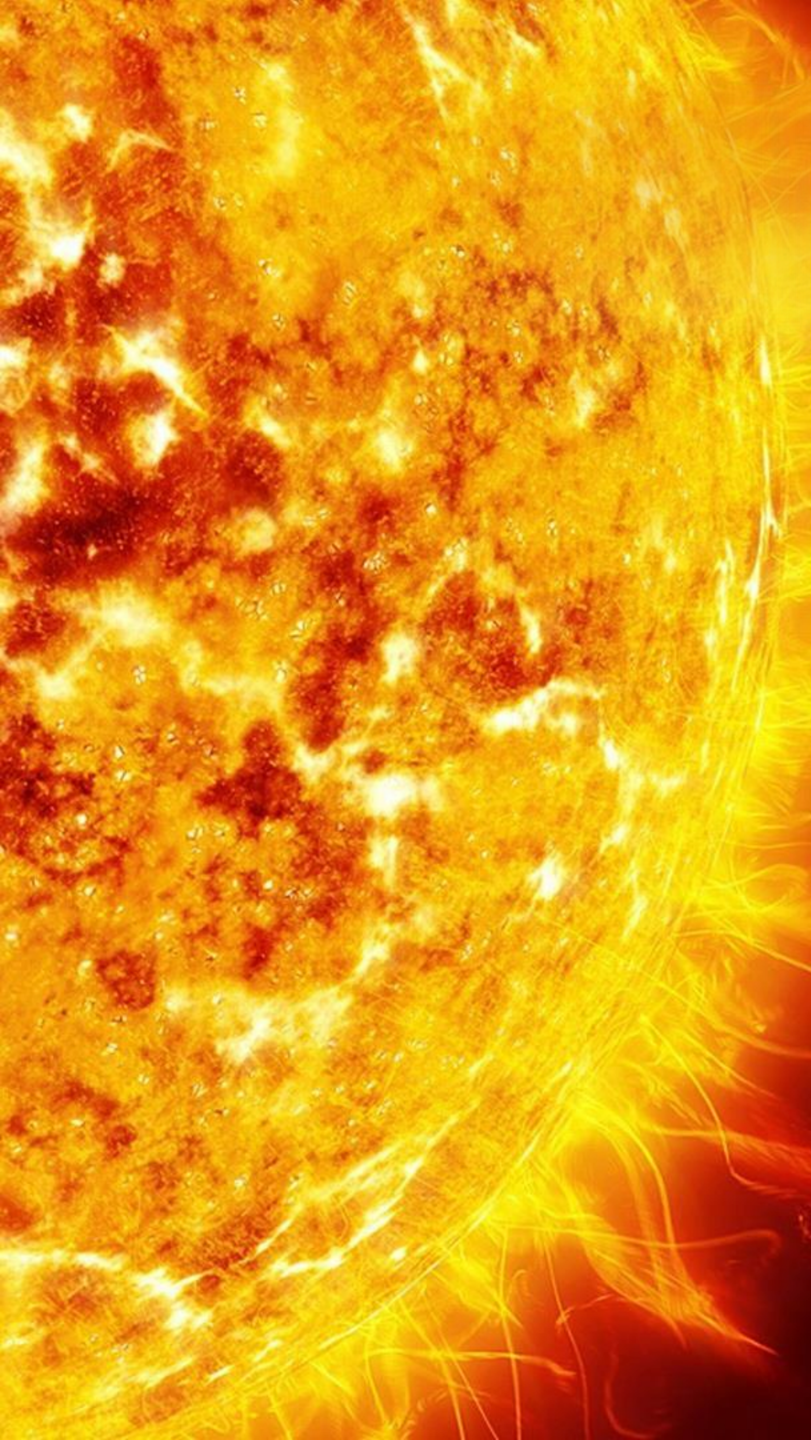

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a faster way to fusion

Dr David Kingham
CEO, Tokamak Energy

IEA, 25 January 2017

the Spherical Tokamak route to fusion power

Conventional tokamaks (eg JET)

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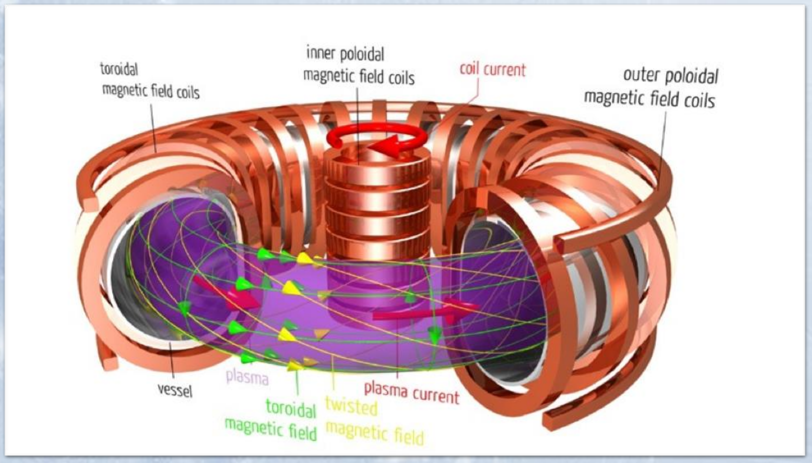

