



14<sup>th</sup> International Particle  
Accelerator Conference

# IPAC '23

7 - 12 May 2023  
VENICE, ITALY

Hosting institutions




Elettra Sincrotrone Trieste



Istituto Nazionale di Fisica Nucleare



A photograph of St Mark's Square in Venice at dusk. The square is paved with a geometric pattern of light and dark stones. On the left, the ornate facade of St Mark's Basilica is visible, featuring Gothic arches and a balcony. In the center, the Lion of Saint Mark stands atop a tall column. The sky is a mix of blue and orange, with clouds. In the background, the Campanile di San Marco is visible.

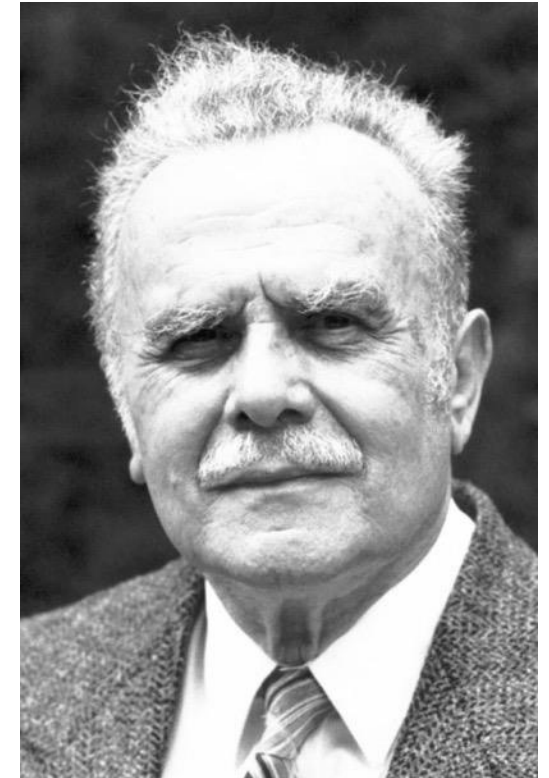
# Accelerator Based Neutron Sources

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

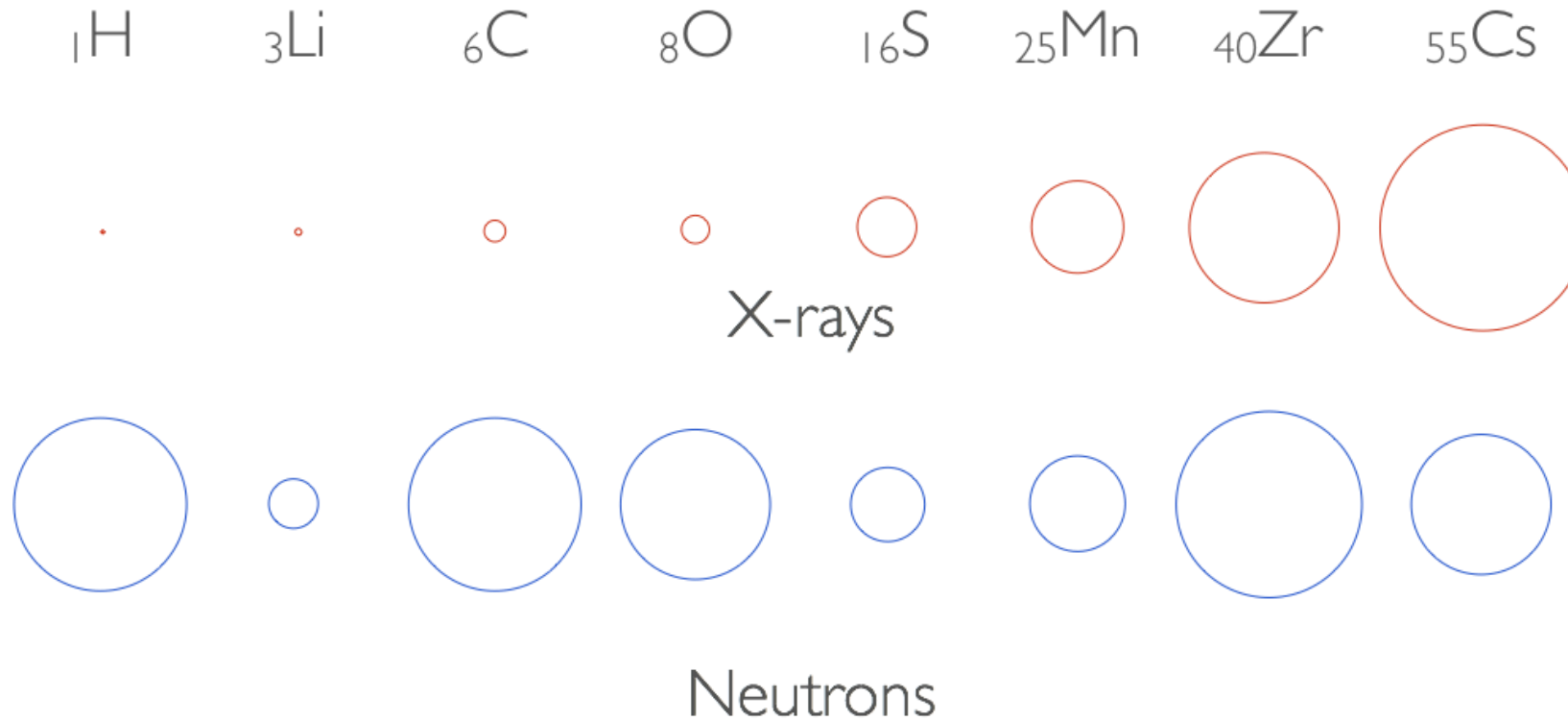
“For pioneering contributions to the development of neutron scattering techniques for studies of condensed matter”



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



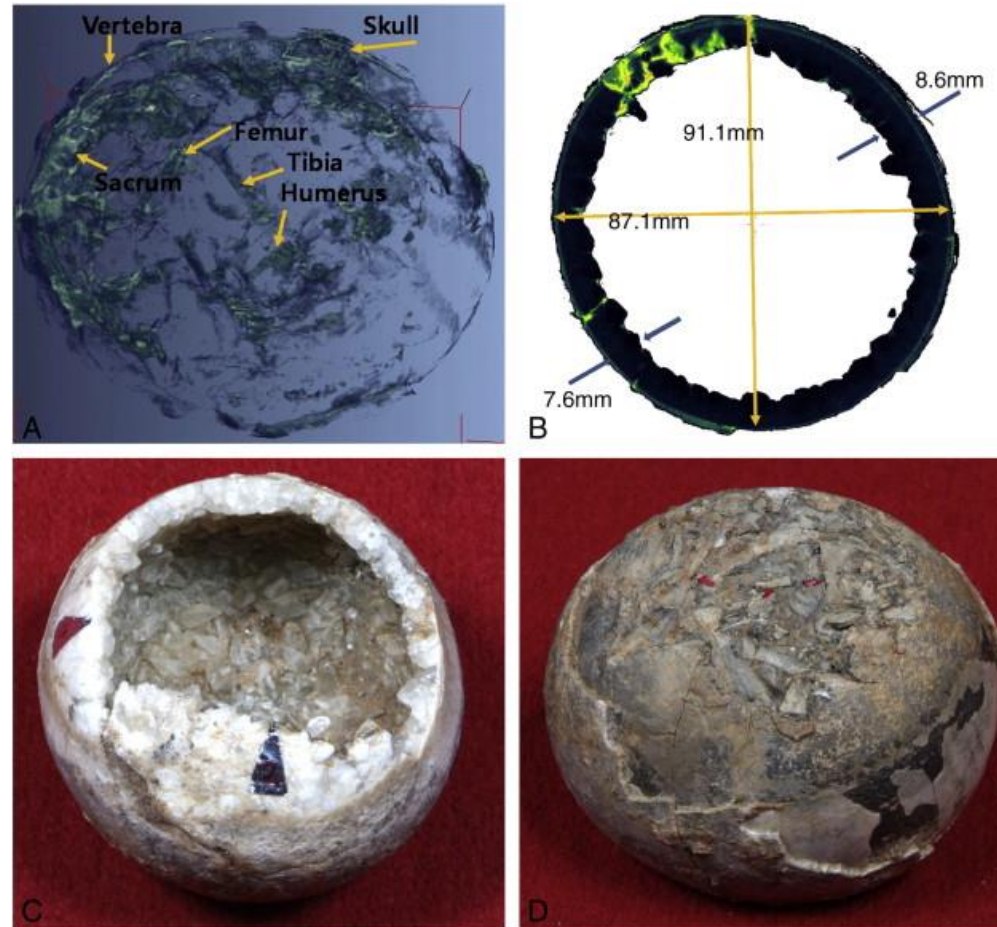
Source: [airbus.com](https://www.airbus.com)

