UPPSALA UNIVERSITET

EUROPEAN SPALLATION SOURCE

Progress of the European Spallation Source

Roger Ruber

Uppsala University

Thanks to all colleagues for materials

Jülich, 1 February 2018

Presentation Outline

- **Reminder of neutron science**

- **Overview of the ESS machine**

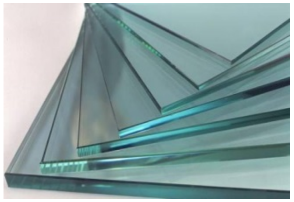
- **Technical highlights**
  - Science instruments
  - Target system
  - Accelerator

- **Outlook**
  - Fundamental physics at ESS
  - Financing and time schedule

Material Science & Innovation

“The Stone Age didn’t end for lack of stone”
Ahmed Zaki Yamani

- Society’s progress has been determined by the development of new materials

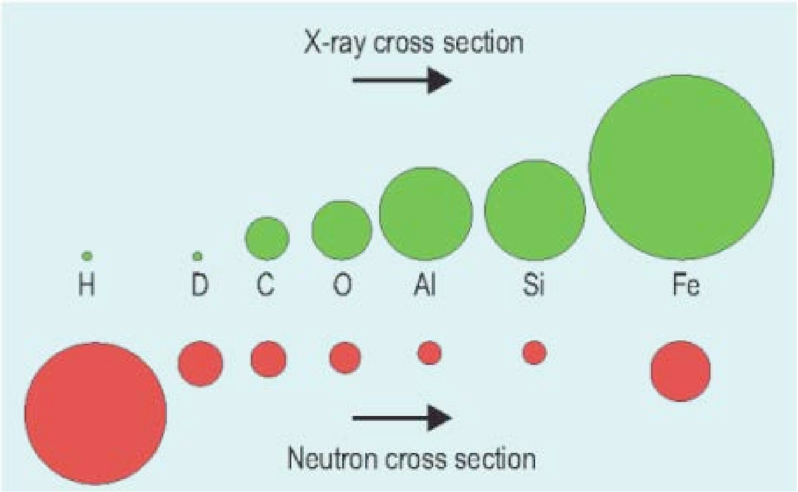
- Wood, glass, stone, bronze, iron, steel, concrete, plastics, silicon…

- ferroelectrics, superionic conductors, giant magnetoresistance, semiconductors, liquid crystals, fullerenes carbon allotropes, high Tc superconductors and more…

We have to build the best facilities
with the best instruments
if we are to develop, understand, and harness New Materials

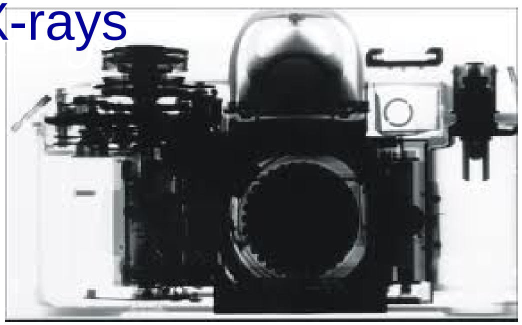
Why to use neutrons?

- Neutral charge
  - deeply penetrating except for some isotopes
- Nuclear interaction:
  - cross section depending on isotope (not Z), sensitive to light elements.
- Spin S = 1/2
  - probing magnetism
  - unstable $n \rightarrow p + e + \underline{\nu}_e$ with life time $\tau \sim 900s$, $I = I_0 \; e^{-t/\tau}$
- Thermal energies result in non-relativistic velocities
  - mass: n ~p; E = 293 K = 25 meV, v = 2196 m/s , λ = 1.8 Å

