ACCELERATOR GROUP
European Physical Society

IPAC23

14th International Particle Accelerator Conference

IPAC '23

7 - 12 May 2023

VENICE, ITALY

Hosting institutions

Elettra Sincrotrone Trieste

INFN
Istituto Nazionale di Fisica Nucleare

IPAC23

Accelerator Based Neutron Sources

Ciprian Plostinar - ESS

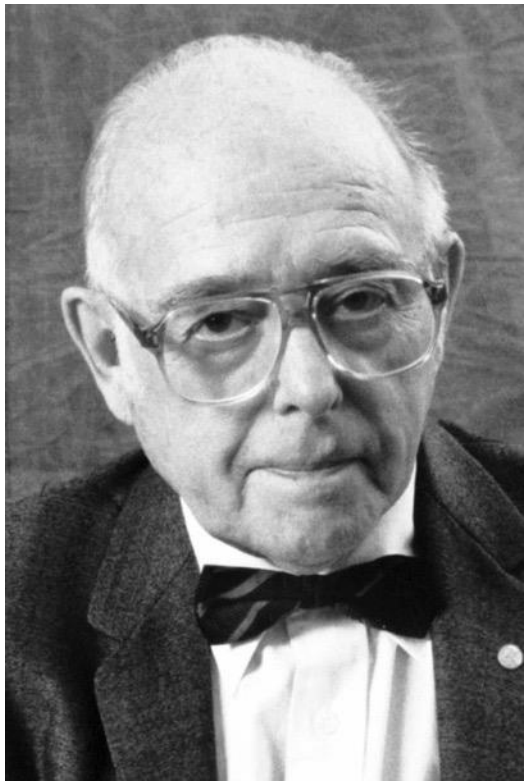
Neutron Science

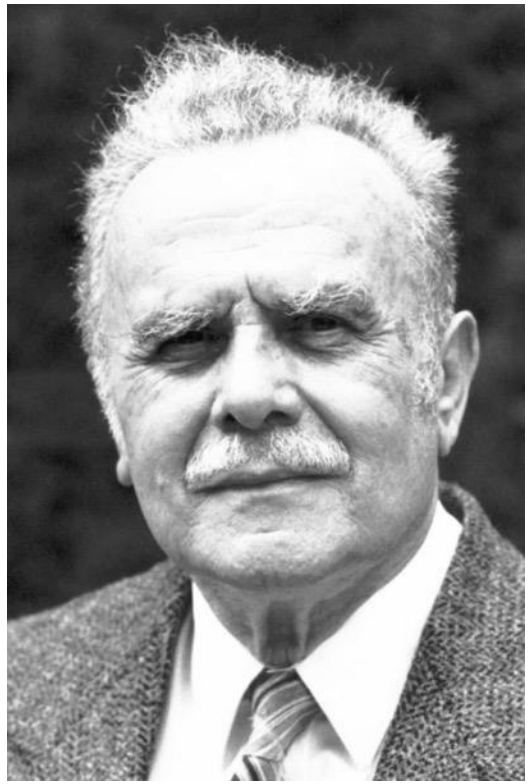
- “Where are the atoms and what do they do?”
  - Diffractometers: Structure
  - Spectrometers: Dynamics

- 1994 Nobel Prize 1994:
  - **Clifford Shull** – neutron diffraction
  - **Betram Brockhouse** – neutron spectroscopy

- Some Neutron Properties:
  - Charge neutral: 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

“For pioneering contributions to the development of neutron scattering techniques for studies of condensed matter”

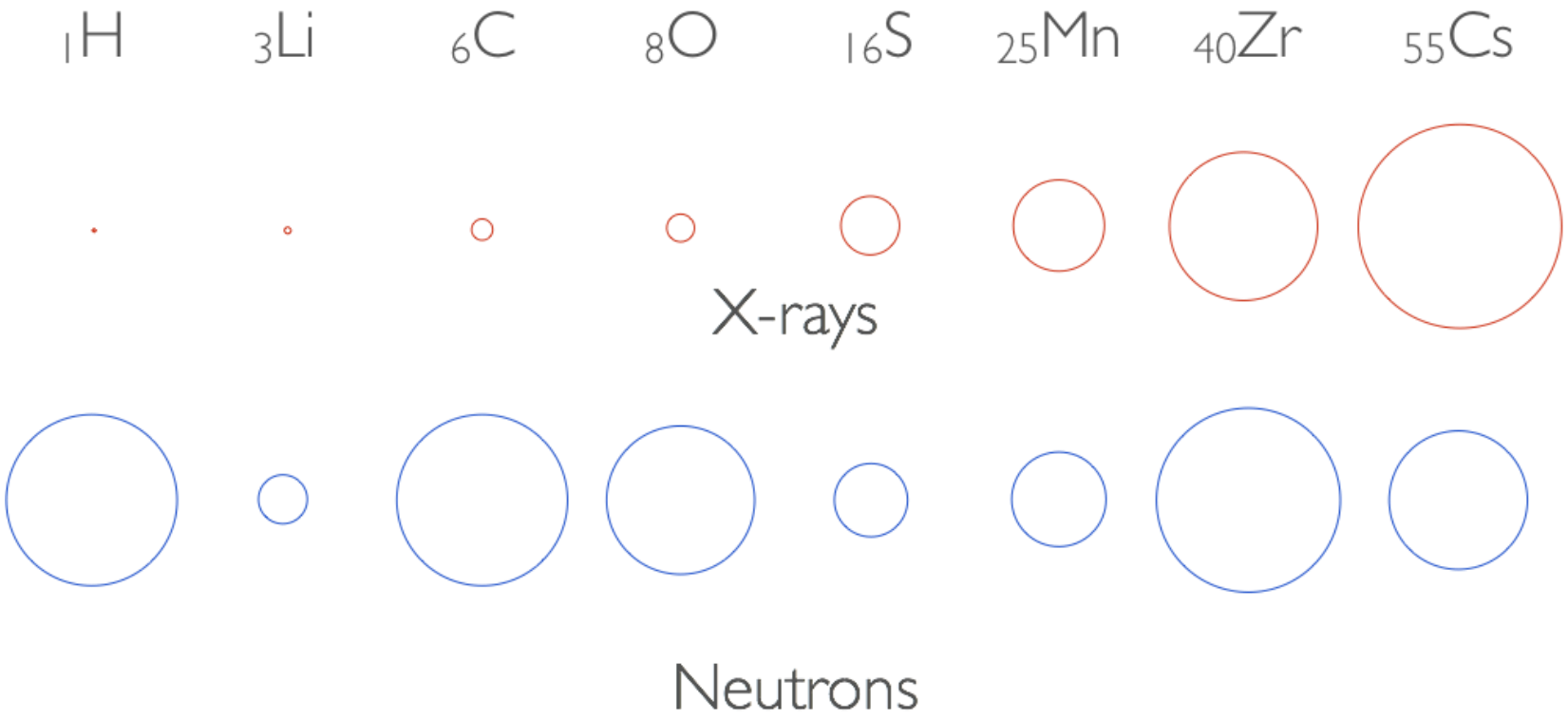




See the 1994 Physics Nobel Prize Press Release

Neutron Science

See **Synchrotron Light Sources** Tutorial
Ryutaro Nagaoka



- Cross-sections of different atoms with photons and neutrons
- Neutrons and X-Rays are complementary
-

Why Neutrons?

Because “planes, trains and dinosaurs (and ice-cream)”!

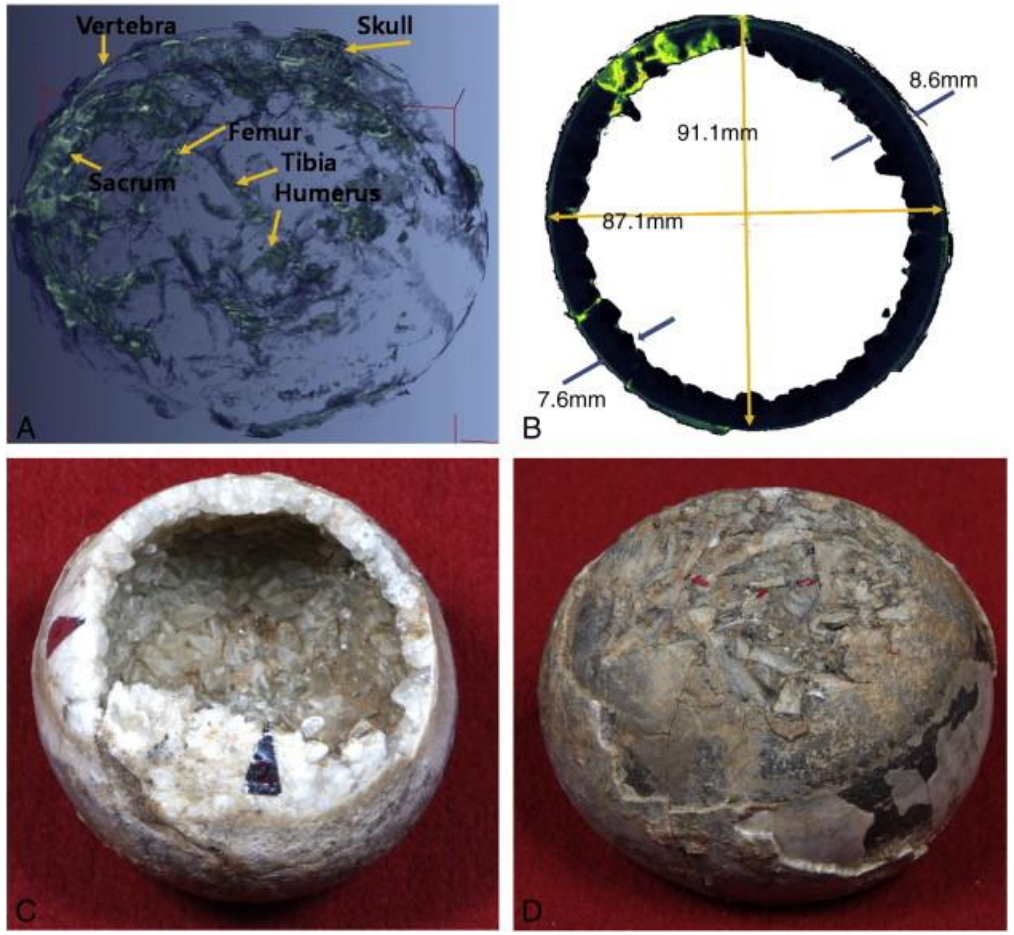
Mapping stress and fatigue in aircraft wings – Airbus research @ISIS Spallation Neutron Source

