tokamak energy

a faster way to fusion

Faster Fusion through Innovations

M Gryaznevich and Tokamak Energy Ltd. Team

FusionCAT Webinar 14 September 2020

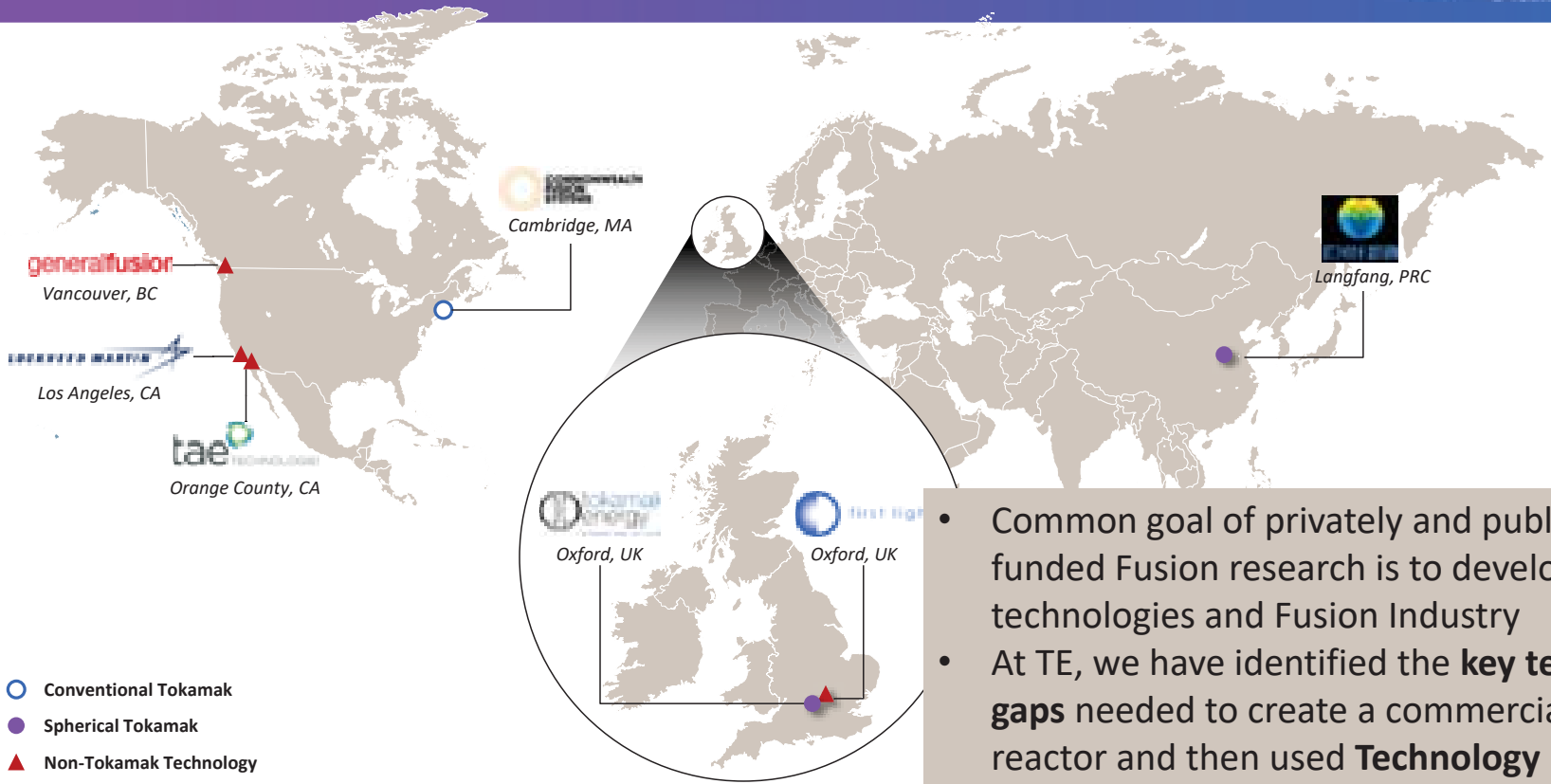
Fusion Research – Public Tokamaks

- Conventional Tokamak
- Spherical Tokamak

- Fusion research is advancing
- However, progress towards Fusion Power is constrained

Note: Tokamaks are operating unless indicated otherwise.
(1) Under construction.
(2) The International Thermonuclear Experimental Reactor ("ITER") megaproject is supported by China, the European Union, India, Japan, Korea, Russia and the United States.
(3) No longer in use.

Fusion Development – Private Funding



- Common goal of privately and publicly funded Fusion research is to develop technologies and Fusion Industry
- At TE, we have identified the **key technology gaps** needed to create a commercial fusion reactor and then used **Technology Roadmapping** as an approach chart our path.

Private Fusion Competitive Landscape - The emergence of the Fusion Industry

https://www.fusionindustryassociation.org/

Private Fusion Competitive Landscape - The emergence of the Fusion Industry

*There is a nascent fusion industry**

- There are many companies, the list is growing
- They are optimizing for things beyond physics
  - Indicators about the fusion value proposition
- They can be extremely capable organizations
  - Move faster than gov't programs
  - Tight focus on deliverables and milestones
  - With less $ (now) and different resources than gov't
  - High-growth potential
- They are serious and thoughtful

*Private companies investing significantly in fusion R&D, not just performing gov. research.

