ISIS Upgrade: 40 Years of the ISIS Neutron and Muon Source

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Science and Technology Facilities Council

ISIS Neutron and Muon Source

Outline

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  - The ISIS Facility
  - 40 Years of ISIS: Milestones and Major Upgrades
- Neutron Sources
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  - Applications of Neutron Sources
  - Spallation Neutron Sources
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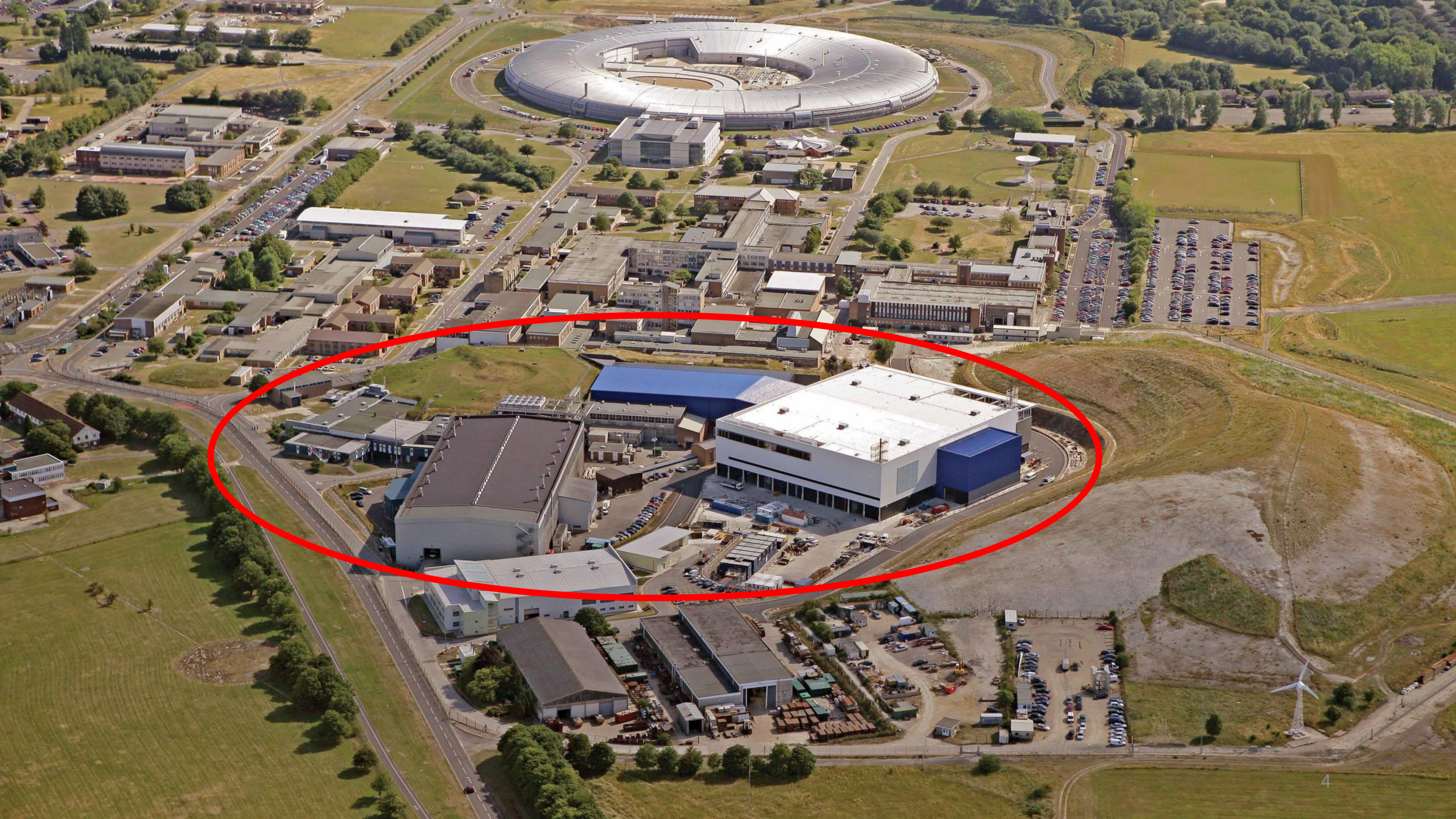
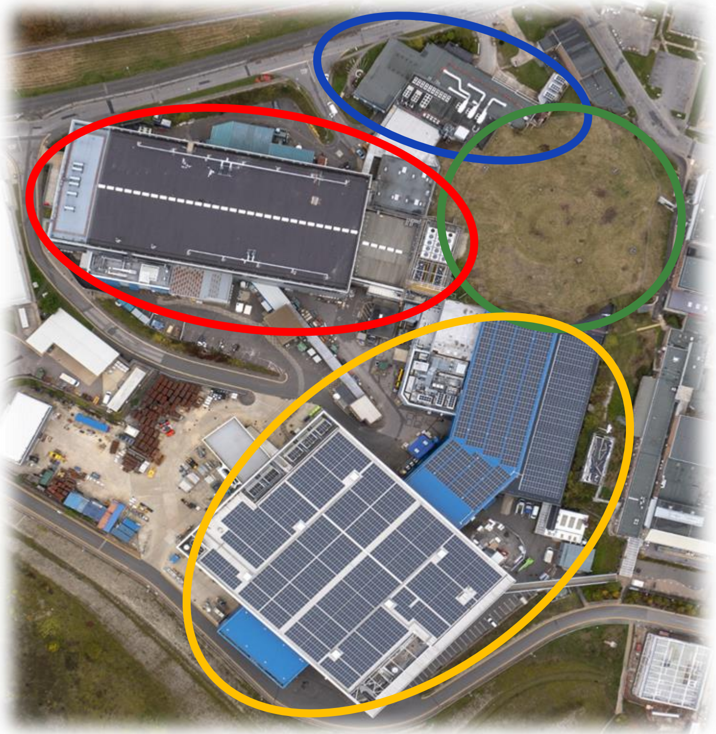
  - MEBT
  - Novel RF Plasma Source
- ISIS-II
  - Design Options
  - Studies Underway
  - FETS FFA

Introduction to ISIS



The ISIS Facility

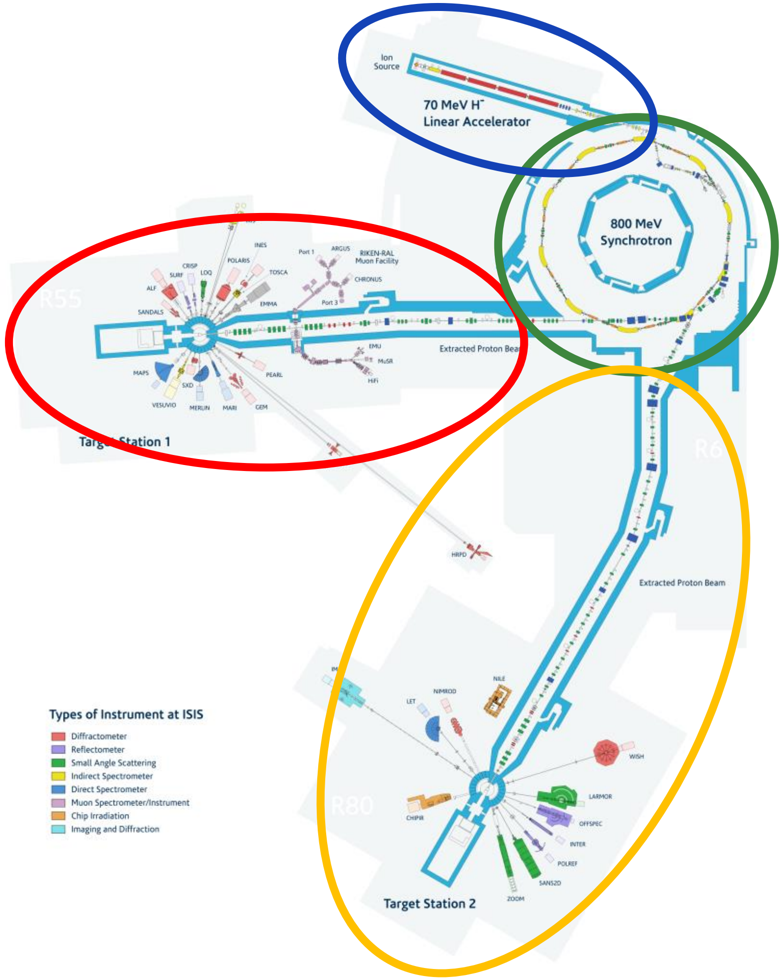


H^- source (RFQ + DTL)

