

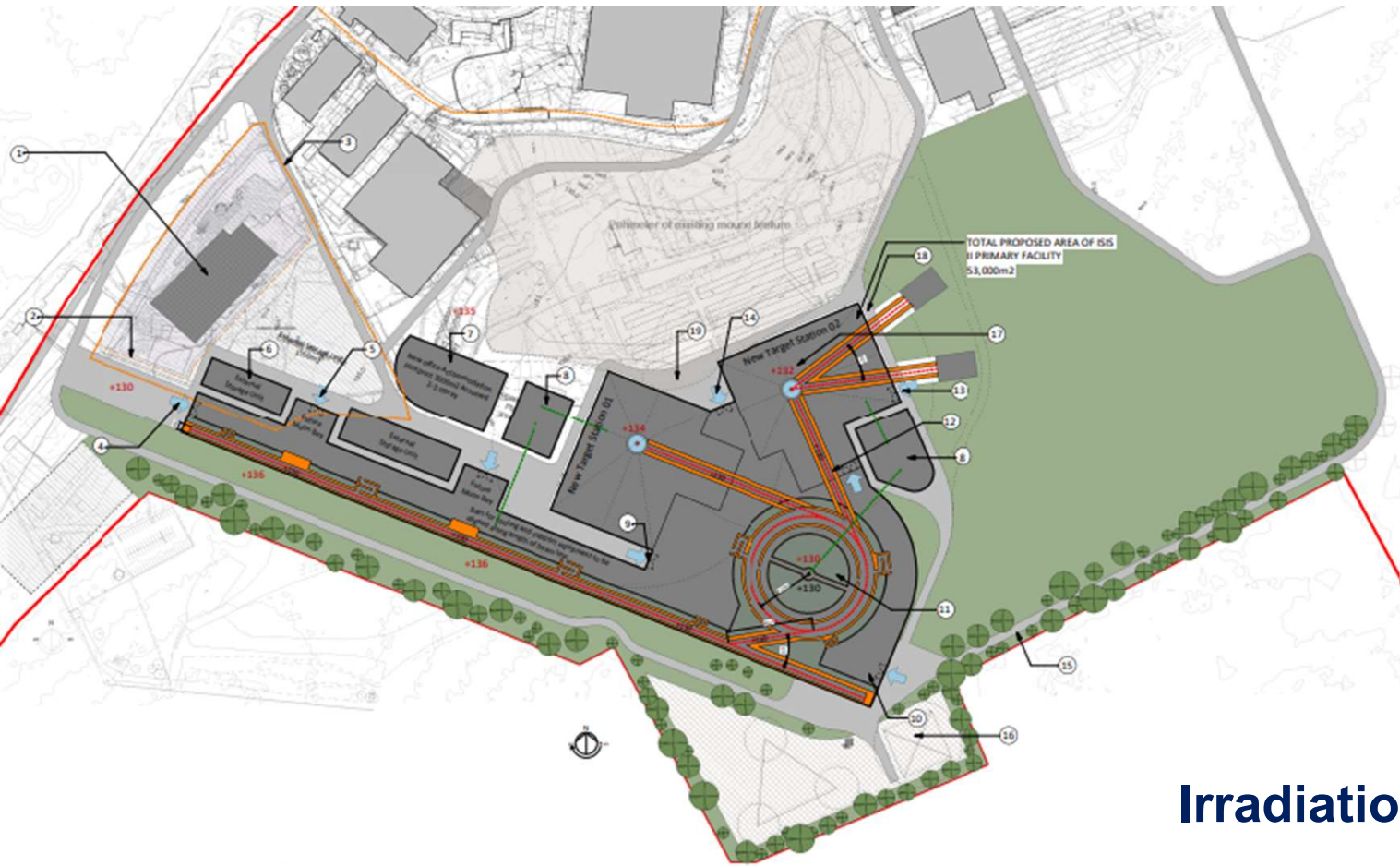
After ChipIr: ISIS-II & Irradiation

Christopher Frost

GB-RADNEXT Workshop 12-13 June 2024



ISIS Neutron and Muon Source



ISIS-II

Next generation neutron source with construction 2030's and operation 2040's.

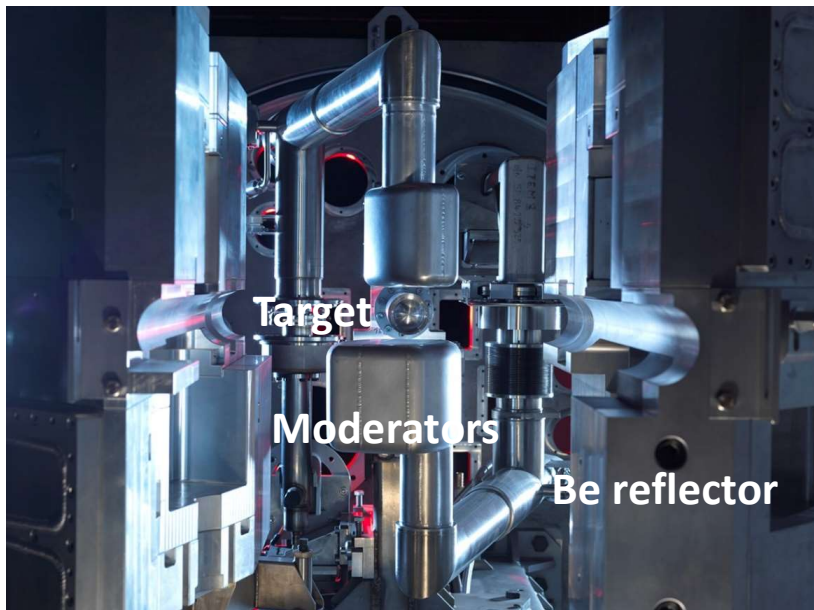
Irradiation Capabilities

ISIS-II provides opportunity to consider UK's and European future irradiation needs

Neutron Irradiation Facilities: Chiplr

In the mid 2000s ISIS developed the idea of creating a new beamline for the accelerated testing of electronics to utilise the fast, high energy neutrons that had not yet been exploited at this kind of generalised neutron sources

Simple idea: extract a high intensity, fast neutron beam to mimic the atmospheric cosmic rays neutron spectrum



'Moderators' and Beryllium 'reflector' are used to optimise high fluxes of **thermal neutrons** for condensed matter studies.

Problem: target complex optimised for **thermal neutron** beamlines; no 'good' direct view of target