# Exploring unconventional superconductors using neutron spectroscopy



Source: wikipedia.org

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



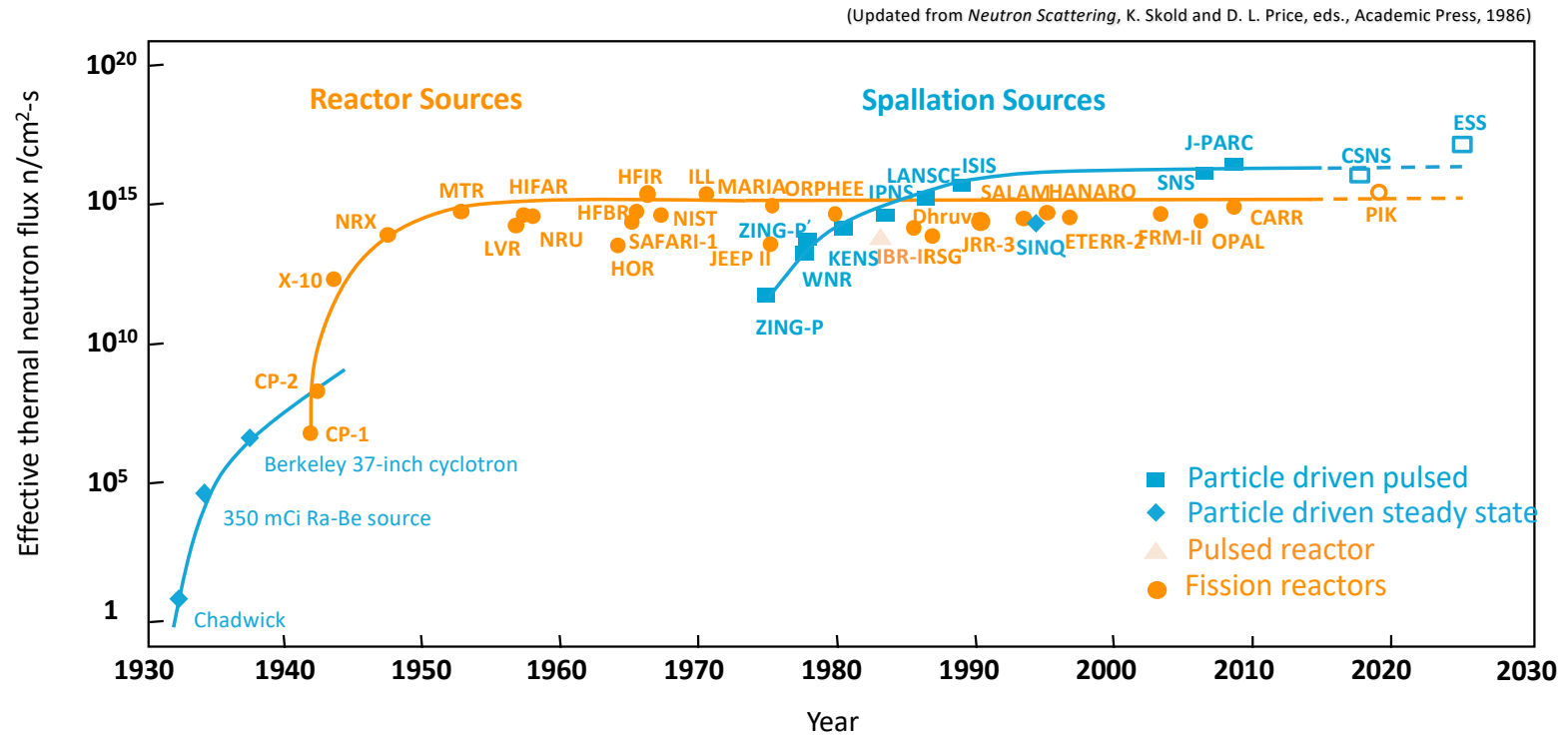


# Using neutrons to study the crystallisation of ice cream in real time



# Neutron Production

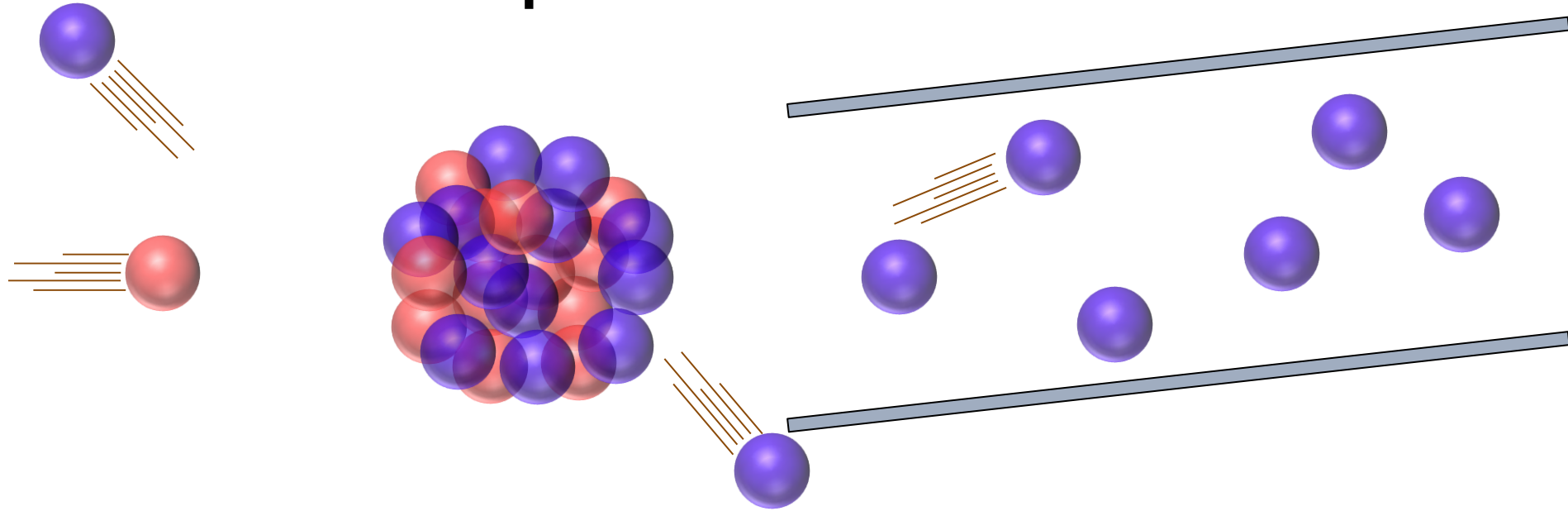
- Small:
  - Alpha (i.e.  ${}^9\text{Be} + \alpha \rightarrow {}^{12}\text{C} + n + \gamma$ )
  - Gamma
  - Spontaneous fission sources
- Reactors
- **Accelerators**



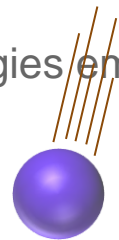
# Neutron Production



# 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).

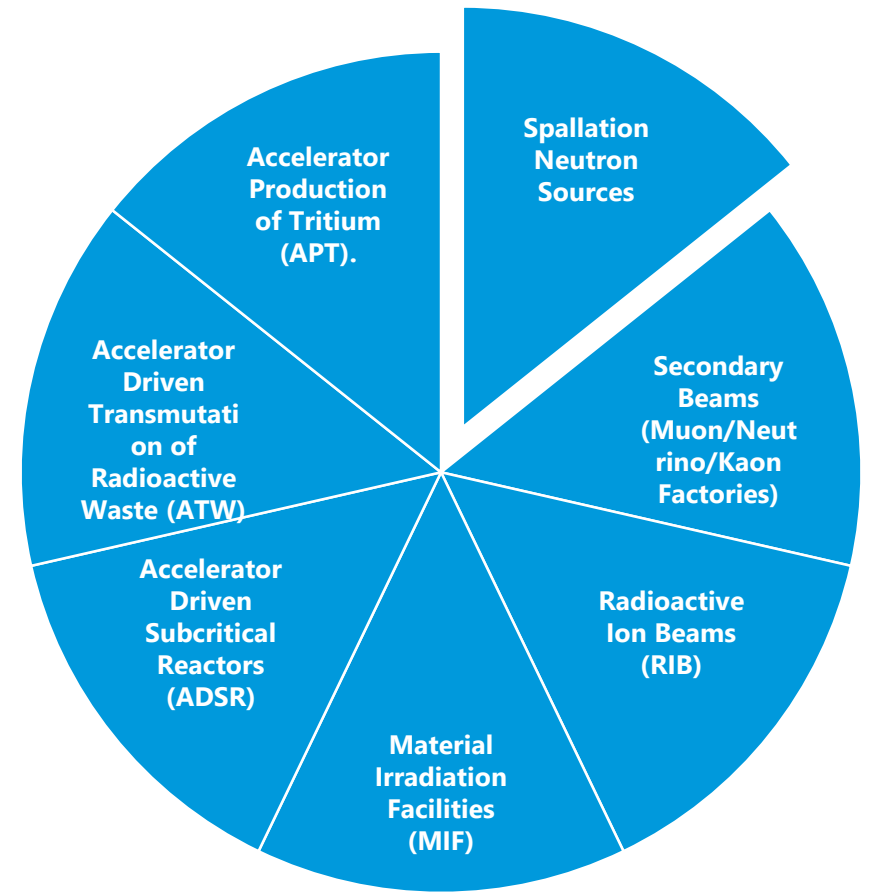
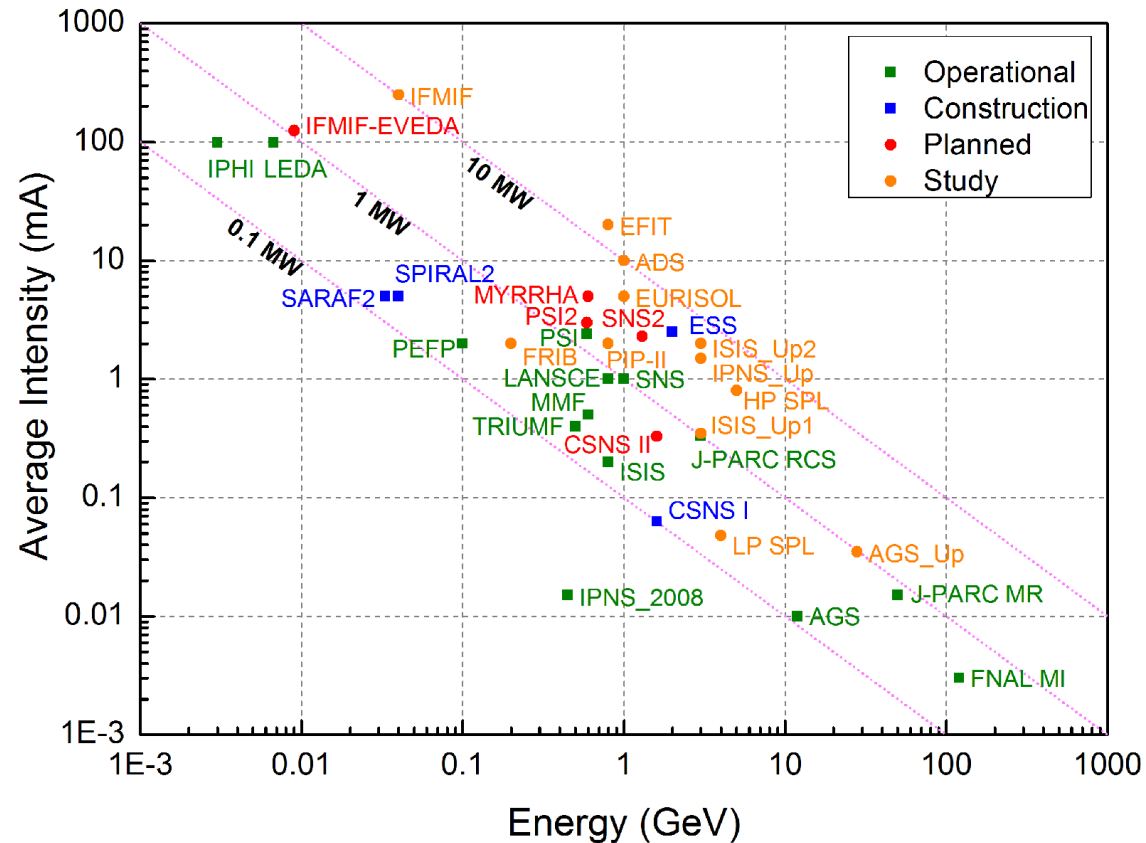
- **Accelerator Driven Transmutation of Radioactive Waste (ATW)**

