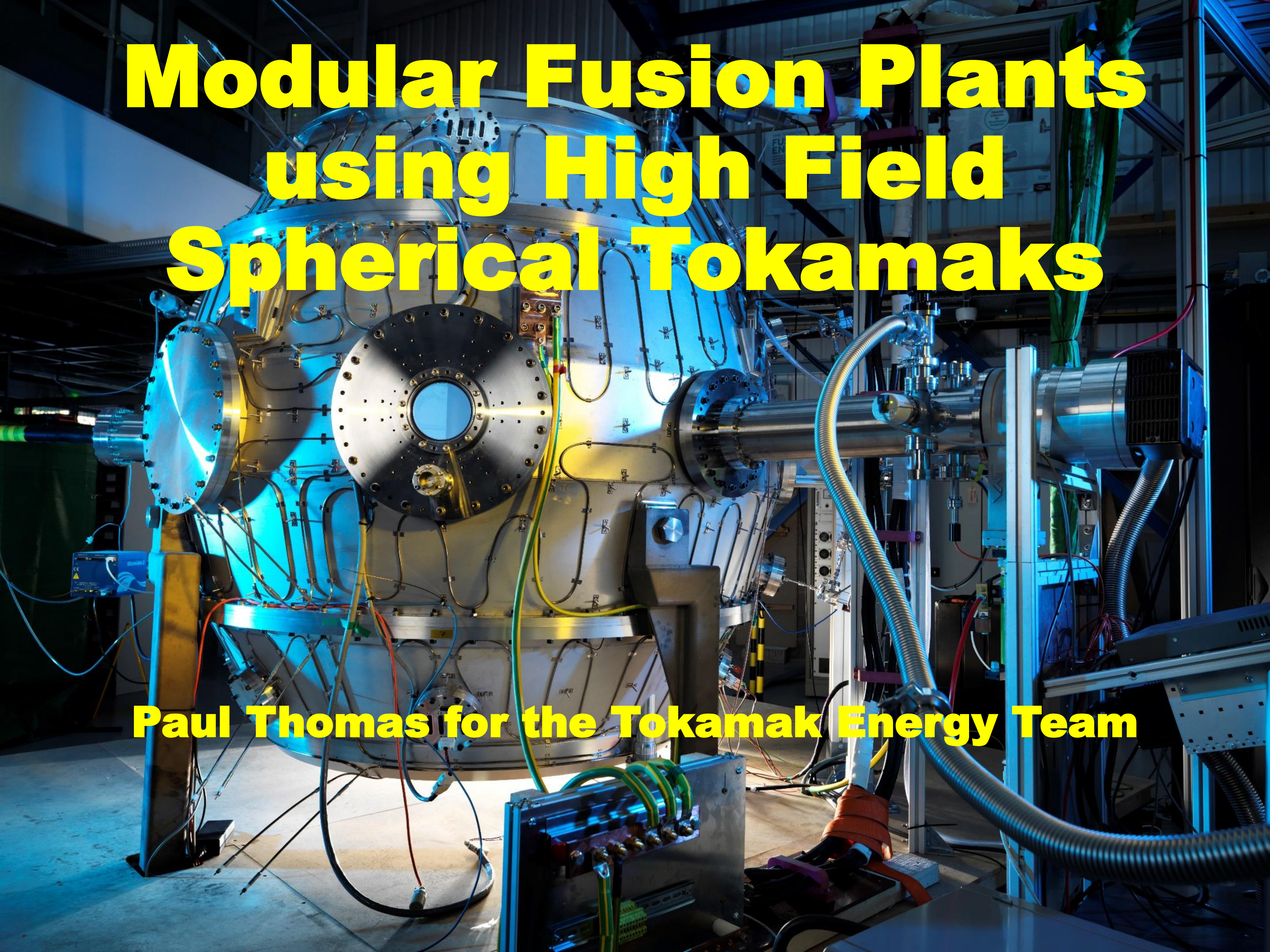
Modular Fusion Plants using High Field Spherical Tokamaks



Paul Thomas for the Tokamak Energy Team

Outline of Talk

- Introduction to Tokamak Energy
- "Modular Fusion"
    - Drivers for Cost of Energy
    - How HTS STs tick all the boxes
    - Target fusion power module
- Tokamak Energy Programme
    - ST25
    - ST40 – Cu coils/High Field(<3T/2MA)
    - HTS development
    - Prototype fusion power module
- Thanks to PPPL for all the help and encouragement.
- Note similarity of FPM to PPPL FNSF

The Tokamak Energy Solution

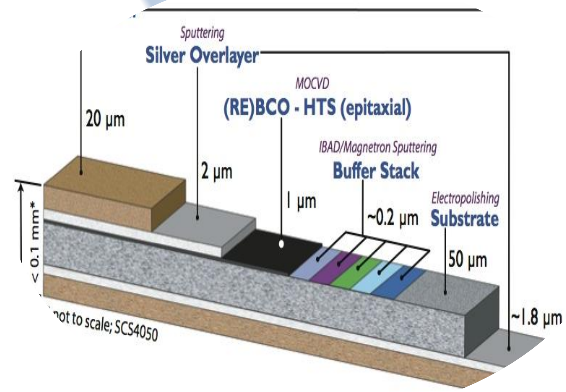
Spherical Tokamaks

Squashed shape

Highly efficient

High Temperature Superconductors

High current at high field

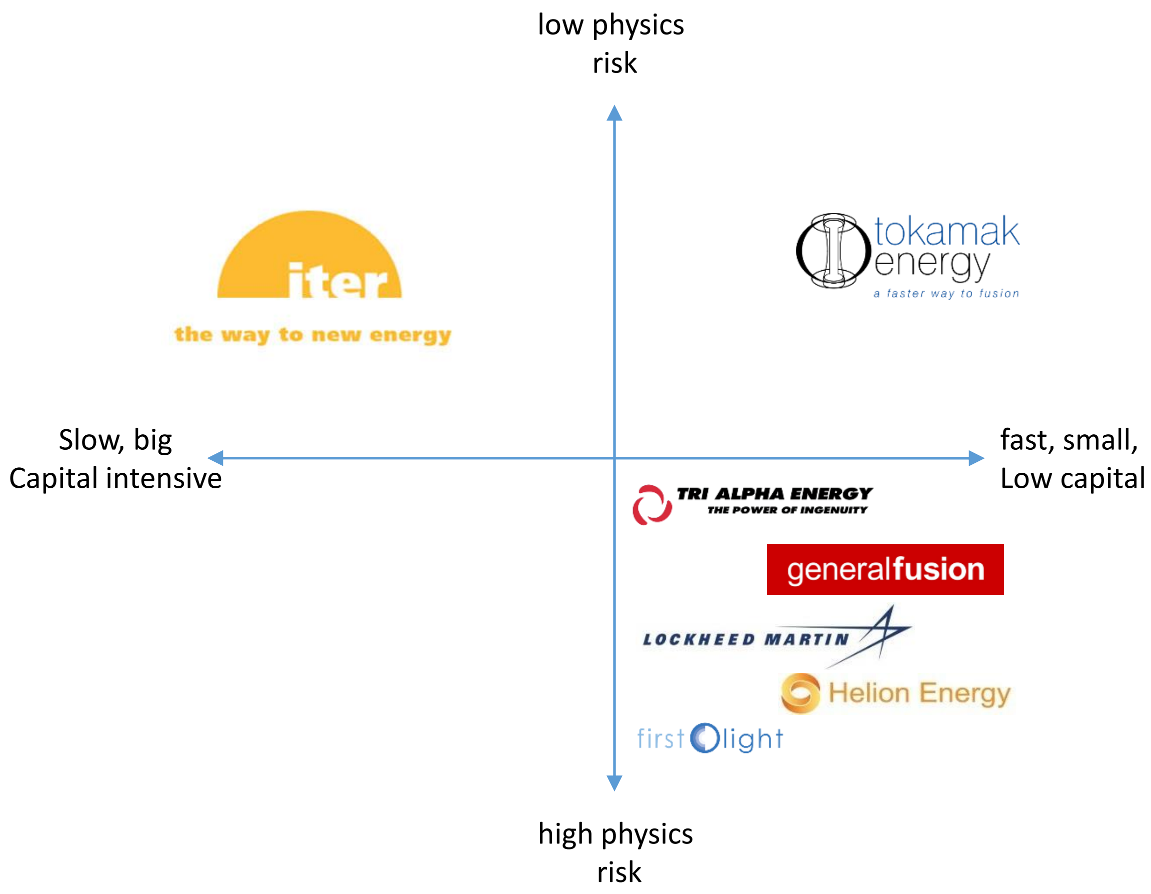


Fusion Power

smaller, cheaper, faster

Competitive Landscape

- In the last decade privately funded companies have emerged
- Prompted by a lack of progress in mainstream publicly funded fusion and the recognition that fusion needs to happen sooner
- $500M – 1Bn of investment
- Competition pursuing high risk, low technology readiness, designs that require scientific validation
- The Tokamak Energy approach is alone in having established theoretical and experimental foundation



Tokamak Energy Ltd.

