The European Spallation Source as a new tools for discovery

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African Conference of Fundamental Physics and Applications

https://www.africanschoolofphysics.org/

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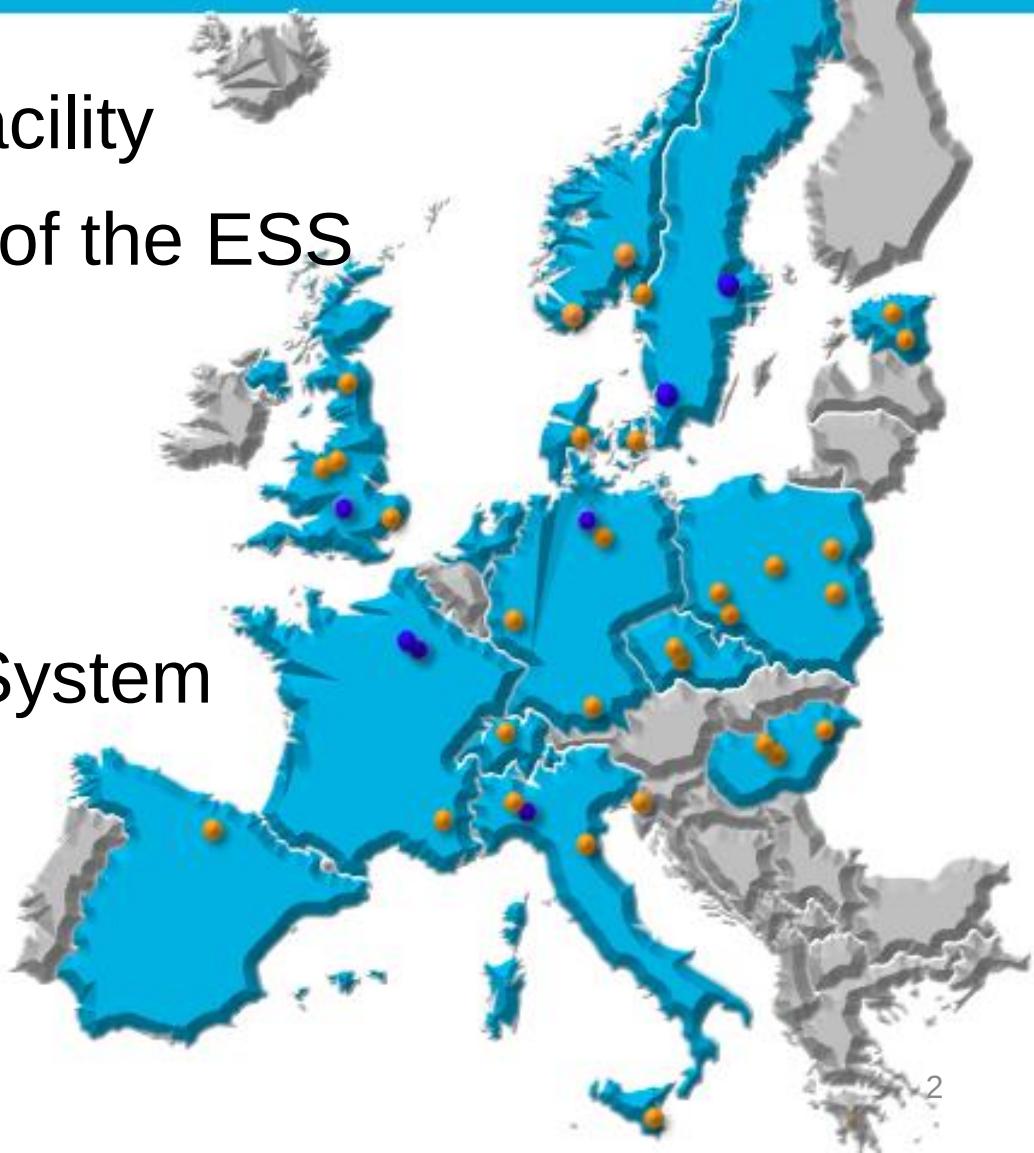
Outline

– Objective of the ESS facility

– Description and status of the ESS

- Instrument
- Target
- Accelerator
- Integrated Control System



ESS : Science for Society

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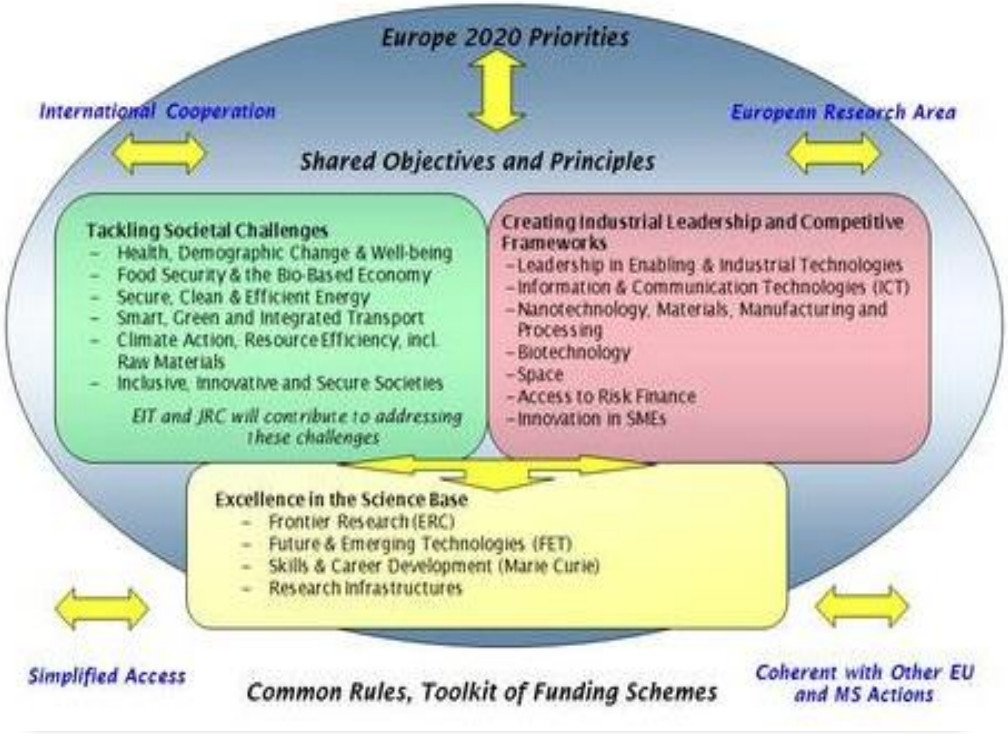
EU Horizon 2020 – strategy

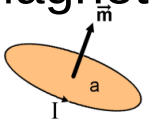
The structure which the EC proposed consists of three basic priorities:

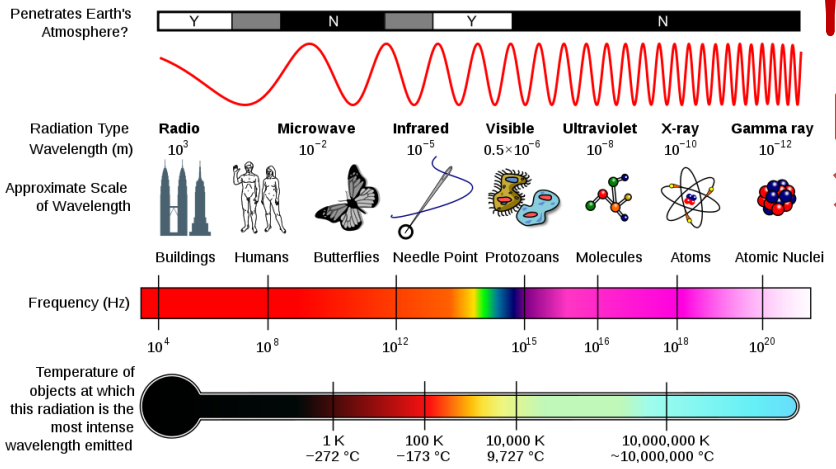
1. **Excellent Science**
2. **Industrial Leadership**
3. **Societal Challenges**



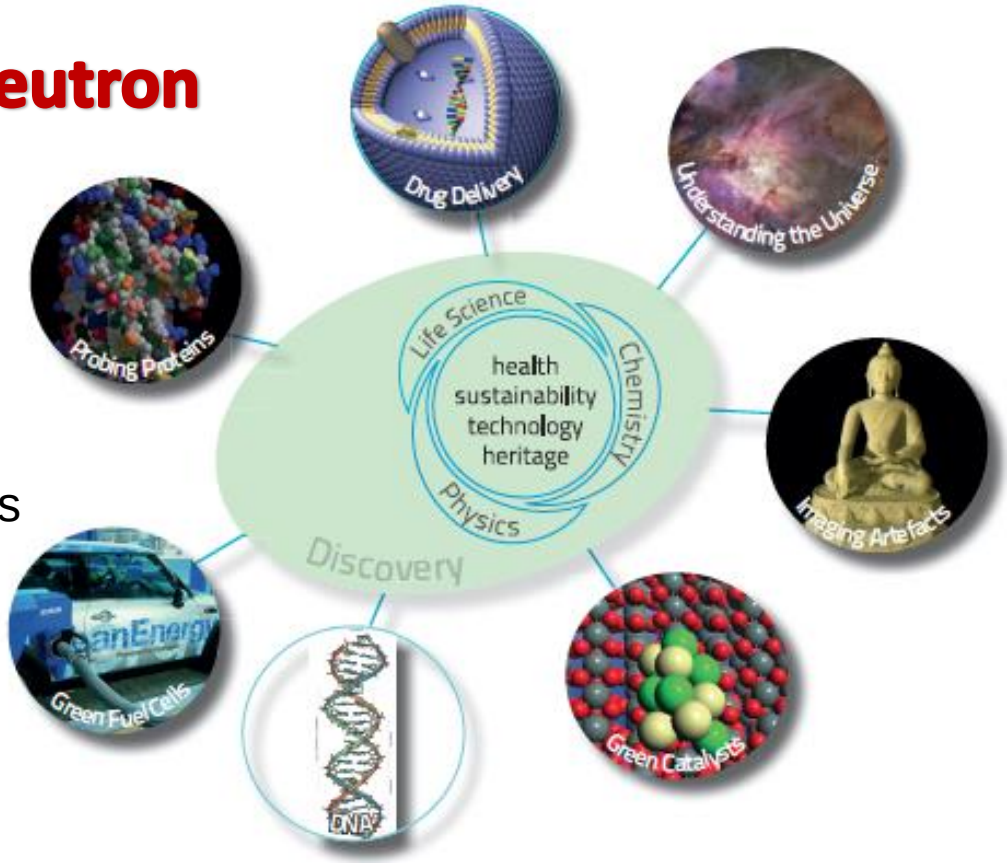
Fields of interest

Wave | Particle | Magnetic moment | Neutral





Neutron



- A wide range of length and timescales
- High sensitivity and selectivity
- Deep penetration
- A probe of fundamental properties
- A precise tool
- An ideal probe for magnetism

Multi-science with neutrons

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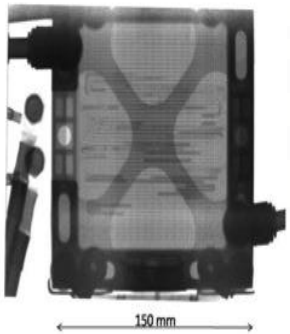
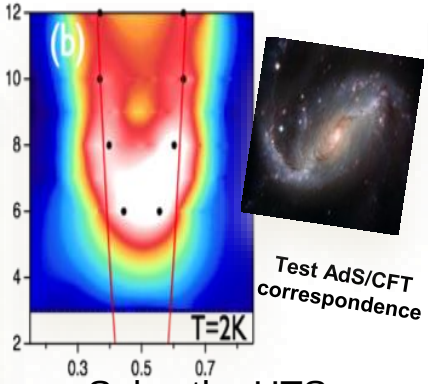
Charge neutral
Deeply penetrating



Li motion in fuel cells

Improve electric cars

Magnetic moment
Probe of magnetism

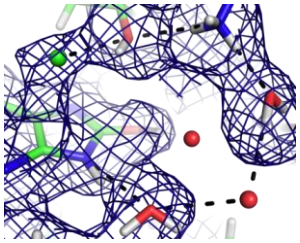


Solve the HTS puzzle

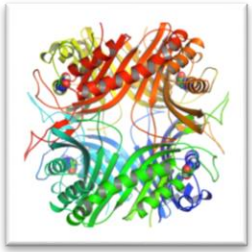
Efficient high-speed trains

Nuclear scattering
Sensitive to light element and isotopes

Test AdS/CFT correspondence



Active sites in proteins



Urate oxidase

Better drugs

- Neutrons can provide unique and information on almost all materials

- Information on both structure and dynamics simulaneously. ”Where are the atoms and what are they doing?”

- 6000 primary users in Europe today and 6000 secondary users

- Science with neutrons is limited by the intensity of today’s sources

Complementarity between X-rays & Neutrons

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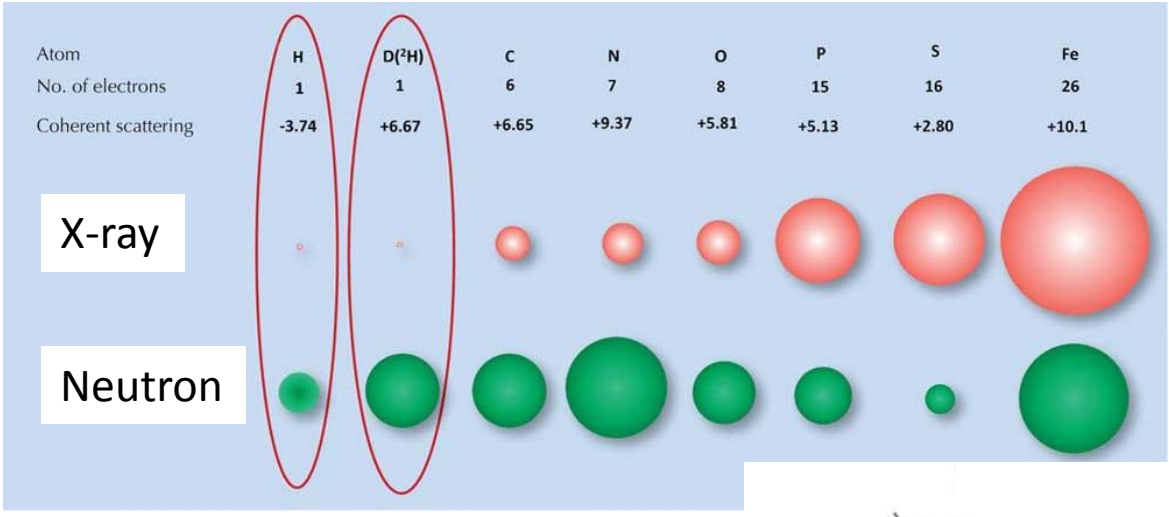
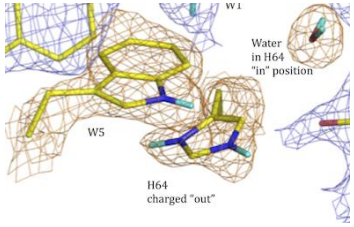
Neutron scattering lengths for different atom types found in biological materials:

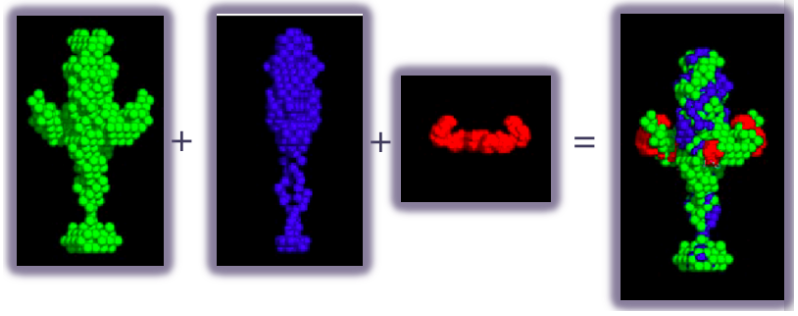


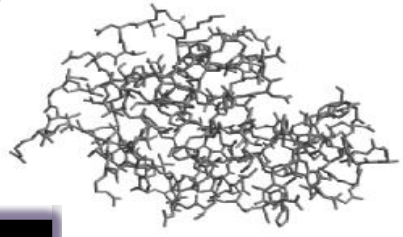
H atoms make up *~50% of atoms of biological macromolecules* (lipids, proteins, nucleic acids, carbohydrates).

Localization of Hydrogen atoms

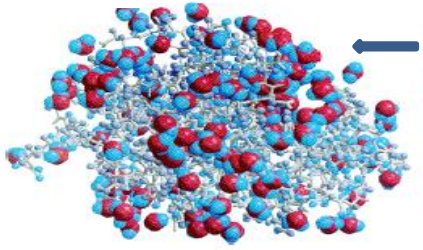


Appropriate isotope labeling is very important (replace H with D wherever possible)





X-rays



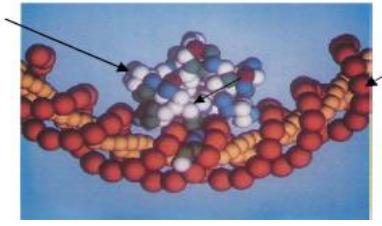
Water molecules Observed with neutrons

N. Niimura, et al.

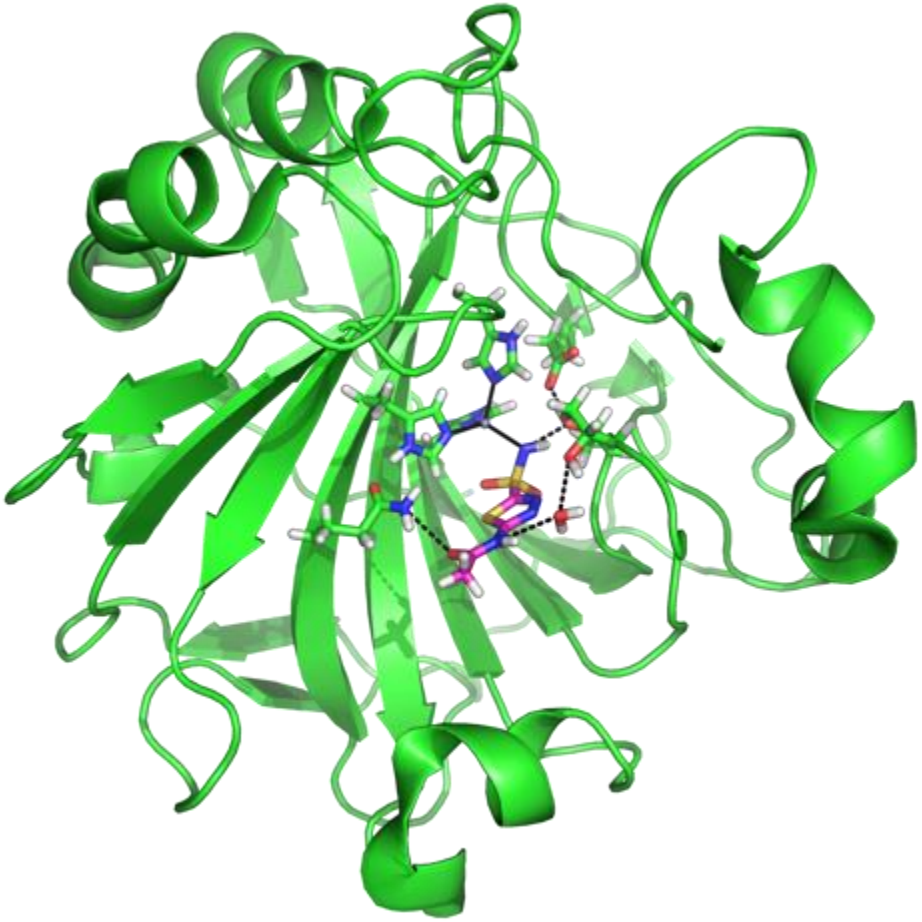
Neutrons

Protein

From structure to function



Neutrons reveal how drugs interact with disease targets



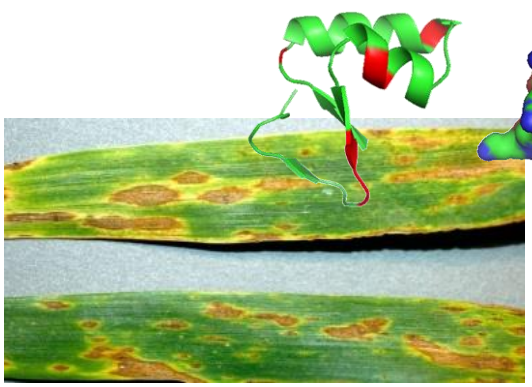
The enzyme carbonic anhydrase transports CO_2 and regulates blood acidity. It is a major player in some cancers, glaucoma, obesity and high blood pressure

Neutron crystallography pinpoints protons and waters in the active site, showing how the drug Acetazolamide binds

Image: Fisher, S. Z. *et al*. 2012 JACS

Plant antimicrobial & antifungal proteins

α-purothionins



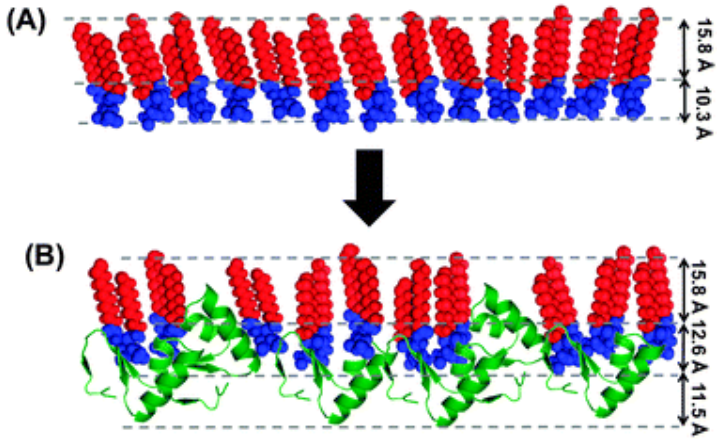
Tan spot (*Pyrenophora tritici-repentis)*

Glumbe Blotch (*Stagonospora nodorum)*

Common Smudge (*Cochliobolus sativus)*

Stripe blight (*Pseudomonas syringie)*

Neutron reflectometry used to determine how plant defence proteins from common wheat interact with cell membranes.



