THE SPHERICAL TOKAMAK PROGRAMME AT CULHAM

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Abstract

The Spherical Tokamak (ST) is the low aspect ratio limit of the conventional tokamak, and appears to offer attractive physics properties in a simpler device. The START (Small Tight Aspect Ratio Tokamak) experiment provided the world's first demonstration of the properties of hot plasmas in an ST configuration, and was operational at Culham from January 1991 to March 1998, obtaining plasma current of up to 300kA and pulse durations of ~ 50ms. Its successor, MAST is scheduled to obtain first plasma in Autumn 1998 and is a purpose built, high vacuum machine designed to have a tenfold increase in plasma volume with plasma currents up to 2MA. Current drive and heating will be by a combination of induction-compression as on START, a high-performance central solenoid, 1.5MW ECRH and 5MW of Neutral Beam Injection. The promising results from START are reviewed, and the many challenges posed for the next generation of purpose-built STs (such as MAST) are described.

1. INTRODUCTION

In 1986 Peng and Strickler outlined many potential theoretical advantages of the 'spherical torus' concept [1], in which the aspect ratio A = R/a of a conventional tokamak is substantially reduced towards unity. It was conjectured [2] that this 'Spherical Tokamak' (ST) plasma would share some of the desirable features of the spheromak and RFP devices but with tokamak - like confinement and MHD stability provided by tokamak values of the safety factor q. Predicted advantages include a naturally high elongation (κ~2); high toroidal β; and near-omnigeneous regions which suggest improved confinement. These predictions have now been verified experimentally, in particular by the START device at Culham [3] but also on a range of smaller ST's (e.g. CDX-U, HIT, TS-3, MEDUSA, ROTAMAK-ST).

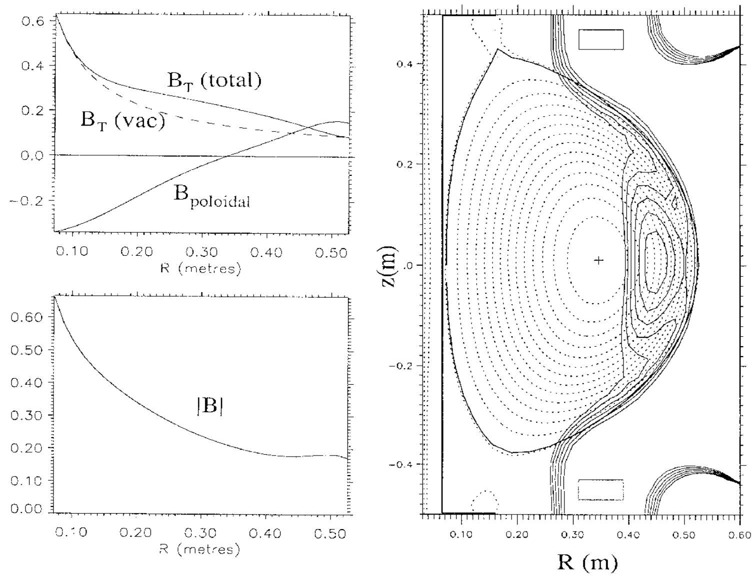
A survey of results and the present understanding is given in Section 2 and it is shown that, although indications are very promising, many questions about confinement, β-limits and stability in the ST remain. These pose an exciting challenge for the next generation of ST experiments including MAST (UK), PEGASUS and NSTX (US), GLOBUS-M (Russian Federation), ETE (Brazil) and TS-4 (Japan).

2. EXPERIMENTAL RESULTS FROM STs

The first STs were obtained by inserting a central rod into an existing fusion experiment, as in the Lucas Heights Rotamak [4], the Heidelberg Spheromak [5], and in the SPHEX 'rodamak' [6]. Each of these small experiments yielded interesting and promising equilibrium and stability results - for example, it was found in the Heidelberg device that a small rod current stabilised the tilt instability of the spheromak, and use of a pre-existing toroidal field in SPHEX improved energy coupling from gun to plasma - but all had cold plasmas. The first test of the ST concept in a hot (> 100eV) plasma was provided by the START (Small Tight Aspect Ratio Tokamak) experiment at Culham [3]. Although built as a low-budget device, START has achieved significant performance with typical parameters: major and minor radii R_o, a ~ 0.3m, 0.23m, aspect ratio ~ 1.3, elongation ~1.8, plasma volume $0.5m^3$, $\langle n_e \rangle$ ~ $5x10^{19}m^{-3}$, central electron and ion temperatures ~ 300eV, vacuum toroidal field at R_o ~ 0.3T and plasma currents of up to 310kA. Considerably higher $\langle n_e \rangle$ and T_{eo} were achieved seperately.

