The SRF Linac Components for the European Spallation Source: First Test Results

Christine Darve - Deputy Leader of SRF Work Packages, WP04 and WP05
ESS Accelerator Division

on behalf of the SRF teams from
CEA/IRFU Saclay [Pierre Bosland]
CNRS/IPN Orsay [Guillaume Olry]
Uppsala and Lund Universities
ESS ERIC

www.europeanspallationsource.se
28 September 2016
Outline

• Introduction to European Spallation Source

• SRF linac design

• SRF linac component performance measurements
• Introduction to European Spallation Source

• SRF linac design

• SRF linac component performance measurements
Spallation Sources

Greenfield: Philosophie a la “Pré-verd”

The European Spallation Source (ESS) is a multidisciplinary research centre based on the world’s most powerful neutron source. This new facility will be up to 100 times brighter than today’s leading facilities, enabling new opportunities for researchers in the fields of life sciences, energy, environmental technology, cultural heritage and fundamental physics.

Collaborative project: >17 European countries

ERIC (European Research Infrastructure Consortium) on October 1, 2015

2014: Start of construction phase
2019: Beam to target
2023: ESS starts user program
2025: Construction Complete

~ 450 employees; for more than 2500 users / year
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~ 450 employees; for more than 2500 users / year
High Power Linear Accelerator:
- Energy: 2 GeV
- Rep. Rate: 14 Hz
- Current: 62.5 mA

Target Station:
- He-gas cooled rotating W-target (5MW average power)
- 42 beam ports

16 Instruments in Construction budget
Committed to deliver 22 instruments by 2028
Peak flux ~30-100 brighter than the ILL

Total cost: 1843 MEuros 2013
Partner institutions responsible for delivering the design & construction of ESS and SRF linac contributions

Aarhus University
Atomki - Institute for Nuclear Research
Agder University
Bergen University
CEA Saclay, Paris
Centre for Energy Research, Budapest
Centre for Nuclear Research, Poland, (NCBJ)
CERN, Geneva
CNR, Rome
CNRS Orsay, Paris
Cockcroft Institute, Daresbury
DESY, Hamburg
Delft University of Technology
Edinburgh University
Elettra – Sincrotrone Trieste
ESS Bilbao
Forschungszentrum Jülich
Helmholtz-Zentrum Geesthacht
Huddersfield University
IFJ PAN, Krakow
INFN, Catania
INFN, Legnaro
INFN, Milan
Institute for Energy Research (IFE)
Institut Laue-Langevin (ILL)
Rutherford-Appleton Laboratory, Oxford (ISIS)
Kopenhagen University
Laboratoire Léon Brillouin (LLB)
Lodz University of Technology
Lund University
Nuclear Physics Institute of the ASCR
Oslo University
Paul Sherrer Institute
Roskilde University
Tallinn Technical University
Technical University of Chemnitz
Technical University of Denmark
Technical University Munich
Science and Technology Facilities Council (STFC)
University of Tartu
Uppsala University
WIGNER Research Centre for Physics
Wrocław University of Technology
Warsaw University of Technology
Zurich University of Applied Sciences (ZHAW)
ESS Linac – A Collaborative Project

See poster: MOPLR062  
W. Wittmer « European Spallation Source (ESS) Normal Conduction Front End Status Report"
See oral: TU2A02
C. Martins
"Pulsed High Power Klystron Modulators for the ESS Linac Based on the Stacked Multi-Level Topology"
Superconducting linac

The SRF section represents 70% of the total length of the linac and 98% of the beam acceleration.
Outline

• European Spallation Source project

• SRF linac design

• SRF linac component performance measurements
Linac redesign to meet ESS cost objective

D. McGinnis

Key parameters:
- 5 MW beam power
- 2.86 ms pulses
- 2 GeV
- 62.5 mA peak
- 14 Hz
- 4 % DC
- Protons (H+)
- Low losses
- Minimize energy use
- Flexible design for mitigation & future upgrades
Spoke cavity and cryomodule design