Source: airbus.com

Exploring unconventional superconductors using neutron spectroscopy

Source: wikipedia.org

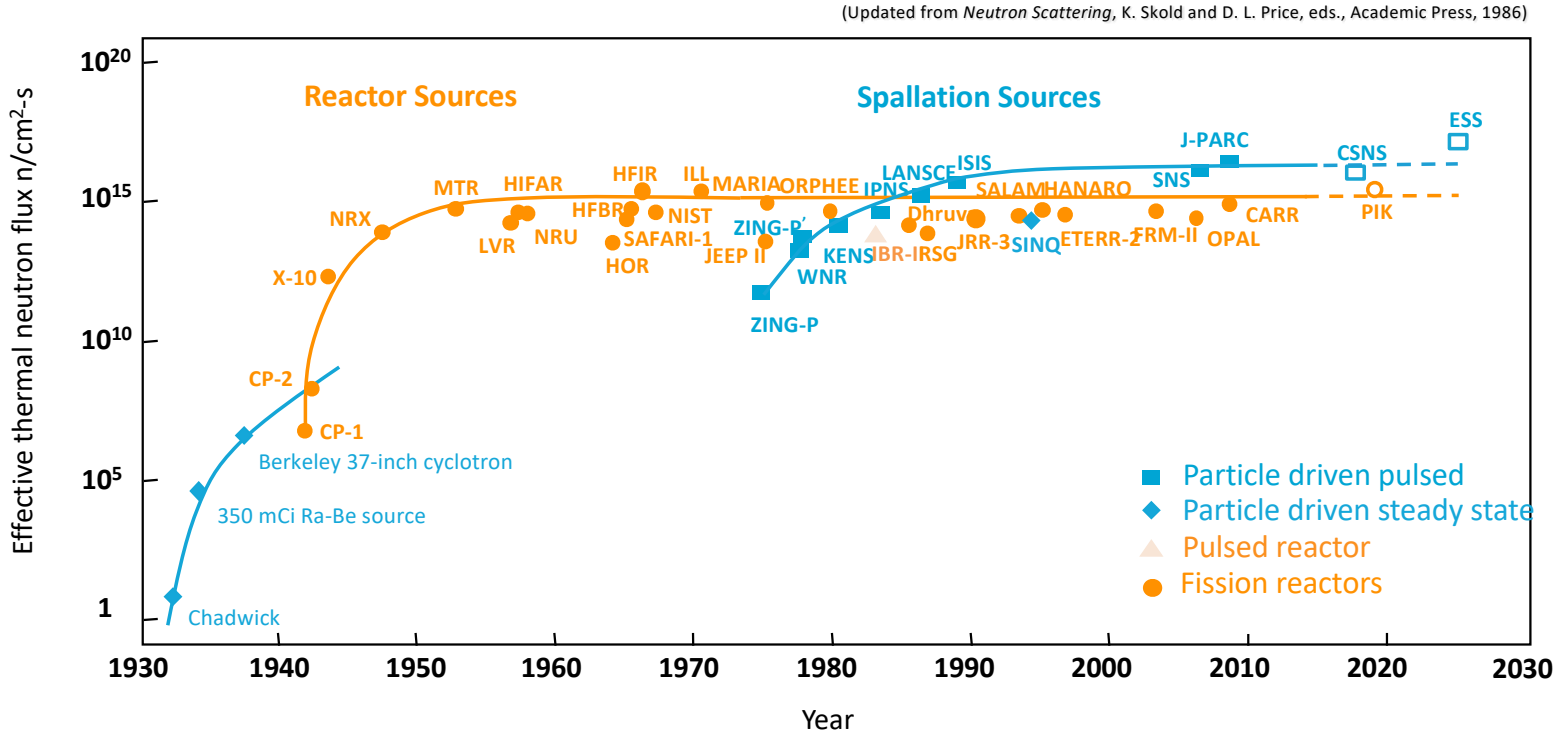
Neutron characterisation reveals fossilised **Titanosaurus embryo** – G. Grellet-Tinner et al.



Using neutrons to study the crystallisation of ice cream in real time

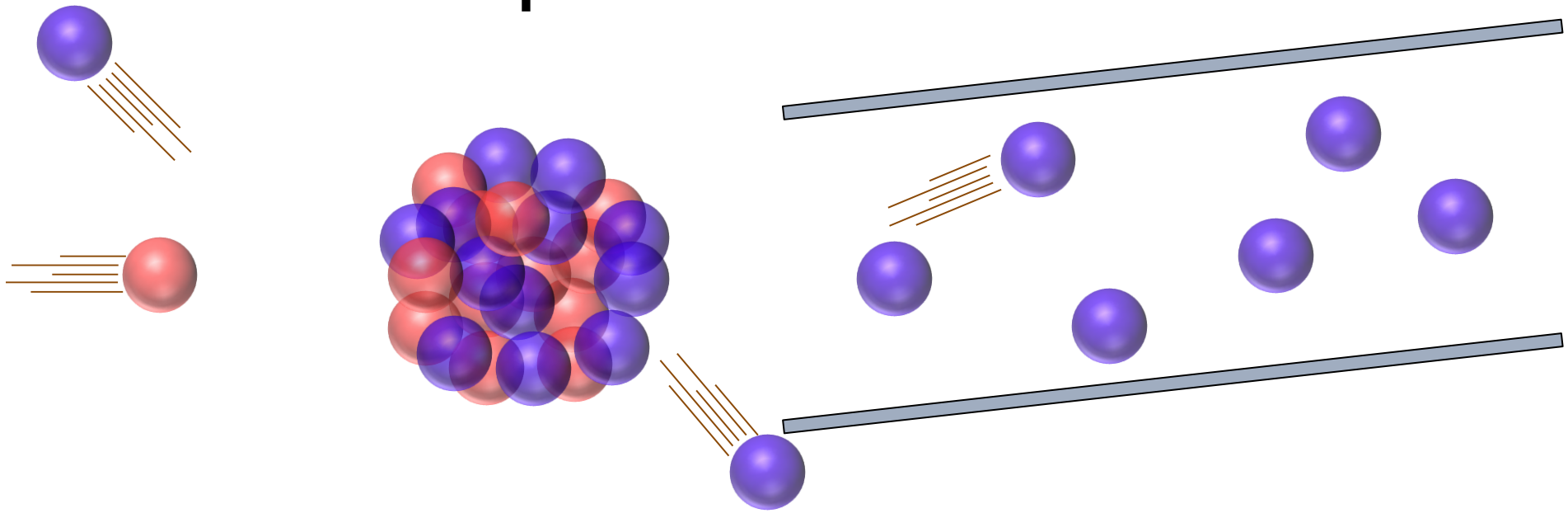
Neutron Production

- Small:
  - Alpha (i.e. $^{9}Be + \alpha \rightarrow {}^{12}C + n + \gamma$)
  - Gamma
  - Spontaneous fission sources
- Reactors
- **Accelerators**

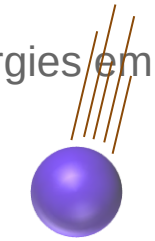


Neutron Production

Spallation Principles



- High energy protons hit a heavy nuclei target
  - Neutrons at different energies emitted

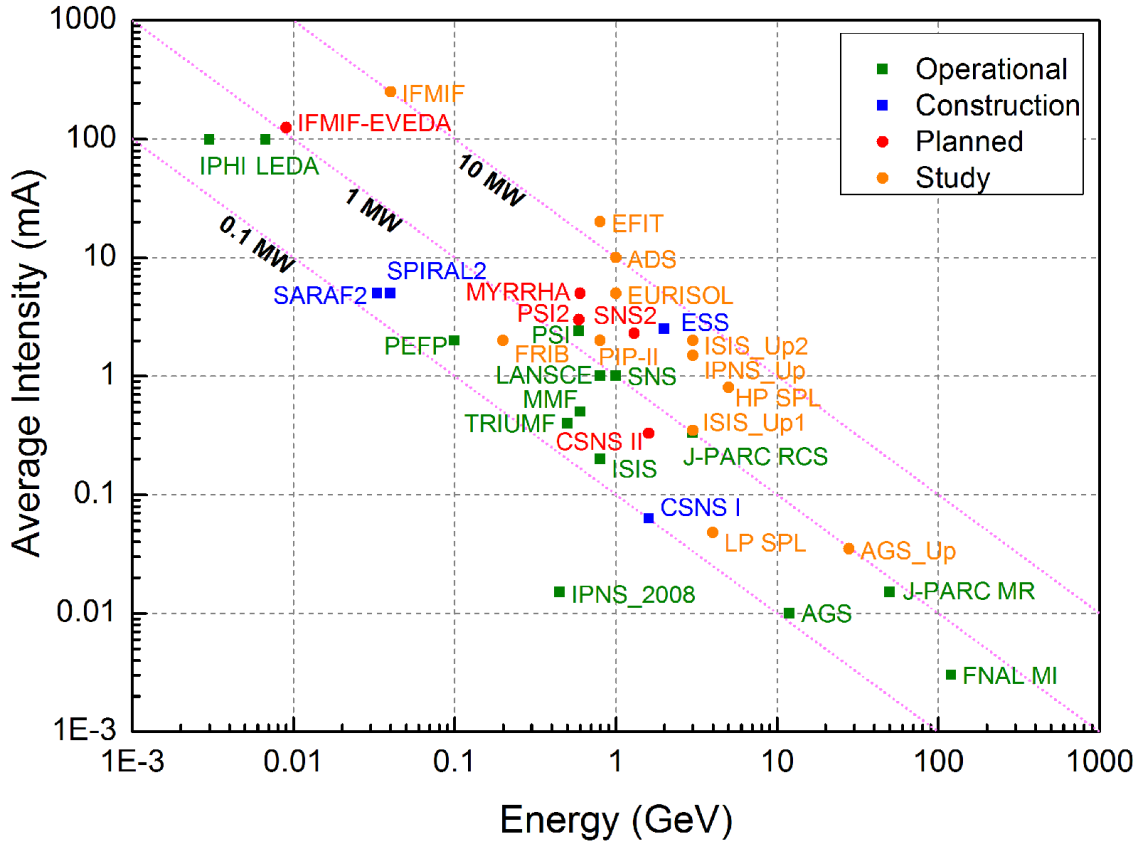


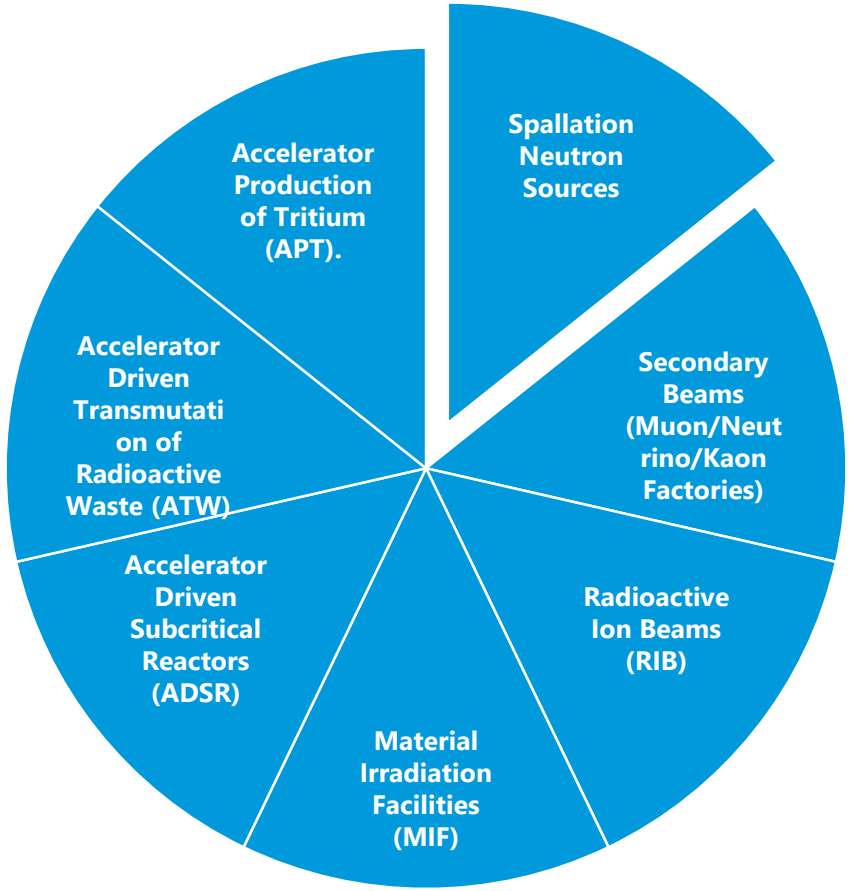
- Complex system:
  - **Accelerator**, Target, Moderators, Instruments, etc.
- Spallation: most effective neutron production method

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)

Global Demand for High Power Beams





Accelerator Beam Power

Optimisation

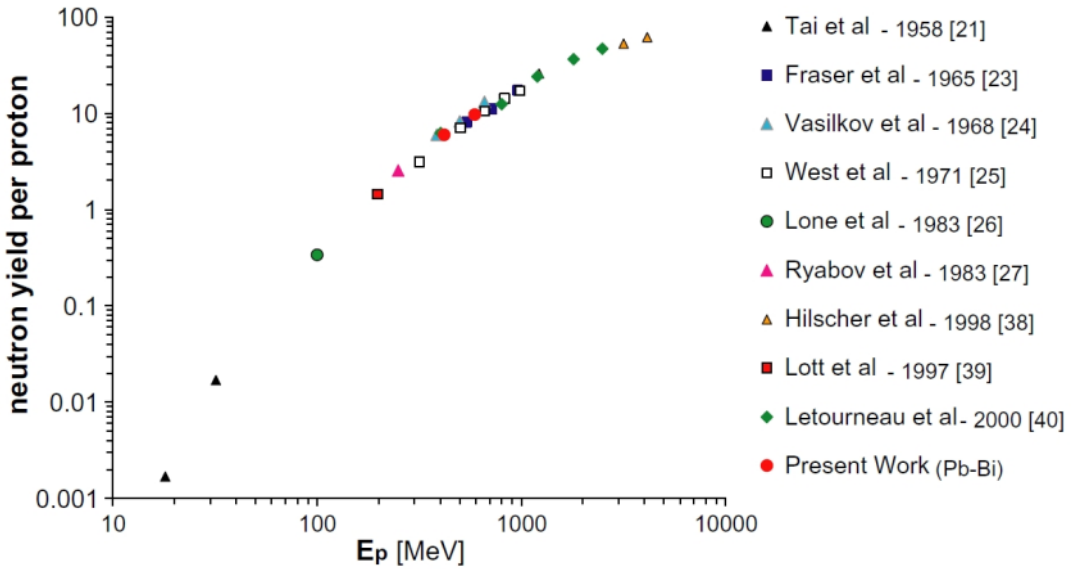
$$P_b = I_b \cdot W_{linac}$$

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

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

Spallation Neutron Sources
Optimisation

- High neutron flux
  - High Beam Power:
    - Intensity
    - Energy
  - Target and moderator design
  - Instruments
  - Practicality



