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Challenges for the cryogenics of the UK Spherical Tokamak For Energy Production (STEP) programme.

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ABSTRACT

The Spherical Tokamak for Energy Production (STEP) is an ambitious programme to accelerate the delivery of sustainable fusion energy. The STEP programme will design and build the world's first compact fusion plant, based on the spherical tokamak, by 2040. STEP is currently in the concept design phase, to produce an outline of the whole power plant, with a clear view on how we will design each of the major systems.

Cryogenics are widely used in tokamak fusion reactors in three main areas. Firstly, to provide cooling to superconducting magnets for plasma confinement. Secondly, to provide the required level of vacuum in the plasma vessel through cryogenic vacuum technology. Thirdly, as part of the fusion fuel cycle, including matter injection, typically pellets of frozen cryogens, and cryogenic separation hydrogen isotopologues.

STEP will be providing power to the UK electricity network, which will present new challenges in the continuous operation of a fusion power plant and its cryogenics. The STEP cryogenic requirement will necessitate a cryo-plant on industrial scale and with a strong focus on efficiency.

The cryogenic challenges and potential solutions of STEP will be presented here.

Keywords: Cryogenics, Fusion.

1. INTRODUCTION

UKAEA is a non-departmental public body researching fusion energy and related technologies with the aim of positioning the UK as a leader in sustainable nuclear energy. UKAEA's mission is to deliver sustainable fusion energy and maximise scientific and economic impact.

The STEP programme is a staged programme to design and build the world's first compact fusion reactor, based on the spherical tokamak, by 2040. It will develop and identify solutions to the challenges of delivering fusion energy, benefiting from UKAEA's breadth of expertise and its suite of research facilities – RACE, Materials Research Facility, H3AT and Fusion Technology Facilities.

The STEP programme aims to:

- Build on UK global leadership in fusion;
- Deliver a prototype power plant by 2040;
- Prove the viability of fusion as a technology for generating electricity.

The UK government has announced £220 million of funding, launching STEP as a collaborative programme that combines the strengths of UKAEA with industry, universities and other organisations.

- Create an investible concept design
- Understand the market and how the reactor will be built
- Enable and inspire the UK's capability and capacity to deliver

After the concept design phase, it is expected that there will be increasing involvement of private-sector companies in the STEP programme, with the technology eventually transferred into the private sector for implementation and production.

The STEP concept design is progressing through a structured gated development process where the concept maturity levels are assessed. The current phase involves examination of many potential concepts in the available trade space and selection of a preferred concept in this year.

2. STEP POWER BALANCE

The target for the STEP prototype plant is to produce 100 MW of net power to the UK electricity network. The fusion power generated by the tokamak will be significantly larger than this to accommodate the losses associated with converting this fusion power into electrical power and the power required to operate the equipment of the plant. This is shown in Figure 1.

