Development For Faster Fusion at Tokamak Energy, UK

Alan Costley

Foundations of Interstellar Studies Workshop
27 – 30 June, 2019
• Metric of fusion progress – the fusion triple product
• The established approach using large devices
• Revisit the physics → new findings potentially open a new path to fusion energy
• Spherical Tokamaks and High Temperature Superconductors (HTS)
• Tokamak Energy development programme
• Parallel developments elsewhere
• Possible relevance to interstellar travel studies – initial thoughts
• Summary
Fusion Triple Product

D + T $\rightarrow$ He\(^4\) + n + 17.6 MeV

n + Li\(^6\) $\rightarrow$ T + He\(^4\) + 4.8 MeV

Pressure x energy confinement time, \( nT \tau_E \)

\[
Q_{fus} = \frac{P_{fus}}{P_{input}} = \frac{5cnT\tau_E}{5 - cnT\tau_E} \quad c = \text{const}
\]

Criterion for net energy gain, \( Q_{fus} > 1 \)

\( nT \tau_E > 3 \times 10^{21} \text{ m}^{-3}\text{keVs} \quad \text{Lawson criterion} \)
Fusion Triple Product

Impressive progress until the late 90s

$Q_{\text{fus}} = 1$
Fusion Triple Product

Impressive progress until the late 90s

$Q_{\text{fus}} = 1$

ITER

Fusion triple product, $nT_e$
Progress has stalled!

Impressive progress until the late 90s

Fusion triple product, $nT_E$

$Q_{fus} = 1$

ITER

A E Costley, Foundations of Interstellar Studies Workshop, 27 - 30 June, 2019
Because the cross field energy transport is dominated by turbulence occurring on multiple, different temporal and spatial scales, we cannot determine $\tau_E$ from first principles.
Because the cross field energy transport is dominated by turbulence occurring on multiple, different temporal and spatial scales, we cannot determine $\tau_E$ from first principles. So we have to do scaling experiments:

$$ (\tau_E)_{\text{scaling}} \propto f(R, B, I, n, \ldots) $$

The reference is known as the ITER scaling (IPB98y2) and has been determined from ~1000 selected plasma pulses on ~15 different tokamaks.
IPB98y2 (ITER) scaling

In engineering parameters:

$$\tau_{98y2} \propto I_P^{0.93} B_T^{0.15} R_0^{1.39} n^{0.41} a^{0.58} k^{0.78} / P_L^{0.69}$$

$P_L$ is the power transported by diffusive conduction from the plasma core through the plasma edge to the containing vessel and exhaust structures = input power + alpha power – radiated power

$I_P$ - Plasma current
$B_T$ - Toroidal magnetic field
$R_0$ - Major radius
$n$ - Plasma density
$a$ - Plasma minor radius
$k$ - Plasma elongation
$P_L$ - Power lost by conduction

$k = b/a$

$A = R_0/a$
IPB98y2 (ITER) scaling

In engineering parameters:

\[ \tau_{98y2} \propto \mu I_P^{0.93} B_T^{0.15} R_0^{1.39} n^{0.41} a^{0.58} k^{0.78} / P_L^{0.69} \]

\( P_L \) is the power transported by diffusive conduction from the plasma core through the plasma edge to the containing vessel and exhaust structures = input power + alpha power – radiated power

Physics parameters

Normalised Larmor radius \( \rho_* \propto T^{1/2} / R B \)

Normalised collisionality \( \nu_* \propto n R / T^2 \)

Normalised pressure \( \beta \propto n T / B^2 \)

\[ \tau_{98y2} \propto \rho_*^{-2.70} \beta^{-0.9} \nu_*^{-0.01} \]
IPB98y2 (ITER) scaling

In engineering parameters:

$$\tau_{98y2} \propto I_P^{0.93} B_T^{0.15} R_0^{1.39} n^{0.41} a^{0.58} k^{0.78} / P_L^{0.69}$$

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Physics parameters

- Normalised Larmor radius: $\rho_* \propto T^{1/2} / RB$
- Normalised collisionality: $\nu_* \propto nR / T^2$
- Normalised pressure: $\beta \propto nT / B^2$

$$\tau_{98y2} \propto \rho_*^{-2.70} \beta^{-0.9} \nu_*^{-0.01}$$
For net fusion gain and useful fusion power, this scaling leads to large machines

Major radius ~ 6 m or more,

Volume ~ 1000 m³ or more
Large size means high cost. As a rough estimate, for a tokamak the cost is ~ $20 M$/m$^3$. So, for 1000 m$^3$ you need 20 B$.

