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Smaller and quicker with spherical tokamaks and high-temperature superconductors

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Research in the 1970s and 1980s by Sykes, Peng, Jassby and others showed the theoretical advantage of the spherical tokamak (ST) shape. Experiments on START and MAST at Culham throughout the 1990s and 2000s, alongside other international STs like NSTX at the Princeton Plasma Physics Laboratory, confirmed their increased efficiency (namely operation at higher beta) and tested the plasma physics in new regimes. However, while interesting devices for study, the perceived technological difficulties due to the compact shape initially prevented STs being seriously considered as viable power plants. Then, in the 2010s, high-temperature superconductor (HTS) materials became available as a reliable engineering material, fabricated into long tapes suitable for winding into magnets. Realizing the advantages of this material and its possibilities for fusion, Tokamak Energy proposed a new ST path to fusion power and began working on demonstrating the viability of HTS for fusion magnets. The company is now operating a compact tokamak with copper magnets, $R_0 \sim 0.4\,\mathrm{m}$, $R/a \sim 1.8$, and target $I_p = 2\mathrm{MA}$, $B_{t0} = 3\,\mathrm{T}$, while in parallel developing a 5 T HTS demonstrator tokamak magnet. Here we discuss why HTS can be a game-changer for tokamak fusion. We outline Tokamak Energy's solution for a faster way to fusion and discuss plans and progress, including benefits of smaller devices on the development path and advantages of modularity in power plants. We will indicate some of the key research areas in compact

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tokamaks and introduce the physics considerations behind the ST approach, to be further developed in the subsequent paper by Alan Costley.

This article is part of a discussion meeting issue 'Fusion energy using tokamaks: can development be accelerated?'.

1. Introduction

The basis of the Tokamak Energy approach to fusion energy is exploiting two emerging technologies to open up the possibility of making more compact machines. These technologies are the efficient 'spherical' tokamak (ST) shape and high-temperature superconductors (HTS).

(a) Spherical tokamaks

STs are low aspect ratio—they have a squashed, compact shape, like a cored apple rather than a ring doughnut. The concept was pioneered in the UK in the 1990s by two of the Tokamak Energy founders, Alan Sykes and Mikhail Gryaznevich. Theoretical work such as that by Sykes [1] and Peng & Strickler [2] had indicated that there could be advantages to the ST shape, particularly that low aspect ratio would optimize beta (β), the parameter in tokamaks that gives a measure of the efficiency of the machine. The START tokamak was built at Culham to investigate this. It operated from 1991 until 1998 and achieved world record levels of plasma beta [3,4]. Its successor was MAST, similar in design—with an outer cylindrical vacuum tank and internal magnetic coils—but bigger. For a comparison of the main parameters, see figure 1.

STs have several advantages:

Efficiency. Being closer to the centre column where the magnetic field is generated, they make more efficient use of the magnetic field than conventionally shaped tokamaks and can achieve higher β.

Stability. ST plasmas are more stable at high elongation because they take the more efficient, elongated plasma shape naturally without artificial stretching, which can make plasmas more susceptible to vertical instability [5]. See, for example, the difference between the natural elongation of the plasma at high- and low aspect ratio in figure 2. (It should be noted, however, that while STs generally have better vertical stability properties due to higher natural elongation, vertical growth rates also depend on the design of the machine, particularly the passive stabilization. For example, a unique combination of effects in MAST leads to strong nonlinearity of vertical instability [6].) In addition, the compressed geometry means particles spend a greater portion of time on the inboard side of the plasma where the magnetic field is high, and the field line curvature acts to stabilize instabilities driven by the pressure gradient.

Higher bootstrap current. Bootstrap current is a toroidal current in the plasma generated by the interplay between trapped and passing particles in the presence of a density or temperature gradient. More information can be found in [7]. Wilson *et al*. [8] derived an approximate scaling for bootstrap current fraction and showed that bootstrap fraction increases with normalized beta β_N and higher elongation, both of which are naturally higher in an ST. A higher bootstrap fraction means a lower requirement for expensive non-inductive current drive.

Lesser disruptions. Evidence suggests that disruptions in STs produce lower halo currents than those in conventional tokamaks, and that the halo currents are more uniform in distribution [9,10].

Improved confinement. STs may exhibit better confinement than conventional tokamaks [11] though more experiments are needed to verify this.

