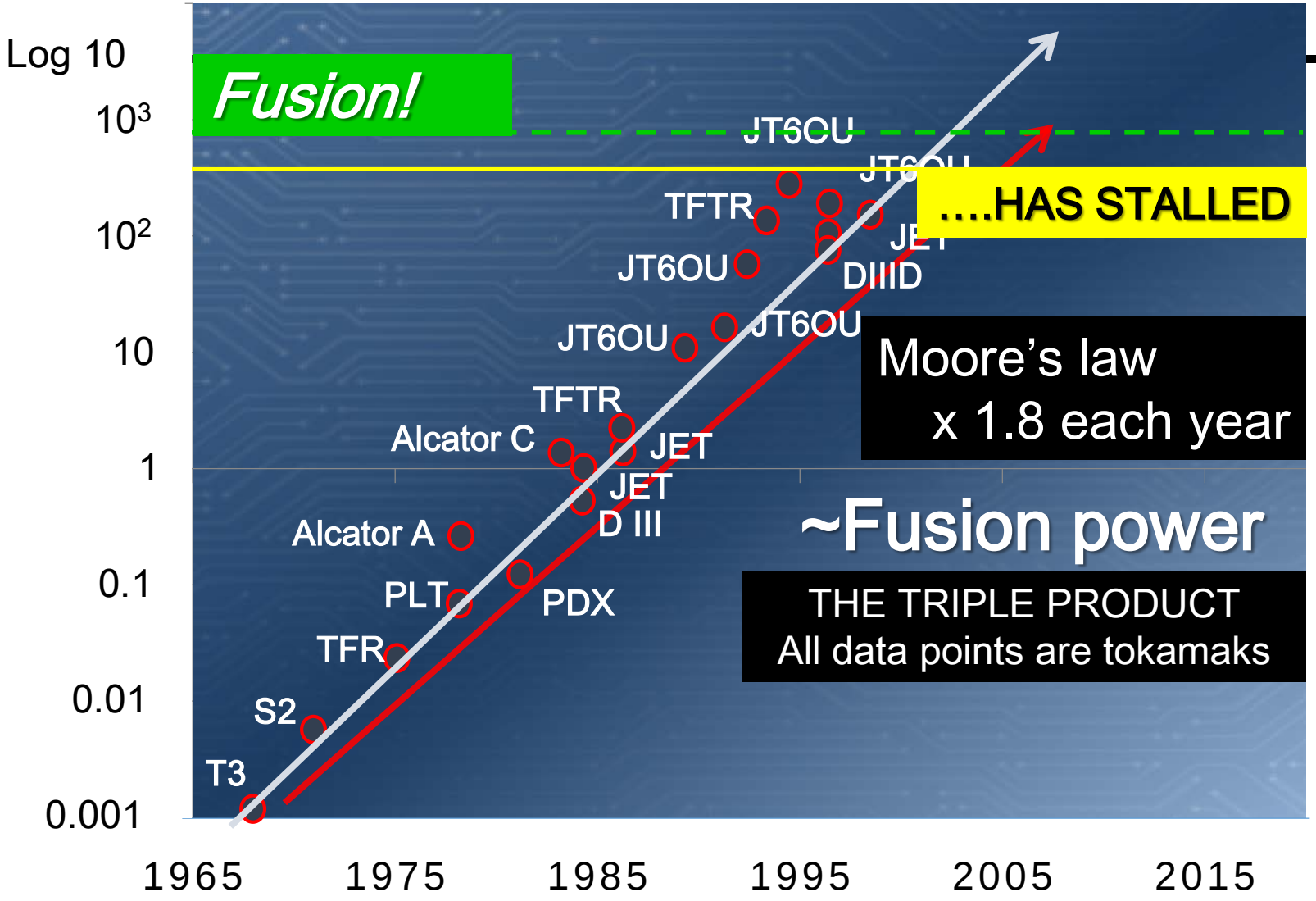
Dr David Kingham
Tokamak Energy
August 2017