High cost, means caution, back-up R&D, contingency…. → slow progress
Construction Status at St-Paul-lez-Durance

Assembly Hall Roof Lift

Tokamak Complex

Large Storage Facility

PF Coil Building Clean Room
Japan is manufacturing half of the 18 giant toroidal field coils needed for ITER. Here, the D-shaped pancake windings are heat treated at 650 °C for 100 hours to react tin and niobium to form the superconducting compound niobium-tin.
TF Coil – a comparison

Mass of (1) TF Coil:
16 m Tall x 9 m Wide, \(~360\ t\)

Boeing 747-300
(Maximum Takeoff Weight) \(~377\ t\)
Tokamaks

Aspect ratio \( (A) = \frac{\text{Major radius (R)}}{\text{Minor radius (a)}} \)

Elongation \( (\kappa) = \frac{b}{a} \)

Tokamak plasmas are subject to operational limits and two important limits are the density limit and the beta limit.

Density limit \( \propto \frac{I}{a^2} \)

Beta limit \( \propto \frac{I}{Ba} \)
Impact of Operational Limits

\[ nT \tau_E \propto \frac{H^2}{q^3} R^2 B_T^3 \left( \frac{\kappa^{7/2}}{A^3} \right) \]

\( H = \frac{(\tau)_{\text{experiment}}}{(\tau)_{\text{scaling}}} \) typically in the range 0.8 – 2.0

\( q = RB_T \kappa / A^2 I_P \) is an operational parameter known as the “safety factor” usually kept to be \( \sim 3 – 4 \).
The question of size becomes one of the following:

\[ nT \tau_E \propto \frac{H^2}{q^3} R^2 B_T^3 \left( \frac{\kappa^{7/2}}{A^3} \right) \]

(size) (field) (shape)

(major radius)

The shape factor is significant. For example, going from the conventional tokamak to the ST, the major radius can be reduced by \(~ \times 5\) or the field by \(~ \times 3\) for the same \(nT \big|_E\).
Impact of Operational Limits

The question of size becomes one of:

\[ nT \tau_E \propto \frac{H^2}{q^3} R^2 B_T^3 \left( \frac{\kappa^{7/2}}{A^3} \right) \]

size \quad field \quad shape

(major radius)

e.g. ITER/EU DEMO \quad MIT/SPARC \quad Tokamak Energy
World Fusion Facilities (Tokamaks)
Toroidal magnetic field versus major radius for given aspect ratio at constant $nT_E$ referenced to ITER
Re-visit the scaling

The IPB98y2(ITER) scaling in engineering parameters:

$$\tau_{98y2} \propto I_P^{0.93} B_T^{0.15} R_0^{1.39} n^{0.41} a^{0.58} k^{0.78} / P_L^{0.69}$$

The scaling can alternatively be expressed in terms of physics parameters:

- Normalised Larmor radius $\rho_* \propto T^{1/2} / RB$
- Normalised collisionality $\nu_* \propto nR / T^2$
- Normalised pressure $\beta \propto nT / B^2$

$$\tau_{98y2} \propto \rho_*^{-2.70} \beta^{-0.9} \nu_*^{-0.01}$$
Re-visit the scaling

Experimental tests have not confirmed the strong beta dependence.

Inverse of the exponent of $\beta$

Dedicated experiments carried out by the International Topical Physics Activity expert group on transport
Re-visit the scaling

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Inverse of the exponent of $\beta$

Dedicated experiments carried out by the International Topical Physics Activity expert group on transport

Developed beta-independent scalings that fit the data almost as well as a free fit. One example is Petty(2008).

$$\tau_{\text{Petty}(08)} \propto \rho_*^{-3.0} \beta^0 \nu_*^{-0.3}$$
Re-visit the scaling

Experimental tests have not confirmed the strong beta dependence.

Dedicated experiments carried out by the International Topical Physics Activity expert group on transport:

\[ \tau_{\text{Petty}(08)} \propto \rho_*^{-3.0} \beta^0 \nu_*^{-0.3} \]

The consequences for reactor design and performance are considerable.