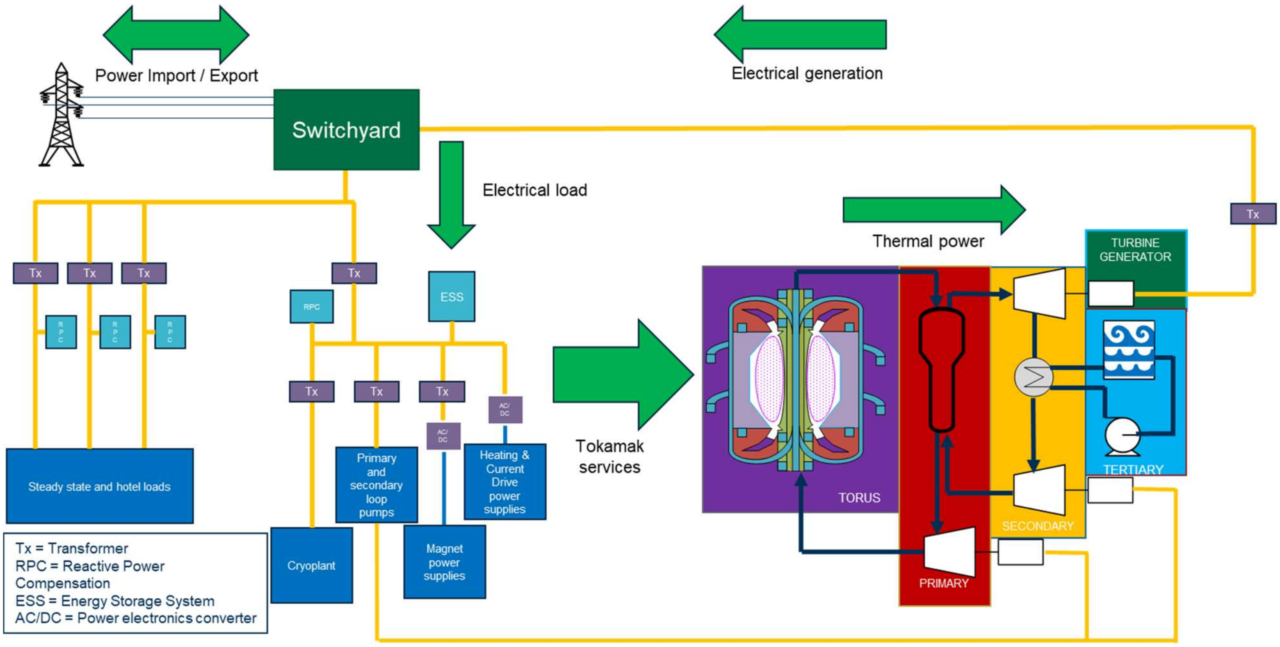


Figure 1, STEP Power Balance Block Diagram

The power required to operate the cryogenic plant normally accounted for as part of the parasitic loads of the plant, but is separated out in Figure 2. Note, HCD refers to Heating and Current Drive systems for the plasma. To maintain the net electrical power output of the plant an increase in fusion power of between 3 and 4 W is required for each additional 1 W of parasitic power.

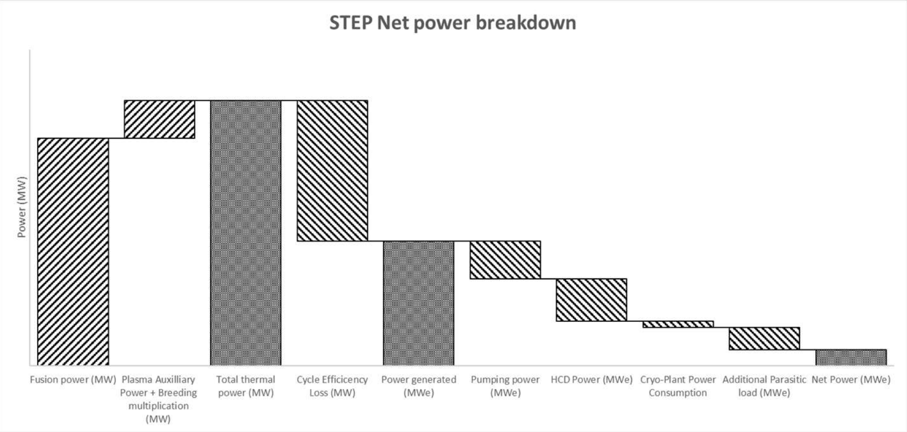


Figure 2, STEP Net Power Breakdown

There is strong pressure to minimise all parasitic loads on the plant. The cryogenic plant must be optimised for efficiency for the STEP prototype plant and also for commercial fusion power plants to be successful.

3. CRYOGENICS IN STEP

The STEP plant will require cryogenics for three primary purposes, plasma magnetic confinement, vacuum pumping, and fuel cycle.

3.1. Magnetic Confinement

The tokamak plasma is primarily contained and manipulated using large magnetic fields. The long plasma pulse duration of a fusion power plant and high magnetic field requirements of the spherical tokamak would see resistive magnets produce significant electrical power loads onto the plant. Superconducting magnets avoid the significant power loads, however they must be cooled to cryogenic temperatures, which creates additional plant power loads.

The STEP confinement magnets will use high-temperature superconductor (HTS) technology. These present advantages over low-temperature superconductor (LTS) technologies. Principally the capability of HTS to perform in higher magnetic fields than LTS, and the elevated temperature present significant advantages over LTS, as shown in the schematic by Bussmann-Holder and Keller (2020) in Fig. 3.