Cost of Electricity (CoE = <cost/MWh>)

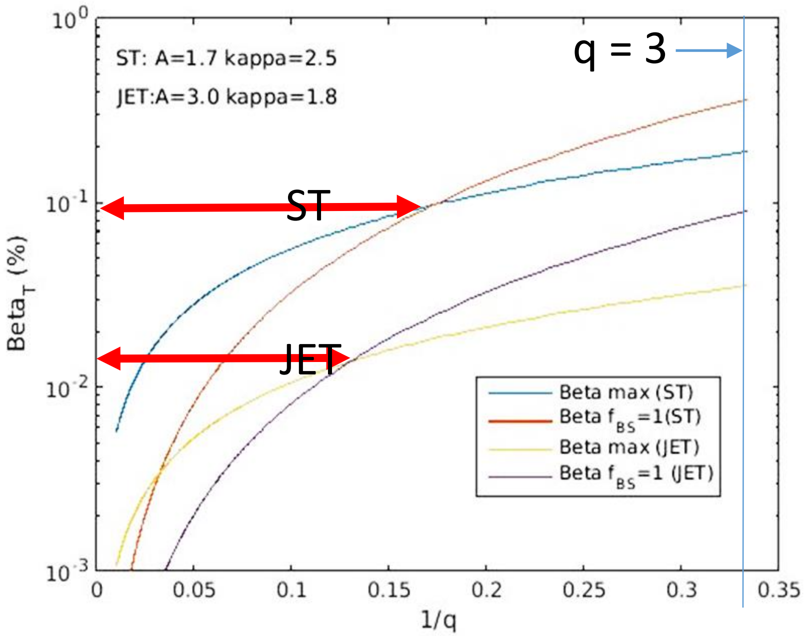
- *For any fusion (or fission) power plant, servicing the capital debt is the primary annual charge ~ 90% of total.*

- Obviously then, the CoE for fusion is minimised by:
    - *Minimising the capital cost*
    - *Maximising the electrical output*
    - *Maximising availability*

- To set the scale, a typical CoE for fission is 140 $/MWh (source Wood MacKenzie).

Minimising the Capital Cost

- *STs permit a high beta operating point with f_{BS} ~ 1*

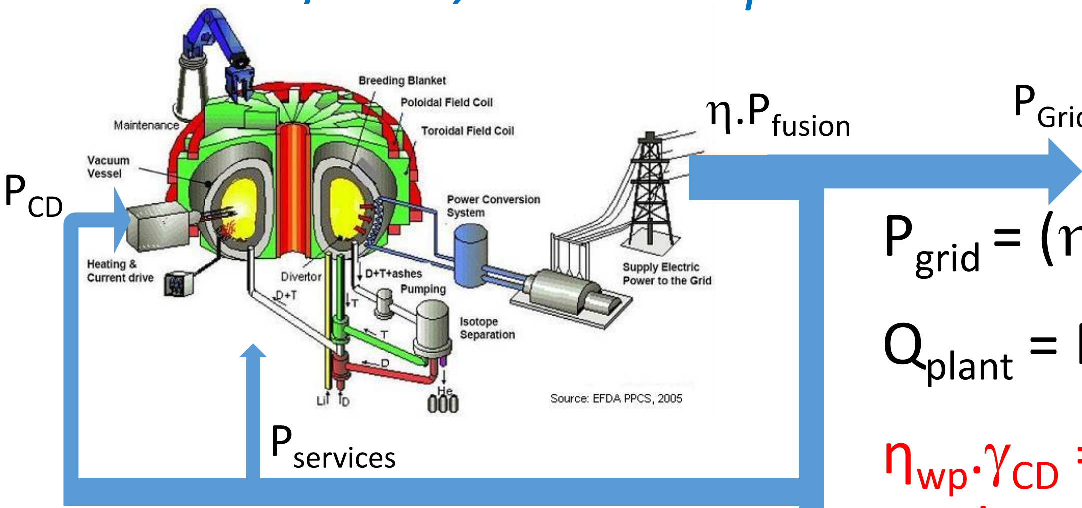


- $\beta_{T,max} \propto (1/q).(1+\kappa^2).A^{-2}$
- $\beta_{T,fbs=1} \propto (1/q)^2.(1+\kappa^2).A^{-1.5}$
- Domains where f_{BS} = 1 is stable are indicated with red arrows.
- ST has β_T < 10%, whereas "JET" has β_T < 1.4%
- STs "readily" stabilized at κ ~ 3.

- *Capital cost of modular reactors by off-site manufacture in series, shared services, including hot-cell, and shared heating and current drive.*

Maximising Electrical Output

- *Minimise the recirculating power by operation at f_{BS} ~ 1 during burn, which STs permit.*



$$P_{grid} = (\eta.Q_{plant} - 1).(P_{services} + P_{CD})$$

$$Q_{plant} = P_{fusion} / (P_{services} + P_{CD})$$

$\eta_{wp}.\gamma_{CD}$ = 0.07-0.14 MA/MW for as-designed ITER systems.

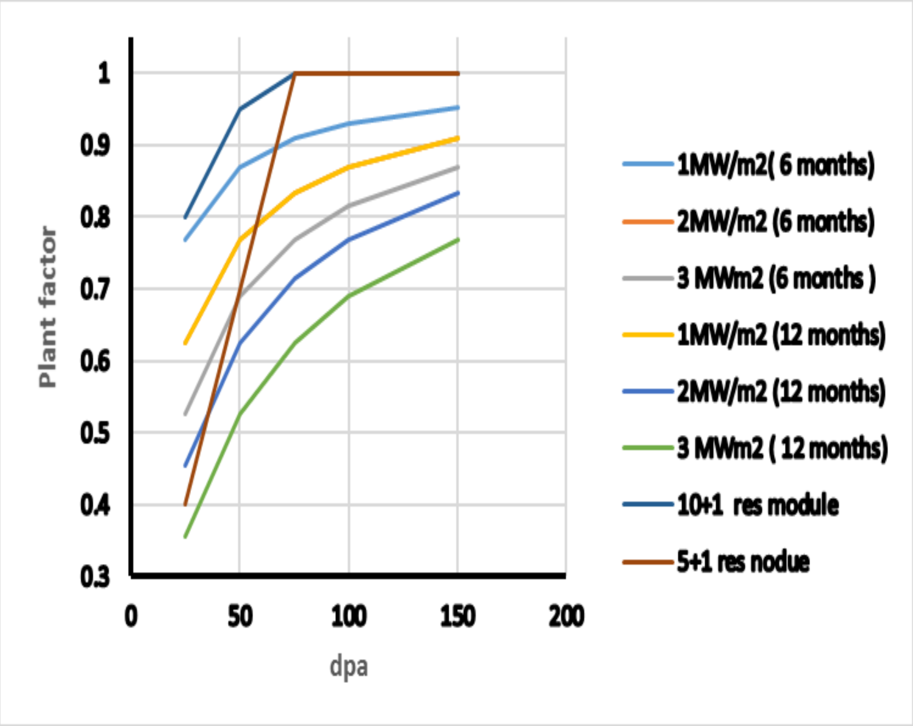
- *High Temperature Superconductors at 20K reduce cryo-power by a factor ~5 per Watt absorbed in coils, compared with Nb_3Sn at 4K.*

External current drive is inefficient

System	"Physics" current drive efficiency γ_{CD}	Wall-plug efficiency η_{wp} (ITER design)	Product $\eta_{wp}\cdot\gamma_{CD}$	Product $\eta_{wp}\cdot\gamma_{CD}$ with improvements
ECCD	0.15	0.44 (upper value)	0.07	0.14 (gyrotron at 70% - K Sakamoto)
ICCD	0.3-0.4 (matching?)	0.48	0.14 - 0.19	HH FWCD ???
NBCD	0.4-0.45	0.32	0.13 – 0.14	0.22 – 0.25 (photon neutraliser)

- No existing Heating and Current Drive system is sufficiently efficient for any concept and P_{cd} availability must much better than that for the plant as a whole.
- *This argues strongly for our assumption that f_{bs}~1 during burn*

Maximising Availability



Plant availability versus DPAs at which scheduled maintenance should occur:

(i) for standard design without a reserve module; and

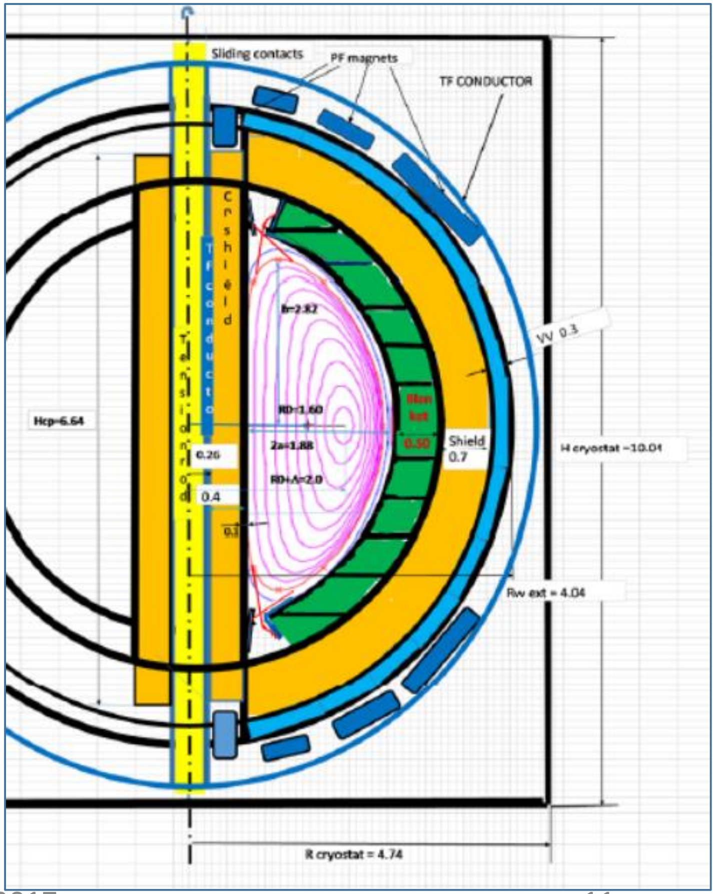
(ii) for modular designs with 11 and 5 modules (P_{wall} = 1 and 2 MW/m^2.).