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

Progress to Fusion Power



Our Technology

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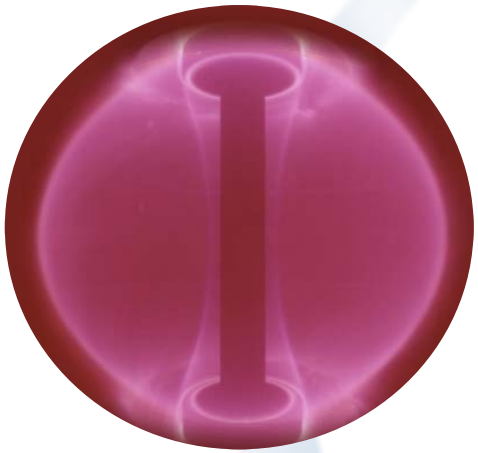
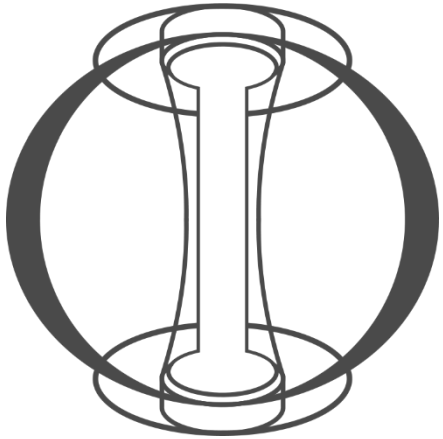
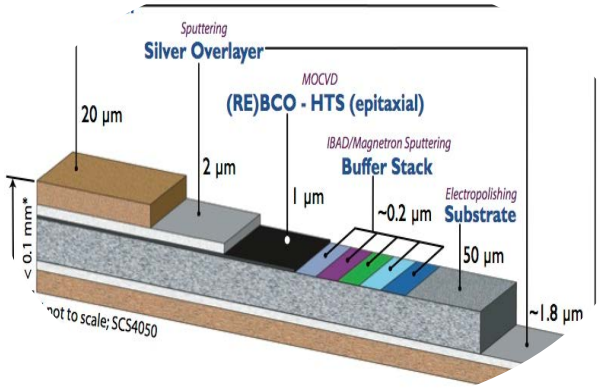
a faster way to fusion

Spherical Tokamak
Squashed shape
Highly efficient – high β

High Temperature Superconductors
High current at high field







Fusion Power

Smaller, Cheaper, Faster...

... With Distinct Competitive Advantage

Spherical Tokamaks (ST)

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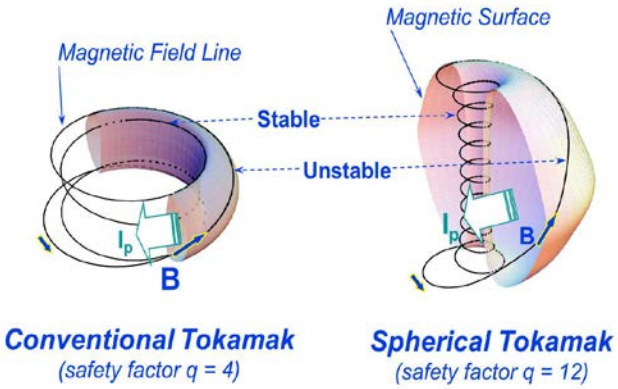
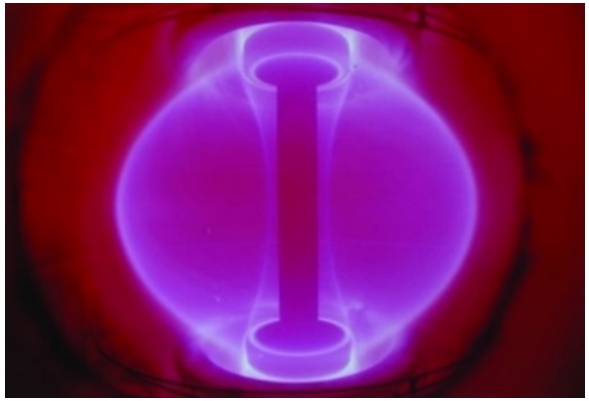
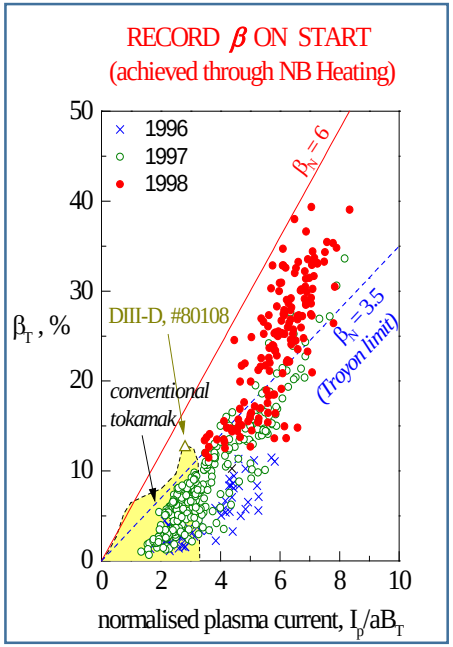
High bootstrap fraction