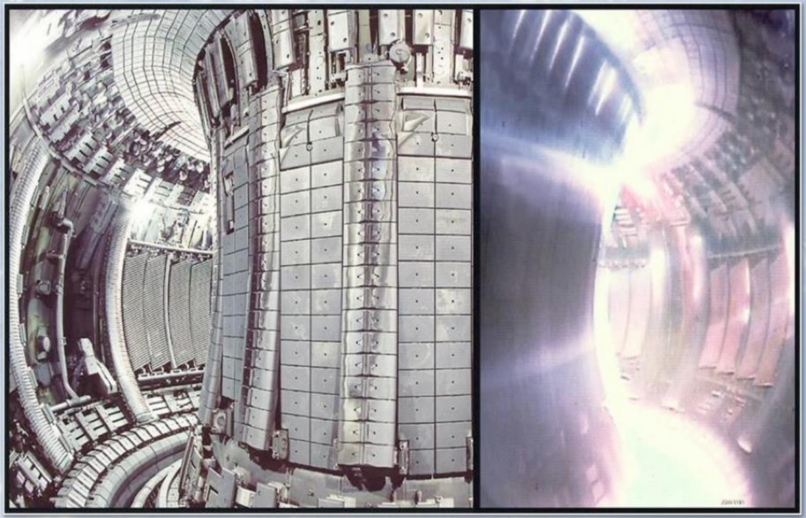

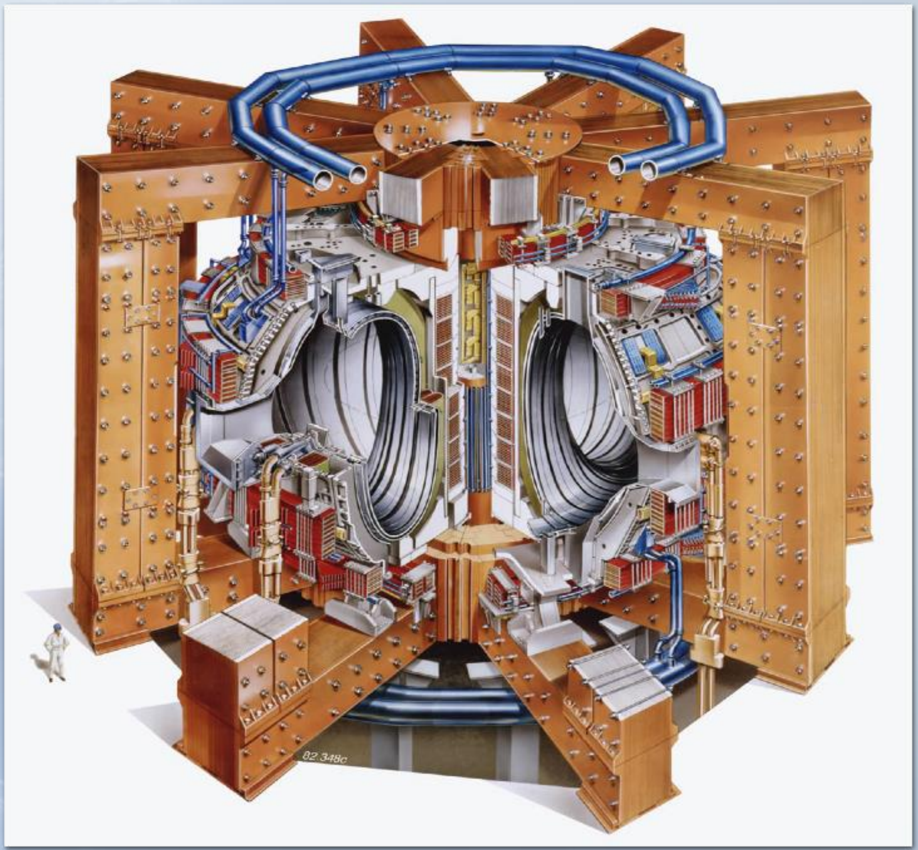

Spherical Tokamaks (ST)

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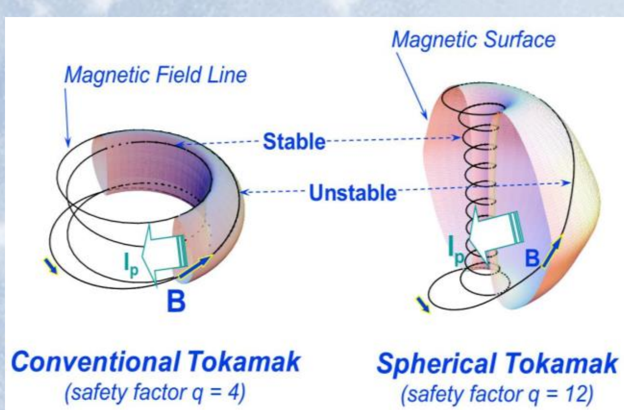
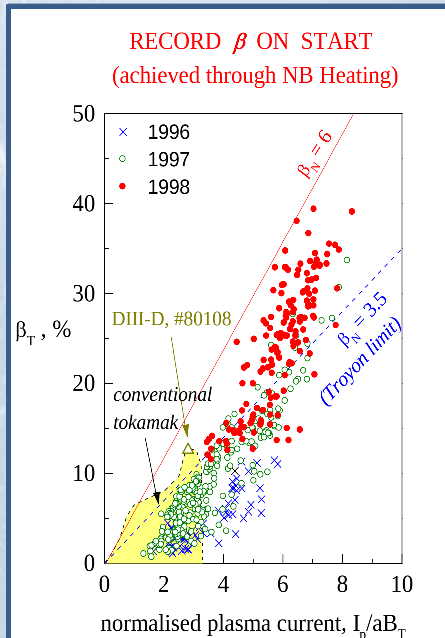
Some advantages of the ST

High safety factor

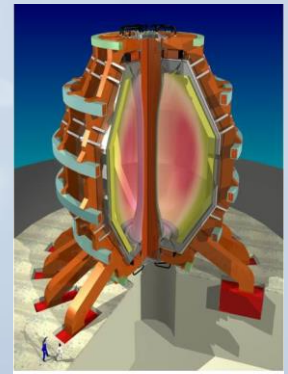


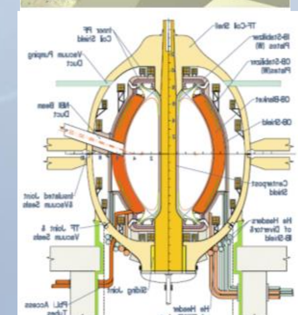
High beta (β)