K. van der Meer, et al., NIM B 217, pp 202 – 220.

Spallation Neutron Sources

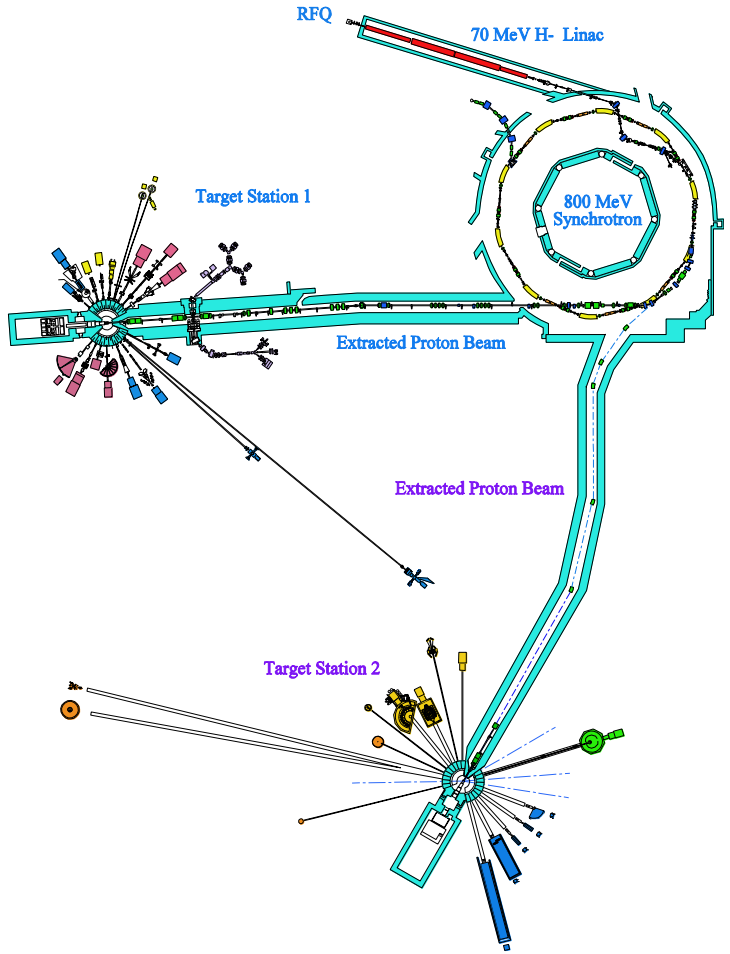
- Short Pulse
  - Synchrotrons or compressor rings
  - Pulse length: ~μs
- Long Pulse
  - Linacs
  - Pulse length: ~ms
- Continuous
  - Cyclotrons

Short Pulse Spallation Neutron Sources

- **Linac-RCS or Linac-Compressor Ring**
- **ZING-P** – First Spallation Neutron Source Prototype
  - Argonne National Laboratory (ANL) – 1974
  - “Recycled”: Built from decommissioned ZGS parts
  - **ZING-P’** – Second Prototype - 1977
- **Intense Pulsed Neutron Source (IPNS)**
  - ANL – 1981 - 2008
  - 450 MeV, 6.4 kW, 30 Hz RCS
- **KENS**
  - @KEK, Tsukuba, 1980
  - 500 MeV, 3.5 kW, 20 Hz RCS
- **ISIS**, **SNS**, **J-PARC**, **CSNS** – operational
- And many other “unsuccessful” proposals along the way

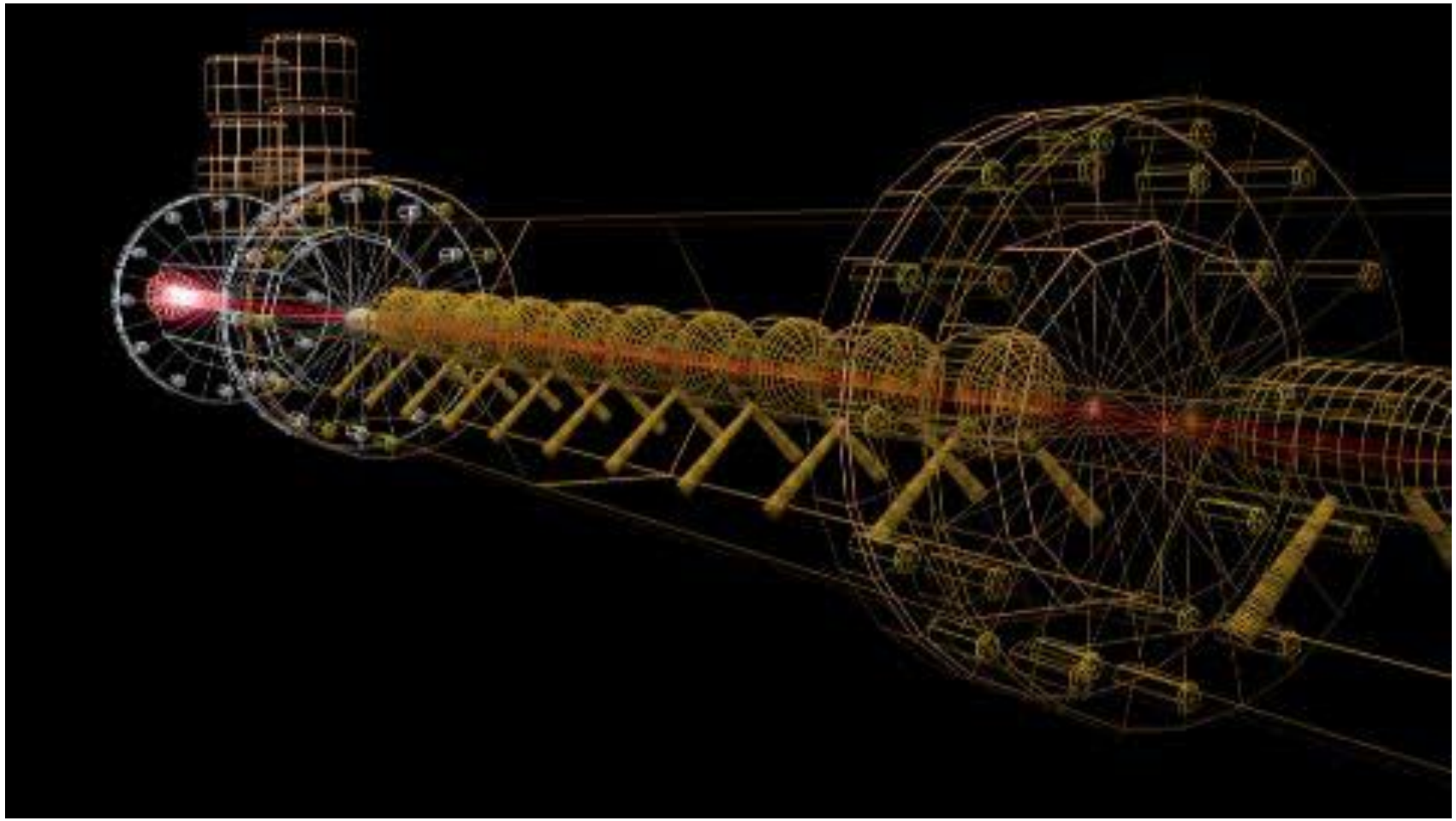
ISIS @ RAL

- Inaugurated in 1984
- Accelerator:
  - H^- Ion Source
  - LEBT
  - 0.665 MeV RFQ, 202.5 MHz
  - 70 MeV Linac (4 DTL Tanks)
  - 800 MeV proton synchrotron
- ~230 μA (2.9*10^13 ppp)
- 50 Hz, 184 kW (~25*IPNS)
  - 148 kW to TS-1 (40 Hz)
  - 36 kW to TS-2 (10 Hz)



ISIS @ RAL

ISIS @ RAL



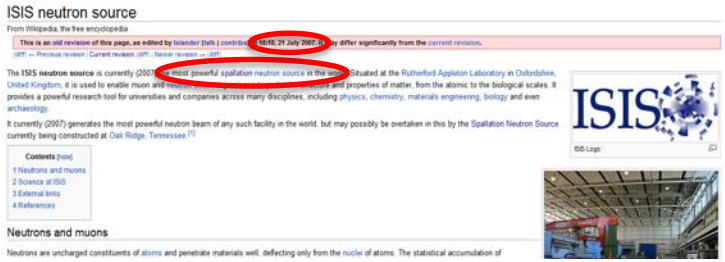
ISIS @ RAL

- Some “recycled” components
- ISIS was originally expected to have an operational life of 20 years
- Its continued success will probably double its expected lifetime.
  - Neutron demand from users
  - Maintenance, refurbishment, investment.
- **ISIS is the prototype for modern spallation facilities.**

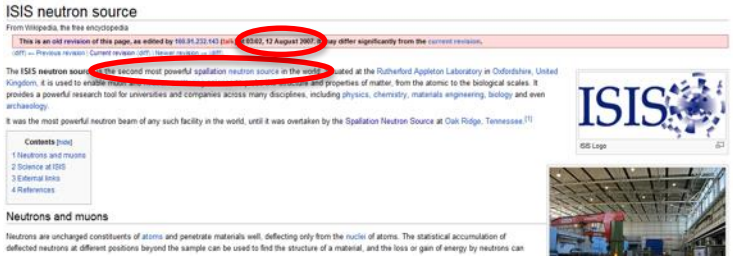
(Beam) Power Supremacy!

(Beam) Power Supremacy! – A Wiki Story

18:18, 21 July 2007, Wikipedia:
ISIS is ”…the most powerful spallation neutron source in the world…”



03:02, 12 August 2007:
ISIS is ”…the second most powerful…”



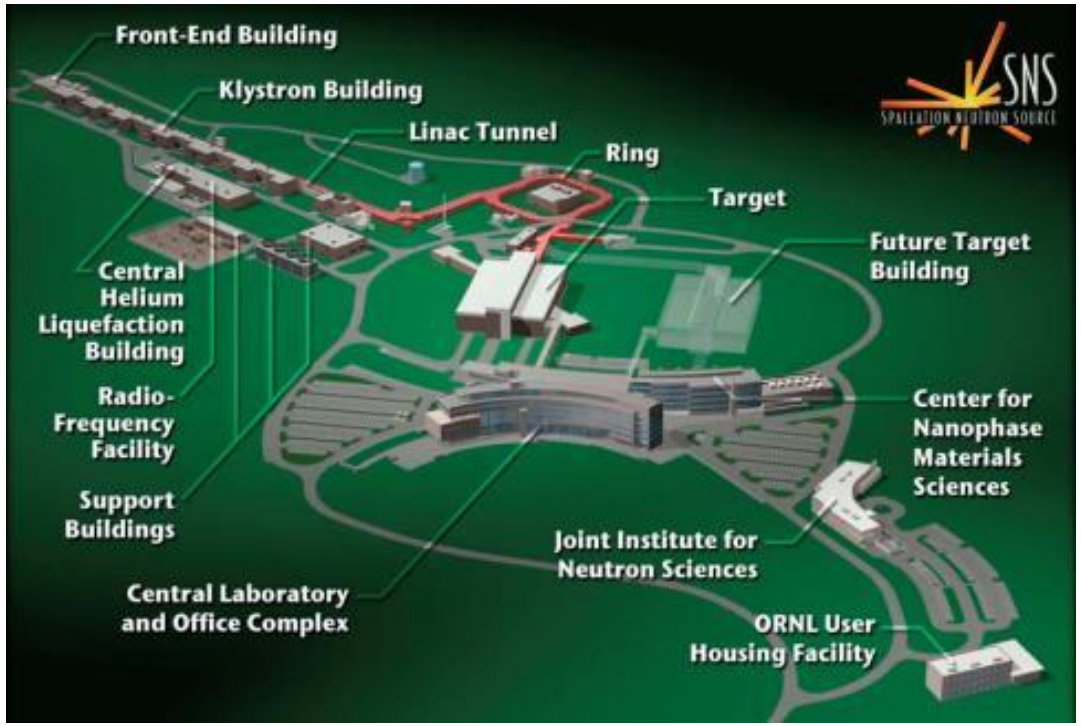
09:52, 18 September 2007:
ISIS is ”…one of the most powerful…”