- TRASCO (IT)

- **Accelerator Production of Tritium (APT).**

- APT@LANL (USA)

# Global Demand for High Power Beams



# Accelerator Beam Power

## Optimisation

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

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

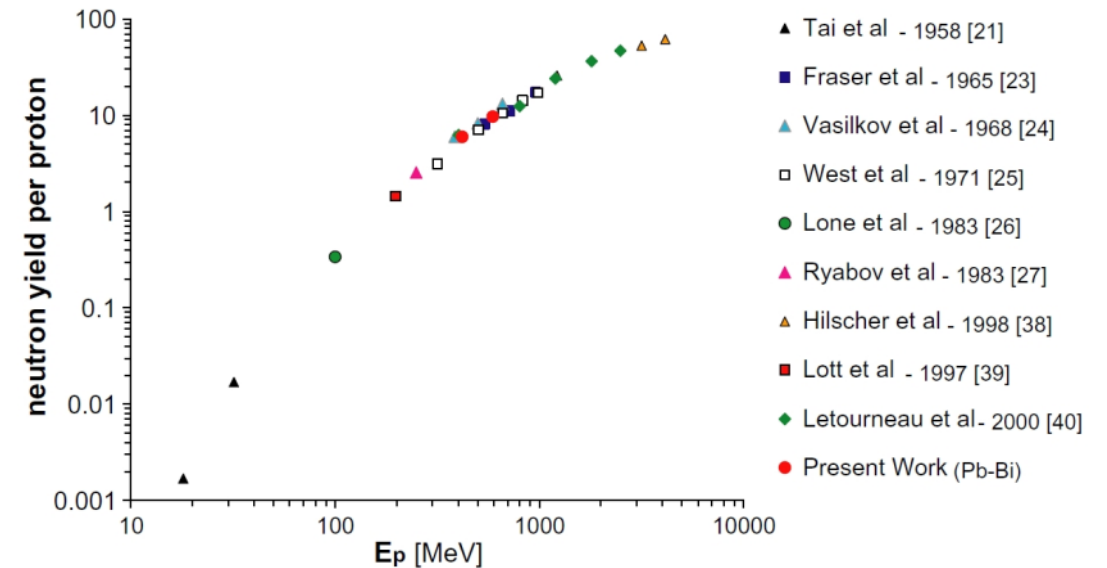
$$W_{linac} = q \sum_i E_{acc_i} T_i L_i \cos(\phi_i)$$



# 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

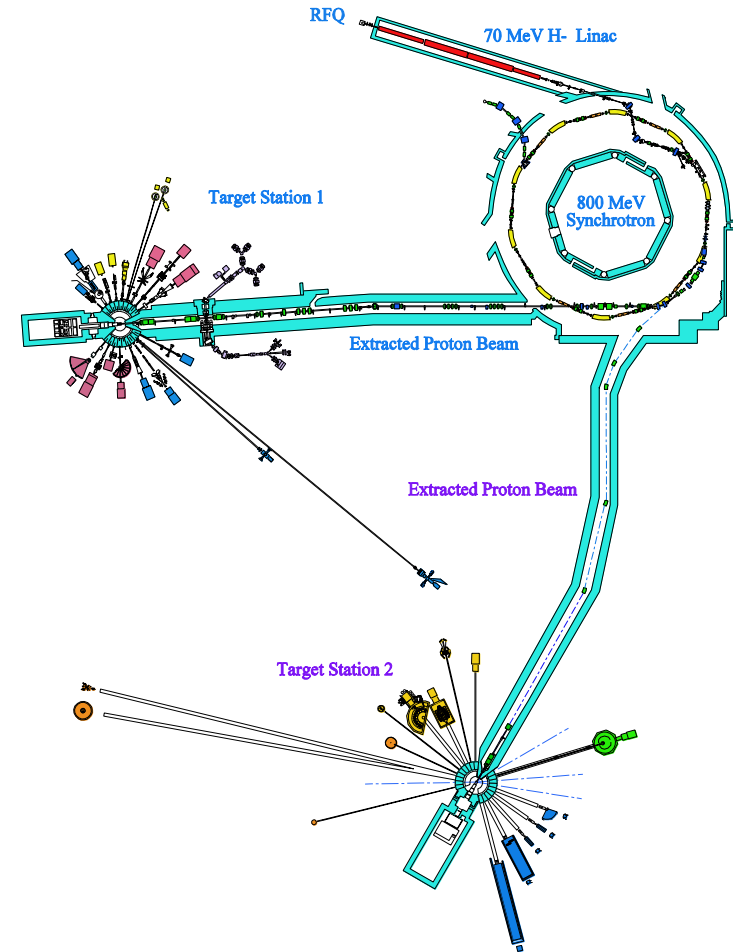
- Short Pulse
  - Synchrotrons or compressor rings
  - Pulse length:  $\sim\mu\text{s}$
- Long Pulse
  - Linacs
  - Pulse length:  $\sim\text{ms}$
- Continuous
  - Cyclotrons

# 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

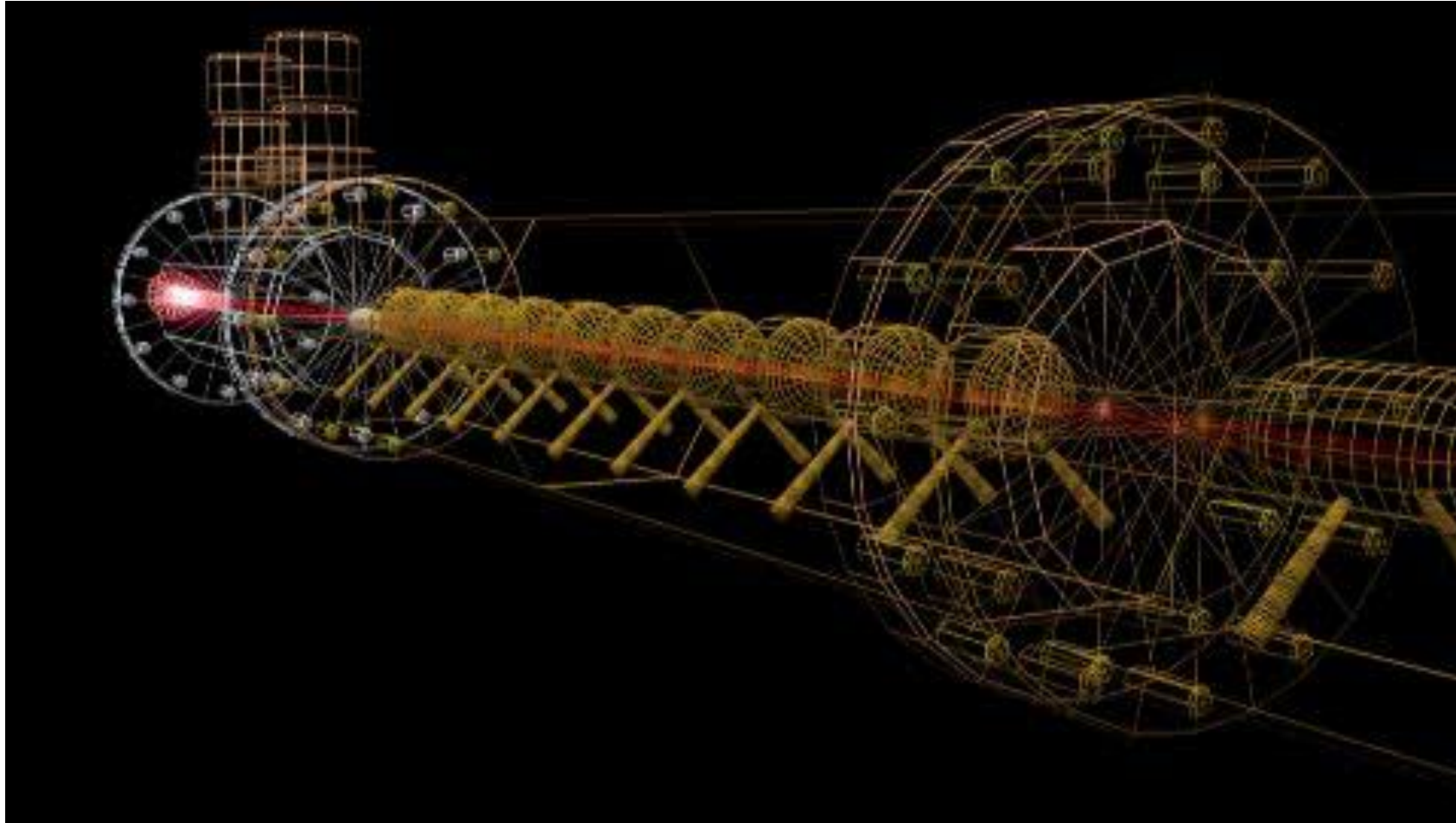
- Inaugurated in 1984
- Accelerator:
  - H<sup>-</sup> Ion Source
  - LEBT
  - 0.665 MeV RFQ, 202.5 MHz
  - 70 MeV Linac (4 DTL Tanks)
  - 800 MeV proton synchrotron
- ~230  $\mu\text{A}$  ( $2.9 \cdot 10^{13}$  ppp)
- 50 Hz, 184 kW (~25\*IPNS)
  - 148 kW to TS-1 (40 Hz)
  - 36 kW to TS-2 (10 Hz)



# 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..."

ISIS neutron source

From Wikipedia, the free encyclopedia

This is an old revision of this page, as edited by Isander (talk) (contrib) on 18:18, 21 July 2007. It may differ significantly from the current revision.

The **ISIS neutron source** is currently (2007) **most powerful spallation neutron source in the world**. It is situated at the Rutherford Appleton Laboratory in Oxfordshire, United Kingdom. It is used to enable neutron scattering experiments and properties of matter, from the atomic to the biological scales. It provides a powerful research tool for universities and companies across many disciplines, including physics, chemistry, materials engineering, biology and even archaeology.

It currently (2007) generates the most powerful neutron beam of any such facility in the world, but may possibly be overtaken in this by the Spallation Neutron Source currently being constructed at Oak Ridge, Tennessee.<sup>[1]</sup>

**Contents** [hide]

- Neutrons and muons
- Science at ISIS
- External links
- References

**Neutrons and muons**

Neutrons are uncharged constituents of atoms and penetrate materials well, deflecting only from the nuclei of atoms. The statistical accumulation of deflected neutrons at different positions beyond the sample can be used to find the structure of a material, and the loss or gain of energy by neutrons can

03:02, 12 August 2007:  
**ISIS** is "...the second most powerful..."

