Advancing Research Towards Steady-state operations: ST40 project

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TE Ltd strategy – steps to Fusion demonstration

**ST25**, Cu/HTS magnets
$B_t < 0.25\, T$, 25sec pulses
OPERATIONAL

**ST40**, Cu magnets
$B_t = 3\, T$, $Q_{fus}$ up to 1
IN CONSTRUCTION

**ST160+**, HTS magnets
$B_t = 5\, T$, $Q_{eng} > 1$
CONCEPT DESIGN

**ST25HTS**, HTS magnets
$B_t < 1.0\, T$
OPERATED 29h at 0.1T

**ST60+**, HTS magnets
$B_t = 4\, T$, R&D and
CONCEPT DESIGN

- Advancing Fusion through innovations: ST + HTS
TE Strategy

- Demonstrate scientific viability of STs as a path to Fusion
- Develop applications of HTS technology towards commercial viability of fusion
- Combine STs and HTS in a series of engineering prototypes

- ST path to Fusion proposed by R Stambaugh in 1996
ST40 – new high field ST, under construction

To advance research towards SSO at burning plasma conditions, TE Ltd is performing R&D in several areas:

- High field compact ST40 (3T/2MA) is under construction to demonstrate advantages of high field STs, i.e. improvement of confinement at high TF in ST, high bootstrap fraction, which for an economic ST reactor should be above 90%, low collisional plasmas etc.

- HTS magnets – the best candidate for magnets in steady-state devices due to high J_{crit} at B up to 20T. Several prototypes are under development by TE.

- Resolving other issues in connection with steady-state DT operations – all range from regulations and safety to tritium plant for a low-power tritium experiment, and, of course, issues connected with physics of steady-state regimes and control in a burning plasma device.

- We consider to conduct limited DT operations (tests) in ST40 to demonstrate the performance of high field STs in burning plasma regimes. The next step TE device will certainly operate in DT and so these issues require urgent advances.

• First plasma in ST40 is expected in April-May 2017
Construction of ST40 is on-going. Plasma expected in April 2017.

Main parameters: \( R_0 = 0.4 \text{–} 0.6 \) m, \( R/a = 1.6 \text{–} 1.8 \), \( I_{pl} = 2 \) MA, \( B_t = 3 \) T, \( k = 2.5 \), \( \tau_{\text{pulse}} \approx 1 \text{–} 10 \) sec, DND, 2 MW NBI, Cu liquid nitrogen cooled magnets and passive plates, power supplies based on 200 MJ of supercapacitors & IGBTs. DD and DT ops.

ST40 can approach \( Q_{\text{fus}} \approx 1 \) with \( P_{\text{fus}} \approx 1 \) MW if ST scalings work at low \( v^* \).
**ST40 in parameters space**

Electron neoclassical limit for ST40

\[ \tau_{E}^{\text{ITER98}} = 0.0562 \cdot I_{p}^{0.93} B^{0.15} n^{0.41} P^{-0.69} G^{IPB(y,2)} \]

\[ \tau_{E}^{\text{MAST}} = 0.252 I_{p}^{0.59} B_{t}^{1.4} R^{1.97} (a/R)^{0.58} M^{0.19} n_{e}^{0.00} k^{0.78} P_{in}^{-0.73} \]

IPB(y,2): \[ B\tau_{E,th} \propto (v^{*})^{0.01}(\rho^{*})^{-2.73}\beta^{-0.88}A^{-0.74}q^{-3}; \]

MAST: \[ B\tau_{E,th} \propto (v^{*})^{-0.82}(\rho^{*})^{-2.5to-3}\beta^{-0.5to0}q^{-0.85} \]

- ST40 plasma can be a test for collisionality confinement scalings

\[ \kappa_{ST40} = \kappa_{\text{MAST}} \]

\[ \rho^{*}_{ST40} = \rho^{*}_{\text{MAST}} \]

\[ \beta_{ST40} = \beta_{\text{MAST}} \]

\[ I_{\text{pl}} \sim I_{\text{pl MAST}} \]

But TF is 6 times higher
Can we achieve burning conditions?

