The environmental impact of the ISIS-II Neutron and Muon Source

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Science and Technology Facilities Council
ISIS Neutron and Muon Source

Overview

1) The intersection of physics and the Climate Crisis
2) The ISIS-II Neutron and Muon Source
3) Environmental Impact & Life Cycle Assessment of ISIS-II
    - Methodology
    - Preliminary Results

The Climate Crisis
is not going away

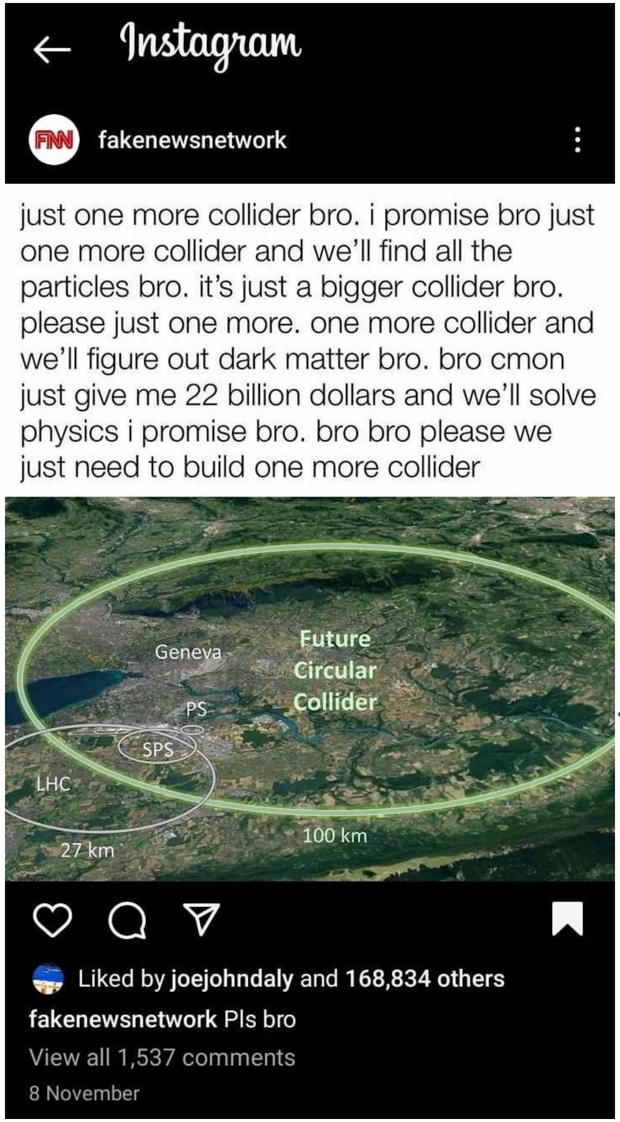
Why do we as physicists, engineers, researchers, etc. need to care?

- Moral and social duty to lead by example.
- Publicly funded.

What do we really mean by environmental impact and "sustainability"?

- Sustainability is "a social goal for people to co-exist on Earth over a long time."

- How does this *actually* relate to the field of physics?



Instagram: @fakenewsnetwork

The climate issue | Nature Astronomy

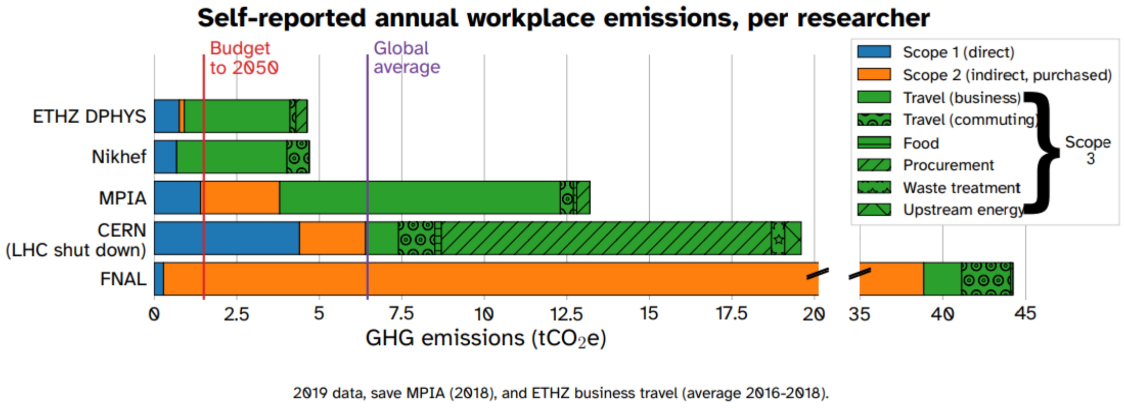
The environmental impact of particle accelerators

Large accelerator facilities are generally <u>unsustainable</u>:

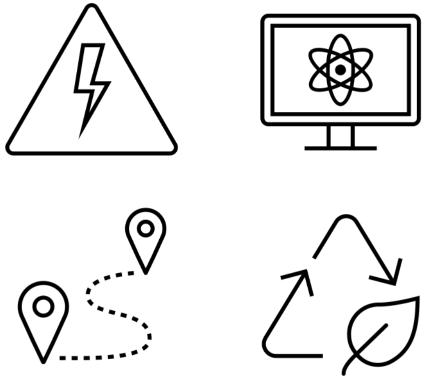
- resource consumptive, and
- next generations aim to grow in size and/or power, and therefore (generally) consumption.

Many efforts ongoing around the world:

- Carbon emissions and impact reports,
- R&D for increased efficiency of machines (klystrons, cryo., etc.),
- Reduction in resource consumption (helium, etc.),
- Sustainability guidelines,
- Air-travel reduction,
- And more...

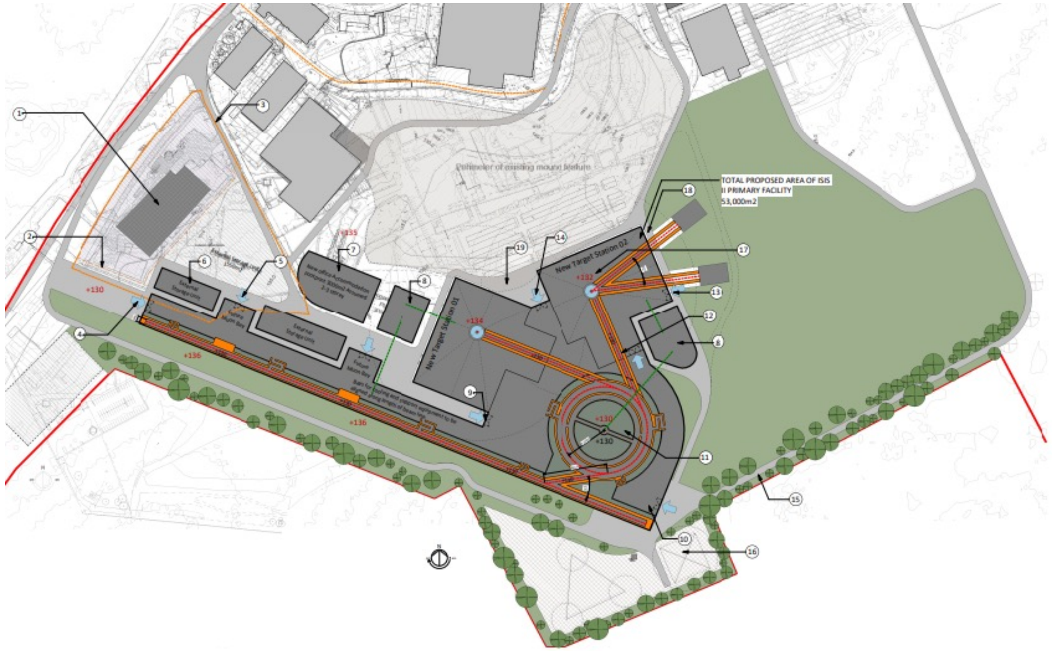


Reported workplace GHG emissions[1].