ISIS neutron source

From Wikipedia, the free encyclopedia

This is an old revision of this page, as edited by 168.91.233.143 (talk) on 03:02, 12 August 2007. It may differ significantly from the current revision.

The **ISIS neutron source** is currently (2007) **the second most powerful spallation neutron source in the world**. It is situated at the Rutherford Appleton Laboratory in Oxfordshire, United Kingdom. It is used to enable neutron scattering experiments and properties of matter, from the atomic to the biological scales. It provides a powerful research tool for universities and companies across many disciplines, including physics, chemistry, materials engineering, biology and even archaeology.

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09:52, 18 September 2007:  
**ISIS** is "...one of the most powerful..."

ISIS neutron source

From Wikipedia, the free encyclopedia

This is an old revision of this page, as edited by Trowan (talk) (contrib) on 09:52, 18 September 2007. It may differ significantly from the current revision.

The **ISIS neutron source** is currently (2007) **one of the most powerful spallation neutron sources in the world**. It is situated at the Rutherford Appleton Laboratory in Oxfordshire, United Kingdom. It is used to enable neutron scattering experiments and properties of matter, from the atomic to the biological scales. It provides a powerful research tool for universities and companies across many disciplines, including physics, chemistry, materials engineering, biology and even archaeology.

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09:52, 03 October 2007:  
**ISIS** is "...a world leading neutron source..."

ISIS neutron source

From Wikipedia, the free encyclopedia

This is an old revision of this page, as edited by 216.194.141.141 (talk) on 09:52, 03 October 2007. It may differ significantly from the current revision.

**World leading neutron and muon source** situated at the Rutherford Appleton Laboratory in Oxfordshire, United Kingdom. It uses the techniques muon beam probe and industry across many disciplines, including condensed matter physics, chemistry, materials engineering, earth sciences, biology and archaeology.

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- Neutrons and muons
- Science at ISIS
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Neutrons are uncharged constituents of atoms and penetrate materials well, deflecting only from the nuclei of atoms. The statistical accumulation of deflected neutrons at different positions beyond the sample can be used to find the structure of a material, and the loss or gain of energy by neutrons can

14:00, 19 October 2007:  
**SNS** is "...the most powerful neutron source in the world..."

Spallation Neutron Source

From Wikipedia, the free encyclopedia

This is an old revision of this page, as edited by 168.91.233.143 (talk) on 14:00, 19 October 2007. It may differ significantly from the current revision.

The **Spallation Neutron Source (SNS)** is an accelerator-based neutron source being built in Oak Ridge, Tennessee, USA, by the U.S. Department of Energy (DOE). Still to be designed and constructed by a unique partnership between Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, Los Alamos, and Oak Ridge. As of September 1, 2007, it is the **most powerful neutron source in the world**.

**Contents** [hide]

- Facility
- Other facilities?
- Site visit
- References
- External links
- Additional Resources

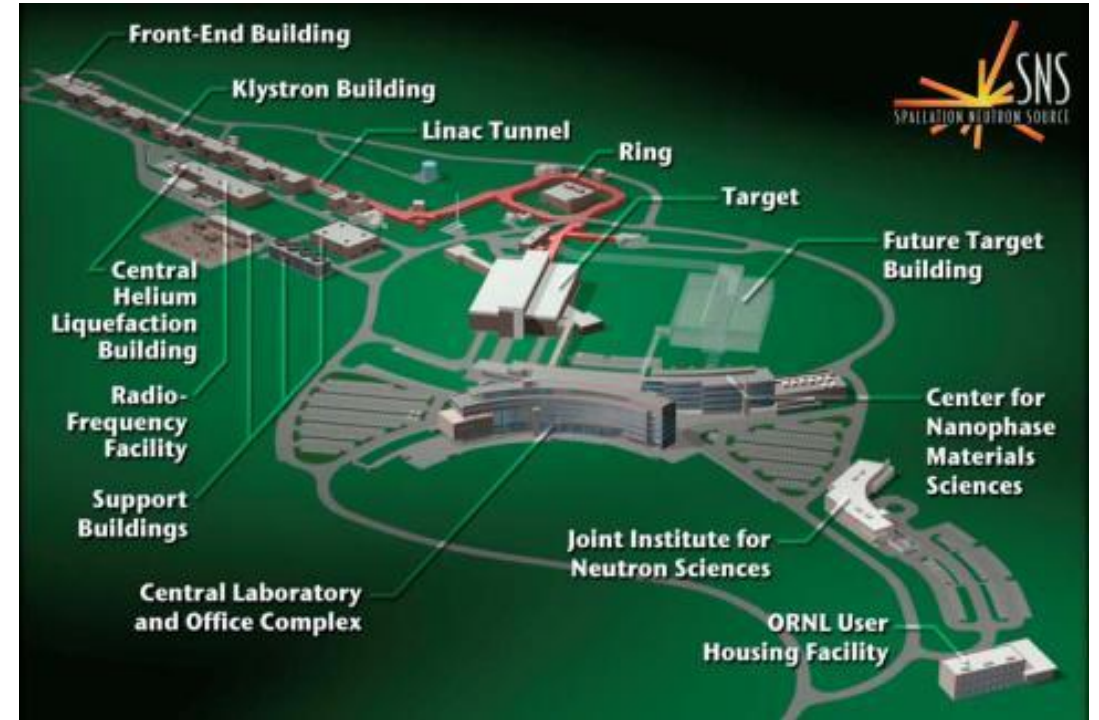
**Facility**

Construction was completed for SNS on time and under budget in 2006. SNS now provides the most intense pulsed neutron beams in the world for scientific research and industrial development. SNS is operating as a user facility that enables researchers from all over the world to study the science of materials that forms the basis for new technologies in energy.



