UKRI Science and Technology Facilities Council

ASTeC

Sustainable Accelerator R&D

Ben Shepherd

Accelerator Science and Technology Centre, STFC Daresbury Laboratory

Sixth Workshop on Energy for Sustainable Science at Research Infrastructures

Grenoble, France

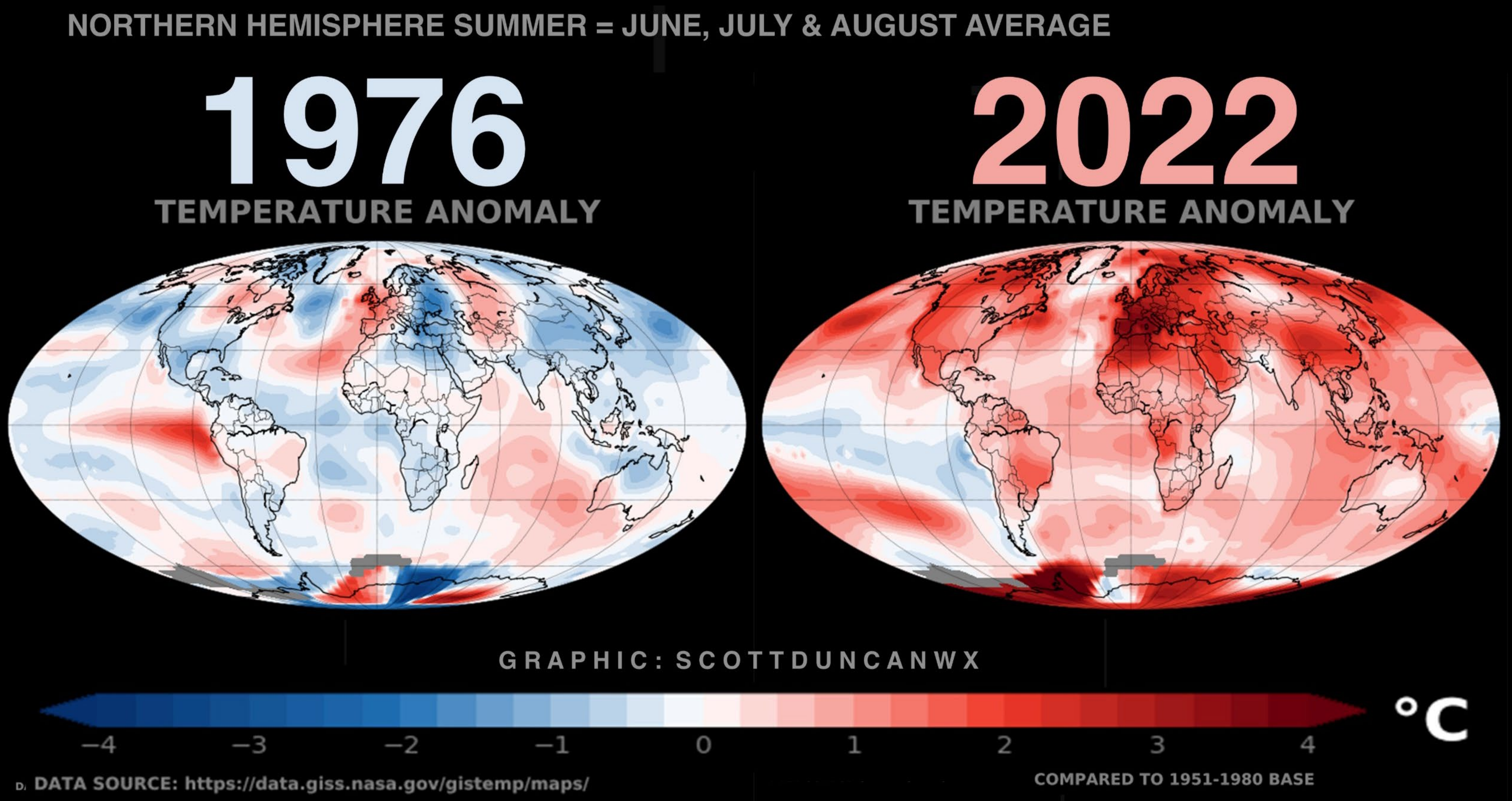
29 September 2022

Overview

- Background and motivation
- Green accelerator R&D projects in the UK
- Accelerator Impact Review

Scott Duncan

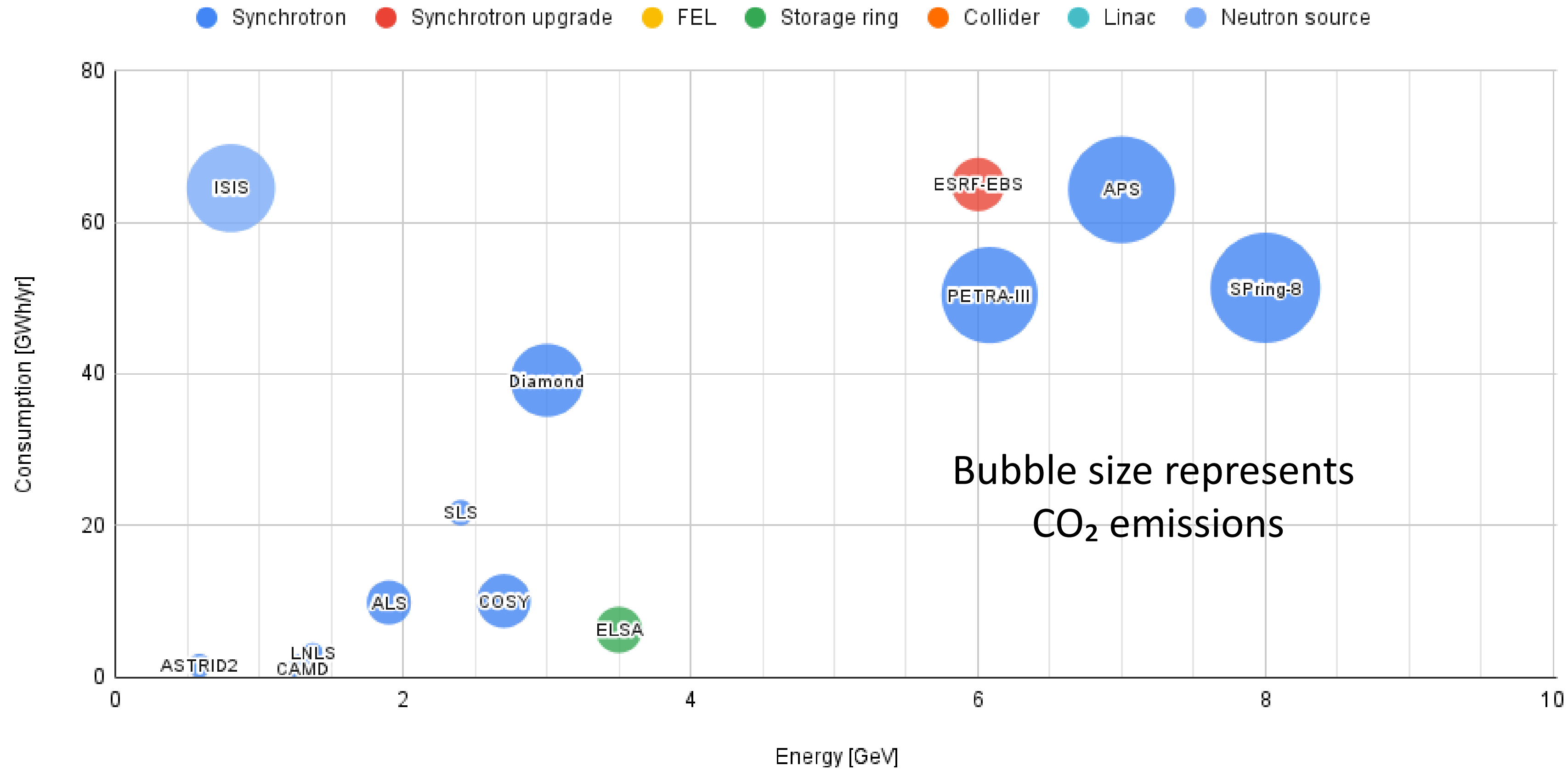
Motivation: Climate Emergency



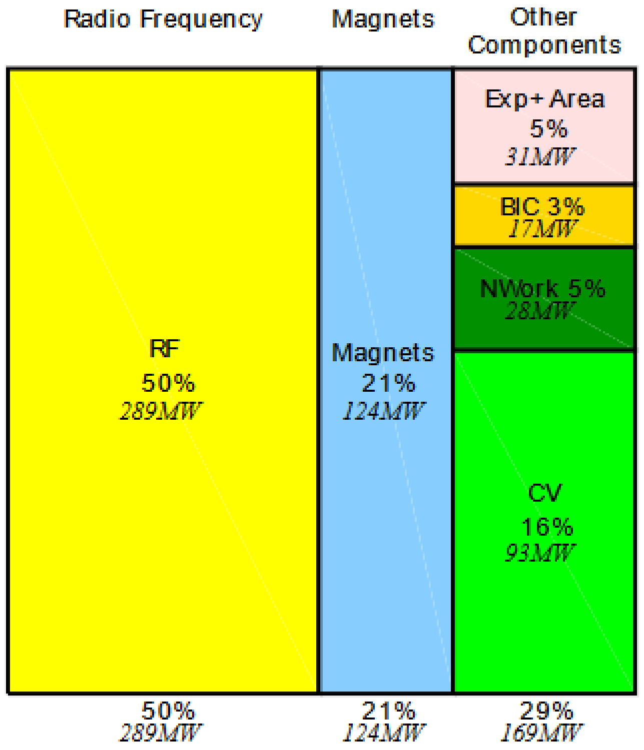
CERN, Electricity Flyer 2015
DLS, tweet
SNS, tweet
CLIC Conceptual Design Report