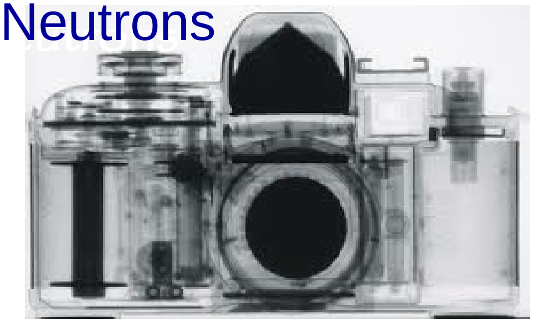


Light

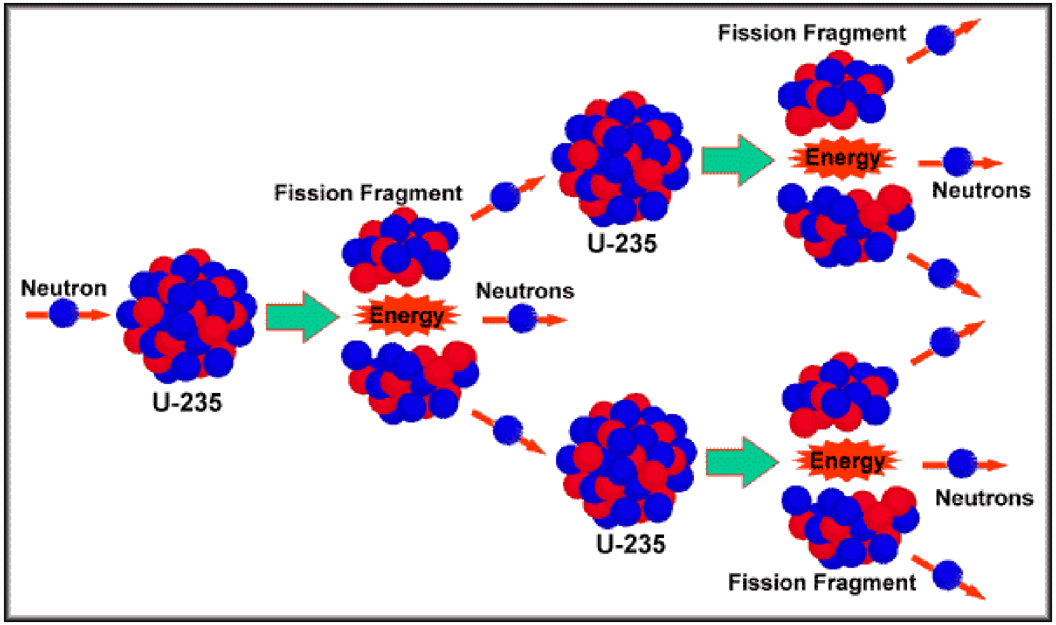
X-rays



Neutrons

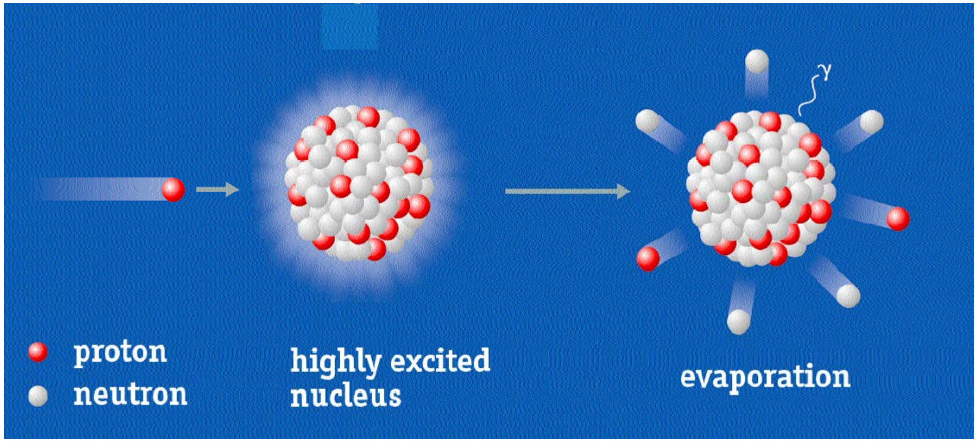


How to produce neutrons

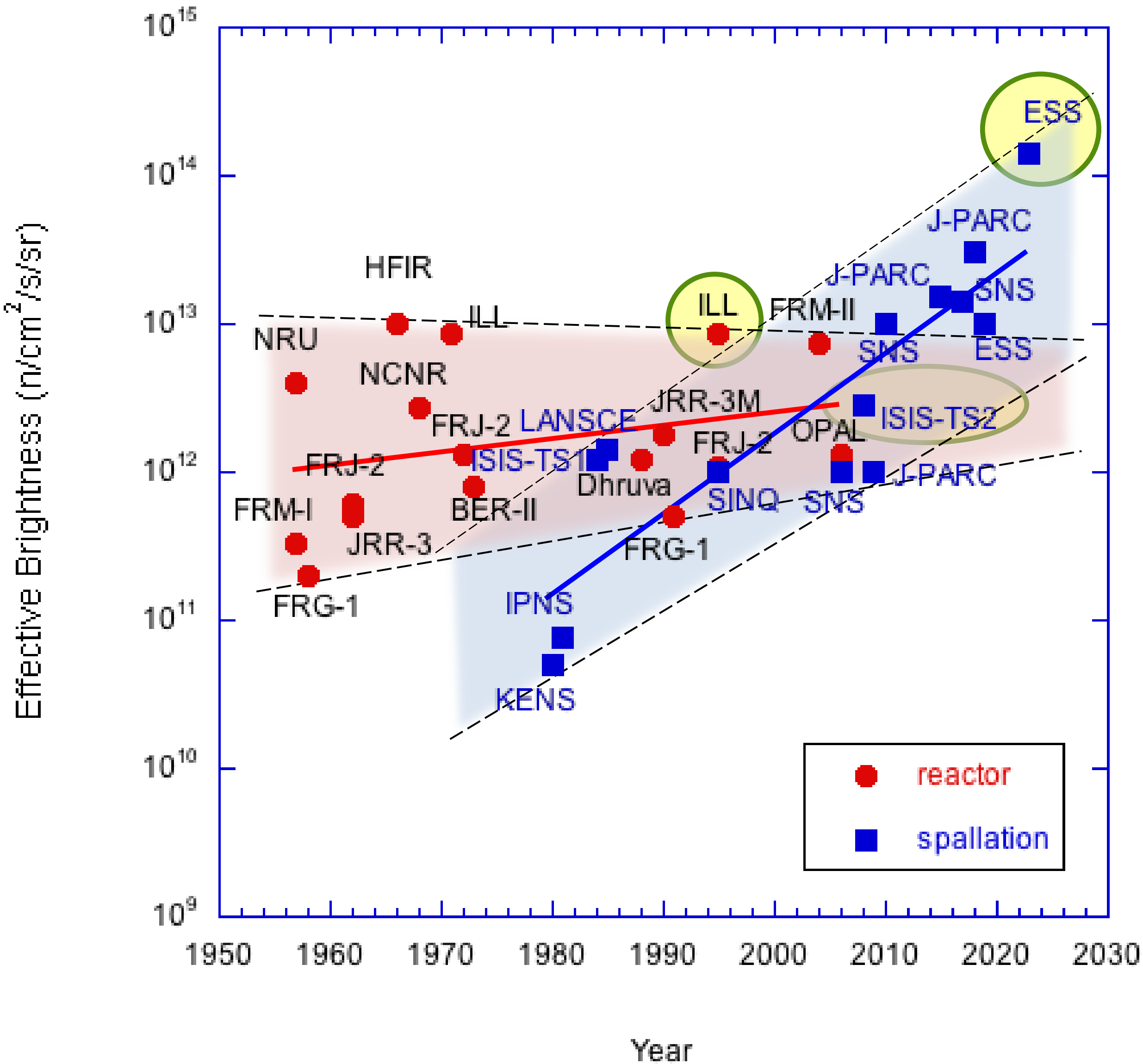


Nuclear Fission
→ reactor

Nuclear Spallation
→ accelerator



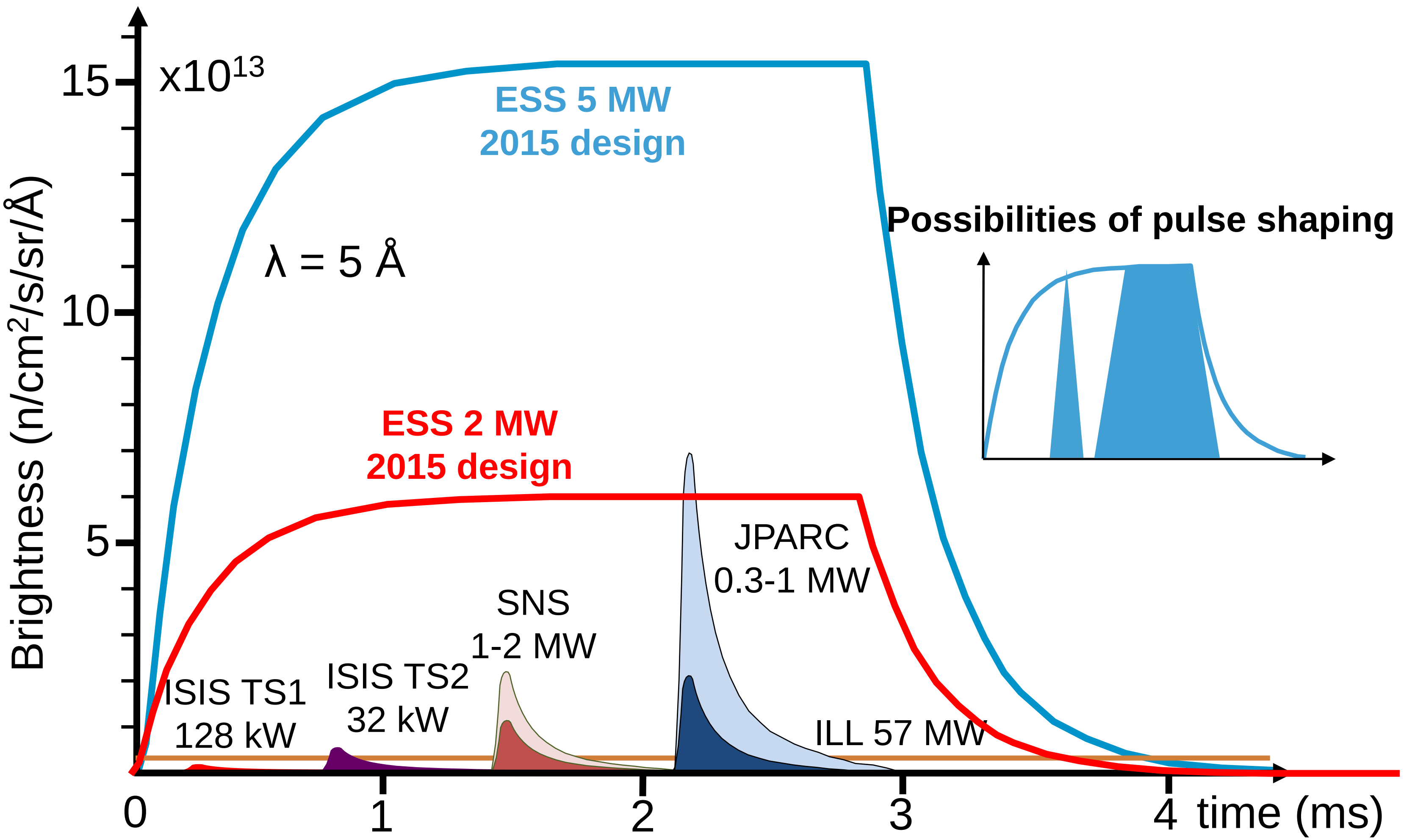
Usable Neutron Brightness



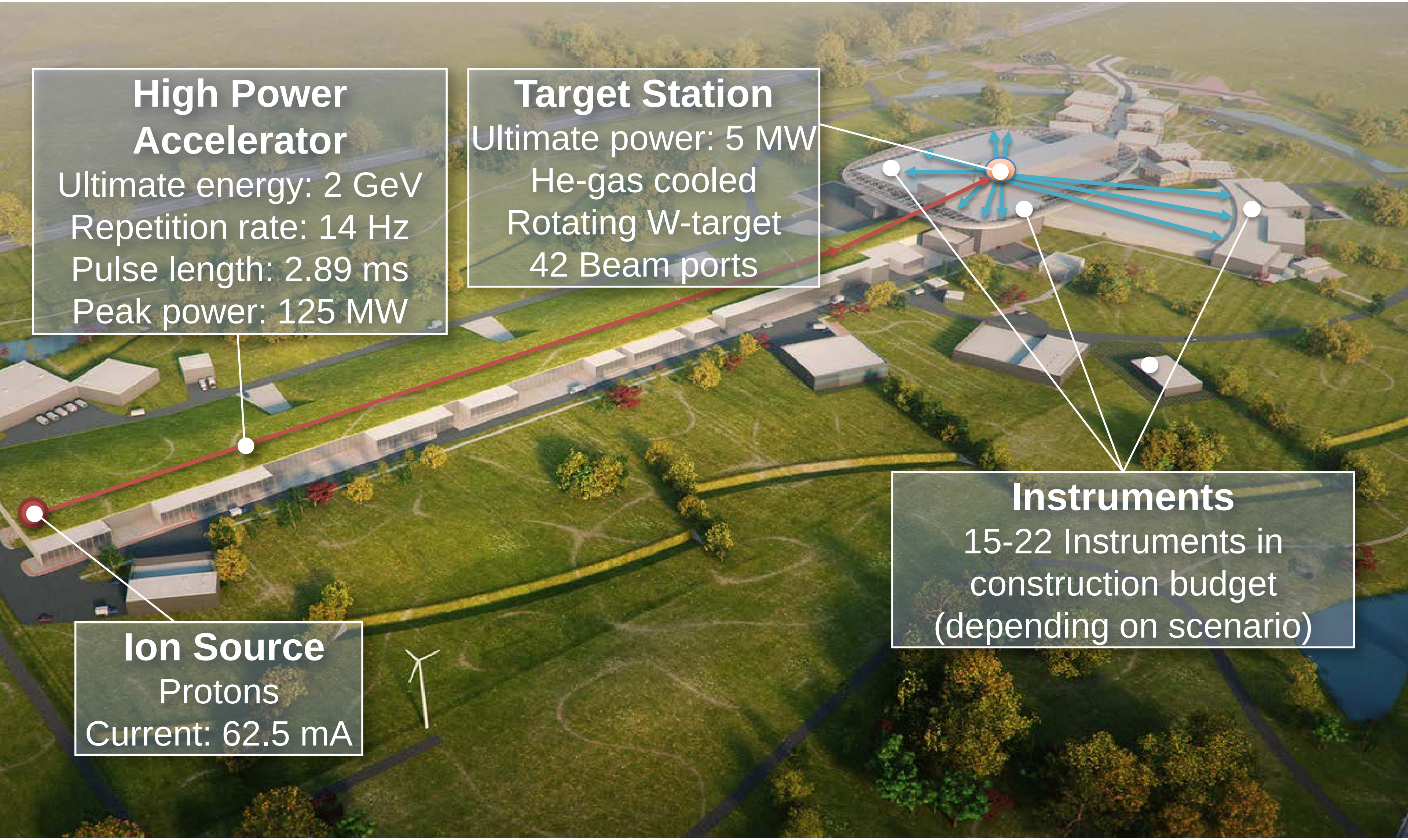
Spallation
4 x per decade

Fission
1.2 x per decade

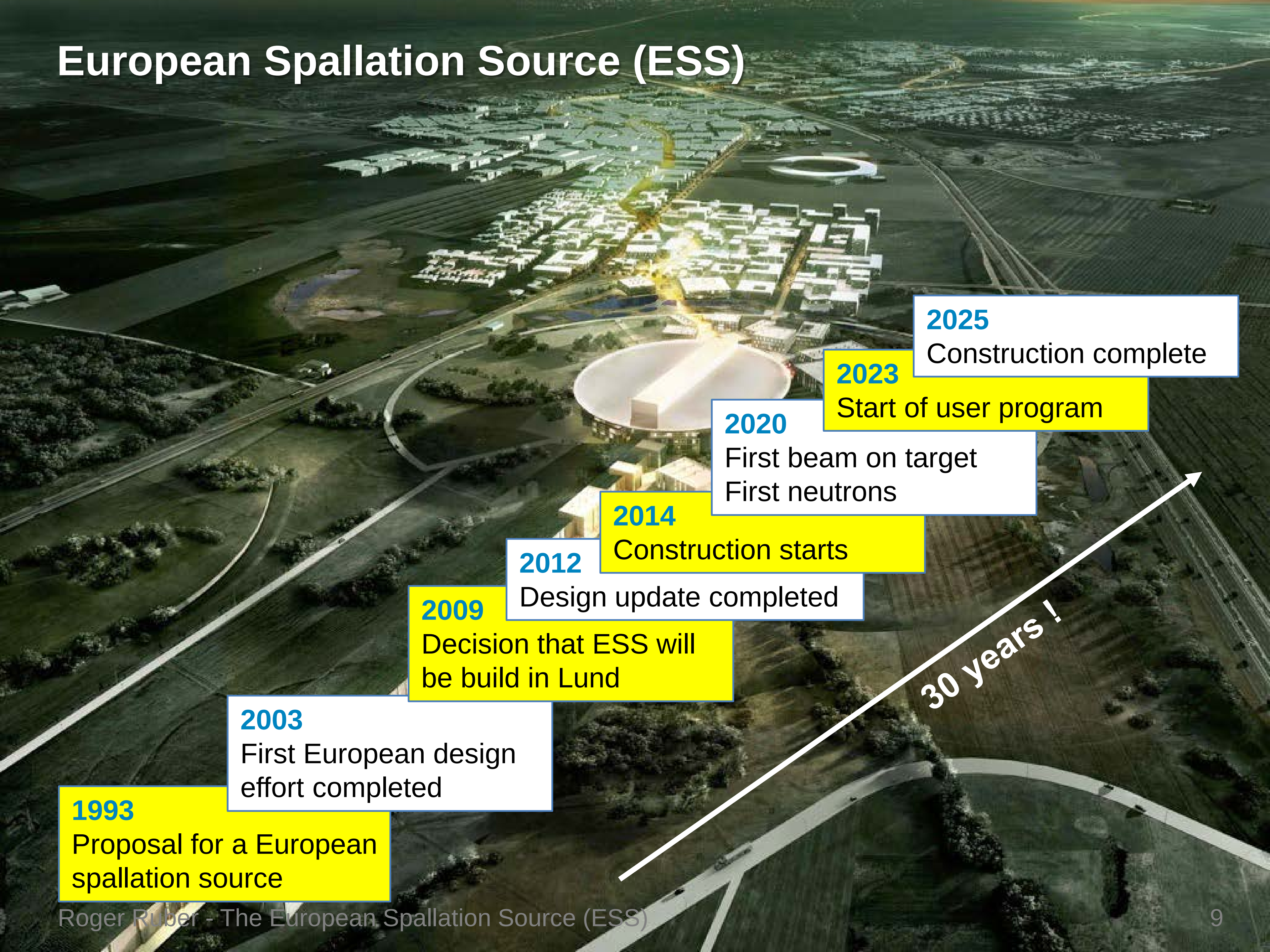
Long Pulse Performance



ESS Basic Design Principles



European Spallation Source (ESS)



1993
Proposal for a European spallation source

2003
First European design effort completed

2009
Decision that ESS will be build in Lund

2012
Design update completed

2014
Construction starts

2020
First beam on target
First neutrons

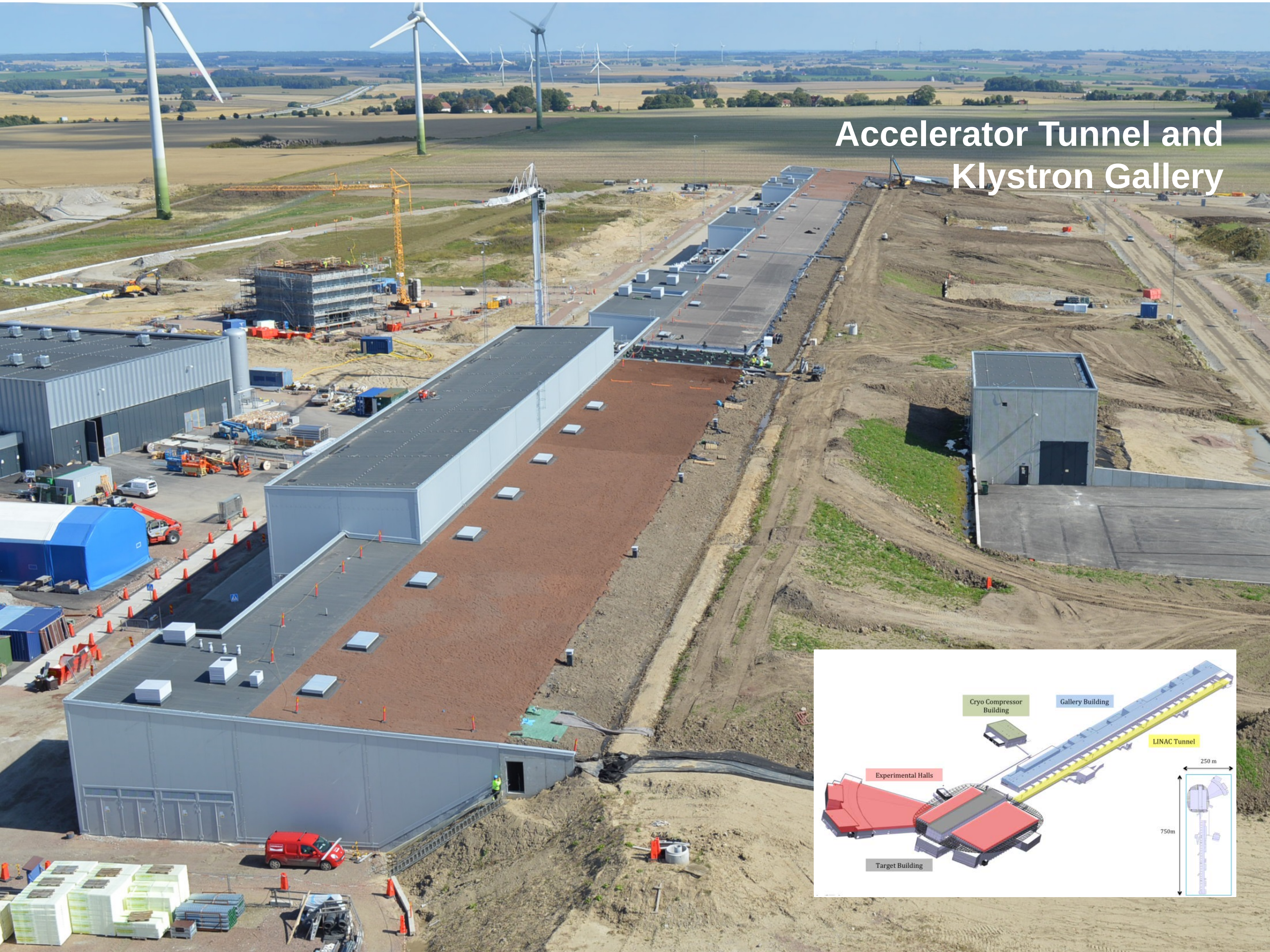
2023
Start of user program

2025
Construction complete

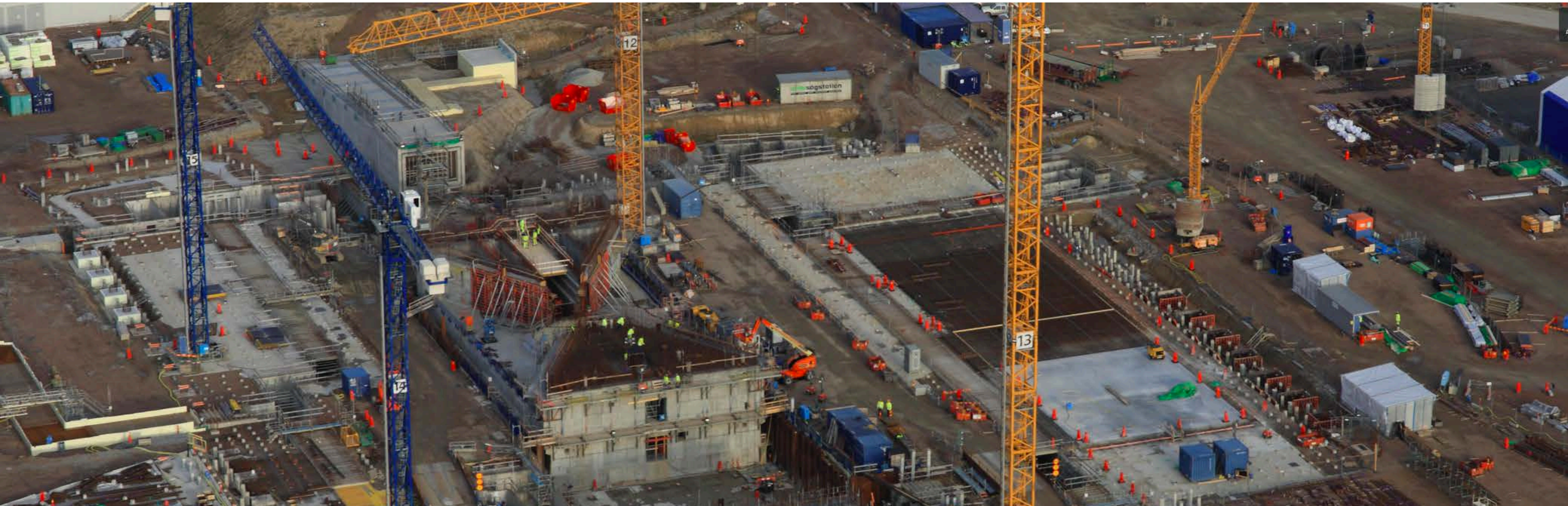
30 years !