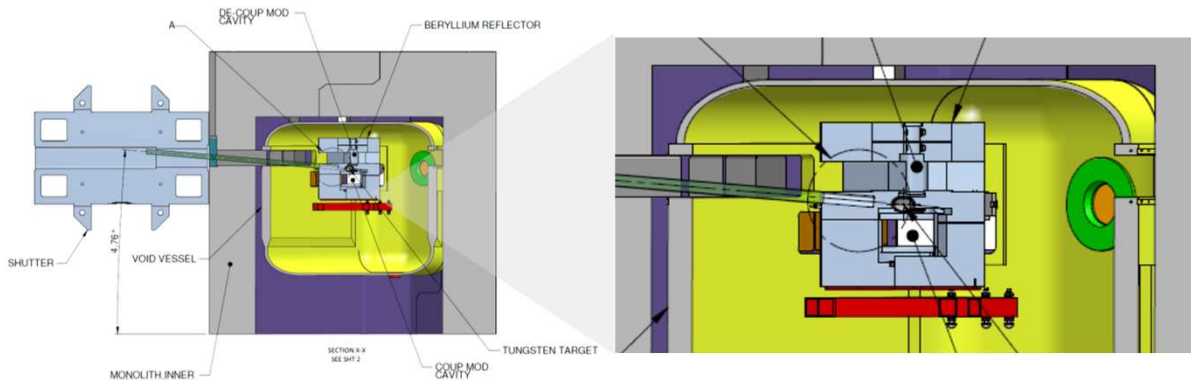
New Approach Needed at ISIS

Neutron Irradiation Facilities: Chiplr

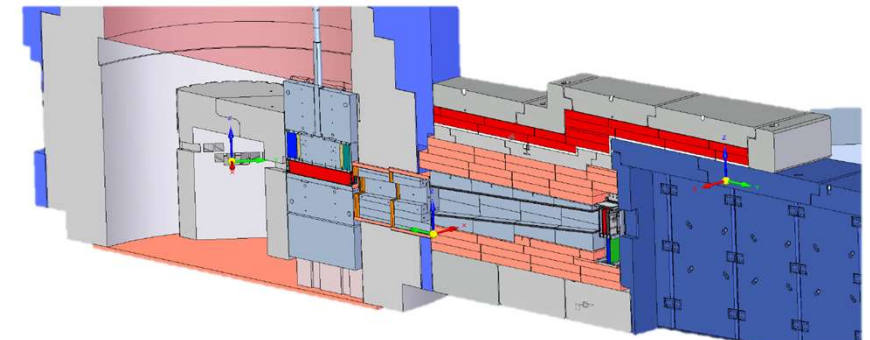
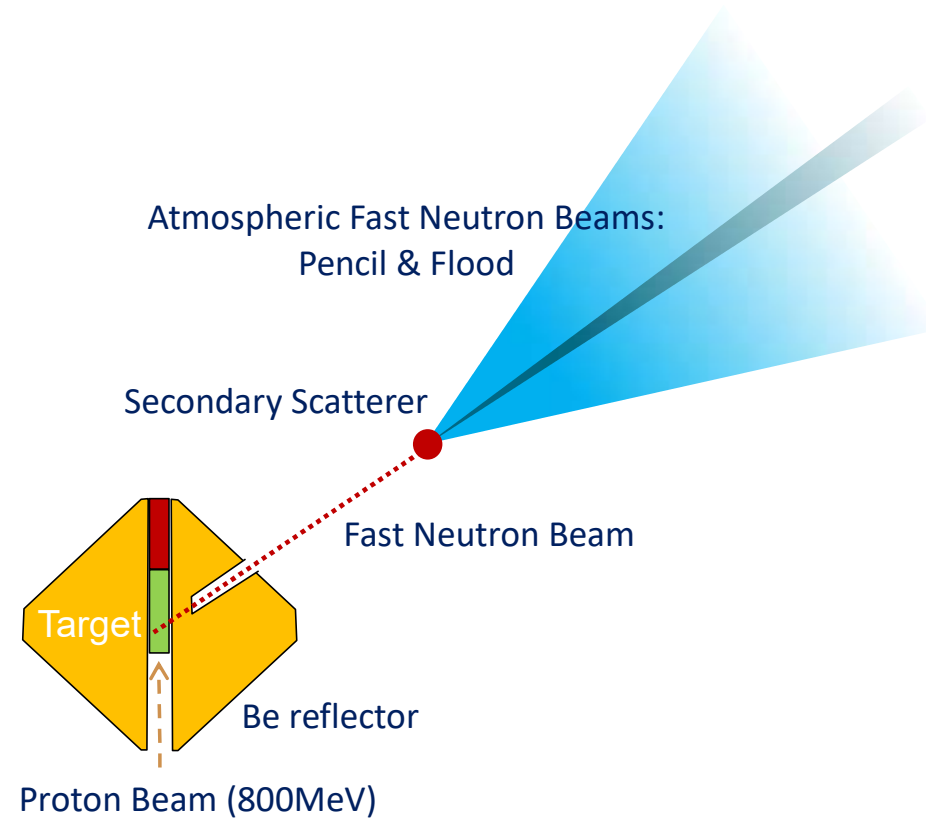
Uses fast neutron flux from ISIS source in two stage process

Quite a simple concept:-

- Create hardened spectrum from Target/Moderator/Reflection
- Illuminate secondary scatterer to produce beams



Fast Neutrons from Target 2



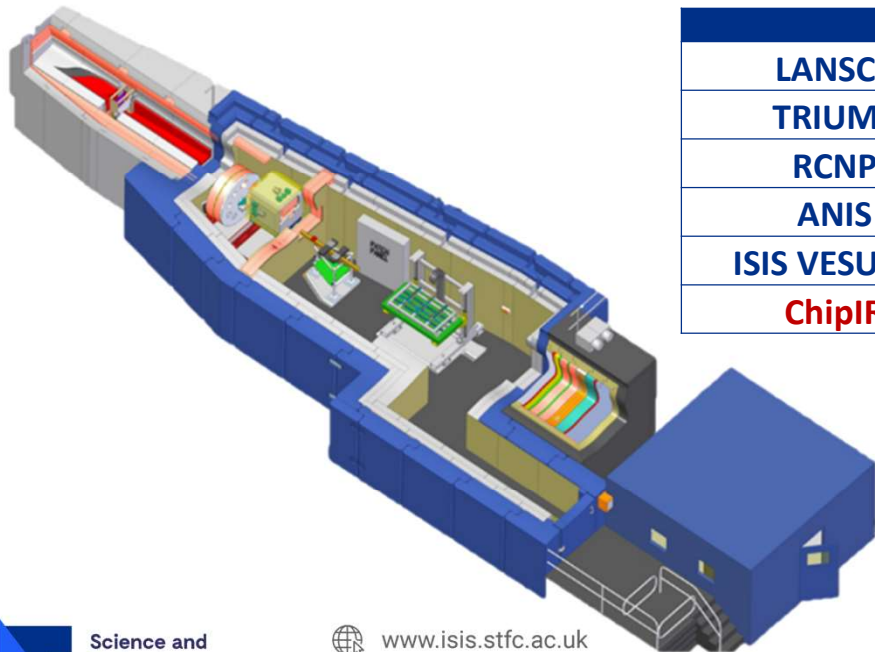
Transport to Chiplr Blockhouse

Neutron Irradiation Facilities: ChipIr

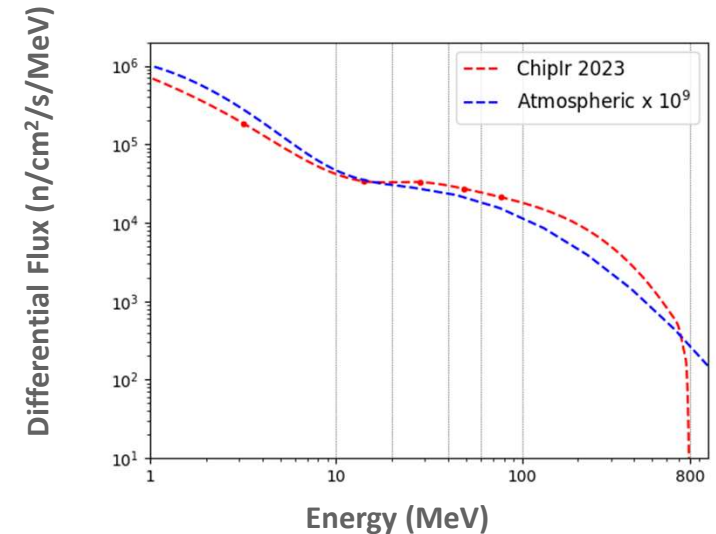
Uses fast neutron flux from ISIS source in two stage process

Quite a simple concept:-

- Create hardened spectrum from Target/Moderator/Reflection
- Illuminate secondary scatterer to produce beams



| | Flux (cm ⁻² s ⁻¹) >10MeV |
|---------------|---|
| LANSCE | 1-2x10 ⁶ |
| TRIUMF | 6x10 ⁶ |
| RCNP | 7x10 ⁵ |
| ANIS | 10 ⁷ |
| ISIS VESUVIO | 5.8x10 ⁴ |
| ChipIr | 5.4 x10⁶ |

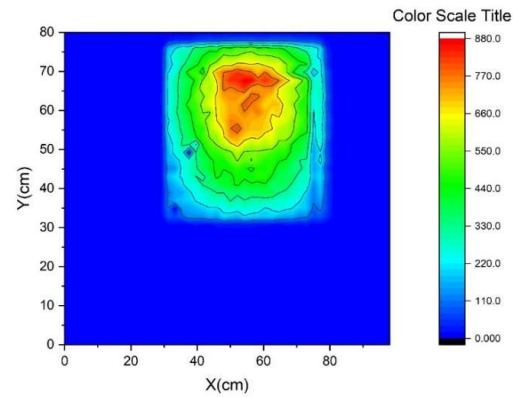
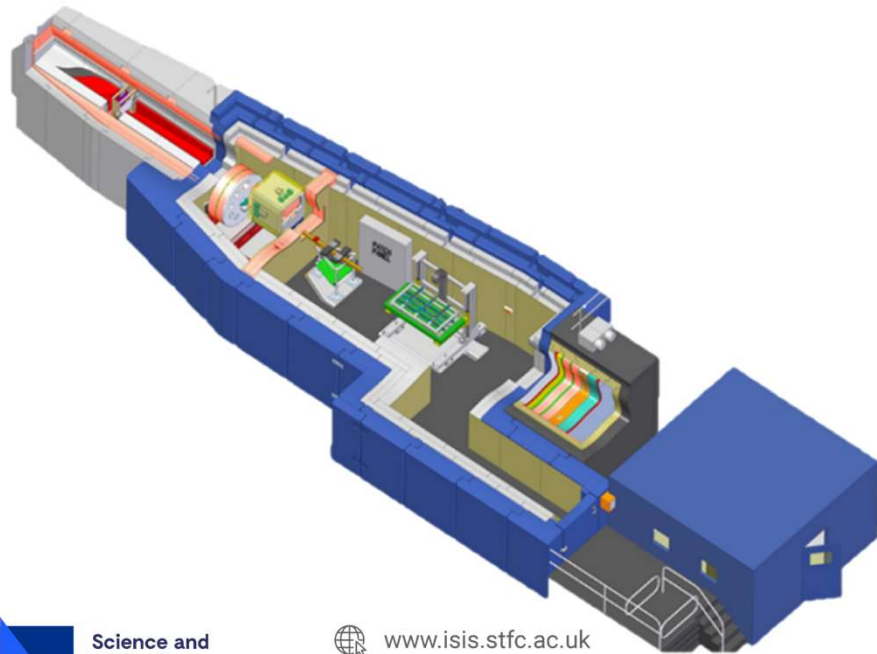


Neutron Irradiation Facilities: ChipIr

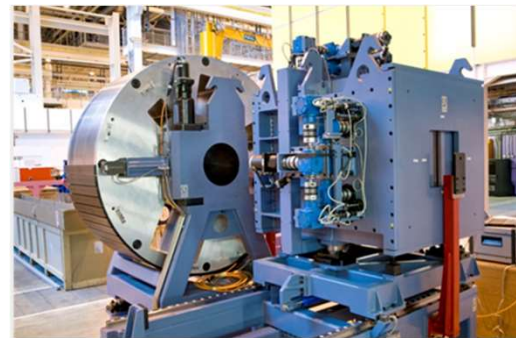
Created highly capable irradiation facility

BUT 'retro-fit' forced compromise in the design:-

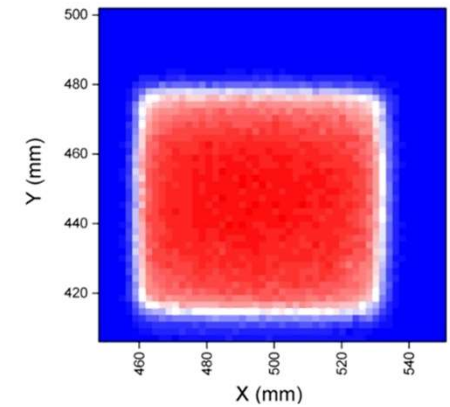
- Angled beam is not ideal
- Collimation more difficult (space and angle)