Mumgaard, CFS

Our approach is based on Innovative Physics and Technology

Spherical Tokamaks

Squashed shape, compact

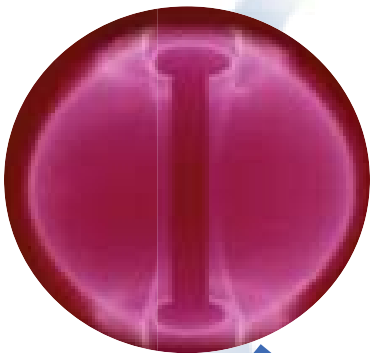
Highly efficient, *high β :*

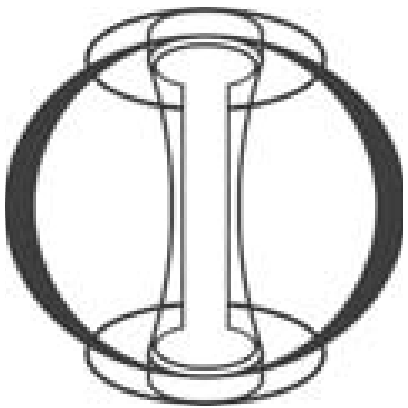
from 12% in DIII-D to 40% in START/NSTX

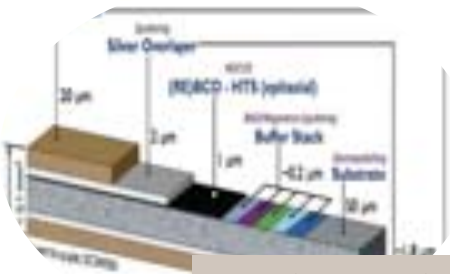
High Temperature Superconductors

High current at high field

Lower cryogenic cooling requirements







It is this combination of the spherical tokamak shape with high temperature superconductors that we believe is the key to development of fusion power.

smaller, cheaper, faster

Together we can make Fusion Faster!

Our principles:

- **Collaboration** in development of Fusion Science and Technologies
- Use of **multiple compact devices** and demonstrators to validate modelling and progress at a **faster pace** and **lower financial risk**

- Strong focus on **industrial 'deliverability'** and **cost** of the commercial device
- Our approach has **common ground with** mainstream Tokamak Fusion (e.g. **ITER**, DEMO, STEP).

We rely on the **same physics** behind the magnetic fusion concept … but we have a faster way to get to a commercially viable device.

Approach to Technology Development

Our development principles:

- The long term nature of fusion development means that many of today's established **technologies** will be **out-of-date by the time** the fusion technology is deployed.
- We have consciously embraced risks around the development of *highly probable* technological advances.
- In a world where technology advances at ever increasing speed, rather than seeking cast iron guarantee that technology is available at the *beginning* of our journey, we have asked ourselves whether it is likely to be present ***when we need*** *it* along the way.
- To use **innovations** efficiently, we need to reduce the build time and have enough test beds, R&D etc

Our approach is based on Innovative Physics and Technology

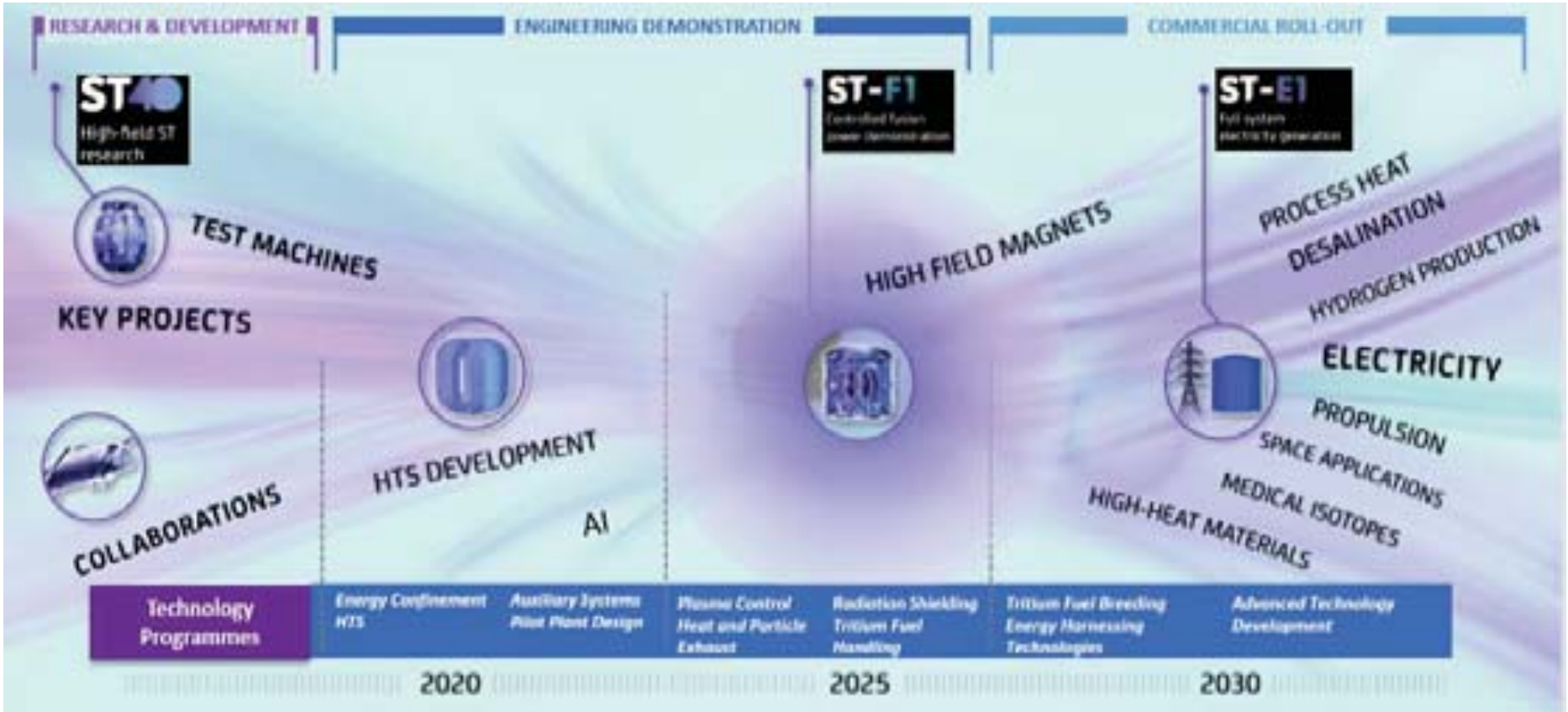
What is Innovation?

