# High intensity proton drivers for neutron, neutrino and muon factories

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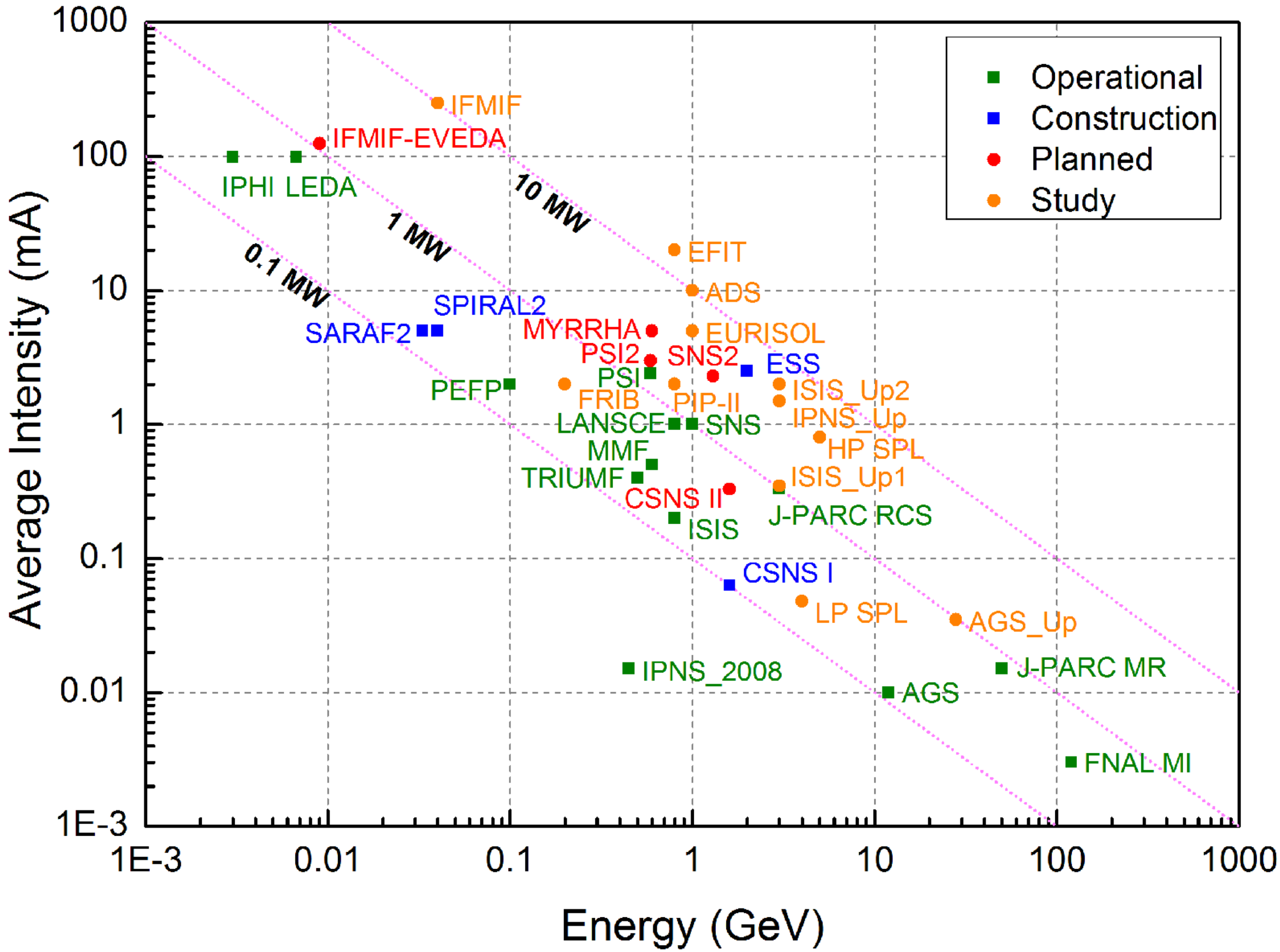
www.europeanspallationsource.se
September 2019

# The Big Picture:
# Global Demand for High Power Beams

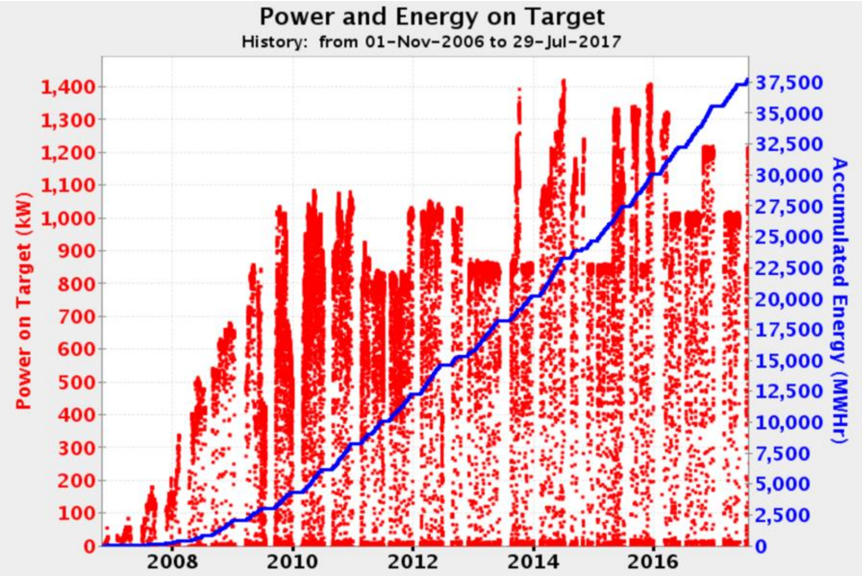
EUROPEAN SPALLATION SOURCE



# The Big Picture: Global Demand for High Power Beams

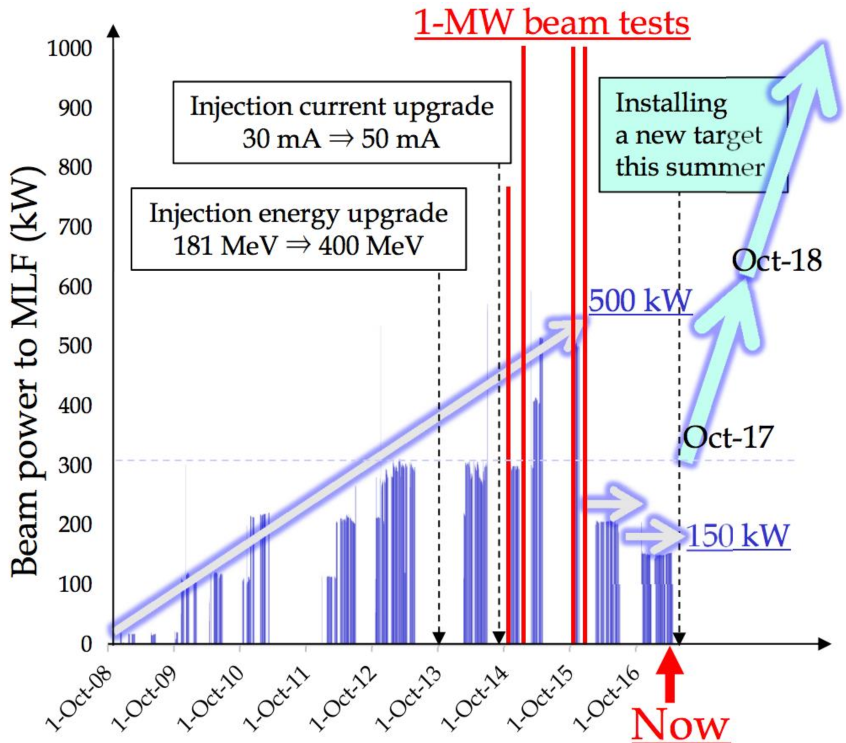
- **Spallation Neutron Sources**
  - ISIS (UK), SINQ@PSI (CH), SNS (USA), J-PARC (JP), LANSCE (USA), CSNS (CN), ESS (SE)
- **Radioactive Ion Beams (RIB)**
  - FAIR@GSI (DE), FRIB (USA), EURISOL (Europe), ISOLDE (CH), RIKEN (JP), SPIRAL2 (FR), SPES (IT), SARAF (IL), etc.
- **Material Irradiation Facilities (MIF)**
  - IFMIF-EVEDA, IFMIF and FAFNIR(Global effort).
- **Secondary Beams (Neutrino/Muon/Kaon Factories)**
  - Linac4/SPL@CERN (CH), PIP-II at Fermilab, (IDS-NF (Global effort), UKNF (UK))
- **Accelerator Driven Subcritical Reactors (ADSR).**
  - ADS (CN), MYRRHA (BE), ThorEA (UK).
- **Accelerator Driven Transmutation of Radioactive Waste (ATW)**
  - TRASCO (IT)
- **Accelerator Production of Tritium (APT).**
  - APT@LANL (USA)

