Upgrade of the ISIS Facility

John Thomason, ISIS Neutron and Muon Source
John Adams Institute, 4 March 2021

ISIS

Science and
Technology
Facilities Council

ISIS Neutron and Muon Source

- ISIS is the UK's neutron and muon facility, based at STFC's Rutherford Appleton Laboratory in Oxfordshire.
- ISIS supports a national and international community of scientists and gives unique insights into the properties of materials on the atomic scale.

~1000 Number of experiments per year

~200 Number of running days per year

~500–600 Number of publications produced per year

~3000 Number of user visit per year

A world of **knowledge**

Neutron scattering
Materials research for modern life

Neutron scattering research impacts on much of modern life…

…from clean energy and the environment, pharmaceuticals and health care, through to nanotechnology, materials engineering and IT.

The unique information that the technique provides is essential in making progress in contemporary materials science and in trying to solve some of the major global challenges of our time.

Energy

Energy created from burning fossil fuels has underpinned the major industrialisation of the modern world over the last 200 years. As we become more concerned with climate change and the security of our energy supply, the desire to harness other forms of energy from solar, wind, wave, hydrogen and nuclear becomes more pressing.

Hydrogen is one of the most promising fuels for the future. Research programmes to discover lightweight materials that can efficiently and safely store and transport hydrogen rely heavily on neutron scattering.

Flexible solar cells based on plastics instead of silicon offer the potential to cheaply cover wide areas of land and harness the abundant energy from the sun.

Engineering studies of components from nuclear power stations allow operating lifetimes to be confidently extended.

→ SEE PAGE 4

Environment and climate

In recent times, we have become acutely aware of the value of a clean and safe environment for healthy living, and the sensitivity of the climate to activity on Earth.

Neutron scattering is being used to help scientists understand the impact of pollution, work towards solutions for reducing or removing carbon dioxide from the atmosphere and industrial processes, and make more efficient use of natural resources.

Taking a molecular view of the world allows the motor industry to design lubricants and fuel additives that are kinder to the environment and to use lightweight alloys to improve fuel efficiency.

→ SEE PAGE 6

Medicine and health

Bioactive glass, artificial hips and gels for use in cleft palate surgery have all benefited from knowledge gained from neutron scattering. Multi-disciplinary teams of medics, physicists, materials scientists, chemists and engineers come together at research centres like ISIS and the ILL to make key breakthroughs in using materials in medicine.

The ability of neutron scattering to accurately determine molecular structures allows the behaviour of proteins, enzymes and cell membranes to be understood. Interactions of pharmaceuticals with biological molecules can be studied and compared with computer simulations, improving the chances of finding drugs to treat life-changing conditions such as Alzheimer's.

→ SEE PAGE 8

Electronics and IT

Over the past 50 years, the amount of information stored and processed has witnessed explosive growth, allowing hundreds of gigabytes of songs, pictures and words to be recorded onto devices which are continually shrinking in size.

The unique ability of neutron scattering to map out magnetism at the atomic scale is being used to pack more gigabytes into smaller areas, create ultra-sensitive sensors to read back the data, and develop new types of computer memory.

Studies of ceramic processing have improved the performance of mobile phone components, and testing semiconductor chips to determine the effects of cosmic ray neutrons is allowing companies to confirm the performance of their electronic systems.

→ SEE PAGE 10

Manufacturing and industry

Millions of tonnes of materials are processed every day across the planet to manufacture the huge range of products that we need for daily life, from soaps, cosmetics and drugs through to cars, planes and industrial solvents. A small amount of molecular knowledge from neutron scattering experiments can go a long way in improving the efficiency, quality and price of industrial products.

Unique information from experiments at the ILL and ISIS is used daily in the manufacture of products used to keep people and their homes clean and fresh. Energy efficient mass production of key industrial chemicals is founded on basic knowledge of molecular interactions. Quality assurance of components in the aerospace and motor industries relies on long-term research programmes confirming the best conditions for making precision components.

→ SEE PAGE 12

Natural world

Our world and universe continue to fascinate, intrigue and surprise. We can learn many lessons from plants and animals on how to solve common problems and gain deeper understanding of our place in the universe by studying the geology and natural processes of the planets.

Neutron scattering is being used to tease the secrets of spinning silk from spiders and how lizards avoid freezing in winter. Understanding how plants can defend themselves against disease offers new potential for crop breeding and medicines.

Replicating the extreme conditions found in the deep earth or the planets of the Solar System is bringing new insight to planetary science. Neutron beams can penetrate through the heavy engineering equipment used to generate high pressures to measure the properties of rocks and fluids needed for computer modelling.

→ SEE PAGE 14

Heritage science

The origins and history of objects from museums and archaeological sites can be safely investigated using neutron scattering without damaging them or affecting their value.

Civil engineering projects rely on archaeologists to assess the significance of ancient remains that will be disturbed. Neutron scattering has been used to examine Roman objects found under the A2 in Kent which have similarities to those found at Pompeii.

Museums across Europe are using neutron techniques to understand how ancient Japanese swords were made during the 14th to 17th centuries.

Fresh thinking about the Battle of Towton is coming from neutron scattering experiments of battlefield weapons. Fought near Tadcaster in Yorkshire in 1461, it was the most dramatic battle of the Wars of the Roses.

→ SEE PAGE 16

https://www.isis.stfc.ac.uk/Pages/impact-of-neutron-scattering-brochure13478.pdf

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Science Highlight from ISIS Neutron and Muon Source

Does it matter if shellfish food is left-handed or right-handed?

Scientists from Evonik Nutrition & Care, Evonik Operations GmbH and the University of Reading have used inelastic neutron scattering alongside other techniques to study the differences between two forms of a new feed supplement for marine organisms.

Tosca

Chemistry

Industry:
Evonik Gmbh

DOI: 10.1038/s41598-020-80385-z

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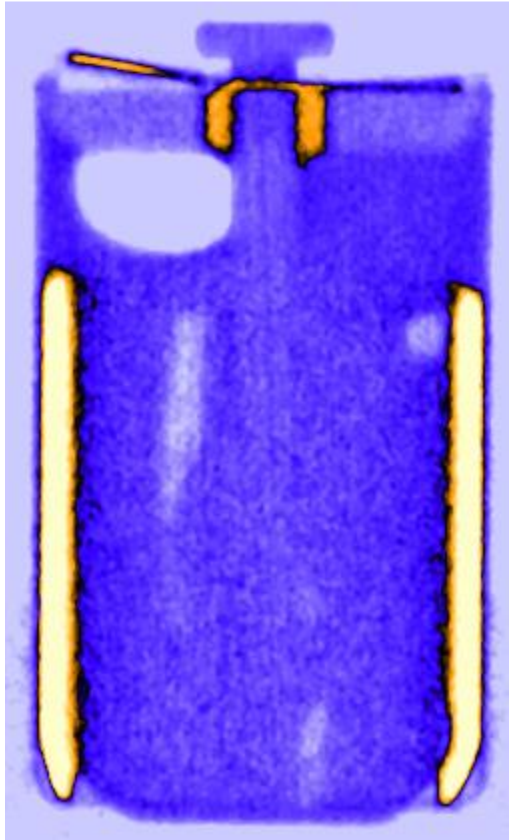
Science Highlight from ISIS Neutron and Muon Source

Investigating battery performance and lifetime at IMAT

Leveraging the unique interaction of neutrons and lithium, researchers have been able to build a unique picture of what’s happening inside a lithium battery as it undergoes cycling.



IMAT

Energy

DOI: 10.1149/1945-7111/abbbbc and DOI: 10.1149/1945-7111/abbfd9
Nature Communications DOI: 10.1038/s41467-019-13943-3

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Science Highlight from ISIS Neutron and Muon Source

Getting to the Point: Neutron analysis of Bronze Age swords reveals how they were used

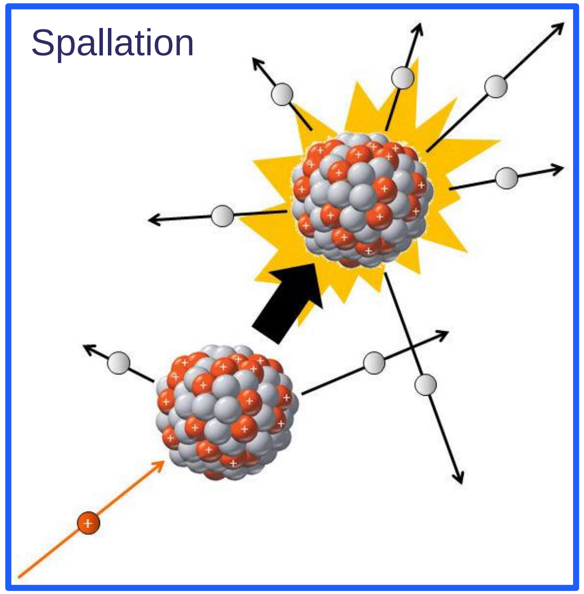
Neutron analysis using GEM has brought us a step closer to defining the moment in European history that the primary use of metal-hilted swords switched from stabbing to cut-and-thrust combat.

GEM

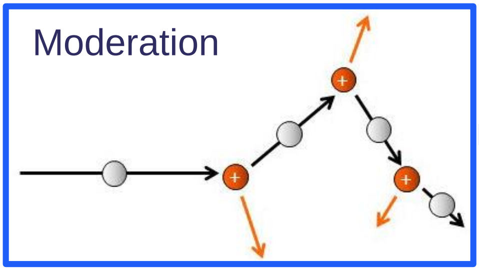
Heritage

Neutron and Muon Production

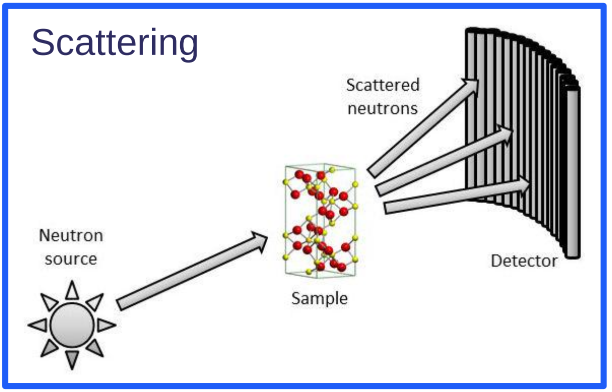
- Neutron Production



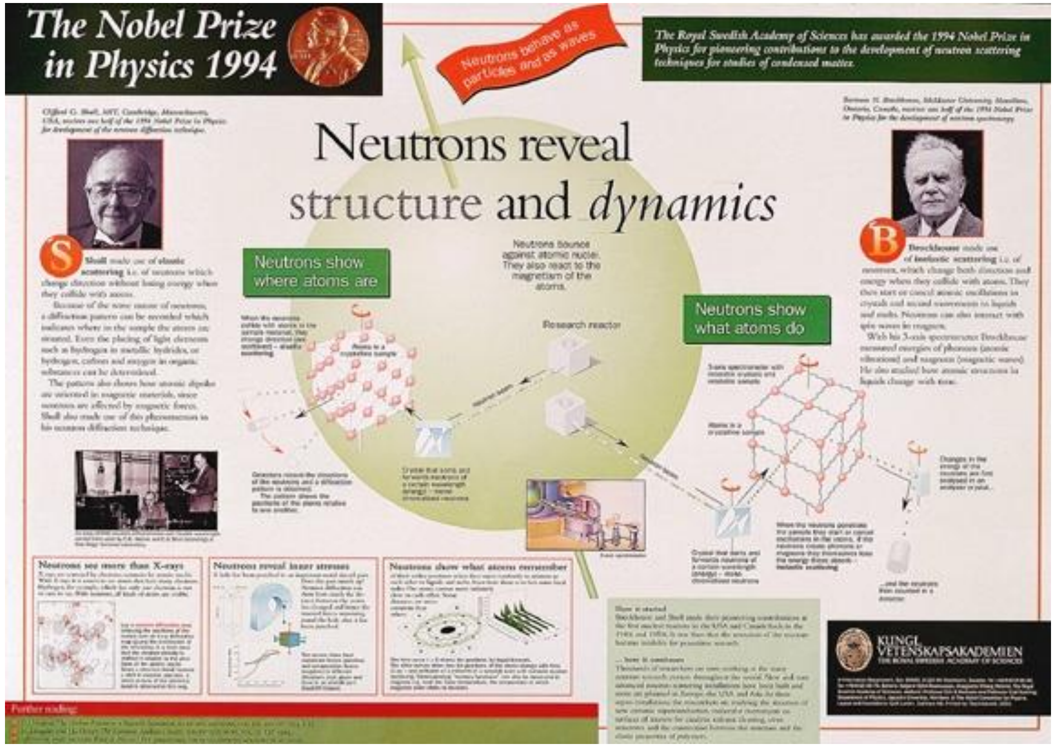
Spallation



Moderation



Scattering



The Nobel Prize in Physics 1994

Neutrons behave as particles and as waves

The Royal Swedish Academy of Sciences has awarded the 1994 Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.