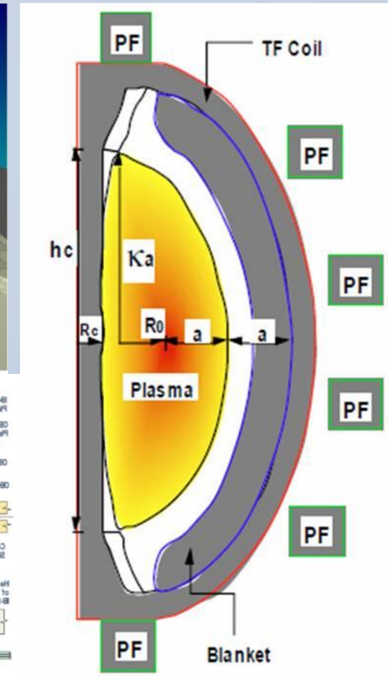


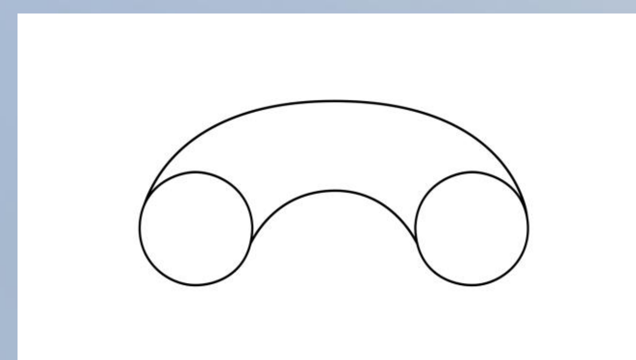
Plasma in START ST, Culham, 1996

ST Power Plant Concepts









The Technology

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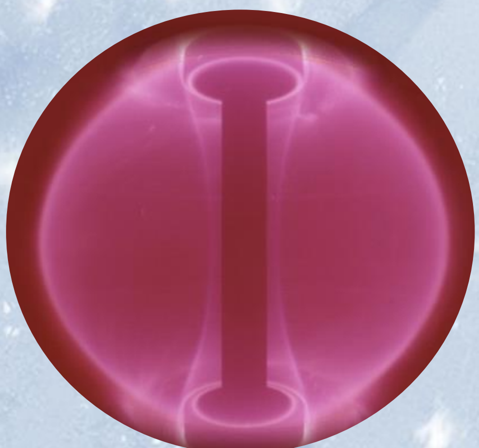
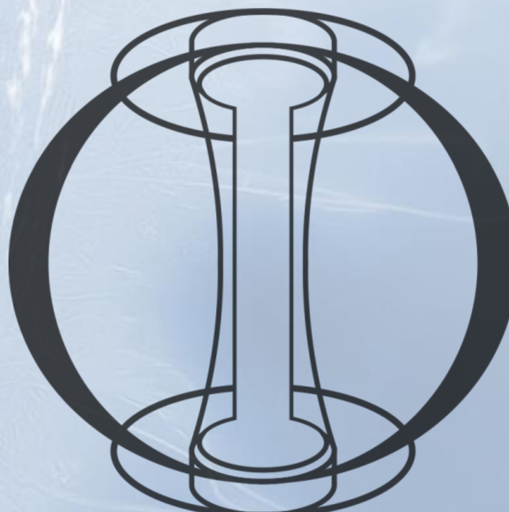
Spherical Tokamaks

Squashed shape

Highly efficient

From 12% to 40% efficiency, β

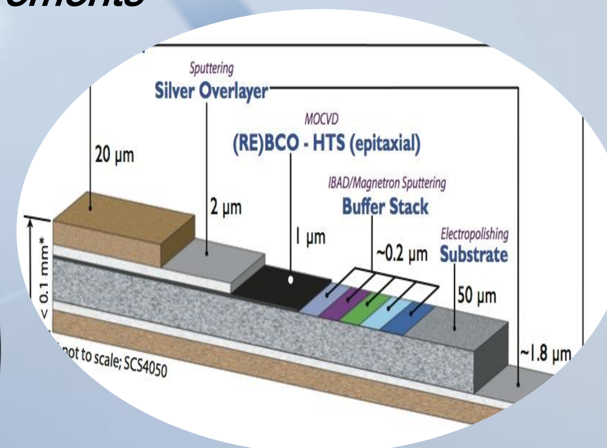




High Temperature Superconductors

High current at high field

Lower cryogenic cooling requirements



smaller, cheaper, faster

Top of the IAEA nuclear fusion charts!

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A.E. Costley *et al* 2015 *Nucl. Fusion* **55** 033001

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Smaller fusion reactors could deliver big gains

Feb 16, 2015 15 comments

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On the fusion triple product and fusion power gain of tokamak pilot plants and reactors

A.E. Costley 2016 *Nucl. Fusion* **56** 066003

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Comment on 'On the fusion triple product and fusion power gain of tokamak pilot plants and reactors', by A. Costley

W. Biel *et al* 2017 *Nucl. Fusion* **57** 038001

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Supporting Evidence

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PPPL PRINCETON PLASMA PHYSICS LABORATORY
A Collaborative National Center for Fusion & Plasma Research

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Stewart Prager, PPPL Director, Testifies Before U.S. House Subcommittee on Energy

