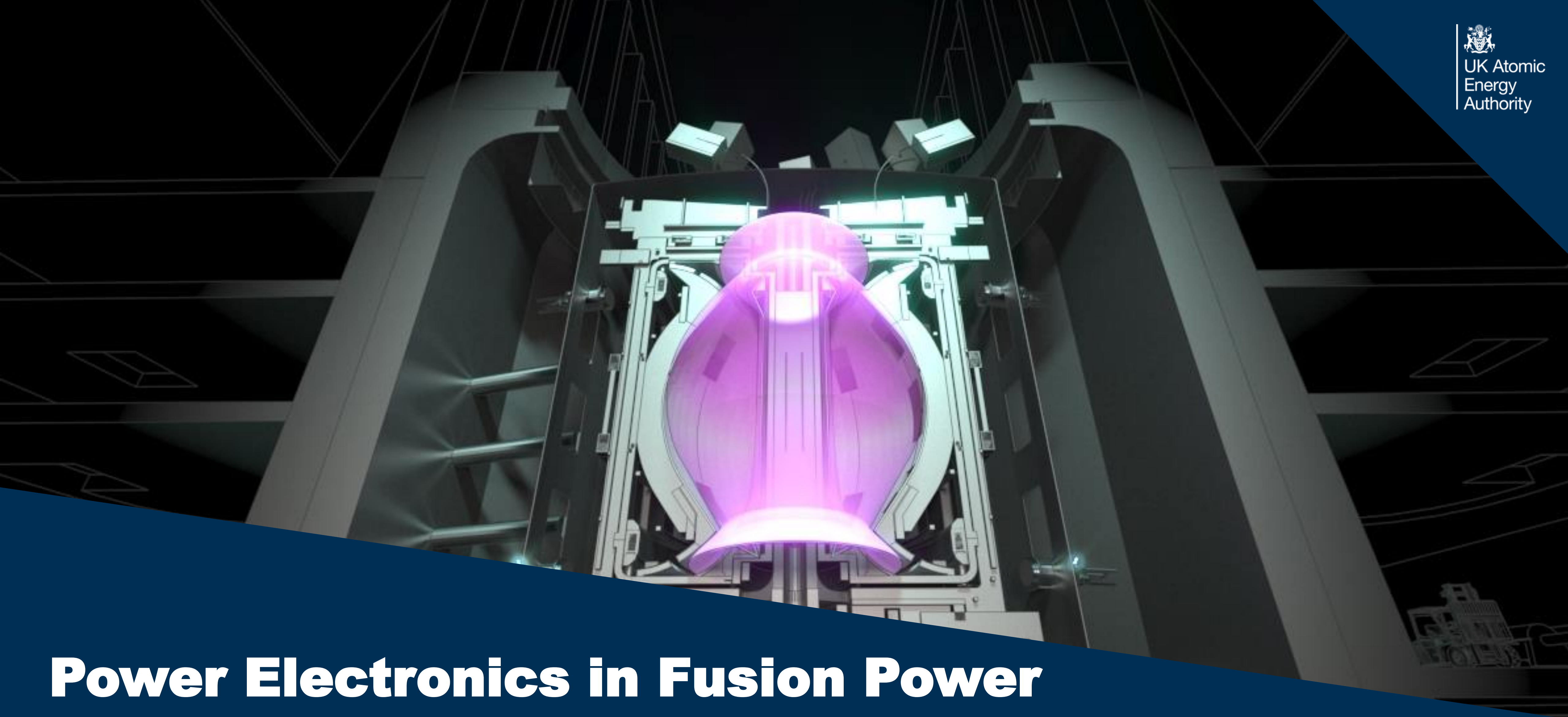
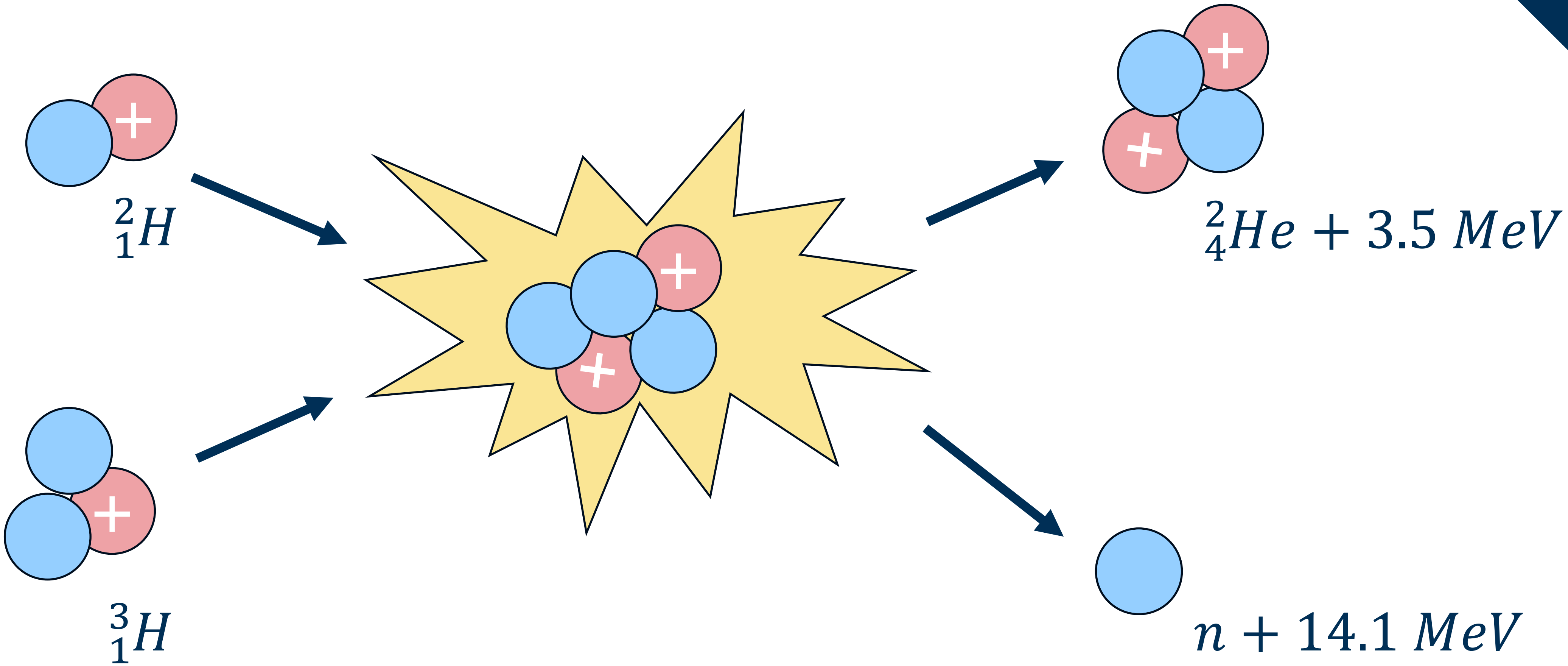


UK Atomic Energy Authority

Power Electronics in Fusion Power Supply Systems

Finlay Christie

What is Fusion?



$$E = (m_1 - m_2)c^2$$

What is Fusion?