09:52, 03 October 2007:
ISIS is ”…a world leading neutron source…”

14:00, 19 October 2007:
SNS is ”…the most powerful neutron source in the world…”

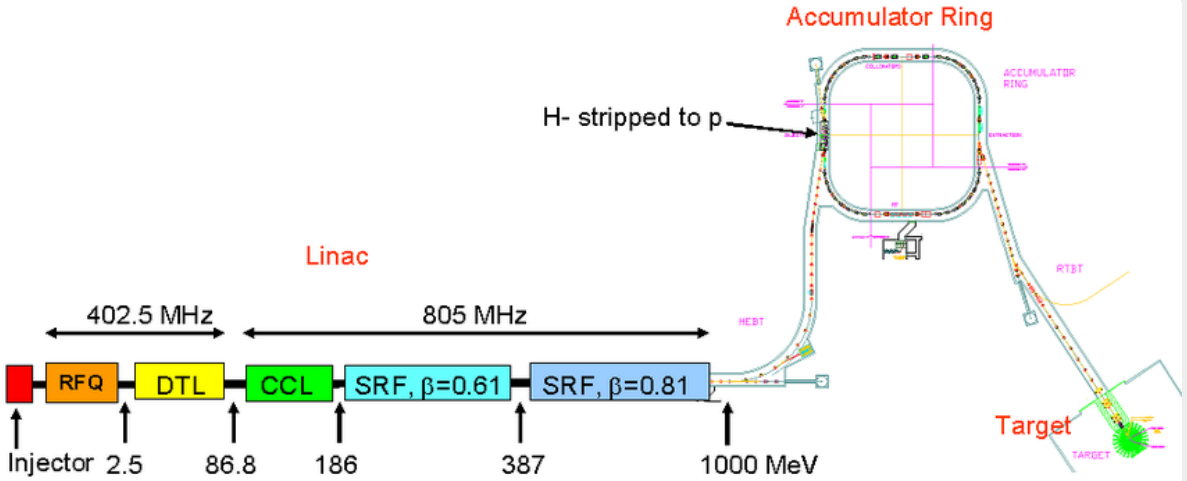
Spallation Neutron Sources

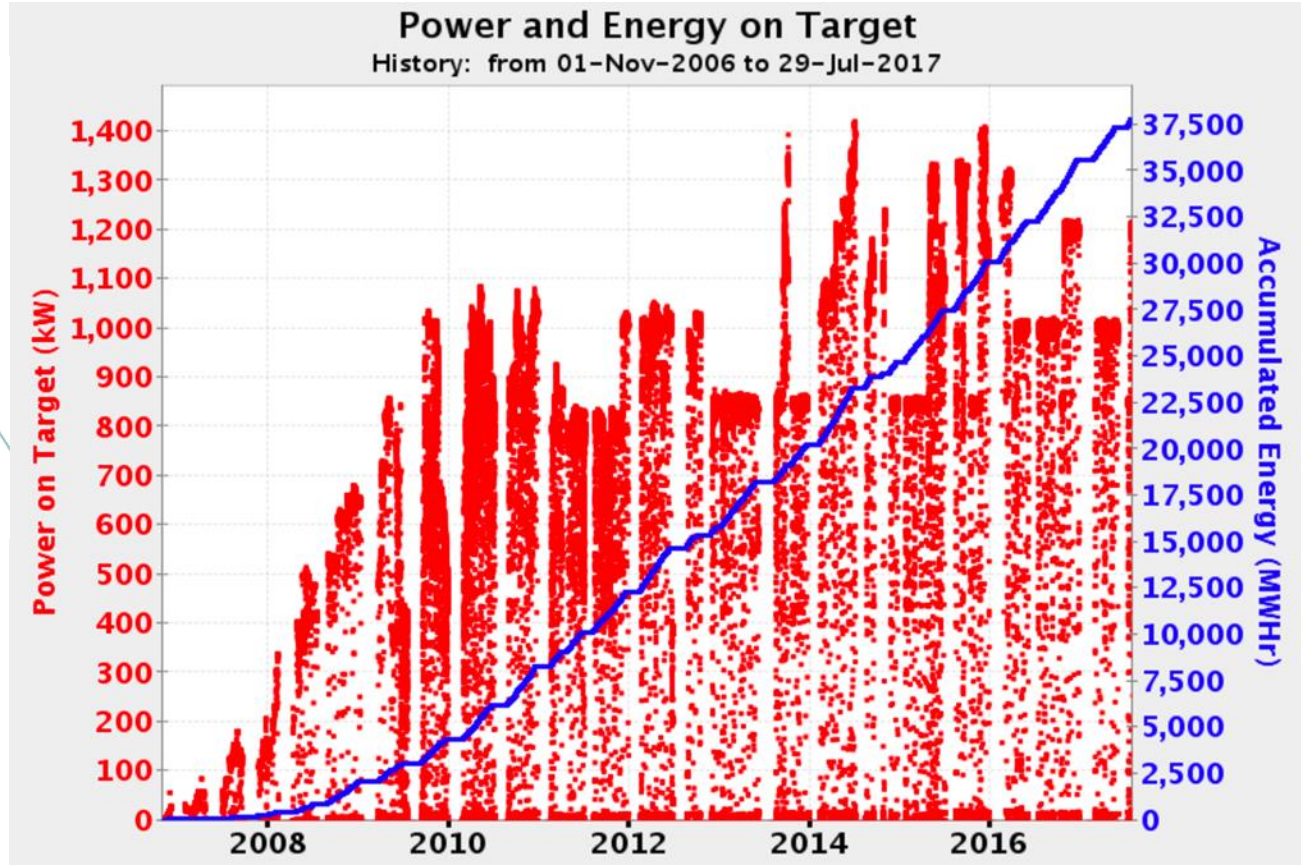
SNS, 2007



Spallation Neutron Sources

SNS: Currently at ~1.55 MW

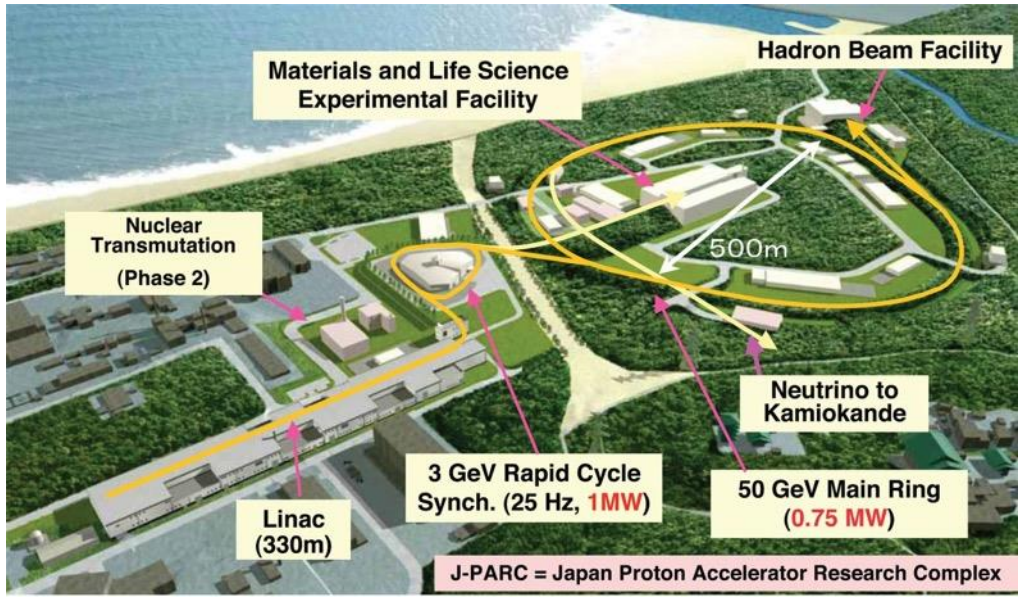




- 1 GeV, NC-SC Linac: DTL,CCL, ELL
- Accumulator Ring: 60 Hz, 1.5 MW
- Upgrades to follow

Spallation Neutron Sources

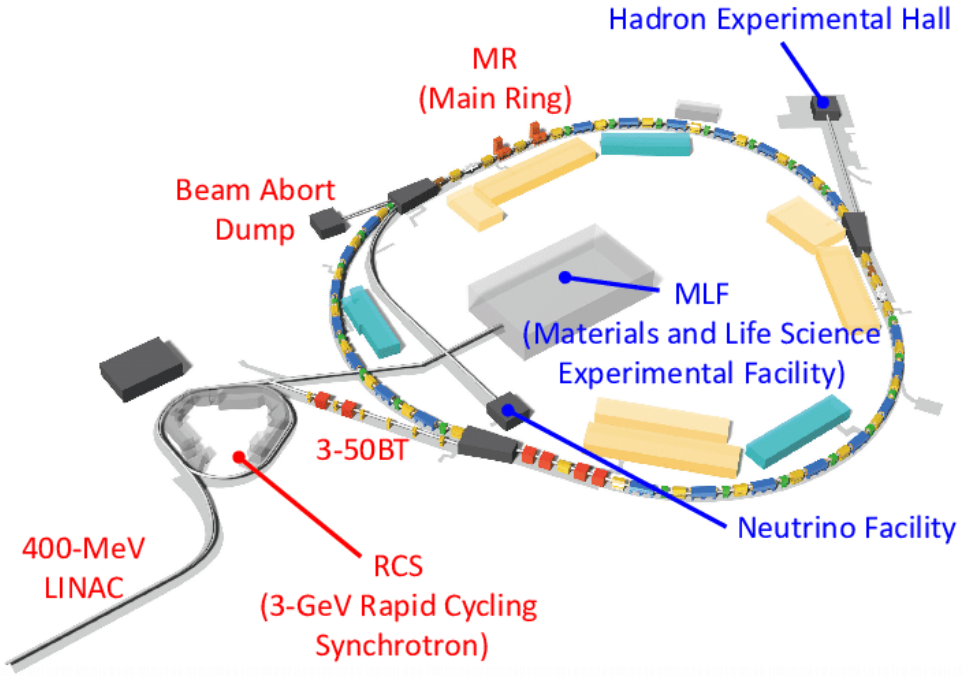
J-PARC, Multi-purpose facility, 2008: ~1 MW