Clifton et al. *Phys. Chem. Chem. Phys.*, 2012, 14, 13569-13579

Scientific challenges

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Solid State Physics

Dynamics of superlattices, wires and dots, molecular magnets, quantum phase transitions

Liquids and Glasses

Solvent structures, influence of molecular structures on protein folding

Fundamental Physics

Left and right handedness of the universe, neutron decay, ultracold neutrons

Soft Condensed Matter

Time resolution, molecular rheology, structures and dynamics

Biology and Biotechnology

Hydrogen and water , membranes, biosensors, functions

Materials Science and Engineering

Real time investigations with realistic dimensions under real conditions

Chemical Structure, Kinetics and Dynamics

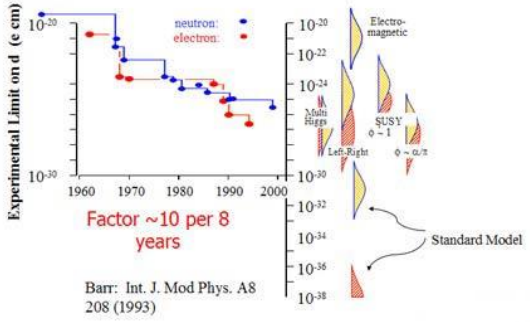
Thin films, pharmaceuticals, supramolecules - structures and functionality

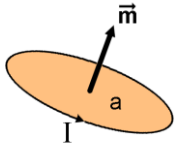
Earth and Environmental Science, Cultural Heritage

Extreme temperatures and pressures simulating the mantle

The visions

- Room Temperature Super Conductors
- Sterile neutrinos
- Hydrogen storage substrate
- Neutron electric dipole moment
- Efficient membrane for fuel cells
- Flexible and highly efficient solar cells
- Carbone nano-tubes for controlled drug release
- Self healing materials – smart materials
- Spin-state as a storage of data (10^{23} gain in capacity)
- CO_2 sequestration
- Graphene ?!





BrightnESS survey

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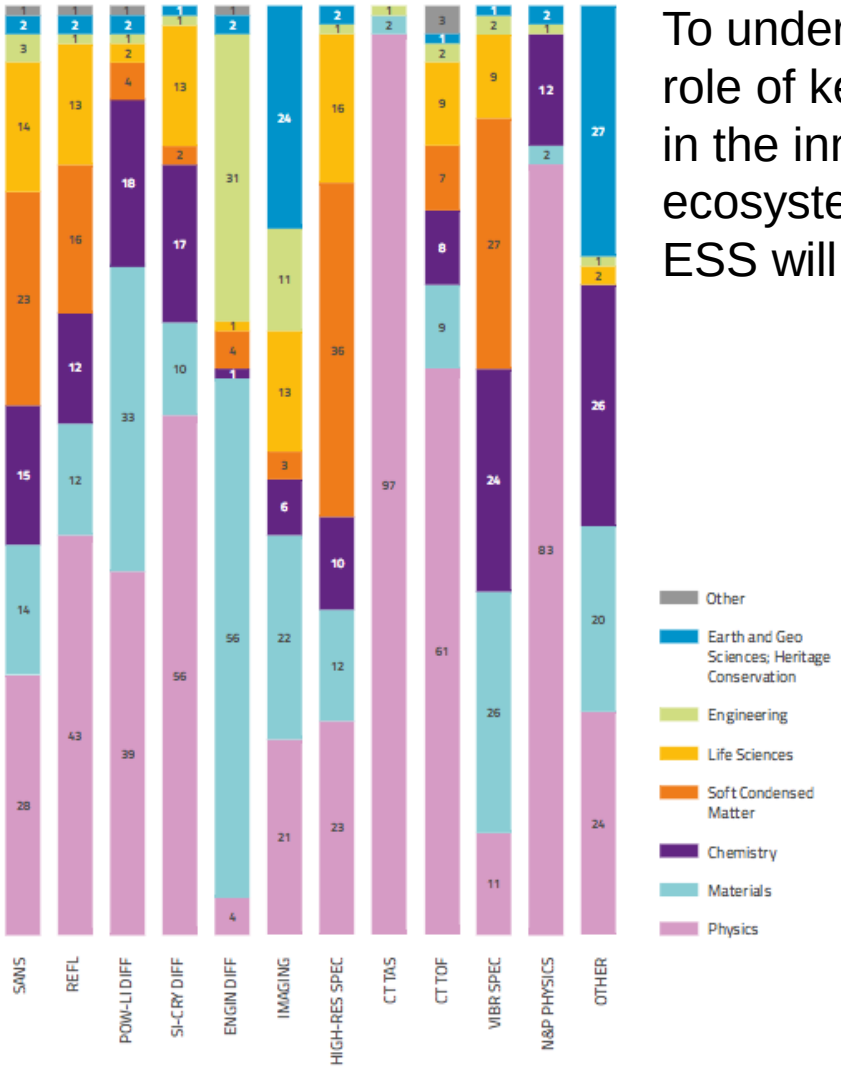
Fig 3.15 Europe: Science fields per method expressed as a percentage of experiments



To understand the role of key players in the innovation ecosystem that ESS will foster !

Fig 3.14 Europe: Horizon 2020 topics and challenges expressed as a percentage of research, averaged over all participating neutron sources

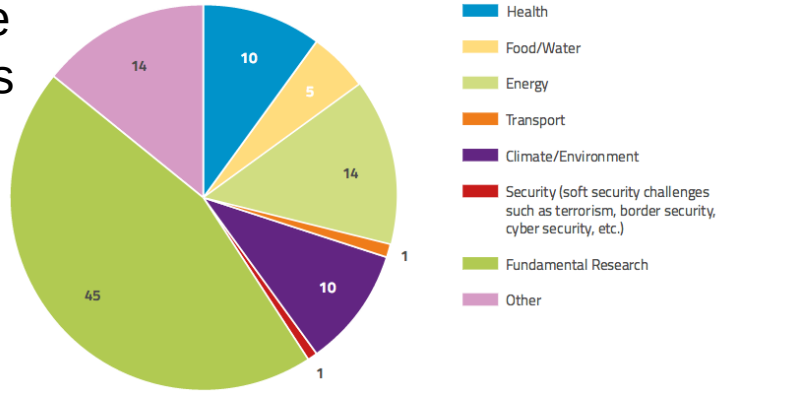


Fig 3.16 Europe: Science fields expressed as a percentage of experiments

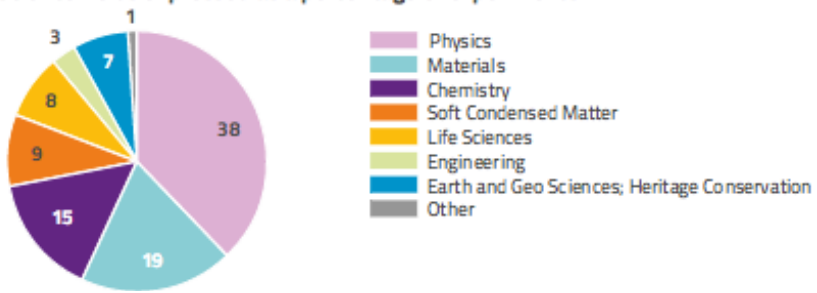
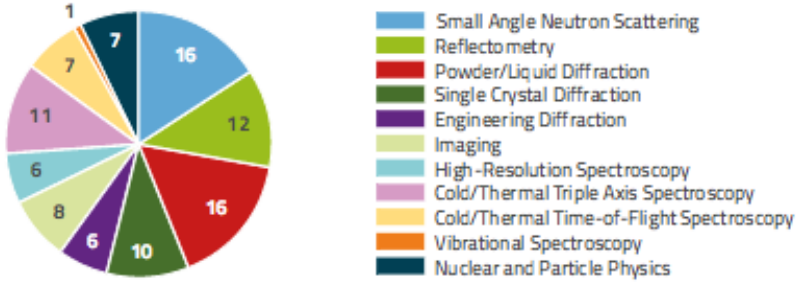


Fig 3.17 Europe: Use of methods expressed as a percentage of beam days



High time average and peak flux

Effective thermal neutron flux n/cm^2-s

Year

Reactor Sources

Spallation Sources

Chadwick

350 mCi Ra-Be source

Berkeley 37-inch cyclotron

X-10

CP-1

CP-2

NRX

MTR

HIFAR

LVR

NRU

HFBR

HFIR

HOR

NIST

SAFARI-1

ILL

MARIA

JEEP II

ZING-P′

ZING-P

WNR

ORPHEE

KENS

LANSCE

IPNS

ISIS

IBR-II

Dhruva

RSG

JRR-3

SALAM

HANARO

SINQ

SNS

J-PARC

ETERR-2

FRM-II

OPAL

CARR

CSNS

PIK

ESS

Particle driven pulsed

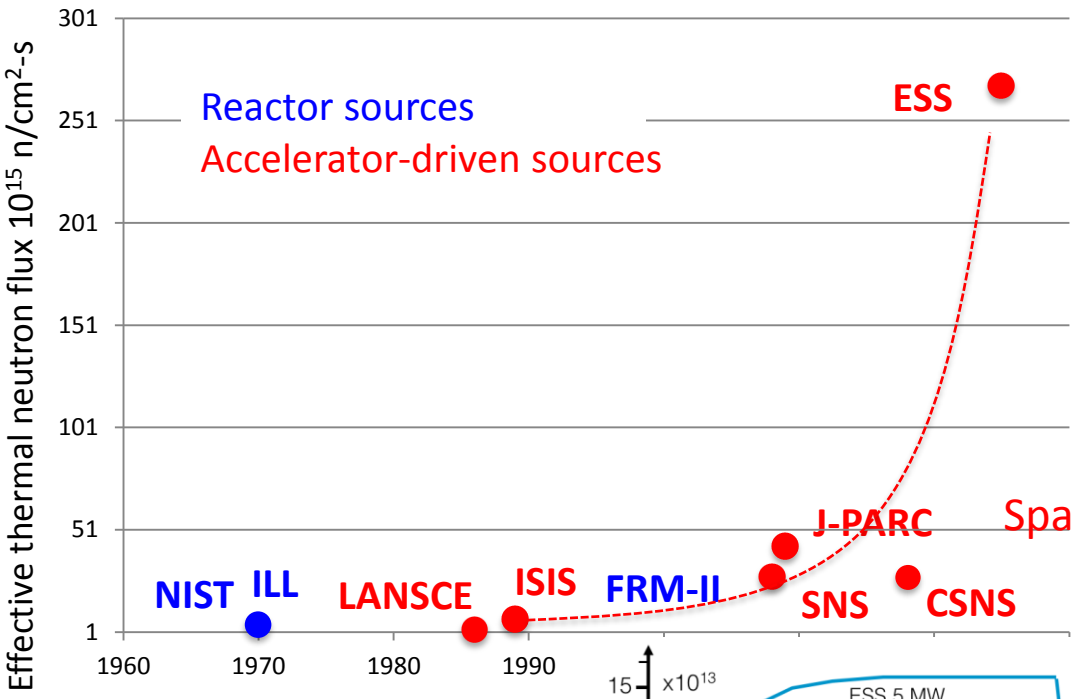
Particle driven steady state

Pulsed reactor

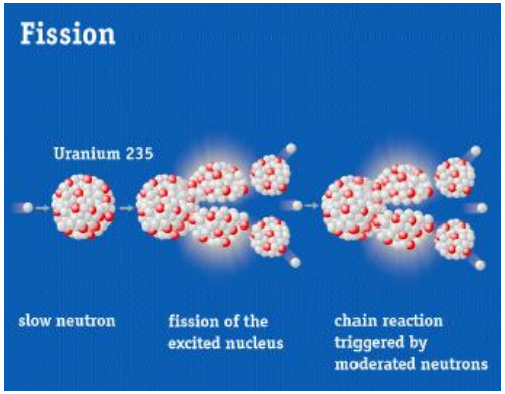
Fission reactors

(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

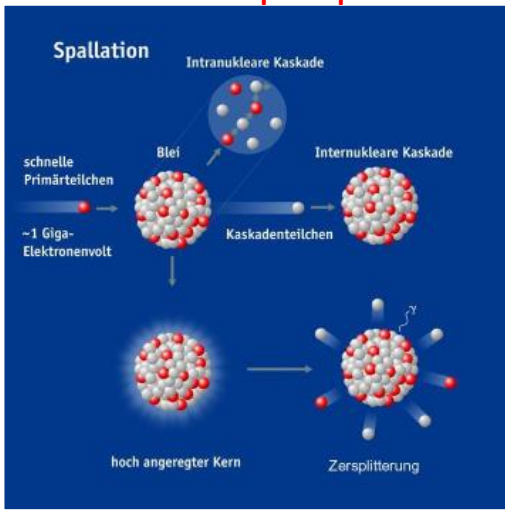
ESS Vision: Build and operate the world's most powerful neutron source



Fission of uranium in nuclear reactor
2-3 neutrons per process

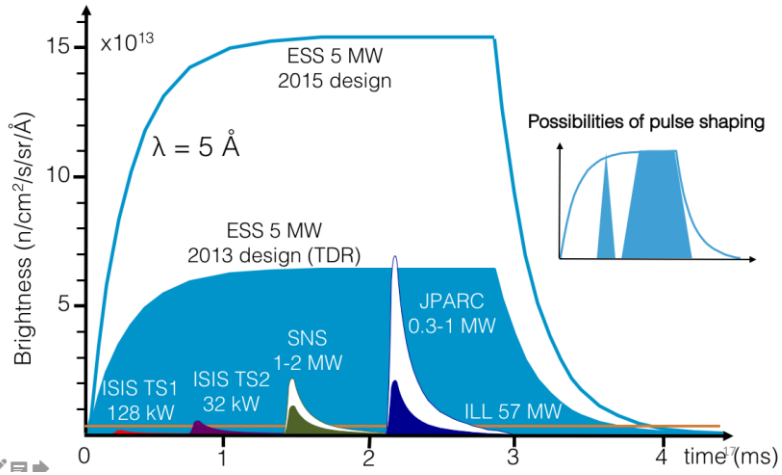


Spallation on target using proton accelerator
30+ neutrons per process

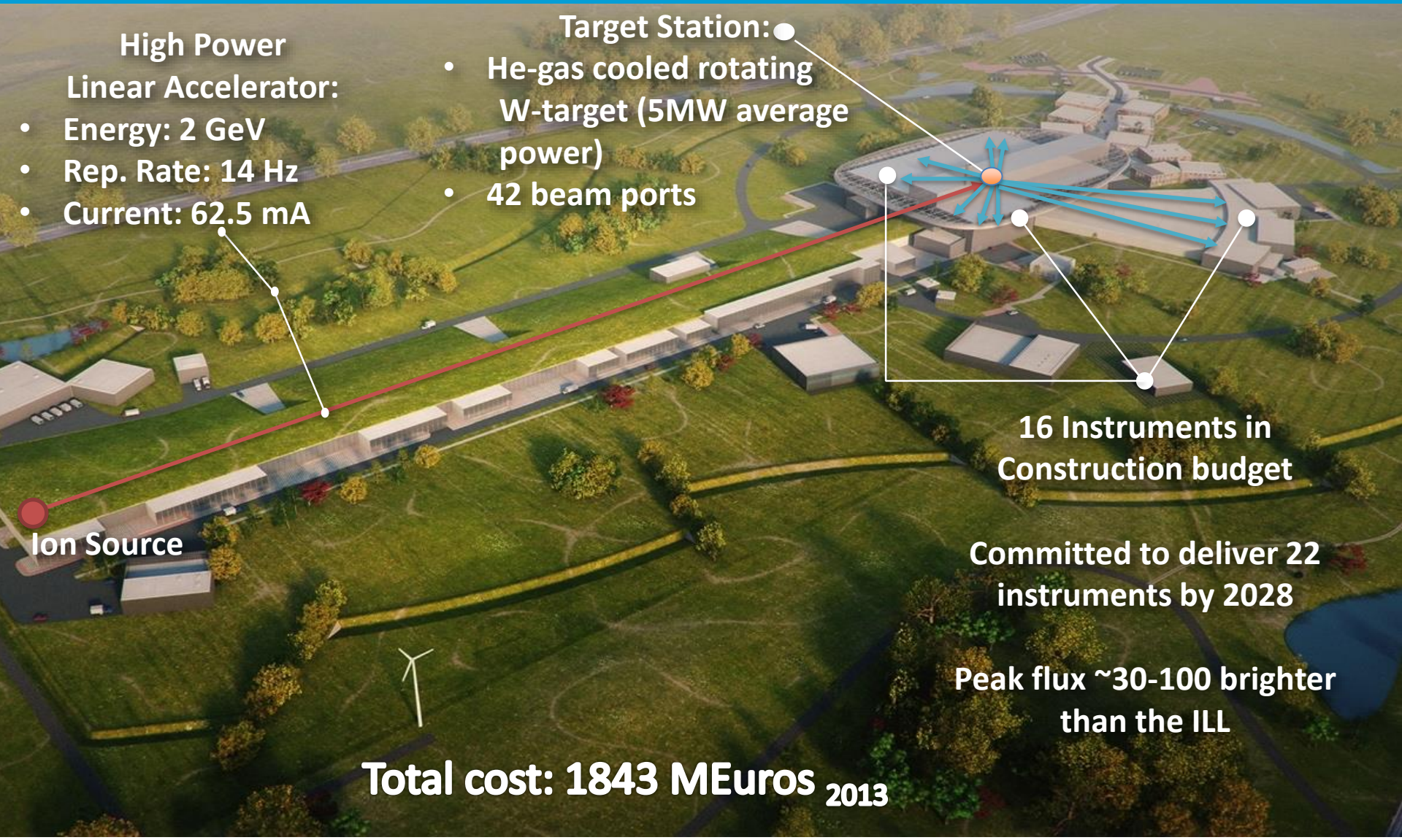


Many research reactors in Eur
Urgent need for a new high flu

- The vast majority of users will
- A large fraction of the users are (approx 2 ms, 20 Hz)
- Existing short pulse sources (I and imminent future need of sh