800 MeV RCS

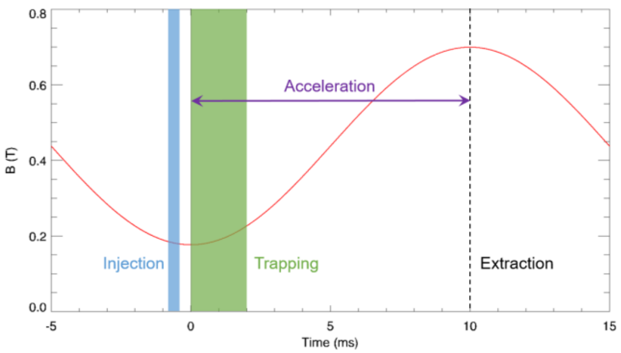
Target Station 1

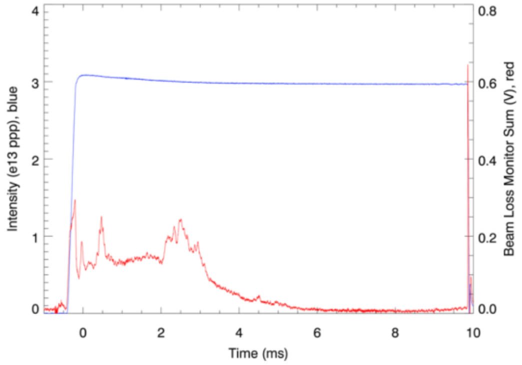
Target Station 2

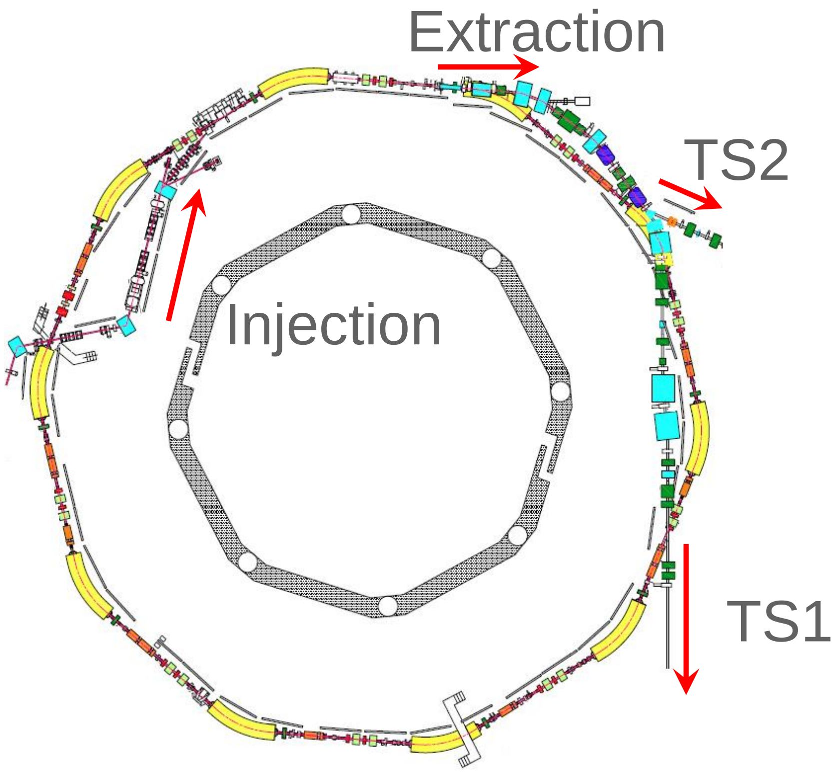


The ISIS RCS

Mean Radius	26 m
Beam Energy	70 – 800 MeV
Intensity	~3e13 ppp
Repetition Rate	50 Hz
Lattice Periodicity	10 SP
Injection	220 µs, 130 turns (charge exchange)
Painting	Dispersive horizontal, injected beam position scanned vertically
Extraction	Single turn, vertical
Betatron Tune	(Q_x, Q_y) = (4.31, 3.83), programmable
Beam Losses	Injection: 2%, Trapping: <3%, Acceleration/Extraction: <0.5%
RF System	6 × fundamental (h=2) @ 160 kV/turn, 4 × 2nd-harmonic (h=4) @ 80 kV/turn







ISIS@40

ISIS celebrates its 40th birthday this year. Major milestones and achievements include:

- First neutrons **Dec 1984**
- Regular runs from **Jan 1985** (25 Hz, 10 μA, 550 MeV)
- Operational phase began in **1986** (50 Hz, 30 μA, 550 MeV)
- First muons **1987**
- Design energy and current achieved **1994** (50 Hz, 200 μA, 800 MeV)
- Most powerful pulsed neutron source in the world in **2004** (now surpassed)
- Longest operational lifetime of any UK accelerator

ISIS named for Egyptian goddess of re-birth, as well as the traditional name of the River Thames as it flows through Oxford:

- Linac originally commissioned as injector upgrade for Nimrod
- RCS constructed in the hall of the old Nimrod accelerator
- Re-used many components of Nimrod and NINA accelerators

ISIS@40: Major Upgrades

- **1987**: 6 fundamental RF cavities operational; new extract septum
- **1989**: orbit correction system
- **1991**: new extraction kickers
- **1993**: diagnostic chopper, betatron Q-control system, MPS (BLM trips)
- **2001**: move to tantalum-coated tungsten target material
- **2002**: collimation system; new extract septum
- **2004**: CW generator replaced with RFQ; 2nd-harmonic RF
- **2008**: Target Station 2 first neutrons

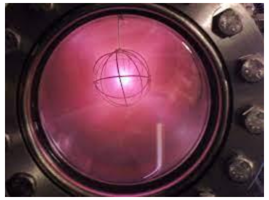
Neutron Sources

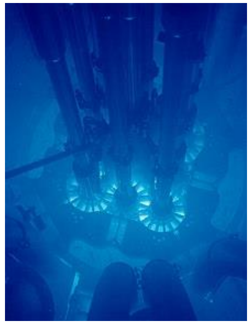
Types of Neutron Sources

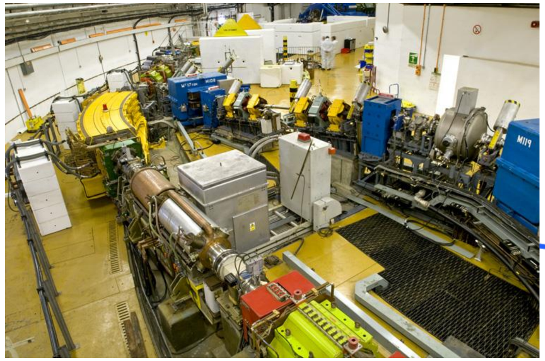
- Many types of sources, of varying size:
- Radioisotope devices (e.g spontaneous fission, alpha-emitters, photo-neutron)
  - Typically capsule sized, filled with powder
  - Unstable nuclei, sometimes mixed with secondary light nuclei
  - Integrated fluxes ~ 10^6 – 10^9 n s^{-1}
- Plasma-based devices (e.g. Z-pinch, inertial electrostatic confinement)
  - Table-top devices
  - Exploit nuclear fusion reactions
  - Z-pinch devices can be pulsed (single-shot, ~10^{12} – 10^{14} n/pulse)
- Nuclear reactor sources
  - Most ubiquitous source of research neutrons
  - Very high continuous flux (10^{14}-10^{15} n $s^{-1}cm^{-2}$), very reliable
  - Very large installations
- Spallation Neutron Sources
  - Pulsed, high rep-rate
  - Very large installations
  - Very high flux (10^{16} – 10^{18} n s^{-1})
  - High(ish)-energy proton accelerator driver