- Can’t rely only on expectations of good confinement
- We will try to get high nT with less dependence on transport

- Merging-compression formation [1]
- Heating due to reconnection $\sim B_{\text{rec}}^2$
- Experimental data from START, MAST, PEGASUS, TST-2, TS-4 indicate that plasma in ST40 should show ignition parameters ($nT\tau_E$) with temperatures up to 10 keV [2]
- Confinement is not degrading during post-merging evolution (experiment)
- Confinement time in sec range can be expected in OH regime due to high TF


- Burning conditions at formation stage – first tests in April
1 MW additionally heated plasma

High ion temperature at low collisionality

- Main assumption of ion neoclassic heat transport at low collisionalities can be confirmed in ST40 in 1 MW externally heated plasma

- NBI heated H-mode plasmas in NSTX and MAST generally have a higher ion temperature compared to the electron temperature, even though a higher fraction of the NBI power (~60%–70%) is estimated to flow into electrons.

- But ST40 has an advantage of 10 times lower ion neoclassic heat conductivity over MAST and NSTX

- High ion temperature mode may be achieved
Towards steady-state operations

- Non-solenoid plasma formation, current ramp and sustainment, divertor and wall loads
- High field ST allows flexibility in the choice of current drive methods
- ST approach can provide very high bootstrap current
- High bootstrap requires high elongation (STs have high natural elongation) and beta (STs achieved record betas)
- As elongation will be much above the natural one, feedback system and passive stabilisation will be required and LN2 cooled passive plates will be installed

- High elongation and betas are required for SSO
Summary of ST40 objectives

- **Main engineering objective:**
  - to demonstrate feasibility of high-field ST

- **Main physics objective:**
  - to demonstrate advantages of high field in ST, aiming at 10 keV-range plasma temperatures

- **Main objectives of possible upgrades:**
  - demonstration of efficient production of neutrons
  - demonstration of $Q_{\text{fus}} \sim 1$ with upgraded NBI system in DD equivalent and with DT subject to site availability and tritium licence.

- ST40 will be the first high field Spherical Tokamak
- Necessary step on the way to steady-state HTS ST
Most of components arrived, assembly has started, 1\textsuperscript{st} plasma in April
Other design issues:
- use of HTS magnets is our way to SSO
- Intensive R&D programme

• HTS magnets are crucial for compact ST reactor
HTS for Fusion Magnets

High Temperature Superconductors (HTS) are very well suited for use in robust, compact, high-field magnets

- HTS has several important characteristics
  - It has **high current density**
  - It is tolerant to **increased temperature**
  - It is tolerant to **high magnetic field**
  - Its **high strength** metal tape construction

- **HTS magnets are crucial for compact ST reactor**
**HTS key technologies**

- **REBCO conductors**
  - $I_c$ surface
  - Boundary resistance
  - Tape construction
  - Quality / variability

- **Quench protection**
  - Current sharing
  - Detection
  - Dump

- **100 kA cable design**
  - AC losses
  - % copper content
  - Cooling

- **Joints**
  - Size, shape, position
  - Heatload - many or few?

- **$I_c$ degradation**
  - Neutron damage
  - Thermal cycling
  - Mechanical
  - Fatigue

- **Power supplies**
  - Current leads
  - Dump circuits
  - Cold rectification?

- **Mechanical design**
  - PF / TF coil locations
  - Forces
  - Demountable coils?