Basic design principle



ESS employees (as of March 2018)

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434
Employees

50
Nationalities

> 40
Collaborating Institutions

ESS in-kind partners make ESS possible…

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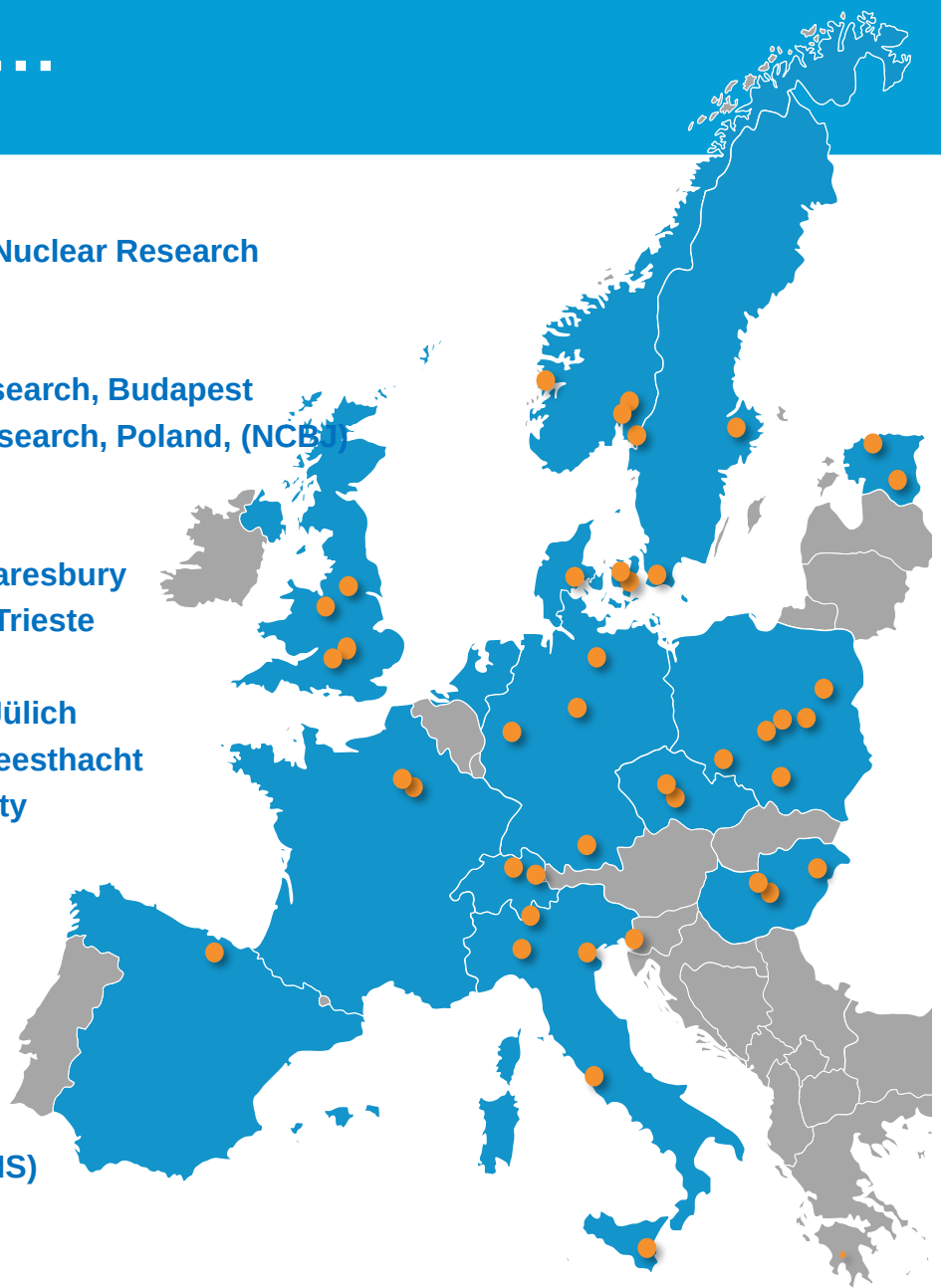
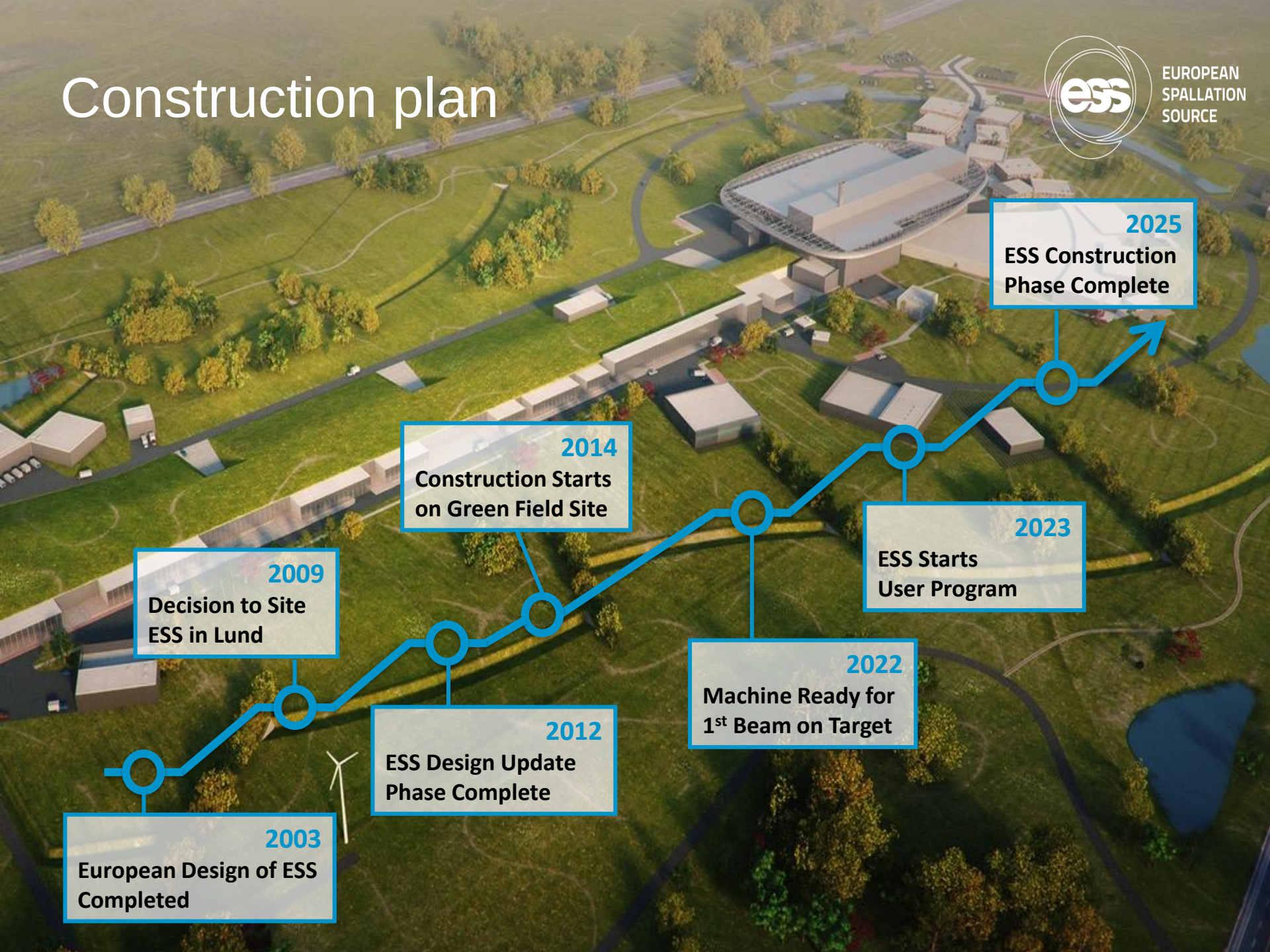
Aarhus University
Atomki - Institute for Nuclear Research
Bergen University
CEA Saclay, Paris
Centre for Energy Research, Budapest
Centre for Nuclear Research, Poland, (NCBJ)
CNR, Rome
CNRS Orsay, Paris
Cockcroft Institute, Daresbury
Elettra – Sincrotrone Trieste
ESS Bilbao
Forschungszentrum Jülich
Helmholtz-Zentrum Geesthacht
Huddersfield University
IFJ PAN, Krakow
INFN, Catania
INFN, Legnaro
INFN, Milan
Institute for Energy Research (IFE)
Rutherford-Appleton Laboratory, Oxford(ISIS)

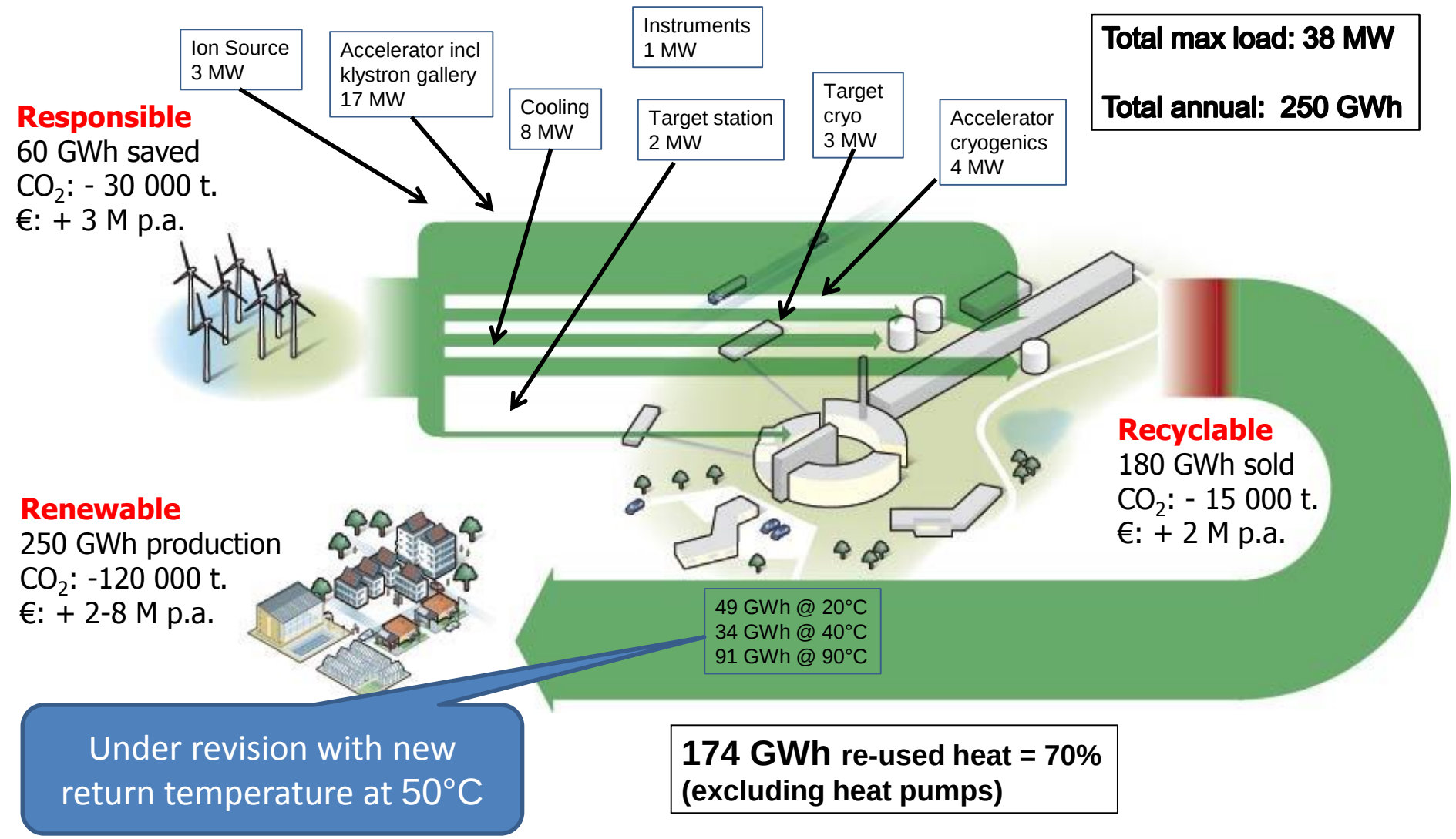


Kopenhagen University
Laboratoire Léon Brilouin (CEA – CNRS – LLB)
Lund University
Nuclear Physics Institute of the ASCR
Oslo University
Paul Scherrer Institute (PSI)
Polska Grupa Energetyczna - PGE
Roskilde University
Tallinn Technical University
Technical University of Denmark
Technical University Munich
Science and Technology Facilities Council
UKAEA Culham
University of Tartu
Uppsala University
WIGNER Research Centre for Physics
Wroclaw University of Technology
Warsaw University of Technology
Zurich University of Applied Sciences (ZHAW)

Construction plan



Heat recovery (2011 figures)



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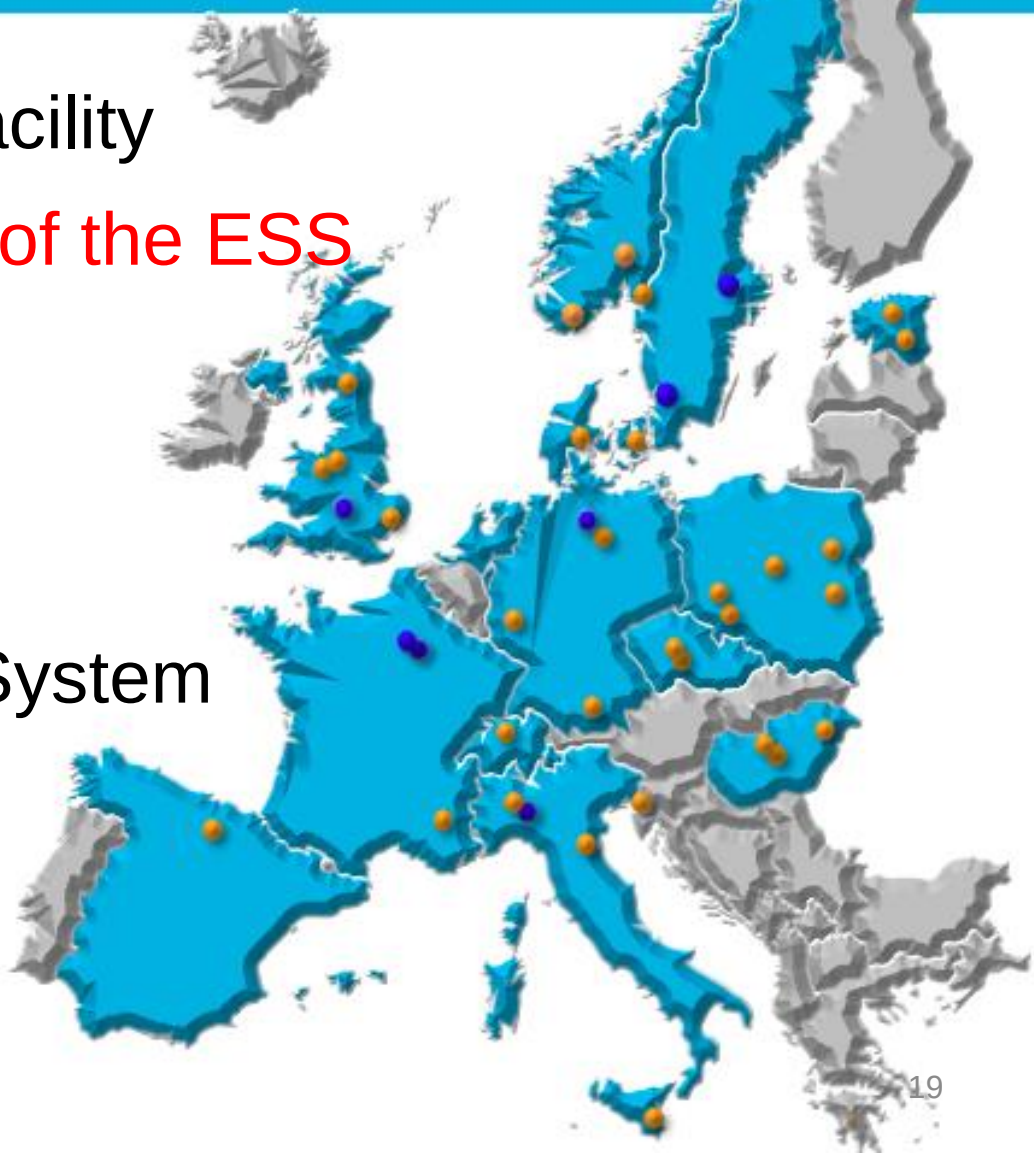
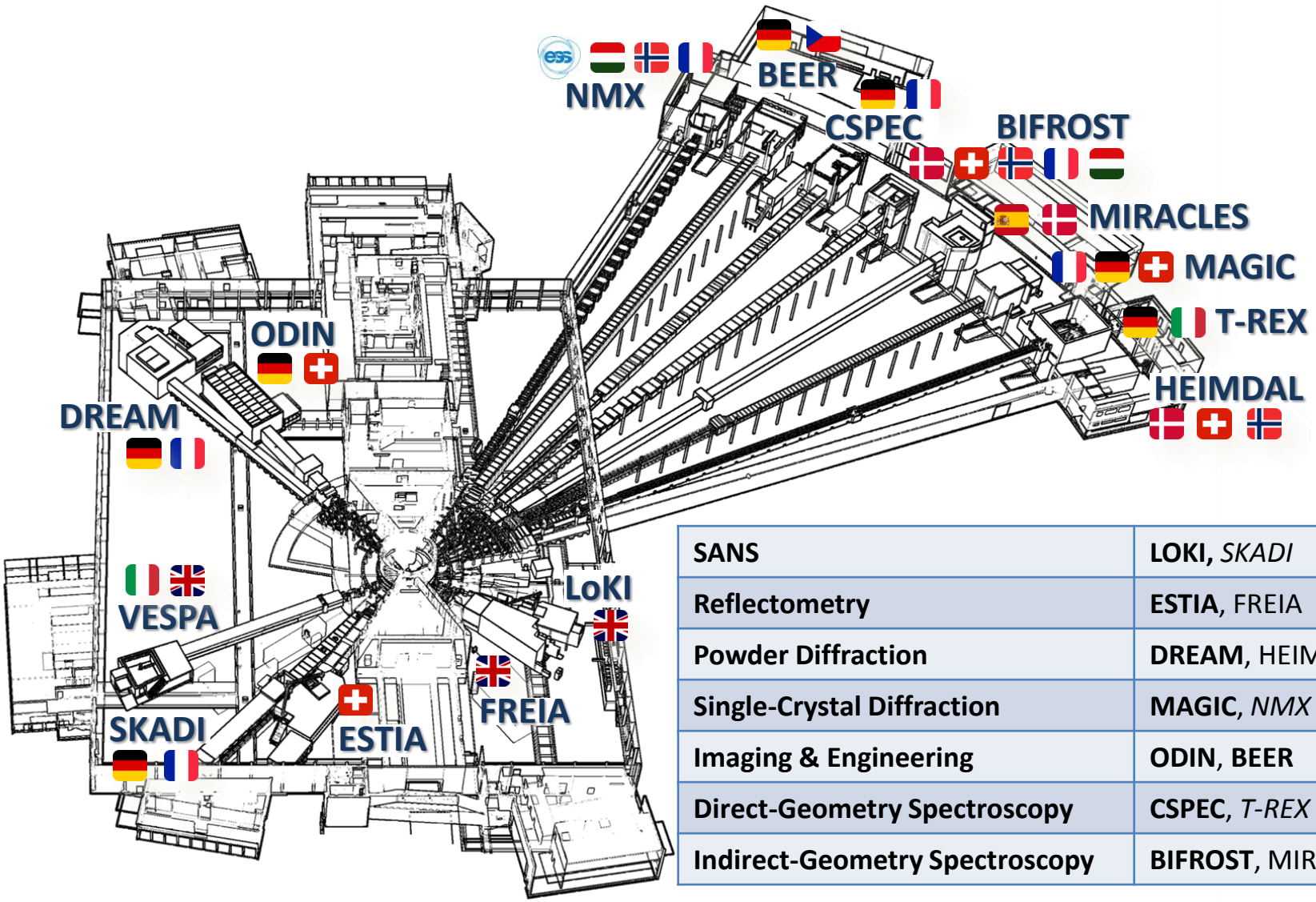


