A faster route to fusion power based on Spherical Tokamaks with High Temperature Superconducting Magnets

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Tokamak Energy
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Progress to Fusion Power

Fusion power

THE TRIPLE PRODUCT
All data points are tokamaks

Moore’s law
x 1.8 each year

Has stalled

Log 10

Fusion!

~Fusion power

A faster way to fusion
Our Technology

Spherical Tokamak
Squashed shape
Highly efficient – high $\beta$

High Temperature Superconductors
High current at high field

Fusion Power
Smaller, Cheaper, Faster...
... With Distinct Competitive Advantage
Spherical Tokamaks (ST)

High bootstrap fraction
High safety factor

Conventional Tokamak (safety factor q = 4)
Spherical Tokamak (safety factor q = 12)

Plasma in START ST, Culham, 1996

High beta ($\beta$)

RECORD $\beta$ ON START (achieved through NB Heating)

ST Power Plant Concepts
Our Credentials

- Jointly authored paper with Princeton Plasma Physics Laboratory: “Fusion nuclear science facilities and pilot plants based on the spherical tokamak”

- Director of Princeton Plasma Physics Laboratory gave evidence to Congress in April 2016 and selected spherical tokamaks with HTS magnets as the most promising route to fusion power

- Common ground with MIT whose ARC Fusion Power Reactor concept combines HTS magnets and tokamaks

- Selected by the International Energy Agency “as one of three most promising innovative fusion concepts” 2017

- Recognised as a Technology Pioneer 2015 by the Davos World Economic Forum

- Our peer-reviewed article “On the power and size of tokamak fusion pilot plants and reactors” is the most downloaded paper ever from the Nuclear Fusion journal
Rapid Innovation

- With investment of just $25m to date, we have
  - Built 3 world leading spherical tokamak prototypes
  - Demonstrated use of high temperature superconductor magnets in our ST25 tokamak
  - Achieved longest continuous plasma of 29 hours with high temperature superconductor magnets

- We are now aiming for a plasma hotter than the centre of the sun by the end of 2017

- We will then
  - Push the plasma temperature up to 100 million degrees (9keV) in 2018
  - Get close to conditions necessary for energy gain from controlled fusion in 2019
Decouple ST40 and HTS demonstrations to enable more rapid progress

### ST40 Demonstrations

<table>
<thead>
<tr>
<th>Device</th>
<th>Milestone</th>
<th>Milestone Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST40 2.0</td>
<td>First plasma</td>
<td>April 2017</td>
</tr>
<tr>
<td>ST40 2.0</td>
<td>15 million degrees</td>
<td>Q4 2017</td>
</tr>
<tr>
<td>ST40 2.1</td>
<td>100 million degrees</td>
<td>Q3 2018</td>
</tr>
<tr>
<td>ST40 2.2</td>
<td>Energy Gain conditions</td>
<td>Q2 2019</td>
</tr>
</tbody>
</table>

### HTS Development / Demonstration

- **HTS 1st Magnet**
  - Milestone: 3T prototype
  - Milestone Date: Q4 2017

- **HTS 2nd Magnet**
  - Milestone: 5T prototype
  - Milestone Date: Q3 2018

- **HTS TF Magnet**
  - Milestone: ST40 scale TF magnet
  - Milestone Date: Q2 2019

Complete validation of concept for the high field HTS spherical tokamak

Ready to use HTS magnets in a compact spherical tokamak to achieve first electricity by 2025
ST40 high field spherical tokamak

- High magnetic field (3T)
- at major radius of plasma (0.4m)
- Plasma pulse length 1.5 - 8s
- Copper magnets (LN$_2$ cooled)
- Neutral beams (1MW at 40keV)
Recent Progress
Summary

