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
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
ESS High-Story: From dreams to reality
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

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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
In-kind Process for Construction Begins

- 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

Courtesy of Allen Weeks
Head of Communications @ ESS
Total construction cost: € 1,84 billion

Target station € 174M

Accelerator € 563M (w/o contingency € 497)

Instruments € 389M

In-kind
Cash

ESS In-kind contributions potential

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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%)
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
The ESS Accelerator
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

The National Center for Nuclear Research, Swierk

Sebastien Bousson

Pierre Bosland

Ibon Bustinduy

Søren Pape Møller

Roger Ruber

Anders J Johansson

CERN

Santo Gammino

Mats Lindroos, Head of Accelerator div. @ ESS
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
Cryomodule is mainly composed of:

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam mode</td>
<td>Pulsed (4% duty cycle)</td>
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<tr>
<td>Frequency [MHz]</td>
<td>352.2</td>
</tr>
<tr>
<td>Beta_optimal</td>
<td>0.50</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>2</td>
</tr>
<tr>
<td>Bpk [mT]</td>
<td>70 (max)</td>
</tr>
<tr>
<td>Epk [MV/m]</td>
<td>35 (max)</td>
</tr>
<tr>
<td>Gradient Eacc [MV/m]</td>
<td>8</td>
</tr>
<tr>
<td>Lacc (=beta optimal x nb of gaps x λ /2) [m]</td>
<td>0.639</td>
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<tr>
<td>Bpk/Eacc [mT/MV/m]</td>
<td>&lt; 8.75</td>
</tr>
<tr>
<td>Epk/Eacc</td>
<td>&lt; 4.38</td>
</tr>
<tr>
<td>Beam tube diameter [mm]</td>
<td>50 (min)</td>
</tr>
<tr>
<td>P max [kW]</td>
<td>300 (max)</td>
</tr>
</tbody>
</table>

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Elliptical Cryomodules – CEA/IPNO

- Helium tank
- 5-cell elliptical cavity
- Cold tuning System
- Power coupler
- Space frame

→ Elliptical Cavities Cryomodule Technology Demonstrator results by the end of 2015
Elliptical Cryomodules – CEA/IPNO

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Elliptical Cryomodules – CEA [TDR]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<tbody>
<tr>
<td>RF frequency</td>
<td>MHz</td>
<td>704.42</td>
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<tr>
<td>Temperature</td>
<td>K</td>
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<tr>
<td>MEDIUM-BETA</td>
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<td></td>
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<tr>
<td>Output energy</td>
<td>MeV</td>
<td>654</td>
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<tr>
<td>Number of cells per cavity</td>
<td></td>
<td>5</td>
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<tr>
<td>Geometric beta</td>
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<td>0.67</td>
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<tr>
<td>Cavity length</td>
<td>m</td>
<td>1.145</td>
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<tr>
<td>Expected gradient, horizontal</td>
<td>MV/m</td>
<td>15</td>
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<tr>
<td>Expected gradient, vertical test</td>
<td>MV/m</td>
<td>17</td>
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<tr>
<td>Cavity Q₀</td>
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<td>$6 \times 10^9$</td>
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<tr>
<td>Fundamental mode $Q_{ext}$</td>
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<td></td>
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<tr>
<td>Fundamental mode $R/Q$</td>
<td>W</td>
<td>340</td>
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<tr>
<td>Average heat load at nominal gradient</td>
<td>W</td>
<td>5.9</td>
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<tr>
<td>Power coupler power forward power</td>
<td>MW</td>
<td>1.2</td>
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<tr>
<td>Maximum Power transmitted to beam</td>
<td>MW</td>
<td>0.6</td>
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<tr>
<td>HIGH-BETA</td>
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<td>Output energy</td>
<td>MeV</td>
<td>2500</td>
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<tr>
<td>Number of cells per cavity</td>
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<td>5</td>
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<tr>
<td>Geometric beta</td>
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<td>0.9</td>
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<tr>
<td>Cavity length</td>
<td>m</td>
<td>1.356</td>
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<tr>
<td>Nominal gradient in the linac</td>
<td>MV/m</td>
<td>18</td>
</tr>
<tr>
<td>Expected gradient, vertical test</td>
<td>MV/m</td>
<td>20</td>
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<tr>
<td>Geometric beta prototype</td>
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<td>0.88</td>
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<td>Optimum beta prototype</td>
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<tr>
<td>Cavity length prototype</td>
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<tr>
<td>Fundamental mode $R/Q$ prototype</td>
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<tr>
<td>Fundamental mode $Q_{ext}$ prototype</td>
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<td></td>
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<tr>
<td>Cavity $Q_0$ at nominal gradient, prototype</td>
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<td></td>
</tr>
<tr>
<td>Average heat load at nominal gradient, prototype</td>
<td>W</td>
<td>4.5</td>
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<tr>
<td>Power coupler power rating</td>
<td>MW</td>
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<tr>
<td>Power coupler forward power</td>
<td>MW</td>
<td>1.2</td>
</tr>
<tr>
<td>Maximum power transmitted to beam</td>
<td>MW</td>
<td>0.9</td>
</tr>
<tr>
<td>Cell to cell coupling</td>
<td>%</td>
<td>1.8</td>
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<tr>
<td>Epk/Eacc</td>
<td></td>
<td>2.2</td>
</tr>
<tr>
<td>Bpk/Eacc</td>
<td>mT/(MV/m)</td>
<td>4.3</td>
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<tr>
<td>Separation between $\pi$ and $4\pi/5$ modes</td>
<td>MHz</td>
<td>1.2</td>
</tr>
<tr>
<td>Iris diameter</td>
<td>mm</td>
<td>120</td>
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</table>