800MeV, largest collimation setting with no jaws



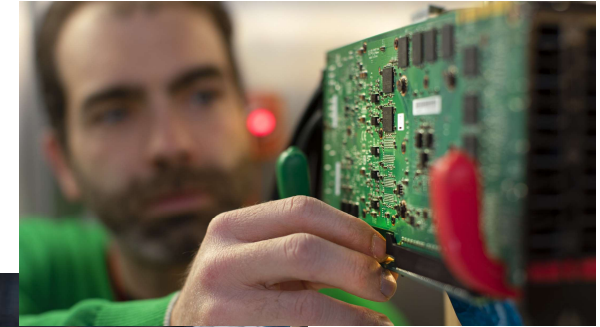
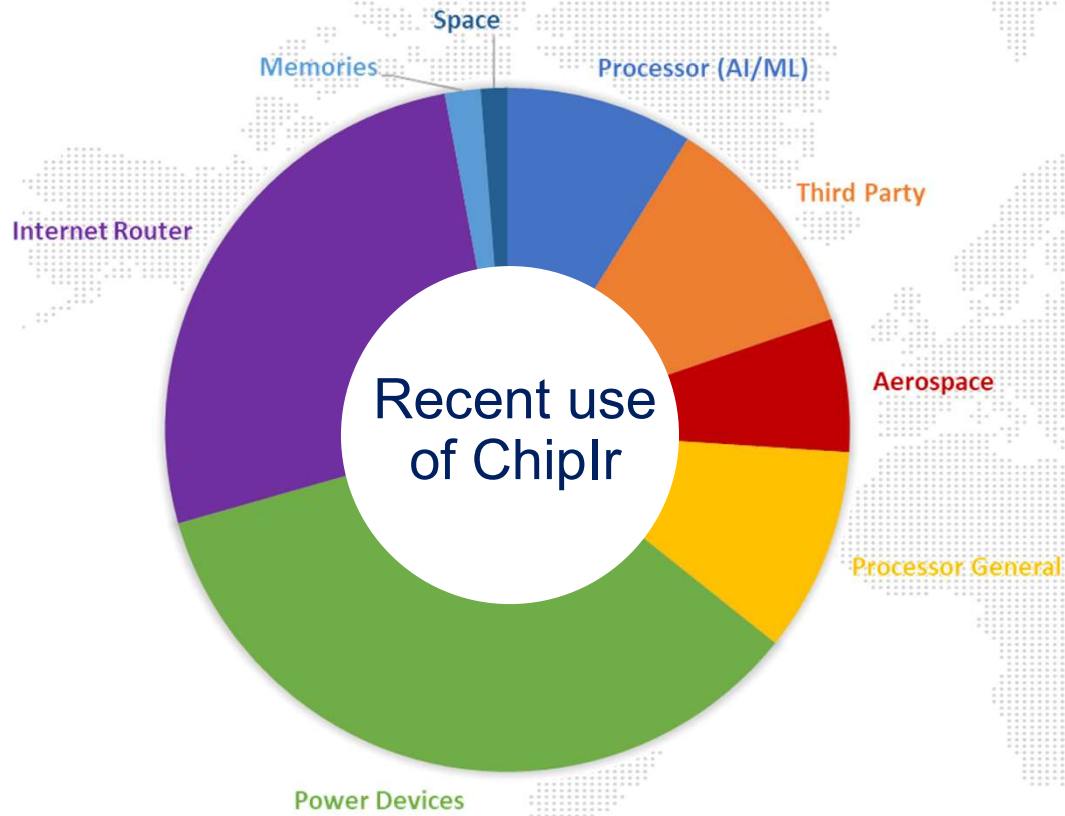
Intensity Maps of ChipIr beam



Typically Collimated beam (70mmx60mm)

Neutron Irradiation Facilities: ChipIrr

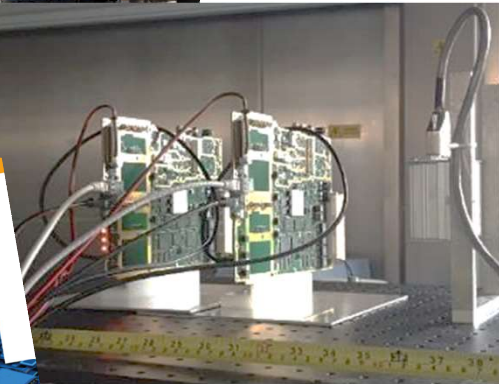
Created highly capable irradiation facility



AI and ML



Power Devices



Aerospace

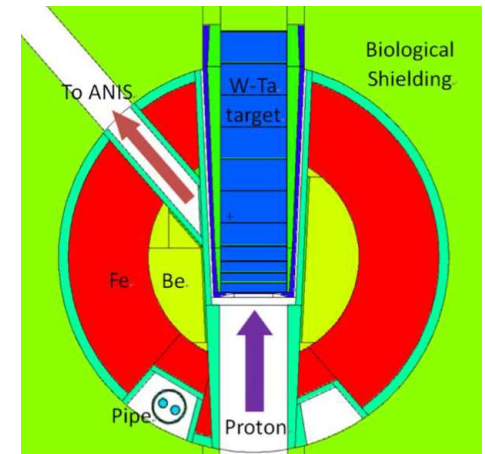
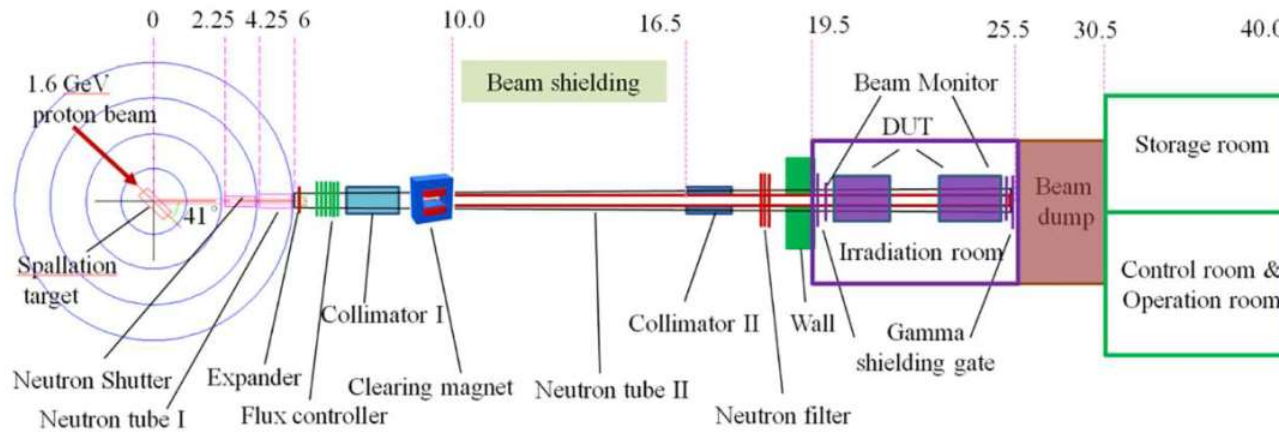
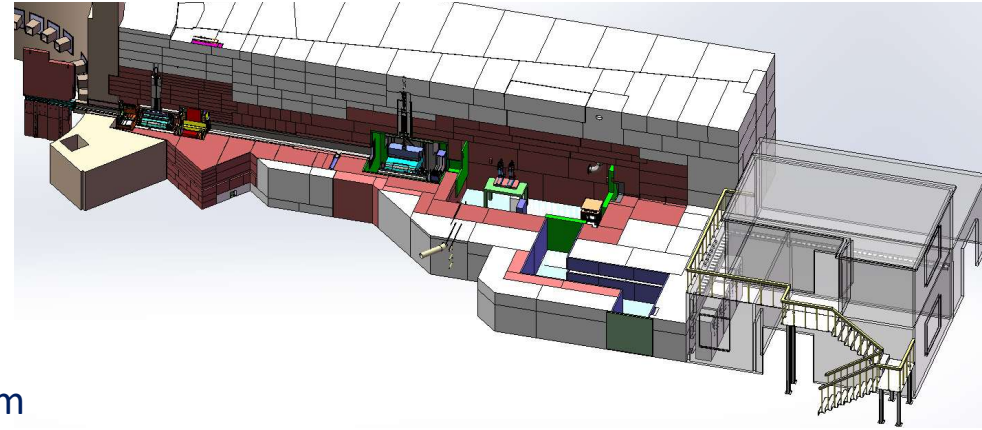