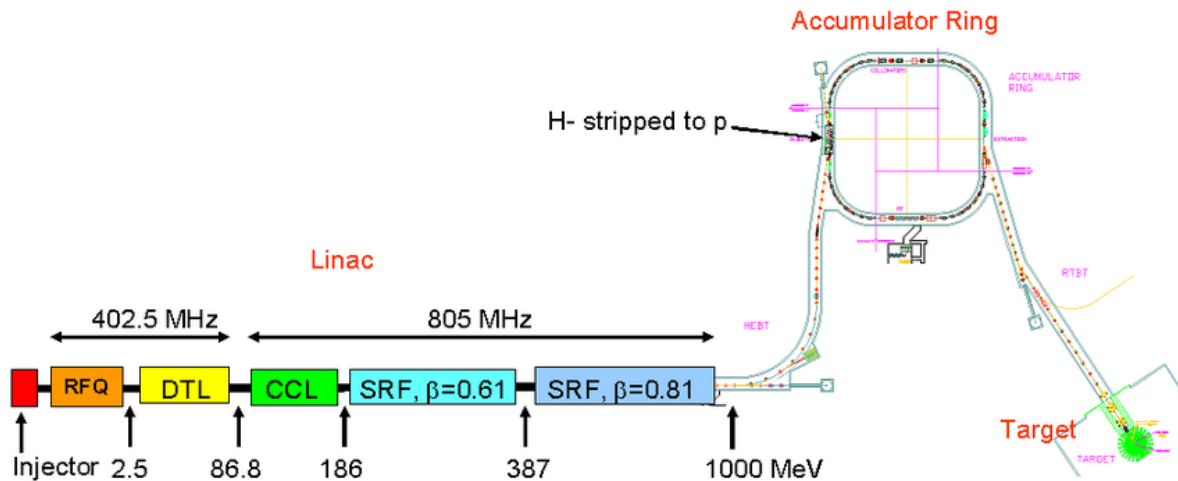
# Spallation Neutron Sources

SNS, 2007

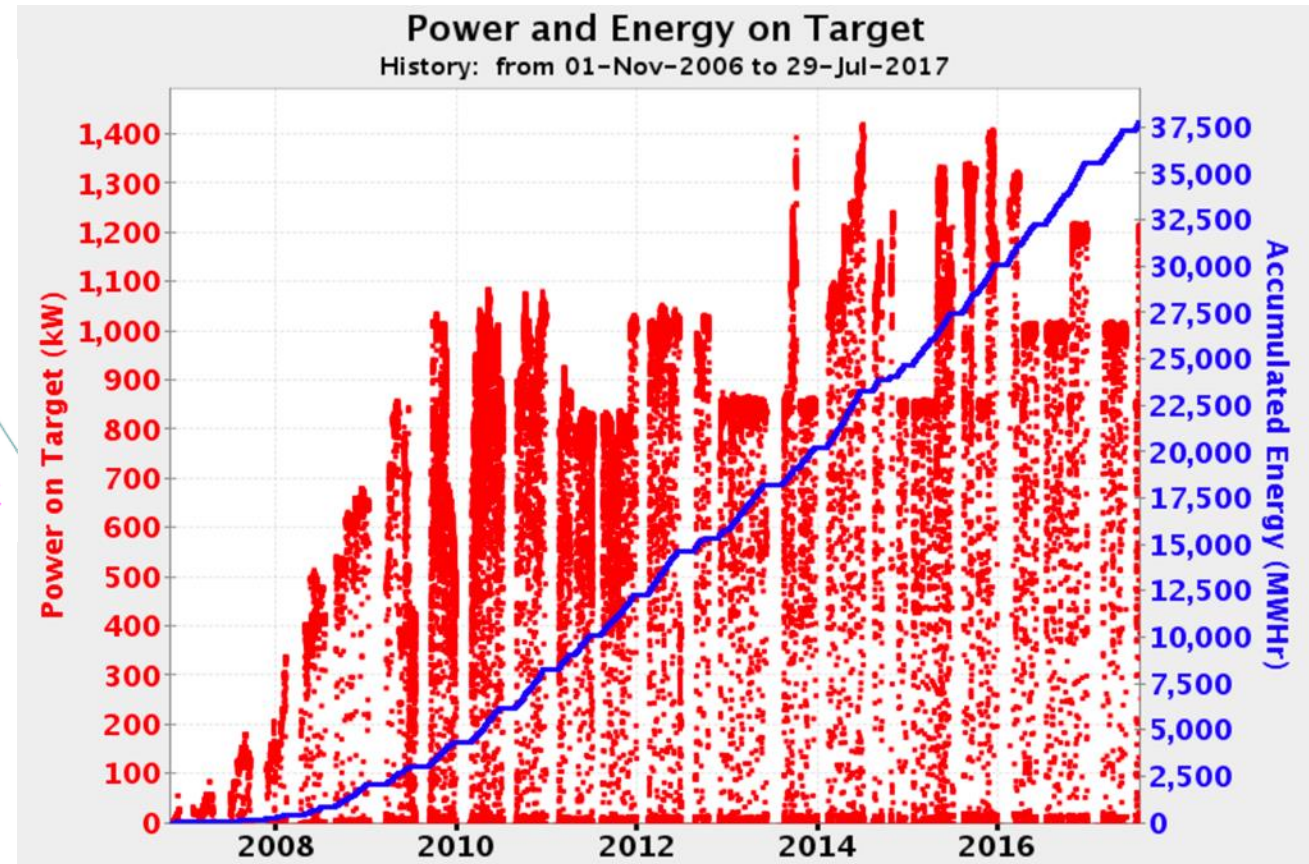


# Spallation Neutron Sources

SNS: Currently at ~1.55 MW

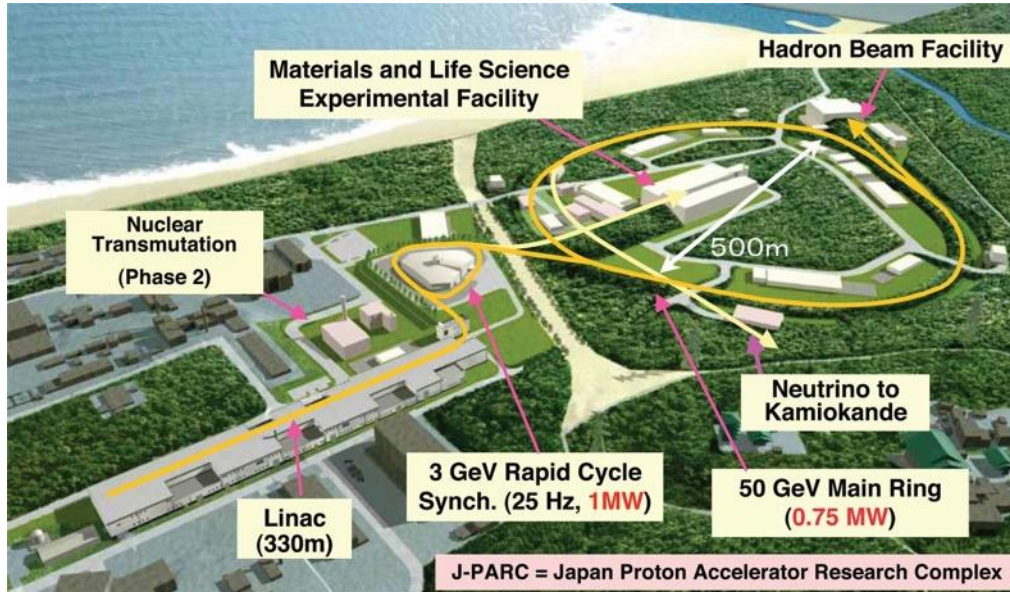


- 1 GeV, NC-SC Linac: DTL, CCL, ELL
- Accumulator Ring: 60 Hz, 1.5 MW
- Upgrades to follow



# Spallation Neutron Sources

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



- Phase 1

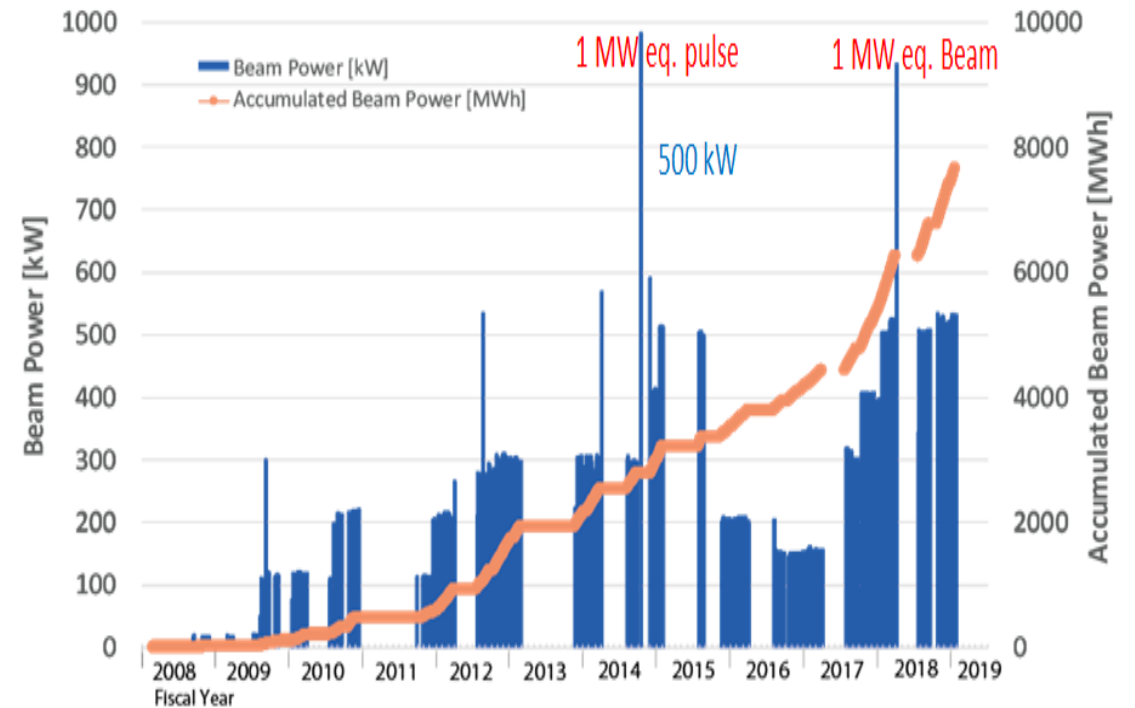
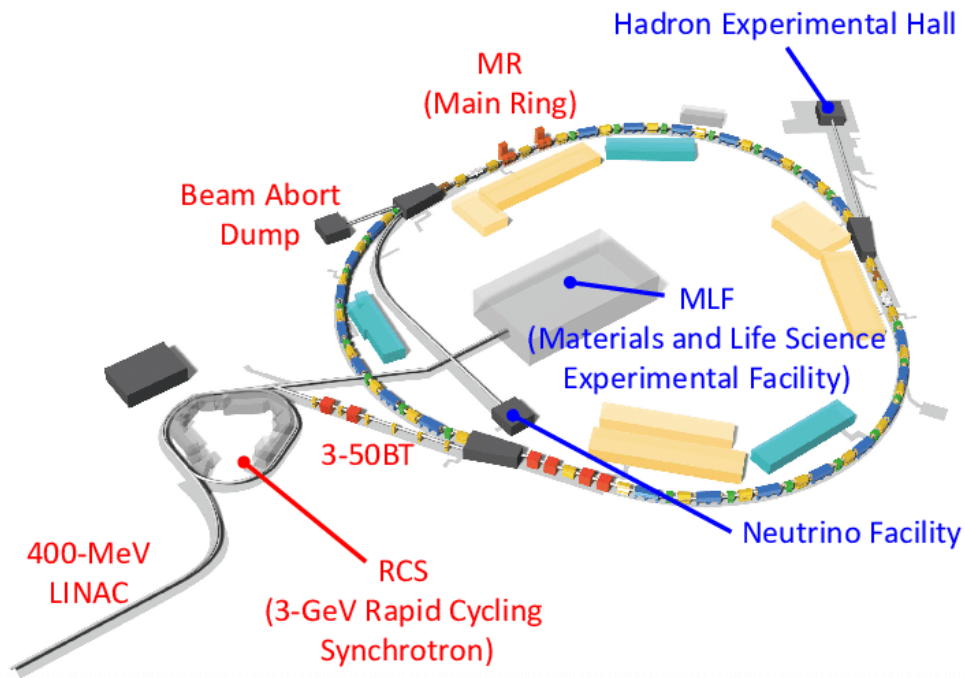
- 180 MeV H- Linac
- 25 Hz, 3 GeV RCS, 0.5 MW
- 30 GeV Main Ring

- Phase 2

- 400 MeV H- Linac (completed 2014),
- 25 Hz, 3 GeV RCS, 1.0 MW
- 50 GeV Main Ring

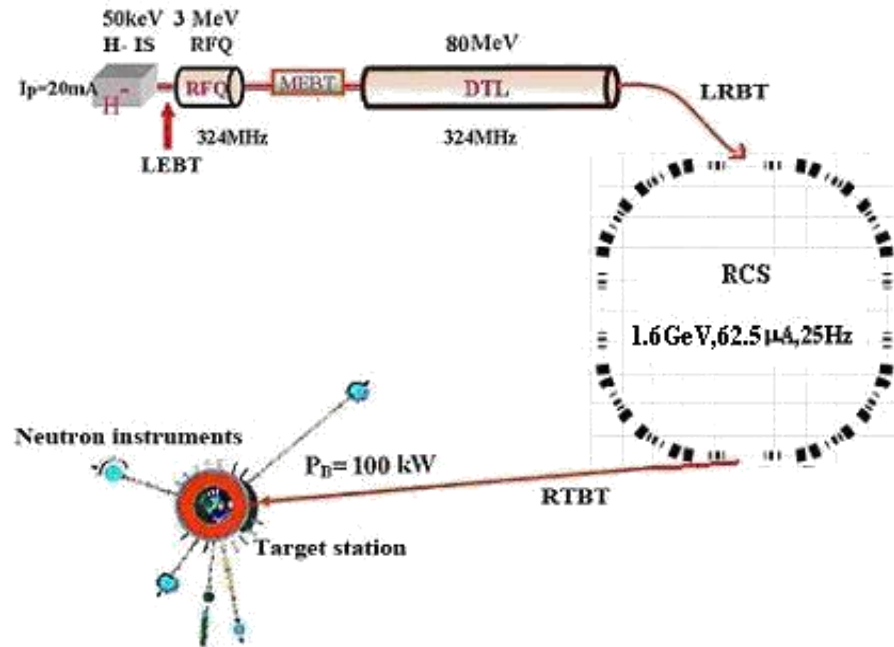
# Spallation Neutron Sources

J-PARC: ~1 MW



# Spallation Neutron Sources

CSNS: 100 kW  $\rightarrow$  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.