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Elliptical cavities for ESS

- $P_{RF} \text{ max} = 1.2 \text{ MW}$
- Piezo tuner
  - <= HIPPI power coupler
  - <= Saclay V tuner (HIPPI / SPL tuner)
- Titanium helium vessel (Thickness: 5 mm), Flanges material: NbTi
- $L_{\text{Pulse}} \times \text{rep rate} = DC: 2.86 \text{ ms} \times 14 \text{ Hz} = 4 \%$
- 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 $\rightarrow 45 \text{ MV/m}$
- Energy $\rightarrow 2 \text{ GeV} \Rightarrow$ Current $\rightarrow 62.5 \text{ mA}$
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
The ESS cryomodules: from design to fabrication

Purification:
- Chemical etching 100-200 μm
- Chemical etching 5-20 μm

Annealing:
- 800°C, 2h (or 600°C, 10h)

Specific rinsing

High pressure rinsing (HPR)

Assembling

Baking, 120°C, 48h

Post processing

Test RF

He processing, HPP

WHY
- Clean welding
- RRR enhancement
- Remove contamination and damage layer
- Get rid of hydrogen
- Remove diffusion layer (O, C, N)
- e.g. remove S particles due to EP
- Get rid of dust particles
- Ancillaries: antennas, couplers, vacuum ports...
- Decrease high field losses (Q-drop)
- Get rid of "re-contamination"?
- Cavity’s performance
- Decrease field emission

COMMENTS
- Nb = getter material.
  If RRR/10 @ welding => Q_i/10
- RRR 300-400 now commercially available
- Limitation: BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility
- Source of H: wet processes
  H segregates near surface in form of hydrides (= bad SC)
  Diffusion layer < ~1μm in bulk, a little higher at Grain Boundaries
- Under evaluation
  HF, H₂O₂, ethanol, degreasing,…
- Not always enough (recontamination during assembly)
- In clean room, but recontamination still possible
  Unknown mechanism, first 10 nm of the surface in concern.
- Under evaluation: dry ice cleaning, plasma
  First naked cavity in vertical cryostat, then dressed in horizontal cryostat/accelerating facility
- RF power with/without He to destroy field emitters (dust particles)
  NB field emission: principal practical problem in accelerators

Courtesy of Claire Antoine/CEA
Cavities’ fabrication scheme vs surface and material properties

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- Forming
  - EB Welding
  - Ti purification
- Chemical etching 100-200 µm
- Annealing 800°C, 2h (or 600°C, 10h)
- Chemical etching 5-20 µm
- Specific rinsing
- High pressure rinsing (HPR)
- Assembling
- Baking, 120°C, 48h
- Post processing
- Test RF
- He processing, HPP

WHY
- Clean weld
- PPR enhancement
- Remove contamination damage layer
- Get rid of hydrogen
- Remove diffusion layer < ~1µm in bulk, a little higher at Grain boundaries
- e.g. remove S particles due to EP
- Under evaluation
- Get rid of dust particles
- Ancillaries: antennas, couplers, vacuum ports...
- Decrease high field losses (Q-drop)
- Get rid of ‘re-contamination’
- Cavity’s performance
- Decrease field emission
- Nb field emission: principal practical problem in accelerators

Surface composition and surface morphology
- Mechanical properties, grain size, strain hardening...
- Purity issues
- Surface composition
- Surface cleanliness
- In clean room, but recontamination still possible
- Unknown mechanism, first 10 nm of the surface in
- Cavity’s performance
- First naked cavity in vertical cryostat, then dressed in
- Decrease field emission

Surface composition
- Surface cleanliness
- Courtesy of Claire Antoine/CEA

8/04/2013 Claire Antoine
ESS Lund | PAGE 26
CEA ISO 5 new clean room

Availability of the clean room: June 2013

ISO 5
51,85 m²

ISO 7
26,1 m²
Water cleaning

High Pressure Rinsing
HPR

⇒ Development of the cryogenics and RF bunker to test the final ECCTD @ CEA Saclay
Additional implementation
• ESS tunnel valve box
• ESS tunnel control system
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
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)

Input
- Scope of contribution
- Value
- Technical & Project Specs
- Interfaces
- Schedule
- Standards
- QA Requirements
- Responsible Person(s)

Output
- Hardware
- Services
- Manpower
- Software
- Documents

Partner Project Responsibility
- Management
- Resources
- Work
- QA Control

Work Unit Confirmation
- Acceptance
- Integration
- Commissioning

Agreement + Technical Annex

Acknowledgement

Courtesy of Allen Weeks