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Spherical tokamaks for compact fusion energy

Colin Windsor, Alan Sykes, Melanie Windridge, Steven McNamara and Giorgio Locatelli discuss the science of compact fusion energy alongside the engineering challenges and economics considerations of the development and operation of modular fusion reactors

In 1955 John Lawson, working at Harwell, defined a condition for fusion power. His condition was the triple product of plasma density n, temperature T and energy confinement time τ_E. Lawson determined that the condition $nT\tau_E$ >3.1021 keVsm^{-3} must be met for fusion reactions to be self-sustaining [1]. The task of fusion research since then has been to approach his fusion condition, but the progress towards it in the last two decades has been slow. Spherical tokamaks could potentially offer a faster route to fusion power through smaller, more compact machines. The triple product can be written as $nT\tau_E \,\alpha\, \beta B_T^2 \tau_E$, which shows that there are three crucial parameters. Having each term as large as possible assists in achieving the Lawson condition. The parameter β is the ratio of the plasma pressure to the magnetic field pressure. It is an important measure of the efficiency of a tokamak. B_T is the toroidal magnetic field along the plasma path. The plasma energy confinement time τ_E defines the time at which heat is lost from the plasma. It scales with size – just as the rate of heat loss from a tea-cup is greater for small cups than for large ones.

These three factors lead to three options for taking fusion forward:
(i) Large size. This has been the option that the world has chosen to take by concentrating on the ITER project. It has a self-consistent design using the best low-temperature superconducting magnets available around 2001 when the design was finalised. But the ITER timescale has already taught us that large size is no easy option.
(ii) High field. This option was promoted by Bruno Coppi. It started with Alcator in 1969, included the FT-U at Frascati and culminated in Alcator C-mod, which sadly closed in 2016. The IGNITOR project, proposed in 1999, would produce a huge field of ~13T for short pulses (as the cooled copper

coils heat up), but long enough for ignition to be achieved. The difficulty with IGNITOR is to see how this concept could evolve into a long pulse fusion power plant.
(iii) High beta. This option uses the spherical tokamak geometry to raise the efficiency β, and so to obtain higher plasma pressure for a given magnetic field. In 1998 the START spherical tokamak team at Culham Laboratory in the UK achieved a breakthrough by reaching β values of order 40%, compared to the 6% or so achieved in JET or the 4% or so expected in ITER.

The high-beta, higher-field approach – spherical tokamaks and high temperature superconductors

Spherical tokamaks have several advantages. Compared to conventional, doughnut shaped devices, they are much more efficient at confining the plasma, largely due to their compressed geometry. In spherical tokamaks the plasma is concentrated close to the centre of the torus where the magnetic field is highest, as shown in Figure 1.

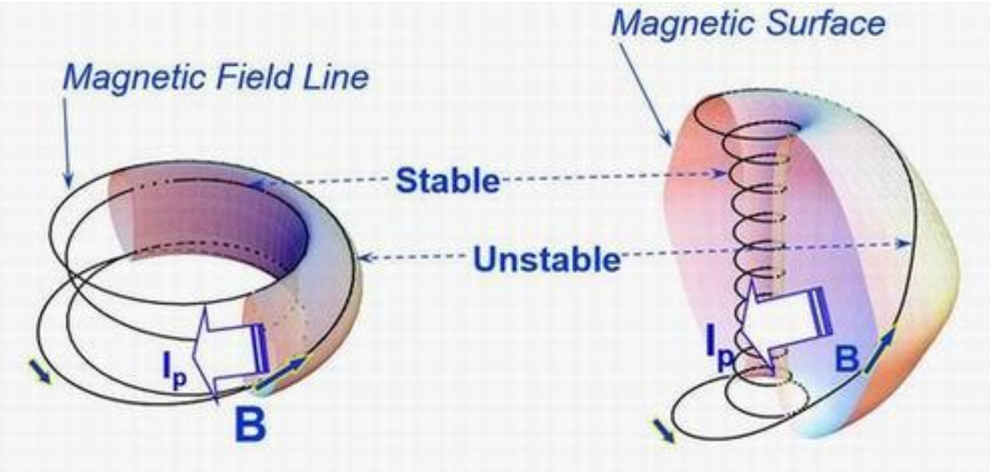


Figure 1: Illustration, copied with permission from Martin Peng, showing how the field lines in a spherical tokamak spend more time in the high field region close to the centre rod. This improves the stability and performance of the spherical tokamak.

Tokamaks have the remarkable ability to produce a self-driven plasma current, known as the bootstrap current. In a spherical tokamak the bootstrap current makes a larger contribution to the total current, reducing the need for expensive external current drive systems.