- UK Research and Innovation (UKRI) recognises **innovation** as "the application of knowledge of ideas for the development of products, services or processes – whether in business, public services, or non-profit sectors."
  - The project must be disruptive in its intended market
  - The projected end-result must be above the current state-of-the-art available
  - The project must result in a product/process/service that is commercially viable

- Innovation doesn't have to be a brand-new invention; in fact, it very rarely is! It can be a novel way to use an existing service, process or product – even in a different industry – or to apply a new technology to improve what's currently available.

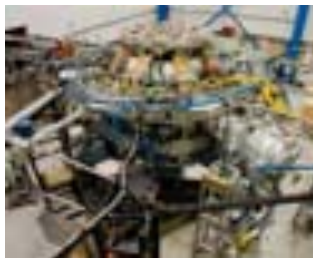
https://www.tbat.co.uk/

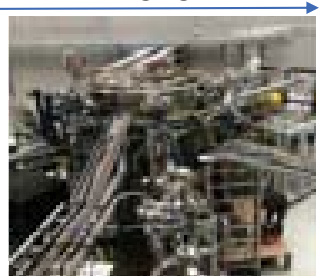
Tokamak Energy Technology Roadmap to Faster Fusion



Achievements & Progress to date

2012 | 2013 | 2014 | 2015 | 2016-19 | **2020**





ST25 1.0	ST25 1.1	ST25 1.2	ST40 1.0	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**	Toroidal Field: 2 T Poloidal Field: Copper Toroidal Field: Copper	Toroidal Field: **3.0 T** Poloidal Field:Copper LN2 Toroidal Field:Copper LN2
Plasma pulse of a few milliseconds (extended to > **20s** with micro-wave current drive)	**Industrial** HTS PF coils, Stable operations	**World First** Tokamak with **all HTS magnets** **29-hour plasma,** RF supported	**ST40 - highest field Spherical Tokamak** first campaign: I_{pl} > 0.5MA, $2x10^{20}m^{-3}$, temperatures in keV-range. I_{pl} > 400 kA from m/c formation	Significant upgrades of PSUs, new PF coils, **divertor,** more diagnostics, bioshield. **Plans for Autumn 2020:** 1 sec flat-top at 3 T, 2 NBI + DNBI

- First **full-HTS** tokamak
- **24.4T** peak field on coil (22T in the bore) in pure-HTS magnet
- Papers published showing **tokamaks do not have to be huge** to achieve Fusion
- ST40 - highest TF in STs
- **Improvements in performance** with TF confirmed

INNOVATIONS

Innovations on the Way to Fusion Power

Three main innovations:

- **Spherical Tokamak** as a solution to Compact Reactor and Modular approach for Fusion Power Plant
- **HTS Magnets** – solution for high field, so better performance and economics
- **Magnetic reconnection** as formation and heating method.

- Plus: Li conditioning, Li divertor, low recycling regime, high field side EBW for start-up, CD and heating, new wall and divertor materials - more welcome! We can adopt innovations:

  - Innovations are indeed easier to test and use in smaller devices that are also cheaper and quicker to build.

Innovations on the Way to Fusion Power

Form recent interview with **Bigot**: “I see all these smaller projects with very positive attitude”. “it is already a success for **ITER** to stimulate these <e.g. TE> projects.

Design of ITER was set in 2007. We could not change the design every day. We will integrate progress, but some progress can’t be integrated.

We are very pleased to work with them <e.g.TE> as often as it is possible. We are not in competition, we are complimentary. I don’t want to illuminate any of them <i.e. STs>. **We can enrich each other”**.

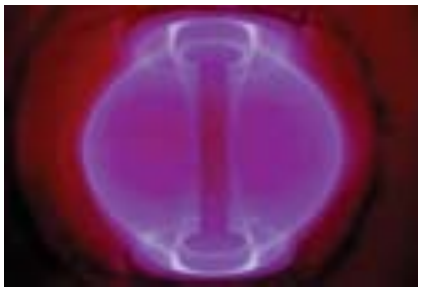
In the US, the National Academy of Science has been asked to develop plans for a US compact fusion pilot plant including drawing up a “List of the principal innovations needed from the **private sector** to address and meet the goals”

Our Innovations in detail

SPHERICAL TOKAMAKS

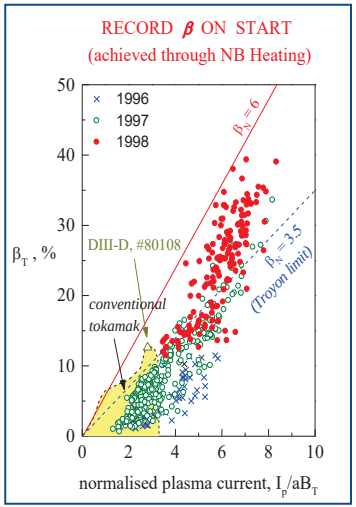
Innovations: Spherical Tokamaks, why?

High safety factor, better stability, better confinement of fast particles



Plasma in START, Culham, 1996
H-mode, improved confinement

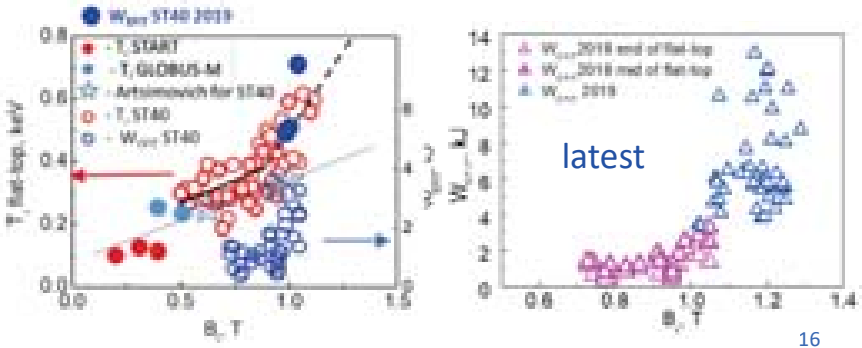
High beta (β), $P_{FUS} \sim \beta^2 B_t^4 V$, so volume (reactor size) can be reduced!