Cf-252 source


Institut Laue-Langevin


IEC fusor


Advanced Test Reactor core

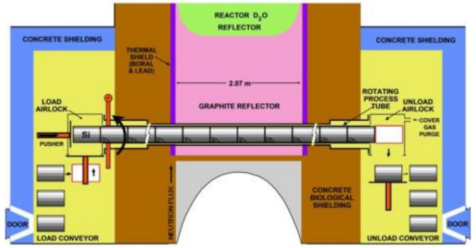

ISIS Synchrotron


European Spallation Source


China Spallation Neutron Source

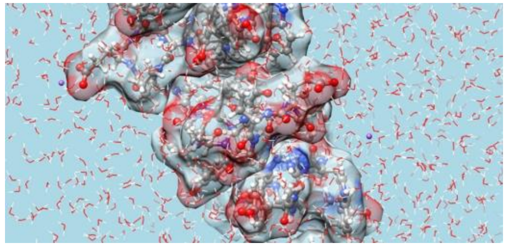
Applications of Neutrons

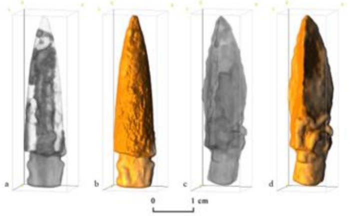
- Industrial Uses
  - Non-destructive materials testing and analysis (neutron radiography)
  - Stress analysis
  - Oil and gas exploration
  - Silicon doping for semiconductor manufacturing



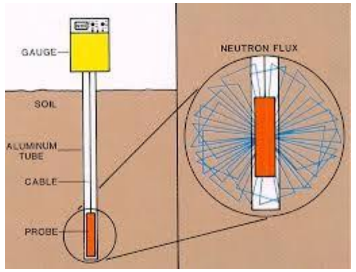
- Medical
  - Cancer therapy (NCT)
  - Medical imaging
  - Radioisotope production

- Research
  - Nuclear fuel development
  - Materials science
  - Biomedical research
  - Cultural heritage
  - Neutron activation analysis
  - Condensed matter research





- Agriculture and Environment
  - Soil moisture and nutrient content
  - Trace element analysis
  - Crop breeding and genetics
  - Nuclear waste analysis



Spallation Neutrons

High energy proton hits a heavy nucleus, generating neutrons as debris from collision

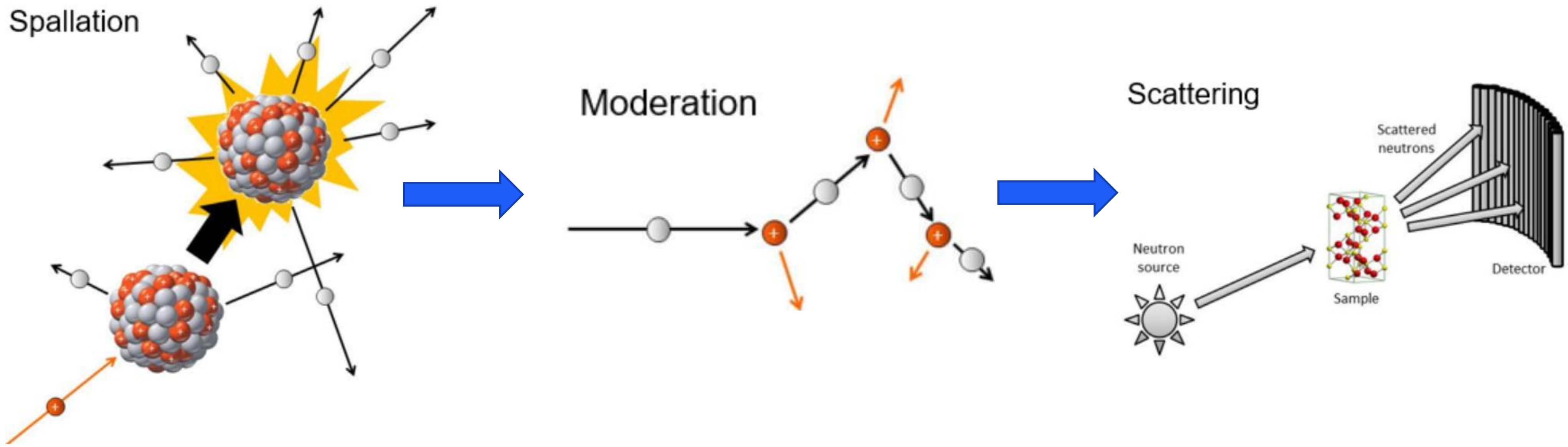


Image credit: J Thomason

Spallation Neutron Sources

ISIS Neutron and Muon Source

- 800 MeV proton beam
- 200-250 μA
- 50 Hz
- 2 Target Stations
- Short pulse
- Also produces muons for spectroscopy
- 2e16 n s^{-1}

J-PARC

- 3 GeV proton beam
- 300-400 μA
- 25 Hz
- Short pulse
- Also produces muons for spectroscopy
- 1e17 n s^{-1}

大強度陽子加速器施設 J-PARC Japan Proton Accelerator Research Complex

SNS

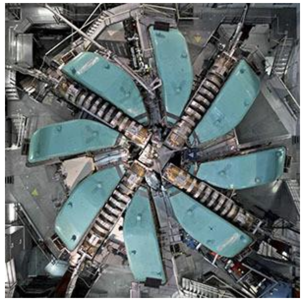
- 1 GeV proton beam
- 1.4 mA
- 60 Hz
- Short pulse
- 1e17 n s^{-1}

OAK RIDGE National Laboratory

ESS

- Still under-construction
- 2 GeV proton beam
- 62.5 mA
- 14 Hz
- Long pulse
- Will be the most powerful source in the world – 5 MW
- 1e18 n s^{-1}

ess EUROPEAN SPALLATION SOURCE



SINQ

- 590 MeV proton beam
- 2.3 mA
- Continuous beam
- Also produces muons for spectroscopy
- 1e17 n s^{-1}

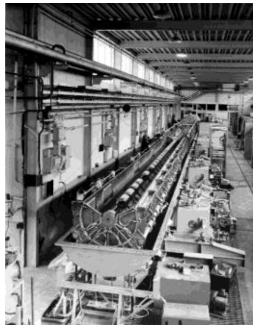
PAUL SCHERRER INSTITUT PSI

Honourable mentions:

- CSNS
- LANSCE
- n_TOF

Recent ISIS Upgrades

Tank 4 Replacement


[1]


[3]

Image Credit:
[1] Atomic Energy Research Establishment Harwell Photographic Group, courtesy AIP Emilio Segrè Visual Archives, Physics Today Collection
[2] Letchford, A. *"UPGRADES AND DEVELOPMENTS AT THE ISIS LINAC"*, LINAC2022
[3] ISIS

ISIS linac is re-purposed from Nimrod:

- 50 → 70 MeV injector upgrade (never realised for Nimrod)
- Tanks 2 & 3 re-purposed from the Proton Linear Accelerator (PLA)
- Tanks 1 & 4 constructed in 1970s (based on Fermilab design)

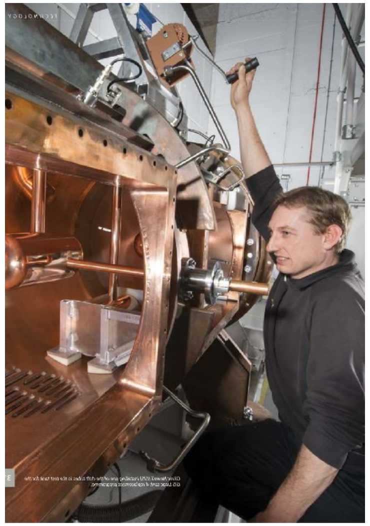

[2]


[2]

New Tank 4 installed during 2021 long shutdown.