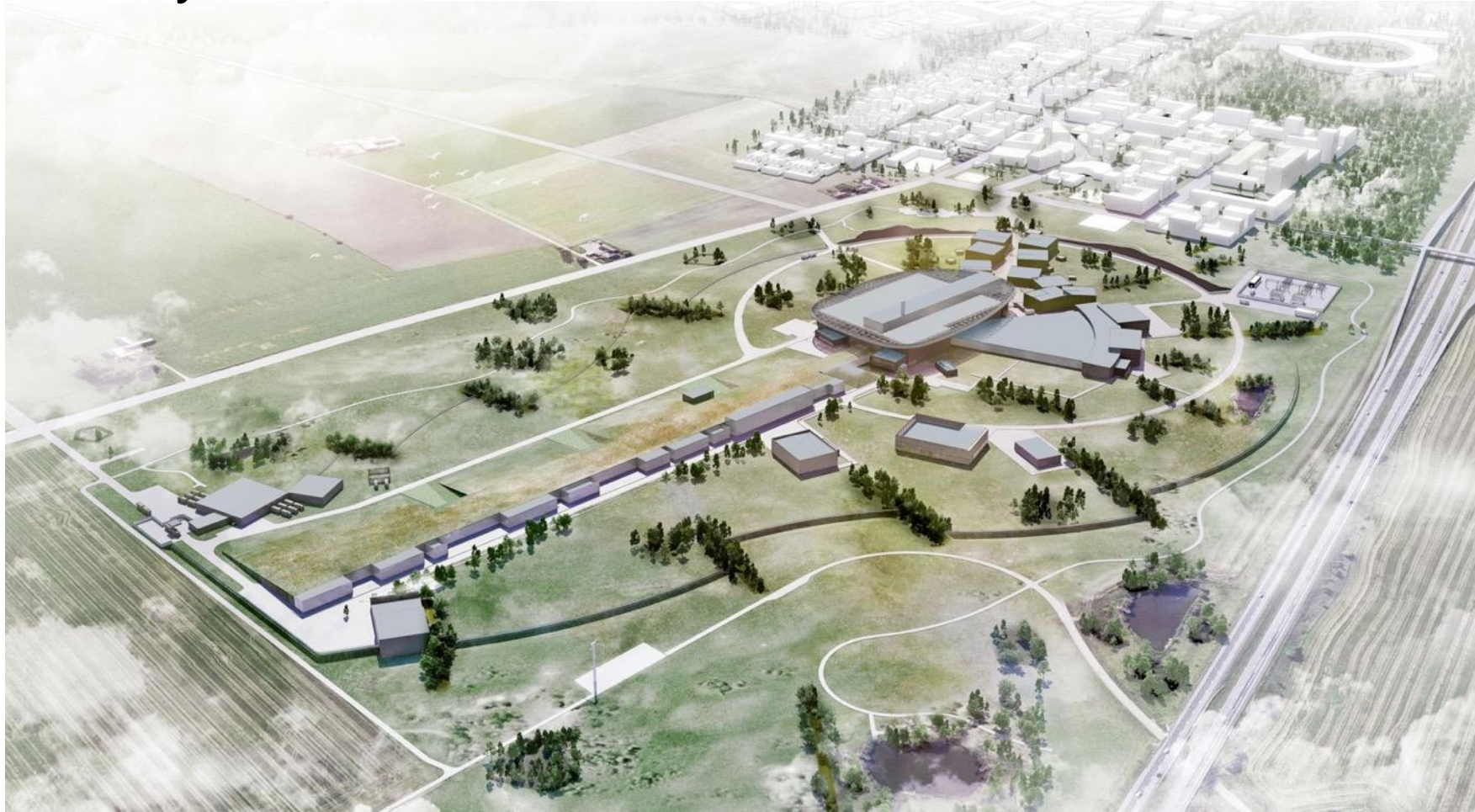
# The European Spallation Source - ESS

A 5 MW Facility!!!



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A 5 MW Facility!!!





# The European Spallation Source - ESS

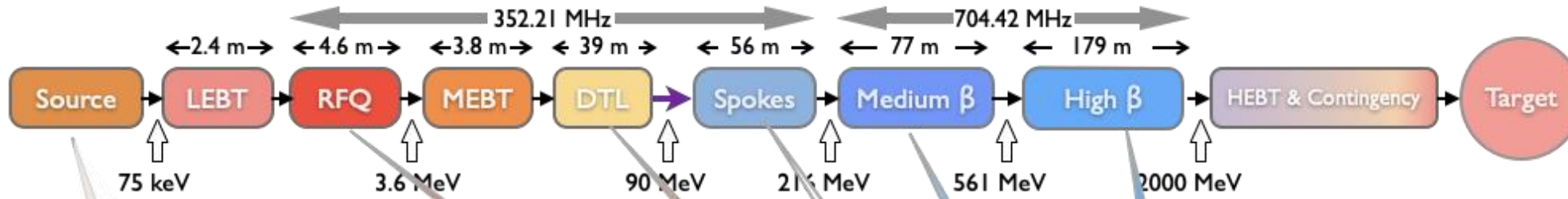
## In Kind Partners

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 Brillouin (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



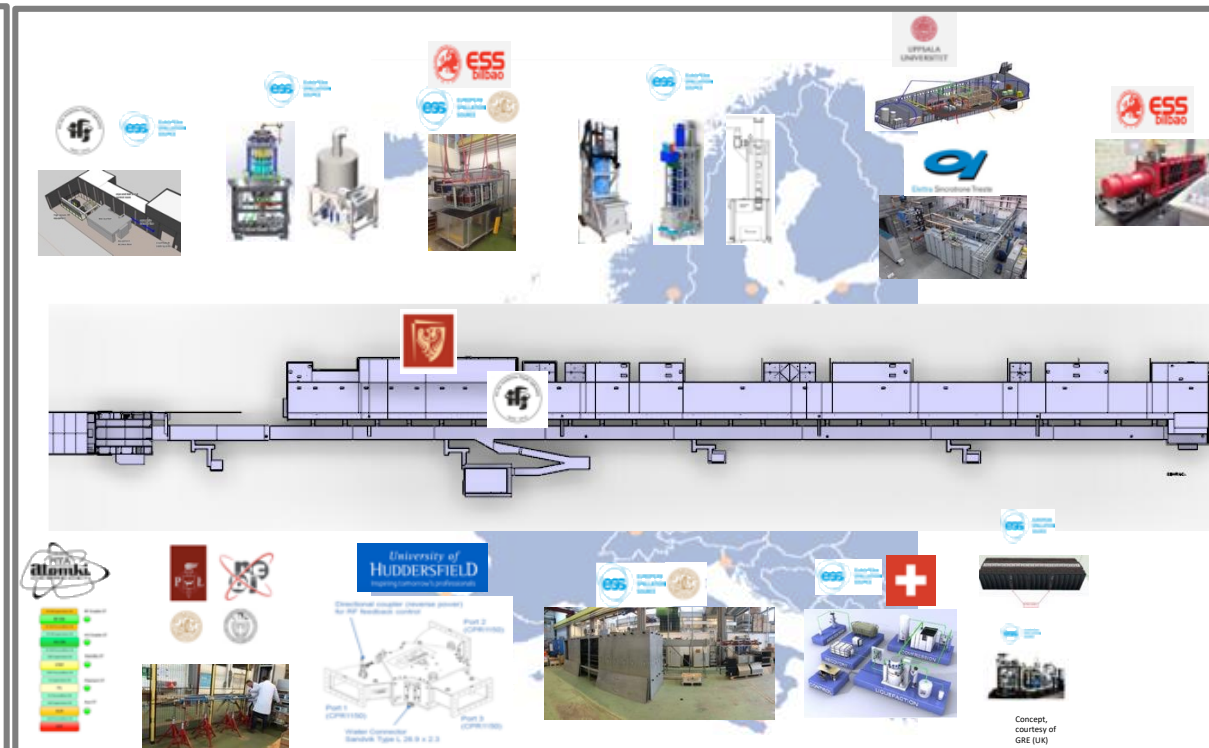
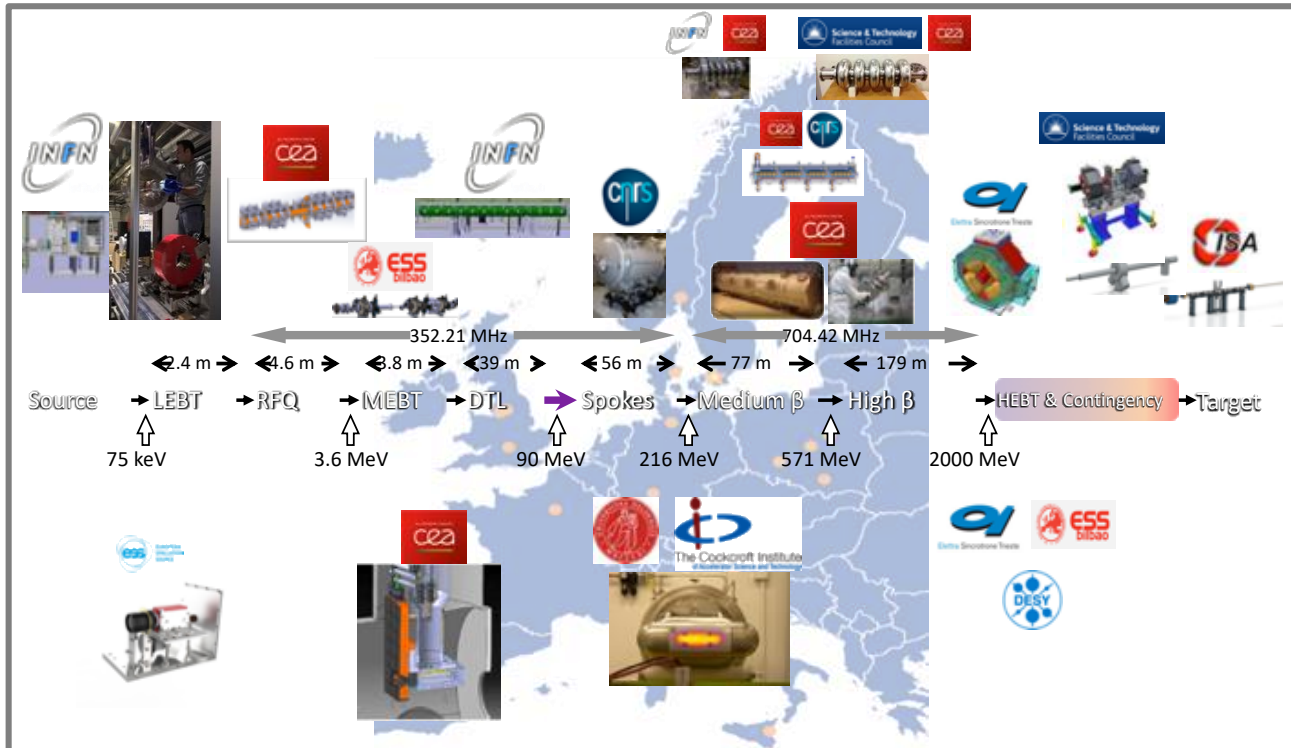
Create protons to be accelerated