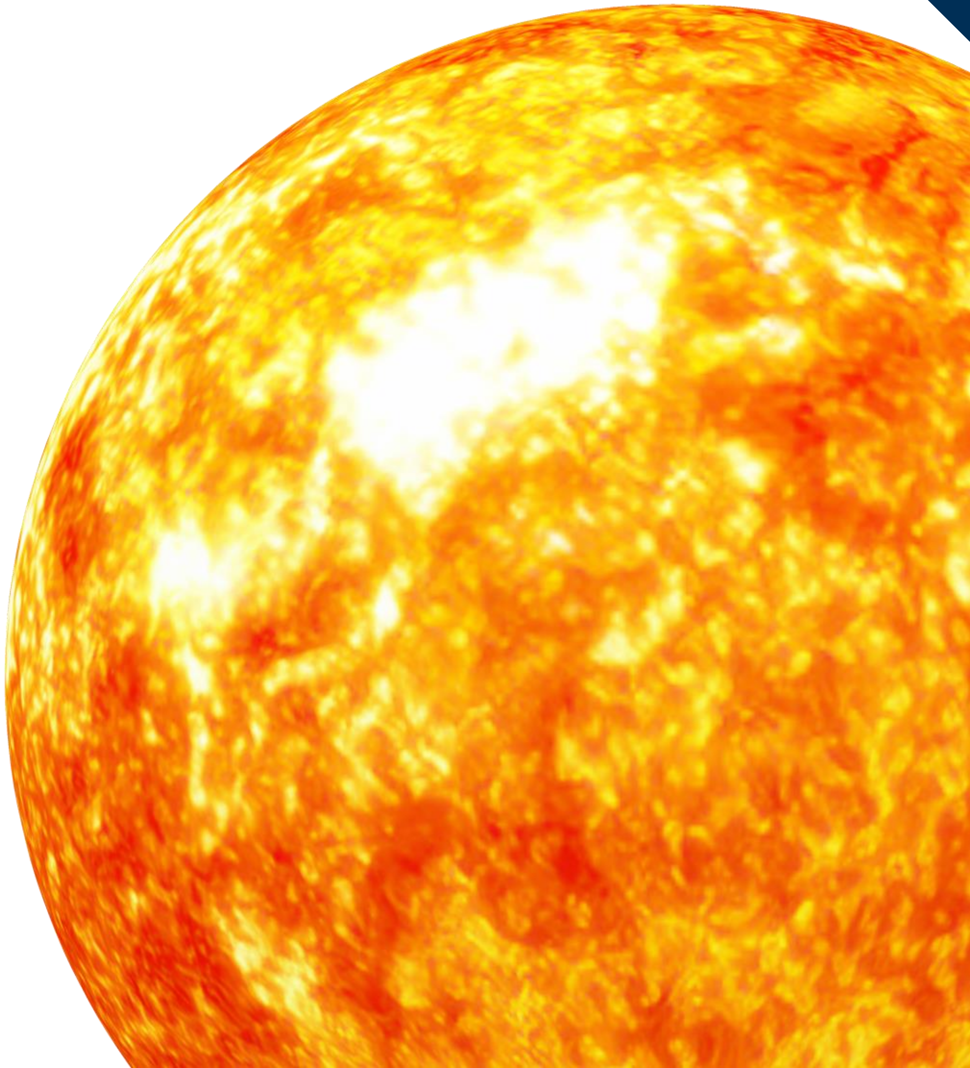
UK Atomic Energy Authority

<u>Fusion occurs naturally inside stars</u>

- **High Temperature:**
  - The suns surface temperature is 5000°C
  - The suns core temperature is 15 million °C

- **Strong Confinement** – Huge gravitational forces hold the sun together and provides huge levels of pressure.

- **High Density at Core** –The suns core is 20 times more dense than iron.



How to Recreate Star Power on Earth?

UK Atomic Energy Authority

<u>Use a Tokamak fusion machine!</u>

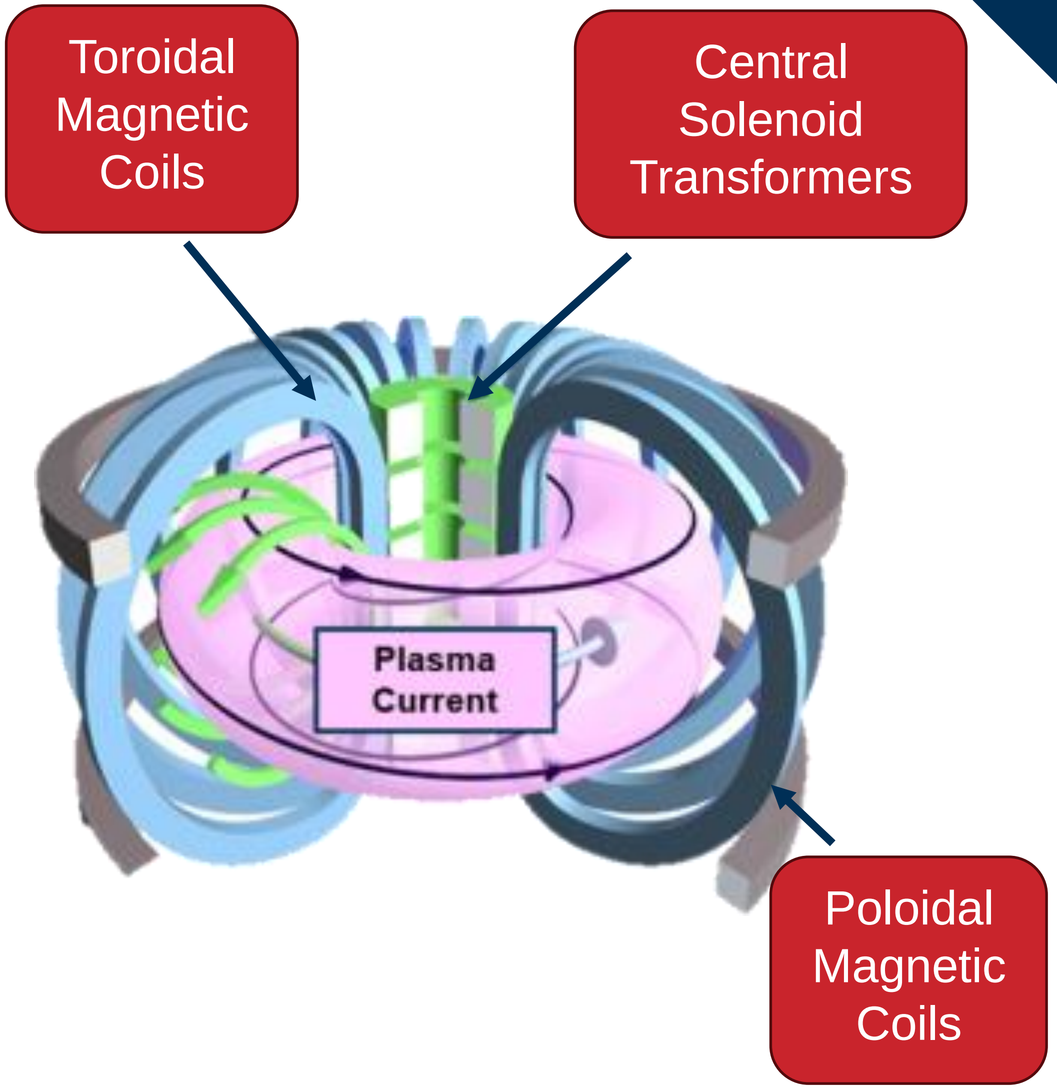
- **Fuse** a fuel mix of light hydrogen (deuterium and tritium) and heat the plasma to extreme temperatures.
- **High Temperature** – Plasma temperature of around 150 million °C.
- **Strong Confinement** – Use strong magnetic fields to hold and shape the plasma.
- **Vacuum conditions** – to remove impurities and cooling effect.

How to Recreate Star Power on Earth?