[1] Environmental sustainability in basic research: a perspective from HECAP+

The ISIS-II Neutron and Muon Source



The ISIS Spallation Neutron and Muon Source

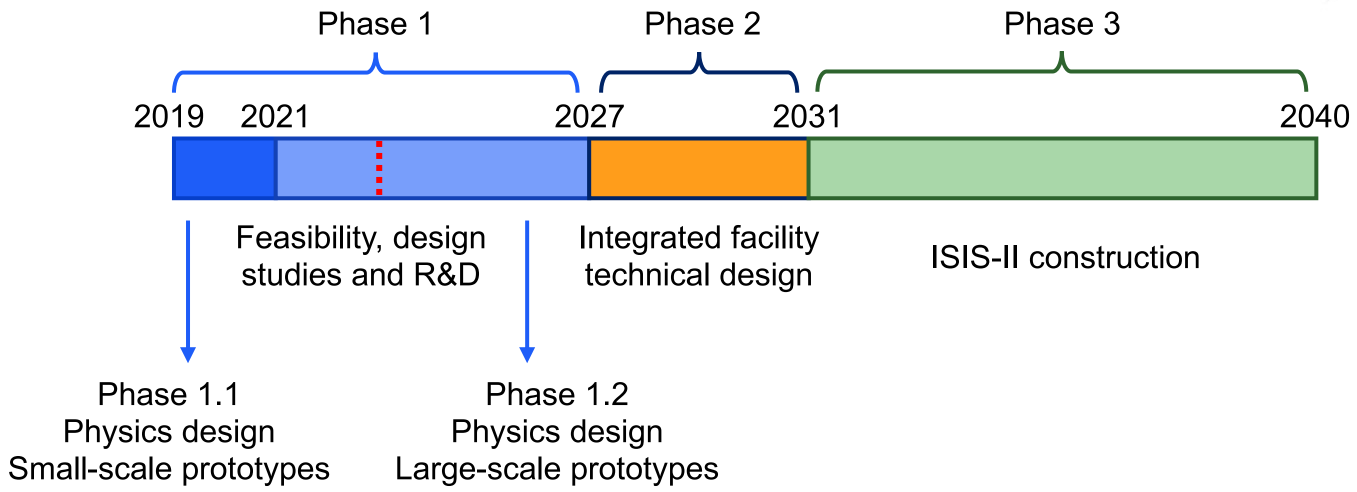
- ISIS is the UK’s two target, pulsed spallation source that produces world leading science.
- Based at the STFC Rutherford Appleton Laboratory (RAL), Oxfordshire, UK.
- This year, ISIS marks it's 40th year anniversary since neutrons!

The ISIS-II Neutron and Muon Source

Science and Technology Facilities Council

- The proposed 1.2 GeV beam upgrade to the ISIS Neutron and Muon Source.
- Again, with two proposed target stations.

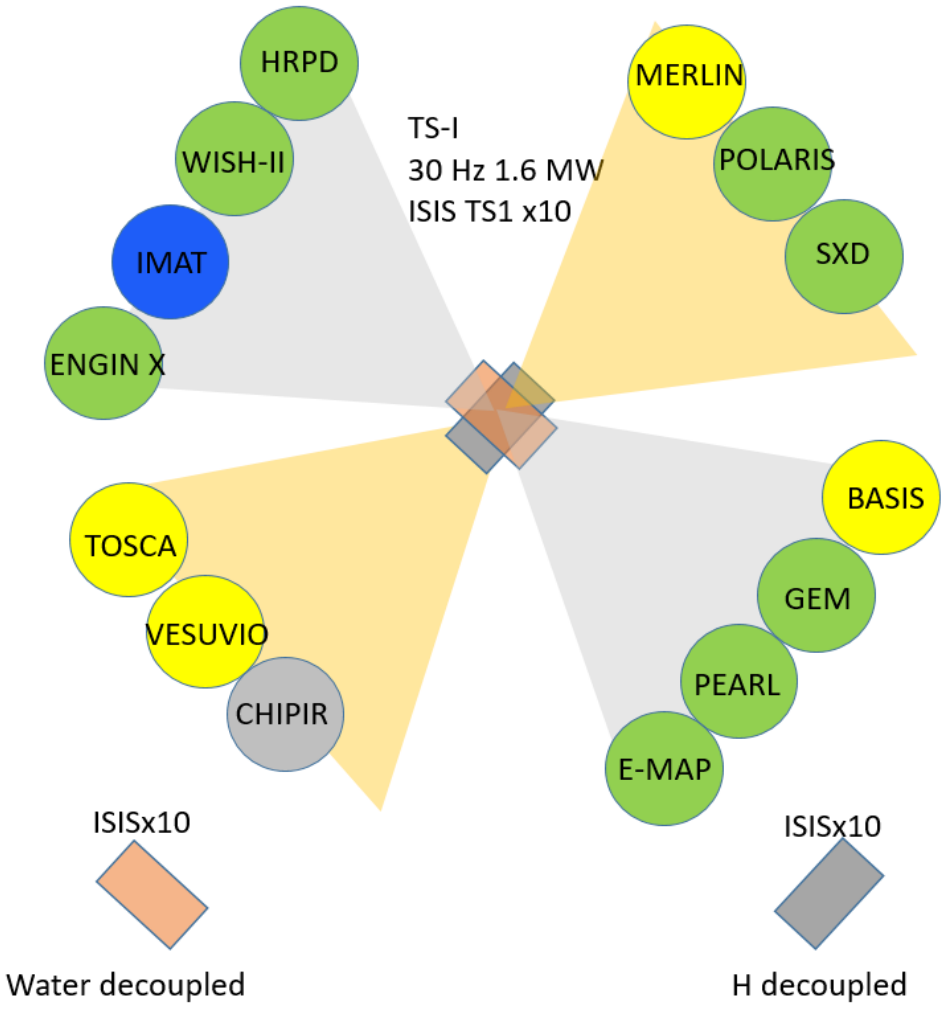
One proposed design option for ISIS-II.



Proposed ISIS-II timeline.

High repetition rate target options

- New 30 Hz 1.6 MW target station.
- High resolution
  - Same or better resolution as current TS1 at ISIS.
- Expect gains to be proportional to power.
- Decoupled water and hydrogen moderators.
- Flux gain of 10 over current TS1 at same resolution.