Neutrons reveal structure and *dynamics*

Neutrons show where atoms are

Neutrons bounce against atomic nuclei. They also react to the magnetism of the atoms.

Research reactor

Neutrons show what atoms do

Neutrons see more than X-rays

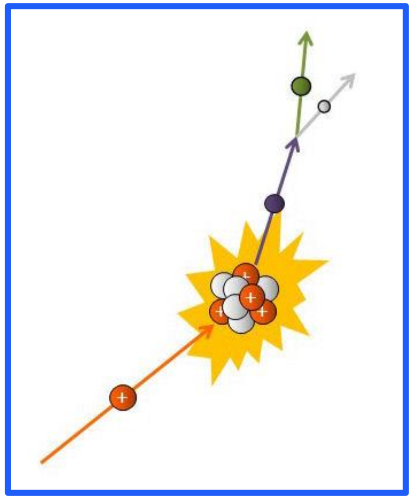
Neutrons reveal inner stresses

Neutrons show what atoms remember

Further reading

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

- Muon Production



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ISIS Neutron and Muon Source

1970

The ISIS injector was built in the 1970s as a new 70 MeV injector for the 7 GeV proton synchrotron Nimrod, but before it could be used Nimrod was closed down. However the new injector for Nimrod was by no means all new – half of it came from the Proton Linear Accelerator (PLA) which ran for ten years between 1959 and 1969. The synchrotron was built specifically for ISIS in the early 1980s in the hall originally occupied by Nimrod.

1978 – 1984
Construction of ISIS reusing infrastructure from the Nimrod high energy physics experimental facility.

1980

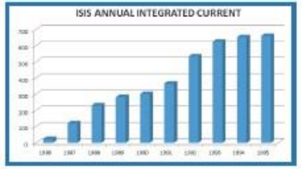
1984
At 19:16 on Sunday 16 December ISIS produced its first neutrons.

1985
Routine operations begin.

On 16 October at its official inauguration the neutron source was named ISIS by Prime Minister Margaret Thatcher.

1985 – 1994
Gradual ramping up of performance to produce annual integrated currents greater than 600 mA-hours

1987
First muons at ISIS were produced on 23 March 1987



1990

ISIS was originally called the Spallation Neutron Source (SNS), but was renamed as a reference to the ancient Egyptian goddess and the local name for the River Thames. The name was considered appropriate as Isis was a goddess who could restore life to the dead, and ISIS made use of equipment previously constructed for the Nimrod and NINA accelerators at the Rutherford and Daresbury Laboratories respectively.

2000

2001
Installation of new collector straight in synchrotron.

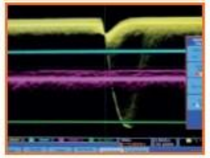
2003
Announcement of ISIS Second Target Station (TS2).

2004
Installation of ISIS RFQ and second harmonic RF system.
ISIS was recognised in the Guinness Book of Records as the most powerful pulsed neutron source in the world.

2004 – 2007
TS2 construction.

2007
Installation of new magnets and muon collimator downstream of the intermediate target, and new switching magnets to direct beam to TS2.

2008
On 3 August the first neutrons were produced at TS2.



2009
Routine operations with initial suite of seven instruments begin on TS2.

2010

2010
Installation of new beam entry window for TS1.

2011
On 14 March 2011, Science Minister David Willetts announced government funding for four new TS2 'Phase II' instruments.

2014
Installation of new magnets around the intermediate target, and refurbished Main Control Room.

2015 – 2017
TS2 Phase II instruments come online.

2020

Using the lessons learned from TS-2, there is an opportunity to redesign the TS1 Target Reflector and Moderators (TRAM) to give improved performance for all TS1 instruments. A feasibility study has concluded that upgrading and refurbishing both the TRAM and the associated services can give useful flux increases to all instruments. The project has moved to the implementation phase, aiming for installation starting in 2020.

2021
TS1 target upgrade and installation of new linac tank 4.

2025
Installation of new linac tank 1.

2030

2030
ISIS-II construction begins.

2034
ISIS' 50th Birthday!

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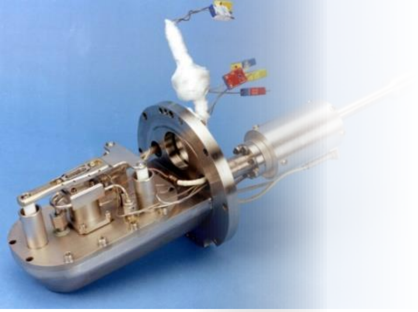
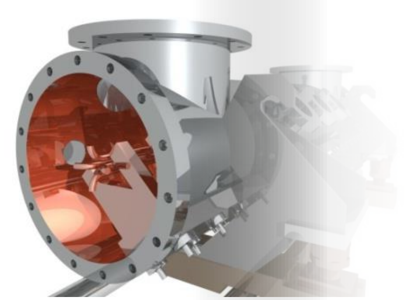
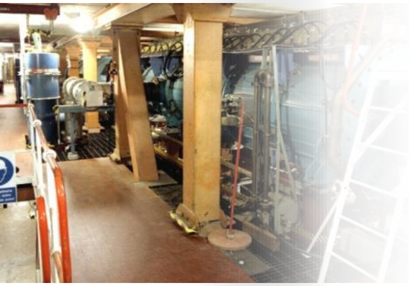
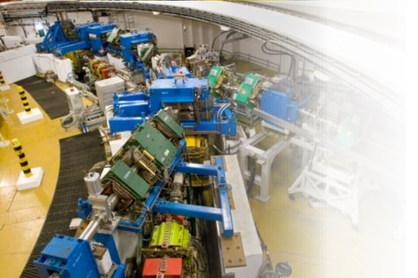
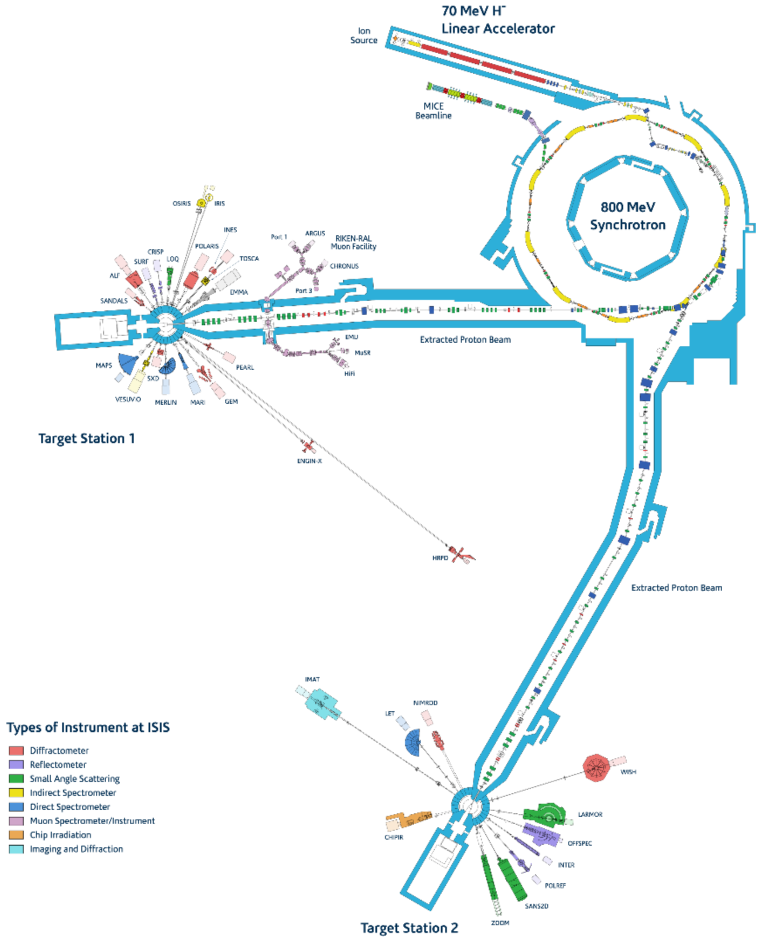






ISIS Accelerators

- H^- ion source (17 kV)
- 665 kV H^- RFQ
- 70 MeV H^- linac
- 800 MeV proton synchrotron
- Extracted proton beam lines

- The accelerator produces a pulsed beam of 800 MeV (84% speed of light) protons at 50 Hz
- Average beam current is 240 µA (3.0×10^{13} ppp) therefore 192 kW on target (160 kW to TS-1 at 40 pps, 32 kW to TS-2 at 10 pps)



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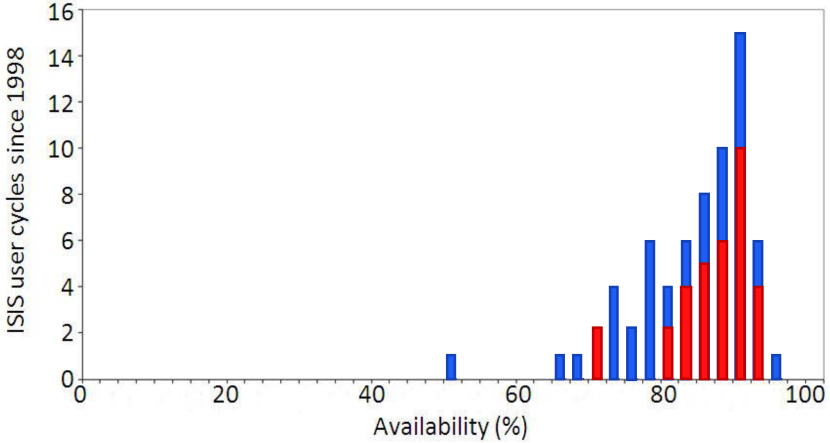
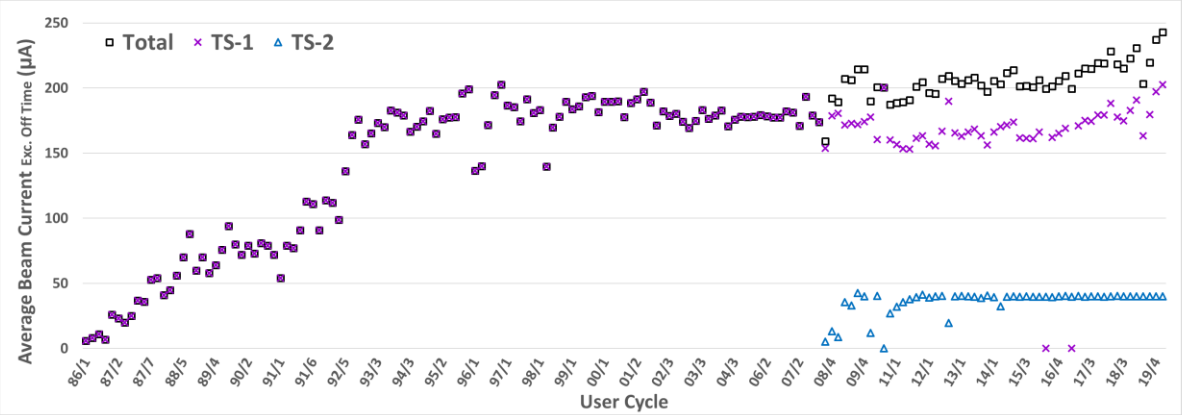
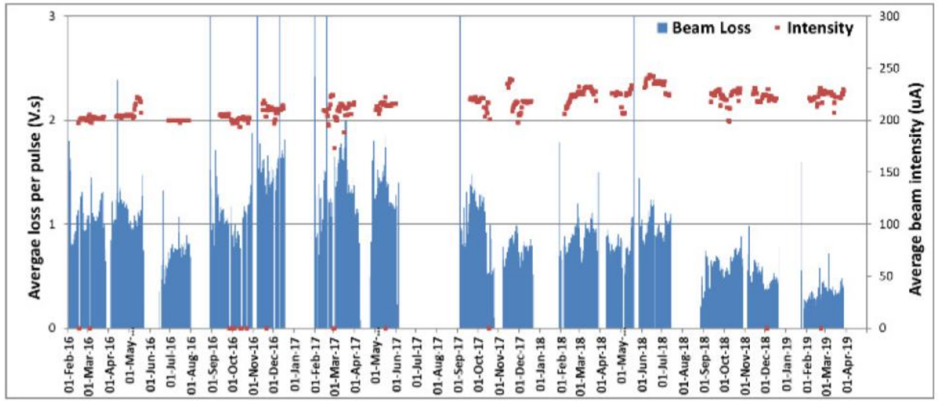
ISIS Accelerator Operations