"Apparently the high beta potential of the ST is so great that the physics of this device will not determine its size".

Ron Stambaugh, "THE SPHERICAL TOKAMAK PATH TO FUSION POWER", FUSION TECHNOLOGY VOL. 33 JAN. 1998

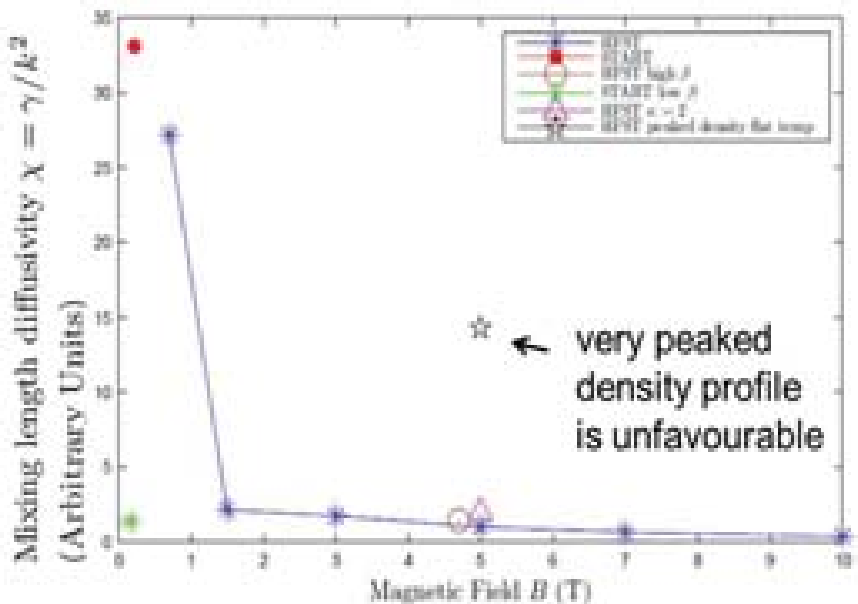
- Improvements in performance with increased field already demonstrated in first experiments **on ST40**
- Field already increased to 2 T, and will be 3T this year



Ion energy and thermal energy W_{EFIT} measured on ST40, START and Globus-M against toroidal field, along with a predicted ion temperature assuming the Artsimovich formula.

Improvement in confinement at higher Toroidal Field

- Observed sharp increase in T_i and W_{therm} at B_t ~ 1T may be connected with the predicted in **GT2 simulations** reduction in transport at higher toroidal field in an ST:



- At **low** magnetic field the mixing length diffusivity is dominated by **electromagnetic** microtearing modes; these are **stabilised at higher B_t,** diffusivity then being dominated by **electrostatic** twisting modes.
- no beta or shape dependence at high field
- **Threshold** toroidal field is quite low, close to one **observed in ST40, ~ 1 - 1.5 T**

TE Path to Fusion, why High field ST?

Fusion power	Efficiency	Field strengh	Volume

$$P \sim \beta^2 \times B_t^4 \times V$$

- Increase in beta allows significant reduction in plasma volume

- Engineering of high field in ST is a real challenge! Physics is good.

HTS FOR TOKAMAK MAGNETS

Why HTS ?

Arguments:

- Only solution for >20T on conductor
- Reduction in cryo power – needed for compact reactors
- Can tolerate some heating (while LTS will quench!)
- Good mechanical properties
- Good performance under neutrons
- Supply chain improving all the time

Why HTS? JET, ITER, European DEMO:

5 Tesla in JET TF coils using High Temperature Superconductor ?

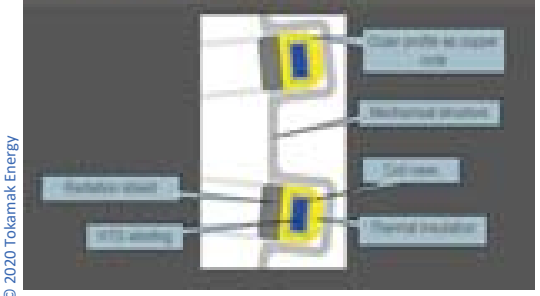
John Last

08 December 2011

Advantage of HTS

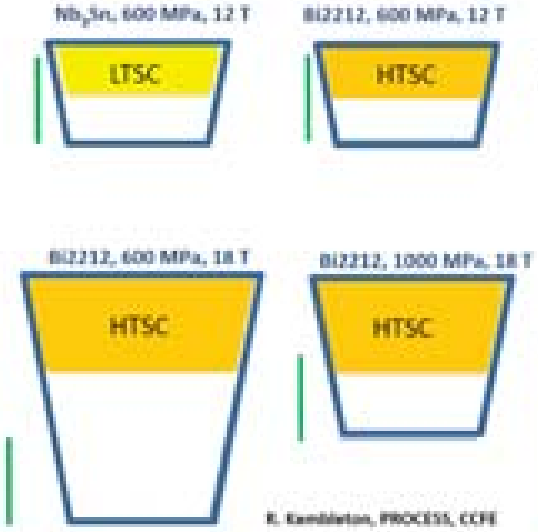
- Current density in JET TF coils is <2.5 kA/cmsq
- HTS in small Tokamak (Golem) operates with current density 16 kA/cmsq
- If HTS can achieve the same current density at 10 Tesla, the high current density might allow space for extra structure & insulation to enable 5 Tesla at plasma major radius