Neutron Irradiation Facilities: ANIS@CSNS

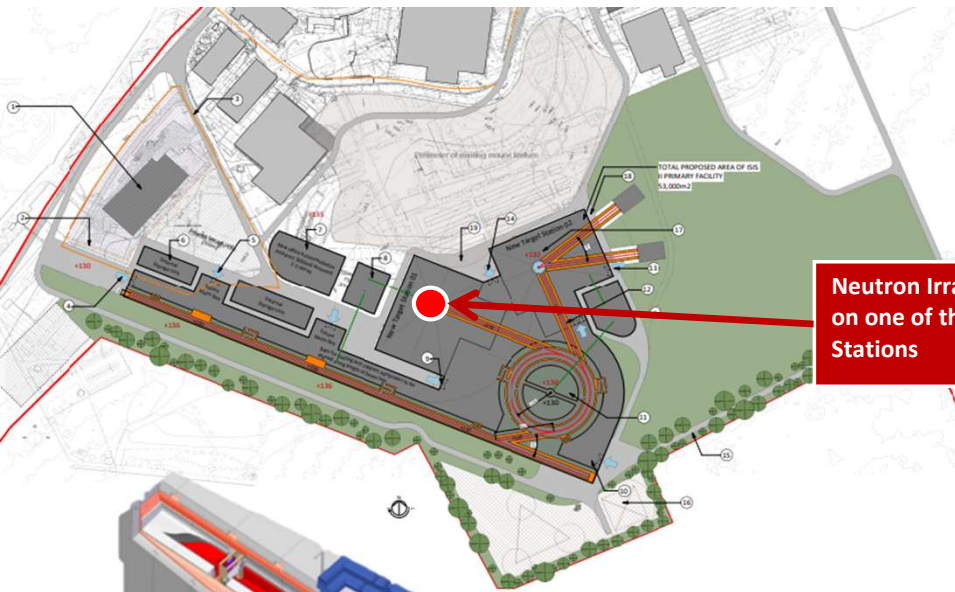
Second iteration of this type of design

Also quite a simple concept:-

- Create hardened spectrum from Target/Moderator/Reflection
- Deliver this to blockhouse with 'optical' components shaping beam

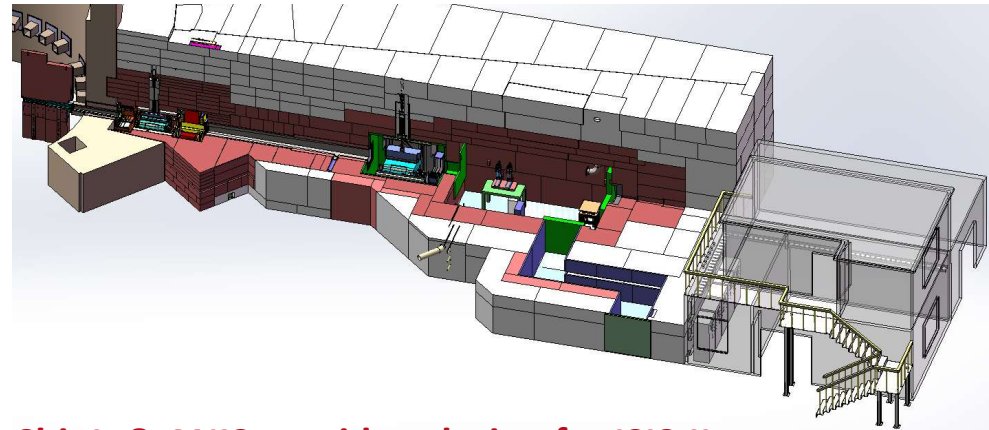


Talk later in session....

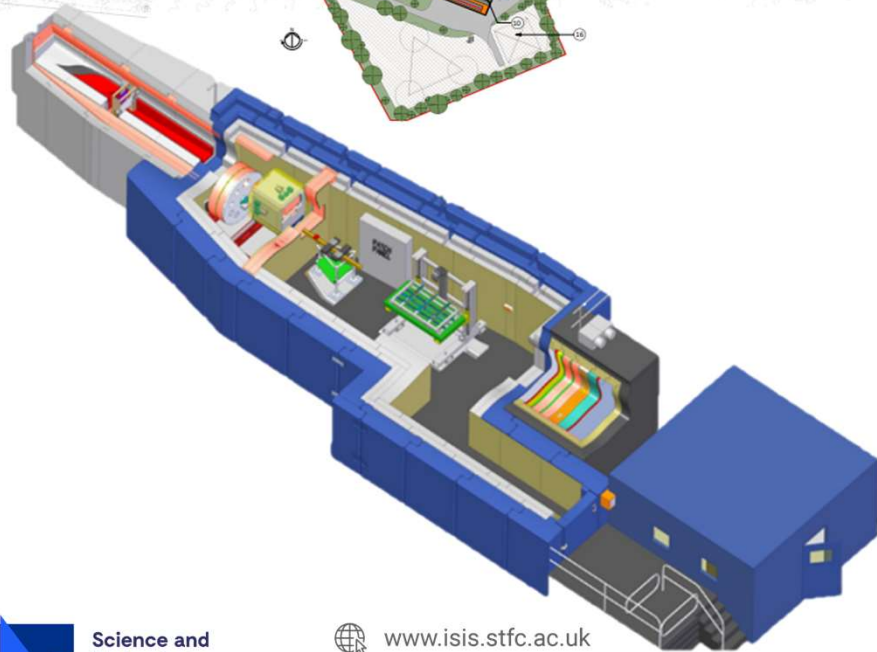


Scenario I

Neutron Irradiation Beamline on one of the ISIS-II Target Stations



ChipIr & ANIS provide solution for ISIS-II



For discussion

| | |
|--|---|
| Proton Driver Energy | >500MeV |
| Proton Beam Delivery | individual proton pulses to generate neutron intensity in test position no greater than current ISIS TS2 (2.8×10^5 neutrons per pulse) >= 10Hz frequency (i.e.no worse than current TS2) |
| Target | W-Ta (static, solid target) |
| Neutron Intensity & Control | $>10^6$ n/cm ² /s integrate above 10MeV at instrument distance ability to control intensity by factor 100 |
| Neutron Spectrum | Atmospheric (matching JEDEC89, IEC) |
| Fast Neutron Channel in Reflector | Forward direction and horizontal with direct view of target from instrument |

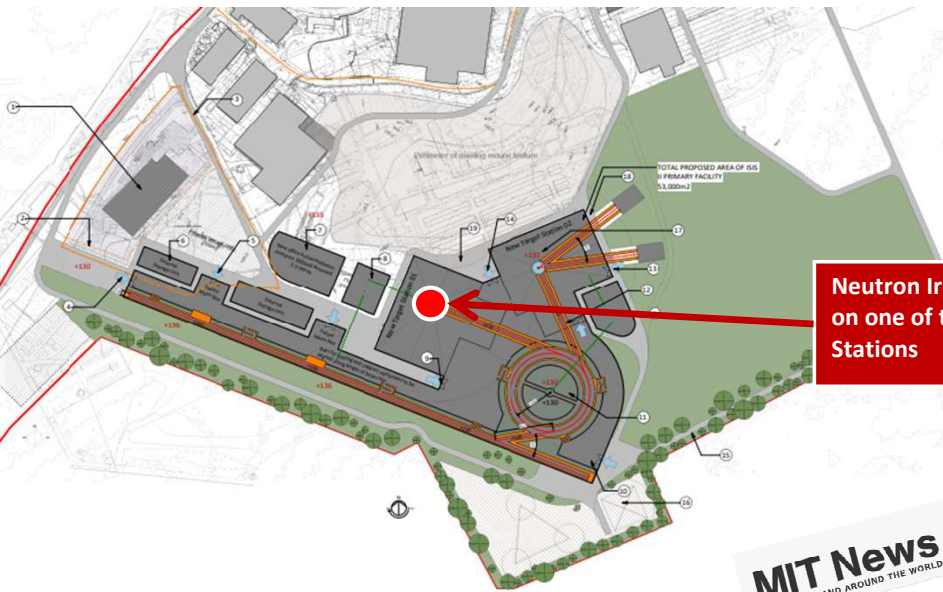


ISIS Neutron and Muon Source

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Scenario I
Neutron Irradiation Beamline on one of the ISIS-II Target Stations

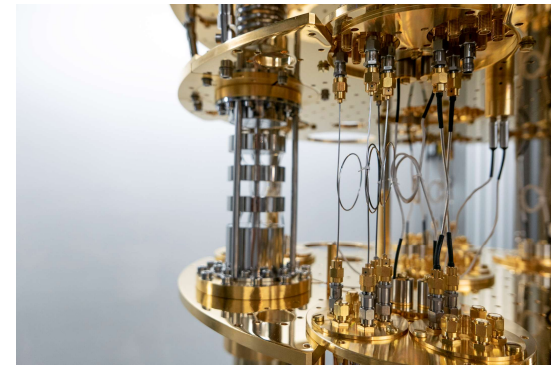


Image Oxford University

Meet Future Challenges

Example: Recent Papers in Nature and Nature Physics show cosmic rays are potentially interfering with quantum computers

MIT News
 ON CAMPUS AND AROUND THE WORLD

Cosmic rays may soon threaten quantum computing
 Building quantum computers and qubits may be needed, research suggests

Jennifer Chu | MIT News Office
 August 26, 2020

physicsworld
 QUANTUM COMPUTING RESEARCH UPDATE
 Cosmic-ray threat to quantum computing greater than previously thought

28 Jul 2021 Margaret Harris

Quantum computers may need a redesign to survive cosmic rays

Article
Impact of ionizing radiation on superconducting qubit coherence

Arvid H. Vepsäläinen^{1,2*}, Amir H. Karamlou^{1,3}, John L. Orrell^{1,4}, Akshay S. Goyal^{1,5}, Ben Liao^{1,6}, Francesco Vasconcelos^{1,6}, David A. Kim^{1,6}, Alexander J. Millard¹, Barbara H. Hendriks^{1,6}, Jennifer A. Hvalby¹, Simon Durrant^{1,6}, Joseph A. Formaggio^{1,6}, Brent A. Vanoverbeek^{1,6}, William D. Oliver^{1,6}

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 Accepted: 5 June 2020
 Published online: 28 August 2020

Check for updates

Over the past 20 years, superconducting qubit coherence times have increased by more than two orders of magnitude due to improvements in device design, fabrication and materials. From less than 10 ns in 1999 to more than 100 µs in current qubits^{1,2}. Nonetheless, to realize the full potential of quantum computing, far longer coherence times will be required to achieve the operational fidelities required for fault tolerance³.