- ~£60M/year operating budget
  (£10M/year for accelerator operation/sustainability)
- ~450 staff - 100 in Accelerator Division
  (+40 in Electrical Systems Division)
- 160 – 200 operating days per year split into 4 or 5 cycles
- Long (6 – 12 month) shutdown every ~5 years



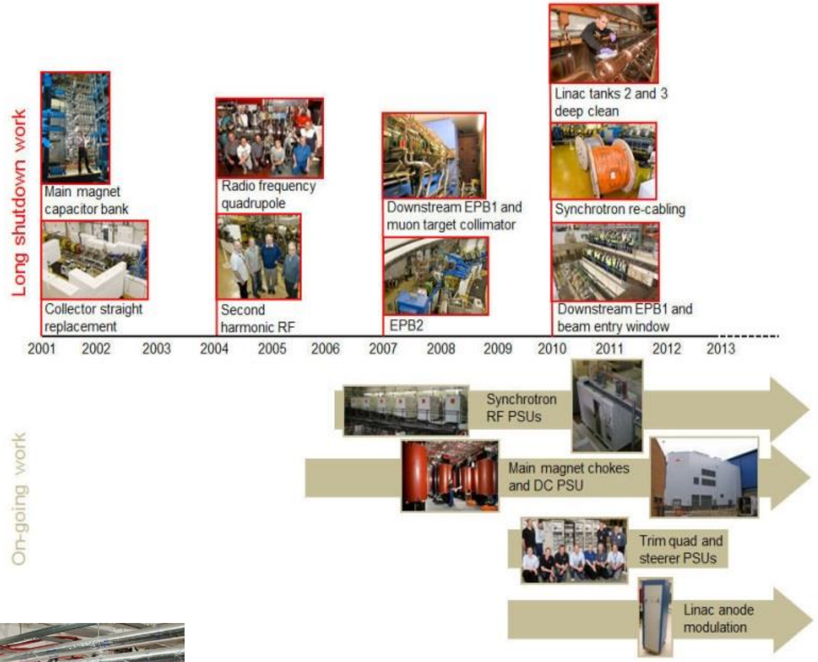


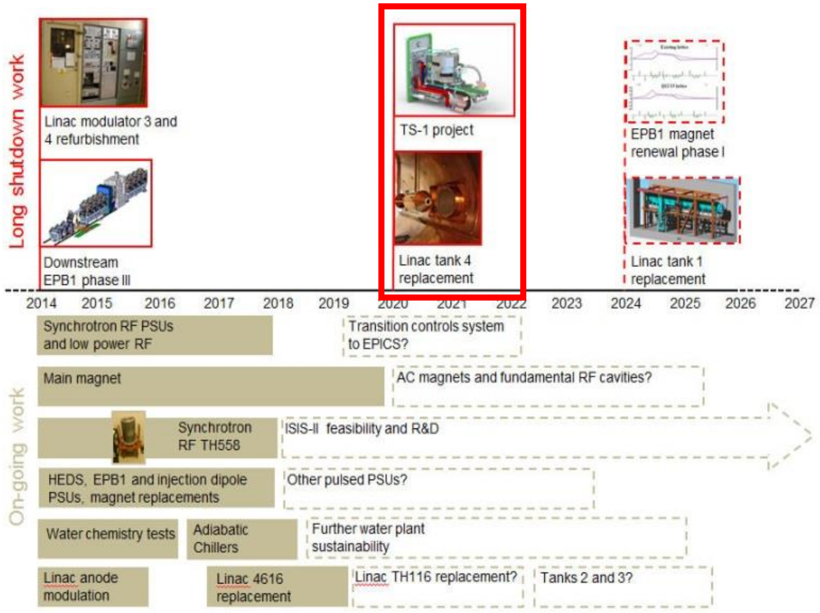


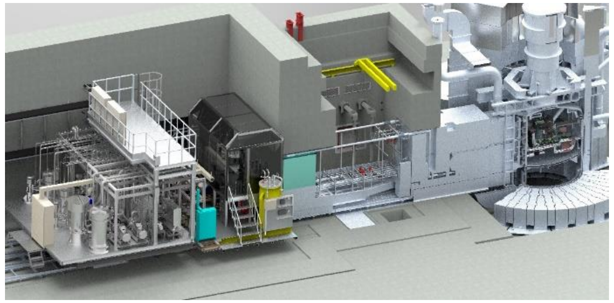
UKRI Science and Technology Facilities Council

ISIS Operations and Sustainability

- ISIS accelerator and target activities are principally aimed at facilitating the programme of equipment renewal and upgrades required to keep the present ISIS accelerators running optimally and sustainably for the lifetime of the facility.





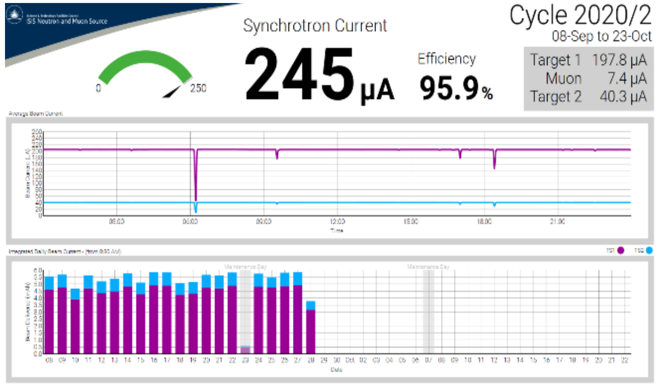


ISIS Operations and Sustainability – Covid-19

- ISIS operations were halted on 18 March 2020 with the global pandemic beginning to stop users from visiting the facility

- The user cycle planned for June 2020 was cancelled, with only essential maintenance activities being carried out on site at RAL
- Lots of Covid-19 risk assessments and method statements had to be generated to allow limited re-opening of buildings and return of some staff under carefully supervised conditions
- Some tasks eventually able to be carried out using PPE to overcome strict 2m social distancing

- Return to operations for September 2020 user cycle. Beam availability (integrated 24-hour beam current) record broken on a number of occasions, ending up at 5.87 mAh
- Operations continued thereafter, with some rearrangement to reschedule long shutdown, now starting June 2021

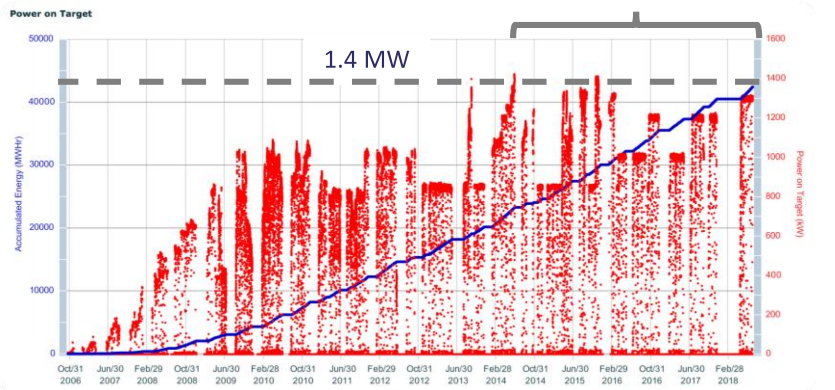


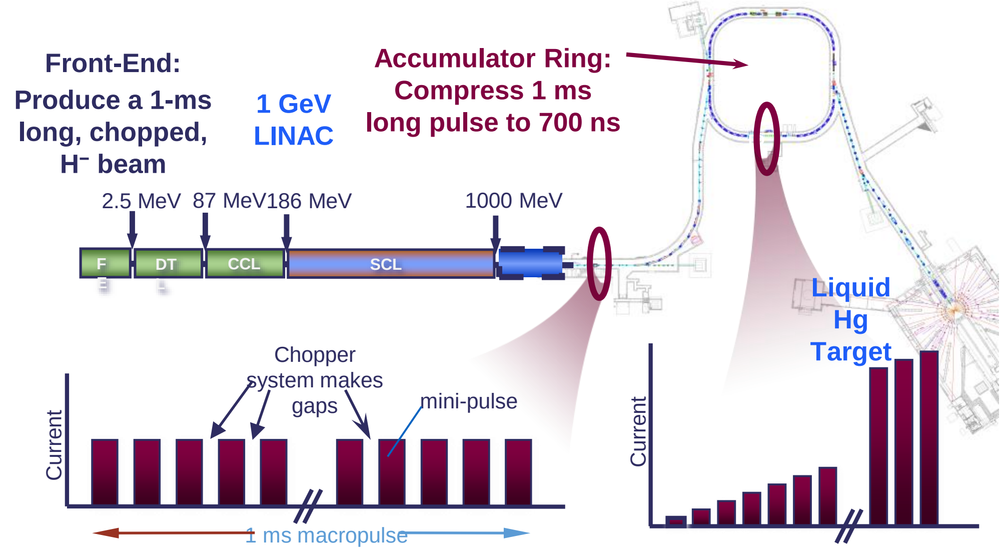
Some other Facilities Worldwide

SNS

Operation at 1.4 MW from September 2018

Beam power administratively limited by target most of this time





Front-End:

Produce a 1-ms long, chopped, H⁻ beam

1 GeV LINAC

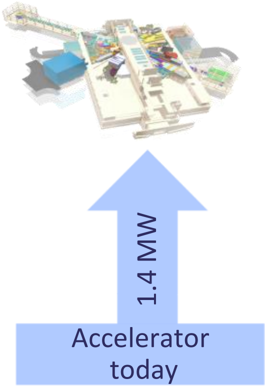
Accumulator Ring: Compress 1 ms long pulse to 700 ns

Liquid Hg Target

Design parameters: 60 Hz, 1.4 MW

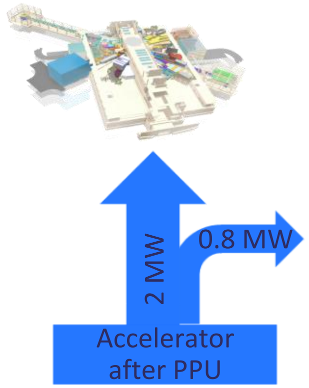
SNS Upgrade Plans

FTS
- 24 instrument positions
- 19 instruments built



Now

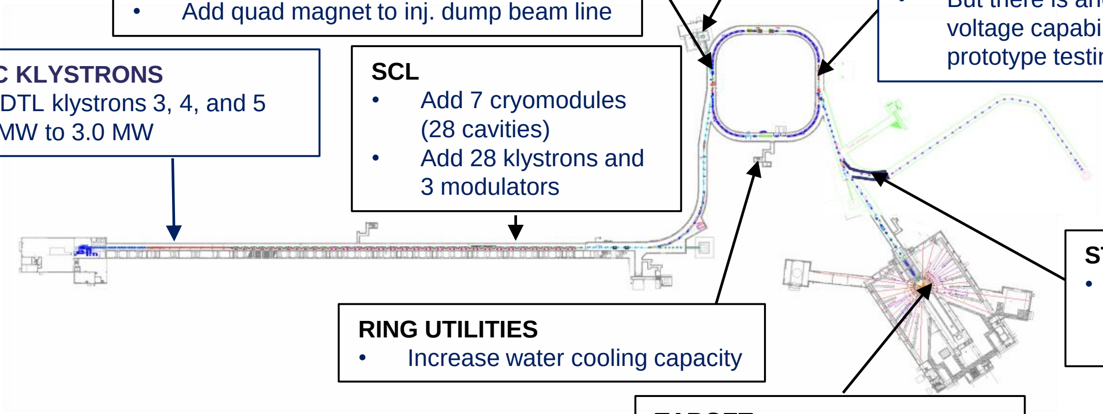
FTS
- 24 instrument positions
- 19 instruments built



After PPU Upgrade

STS
- 22 instrument slots
- 8 initial instruments

After STS Upgrade



INJECTION DUMP
- Re-assess 150 kW power rating
- Add view screen imaging system

RING INJECTION
- Replace 2 chicane magnets
- Replace inj. dump septum magnet
- Upgrade 8 inj. kickers
- Add quad magnet to inj. dump beam line

RING EXTRACTION
- Add 2 more kickers to the existing 14 kickers.
- But there is another way: to upgrade the voltage capability of the existing 14 kickers -- prototype testing is in progress.

