Science and Technology Facilities Council

ASTeC

IOP Institute of Physics

Sustainable Accelerator R&D in the UK

Ben Shepherd

on behalf of ASTeC's Sustainable Accelerators Task Force

Accelerator Science and Technology Centre, STFC Daresbury Laboratory, UK

Sustainable HEP Workshop × IOP PAB Conference

10-12 June 2024

Ben Shepherd
Magnets

Alan Wheelhouse
RF

Anthony Gleeson
Business

Gary Hughes
Facilities

Storm Mathisen
Diagnostics

Hywel Owen
Acc Physics

Andrew Vick
Vacuum

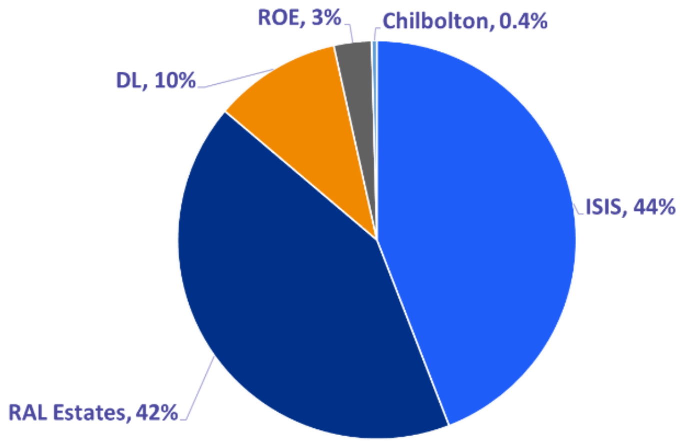
Katie Morrow
Lasers

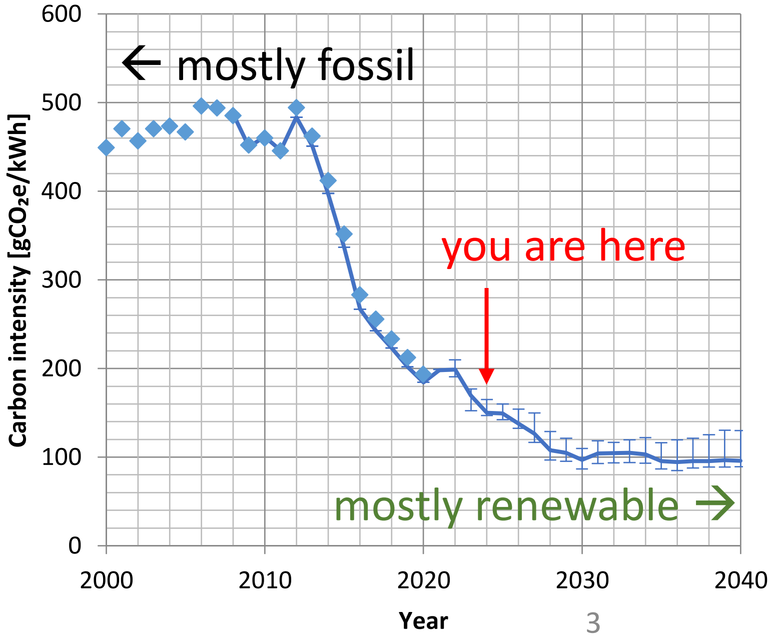
Overview

- Sustainable accelerator technologies
  - Thin film superconducting RF
  - Permanent magnets
- The CESA proposal: a new UK centre of excellence
- Accelerator carbon footprint: the RUEDI case study

Accelerator Context

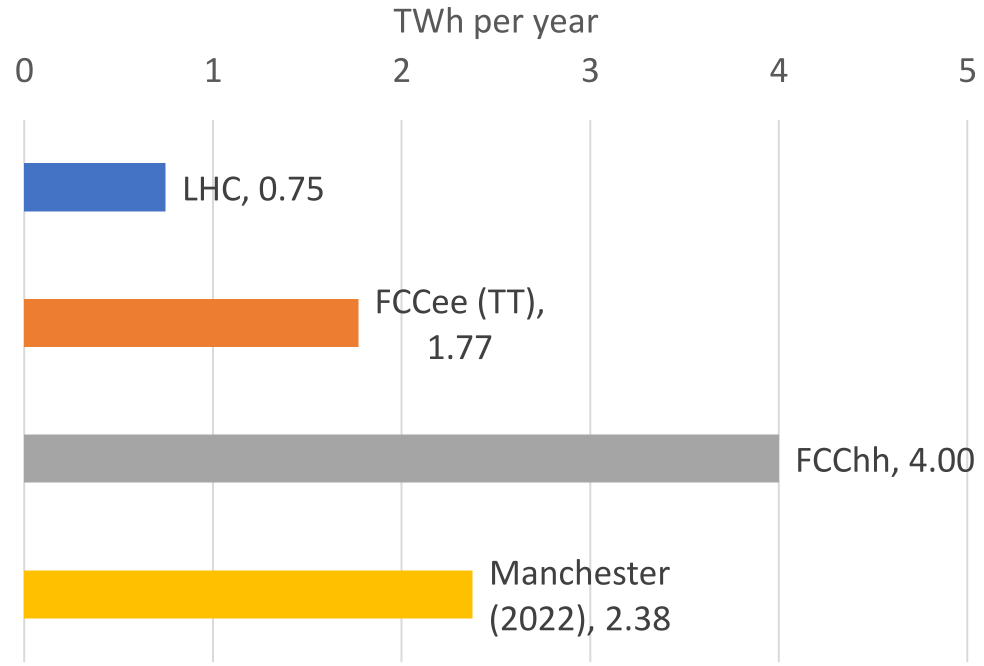
- UKRI has committed to reach **Net Zero by 2040**
- Electricity usage is **75%** of STFC's emissions – mostly big facilities ➔
- Particle Accelerators are core to many of our major science facilities:
  - ISIS Neutron and Muon Source
  - Diamond Light Source
  - CLARA electron beam test facility
  - Large Hadron Collider at CERN
  - European X-ray Free Electron Laser in Hamburg
  - ESRF in Grenoble
  - *… and more in the pipeline*: ISIS-II, Diamond-II, HL-LHC, RUEDI, EPAC, PIP-II, ESS, ITRF, UK-XFEL, EIC, …
- They are essential tools for enabling green research, but…
- They consume large amounts of electrical power and other resources
- The UK electricity grid is decarbonising *but not to zero*
  - Last coal plant closing Sep '24
  - Phase change fossil → renewable
  - Expect **100 gCO_2e/kWh** by 2030, ~20% of 2000 value





Bigger and Better?

- In general, the next generation facilities are physically larger and consume more power and other resources during operations than their predecessors
- **Example:**
  - **Future Circular Collider** is being proposed as a potential successor to **HL-LHC**
  - Tunnel: 26 → 90km
  - Energy consumption: 0.75 → **4.0 TWh/year**



JP Burnett, FCC Week 2023
F Gianotti, FCC Week 2023

Thin Film Superconducting RF

Why a TF SRF programme?