Current Status

← From September 2014, green field

To June 2018, concrete blocks →

Instrument Suite



SANS	**LOKI,** *SKADI*
Reflectometry	**ESTIA**, FREIA
Powder Diffraction	**DREAM**, HEIMDAL
Single-Crystal Diffraction	**MAGIC**, *NMX*
Imaging & Engineering	**ODIN**, **BEER**
Direct-Geometry Spectroscopy	**CSPEC**, *T-REX*
Indirect-Geometry Spectroscopy	**BIFROST**, MIRACLES, VESPA

Science Drivers for the Reference Instrument Suite

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Large-Scale Structures

- **Multi-Purpose Imaging ODIN**
- **General-Purpose SANS SKADI**
- **Broadband SANS LOKI**
- Surface Scattering
- **Horizontal Reflectometer FREIA**
- **Vertical Reflectometer ESTIA**

Diffraction

- **Thermal Powder Diffractometer HEIMDAL**
- **Bispectral Powder Diffractometer DREAM**
- Monochromatic Powder Diffractometer
- **Materials Science Diffractometer BEER**
- Extreme Conditions Diffractometer
- **Single-Crystal Magnetism Diffractometer MAGICS**
- **Macromolecular Diffractometer NMX**

Spectroscopy

- **Cold Direct Geometry Spectrometer C-SPEC**
- Wide Bandwidth Direct Geom. Spectrometer VOR
- **Bispectral Direct Geometry Spectrometer TREX**
- **Cold Crystal-Analyser Spectrometer BIFROST**
- **Vibrational Spectrometer VESPA**
- **Backscattering Spectrometer MIRACLES**
- High-Resolution Spin-Echo
- Wide-Angle Spin-Echo

Fundamental & Particle Physics

- life sciences
- soft condensed matter
- chemistry of materials
- energy research
- magnetism & superconductivity
- engineering & geo-sciences
- archeology & heritage conservation
- fundamental & particle physics

Tentative Instrument Ramp-up

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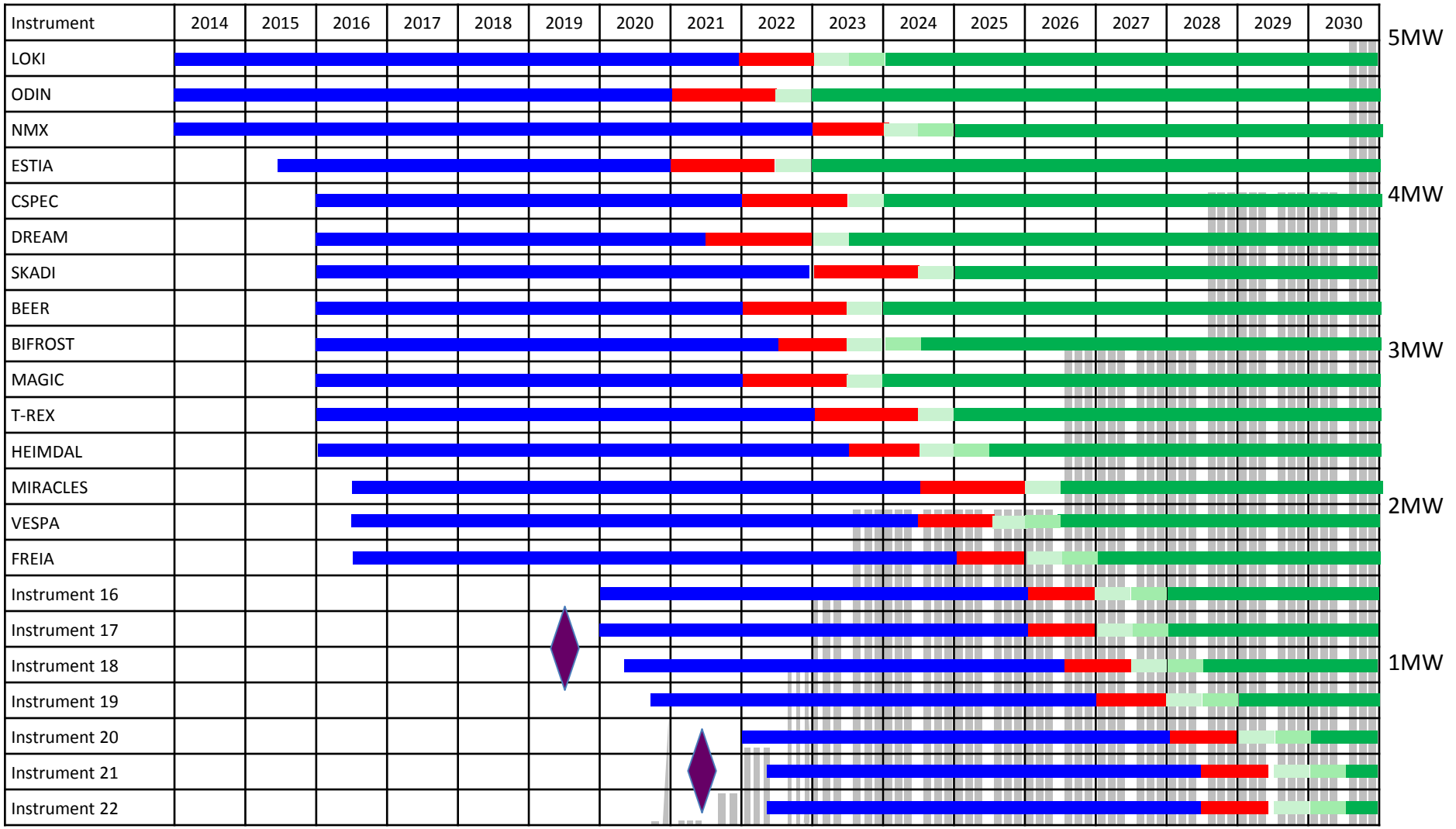
based on Instrument Construction Working Schedule V3.4, 15/9/2017



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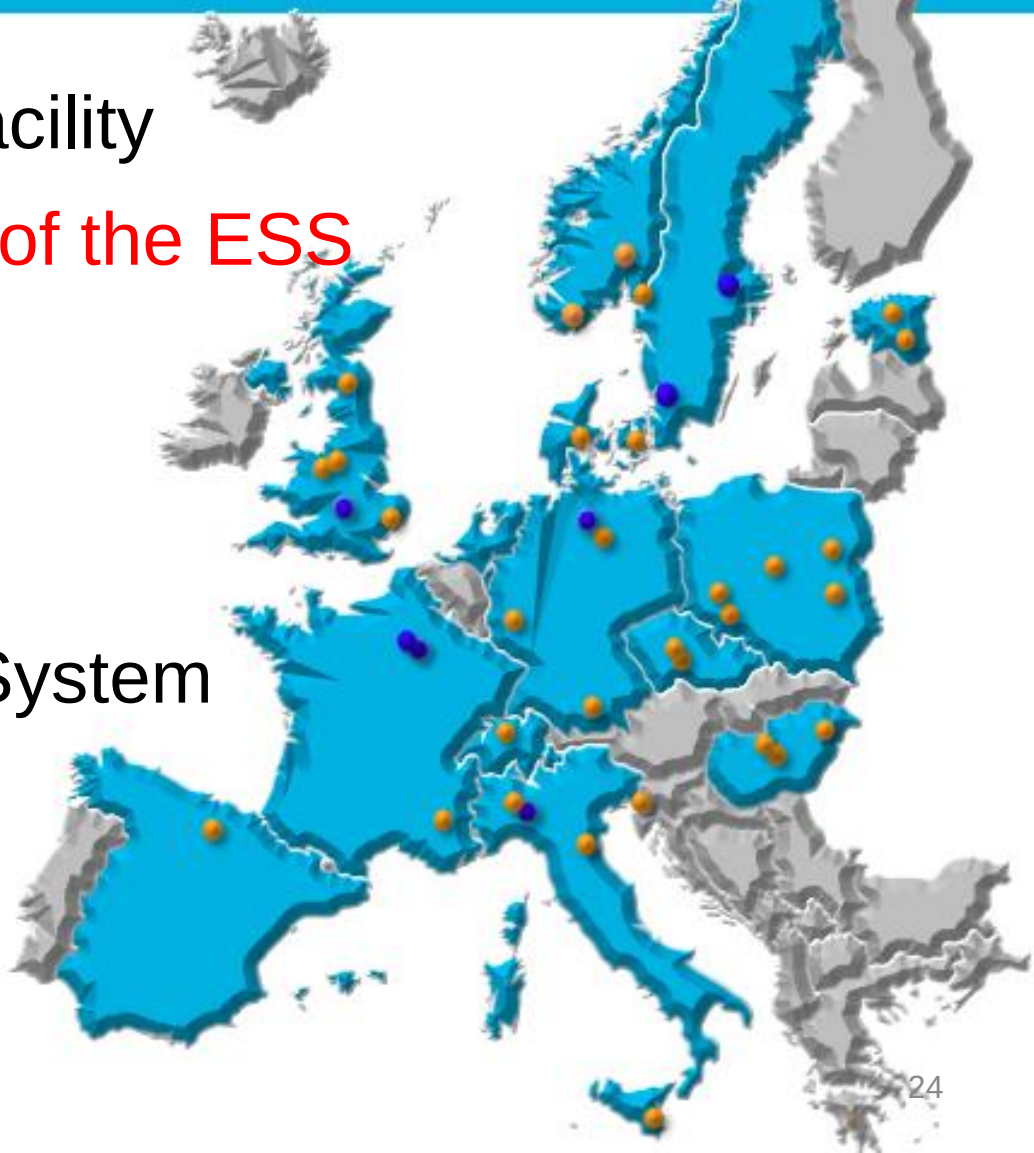

ESS Target and Target building

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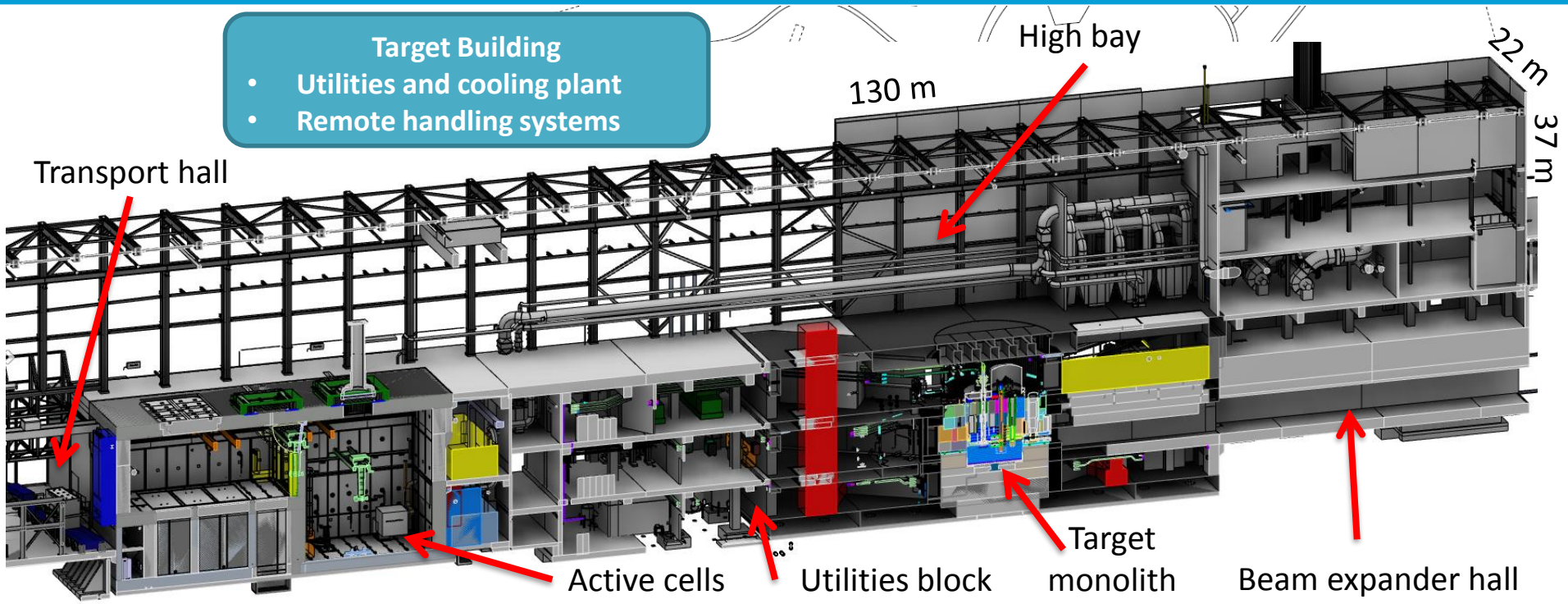
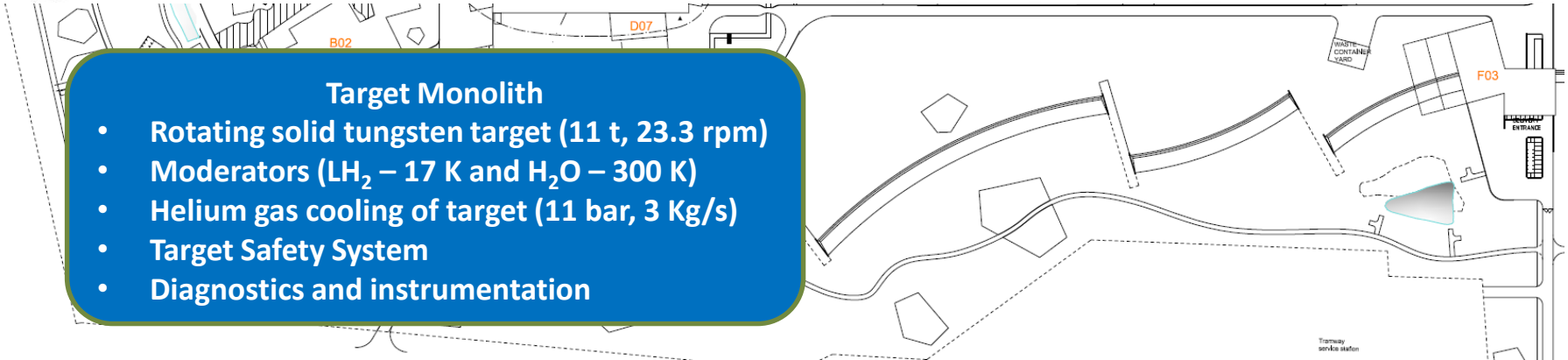
Target Building
- Utilities and cooling plant
- Remote handling systems



Target Monolith
- Rotating solid tungsten target (11 t, 23.3 rpm)
- Moderators (LH_2 – 17 K and H_2O – 300 K)
- Helium gas cooling of target (11 bar, 3 Kg/s)
- Target Safety System
- Diagnostics and instrumentation



Key features of the ESS Target Station

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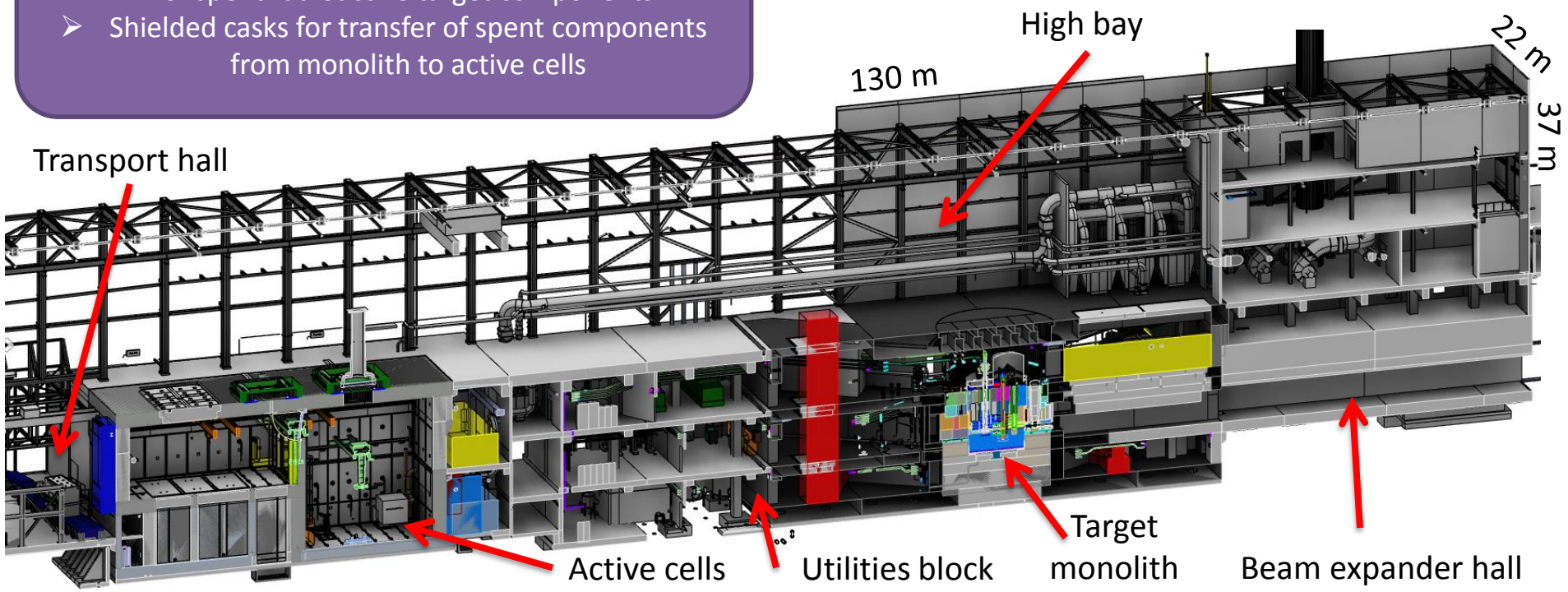
Utilities and cooling plant

- Helium cooling of target wheel
- Water cooling of moderators, plugs and shielding
- Intermediate water loops between primary circuits and conventional facility utilities
- Helium cryoplant for refrigeration of cold moderator system
- Nuclear grade HVAC system

Remote handling systems

- Large active cells for safe storage and processing of spent radioactive target components
- Shielded casks for transfer of spent components from monolith to active cells