WARM LINAC KLYSTRONS
- Upgrade DTL klystrons 3, 4, and 5 from 2.5 MW to 3.0 MW

SCL
- Add 7 cryomodules (28 cavities)
- Add 28 klystrons and 3 modulators

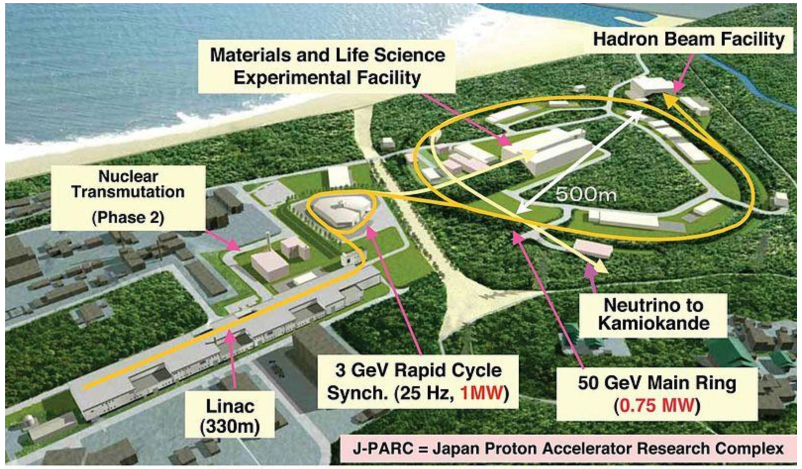
Future beam line to second target station

STS STUB
- Build first part of beam tunnel to future second target

RING UTILITIES
- Increase water cooling capacity

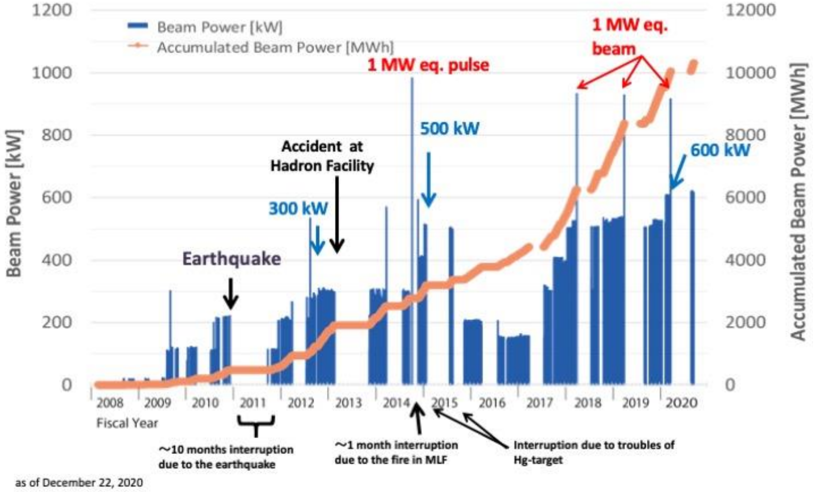
TARGET
- Increase power capability from 1.4 to 2.0 MW

J-PARC



Joint Project between KEK and JAEA

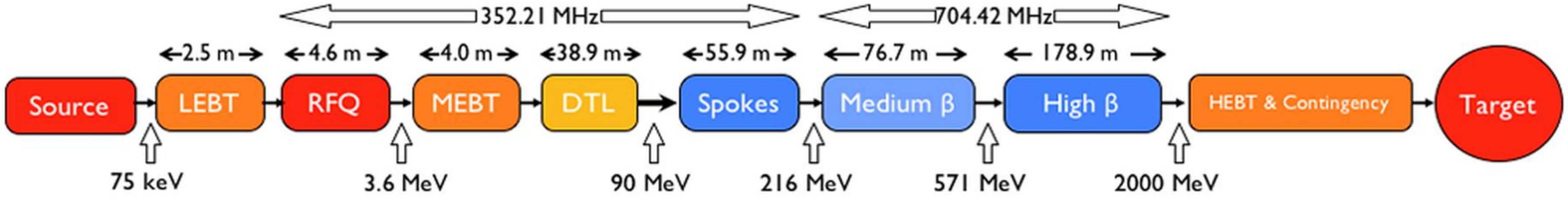
- The J-PARC proton beam is accelerated by a series of accelerators, which consists of:
  - 400 MeV H^- linear accelerator
  - 3.2 GeV rapid cycling synchrotron (RCS)
  - 50 GeV main ring (MR)
- J-PARC have successfully demonstrated stable operation of the Materials and Life Science Experimental Facility at 1 MW from the RCS, but with duration limited by target performance.



ESS

- The **European Spallation Source** (**ESS**) is a multi-disciplinary research facility based on what will be the world's most powerful pulsed neutron source. At least 17 European countries will act as partners in the construction and operation of ESS in Lund, Sweden. As the world's next-generation neutron source, ESS will enable scientists to see and understand basic atomic structures and forces at length and time scales unachievable at other spallation sources. ISIS will contribute to 3 ESS instruments (Loki, Freia and Vespa). UK accelerator contributions total £42M.

- Accelerator RBOT is August 2023 driving BOT to September 2023
- Target RBOT is July 2023
- First Science is June 2024



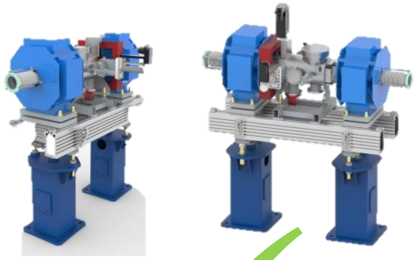
ESS

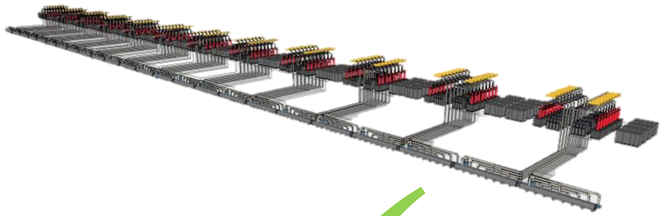
- UK Accelerator In-kind Delivery

High Beta Cavities (88 Total)

Linac Warm Units (75 Total)

RF Distribution (146 HPRF Feeds)





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ISIS-II

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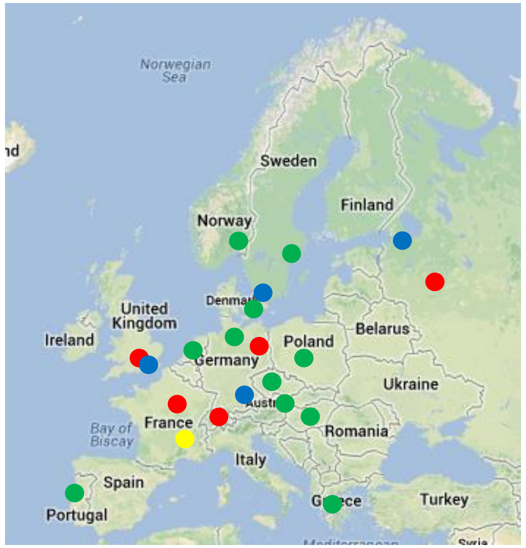
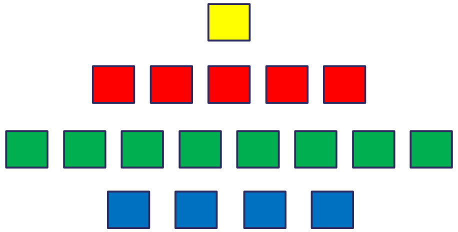
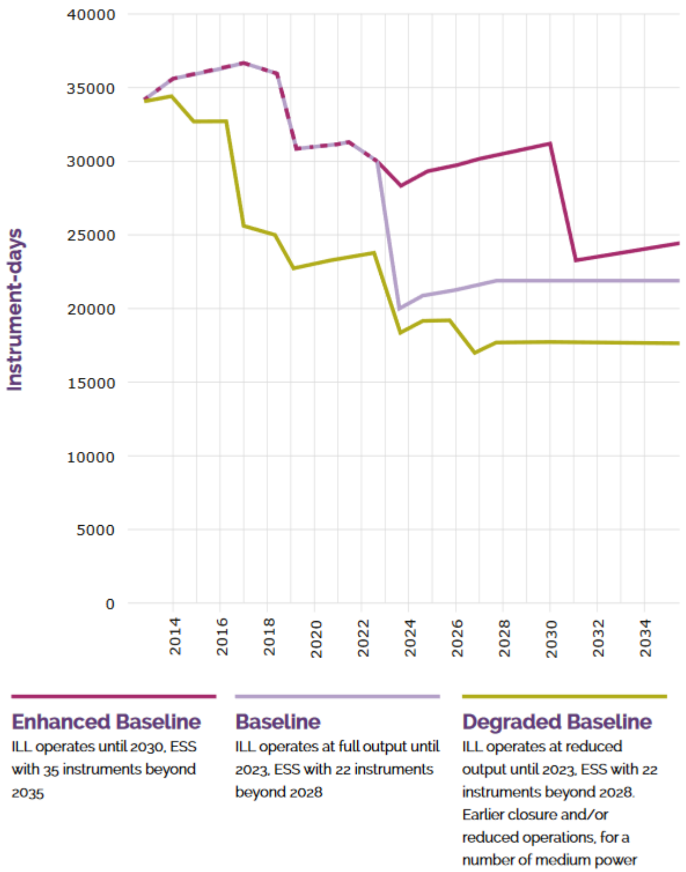
Purpose and Business Case

- Europe (including the UK) is a world leader in neutron-based science
- Potential for a European neutron drought in the coming decade