- Future challenge identified - niobium reaching performance limit
- Technology development required for next generation of machines to meet challenging specifications
- Fits our skills and strategy
- Sustainability advantages can not be ignored

- Vision: *To deliver high performing* ***thin film SRF*** *cryo modules to future infrastructure projects*

Replacing Nb bulk cavities

Use Of Thin Films On Copper

- Reduce **costs**
- Easier to **machine**
- Higher **thermal conductivity** than Nb

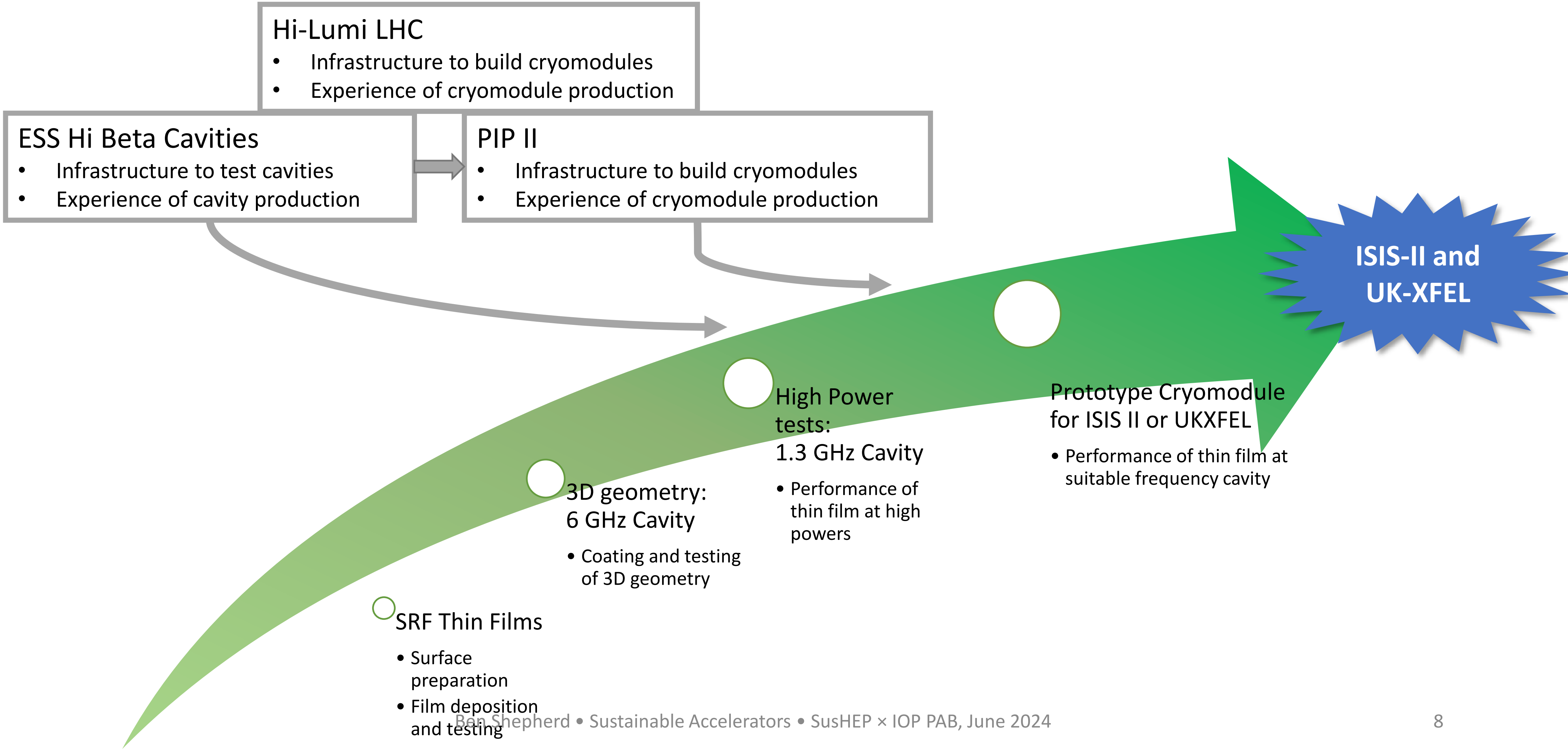
Improve Accelerator Performance

- Reach higher $\boldsymbol{Q_0}$ and $\boldsymbol{E_{acc}}$
- Utilise various **high T_c** materials
  e.g. Nb_3Sn, V_3Si, NbN, NbTiN, MgB_2
- Multilayers

More Sustainable Accelerators

- Bulk Cu vs Bulk Nb
- Reduce cryogenic power consumption
- Shorter accelerator structures
- Up-cycling existing cavities

Strategy



Hi-Lumi LHC
• Infrastructure to build cryomodules
• Experience of cryomodule production
ESS Hi Beta Cavities
• Infrastructure to test cavities
• Experience of cavity production
PIP II
• Infrastructure to build cryomodules
• Experience of cryomodule production
ISIS-II and UK-XFEL
SRF Thin Films
• Surface preparation
• Film deposition and testing
3D geometry: 6 GHz Cavity
• Coating and testing of 3D geometry
High Power tests: 1.3 GHz Cavity
• Performance of thin film at high powers
Prototype Cryomodule for ISIS II or UKXFEL
• Performance of thin film at suitable frequency cavity

Thin Film SRF

For more info, see **Daniel Seal**'s talk this week at IOP PAB conference

Surface preparation
- Cleaning, etching,
- Polishing, passivating

Thin film deposition
- **PVD**: DC, pulsed, HIPIMS…
- (PE)CVD, (PE)ALD
- **Nb, NbN, Nb_3Sn**, MgB_2, SIS, etc.

Film characterisation
- SEM, FIB, AFM,
- XPS, XRD, RBS, TEM…

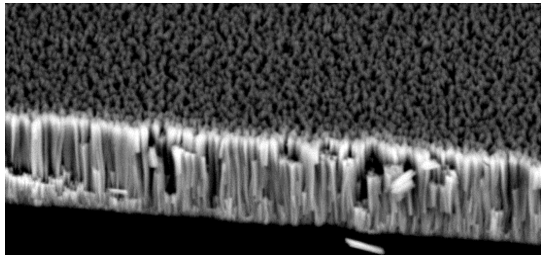
Superconducting properties measurement

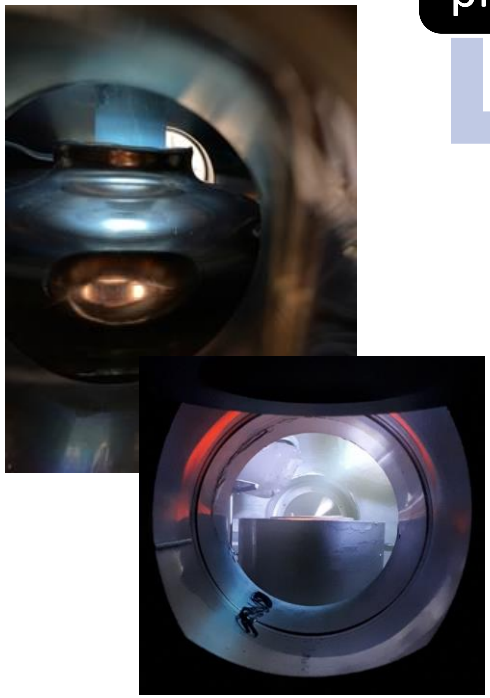
RRR, H_c, H_{fp}, H_{sh}, …
DC magnetic susceptibility,
Field penetration

Superconducting RF properties evaluation
- Choke cavity

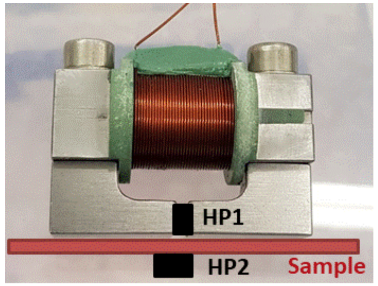
Real cavity measurement
- 1.3 & 6 GHz elliptical
- 1.3 & 6 GHz split cavities