Developed beta-independent scalings that fit the data almost as well as a free fit. One example is Petty(2008).
System Codes

Systems codes capture the main physics and engineering aspects of tokamaks so that the interplay between these aspects, and especially the main performance limiting aspects, can be explored and an optimum integrated design determined. The Tokamak Energy System Code is one such code. The scaling of the energy confinement time is an important component in the code: different scalings are included.
Set $Q_{\text{fus}} = 30$, $A = 3.2$. Calculate minimum fusion power to operate reactor for both IPBy2 beta dependent scaling and for different beta-independent scalings.
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Region for large machines, ITER scale and larger:
$V \sim 800 \text{ m}^3$, $n_w \sim 1.4 \text{ MW/m}^2$, $P/R \sim 35 \text{ MW/m}$
Set $Q_{\text{fus}} = 30$, $A = 1.8$. Calculate minimum fusion power to operate reactor for both ITER beta dependent scaling and for the different beta-independent scalings.

Potential region for relatively small machines, $V \sim 38 \text{ m}^3$, $n_w \sim 3.6 \text{ MW/m}^2$, $P/R \sim 46 \text{ MW/m}$
Candidate Compact Fusion Pilot Plant

Candidate pilot plant, ST135, $R = 1.35\,\text{m}, V = 38\,\text{m}^3$, $B = 3.7\,\text{T}, I = 7.0\,\text{MA}$, $P_{\text{fus}} \sim 185\,\text{MW}$, $Q_{\text{fus}} \sim 5$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value from TESC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0 (\text{m})/a (\text{m})/A/g (\text{m})$</td>
<td>1.35 / 0.75 / 1.8 / 0.05</td>
</tr>
<tr>
<td>$\kappa/\delta$</td>
<td>2.64 / 0.5</td>
</tr>
<tr>
<td>$V_p (\text{m}^3)/S_p (\text{m}^2)$</td>
<td>38.0 / 72</td>
</tr>
<tr>
<td>$Q_{\text{fus}}$</td>
<td>5.0</td>
</tr>
<tr>
<td>$P_{\text{fus}} (\text{MW})/P_{\text{cd}} (\text{MW})$</td>
<td>185 / 37</td>
</tr>
<tr>
<td>$B_T (\text{T})/I_P (\text{MA})$</td>
<td>3.69 / 7.0</td>
</tr>
<tr>
<td>$W (\text{MJ})$</td>
<td>35.4</td>
</tr>
<tr>
<td>$T_0 (\text{keV})/\bar{n}/n_{GW}$</td>
<td>16.3 / 0.8</td>
</tr>
<tr>
<td>$\beta_N/f_{hs}$</td>
<td>4.5 / 0.75</td>
</tr>
<tr>
<td>$f_{\text{He}}/f_{\text{imp}}/Z_{\text{imp}}/Z_{\text{eff}}$</td>
<td>0.02 / 0.01 / 10 / 1.94</td>
</tr>
<tr>
<td>$\beta_T(%)/n_e/\rho_s$</td>
<td>11.4 / 0.05 / 0.007</td>
</tr>
<tr>
<td>$n_w (\text{MW} m^{-2})/P/R (\text{MW} m^{-1})$</td>
<td>1.8 / 33.5</td>
</tr>
<tr>
<td>$H(\text{Petty2008})/H(\text{IPB98y2})$</td>
<td>1.53 / 1.88</td>
</tr>
</tbody>
</table>
Advantages of the spherical tokamak

Tighter spiralling of magnetic field surfaces

Conventional Tokamak  
(safety factor $q = 4$)

Spherical Tokamak  
(safety factor $q = 12$)

high $\kappa$ (‘natural’ elongation)
Advantages of the spherical tokamak

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Advantages of the spherical tokamak

Tighter spiralling of magnetic field surfaces

Conventional Tokamak (safety factor \( q = 4 \))

Spherical Tokamak (safety factor \( q = 12 \))

Operation at high beta with a higher self-driven current, and possibly higher confinement...