Key features of the ESS Target Station

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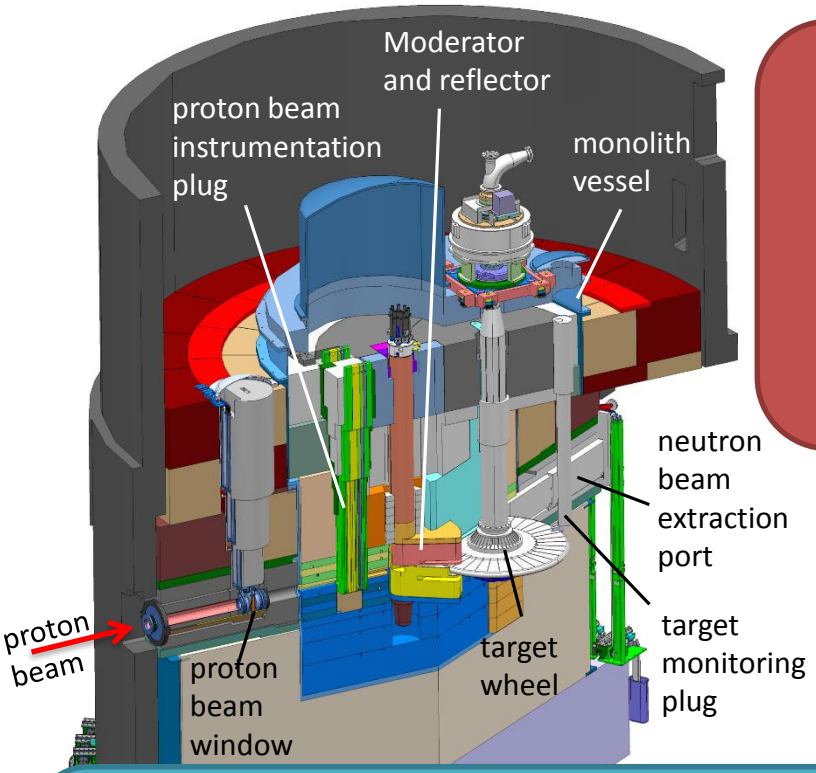


Target Safety System

- Monitors target coolant flow, pressure and temperature, monolith pressure, & target wheel rotation
- Prohibit beam on target if parameters are outside specified limits

Helium cooling of target material

- Mass flow 3 kg/s
- Pressure 11 bar
- Temperature inlet/outlet 40 °C/240 °C

Rotating solid tungsten target

- 36 sectors
- Mass, total 11 tonnes, whereof 3 tonnes of W
- Rotates 23.3 rpm, synchronized with pulsed proton beam 14 Hz

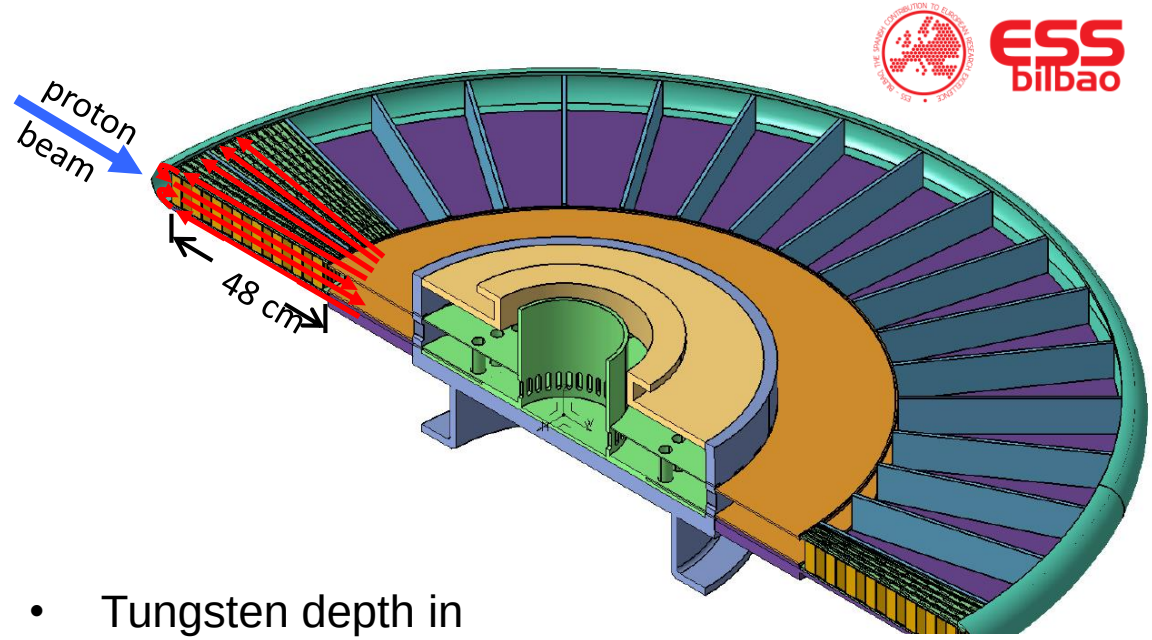
Moderators

- Provisional locations of moderators above and beneath the target wheel, i.e. monolith centre
- 1st MR plug exploits the upper space, offering:
  - ✓ Cold, 30 mm high, liquid H_2 moderators, 17 K
  - ✓ Thermal, 30 mm high, H_2O moderator, 300 K

Diagnostics and instrumentation

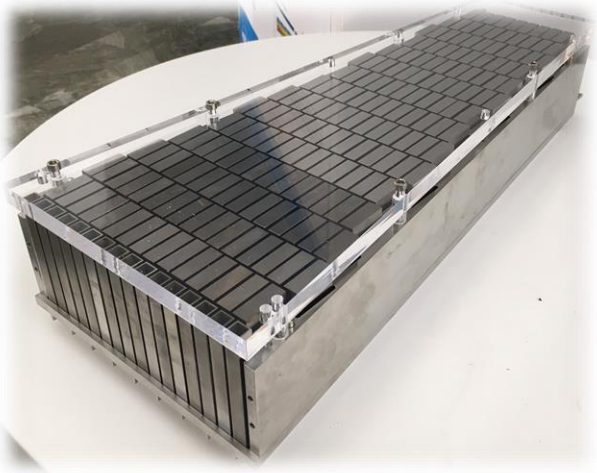
- Controlled and integrated commissioning and operation of the accelerator and target
- Fluorescent coating of PBW and target front face
- Optical paths, grid profile monitor, aperture monitor
- Wheel monitoring including position, temperature, vibration, as well as internal structure

The Target disk has 36 sectors of tungsten-filled cassettes



Tungsten bricks

- Tungsten depth in the proton beam direction is 45 cm
- The range of a 2-GeV proton in tungsten is 74 cm
- Brick dimensions: 10 W x 30 D x 80 H mm^3
- 190 bricks per sector, 6840 bricks in total
- Helium flows
  - radially outward above and below the cassette,
  - reverses direction at the wheel rim,
  - and returns through the tungsten



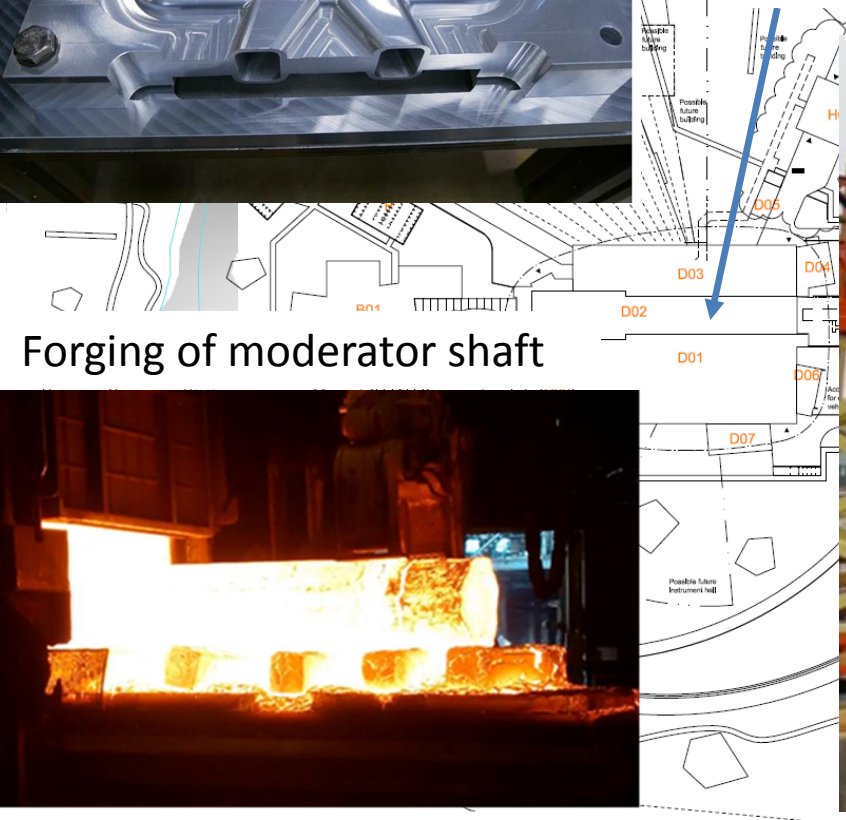
Cassette

Progress on Target and moderators

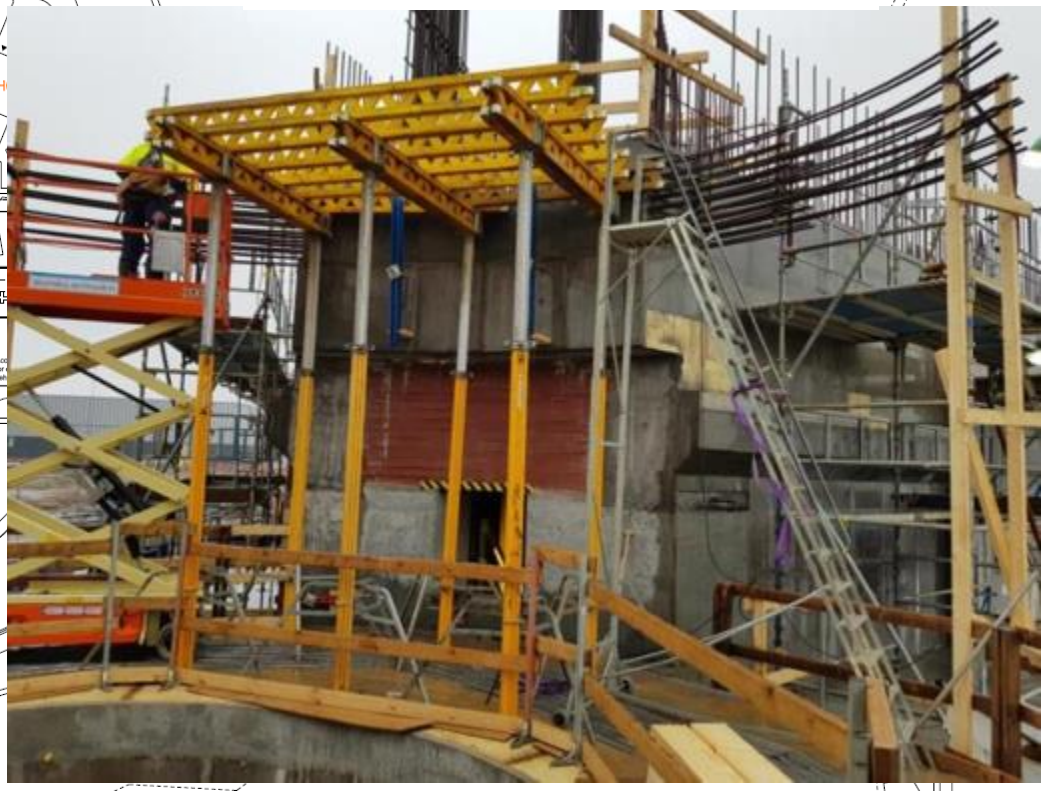
EUROPEAN SPALLATION SOURCE

Cold moderator vessel

Target



Shielding plates installed



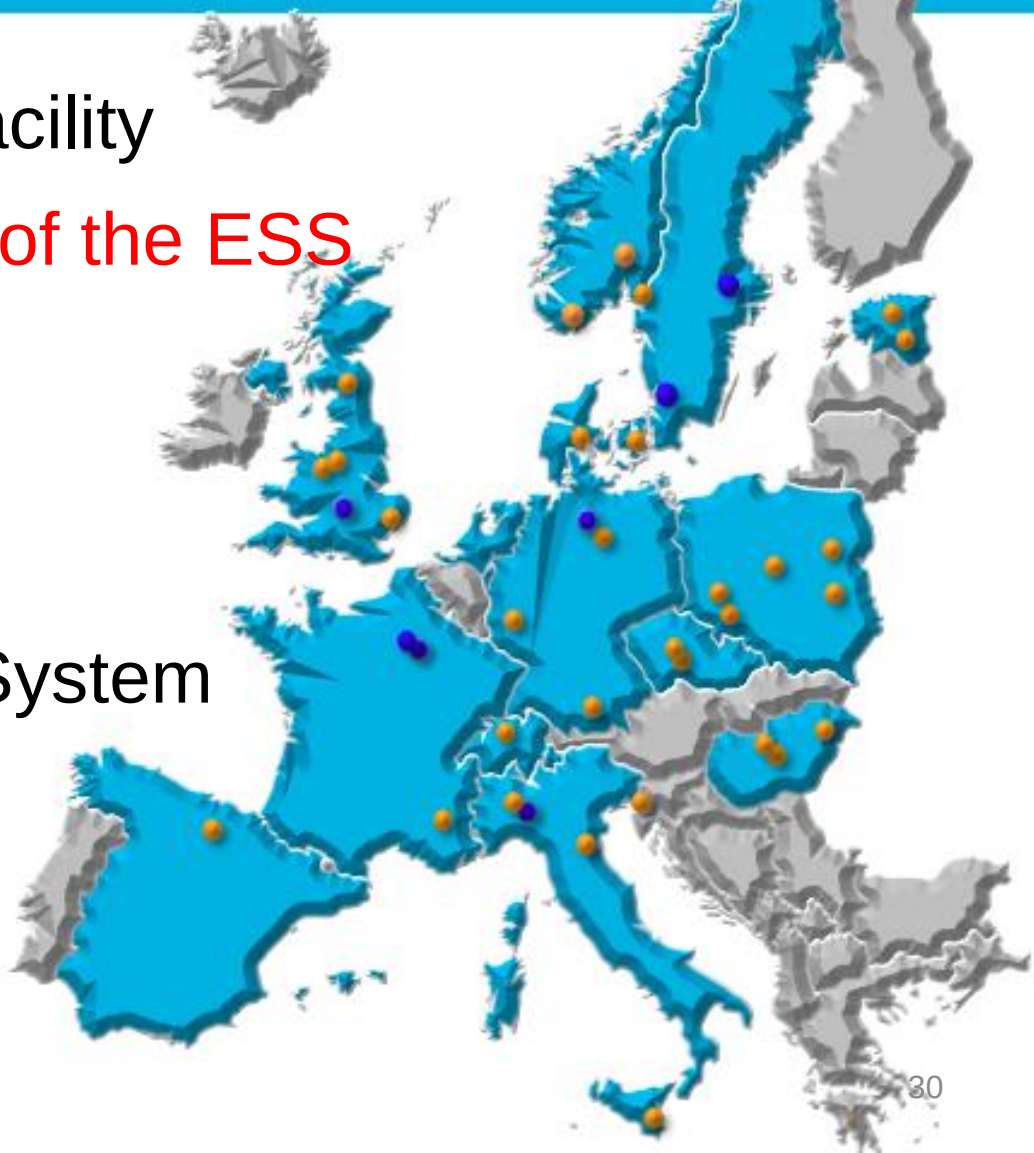
Forging of moderator shaft

Outline

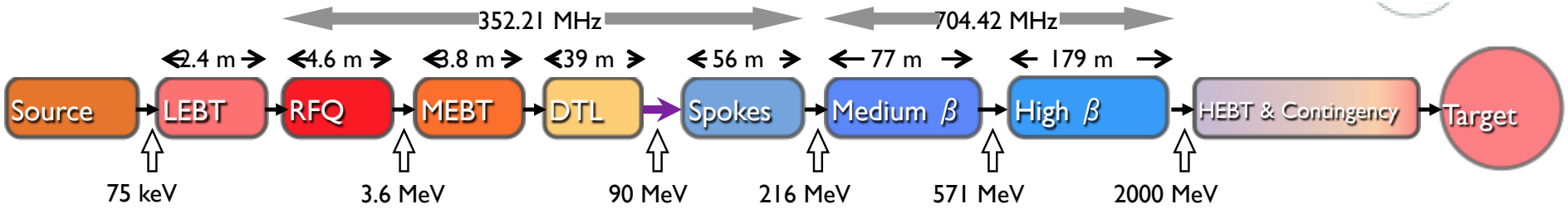
– Objective of the ESS facility

– Description and status of the ESS

- Instrument
- Target
- Accelerator
- Integrated Control System



Linear Accelerator layout



The ESS linac will be the most powerful proton linac ever built:

- Average beam power of up to 5 MW (ultimate)
- Peak beam power of up to 125 MW (ultimate)
- Acceleration up to 2 GeV (ultimate)
- Peak proton beam current of 62.5 mA
- Pulse length of 2.86 ms at a rate of 14 Hz (4% duty factor)

More information @ https://confluence.esss.lu.se/display/CRYOM

Constraints:

- Low losses
- Minimum energy use & energy recovery
- Flexibility for mitigation or upgrade

96% of acceleration will be provided by superconducting cavities supplied by dedicated high power RF sources (one per cavity):

- Construction scope: 1.3 GeV with 11 powered High β cryomodules (44 x 1.5 MW klystrons)
- Nominal scope: 2 GeV with 10 more powered High β cryomodules (+40 x 1.5 MW klystrons)

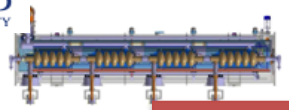
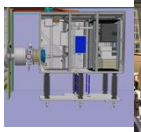
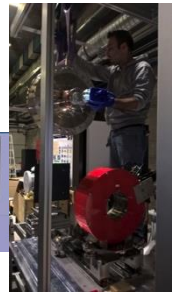
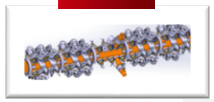
ESS Linac – A Collaborative project

EUROPEAN SPALLATION SOURCE

WP03	WP04	WP05	WP05
NC FE	Spoke	M-β	H-β







	Spoke	M-β	H-β
β	0.5	0.67	0.86
# CM	13	9	21
Cav. /CM	2	4	4
# Cav.	26	36	84
CM L [m]	2.9	6.6	6.6
L [m]	56	77	179