Outer leg of TF coil using HTS



EU DEMO doesn't (currently) use high B TF coils

- Any increase in B inherently leads to higher stresses ($\sigma \propto B^2$)
  - ➔ TF coil nose grows to accommodate field, offsetting gains in R_0
- To really see benefit of high B_T in the machine size (R_0), we would need higher strength cryogenic steels



"ITER-like" DEMO magnets with LTS and HTS

(Green line = 1m)

High-field magnets (18T) with HTS: current structural materials and high-strength materials

The development of HTS coils is not a useless endeavour; there are many aspects of HTS conductors which are very promising. In the EU R&D is ongoing (see following slides)

G. Federici & PPPT Team | Meeting NAS, Cadarache, 13 Feb. 2018 | Page 23

HTS development at TE Ltd

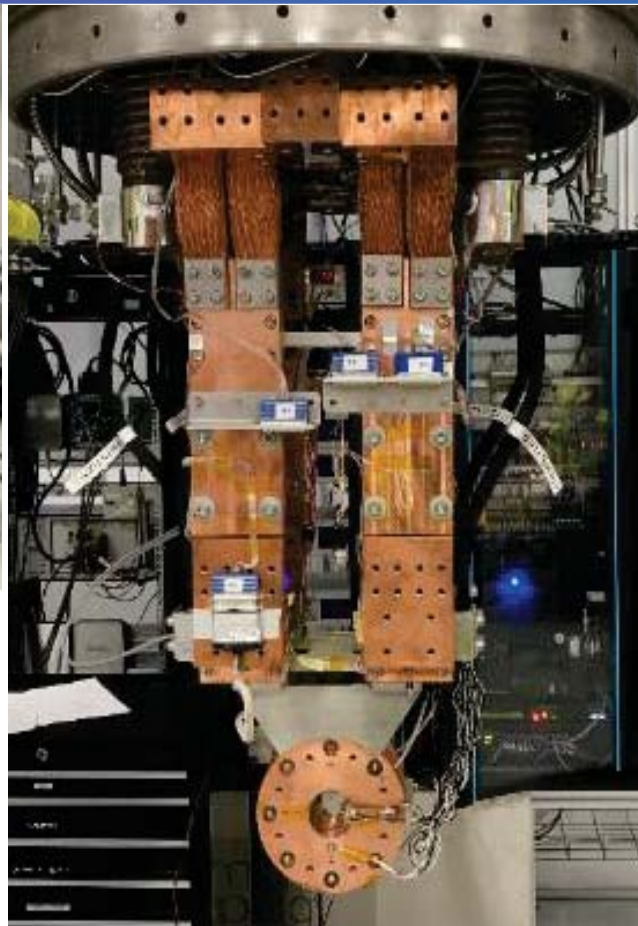
Progress:

- **Choice of tape => done**
  - 6 tapes checked, all good, production of needed quantity and good quality is main challenge
- **Choice of cable => done**
  - cables up to 100 kA tested at NIFS, we can work at lower current
  - our own design, patented
  - joints, feeds => all has solutions
- **Magnets – research on-going**
  - 20+ coils tested, > 20T @20K
  - Quench studies and quench protection
  - TF + PF prototype is under construction. It will test key technologies for future pilot plants as far as possible under relevant magnet operating conditions.

10 T at 0.25m

David Hawksworth Magnet Laboratory

- Coil winding & assembly
- 77 K test facilities
- Instrumentation & magnet integration capability
- 4 kA, 12-50 K conduction-cooled cryogenic test rig
- One QA coil made and tested **per week**



HTS development at TE Ltd

R Slade
3 Sept 2019
2-LO-FH-02S
Dochart room, 16:45

- Modular, robust & scalable high field HTS magnets
- Simple assembly and disassembly (no soldering)
- **24.4 T achieved conduction cooled at 21 K**
- Survives repeated fast (LTS-like) quenches
- High voltage insulation is not required
- Defect and damage tolerant
- No need for long tape lengths (~20 m is OK)

Our QA coil technology is ready also for non-fusion application !

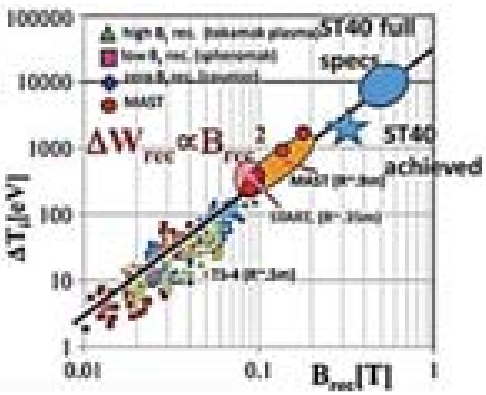
Scale up plan for fusion:

- Retain benefits of quench protection with fast ramp capability using novel partial insulation
- No twisting / transposition (enables > 300 A/mm^2)
- Ex-situ cooling & structural support – simple large coil manufacture
- Neutron-resistant HV insulation not required

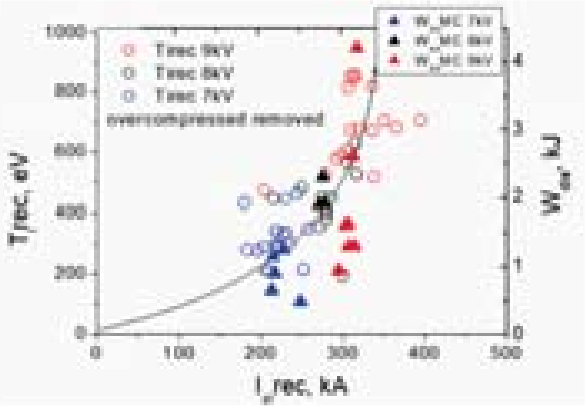
MAGNETIC RECONNECTIONS FOR FORMATION AND HEATING

Better use of Magnetic Field: reconnection heating

- Magnetic confinement is based on containment of hot plasma and insolation of it from the wall of the vacuum vessel, by the externally applied magnetic field.
- It is possible to transfer **magnetic energy** directly into the plasma **thermal energy** with a very high efficiency (up to 90%), thus using magnetic field **not only for the containment**, but also **for** the plasma **heating**.
- This can be achieved using magnetic reconnections during merging-compression formation of the tokamak plasma as used on START and MAST
  - Reconnection theory has been developed in astrophysics in 60-70th
  - According to theory that predicts heating due to reconnection ~ B^2, and experimental data from START, MAST and Japanese devices, plasma in ST40 should show burning conditions (nT) with temperatures ~10 keV
  - First results from ST40 already confirm these predictions.