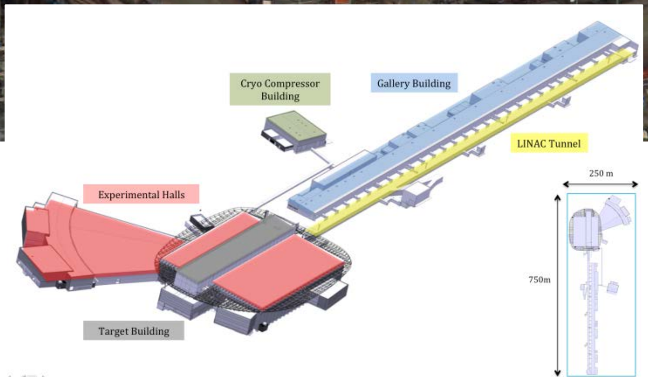

EUROPEAN
SPALLATION
SOURCE
April 2017
Primary Substation
Distribution Substation
Central Utility Building
Exp. Hall E01
Cryo Compressor Building
Klystron Gallery
Front End Building
Active Cells
Target Monolith
High Energy Loading Bay
Cryo Compressor Building
Gallery Building
LINAC Tunnel
Experimental Halls
Target Building
250 m
750m

Accelerator Tunnel and Klystron Gallery



Target Buildings

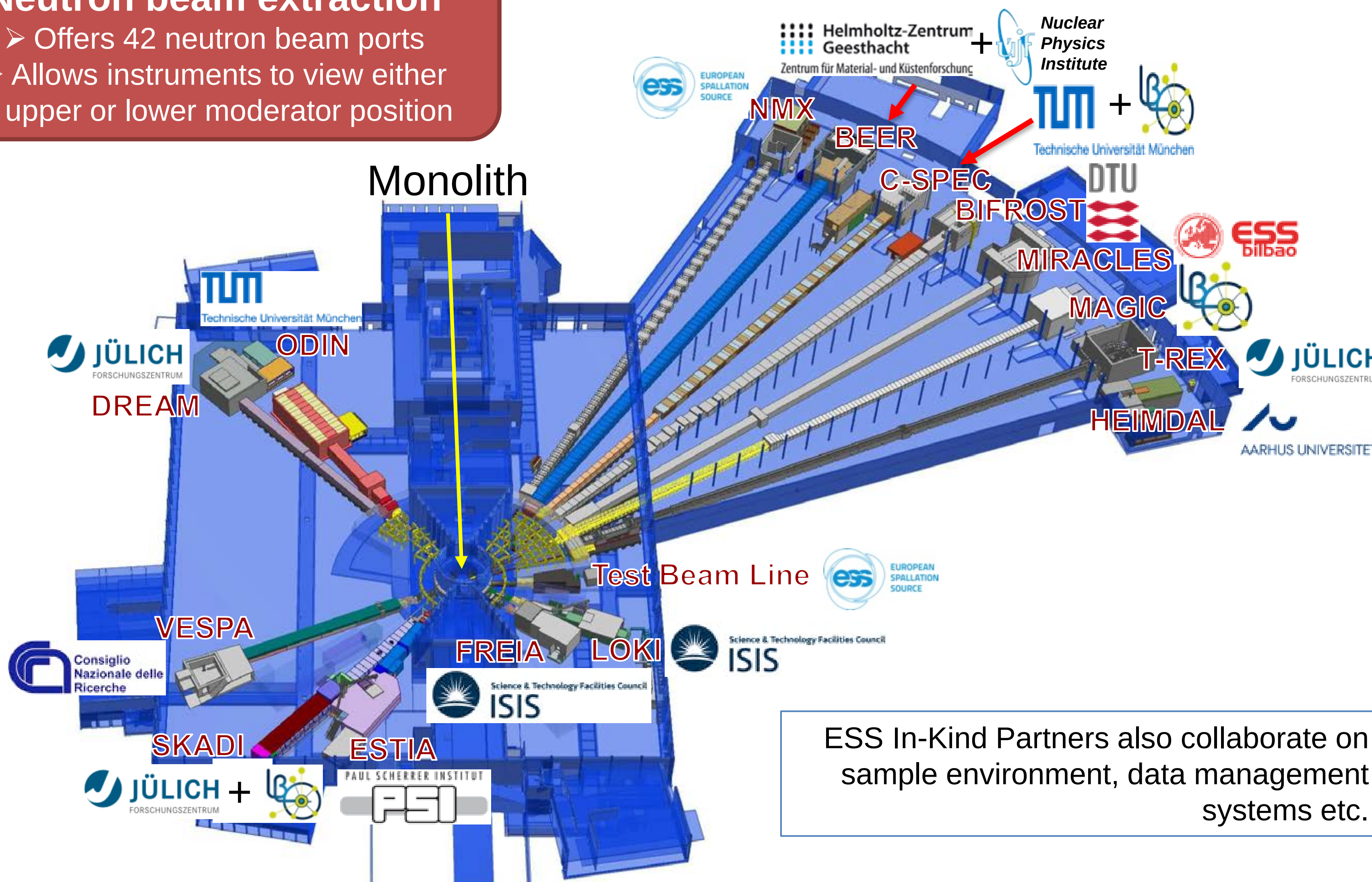





Experiment Hall
December 2017
Cryo Compressor Building
Gallery Building
LINAC Tunnel
Experimental Halls
Target Building
250 m
750m

First 15 Neutron Science Instruments

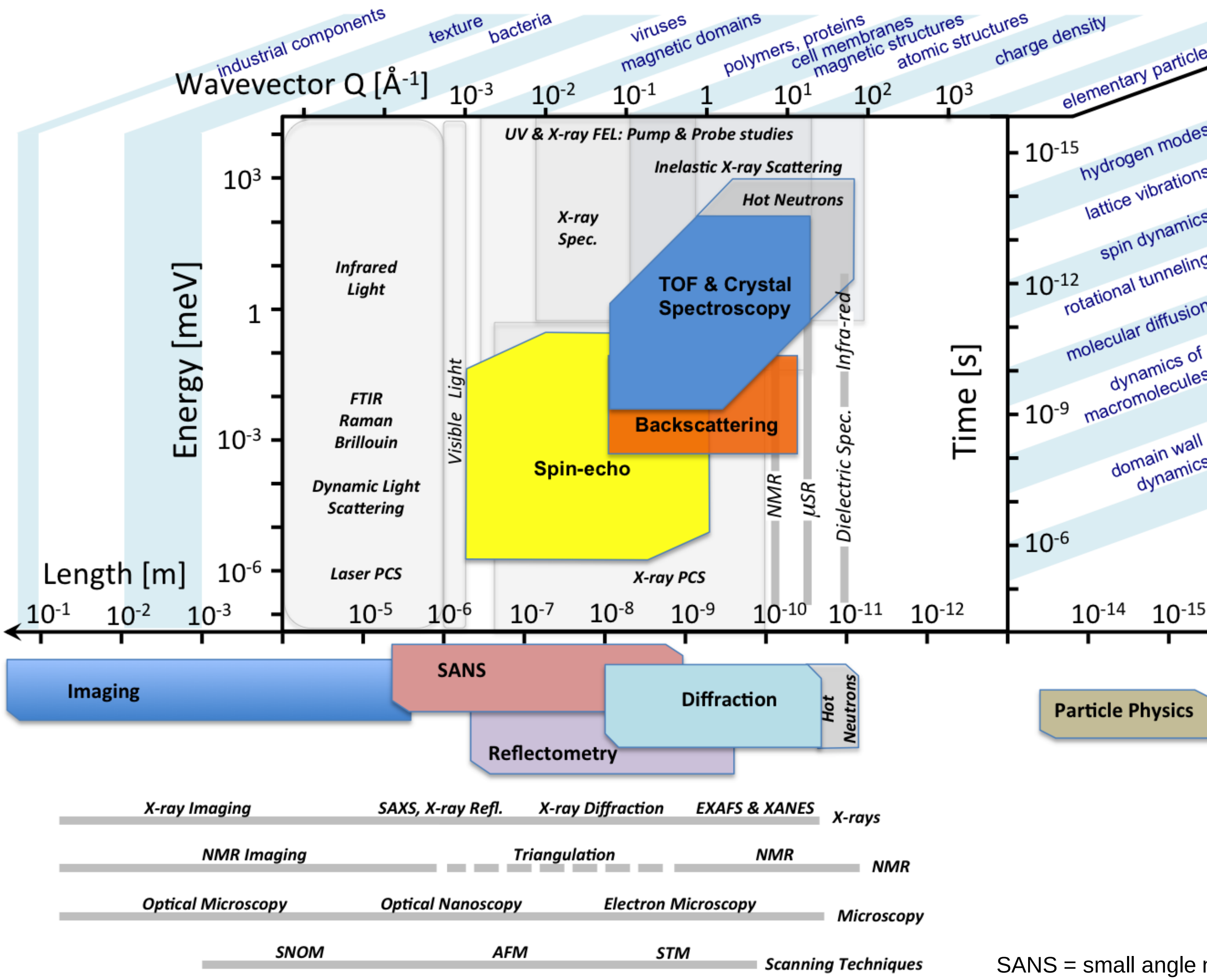
Neutron beam extraction
- Offers 42 neutron beam ports
- Allows instruments to view either upper or lower moderator position



ESS In-Kind Partners also collaborate on sample environment, data management systems etc.

ESS Instrument Layout (September 2017)

Length and Energy Scales



SANS = small angle neutron scattering

15 Instruments in project scope

First 8 to be in user operation by 2023

EUROPEAN SPALLATION SOURCE

Large-Scale Structures

- ODIN imaging
- SKADI GP-SANS
- LOKI Broadband SANS
- Surface Scattering
- FREIA Hor. Refl.
- ESTIA Ver. Refl.

Diffraction

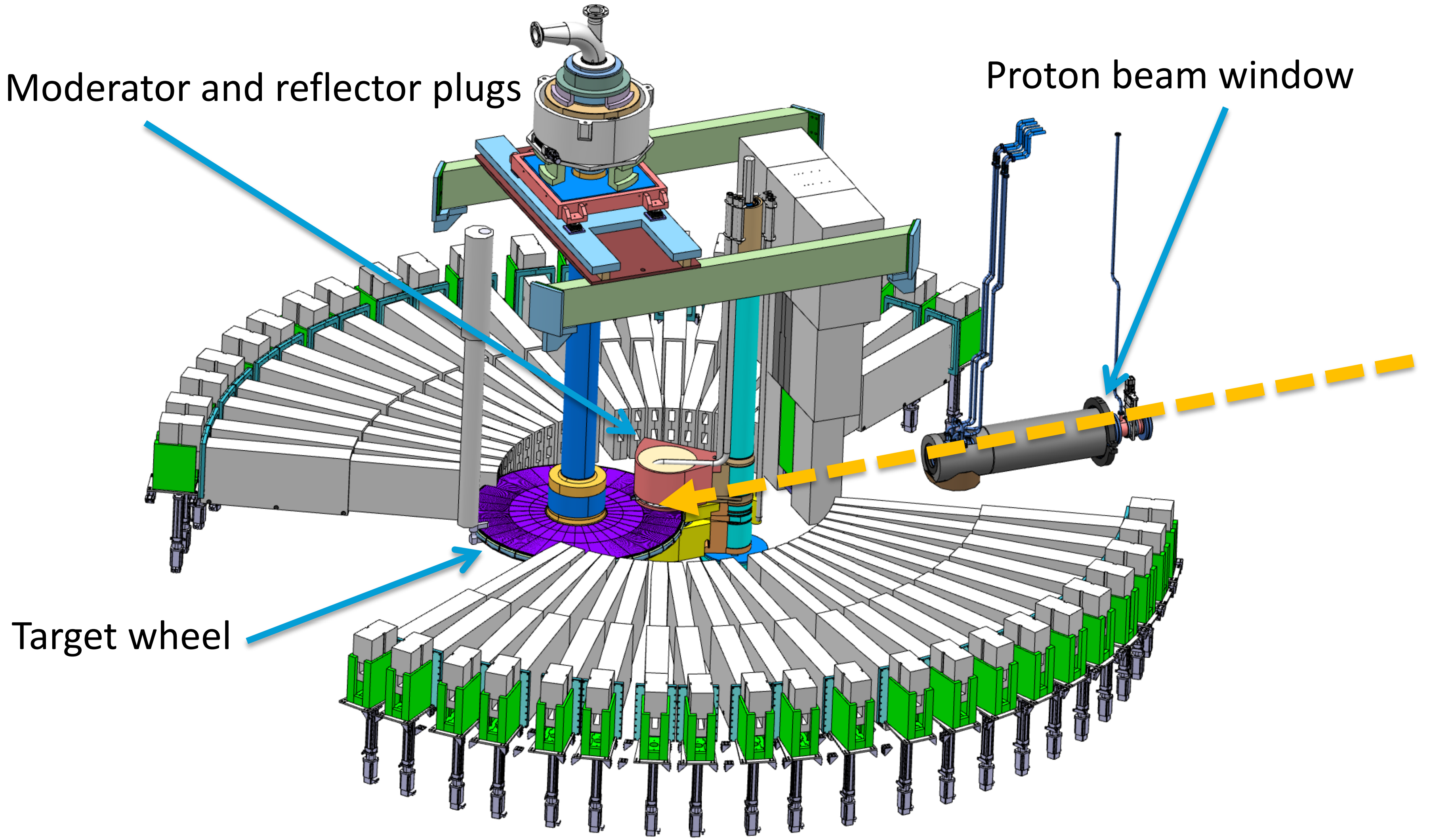
- HEIMDAL Pow. Diffr.
- DREAM Pow. Diffr.
- Monochromatic Powder Diffractometer
- BEER Eng. Diffr.
- Extreme Conditions Diffractometer
- MAGIC Magn. Diffr.
- NMX Macromol. Diffr.