April 20, 2016

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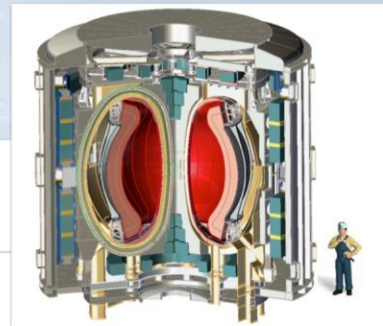
IAEA **nuclear fusion**



PAPER

Fusion nuclear science facilities and pilot plants based on the spherical tokamak

J.E. Menard[1], T. Brown[1], L. El-Guebaly[2], M. Boyer[1], J. Canik[3], B. Colling[4], R. Raman[5], Z. Wang[1], Y. Zhai[1], P. Buxton[6] Show full author list

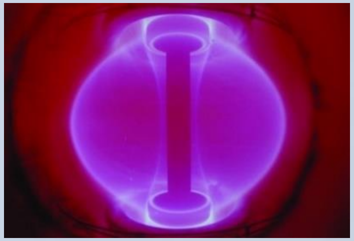
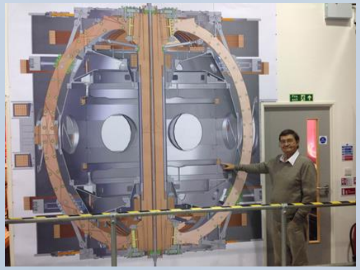
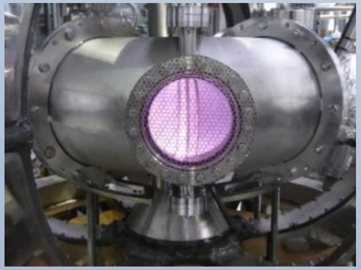
Published 16 August 2016 • © 2016 IAEA, Vienna

Nuclear Fusion, Volume 56, Number 10

The ST concept investigated by NSTX-U can operate at high plasma pressure (which provides more fusion power) and at relatively weak magnetic field (which reduces cost) compared to conventional tokamaks. The practical impact is that this offers the possibility, for example, of designing a fusion pilot plant or fusion nuclear science facility of a size significantly reduced from that based on conventional tokamaks. A fusion pilot plant would generate net electricity and perform an integrated test of a full fusion energy system, including testing materials

Achievements

- Patent applications (HTS magnets)
- Private investment of £20M
- Designed ST40 spherical tokamak
- Established HTS magnet development team and laboratory
- Demonstrated a small tokamak ST25 1.0
- Demonstrated a second small tokamak will all HTS magnets
- World Economic Forum Technology Pioneer 2015


Milestones 2017-2019

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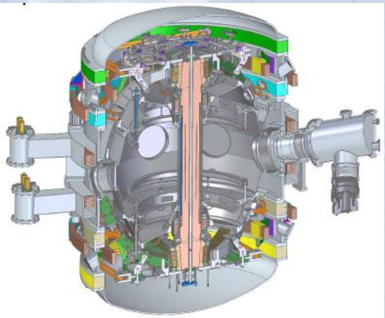
ST40 tokamak demonstrations

First plasma	Q1 2017
15 million degrees	Q3 2017
100 million degrees	Q3 2018
Energy Gain conditions	Q2 2019

HTS magnet demonstrations

3 tesla prototype	Q3 2017
5 tesla prototype	Q3 2018
ST40 Toroidal Field magnet	Q2 2019



Complete validation of concept for the high field HTS spherical tokamak

Ready to receive major investment (e.g. IPO)

Breakthrough Energy Ventures

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Climate Impact
- technologies that have the potential to reduce greenhouse gas emissions by at least half a gigaton.

other investments
- companies with real potential to attract capital from sources outside of BEV and the broader Breakthrough Energy Coalition.

scientific possibility
- technologies with an existing scientific proof of concept

filling the gaps
- companies that need the unique attributes of BEV capital.

Why now?

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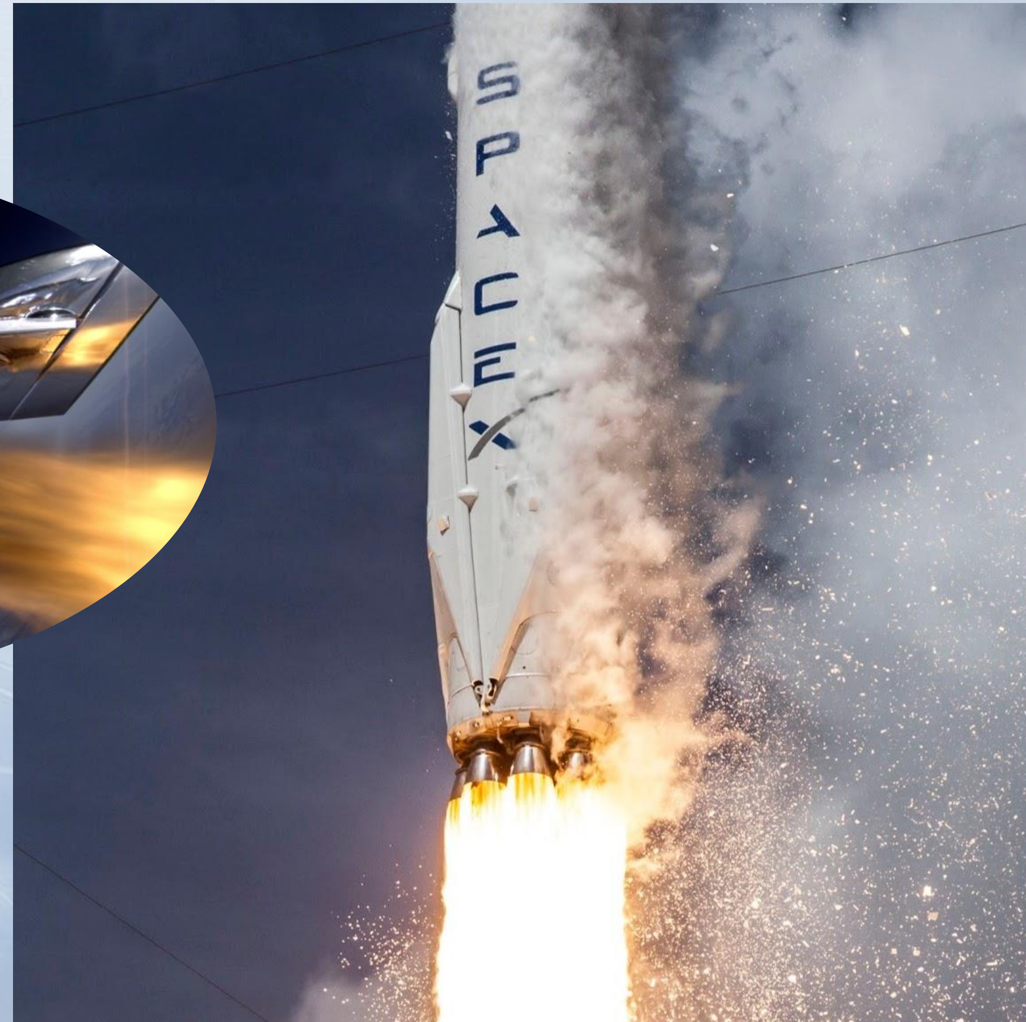