1998





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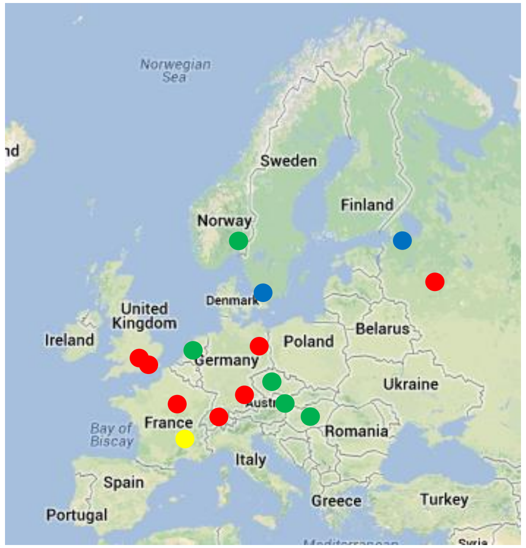
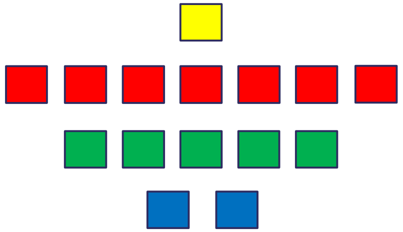
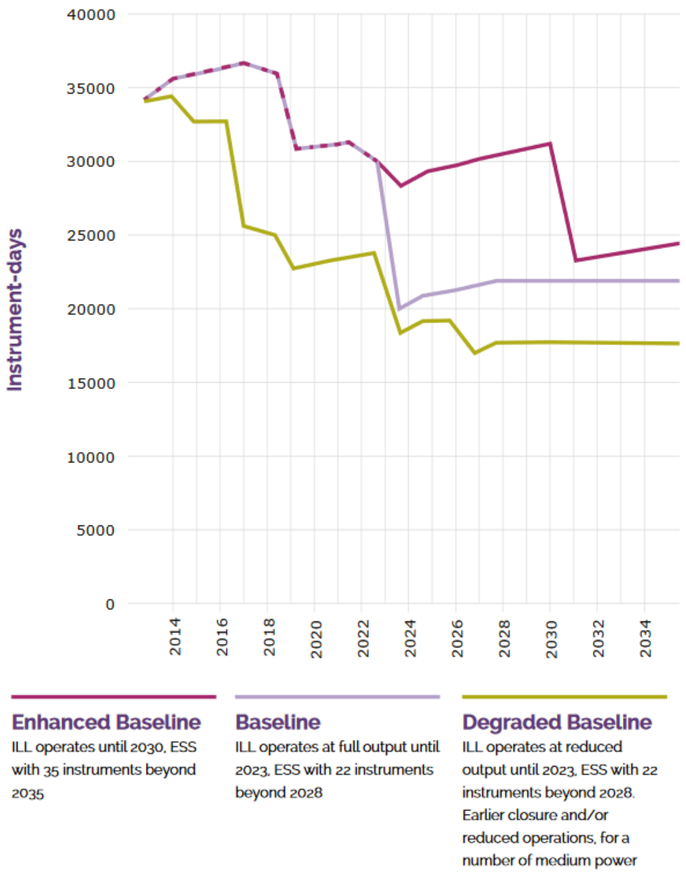


2014





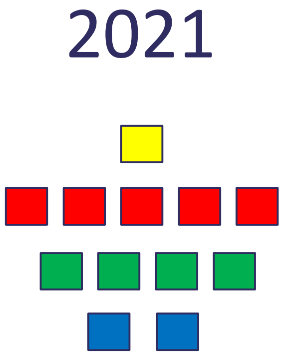
Enhanced Baseline
ILL operates until 2030, ESS with 35 instruments beyond 2035

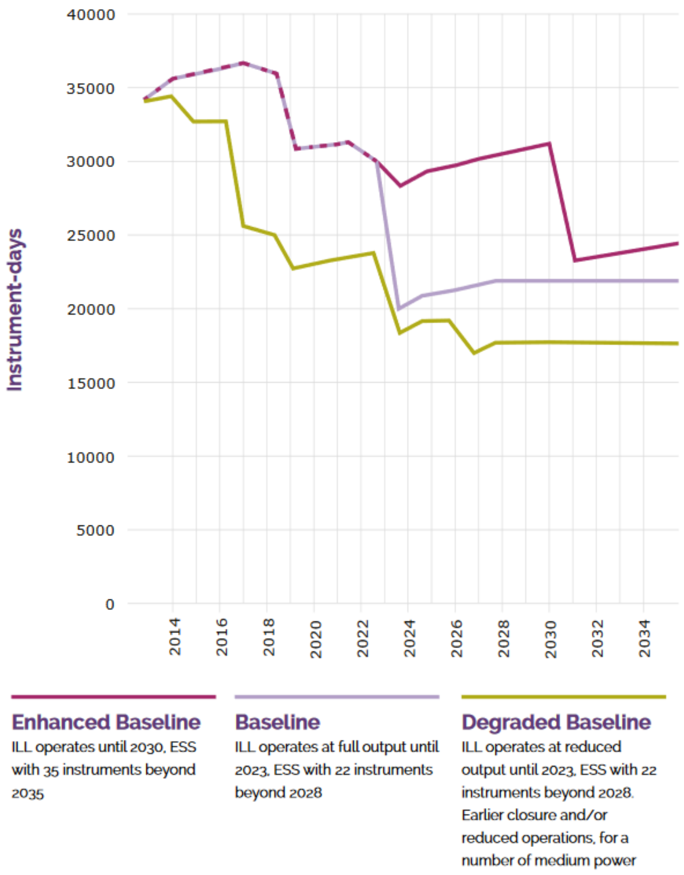
Baseline
ILL operates at full output until 2023, ESS with 22 instruments beyond 2028

Degraded Baseline
ILL operates at reduced output until 2023, ESS with 22 instruments beyond 2028. Earlier closure and/or reduced operations, for a number of medium power

Purpose and Business Case

- Europe (including the UK) is a world leader in neutron-based science
- Potential for a European neutron drought in the coming decade





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Baseline
ILL operates at full output until 2023, ESS with 22 instruments beyond 2028

Degraded Baseline
ILL operates at reduced output until 2023, ESS with 22 instruments beyond 2028. Earlier closure and/or reduced operations, for a number of medium power

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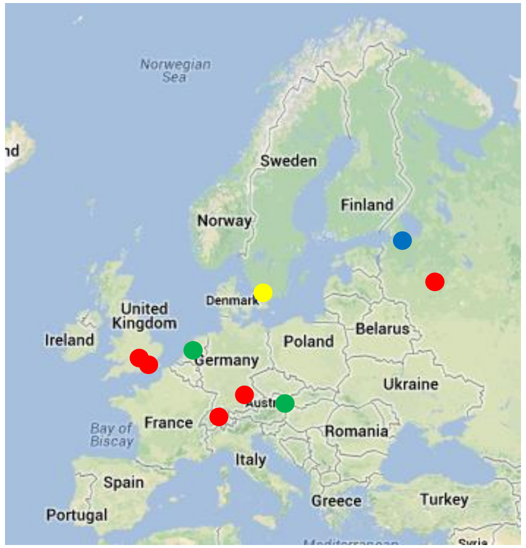
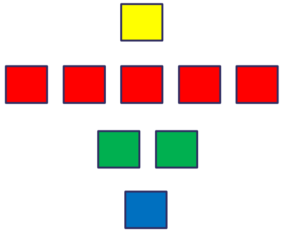
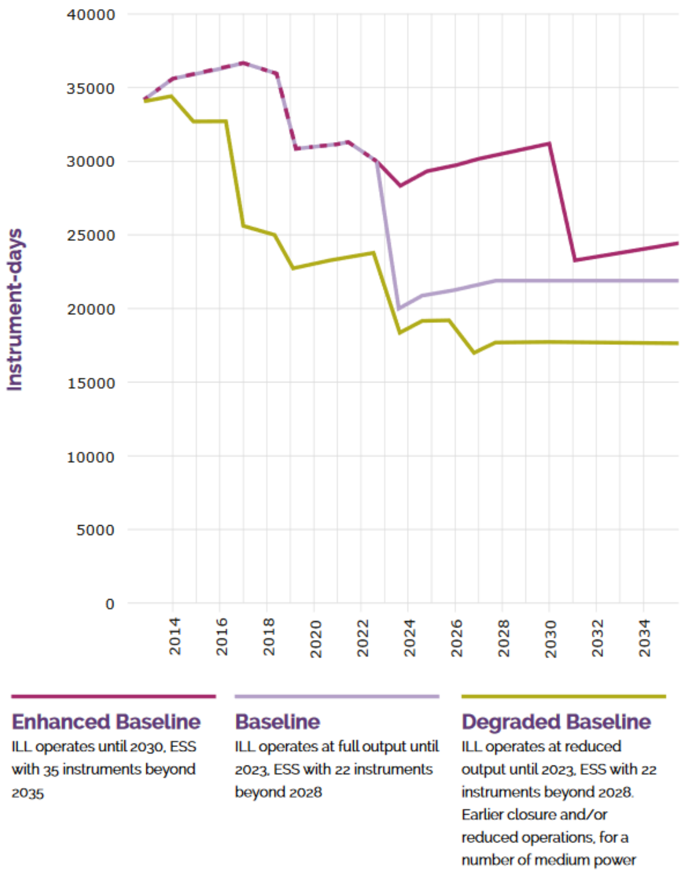
Purpose and Business Case

- Europe (including the UK) is a world leader in neutron-based science
- Potential for a European neutron drought in the coming decade



2030?





Enhanced Baseline
ILL operates until 2030, ESS with 35 instruments beyond 2035

Baseline
ILL operates at full output until 2023, ESS with 22 instruments beyond 2028

Degraded Baseline
ILL operates at reduced output until 2023, ESS with 22 instruments beyond 2028. Earlier closure and/or reduced operations, for a number of medium power

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Purpose and Business Case

ESFRI Neutron Scattering Facilities in Europe Report

…by far the most cost effective solution would therefore be to build a MW-class short pulse facility at ISIS, reusing existing infrastructure and facilities as well as drawing upon on-site competences. The current facility could operate until the new facility is operational with its initial suite of instruments.

STFC Accelerator Strategy Review

- *Investment in high power proton beams and targets is recommended to support … neutron facilities research and development.*
- *Collaboration with international partners on facility development and accelerator research activities is recommended, where appropriate.*
- *The UK national laboratories should be charged with the co-ordination of research and development activities across stakeholders in development of future neutron sources.*

STFC Neutron Science and Facilities – An Update to the 2017 Strategic Review

The concept of an ISIS-II short pulse facility is exciting, and it has the potential to be very complementary to other sources. Continued exploration is strongly encouraged as a long-term option.

…the concept demonstrates visionary forward thinking and could create an exciting technical challenge to engage the whole UK community in.

ISIS-II Working Group

- Experts from accelerator, target, neutronics, instrument science, detectors and engineering – what would an optimal MW-class short pulse neutron and muon facility at ISIS with the best balance of technical capability and lifetime cost – ISIS-II – look like?

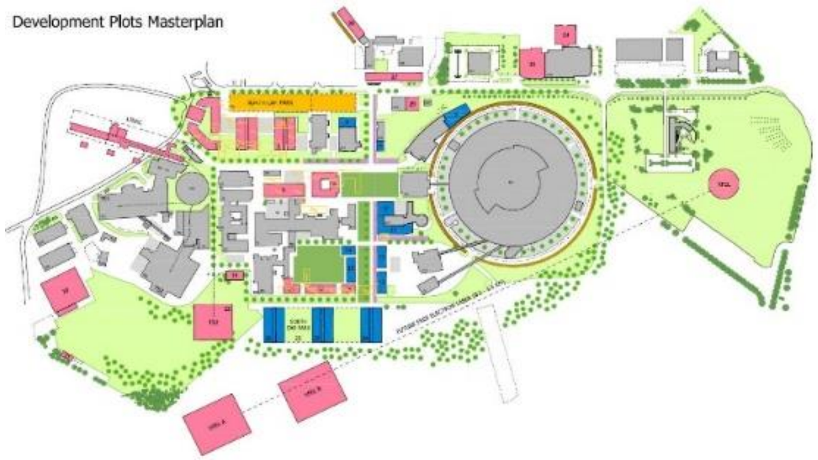
- Pre-requisites of looking at a short pulse (rather than long pulse) and a large scale facility (rather than a compact source)

- Considered multiple day-one target stations, variety of repetition rates, FFA options and muon production in the context of a facility upgrade, not simply an accelerator upgrade.