- *This demonstrates the benefit of having a reserve module.*
- The service timescale is realistic for HTS ST modules because of relatively small weight and size of components.

CoE for Modular Fusion

CoE = 56 \$/MWh for 1st plant of a kind

- Cost algorithms used in previous reactor studies. Made in 2009 USD. 10+1 modules for 100% plant factor. Series manufacture and shared balance of plant reduces capital cost.
- Sensitivity to neutron wall load, service interval and time was studied.



CoE for Modular Fusion

Parameter	Value	Parameter	Value
Impurities	4% He, 2% H	Wall surface m^2	116
T mean keV	14	Density 1E20 $/m^3$	0.97
Aspect ratio	1.7	Plasma energy MJ	51.13
Fusion power MW	**172**	**Toroidal magnetic field T**	**3.17**
Blanket energy mult. factor	1.34	**Plasma current MA**	**6.7**
Thermal power MW	**218.4**	Radiation losses MW	2.2
Total thermal efficiency	35. 4%	Energy confinement time sec	1.6
Electrical power MW	80.7	beta toroidal %	10.7%
Plasma major radius m	**1.6**	**beta poloidal**	**2.6**
Plasma minor radius m	**0.94**	Neutron wall loading MW/m^2	1.18
Elongation	3	Neutron Shield thickness, m	0.4
Triangularity	0.5	Maximum value of TF field T	19.6
Plasma volume m^3	80	TF coil MA turns	25.4

Overall Plant Costs

Item	Cost (11 modules) (M$)
fusion modules	2034.9 (261.8 for first)
reactor plant	455.1
conventional plant & bdgs	974.1
Direct Capital	**3464.1**
Indirect Capital Costs	1558.8
Total	**5022.9**

- Including:
  - 5 years construction
  - 30 years operation
  - 10 years decommissioning
  - 5% interest rate
- Capital Cost Charge = 359M$
- Net electrical output = 767MW

⇨ ***CoE = 56$/MWh***

Modular Fusion Power Plants

Based on CoE ⇨ compelling arguments for fusion plants based on:

Spherical Tokamaks

- *~100% bootstrap current to reduce recirculating power*
- *High beta operating point to reduce capital cost*
- *Confinement has potential for ignited operation at moderate P_{fus}*

High Temperature Superconductors

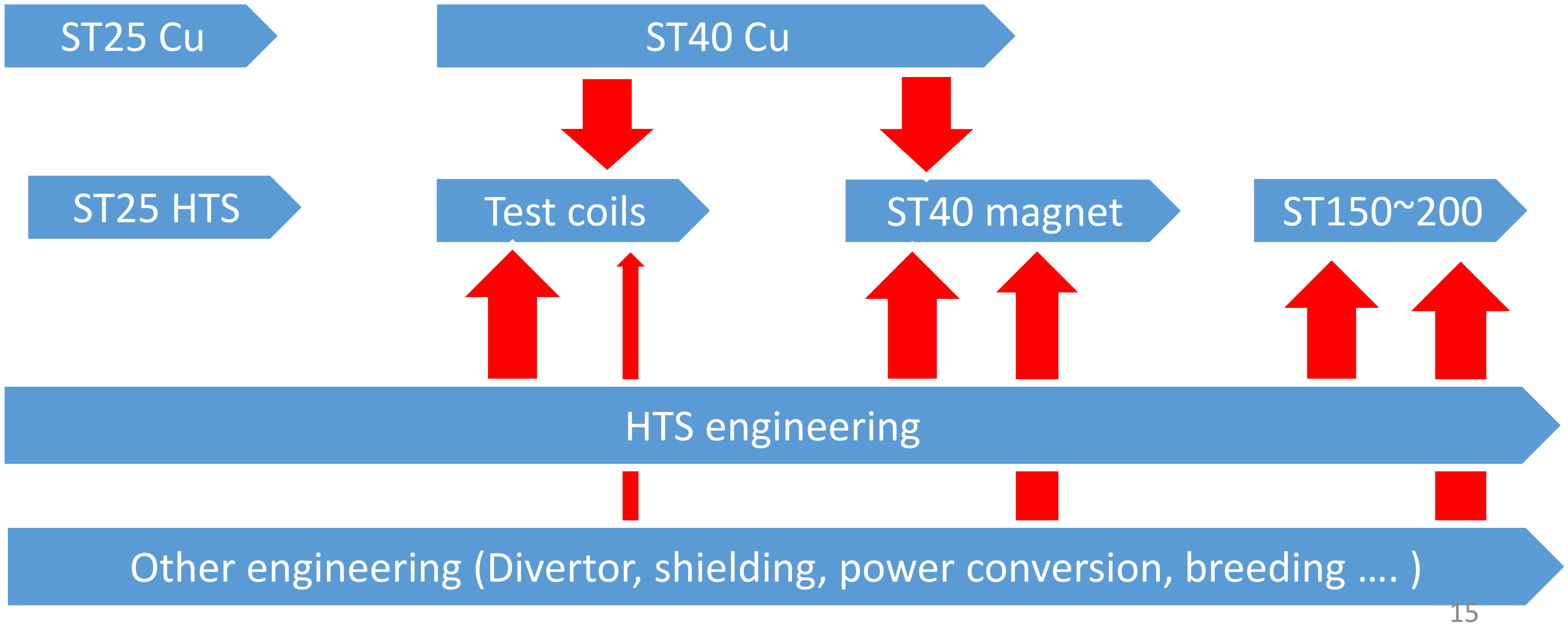
- *20K operation to reduce recirculating power for refrigeration*
- *High critical field (>20T) at reasonable J $\Rightarrow$ high P_{fus} relative to size*

Fusion Power Modules

- *Reduced capital cost of modules due to "series manufacture"*
- *100% availability with reserve module to maximise revenue*
- *Shared services and CD systems further reduce capital cost.*

Tokamak Energy Program

1. Demonstrate scientific viability of STs
2. Develop HTS technology towards commercial viability
3. Combine STs and HTS in a series of engineering prototypes



ST25-HTS

- ST25-HTS constructed in collaboration with Oxford Instruments
- 20^0K operation – 6 limb cryostat
- ST25 equipped with 3kW/18MHz
- Low current/temperature but tokamak configuration.
- Demonstrated HTS tokamak for the first time.

ST25-HTS: Milestones ⇔ Publicity ⇔ Funding

Further evolution secures a new fusion world record

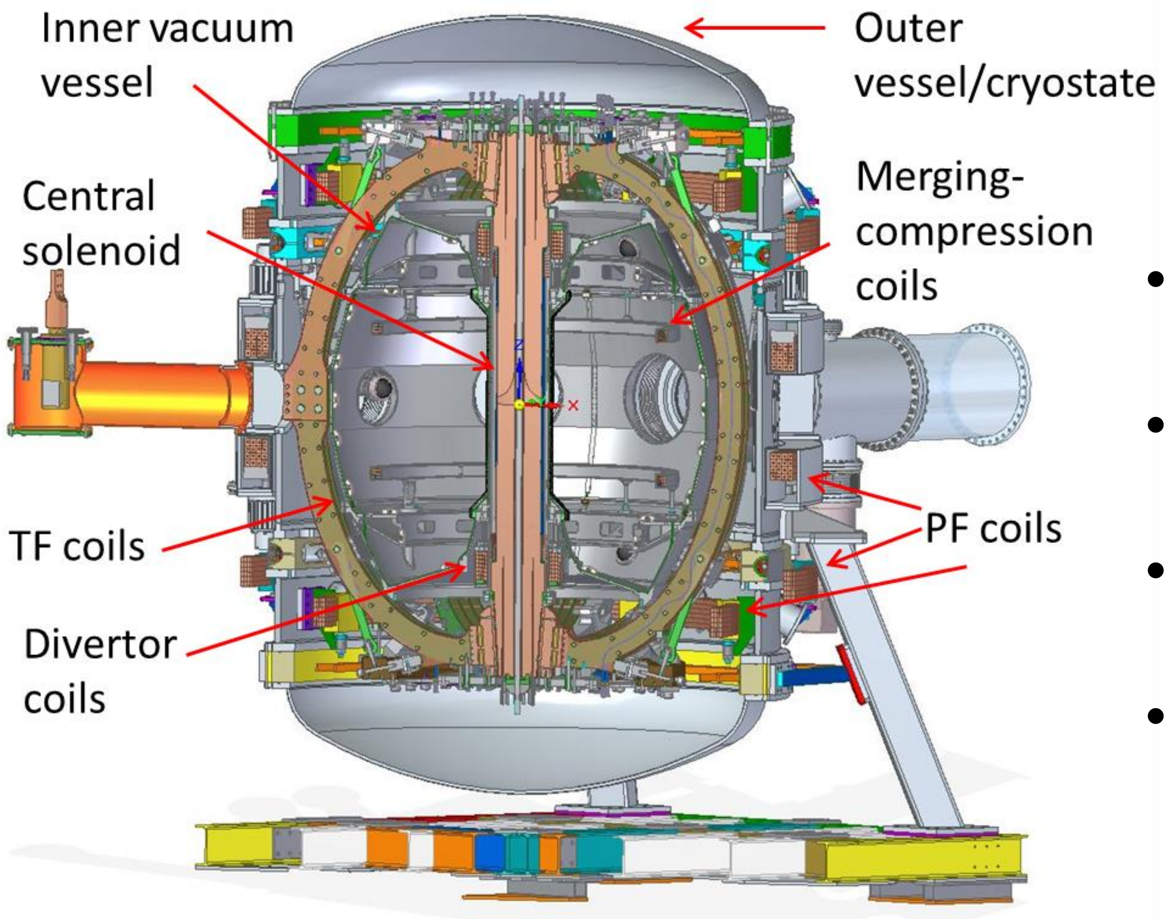
Progressing from the HTS tests on the ST25, we built a whole new tokamak of the same size but this time all its magnets made from HTS material. This new machine was dubbed ST25-HTS.