A few thoughts…

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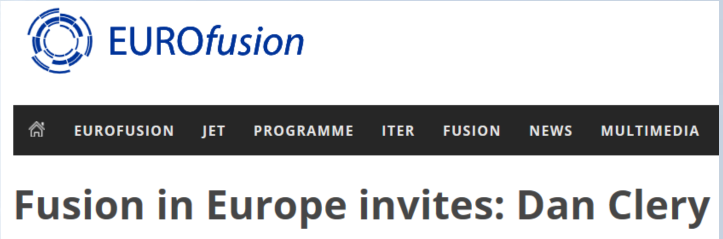
Does fusion research lack diversity?
Dan Clery, Dec 2014,
in Eurofusion News



The energy and initiative of the private companies could give fusion a much needed shot in the arm, and for them to take the next step towards viability they will need much more money, and could use support rather than disdain.

Perhaps in fusion, as in biology, diversity will promote health and vitality. And you never know, one of them might actually work.

Summary

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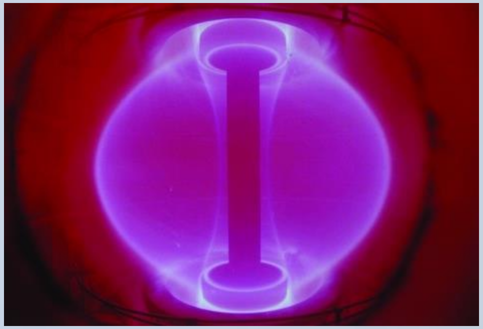
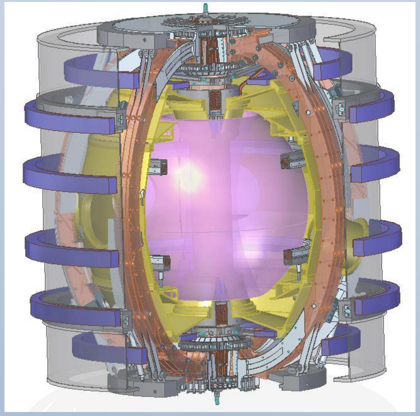
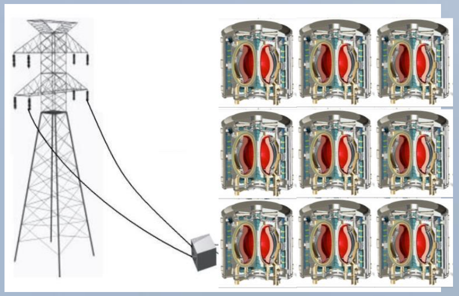
- Fusion energy is a goal worth pursuing!
  - Private investors are getting interested
  - We are the only venture developing tokamaks.
  - The evidence for our route to fusion is growing.

- Our clear goals will enable us to raise more investment.
- Even partial success will inject excitement into fusion
- But we will work with investors and partners to succeed completely!







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Thank you

@TokamakEnergy

www.tokamakenergy.co.uk

Back up slides

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High temperature superconductors

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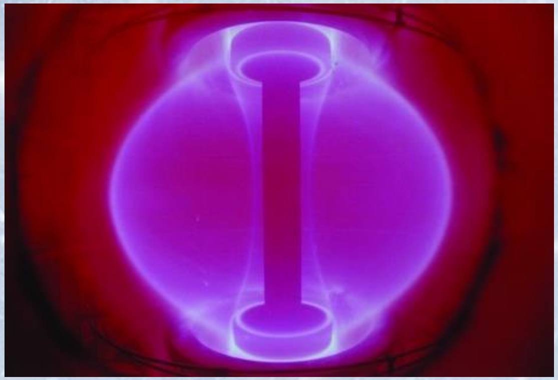
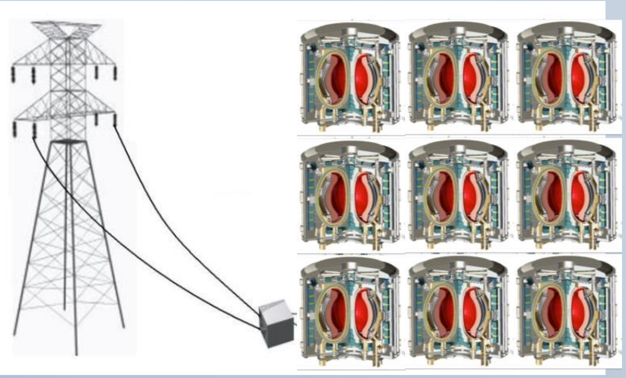
Our Solution – A faster way to fusion