Motivation: electricity consumption

- Particle accelerators are big energy users



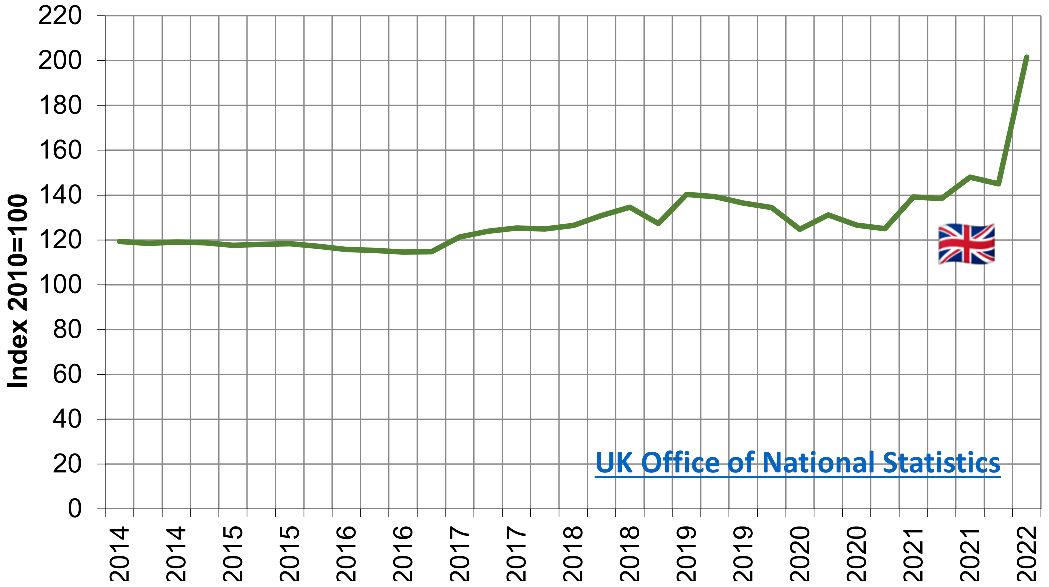
CLIC power consumption estimates

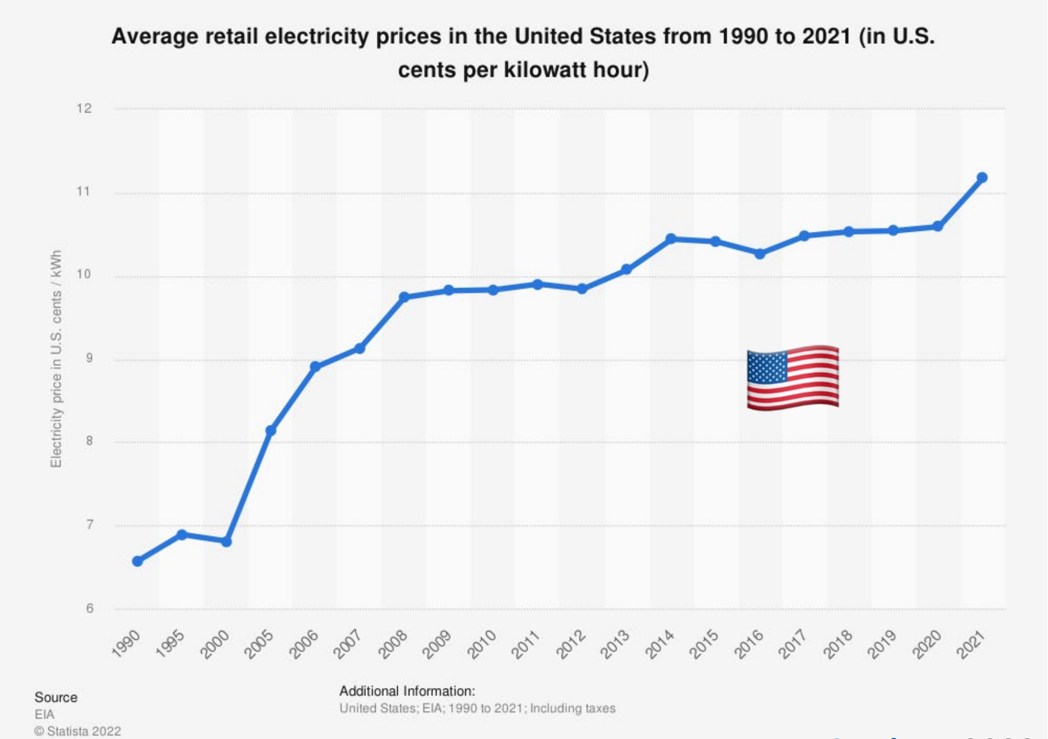


BIC = beam instrumentation + control
CV = cooling + ventilation
NWork = electrical network losses
Exp+Area = experiments and surrounding area

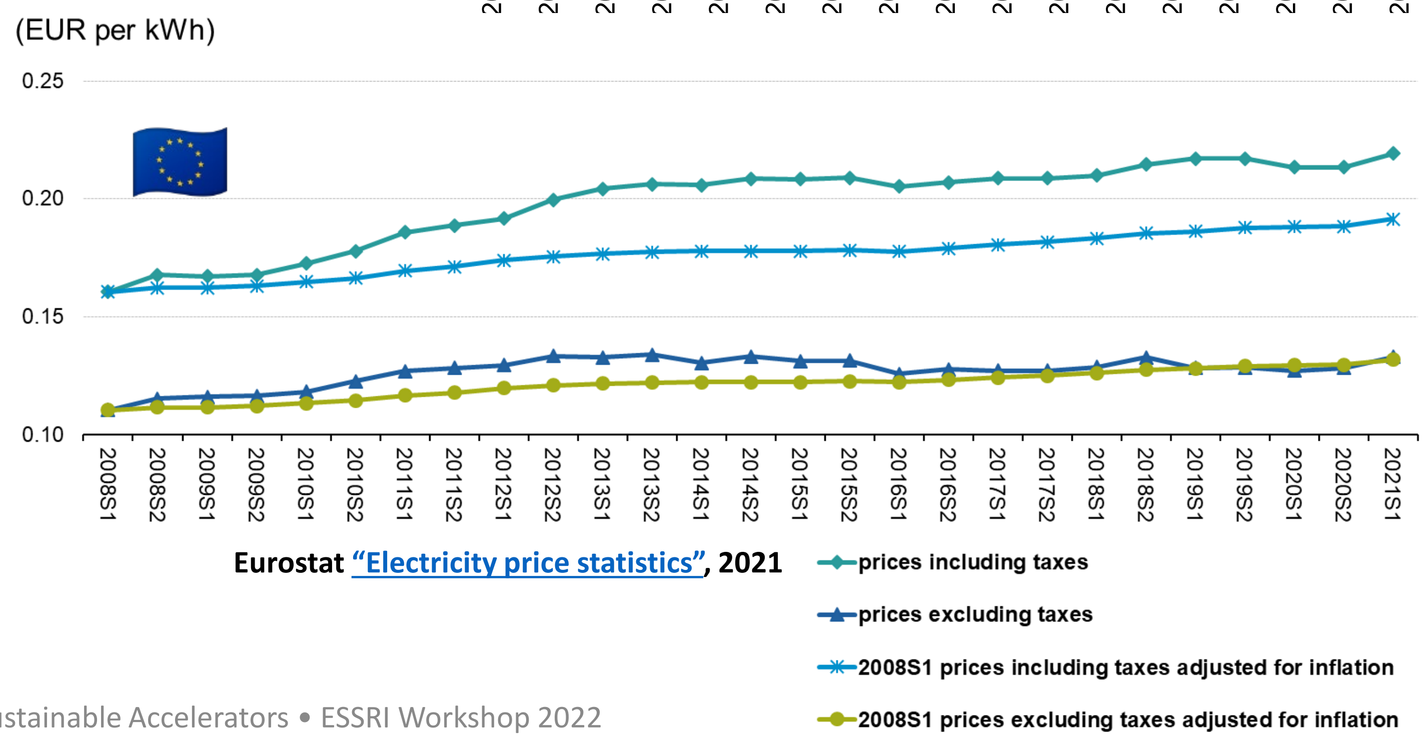
Motivation: electricity cost

- Cost of electricity is going up and will keep going up





Statista, 2022



Eurostat "Electricity price statistics", 2021

Sustainable Accelerators Task Force

- Development of technologies and projects that can reduce emissions
  - Identify **existing** – things we're already working on
  - Ideas for **new** ones
  - Other groups working in this area in other institutes
- For existing projects without any green aspects – can we do more to improve them?
  - Operation of our accelerator laboratories
  - Procurement and build of accelerator components
  - Accelerator operation
- Don't do less R&D, but do existing R&D more efficiently!
- **Centre for Sustainable Accelerator Research** (CSAR) at STFC's Daresbury Laboratory
  - Currently putting together business case for CSAR
  - Aim: keep all our sustainable accelerator R&D activities under one roof


Ben Shepherd
MaRS


Louise Cowie
RF


Anthony Gleeson
Business


Gary Hughes
Facilities


Storm Mathisen
Diagnostics


Hywel Owen
Acc Physics


Andrew Vick
Vacuum


Katie Morrow
Lasers

photo: Gareth Bailey

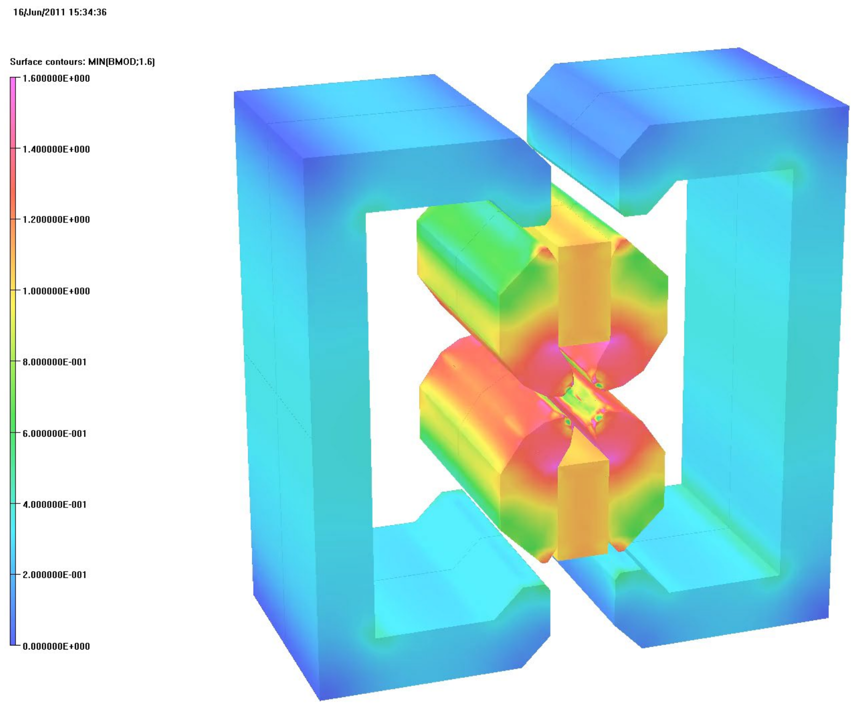
Green Accelerator Projects

Existing projects with an environmental sustainability angle

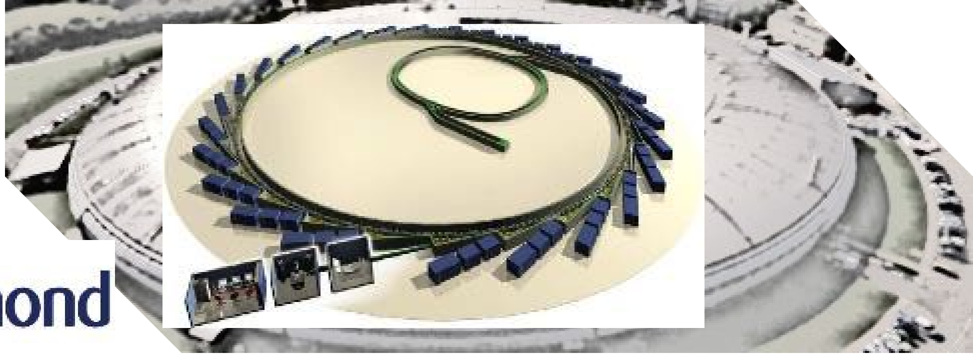
Shepherd *et al*, IPAC2014 TUPRO113

Green Projects: ZEPTO

- **Ze**ro-**P**ower **T**unable **O**ptics
- Tunable 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 prototypes built at STFC 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

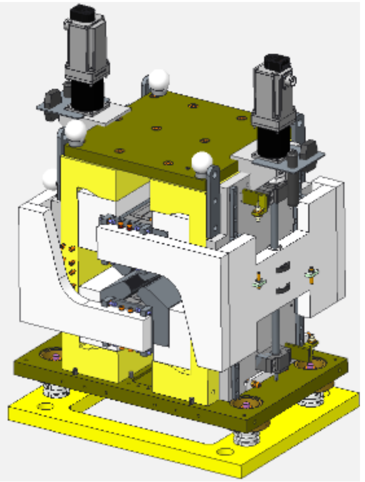


Bainbridge *et al*, IPAC2022

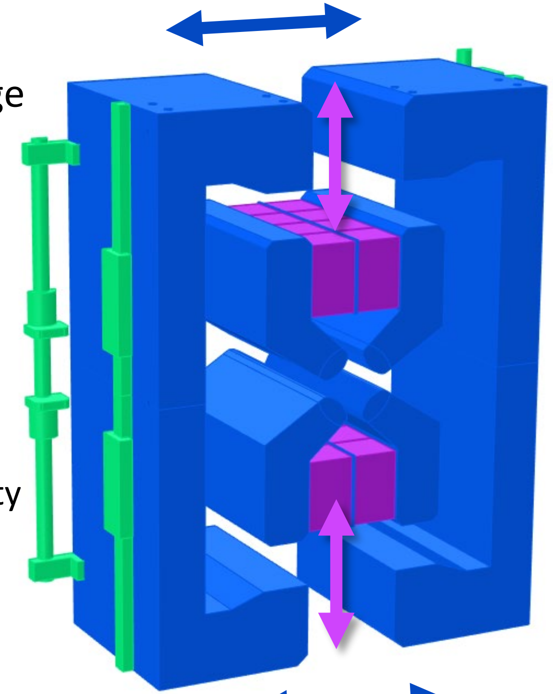


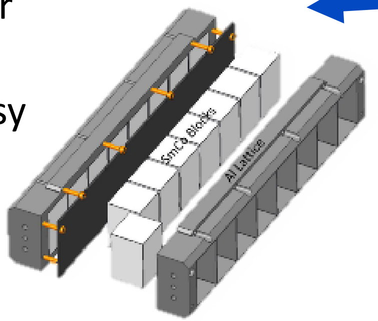
ZEPTO at Diamond Light Source

- Aim: demonstrate operation of a ZEPTO quadrupole on a working accelerator
- Use a **tunable PM quadrupole** as a drop-in replacement for an electromagnet
- Step towards **commercialisation** of ZEPTO technology
- Assembly and testing at Daresbury **complete**
- Installed at Diamond in August 2022 shutdown