# High Power Facilities
# SNS ~1.4 MW



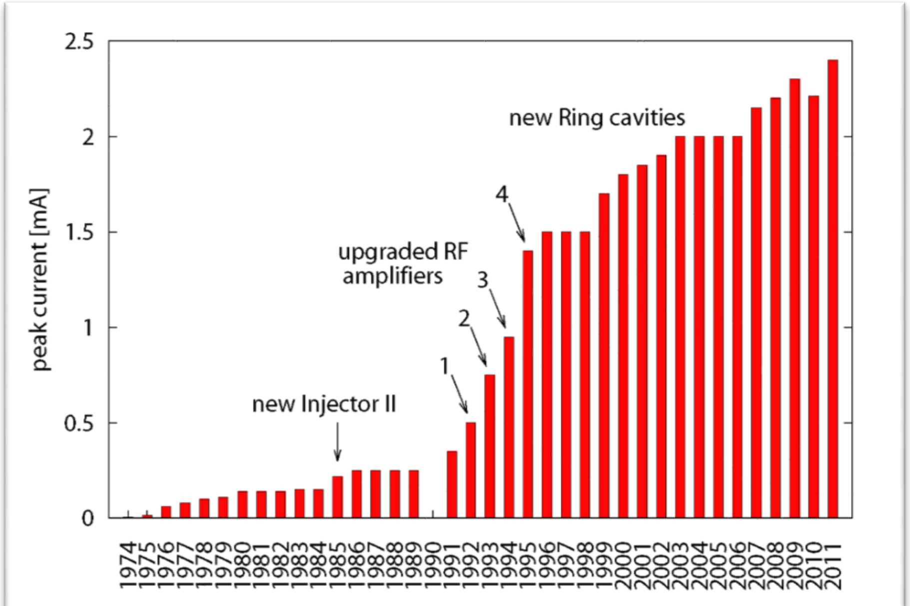

www.ornl.gov

# High Power Facilities
# J-PARC ~1 MW



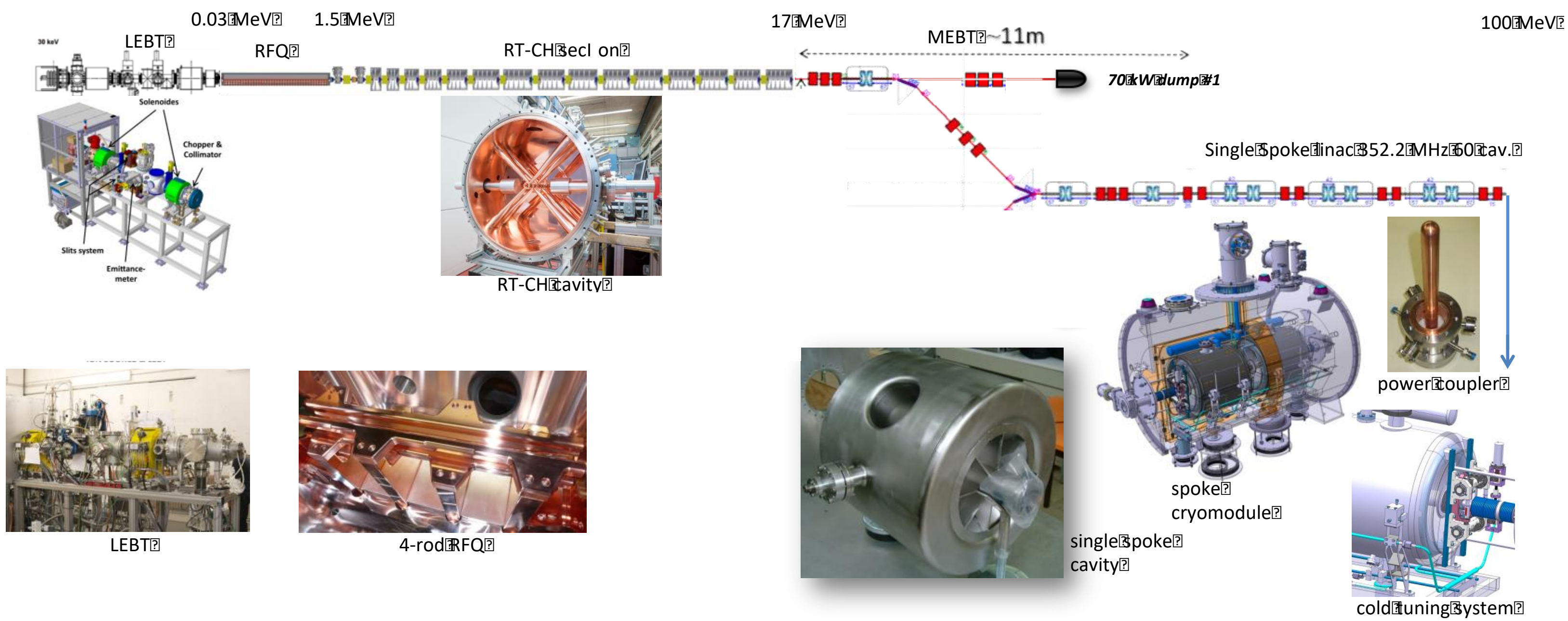

Courtesy of H. Hotchi

# High Power Facilities
# PSI ~1.3 MW



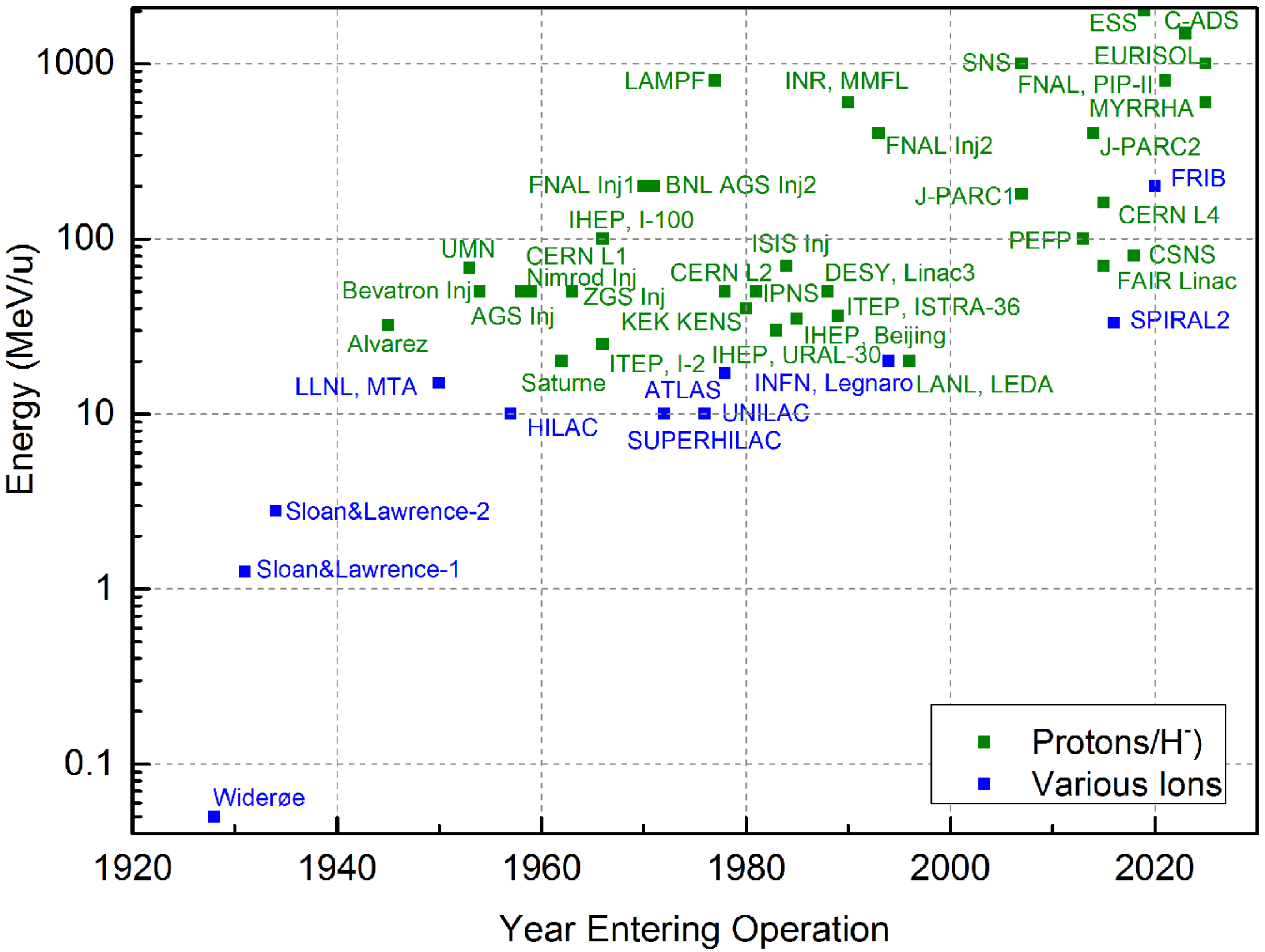
Courtesy of D. Reggiani

# Next in EU: MYRRHA Phase 1, 100 MeV linac overview




- Tendering for most hardware in in 2022-2025 with most deliveries in 2025-2026

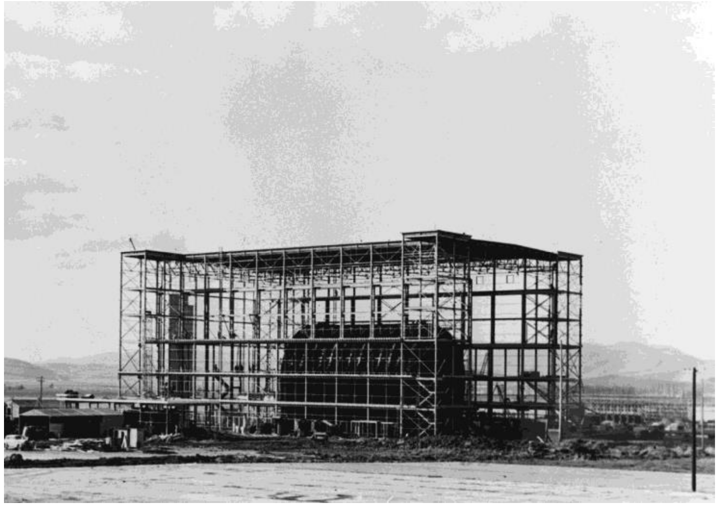