Spectroscopy

- CSPEC ColdChopSp
- VOR BroadbandSp
- T-REX ThChopSpec
- BIFROST Xana Spec
- VESPA Vibr.Spec.
- MIRACLES BckScatt
- 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

The ESS Target



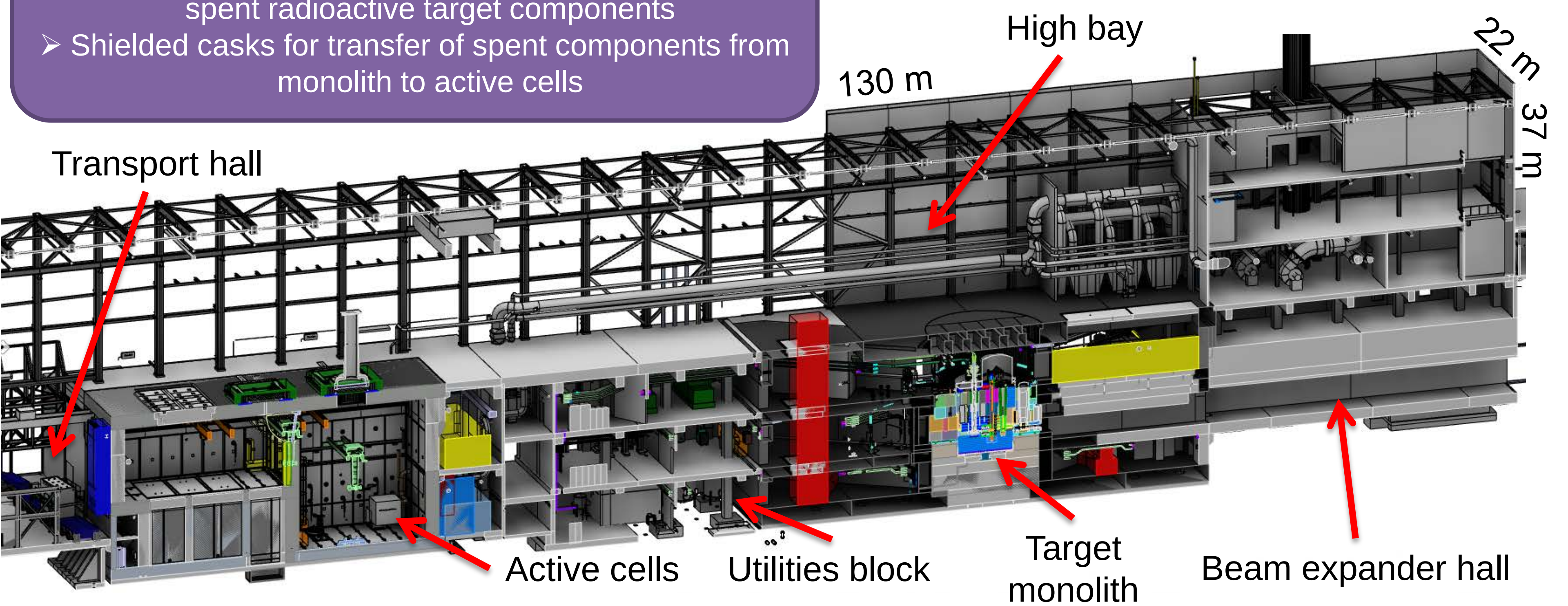
The Target Building

Utilities and cooling plant

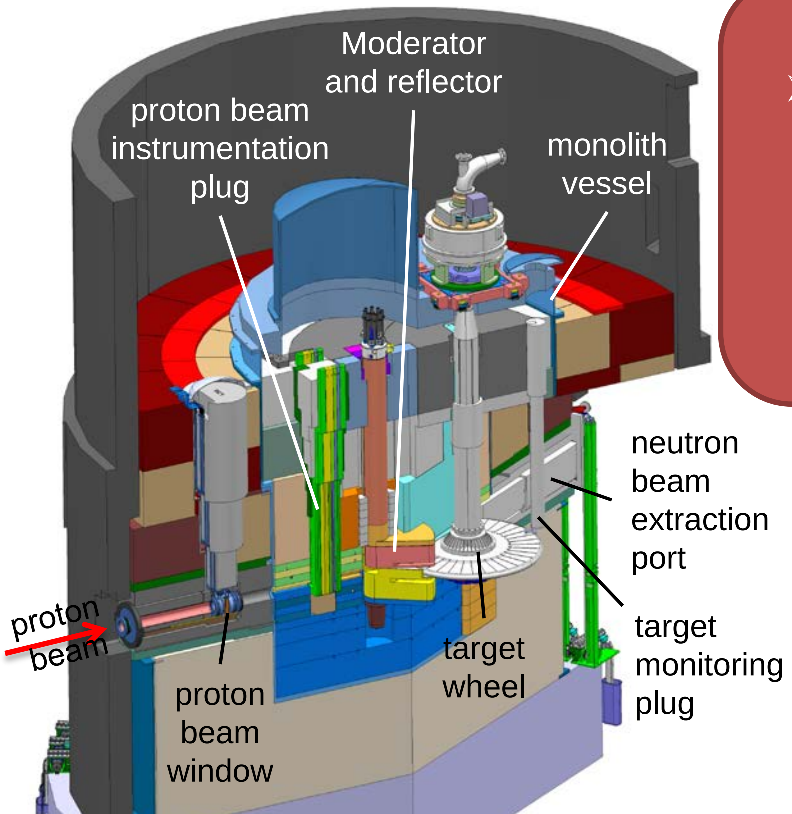
- Helium cooling of target wheel
- Water cooling of moderators, plugs and shielding
- Intermediate water loops between primary circuits and conventional facility utilities
- Helium cryoplant for refrigeration of cold moderator system
- Nuclear grade HVAC system

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



The Target Station



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

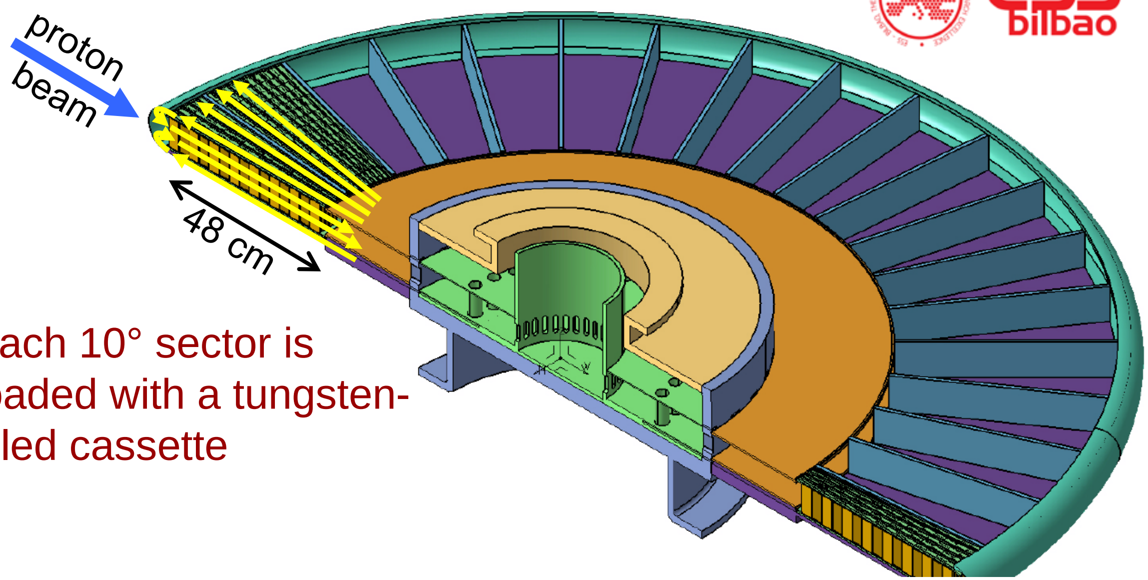
Moderators

- 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

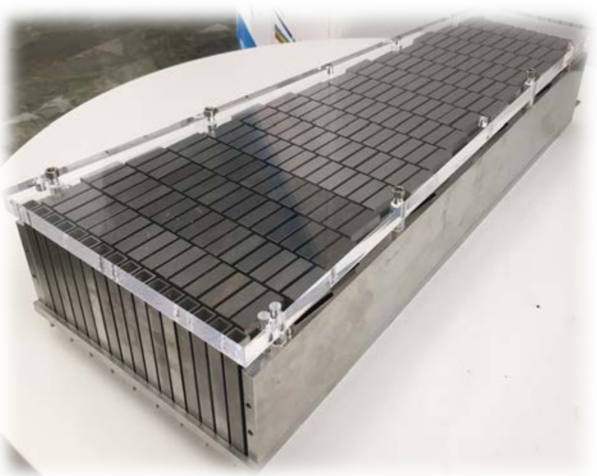
The Target Wheel



Each 10° sector is loaded with a tungsten-filled cassette

Tungsten bricks

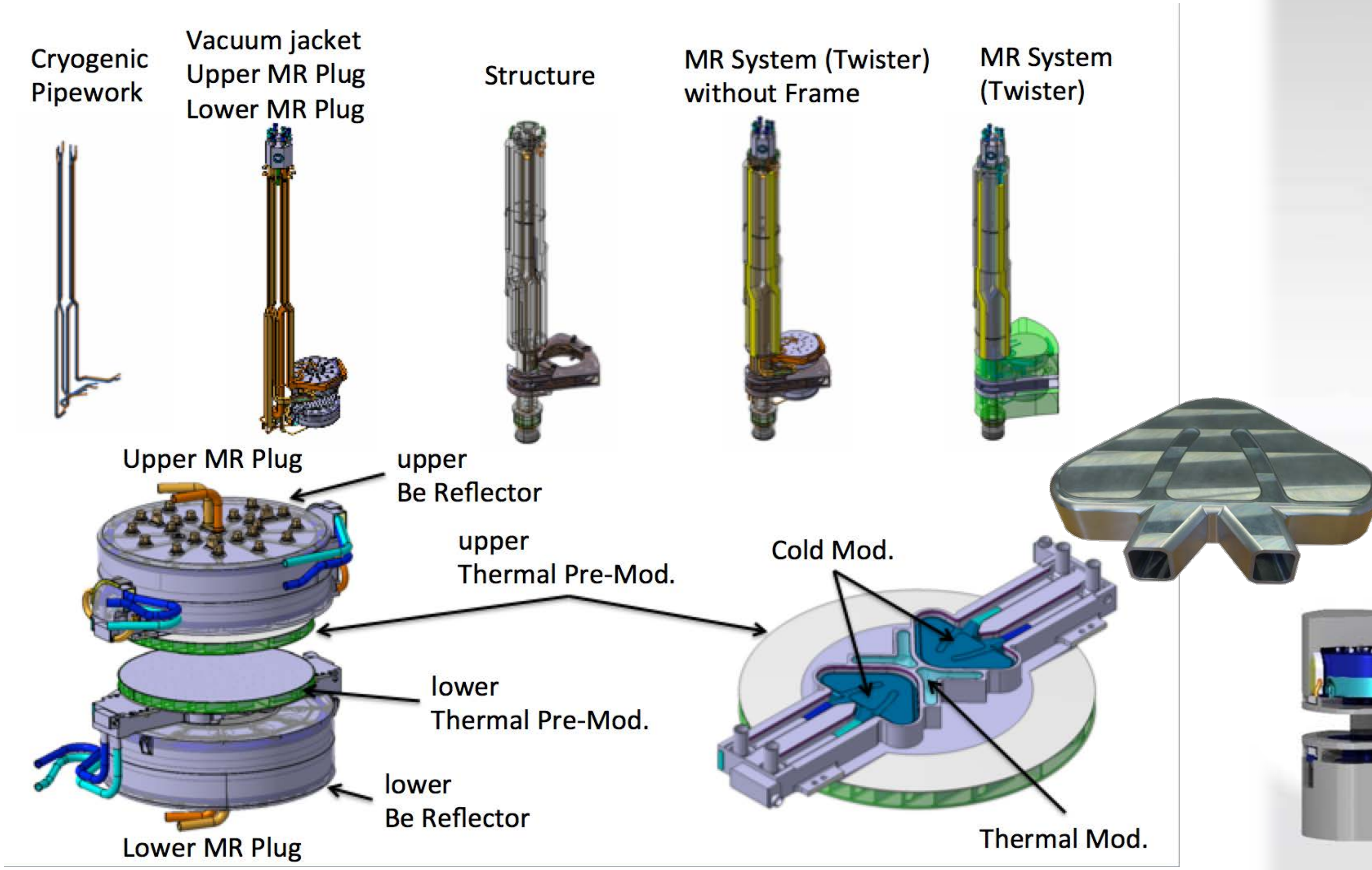
- Tungsten depth in proton beam direction is 45 cm
- The range of a 2-GeV proton in tungsten is 74 cm
- Brick dimensions: 10 W x 30 D x 80 H mm3
- 190 bricks per sector, 6840 bricks in total
- Helium flows
  - radially outward above and below the cassette,
  - reverses direction at the wheel rim,
  - and returns through the tungsten

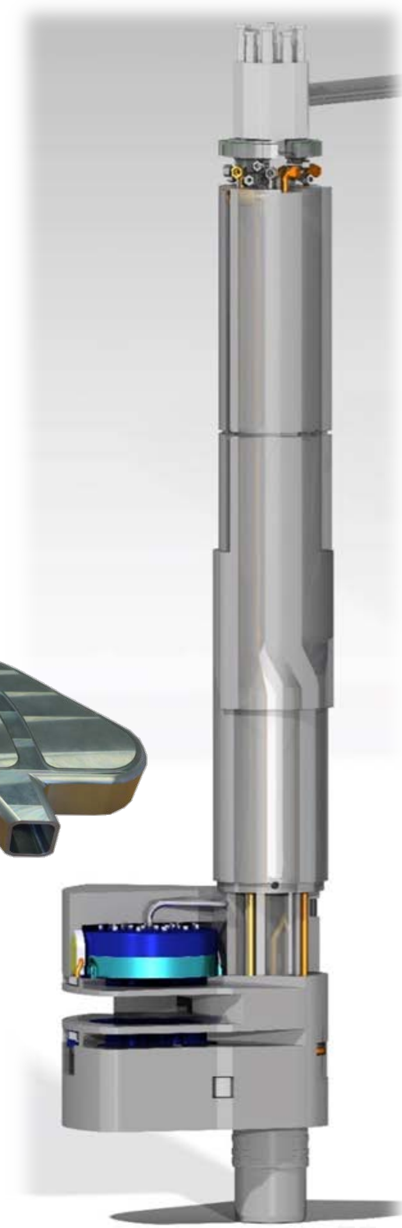


Cassette

Moderator and Reflector Systems

- Moderate neutrons to low energies, thermal and cold,
  - useful for the neutron scattering
- Cooling the radiation heat in liquids and solid metal bodies