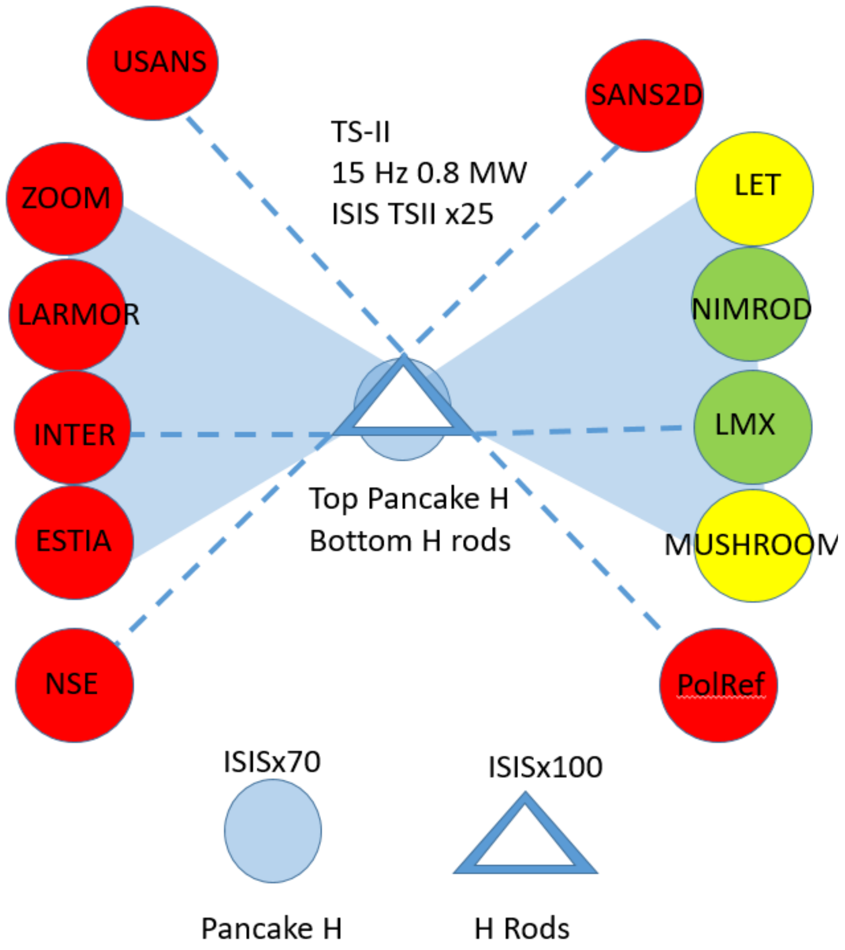


Proposal of TS1 instruments.

Thanks to Dr. John Thomason for these slides.

Low repetition rate target options

- TS2 - 15 Hz 0.8MW.
- TS2 would focus on cold neutrons and high brightness.
- The preliminary concept looks a lot like SNS Second Target Station, ORNL.
- Flux gain of 70-100.
- There are several options for muon production, such as intermediate targets or standalone stopping targets.

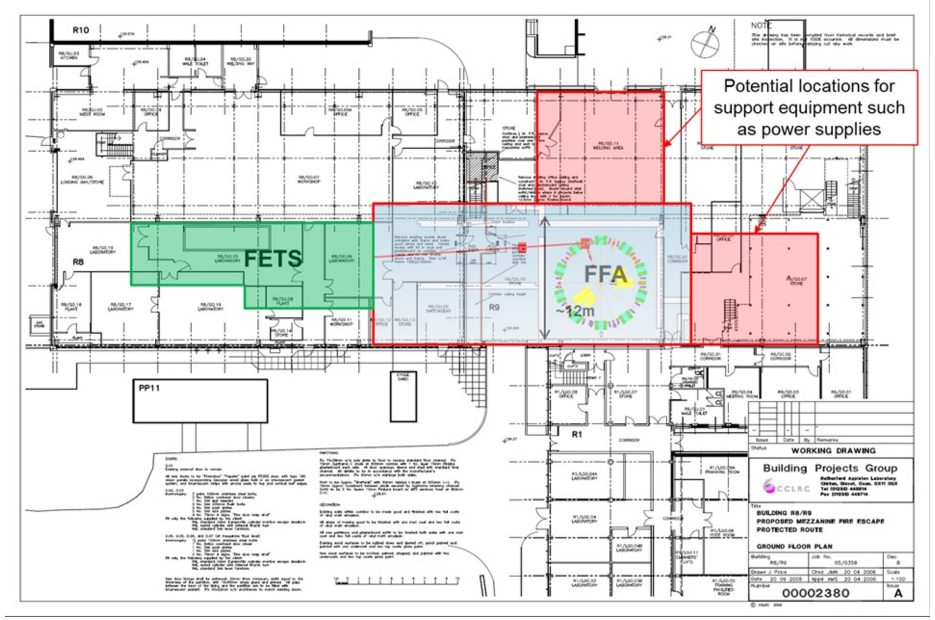


Proposal of TS2 instruments.

Thanks to Dr. John Thomason for these slides.

ISIS-II project phase 1.2b plan

- 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.
- Completion of target, moderator and shielding design for high and low repetition rate neutron targets and a muon target.
- Production of an optimal concept design with credible initial cost estimates.



Proposal of ISIS-II FFA drawing.

Thanks to Dr. John Thomason for these slides.

What might ISIS-II look like?

Proposal of ISIS-II "Green Field" location at RAL

Thanks to Dr. John Thomason for these slides.

The environmental impact and Life Cycle Assessment of ISIS-II

What do we hope to achieve?

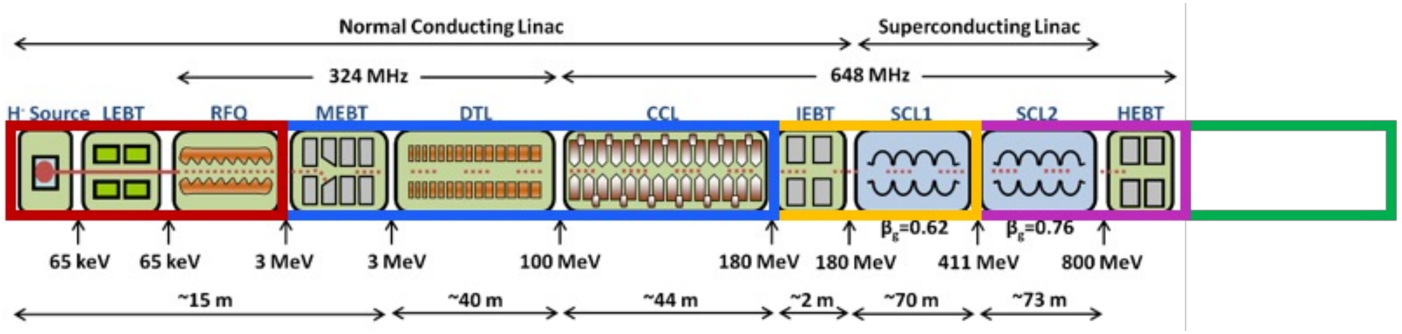
- To inform ISIS-II design options.
- To report on the full lifetime environmental impact expected at ISIS-II.
- To identify hotspots of environmental impact to allow focus to reduce these impacts.
- To help develop a methodology that can be used by other future facilities.