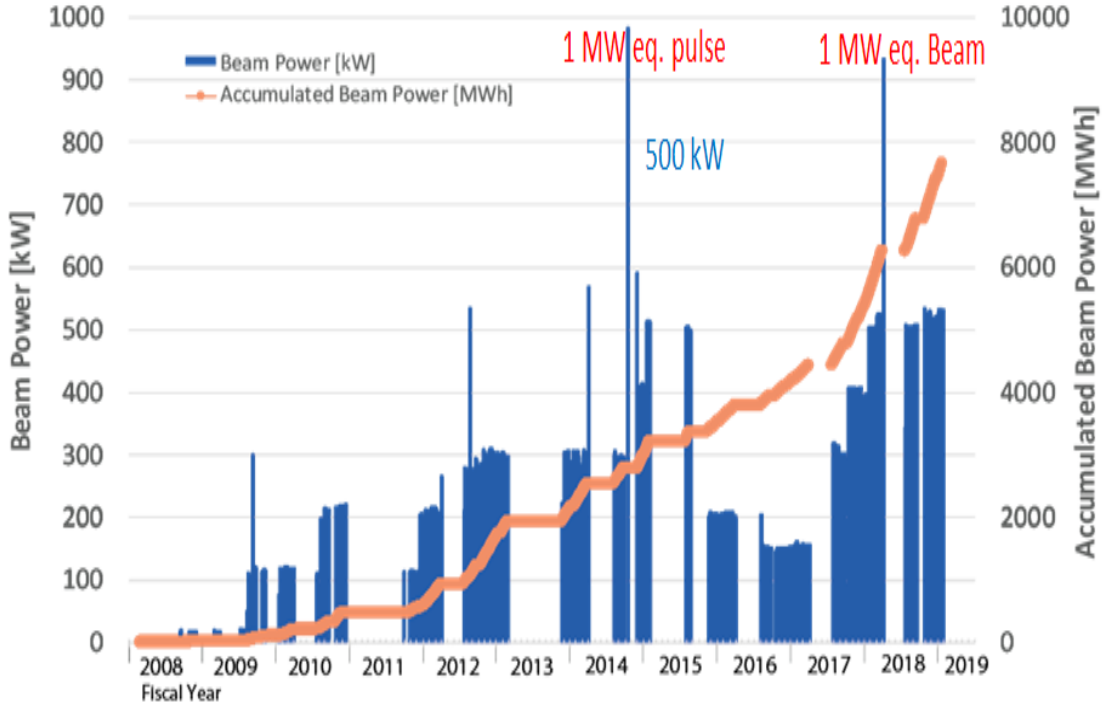


- Phase 1
  - 180 MeV H- Linac
  - 25 Hz, 3 GeV RCS, 0.5 MW
  - 30 GeV Main Ring
- Phase 2
  - 400 MeV H- Linac (completed 2014),
  - 25 Hz, 3 GeV RCS, 1.0 MW
  - 50 GeV Main Ring

Spallation Neutron Sources

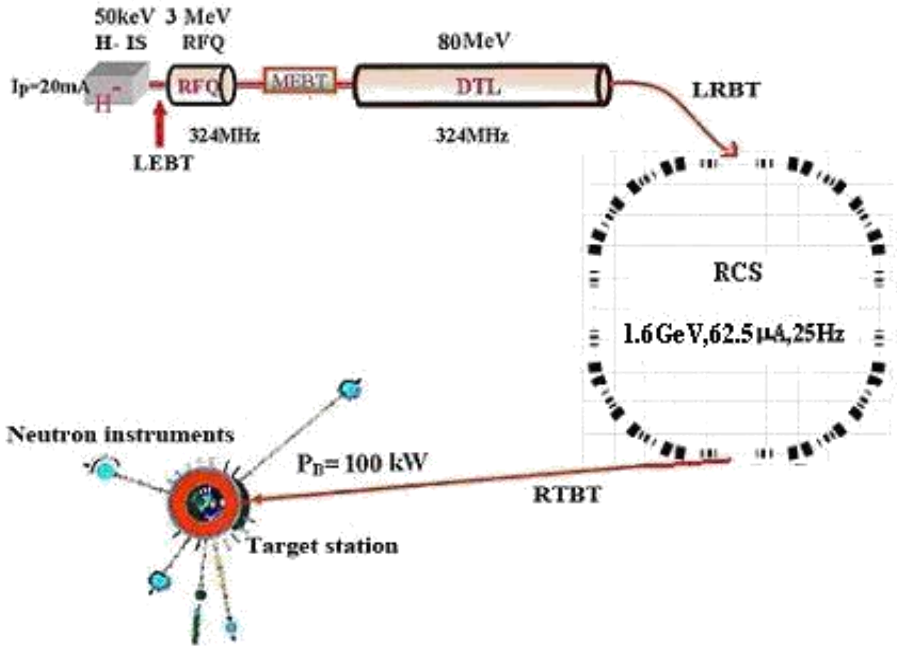
J-PARC: ~1 MW





Spallation Neutron Sources

CSNS: 100 kW -> 500 kW (upgrade)



Long Pulse Spallation Neutron Sources

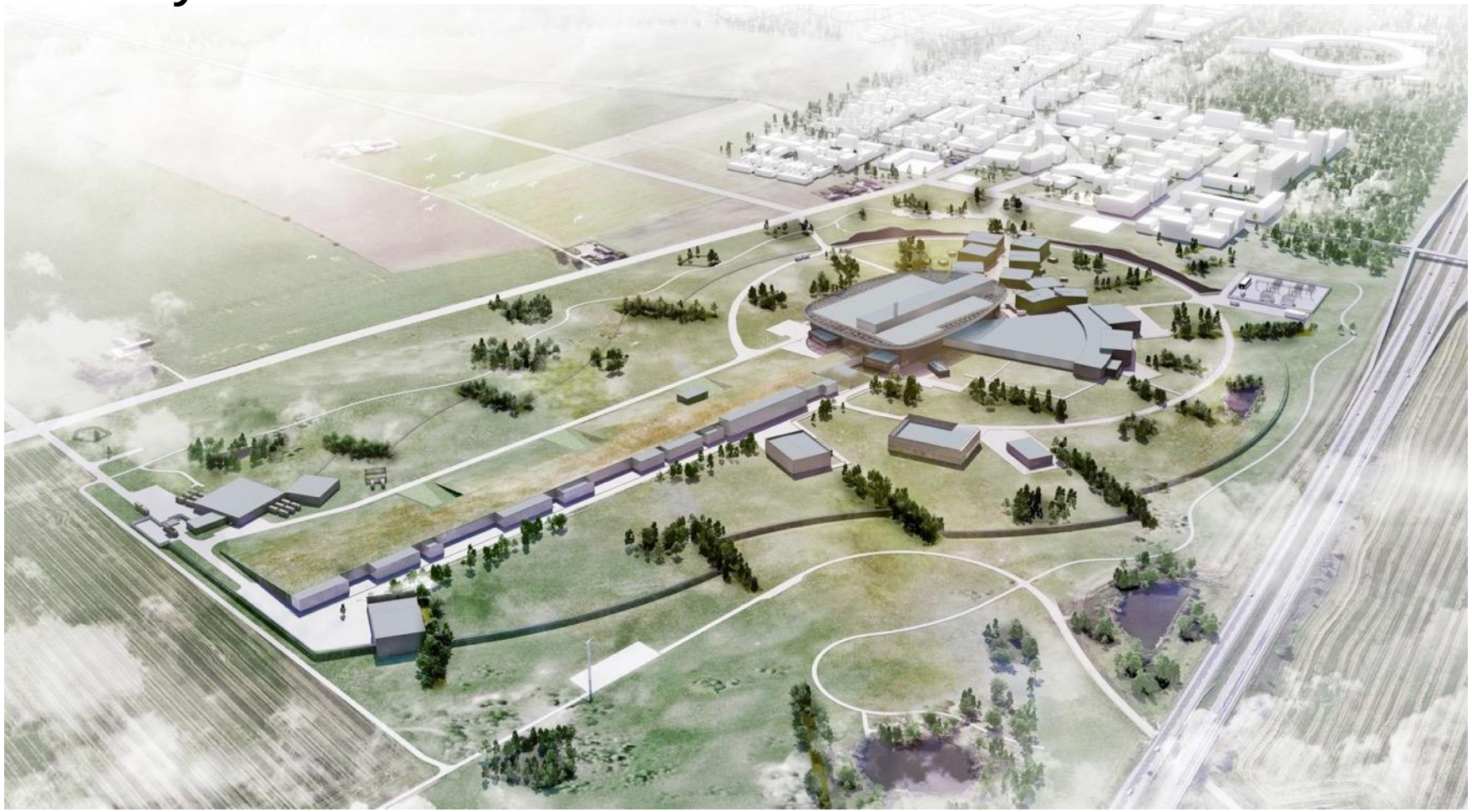
- Linac + Target
- **LAMPF (LANSCE)** – first facility
  - Los Alamos, 1977 – WNR Centre
  - 800 MeV NC Linac (DTL 202.25 MHz, SCL 805 MHz)
- High Power Operation
  - Beam Intensity:
    - space charge, resonances, halo, losses (1 W/m), front end design, etc.
  - Beam Energy:
    - NC, SC, RF Frequency choice, Efficiency (tunnel length), etc.

The European Spallation Source - ESS

A 5 MW Facility!!!

The European Spallation Source - ESS

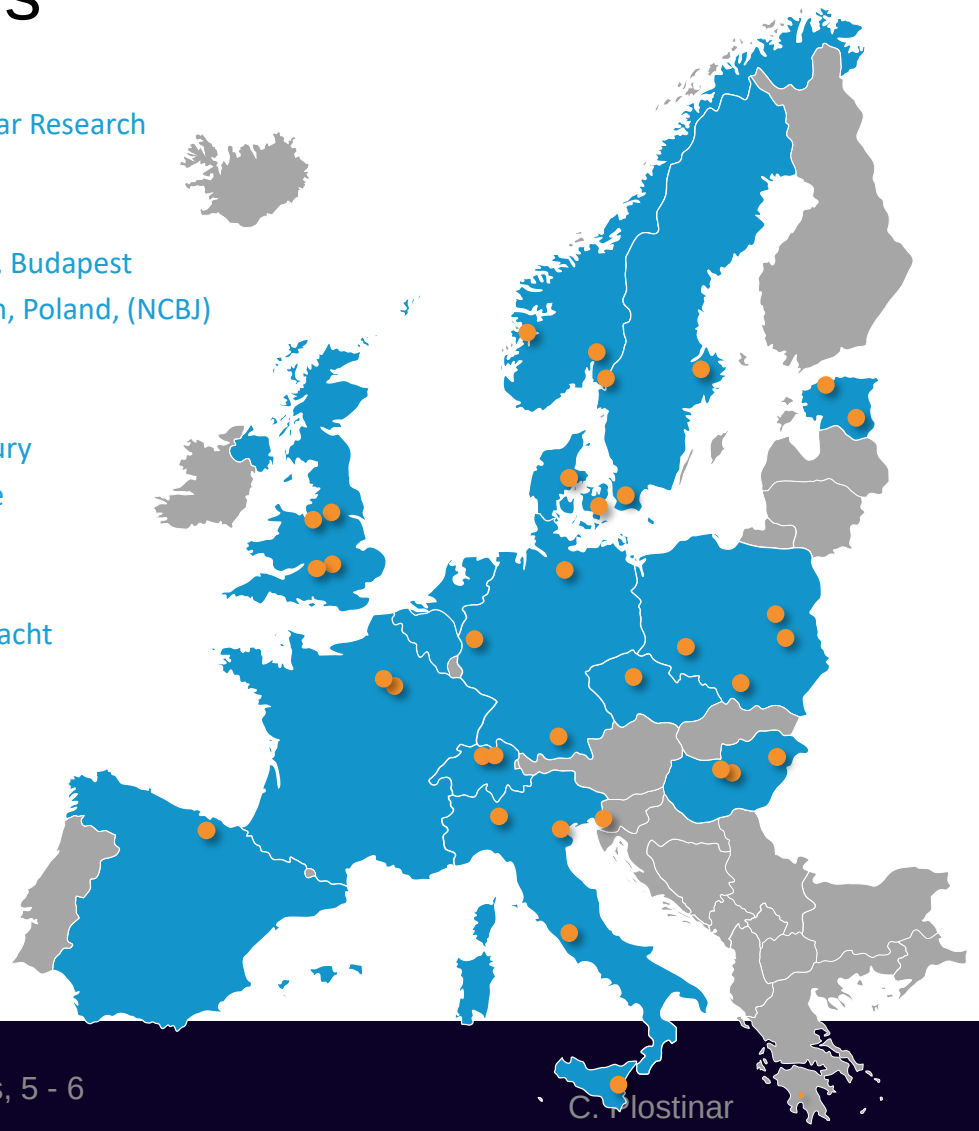
A 5 MW Facility!!!