High safety factor



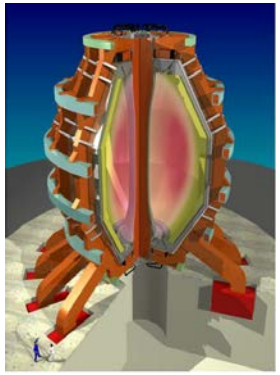


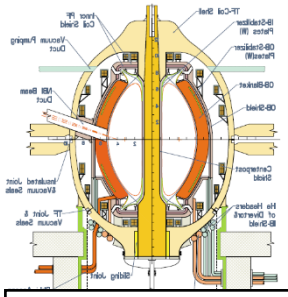
High beta (β)

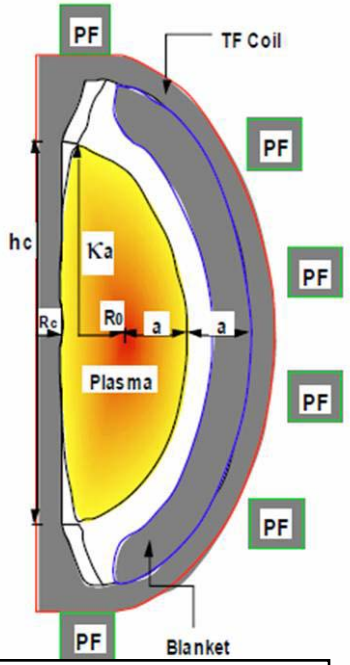


Plasma in START ST, Culham, 1996

ST Power Plant Concepts

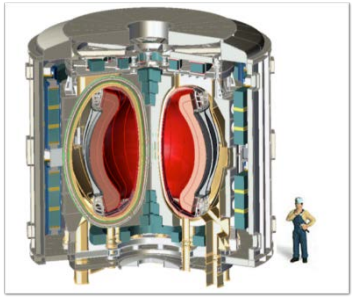




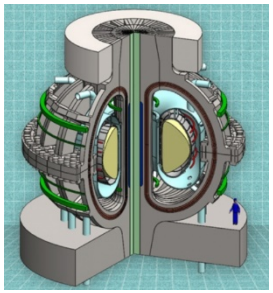


Our Credentials

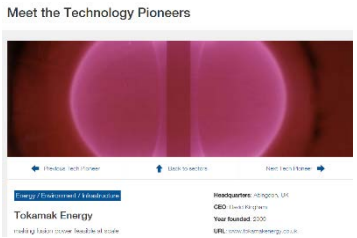
- Jointly authored paper with **Princeton Plasma Physics Laboratory**: “Fusion nuclear science facilities and pilot plants based on the spherical tokamak”
- Director of **Princeton Plasma Physics Laboratory** gave evidence to **Congress** in April 2016 and selected spherical tokamaks with HTS magnets 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



Princeton/ Tokamak Energy Pilot Plant



MIT’s “ARC” Fusion Power Plant concept



Rapid Innovation

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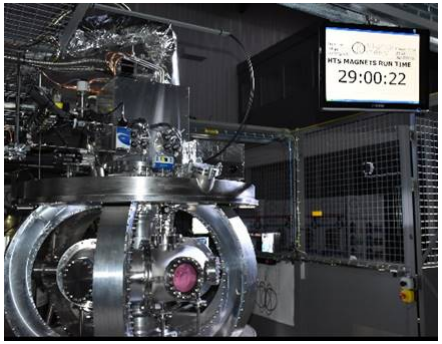
- With investment of just $25m to date, we have
  - Built 3 world leading spherical tokamak prototypes
  - Demonstrated use of high temperature superconductor magnets in our ST25 tokamak
  - Achieved longest continuous plasma of 29 hours with high temperature superconductor magnets
- We are now aiming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