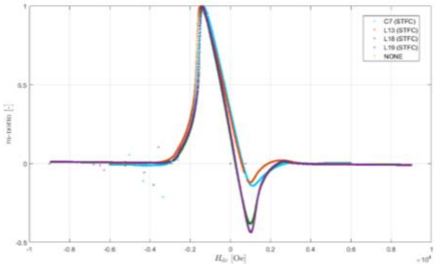
SEM image of a NbN thin film





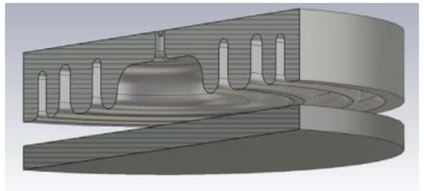
Film deposition





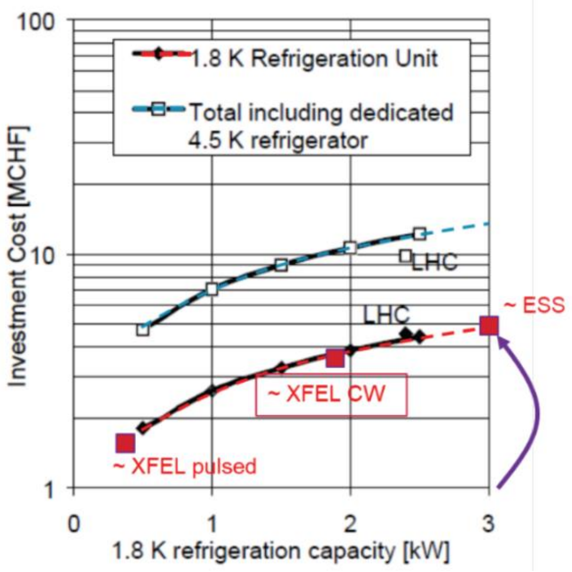
DC magnetisation

Test cavity



Thin Films: impact on cost and energy usage

- Capital costs:
  - Cooling to 1.8 K represents **35-40%** of the total →

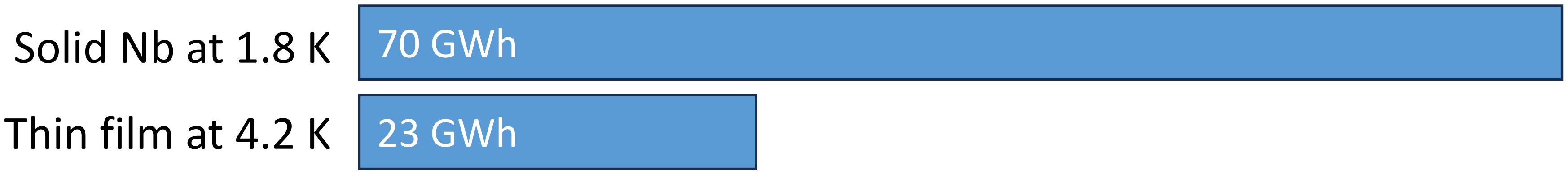


- Operating costs:
  - Combination of Carnot efficiency (thermodynamic limit) and refrigerator efficiency (technological limit)

$$\eta_C = \frac{T_{cold}}{T_{hot} - T_{cold}}$$

	1.8 K	4.2 K
η_C	0.6%	1.4%
η_{th}	15-20%	25-30%

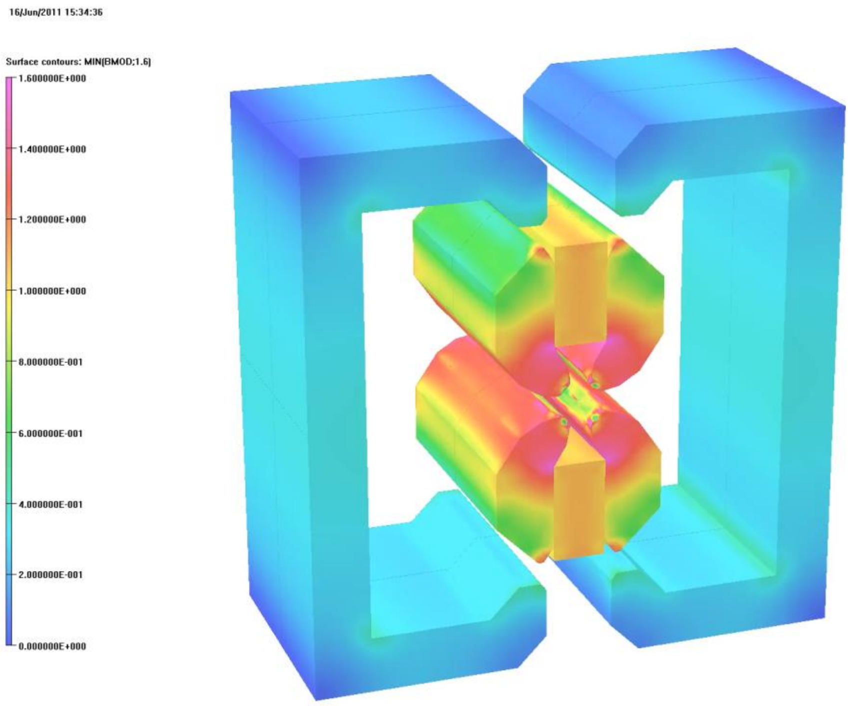
  - **3x lower cooling power at 4.2 K**
  - Approx annual figures for an 8 GeV SC linac



Permanent Magnets

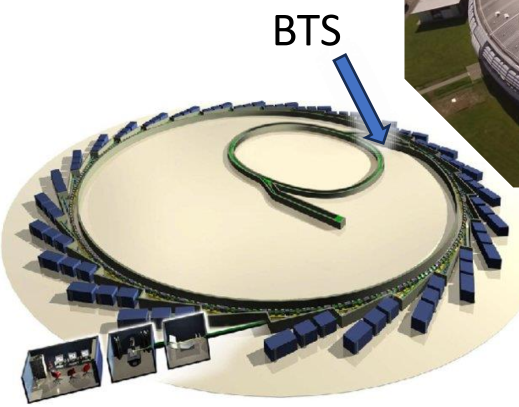
The ZEPTO concept

- **Ze**ro-**P**ower **T**uneable **O**ptics
- Highly adjustable PM quadrupole and dipole magnets to replace electromagnets
    - Large **tuning range** using motors to move PMs
    - Same **physical footprint**
    - No **energy usage**
      (except a tiny amount when adjusting)
    - Less **infrastructure** required
      (no big current cables, power supplies, cooling)
- Two prototype quads built at Daresbury Laboratory
    - **27 mm** aperture
    - **230 mm** length
    - **15-60 T/m, 4-35 T/m** ranges
    - Fixed poles, movable PMs
    - Simple control system with one motor

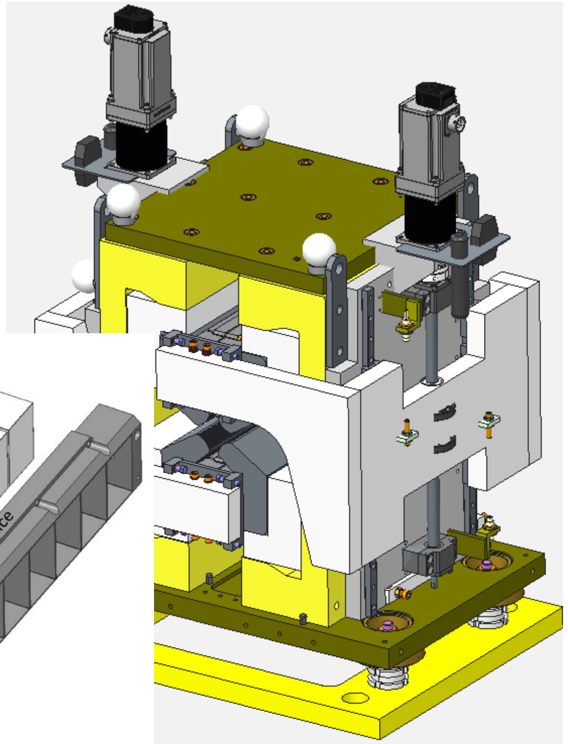


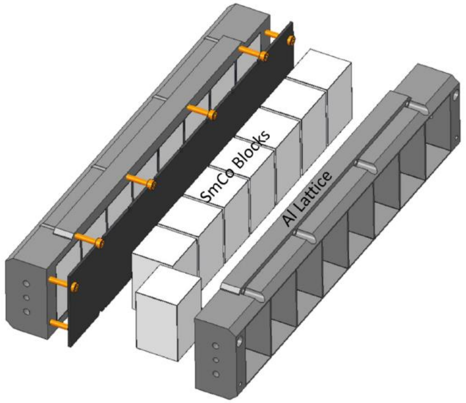
ZEPTO Diamond Quadrupole

- Aim: demonstrate operation of a ZEPTO quadrupole on a working accelerator
- Install a tuneable PM quad as a drop-in replacement for an EM quadrupole
- Installed at Diamond Light Source, on the BTS transfer line
- Enabled by STFC's Proof of Concept Fund
  - Step towards commercialisation of ZEPTO
- Assembled and tested at Daresbury
- Installation at Diamond in August 2022 shutdown
- Operated successfully at Diamond for 12 months
- Next steps: remove, retest, ensure no radiation damage