# Proton/Ion Linac Development



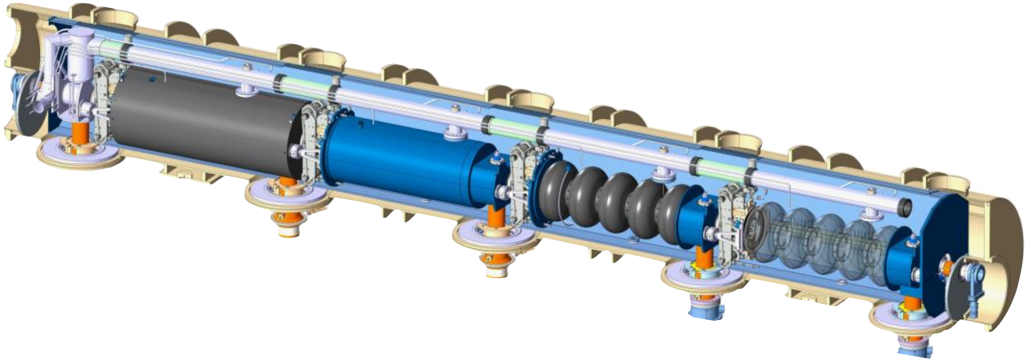
# Proton Linac Development

- The optimisation of the above parameters towards high power beams can be summarised by several notable developments:
  - Accelerator Front End
  - Technology
    - Normal Conducting, Superconducting, RF Systems (Klystrons, Modulators, etc.)
  - Beam dynamics
    - Beam loss control and mitigation
  - Etc.

# Proton Linac Development:
## Technology



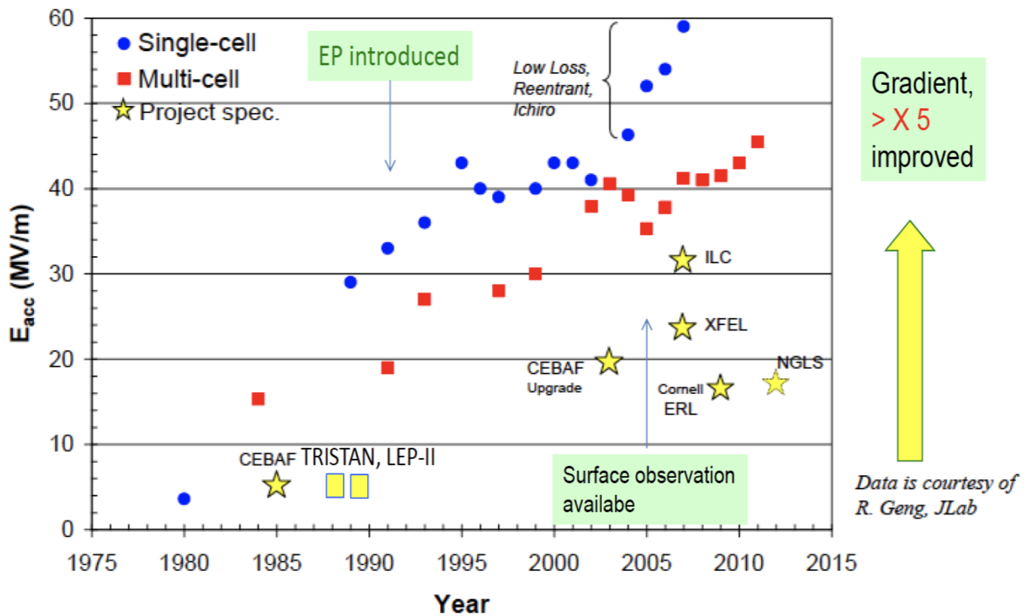
Materials Testing Accelerator (1950) – www.llnl.gov