Double spoke cavity

Ti. Helium tank
48 liter

<table>
<thead>
<tr>
<th>Item</th>
<th>Values</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Beam mode</td>
<td>Pulsed (4 % duty cycle)</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>352.21</td>
<td>MHz</td>
</tr>
<tr>
<td>Optimal β</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>2</td>
<td>K</td>
</tr>
<tr>
<td>Bpk</td>
<td>70 (max)</td>
<td>mT</td>
</tr>
<tr>
<td>Epk</td>
<td>39 (max)</td>
<td>MV/m</td>
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<tr>
<td>E acc</td>
<td>9</td>
<td>MV/m</td>
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<tr>
<td>L acc</td>
<td>0.639</td>
<td>m</td>
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<tr>
<td>Bpk/E acc</td>
<td>6.80</td>
<td>mT/(MV/m)</td>
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<tr>
<td>Epk/E acc</td>
<td>4.28</td>
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<tr>
<td>Beam tube dia.</td>
<td>56</td>
<td>mm</td>
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<tr>
<td>Pmax</td>
<td>335</td>
<td>kW</td>
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</table>
Elliptical cavity design

<table>
<thead>
<tr>
<th>Iris diameter (mm)</th>
<th>Medium</th>
<th>High</th>
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<td></td>
<td>94</td>
<td>120</td>
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<table>
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<th>Cell to cell coupling k (%)</th>
<th>Medium</th>
<th>High</th>
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<tr>
<td></td>
<td>1.22</td>
<td>1.8</td>
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<table>
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<th>π and 5π/6 (or 4π/5) mode separation (MHz)</th>
<th>Medium</th>
<th>High</th>
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<tr>
<td></td>
<td>0.54</td>
<td>1.2</td>
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</table>

<table>
<thead>
<tr>
<th>$E_{pk}/E_{acc}$</th>
<th>Medium</th>
<th>High</th>
</tr>
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<tr>
<td></td>
<td>2.36</td>
<td>2.2</td>
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</table>

<table>
<thead>
<tr>
<th>$B_{pk}/E_{acc}$ (mT/(MV/m))</th>
<th>Medium</th>
<th>High</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>4.79</td>
<td>4.3</td>
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</table>

<table>
<thead>
<tr>
<th>Maximum. $r/Q$ (Ω)</th>
<th>Medium</th>
<th>High</th>
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<tbody>
<tr>
<td></td>
<td>394</td>
<td>477</td>
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</table>

<table>
<thead>
<tr>
<th>Optimum β</th>
<th>Medium</th>
<th>High</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0.705</td>
<td>0.92</td>
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<table>
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<tr>
<th>$G$ (Ω)</th>
<th>Medium</th>
<th>High</th>
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<tr>
<td></td>
<td>196.63</td>
<td>241</td>
</tr>
</tbody>
</table>

### Geometrical beta
- Medium: 0.67
- High: 0.86

### Frequency (MHz)
- 704.42

### Operating temperature (K)
- 2

### Maximum surface field in operation (MV/m)
- 45

### Nominal Accelerating gradient (MV/m)
- Medium: 16.7
- High: 19.9

### Nominal Accelerating Voltage (MV)
- Medium: 14.3
- High: 18.2

### $Q_0$ at nominal gradient
- Medium: > 5e9

### Cavity dynamic heat load (W)
- Medium: 4.9
- High: 6.5

### $Q_{ext}$
- Medium: 7.5 x 10^5
- High: 7.6 x 10^5

- **Challenging accelerating gradients and $Q_0$**
- **No HOM couplers**

HOM frequencies and internal cavity shape must be carefully controlled.

G. Devanz, J. Plouin, G. Constanza
Spoke cryomodule design

Power Coupler
- Ceramic disk, 100 mm diameter
- 400 kW peak power (330 kW nominal)
- Antenna & window water cooling
- Outer conductor cooled with LHe
- Doorknob transition from coaxial to ⅞ height WR2300 waveguide

Double Spoke SRF Cavities
- Double spoke cavity (3-gaps), 352.2 MHz, $\beta=0.50$
- Goal: $E_{acc} = 9 \text{ MV/m}$ [$B_p = 72 \text{ mT}$; $E_p = 39 \text{ MV/m}$]
- 4 mm (nominal) Niobium thickness
- Titanium Helium tank, Ti stiffeners
- Lorentz detuning coeff. : $-4.4 \text{ Hz/(MV/m)^2}$
- Tuning sentivity $\Delta f/\Delta z = 128 \text{ kHz/mm}$

Cold Tuning System
- Slow tuner (stepper motor):
  - Max tuner stroke: 1.28 mm
  - Max tuning range: ~ 170 kHz
  - Tuning resolution: 1.1 Hz
- Fast tuning by 2 piezo-actuators
  - Noliac 50x10x10 or PI 36x10x10 mm
  - Applied voltage up to +/- 120 V
  - Estimated tuning range at 2K: 800 Hz
Elliptical cryomodule design