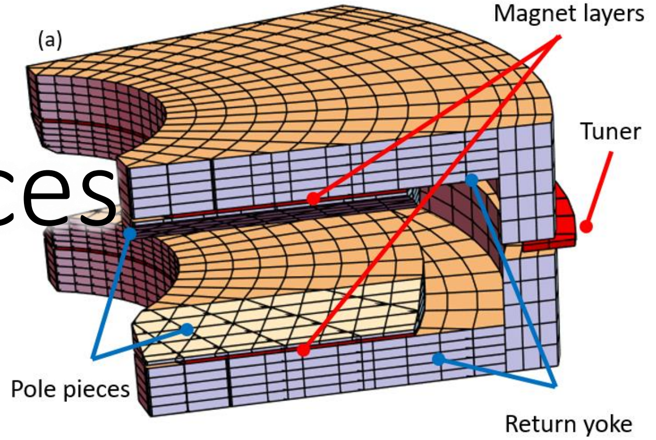
- Similar design to ZEPTO-Q2
  - Outer shell for large tuning range
- Max gradient **19 T/m**
- Min gradient **0.5 T/m**
- Movement range **90 mm**
- Aperture diameter **32 mm**
- **Improvements to design:**
  - **SmCo** blocks
    - improved temperature stability
    - radiation resistance
  - **Splittable** to allow installation around vacuum chamber
  - **Two independent motors** for magnetic centre correction
  - **Ice cube tray** concept for easy installation of PM blocks

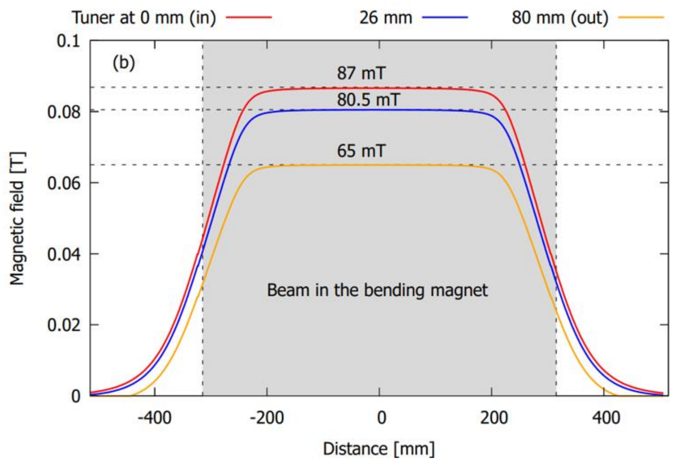




Olli Tarvainen *et al*, Nuclear Physics B (2022)

ECRIS: adjustable PM dipole for ion sources





- Compact ion source applicable to
  - Thin Films centre
  - Materials characterisation at ISIS
- Includes PM-based m/q separator
  - Simpler than traditional EM-based system
- Mechanical adjustment: **65-87 mT**
- Assembled and tested at DL in 2022
- Excellent agreement with modelling
- Field quality **5×10^{-4}**
- Installed and operating at Jyväskylä, Finland
- Transported Ar^{6+} to Ar^{12+} beams, May 2024
  - Magnetic adjustment “works really well”

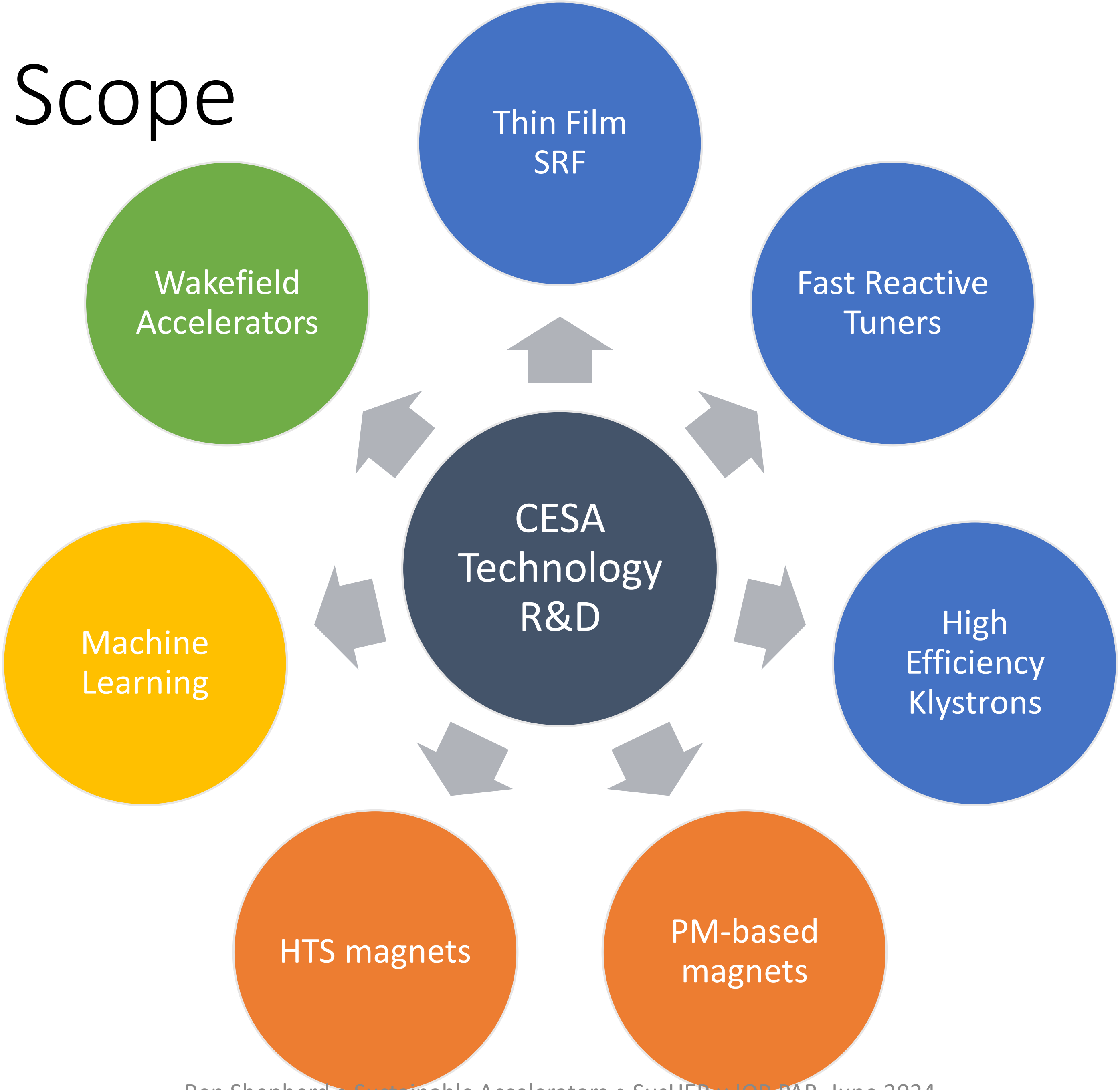
CESA: Centre of Excellence in Sustainable Accelerators

What is CESA?