Being fully HTS, allows the tokamak to run continuously – something that will be vital when using fusion reactions to create energy on a commercial scale.

The ST25-HTS device achieved a world first in July 2015, transmitted live to our stand at the Royal Society Summer Exhibition (a prestigious event held by the world's oldest scientific academy). ST25-HTS succeeded in sustaining plasma continuously for 29 hours until it was switched off.

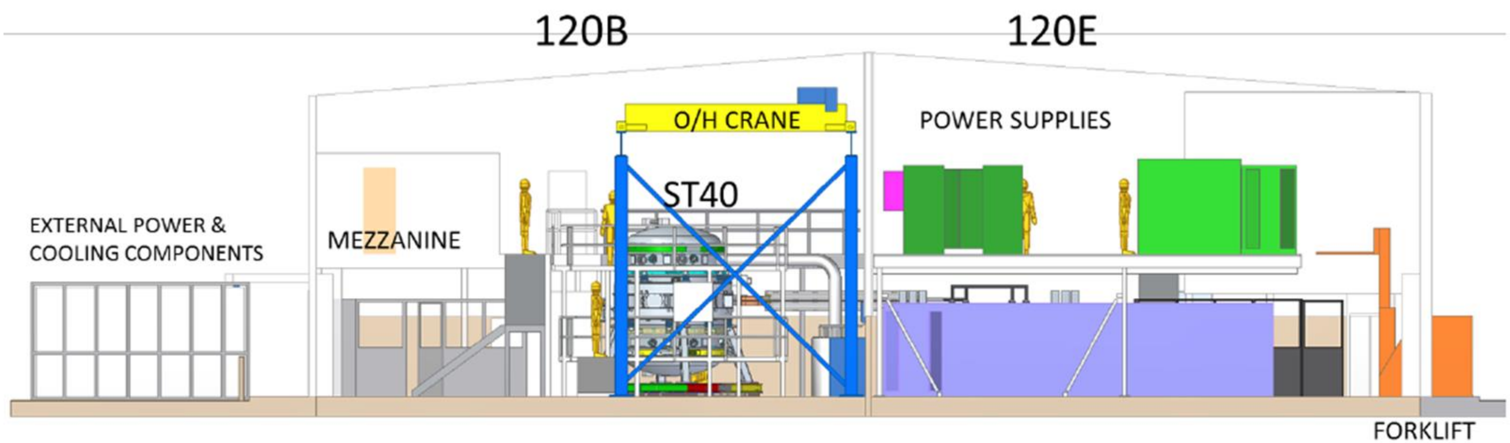
Testing on ST25 and ST25-HTS demonstrated the suitability of high temperature superconductors for use on tokamaks, while theoretical studies showed their potential. The combination of high temperature superconductors and spherical tokamaks allows us to design revolutionary compact tokamaks.

ST40: 3T, 2MA Cu Coils

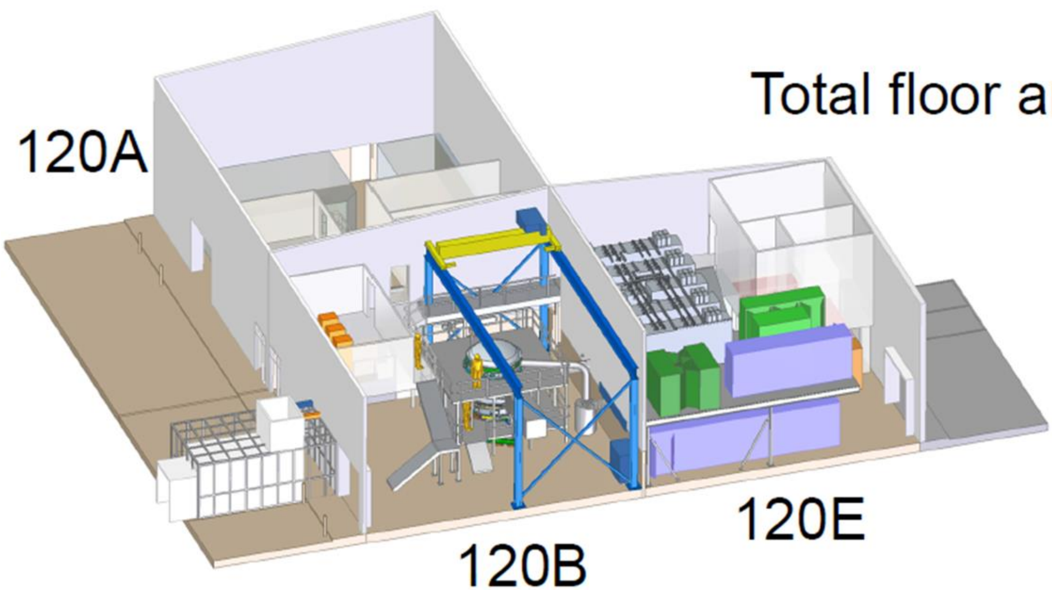


- R_0=0.4-0.6m
- R/a=1.6-1.8, κ=2.5
- I_{pl}=2MA, B_t=3T
- τ_{pulse}~1-10sec

ST40 building layout



Total floor area ~650 m^2



First power supplies in place

- ST40 power supply units (PSUs) based on ultracapacitors
- TF first to arrive (70 MJ), installed and tested
- To be expanded to 250kA and 175MJ to provide B_t=3T
- MC p/s commissioned
- BvL p/s being commissioned

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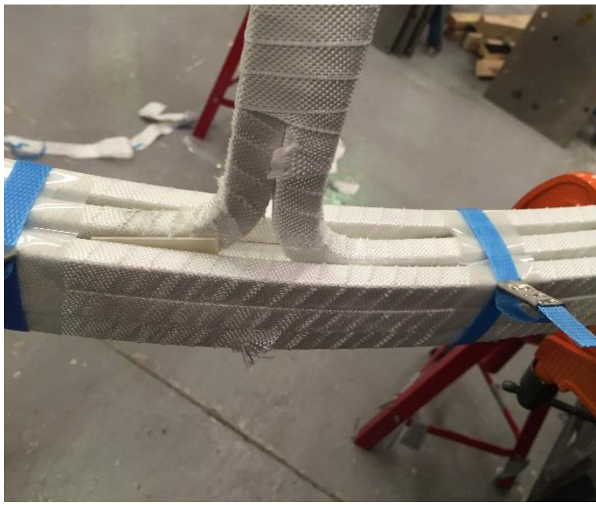
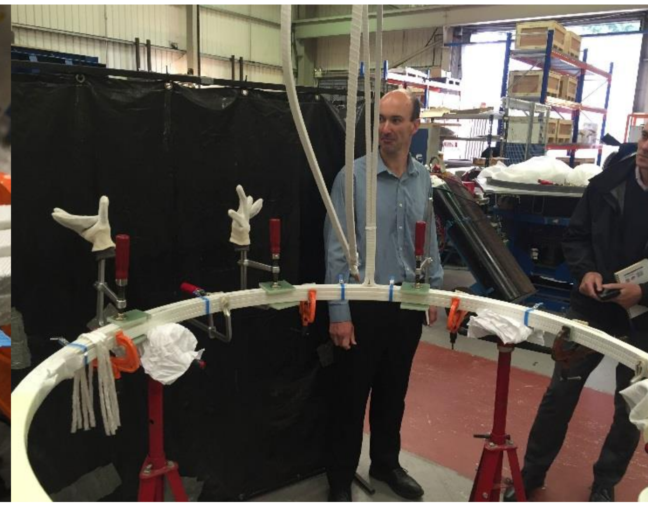
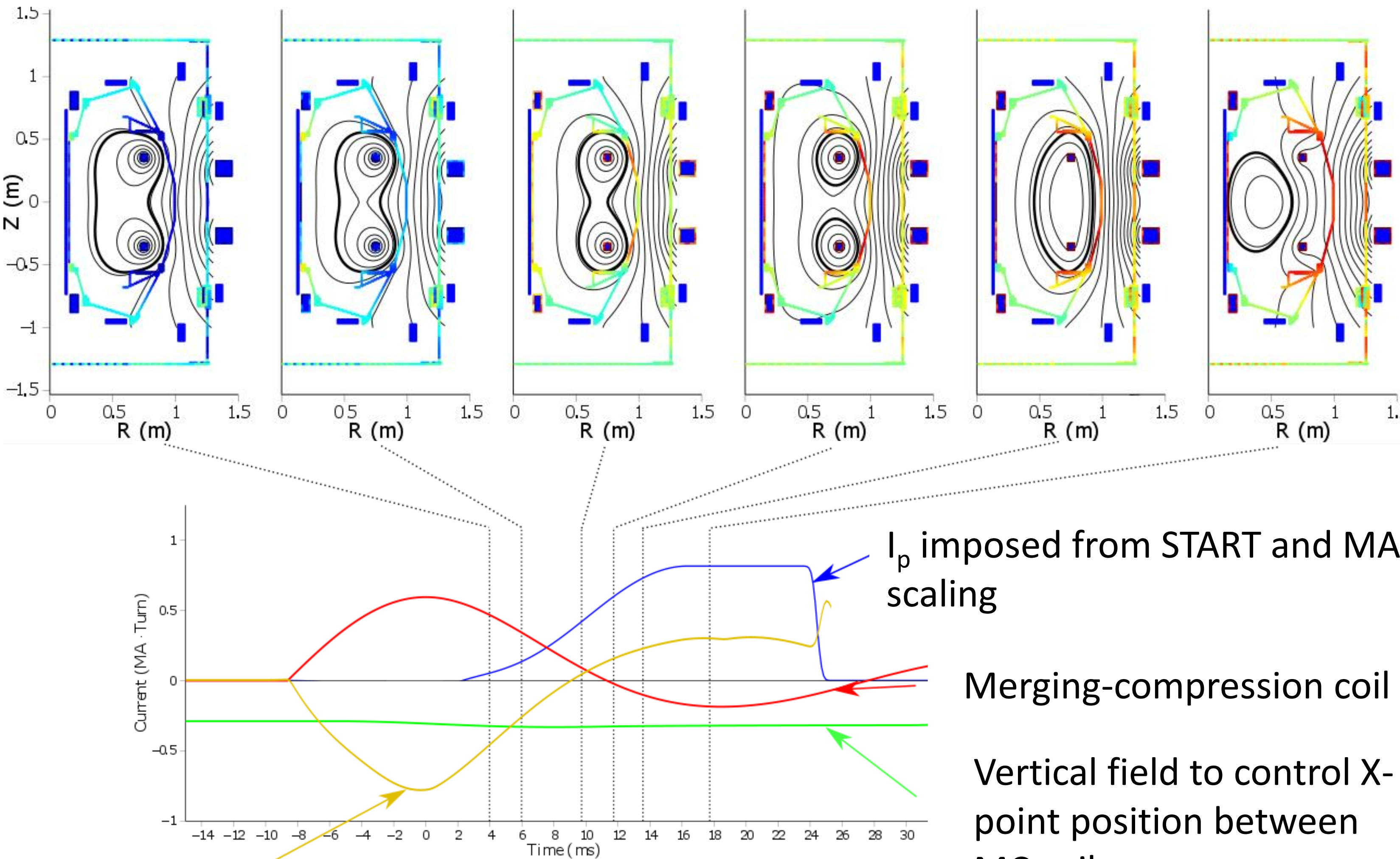
a faster way to fusion