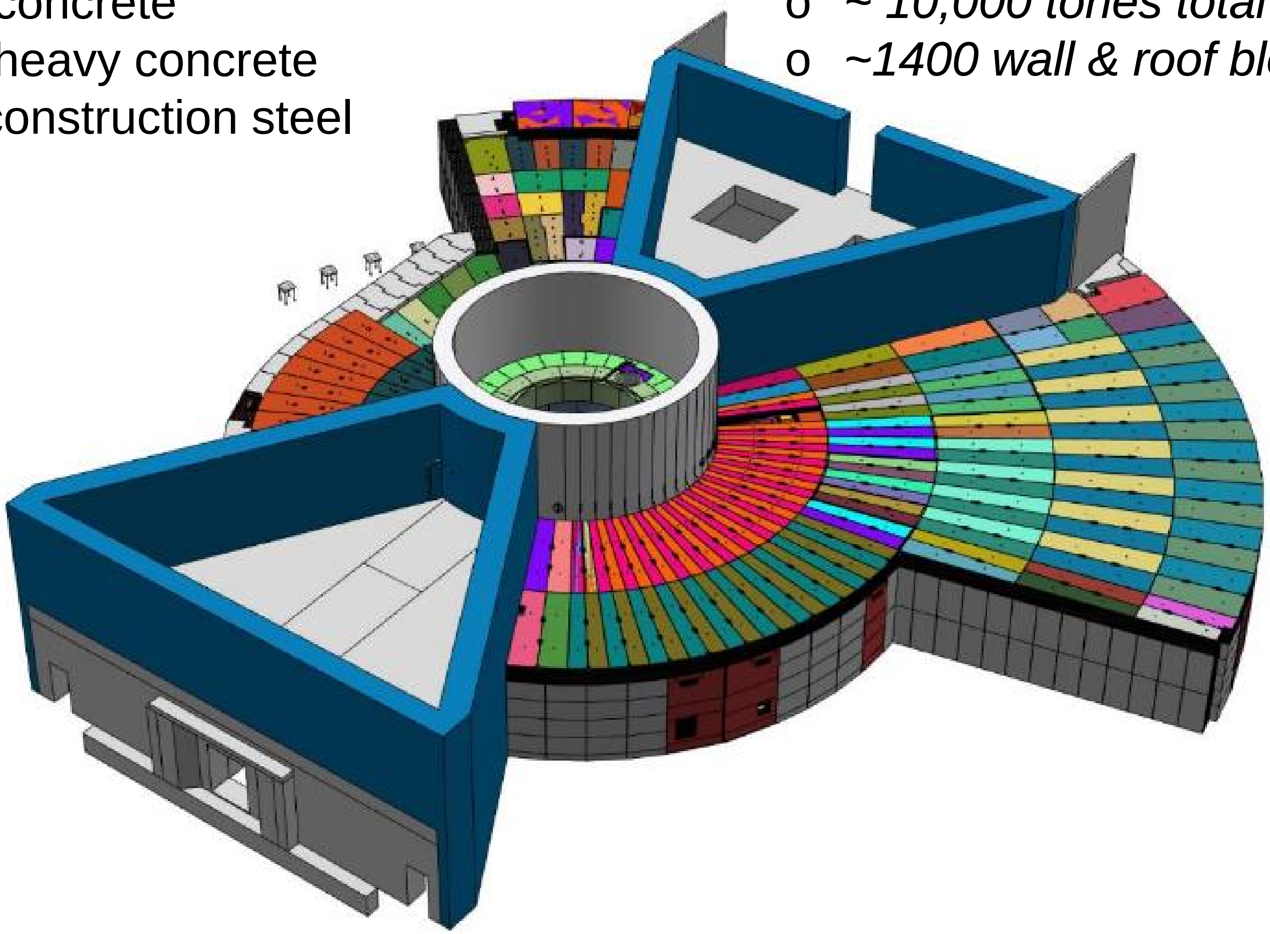




The Bunker Design

- ~ 7000t of steel
- ~ 300t of Borated HDPE
- ~ 750t of virgin HDPE/LDPE
- ~ 620t of concrete
- ~ 970t of heavy concrete
- ~200t of construction steel

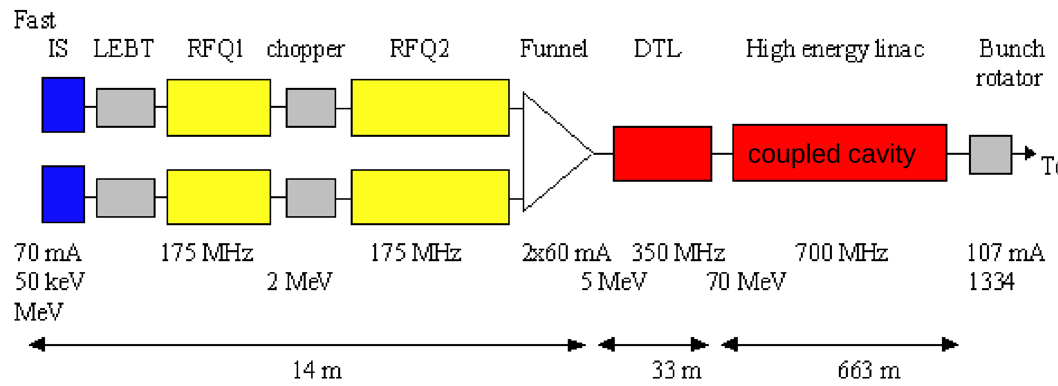
- *Each bunker side measures approx. 40m long x 26m wide x 5m high*
- *~ 10,000 tones total mass*
- *~1400 wall & roof blocks*

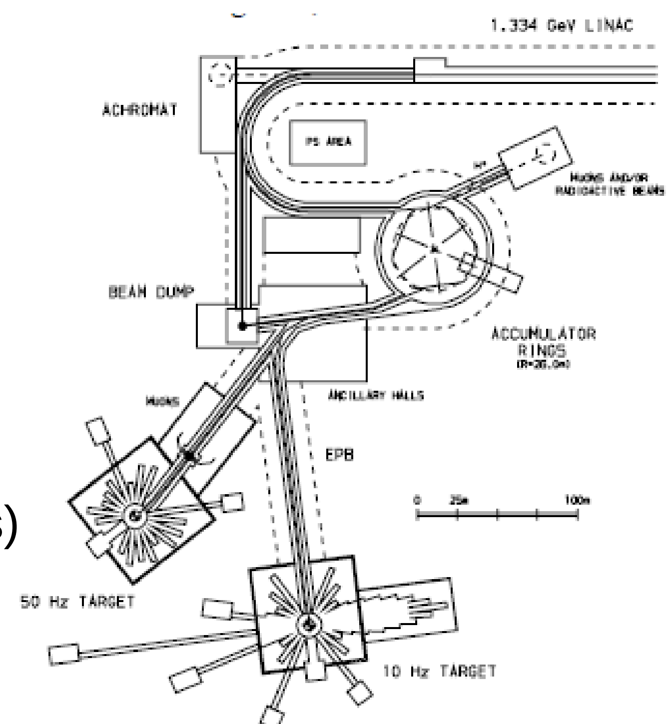


1996 ESS Design: Feasibility Study

EUROPEAN SPALLATION SOURCE
UPPSALA UNIVERSITET

- 5 MW beam power
- 1.334 GeV H^- Linac
  - synchrotron option discarded
    - to complex for E <3GeV
  - normal conducting linac
    - SC linac under consideration
  - 6% duty cycle
  - 107 mA, 0.6 ms pulse
  - 2 x 70 mA sources
    - not yet achieved at time of proposal

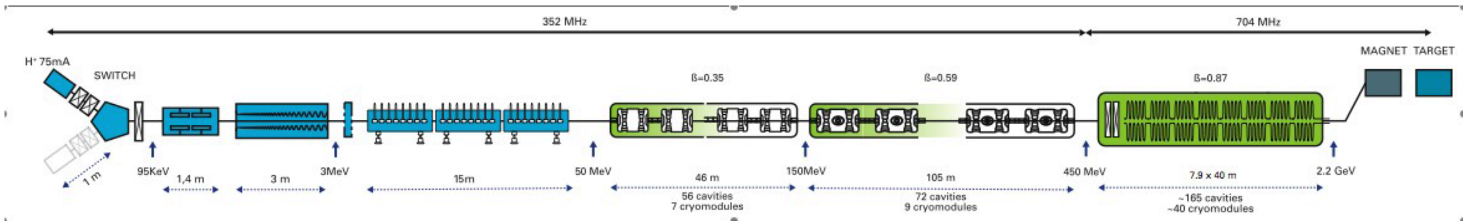




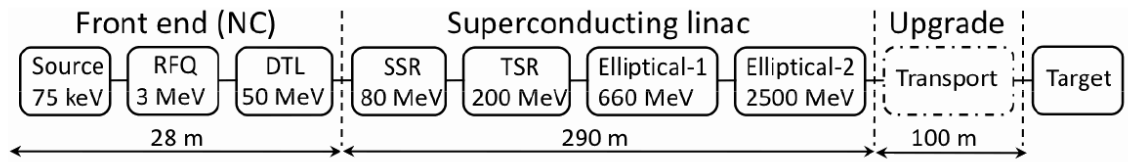
- 2 accumulator rings → 2 targets
  - 1 μs pulse compression (from 2 injection pulses)
  - 10 Hz and 50 Hz target operation

PAC97 - 9W013: Status of the European Spallation Source Design Study
ESS A Next Generation Neutron Source for Europe, Volume 3, The ESS Feasibility Study, March 1997.

2009 ESS Accelerator Design Update



- SC linac option (5 MW)
  - 1 GeV, 150 mA, 16⅔ Hz



- Simplify the linac design and increase reliability
  - proton pulse length ≥ 1 μs, energy ≥ 1 GeV (and ≤ 3 GeV)
  - synergies with CERN Linac4 + SPL development work
  - decrease the current to 75 mA
    - single source
    - can increase cavity gradient to 15 MV/m
  - increase the energy from 1 to 2.2 GeV
  - increase the repetition rate to 20 Hz
  - decrease pulse length to 1.5 ms from 2 ms

System	T [K]	Energy [MeV]	Freq. [MHz]	β Geom.	Length [m]
Source	300	0.075	–	–	2.5
LEBT	300	–	–	–	1.1
RFQ	300	3	352.2	–	4.0
MEBT	300	–	352.2	–	1.1
DTL	300	50	352.2	–	19.2
SSR	4	80	352.2	0.35	23.3
TSR	4	200	352.2	0.50	48.8
Ellipt-1	2	660	704.4	0.65	61.7
Ellipt-2	2	2500	704.4	0.92	154.0

PAC09 - TU6PFP083: Conceptual Design of the ESS-Scandinavia

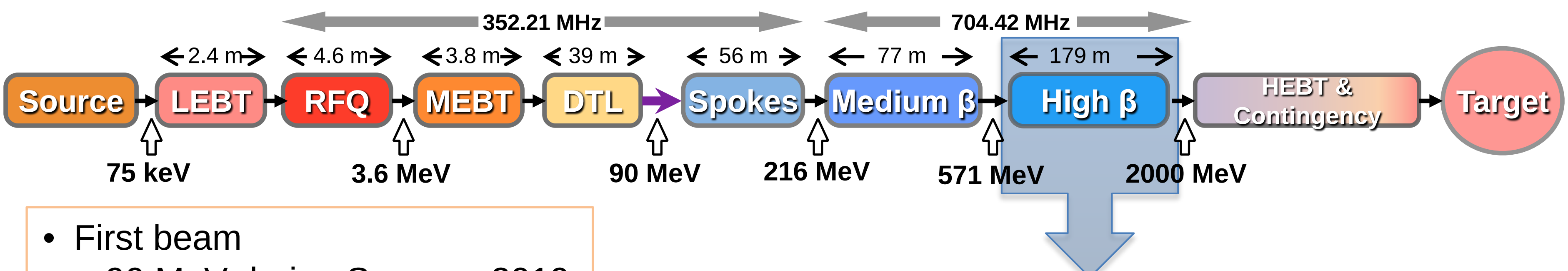
2013 ESS Accelerator Design

Design Drivers:

- High Average Beam Power
  - 5 MW
- High Peak Beam Power
  - 125 MW
- High Availability

Key parameters:

- 2.86 ms pulses
- 2 GeV
- 62.5 mA peak
- 14 Hz
- Protons (H+)
- Low losses
- Minimize energy use
- Flexible design for mitigation and future upgrades

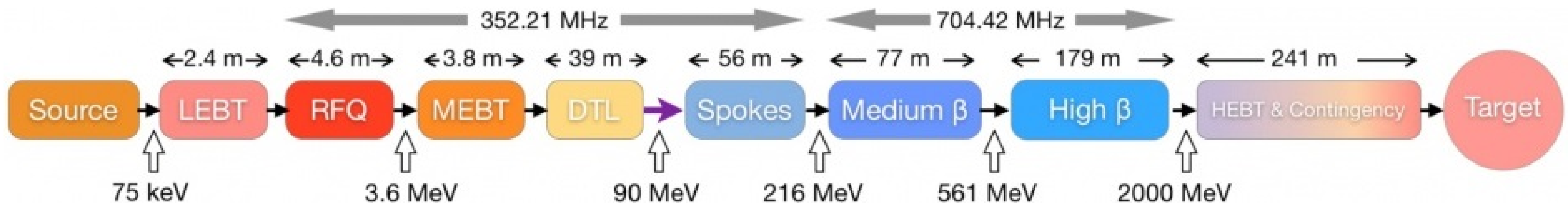


- First beam
  - 90 MeV during Summer 2019
  - 571 MeV during Fall 2020
- 5 MW capacity after 2025