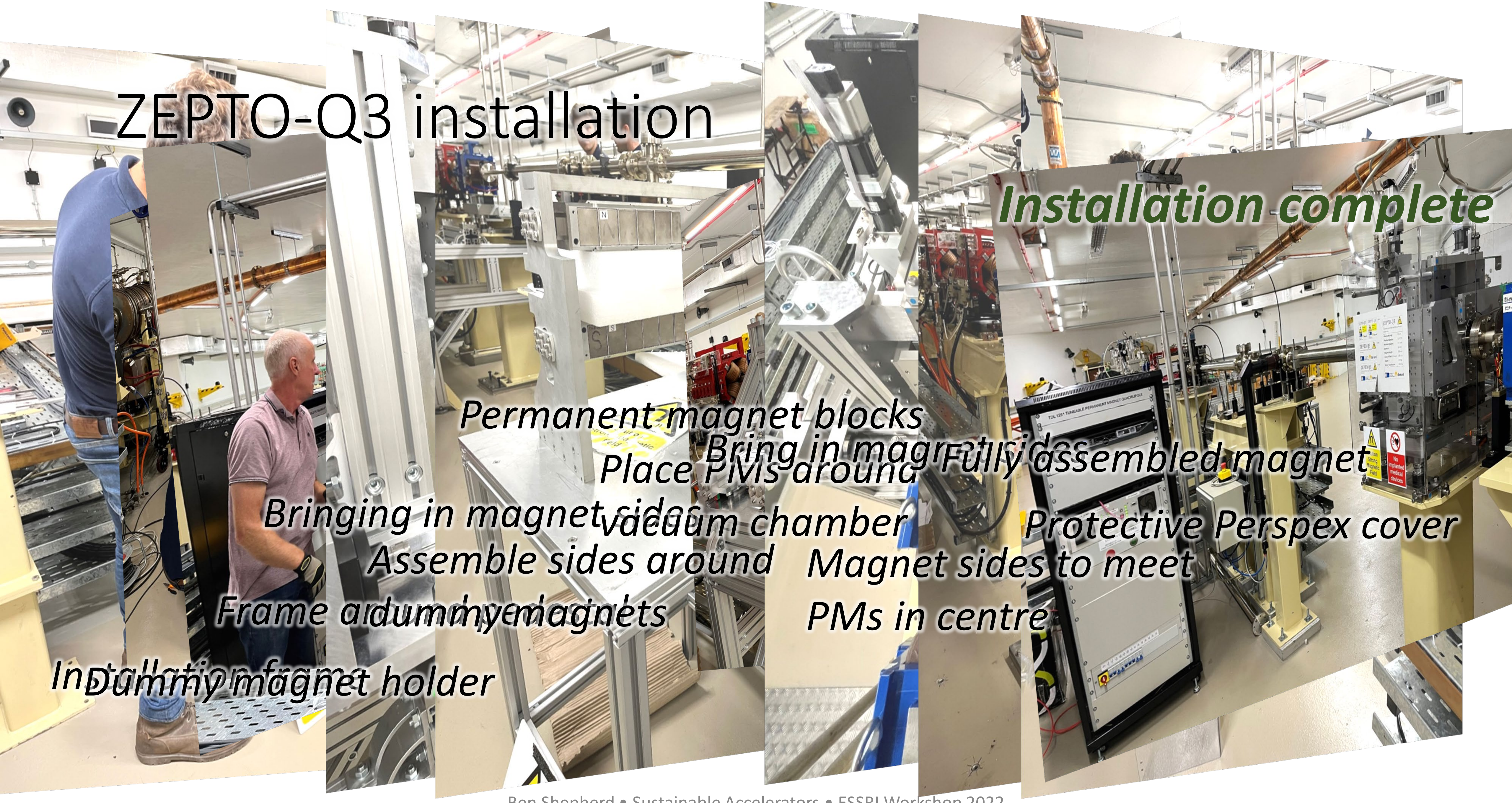


- Similar design to ZEPTO-Q2
  - Outer shell for large tuning range
- Gradient range **0.5-19 T/m**
- Movement range **90 mm**
- Aperture diameter **32 mm**
- **Improvements to design:**
  - **SmCo** blocks
    - improved temperature stability
    - better radiation resistance
  - **Splittable** to allow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





ZEPTO-Q3 installation



Update today, 29 Sep 2022

ZEPTO v... ce

ZEPTO Update ZEPTO

BA Bainbridge, Alex (STFC,DL,AST)
To: Shepherd, Ben (STFC,DL,AST); Rogerson, Helen (STFC,DL,BID)
Thu 29/09/2022 09:44

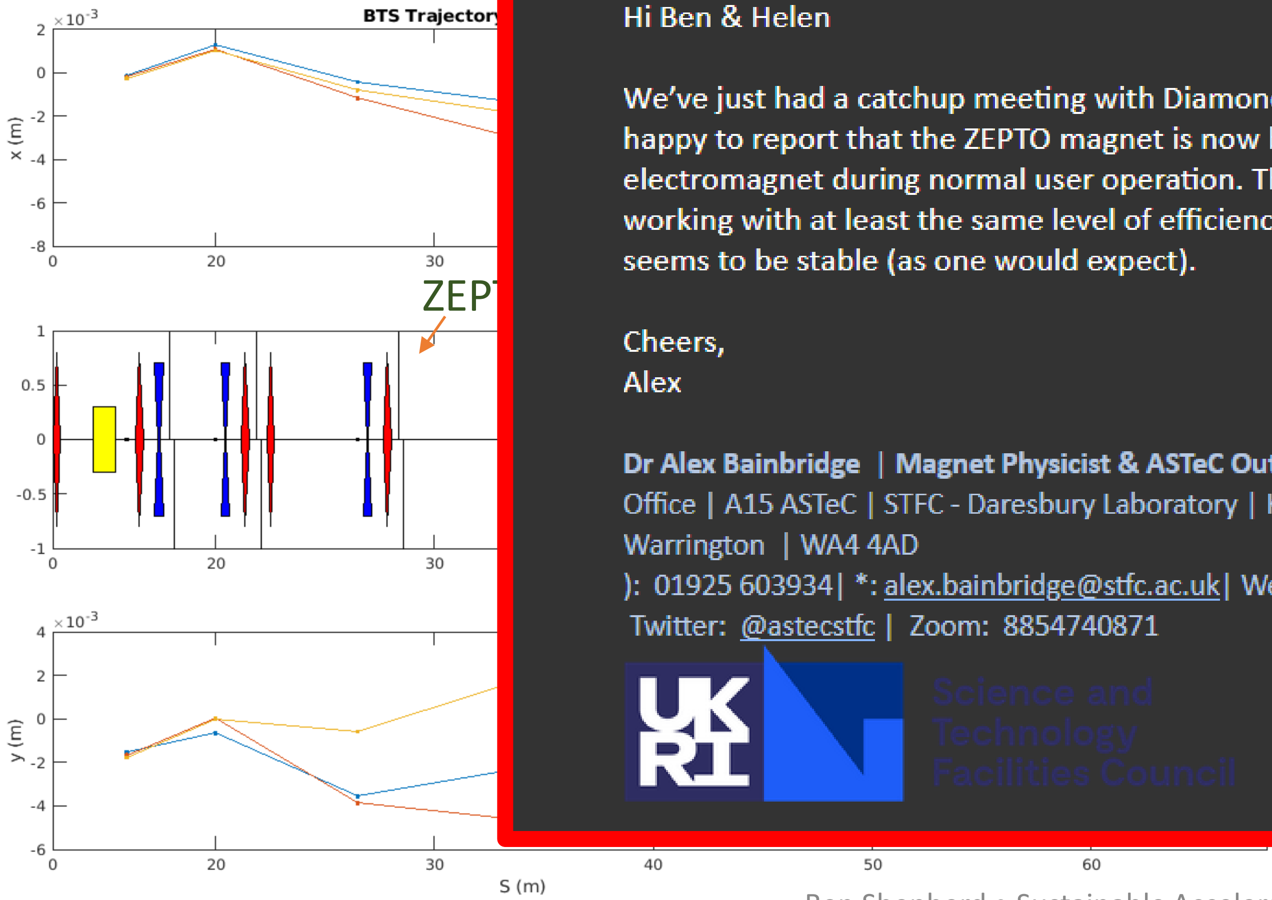
Hi Ben & Helen

We've just had a catchup meeting with Diamond about the ZEPTO magnet. I'm happy to report that the ZEPTO magnet is now being used in place of the electromagnet during normal user operation. The top-up injection process is working with at least the same level of efficiency as before, and the magnet seems to be stable (as one would expect).

Cheers,
Alex

Dr Alex Bainbridge | **Magnet Physicist & ASTeC Outreach Lead**
Office | A15 ASTeC | STFC - Daresbury Laboratory | Keckwick Lane | Daresbury | Warrington | WA4 4AD
): 01925 603934| *: alex.bainbridge@stfc.ac.uk| Website: www.astec.stfc.ac.uk |
Twitter: @astecstfc | Zoom: 8854740871

Science and Technology Facilities Council

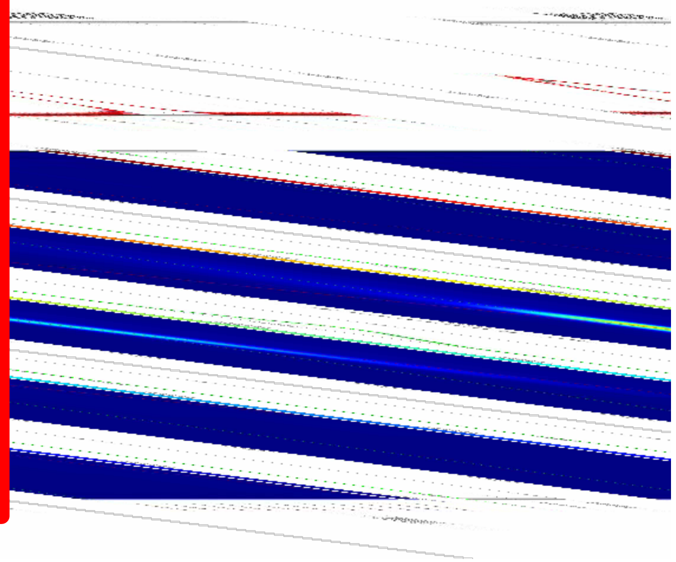


...y corrections after ...p to nominal field

...ncy returned to ...%)

...screen for same field:

ZEPTO

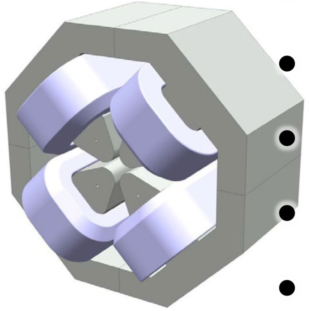


ZEPTO: comparing carbon footprints

- Electromagnetic quadrupole
- Main materials: steel, copper
- Manufacture impacts

steel 201kg | copper 52kg

- Operation costs
  - 856W at 100% excitation
  - Another 250W for cooling
  - Assume 251 days / year operation
  - 6.7 MWh / year
  - EU avg intensity 225 gCO_2e/kWh



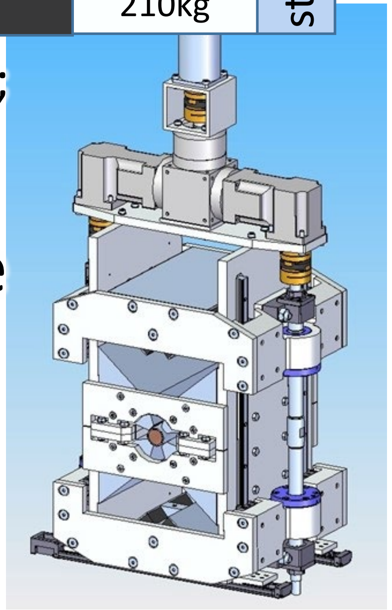
electricity 1160 kgCO_2e / year | cooling 340 kgCO_2e / year

- Permanent magnet quadrupole
- Main materials: steel, NdFeB, aluminium
- Manufacture impacts (kgCO_2e)

NdFeB 1097kg | aluminium 210kg | steel 91kg

(big uncertainties in NdFeB footprint; using recycled magnets could significantly reduce it)

- Operation costs: negligible
- “Carbon payback”: 1 year



Thin Film Superconducting RF

- **Bulk niobium cavities** have been the choice for SRF for the last 50 years
- Use a considerable amount of natural material
- Performance limit of niobium has been reached
- Costly to produce
- Run at a temperature of 2 K
  - A considerable cryogenic demand and energy load

Benefits of thin films

- Use a copper supporting cavity
  - Better thermal properties, cheaper material and production
- Use different superconducting materials (e.g. Nb_3Sn, NbN and MgB_2)
  - Better performing materials than Nb that can't be formed into solid cavities
- Higher operation temperature of new alloys
- Reach higher accelerating gradients

Slide: Andrew Vick

Benefits of Thin Film SRF

- Increasing the quality factor *Q* reduces heat produced and hence the electricity consumption of the cryogenic system during RF cavity operation
- Using high T_c superconducting materials allows RF cavities to operate at **4.2 K**, instead of the **1.9 K** used for high-performance Nb cavities, more than doubling the efficiency of the cryogenic system
    - ALICE at Daresbury used ~200kW for a 1.8K system; could be halved for 4K
- Increasing the cost-effective acceleration field *E* (at present the minimum cost is achieved at just over **30 MV/m**) will result in significant savings in the infrastructure (tunnel, LHe supply and He recovery lines, electric cables, controllers, cryostats, pumps, etc.)
    - For example, a 20% increase in the acceleration field allows a 20% reduction in the accelerator length, which could allow the 60 km ILC tunnel to be reduced to 50 km.