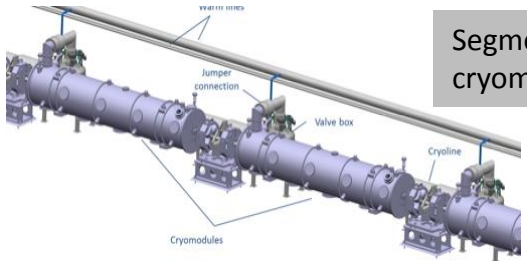
352.21 MHz

704.42 MHz

2.4 m | 4.6 m | 3.8 m | 39 m | 56 m | 77 m | 179 m

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Contingency → Target

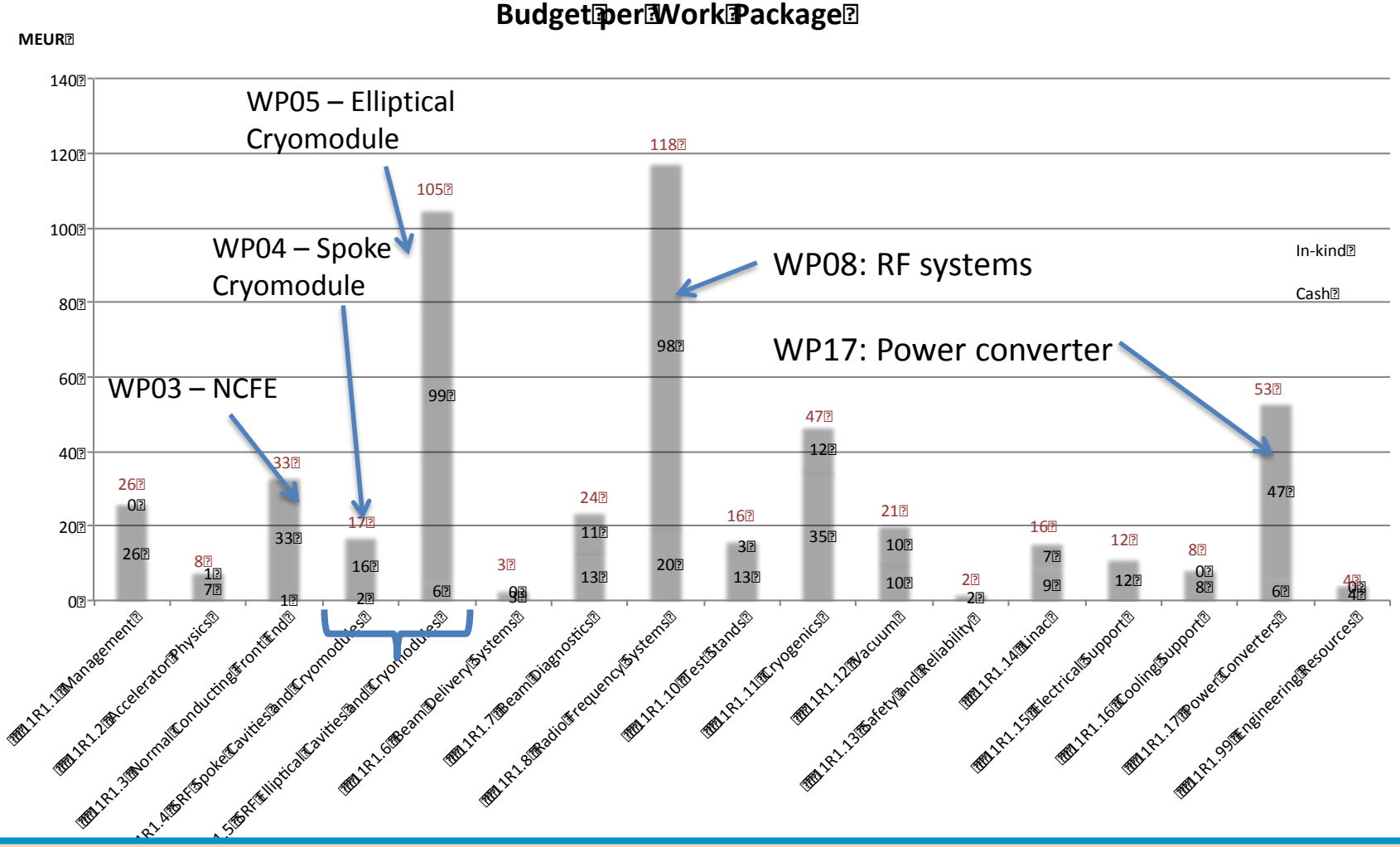
75 keV | 3.6 MeV | 90 MeV | 216 MeV | 571 MeV | 2000 MeV

Segmented cryomodules section

96 % of the beam acceleration by SRF

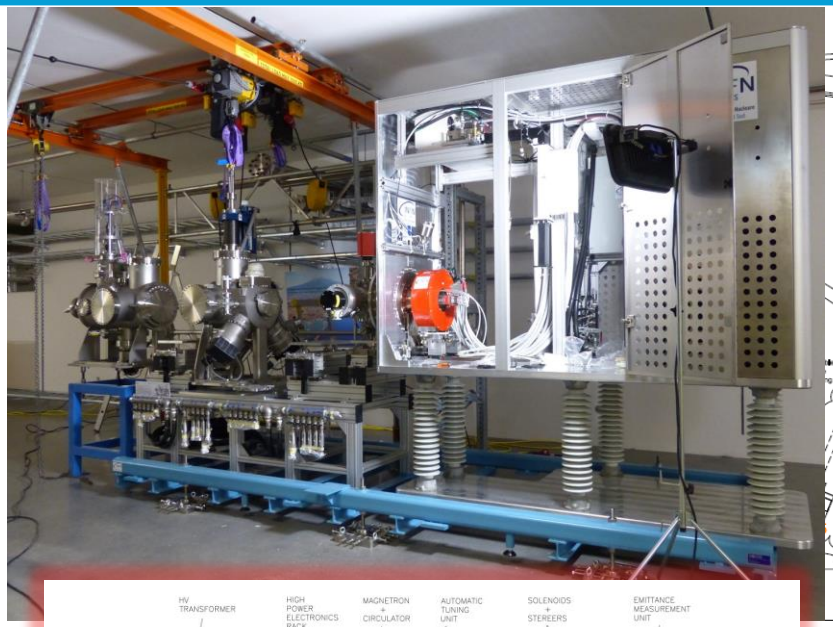
ESS ACCSYS project organization

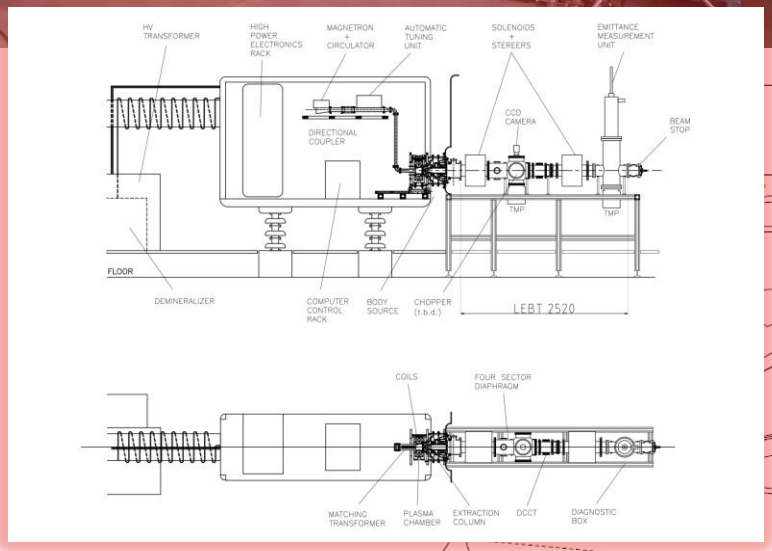


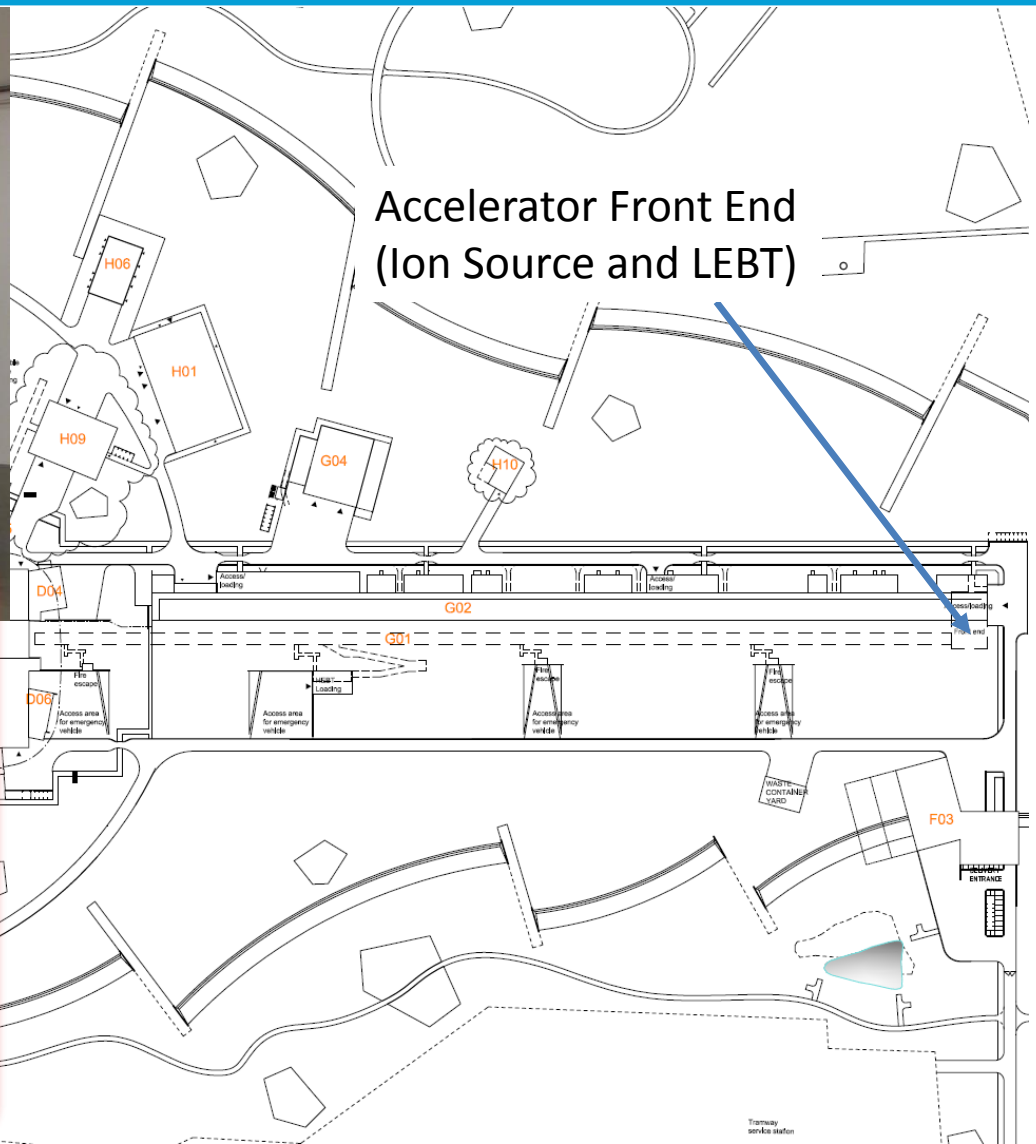
External WP → Cooperation agreements - Prototypes to Kick-start the linac design and production !

In-kind equipment starts being installed in Lund [e.g ion source from INFN (+ CEA)]…

EUROPEAN SPALLATION SOURCE

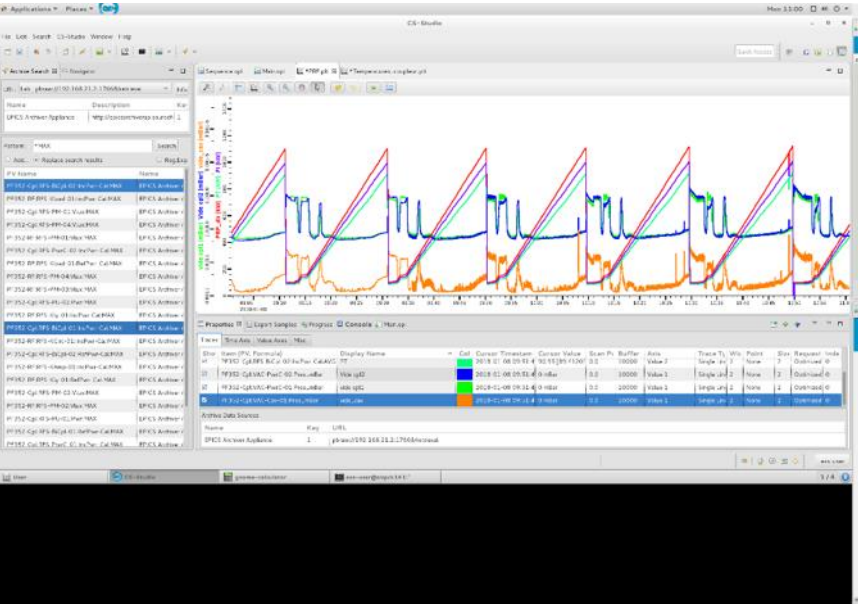


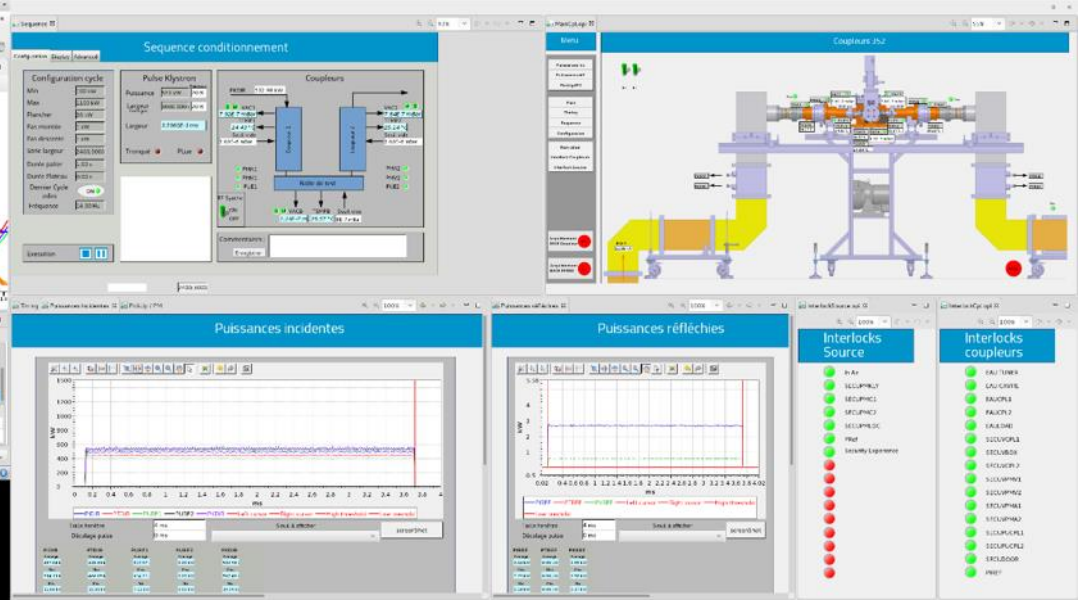




CEA IRFU RFQ :couplers conditioned at 1 MW

EUROPEAN SPALLATION SOURCE



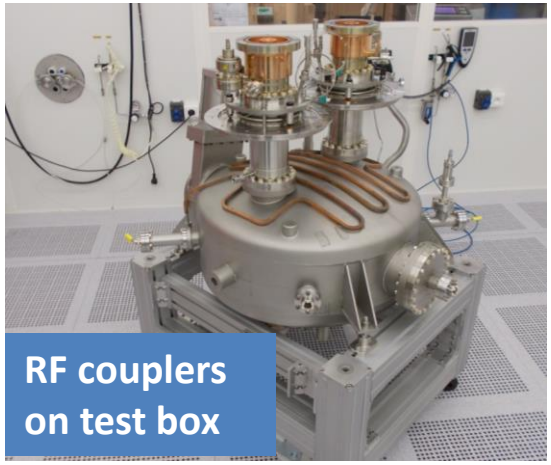


INFN Legnaro DTL

Bead pulling and tuning on DTL Aluminum model (Tank #2 as mock-up) on going in Legnaro

DTL Tank section 4 -1 at the GSI plating Facility

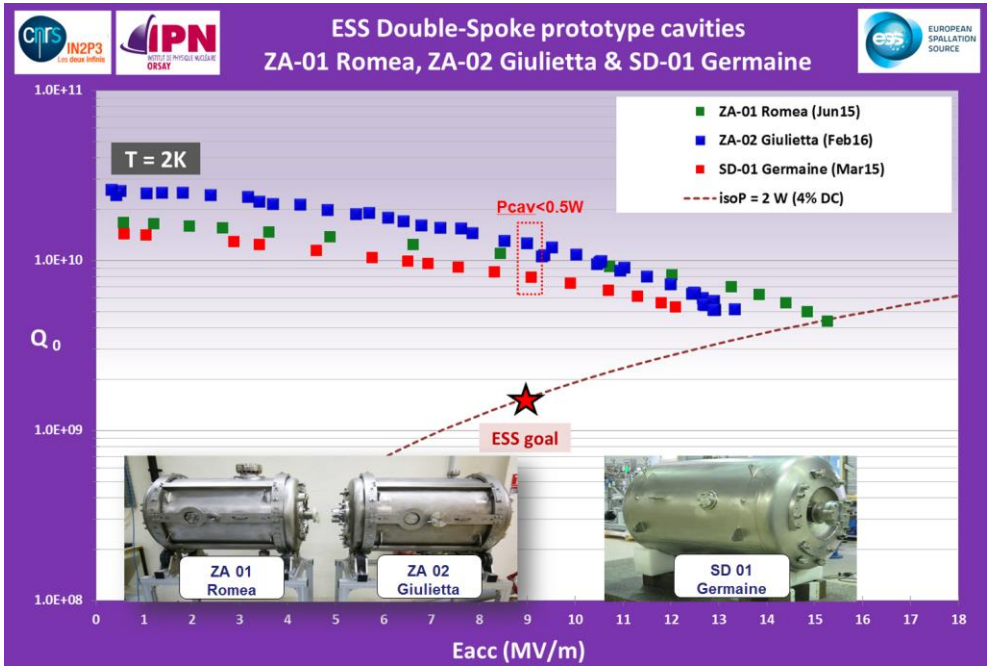
Equipment construction is progressing at in-kind partners (e.g. CNRS IPNO)



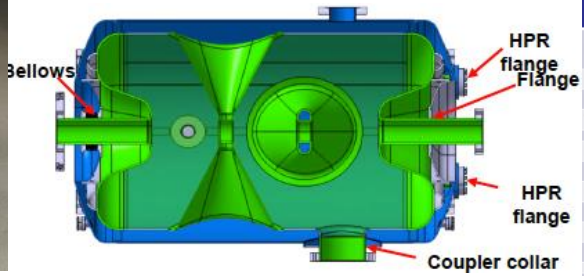
RF couplers on test box

Spoke cavities and cryomodules (CNRS-Orsay)

- The 3 prototype cavities largely exceeded specs.