RF sources for HB part are scope contingency for accelerator

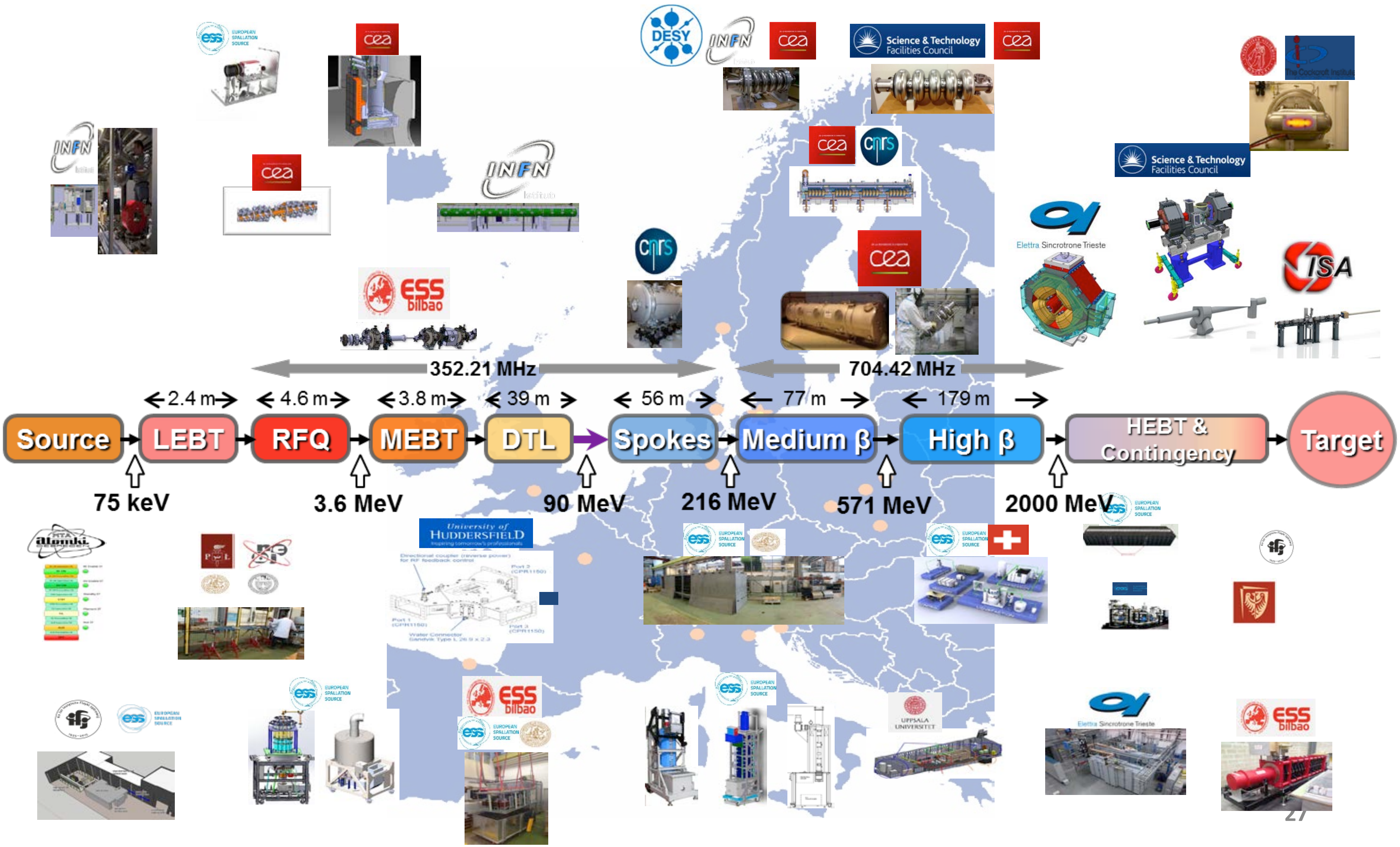
IPAC13 - THPWO072: Design Options of the ESS Linac

The ESS Accelerator



	Length [m]	No. Cavities	β	No. Magnets	No. Steerers	No. Sections	Power [kW]
LEBT	2.38			2 Solenoid	2 x 2	1	
RFQ	4.6	1				1	1600
MEBT	3.83	3		11 Quad	10 x 2	1	15
DTL	38.9	5		PM-Quads	15 x 2	5	2200
LEBT + Spoke	55.9	26	0.50	26 Quad	26	13	330
Medium Beta	76.7	36	0.67	18 Quad	18	9	870
High Beta	178.9	84	0.86	42 Quad	42	21	1100
HEBT	130.4		(0.86)	32 Quad	32	15	
DogLeg	66.2			12 Quad + 2D	14		
A2T	46.4			6 Quad + 8 Raster			
	604.21	**155**					

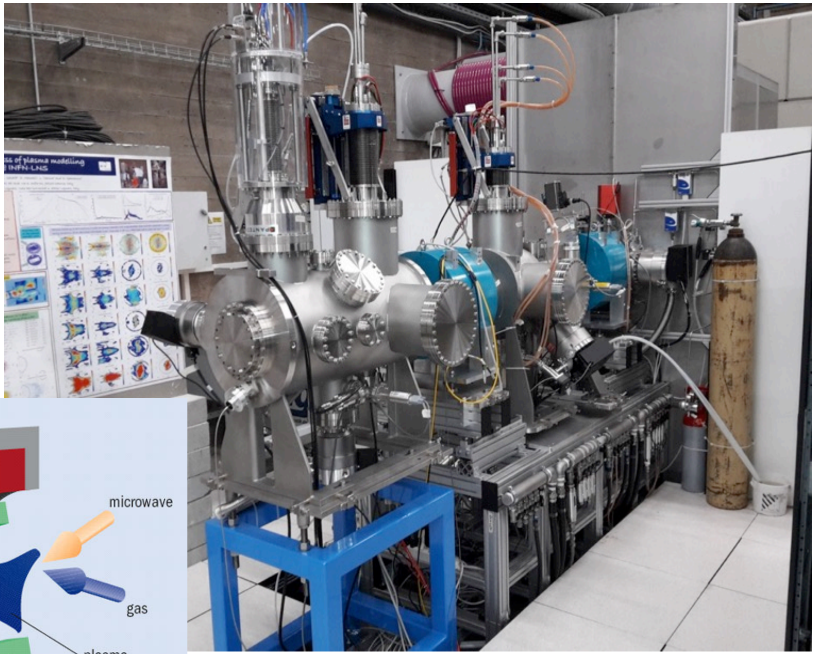
ESS Accelerator Collaboration

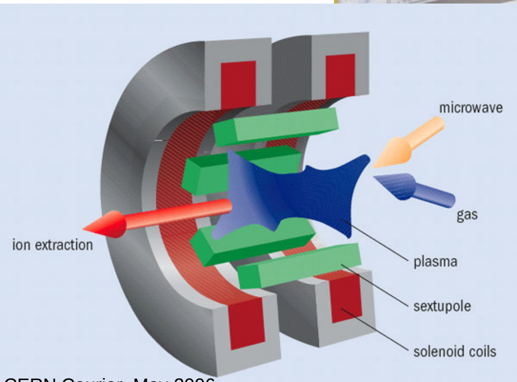


Ion Source & Low Energy Beam Transport

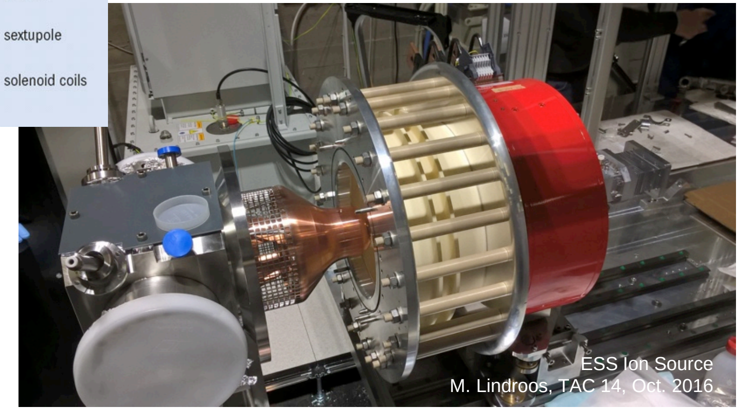
- Nominal performance achieved in INFN-Catania.
- Start installation in January 2018.

Parameters	Value
Nominal proton peak current	74 mA
Proton fraction	> 80 %
Stable operation current range	60-74 mA
Current stability(over 50us period)	± 2 %
Pulse to pulse variation	± 3.5 %
Beam Energy	75 keV (±0.01)
Distance between pulses	1 Hz< f <14 Hz
Restart after vacuum break Restart after cold start	<32 h <16 h



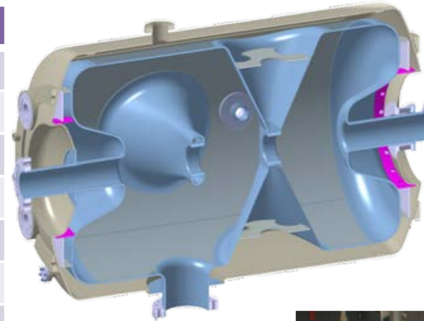


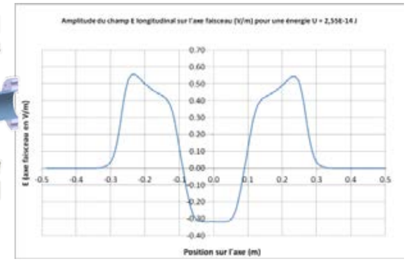
CERN Courier, May 2006

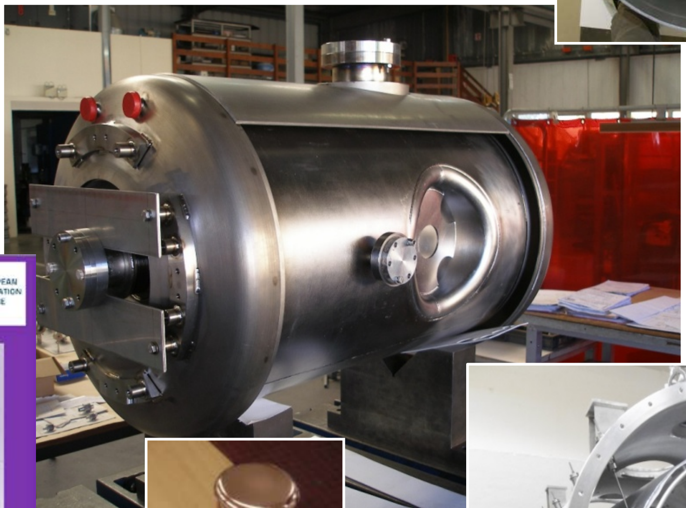


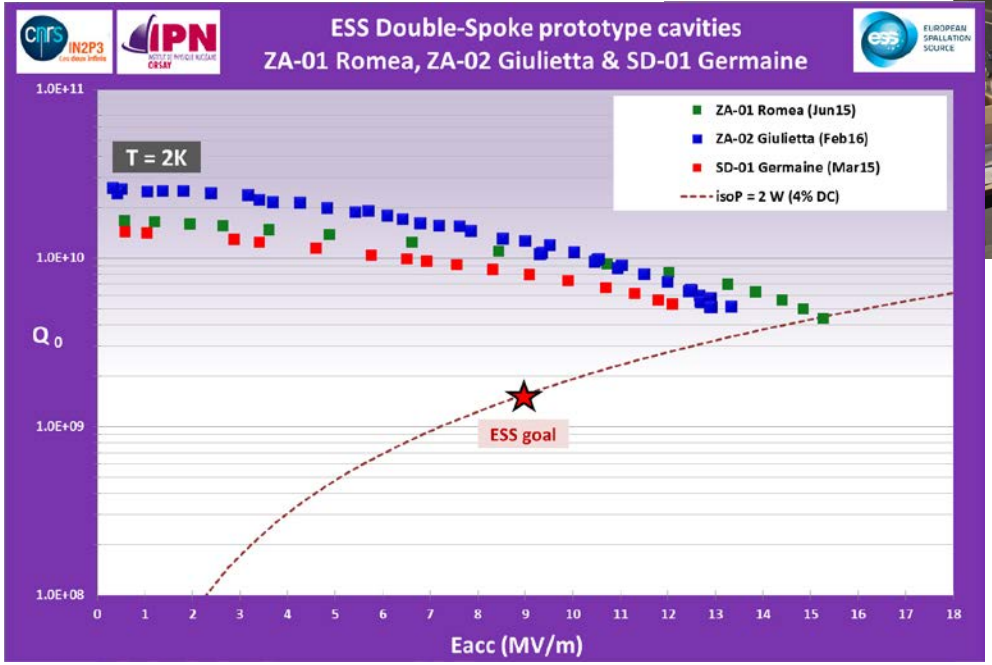
Double Spoke Resonators

DOUBLE-SPOKE CAVITY	
Frequency [MHz]	352.21
Beta_optimum	0.50
Operating gradient [MV/m]	9.0 (8.8)
Temperature (K)	2
Bpk [mT]	61
Epk [MV/m]	38
G [Ohm]	133
r/Q [Ohm]	427
Lacc (=beta optimal x nb of gaps x λ /2) [m]	0.639
Bpk/Eacc [mT/MV/m]	6.8
Epk/Eacc	4.3
P max [kW]	335



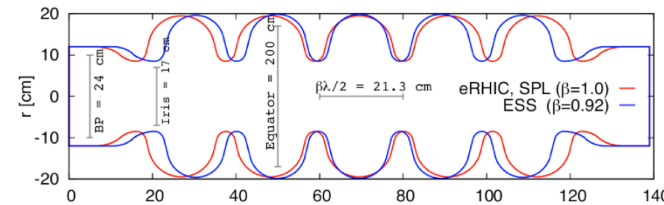


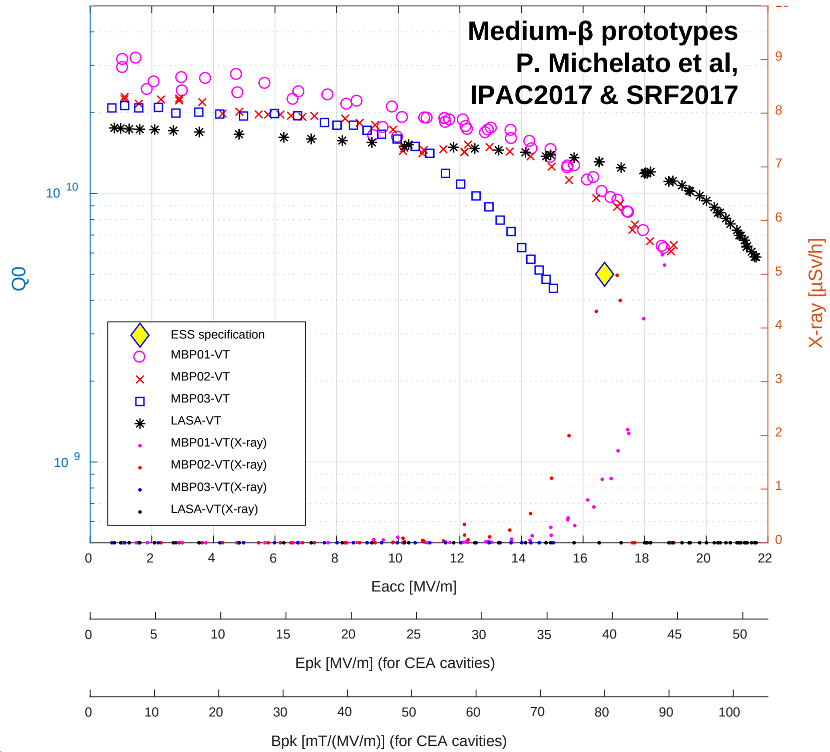




Medium & High Beta Elliptical Cavities

	MEDIUM-β	HIGH-β
β	0.67	0.86
# cells/cavity	6	5
# CM	9	21
Cav. /CM	4	4
# Cav.	36	84
CM L [m]	6.584	6.584
Sector L [m]	77	179