Accelerating the development of fusion power by combining two emerging technologies to design a commercially focused modular reactor





Spherical tokamaks (ST)

Characterised by efficient plasma confinement and improved stability allowing for high performance in a compact geometry

High temperature superconducting magnets (HTS)

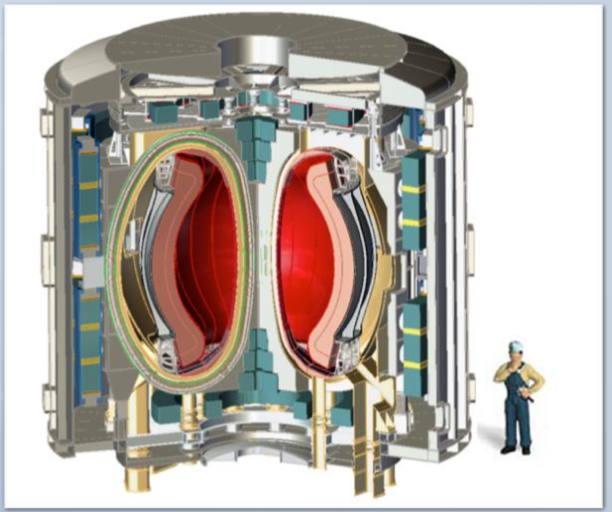
The key enabling technology that produces the large magnetic fields needed for economical fusion power

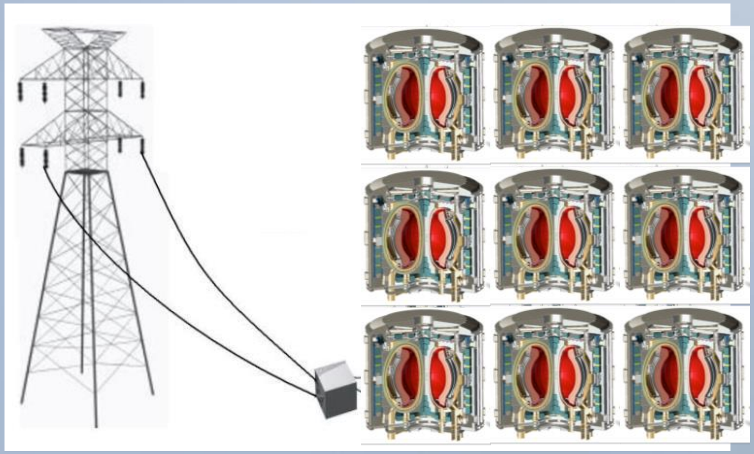
Modular reactor design

Smaller reactors accelerate commercialisation by allowing for rapid development while reducing the risk associated with a first of a kind reactor

Modular Reactors

- Small reactors, designed to produce 100MWe, can be combined into a GWe scale power plant or used in locally distributed power networks
- Cost of Electricity (CoE) is dominated by capital costs
  - The high β and bootstrap current fraction achievable in spherical tokamaks minimises the capital cost of the magnet and current drive systems and improves overall efficiency
  - Shared services and sub-systems can reduce capital cost
  - Reactor designed to minimise CoE
- Reserve modules allow for off line servicing whilst maintaining plant availability
- Potential for off-site assembly-line manufacture and associated cost savings
- Initial operator outlay and risk is low when compared to a single, GWe scale unit





Achievements & Progress to date

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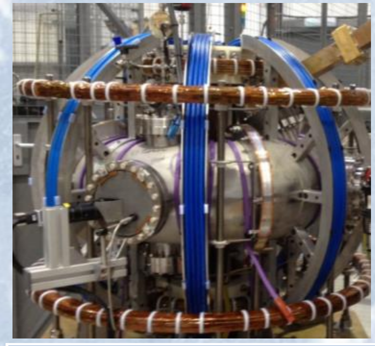
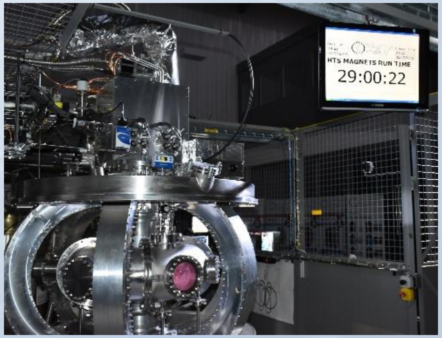
2012 | 2013 | 2014 | 2015 | 2016





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

Timeline to Fusion Power

Challenge	Aim	Technical Details
Hotter than the sun	2017	Use alternative technique of ‘merging compression’ to start machine and attain temperatures of over 15 million degrees.
100 million degrees	2018	Refine merging compression technique to heat the plasma to 100 million degrees (fusion temperatures). Opens up route to smaller tokamaks with higher magnetic fields.
Fusion energy gain	2019/20	Hold plasma hot enough for long enough to pass energy breakeven conditions. (May need to be demonstrated without full fuelling to avoid regulatory delays). Demonstrate high toroidal field superconducting magnet for an ST40 scale device.
First electricity	2025	Combine improved high temperature superconducting magnets (higher field) with knowledge of fast plasma control in a compact design to achieve first electricity.
Electricity into the Grid	2030	Engineer a fusion power plant suitable for long-term commercial operation, ensuring plant longevity under hostile conditions. A collaborative effort, building on research from around the globe.