Slide: Oleg Malyshev

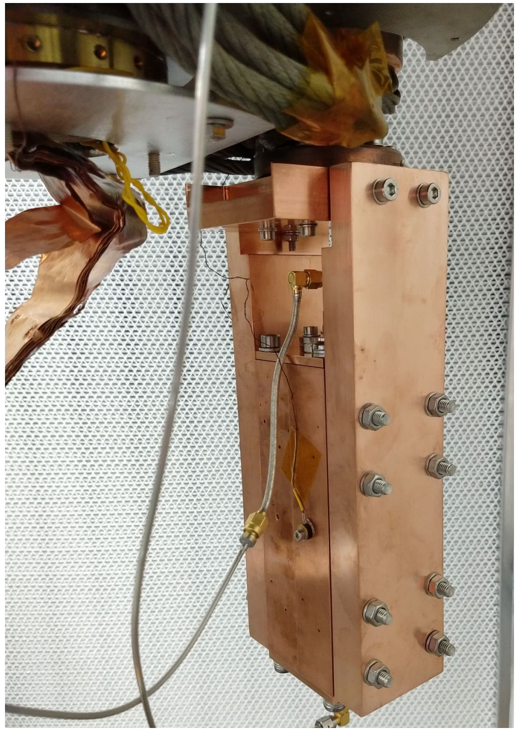
Thin Film SRF Activities at STFC

- **Main objectives**:
  - Developing coating technology for **superconducting thin films** (STF)
    - Deposition of Nb, Nb_3Sn, NbTiN, Mg_2B, … and SIS structures
    - Thin film characterisation
    - AC/DC superconductivity evaluation
  - Developing **cavity deposition** expertise
    - Copper cavity production
    - Polishing and cleaning
    - Building deposition facilities
    - Optimising deposition parameters
  - **SRF testing** at DL
    - 1.3 GHz cavity testing as 1st step
    - Scaling up to a routine cavity coating and testing

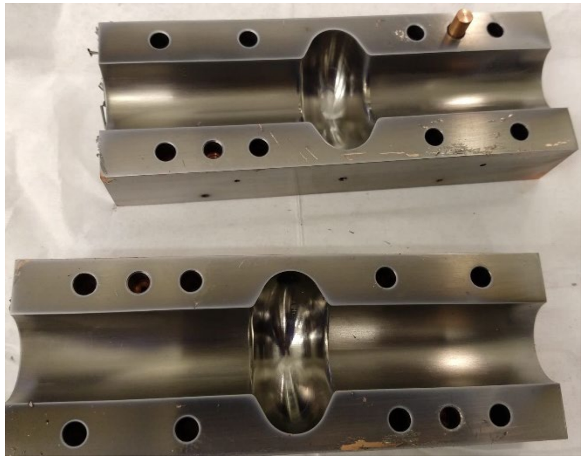
6 GHz split cavity

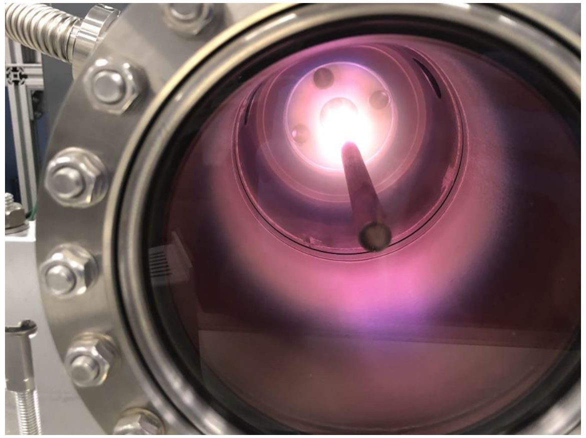
- Easy to coat with either conventional planar magnetron or in tubular geometry used for RF cavities
- Easy to inspect
- Three 6 GHz cavities have been manufactured, mechanically polished and tested at RT and T = 4.2 K
- 1st cavity Nb coated and tested at 4.2-9.5 K

Split cavity mounted on the cold head for cryogenic measurements



6 GHz split cavity with Nb coating

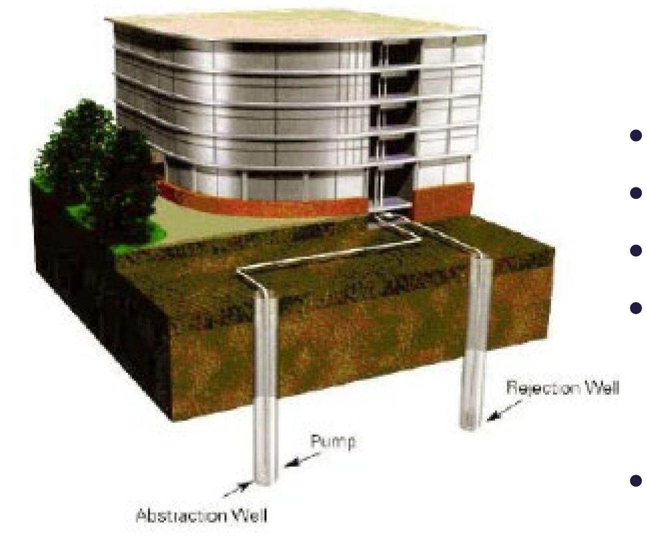


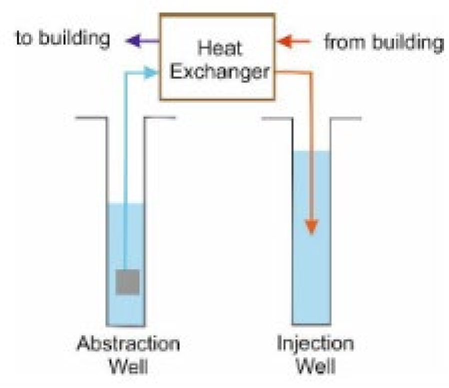


Cylindrical magnetron

Slide: Andy Goulden

Ground Water Cooling



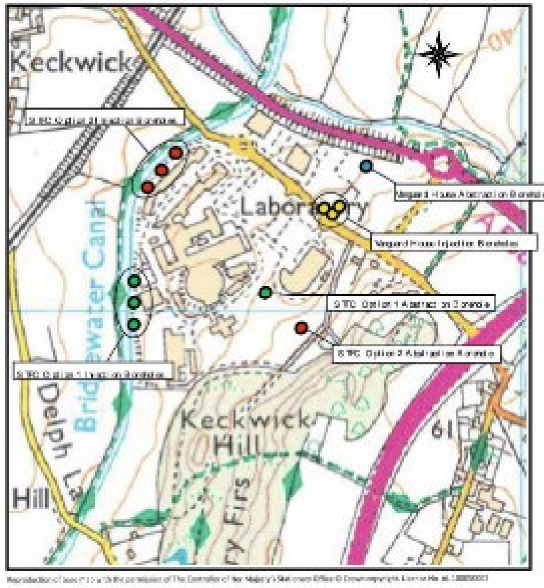


- Feasibility and modelling study
- Envireau Water, 2017
- Potential **2 MW** cooling scheme
- Support the cooling of ASTeC's suite of particle accelerator test facilities

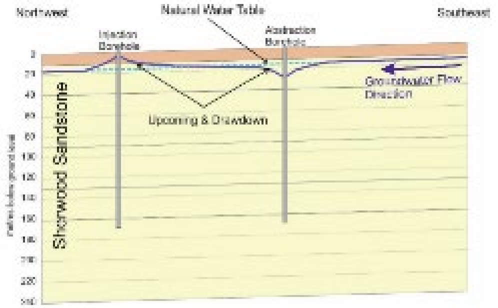
- Would reduce electricity consumption by **4000 MWh** (> £1m / year*)
- Initial cost would be about £2m

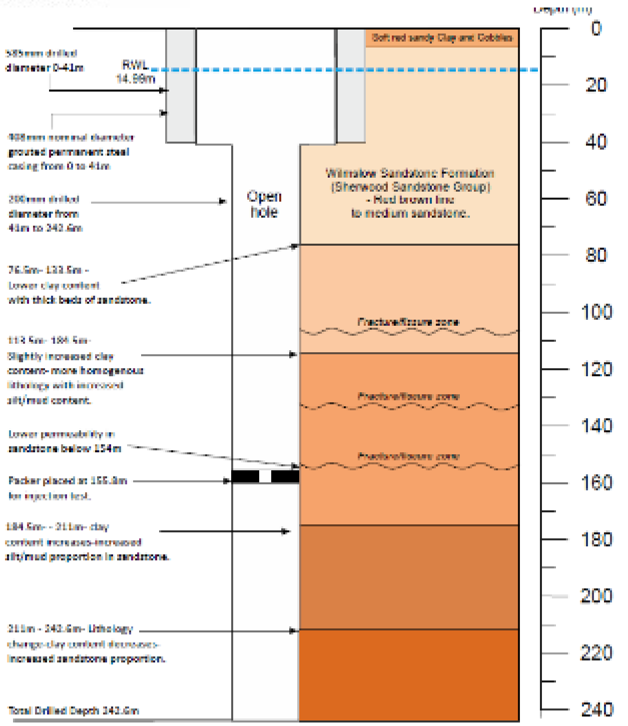
Feasibility Study and Numerical Modelling showed positive results:

- **48 L/s** abstraction
- Fixed temperature differential of **10°C**
- STFC Abstraction temperature rise of **2.3°C**
- Delivering **2 MW** of cooling



- Minimise thermal feedback





*using 2022 prices, 30p / kWh

Ground Water Cooling – Trial Borehole

A **single trial borehole** was drilled at Daresbury in 2018 to provide :

- Ground proofing of hydraulic properties at multiple depths
- Testing water chemistry
- Fine tuning of model

Located so that it can be used as an injection well for the final scheme when approved

McCay et al (2019) – drilling estimates

Ground Water Cooling: carbon footprint

- Emissions from drilling boreholes
  - 3 abstraction boreholes, 6 recharge boreholes, all 160m deep
  - Assume 500h drilling using diesel rig: 970 tCO_2e

drilling 970 tCO_2e

- Emissions from cooling using grid electricity
  - 4000 MWh / year, UK grid intensity 212 gCO_2e / kWh (2021)

electricity 848 tCO_2e / year

Slide: Graeme Burt
CERN Courier article

High Efficiency Klystrons

- A large amount of the waste energy of a particle accelerator is caused by the inefficiency of the RF source (typically <65%)
- **Klystron** amplifier technology covers almost all RF frequency/power demands of modern accelerators
- Taking FCC going from 65% to 80% efficiency as an example
  - Potential saving are **1.04 TWh** in 10 years (**84 MCHF in 10 years**).
  - Reduced environmental impact (cooling and ventilation)
  - Reduced installation cost (stored energy in modulators)
  - Reduced maintenance cost (klystron lifetime)

Project	Efficiency	Technology	Industrial partner
LHC 400 MHz, 350 kW CW	70%*	CSM	Thales
FCC 400 MHz 600 kW CW	88%	TS MBK or CSM	Thales?
FCC 800 MHz 1.3 MW CW	88%	TS MBK or CSM	Thales?
ILC 1.3 GHz 10 MW pulsed	85%	TS MBK	Thales/Canon/CPI
CLIC 1 GHz 24 MW pulsed	85%	TS MBK	Thales/Canon/CPI
X-band 8 MW pulsed	56%*	COM	Canon
X-band 50 MW pulsed	70%*	COM	CPI
36 GHz 2.5 MW	35%	HOM MBK	On hold

*retrofit

CERN, supported by Lancaster University, are designing klystrons for a range of future accelerators based on several novel design concepts that all aim at **>80% efficiency**