With these advantages, and following the impressive efficiencies of β= 40% achieved on START, several groups around the world considered the economics of a spherical tokamak power plant. The problem of spherical tokamaks is that they imply a slender central core, with minimal space for shielding. A copper centrepost using steady-state water cooling is feasible and can be replaced when neutron damaged. However all studies came to a similar conclusion: that the heat dissipated in the copper limited the toroidal field to around 2T, necessitating large plasma size for fusion gain. Using low temperature superconductors was not an option, as the large neutron shield to prevent neutron bombardment from heating the superconductor beyond the necessary

For short pulse research devices ohmic heating in a copper core is manageable by cooling the copper to liquid nitrogen temperatures, and allowing the core to heat up during the pulse. This is the option being explored in the ST40 tokamak currently being assembled at Tokamak Energy which was described in a previous Nuclear Future article [2]. The discovery of high temperature superconductor (HTS) materials by Bednorz and Muller in 1986 offered new possibilities. The change in operating temperature from 4.2 to 20 or 30K implied a factor of 5 or more reduction in cryogenic power and quite changed the viability of the plant. A fusion pilot plant could be built with a neutron shield thin enough to allow a relatively small device and thick enough to allow the HTS centre rod to be cooled by a cryoplant of acceptable size.

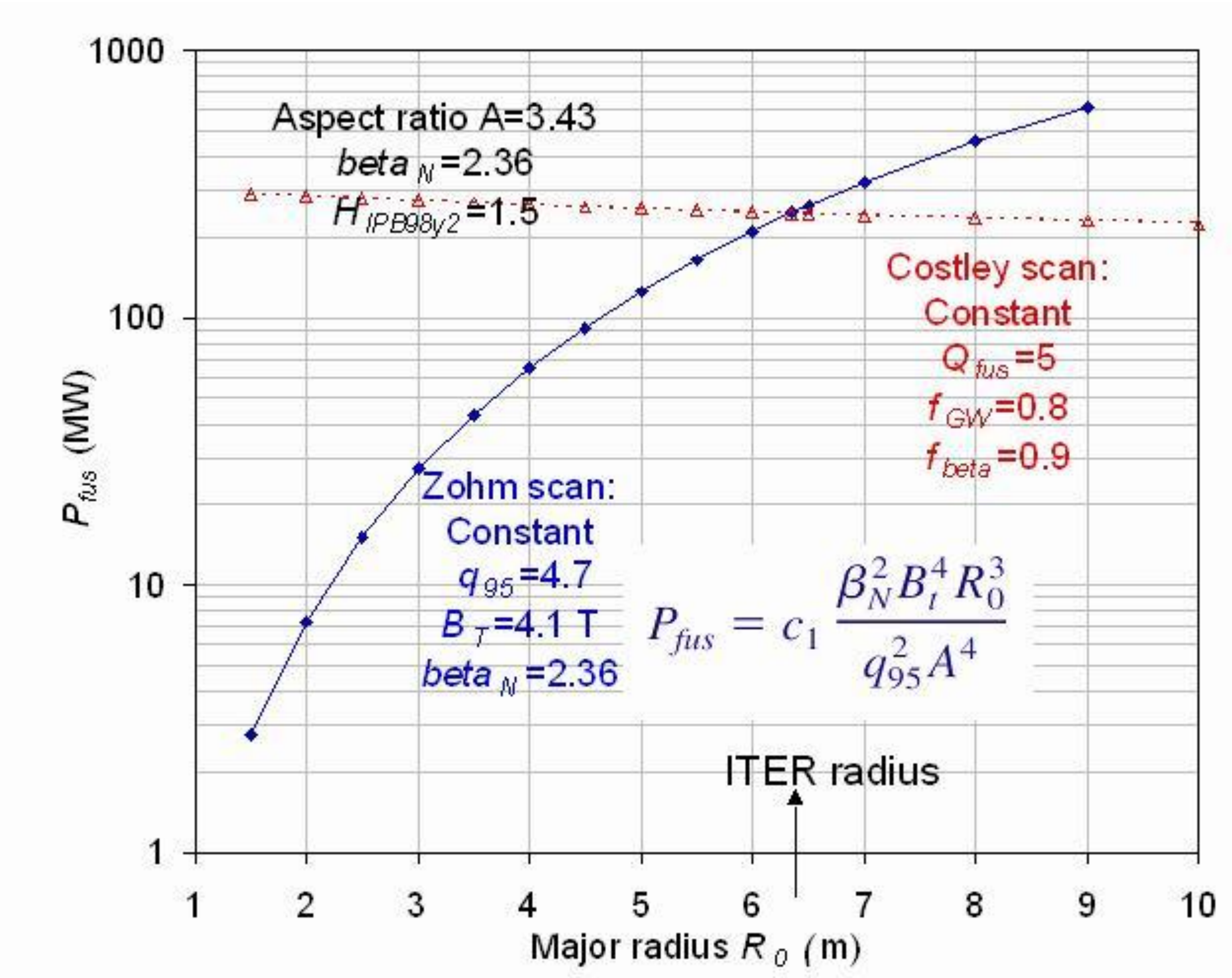


Figure 2: The fusion power *P_{fus}* in a conventional tokamak of aspect ratio *A*=3.43 as a function of plasma major radius for: in blue, the Zohm

assumptions of constant q_{95}, B_T and $beta_N$: in red the Costley assumptions of constant Q_{fus}=5, f_{GW}=0.8 and f_{beta}=0.9.

Tokamak Solutions was set up in 2009 specifically to explore the possibilities of spherical tokamaks using HTS magnets for neutron production. In 2014 the company became Tokamak Energy – to explore the prospects for fusion power with the same technology. How small could a fusion power plant be? The conventional view supporting large tokamaks is well described by Hartmut Zohm in his 2010 paper "*On the minimum size of DEMO*": the proposed demonstration fusion reactor [3]. As shown in blue in Figure 2, equation 1 of his paper says that when the normalised plasma pressure β_N, the toroidal field B_T, the safety factor q_{95} and the aspect ratio A are all kept constant, the fusion power increases as the 3rd power of the major radius. The case for large machines appeared strong.

Alan Costley, Figure 3, has had a successful career in fusion spanning over 40 years. After working on JET at Culham, Costley worked for 16 years within the ITER project in San Diego, Naka and Cadarache. When he retired from his last post as head of Diagnostics Division at ITER in 2013, he joined Tokamak Energy in a consultancy role.