- **Cryogenics**
  - Neutron heating
  - Joint heating
  - Suspension
  - Vacuum vessel

- **I C degradation**
  - Neutron damage
  - Thermal cycling
  - Mechanical
  - Fatigue

- **Interplay with PF system is important issue**
# HTS TRLs and our plans

<table>
<thead>
<tr>
<th>Targets</th>
<th>as of Feb-17</th>
<th>2017 target</th>
<th>2018 target</th>
<th>2019 target</th>
<th>Fusion demo</th>
<th>D-T reactor</th>
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<tbody>
<tr>
<td>Cable design</td>
<td>3</td>
<td>5</td>
<td>6</td>
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<td>Joint design</td>
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<tr>
<td>REBCO tape characterization</td>
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<td>5</td>
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<td>Core model</td>
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<td>4</td>
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<td>TF EM model</td>
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<td>PF EM model</td>
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<td>5</td>
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<td>Integrated magnet EM model</td>
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<td>Magnet mechanical design</td>
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<td>9</td>
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<tr>
<td>Quench Detection system</td>
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<td>5</td>
<td>6</td>
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<td>8</td>
<td>9</td>
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<tr>
<td>Quench Protection system</td>
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<td>9</td>
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<tr>
<td>Cryoplant</td>
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<td>3</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

- **12 patent applications**

[Diagram showing TRL levels for different targets]

- **TRL 9** • Actual system “flight proven” through successful mission operations
- **TRL 8** • Actual system completed and “flight qualified” through test and demonstration (ground or space)
- **TRL 7** • System prototype demonstration in a space environment
- **TRL 6** • System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- **TRL 5** • Component and/or breadboard validation in relevant environment
- **TRL 4** • Component and/or breadboard validation in laboratory environment
- **TRL 3** • Analytical and experimental critical function and/or characteristic; proof-of-concept
- **TRL 2** • Technology concept and/or application formulated
- **TRL 1** • Basic principles observed and reported
100-kA-class High-Temperature Superconducting (HTS) conductor renovates the world record 100 kA current sustained for 1 hour [1, 2]

Tensile test for a single-tape joint was conducted. Contact pressure of 50 MPa is needed to withstand the shear strength evaluated by 3D-FEM [3]

1. N. Yanagi et al., FIP/P8-21, 25th IAEA Fusion Energy Conference (2014), St. Petersburg, Russia.

Detailed studies of joints and cables on-going at TE Ltd HTS Lab

HTS magnets are crucial for compact ST reactor
From hand-made to industrial approach

From 1st HTS coils on GOLEM (2011) to OI-made HTS coils and full-HTS tokamak (2014)

From studies of spontaneous hot spots and quenches to fully controllable tests

- Hot spots type damage in HTS tape made by laser punching
- HTS magnets are crucial for compact ST reactor
ST Path to Fusion – our approach

- Compact high field ST with HTS magnets
How can we advance Fusion?

• We propose advancing Fusion through innovations.
• Use of innovations is difficult to implement at ITER/DEMO scale.
• Our path is to address numerous issues on the way to Fusion power not in a single big project, but spreading them over a number of smaller, and so affordable, customised devices, funded by combination of private investments and public funds.

• As TE approach is via compact high field ST with HTS magnets, we propose a number of devices to address relevant issues.
• Funding, resources and time constraints require analysis of possible steps.
• So we compare here 3 devices – ST40 which is under construction, and two possible next steps.

• Modular approach, low power reactor
Scientific Requirements for possible next steps (V Chuyanov)

<table>
<thead>
<tr>
<th>n</th>
<th>Requirement</th>
<th>ST-40 Copper machine. No shielding</th>
<th>ST-60+ HTS Magnet No/little shielding</th>
<th>ST-160+ HTS Magnet. Full neutron shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Improving of the confinement with high toroidal field (+ size dependence)</td>
<td>First hints of confinement improvement?</td>
<td>May be studied in detail in D plasmas</td>
<td>Yes. Full confirmation in relevant conditions</td>
</tr>
<tr>
<td>2</td>
<td>Achievement of “fusion relevant” temperatures ($T_0 \sim 10$ keV).</td>
<td>Maybe as a short burst initially</td>
<td>May be studied in detail in D plasmas, no SSO in DT</td>
<td>Yes. Full confirmation in reactor relevant conditions</td>
</tr>
<tr>
<td>3</td>
<td>Demonstration of the current ramp scenario</td>
<td>Perhaps</td>
<td>Yes, but not fully relevant for a future device</td>
<td>Yes. Full confirmation in relevant conditions</td>
</tr>
</tbody>
</table>