www.esss.se

# Proton Linac Development:
## Superconducting Technology

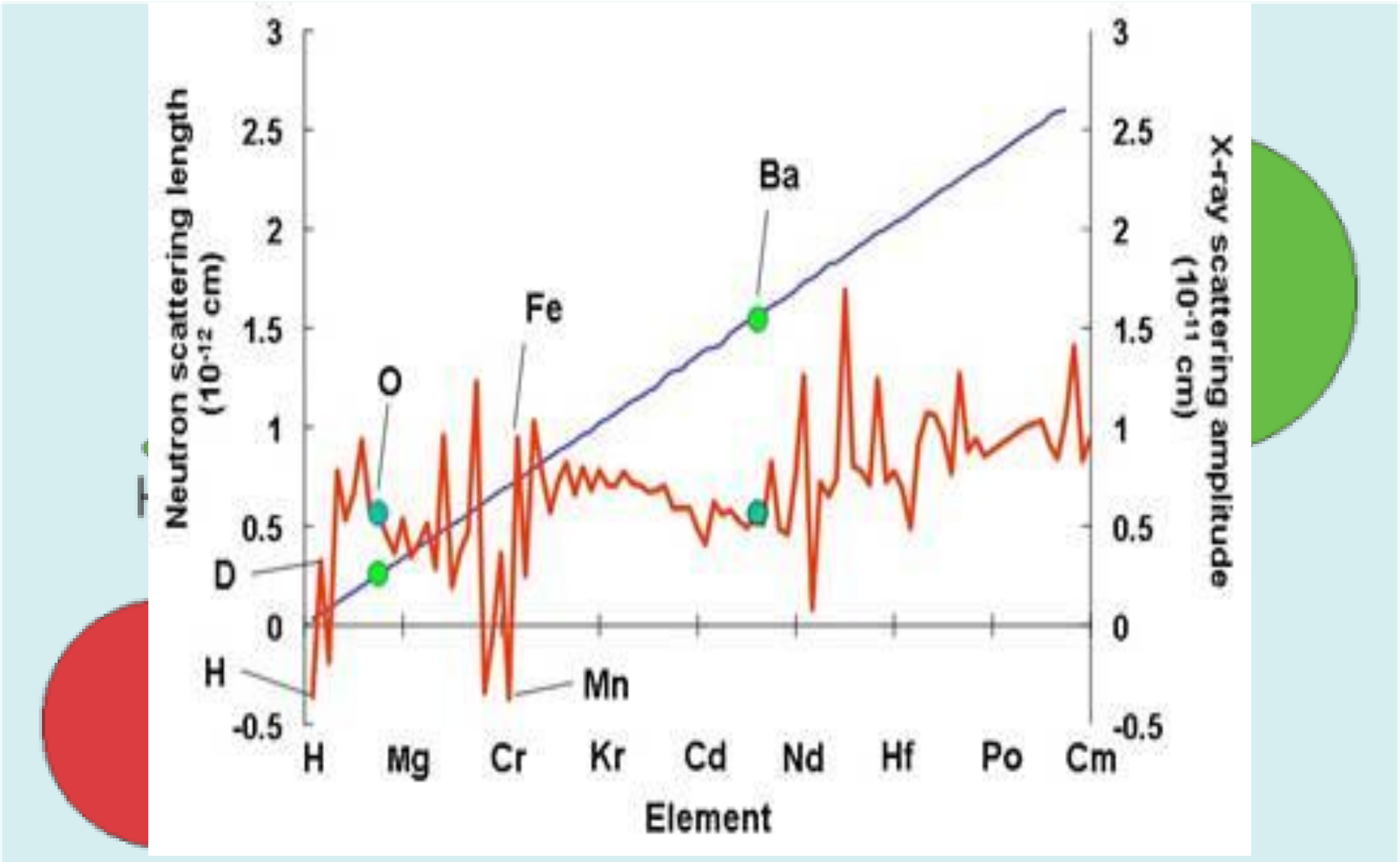
- SRF is key for extending field gradient and fundamental for pushing the power frontier.
- Astonishing developments over the last two decades
  - Over 2000 cavities in the last 10 years.



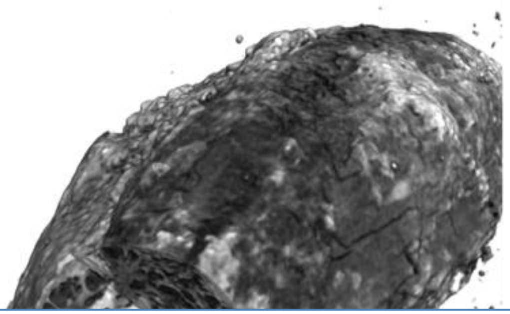

G. Ciovati, "Where Next with SRF", Proc. of IPAC'13, Shanghai, China

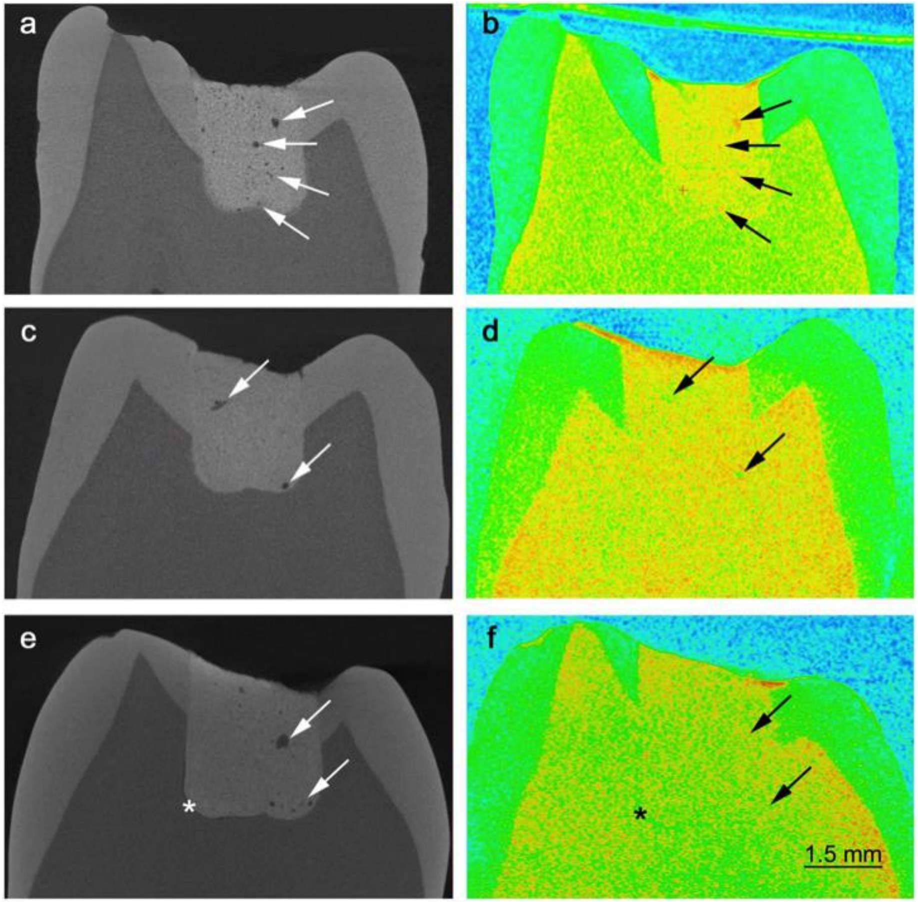
# A European example of a research center with a high power driver