Predictions

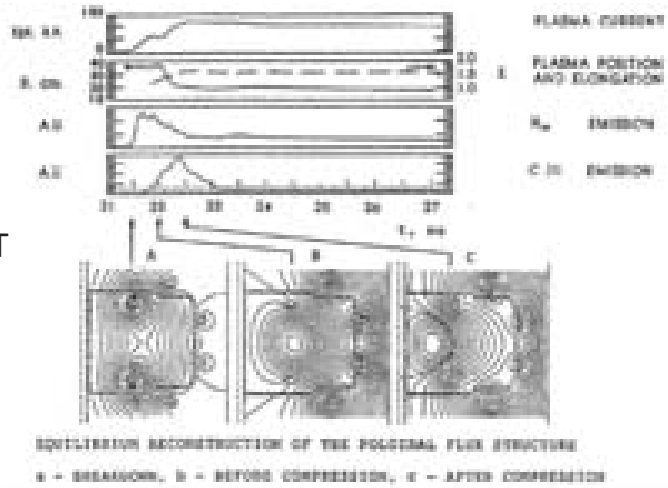


First results: scaling confirmed!

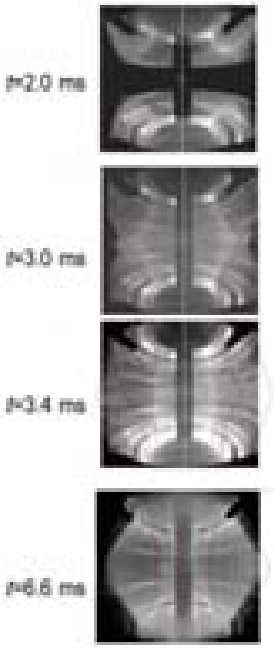
Merging-compression plasma formation

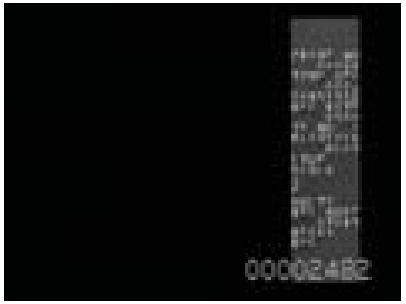
- First used on START, at Culham, in 1991. Successfully applied on MAST to achieve first plasma in 1998. Recently studied in detail on MAST, UTST, VEST, ST40.

START



- 3 stages:
  - *plasma around coils*
  - *merging (reconnection)*
  - *compression*



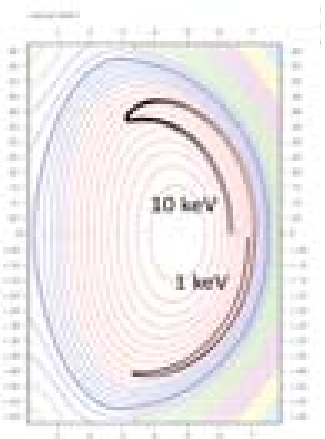


MAST

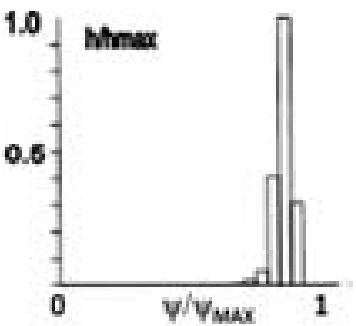
- Plasma currents 200-500kA without CS assistance
- keV-range temperatures

Reconnection heating – injection of fast ions

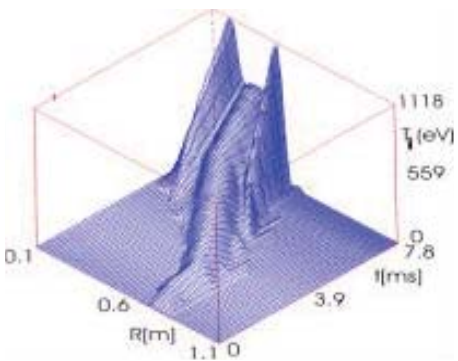
- To model merging-compression process codes **NFREYA, TSC and Torus II** have been used.
- NFREYA – Monte Carlo simulations are based on the assumption that the ions formed during the reconnection reach the poloidal Alfven energy and are mainly running in co-direction
- Assuming reconnection heating power of 20 MW with the deposition D(r) and a heating time of 3 ms, temperature of T_i ~1 keV is obtained in rough agreement with MAST & ST40 results



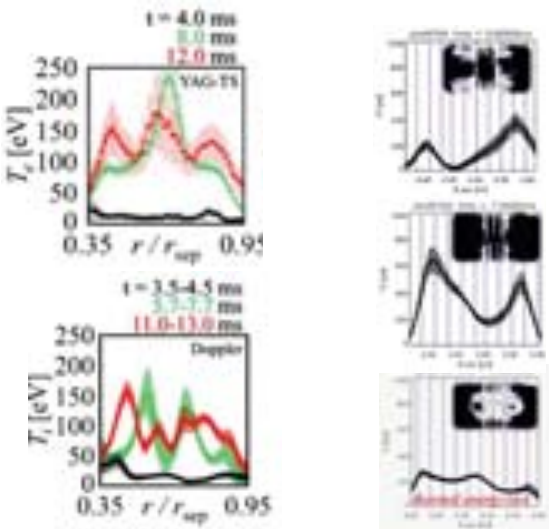
Orbits of the ions produced by reconnection