Merging compression coils


Merging-compression



I_p imposed from START and MAST scaling

Merging-compression coil

Vertical field to control X-point position between MC coils

Total induced current in the vessel

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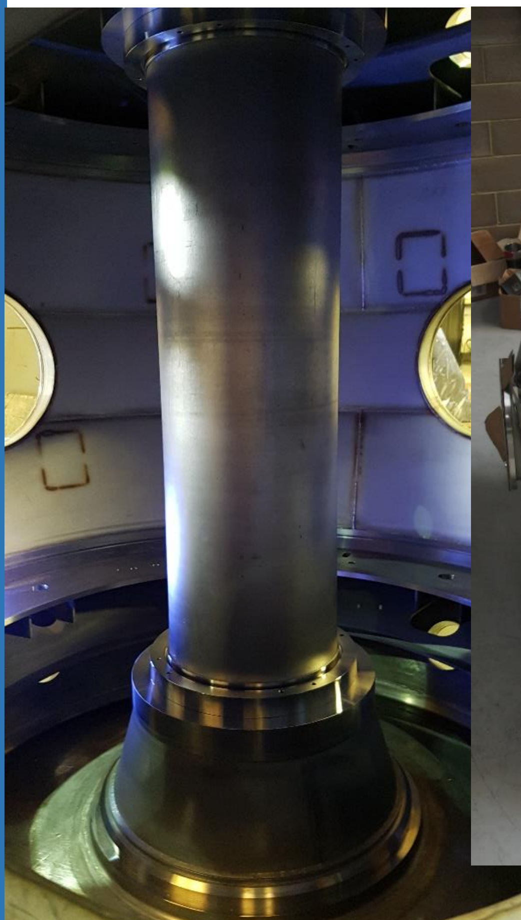
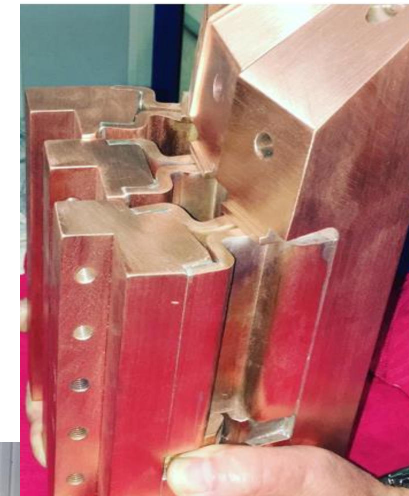
a faster way to fusion