**Record \( \beta \) on start**
(achieved through NB Heating)

- \( \beta_N = 6 \)
- \( \beta_N = 3.5 \) (Troyon limit)

\[ \beta_T, \% \]
(normalised plasma current, \( I_p/aB_T \))

DIII-D, #80108


First paper has had > 36,000 downloads, that is, by a large margin, more than any other paper published in Nuclear Fusion


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Superconductors

Low temperature superconductors

\[ \sim 4 \text{ deg K} \]
High Temperature Superconductors (HTS)

Can operate in much higher magnetic fields and at higher temperatures than conventional low temperature superconductors.
Low temperature superconductors  
~ 4 deg K  

High temperature superconductors  
up to ~ 77 deg K  

“HTS is a potential game changer for fusion”  

Professor Dennis Whyte, MIT
Tokamak Energy Approach

Spherical Tokamak
Improved geometry, highly efficient

High Temperature Superconductors (HTS)
High current at high field

Smaller, cheaper, faster...... with distinct competitive advantage

A E Costley, Foundations of Interstellar Studies Workshop, 27 - 30 June, 2019
Tokamak Energy is a privately funded company seeking to develop a faster route to fusion power. Established 2009. Based at Milton Park, Didcot, with offices at the Innovation Centre, Culham

Thus far has raised over £50m all invested towards the company’s ambitious goal and will be making an announcement shortly about additional investment

An open innovative approach. Key results are presented at conferences and published in peer reviewed scientific literature

~ 60 permanent staff and a similar number of consultants so ~ 100 people on site each day. Several of the consultants have held senior positions in the established government funded projects such as JET and ITER
Recently appointed Professor Laurence Williams, Imperial College, to chair the TE Regulatory and Safety Advisory Committee

Multiple collaborations including, PPPL, MIT, Imperial College, University of York, University of Oxford, Open University

Guided by a Scientific Advisory Panel:

Lord (Julian) Hunt, FRS
Professor George Smith, FRS
Professor Jack Connor, FRS
Professor Bill Lee, FREng
Dr Colin Windsor, FRS
Essentially there are three main elements to the Tokamak Energy Programme:

- **Concept development** of relatively small, compact, fusion power modules based on spherical tokamaks specifically using magnets made with high temperature superconductors. This extends all the way up to GW level power plants based on a modular approach and includes analysis of the economics of this approach.

- **Experimental programme** including development and exploitation of a series of devices aimed at key aspects/high leverage points identified in the concept work.

- **Parallel R&D** on a few key aspects for example toroidal magnets using HTS tape.
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**Overall aim is to develop a Modular Approach to Fusion**
Modular approach to fusion

Conventional Approach
Single 1 – 3 GW Large Fusion Device

Modular approach ~ 10 modules each ~ 200 MW sharing balance of plant facilities
Modular approach to fusion

Conventional Approach
Single 1 – 3 GW Large Fusion Device

Modular approach ~ 10 modules each ~ 200 MW sharing balance of plant facilities

Expect much faster development
Tokamak Energy Experimental Programme

ST25
Copper

HTS

ST40 (phase 1)

ST40 (phase 2, 3 T)

Fusion power module

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A E Costley, Foundations of Interstellar Studies Workshop, 27 - 30 June, 2019

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Tokamak Energy Experimental Programme

Operational
Copper
HTS
Mission complete!

Initial operation
ST40 (phase 1)
Under construction
ST40 (phase 2, 3 T)
Concept development
Fusion power module
OBJECTIVES: Demonstrate:
(i) Feasibility of constructing and operating a high field ST
(ii) Benefits of a high field in ST, e.g. enhanced confinement
(iii) Achieve fusion relevant conditions, i.e., high $nT\tau_E$
R = 0.4 - 0.6 m, A = 1.8 - 1.5, B_T = ≤ 3T

OBJECTIVES: Demonstrate:
(i) Feasibility of constructing and operating a high field ST
(ii) Benefits of a high field in ST, e.g. enhanced confinement
(iii) Achieve fusion relevant conditions, i.e., high nT\tau_E
Early ST40 Operations Feb 2018
Some Key Engineering Aspects

HTS development

For a successful tokamak magnet there are several key engineering aspects that have to be considered and feasible solutions found:

• Cable design
• Quench protection
• Cryogenics
• Joints
• Possible performance degradation under neutron bombardment
• etc
Tokamak Energy World Leading HTS Development Laboratory and Team

The David Hawksworth Magnet Laboratory

Multi-step development programme
Tokamak Energy World Leading HTS Development Laboratory and Team

Simon Bradford, Trevor Husband, Rod Bateman, Chris Buckley, Tony Langtry, Marcel Kruip, Greg Brittles, Rob Slade, Bas van Nugteren
Not shown: Enrique Ruiz de Villa Valdés, John Teah, Alun Down, Georgina Howes
Recent results

- Double pancake, solder encapsulated
- Conduction cooled (< 12 K)
- Six QA coils tested with REBCO tape from different suppliers

Raise injected current in $\tau \sim 1000$ s and measure: coil temperature, magnetic field and coil voltages
Tokamak Energy HTS Development

• At ~ 2,500 A inner turns reach capacity, field rolls over

• No quench! Excess current bleeds radially!