Costley began his work on the size of tokamaks because he wanted to check for himself whether the HTS spherical tokamak scenario was likely to be a viable proposition. He set up his own system code, combining together all the known equations and limits for tokamak operation. After validation against other codes, he searched for viable solutions with smaller size.

Figure 3: Alan Costley

The crucial parameter for a fusion plant is the gain factor, Q_{fus}, which needs to be greater than one for energy breakeven, and large to make a viable power plant. Costley's idea was to make fusion gain Q_{fus} a constant input parameter to the calculations, so that the conditions leading to high fusion gain in a compact device could be more easily identified.

At the same time, he introduced checks to ensure that the wellknown limits to plasma stability were satisfied. Tokamaks are subject to operational limits, which mean that they will not work if an important variable exceeds a particular value. Take the density limit, for example. Generally, increasing plasma density improves performance – until we reach a point where the plasma suddenly collapses and confinement is lost. So Costley set the actual plasma density divided by the Greenwald limit f_{GW} to be at most 0.8, and set the normalised plasma pressure β_N divided by the Troyon beta limit f_{beta} to be at most 0.9. Since high density and high plasma pressure are both desirable for high fusion gain, the best plasma conditions would be those that would approach these limits.

A further condition Costley imposed was to do with the crucial parameter of energy confinement time τ_E. The "*H* factor" is the ratio of energy confinement time to its value predicted from scaling laws. Costley set it to be at an optimal defined value consistent with recent results from leading experiments.

What he discovered using this code surprised even him. The red dashed line in Figure 2 shows the nearly constant fusion power with plasma radius given by Costley's Tokamak Energy system code with the aforementioned assumptions and fusion conditions similar to a nominal ITER configuration. Under these conditions, the performance of the tokamak does not change with size. This was an unexpected result because traditional thinking was that as devices get larger their performance improves. As Costley and his colleagues have shown, this lack of improvement with size is due to the interaction of the positive size scaling in the confinement time with the negative size scaling in the operational limits, especially the density limit.

There was another unexpected and important finding from this work. Since it is not possible to determine the confinement time from first principles, scaling laws are developed based on large quantities of tokamak experimental data. In the early 2000s, it was thought that the confinement time scaled inversely with the plasma beta. However, dedicated experiments on several individual tokamaks showed that the scaling is almost independent of beta, and alternative beta independent scalings were developed. Costley and his colleagues examined the impact of these scalings and found that the power needed to achieve a significant fusion gain was a factor of two to four lower than previously thought necessary.