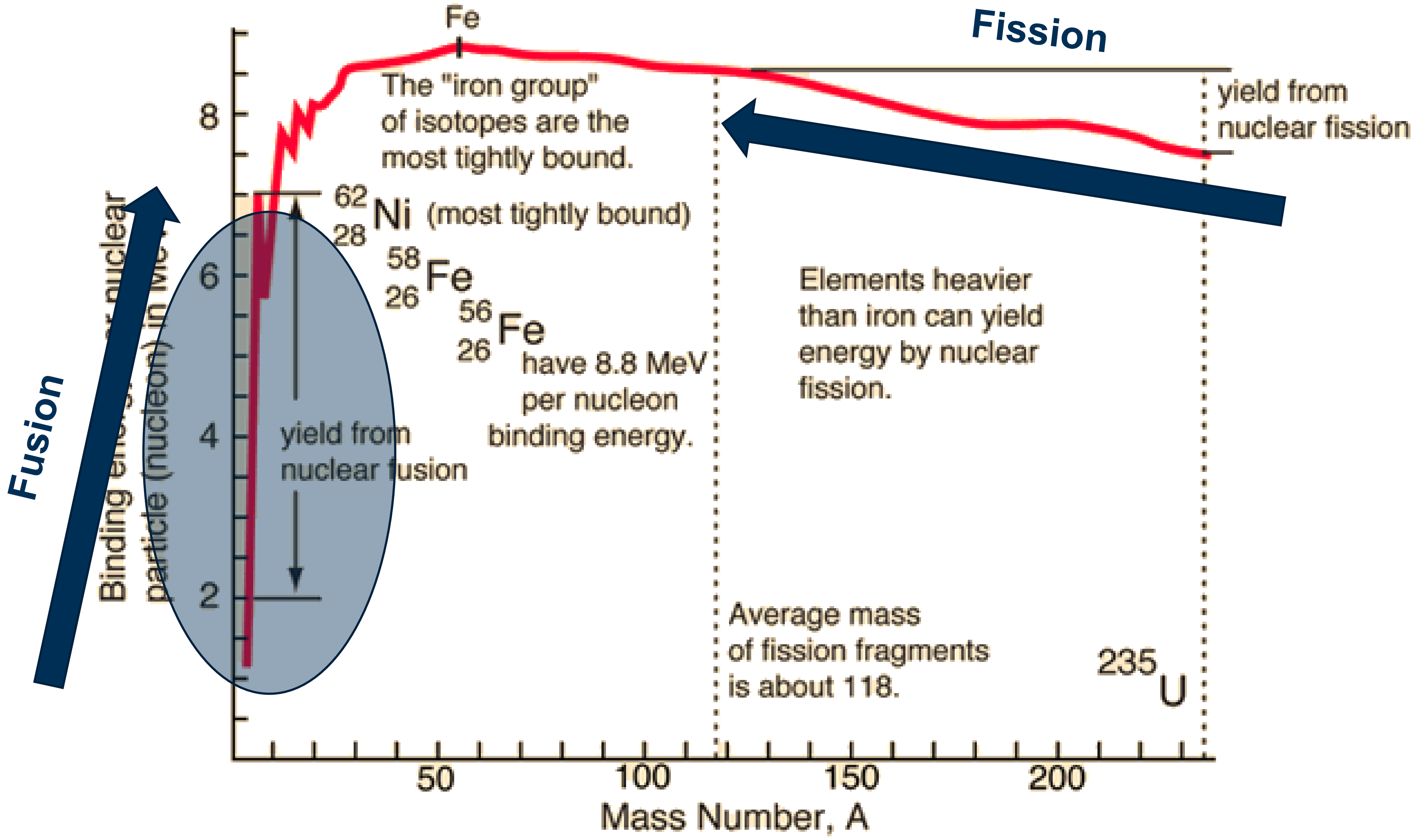
UK Atomic Energy Authority

Use a Tokamak fusion machine!

- **Fuse** a fuel mix of light hydrogen (deuterium and tritium) and heat the plasma to extreme temperatures.
- **High Temperature** – Plasma temperature of around 150 million °C.
- **Strong Confinement** – Use strong magnetic fields to hold and shape the plasma.
- **Vacuum conditions** – to remove impurities and cooling effect.



Differences Between Fusion and Fission



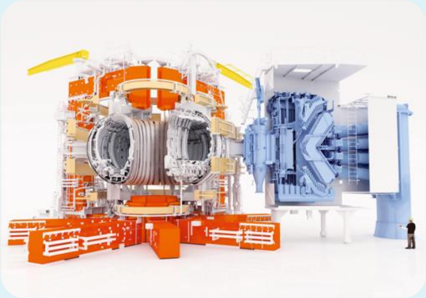
Binding Energy Curve, source: http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/imgnuk/bcurv.gif

Tokamak Design Development Plan

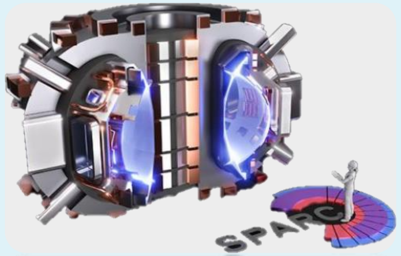
UK Atomic Energy Authority

2021 | 2025 | 2030 | 2035 | 2040

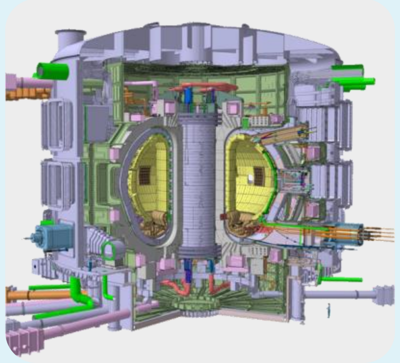
JET DT2 + DT3



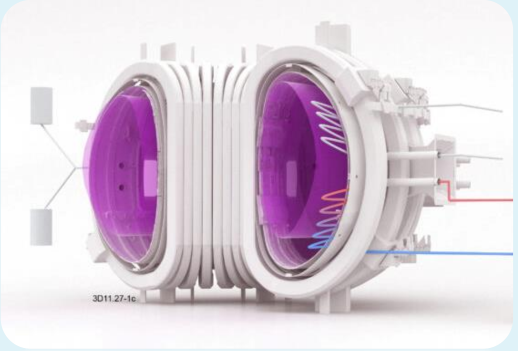
SPARC



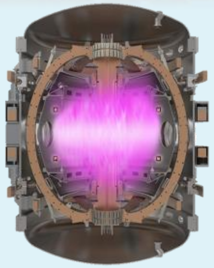
ITER ?



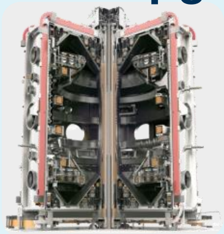
EU DEMO



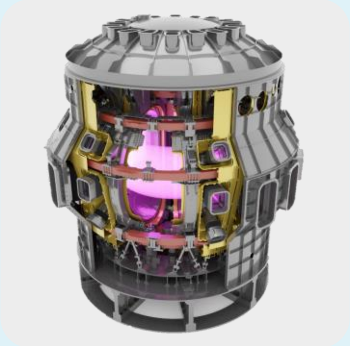
ST40



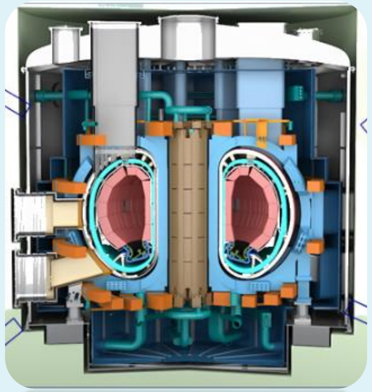
MAST-Upgrade



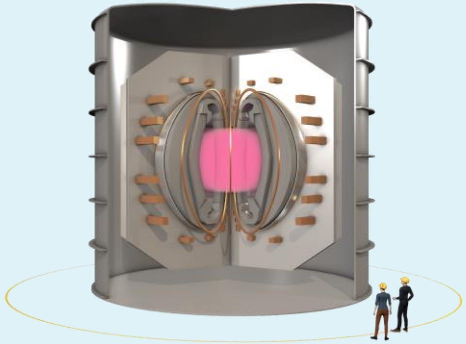
JT-60SA



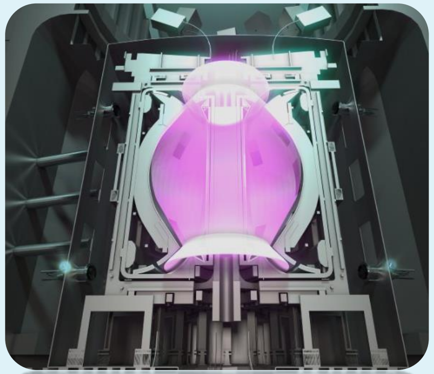
CFTER



ST-E1



SPP



To lead the delivery of sustainable fusion energy and maximise the scientific and economic benefit.

UKAEA mission

Deliver a UK prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion.

STEP mission

What is STEP?

“Deliver a UK prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion.”

