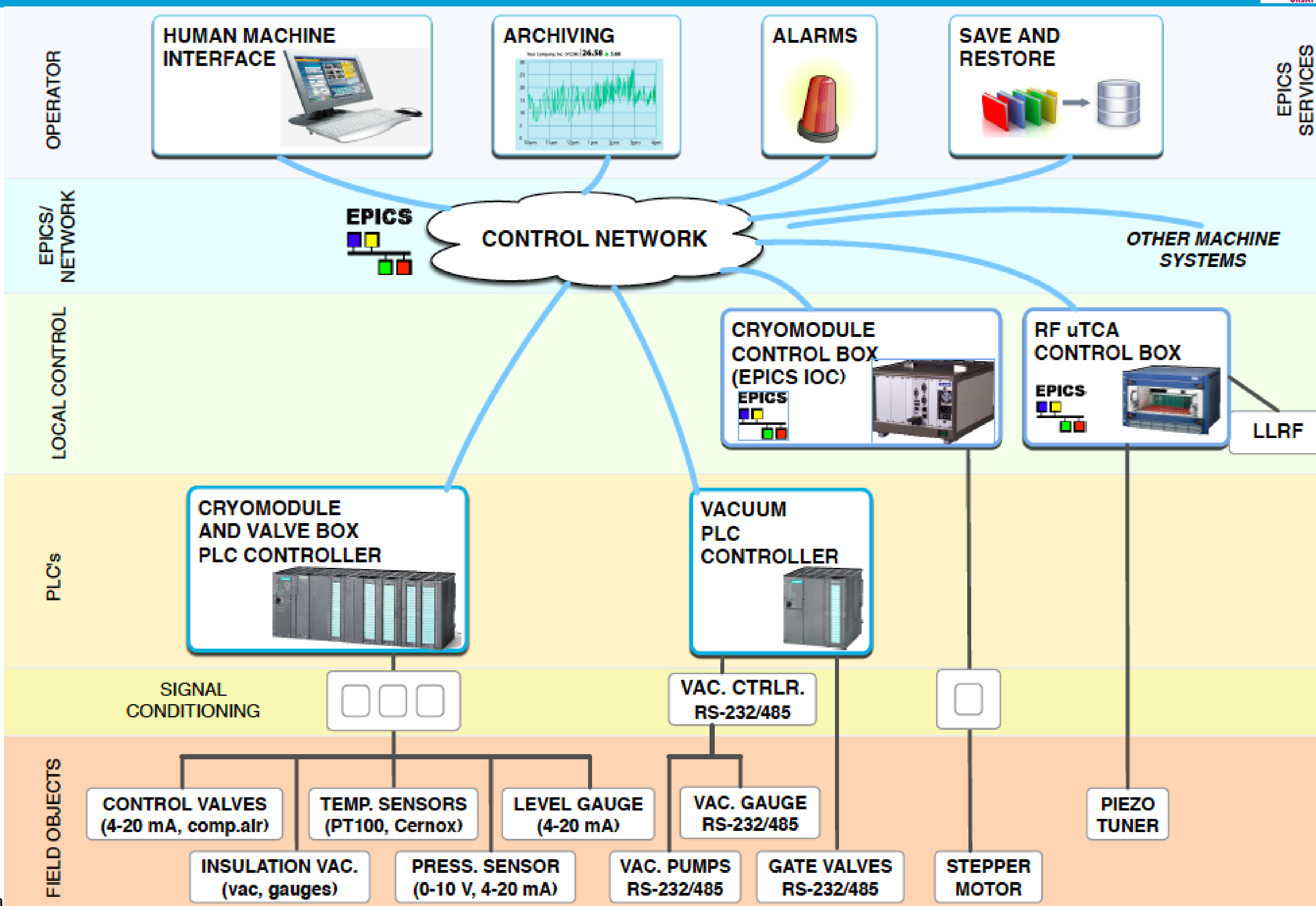