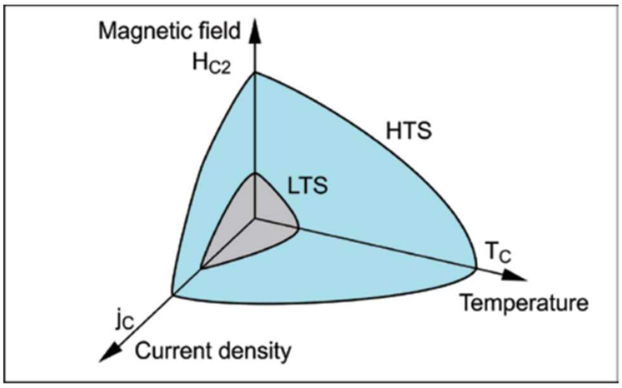


Figure 3, Schematic diagram of the critical parameters (critical temperature T_c, critical current density j_c, and upper critical magnetic field H_c) of a superconductor (LTS, low-temperature superconductor; HTS, high-temperature superconductor).

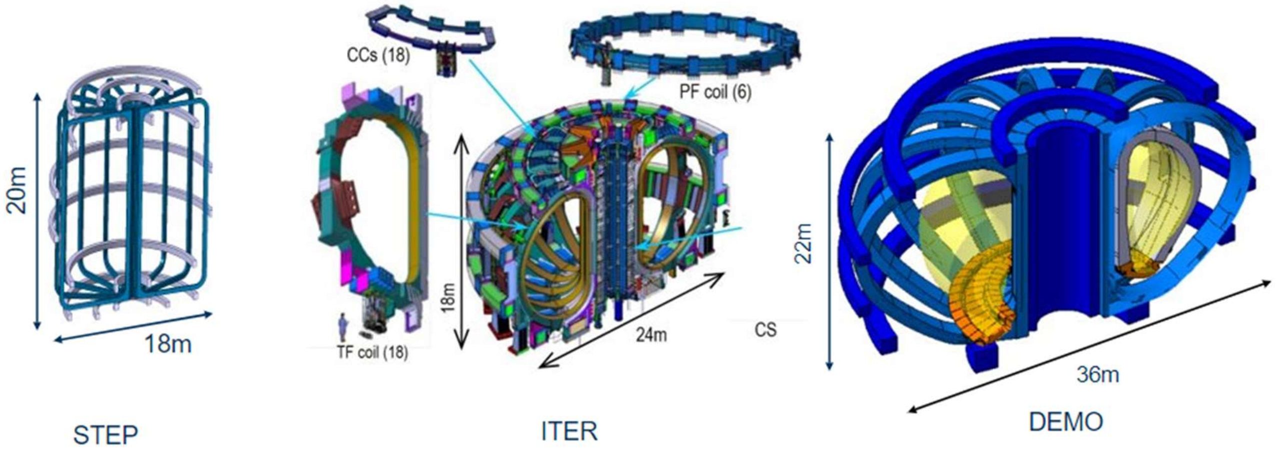


Figure 4, Approximate geometry and sizing of confinement magnet systems of STEP, ITER and DEMO.

The size of the STEP magnetic confinement system is compared to ITER and DEMO in Fig. 4. The coils will be made of multiple turns of a REBCO based cable with cooling channels allowing the flow of supercritical helium gas for cooling purposes. STEP will include re-mountable joints with the toroidal field (TF) magnet system to enable the positioning and removal of components within the TF magnet cage, such as poloidal field (PF) magnets and the plasma containing vacuum vessel. A central solenoid (CS) magnet is also expected to be included.

The HTS magnets provide the opportunity for higher operating temperatures for the confinement magnets than typically used with LTS magnets. The temperature of 20 K has been chosen as a balance of cost and performance. The confinement magnet system will experience 3 primary heat loads, neutronic, AC (alternating current) losses and ohmic heating in joints.

Neutronic heating is caused by neutrons and gamma rays emitted from the plasma colliding with the magnet conductor. This is highest in the central column of the TF coil set and the CS magnet. The spherical tokamak concept produces a high demand on minimising the radial build of the central section and it is not possible to produce a working design with enough shielding to eliminate the neutronic heating of the magnets. The high heat flux in the central section and sudden introduction of the heat load present challenges to the cryogenic cooling circuit.