# Neutrons and light: similar but still different



# Neutrons and light: similar but still different

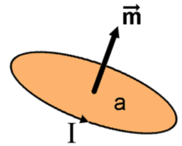


# Neutrons are beautiful!

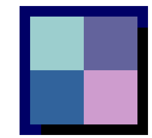
Wave

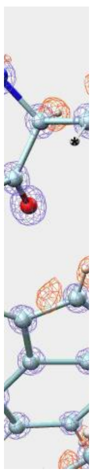
Magnetic moment




Particle

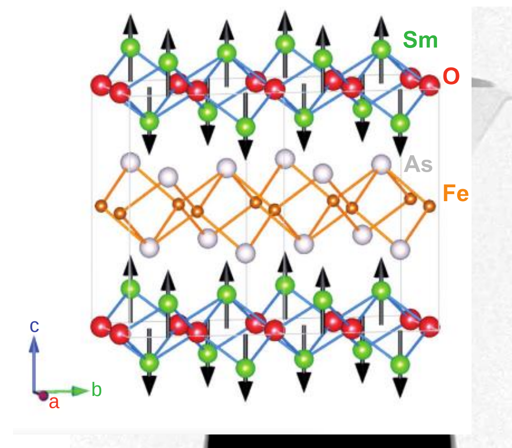
Neutral





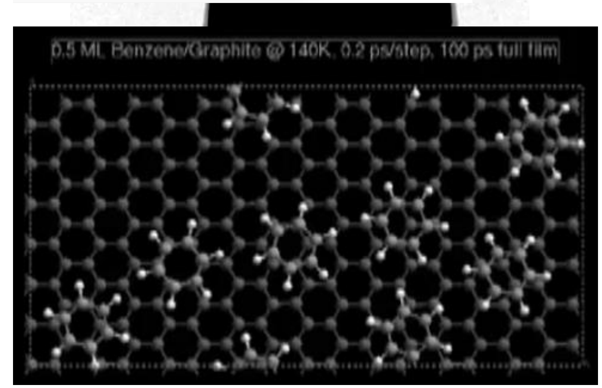
## Diffractometers - Measure structures

– Where atoms and molecules are




## Spectrometers - Measure dynamics

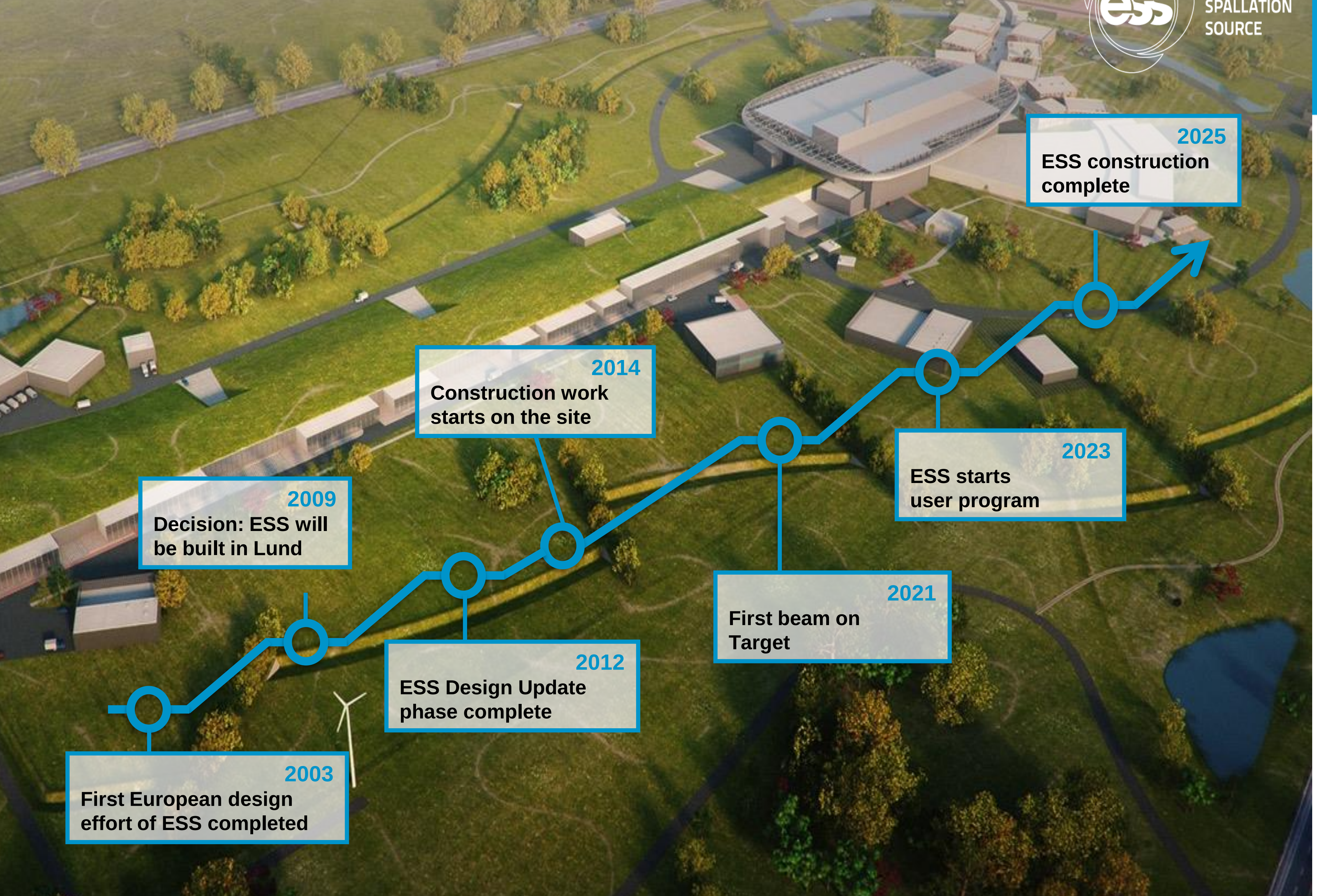
– What atoms and molecules do



# Some visions for neutron and light source science

- Higher (Room?) Temperature Super Conductors
- Hydrogen storage substrate
- Efficient membrane for fuel cells
- Flexible and highly efficient solar cells
- Understanding liquid membranes
- Nano scaled structures for controlled drug release
- Self healing materials – smart materials
- Spintronics - Spin-state as a storage of data ($10^{23}$ gain in capacity)
- $CO_2$ sequestration
- Neutron electric dipole moment
- Neutron oscillations
- And much more…

# European Journey to deliver ESS



# Unique international project

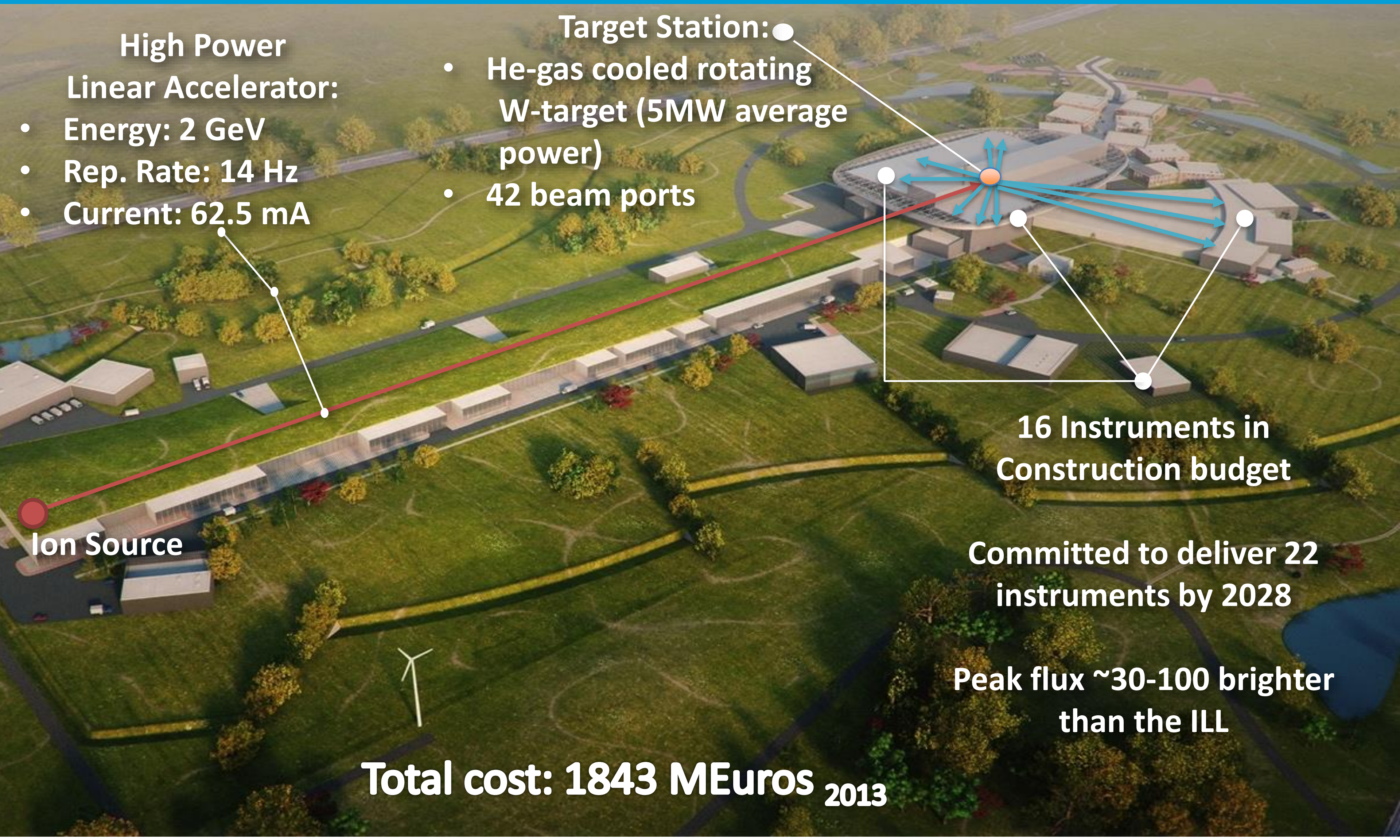
Aarhus University
Atomki - Institute for Nuclear Research
Bergen University
CEA Saclay, Paris
Centre for Energy Research, Budapest
Centre for Nuclear Researc
CNR, Rome
CNRS Orsay, Paris
Cockcroft Institute, Daresb
Elettra – Sincrotrone Tries
ESS Bilbao
Forschungszentrum Jülich
Helmholtz-Zentrum Geest
Huddersfield University
IFJ PAN, Krakow
INFN, Catania
INFN, Legnaro
INFN, Milan
Institute for Energy Research (IFE)
Rutherford-Appleton

**COLLABORATION**

Laboratory, Oxford(ISIS)
Copenhagen University
Laboratoire Léon Brillouin (CEA/CNRS/LLB)
Lund University
Nuclear Physics Institute of the ASCR
e (PSI)
up (PEG)
ersity
of Denmark
Munich
ogy 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)