The European Spallation Source - ESS

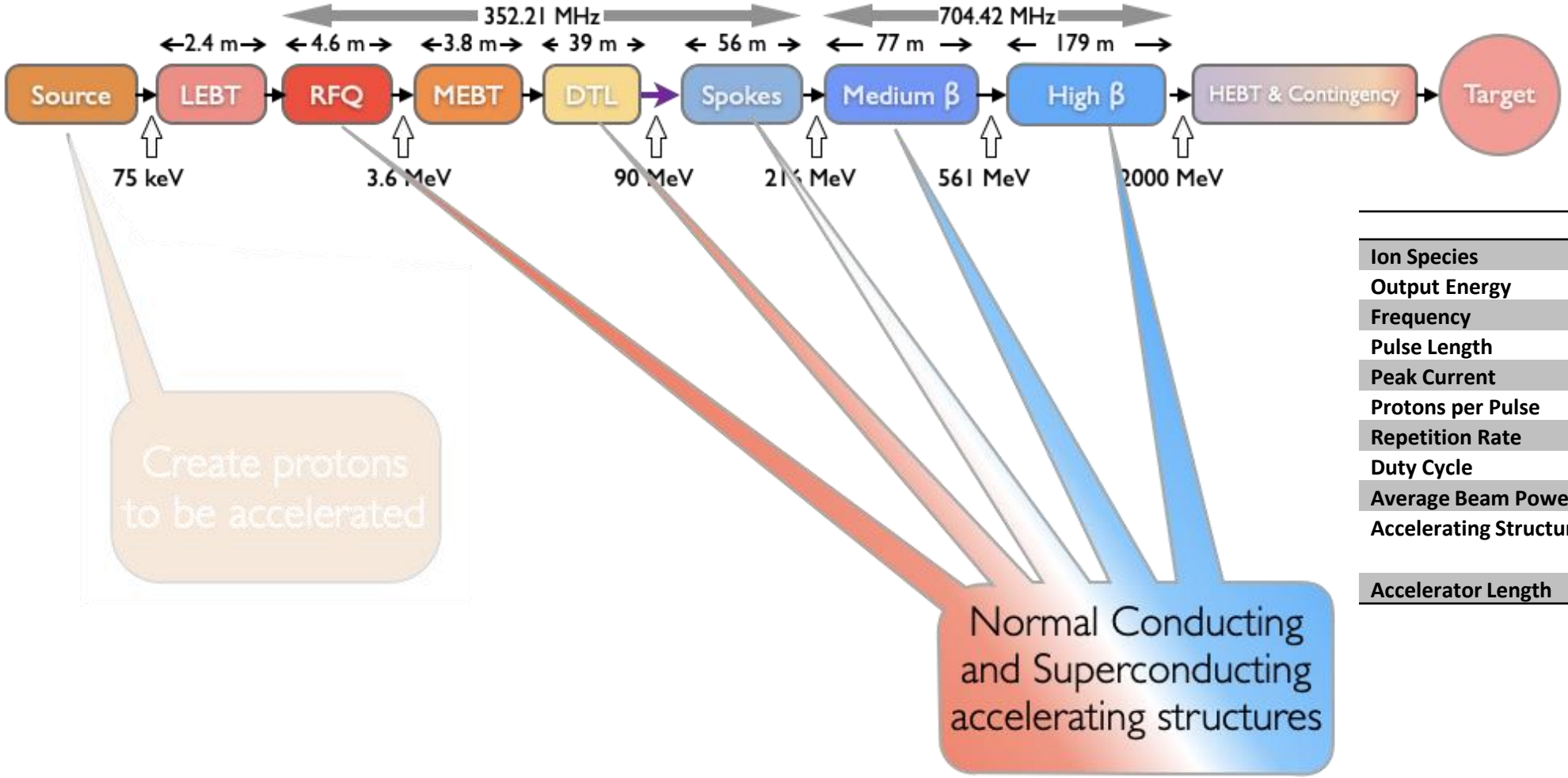
In Kind Partners

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)



ISIS - Rutherford-Appleton Laboratory, Oxford
Laboratoire Léon Brilouin (LLB)
Lund University
Nuclear Physics Institute of the ASCR
Oslo University
Paul Scherrer Institute (PSI)
Polish Electronic Group (PEG)
Roskilde University
Tallinn Technical University
Technical University of Denmark (DTU)
Technical University Munich (TUM)
Science and Technology Facilities Council
University of Copenhagen (KU)
University of Tartu
Uppsala University
Wigner Research Centre for Physics
Wroclaw University of Technology
Warsaw University of Technology
Zurich University of Applied Sciences (ZHAW)

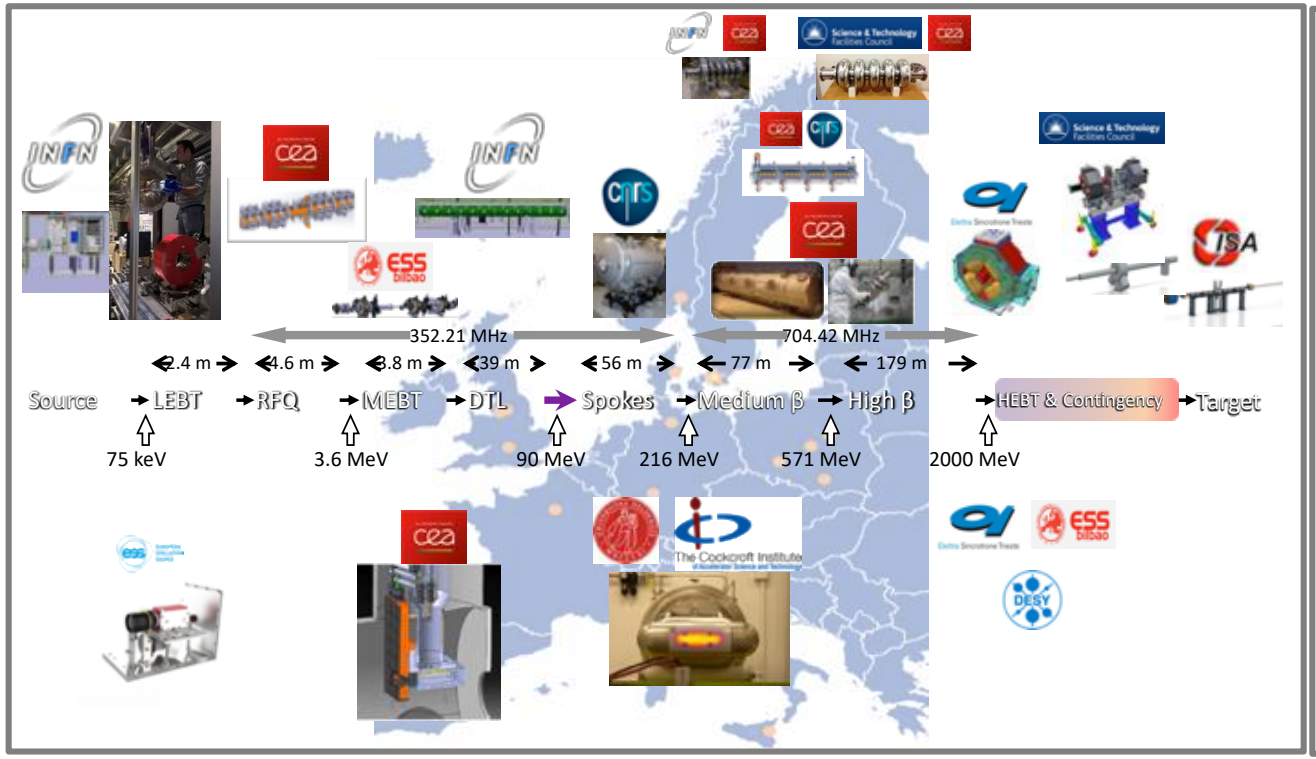
The European Spallation Source - ESS

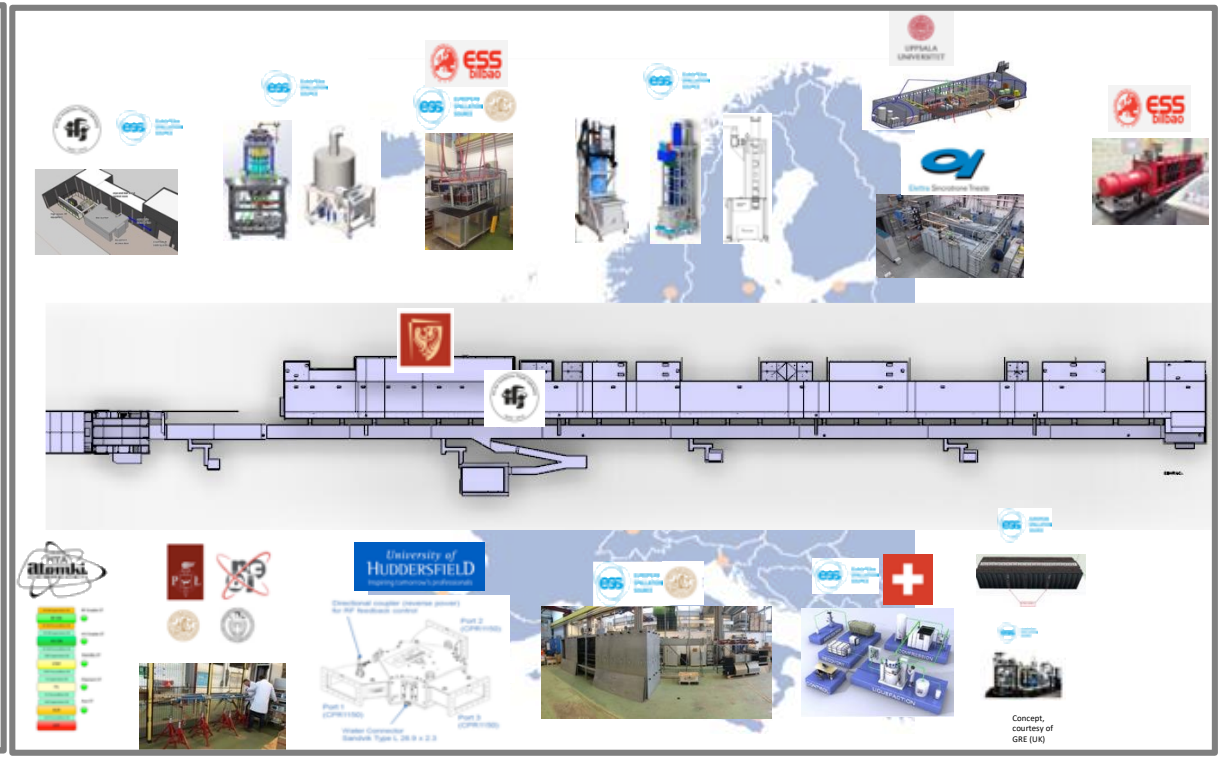


Ion Species	Protons	
Output Energy	2	GeV
Frequency	352.21/704.42	MHz
Pulse Length	2.86	Ms
Peak Current	62.5	mA
Protons per Pulse	1.1×10^{15}	
Repetition Rate	14	Hz
Duty Cycle	4	%
Average Beam Power	5	MW
Accelerating Structures	RFQ, DTL, SC Spokes/Elliptical	
Accelerator Length	~365	m