• Eventually entire coil is saturated with “transport” current

• Temperature increases, Ic decreases, field decreases

• Eventually hit PSU limit or temperature reaches Tc

• Peak field > 12T at 30K
Simulated coil quench behaviour by Jeroen van Nugteren at CERN

Conclusions thus far

- Remarkable saturated mode operation
- Amazing quench-and-recovery operation observed
- Defect tolerance

Possible new operating mode for HTS. Perhaps useful for MRI, NMR and accelerator applications
HTS Development: High Field Demonstrator

- World largest HTS magnet to develop and demonstrate HTS technology and manufacturing methods
- Approach conditions expected in reactors:
  - Exceed 20T on HTS surface
  - Exceed 250Mpa compressive stress is centre column
- Demonstrate quench protection
Some Key Engineering Aspects

Inner radiation shield

The central column will be surrounded by a neutron shield to protect the HTS magnet. Design of this shield is under study; in particular MCNP calculations are being carried out on candidate materials and the results integrated into the TE System Code.

Calculations carried out by C Windsor and G Morgan at Tokamak Energy have identified that a shield comprising concentric annular volumes composed of tungsten carbide or borid alloy, separated by water constitutes a very effective neutron and gamma ray absorber.

C Windsor and G Morgan, Nucl Fusion 57 (2017), 116032
Some Key Engineering Aspects

Divertor

Power and particles are exhausted through the divertor. Here the plasma comes into contact with a solid, and power levels can be very high, up to 10 MW/m². Materials used are tungsten and carbon fibre. Novel designs, which extend the plasma/surface interaction area, are under development.

Super-X divertor, ~ 5x enlargement of plasma surface interaction area
Some Key Engineering Aspects

Divertor

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Tokamak Energy, working with collaborators, is exploring the use of a novel divetor employing flowing liquid lithium. This would act as a pump of hydrogen lowering recycling of hydrogen from the walls of the vacuum vessel and a self-repairing divertor surface.
## Milestones 2018-2021

### ST40 tokamak demonstrations

<table>
<thead>
<tr>
<th>Event</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First plasma</td>
<td>Feb 2018</td>
</tr>
<tr>
<td>15 million degrees</td>
<td>2018</td>
</tr>
<tr>
<td>100 million degrees</td>
<td>2019/20</td>
</tr>
<tr>
<td>Approach Energy Gain</td>
<td>2020/21</td>
</tr>
</tbody>
</table>

### HTS magnet demonstrations

<table>
<thead>
<tr>
<th>Event</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 tesla prototype</td>
<td>2018</td>
</tr>
<tr>
<td>10 tesla prototype</td>
<td>2019</td>
</tr>
<tr>
<td>12 tesla prototype</td>
<td>2021</td>
</tr>
</tbody>
</table>

Complete validation of concept for the high field HTS spherical tokamak
Fusion Module Concept Development

Physics and engineering aspects are being integrated in the TE System Code. Still under development but some results have been obtained and published, e.g. studies recently carried out for a device operating at \( Q_{\text{fus}} = 5 \), \( P_{\text{fus}} = 200 \text{ MW} \). The extra space made available by increasing the major radius has been divided in the ratio 92\% to the shield thickness \( T_{\text{shield}} \) and 8\% to the HTS core radius.
Parallel Developments Elsewhere

ST FNSF (PPPL)

- $R_0 \leq 1.7 \text{ m}$, $A = 1.8$
- $P_{\text{fus}} = 160 \text{ MW}$, $60 \text{ MW}$
- $Q_{\text{fus}} \sim 10$ (?)
- Cu or HTS magnets

ARC (MIT)

- $R_0 = 3.3 \text{ m}$, $A = 3$
- $P_{\text{fus}} = 500 \text{ MW}$,
- $Q_{\text{fus}} \sim 14$, TBR $> 1$
- $Q_{\text{eng}} \sim 4$, HTS magnets

SPARC (MIT)

- $R_0 < 3 \text{ m}$
- $P_{\text{fus}} = 50 - 200 \text{ MW}$
- $Q_{\text{fus}} \sim 2$.
- Short pulse
- HTS magnets
A new privately funded company, spin-off from MIT, Commonwealth Fusion Systems, was launched in March, to develop the high field route (SPARC). Essentially it is the same physics and technology as that pursued at Tokamak Energy but is a different optimisation of size, field and shape. There is real competition now!