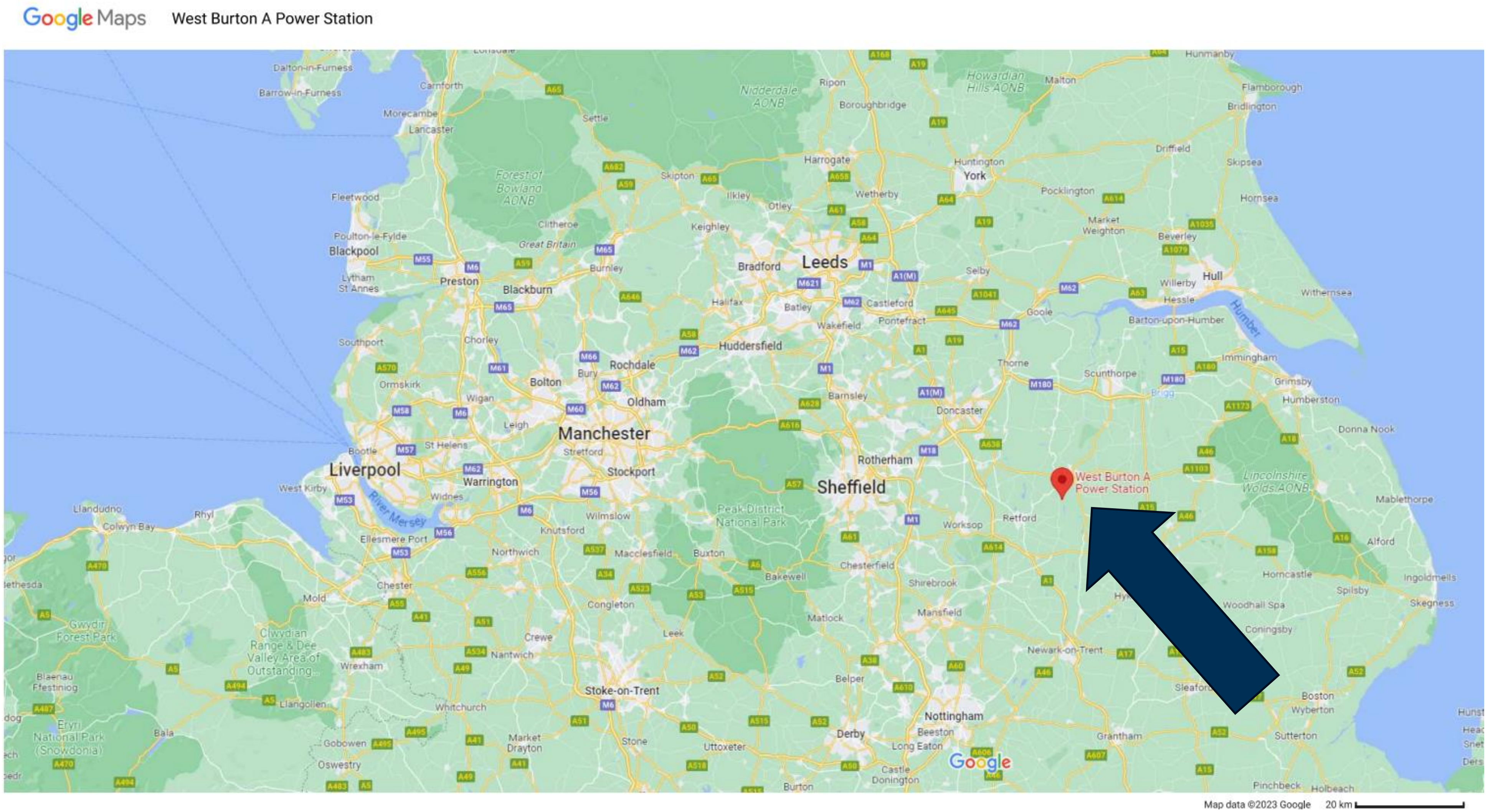
Commercially driven design basis:

- Predictable net electricity production
- Fuel self-sufficiency
- Credible maintenance solution
- Spherical tokamak design – potentially lower cost than other tokamak design types.

UK Atomic Energy Authority

Where is STEP?

UK Atomic Energy Authority



An Infrastructure Project – SPP

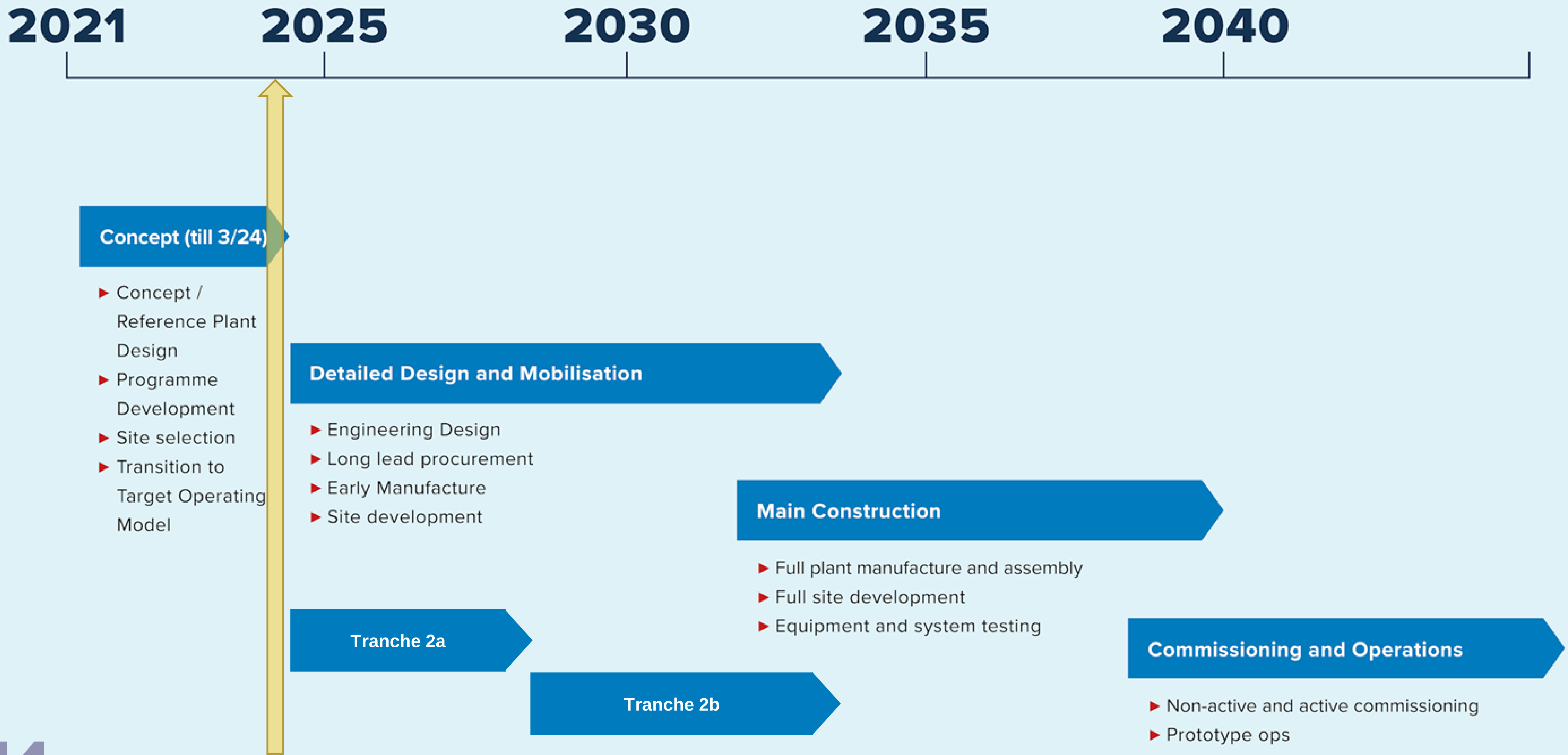
An Infrastructure Project

UK Atomic Energy Authority

Source: UK mulls associate membership of ITER fusion project after ditching full participation | Science|Business (sciencebusiness.net)