- Tokamak Energy is a game-changing opportunity for rapid development of fusion energy
- We are an agile, innovative, highly driven and privately funded team
- We are moving rapidly to apply unique thinking to well understood fields of physics and engineering
- Our combination of technologies is compelling and our intellectual property is secure
- The overall investment is already substantially de-risked

www.tokamakenergy.co.uk
## Milestones to 2016

<table>
<thead>
<tr>
<th>Year</th>
<th>ST25 1.0</th>
<th>ST25 1.1</th>
<th>ST25 1.2</th>
<th>ST40 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>HTS</td>
<td>HTS</td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper</td>
<td>HTS</td>
<td>Copper</td>
</tr>
<tr>
<td>2013</td>
<td>Plasma pulse of a few milliseconds (recently extended to 20s)</td>
<td>Plasma pulse of 5s</td>
<td>A World First: Tokamak with all HTS magnets Plasma pulse of &gt;100s in 2014 29 hour plasma in 2015</td>
<td>Construction of ST40 (the world's first High Field Spherical Tokamak) is well underway.</td>
</tr>
<tr>
<td>2014</td>
<td>We can build a small tokamak quickly</td>
<td>We can extend plasma pulse</td>
<td>Long pulses feasible with HTS and RF (micro-wave) current drive</td>
<td>A high magnetic field in a small tokamak is the key to compact fusion energy</td>
</tr>
<tr>
<td>2015</td>
<td>First patent application filed on fusion power from compact spherical tokamak with HTS magnets</td>
<td>Patent filed on fusion power from low power spherical tokamak</td>
<td>Papers published showing tokamaks do not have to be huge to be powerful First patent grant, four new patent applications on HTS magnets</td>
<td>Paper on physics, engineering and financial viability of compact fusion submitted for publication Three further patent applications on HTS magnets</td>
</tr>
<tr>
<td>2016</td>
<td></td>
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</tbody>
</table>
High Temperature Superconductors

- Discovered in 1986
- We have used “ReBCO” 2nd generation HTS supplied by SuperPower
- Competition to manufacture REBCO HTS
  - SuperPower (Furakawa)
  - Fujikura
  - SUNAM (Korea)
  - STI (US)
  - Teva (Germany)
  - Several others
- Now available as an engineering material
- Performance rapidly improving
- Much more expensive than low temperature superconductor (LTS), but cost per amp metre falling fast

HTS Tape structure, courtesy of SuperPower
Advantages of High Temperature Superconductors (HTS)

- High current density, even at fields >20T
- Strong material suitable for exceptionally high field magnets
  - 41T HTS magnet proven at National High Magnetic Field Lab, Florida
- Optimum operating temperature in a spherical tokamak ~30K
  - Much better performance than at 77K
  - Some magnet heating can be tolerated unlike conventional low temperature superconductors (LTS)
- Newly available as an engineering material
  - Rapid performance improvements
  - Opportunity for Tokamak Energy to take a world lead in HTS Magnet Development
  - Tokamak Energy has filed twelve families of patent applications on HTS magnets for Tokamaks
  - Some patents also apply to wider applications of HTS magnets
- Resistant to neutron damage
  - Neutron bombardment improves tape performance at least up to $2.3 \times 10^{22} \text{ n/m}^2$
**Private fusion machines aim to beat massive global effort**
Startups avoid ITER’s path with new prototype reactors

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**Great balls of fire**
Three startup fusion companies are challenging ITER, an over-budget and overdue public project.

<table>
<thead>
<tr>
<th>NAME</th>
<th>LOCATION</th>
<th>TECHNOLOGY</th>
<th>STAFF</th>
<th>FUNDING</th>
<th>STATUS</th>
<th>TARGET TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tri Alpha Energy</td>
<td>Foothill Ranch, CA</td>
<td>Beam-driven plasmarings</td>
<td>160</td>
<td>$&gt;500 million</td>
<td>New C-2W device in 2017</td>
<td>30 million degrees</td>
</tr>
<tr>
<td>General Fusion</td>
<td>Burnaby, Canada</td>
<td>Target implosion</td>
<td>65</td>
<td>$&gt;75 million</td>
<td>Prototype in 3–5 years</td>
<td>100 million degrees</td>
</tr>
<tr>
<td>ITER</td>
<td>Cadarache, France</td>
<td>Tokamak</td>
<td>2300</td>
<td>$20 billion</td>
<td>Under construction, First plasma in 2025</td>
<td>150 million degrees</td>
</tr>
</tbody>
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