2.1 Equilibrium properties

A feature of the ST is the increasingly efficient use of the toroidal field as aspect ratio A reduces, due to the large increase in edge safety factor q_a produced by toroidal effects.



	#35533 @ t = 40.5m
R	0.30m
a	0.228m
κ(elongation)	1.78
R/a	1.31
I_p	0.246MA
I_{rod}	0.228MA
I_N	7.1
$B_T(R)$	0.152T
P_{NBI}	0.8MW
plasma volume	$0.47m^3$
q^*	2.67
q_{95}	3.14
q_{cyl}	0.54
β_T	37.7
β_N	5.3

- - flux surfaces (EFIT

— |B| = const

Fig 1 *Equilibrium features of high-beta START discharge #35533. The dashed lines indicate flux surfaces, full lines |B| contours. A true magnetic well appears at high beta*

Whereas in the centre of the plasma the flux surfaces appear as in a conventional tokamak, near the edge of an ST plasma the field lines dwell in the high-field inboard region, so that q is greatly increased. An example is shown in Fig 1; the value of q_{95} in this reconstruction of a high-beta START discharge is 6 times larger than the cylindrical, circular-section 'equivalent' given by $q_{cyl} = 5a^2B_T / RI_p$ (mT / MA). The increase in q at ultra-low aspect ratio is even larger, as can be seen from equilibrium calculations and has been directly shown by probe measurements of the magnetic field in the Rotamak - ST at Flinders [7]; at aspect ratio ~ 1.1 the edge safety factor is some 30 times the cylindrical, circular - section equivalent.

This increase in safety factor q has several consequences. For example, the toroidal field in the centre of present and next-generation ST experiments is typically a factor 10 lower than in conventional tokamaks, and high values of normalised current $I_N = I_p / (aB_o)$ [MA / mT] can be achieved before q_{95} falls below 2. Since, from Troyon scaling, the maximum obtainable β (before the plasma becomes unstable to ballooning or kink modes) is proportional to I_N this implies that high β should be obtainable if the Troyon scaling applies to the ST (next Section). An additional feature is that at the high β values attained in START the diamagnetic effect of the high β counters the paramagnetic effect of the high normalised current, and a local magnetic minimum in |B| can appear, as shown in Fig 1. This should improve stability [8] and also modify particle orbits, reduce trapping and therefore increase current drive efficiency.

A simple parameter reflecting this efficient use of toroidal field is the ratio of plasma current to centre rod current, $I_p/I_{rod.}$ In recent ST experiments I_p/I_{rod} ratios exceeding unity have been attained. START has achieved I_p/I_{rod} = 1.2 in plasmas of aspect ratio A = 1.3 [3], and recently, the Rotamak-ST has reached I_p/I_{rod} = 1.1 at A = 1.1 with no sign of any MHD limit [7]. The TS-3 device at Tokyo has explored the spheromak / ST interface, and shown that I_p/I_{rod} can increase substantially at ultra-low A, exceeding 3 at A = 1.1, in agreement with modelling [9].

2.2 High β properties

The ratio β of the plasma pressure to the magnetic pressure is a measure of the efficiency of a fusion device, and using a 1MW Neutral Beam heating system loaned from Oak Ridge National Laboratory, US, START has reached average β ~ 40%, Fig 2, more than three times the highest value obtained in a tokamak of conventional aspect ratio. Injection was of hydrogen at ~ 30keV.

In Fig 2 β is defined as $\beta_T = 2\mu_o \int pdV / (VB_o^2)$ where V is the plasma volume, B_o the vacuum toroidal field at the geometric centre of the plasma. The ratio β_N of β to the normalised current I_N has been raised to β_N ~ 5.9 and in addition it is shown that high β values of β_T > 30% and β_N > 4 can be sustained for several energy confinement times [10].

The points shown in Fig 2 are determined by equilibrium reconstruction using EFIT [11]. Good agreement is usually obtained between this magnetic method and the kinetic method where electron temperature and density profiles are obtained from the 30-point Thomson scattering (TS) diagnostic, the thermal ion temperature profile measured by the CELESTE charge exchange diagnostic, and the fast ion component (typically 20%) derived from Monte Carlo modelling.