Electro-magnetic heating, known as AC losses, caused by rapidly varying the current in a coil or the magnetic field imposed on a coil may cause high heating of coils during start-up and plasma operation. In the case of plasma start-up there are significant changes in field and operating currents in the CS. The rapid field changes can cause significant temperature rises in the CS itself and nearby PF coils and TF central column. During operation there will be smaller amplitude, high frequency changes in PF and CS magnet current which can create an effective steady state heating which must be allowed for in the cooling specification. Plasma instabilities and disruptions may also require large amplitude, high frequency changes in the PF and CS magnet currents.

The TF coil set re-mountable joints will produce ohmic heating as the current is passed from one superconductor, through resistive materials and their interfaces to the next superconductor. This ohmic heating will be determined by the design of the joint and the materials used. Variation in contact resistances can be significant and there is significant work being carried out to address this. The key cryogenic challenge is the high heat flux that must be achieved to remove heat from the joint within a small spatial envelope of the joint design.

In addition to these there will be heat loads from thermal radiation and thermal conduction from room temperature. Thermal shields will be provided with cryogenic cooling, at around 100 K, to minimise the thermal radiation. Thermal intercepts on the gravity supports will be cryogenically cooled to similar temperature as the thermal shields. Magnet current feeders will require cryogenic cooling to transfer current form room temperature power supplies to the cryogenically cooled magnets. The magnet cool down to cryogenic temperature and warm up will also need to be managed.

3.2. Fuel Cycle

The STEP programme requires a fuel cycle to ensure adequate fuelling of the plasma in order to produce net electricity. Tritium and or deuterium fuel must be injected into the tokamak plasma where it produces helium and energy. Exhaust is extracted from the outlet of the plasma, then separated to retrieve the deuterium and tritium for reinjection to complete the cycle. A closed cycle with fast turnaround is essential for power plant operation. Cryogenics application for fuel cycle includes, vacuum pumping, matter injection, isotope adjustment, and tritium extraction and purification. The processes and technology to be used by STEP are yet to be finalised, some examples are discussed below.

Cryo-pumps are commonly used in tokamaks to maintain the vacuum within the plasma chamber, and to capture tritium and deuterium from the plasma exhaust. STEP cryo-pumps operate at higher temperature than typical tokamak cryo-pumps in order to simplify the exhaust processing by avoiding the capture of helium. Temperatures in the order of 15 – 25 K will be used to capture and separate hydrogen isotopes on the cryo-panels. Higher temperature panels are used to capture waste molecules which will not be processed and turbo molecular pumps will be used to remove helium molecules. Cryo-pumps must be regenerated, by thermal cycling, to release the captured molecules. To obtain steady state operation, pumps are regenerated in batches. The temperature and high turnaround times during operation are novel in the use of cryo-pumps.

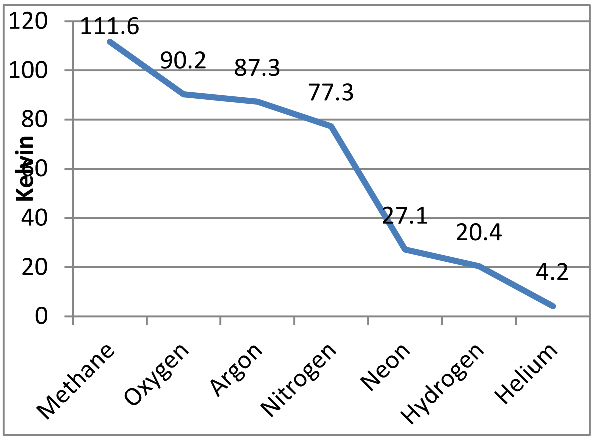
Matter injection is achieved by firing frozen pellets of hydrogen, deuterium, tritium and other seeded impurities into the plasma. The production of these pellets requires cryogenics and the number, distribution and high production rate will be challenges in their design.

Isotope adjustment, tritium recovery and purification can be accomplished with a combination of cryogenic distillation, thermal cycling adsorption process (TCAP), cryogenic molecular sieve bed (CMSBs), and cold traps.