Deposition profile of reconnected ions D(r)



*Time evolution of T_i due to reconnection heating, **TSC***



Time evolution of $T_{e,i}$ on MAST and of T_i on ST40

MODULAR APPROACH

Modular Power Plant

- From 2014, Tokamak Energy Ltd. is developing a **modular design** of a fusion power plant.
  - *Gryaznevich, Journal of Physics: Conference Series **591** (2015) 012005; Chuyanov, FED **122** (2017) 238*

- In this **new alternative route** the economically feasible fusion power, plant will consist of several low power modules and the auxiliaries are shared between modules
- In all modular approaches, regular necessary maintenance is set off line in a module-to-module way, providing **high availability** of the power plant and **lower cost of maintenance**
- The approach permits saving time and resources needed for the development, to improve reliability by the cheap reservation, to use economy of mass production

Modular Approach for Power plant

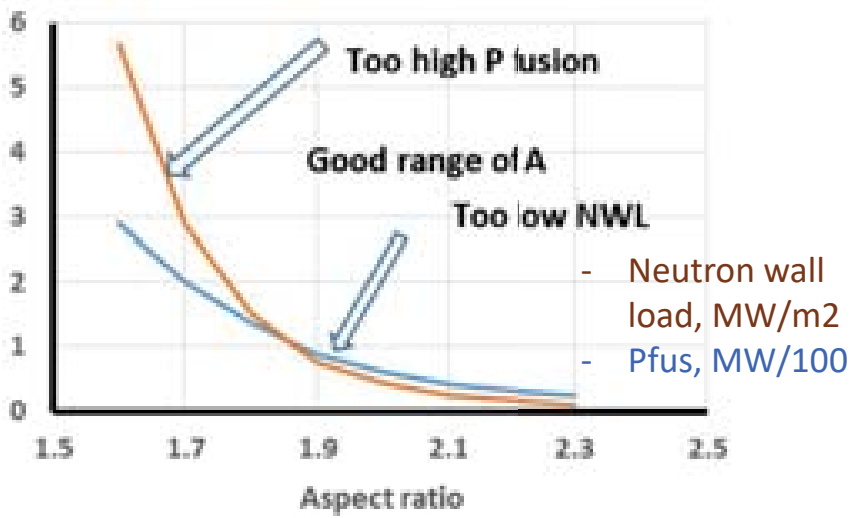
- A modular fusion plant consisting of several **compact, low-power high field ST modules** and some common auxiliary systems. This decreases the cost of prototypes (one module is a DEMO) and the risk of fusion development. *Chuyanov, FED, 2015*

- Modular approach combines advantages of "**economy of scale**" for conventional part of the plant and "**economy of mass production**" for fusion core of the plant and does not lead to increase of the capital cost of the plant.

- At the same time it permits to design very efficient ST-based **fusion power plant**:
  - High availability due to reduced duration of the first wall change and maintenance. Modules can be **serviced in turn**, so electricity supply can be maintained;
  - Units can **share** start-up (gyrotrons) and remote access facilities, and a hot cell for maintenance;
  - Many small units is attractive for manufacturers – **sustainable supply chain**;

Modular Approach for Power plant

- Modules with acceptable fusion power and neutron wall loading are in a narrow range of aspect ratios between 1.65<R/a <1.9



One example of system code calculations

Aspect ratio	1.7
Fusion power	172 MW
Plasma major radius	1.6 m
Plasma minor radius	0.94 m
Elongation	3
Toroidal magnetic field	3.17 T
Maximum value of TF field	19.6 T
Energy confinement time	1.65 sec
β toroidal %	10.6%
Plasma current	6.67 MA
Neutron Shield thickness	0.4 m

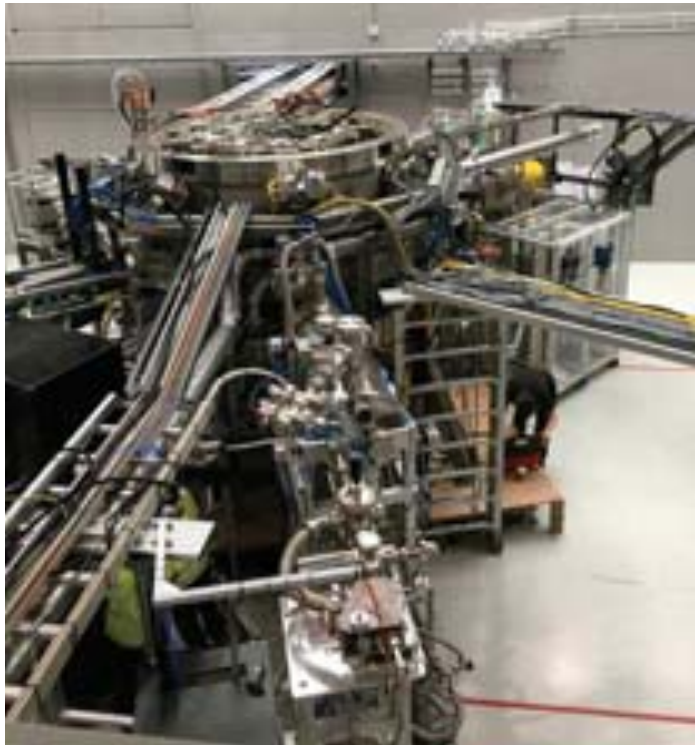
- Cost estimates show reasonable price of the first module

CONCLUSIONS

- Demonstration of burning plasma in a compact high-field ST is the current challenge for Fusion

- The ST path to commercial application of Fusion can start from Compact ST with R as low as 0.4 m