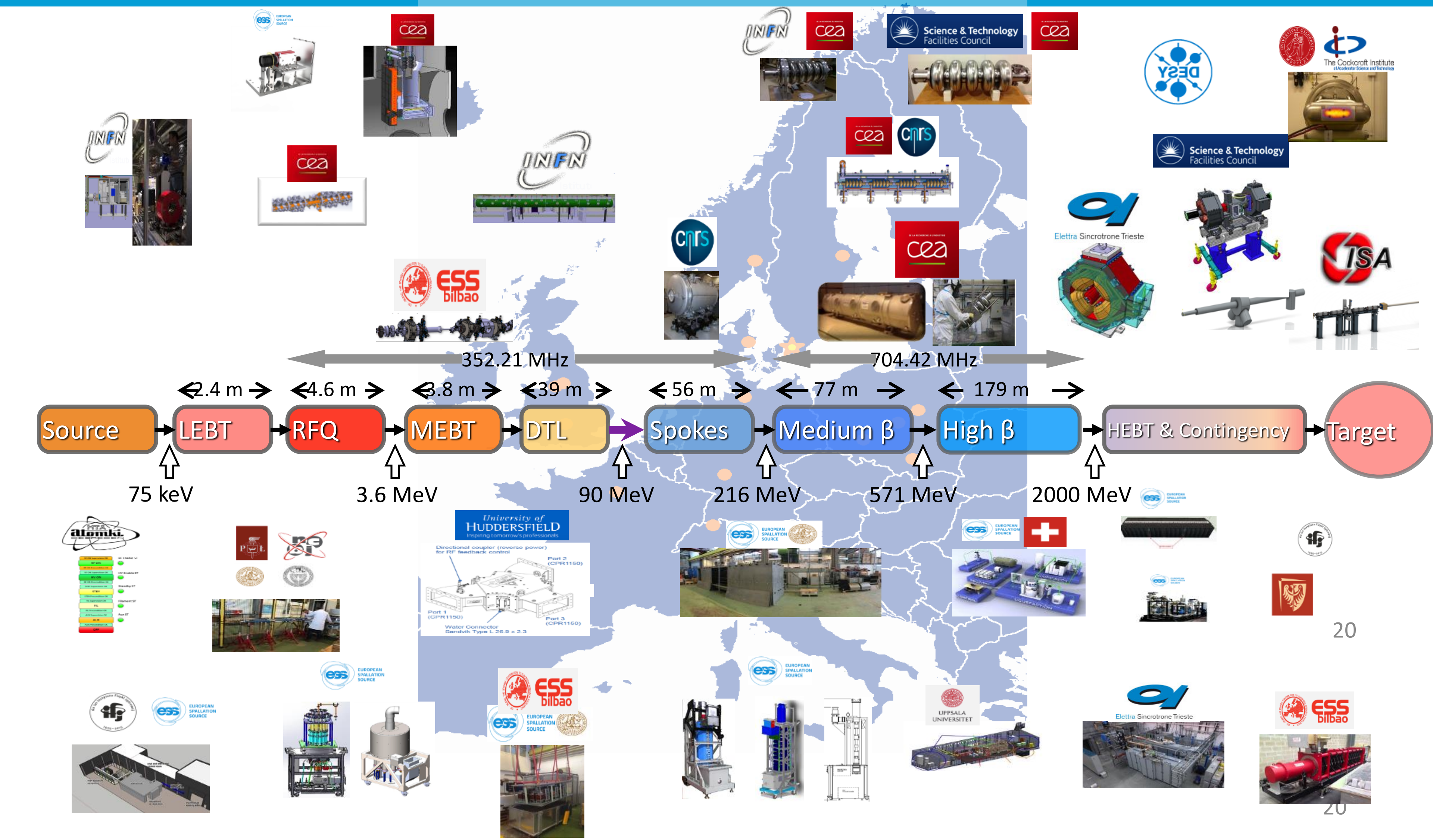
# ESS design

EUROPEAN SPALLATION SOURCE



# Accelerator Collaboration – Accelerator

## Formed by members of EU Design Studies and networks

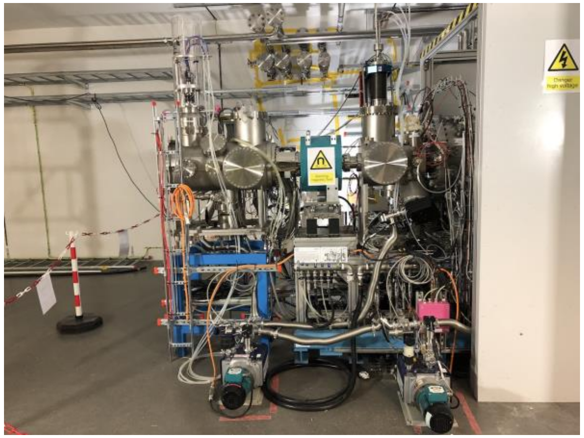


# Accelerator & Klystron Gallery

EUROPEAN SPALLATION SOURCE

# ESS accelerator status

- Ion-source & Low Energy beam transport commissioned and Medium Energy beam transport & Radio Frequency Quadrupole (RFQ) installation are under way (INFN, ESS-Bilbao, CEA and ESS)
- ESS cryoplants operating and delivering liquid Helium to clients (ESS)
- Drift Tube Linac tank (DTL) assembly started on ESS site (INFN)
- 3 ESS designed modulators and 27 klystrons delivered to ESS (ESS-Bilbao, ESS)
- 23 out of 30 valve boxes with interconnections for elliptical linac installed (Wroclav University)
- Installation of RF distribution well under way (IFJ-PAN)



# ESS accelerator progress in pictures



# ESS target from ESS Bilbao

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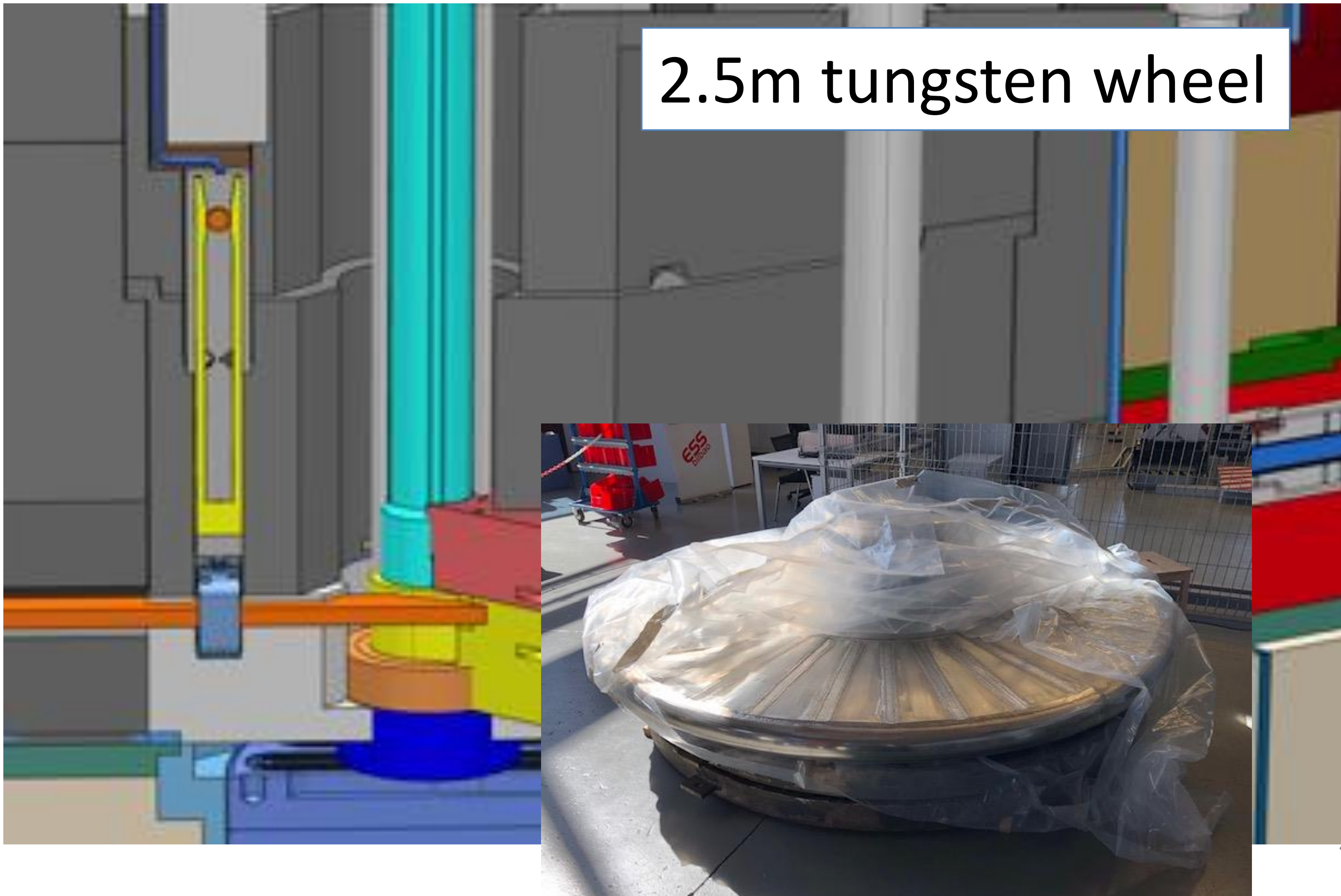
2.5m tungsten wheel