CERNCOURIER Reporting on international high-energy physics

Physics Technology Community In focus Magazine

ACCELERATORS | NEWS

CERN and Canon demonstrate efficient klystron

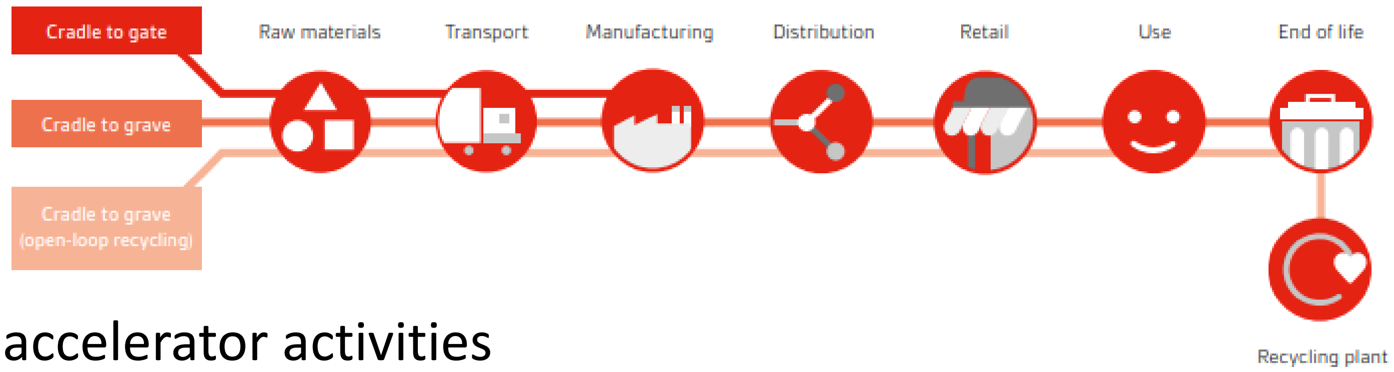
5 September 2022

The radio-frequency (RF) cavities that accelerate charged particles in machines like the LHC are powered by devices called klystrons. These electro-vacuum tubes, which amplify RF signals by converting an initial velocity modulation of a stream of electrons into an intensity modulation, produce RF power in a wide frequency range (from several hundred MHz to tens of GHz) and can be used in pulsed or continuous-wave mode to deliver RF power from hundreds of kW to hundreds of MW. The close connection between klystron performance and the power consumption of an accelerator has driven researchers at CERN to develop more efficient devices for photo: Gareth Bailey

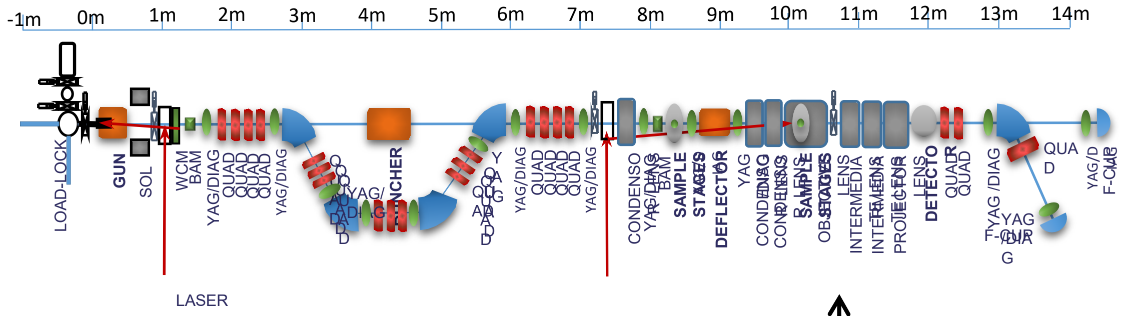
Accelerator Impact Review

Lifecycle analysis techniques applied to accelerators

Lifecycle analysis



- Detailed review of the climate impact of accelerator activities
- Where are the Big Sources of emissions?
  - Manufacturing? Steel / Copper / Aluminium / Concrete
  - Operations? Running RF and magnet systems. Cooling & AC
  - Disposal? End of life of components
- How could we reduce these for the biggest impact?
  - Using different materials
  - Smart powering schemes
- **RUEDI*** is our 'model facility' for this exercise
- Consider wider applicability for other accelerators too
- Figure of merit should be $kgCO_2e$ per "delivered unit"
  - So at the end, we should have a database listing carbon emissions for components in every area
- Look at the big picture; **not** every gram of CO_2 - not a bean-counting exercise!



*RUEDI = Relativistic Ultrafast Electron Diffraction & Imaging
Working towards CDR now

Slide: Louise Cowie

RF systems

- Main power usage: klystron modulator
- RUEDI RF photoinjector: approximate energy use is **10 kW**
- **16 $kgCO_2e$** per 8 hr shift

electricity 4 tCO_2e / yr

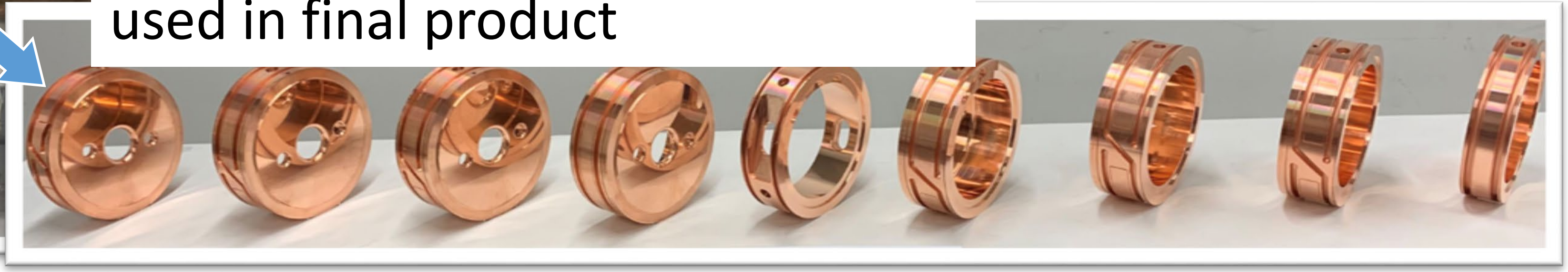
The majority of the RF system is high purity copper

- Estimate **5000 $kgCO_2e$** for copper parts of one RF system including material and manufacture

brazing, machining 2.7 tCO_2e	copper 2.3 tCO_2e

- Rest of RF system is mostly electronics, don't have a good estimate for these yet.
- RUEDI has 3 RF systems

RF cavity is turned/milled from bulk copper but less than 50% used in final product



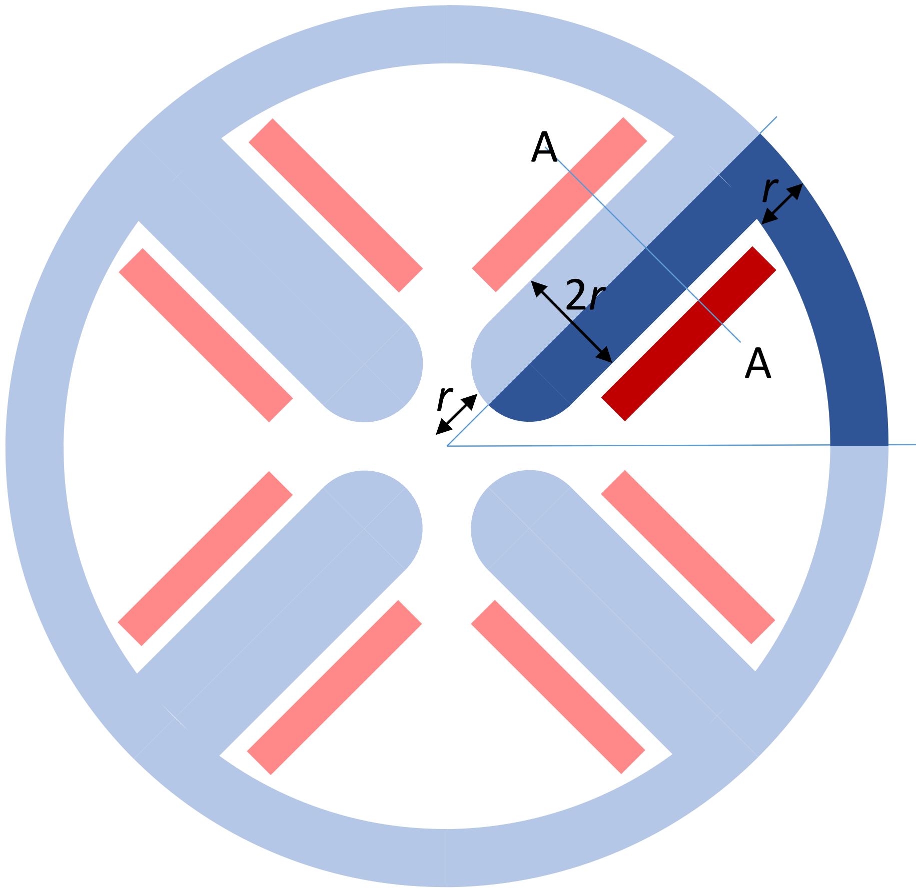
Resistive Magnets

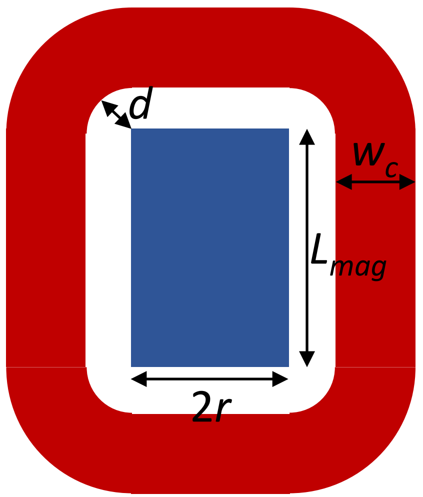
- Produce a simple quadrupole model
- Sketch out geometry
- Interaction of different variables
- Mass of copper and steel; power used