- Innovations can make Fusion sooner and cheaper



- ST40 is the first high field Spherical Tokamak

back-up slides

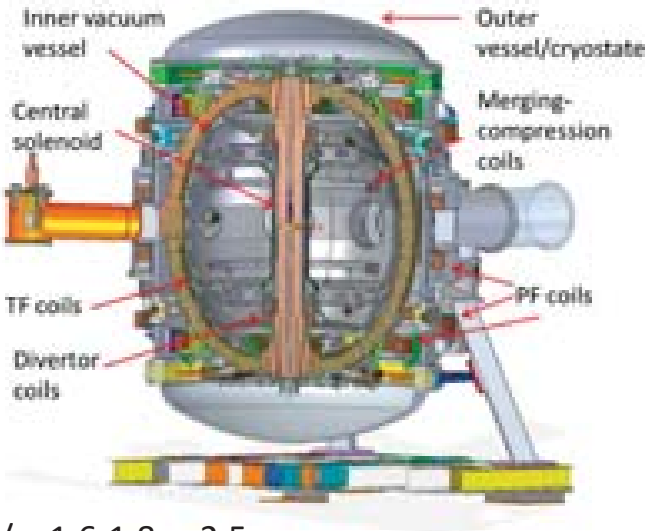
Collaboration and employment opportunities

- We welcome collaborations in many areas:
  - Multiphysics modelling of fusion reactor components including coupling of fluid dynamics, thermodynamics and neutronics
  - Modelling of high temperature superconductors
  - Modelling of plasma heating (NBI and ICRF) and fast particles
  - Large-scale modelling of fusion materials using density functional theory
  - Dynamic modelling of supercritical CO2 power cycles
  - Modelling, analysis and design of accelerator components for fusion materials research facilities (IFMIF-DONES)

Collaboration and employment opportunities

- We welcome collaborations in many areas:
  - Diagnostic systems
  - Tritium and lithium sensors and fabrication of PbLi alloy
  - Catalytic membrane reactors for hydrogen isotope recovery and fuel clean-up systems
- For employment opportunities please visit www.tokamakenergy.co.uk
  - We are hiring!

Present Status



- B_t =3T (2T achieved in 2019), I_p =2MA (0.5MA), R_0 =0.4-0.6m, R/a=1.6-1.8 κ=2.5
- start-up using merging-compression
- 2 – 4 MW of auxiliary heating (NBI / ECRH, 1MW 25kV operational, 1MW 50kV under commissioning; 1 MW gyrotron ordered)
- Pulse flat-top 1s at nominal 3T, 2-3 sec at lower TF
- LN2 cooled Cu magnets

ST40 Diagnostics

Diagnostic Neutral Beam Injector (DNBI)
0.15 MW 50 keV, 1 s

NIR Retro-reflector

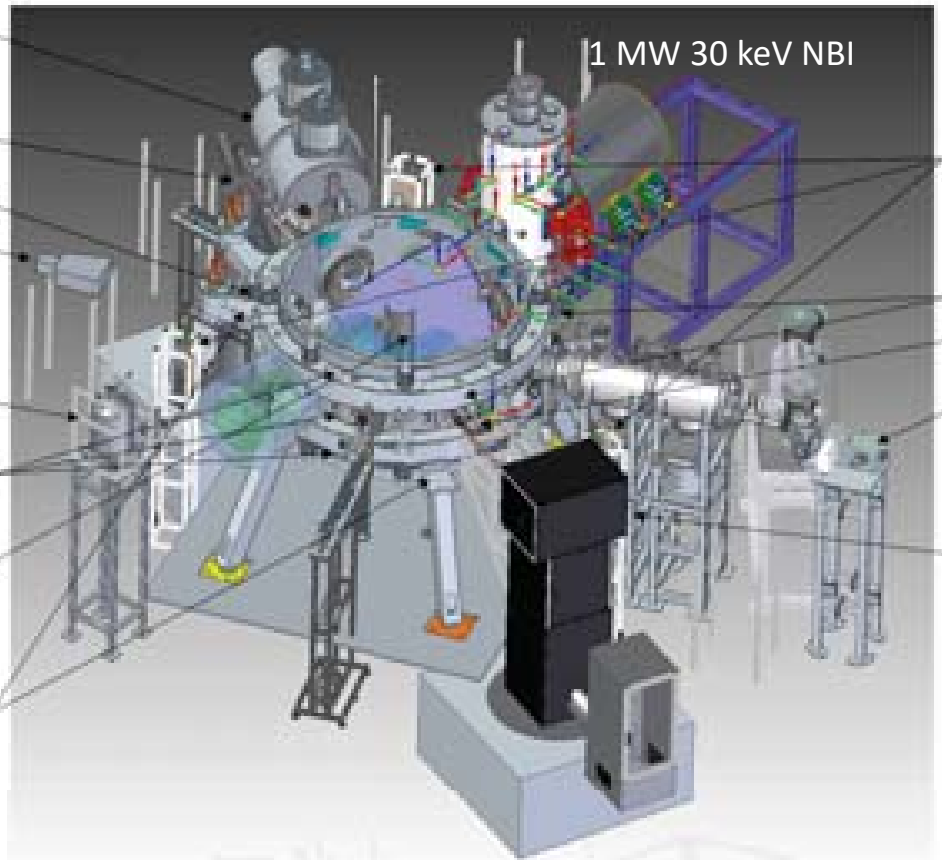
UV/Visible Doppler (Avantes) (Princeton) Spectrometers

Soft X-ray (Canberra) Spectrometer

Foil Filtered Soft X-ray Linear Arrays/Cameras

Panoramic (Ocean) Spectrometer

Line Emission Monitors



Hard X-ray & Gamma Detectors

Fast Visible & H-alpha Cameras

Infrared Camera

Neutral Particle Analyser (NPA)

Vibration Isolated Diagnostic Tower provides support for:

- SMM Interferometer
- NIR Interferometer
- ECE Radiometer

Future Plans