Comment from Bob Mumgaard, CEO. “The aspiration is to have a working power plant in time to combat climate change. We think we have the science, speed and scale to put carbon-free fusion power on the grid in 15 years.”

https://www.cfs.energy/
Relevances to Interstellar Travel Studies

• On present plans, Tokamak Energy will be the first to demonstrate net energy gain from fusion and thus will be the first to learn how to produce and control a fusion burning plasma

• Several technology elements could be applicable: e.g.
  - high temperature superconductor magnets
  - high heat flux components
  - radiation shields
  - materials

• Tokamak Energy System codes enable designs of candidate tokamak fusion modules to be explored and optimised against specific performance criteria. This could include a fusion engine for interstellar travel
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  - high heat flux components
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  and this is interesting....
Relevances to Interstellar Travel Studies

Realizing "2001: A Space Odyssey": Piloted Spherical Torus Nuclear Fusion Propulsion

Craig H. Williams, Leonard A. Dudzinski, Stanley K. Borowski, and Albert J. Juhasz
Glenn Research Center, Cleveland, Ohio

<table>
<thead>
<tr>
<th>Table 8: Fusion Reactor Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Major radius (m)</td>
</tr>
<tr>
<td>Minor radius (m)</td>
</tr>
<tr>
<td>Aspect ratio</td>
</tr>
<tr>
<td>Elongation</td>
</tr>
<tr>
<td>Plasma volume (m³)</td>
</tr>
<tr>
<td>Safety factor (edge)</td>
</tr>
<tr>
<td>Safety factor (axis)</td>
</tr>
<tr>
<td>Fuel ion density (10¹⁰/m³)</td>
</tr>
<tr>
<td>Electron density (10¹⁰/m³)</td>
</tr>
<tr>
<td>Plasma temperature (keV)</td>
</tr>
<tr>
<td>Volume averaged beta</td>
</tr>
<tr>
<td>Confinement time (sec)</td>
</tr>
<tr>
<td>Average neutron wall load (MW/m²)</td>
</tr>
<tr>
<td>Average radiation wall load (MW/m²)</td>
</tr>
<tr>
<td>Ignition margin</td>
</tr>
<tr>
<td>Toroidal magnetic field (centerline) (T)</td>
</tr>
<tr>
<td>Maximum magnetic field (coil surface) (T)</td>
</tr>
<tr>
<td>Gain factor (Q)</td>
</tr>
<tr>
<td>Plasma current (MA)</td>
</tr>
<tr>
<td>Bootstrap current fraction (overdriven)</td>
</tr>
<tr>
<td>Wall reflectivity (effective)</td>
</tr>
<tr>
<td>Number density profile shape factor</td>
</tr>
<tr>
<td>Temperature profile shape factor</td>
</tr>
</tbody>
</table>
Relevances to Interstellar Travel Studies

From Tokamak Energy System Code using latest physics understanding (D – $^3$He fusion)

Very preliminary calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value from TESC</th>
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<tbody>
<tr>
<td>$R_0$ (m) / a (m)</td>
<td>1.3 / 0.65</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>3.0</td>
</tr>
<tr>
<td>$V_P$ ($m^3$)</td>
<td>31.2</td>
</tr>
<tr>
<td>$Q_{\text{H}}$</td>
<td>30</td>
</tr>
<tr>
<td>$P_{\text{fus}}$ / $P_{\text{ed}}$ (MW)</td>
<td>417 / 14</td>
</tr>
<tr>
<td>$P_{\text{charge particles}}$</td>
<td>376</td>
</tr>
<tr>
<td>$B_T (T) / B_C (T) /</td>
<td>I_P (MA)</td>
</tr>
<tr>
<td>$T_0$ (keV) / $n_0$(bar)/$n_{\text{GW}}$</td>
<td>50 / 0.7</td>
</tr>
<tr>
<td>$\beta_n / f_{\text{ns}}$</td>
<td>8.1 / 0.94</td>
</tr>
<tr>
<td>$\beta_T$ (%)</td>
<td>31</td>
</tr>
<tr>
<td>$n_{\text{ns}}$ (MW/m$^3$)</td>
<td>0.5</td>
</tr>
<tr>
<td>$H$(Petty2008) / $H$(IPB98y2)</td>
<td>1.6 / 2.5</td>
</tr>
</tbody>
</table>