Similar medium and high-beta cavity cryomodules

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

Only minor differences:
- Length of the intercavity bellows,
- Details in cryo piping, beam pipe bellows
- Penetration of the antenna for $Q_{ext}$ adjustment
- Tuner piezo frames
Power-coupler designs

- **Spoke: 335 kW**
  - Inner conductor (water-cooled)
  - WR2300

- **Elliptical: 1.1 MW**
  - Outer conductor double-wall helium cooling circuit
  - Vacuum gage
  - Electron pick-up
  - Arc detectors
  - WR1150

- **Components:**
  - Antenna
  - Beam vacuum
  - Al₂O₃ ceramic disc
  - Doorknob transition
  - Short circuit
  - Doorknob
  - RF input
  - Bias system

- **Bias system:**

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Linac'16
Cold Tuning System designs

**Spoke CTS**
- Max tuner stroke: 1.28 mm
- Max tuning range: ~ 170 kHz
- Tuning resolution: 1.1 Hz

**Elliptical CTS**
- Type V ; 5-cell prototype
- +/- 3 mm range on cavity
- Stepper motor and planetary gearbox (1/100e) at cold and in vacuum

**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

Noliac 50x10x10 or PI 36x10x10 mm
- Applied voltage up to +/- 120 V
- Estimated tuning range at 2K: 800 Hz

2 piezo actuators

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Assembly Procedures

Cavity string assembly in clean room

Cold mass assembly (outside the clean room)

Spaceframe

Thermal shield

Vacuum vessel

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

Design concept of the tooling: most of parts will be used for both types of elliptical cryomodules
Infrastructures (ex. Clean room in Saclay)

Clean room for the M-ECCTD (and H-ECCTD)

- High Pressure Rinsing HPR
- ISO 5
- 52.69 m²
- Water cleaning

Assembly room in Saclay
- Uses the current infrastructure of XFEL
- Benefits from the experience of the XFEL cryomodule assembly (ALSYOM)

The clean room inauguration on May 13th 2014
• Introduction to European Spallation Source
• SRF linac design
• SRF linac component performance measurements
Spoke and cryomodule prototypes

- Romea
- Giulietta
- Germaine

- View of the spoke cavity bars
- Inter-cavity bellows
- Thermal shield
- Magnetic shield
- Cold Tuning System
- Spoke cryomodule vacuum vessel: Fabrication achieved (FAT done)
Spoke cavity surface preparation

- Ultra-sonic degreasing

- Chemical etching: BCP
  Goal: 200 μm (min)
  - Phase 1: Horizontal, 120 minutes
  - Phase 2: Horizontal (180° rotation), 120 minutes
  - Phase 3: Vertical, 240 minutes

Why H & V positions?
- Better homogeneity
- Frequency shift compensation: $\Delta f_{200\mu m} < -20$ kHz

- HPR: 4 passes through all ports (6000 liters & 12h /cavity)

➡ No Baking and no heat treatment on the prototype cavities
Spoke cavity performances @ IPNO

- Spoke cavity exceeding ESS requirements in vertical test on both Eacc and Qo

- Eacc_max = 15.3 MV/m achieved with “Romea”
- Several MP barriers but easily processed.
- Qo > 1.6 \times 10^{10}
- Strong FE at max gradient
- Limitation is the cooling capacity (unstable conditions, cavity in vertical position)

No Baking
No heat treatment

\( H_{pk} = 105 \text{ mT} \)
\( E_{pk} = 66 \text{ MV/m} \)
Spoke power-coupler performances @IPNO

One spoke power coupler reached ESS requirements (sept. 2016)

RF conditioning stopped after output coupler failure (vacuum level raised up to 0.01 mbar)

Power coupler conditioning bench: all parts realized, dry assembly done.
Horizontal SRF Test Stand @ Uppsala University

RF Power Source + LLRF

Control System

Cryogenics + valve box

SRF Cavity

HNOSS Horizontal Cryostat

(Broke Cryomodule)

SSA Power Station

Bunker

Helium Cold Gas Heater

Helium Liquefier

Tetrode Power Station
Spoke cavity performances @ Uppsala University

Spoke cavity (Germaine) exceeding ESS requirements in vertical test on both Eacc and Qo

ESS Goal:
Eacc_max > 9 MV/m
Qo > 1.5 \times 10^9
Elliptical selected technologies