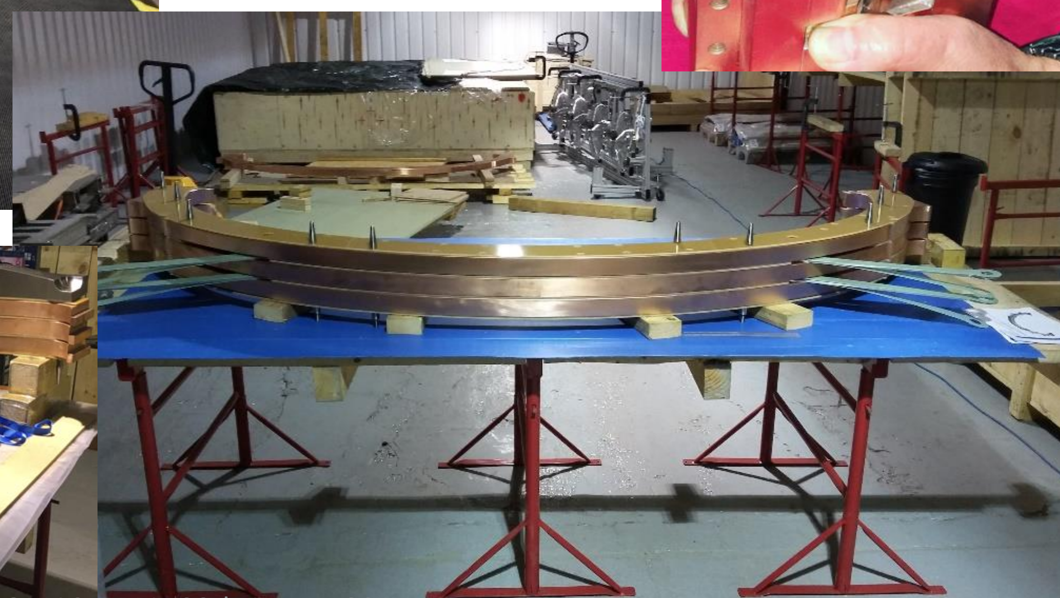
Inner Vacuum Case

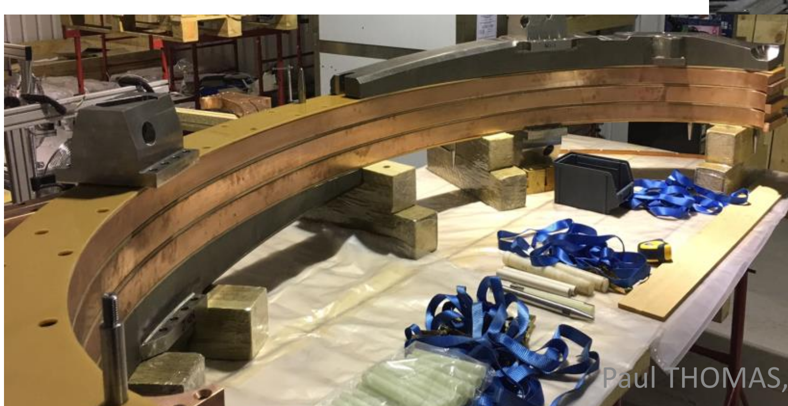


Inner vacuum case and centre column

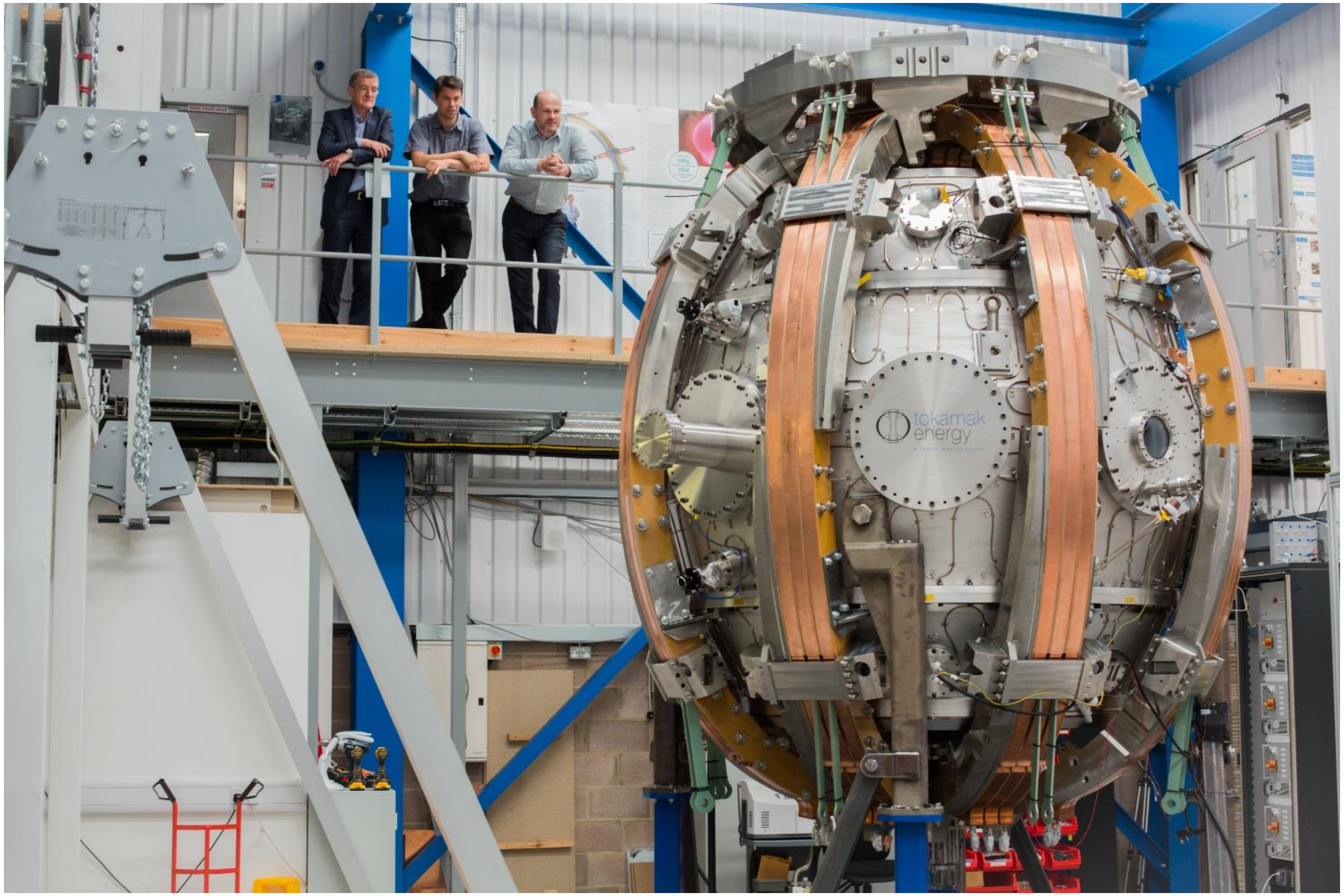
TF coils



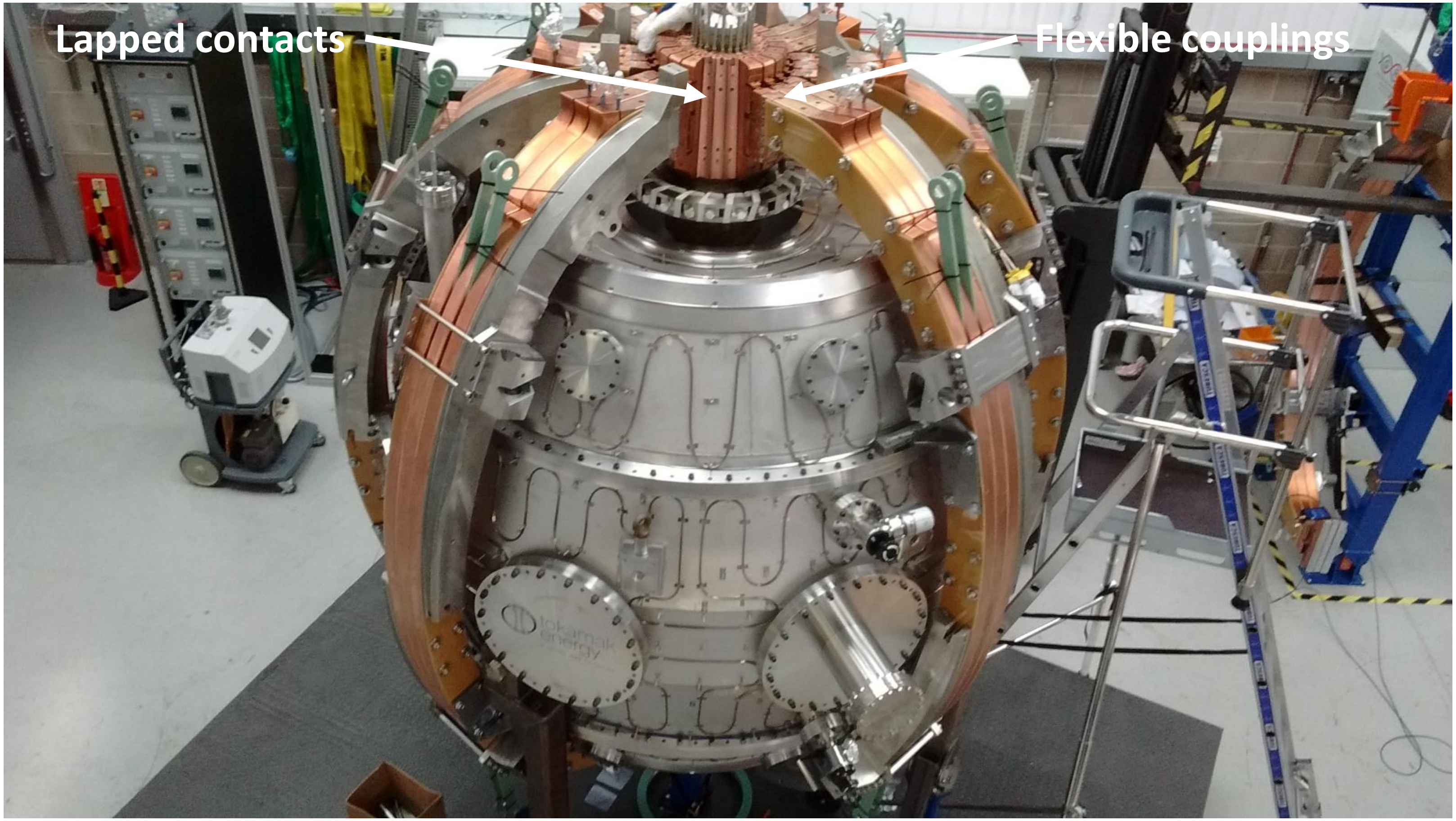




ST40 TF Coil Trial Fit

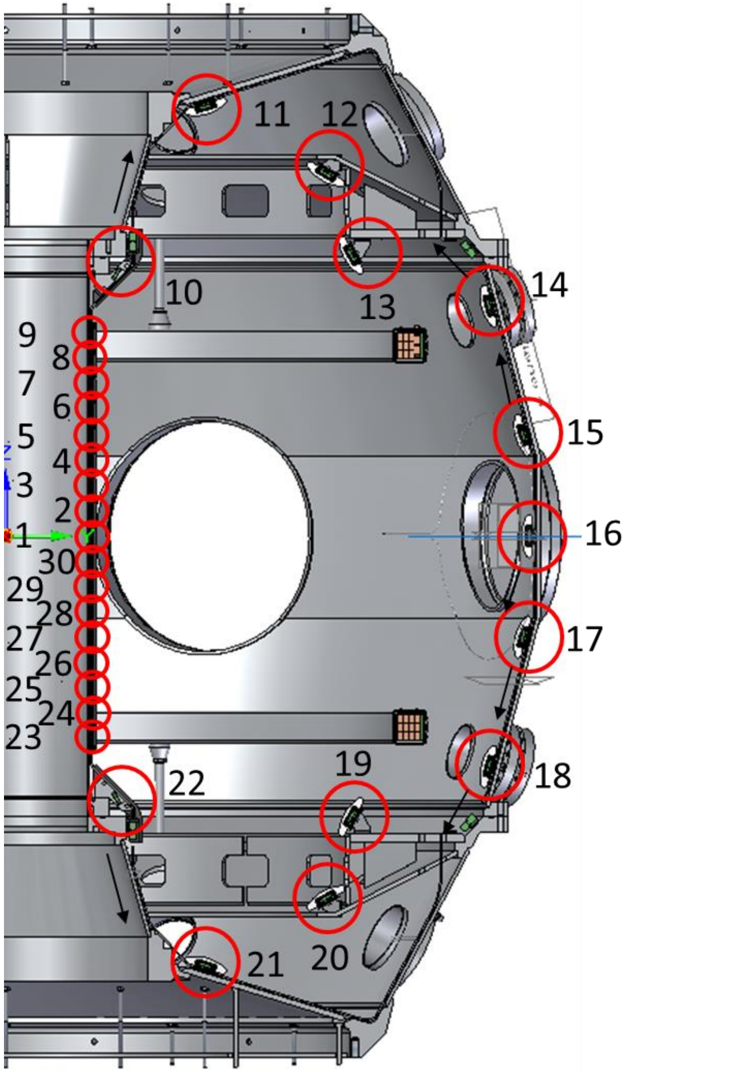


ST40 TF Coil Detail



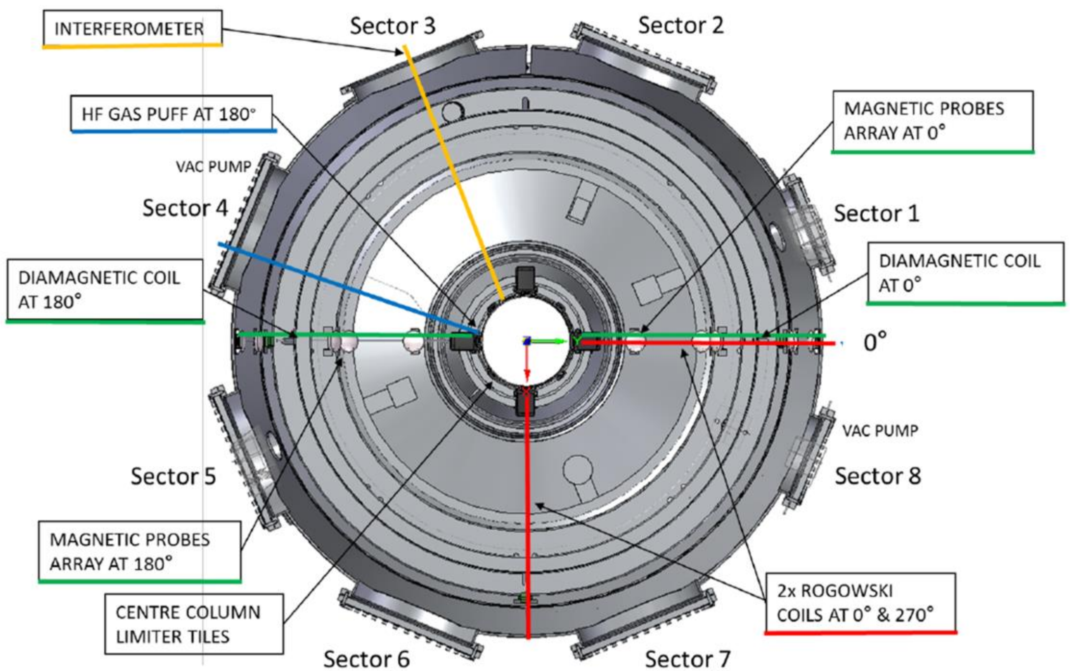
Diagnostics

- Machine monitoring: vacuum, mass spectrometer, fast ion gauge, thermocouples, position monitoring, TF joint testing
- Magnetics: Bp&Bt probes, flux loops, Rogowski coils, saddle loops, diamagnetic loops
- Cameras: Fast high resolution visible (500&80 fps), IR