The European Spallation Source - ESS

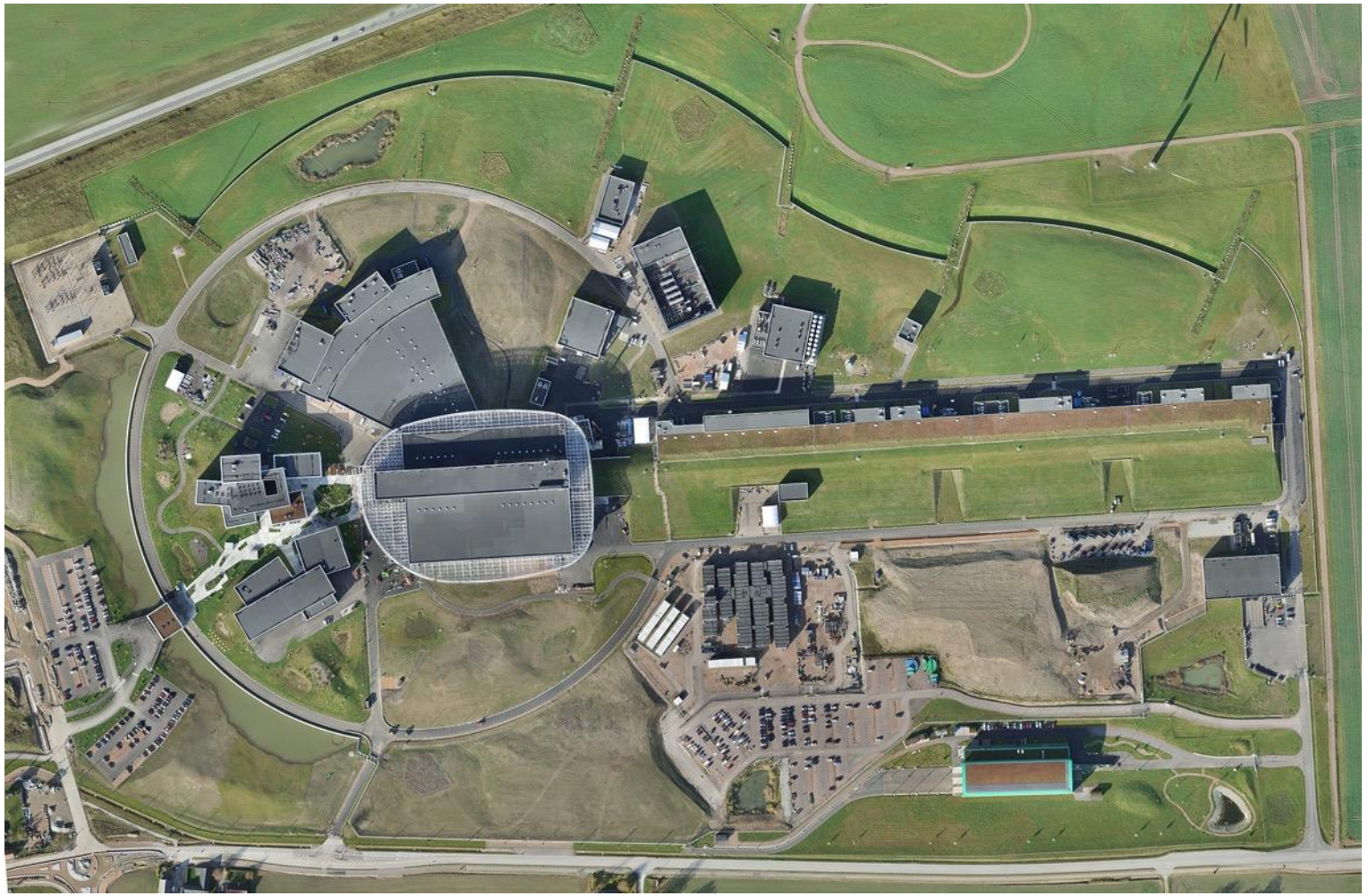
IK Partners





The European Spallation Source: 2017

The European Spallation Source: 2022



The European Spallation Source - Science

Large-Scale Structures

- **Multi-Purpose Imaging ODIN**
- **General-Purpose SANS SKADI**
- **Broadband SANS LOKI**
- Surface Scattering
- **Horizontal Reflectometer FREIA**
- **Vertical Reflectometer ESTIA**
- **Thermal Powder Diffractometer HEIMDAL**
- **Bispectral Powder Diffractometer DREAM**

Diffraction

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

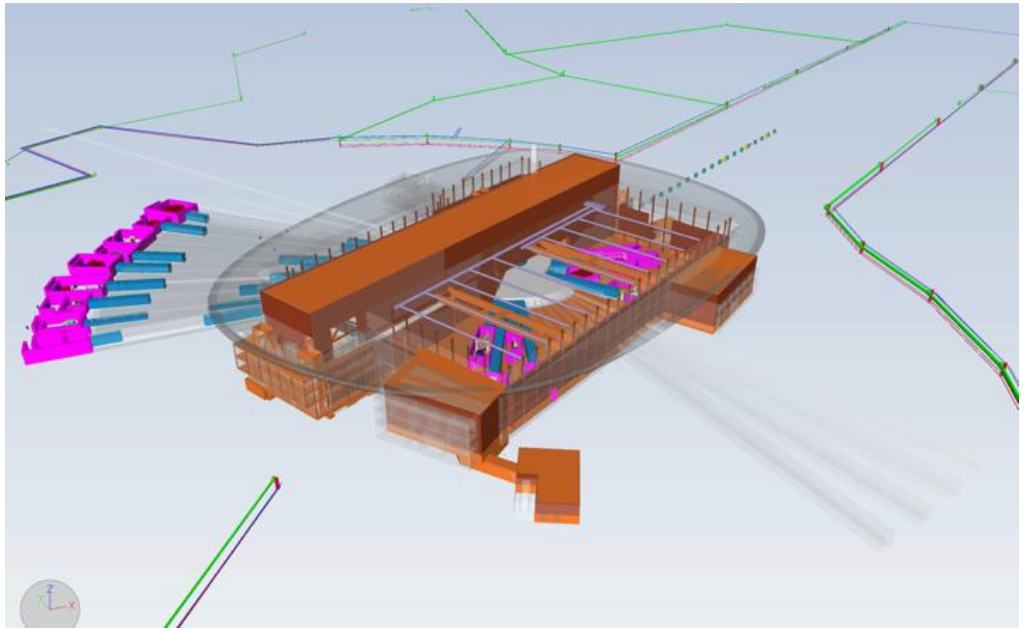
Spectroscopy

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

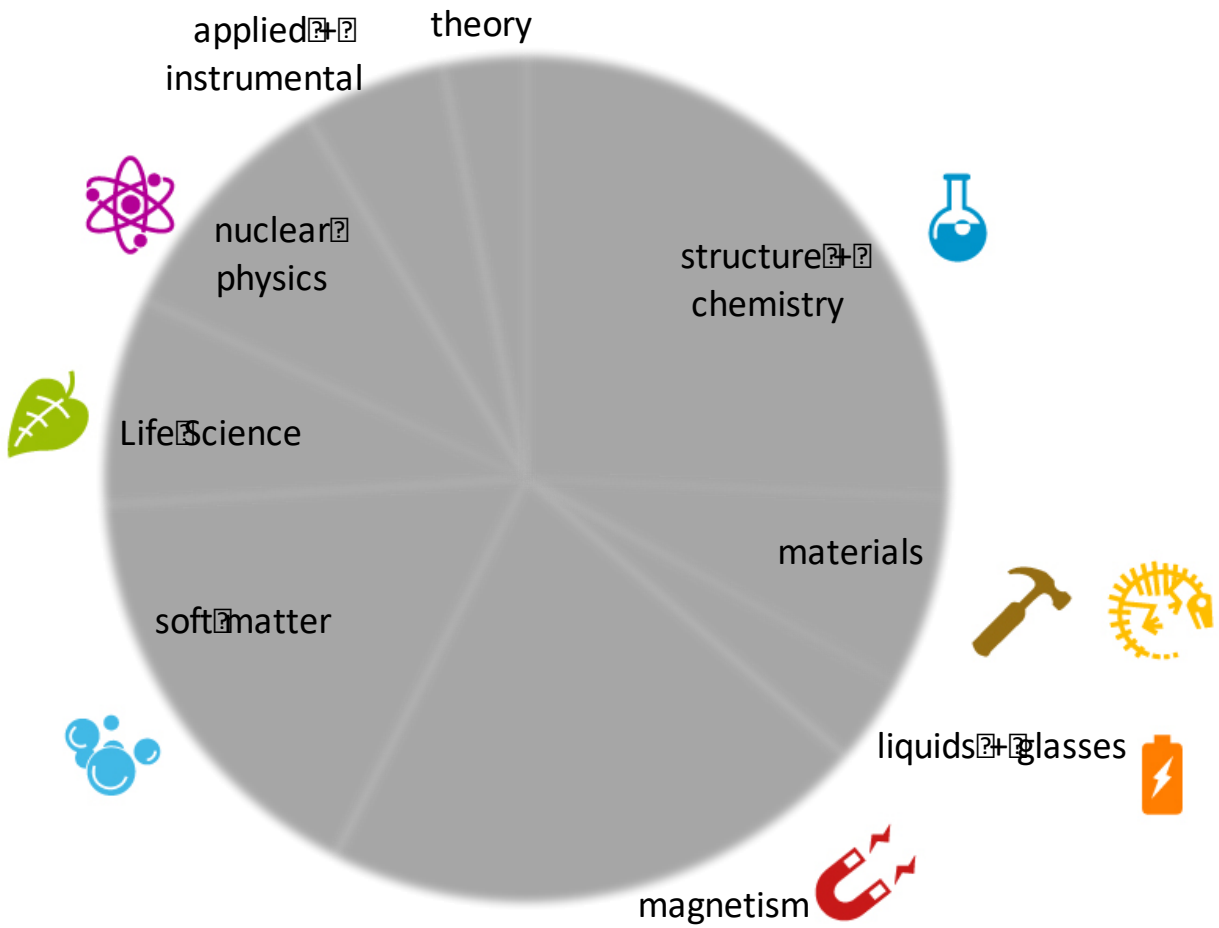
Fundamental & Particle Physics

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

Courtesy of A. Hiess



The European Spallation Source - Science

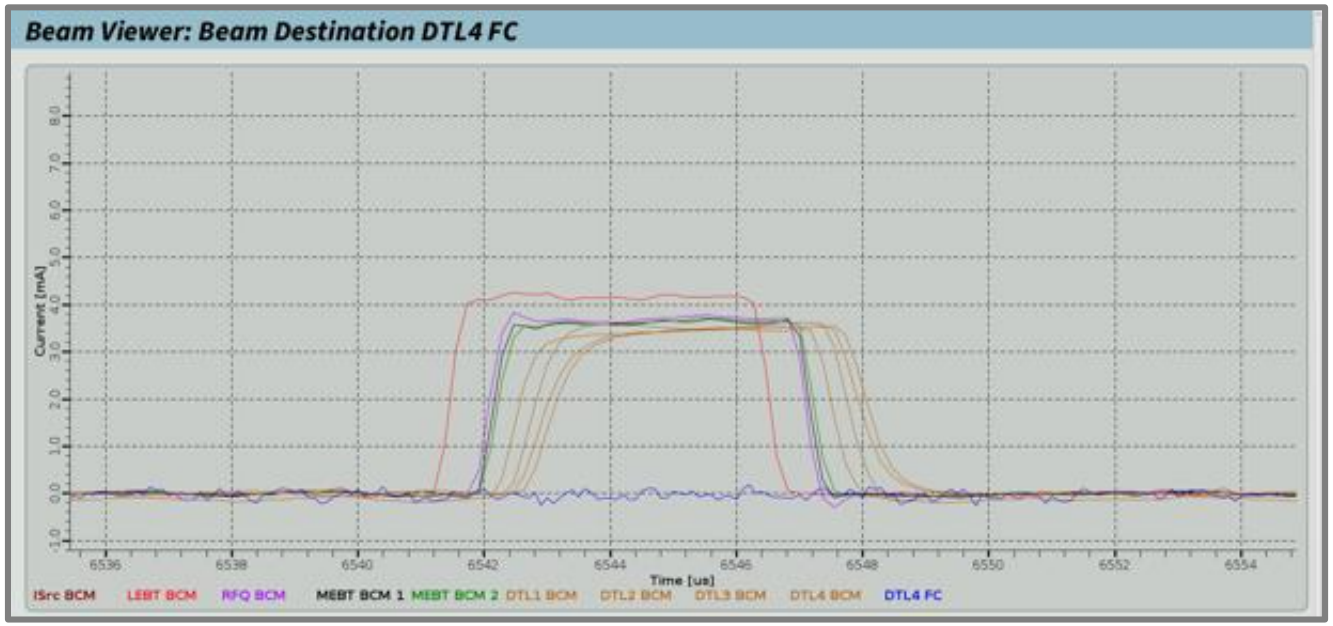


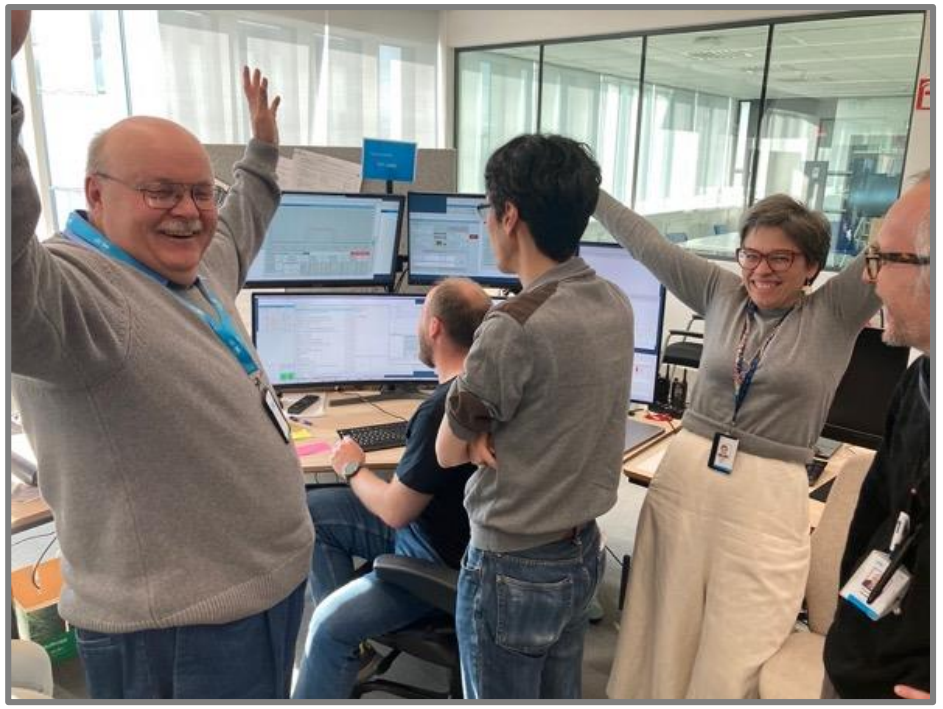
21st Century Challenges

- Medicine and biotechnology
- Energy
- Fuels
- Batteries
- Environment
- New materials/Intelligent Materials
- Day to Day Chemistry
- Food
- Etc.