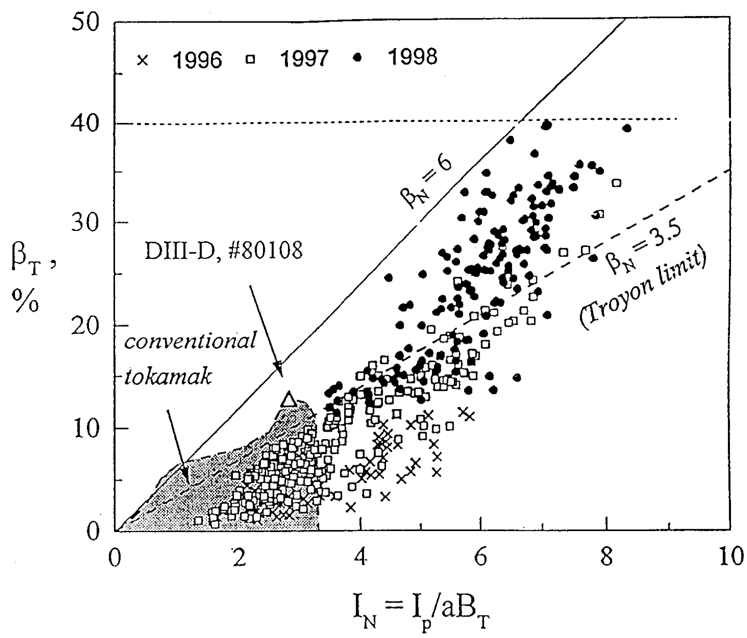


Fig 2 *Measurements of average β_T values in START; data obtained from magnetic reconstruction using EFIT*