$$m_{Cu} \propto G r^2 L_{mag}$$

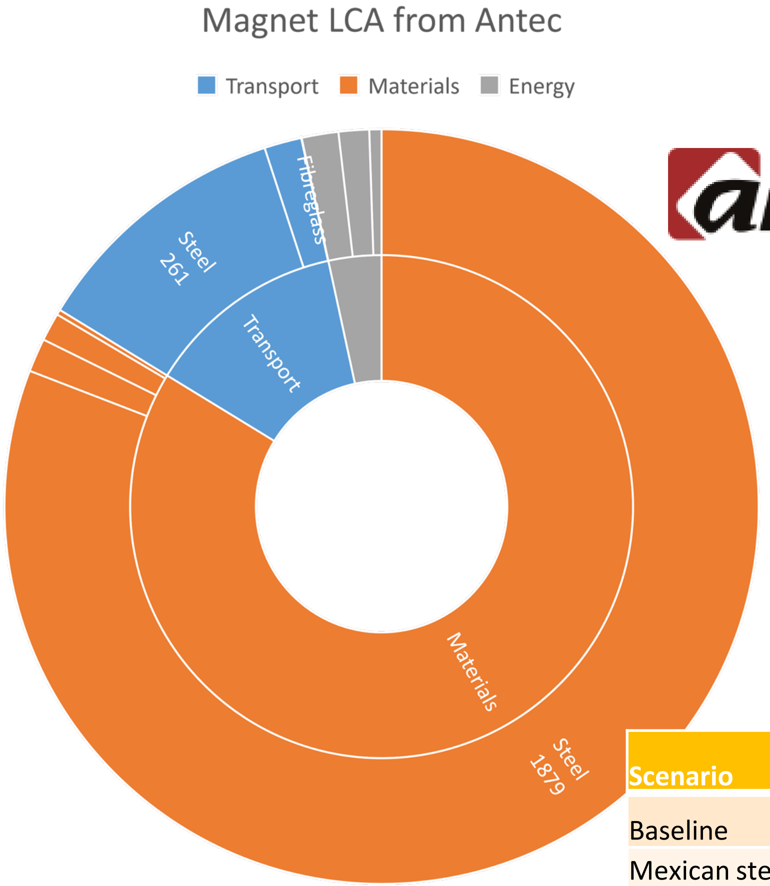
$$m_{st} \propto G r^2 L_{mag}$$

$$P \propto G^2 r^4 L_{mag}$$



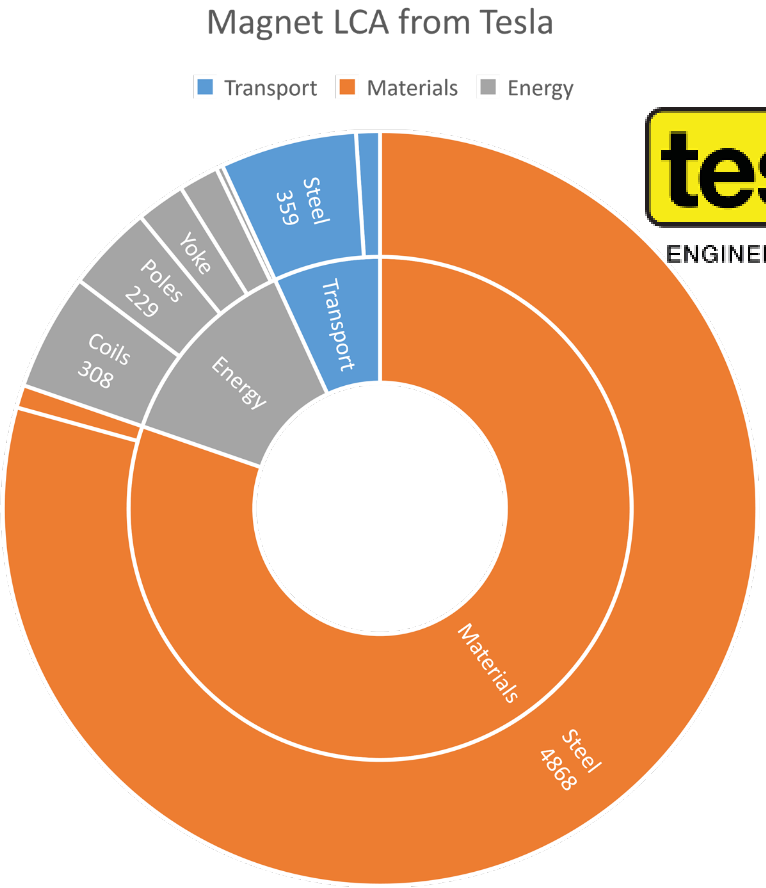


Magnet Carbon Footprints



Scenario	$kgCO_2e$	% change
Baseline	2324	0%
Mexican steel	1449	-38%
Rail freight for steel	2091	-10%
EU-average for copper	2393	+3%

Total **2.3 tCO_2e**
($3\ kgCO_2e$ / kg of finished product)



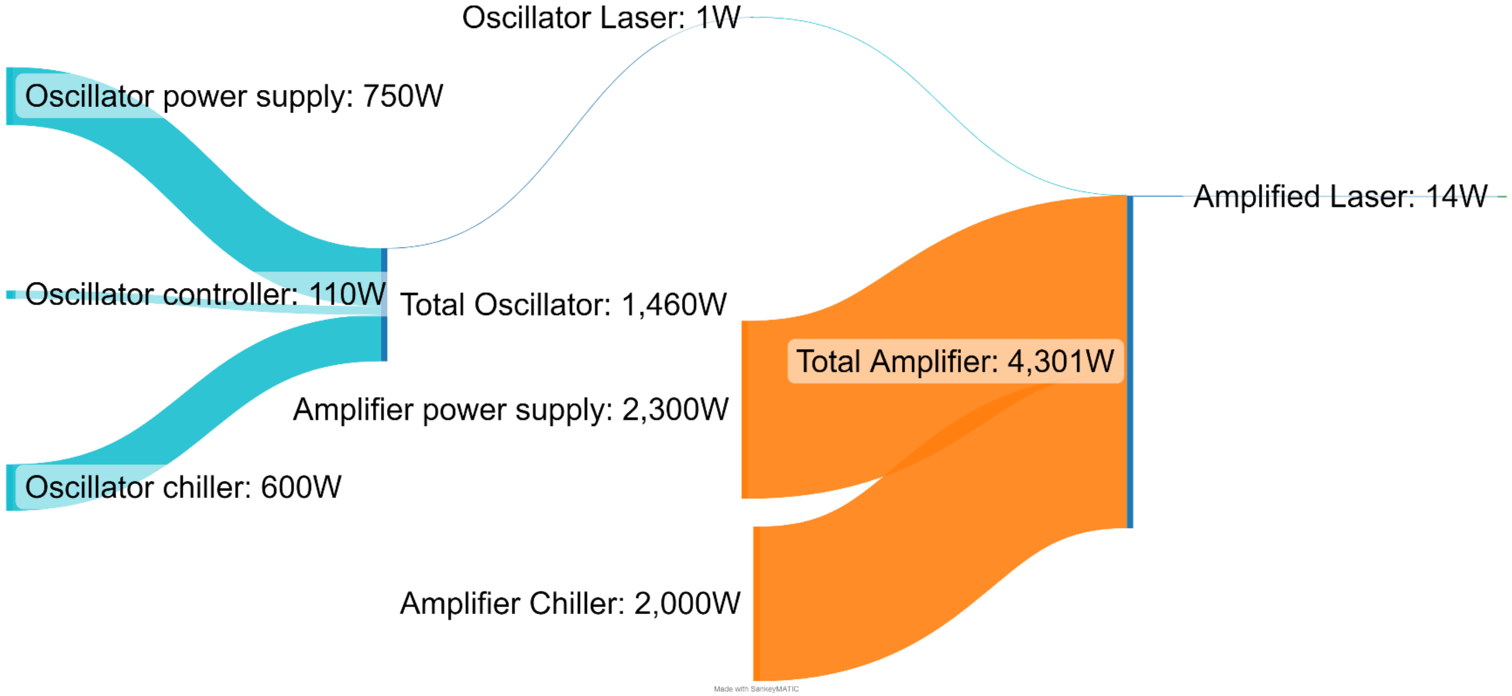
Total **6.2 tCO_2e**
($2.9\ kgCO_2e$ / kg of finished product)

Slide: Katie Morrow

Lasers

- Lasers are very power hungry due to their inefficiency
- Often lasers are used as pumps to make new lasers, compounding the inefficiency

RUEDI oscillator + amplifier



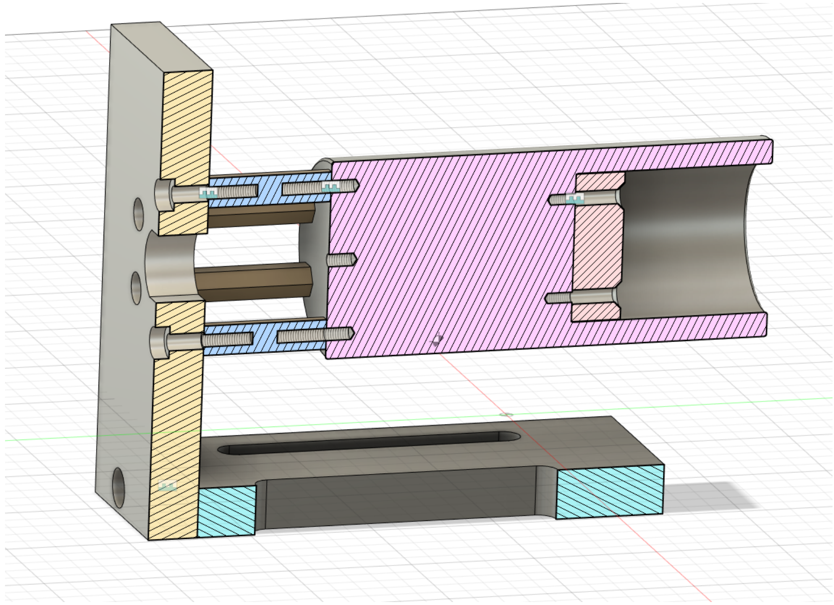
- Altogether the oscillator + amplifier power supplies produce >8 tonnes of CO_2
- The most effective way to reduce the CO_2 emissions from the laser system is through improvements in efficiency

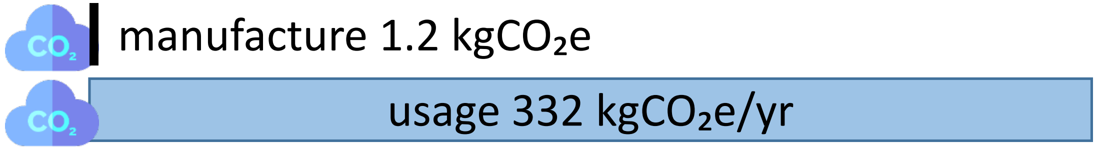
Slide: Storm Mathisen

Analysis of Material Efficiency Requirements of Enterprise Servers, IES, European Commission JRC (2015)

Diagnostics and Controls

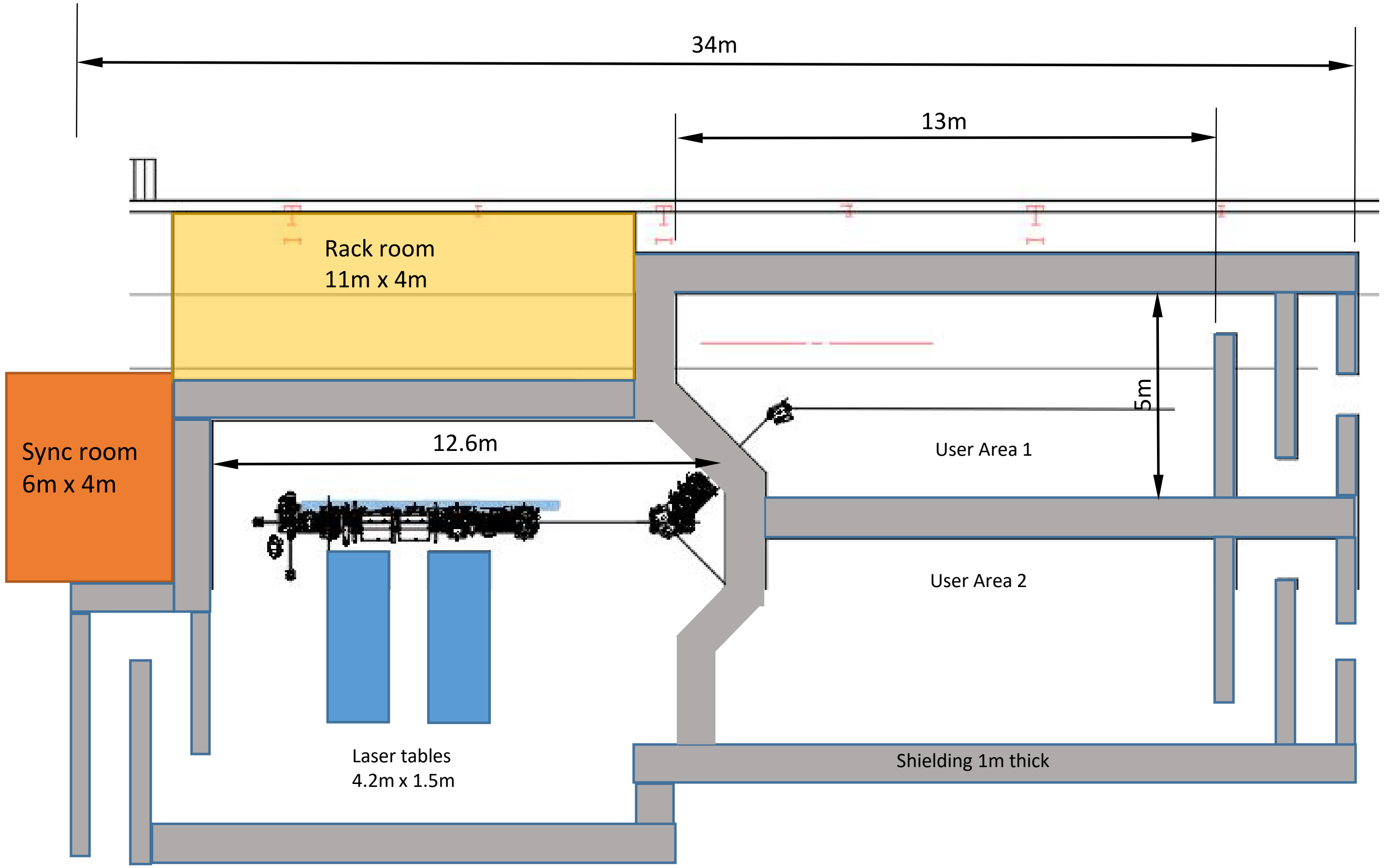
- Major sources:
  - Manufacturing of **diagnostic devices** – Faraday cups, imaging stations, etc
  - Manufacturing of **computing devices** and **electronics** – Circuit boards, servers, cables
  - Energy for operations – Computers on 24/7
- Example – Rack mounted server
  - Notional server used as basis for analysis
  - Total energy for manufacture and assembly: **6 kWh**
  - Annual power consumption: **1,661 kWh**
  - End of life consumption not considered
  - Outcome: For computers manufacture and assembly can be disregarded, assuming only concern is power consumption derived emissions