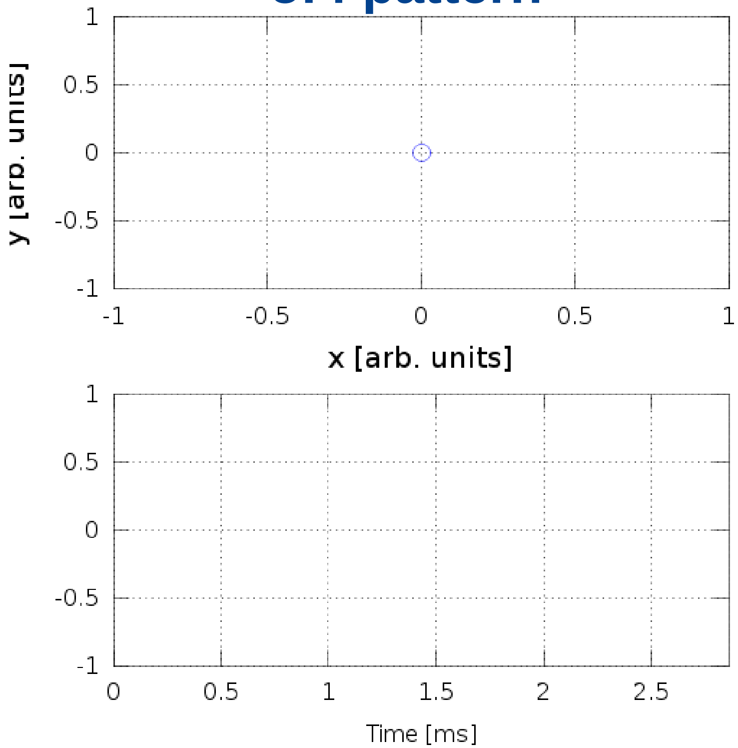


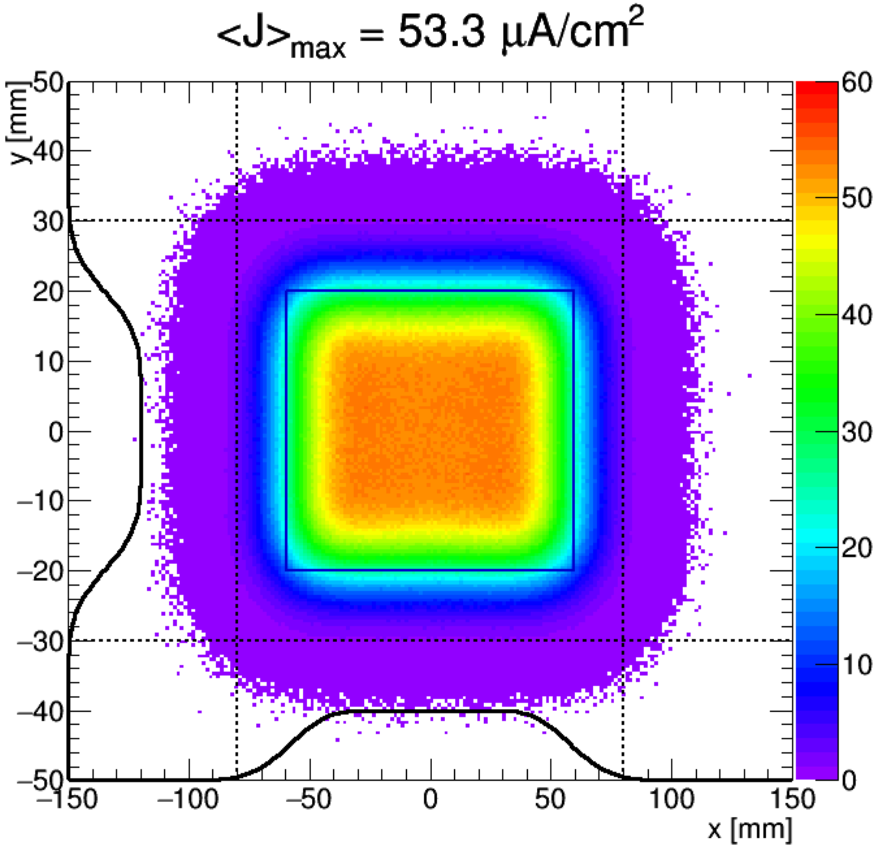


Beam Raster Scanning on Target

- Raster system sweeping beam in 2D pattern @ target
- 8 colinear magnets, individually powered
- Crosshatch pattern (f_x/f_y, ϕ_{xy}, a_x, a_y) within 2.86 ms pulse

5:4 pattern





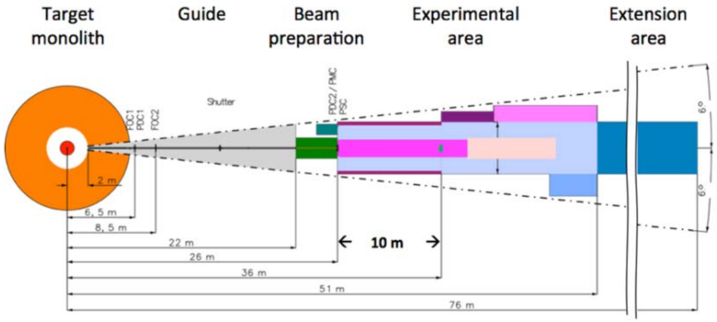
Overview of the ESS organization, time schedule and ideas for the future

OUTLOOK

Fundamental Physics at ESS

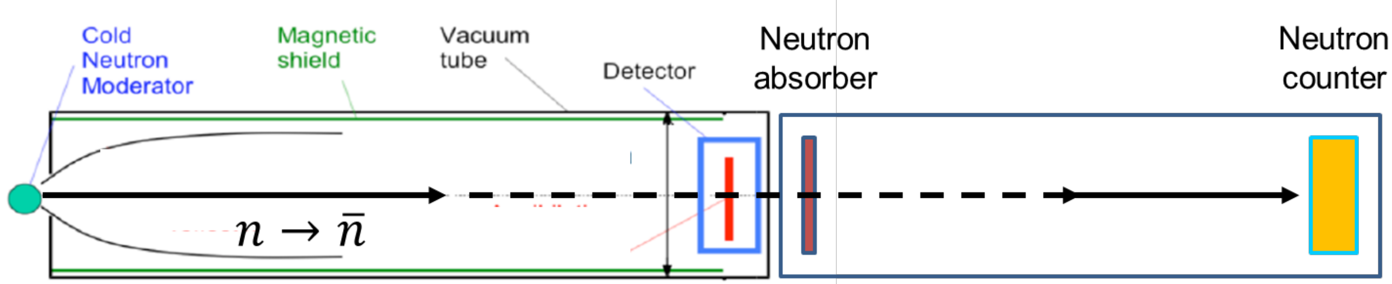
Four proposals

- **ANNI**
  – precise measurements of
    - neutron beta decay,
    - hadronic weak interaction (input to theory),
    - electromagnetic properties: dipole moment, CP-violation.
- **UCN**
  – ultra-cold neutron source
- **NNbar/HiBEAM**
  – neutron-antineutron oscillations search
    - aims at least a factor of 1000 greater sensitivity to the oscillation probability than similar ILL experiment (after 3 years of operation)



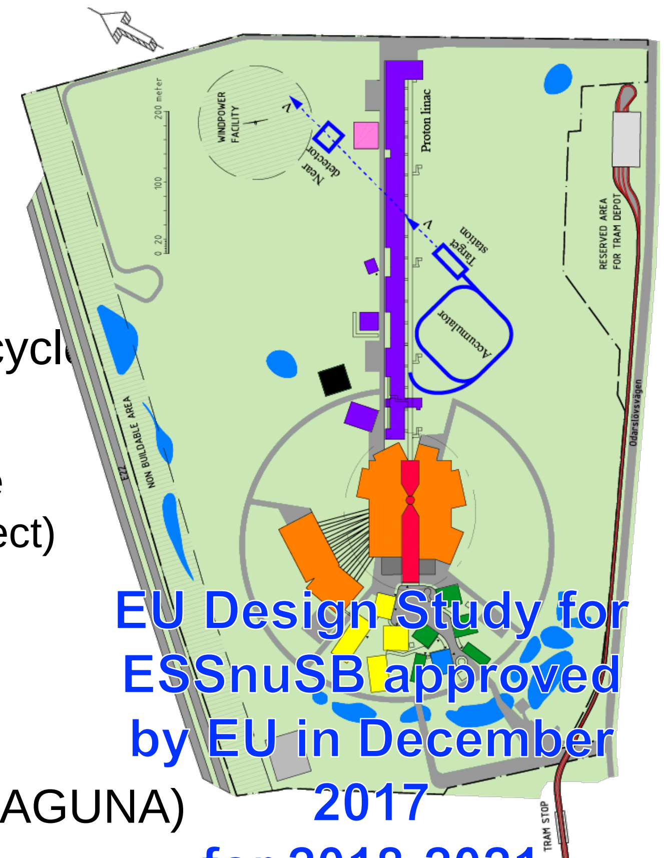
ANNI

HIBEAM

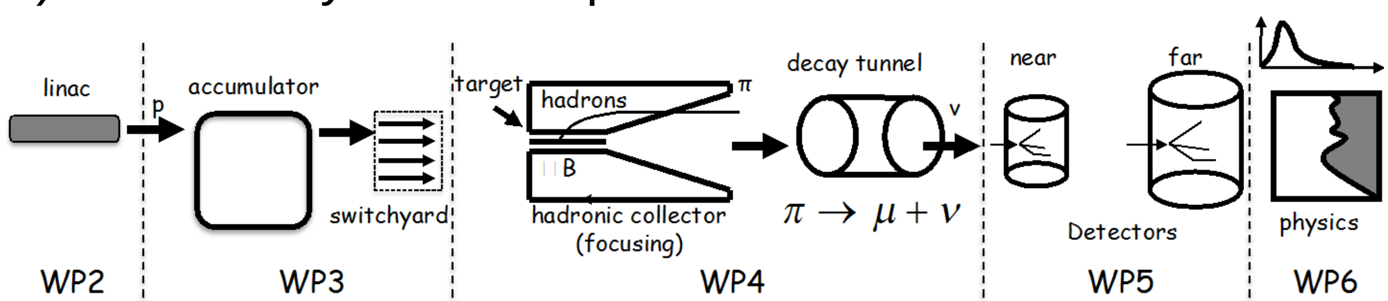


ESSnuSB Proposal for a Neutrino Super Beam

- Study neutrino oscillations (CP-violation)
  - neutron program must not be affected
  - if possible synergetic modifications.
- Linac modifications:
  - double rep. rate: 14 Hz → 28 Hz (4% to 8% duty cycle)
  - add accumulator ring (Circ~400 m)
    - to compress proton pulses to few μs, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - H- source (instead of protons)
    - space charge problems to be solved.
- ~300 MeV neutrinos.
  - target station (EUROν) & underground detector (LAGUNA)
- Short pulses (~μs) allow decay-at-rest experiments using the neutron target



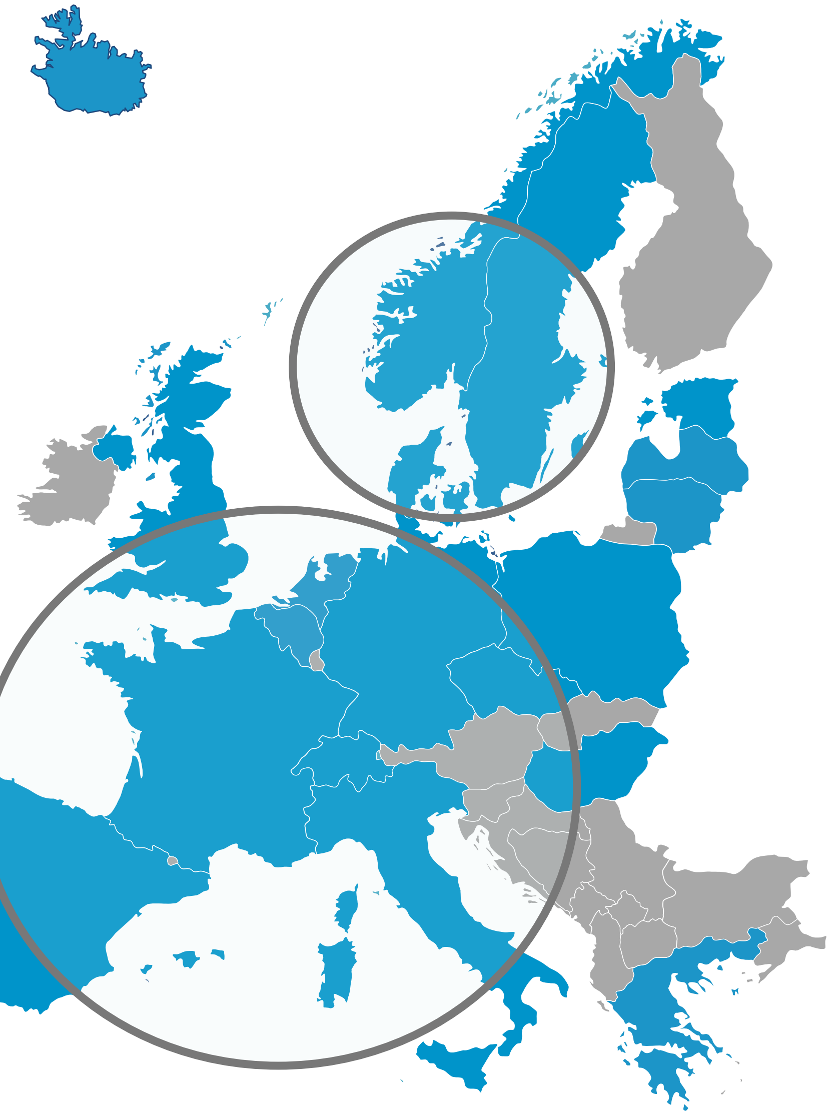
EU Design Study for ESSnuSB approved by EU in December 2017 for 2018-2021