ST40, with possible minor modifications

R$_0$~0.6-1m, Cu or HTS, DD or DT

R$_0$~1.6-2m, HTS, DT
**Scientific Requirements for possible next steps**

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<tr>
<td>4</td>
<td>Achievement of long pulses. Quasi steady state operation</td>
<td>No</td>
<td>Yes, but not in DT for HTS option</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>Demonstration of alpha-particle confinement at relatively low plasma currents</td>
<td>Attempts/limited</td>
<td>Yes, but not fully relevant for a future device</td>
<td>Yes. Fully relevant</td>
</tr>
<tr>
<td>6</td>
<td>Achievement of highest possible densities to check density scaling</td>
<td>Limited possibility</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>Demonstration of alpha-particle heating. Achievement of regimes close to ignition - substitution of additional heating with alpha-particle heating and density rise with alpha heating.</td>
<td>No</td>
<td>Maybe</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>Demonstration of energy conversion (1 module) and T generation (may be not self-sufficient)</td>
<td>No</td>
<td>No</td>
<td>Yes. Is this necessary?</td>
</tr>
</tbody>
</table>
Technology Requirements for possible next steps

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<tr>
<th>n</th>
<th>Goal</th>
<th>ST-40 Copper machine. No shielding</th>
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<th>ST-160+ HTS Magnet. Full neutron shielding</th>
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<tbody>
<tr>
<td>1</td>
<td>Build a spherical tokamak with high temperature superconducting coils and toroidal fields 5 – 10 times higher than in all operating STs</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Develop start up technology to achieve several MA plasma currents without a central solenoid</td>
<td>Yes, as a first step but not very relevant for reactor</td>
<td>Yes, as a first step but not very relevant for reactor</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Master and implement needed technologies of additional heating / CD</td>
<td>Yes –especially if ECH installed</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
## Technology Requirements for possible next steps

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</thead>
<tbody>
<tr>
<td>4</td>
<td>Develop efficient neutron shielding</td>
<td>No</td>
<td>No/limited</td>
<td>Yes – perhaps “efficient” =&gt; “sufficient”?</td>
</tr>
<tr>
<td>5</td>
<td>Master and implement needed elements of tritium technology.</td>
<td>Limited possibility</td>
<td>Limited possibility</td>
<td>Yes but is this TE’s job?</td>
</tr>
<tr>
<td>6</td>
<td>Master and implement blanket (tritium breeding and energy conversion)</td>
<td>No</td>
<td>No</td>
<td>Yes but is this TE’s job?</td>
</tr>
<tr>
<td>7</td>
<td>Net engineering Q &gt; 1</td>
<td>No</td>
<td>No</td>
<td>Yes – even if power conversion not attempted</td>
</tr>
<tr>
<td>8</td>
<td>Operation up to 75dpa (criterion used for 100% availability of modular fusion plant)</td>
<td>No</td>
<td>No</td>
<td>No – would need 100% tritium breeding</td>
</tr>
</tbody>
</table>
How can we advance Fusion?  
Modular approach

• The modular approach is currently widely discussed in US designs of modern (Gen IV) multi-active core fast reactors. However application of such approach for Fusion exposed many specifics (*FED 2017, V Chuyanov et al*)

• One example: Reaching SSO with high bootstrap will require heating power of 10-40 MW for module. A substantial part of this power will be needed for CD nearby the magnetic axis where the bootstrap current is zero (but potato orbits contribute). However, profile alignment in burning plasmas is a subject of experimental studies, so real requirements are still unknown.

• In our approach this power is only needed for short start-up phase and can be shared between modules, significantly reducing the cost. Profile alignment/control will be required during SSO, so some (small) auxiliary power may be needed for SSO in each module and options are considered.

• Modular approach also allows sharing of other systems, i.e. remote handling, hot cell, tritium plant etc. This also leads to big savings.