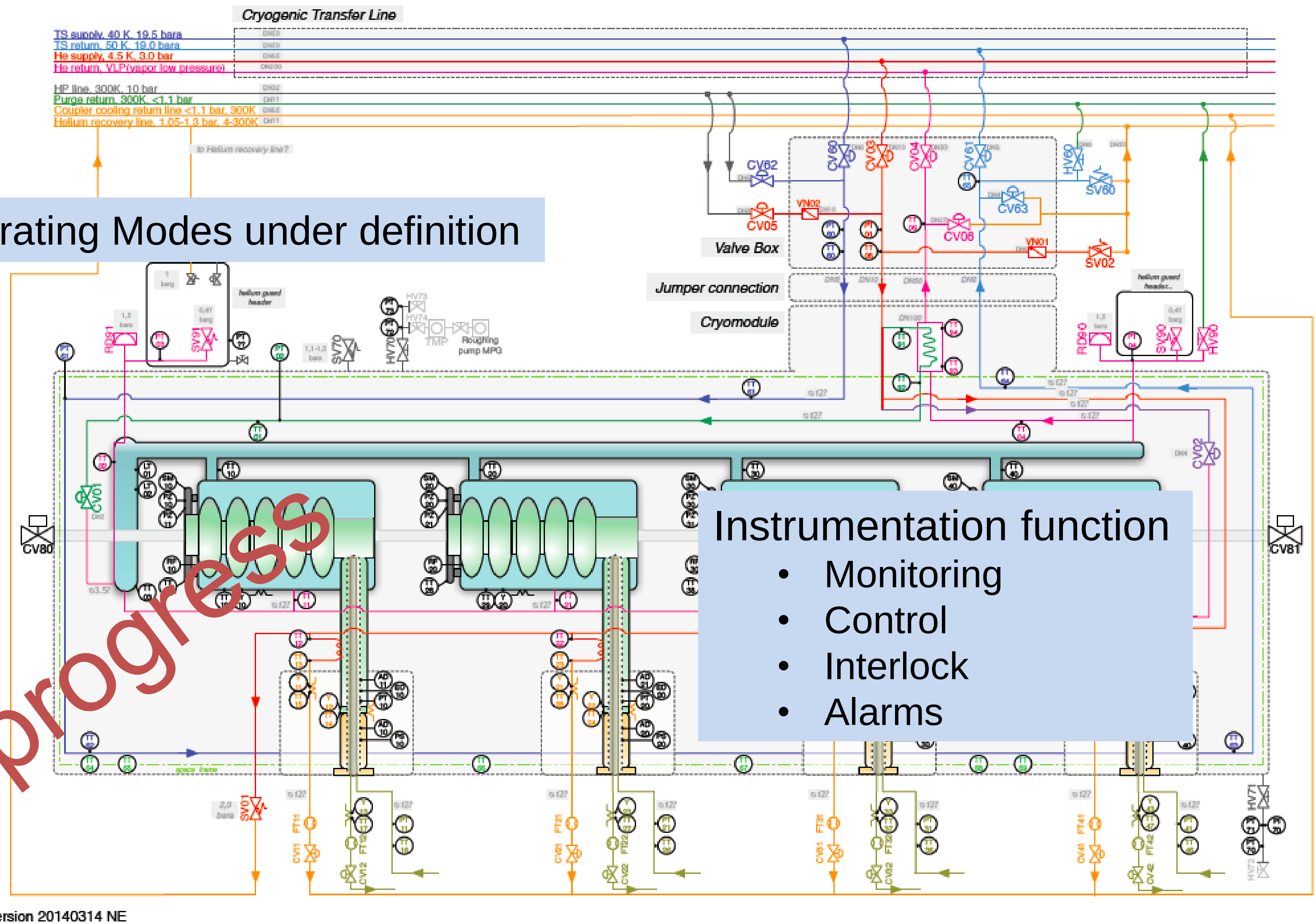
ESS Control and Command System