Normal Conducting and Superconducting accelerating structures

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	$1.1 \times 10^{15}$	
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



Diffractometer

Monochromatic Powder  
Diffractometer



Materials Science  
Diffractometer BEER



Extreme Conditions  
Diffractometer



Single-Crystal Magnetism  
Diffractometer MAGICS



Macromolecular  
Diffractometer NMX



C. Plostinar

Cold Direct Geometry  
Spectrometer C-SPEC



Wide Bandwidth Direct  
Geom. Spectrometer  
VOR



Bispectral Direct  
Geometry Spectrometer  
TRES



Cold Crystal-Analyzer  
Spectrometer CAMEA



Spectroscopy

Vibrational  
Spectrometer VESPA



Backscattering  
Spectrometer  
MIRACLES



High-Resolution Spin-  
Echo



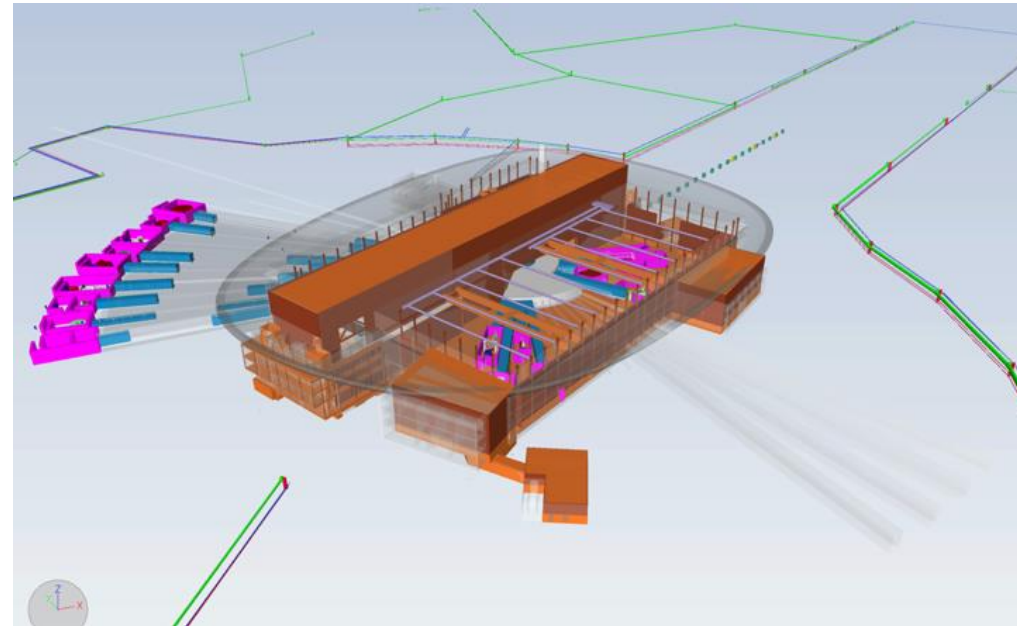
Wide-Angle Spin-Echo



Fundamental & Particle

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

Courtesy of A. Hiess

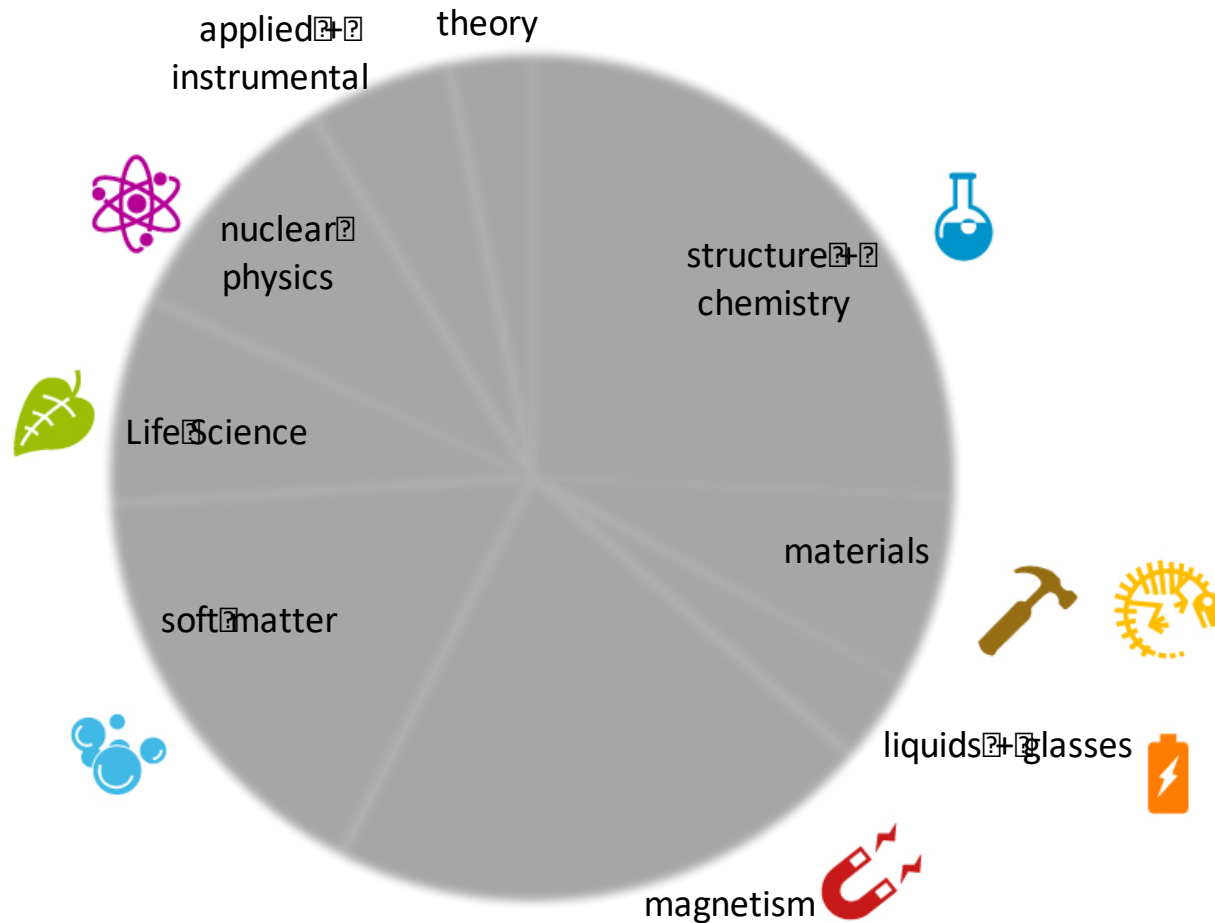


5 - 6 May  
2023

Student Tutorials, 5 - 6  
May 2023

C. Plostinar

# The European Spallation Source - Science

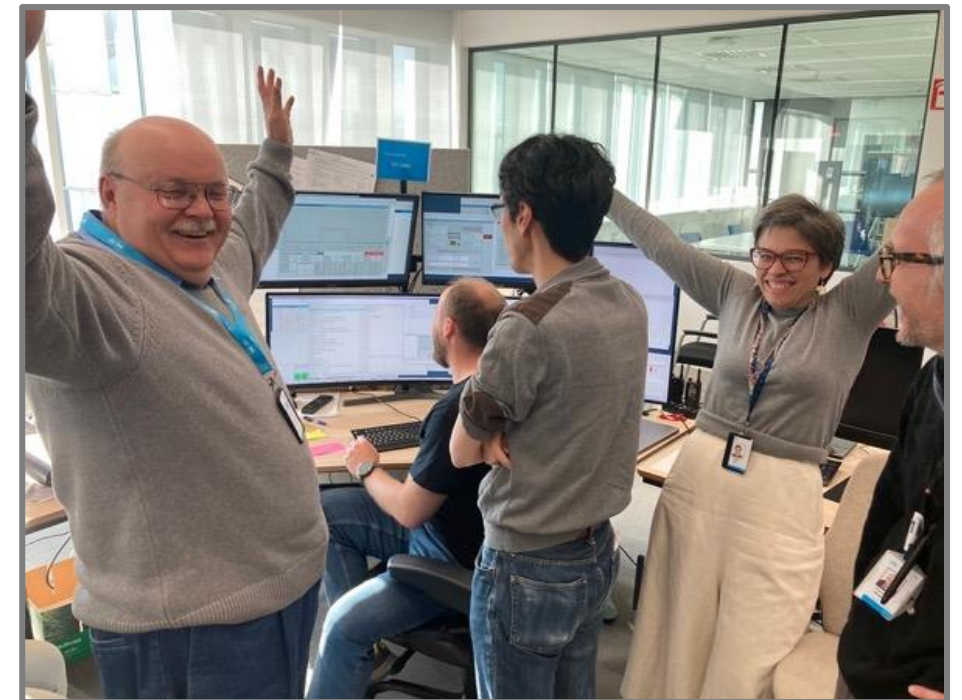
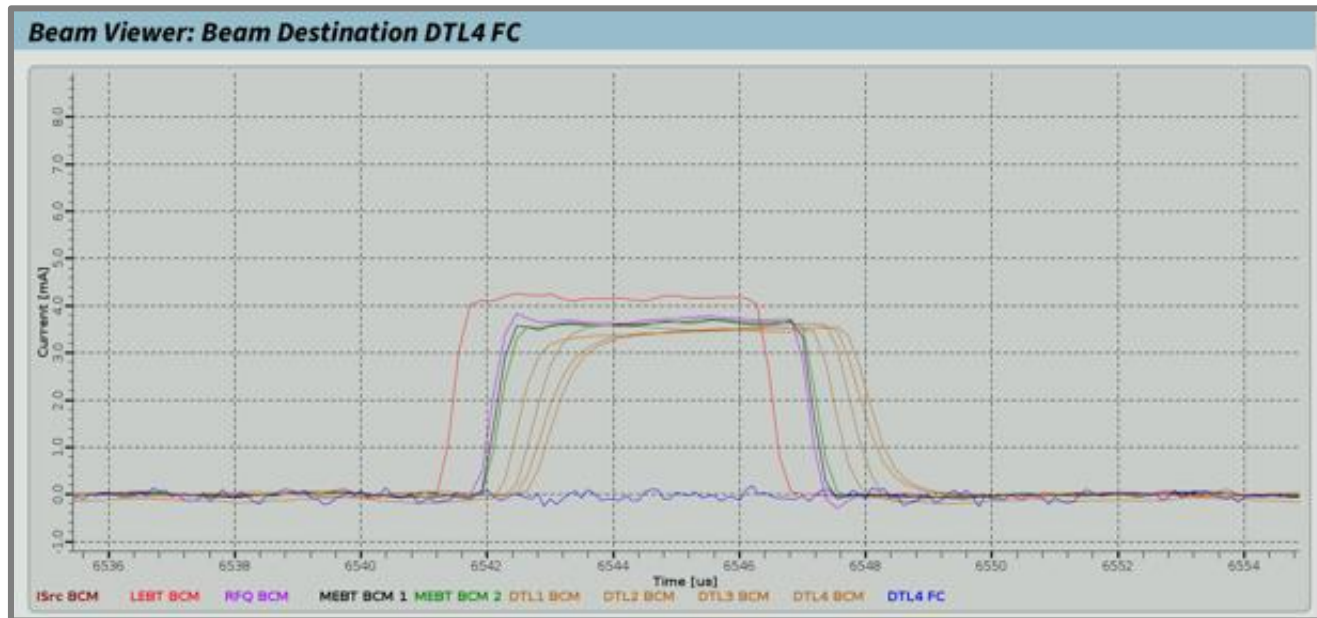