Table 8: Fusion Reactor Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius (m)</td>
<td>2.48</td>
</tr>
<tr>
<td>Minor radius (m)</td>
<td>1.24</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>2.0</td>
</tr>
<tr>
<td>Elongation</td>
<td>3.0</td>
</tr>
<tr>
<td>Plasma volume ($m^3$)</td>
<td>225.8</td>
</tr>
<tr>
<td>Safety factor (edge)</td>
<td>2.50</td>
</tr>
<tr>
<td>Safety factor (axis)</td>
<td>2.08</td>
</tr>
<tr>
<td>Fuel ion density ($10^3/m^3$)</td>
<td>5.0</td>
</tr>
<tr>
<td>Electron density ($10^3/m^3$)</td>
<td>7.5</td>
</tr>
<tr>
<td>Plasma temperature (keV)</td>
<td>50</td>
</tr>
<tr>
<td>Volume averaged beta</td>
<td>0.318</td>
</tr>
<tr>
<td>Confinement time (sec)</td>
<td>0.552</td>
</tr>
<tr>
<td>Average neutron wall load (MW/m$^2$)</td>
<td>1.03</td>
</tr>
<tr>
<td>Average radiation wall load (MW/m$^2$)</td>
<td>5.20</td>
</tr>
<tr>
<td>Ignition margin</td>
<td>1.235</td>
</tr>
<tr>
<td>Toroidal magnetic field (centerline) (T)</td>
<td>8.9</td>
</tr>
<tr>
<td>Maximum magnetic field (coil surface) (T)</td>
<td>32.3</td>
</tr>
<tr>
<td>Gain factor (Q)</td>
<td>73.1</td>
</tr>
<tr>
<td>Plasma current (MA)</td>
<td>66.22</td>
</tr>
<tr>
<td>Bootstrap current fraction (overdriven)</td>
<td>1.16</td>
</tr>
<tr>
<td>Wall reflectivity (effective)</td>
<td>0.98</td>
</tr>
<tr>
<td>Number density profile shape factor</td>
<td>1.0</td>
</tr>
<tr>
<td>Temperature profile shape factor</td>
<td>2.0</td>
</tr>
</tbody>
</table>

$P_{\text{fus}} = 7,900$ MW, $P_{\text{charged particles}} = 7,600$ MW, $\text{Vol} = 225$ m$^3$

$P_{\text{fus}} = 417$ MW, $P_{\text{charged particles}} = 376$ MW, $\text{Vol} = 31$ m$^3$
Summary

• A re-evaluation of tokamak performance has shown that smaller and lower power tokamak fusion power modules should be possible.

• Spherical tokamaks (STs) combined with high temperature superconductor magnets offer the possibility of realising this potential.

• Tokamak Energy has an ambitious development programme to bring this to reality in the near term.

• Others, particularly PPPL and MIT have realised this opportunity too. There is competition which is healthy. The next few years promise to be very interesting!

• Initial thoughts give several points of direct relevance to studies of interstellar travel.
Roadmap for Faster Fusion

**Key Projects**
- **ST40**
  - High-field ST research
  - Test Machines
- **ST40 x**
  - Higher performance experimentation
- **ST-F1**
  - Controlled fusion power demonstration
- **ST-E1**
  - Full system electricity generation

**Collaborations**
- Artificial Intelligence
- Energy confinement
- Plasma control
- Auxiliary systems
- Pilot plant design
- High temperature superconductors (HTS)
- Heat & particle exhaust
- Radiation shielding
- Tritium fuel handling

**Electricity**
- Process heat
- Desalination
- Hydrogen production
- Propulsion
- Space applications
- Medical isotopes

**Timeline**
- 2020
- 2025
- 2030
Thank you for your attention!