- Direct "plug-in" replacement of original tank
- Increased reparability with new maintenance hatches
- Sections bolted together (originals welded)
- New drift-tube design improving TTF


[2]


[3]

Science and Technology Facilities Council

ISIS Neutron and Muon Source

www.isis.stfc.ac.uk

@isisneutronmuon

uk.linkedin.com/showcase/isis-neutron-and-muon-source

Synchrotron RF Upgrade

Fundamental RF high-power drives (HPDs) replaced during 2021 long-shutdown

Old HPDs use pair of Burle valves: concern over obsolescence and sourcing of replacements

New HPD runs off single Thales valve

2nd-harmonic systems to receive similar update at next long shutdown

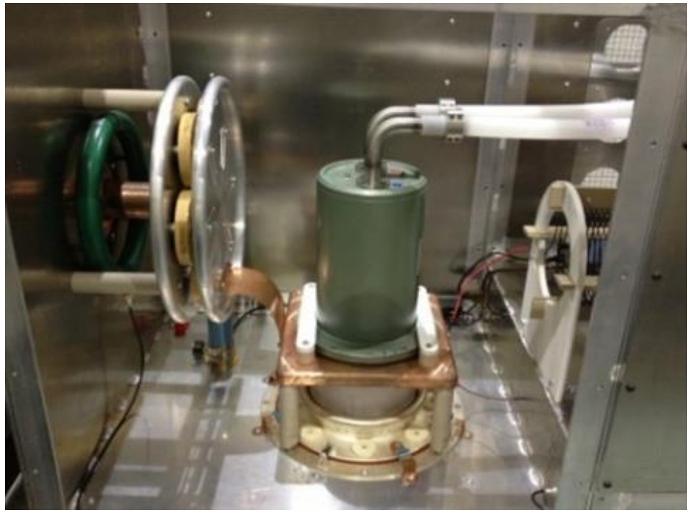


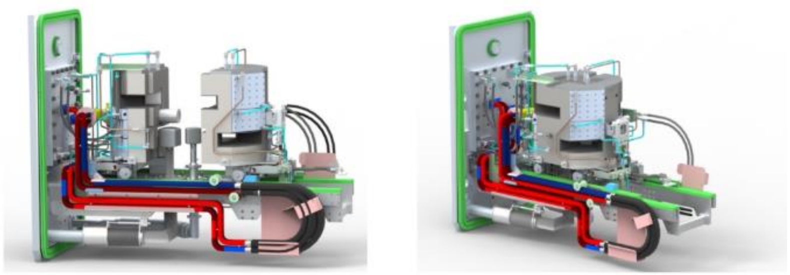
Image Credit: ISIS

Target Station 1 Upgrade

Target reflector and moderator (TRAM) assembly also upgraded in 2021 long shutdown.

New TRAM provides:

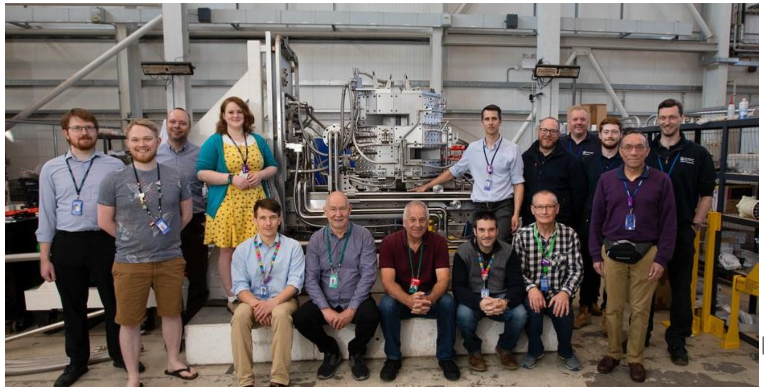
- Extended lifetime for TS1
- Improved neutron flux, due to solid Be reflector
- Easier remote handling capability
- Simplified decommissioning



[1]

Commissioning began 4 Nov 2022, fully commissioned 2023

[1]



[2]

Image Credit:
[1] Coates, D. *"ISIS Target Station One Upgrade Project – An overview of the development work being undertaken to improve the Target, Reflector and Moderator (TRaM) support systems"*, J. Phys.: Conf. Ser. 1021 012059, doi :10.1088/1742-6596/1021/1/012059
[2] ISIS

Ongoing and Upcoming Ugrades

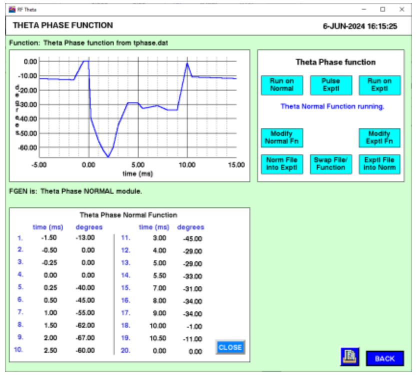
EPICS Migration

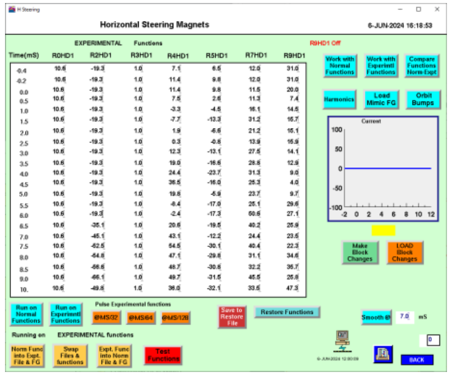
Current VSYSTEM-based control software has been running since the 90's

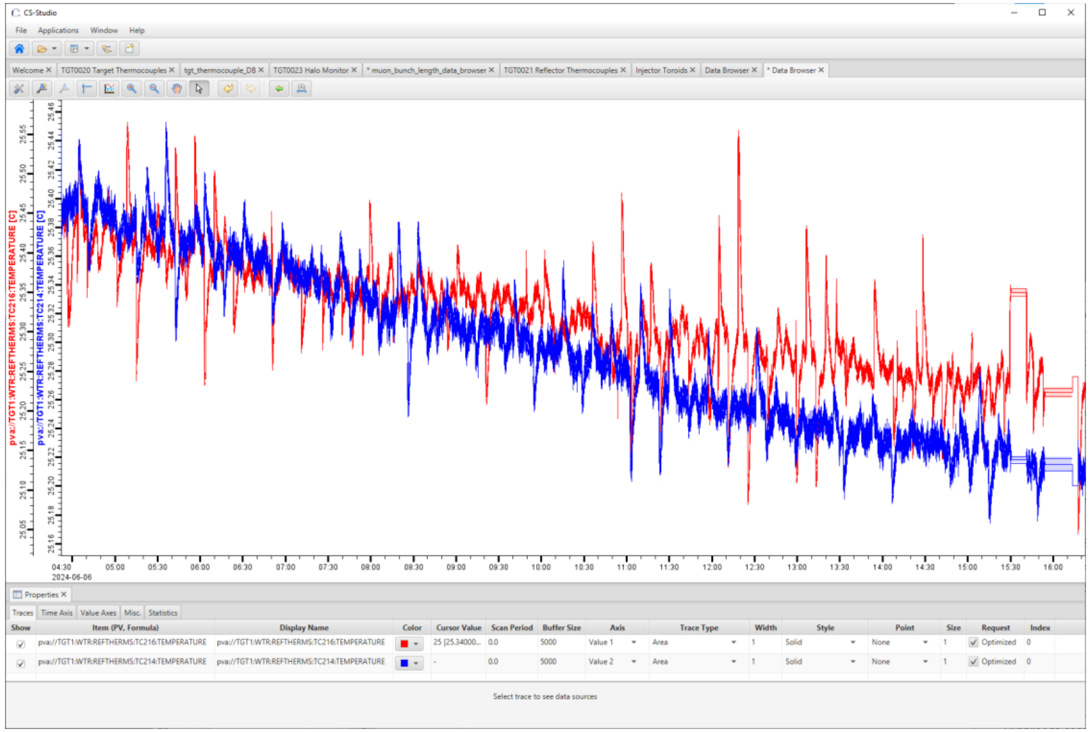
Instrumentation has been using EPICS-based (IBEX) since 2018

Migration to EPICS currently underway:

- Easy interfacing with custom python scripts
- Opportunity to revisit/redesign accelerator controls and add functionality
- Facilitates easy-access to time-series data of set/read values and measurements
- Removal of obsolete/unused control screens







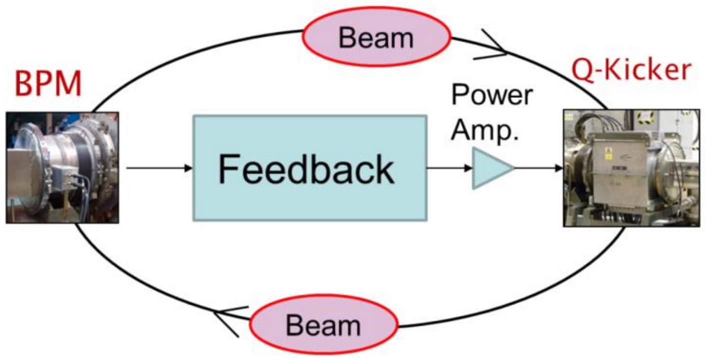
Q-kicker Damping System

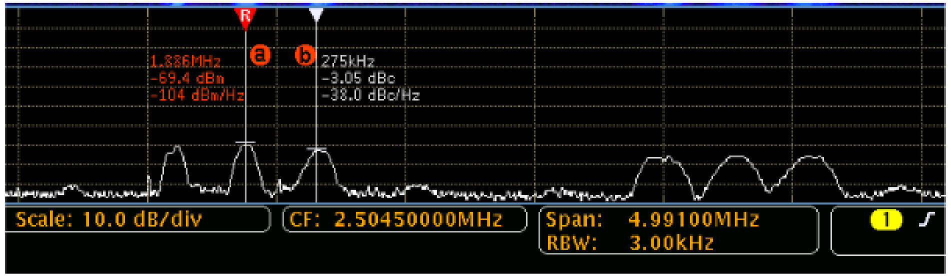
Head-tail instability is a significant limit on ISIS intensity.

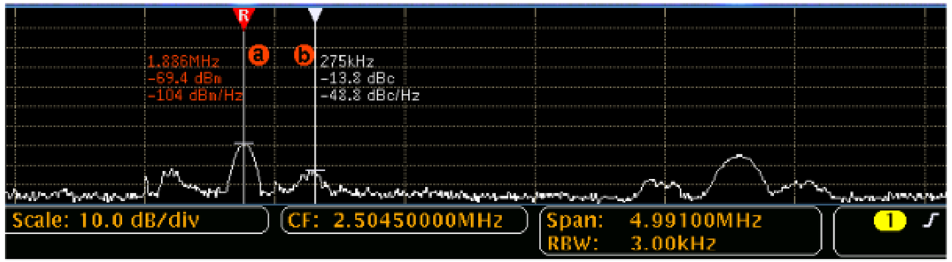
- Vertical displacement oscillation
- Mode structure longitudinal
- Driven by characteristic ring impedance

Multi-pronged effort to:

- Characterise the instability
- Diagnose the source impedance
- Develop methods for mitigation







The Q-kicker is a ferrite-loaded electromagnetic kicker, already installed on ISIS, used for tune measurements.

A feedback system using a ring beam position monitor and the Q-kicker are under development, with the aim of damping vertical oscillations.

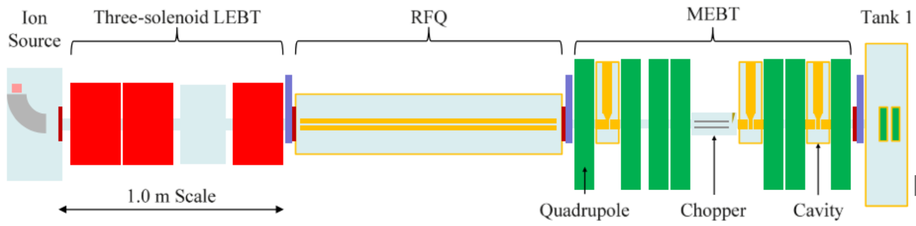
Initial tests demonstrate reduction in instability, but not fully commissioned for 50 Hz operations

Image Credit: Pertica, A. *"EXPERIMENTAL DAMPING SYSTEM WITH A FERRITE LOADED KICKER FOR THE ISIS PROTON SYNCHROTRON"*, IBIC2017

MEBT Installation

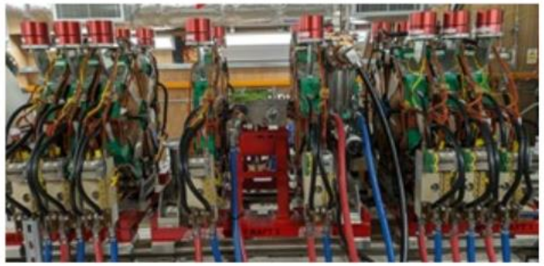
Currently, no matching performed between RFQ and DTL:

- Limit injector efficiency (lower energy losses)
- Limit injection efficiency (70 MeV losses)



[1]

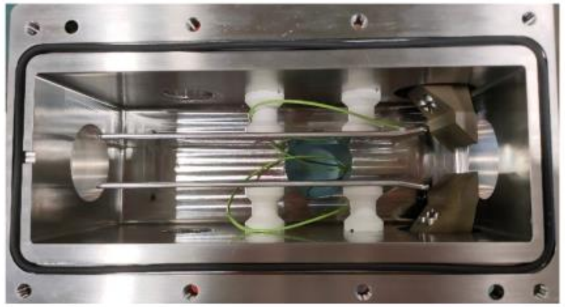
Medium energy beam transport (MEBT) section planned installation during next long shutdown



[2]

Addition of quadrupole focusing, rebunching cavity, diagnostics, and electrostatic chopper

- 6-dimensional matching into DTL
- Better operational tuning of injector
- Longitudinal matching of pulse train to synchrotron RF acceptance



[2]

Image Credit:
[1] Wood, T. et. al. *"The ISIS pre-injector reconfiguration"*, Rev. Sci. Instrum. 87, 02B121, doi:10.1063/1.4934658
[2] Speed, J. et. al. *"PRACTICAL DESIGN AND MANUFACTURING OF THE NEW ISIS MEBT CHOPPER"*, IPAC2024

RF Ion Source

Current ISIS ion source is Penning-type caesiated surface-plasma H^- source

Caesium limits lifetime (typically ~ 2-3 weeks):

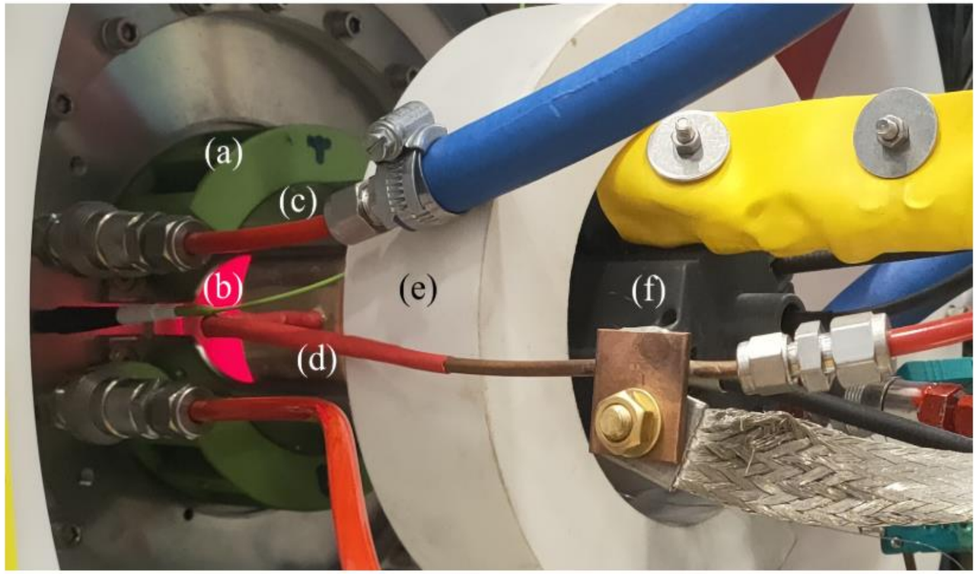
- Significant technical effort to maintain hot spares
- Limits availability to neutron users
- Can pose limit on machine optimisations

Examining possibilities of upgrade to a volume-plasma RF-driven source:

- Significantly improved lifetime
- No requirement of caesium
- Potential to increase synchrotron current through longer pulse length

Required spec:

- 30 mA H^- current
- 4-rms emittance < 1.5 π mm mrad
- 200 μs pulse length



The RF ion source installed and operating at full duty cycle. Visible components include filter magnets (a), plasma light visible through translucent plasma chamber and cooling jacket (b), main support housing (c), RF coil (d), cooling jacket connection manifold (e) and ignition gun (f).