- Our vision is that CESA is a **centre of mass** for UK-based accelerator R&D with a specific mission to **make accelerators significantly more sustainable**
  - Receives sufficient funding for a coherent and targeted **R&D programme** enabling a step change in the rate of progress at a timescale relevant to our future pipeline
  - Collaborating directly with **industry** so that new products can be procured commercially as they are developed and proven, enhancing the UK economy and return from CERN
  - Has a small core team who provide training to engineers, technicians and scientists in **sustainable design practices** backed up by providing access to sustainability **software tools** and databases
  - Works collaboratively with **international partners**

- We need to invest now to ensure we are ready in time for the potential mega-projects which are on the horizon – such as ISIS-II, UK XFEL, and FCC
  - It will take many years to demonstrate new technologies
  - We still have time but need to get going as they aim to start construction in the early ‘30s

Initial R&D Scope



CESA Technology R&D Areas: one-page overview

	CA1 Thin Film SRF cavity development	CA2 Fast reactive tuners for SRF cryomodules	CA3 High Efficiency Klystrons	CA4 Permanent Magnets for beamline magnets and klystrons	CA5 HTS Magnets	CA6 Machine Learning and AI applied to accelerators	CA7 Plasma Wakefield Accelerators
Cost	💰💰💰💰💰💰	💰	💰💰	💰	💰💰💰	💰	💰💰💰
Lab space	🏢🏢🏢🏢🏢🏢	🏢	🏢🏢	🏢🏢🏢🏢🏢🏢	🏢🏢🏢🏢🏢🏢	none	🏢🏢🏢
CO_2 and opex savings	☁️☁️☁️☁️☁️☁️	☁️	☁️☁️☁️☁️☁️☁️	☁️☁️	☁️☁️☁️☁️☁️☁️	☁️☁️	☁️☁️
Other benefits*	🏭🧑‍🔧💡	🏭🧑‍🔧⚙️	🏭🧑‍🔧	🏭🧑‍🔧💡	🏭🧑‍🔧⚙️💡	🧑‍🔧	🏭🧑‍🔧⚙️

*🏭 partnership with industry; 🧑‍🔧 skills development; 💡 development/exploitation of IP; ⚙️ enabler for other green technologies

CESA’s Objectives

- R&D in **key technology areas** to drive sustainability improvements for **current** and **next-generation** accelerators
- Tools, expertise and support to measure and optimise **lifecycle carbon emissions** in support of UKRI’s Net Zero 2040 target
- Develop strong **international collaborations** with other international accelerator institutes, and industrial partners
- **Training** for new and current accelerator designers in **sustainable design**; knowledge sharing
- **Education and outreach** on the themes of sustainability and accelerator technology

Power / cost / CO_2 savings illustration: UK-XFEL

- UK-XFEL conceptual design & options analysis in progress
- Baseline:
  - 8 GeV, 1.3 GHz superconducting linac, solid Nb cavities
  - Room temperature electromagnets
- Energy consumption estimates:

Total per year: **113 GWh**, **£29m**, **7900 tCO_2e**

- Using **CESA-developed technologies**:

Potential **annual savings** on the order of **85 GWh, £24m, 6600 tCO_2e**

CESA will pay for itself many times over during the 40+ year lifetime of a mega-project

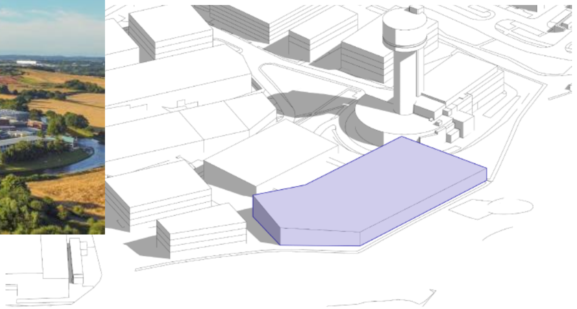
Thin film SRF: 1.8K → 4.2K; x3 reduction in cryo power

FRTs: higher Q → x10 reduction in RF power

HTS / PM: x10 reduction in magnet power

Options for CESA

- Initial options analysis carried out
- Evaluated each option against *key criteria*
    - Delivery of core R&D
    - New lab space
    - Innovation & collaboration
    - Workforce development
    - Value for money
    - Net Zero targets
    - UK leadership
    - Deliverability within 5 years
- and also against *delivery of core R&D*



Preferred Option

New building
- At DL or RAL
- Space reserved by Estates

key criteria *core R&D*

Repurpose existing building
- At DL or RAL

Distributed centre
- Across several different sites
- ‘Hub and spoke’?

Virtual entity

Hybrid entity
- A new/existing centre with a major virtual presence

Engage with international effort
- Collaborate with other sustainability groups

CESA Next Steps

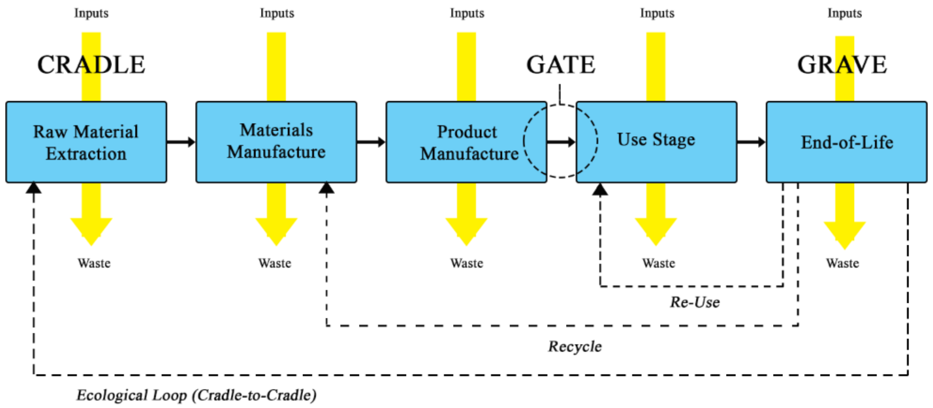
Questions? Feedback? Want to get involved?
Contact us: ben.shepherd@stfc.ac.uk
Coming soon: www.cesa.ac.uk

- We have written a **Viability Case** (a mini business case) for CESA and presented it to an internal STFC Viability Panel (this is an STFC process for major new initiatives)
- Received very positive feedback to help us strengthen the Case
- Updating the Viability Case now, to be presented to **STFC Executive Board** in June
- We will take on board their feedback and begin drafting the **Outline Business Case**

- We will be asking for funding to **ramp up from 2025** – this could come from the next government Spending Review, the UKRI Infrastructure Fund, or a specific Net Zero fund

Accelerator Carbon Footprint: RUEDI

Aims

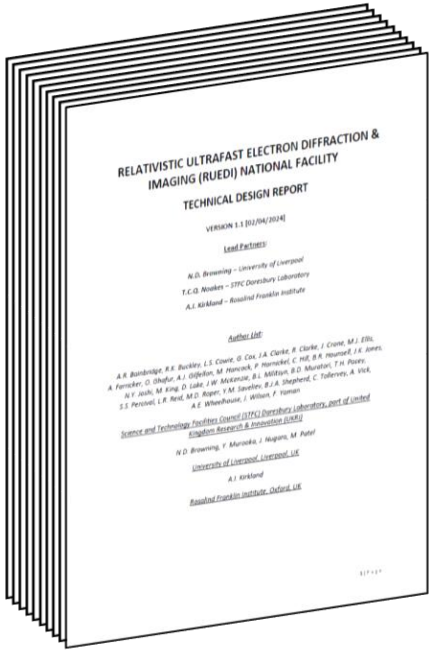


- Answer the question:
  "What is the carbon footprint of an accelerator?"
- Hard to find an accurate and definitive answer
  - Especially before the design is complete
  - But this is the critical time to do it
- Can we provide some guidance though?
- Look for the biggest possible gains
- Influence the design to minimise overall lifetime emissions