First 2 production cavities



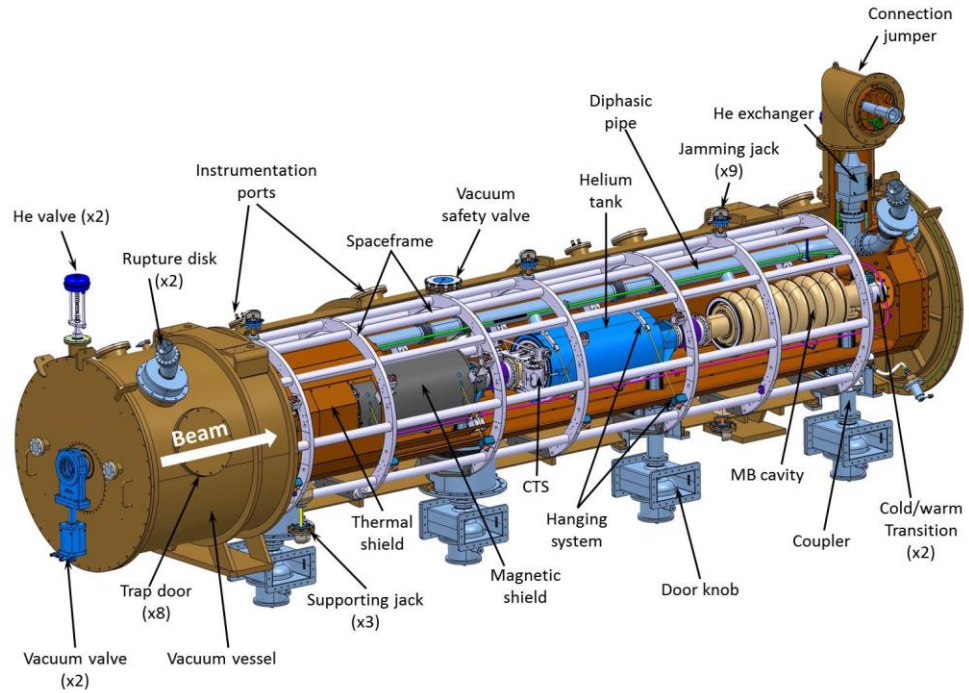
DOUBLE-SPOKE CAVITY SPECIFICATIONS	
Beam mode	Pulsed (4% duty cycle)
Frequency [MHz]	352.2
Beta_optimal	0.50
Temperature (K)	2
Bpk [mT]	70 (max)
Epk [MV/m]	35 (max)
Gradient Eacc [MV/m]	8
Lacc (=beta optimal x nb of gaps x λ /2) [m]	0.639
Bpk/Eacc [mT/MV/m]	< 8.75
Epk/Eacc	< 4.38
Beam tube diameter [mm]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

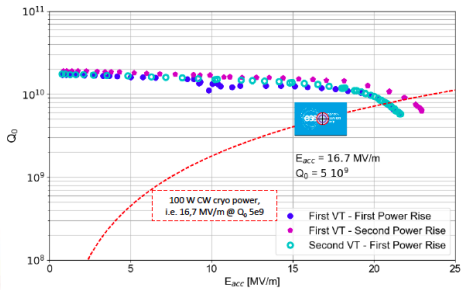
Prototypes are built/under construction by partners and provide lessons

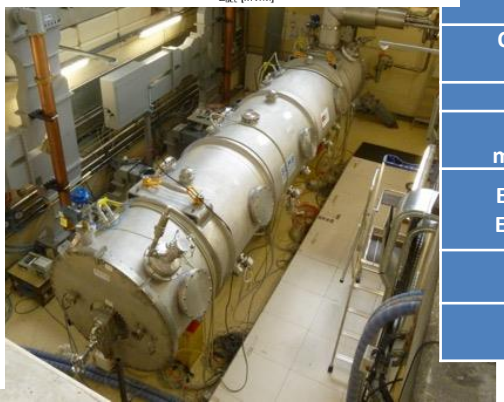
Cavities string under assembly

RF Power couplers

Cryomodule vacuum vessel

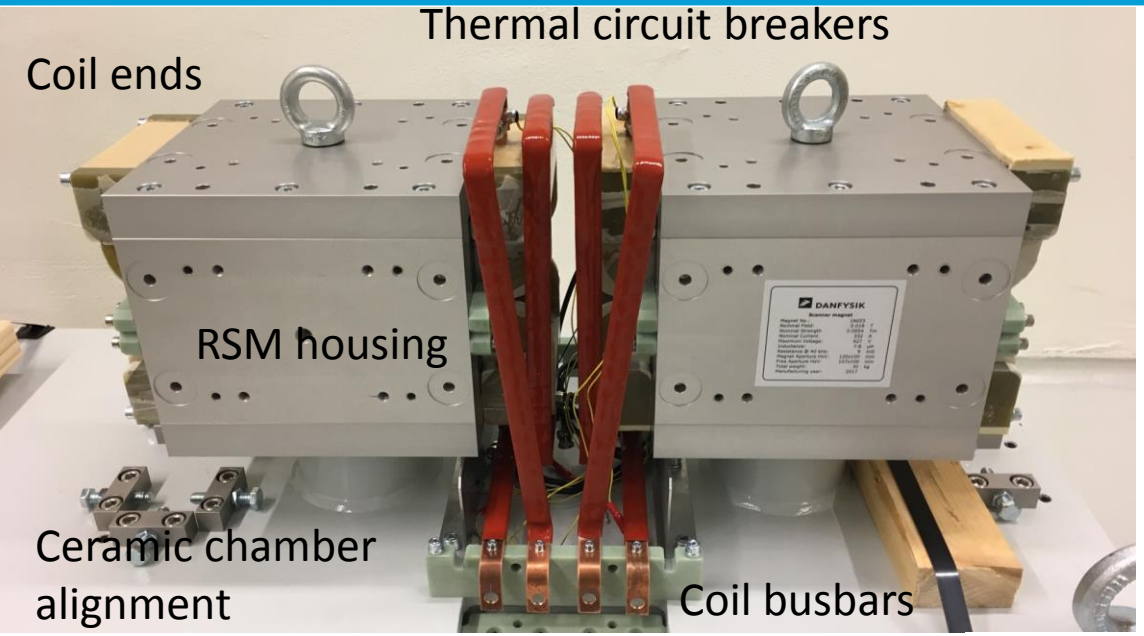




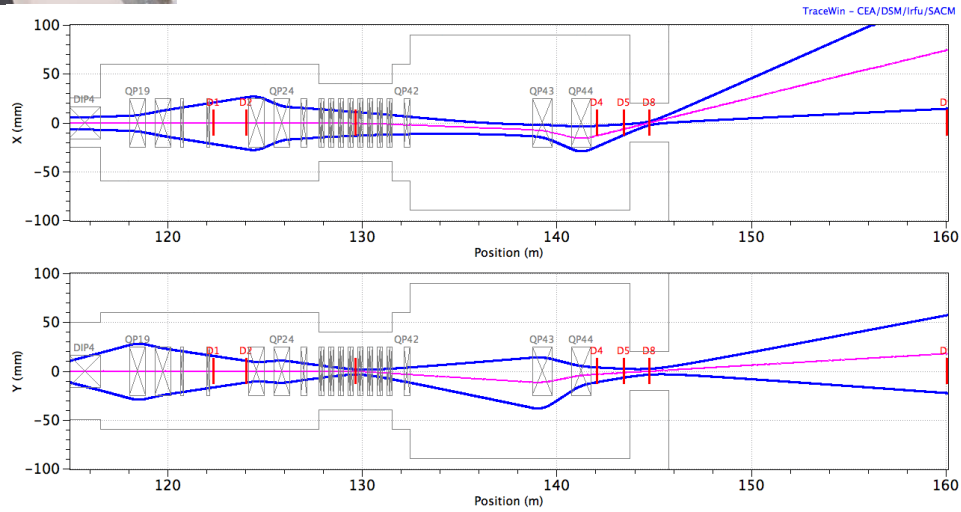


Parameter	Medium beta	High beta
Frequency [MHz]	704.42	
Accelerating length [mm]	0.855	0.915
# cells	6	5
Operating T	2K	
Beta	0.67	0.86
Nominal E_{acc} [MV/m]	16.7	19.9
Q_0 at nominal E_{acc}	>5x10^9	
E_{pk}/ E_{acc}	2.36	2.2
B_{pk}/ E_{acc} mT/(MV/m)	4.79	4.3
E_{pk} at nominal E_{acc} [MV/m]	39.4	43.8
G [Ω]	196.63	241
Cell to cell coupling	1.2%	1.8%

Aarhus university RSM Pair



Nominal field 106 Gauss
Designed for 60% cont.
Power average 30W.
Air cooled!



FREIA Laboratory

EUROPEAN SPALLATION SOURCE

State-of-the-art Equipment

cryogenics
- liquid helium
- liquid nitrogen

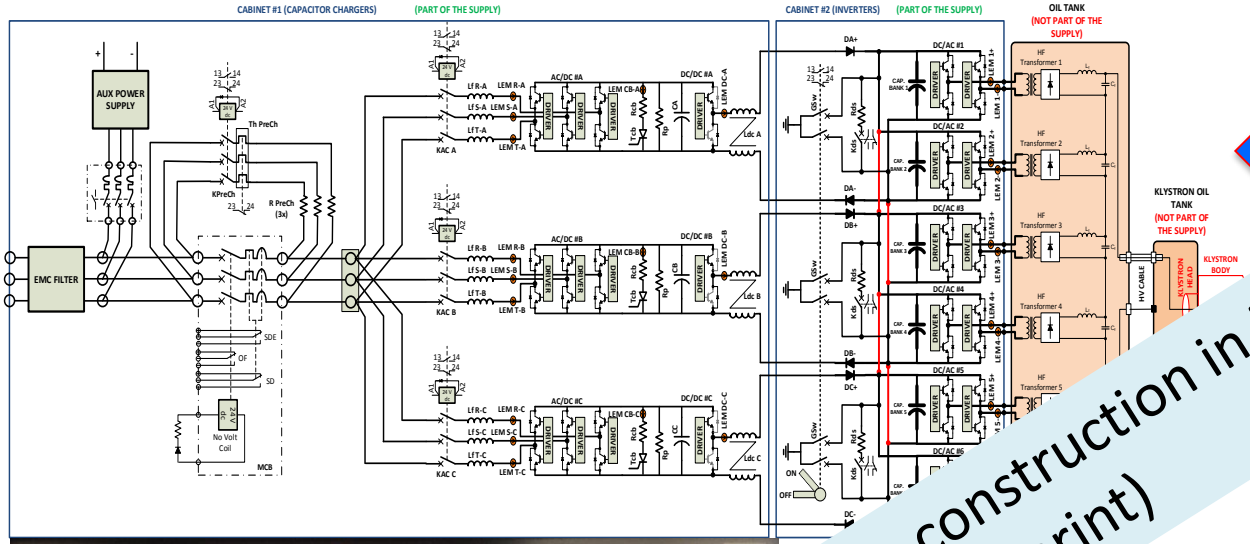
control room
- equipment controls
- data acquisition

vertical cryostat

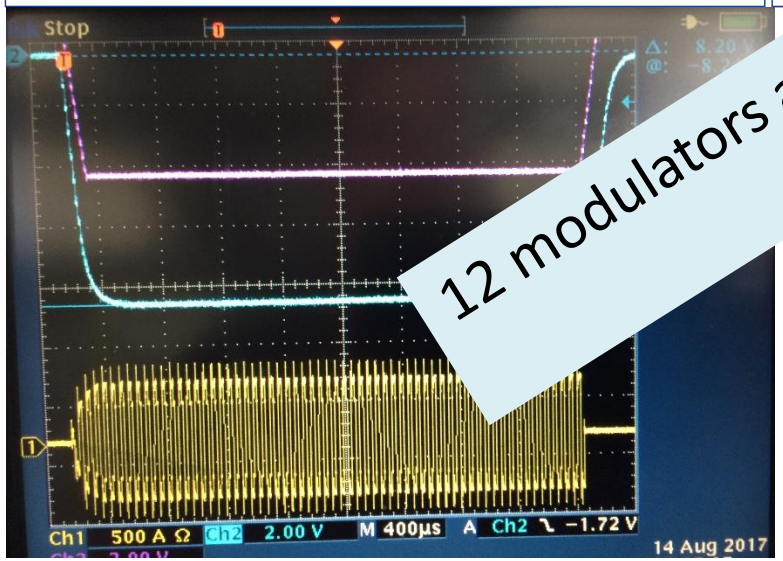
3 bunkers
with test stands
horizontal cryostat

radio-frequency (RF) power
sources

ESS development of high power/ compact/ high efficiency modulator is successful



Electrical schematic of Stacked Multi-Level (SML) modulator



12 modulators are in construction in industry (build-to-print)

...totype ...odulator ...cessfully powered a Toshiba Klystron up to 1 MW RF

Happy Engineers!

Cryogenic Systems are under commissioning

EUROPEAN SPALLATION SOURCE

Helium Recovery System Compressors

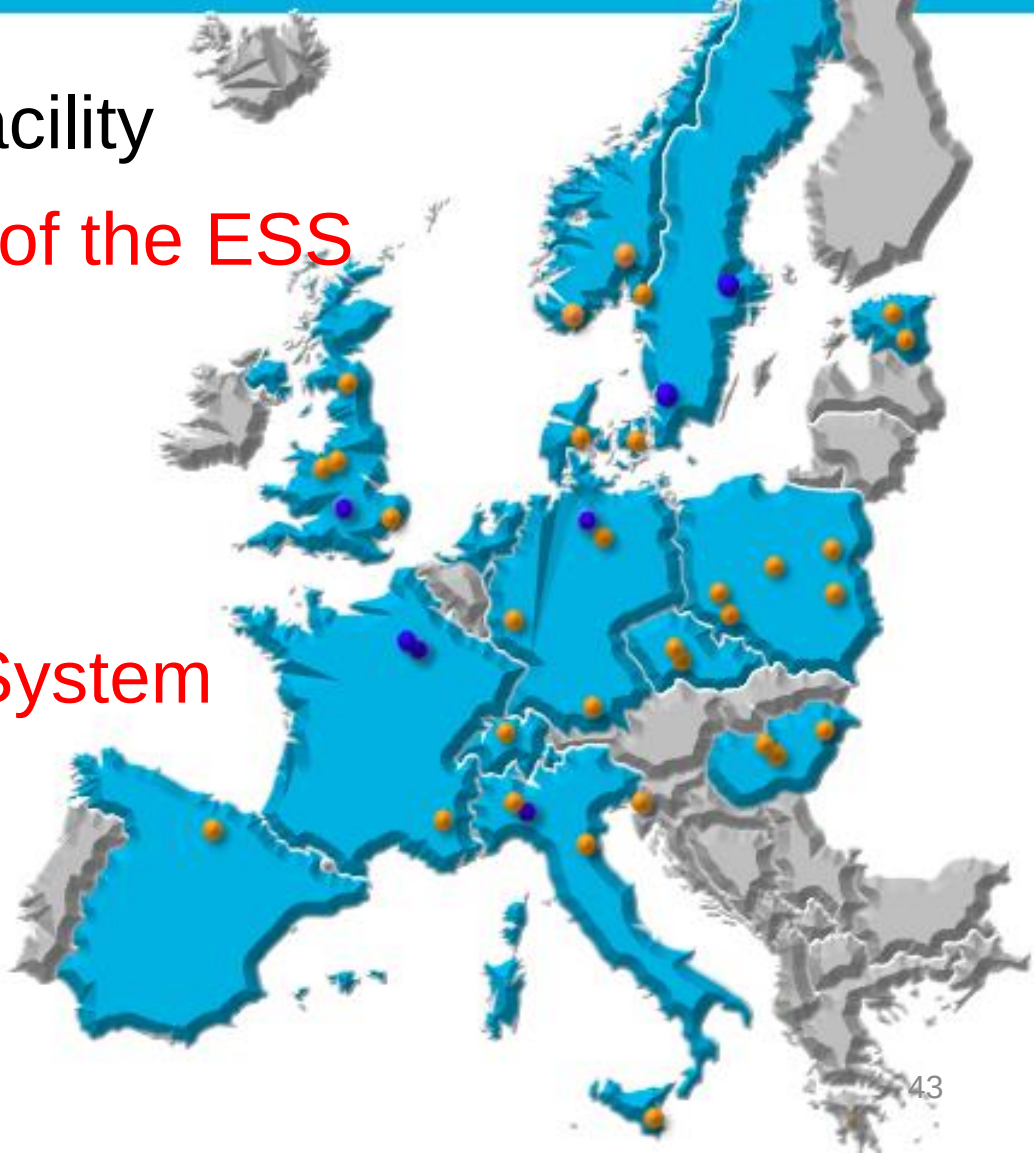
ACCP compressors and oil removal system

Outline

– Objective of the ESS facility

– Description and status of the ESS

- Instrument
- Target
- Accelerator
- Integrated Control System

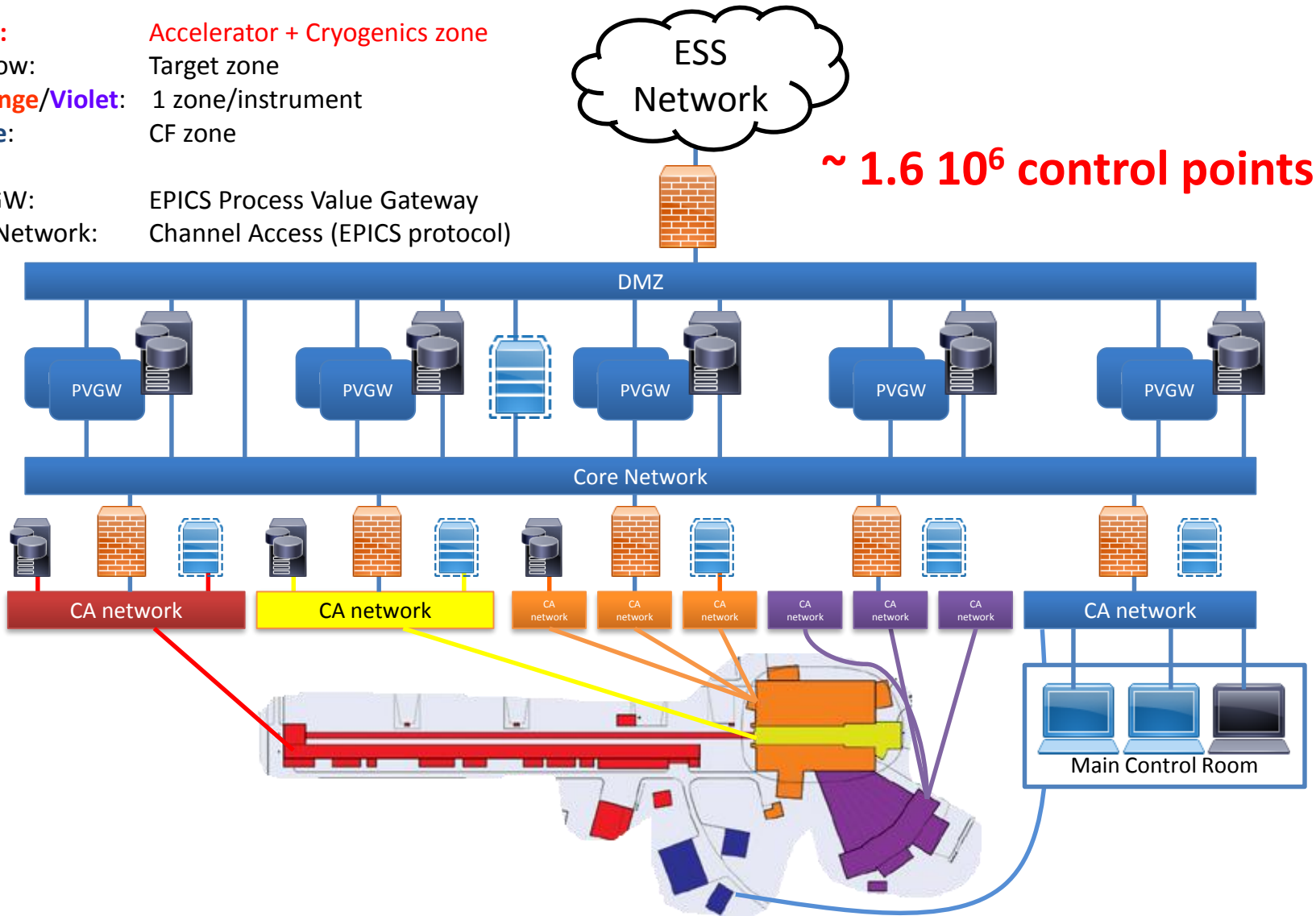


ESS Control System network

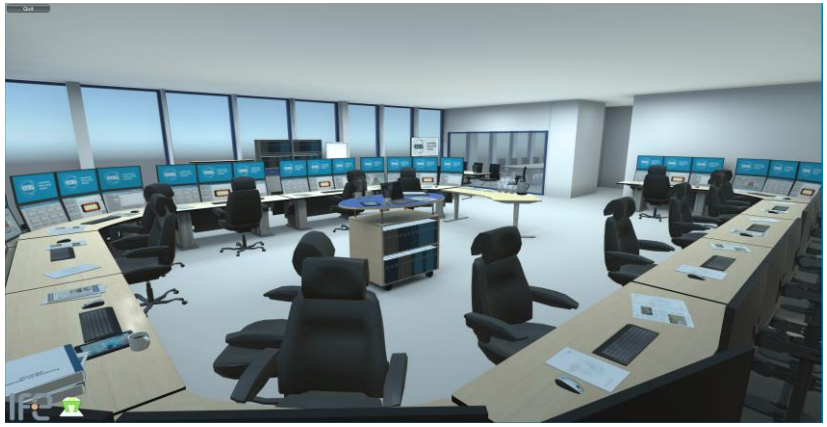
Red: Accelerator + Cryogenics zone
Yellow: Target zone
Orange/**Violet**: 1 zone/instrument
Blue: CF zone

PVGW: EPICS Process Value Gateway
CA Network: Channel Access (EPICS protocol)

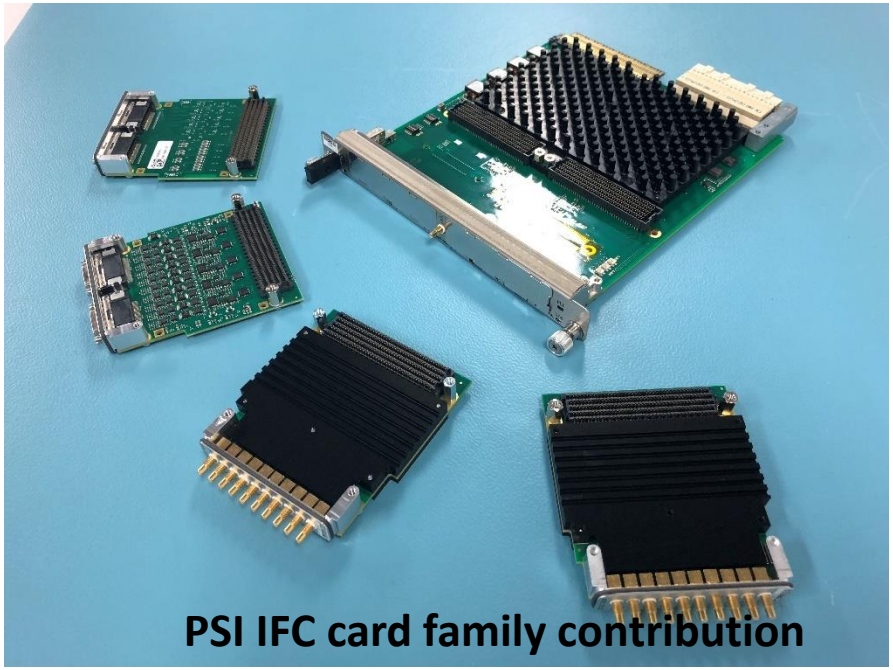
~ 1.6 10^6 control points!