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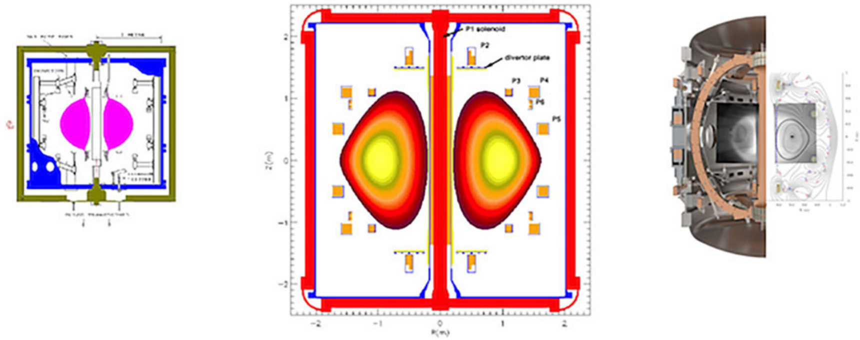

	START	MAST	ST40
major radius R_0	~0.32 m	~0.8 m	0.4 m
aspect ratio R/a	1.3	1.3	1.8
max centre column current	0.5 MA	2.2 MA	6 MA
max $B_t(R_0)$	0.31 T	0.55 T	3 T
plasma current I_p	<310 kA	1.35 MA	target 2 MA

Figure 1. Images of the START, MAST and ST40 STs and their main parameters. Images: EUROfusion, Tokamak Energy.

Despite the advantages of the ST design, in the START and MAST days the concept was accepted as theoretically interesting but was dismissed as a contender for a fusion power plant because of the lack of space in the centre of the machine. This meant that it would be too difficult to generate the high magnetic fields required for fusion while also protecting the centre column from neutron bombardment with sufficient shielding [12]. This remains a challenge, but advancing technologies such as improved materials are beginning to have an impact.

(b) Conventional tokamak development

Concurrent with progress on START and MAST, the JET tokamak (a conventional tokamak) was also performing well and achieved world record fusion power in 1997 (16 MW, $Q_{\text{fus}} = 0.65$). Progress towards fusion conditions nT $\tau > 3.10^{21}$ m^{-3}keVs had been fairly steady since the 1960s, but the energy confinement time τ still needed to be increased further, see Fig. 26 in [13]. ITER was designed as the next-step fusion device after JET—a worldwide collaboration to deliver fusion energy.

When designing ITER, it was known that increasing magnetic field would lead to better plasma confinement via the possibility of operating at higher current while staying below the beta limit. But the magnetic field is an expensive part of the machine and is subject to engineering restrictions (conventional copper magnets would consume too much power for a reactor; low-temperature superconducting magnets are limited in the current they can carry and also require a lot of thermal shielding). However, experimental scalings for energy confinement time showed other plasma and device parameters that could be adjusted to improve confinement, with the main dependences as follows [14]:

$$(\tau_E)_{\text{scaling}} \propto \frac{I_p R^2 n_e^{1/2}}{A^{1/2} P_L^{1/2}}.$$

Here R and P_L are the major radius and total power loss, respectively, $A = R/a$ is the plasma aspect ratio and n_e is the electron density. Clearly, increasing device major radius increases the projected confinement time. Additionally, the negative beta dependence of τ in the scaling laws

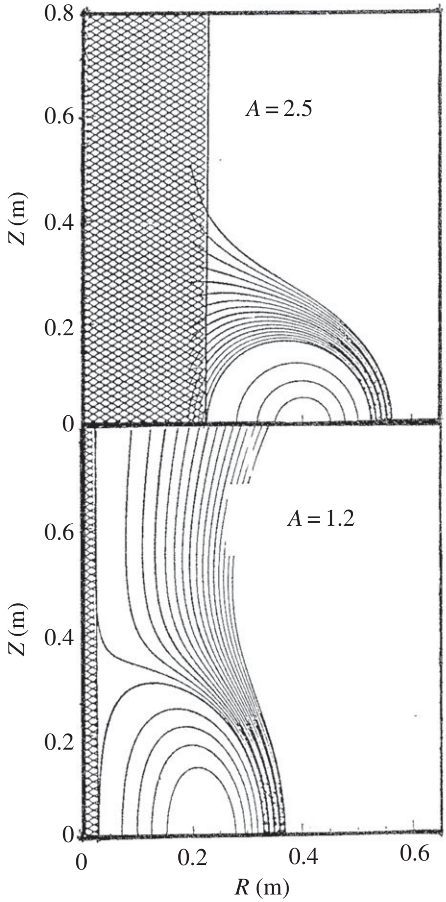

Figure 2. Comparison of natural elongation in a conventional tokamak and ST. Low aspect ratio STs (bottom) exhibit natural elongation because the close proximity of the centre column and the opposite side of the plasma forces the plasma away and flattens its inboard edge, elongating the plasma with no contribution from the external magnetic field. Image: A. Sykes.

used to design ITER suggested the use of powerful devices operating at high/moderate field and current, which would have to be large in order to handle the high power. (Experiments since have suggested that the scaling could in fact be β independent, which could have significant impact on the optimization of tokamak fusion performance [15].)