Methodology

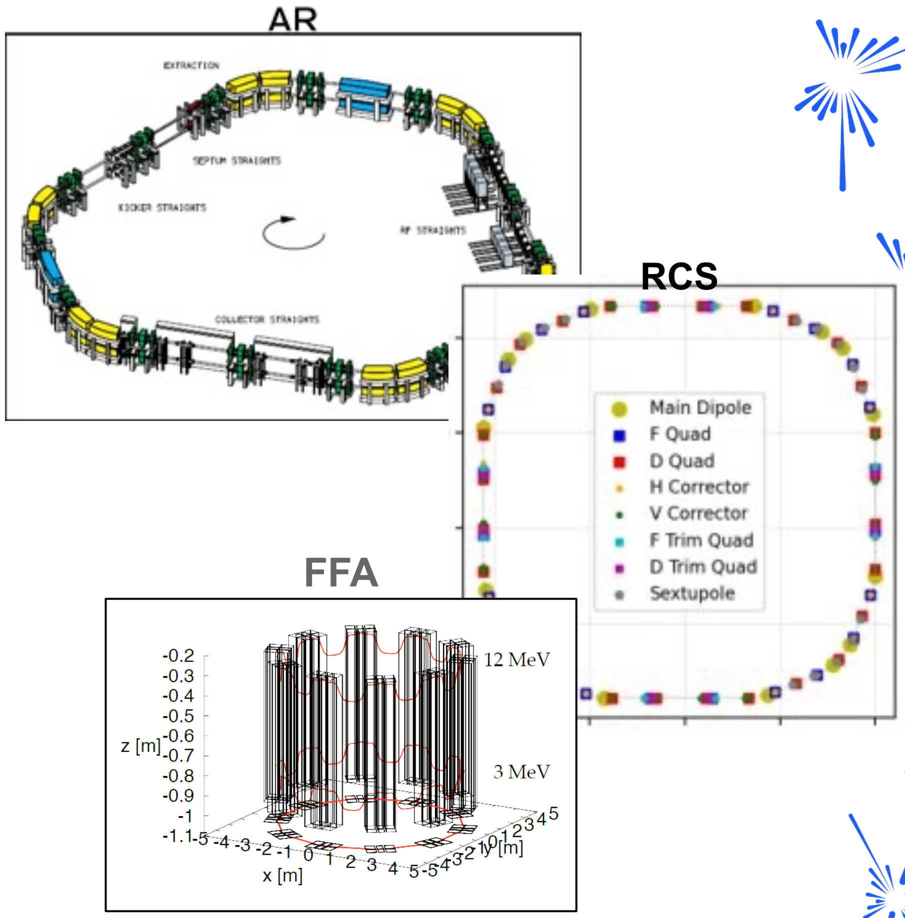
How can we achieve that?

Two key stages to this analysis:

1. Core components of ISIS-II and an estimation of their environmental impact through modelling and simulation.
2. (Simplified) **Life Cycle Assessment** (LCA)
    - to compare the compression ring options for ISIS-II, to inform ISIS-II phase 1.2b bid



LINAC design proposal.



3 ring options for ISIS-II.

A first look at the environmental impact of ISIS-II

Disclaimer:

- Assumptions, assumptions, assumptions!
- Models updated very regularly.
- Studies ongoing and future studies to come!

ISIS-II Components

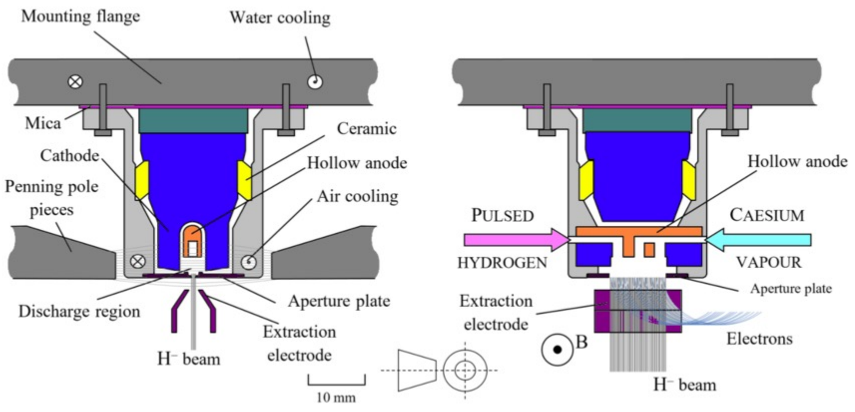
(many of the most common components of accelerators)

- Source and pre-injector
- Acceleration:
  - LINAC
  - **Compression Ring (Options)**
- Extraction: Extraction Proton Beamlines (EPBs)
- Collision: Target(s)
- Measurements: Instruments

- Ancillaries

Ion Source and pre-injector

- Assuming ISIS H- Penning ion source
- Modelled using Front End Test Stand (FETS) at RAL



Tarvainen, Olli & Faircloth, Dan & Lawrie, Scott. (2023)
10.1088/1748-0221/18/05/C05023.

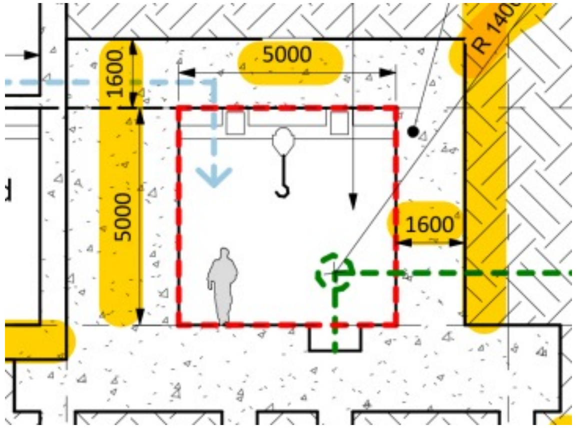
Example: machining of materials potentially optimizable

- FETS RFQ
- 16 blocks of oxygen-free copper totalling 4 tonnes
- Machined to16 vanes: 8 major (80kg ea), 8 minor (20kg ea)
- 3.2 tonnes of copper, i.e. 80%, wasted.
  - Swarf and off cuts were recycled via commercial metal recycling.

LINAC

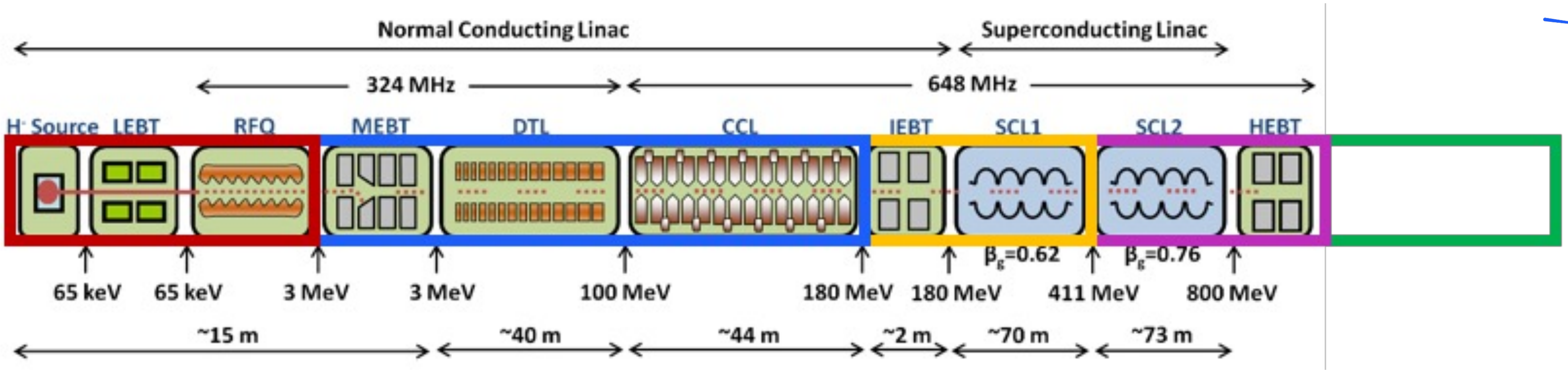
- Low energy linac with RCS
- Low energy linac with FFA
- Full energy linac with AR
- Fall back option: 180 MeV linac upgrade to ISIS

- Modelled using ISIS-II expectation and ancillaries used worldwide (SNS, ESS,...)