World Economic Forum

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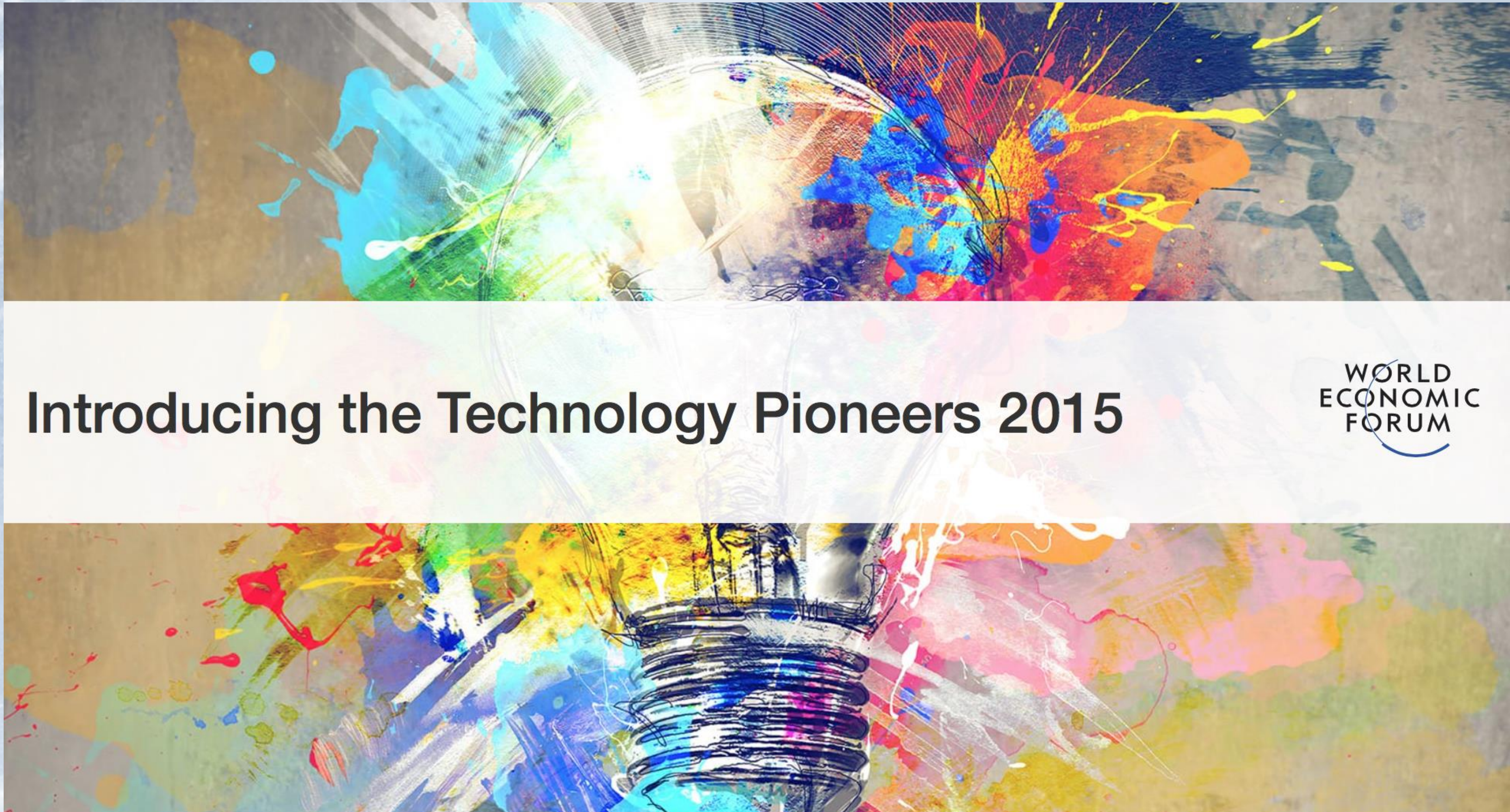

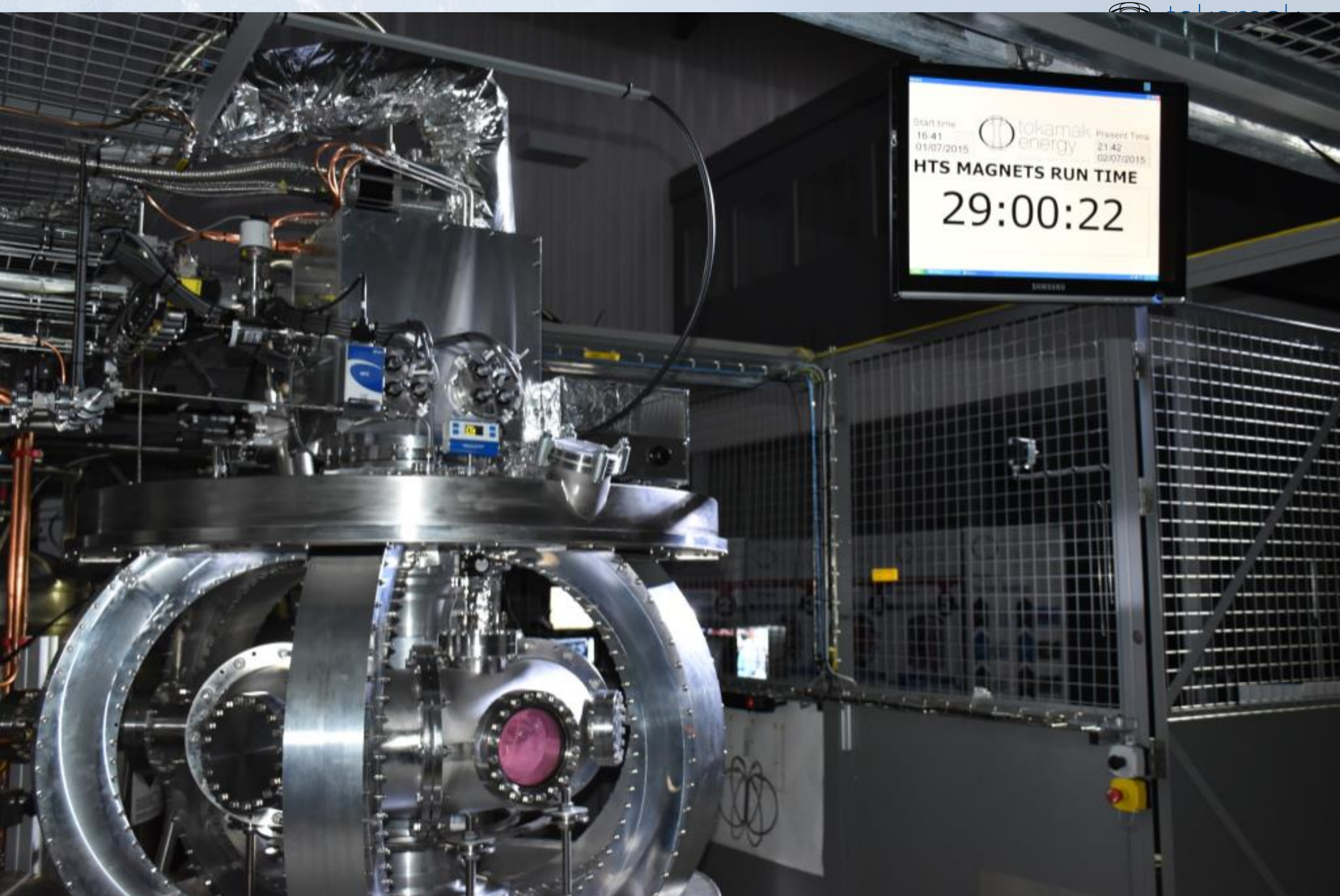
Start time
16:41
01/07/2015
tokamak energy
Present Time
21:42
02/07/2015
HTS MAGNETS RUN TIME
29:00:22