Image and text sourced from:
Lawrie, S. et. al. *"Plasma commissioning in a high power external RF-coil volume-type H− ion source"*, J. Phys.: Conf. Ser. 2244 012033

ISIS-II

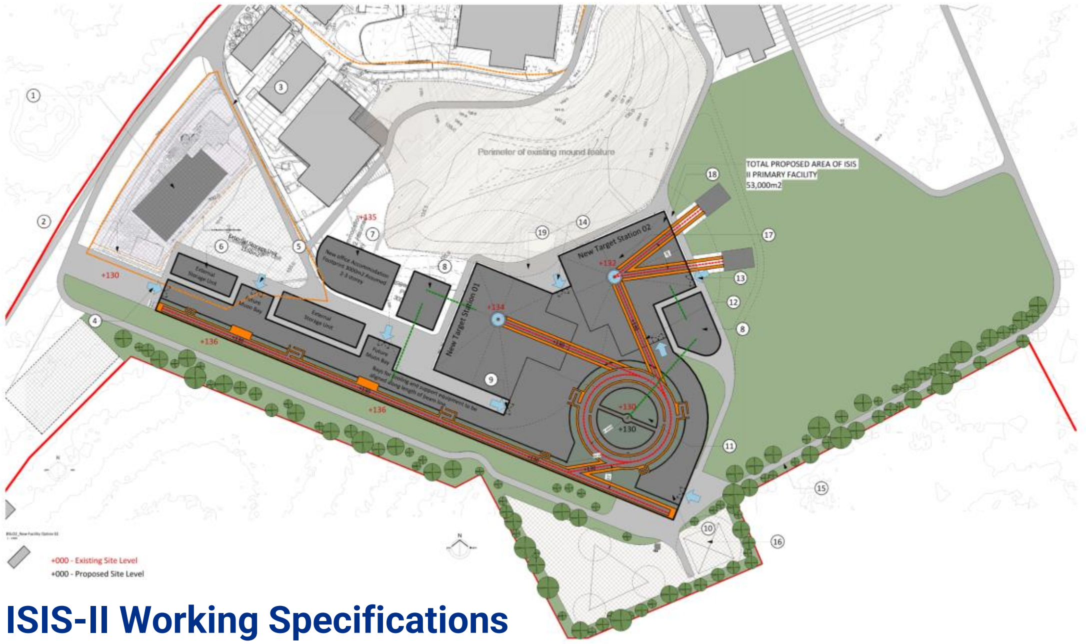
ISIS-II Megawatt Upgrade

- Europe (incl. UK) is a world leader in neutron-based science
- Decommissioning of reactor sources of neutrons
- Potential European “neutron drought”
- ISIS-II vital to maintain European competitiveness with Japanese (J-PARC) and American (SNS) short-pulse neutron sources

ESFRI Neutron Scattering Facilities in Europe Report (2016)

*“…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.”*

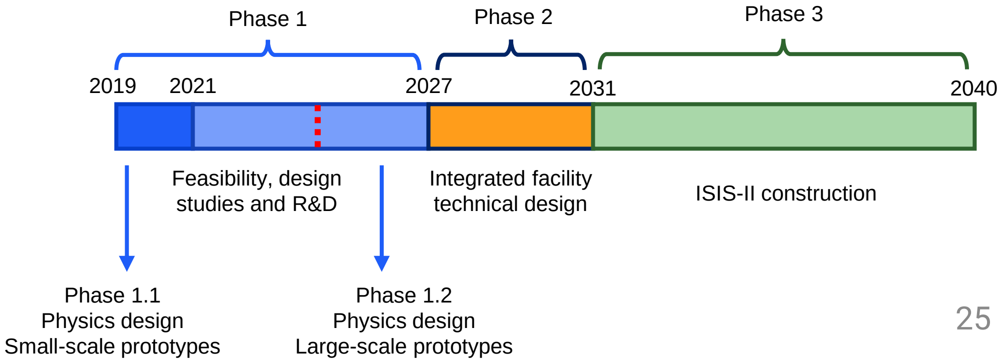
Sentiment echoed in UKRI Infrastructure Opportunity Report (2023)



ISIS-II Working Specifications

1.25 MW proton accelerator
1.2 GeV beam on target
0.1% beam-loss
Conventional Ring (RCS, AR) and FFA options being explored
Special focus on

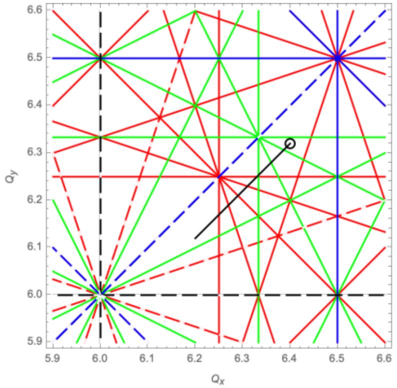
- Sustainability of the future machine
- Ensuring health of the neutron user community during construction phase



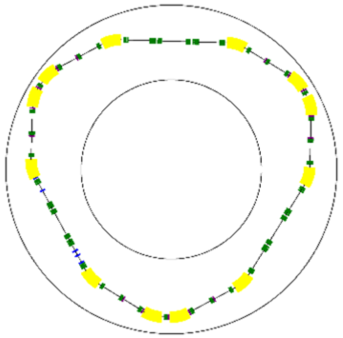
ISIS-II “Conventional” Rings

- Completed exploratory designs Feb 2022
  - 2 x Rapid Cycling Synchrotron
  - 2 x Accumulator Rings
- New sustainability-focussed designs under investigation