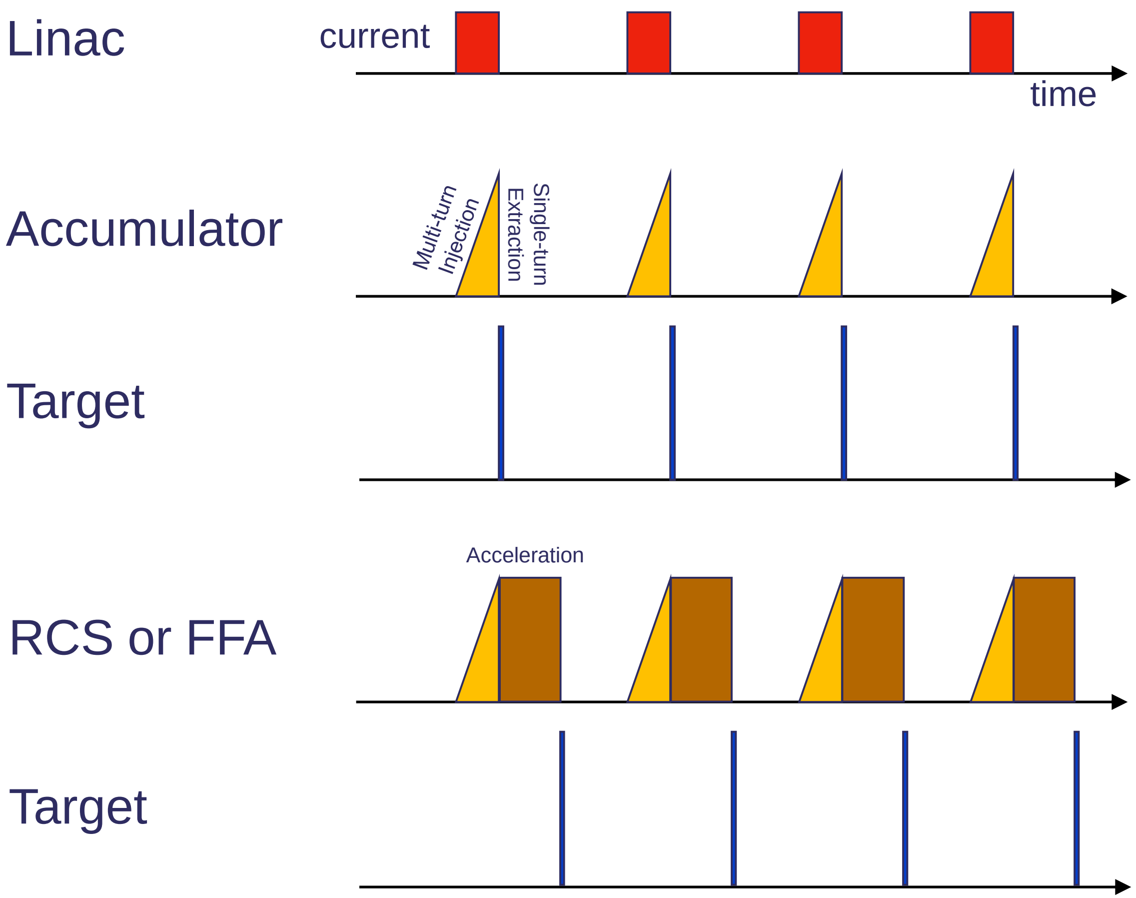
- Looking primarily at options for:

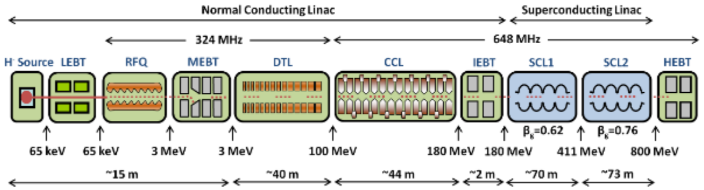
1) Stand alone facility

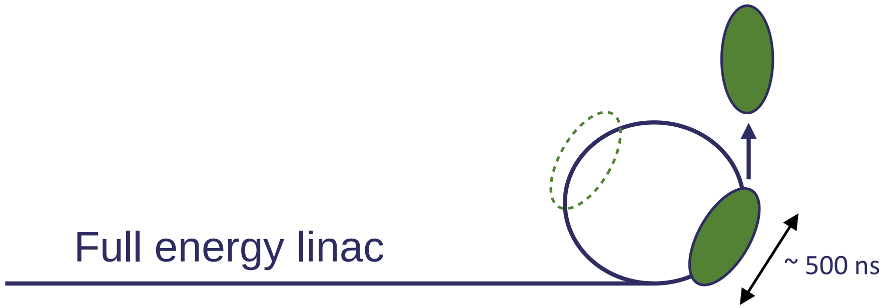
2) Re-use of ISIS infrastructure

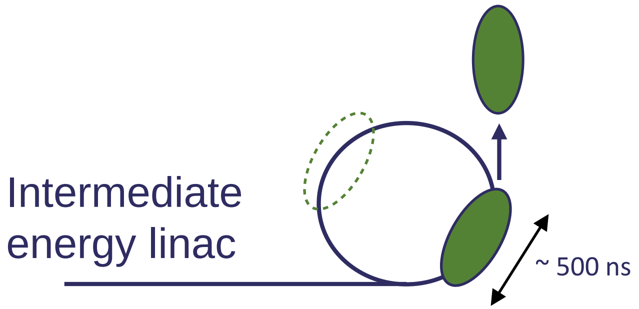


- For short pulse source need linac + ring









Beam power (MW)	= **Beam Energy (GeV)**	× **Linac peak current (mA)**	× **Linac pulse length (ms)**	× **Frequency (Hz) (÷ 1,000)**
ISIS				
0.192	0.8	24	0.2	50
‘ISIS-II’				
1.25	1.2	57	0.6 (60% chopped)	50
‘ISIS-II – 10 Hz’				
1.25	3.2	80	0.8 (60% chopped)	10

Higher power → less efficient conversion to neutrons, could offset by multiple targets

Higher energy → larger ring (or stronger magnets) & less efficient conversion to neutrons

Higher intensity → more space charge, harder to control beam loss

Longer pulse → higher intensity in ring (larger apertures, bigger ring or stacked rings), more linac RF

Frequency change has big effect on accelerator design → need to fix this early

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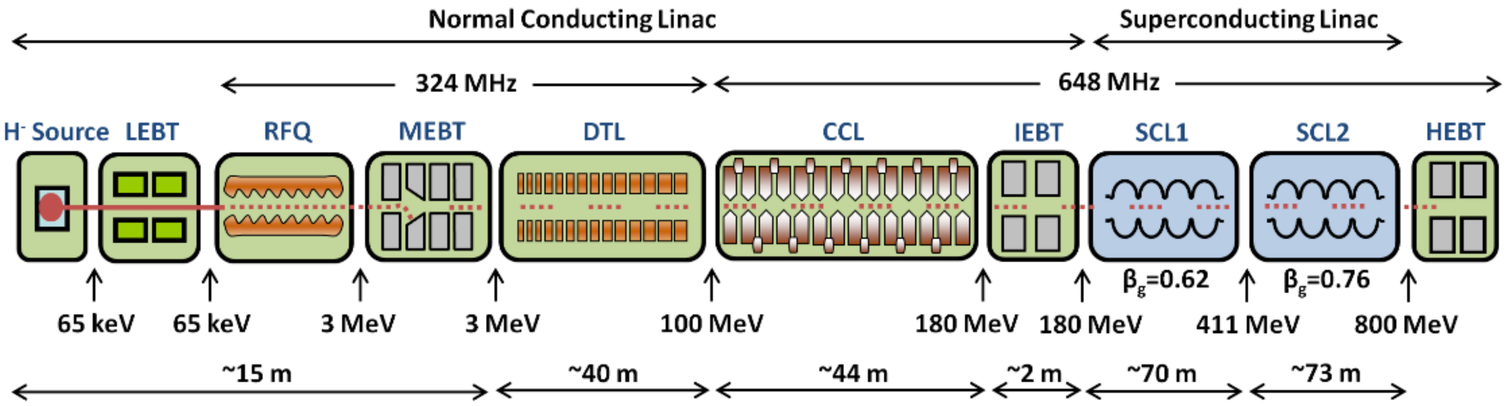
Accelerator Options



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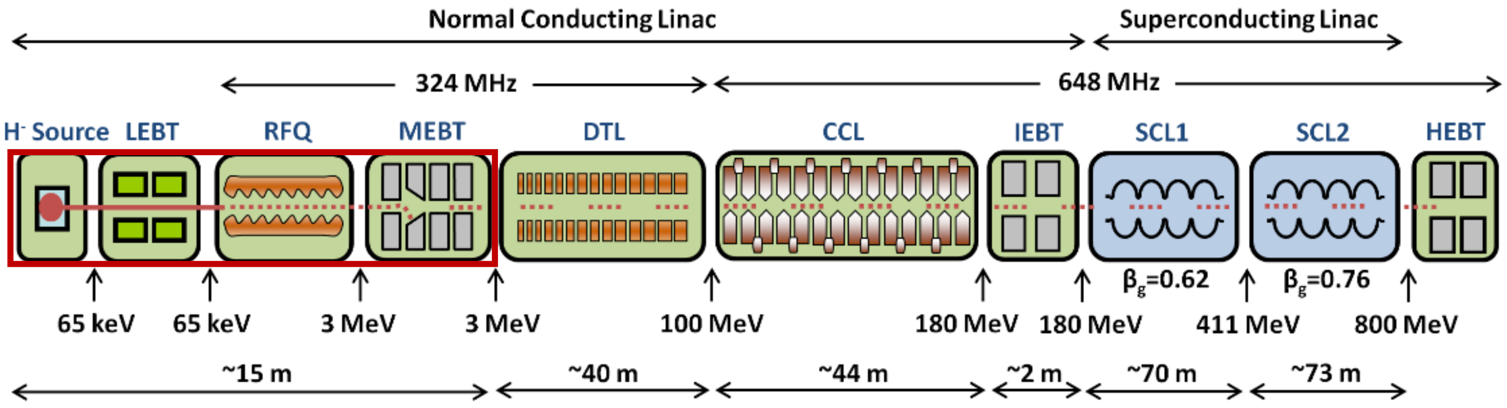
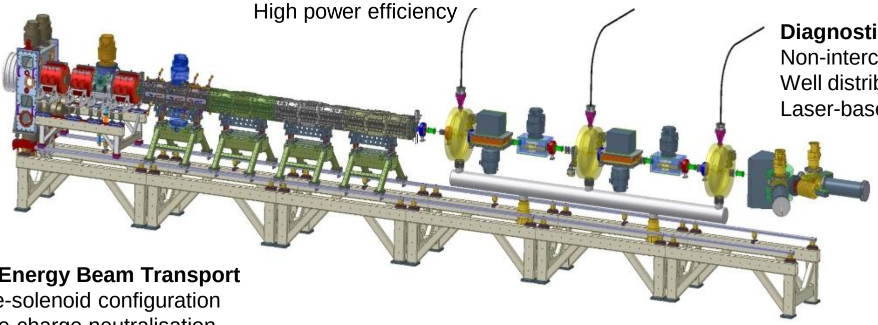
Accelerator Options



- Linac front end to 3 MeV would be based on Front End Test Stand (FETS) frequency and architecture.