The European Spallation Source - ESS

18 April 2023: First Beam to DTL4



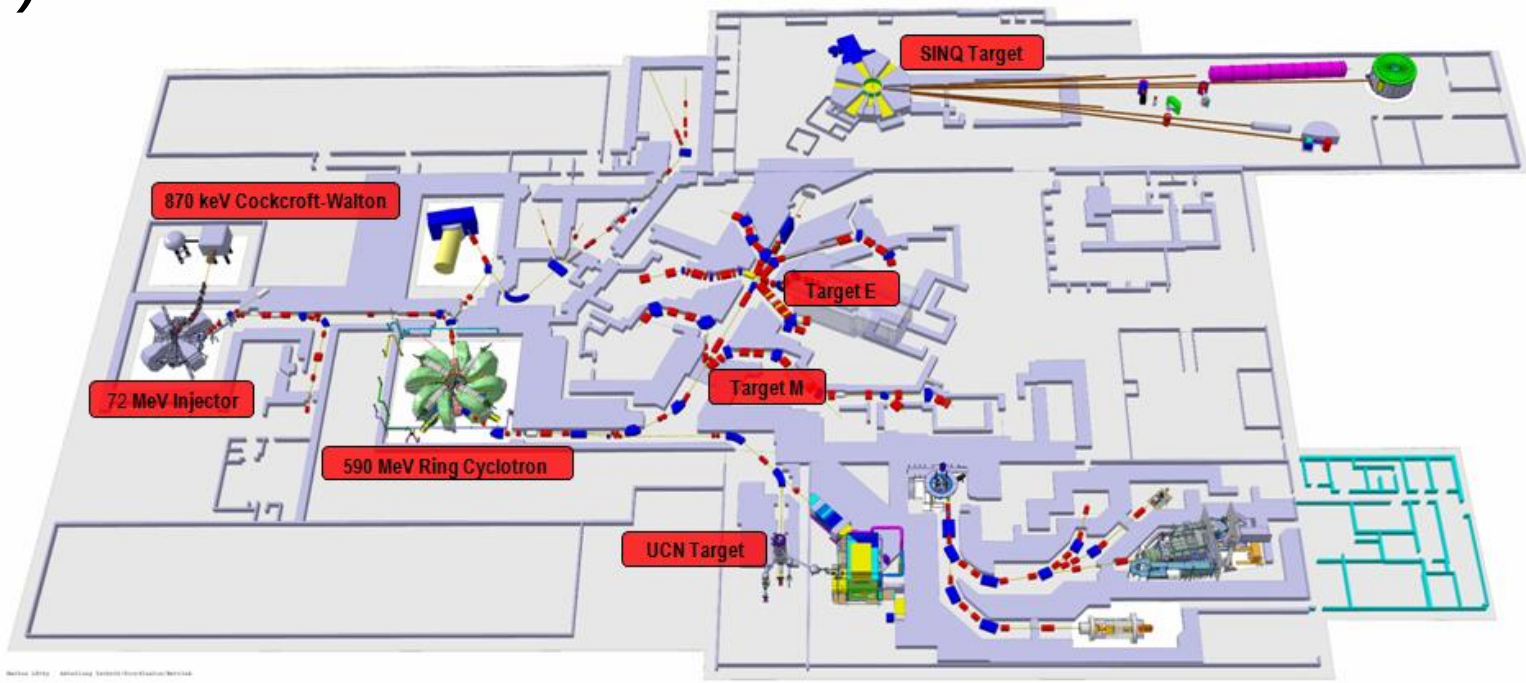


CW Spallation Neutron Sources

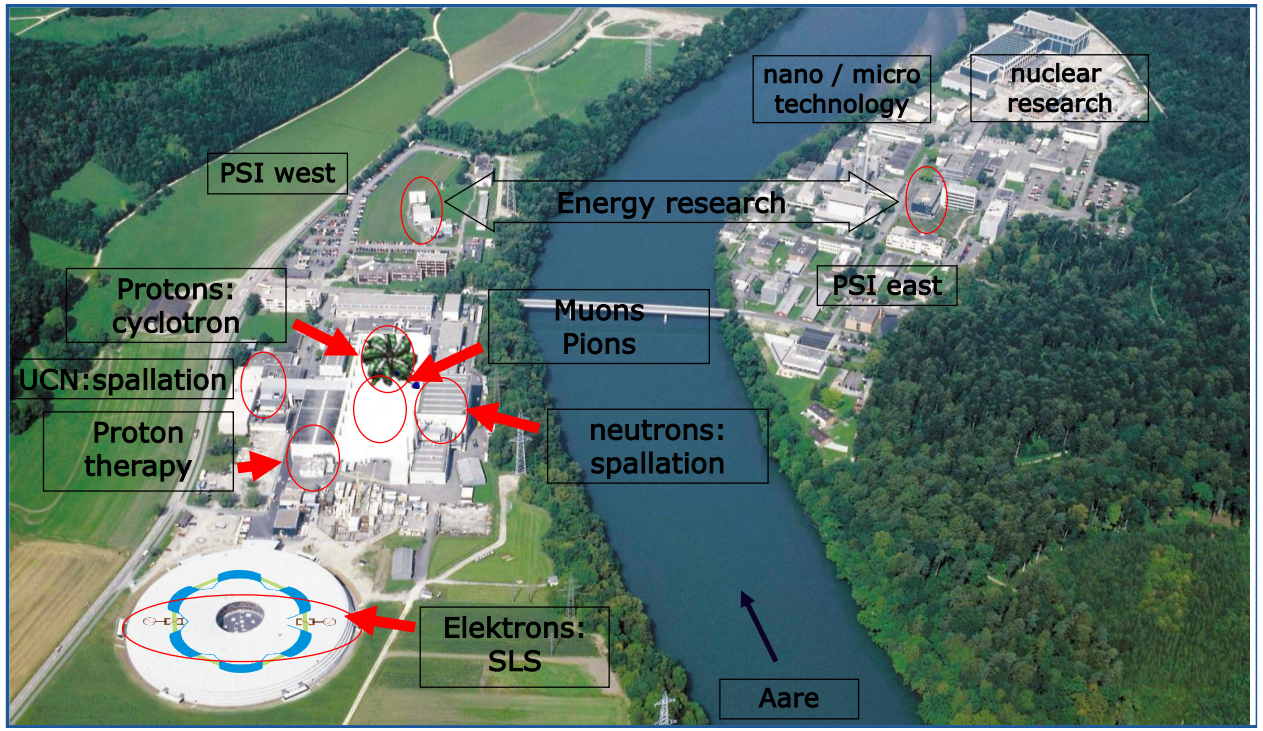
- Cyclotrons
  - Long history (1931)
  - Many applications
  - CW injection, acceleration and extraction
  - High beam power
  - Sector Magnets, RF Cavities, Injection, Extraction, etc.
    - No frequency sweeping or field ramping
    - Magnets rather heavy and complex
  - Issues
    - Beam loss
    - Clean extraction
    - Space charge forces can limit high intensity operation
    - For high power, larger diameter is needed

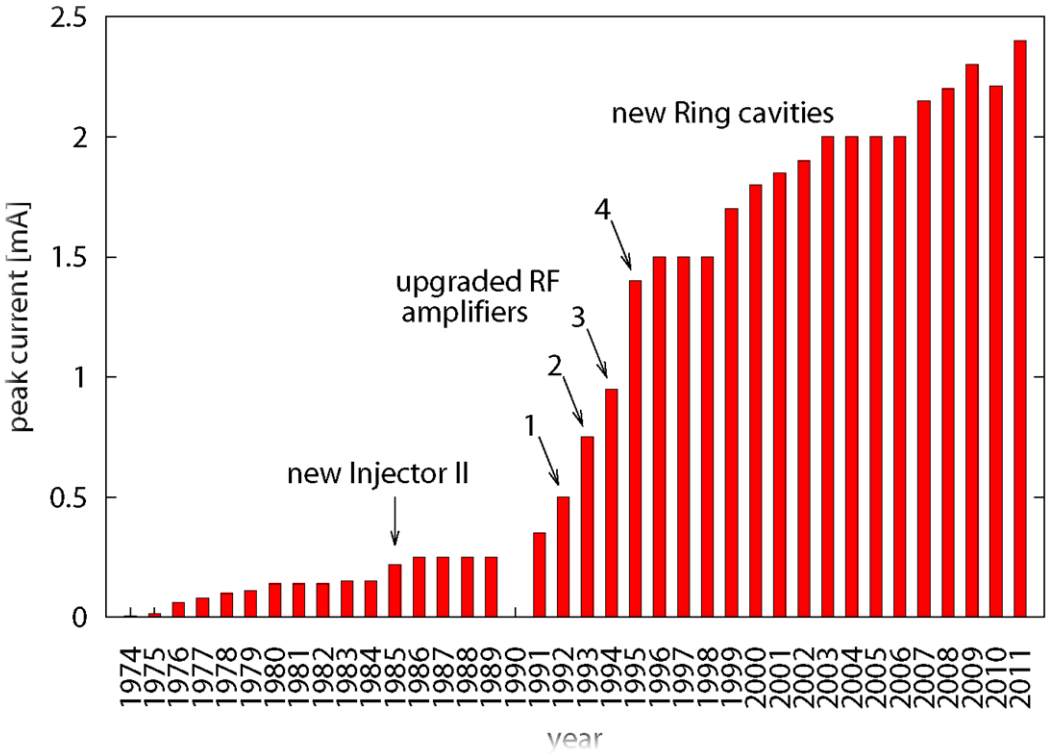
PSI

- Multipurpose facility (1974)
- 1.3 MW beam power
  - 0.86 MW for spallation (SINQ)
- Accelerator: 2.2 mA CW
  - CW, 72 MeV Injector (Cyclotron), 590 MeV Cyclotron



PSI


nano / micro technology
nuclear research
PSI west
Energy research
PSI east
Protons: cyclotron
Muons Pions
UCN:spallation
Proton therapy
neutrons: spallation
Elektrons: SLS
Aare


peak current [mA]
2.5
2
1.5
1
0.5
0
new Ring cavities
upgraded RF amplifiers
new Injector II
1
2
3
4
1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011
year

Compact accelerator based neutron sources (CANS)

- From large facilities (SNS, ISIS, ESS, etc) to small local machines
  - Important cost aspects, users/community needs
- Neutrons are produced by the nuclear capture reaction between a low energy beam and light elements as beryllium or lithium.
- Some examples:
- Jülich Centre for Neutron Science: electrostatic tandem accelerator producing a pulsed proton beam of 10 MeV at 1 mA peak current and an average power of 400 W. Beryllium target.
- PC-CANS (proposed – Canada): IS, LEBT, RFQ, MEBT, DTL. 10 MeV proton beam.

Conclusion

https://www.youtube.com/watch?v=VESMU7JfVHU

PhD and Postdoc position at ESS

- We are looking for motivated students and young scientists to work, together with the ESS team, on future high intensity hadron machines.
- We have a **PhD position** already open (see ESS vacancies website) to work on high intensity effects and a simulator package for linac and rings.
- We will open soon a **Postdoc position** to work directly on the design and simulation of an accumulator and compressor ring for a future Muon Collider Facility (this is a EU project in connection with CERN and many other EU labs.)
- Contacts:
  - Natalia Milas (Natalia.milas@ess.eu)
  - Emanuele Laface (Emanuele.laface@ess.eu)