STEP high-level schedule

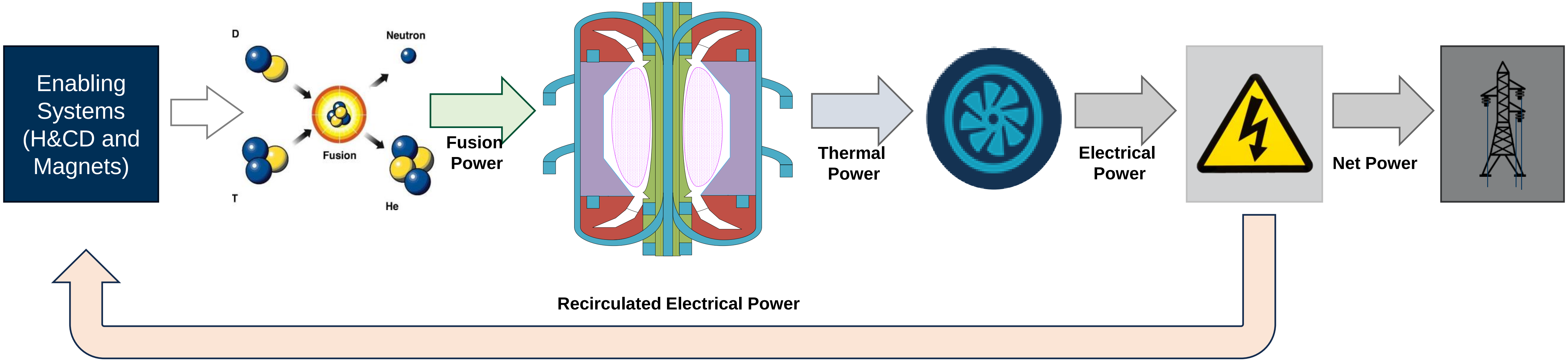
UK Atomic Energy Authority



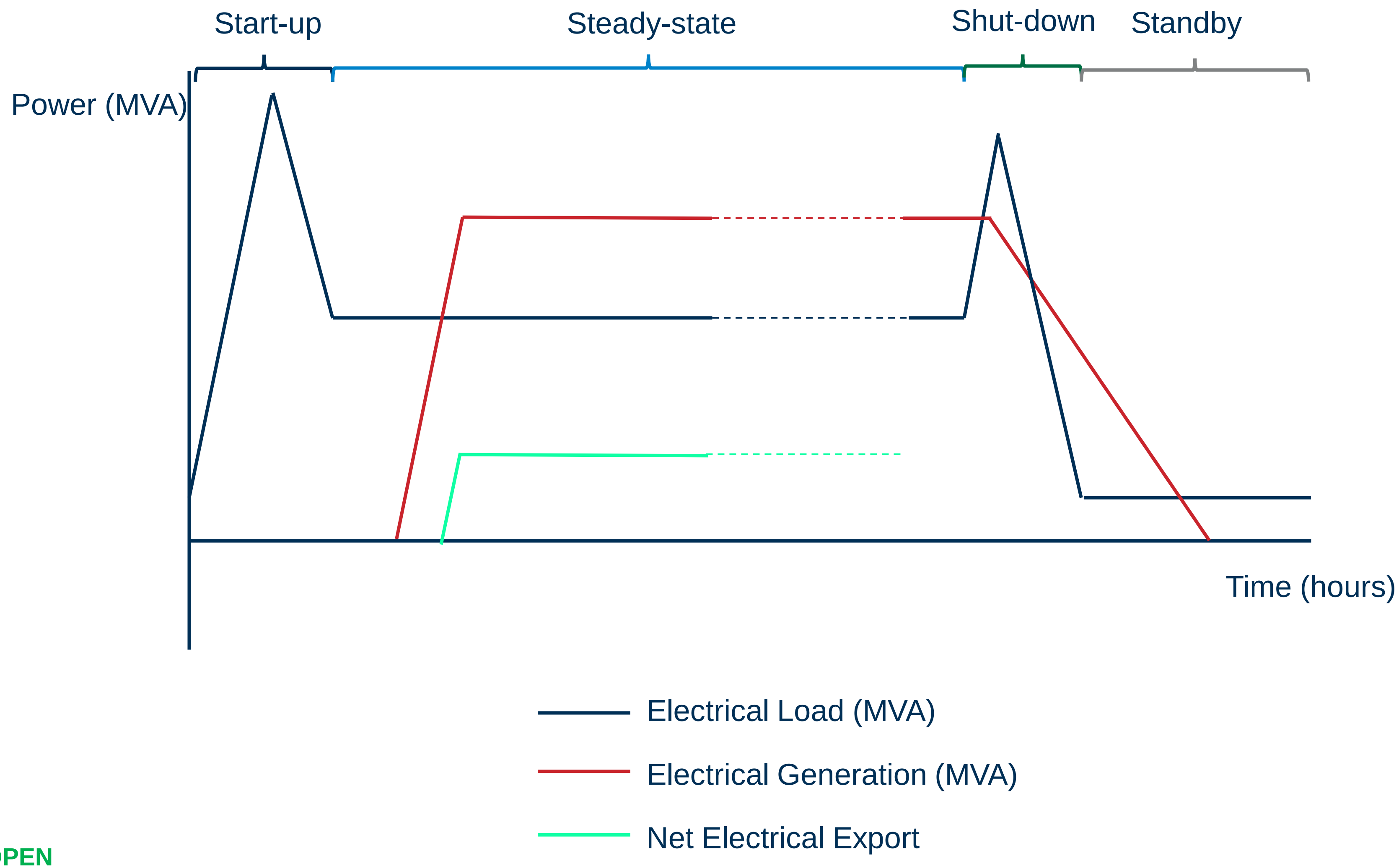
UK Atomic Energy Authority

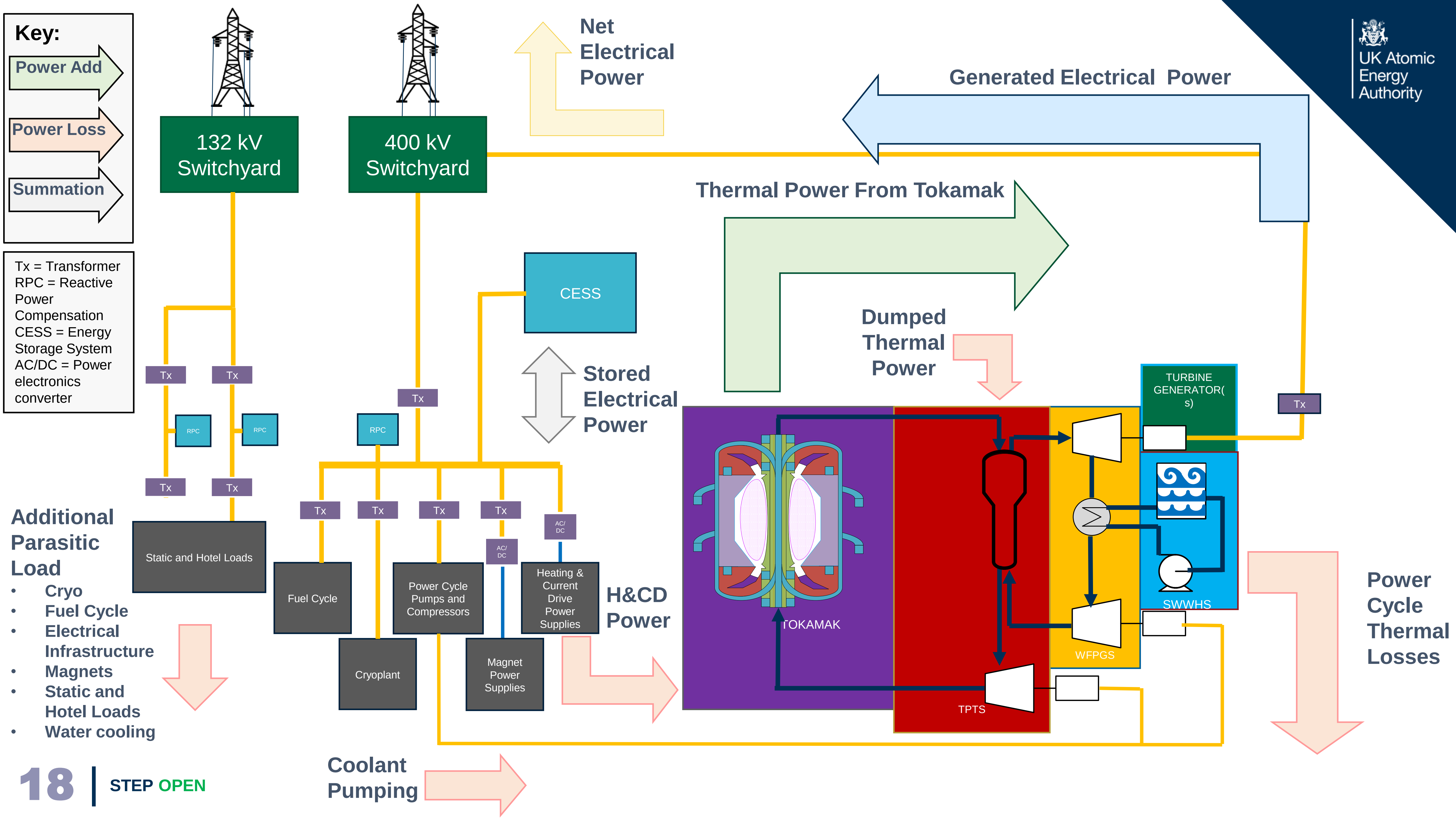
STEP Power Infrastructure

STEP Net-Power Generation Flowsheet

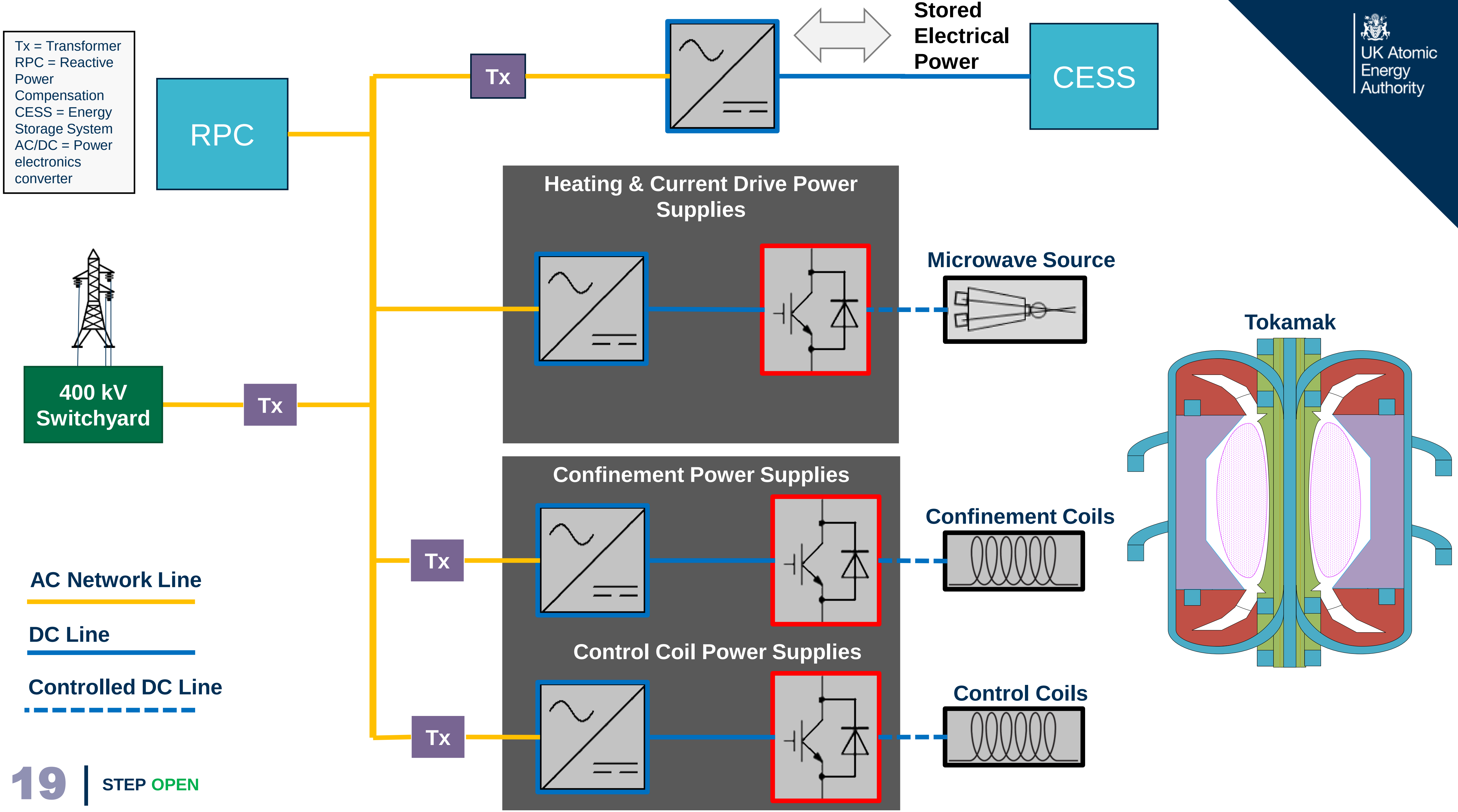


SPP Load and Generation Profiles





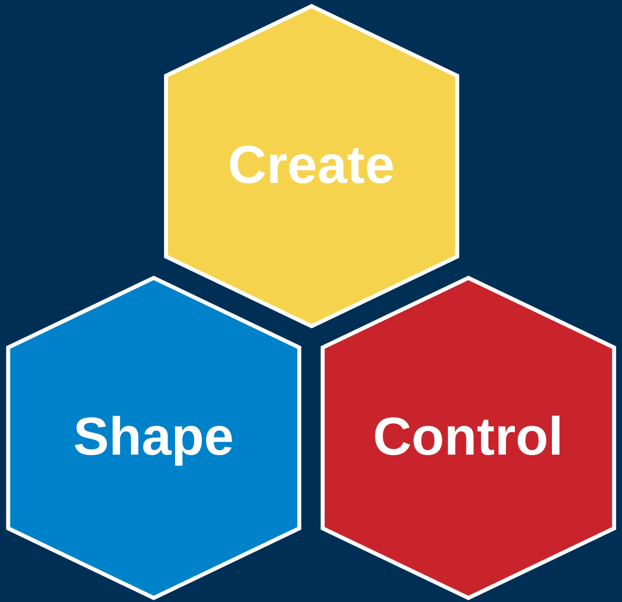
Key:
Power Add
Power Loss
Summation
Tx = Transformer
RPC = Reactive Power Compensation
CESS = Energy Storage System
AC/DC = Power electronics converter
132 kV Switchyard
400 kV Switchyard
Net Electrical Power
Generated Electrical Power
Thermal Power From Tokamak
CESS
Stored Electrical Power
Dumped Thermal Power
Tx
RPC
AC/ DC
TURBINE GENERATOR(s)
SWWHS
WFPGS
TPTS
TOKAMAK
Additional Parasitic Load
• Cryo