Medium beta cavity prototype

High beta cavity prototype with its helium tank

Magnetic shield

Blank assembly of the spaceframe inside the vacuum tank

Tubes for rupture disks under manufacturing (left), inter-cavity bellows (middle) and cold-warm transitions (right)

Blank assembly of the jumper cryogenic connection

Validation tests of cavity string handling tools for clean room assembly (using a cavity mock-up)

New barometric compensation system for coupler flange under test
Field flatness tooling @ CEA-Saclay

Tooling for high beta ready

Tooling for medium beta

Exemple of cavity tuning (High beta Prototype n°2 from RI)

Not adapted for large series cavities production
Cavity clean room assembly with High Pressure Rinsing @ CEA-Saclay

HPR 100 bars - Ultra pure water

Flanges and antenna pick-up assembly under class 100 laminar flow

F. Eozenou, C. Servouin
High-beta cavity results, HBP01, HBP02

Q curves of the cavities HBP01 and HBP02 exceeded ESS goal, w/o heat treatment

- Heat treatment for hydrogen removing, performed on the high-beta cavity, HP01, failed to improve the accelerating gradient.
- Lessons learned: heat treatment process has been studied with industry and successfully implemented for medium-beta cavities.

Mounting on vertical insert, Connexion to RF system and vacuum pumping station
Medium-beta cavity results, MBP01

- MBP01 reached the ESS goal after proper heat treatment (July 2016)
- MBP02 tested after 200μm BCP shows better results than MBP01 at the same phase (September 2016)

Lessons learned:
- Mechanical and Freq stats
- BCP
- Heat treatment
- Neutron during VT

See poster: TUP106
E. Cenni et al. "Vertical Test Results on ESS Medium Beta Elliptical Cavity Prototype"
Heat treatment, MBP01

Heat treatment at 600°C for 10 hours proved to be effective to improve cavity performance, MBP01 (May 2016)

Cavity in oven @ Zanon

![Graph showing Rs vs 1/T for different processes](image)

<table>
<thead>
<tr>
<th>Process</th>
<th>Rs @2K [nΩ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCP ~200µm</td>
<td>205</td>
</tr>
<tr>
<td>Heat treat.+HPR</td>
<td>20</td>
</tr>
<tr>
<td>HT+BCP ~20µm</td>
<td>10</td>
</tr>
</tbody>
</table>
BCP preparation, MBP02

All BCP on P02 were done with acid temperature less than 15°C in the tank.
Lessons learned: Manufacture

From Dumbbell measurement it is possible to compute cavities frequency and length. The observed deviation are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average deviation respect computed values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>0.767 mm</td>
</tr>
<tr>
<td>π-mode frequency</td>
<td>0.292 MHz</td>
</tr>
</tbody>
</table>

Length can be predicted within 1 mm accuracy and frequency within 300kHz.

RF measurements system (on half cell) | Dumbbells after welding in the control area | Dumbbells RF measurements for 0-mode (blue) and π-mode (red). Each bin has 0.2MHz width. | π-mode frequency measurement welding (red), trimming (blue) and trimming+welding shrinkage (green).
1.1 MW power-coupler conditioning

The coupler is equipped with different diagnosis elements: on the window, a pressure jauge, an electron pick-up (that is also used to measure the RF power close to the ceramic level) and a photomultiplier are mounted.

A baking is performed with silicon heating tapes: the temperature of the coupler and the box is set up at 170 °C for 96 hours and the vacuum pumping group at 120 °C for 48 hr then 60 °C for 48 hr.
1.1 MW power-coupler conditioning

- First results for the conditioning of the coupler loaded by 50 ohm in traveling wave.
- Successful test with 14 Hz, 3.6 ms. Power increased up to 1.2 MW.

Pulse repetition period: 1.2 s

Pulse repetition period: 72 ms
First results from LASA and STFC

@ LASA: Medium-beta cavity after electron beam welding

@ STFC: Cavity testing in cryostat

Preparation for DumbBell Frequency measurement
• A new collaborative project for Spallation.
• The first results for the SRF linac are promising even if many challenges still need to be addressed.
• Many lessons learned from results and other experiments.
• Build further capacity using industrialization process.
• Coordination of interfaces and integration is a challenging and on-going effort!

Acknowledgment and thanks to the excellent progress of the ESS SRF teams
CEA and IPNO test areas people

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Linac'16
More reading