Indeed, the performance of superconducting qubits is limited in part by the qubit operation – a phenomenon known colloquially as ‘spontaneous decoherence’. Although it was suggested⁴ and recently confirmed⁵ that high-energy cosmic rays represent a source of ‘spontaneous’ decoherence, the quality factor in superconducting qubits is not yet understood. Here we have been the first to quantify the impact of environmental radiation on superconducting qubit performance. We develop a model and demonstrate the effect of environmental ionizing radiation on superconducting qubit performance. We develop a model and demonstrate the effect of environmental ionizing radiation on superconducting qubit performance. We develop a model and demonstrate the effect of environmental ionizing radiation on superconducting qubit performance.

For emerging quantum processors, one of the most commonly used architectures is the superconducting qubit⁶, which comprises a Josephson junction and a shunt capacitor. The intrinsic non-linear inductance of the junction, in combination with the linear inductance of the shunt capacitor, creates an anharmonic oscillator⁷. The non-degenerate spacing energies of such an oscillator are typically millielectronvolts, and the energy levels are separated by a factor of 10³ from the thermal energy. In all but the most advanced qubits, the energy levels are separated by a factor of 10³ from the thermal energy. In all but the most advanced qubits, the energy levels are separated by a factor of 10³ from the thermal energy.

Nature | Vol 584 | 27 August 2020 | 593

physicsworld
 QUANTUM COMPUTING RESEARCH UPDATE
 Quantum computers may be heading underground to shield from cosmic rays

26 August 2020

New Scientist
 Quantum computers may be destroyed by high-energy particles from space

26 August 2020

a big problem for quantum computers, because cosmic rays can disrupt their fragile internal calculations they may not stay perfect.

Quantum bits, or qubits, which are used to store and manipulate quantum information, are extremely sensitive to their environment. One of the most significant threats to their performance is cosmic radiation. Cosmic rays, which are high-energy particles from space, can interact with the qubits and cause errors in their calculations. This is a major concern for quantum computing, as it could limit the size and complexity of the devices that can be built.

Researchers are now exploring ways to protect qubits from cosmic rays. One approach is to shield the qubits with lead or other heavy materials. Another approach is to use qubits that are less sensitive to radiation. A third approach is to use error correction codes to detect and correct errors caused by cosmic rays.

Quantum computing is still in its early stages, and there are many challenges that need to be overcome before it can be used for practical applications. One of the most significant challenges is the problem of quantum decoherence. Quantum decoherence occurs when a quantum system interacts with its environment, causing it to lose its quantum properties. This is a major obstacle to the development of quantum computing, as it limits the time that a quantum system can remain in a coherent state.

Researchers are working to understand the causes of quantum decoherence and to find ways to prevent it. One of the most promising approaches is to use quantum error correction codes. These codes allow researchers to detect and correct errors in a quantum system without measuring it, which would destroy its quantum properties. This is a major breakthrough in quantum computing, as it allows researchers to build larger and more complex quantum systems.

Quantum computing has the potential to revolutionize many fields, from cryptography to materials science. However, it is still a long way from being a practical technology. Researchers need to continue to work on the challenges of quantum decoherence and cosmic radiation if they want to realize the full potential of quantum computing.

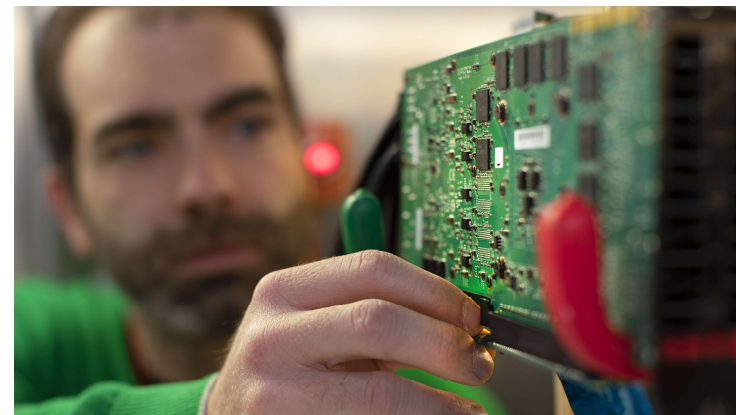
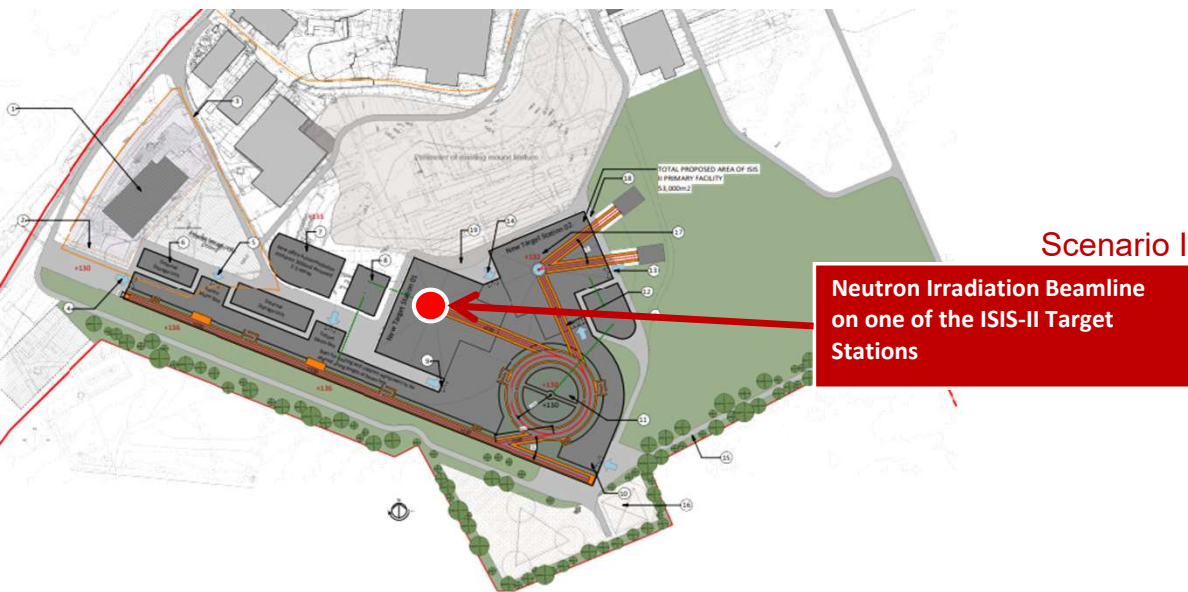


- www.isis.stfc.ac.uk
- @isisneutronmuon
- uk.linkedin.com/showcase/isis-neutron-and-muon-source

ISIS Neutron and Muon Source

McEwen, M., Faoro, L., Arya, K. et al. . *Nat. Phys.* **18**, 107–111 (2022).
 Vepsäläinen, A.P., Karamlou, A.H., Orrell, J.L. et al. . *Nature* **584**, 551–556 (2020).

Scenario I



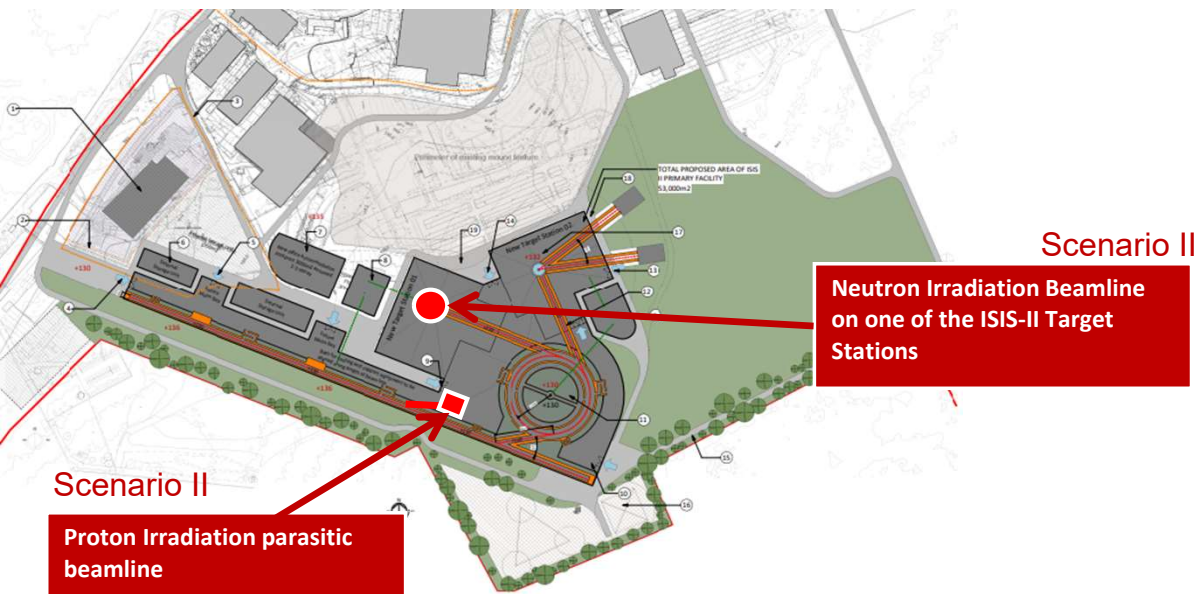
| | Advantage | Disadvantage |
|----------|---|--|
| Neutrons | <ul style="list-style-type: none"> design technically possible clear improvement on Chiplr lowest total cost (typical instrument cost) | <ul style="list-style-type: none"> more complex design (as part of target/reflector design) |

Development Level: LOW

Delivers:

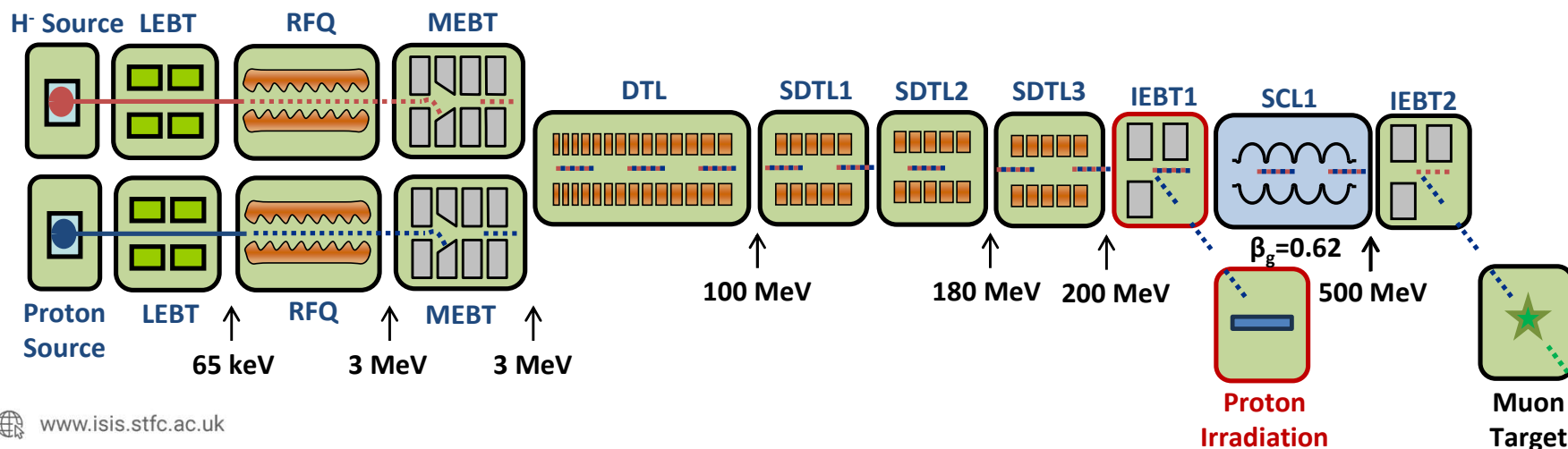
- Basic requirement by (neutron) irradiation community
- Continuity of provision if 'Day One' instrument

Scenario II

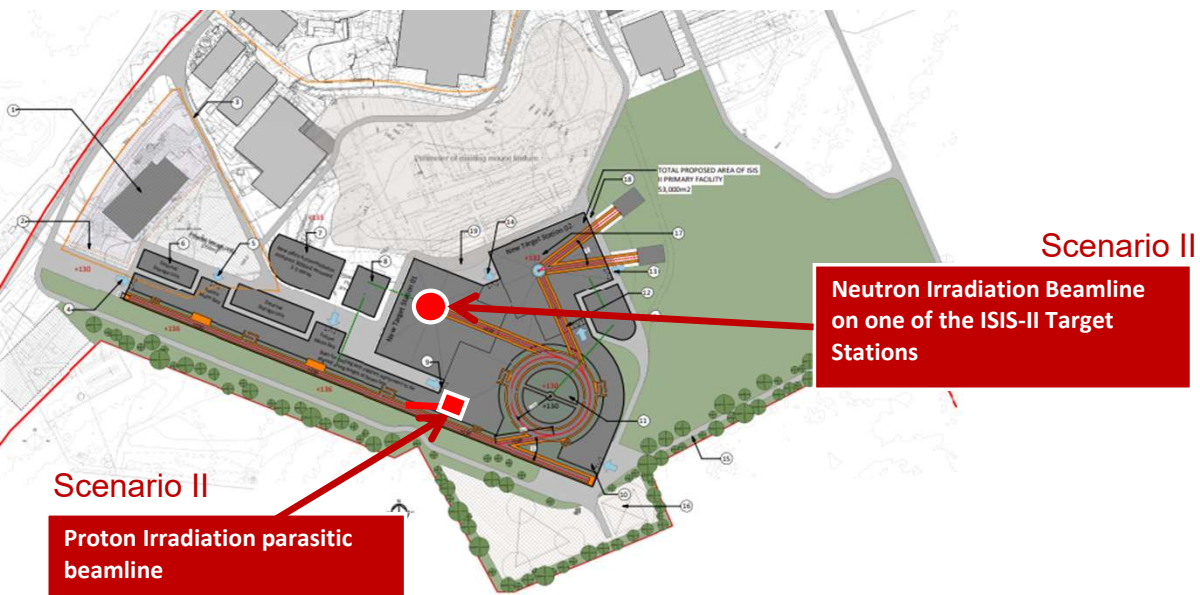


Extension of Scenario I
Add Parasitic 200MeV Proton Beamline

Extract protons at 200MeV point possibly driven by a proton pulse train interleaved with the H⁻ pulse train

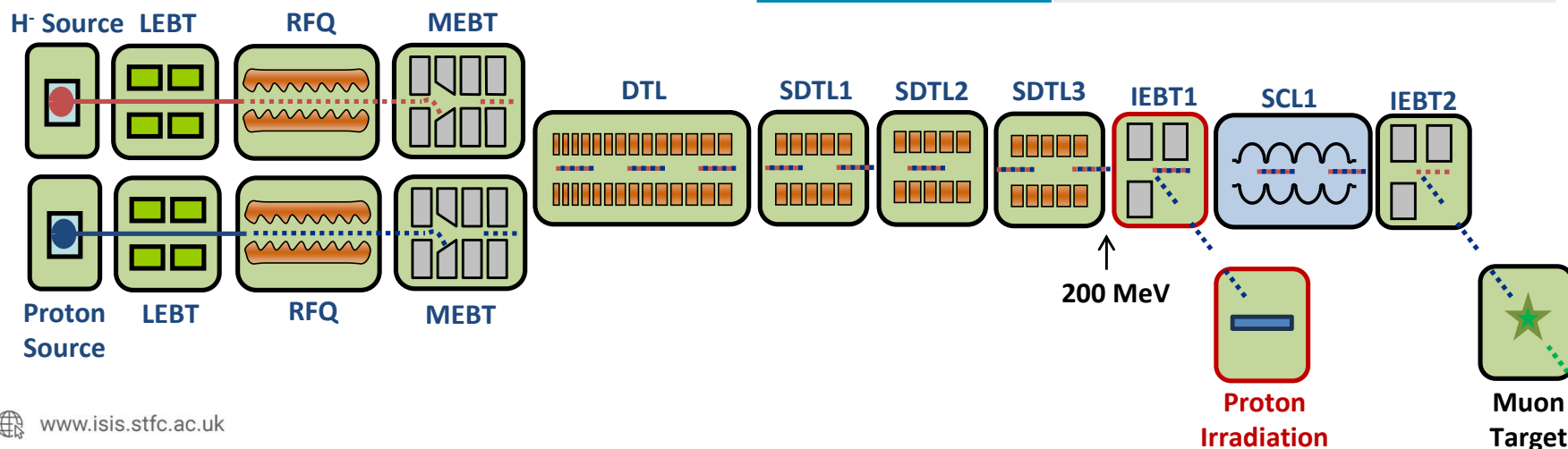


Scenario II



For discussion

| | |
|----------------------|---|
| Proton Energy | 125MeV to >200MeV |
| Beam Characteristics | Quasi-Continuous/Long pulse preferred to short bright pulses to reduce peak intensity |
| Flux | $10^7 - 10^9$ p/cm ² /s |
| Typical test fluence | $10^9 - 10^{11}$ p/cm ² (hours to days) |
| Beam size | Variable 1x1cm ² to 15x15cm ² |
| Beam uniformity | >80% |



ISIS Neutron and Muon Source

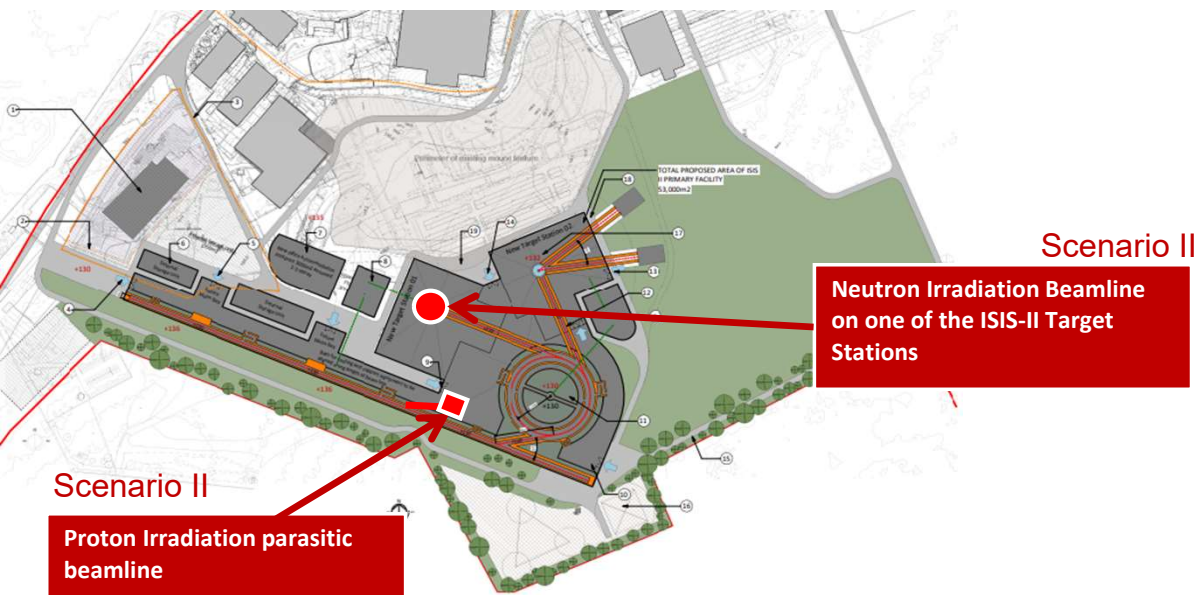
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[uk.linkedin.com/showcase/isis-neutron-and-muon-source](https://www.linkedin.com/showcase/isis-neutron-and-muon-source)