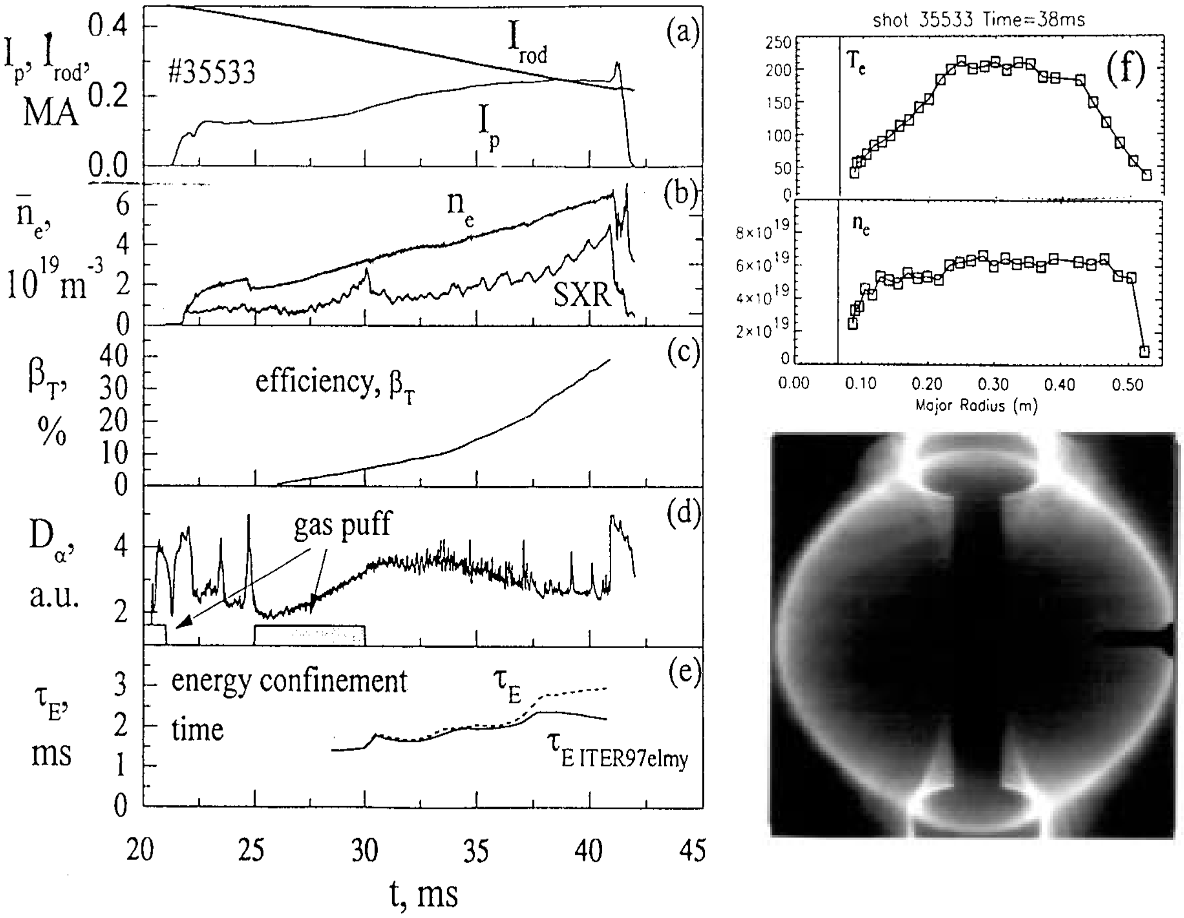


Fig 3 (a) - (e) Waveforms for high β #35533. Features associated with improved confinement appear from t ~ 36ms (f) Electron temperature and density profiles at t=38ms, measured by TS (g) image from high speed video camera at t=38ms

Several of the highest beta discharges exhibit features associated with improved confinement regimes in the conventional tokamak, for example the ELM-like eatures on D_α traces (Fig 3d), a steepening in edge profiles indicated by TS measurements (Fig 3f) and the sharply-defined plasma edge seen on optical diagnostics such as the high-speed video camera (Fig 3g). It is also noticeable that at the onset of this regime the energy confinement begins to exceed that predicted by the usual ITER scalings (Fig 3e).

It is a very promising feature that high β and good confinement can be achieved simultaneously. However it is known that additional care is required in the parameterisation of the EFIT reconstruction to accurately represent these sharp-edged configurations which may have substantial edge currents and detailed modelling (comparing magnetic and kinetic evaluations) is in progress and may lead to slight (less than 5%) changes in the β_T values shown in Fig 2.

2.3 Central beta in START

The central β, defined here by $\beta_o = 2\mu_o\, p_a / B_a^2$ where p_a and B_a are the plasma pressure and vacuum toroidal field at the plasma magnetic axis, can exceed 100% in START. Whereas the average beta can be adequately determined by a careful reconstruction of magnetic data using EFIT, the central beta is not so well determined and requires a kinetic derivation. The individual components are shown in Fig 4 at time t=38ms in #35533, when the Thomson Scattering data (30-point electron temperature and density profiles) and charge exchange spectroscopy data (ion temperature) is taken. The fast ion component is derived self-consistently by iterating with the EFIT equilibrium reconstruction (dashed line). At t=38 this process gives β_o = 91% which, assuming the profile can be extrapolated to the end of the shot at 40.8ms, indicates β_o = 153%.

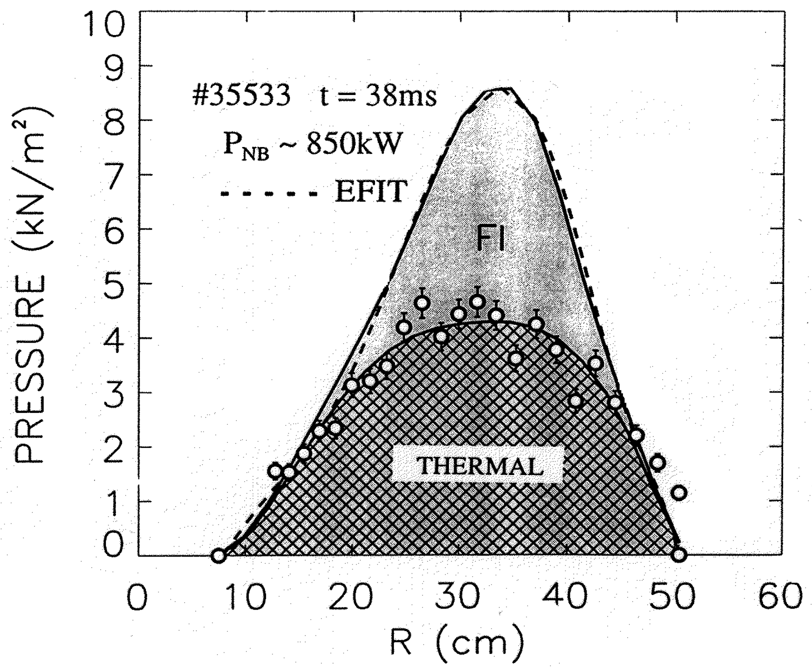


Fig 4 *Measurements of central β values in START by kinetic method at t=38ms. The full line is the sum of the thermal energy, determined from Thomson scattering and CX spectroscopy, and the fast ion pressure. The dashed line is the self-consistent EFIT reconstruction*