10s ktCO$_2$

LINAC shielding proposal.



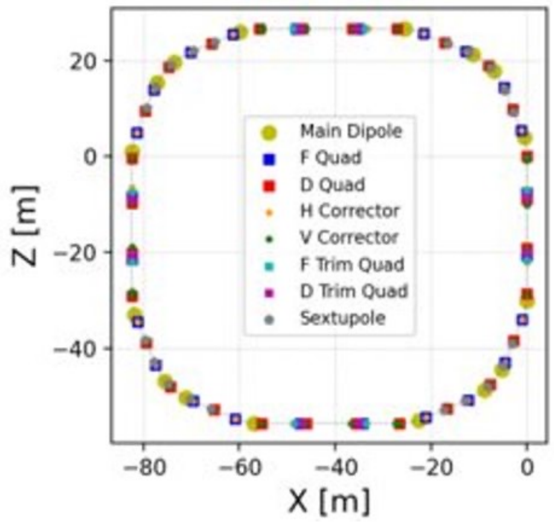
LINAC design proposal.

Compression rings (options)

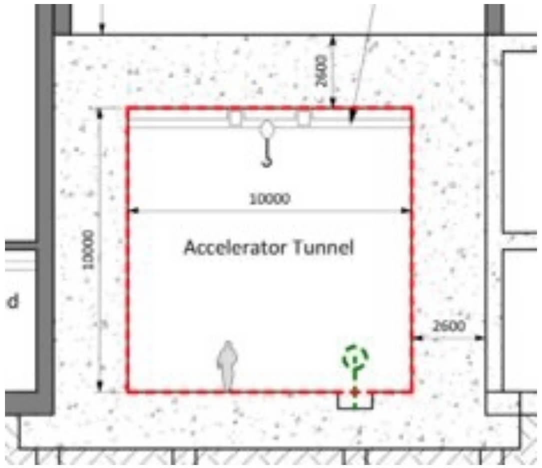
A first look at environmental impacts is underway.

Lattice magnet design differs in AC and DC currents therefore power distribution varies between a RCS and AR, however total power consumption will be similar.

Options will be considered in depth in LCA in the near future.



RCS magnets proposal.

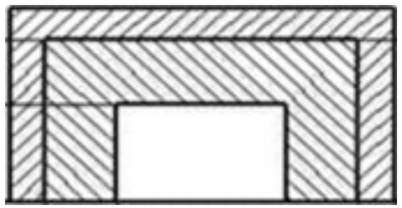


10s $ktCO_2$

Ring tunnel and outer shielding proposal.

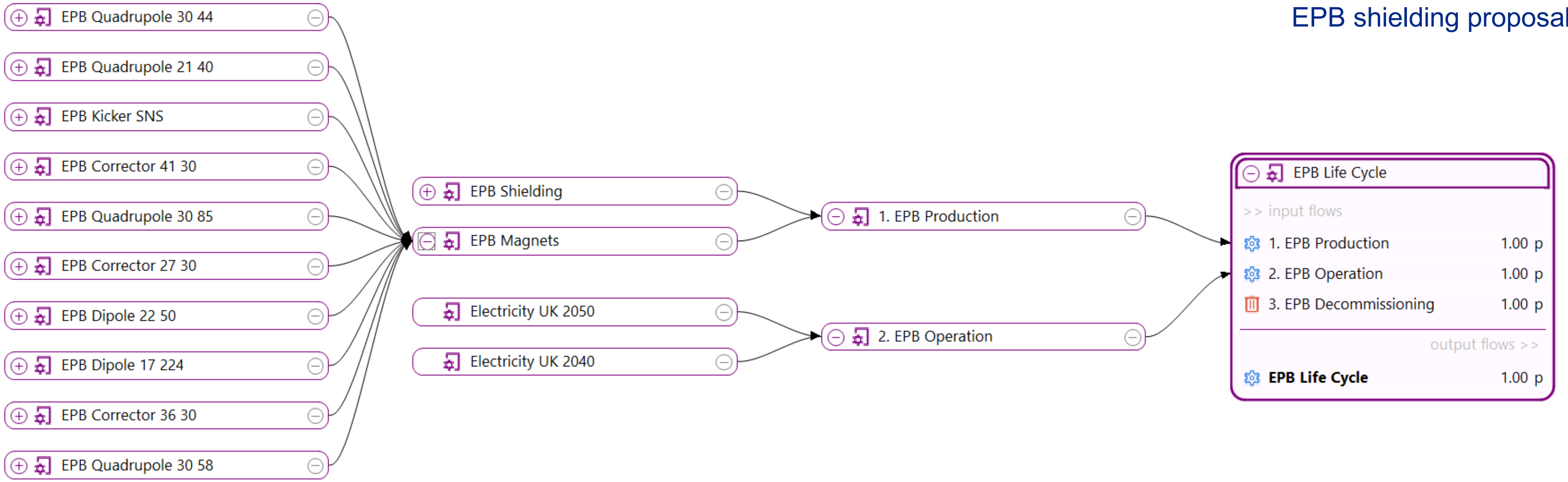
Extraction Proton Beamlines (EPBs)

- The EPBs design is modelled using the SNS Ring to Target Transport Line (RTBT) design.

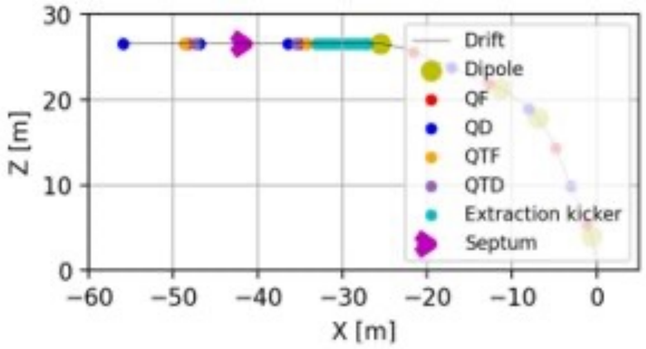


100s $ktCO_2$

EPB shielding proposal.



- Designs for ISIS-II are in progress and models will be updated when available.