Combined with the result of the independence of the performance with size, this opens up the possibility of relatively small tokamaks operating at relatively low power but still achieving high fusion gain. This work was published in the Costley, Hugill, Buxton 2015 paper [4] with the important conclusion that, under his specified conditions, the fusion gain Q_{fus} depends on fusion power P_{fus} and on the *H* factor, but only weakly on size R_0. The paper caused a stir in the fusion community and has remained the most downloaded paper in nuclear fusion since its publication. Interest expanded with a second paper from Costley [5] in 2016 detailing the argument in the more familiar terms of the Lawson triple product. This paper soon reached number two in the nuclear fusion download lists.

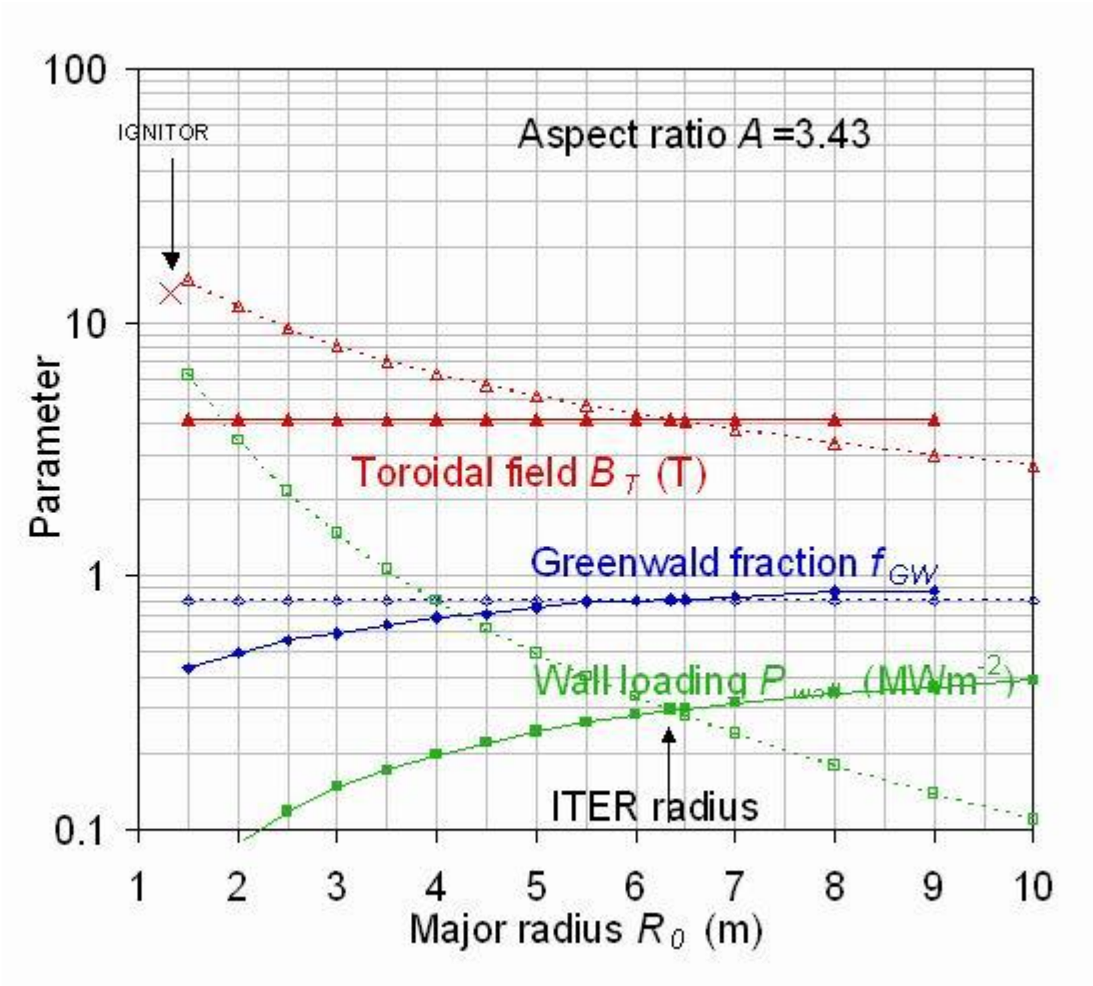
There is no criticism of the ITER design in Costley's results. ITER was designed using the available scaling laws and technology, especially the low temperature superconductors, around 2000. The superconductors required shielding of order 1m thick, and inevitably implied a large device. Spherical tokamaks were in their infancy at the time of the ITER design, as were HTS magnets. Costley's results imply that the performance of ITER will be better than originally expected because the device can operate at high fusion power.