ITER was designed to be two to three times larger than JET in linear dimensions, with a 10-fold increase in plasma volume. The main ITER design parameters are $R = 6.2\,\text{m}$, $V \sim 850\,\text{m}^3$, B_T(at R) = 5.3 T. The unique international nature of ITER along with its size and engineering complexity have resulted in cost over-runs and delays, and led some researchers to consider alternative approaches, particularly as new technologies have become available over the intervening timeframe.

(c) High-temperature superconductors

One of these technologies is the 'high-temperature superconductor' and at Tokamak Energy we believe that this could be the key enabling technology that produces the large magnetic fields needed for economical fusion power. HTS could be the game-changer for fusion. This class of materials—a ceramic—has been around since the 1980s, but it is only recently that the superconductor has been fabricated in such a way that they can be wound into coils. Commercial

HTS is manufactured as a thin HTS ceramic layer on a high-strength steel tape, with a coating of copper.

Superconductivity is the property of certain materials to lose all resistance when they get cold enough, conventionally around 4 K (−270°C). Second-generation HTS start to work at around 90 K (−180°C) [16], but their performance improves as they are made colder. Operation at 20–40 K allows a huge saving in cryogenic cooling power compared to conventional 4 K operation.

For steady-state tokamak operation, the magnetic coils will have to be superconducting. Tokamaks such as ToreSupra (now WEST) in France and EAST in China operate with superconducting coils of niobium titanium [17,18], and ITER will use niobium titanium (poloidal field and error field correction) and niobium tin (toroidal field and central solenoid) for its superconducting magnets [19].

HTS can carry very high current density at high magnetic fields (well above 20 T), so they can generate a higher confinement field than conventional superconductors in a smaller device. Moreover, they can do this at intermediate cryogenic temperatures and their construction means they take up less space, thereby providing the possibility to reduce centre column diameter and hence device size.

Advantages of HTS:

High current density at high field. HTS has a higher critical current density (i.e. the current per unit area at which the superconductor ceases to be a superconductor) and so can generate and withstand higher fields.

Power savings. Operating at higher cryogenic temperatures offers a significant energy saving. Tokamak Energy plans to operate future HTS tokamaks at between 20 and 40 K, which offers up to a fivefold energy saving over conventional superconductors.

Low-profile construction. The high current density of HTS means that a smaller centre column is possible, releasing space for structural support and shielding, and so offering the possibility of smaller devices.

Better flexibility and easier maintenance. High-temperature operation makes it possible to tolerate a higher heat leak so the system is easier to manage and control.

An engineering consideration for future power plant design is the additional structural support that would be necessary to counteract the higher forces associated with the higher magnetic fields attainable using HTS. The stresses on the centre column are particularly important. Study is underway in this area at Tokamak Energy, alongside other engineering considerations, and these are detailed in [20].

2. The tokamak energy approach

The basic approach being taken by Tokamak Energy is simple—to combine the two aforementioned technologies to unlock the potential of fusion power in more compact devices, and to do whatever development, testing and iteration are necessary on smaller machines in order to reduce construction timescales and to progress faster.

Smaller reactors along the development path could accelerate commercialization by allowing for rapid and adaptable development while reducing the risk associated with a first-of-a-kind reactor. A modular reactor design for future power plants is also being investigated, as outlined by Thomas at this meeting [21] and in [22]. A gigawatt-scale power plant consisting of a number of lower-power modules would have the advantages of factory production (including cost reductions from economies of scale and economies of multiples) and more flexible plant operation.

Over the last several years, Tokamak Energy has been building up evidence for the compact fusion approach.

Costley *et al*. [14] used a system code to explore possible steady-state, high gain fusion devices. They showed that when the plasma was operated in a steady state within reasonable fractions of the Greenwald density limit and the Troyon beta limit (say 0.8 and 0.9), then the fusion energy gain $Q_{fus} = P_{fus}/P_{in}$ depends mainly on the absolute level of the fusion power and the energy confinement. It only depends weakly on the device size. The scaling law used also has a strong effect on Q_{fus}. An alternative, beta-independent scaling law may be more appropriate than that used to design ITER (the IPB98y2 scaling, usually known as the 'ITER' scaling) because it fits the multi-machine experiments almost as well but also agrees with the beta-dependence obtained in the single-machine experiments. A recent major review of JET results in support of ITER [23] confirmed the beta-independence, which is positive because it means that confinement time τ in ITER should be better than originally predicted, and it indicates that smaller, low-power reactors may be a possibility.