Milestones 2017-2019

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Decouple ST40 and HTS demonstrations to enable more rapid progress

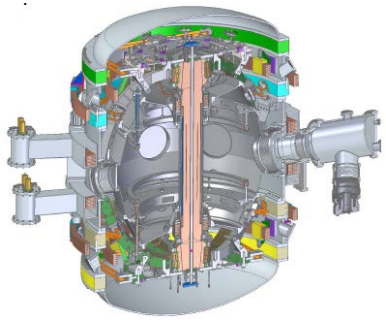
ST40 Demonstrations

Device	Milestone	Milestone Date
ST40 2.0	First plasma	April 2017
ST40 2.0	15 million degrees	Q4 2017
ST40 2.1	100 million degrees	Q3 2018
ST40 2.2	Energy Gain conditions	Q2 2019

Concept Design of Fusion Power Demonstrator

HTS Development / Demonstration

Device	Milestone	Milestone Date
HTS 1st Magnet	3T prototype	Q4 2017
HTS 2nd Magnet	5T prototype	Q3 2018
HTS TF Magnet	ST40 scale TF magnet	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

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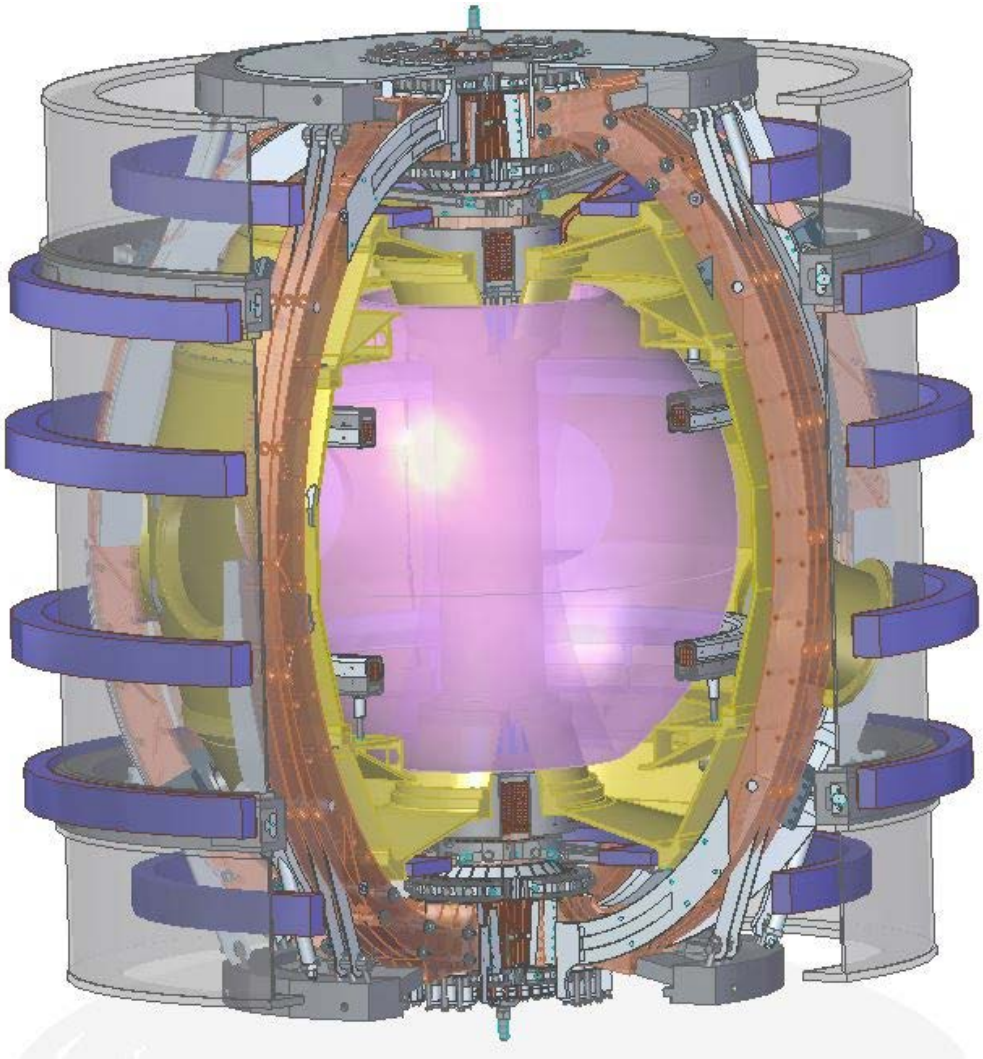
- High magnetic field (3T)
- - at major radius of plasma (0.4m)
- Plasma pulse length 1.5 - 8s
- Copper magnets (LN_2 cooled)
- Neutral beams (1MW at 40keV)