• Fuel Cycle
• Electrical Infrastructure
• Magnets
• Static and Hotel Loads
• Water cooling
Static and Hotel Loads
Fuel Cycle
Power Cycle Pumps and Compressors
Heating & Current Drive Power Supplies
Cryoplant
Magnet Power Supplies
H&CD Power
Coolant Pumping
Power Cycle Thermal Losses
UK Atomic Energy Authority


Tx = Transformer
RPC = Reactive Power Compensation
CESS = Energy Storage System
AC/DC = Power electronics converter
RPC
Tx
Stored Electrical Power
CESS
Heating & Current Drive Power Supplies
Microwave Source
Tokamak
400 kV Switchyard
Tx
Confinement Power Supplies
Confinement Coils
Tx
Control Coil Power Supplies
Control Coils
Tx
AC Network Line
DC Line
Controlled DC Line

Magnet Power Supplies Overview

UK Atomic Energy Authority

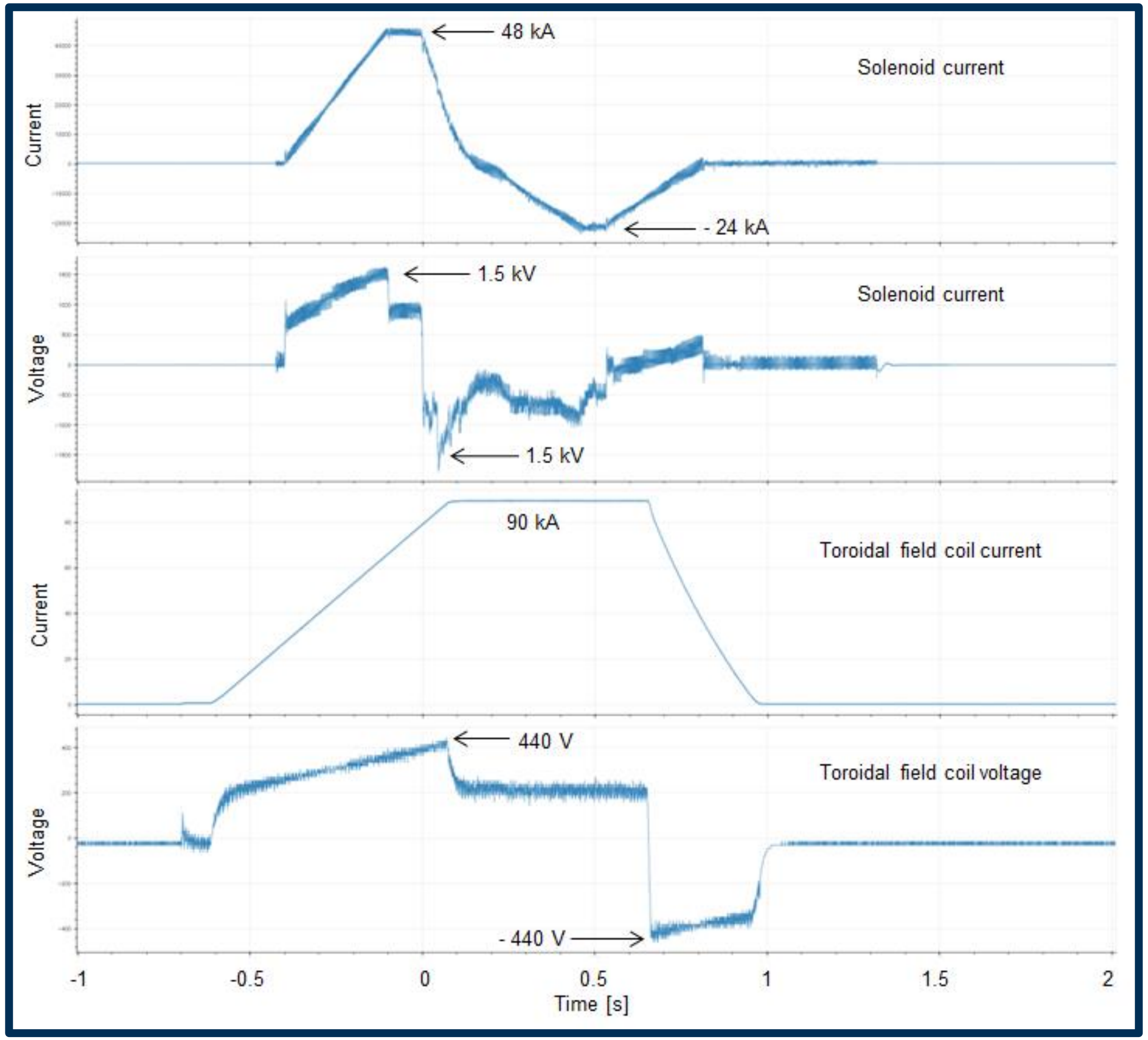
Primary functions:



Primary requirements

- High output currents (typ >10 kA)
- Low(ish) voltage (typ <10 kV)
- Very steep current gradients

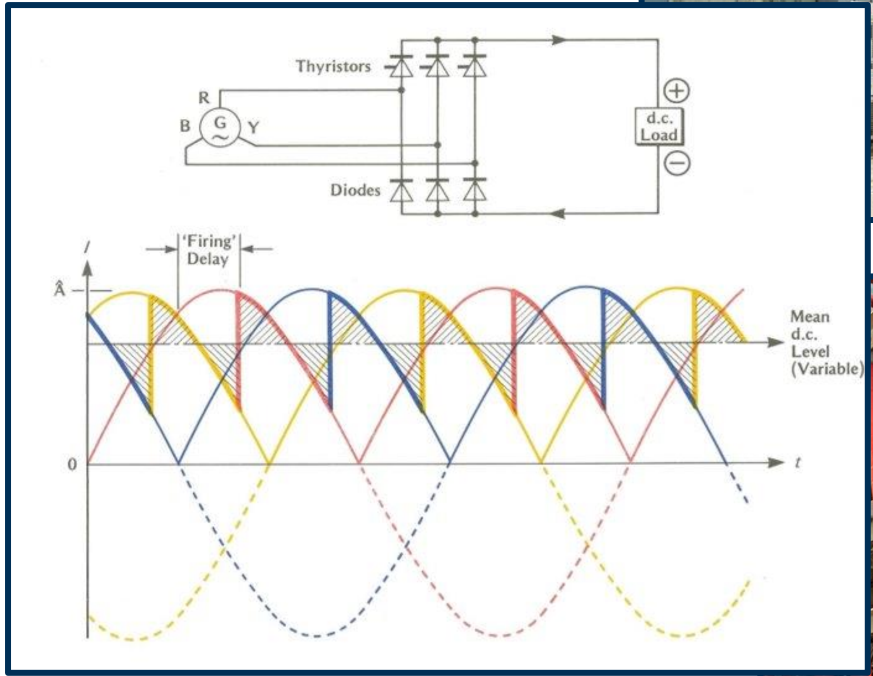
Typical current and voltage waveforms for a fusion device:

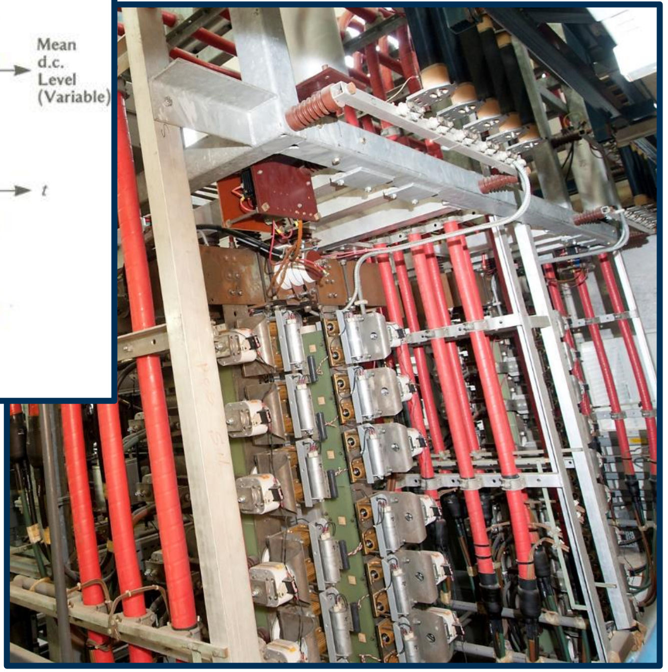


Plasma Confinement Power Supplies

Confinement power supplies, typical requirements:

- Multiphase transformers.
- Thyristor based controlled rectification.
- Snubbers to absorb voltage transients.
- Techniques and technologies from “low-current electronics”, only at high power.
- Many devices in parallel – which can lead to difficulty achieving a uniform current.
- A complex control system that must be guided by the wider plasma control system.





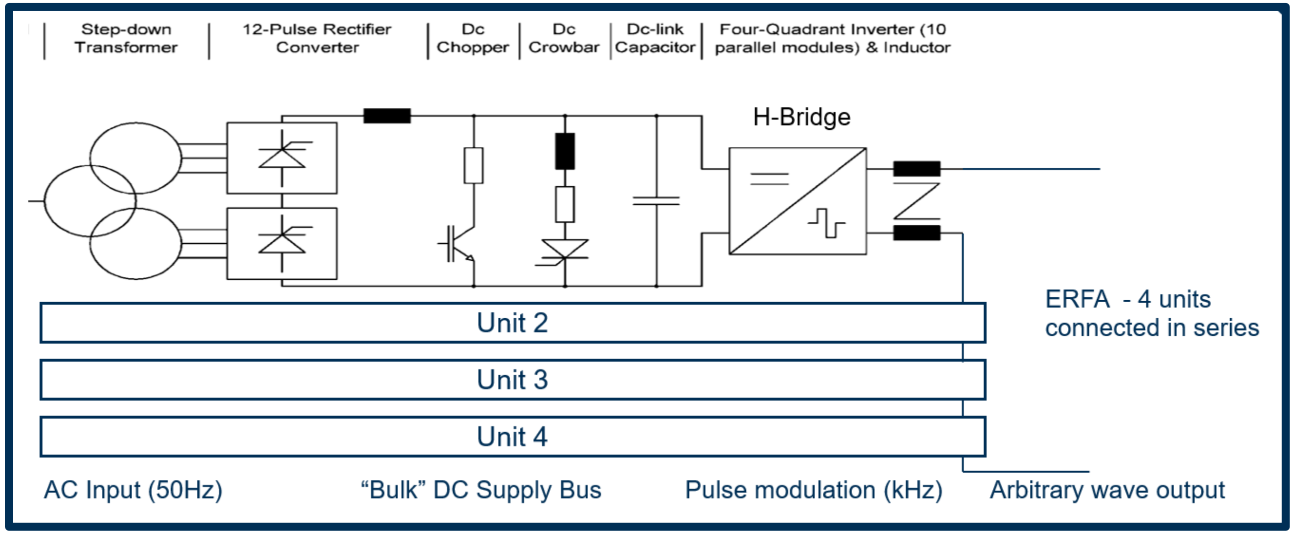
Plasma Control Power Supplies

UK Atomic Energy Authority

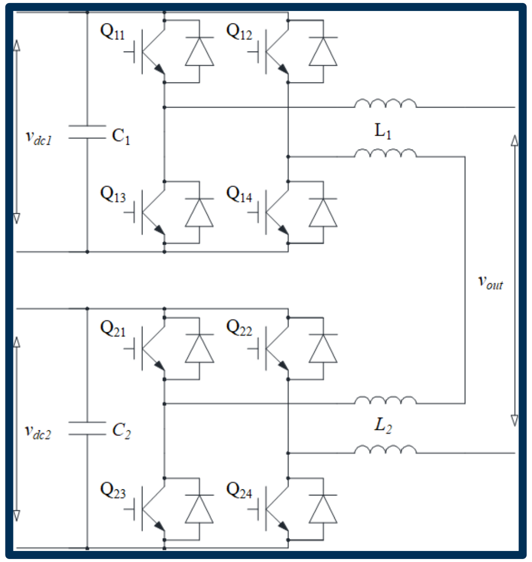
Plasma control power supplies, typical requirements:

- Fast response
- Bidirectional capabilities
- IGBT-based converters are suitable to deliver the requirements of control coils

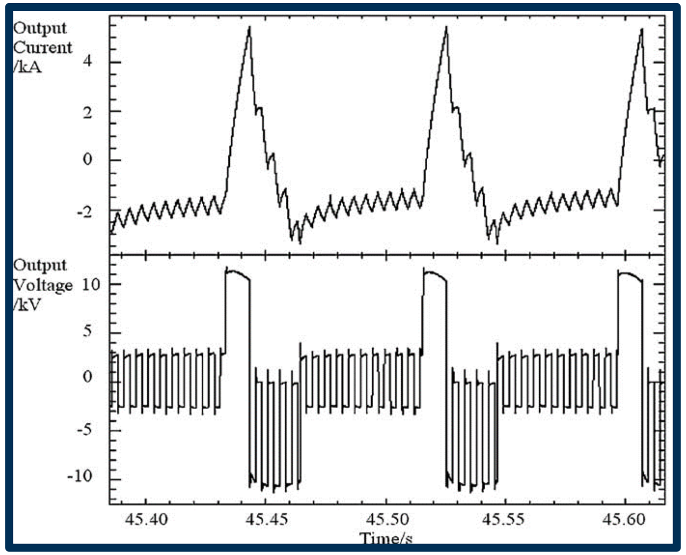
H-Bridge application to ERFA (simplified)



Cascade H-bridge converter



Plasma vertical stabilisation system typical waveforms

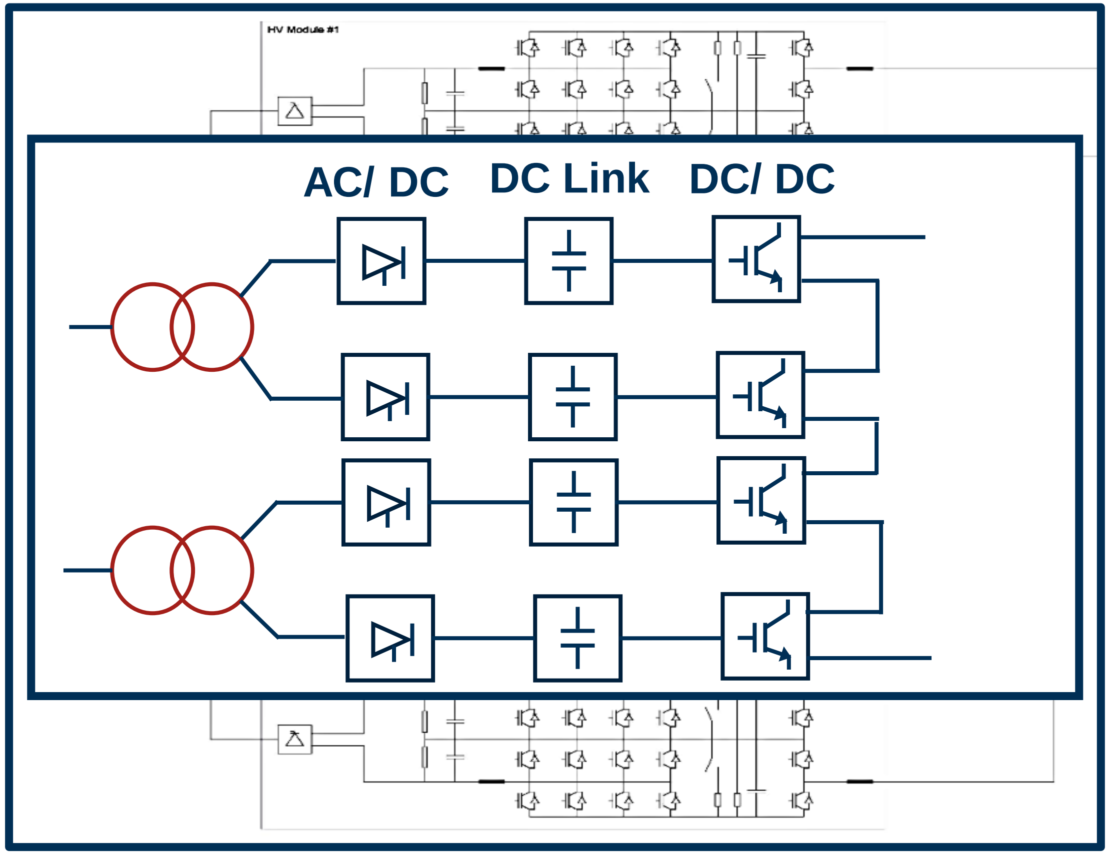


Heating and Current Drive Power Supplies

Heating and current drive (H&CD) power supplies, typical requirements:

- High efficiency (>95%).
- Modular (many HV modules connected in parallel).
- MW-class converters with high voltage output.
- IGBT based systems with fast switching.
- Harmonic compensation often required.
- Fast response rate to allow for quick shutdown (micro-seconds).

JT60 Power supply architecture (*4 HV Modules per HV transformer)*

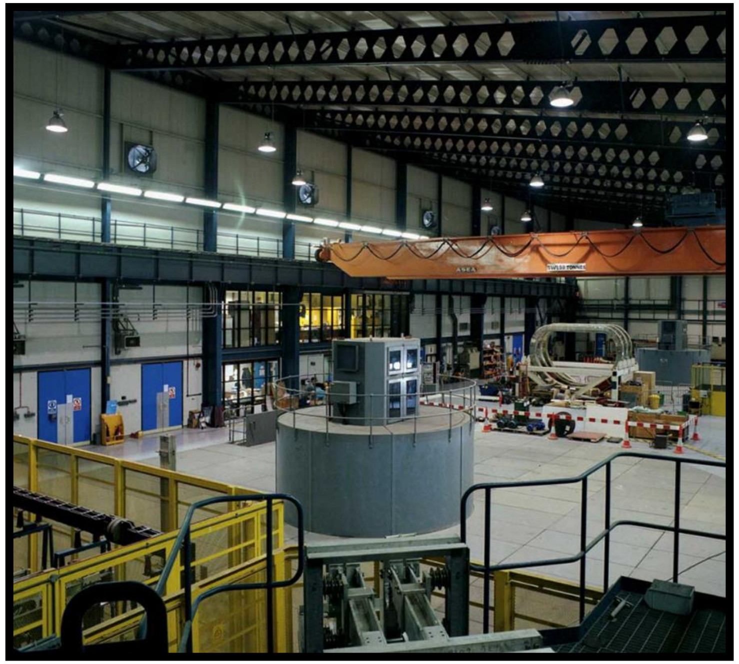


Energy Storage System Converters

UK Atomic Energy Authority

ESS key considerations:

- Power electronics are required to form the interface between the ESS (DC) and the site electrical distribution system (AC).
- The converters must be fully controllable to ensure grid compliance.
- Current candidate technologies for SPP's ESS are:
  - Batteries
  - Flywheels
  - Supercapacitors
- The interface must be linked to a wider plant energy management system.
- Possibility of providing grid services during non-operational phases of SPP lifetime.



Challenges and Opportunities

UK Atomic Energy Authority

Challenges:

- High performance power supplies needed:
  - Reliability
  - Reactive power
  - High efficiency
- Low available footprint near tokamak machine.
- Highly dynamic loads.
- UK supply chain.
- High volume required.

Opportunities:

- The STEP programme is the centrepiece of the UK government strategy to stimulate a UK fusion supply chain.
- Fusion is a new market with new business development.
- Possible commercialisation of technologies to other sectors.
- Power semiconductor device technology and packaging.

Conclusions

UK Atomic Energy Authority

- Fusion energy can create a new source of electrical power.
- There are multiple fusion reactors in construction around the world and many in concept design stage.
- STEP will be the UK's flagship fusion programme.
- Power electronics systems are a key technology for control and operation of fusion power plants.
- There are several technical challenges to surpass.
- Demand of power electronic systems will stimulate new markets and skills.

UK Atomic Energy Authority

Thanks for your attention, I hope you enjoyed the CPE conference.

Please feel free to contact me with any questions or queries, finlay.christie@ukaea.uk

Thank you to Ioannis Antoniou and Eduardo Sato for their support.