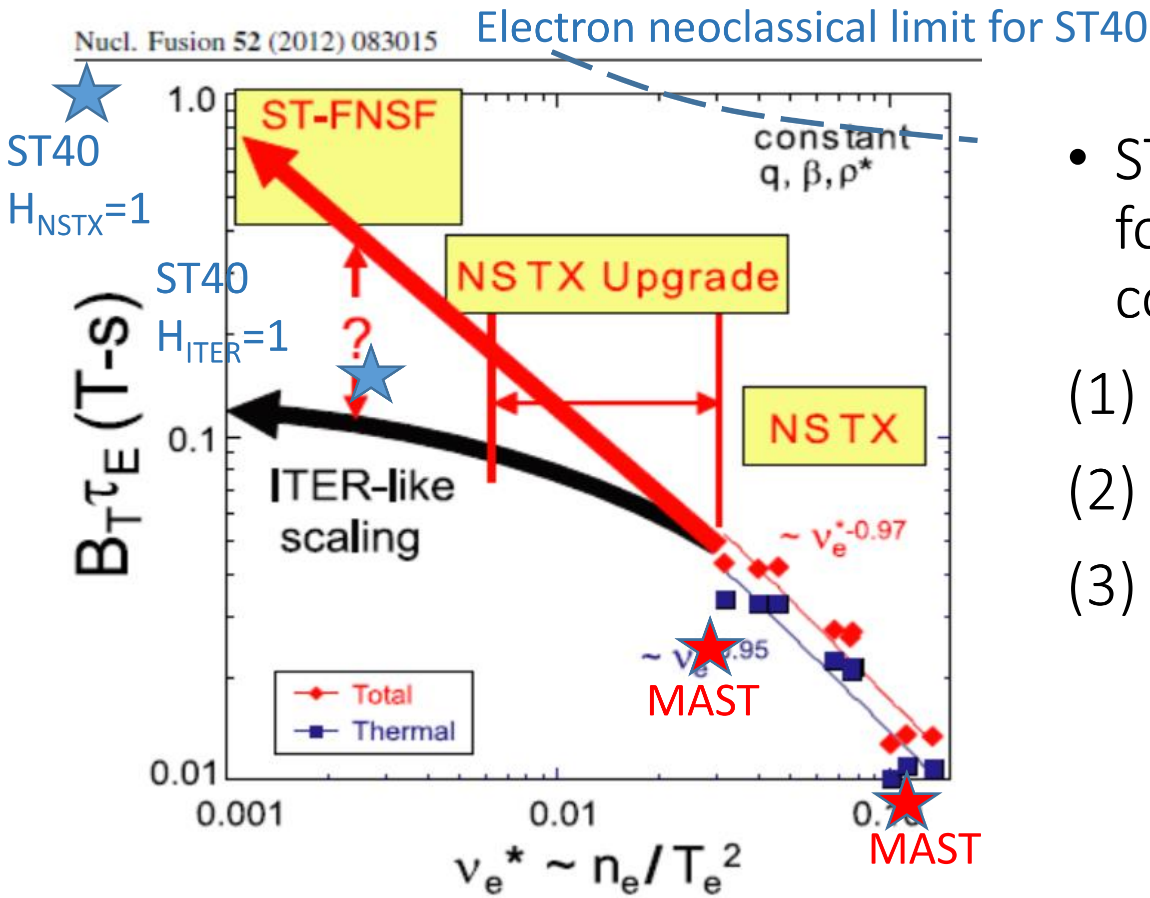


Diagnostics

- Multifoil X-ray camera (4x3x20 channels), UV/visible spectrometer w/ impurity Doppler, interferometer (195 μm, 2 chords), hard X-ray spectrometer
- Planned: neutron spectrometer, NPA, ECE imaging, ECE Doppler radiometer, Langmuir probes & multi-channel TS



ST40 in parameter space



- ST40 plasma can be a test for collisionality confinement scalings

(1) $\tau_E \sim \nu^* - 0.8$

(2) $\rho^*_{ST40} = \rho^*_{MAST}$

(3) $\beta_{ST40} = \beta_{MAST}$

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

MAST : $B\tau_{E,th} \propto (\nu^*)^{-0.82}(\rho^*)^{-2.5\mathrm{to}-3}\beta^{-0.5\mathrm{to}0}q^{-0.85}$