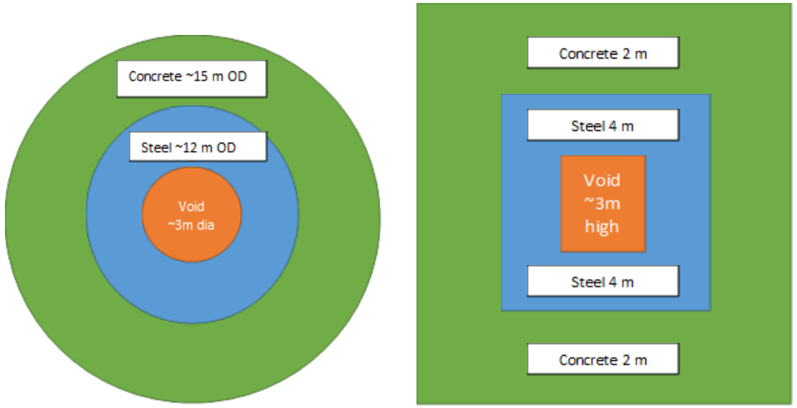


Targets

- TS1: water and H-decoupled moderators
- TS2: top pancake H, bottom H rods.

- Current design suggestions either
  - Target Station basically a copy of ISIS or
  - ~1 MW target station (similar to SNS STS).

- Important consideration here is the target material, radiation damage and replacement rate of the target.



10s ktCO_2

Target monolith (shielding) proposal.

Instruments

- ISIS-II is proposed to host 26 – potentially 40 instruments (by ~10 year mark).
- STFC recently succeeded in gaining funding for the Endeavour program at RAL. Endeavour instruments and ESS instruments are state-of-the-art and are not expected to change significantly in technology over the construction timescale of ISIS-II.
    - Therefore, these can be used as a model for instrument impacts.

- One model for neutron (HRPD-X) and one for muon (SuperMuSR) instruments due to differences in construction.
- Cherry-pick the more usual components.
- ISIS instrument and laboratory gas consumption each year recorded through gas canister orders used as a first estimate.

- How do we expect the data rates to change? How will ISIS-II data scale compare to, say, CERN/ESS?

Ancillaries

- Such as Klystrons, power sources, etc.
- Are being modelled individually using information from suppliers where possible,
- Where not possible, estimations will be made using existing facilities (SNS, ESS, …)

- Studies will be performed to determine optimal ancillaries in terms of environmental impact.
- These can then be considered in design stages.

Construction: Concrete

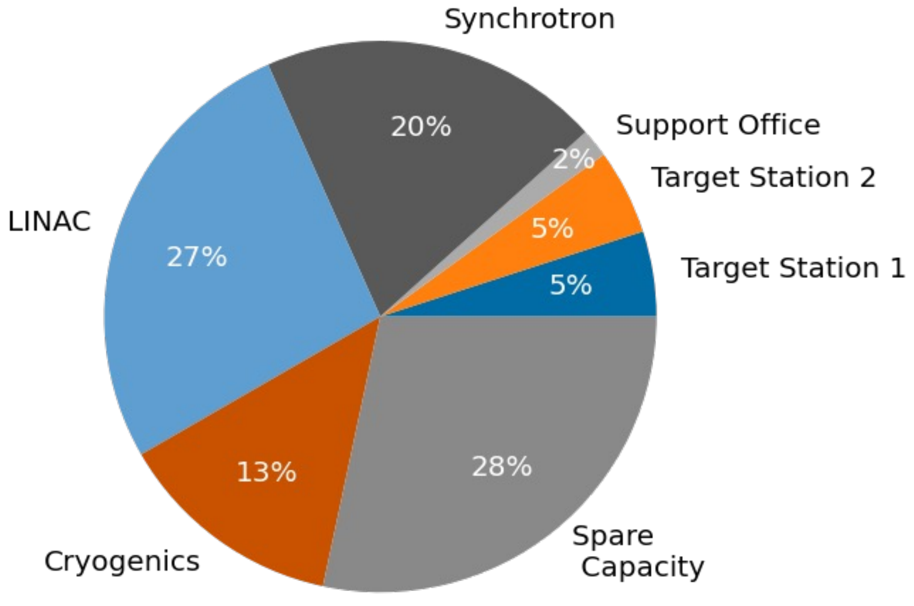
One of the largest expected environmental impacts is of the use of concrete in construction of ISIS-II. At this stage in the analysis, it is expected that emissions of CO_2e are expected to be of a similar order of magnitude of the power consumption of ISIS-II over its entire lifetime!

Thus efforts are ongoing to evaluate the potential for the use of more environmentally friendly materials.

Operation: Power

A first estimation of the emissions of CO2e due to the power consumption of ISIS-II over its lifetime.

Power	Big Science Scheme	
	[MVA]	Lifetime CO2e [tCO2e]
Target Station 1	1.5	30,156
Target Station 2	1.5	30,156
Support Office	0.5	10,052
Synchrotron	6	120,625
LINAC	8	160,834
Cryogenics	4	80,417
Spare Capacity	8.5	170,886
TOTAL	**30**	**603,126**



Big Science Scheme

The power values are assumed to reflect the predicted beam on/off ratio of ISIS-II and present the 60-year operational lifetime CO2e impact of ISIS-II, including current predicted "decarbonization of the UK grid" estimates.

Operation: Power (Computing)

The emissions of CO2e due to the power consumption and materials use of computing of ISIS-II over its lifetime is in the process of being modelled.

It is expected that the computing requirements compared to ISIS will be much larger.

Estimation work is ongoing, but it - as one of the largest power consumers in High Energy Physics - deserved a mention!

Operation: Local travel

Using ISIS local transport data, a first “back of envelope” calculation
is performed (i.e. high level of uncertainty)

Assumptions:

- 2026 estimates of staff modes of travel and distance travelled,
- 2022 percentages of onsite staff per day,
- 2050 estimates of public transit decarbonisation, and guesstimate of 2050 car emissions.

ISIS and ISIS-II permanent staff predictions:
Now: ~ 580 staff
2024-28: ~ 640 staff
2028-32: ~ 700 staff
2032-45: ~ 1050 staff
2045-2100: ~ 700 staff

A first estimation expects

$\boxed{\sim 2\ ktCO_2}$

for the lifetime of ISIS-II.

Operation: User travel (national and international)

Using ISIS user transport data, a first “back of envelope” calculation is performed
(i.e. high level of uncertainty)

ISIS and ISIS-II user predictions:
Now: ~ 3500 visitors per annum
2040+: ~3500 visitors per annum

Assumptions:
- 25% of users are international:
  Italy, The Netherlands, Sweden, Japan.

A first estimation expects:

~2.4 ktCO_2

Emitted by national users through travel

~2.2 ktCO_2

Emitted by international users through travel

Decommissioning

- ISIS-II decommissioning 2100 – 2170 (decay storage limit of 70 years).

- Estimation of the radioactive waste at ISIS-II will be modelled using:
  - the ISIS radioactive waste and disposal records,
  - Plans for ISIS decommissioning (2045-2090)
  - expected radioactive waste at ISIS-II,
  - other facilities of higher beam energy's estimations of waste (ESS).
- Highly dependent on country.

A first look at specific areas of environmental impact of ISIS-II

Area	Estimated carbon emissions from power consumption [ktCO_2e]	Estimated embodied carbon from buildings [ktCO_2e]	Estimated carbon emissions from tunnelling [ktCO_2e]	Estimated carbon emissions from shielding materials [ktCO_2e]
Target Station 1	30			~15
Target Station 2	30			~15
Support Office	10			-
Synchrotron	120			~10
LINAC	160		~10	~40
Cryogenics	80			-
Spare Capacity	170			-
Other (inc. support hall, EPBs)	-			~150
TOTAL	**~600**	**~100**	**TBC + ~10**	**~230**

NB: More studies ongoing and to come!