A critical comment on this work was submitted by Biel *et al* [6]. Its argument centred on the differing parameters that were held constant in each scan: $ß_N$,B_T , *H* factor and q_{95} in the Zohm scan; and the fusion gain Q_{fus}, density and beta limit fractions in the Costley scan. A reply was also published [7].

Figure 4 shows other variables that help to understand why the two scans have such dramatic differences. For example, in the Costley scan the toroidal field B_T increases to keep the beta limit constant as the plasma radius decreases. The red cross pointed at by the arrow shows the toroidal field of the IGNITOR proposal mentioned earlier. Biel *et al* argued that the higher toroidal fields had long been known to lead to smaller fusion devices and this is certainly one factor contributing to higher fusion gain. But it is only part of the story – the impact of the beta-independent scaling is also important as Costley and colleagues have shown.

Biel *et al* [6] also argued that engineering constraints would limit any reduction in size. The wall loading P_{wall} is the power deposited on each square metre of the plasma wall. Decreasing the plasma radius eases the wall loading in the Zohm scan, as P_{fus} falls very rapidly as shown in Figure 2, but causes an appreciable increase in the Costley scan. Such considerations severely limit how much the plasma radius could be decreased. The DEMO wall load of 2.3 MWm^{-2} would be reached at a plasma radius just under 2.5 m within the Costley scan.

Figure 4. Plots of the



toroidal field, density limit fraction and wall loading, as they change (or remain constant) during the Zohm scan (full symbols and continuous lines) and Costley scan (open symbols and dashed lines). These plots are for the same large aspect ratio as in Figure 2.

The density limit fraction is maintained in the Costley scan while it decreases significantly in the Zohm scan as seen by f_{GW} in Figure 4. At a radius of 2 m in the Zohm scan, the Greenwald density limit fraction is only around 0.5 compared with the 0.8 of the Costley scan. The density is a critical factor in the Lawson criterion.

We conclude that, for conventional aspect ratio, smaller size fusion devices of Q_{fus} around 5 are inevitably of the high field IGNITOR type and have high wall loadings. However we will show that when applying the Costley scaling at the low aspect ratio of the Spherical tokamak much more promising solutions can be found.

What shape should a fusion power plant be?

The advantages of fusion power plants based on spherical tokamaks are demonstrated in Figure 5, which differs from figure 4 in being for a spherical tokamak with aspect ratio 1.8 and a correspondingly higher H factor of 1.9.

Results are calculated using the Tokamak Energy system code for a constant fusion gain of 5. In this study the fusion power P_{fus} is deliberately reduced to 200MW, to enable a smaller module which has high energy gain but at acceptable wall loading. Compared with Figure 3 the plasma radius scale is reduced by a factor 4 yet the toroidal magnetic field is actually less. The wall load power is generally larger and again increases with decreasing radius, but stays below the 2.3 MWm^{-2} limit for R_0 > 1.3 m.

Several engineering parameters are shown in Figure 5. The stresses caused by the current down the centre rod interacting with the toroidal field are compressive and roughly constant with radius, with values which are high but manageable. Another important parameter is the magnetic field at the outer edge of the superconducting conductor denoted by B_{cond}. If this field becomes higher than a limiting value, say 25T for HTS tapes held at 30K, then a quench may occur. The values of around 20 T of this field across the figure are large but acceptable.

For long-pulse operation, using HTS is the only option for a steadystate Spherical Tokamak. Then a key engineering parameter is the heat deposition into the central superconducting core P_{heat}. This is seen from Figure 5 to reduce exponentially with radius over a wide range. The 100 kW heating at radius 1.35 m is manageable. as the cryogenic power P_{cry}, is then some 5 MW, a small fraction of the 200 MW fusion power.

Another concern is the degradation of the HTS tape performance that may occur during irradiation from the neutron and gamma flux entering the central core after passing through the neutron shield. The full triangles in Figure 5 show the neutron flux above 0.1 MeV for the outer surface of the superconducting core as measured in the central mid-plane region where the flux is highest.

It remains an unanswered question how HTS tapes, held at 20 to 30K temperatures, will respond to the particular neutron flux energy distribution behind a neutron shield. Experimental studies have been performed by Eisterer and colleagues [9], to test the performance of irradiated HTS tapes in the Vienna TRIGA Mark II fission reactor. The neutron dose was estimated by placing a nickel foil adjacent to the specimens, and calculating the fast neutron fluence (E>0.1 MeV). Experiments were performed up to a neutron fluence of 3.9×10^{22} m^{-2}.