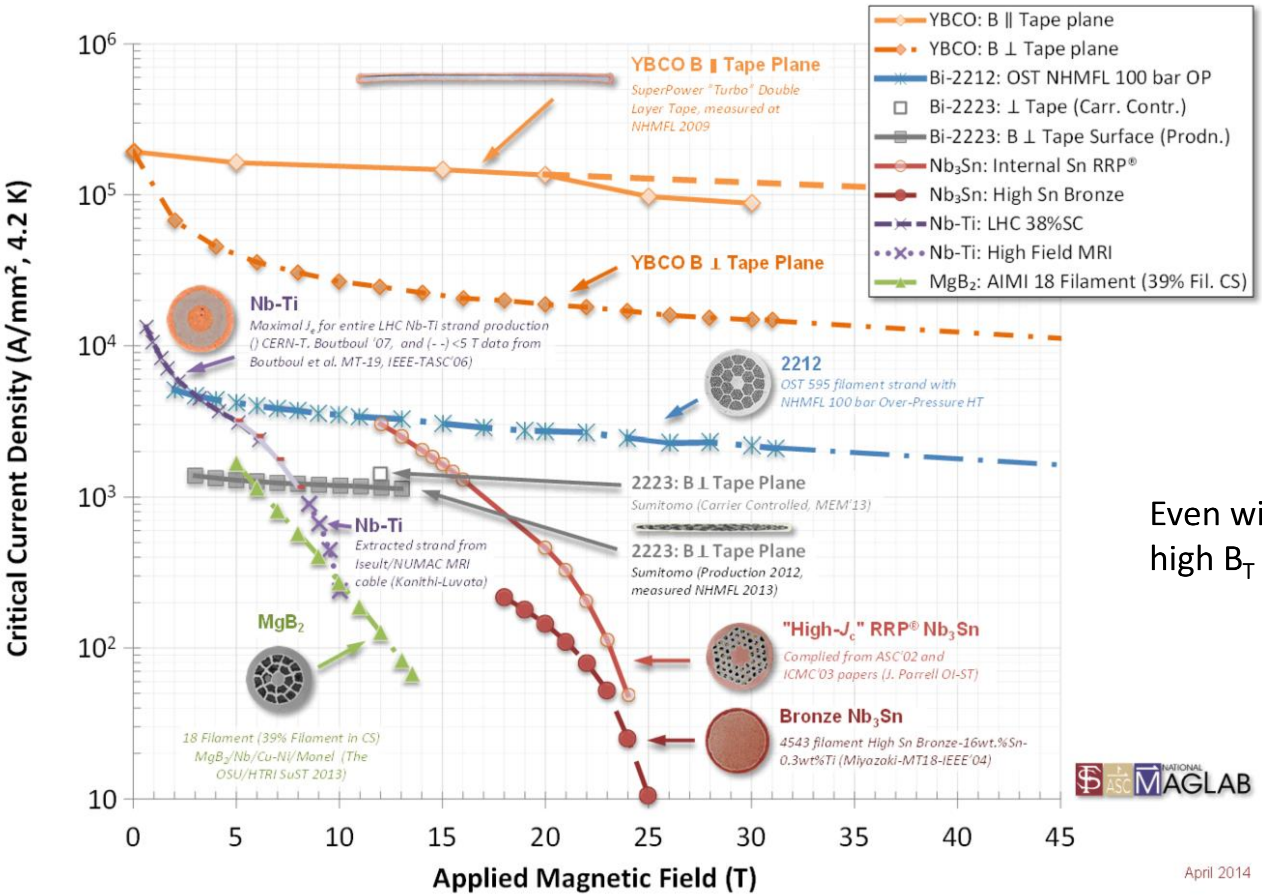
ST40 experimental programme

Stage one

Stage two

m/c early tests Commissioning of P3 coils and PSU; attempt of b/d around coils	TF trial fit BvL and new MC coil and p/s tests	**Construction,** Partial assembly and first plasma 15 M degrees milestone attempt	**Commissioning for Day 1 specs,** 15 M degrees milestone	**Experimental programme 1** 100M degrees milestone attempt	**Experimental programme 2** 100 M degrees milestone
Completed	**Main hardware requirements:**				
IVC with P3 coils; 10^{-6}, old central tube; P3 PSU 430kAt; GDC in He, puff and pumping as in 2016; min magnetics and other diagn.		IVC with both m/c coils, TF assembled for 10kA with perm 24th limb, BVL, OVC central belt; IVC with new tube	ST40 assembled **with new TF post 1.2T;** PS coils and PSUs for Day 1 specs. Full OVC. **Sol, BVU, BVL, Div coil.**	**1.2T/**1.5MA supported by PSUs and control system. All PF coils but SX.	**2.4T/**1.5MA All PF coils. New IVC with divertor and passive plates; AIST NBI; Li, boronisation, advanced diagnostics
May 2017	**July-August 2017**	**Q4 2017**	**Q1-2 2018**		**Q3-4 2018**

HTS Magnet Development



Even with shielding we can have high B_T in plasma

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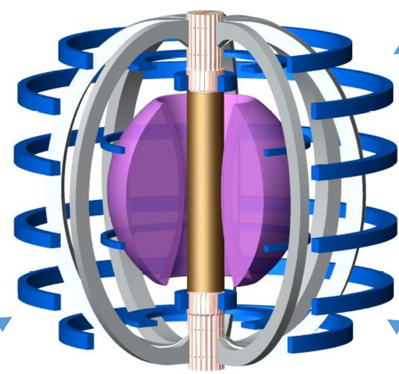
HTS key technologies

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 ?



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

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

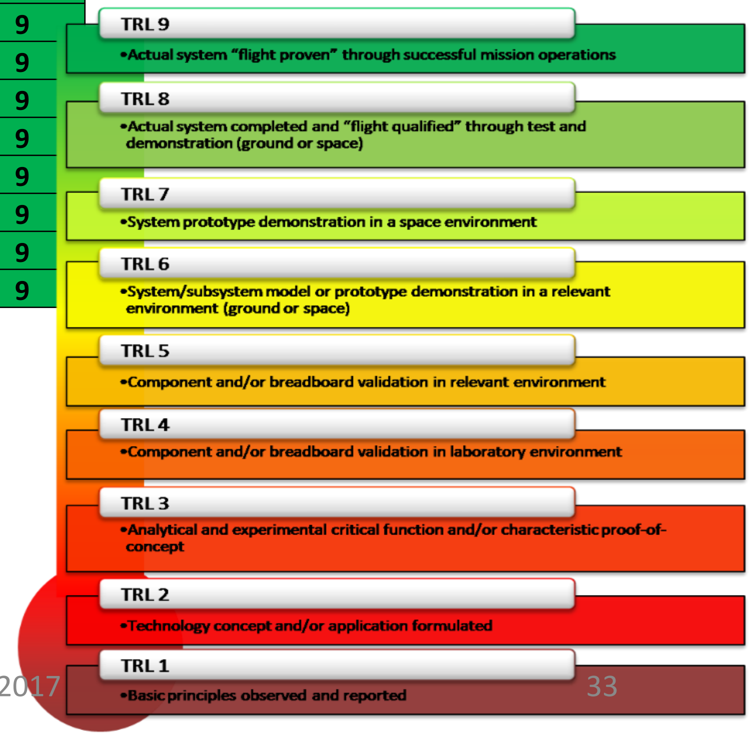
Power supplies
- Current leads
- Dump circuits
- Cold rectification ?

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

TRLs for HTS Coil Development

	as of Feb-17	Targets: 2017 target	2018 target	2019 target	Fusion demo	D-T reactor
Cable design	3	5	6	6	8	9
Joint design	2	4	5	6	8	9
REBCO tape characterization	3	5	6	6	8	9
Core model	2	4	5	6	8	9
TF EM model	3	5	6	7	8	9
PF EM model	1	5	6	7	8	9
Integrated magnet EM model	3	5	5	6	8	9
Magnet mechanical design	1	3	4	6	8	9
Quench Detection system	2	5	6	7	8	9
Quench Protection system	2	5	6	7	8	9
PSU	2	4	5	6	8	9
Current leads	2	3	5	6	8	9
Cryostat	2	3	5	6	8	9
Cryoplant	2	3	5	6	8	9

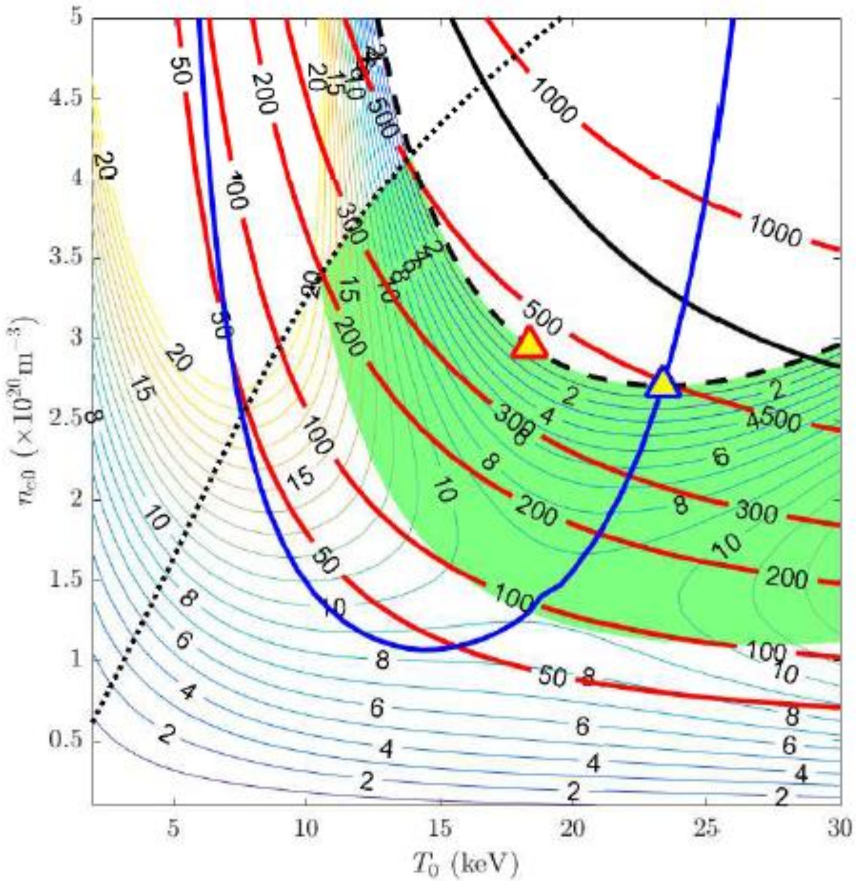
Prototyping in “relevant environment” completed.



Fusion Demonstration

- HFS radial build determines the major radius of a device that will produce a significant fusion power.
  - Practical average current density in centre rod coming out at ~ $100A/mm^2$
  - Need >30-40cm neutron shield to keep HTS temperature < 30^0K
  - Space needed for thermal shield, vacuum vessel, PFC and gap to plasma.
- So far, scoping studies have shown that R ~ 1.8-2m and Bt ~ 3.5-4T is consistent with all the constraints, except.....
- Fusion power at ignition is such that the divertor power handling is likely to be as much of a technical challenge as HTS magnets.
- Supply chain “challenged” by length (~2000km) of tape needed.

Operating Range for FPD



Parameter	Value
R_0/a	1.8/1.06
κ/δ	3.0/0.5
B_T(T)	4
I_p(MA)	6.5 – 9.5
P_{aux}(MW)	12
P_{fus}(MW)	100 – 500
Q	10 – ∞
$n_{e0}(\times 10^{20}\mathrm{m}^{-3})$	1 – 4
T_0(keV)	10 – 25
$\beta_N/\beta_T(\%)$	(2.5 – 4.5)/(4 – 10)

Future plans

- Move to new site (several options considered, incl. Culham)
- ST40:
  - Add divertor and LN cooled Cu vertical stabilization plates, and satisfy the requirements for tritium operation
  - Neutral beam injection (NBI): 2 systems under consideration, one to assist start-up (already during Phase 1), one for heating during flat-top in DD
  - ECRH/EBW project started
  - Likewise for pellet injector
- Following test magnet programme, prototype HTS TF magnet
- Conceptual design of Fusion Demonstration device has started and will be completed early next summer.

Concluding Remarks

- Working in a private company is different!
- The Modular Fusion concept provides an easily articulated and justifiable strategy for the business.
- Milestones and publicity often seem naïve to fusion insiders and are a cause of antagonism.
- HTS IP values TE at many times the total investment.
- Investors content to balance this return against risks associated with fusion science/technology.
- Real test will be when TE calls for ~£1bn for fusion power demonstration – *2000km REBCO tape long-lead*