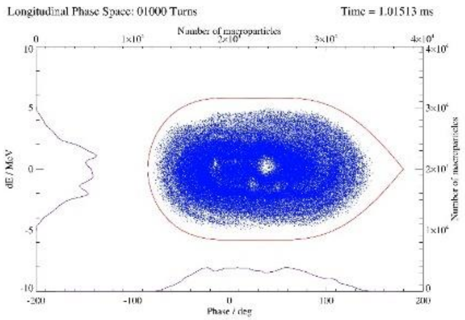
Working Point

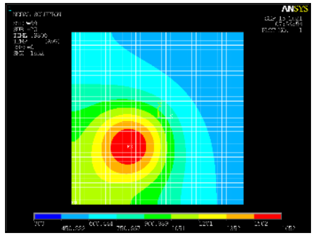


Lattice Design

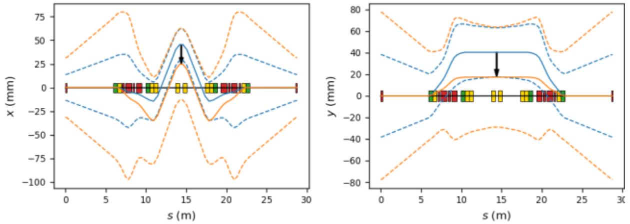


Longitudinal Simulations





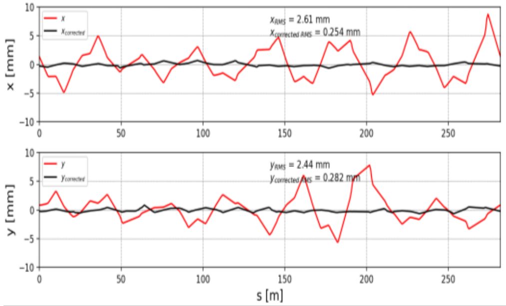
Injection Straight & Foil Temperature



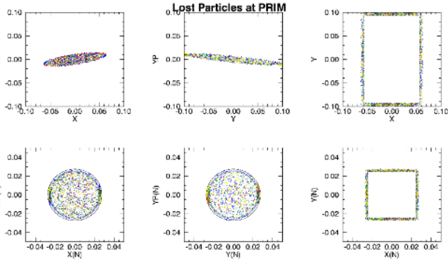
Life-Cycle Analysis

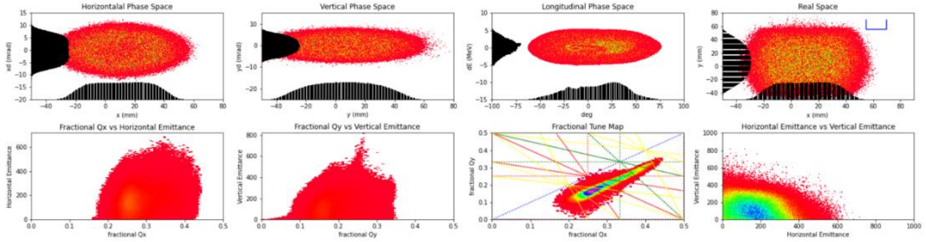
Component	Sub-component	Part	BS EN 17472	Impact	Value	Unit
Shielding	NELCO MegaShield 147 Block	Off 0.914 m x 0.61 m 0.61 m	A1-3	Concrete	28.908449	m3
Shielding	NELCO MegaShield 147 Block	Off 0.914 m x 0.61 m 0.61 m	A4	Fuel, lorry		tkm
Shielding	NELCO MegaShield 147 Block	Off 0.914 m x 0.61 m 0.61 m	A5			
Shielding	NELCO MegaShield 147 Block	Off 0.475 m x 0.61 m 0.61 m	A1-3	Concrete	0.8837375	m3
Shielding	NELCO MegaShield 147 Block	Off 0.475 m x 0.61 m 0.61 m	A4	Fuel, lorry		tkm
Shielding	NELCO MegaShield 147 Block	Off 0.475 m x 0.61 m 0.61 m	A5			
Shielding	NELCO MegaShield 147 Block	Off 1.829 m x 0.61 m 0.61 m	A1-3	Concrete	0.6805709	m3
Shielding	NELCO MegaShield 147 Block	Off 1.829 m x 0.61 m 0.61 m	A4	Fuel, lorry		tkm
Shielding	NELCO MegaShield 147 Block	Off 1.829 m x 0.61 m 0.61 m	A5			
Shielding	NELCO MegaShield 147 Block	Off 2.745 m x 0.61 m 0.61 m	A1-3	Concrete	3.0642435	m3
Shielding	NELCO MegaShield 147 Block	Off 2.745 m x 0.61 m 0.61 m	A4	Fuel, lorry		tkm
Shielding	NELCO MegaShield 147 Block	Off 2.745 m x 0.61 m 0.61 m	A5			

Closed Orbit Correction



Collimation Simulations





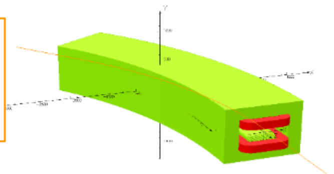
3D Simulations

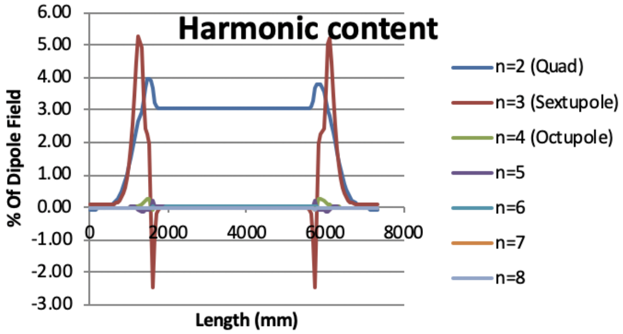
ISIS-II "Conventional" Rings R&D

Understanding loss mechanisms key to success of ISIS-II design

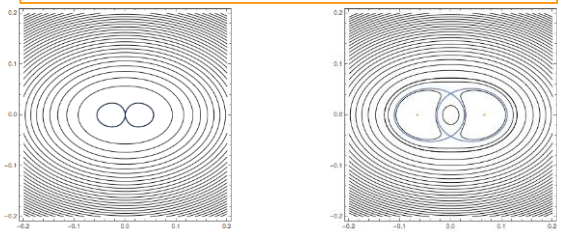
- Reliable prediction of loss (~0.01%)
- Understanding of beam halo dynamics
- Origin of losses