Financing and In-kind Contributions

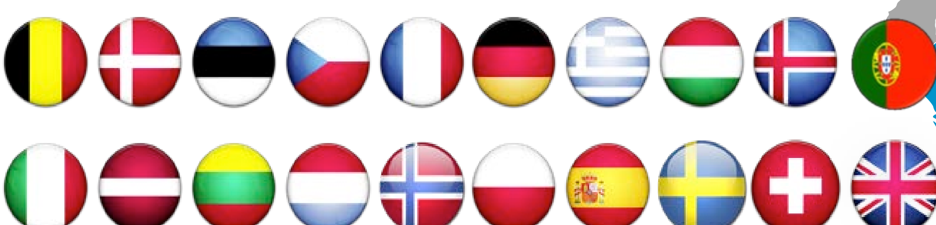
Host Countries of Sweden and Denmark

- Construction 47,5%
- Operations 15%
- **In-kind Deliverables ~ 3%**
- **Cash Investment ~ 97%**



Non Host Member Countries

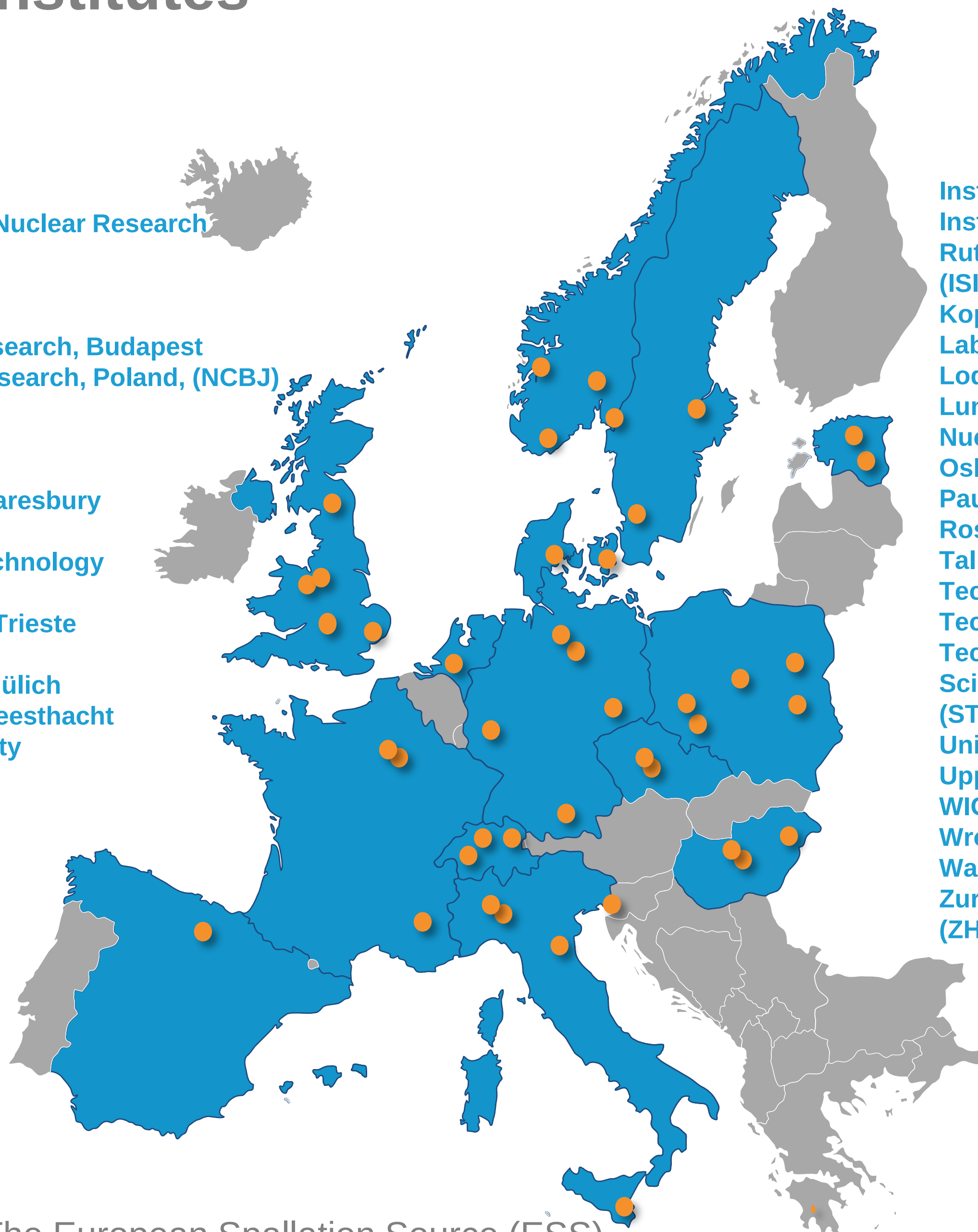
- Construction 52,5%
- Operations 85%
- **In-kind Deliverables ~ 70%**
- **Cash Investment ~ 30%**



Partner Institutes

EUROPEAN SPALLATION SOURCE

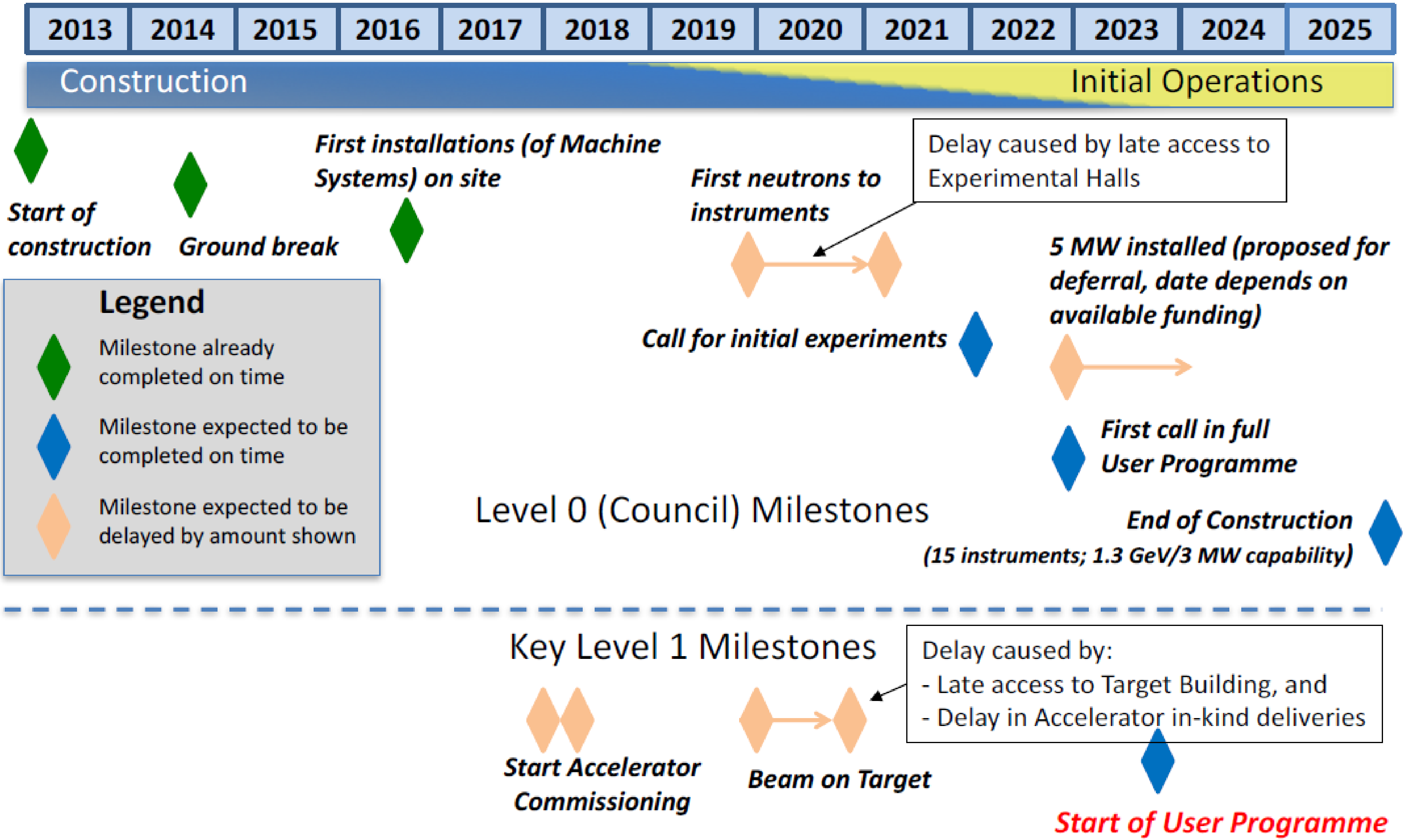
UPPSALA UNIVERSITET



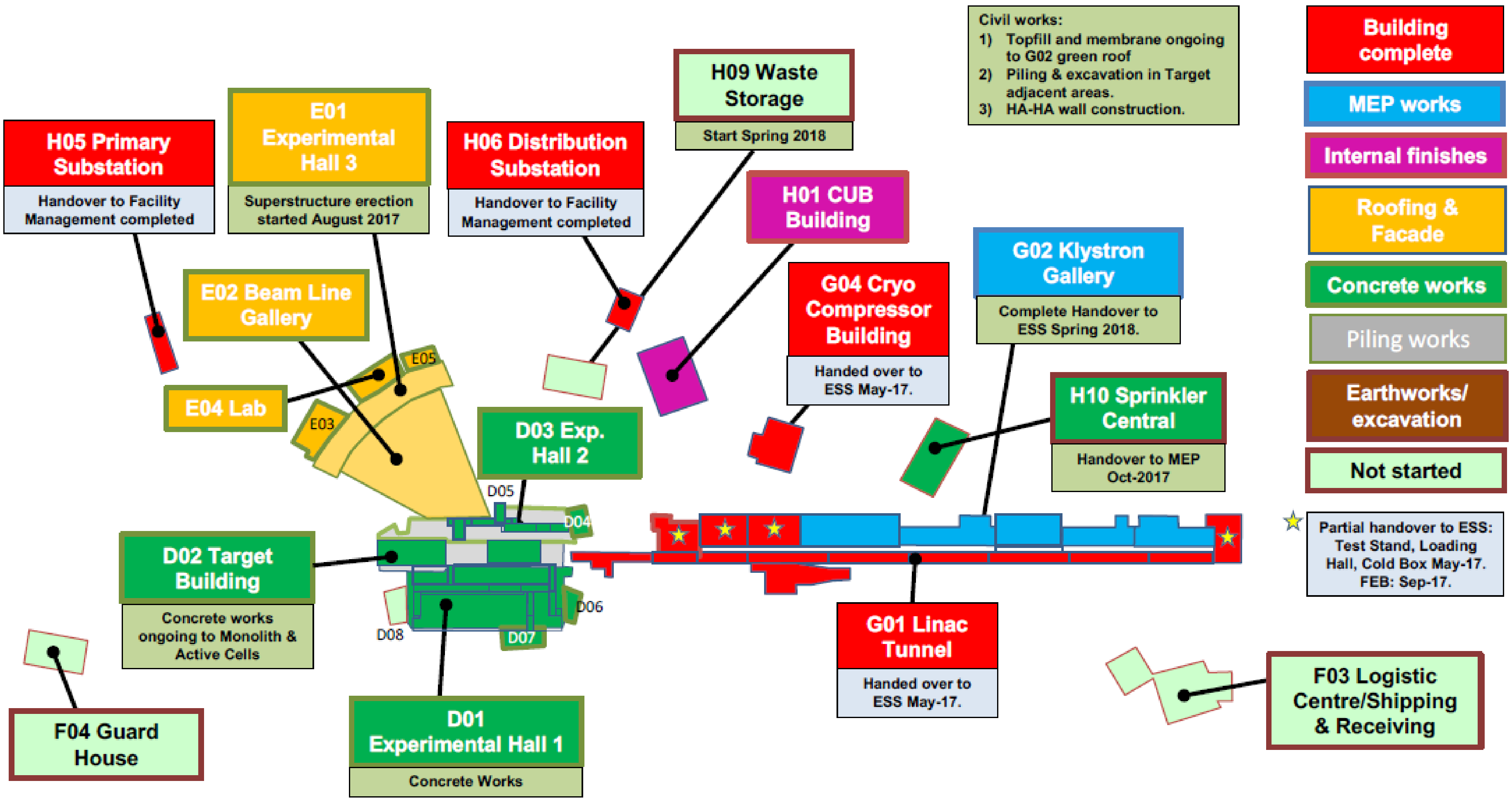
Aarhus University
Atomki - Institute for Nuclear Research
Agder University
Bergen University
CEA Saclay, Paris
Centre for Energy Research, Budapest
Centre for Nuclear Research, Poland, (NCBJ)
CERN, Geneva
CNR, Rome
CNRS Orsay, Paris
Cockcroft Institute, Daresbury
DESY, Hamburg
Delft University of Technology
Edinburgh University
Elettra – Sincrotrone Trieste
ESS Bilbao
Forschungszentrum Jülich
Helmholtz-Zentrum Geesthacht
Huddersfield Univesrity
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 Brilouin (LLB)
Lodz University of Technology
Lund University
Nuclear Physics Institute of the ASCR
Oslo University
Paul Sherrer Institute
Roskilde University
Tallinn Technical Univesrsity
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
Wroclaw Univesrity of technology
Warsaw University of Technology
Zurich University of Applied Sciences (ZHAW)

Updated Schedule (Oct. 2017)



Civil Construction Status (Dec. 2017)



From ESS Construction Project to full scope delivery:

EUROPEAN SPALLATION SOURCE

Construction Project Delivery (Construction completion Scenario 1):

- 15 Neutron Instruments (typically ~ 50 % of potential capability & count rate)
- 2 MW beam power (~ 40 % of potential beam performance)
  - **All Instruments expected to perform higher than current world best in class at 2 MW source power**
  - **Average gain factor of 20 over benchmark instruments**

Additional investment for full scope (Construction completion Scenario 2):

Capital Investment	Cost (M€)	Effect (Increase)	Gain factor
Upgrade to first 15 Neutron Instruments	62.4	count rate	2.4
		scientific capability	2.9
Build neutron instruments 16 – 22 (incl. bunker)	126.1	scientific capability	1.5
Upgrade accelerator to 5 MW	30	count rate	2.5

- Overall increase in scientific output by factor of ~ 10

Summary

- Construction is on track for the start of the user program in 2023 with 2 MW of beam power,
  - the 570 MeV accelerator will start late in 2020
  - instrument commissioning start in 2021

- All ESS staff will **move to the construction site in 2018**

Thanks to all colleagues for the material

- special thanks to Colin Carlile, Roland Garoby, Mats Lindroos