• Economy of a mass production in important
GAPS Analysis, A Costley

- A **Gap Issue** is a significant physics or technical aspect where there is presently considerable uncertainty or lack of knowledge and that uncertainty leads to uncertainty in the design and performance of an optimised fusion module.
- Such issues must be overcome, mitigated or avoided, so that a **demonstration fusion power module** can be designed, constructed and operated with a high degree of certainty of performance.
- **Demonstration Fusion Module** would aim to demonstrate long pulse plasma operation (SSO) with high fusion power gain \( Q_{\text{eng}} > 1 \), and possible demonstration of tritium breeding and fusion-power-to-electrical-power conversion. It would not aim to be fully self-sufficient in tritium or to produce net electrical power.

- 17 Gap Issues have been identified.
GAPS Analysis

- GAPS analysis identified several areas where development is needed, some of them need to be addressed already on the way to ST reactor module.
- Examples of GAPS:

<table>
<thead>
<tr>
<th></th>
<th>Net energy gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thus far fusion plasmas have not produced net energy (or power): i.e. $Q_{fus} = P_{fus}/P_{aux}$ has always been &lt; 1. The clear demonstration of $Q_{fus} &gt; 1$ is a major milestone in fusion development. An associated, high-leverage, aspect of this issue is energy confinement. To first order, the energy confinement time determines the minimum fusion power needed for $Q_{fus} &gt; 1$, and that in turn impacts how small the fusion device can be.</td>
</tr>
<tr>
<td>4</td>
<td>Heating, Current Drive, and Diagnostics</td>
</tr>
<tr>
<td></td>
<td>Dedicated methods and technology will be needed for heating the plasma, driving current (non-bootstrap fraction), and for measuring key plasma and first wall parameters. Much relevant work is ongoing in the large device programme but TE will need specific solutions for burning plasma operation on STs.</td>
</tr>
</tbody>
</table>

- 17 Gap Issues have been identified.
## GAPS Analysis

<table>
<thead>
<tr>
<th>#</th>
<th>Issue</th>
<th>In house on TE devices (ST40, ST60 etc)</th>
<th>In house as a separate project</th>
<th>Jointly with partners</th>
<th>Others will do it, watching, partners</th>
<th>Minimise, eliminate, defer, avoid</th>
<th>Where to watch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Net energy gain</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>JET</td>
</tr>
<tr>
<td>2</td>
<td>High gain/burning plasma physics</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>ITER/DEMO programme</td>
</tr>
<tr>
<td>3</td>
<td>Start up/ramp down, control of burning plasmas</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>ITER/DEMO programme</td>
</tr>
<tr>
<td>4</td>
<td>Heating, current drive, diagnostics</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>ITER/DEMO programme</td>
</tr>
<tr>
<td>5</td>
<td>HTS magnets</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tbody>
<tr>
<td>6</td>
<td>Exhaust power handling / divertor</td>
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<td></td>
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<td>PPPL, CCFE, WEST others?</td>
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<td>First wall, low erosion</td>
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<td>X</td>
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<td>DEMO programme</td>
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<td>Radiation shield for centre column</td>
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<td>9</td>
<td>Materials: neutron resistant and high temp. operation</td>
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<td>X</td>
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<td>DEMO programme; jet engine manufacturers</td>
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<tr>
<td>10</td>
<td>Remote handling, maintenance</td>
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<td>X</td>
<td></td>
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<td>JET, ITER, DEMO</td>
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<td>11</td>
<td>Tritium supply</td>
<td>X</td>
<td>X</td>
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<td>Tritium handling</td>
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<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>JET, PPPL, ITER DEMO prog.</td>
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<tr>
<td>13</td>
<td>Tritium breeding and ultimate self-sufficiency</td>
<td>X</td>
<td></td>
<td>X</td>
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<td>ITER, DEMO</td>
</tr>
<tr>
<td>14</td>
<td>Power conversion</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>PPPL, ITER</td>
</tr>
</tbody>
</table>
## GAPS Analysis