ST40

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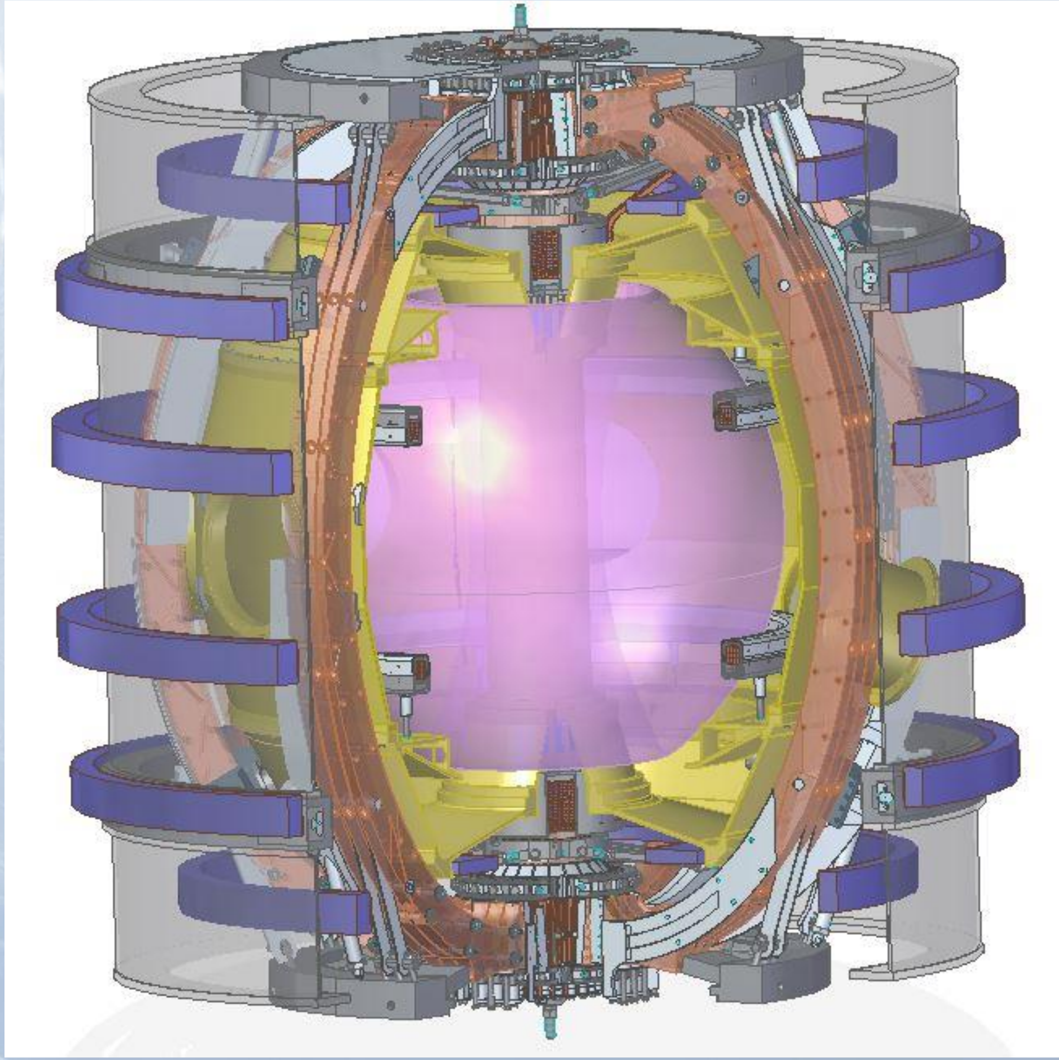
High magnetic field (3T)

Plasma pulse length 1.5 - 8s

Copper magnets (liquid nitrogen cooled)



Reactor considerations

Materials

Engineering