Recent Progress

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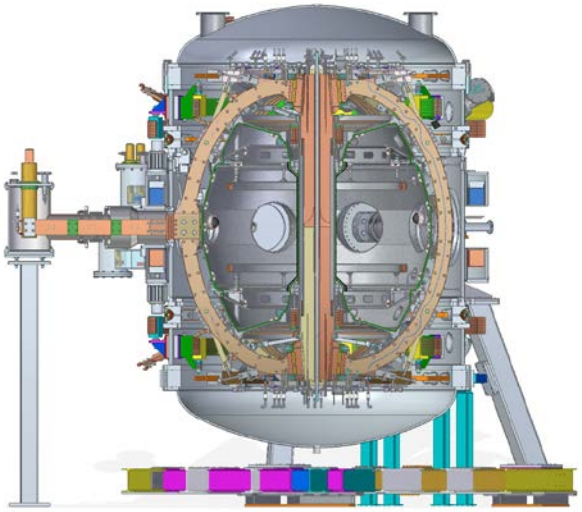
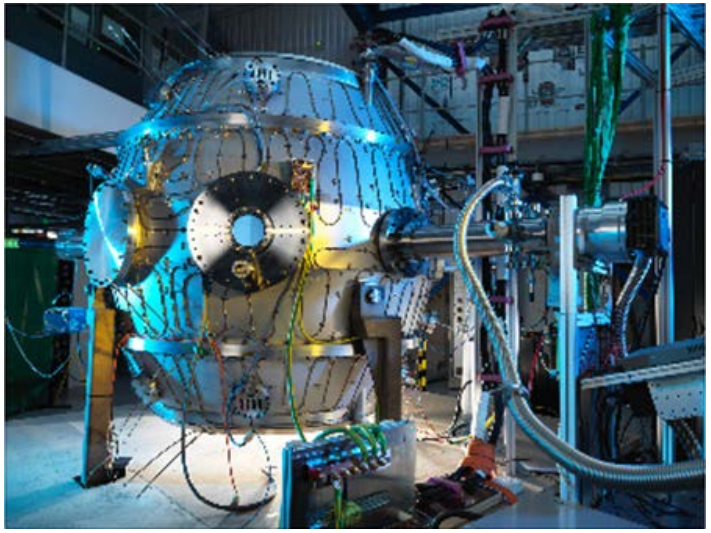
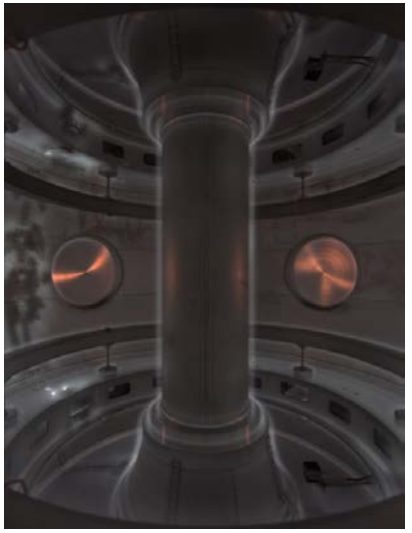
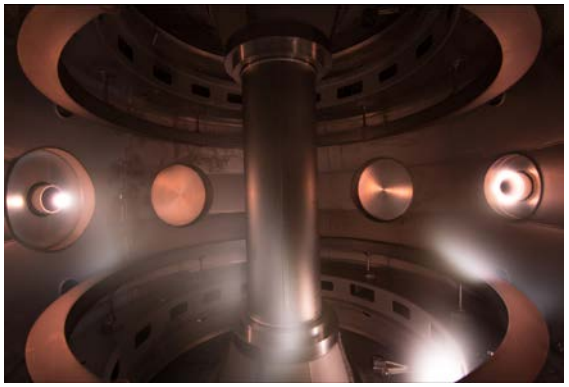
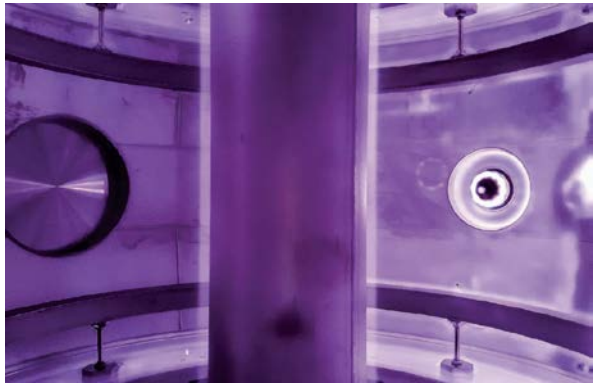
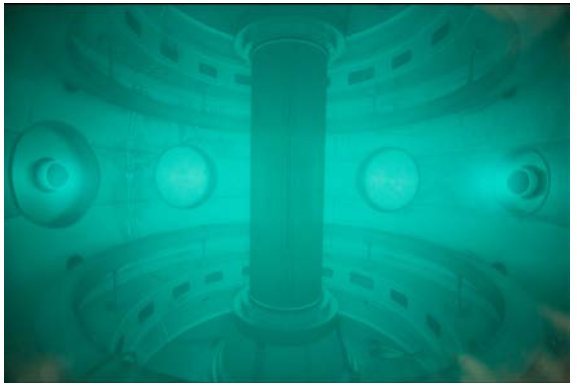