Cryogenic distillation required continuous flows of cold helium gas around 20 K. TCAP is a process involving thermal cycling within cryogenic temperature ranges and from cryogenic to above room temperature ranges. CMSBs and cold traps typically operate around liquid nitrogen temperature and require thermal periodic cycling for regeneration.

4. Cryogenic Plant Operating Requirements

The cryogenic cooling within the tokamak must be achieved using helium gas. The common cryogens with their boiling points are shown in Fig. 5. Of these methane and hydrogen are problematic due to tritium permeation and exchange. Nitrogen produce radioactive isotopes when exposed to neutron and gamma radiation, so cannot be used. This leaves helium as the only practical cryogen for use at the desired operating temperatures.



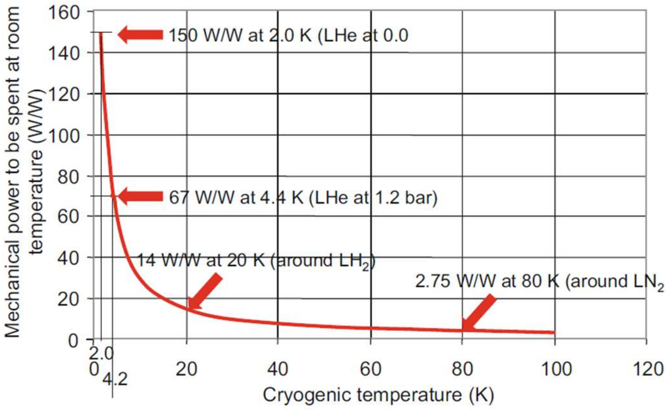


Figure 5, Boiling points of common cryogens at atmospheric pressure

Figure 6, Energetical cost of isothermal cryogenic power, Gistau Baguer (2020)

The operating temperature of the confinement system and cryo-pumps for STEP are higher than used in other superconducting tokamaks. The relationship between room temperature compressor power and cryogenic operating temperature is well known and Fig. 6 shows the plot from Gistau Baguer (2020). We can see that by choosing an operating temperature of 20 K provides a power saving of approximately a factor of 4.8, compared to operating at 4.2 K, although the cryo-plant operating temperature will be lower than this to account for heat transfer in the distribution system.

At this stage of the project it is assumed that a single cryo-plant will provide the required cryogenically cooled helium gas for all STEP requirements. A distributions system will send the cryogenically cooled helium gas to the area it is needed. A primary cooling circuit will provide cooling directly where needed at higher pressure and mass flow than the refrigerator helium flow. This primary circuit will interface with the refrigeration circuit, through a heat exchanger. Cryogenically cooled supercritical helium, with no phase transition, will be used.

When tokamaks are designed for operation at liquid helium temperatures, a liquid helium bath is often incorporated in the cooling circuit even if the item itself is cooled with supercritical helium. This arrangement is used on ITER as described by Serio, L. and shown in Fig. 7. The liquid helium bath disconnects the refrigerator from the primary cooling circuit and prevents large temperature changes during periods of high transient heat load. With operation of STEP at around 20 K, the use of liquid helium would be highly inefficient and an alternative method of isolating the refrigerator from transient heat loads will be required.

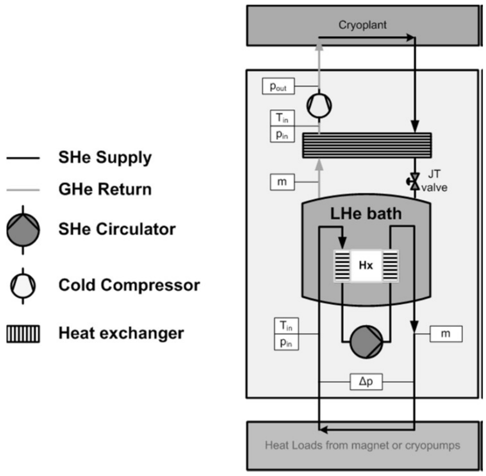


Figure 7, ITER magnets and cryopumps cooling scheme, Gistau Baguer (2020)

5. CONCLUSIONS

The primary challenges for cryogenics of the STEP programmes are presented here. A large scale, highly efficient and flexible cryo-plant is required to meet the needs of STEP. STEP will require significant engagement with the cryogenics research community and industry to address these challenges.

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