Non-linear components

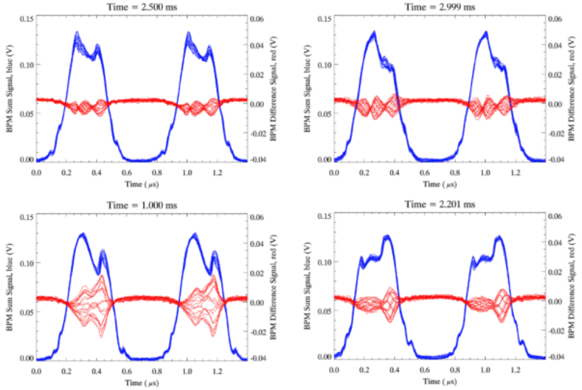




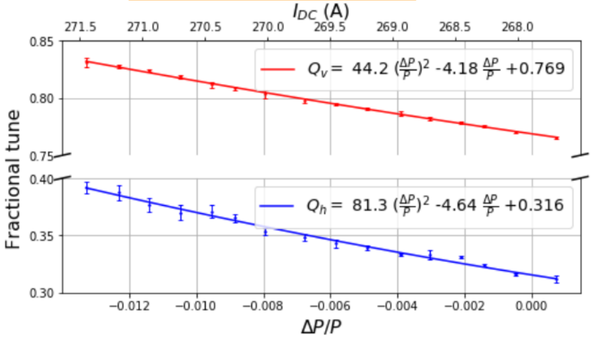
Frozen space charge halo



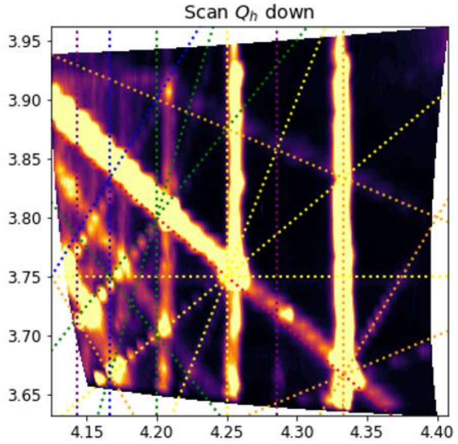
Beam Instability Studies



Chromaticity

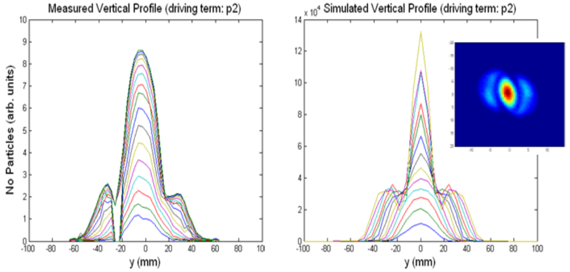


Tune Plane Measurements



Transverse Profiles

Measured *ORBIT*



Likely need to develop custom beam dynamics and design codes

- Benchmark against other codes
- Benchmark against measurement

ISIS-II FFA Option

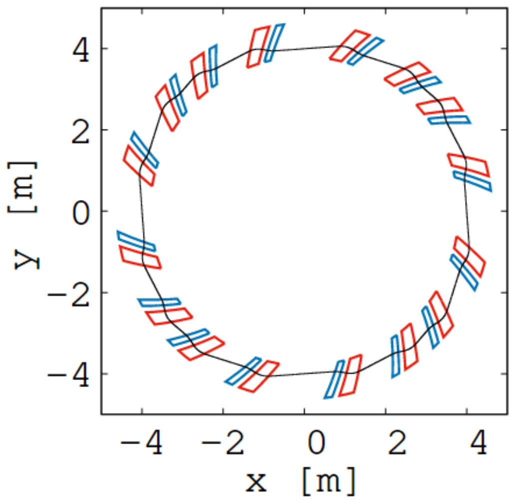
FFA-option aims for

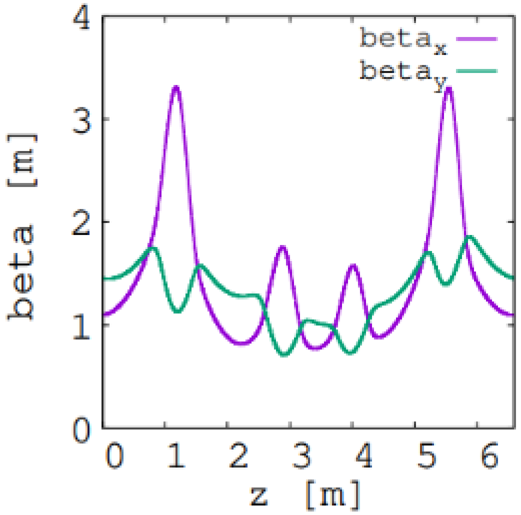
- Sustainability
- Reliable operation
- Capacity
- Capability

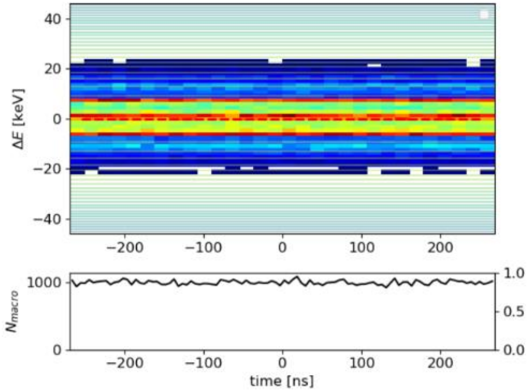
Currently, proof-of-concept machine under development (FETS FFS)

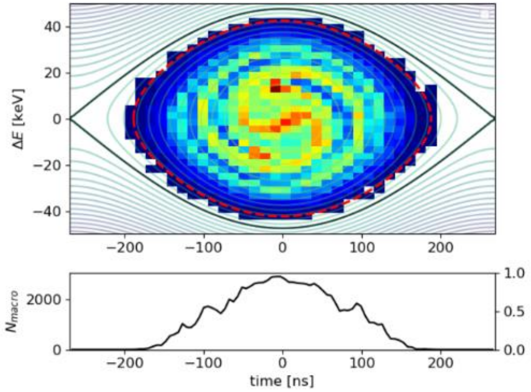
Platform for development of ISIS-II FFA driver

Experimental study of injection painting, orbit correction, resonances, collimation, *etc.*







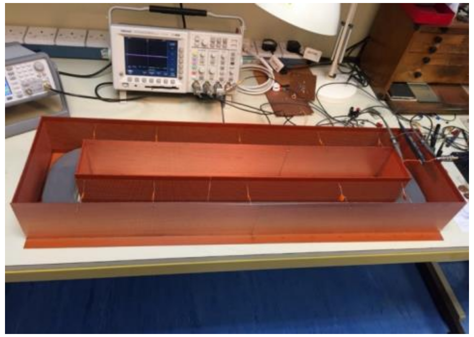


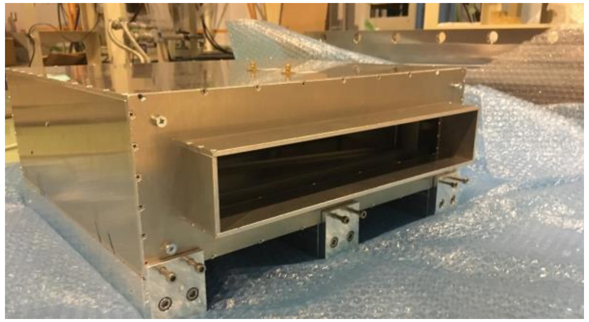
ISIS-II FFA R&D: FETS FFA

- 3 – 12 MeV
- 4 – 4.4 m radius
- 50 Hz beam repetition
- 3×10^{11} protons per bunch
- 30 W power
- Space charge tune shift ~-0.35

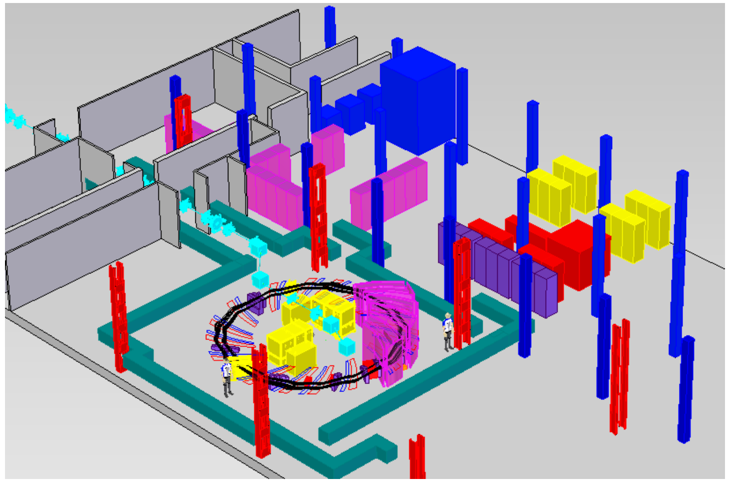
- Still a work in progress
- Completion of CDR by March 2025

HV-testing underway for RF cavity magnetic alloy and ferrite cores





Prototype BPM and wire scanner tests at KURNS



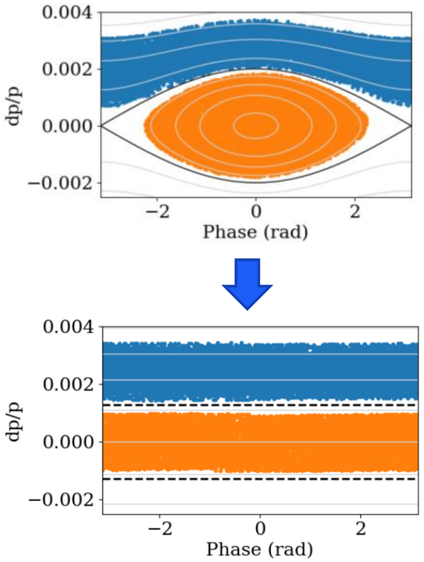
ISIS-II FFA R&D: Beam Stacking

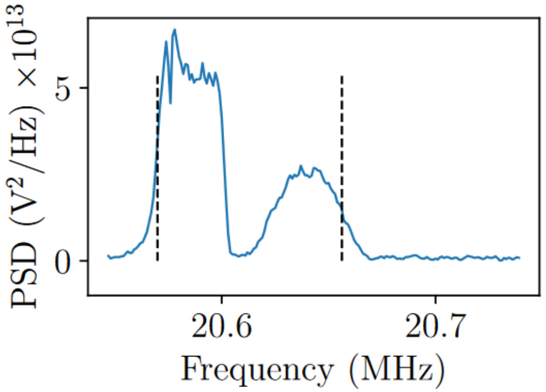
Beam stacking is a method for increasing the circulating current in FFA

- Inject, accelerate, and de-cohere beam at top energy
- Inject and accelerate second beam
- Stack in longitudinal phase space

Experimental verification of beam stacking at KURNS FFA:

- Schottky analysis of incoherent signals
- Determine energy and energy spread stacked beams
- Potential use at ISIS as diagnostic tool
- Studies underway to repeat experiment on the ISIS RCS





Summary

- ISIS has seen many changes over 40 years
  - Numerous challenges encountered
  - Numerous upgrades
  - Lots of re-purposed equipment
  - Huge collaborative effort
- ISIS is still one of the most productive neutron sources in the world
- Continued development and refurbishment are aimed at extending ISIS' operational lifetime
- ISIS (along with FETS) will be the test-bed upon which ISIS-II is developed
- Several design options still under consideration for ISIS-II, each with its own challenges and research questions