High brightness H⁻ ion source
4 kW peak-power arc discharge
60 mA, 0.25 π mm mrad beam
2 ms, 50 Hz pulsed operation

Radio Frequency Quadrupole
Four-vane, 324 MHz, 3 MeV
4 metre bolted construction
High power efficiency

Diagnostics
Non-interceptive
Well distributed
Laser-based

Low Energy Beam Transport
Three-solenoid configuration
Space-charge neutralisation
5600 Ls^{-1} total pumping speed

Medium Energy Beam Transport
Re-buncher cavities and EM quads
Novel 'fast-slow' perfect chopping
Low emittance growth

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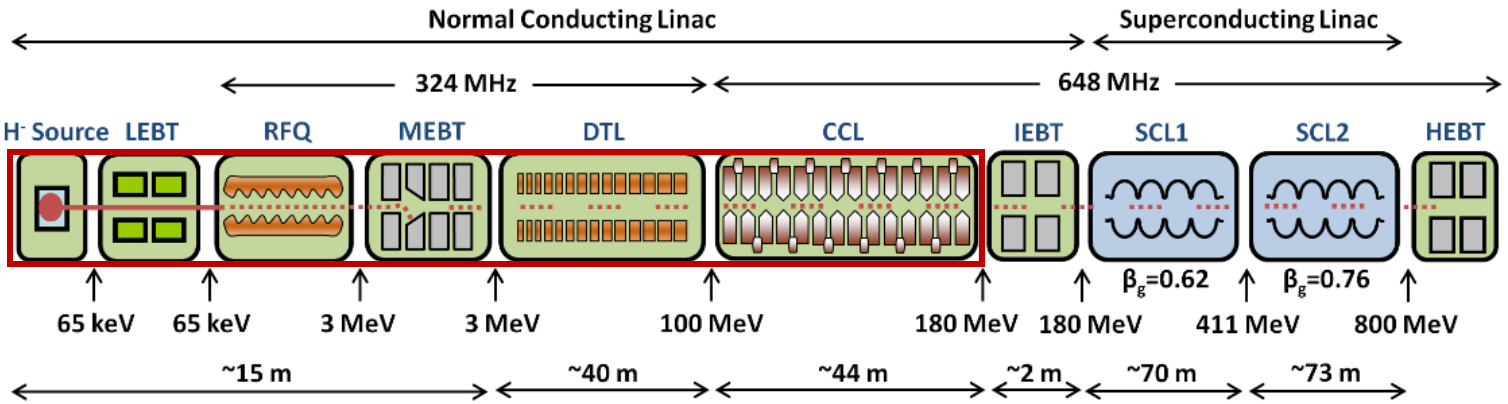
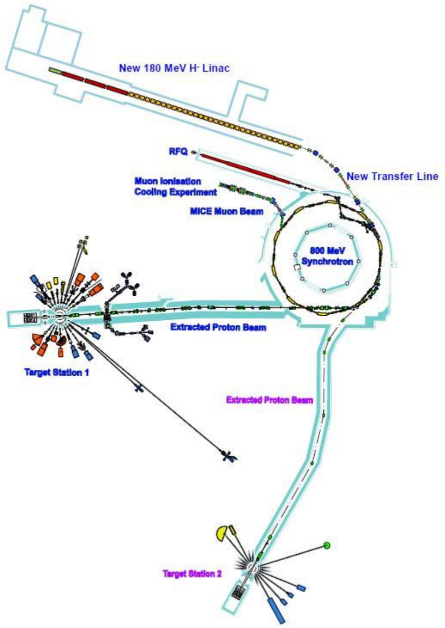
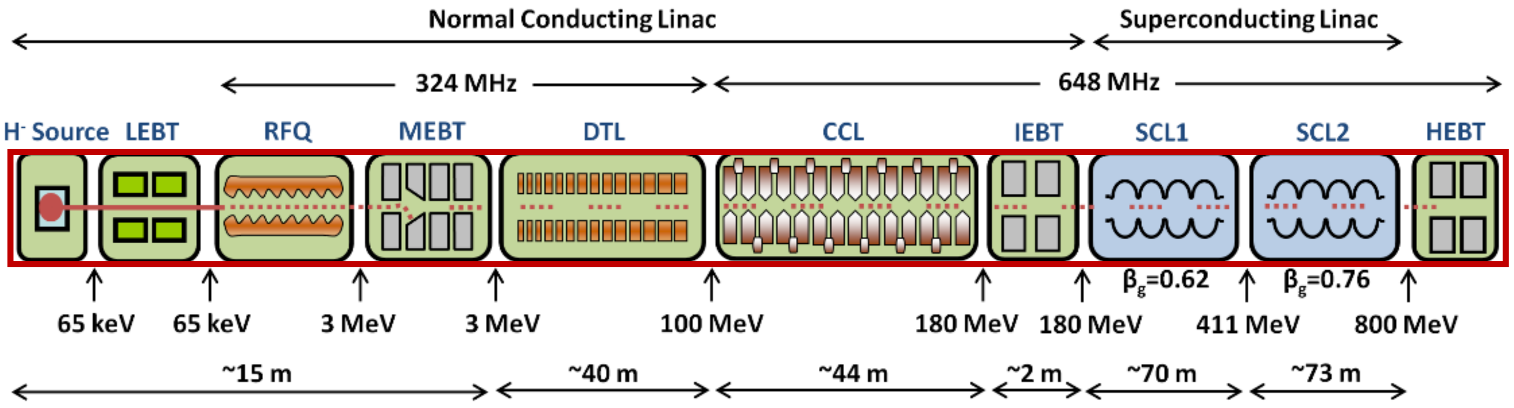
Accelerator Options





- Design to 180 MeV has been shown to be compatible with present ISIS synchrotron to produce 0.5 MW with relatively little change needed except for the injection straight.

Accelerator Options



- 800 MeV SCL design shown here could be curtailed at lower energy for injection to a rapid cycling synchrotron (RCS) or fixed-field accelerator (FFA) or extended to 1.2 GeV for injection into an accumulator ring (AR).

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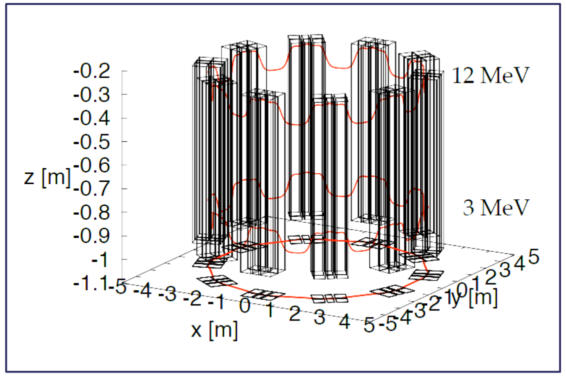
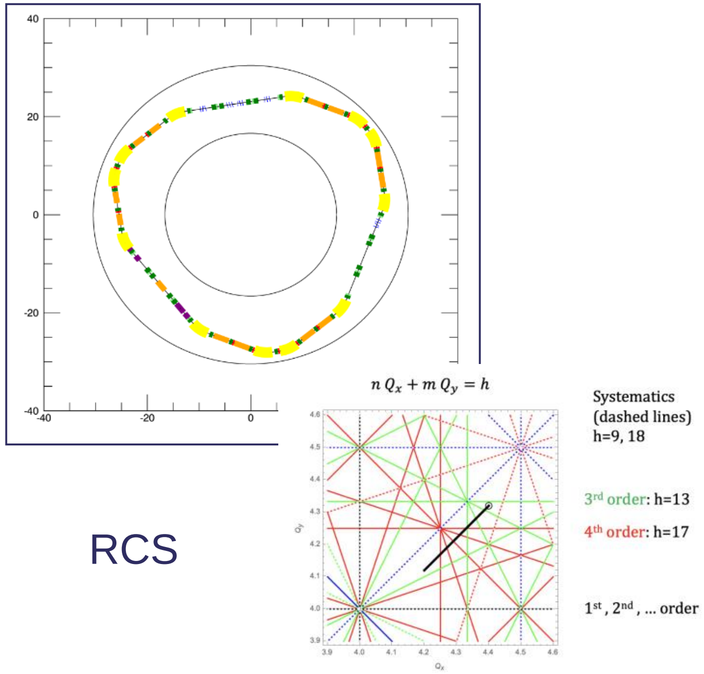
Accelerator Options

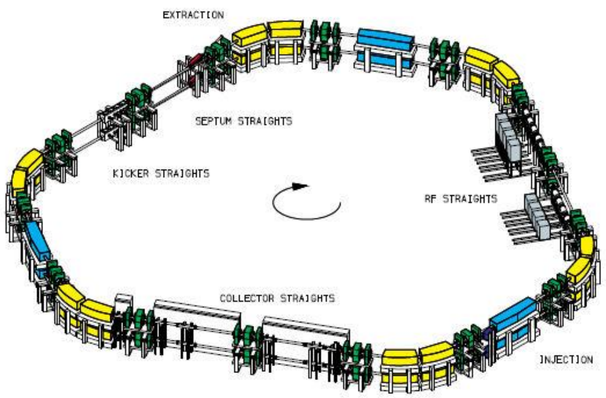
- Options for pulse compression to < 1 μs pulse train