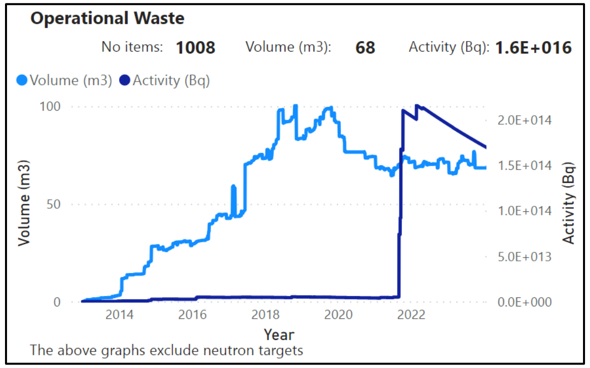
Overall environmental impact of ISIS-II

Costs		Quantity	Unit	£/rate	£ Total
Demolition and Site Clearance					
Site strip and levelling		151,700	m2	30.0	4,550,000
Disposal		151,700	m2	50.0	7,590,000
Mounding to new structure		53,550	m2	90.0	4,820,000
Sub-total		151,70[illegible]		111.8	16,960,000
Linac and transfer tunnels					
Linac Tunnel		[illegible],455	m2	6,935.5	127,995,000
Beam Transfer		7,470	m2	13,332.3	99,592,300
MEP - Linac		18,455	m2	1,664.5	30,717,690
Sub-total	GIA	18,455	m2	13,996.5	258,304,990
Synchotron					
Synchotron		9,850	m2	14,999.3	147,742,800
MEP - Synchotron		9,850	m2	1,263.3	12,443,629
Sub-total		9,850	m2	16,262.6	160,186,429

Construction

Element	Electrical Allowances [MVA]	
	Big Science Scheme	180 MeV Scheme
Target Station 1	1.5	1.5
Target Station 2	1.5	N/A
Support office	0.5	N/A
Synchrotron	6	As existing
LINAC	8	2
Cryogenics	4	2
Spare Capacity	3	1
Total	24.5	6

Operation

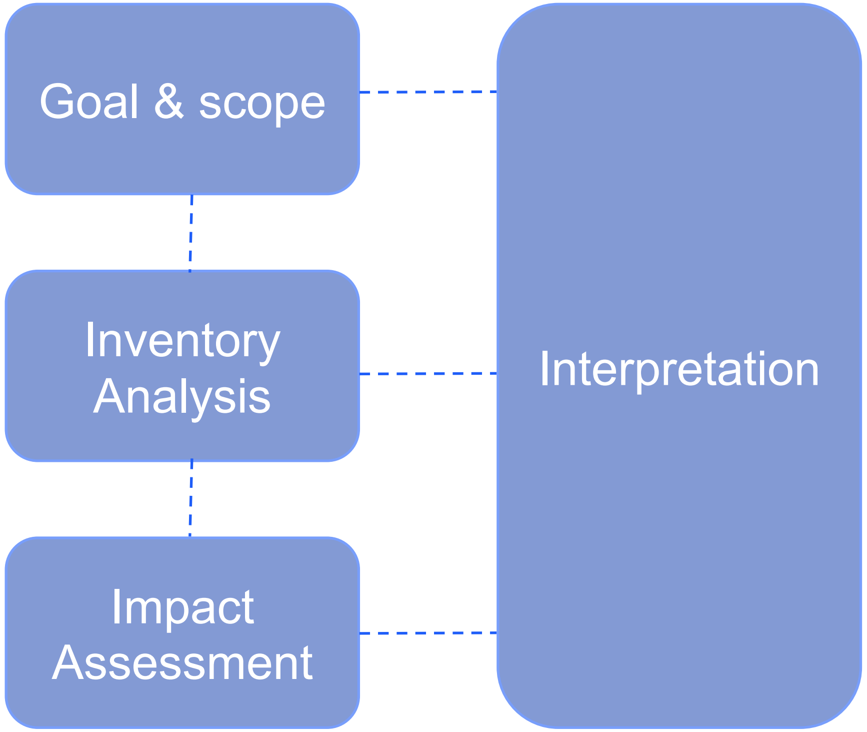


Decommissioning

What's next?

Life Cycle Assessment of ISIS-II

Life Cycle Assessment/Analysis (LCA):



LCA steps.

Goal & Scope

Goal

- To evaluate and inform the design of ISIS-II with a comparison of the options available for the compression rings of ISIS-II.

Scope

- The 4 ring design options of ISIS-II:
    - **RCS (low energy LINAC)**
    - FFA (low energy LINAC)
    - **AR (full energy LINAC)**
    - Fall back option: 180 MeV LINAC upgrade to ISIS
- Initially CO_2e is used as assessment parameter but other environmental impacts will not be ignored and not deemed negligible for the comparison.
- Currently the functional unit is "ISIS-II", with the view to investigate updating this in the future to, e.g., "user hours".

Inventory Analysis

Data collection and quality control:

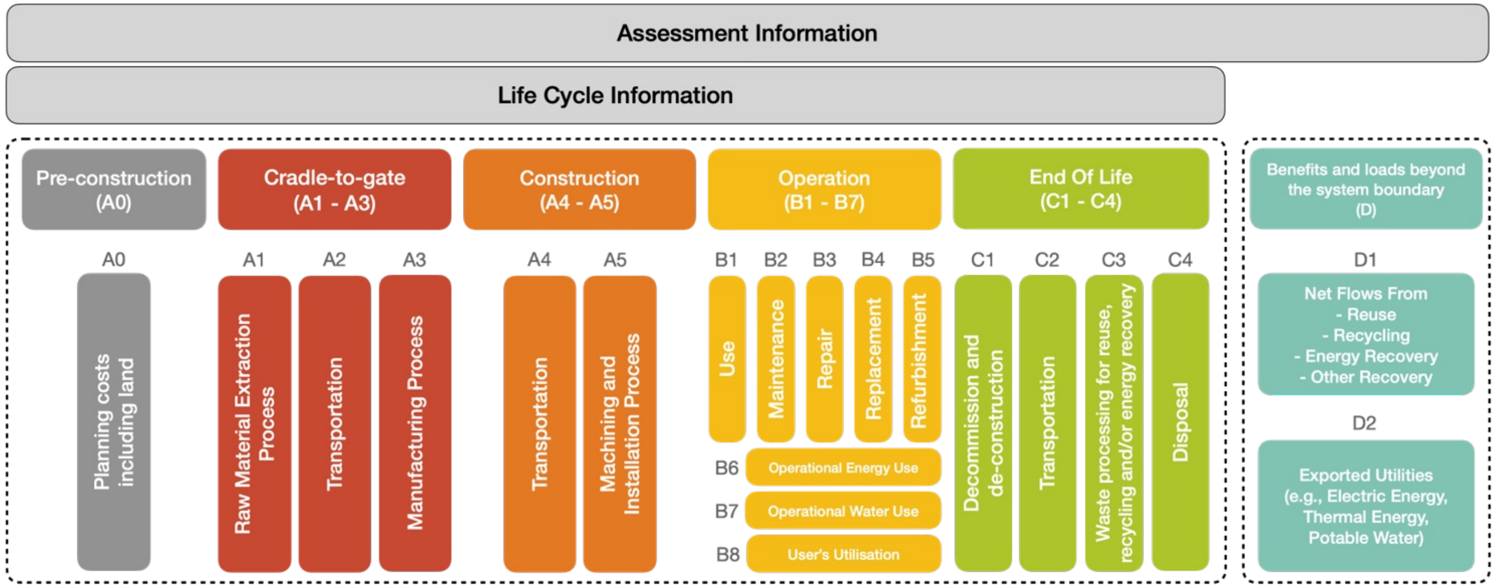
- **Construction**
- Facility
- Machine
- Shielding
- Computing
- Location