# What are the limits?

## My guesses today for the 10 year perspective

- High intensity linacs for neutrino beams, anti-protons, muons and neutron EDM
  - 10-15 MW, limited by losses
  - $H^-$ machines have an additional loss mechanism through intra-beam stripping
- High intensity hadron rings for anti-protons, muons, Neutrino superbeams and other fixed target physics
  - 3-5 MW, limited by losses and space charge
- High intensity cyclotrons for neutron EDM and muons
  - 2-5 MW, limited by losses at extraction and space charge

# Collaborative R&D within Academia and with industry

- Energy efficient and cheaper RF sources
- High reliability power supplies and modulators
- High $Q_0$ (more energy efficient) and higher gradient superconducting cavities
  - Industry have made reliable mass production of high performance cavities possible!
- High space charge accumulation (and accelerating) rings low loss injection and extraction systems
- New Target concepts and technology
- Radiation protection issues including monitoring and robotics in hot cells
- Machine learning and artificial intelligence to optimise energy consumption and efficiency
- New high performance imbedded systems and “super reliable” (safety classified) PLC based slow control
- High performance computing

# Summary

- High Intensity proton drivers are in high demand!
- Developments for Accelerator Front End, Technology and a better understanding of beam dynamics has enabled 5 MW machines to be built and 10 MW to be within reach
- Close future:
  - In **Europe** the MYRRHA (MINERVA) construction at SCK-CEN is the next high power proton driver project.
  - In the **US** the SNS upgrade (2 MW) and Fermilab PIP-Iiwith European collaborators is underway
  - In **China** the Chinese ADS project is underway
  - **ESS** will continue to build to reach 5 MW with more modulators and RF sources being ordered
- Most future large scale project are likely to be IK projects and this is a very powerful model. Together we are strongest!

# Many thanks to all my colleagues in the ESS accelerator collaboration

# Thank you for listening!

EUROPEAN
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SOURCE

# A partnership of 17 European nations

# Beam Power Optimisation

$$P_b = I_b \cdot W_{linac}$$

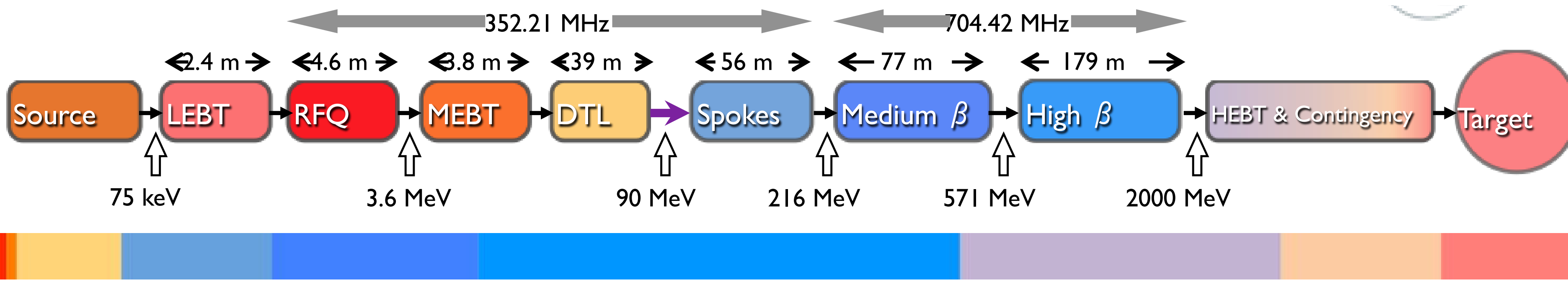
$$I_b = I_{max} \cdot f_{pulse} \cdot L_{pulse} = I_{max} \cdot d.c.$$

$$W_{linac} = q \sum_i E_{acc_i} \, T_i \, L_i \, \cos(\phi_i)$$

# High power 5MW proton accelerator

## Design based on EU sponsored collaborative research

EUROPEAN SPALLATION SOURCE




Accelerating protons to almost the speed of light

in pulses hitting the target 14 times per second.

Energy per pulse equals to

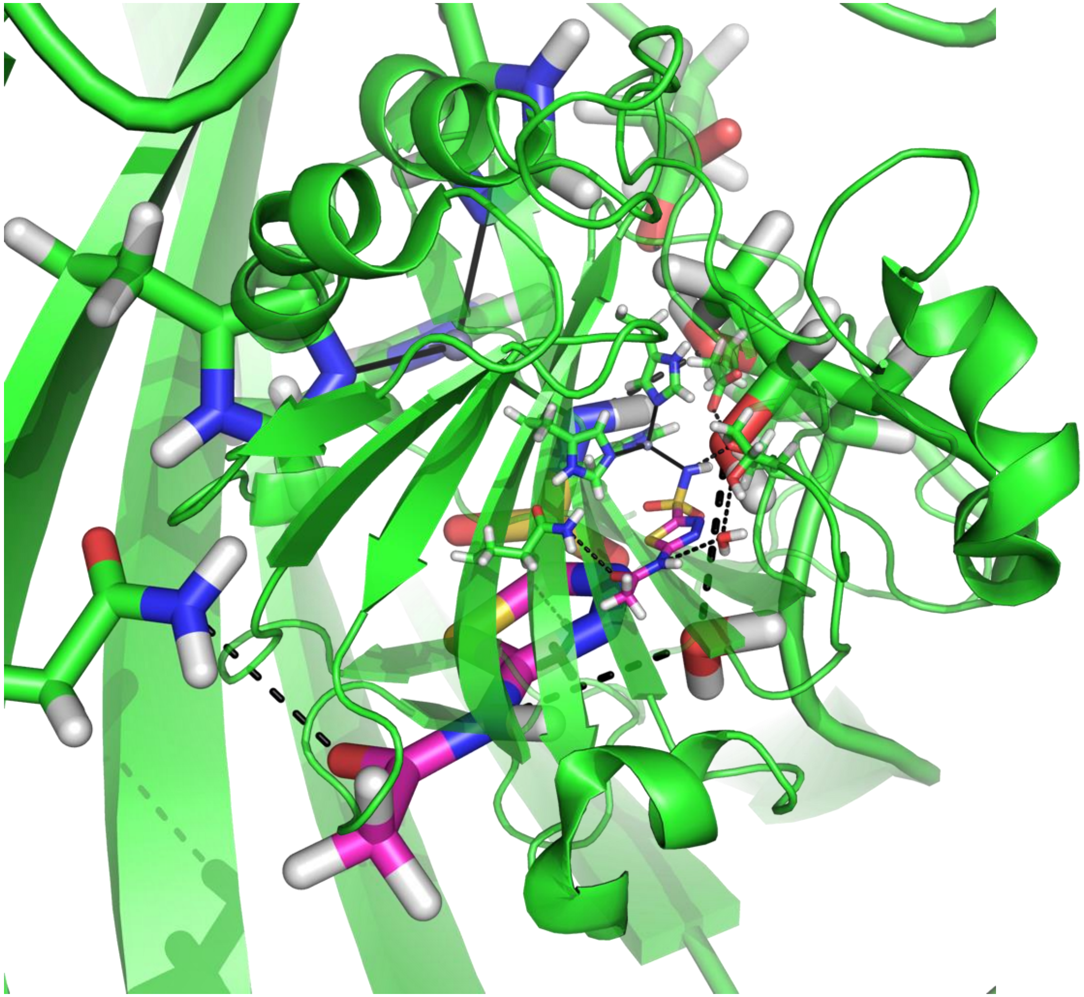
- 16lb (7,2kg) shot travelling with 1100 km/h.
- melting approx. 1 kg (1 liter) of ice …

…. *and next pulse boils it.*


# Examples of Procurements at Accelerator

- 5 HB modulators (ESS design), Opens Q4 2019
- Spare parts for Beam diagnostics, Vacuum, Cryogenics, RF, Modulators and Power supplies, on-going in 2019 and will be on-going
- Helium, cables, cable trays etc
- Services such as specialised welding, oil for modulator transformers, industrial gases etc.