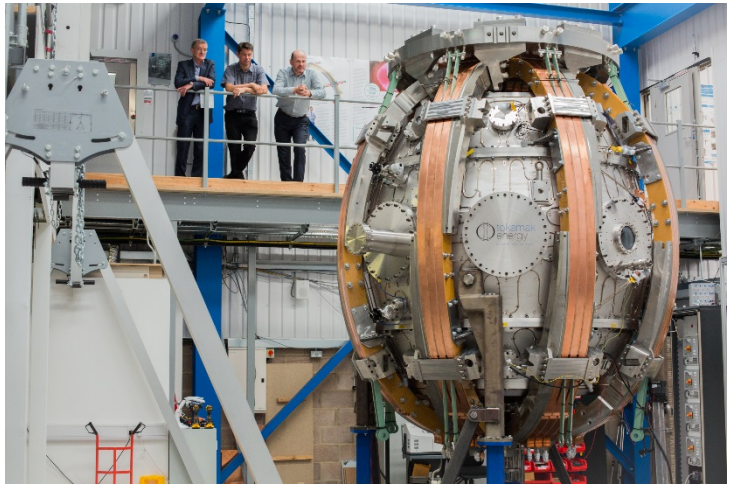


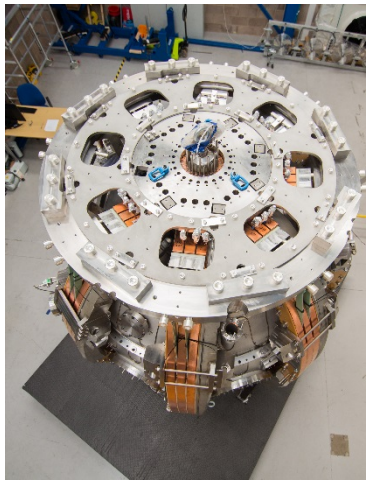


Summary

- 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





Additional Slides

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Milestones to 2016

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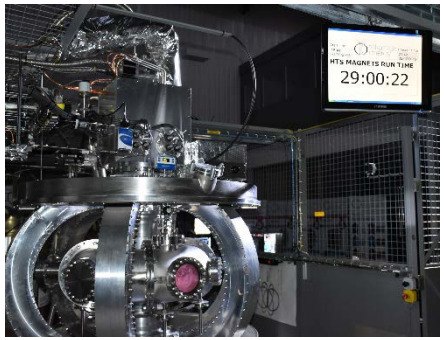
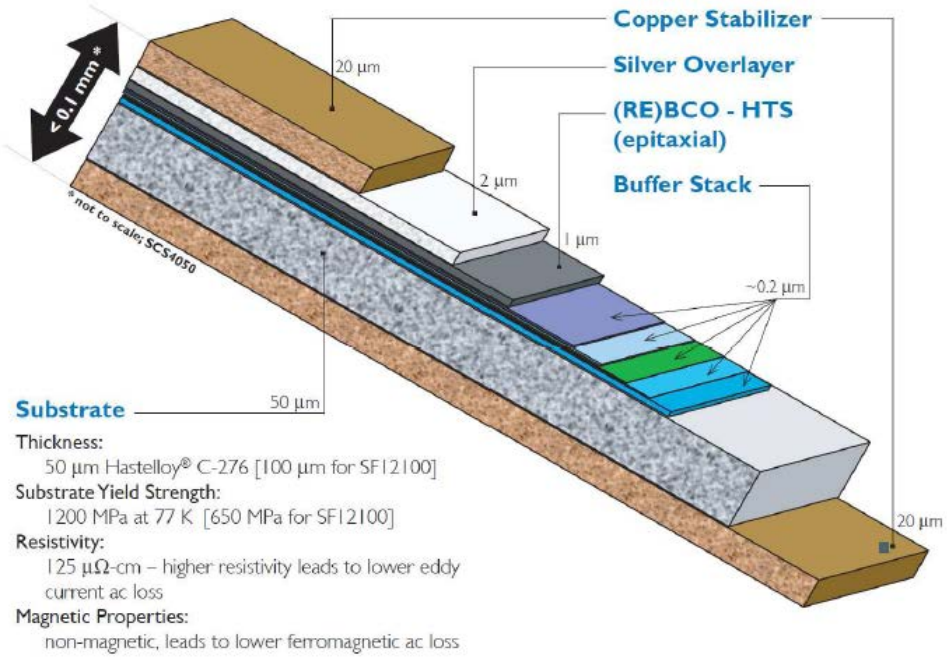
2012	2013	2014	2015	2016



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

High Temperature Superconductors

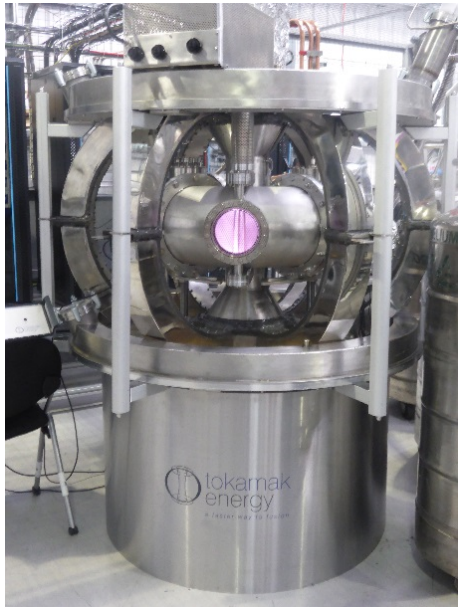
- Discovered in 1986
- We have used "ReBCO" 2nd generation HTS supplied by SuperPower
- Competition to manufacture REBCO HTS
  - SuperPower (Furakawa)
  - Fujikura
  - SUNAM (Korea)
  - STI (US)
  - Teva (Germany)
  - Several others
- Now available as an engineering material
- Performance rapidly improving
- 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 x 10^{22} n/m^2



Science Magazine, April 2017

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Private fusion machines aim to beat massive global effort

Startups avoid ITER's path with new prototype reactors

Great balls of fire

Three startup fusion companies are challenging ITER, an over-budget and overdue public project.

NAME	LOCATION	TECHNOLOGY	STAFF	FUNDING	STATUS	TARGET TEMPERATURE
Tokamak Energy	Milton, U.K.	Spherical tokamak	35	$25 million	New ST40 device in 2017	100 million degrees Celsius
Tri Alpha Energy	Foothill Ranch, California	Beam-driven plasma rings	160	>$500 million	New C-2W device in 2017	30 million degrees Celsius
General Fusion	Burnaby, Canada	Target implosion	65	>$75 million	Prototype in 3–5 years	100 million degrees Celsius
ITER	Cadarache, France	Tokamak	2300	$20 billion	Under construction. First plasma in 2025	150 million degrees Celsius