- **Operation/Active life**
- Energy consumption
- Resource consumption inc. leakage
- Failure likelihoods/risks inc. replacement/repair

- **Decommissioning**
- Storage of radioactive materials

Input
(resources, materials, semi-products, products)
vs.
Output
(emissions, waste, valuable products)

Impact Assessment



BS EN 17472:2022

A. Construction
B. Operation
C. Decommissioning

- Following the EN 17472:2022 standard as a basis.
- Using the ReCiPE:2016 Midpoint (H) Life Cycle Impact Assessment Method.
- Using openLCA with the Idemat database (currently, fluid, incomplete database for study)
    - One good outcome of this: naturally creates a database with key particle accelerator components such as magnets.

Summary and Conclusion

- Understanding and reducing the environmental impact of fundamental research is necessary.
- ISIS-II is the next proposed upgrade to the ISIS Neutron and Muon Source facility in the UK.
- To evaluate the environmental impact of ISIS-II, an impact analysis is well underway.
- To inform the design options for ISIS-II and the next funding bid, a Life Cycle Assessment will be performed.

Thank you for your attention, questions welcome!

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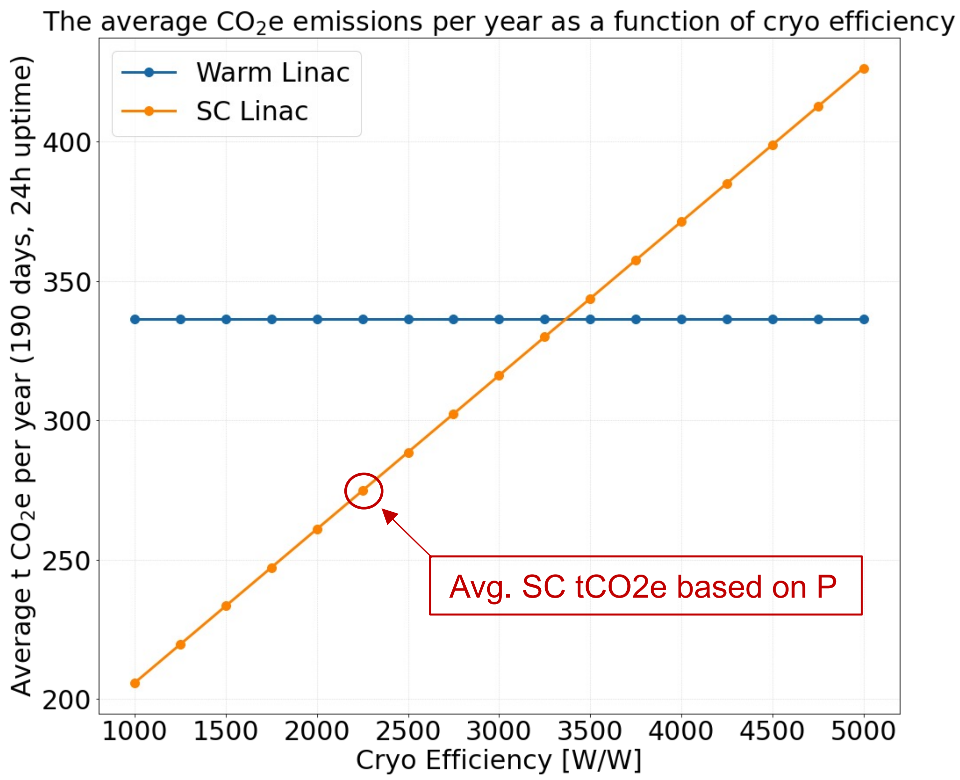
Additional resources for interest

HECAP+ Document

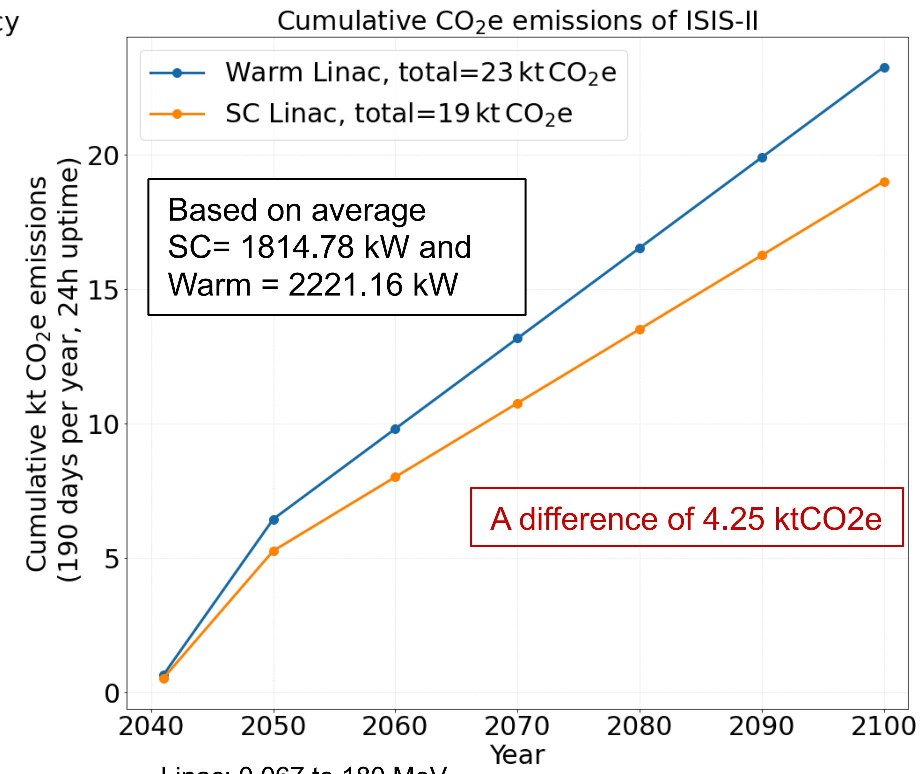
Operation: a comparison of warm LINAC and SC LINAC

(From A. Letchford's efforts)



Comparison of warm and SC LINAC as a function of cryo efficiency

(using 2050 energy CO2e emissions per kWh)



Linac: 0.067 to 180 MeV

Cumulative CO2e emissions with comparison of SC vs. warm LINAC using total wall plug power (note **k**t CO2e)

Year	CO_2 emissions [t CO_2/ kWh]
2020	1.415×10^{-4}
2030	8.51×10^{-5}
2040	6.36×10^{-5}
2050	3.32×10^{-5}

Aurora Energy Research

Decommission: Radiation

Would the use of Zepto-magnets have an increased radiation impact due to the large use of Neodymuim?

- Perhaps not a bad as originally feared.
- Ability to recycle (and the corresponding decay storage time needed) will be sensitive to the Co-60 activity with a half-life of ~5 years, just as it is with conventional electromagnets.

NB: The only way to accurately know what will form in a magnet is to model it properly with activation codes.