Their results showed that the critical current, when superconductivity was lost, actually increased for low fluences of order 10^{22} m^{-2}, but that at larger doses the critical current and critical temperature decreased. These results must be treated with caution as they were made at ambient temperatures rather than the 30K or so expected during operation. Superconductivity tests were done over temperature ranges from around 30K to 80K, and showed that below 60K, radiation improved conductivity. Above 60K, it reduced it. Clearly work is needed with irradiation fluxes closer to that expected behind the neutron shield of a fusion plant.

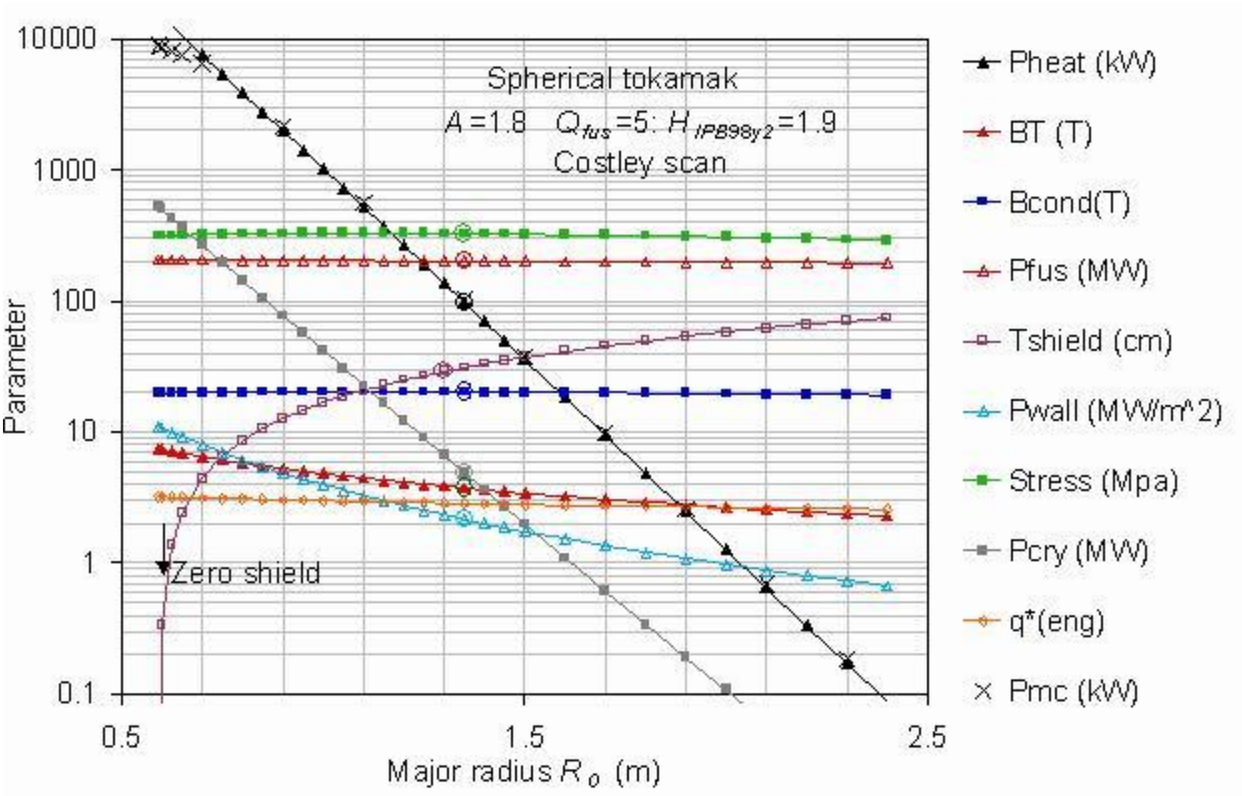


Figure 5. The radial dependence of plasma parameters for a spherical tokamak fusion module of aspect ratio A=1.8 and constant $H_{IPB98y2}$= 1.9. The central temperature adjusted to give 0.8 of the Greenwald density limit, and the toroidal field adjusted to give 0.9 of the beta limit. The extra space made available by increasing the major radius has been divided in the ratio 92% to the shield thickness T_{shield} and 8% to the HTS core radius across the plot. The crosses represent MCNP computations of P_{heat}. Further details of this scan are given in [8]

Accordingly, the black lines in Figure 6 showing the full power running time (in seconds) before the fluence reaches a value of 10^{23} m^{-2} must be treated with caution. However it suggests that a month continuous running of this 200MW module would be possible at 1.7 m radius and 10 years of running at 2.4 m.