Table: Kenneth A. LaBel, Thomas L. Turflinger; "Protons, Aerospace, and Electronics: A National Interest"

Scenario II



Delivers:

- Scenario I - Neutrons
- Additional laboratory-based proton facility
- Proximity to neutron capability

| | Advantage | Disadvantage |
|----------|--|---|
| Neutrons | <ul style="list-style-type: none"> • design technically possible • clear improvement on ChiPr • lowest total cost (typical instrument cost) | <ul style="list-style-type: none"> • more complex design (as part of target/reflector design) |
| Protons | <ul style="list-style-type: none"> • Provides UK capability • Increased European provision | <ul style="list-style-type: none"> • unknown design, particularly energy and flux control • cost unknown; but likely to be on scale of neutron instrument • temporal structure (pulsed beam) |

Development Level: MEDIUM

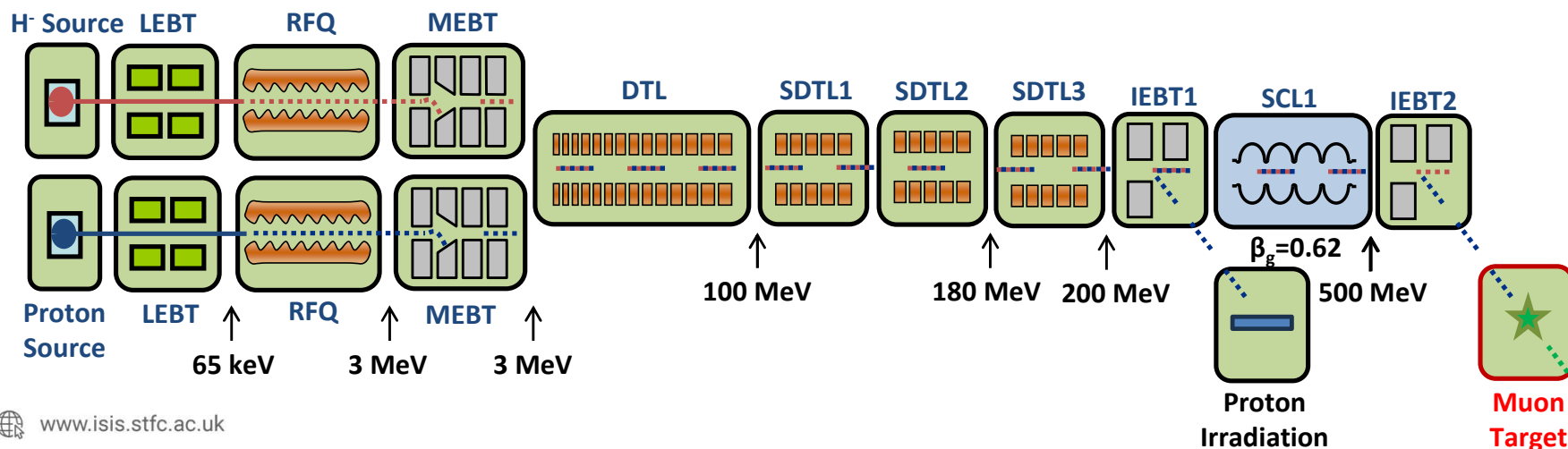
Scenario III

Abandon Scenarios I & II

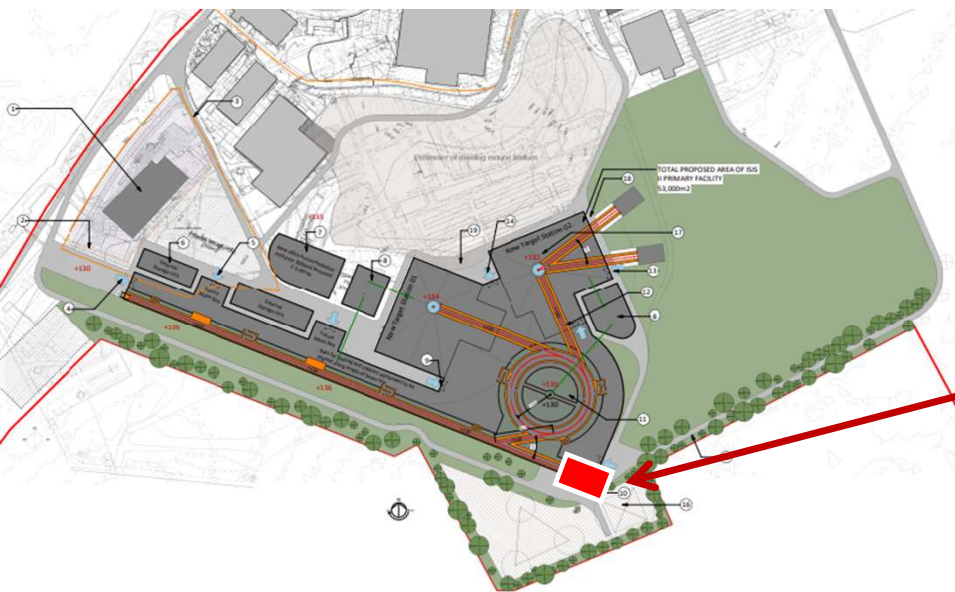
Exploit Proposed 500MeV Proton Beamline for Muons

Proposal to extract protons at 500MeV for Muon capability at end of Linac. Again could be driven by a proton pulse train interleaved with the H⁻ pulse train

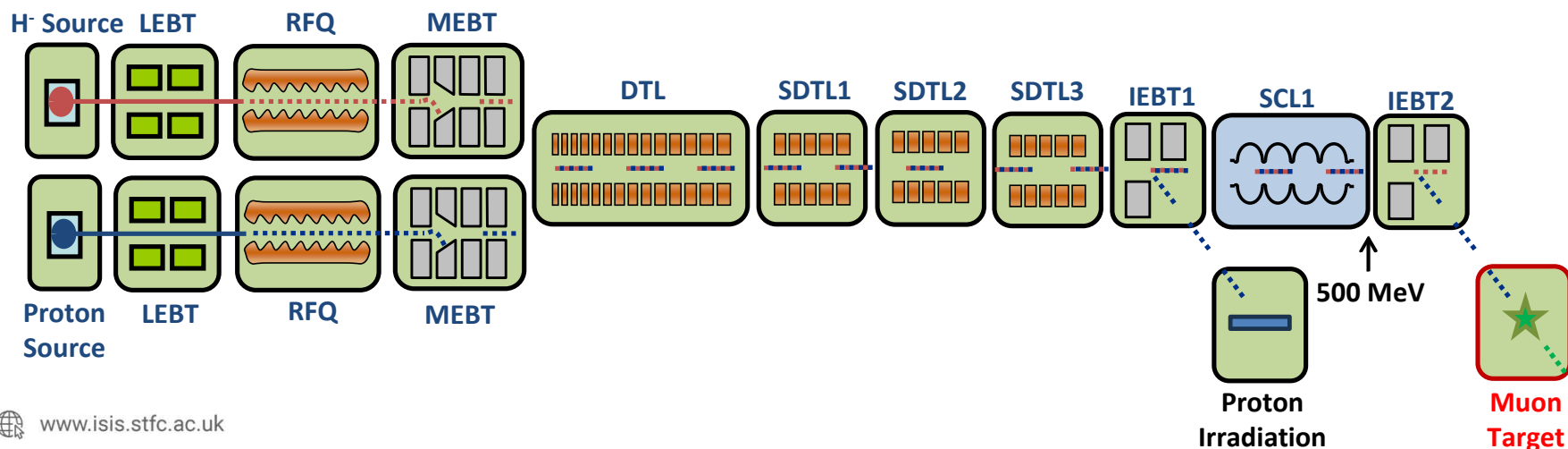
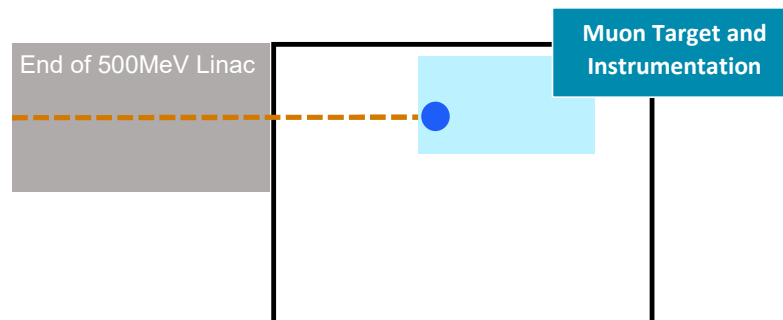
...opportunity for combined facility?