A follow-up paper by Costley [24] further investigated this result analytically and showed that any advantage that increased size confers by the way of increasing $nT\tau$ is eliminated by a conflicting effect of the operational limits. Thus, the fusion gain of a tokamak is only weakly linked to the size of the reactor, contradicting traditional assumptions that have steered worldwide research efforts towards larger devices until now. Lower power, smaller (and thus potentially lower cost) reactors may indeed be possible.

The important result of this work is that energy gain Q_{fus} can be high in small reactors with low fusion power (approx. 100 MWe), and that these kinds of smaller devices on the development pathway would lead to quicker and cheaper development iterations and faster progress. Costley goes into further detail in his contribution to this meeting [25].

Tokamak Energy is not alone in considering the application of HTS materials to fusion. Researchers at MIT have published papers on a design that combines a JET-sized compact shape with HTS magnets, dubbed the ARC reactor [26] that is part of their 'smaller and sooner' route to fusion energy. Dennis Whyte provided further information about ARC and the smaller SPARC [27]. The MIT work provides opportunities for collaboration as well as giving confidence in our approach.

3. Key research areas

Tokamak Energy has developed a roadmap for the 'faster fusion' approach, which includes several key research areas on the path to commercialization. Some will be proprietary; most will be collaborative. The roadmap is addressed in greater detail by Costley [25]; what follows is a summary of key areas.

Tokamak Energy has demonstrated capabilities with a small tokamak called ST25 ($R_0 = 0.25$ m), and in 2015 showed the potential of HTS materials as tokamak magnets when plasma was held for 29 h in the fully-HTS upgrade ST25HTS. The company is now operating ST40, a compact tokamak with copper magnets, $R_0 \sim 0.4$ m, $R/a \sim 1.8$, and target $I_p = 2$MA, $B_{t0} = 3$ T, while in parallel developing a 5 T HTS demonstrator tokamak magnet.

ST40 is designed to investigate plasma behaviour and energy confinement in a high-field, low-aspect ratio domain. It uses the technique of merging compression [28], pioneered on the START and MAST tokamaks at Culham [29], to heat the plasma during start-up. ST40 is aiming to achieve 10 keV temperatures at densities approximately 1–5.10^{20} m^{-3} within 2 years, perhaps using NBI or ECRH for additional heating. If successful, this would be an exciting achievement, showing that it is possible to attain fusion conditions in a significantly smaller machine than previously imagined.

A key development at Tokamak Energy is that of HTS tokamak magnets. Working with tapes from different suppliers we are establishing handling, construction and operational techniques on small magnet prototypes with a view to creating a full-scale tokamak magnet. This knowledge will feed into our future pilot plant, which will use HTS magnets.

Another key area of research is neutron shielding. In a power plant, many high-energy neutrons will be produced and significant knowledge gaps remain around HTS irradiation and magnet protection. An efficient neutron shield must be designed to protect the centre column from heat deposition and to reduce radiation damage, but a difficulty created by reducing tokamak reactor size is the lack of space for shielding materials. Work by Colin Windsor *et al.* suggests that a shield comprising layers of tungsten carbide separated by cooling water could provide good shielding capabilities, and they are working on optimizing the neutron shielding to reduce the thickness required [30]. Further numerical studies [31], aimed at improving performance of the shielding, have investigated the relative thickness of the water layers and also found that the use of tungsten boride instead of tungsten carbide near the core made a positive difference. They find that each increase of shielding thickness by 0.307 m reduces the power deposition by an order of magnitude. Increasing the plasma radius also decreases power deposition. On-going design work attempts to find the optimal size of a future power plant—balancing cryogenic requirements, mechanical engineering limits and the general engineering considerations pertaining to parameters such as costs and lifetime.

Further work, often collaborative, will investigate plasma control, disruptions and mitigation, heat and particle exhaust, divertor loads and bootstrap current as we work on optimizing ST40 performance. This will lead into tritium breeding/handling and advanced technology development, including energy harnessing, as we progress from fusion power demonstration to full electricity generation.

4. Summary

The Tokamak Energy approach combines HTS magnets with the more efficient ST shape to develop compact fusion machines. HTS could be a game-changer for fusion by enabling tokamaks with high magnetic fields and improved plasma confinement without needing to unduly increase plasma volume. HTS opens up an ST route to fusion power with the possibility of smaller, modular machines that are cheaper and more flexible.

The evidence for this ST route to fusion power is strong and we believe that progress can be more rapid than on the conventional route. Since decarbonizing global energy supply is now a pressing concern, we believe that we have an obligation to pursue this route in an attempt to accelerate the development of fusion energy for the benefit of all.

Data accessibility. This article has no additional data.

Competing interests. I declare I have no competing interests.

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