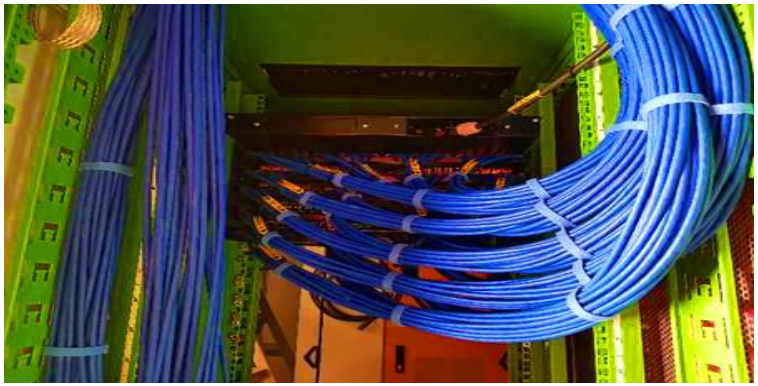
In-kind contributions to ICS are materializing and installation has started



IFE control room contribution



PSI IFC card family contribution

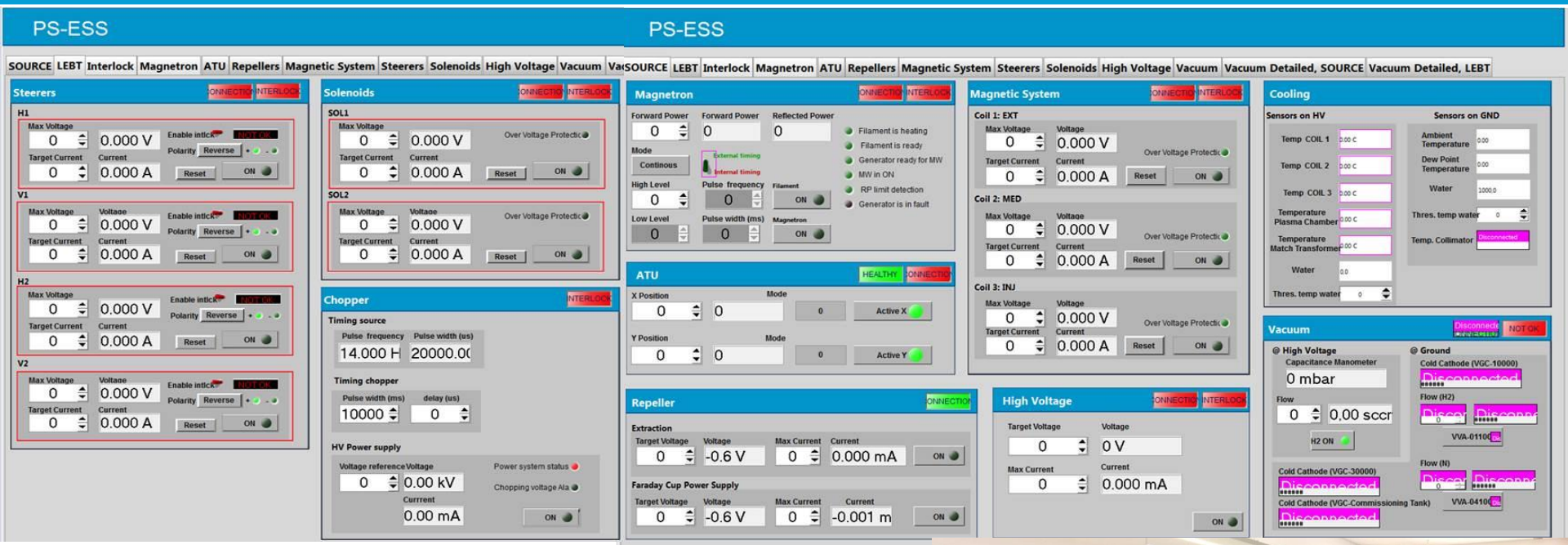


Cabling on site

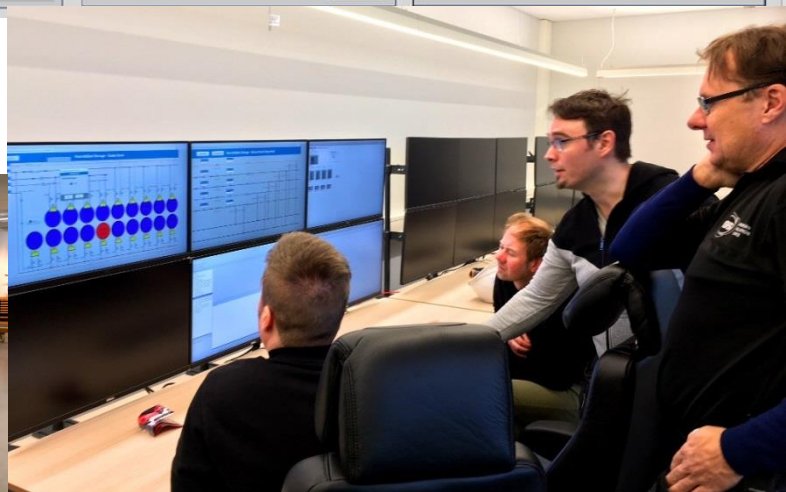
Oxygen Deficiency Hazard system

First steps of commissioning from the local control room

EUROPEAN SPALLATION SOURCE



- Recent achievements include controlling the pure Helium storage and parts of the ion source and LEBT from the local control



Updated schedule

Milestone Acronyms

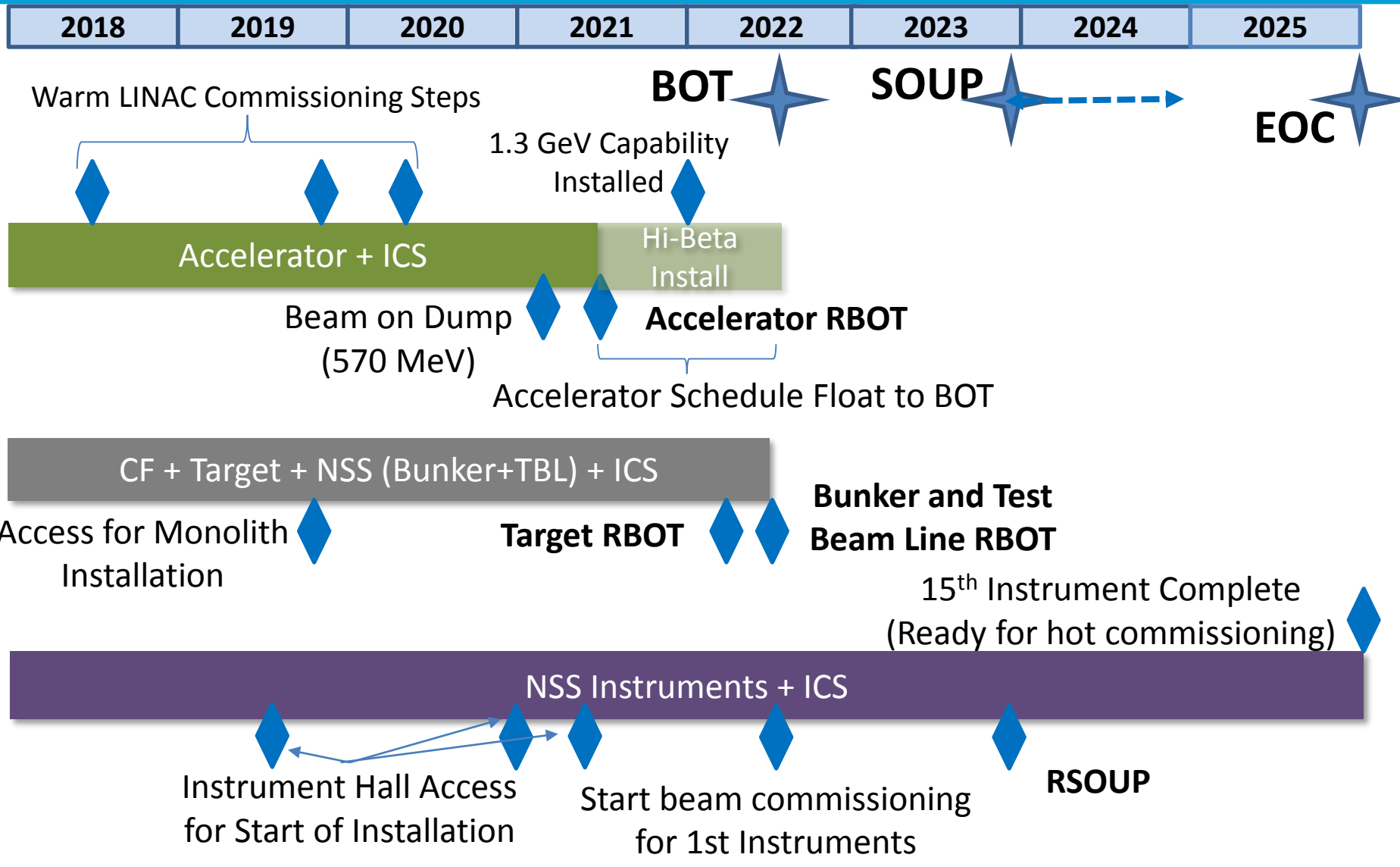
BOT - Beam on Target

SOUP - Start of User Programme

EOC - End of Construction

Rxxx - Ready for xxx

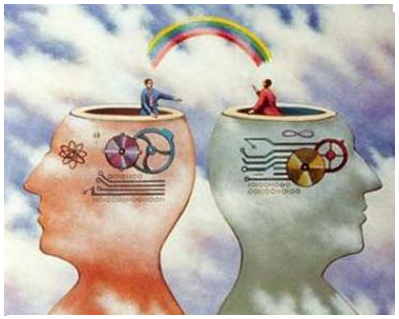
EUROPEAN SPALLATION SOURCE



Summary

EUROPEAN SPALLATION SOURCE

- The ESS facility is built by a collaboration of some 100 research institutes and universities around the word
- Manufacturing of all major accelerator systems have now been launched and first parts are now being installed
- First beam for science 2023



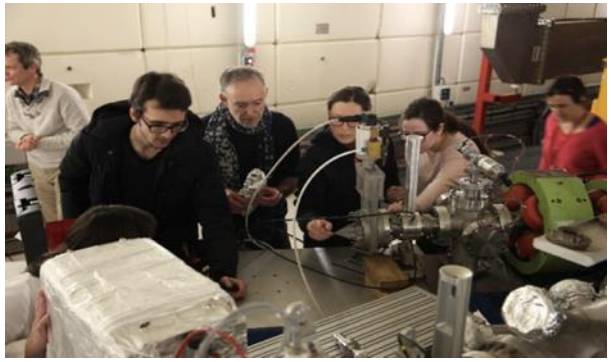
Fractality and entanglement

- Most future large scale project are likely to be IK projects and this is a very powerful model !

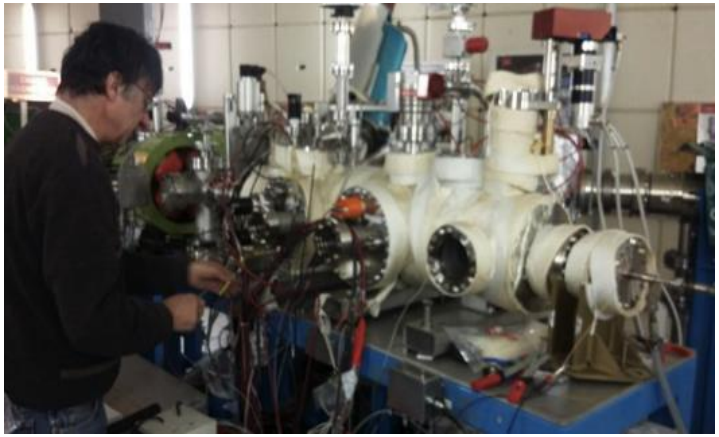
Thank you for your attention!

EXTRA SLIDES

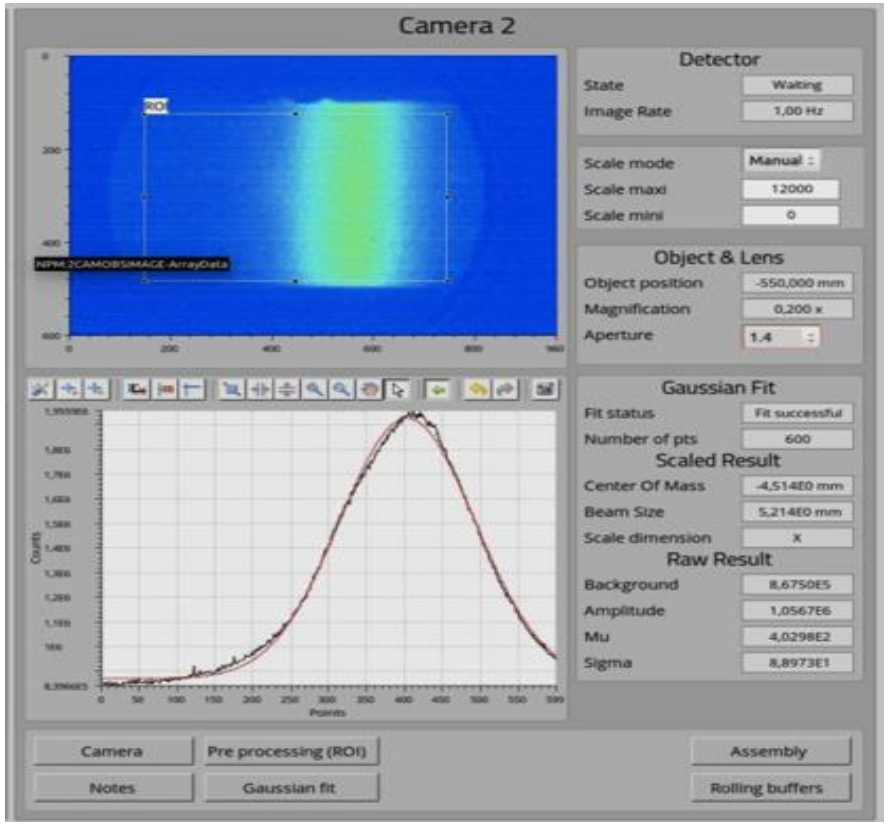
Beam Diagnostics:
IPM prototype tests running on IPHI.



The IPM team in Saclay.



The IPM test chamber



Measurement results for the proton beam at IPHI showing good performance and agreement with simulations.

Elettra In-kind Contributions

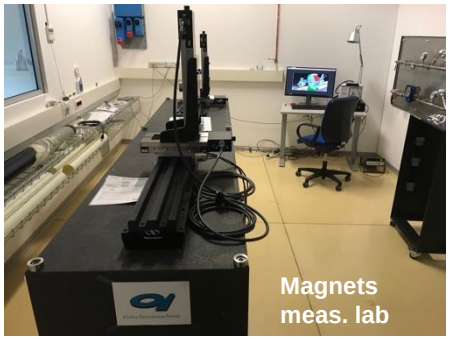
Elettra Sincrotrone Trieste

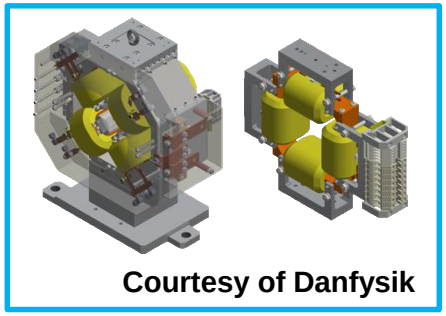
- **Magnets for the ESS linac (AIK2.1), Trilateral IKCA (Elettra, ESS, INFN)**
- **Power Converters for Magnets (AIK17.2), Trilateral IKCA (Elettra, ESS, INFN)**
- **Spoke RF Power Stations (AIK 17.7), Trilateral IKCA (Elettra, ESS, INFN)**
- **Beam Diagnostics Wire Scanner Acquisition System (AIK 7.4), Approved by Elettra Board of Directors**
- **Technical Support for Installation and Commissioning (UNDER DEFINITION)**

HIGHLIGHTS (MORE IN THE POSTER SESSION):

MAGNETS (AIK2.1)

- LWU Magnets (Q5,Q6,Q7 and C5, C6)
  - Contract assigned to Danfysik
  - CDR by end of April 2018
  - First pre-series corrector magnets C5, C6: July-August 18
  - First pre-series corrector magnets Q5, Q6, Q7: September-October 18
- Magnets D1, Q8 and C8: bids received, under evaluation
- Dedicated magnetic Lab at Elettra: under completion

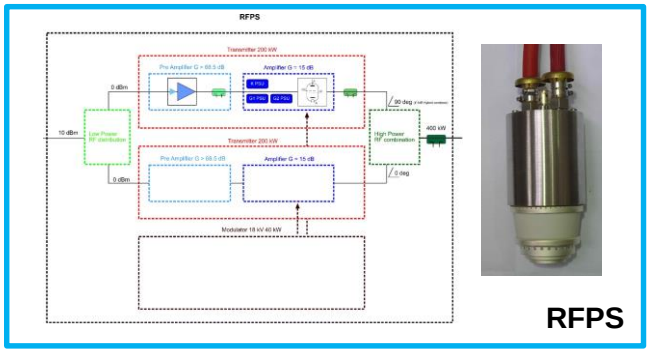

Magnets meas. lab


Courtesy of Danfysik

POWER CONVERTERS (AIK17.2)

- Power converters for dipole and quadrupole magnets: bids received, under evaluation
- Assembly of power converters for correctors (Elettra design): bids received, under evaluation
- Bulk&Aux DC/AC Power supplies with Step Diode: **DELIVERED TO ESS**


Delivery at ESS

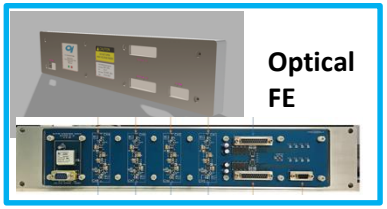


RFPS

RF POWER STATIONS (AIK17.7)

- RF Power stations: bids received, under evaluation
- Tetrodes: offer received, under evaluation


Corrector PC


Optical FE

WIRE SCANNER ACQUISTION SYSTEM (AIK 7.4)

- Evaluation test on Linac4 (analog FE, Back end and software) performed in autumn 2017
- CDR performed in March 18.