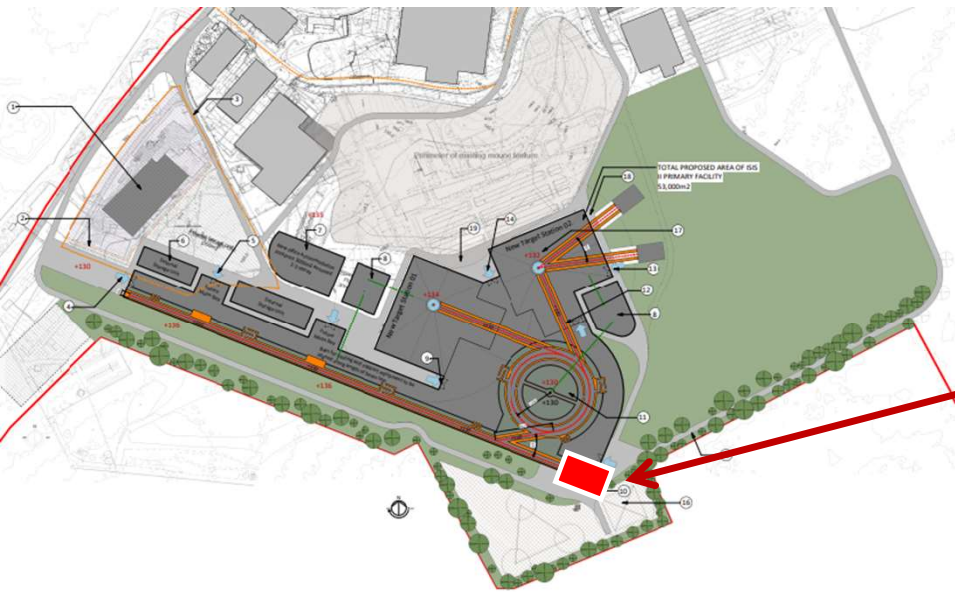


Scenario III



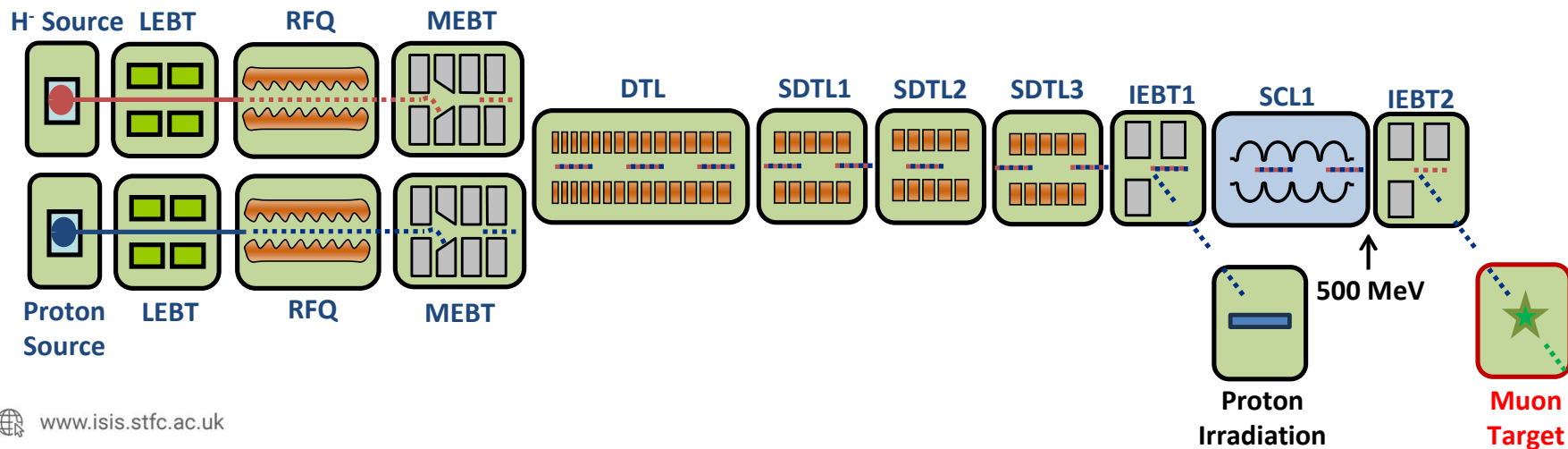
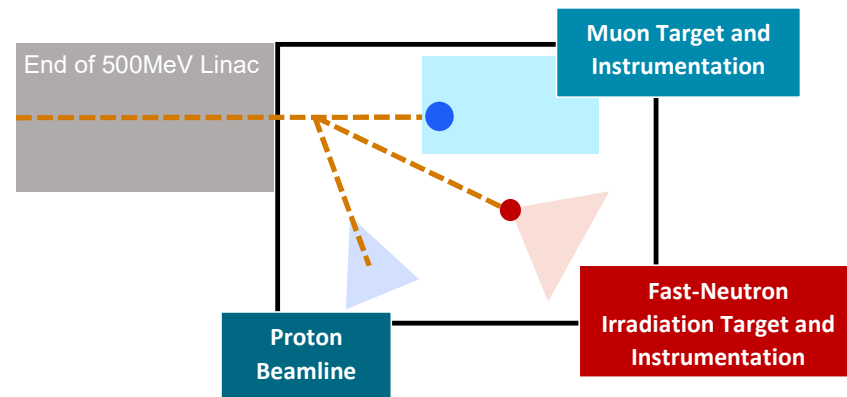
Scenario III
 Muon and Irradiation
 'Target Hall'



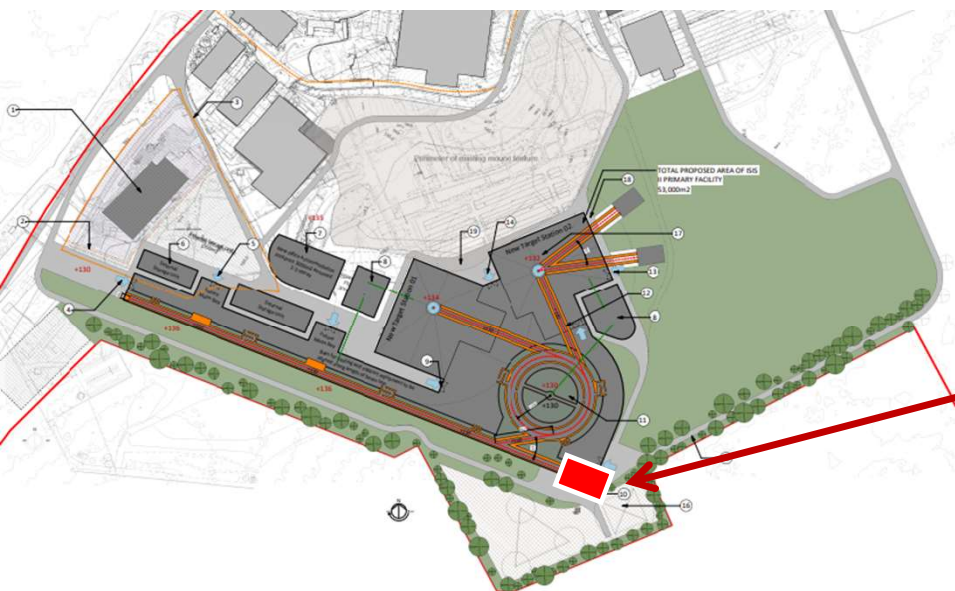


Scenario III
 Muon and Irradiation
 'Target Hall'

Scenario III



Scenario III



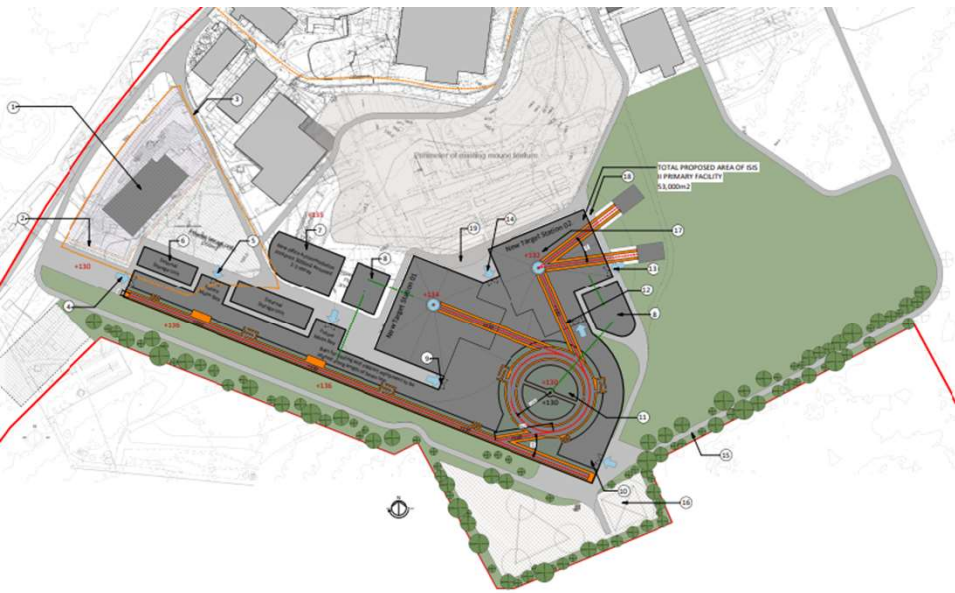
Scenario III
 Muon and Irradiation
 'Target Hall'

Delivers:

- Combined Neutron, Proton (and Muons)
- Flexibility

| | Advantage | Disadvantage |
|----------|--|---|
| Neutrons | <ul style="list-style-type: none"> • design technically possible • clear improvement on ChiPlr • simpler neutronic design • potential for more flexible control of flux/beams • low cost beamline | <ul style="list-style-type: none"> • highest cost facility (as hall infrastructure required and neutron target costs) |
| Protons | <ul style="list-style-type: none"> • Provides UK capability • Increased European provision • potentially more flexible design | <ul style="list-style-type: none"> • unknown design, particularly energy and flux control • cost unknown; but likely to be of similar scale as typical beamline |

Development Level: MEDIUM/HIGH



Points for discussion...

- Neutron beams: flux and pulse structure
- Neutron beams: flux control + size
- Neutron spectrum: maximum energy & < 10MeV
- Thermal neutrons & Mono-energetic provision
- Proton provision and requirements