# Better drugs from detailed protein maps



10$^{-9}$ m

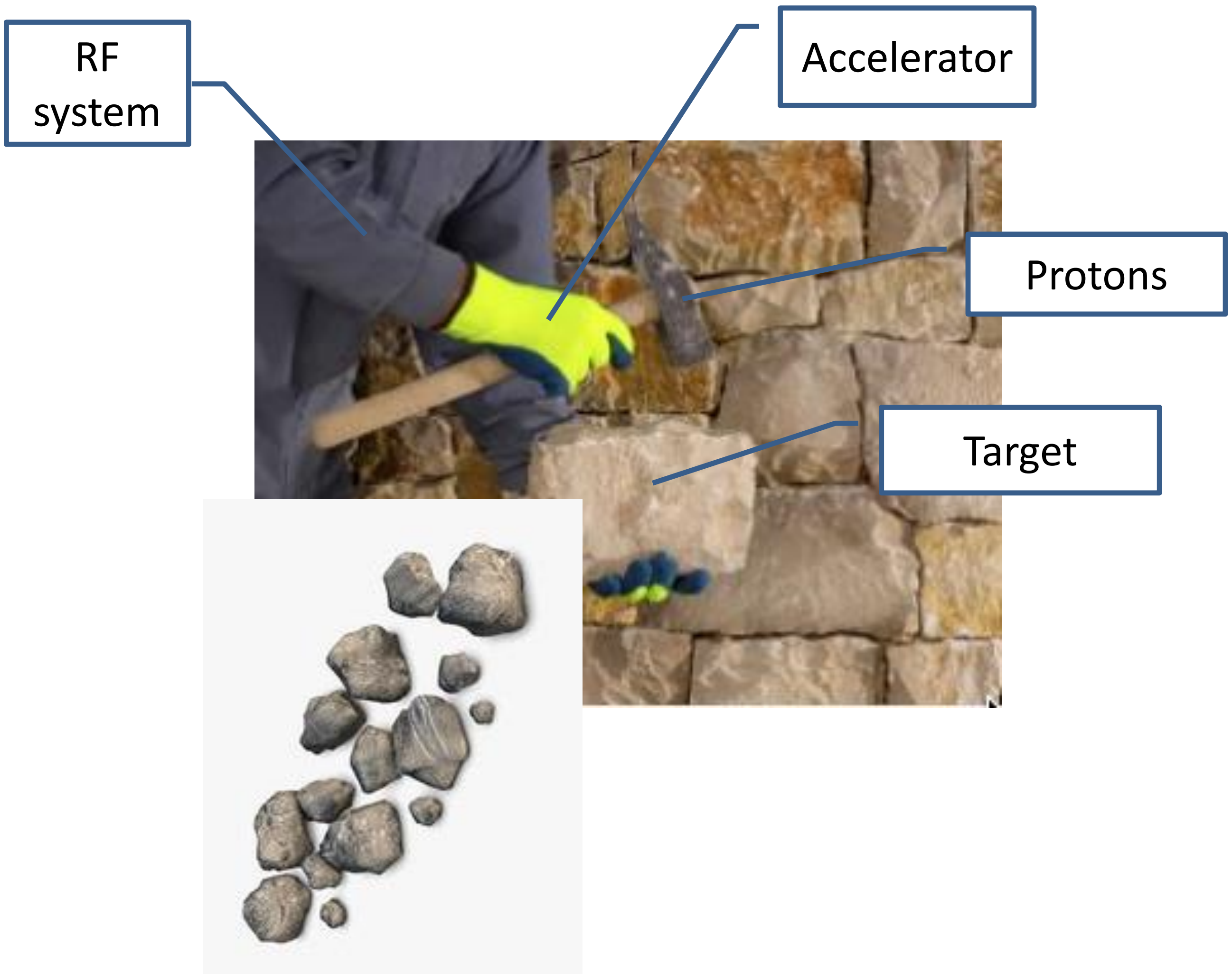
This enzyme transports $CO_2$ and regulates blood pH.

It is a major player in some cancers, glaucoma, obesity and high blood pressure

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

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

# Spallation source?



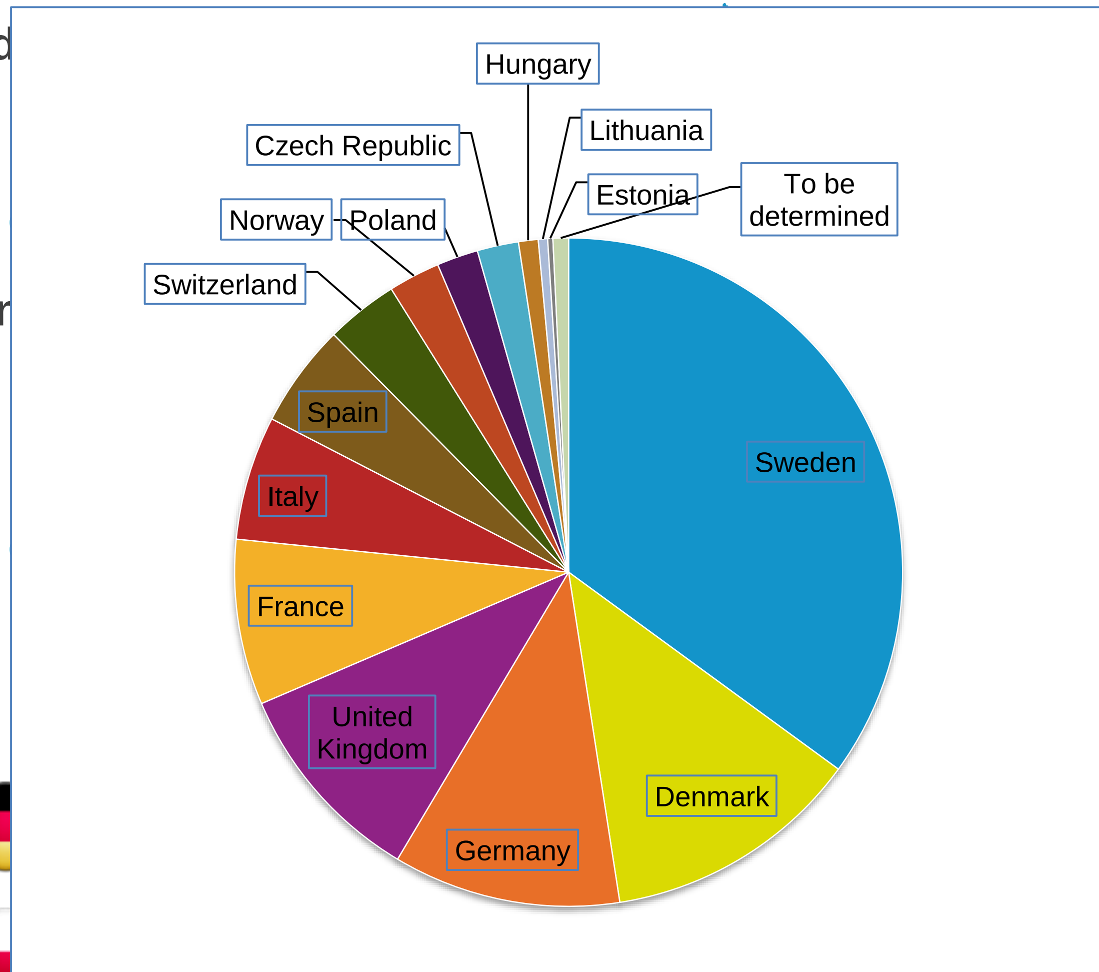
# Financing includes cash and deliverables

### Host Countries of Swed

Construction 47.5%
Operations 15%

### Non Host Member Cour

Construction 52.5%
Operations 85%




# ESS – the sale pitch!