## 21<sup>st</sup> Century Challenges

- 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



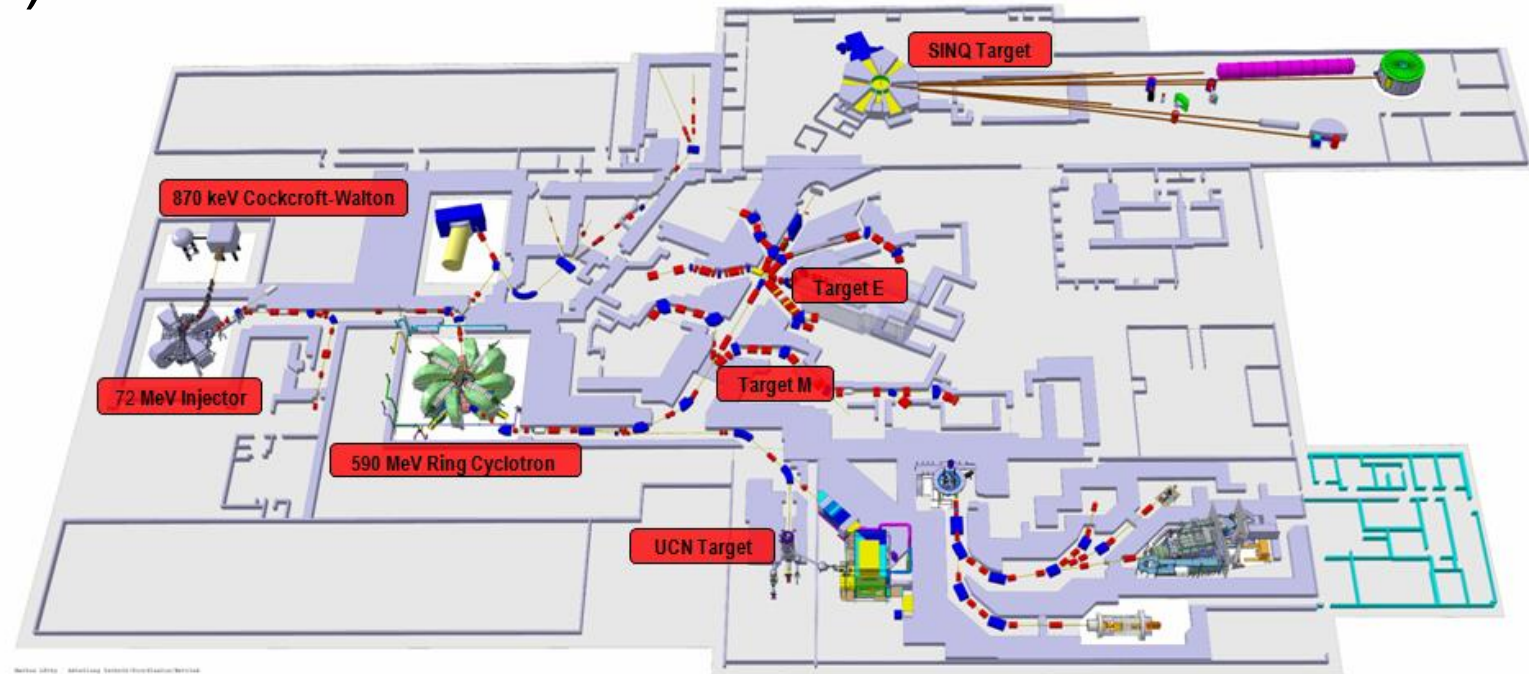


# CW Spallation Neutron Sources

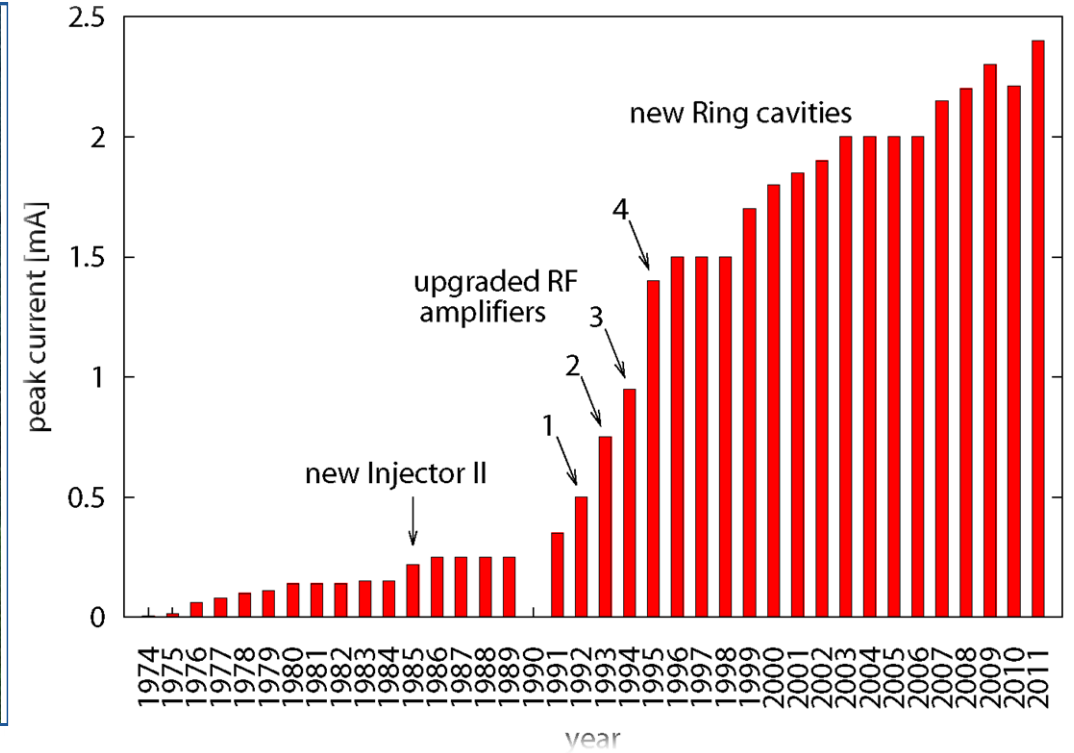
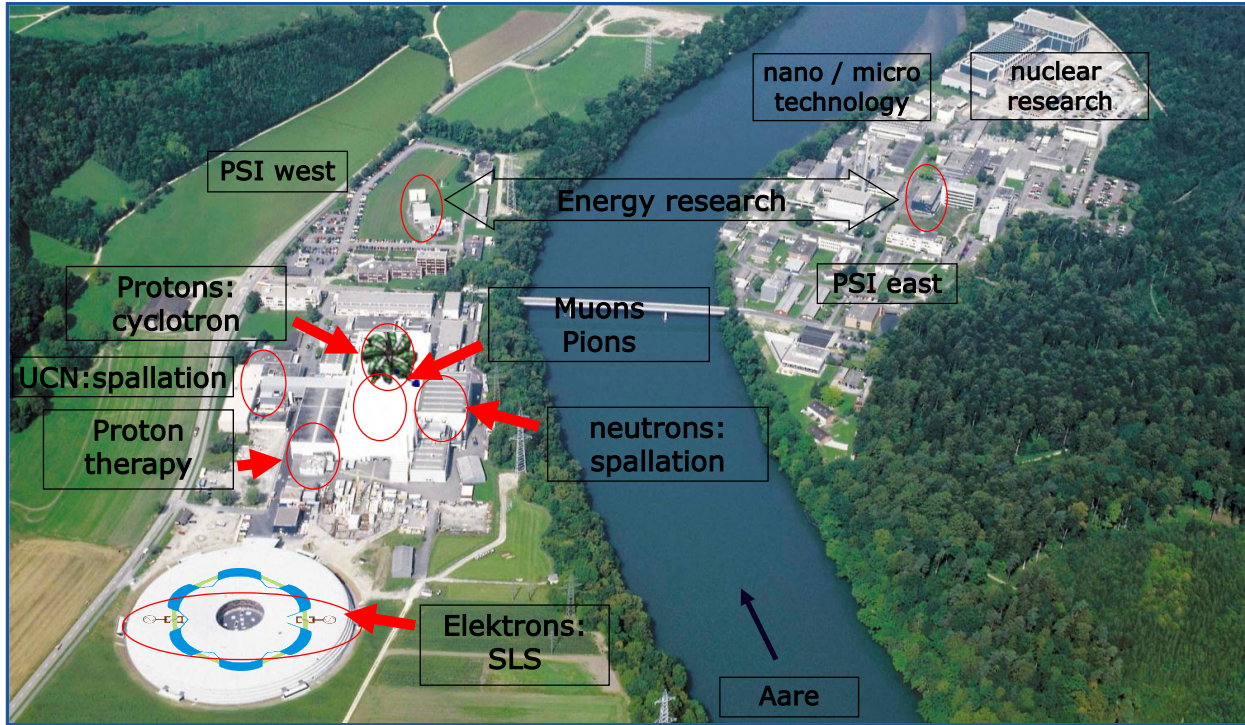
- Cyclotrons
  - Long history (1931)
  - Many applications
  - CW injection, acceleration and extraction
  - High beam power
  - Sector Magnets, RF Cavities, Injection, Extraction, etc.
    - No frequency sweeping or field ramping
    - Magnets rather heavy and complex
  - Issues
    - Beam loss
    - 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



# 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](mailto:Natalia.milas@ess.eu))
  - Emanuele Laface ([Emanuele.laface@ess.eu](mailto:Emanuele.laface@ess.eu))