RUEDI NATIONAL FACILITY

https://ruedi.uk/

- Relativistic Ultrafast Electron Diffraction and Imaging
- Facility to be built at STFC's Daresbury Laboratory
  - 4 MeV; diffraction at 10-100 fs; imaging at 10-100 nm; fC-pC bunches
- TDR was completed early 2024
  - Not published yet; available on request
- £124m for construction announced March 2024


RELATIVISTIC ULTRAFAST ELECTRON DIFFRACTION & IMAGING (RUEDI) NATIONAL FACILITY

TECHNICAL DESIGN REPORT

VERSION 1.1 [02/04/2024]

Lead Partners:

N.D. Browning – University of Liverpool
T.C.Q. Noakes – STFC Daresbury Laboratory
A.I. Kirkland – Rosalind Franklin Institute

Author List:

A.R. Bainbridge, R.K. Buckley, L.S. Cowie, G. Cox, J.A. Clarke, R. Clarke, J. Crone, M.J. Ellis, A. Farricker, O. Ghafur, A.J. Gilfellon, M. Hancock, P. Hornickel, C. Hill, B.R. Hounsell, J.K. Jones, N.Y. Joshi, M. King, D. Lake, J.W. McKenzie, B.L. Militsyn, B.D. Muratori, T.H. Pacey, S.S. Percival, L.R. Reid, M.D. Roper, Y.M. Saveliev, B.J.A. Shepherd, C. Tollervey, A. Vick, A.E. Wheelhouse, J. Wilson, F. Yaman

Science and Technology Facilities Council (STFC) Daresbury Laboratory, part of United Kingdom Research & Innovation (UKRI)

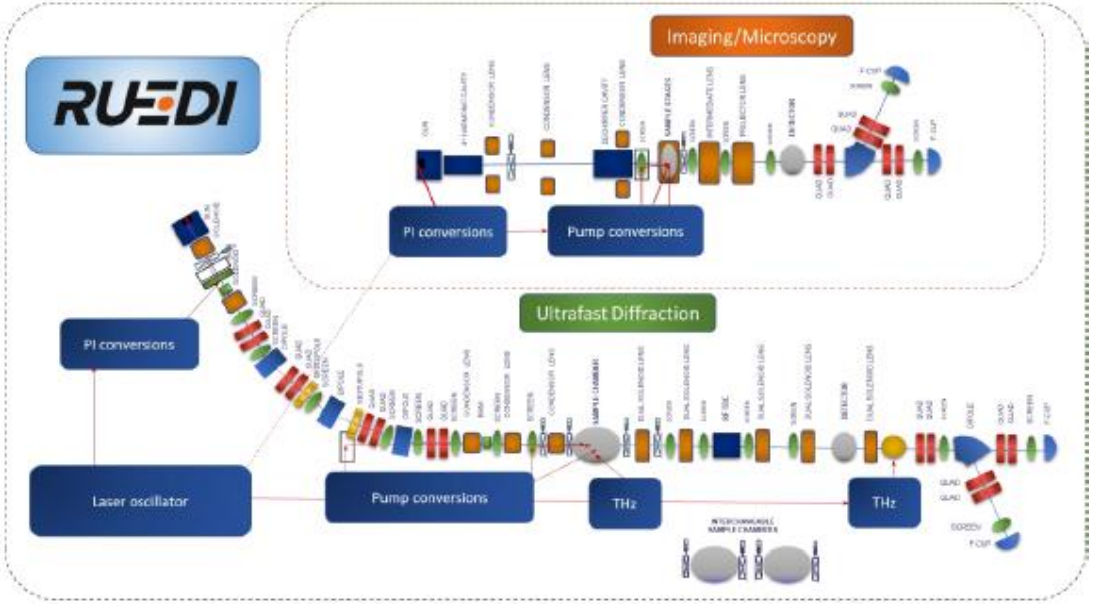
N.D. Browning, Y. Murooka, J. Nugara, M. Patel

University of Liverpool, Liverpool, UK

A.I. Kirkland

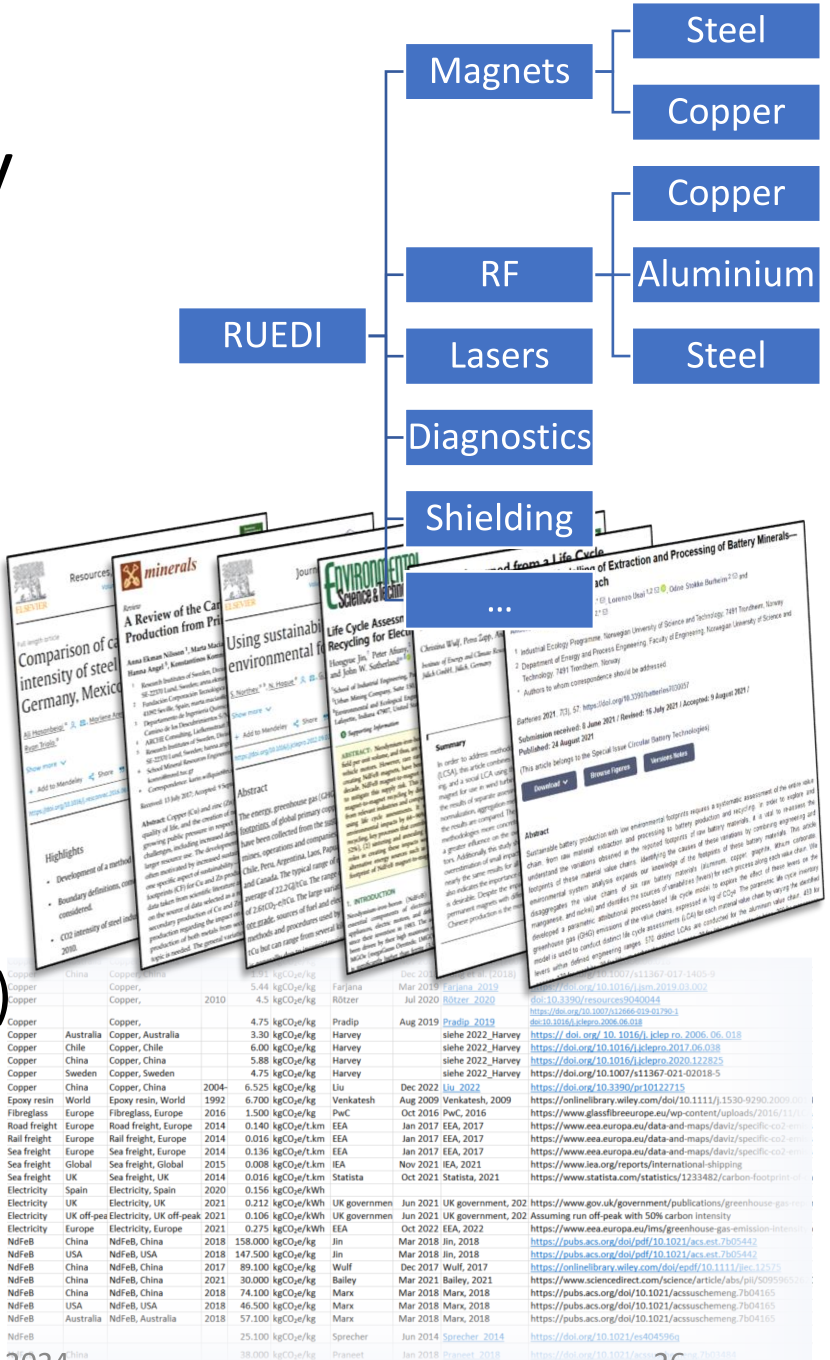
Rosalind Franklin Institute, Oxford, UK

- 2022: Conceptual Design Review (CDR)
- 2023: Technical Design Review (TDR) and capital funding bid
- 2024: Final detailed design
- 25-26: Procurement
- 26-29: Construction and assembly
- 28-29: Technical systems commissioning
- 29-30: Science commissioning and initial user programme
- 31-35: First five-year operational run