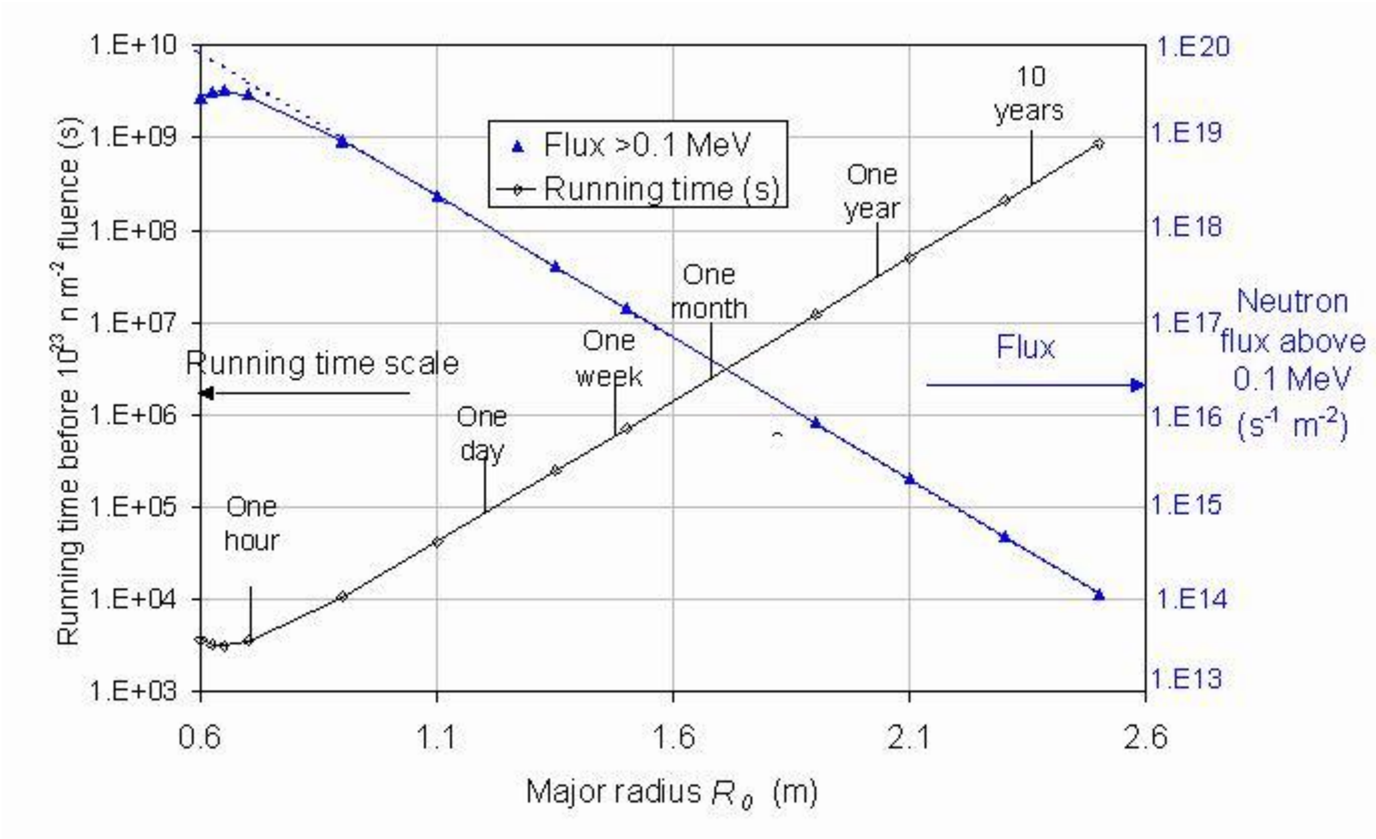


Figure 6. The calculated neutron flux across the outer surface of the mid-plane region of the superconducting core for neutron energies above 0.1 MeV is shown by the full blue triangles (right-hand scale). The number of seconds of continuous full power running which correspond to a total neutron fluence of 10^{23} m^{-2} are shown by the open diamonds (left hand scale).

From these studies, it appears that a ST fusion module of around 100-200 MW fusion power and with useful fusion gain should be viable; the main uncertainty being the lifetime of the HTS tape under neutron irradiation. A short lifetime would require use of a thicker shield, leading to a larger and less economic module; however it is quite possible that more resilient HTS tapes could be developed especially for fusion applications.