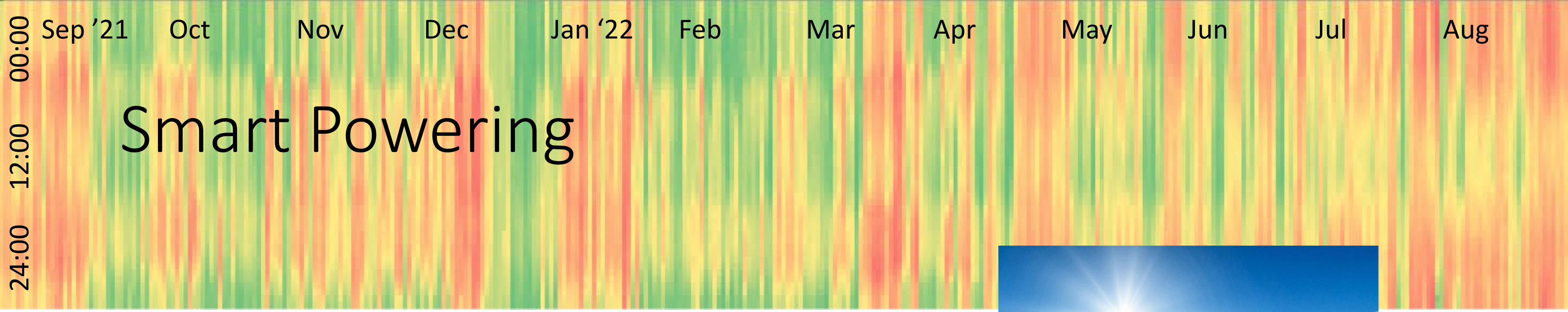


Slide: Hywel Owen

Concrete and CO_2



- Structural materials ('the building') and radiation shielding is a major component of nearly all particle accelerator infrastructure; these use **large quantities of concrete**
- Old 'rule of thumb' is half a project cost is accelerator, half is building
- Today's cement production accounts for 8% of global CO_2 emissions: **900 kgCO_2e/ton**
- CO2 production during cement manufacture is mainly due to clinker intermediary
- Possible mitigation strategies to be examined in sustainability report:
    - **Modular**/standardised shielding (blocks and beams), e.g. v-blocks, can be re-used/reconfigured
    - **Frame and infill** construction using (local) aggregates, earth, sand etc.
    - Replacement of clinker with **recycled materials** (fly ash, GBBS) – used in STFC EPAC project
    - **Alternative** shielding materials and combinations, e.g. for neutron shielding



Smart Powering

- Grid intensity (gCO_2e / kWh) depends strongly on time of day and season
  - Affected by demand, and availability of renewables
- Possible to reduce carbon by **time-shifting** demand
- Some systems could be run at off-peak times
  - Water cooling – secondary circuits to provide a cold reservoir at peak times
  - Helium liquefaction
  - Vacuum bakeout

Conclusions

- ASTeC aims to be the go-to place for expertise in **Sustainable Accelerators**
- We are developing several key technologies with the potential to drastically improve the efficiency of particle accelerators
- Future UK initiatives such as RUEDI and UK-XFEL will need to take account of carbon footprints in construction and operation
- Our **Accelerator Impact Study** will give us a strong framework to find the best areas for improvement

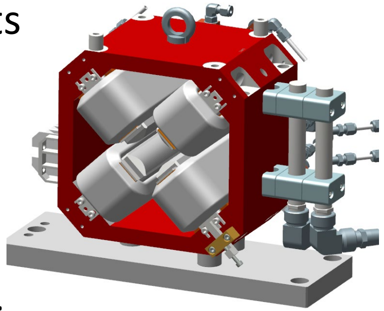
- *Acknowledgements*: Louise Cowie, Anthony Gleeson, Gary Hughes, Storm Mathisen, Hywel Owen, Andrew Vick, Katie Morrow (SATF); Alex Bainbridge, Walter Tizzano (ZEPTO); Oleg Malyshev, Taaj Sian (TF-SRF); Andy Goulden (GWC); Paul Surtees, Mike Glover (ISIS)

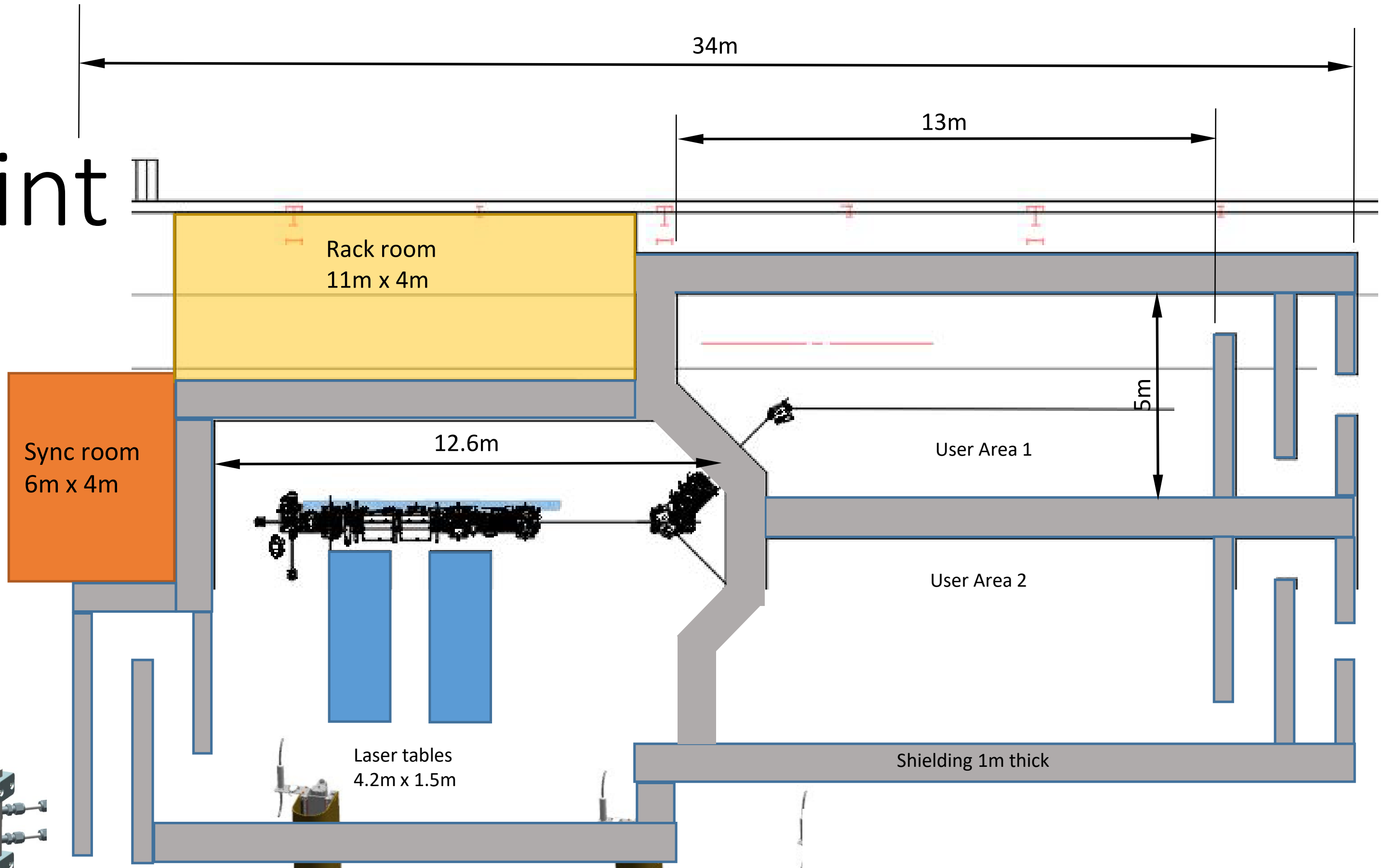
Cloud icon: Freepik

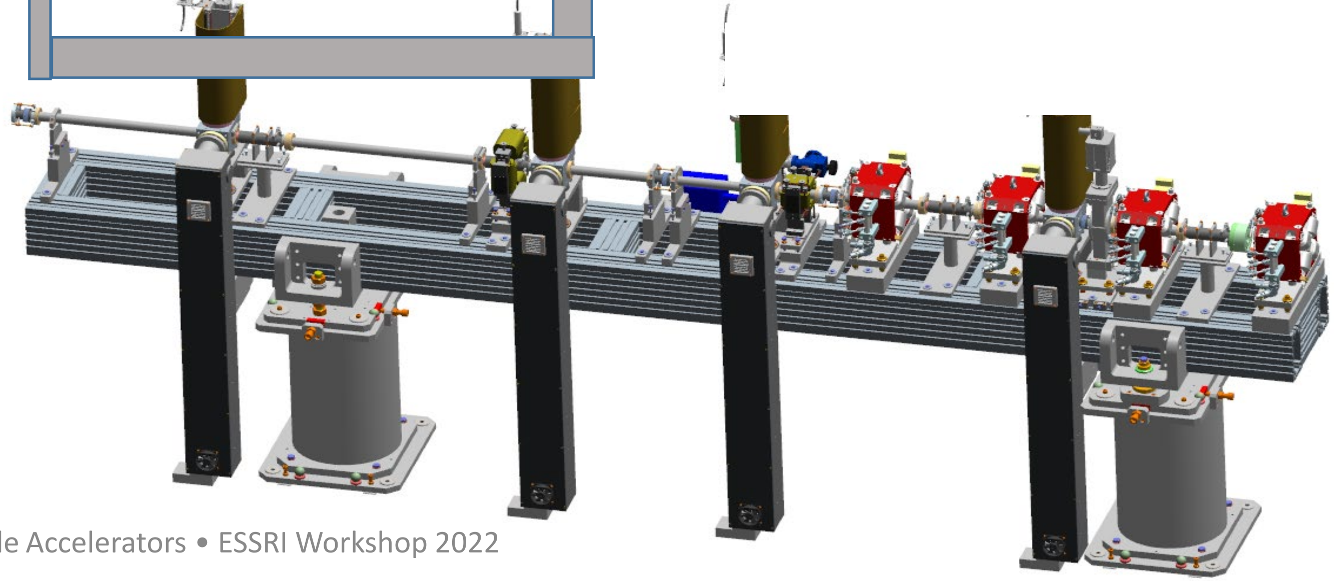
Backup slides

Construction footprint

- *Numbers for a sense of scale only*
- **Concrete** shielding
  - Walls: ~900 tonnes
  - Roof: ~800 tonnes
  - Intensity: 1.25 tCO_2e / tonne
  - Total: ~2200 tonnes CO_2e
  - Other materials are available
  - Need to consider radiation safety requirements
- **Magnets**
  - Typical values: 8 kg Cu, 45 kg steel
  - About 30 magnets needed
  - Total: 2.7 tonnes CO_2e, plus cables and power supplies
- **Girders**
  - Need about 780 kg aluminium for a 4.8m girder
  - About 5 girders needed
  - Total 26 tonnes CO_2e







Materials choice and sustainability

- Sustainability also high on industrial company agendas
- Pay attention to particular material usage with disproportionate CO_2 impact
- Example:
  - Elekta radiotherapy linacs use collimators to shape X-ray therapy beams
  - Traditional tungsten collimators have very large CO_2 emissions associated with primary material extraction – despite small mass and low-ish cost, is a major CO_2 impact of entire product
  - Replacing tungsten with lead significantly reduces CO_2 impact of device

Activities at other labs

CERN

- High efficiency klystrons
  - J. Cai and I. Syratchev, "KlyC: 1.5-D large-signal simulation code for klystrons", IEEE Trans. Plasma Sci. **47**, 1734 (2019)
  - I. Syratchev and J. Cai, "Efficiency frontiers of the high power klystrons", CLIC Mini Week, September 2020 (see next 2 slides)
- Fast ferroelectric tuners – enable control of microphonics
  - N. Shipman *et al*, "A ferroelectric fast reactive tuner for superconducting cavities", SRF2019 WETEB7
  - N. Shipman *et al*, "A FerroElectric Fast Reactive Tuner (FE-FRT) for ERLs", Electrons for the LHC, Oct 2019
- Energy Management Panel
  - E. Jensen, "Energy Efficiency of HEP Infrastructures", talk at CERN Council Open Symposium on the Update of European Strategy for Particle Physics, May 2019
- District heating from LHC P8 for Ferney-Voltaire

- JLab: cavity nitrogen doping for higher efficiency
  - A. Grassellino et al, "Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures", Supercond. Sci. Technol. 26 102001 (2013)
- ESS: design of a sustainable research facility
  - Keep power below target 270 GWh / year
  - Commit to renewable energy
  - Recycle waste heat