Carbon inventory: methodology

- Break accelerator down into **subsystems**
  - Mirrors organisational structure of our department
- For each one, make a guess at what **parts** are needed
  - Not always specified in detail
  - Makes it harder but also more valuable
  - This is the best time to do it –
    not afterwards when all the decisions are made
- Use this to build up a **materials inventory**
  - Make an educated guess about sources of materials
  - Concentrate on biggest items (by mass)
  - Assume smaller things have less of an impact
- For each material, establish a **carbon intensity** (kgCO_2e / kg)
  - Use published literature
  - Try to find multiple sources
  - Build up database – makes the process easier next time
  - Open data: available to share on request



Included and excluded

✓ Raw materials – yes
- BUT not everything
- Biggest contributors by mass

X Processing at factory - no
- Often proprietary data, or too hard for manufacturers to estimate
- BUT – got some interesting info from magnet manufacturers – see later

X Transport to our site – no
- Not easy to estimate distances
- Probably small compared to materials extraction anyway

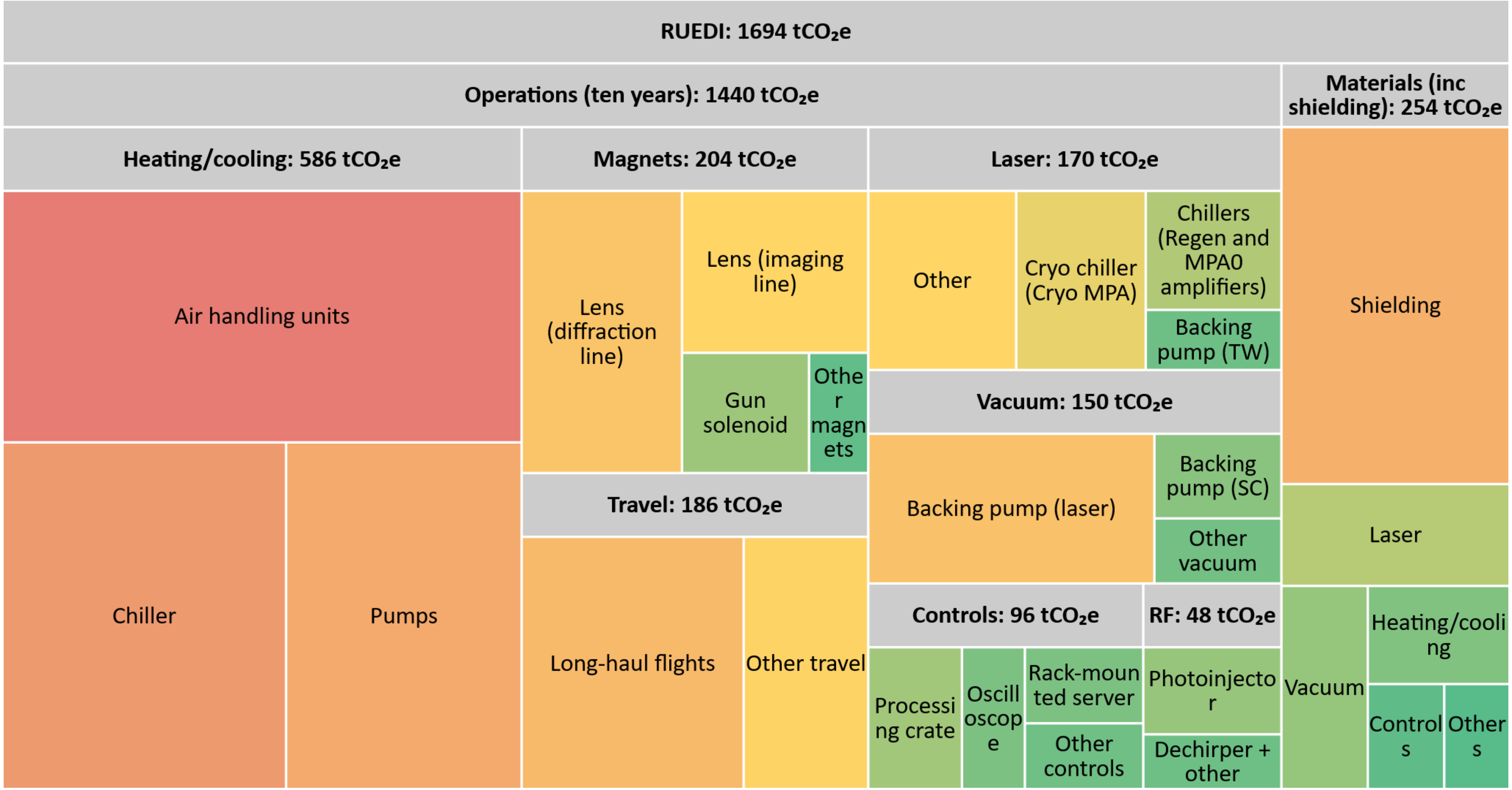
✓ Operations – yes
- Electricity use only
- Grid of 2030-40 assumed 50% greener than today; 2500 operating hours per year

X Maintenance and repair – no
- Too hard
- Probably not significant

X End of life – no
- Too many questions about where materials end up

Results

RUEDI report:
bit.ly/ruedi-sus



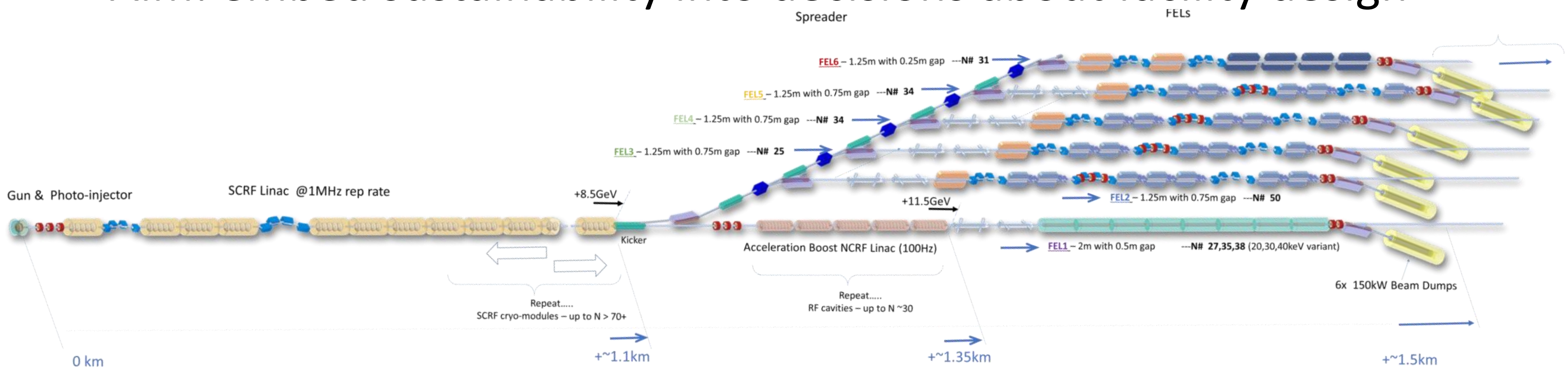
Recommendations

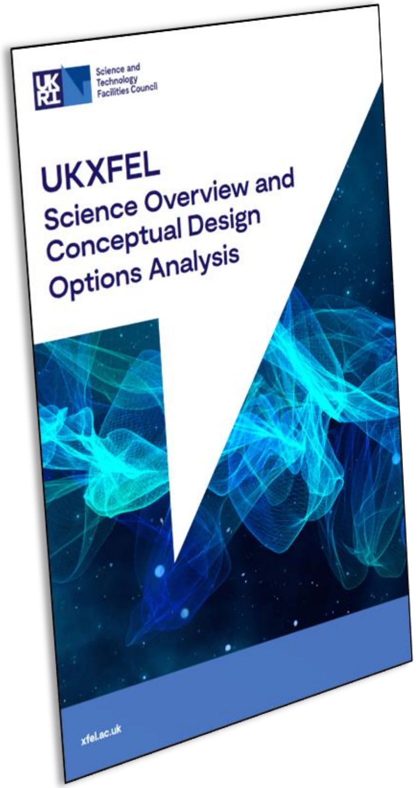
1. **Reuse shielding** from previous projects
   - New blocks to be standardised and made from low-carbon concrete
2. **Temperature stability**
   - Consider variable-speed drives, free cooling
3. **Permanent magnets**
   - Tricky but possible for solenoid lenses?
4. **Consolidate cooling**
   - Integrate + centralise laser system cooling
5. **Reuse waste heat**
   - Use heat removed from the accelerator to heat offices in winter
6. **Demand shifting**
   - Schedule heavy energy use for windy or sunny periods
7. **Submetering**
   - Look for energy consumption hotspots