EUROPEAN SPALLATION SOURCE



Process and Instrumentation



In progress

Operating Modes under definition

Instrumentation function

- Monitoring
- Control
- Interlock
- Alarms

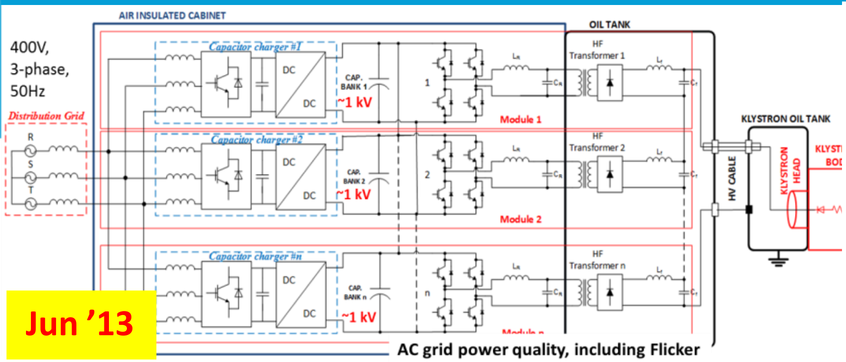
R&D on High Voltage and High Power Klystron Modulators for the ESS accelerator

An effective collaborative effort in Skåne

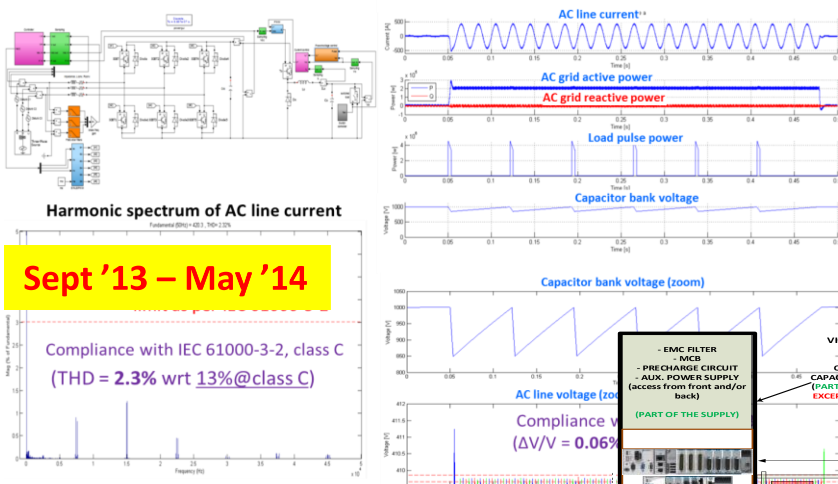
INSTITUT DE PHYSIQUE NUCLEAIRE ORSAY

- **ESS has established an innovative R&D program with LTH – Lund University, involving local industry…**
  … for the design, construction and testing of
  … a reduced scale technology demonstrator of
  … a High Voltage High Power Klystron Modulator rated at
  … 115 kV (pulse voltage), 2.3 MW (pulse power), 3.5 ms / 14 Hz
  (pulse length and repetition rate)
- **Worldwide unique technology**, at this power level, requiring new concepts and new construction techniques;
- **Project development period:**
  From June 2013 to April 2015;
- **35 units will be required for ESS accelerator**, with a power rating 5x higher than the reduced scale technology demonstrator

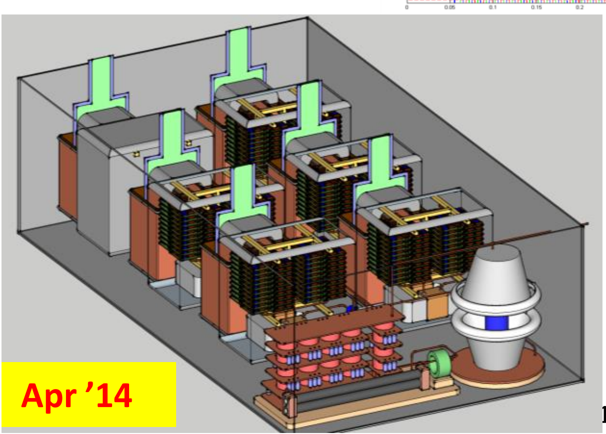
From a conceptual design to reality…



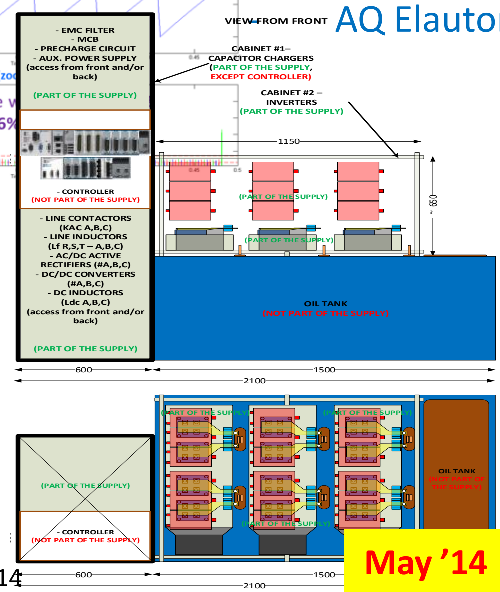
Jun '13



Sept '13 – May '14



Apr '14



May '14

Design and specifications:

- ESS and LTH;

R&D and training of Highly Qualified Personnel:

- LTH (3 MSc thesis, 5 Research associate, 1 PhD thesis starting Jan 2015);

Control system hardware :

- National Instruments AB, Skåne business center;

Control system software :

- Lund University Innovation System (LUIS) AB;

Construction (Low Voltage part):

- AQ Elautomatik AB, in Lund;

Aug '14

Conclusion

A new collaborative Project for Spallation in Europe

- **Technology Demonstrators will validate new SRF cavity and cryomodule component designs by the end of 2016**
- **Build further capacity in industrialization process**
- **Strengthen the scientific worldwide partnership for SRF Technology !**

Thanks for your attention !

and thanks to our current and future partners (institutes, laboratories, companies)