FFA

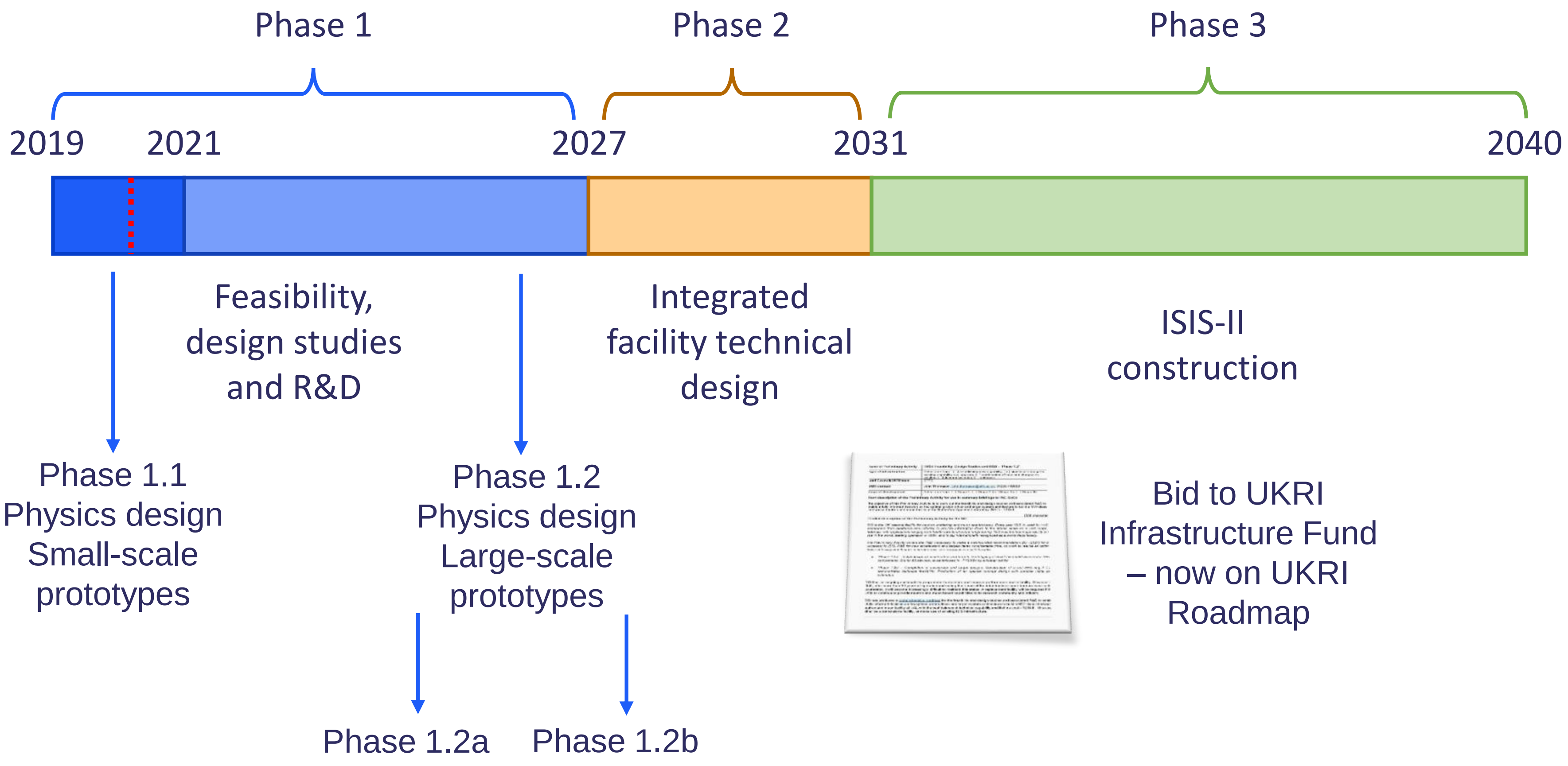


RCS



AR

Schedule and Phased Approach



Phase 1

Phase 2

Phase 3

2019

2021

2027

2031

2040

Feasibility, design studies and R&D

Integrated facility technical design

ISIS-II construction

Phase 1.1
Physics design
Small-scale prototypes

Phase 1.2
Physics design
Large-scale prototypes

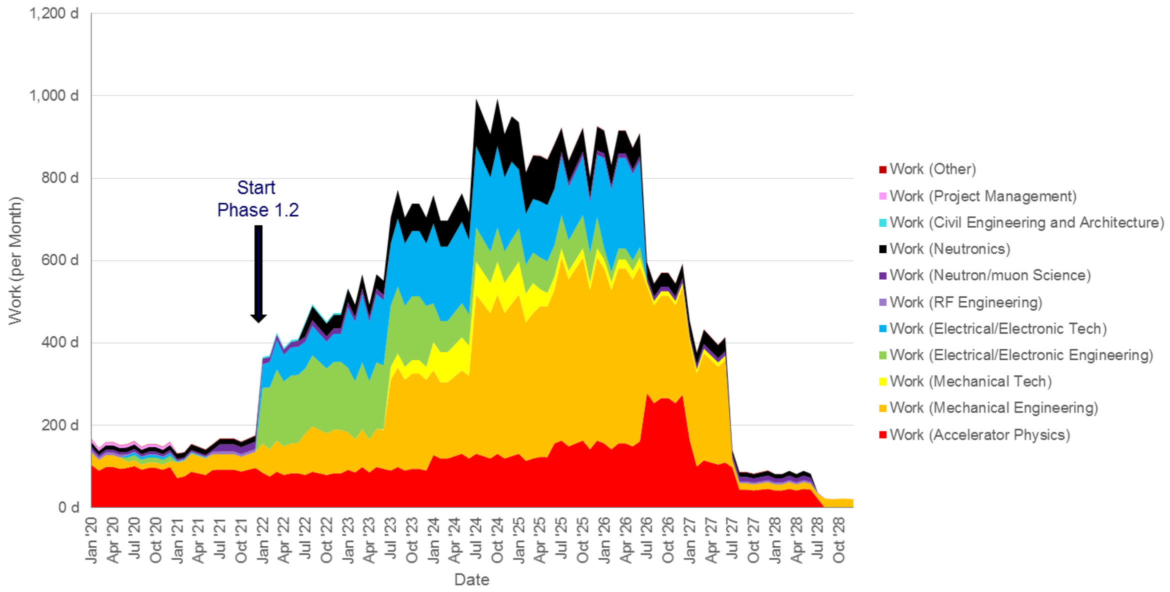
Phase 1.2a

Phase 1.2b

Bid to UKRI Infrastructure Fund – now on UKRI Roadmap

Phase 1 Tasks

- Three accelerator ring types investigated
  - Rapid cycling synchrotron (RCS)
  - Accumulator ring (AR)
  - Fixed-field alternating gradient (FFA)
- Linear accelerator design to feed into ring
- Target, moderator and shielding feasibility designs
- Full scale prototypes as necessary to inform decisions
- Production of an optimal conceptual design to take into detailed facility design



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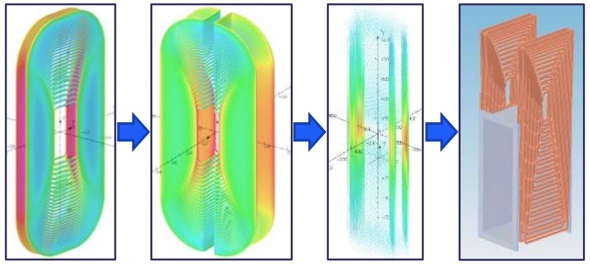
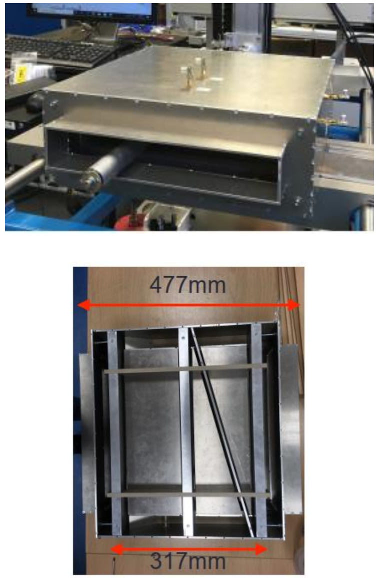
Phase 1.1 Tasks

- Greenfield and existing facility designs of the RCS, AR and FFA
  - MW-class short pulse designs
- Design of FETS-FFA test ring
- Small-scale component prototypes for FFA

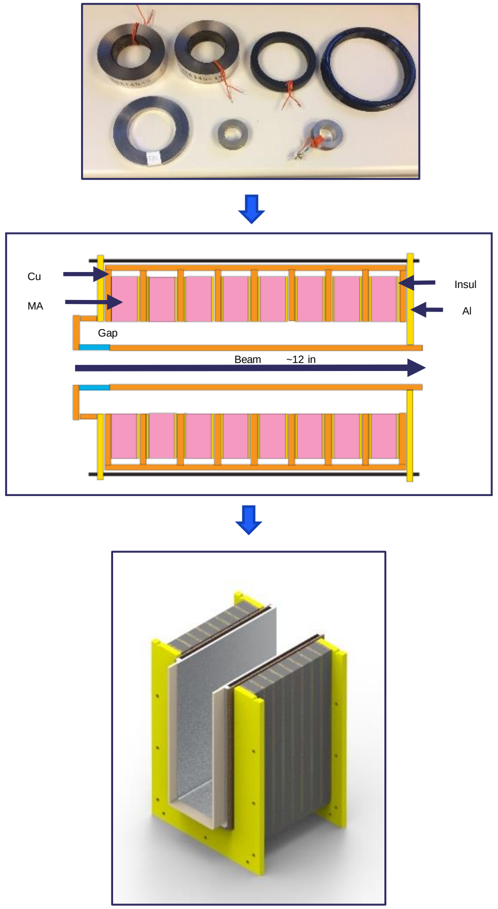
Magnets



Diagnostics



Accelerating cavities



- Target and moderator design and manufacturing R&D
- Science facility parameters review

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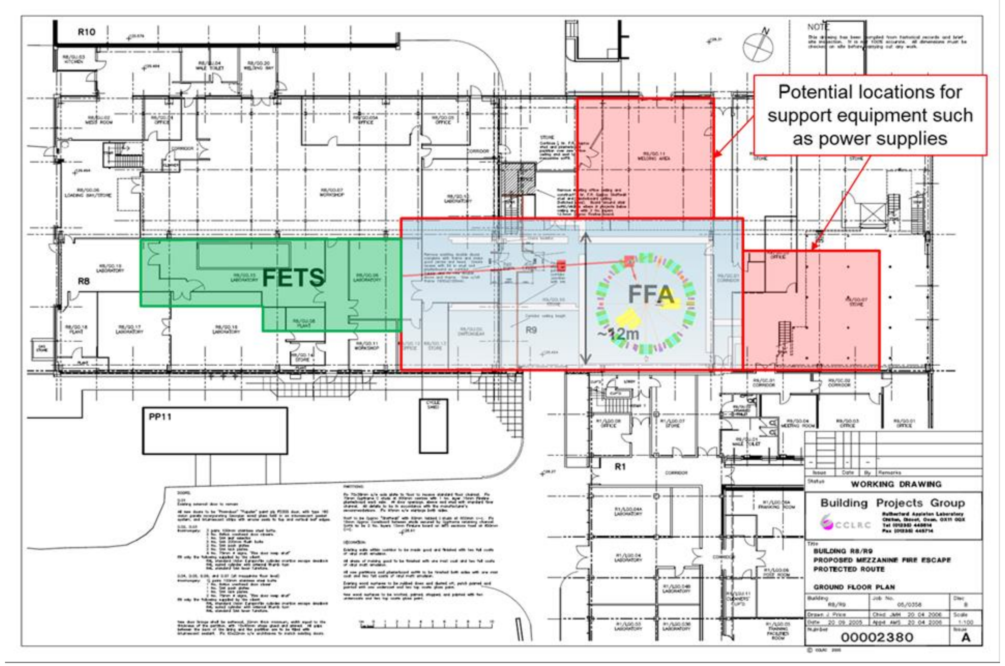
Phase 1.2a Tasks

- Provision of a robust methodology to demonstrate the technical decision making process for ISIS-II, and provide a strong foundation for further work going forward.
- Initial development of pulse compression ring designs for rapid cycling synchrotron (RCS), accumulator ring (AR) and fixed-field accelerator (FFA) options.
- Prototyping necessary FFA components and subsystems to demonstrate technical feasibility. Exploration of more novel technologies such as the FFA, which may present the possibility for a more energy efficient facility, perhaps using superconducting and/or permanent magnets, and also has advantages in more flexible pulse generation.
- Initial target, moderator and shielding feasibility for 1 MW, 40 Hz and 0.25 MW, 10 Hz neutron targets and a muon target.

Phase 1.2b Tasks

- Construction of a small FFA test ring on the end of the Front End Test Stand (FETS) at RAL in order to explore the beam dynamics fully.
- Completion of compression ring designs.
- Linear accelerator design integrated with choice of pulse compression ring, drawing on emerging SCRF strength in ASTeC.
- Completion of target, moderator and shielding design for 1 MW, 40 Hz and 0.25 MW, 10 Hz neutron targets and a muon target.
- Production of an optimal concept design with credible initial cost estimates.



Potential locations for support equipment such as power supplies

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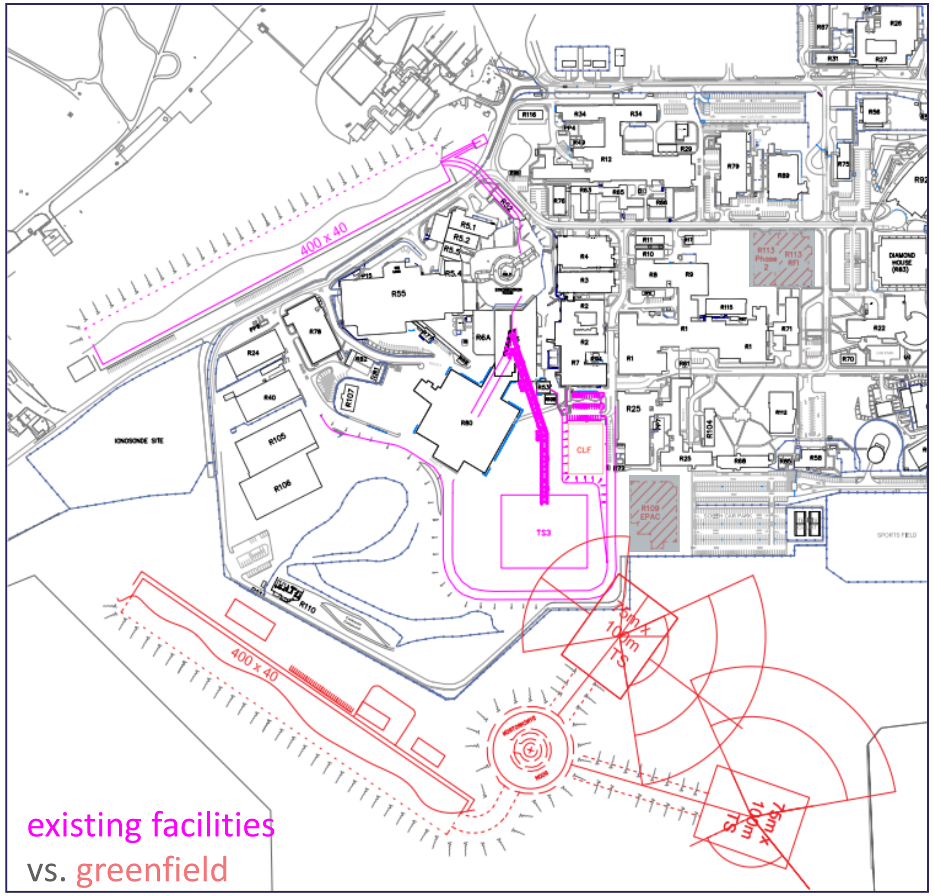
Campus Land Proposals

- Layouts of ISIS-II have been presented for the land to ensure all options remain accessible



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Thank you