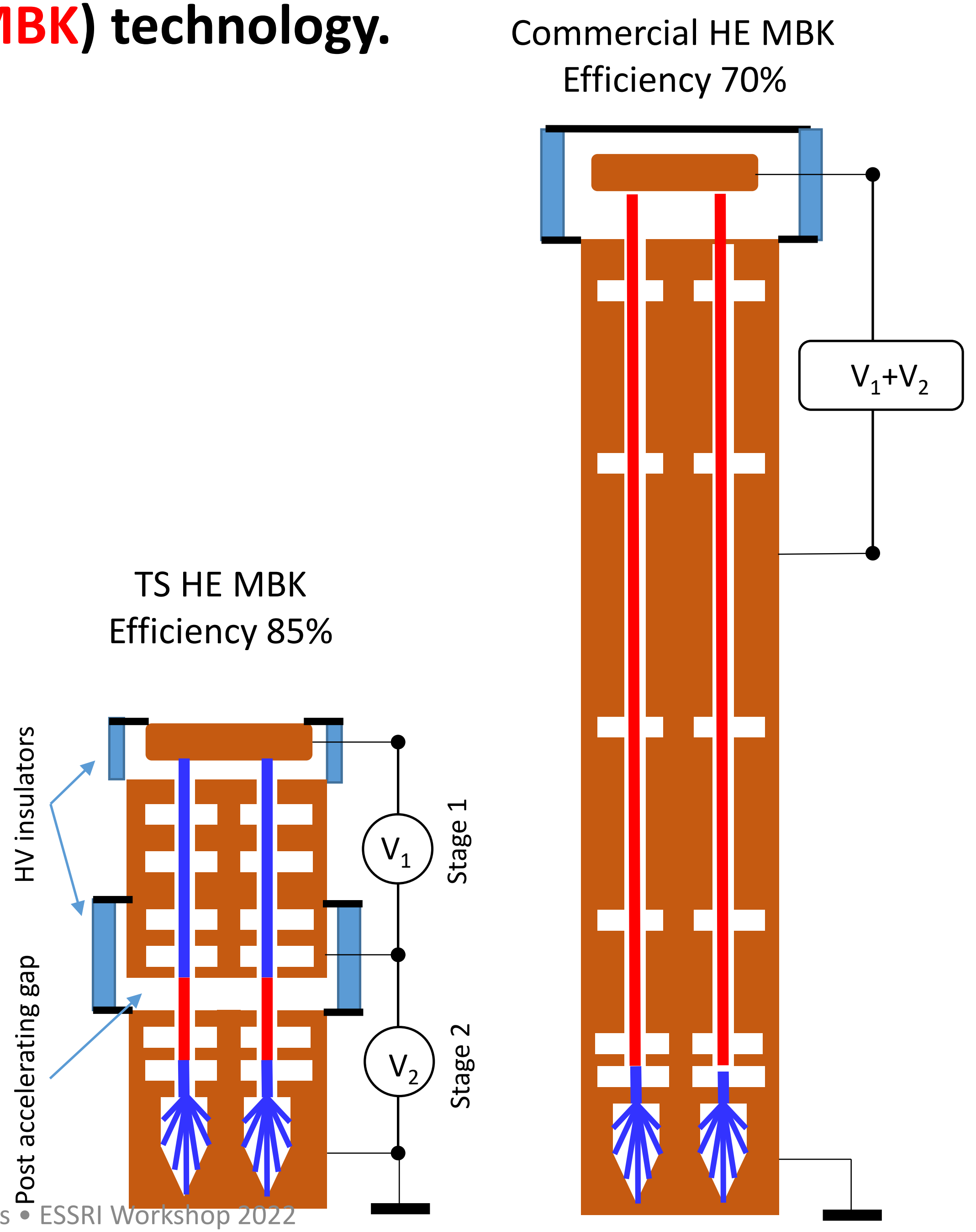
Two-Stage Multi Beam Klystron (TS MBK) technology.

Specific features

1. Bunching at a low voltage (high perveance). Very **compact RF bunching circuit.**
2. Bunched beam acceleration and cooling (reducing $\Delta p/p$) along the short DC voltage post-accelerating gap.
3. Final power extraction from high voltage (low perveance) beam. **High efficiency.**

Additional advantages:

1. The second HV stage can be operated in DC mode. Thus simplifying the modulator topology (cost/volume) and increasing the modulator efficiency (in pulsed mode).
2. Simplified feedback for the first stage pulsed voltage. Improved klystron RF phase and amplitude stability.
3. Gap's accelerating DC voltage is a natural barrier for reflected electrons. Improved tube stability.



TS MBK Summary

- The high efficiency (~85%) TS MBK is most practical when the generation of low frequency (UHF and L-band) and high power (Multi Mega Watts) microwave signals is required. This technology could be considered as an appropriate choice for **CLIC, ILC, FCC and CEPC large-scale electron accelerators and high power proton Linacs (ESS, MYRRHA, etc.)**
- Apart from the potential savings of electricity, the compact TS MBK layout, together with the reduced cooling capacity needs and possible cost/volume reduction of the HV modulator shall be beneficial for the RF power system of the future high-energy accelerator, which is located in an underground tunnel environment.

Why use an FE-FRT?

- No moving parts
- Outside cryomodule
- Continuous tuning range
- No need to generate a large magnetic field
- Intrinsic speed $< 10\,\mathrm{ns}$[3]
- Low losses/small increased bandwidth

[3] S. Kazakov *et al.*,"Fast Ferroelectric L-band Tuner", in *Proceedings of the 12th AAC Workshop*, Lake Geneva, WI, USA, Jul. 2006, AIP Conf.Proc. (877), pp. 331–338.

Newly Developed Ferroelectric

- Suitable material only recently developed.[4]
  - $BaTiO_3$ - $SrTiO_3$ solid solution (BST)
  - Added linear (non-tunable) Mg-based ceramic component[5]
  - Enhanced tunability with low losses

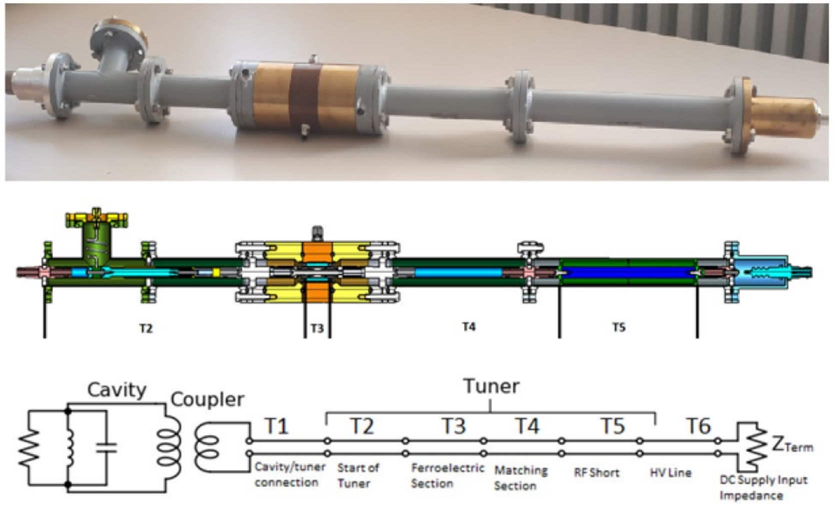
Table: Material Properties at $\approx 800\,\mathrm{MHz}$

Parameter	Value
Max. ϵ_r	140
Min. ϵ_r	131.6
$\tan\delta$	9.1×10^{-4}
$\frac{\Delta\epsilon_r}{E}$	$0.6\,\mathrm{kV^{-1}cm}$
τ	$< 10\,\mathrm{ns}$

[4] E. Nenasheva *et al.*,*Journal of European Ceramic Society*, vol. 30, pp. 395–400, Jan. 2010.

[5] A. Kozyrev *et al.*, *Appl.Phys. Lett.*, vol. 95, pp. 1–5, Jul. 2009.

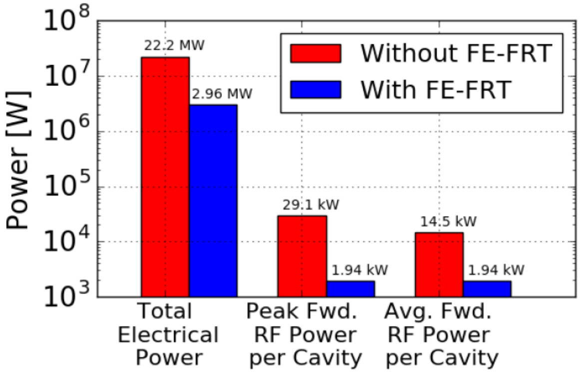
Prototype Tuner



Prototype Tuner, 3D model and transmission line model.

Case Studies - LHeC

$$P_{RF} = \frac{V_c^2}{4 R/_Q Q_L} \frac{\beta + 1}{\beta} \left[1 + \left(2 Q_L \frac{\Delta\omega_\mu}{\omega_0}\right)^2\right]$$



- Peak power per cavity $29.1\,\mathrm{kW} \rightarrow 1.94\,\mathrm{kW}$
- Total Electrical Power **$22.2\,\mathrm{MW} \rightarrow 2.96\,\mathrm{MW}$**

CERN Energy Management Panel

Introduced in 2015, the CERN EMP is now an essential tool to save both money and energy!

Mandate: The CERN Energy Management Panel reports to the Director of Accelerators, and is expected to bring all main energy consumers and stakeholders at CERN together in order to:

- Make the main energy consumers aware of the new conditions and rules under CERN's new energy supply contracts. ("virtual invoices")
- Compile estimates of CERN's projected power and energy consumption up to and including HL-LHC, in coordination with the various users and EN-EL power network operations.
- Manage CERN energy consumption, with regular checks against planned consumption.
- Define how CERN will handle changes to projected energy consumption due to changes in programs, both foreseen and unforeseen.
- Implement the mechanism by which CERN will inform CERN's energy supplier(s) of changes to the projected energy consumption. The mechanism itself will be defined in the supply contract(s).
- Develop degraded operation scenarios for periods of reduced power availability. EN/EL will provide the estimations for the reduced available power.
- Define and implement the mechanisms by which the degraded operation scenarios, as defined above, will be triggered.
- Make recommendations to reduce CERN's energy bill with minimal impact on CERN's operations.

- Recent results:
  - Computer centre: free cooling and air flow optimisation (-5 GWh/y)
  - LHC cryogenics: optimisation of cryo plant usage and operation modes (-20 GWh/y)
  - SPS magnetic cycles and stand-by modes (-40 GWh/y)
  - Exact prediction of energy use allowed negotiation of better supply contract conditions.
  - Online tool to monitor energy consumption developed and deployed successfully (https://energy.cern.ch)

S. Claudet/CERN

ISIS Energy Consumption

Mode	Energy Total	2017 Baseline CO_2 Equivalent tonnes per annum	2020 CO_2 Equivalent tonnes per annum	
ISIS-I				
• 240 Day 5 cycle plus Machine Physics & Start Up	64.5 GWh/annum	22,700	16,300	
• 90 Days Long Shutdowns	13.4 GWh/annum	4,700	3,400	
• 35 Days Short Shutdowns	7.2 GWh/annum	2,500	1,800	
• 365 Operation	85.1 GWh/annum	29,900	21,500	**-8,400**
ISIS-II				
• 240 Day 5 cycle plus Machine Physics & Start Up	172.7 GWh/annum	60,700	43,700	
• 90 Days Long Shutdowns	35.9 GWh/annum	12,600	9,100	
• 35 Days Short Shutdowns	19.3 GWh/annum	6,700	4,900	
• 365 Operation	227.9 GWh/annum	80,000	57,700	**-22,300**

This is just the electrical energy that we use in running the ISIS Facility

- **It does not include any of the carbon footprint associated with:**
  - **With carbon lifecycle assessments.**
  - **Materials for new accelerator components or Beamlines.**
  - **Our Business as usual activities.**
  - **The ISIS facility is a particle accelerator**
  - **It will never have a low carbon footprint**
  - **This does not mean we can ignore that footprint.**

The ISIS facility is a particle accelerator

- **It will never have a low carbon footprint**
- **This does not mean we can ignore that footprint.**
- **We cannot rely on the greening of the electricity supply to reduce our footprint.**

2017 Baseline UKRI GOV.UK conversion factor — Electricity 1kWh = 0.35156 $kgCO_2e$

2020 UKRI GOV.UK conversion factor — Electricity 1kWh = 0.25319 $kgCO_2e$