Economics of compact, modular fusion

Most are familiar with economies of scale. For energy projects this principle leads to the assumption that the cost per MWh of electricity can be reduced by increasing the plant size. Certain costs, such as site acquisition, construction and operation, increase only modestly with size and are outweighed by the increased power output.

However, as the size of the project grows, so too does the complexity, not just of engineering, but of management, funding and political influence. Energy sector studies into large, so called megaprojects, such as hydroelectric dams and nuclear reactors, have shown that they have the “greatest amount and frequency of cost overruns, even when normalised to overrun per installed MW” [10, 11].

Pursuing a modular approach keeps fusion power plants from becoming megaprojects. The benefits of economies of scale are still seen in the manufacturing processes, for example, by achieving cost reductions in the production of HTS tape as more is produced, or by designing tokamaks with components suitable for factory production.

Modular reactors also benefit from economies of multiples, where cost savings are introduced when the same identical plant (e.g. a fusion plant) is delivered several times. This is rooted in the idea of mass production, a concept born in the automotive industry and aerospace. Repetition leads to industrial learning, which ultimately results in cost reductions. This is not only true of manufacturing but also of construction and plant operation.

Deploying numerous lower power units, 100-200MW, on a single site also offers greater flexibility to modify the power output by adding or removing reactor modules. Making incremental capacity additions leads to savings, as the upfront siting costs have already be carried out. The more power plant units per site, the lower the investment cost per unit. The benefits of economies of scale are realised without the inherent risk of megaprojects, and with the added benefits of mass production and learning economies.

There are further operational advantages of the modular approach. A fusion reactor will require a dedicated maintenance area, known as a hot cell, where it may be serviced safely. Multiple smaller reactors operating on a single site could share such resources, greatly reducing their size and cost. Reactor modules could also be serviced in turn allowing continuity of electricity supply and reducing the impact of faults.

Small, modular fusion plants, such as those proposed by Tokamak Energy, will be able to benefit from these various factors.

Reducing the size of the final reactor also means prototypes can be developed quickly and at greatly reduced cost. Scientists can rapidly test and advance their hypothesises, while engineers can complete the design-procure-manufacture cycle on much shorter time scales, taking advantage of the latest techniques and materials. Smaller machines also offer access to a wider range of suppliers and the chance to develop supply chain relationships and drive improvements in supplier capabilities.

Taking advantage of experience in the nuclear industry

Tokamak Energy plans to accelerate the deployment of fusion power by combining the high efficiency and improved stability of the spherical tokamak with the strong magnetic fields and lower cryogenic power requirements (compared to low temperature superconductors) of HTS magnets. In combination, these complimentary technologies could allow for efficient energy production in a compact device of modest power output, a concept otherwise unachievable.

Reducing the size of the final reactor means prototypes can be developed quickly and at greatly reduced cost. Working close to the mainstream, but able to tolerate greater risks, a feature inherent to the compact approach, creates an attractive proposition for private investment.

The task of delivering fusion power is no longer only the responsibility of national laboratories and global megaprojects. Privately funded ventures working in conjunction with established industrial partners and universities could make significant progress.

Fusion must take advantage of the experience and capabilities of the existing nuclear industry, such as small modular fission reactors and decentralised power distribution.

About the authors

Colin Windsor

Colin Windsor joined Tokamak Energy in 2013 after a career at Harwell working on materials using neutrons. He came to Culham in 1994 to work on control of the COMPASS-D tokamak and on the JET tritium campaign. He now works on the neutronics of high temperature superconductor tokamaks.

Melanie Windridge

Melanie Windridge is a physicist, speaker, writer and communications consultant to Tokamak Energy. Her PhD focused on vertical stability on the MAST tokamak at Culham Centre for Fusion Energy. She has published an introductory book on fusion called “Star Chambers” and a narrative science book called “Aurora”.

Alan Sykes 

Alan Sykes is one of the founders of Tokamak Energy and a pioneer of the spherical tokamak concept. He had a fruitful career in fusion energy at Culham Laboratory from 1965 to 2008 spanning theory and experiment and leading on the record-breaking START machine.

Steven McNamara

Dr Steven McNamara recently joined Tokamak Energy as a plasma physicist after completing his PhD at Imperial College London. During his PhD Steven investigated the potential application of fusion as a compact, high flux neutron source.

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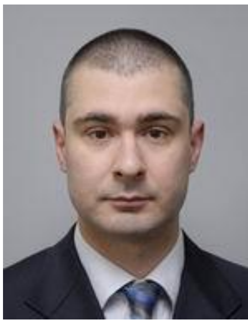

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