<table>
<thead>
<tr>
<th>#</th>
<th>Issue</th>
<th>In house on TE devices (ST40, ST60 etc)</th>
<th>In house as a separate project</th>
<th>Jointly with partners</th>
<th>Others will do it, watching, partners</th>
<th>Minimise, eliminate, defer, avoid</th>
<th>Where to watch</th>
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</thead>
<tbody>
<tr>
<td>15</td>
<td>Fusion Module conceptual integrated design development</td>
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<td>16</td>
<td>Site location, licence and safety</td>
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<td>X</td>
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<td>ITER/Demo programme</td>
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<td>Economics of modular approach.</td>
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<td></td>
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<td>Uni of Eindhoven and others.</td>
<td></td>
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</tbody>
</table>
Technology Requirements for possible next steps

• The Company’s expertise and IP lies mainly in two areas:
  • High temperature superconducting magnets for fusion applications; and
  • High field spherical tokamaks.
• For the realisation of Modular Fusion there are many other technological steps for which the Company does not possess the necessary expertise:
  • High heat flux components;
  • Gas cooling (CO₂? He?), since water cooling is a “no-no” with tritium;
  • Tritium breeding and processing (note that this is a significant challenge);
  • Power conversion;
  • Industrial plant integration; and
  • Licensing and associated approval processes.

• The primary commercial objective, therefore, is to establish partnership in relevant areas.

• Partners, collaboration
Low Power Tritium experiment / tests
Why do DT Tests on ST40?

There are strong reasons for DT tests on ST40.

• As a high field, spherical tokamak, ST40 should be capable of, at least approaching, “breakeven” conditions.

• The preferred device after ST40 will involve much larger tritium inventories and neutron rates at the level of a fusion module.

• Therefore, TE should demonstrate the capabilities required and procedures to do so safely.

• Introduction of tritium in ST40 will serve several purposes:
  • A strong signal that compact, high field, Spherical Tokamaks can deliver the performance required for fusion power production in ST160+;
  • Training/education for the TE Team, especially in respect of safety culture and the necessary QA/QC; and
  • Reassurance for investors and regulators that risks are minimised.

• DT test on ST40
Future Plans

• Move to new site (several options considered, incl. Culham) for full DD and DT operations

• Add full divertor and LN2 cooled Cu vertical stabilization plates, and satisfy the requirements for tritium operations

• Neutral beam injection (NBI)
  • 3 beams under consideration, one to assist start-up (already during Phase 1), one for heating during flat-top in DD, and one for fuelling and heating in DT
  • 1st and 2nd beams exist, 3rd to be designed and built

• ECRH/EBW under consideration

• Upgrade using prototype HTS magnet under consideration

• Design of next step device started in 2017, options include short pulse (<100sec) small device (R~ 0.6-0.8m) and steady-state device with HTS magnets and sufficient shielding (R~1.5-2m)

• Resources, funds, R&D
CONCLUSIONS

• Demonstration of burning plasma is the current challenge for Fusion and can be achieved in a compact high-field ST

• Non-inductive current drive and start-up are crucial for steady-state operations and can be demonstrated in a compact high-field ST

• The ST path to commercial application of Fusion can start from compact ST with R as low as 0.4 m with support of world-wide Fusion research

• Innovations can make Fusion sooner and cheaper

• ST40 will be the first high field Spherical Tokamak
Who are we?

Tokamak Energy Ltd is a private company funded by private investors, it is based at Milton Park, near Culham, UK.
Merging - compression coils

Required for start up – our solenoid is fairly small
Inner vacuum case

Inner vacuum case and centre column
TF coils
PSU manufacture

Other than merge compression power supplies are based on ‘transport’ super-capacitors.

Phase one TF PSU has been installed
MERGING - COMPRESSION

- $I_p$ imposed from START and MAST scaling
- Merging-compression coil
- Vertical field to control X-point position between MC coils

• Burning conditions at formation stage – first tests in April
Merging-compression plasma formation

- M/c on START, ST40 and MAST, same scale. ST40 plasma footprint shown in blue in all pictures:

- START and ST40 are similar in geometry
- ST40 has more compression

- START and MAST demonstrated 1keV temperatures
Assembly video