xfel.ac.uk

Next steps

- Liaise with RUEDI team and implement recommendations
- Outline carbon accounting for **UK-XFEL design study**
  - Baseline: 8 GeV, 1.3 GHz SC RF linac, 1.1km length
  - Definitely not LCA-standard!
    Make a set of assumptions, produce rough figures for comparison
  - Design is evolving
  - Aim: embed sustainability into decisions about facility design





Summary

- Our accelerators are vital tools for science
- We need to ensure they operate in the most efficient way
- ASTeC aims to be the **go-to place** for **sustainable accelerator technology**
- We are developing cutting-edge green technologies,
  as well as tools to understand our footprint
- We have an ambitious plan to build a global Centre of Excellence: **CESA**

- Acknowledgements
  - *SATF*: Alan Wheelhouse, Anthony Gleeson, Gary Hughes, Rachael Buckley, Storm Mathisen, Hywel Owen, Andrew Vick, Katie Morrow, Hannah Wakeling
  - *RUEDI*: Julian McKenzie, Alex Bainbridge, Mike Ellis, Tim Noakes
  - Icon credits: brick wall, heat pump, magnetic field, cold, heater, solar energy, mining cart, factory, truck, light bulb, maintenance, recycling


ESSRI Workshops
Energy for Sustainable Science at Research Infrastructures
CERN
ESRF
DESY.
PAUL SCHERRER INSTITUT PSI
ess EUROPEAN SPALLATION SOURCE
ERF-AISBL
SUPPORTED BY:
ICFA
The International Committee for Future Accelerators
I.FAST
Innovation Fostering in Accelerator Science and Technology H2020-RIA project.
CIEMAT
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
uc3m
Universidad Carlos III de Madrid. Puerta de Toledo Campus.
ICFA
iFAST
Ciemat
uc3m Universidad Carlos III de Madrid
7th Workshop
Energy for Sustainable Science at Research Infrastructures
September 25th to 27th, 2024 - Madrid, Spain.
September 25th to 27th, 2024
https://agenda.ciemat.es/e/ESSRI2024

Spare slides

Shielding

- Concrete: almost the ideal shielding material
  - Absorbs gammas and neutrons well
  - Long-lasting and durable
  - Easy to manufacture
  - Acts as a structural material
- BUT: big carbon impact
  - High temperatures involved in cement production (1450°C)
  - Concrete production accounts for 8% of global CO_2 emissions
- For RUEDI, need 0.7m thick walls, plus roof
  - Using existing building, no need for new floor
  - Total 927 tonnes of concrete ➔ 137 tonnes CO_2e
- Can we do better?
  - Reuse old blocks (long history of this at our 60-year old lab)
  - Use concrete with additives in place of 100% cement
  - Including 50% GGBS can reduce carbon intensity of concrete by 42%

Shielding

Heating and cooling


Image credit: AirFixture

- Some systems (RF, magnets, laser) have water cooling – this is counted as an overhead for those areas (rule of thumb: 35%)
- In addition, need to keep the accelerator hall stable to 0.1°C

Heating/cooling: 586 tCO_2e

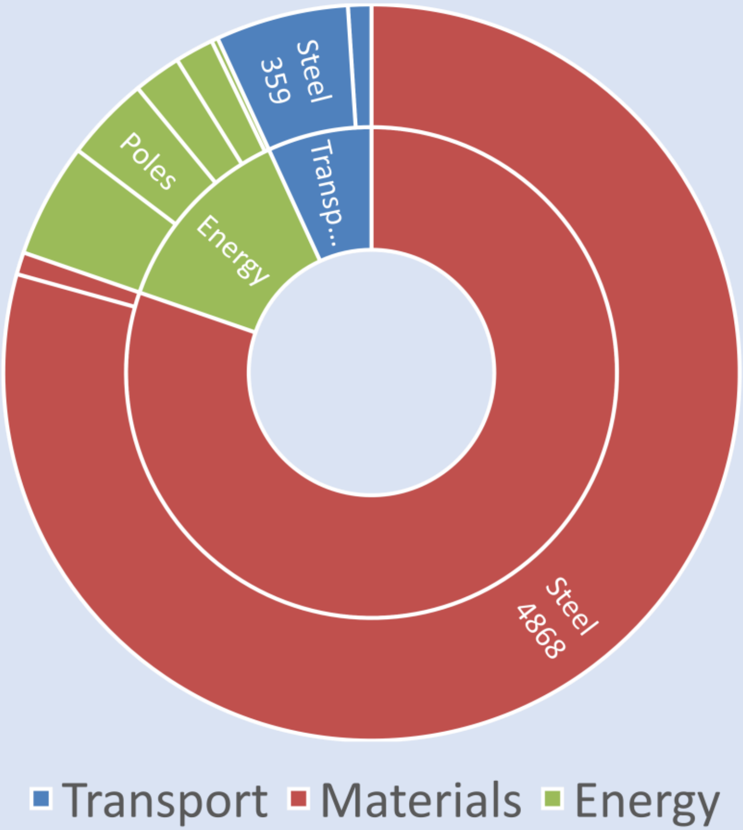
Item	Count	Power demand [kW]	Operating hours per year	Energy usage [MWh/year]	Carbon emissions [tCO_2e/year]
Air handling units	11	36.5	8766	320	24.8
Chillers	11	96.1	2500	240	18.6
Pumps	2	22.5	8766	197	15.3
Total		**155**		**758**	**58.6**

Magnets

- RUEDI is a low energy machine (4 MeV)
- Need a few dipoles and quadrupoles
  to transport the beam (52 magnets, total 600W)
- Biggest impact is solenoid focusing lenses
  - 9 magnets, total **77 kW**
- Hard to replace with alternatives
  - PM solenoids – not easy to build
  - Quadrupole focusing – introduces more aberrations

Magnets: 204 tCO_2e

- Note that due to low energy, RF is a tiny fraction of emissions
  - Photoinjector, TDC, dechirper – no linacs. Total **24kW**
  - Would be very different for a GeV-level facility (synchrotrons, FELs)



Analysis of processes to produce a 'typical' accelerator quadrupole. Emissions for **raw materials** are the dominant source. Credit: Tesla Engineering, UK.

Travel


Image credit: iStock


Image credit: Southeastern Railway


Image credit: Sky News

- RUEDI is a **national** facility – assume most users are from the UK
- Occasional long-haul trips (3 per year) made by facility staff to present at conferences
- Adds up to a significant contribution
- User site visits are more frequent but have less impact
- The message:
  reduce long-haul flights
  wherever possible

Mode	Yearly trips	One way distance [km]	Carbon emissions [tCO_2e/year]
Rail	40	300	0.318
Petrol car	30	300	2.95
Electric car	30	50	0.029
Short-haul flight	6	1500	3.29
Long-haul flight	3	10000	12
Total			**18.6**