2.4 Operating Space

2.4.1 density limit: In these high pressure regimes, high densities with $n_e \geq 10^{20}m^{-3}$ have been obtained on START , with Greenwald number G $=\pi a^2 \bar{n}_e/I_p$ $[10^{20}m^{-1}/MA]$ ~ 1, as shown in Fig 5. The operating space has been further extended by use of pellet injection (in a collaboration with ENEA Frascati and Ris). This was used to inject a single pellet of frozen deuterium into a START plasma, launching from the top / inboard side; the pellet ablates and can fuel the plasma close to the centre. Results on START show increases in plasma density of up to a factor three, and extend the operating space as shown in fig 5, approaching Greenwald number G ~ 1.5 and Murakami parameter M = $\bar{n}_e R/B$ $[10^{20}m^{-2}/T]$ ~ 2.4 [12].

Injection of a frozen deuterium pellet into an ELMing NBI heated discharge #34881 produced the traces shown in Fig 6. There is a two-fold increase in line average density; the sawtoothing stops; but the Edge Localised Mode activity continues, consistent with successful central refuelling of this discharge.

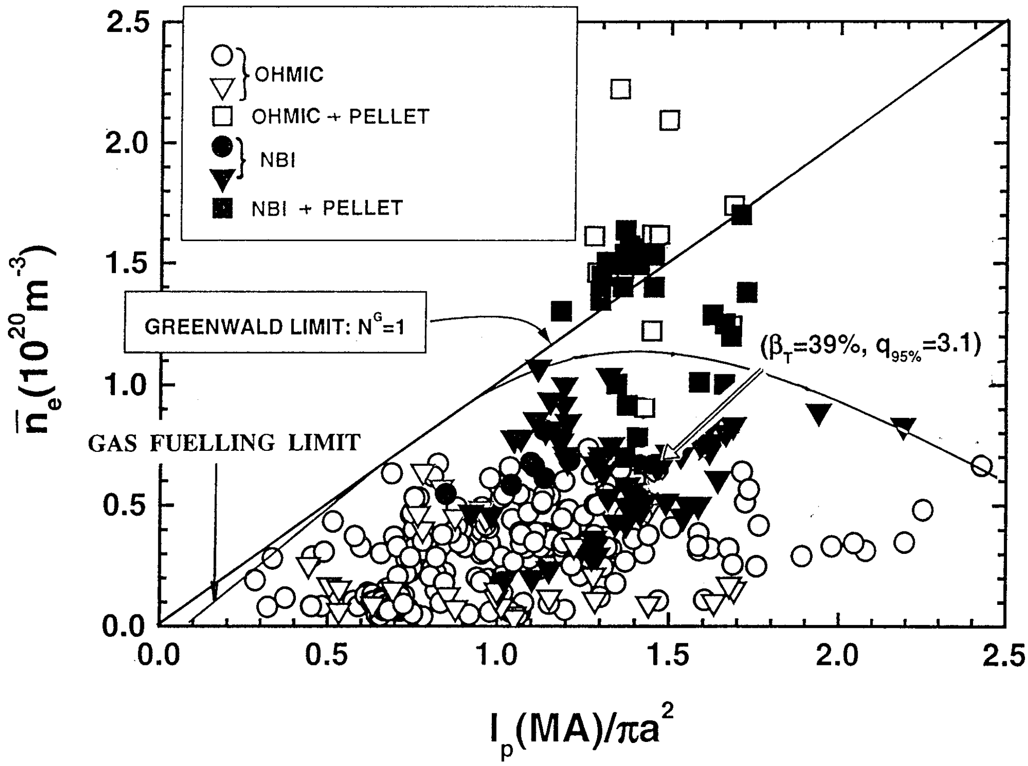


Fig 5 *Operating space for START, showing increased accessibility provided by pellet injection using the Frascati / Ris pellet injector. The operational limit on START for gas puff-valve fuelled discharges is shown*

2.4.2 q limits: A remarkable feature of the Double-Null Divertor (DND) high beta discharges is that operation is possible at q_{95} values as low as 2.3. Earlier modelling used a limiter plasma model which suggested a q-edge limit of ~ 4 for low aspect ratio, highly shaped discharges. More recent modelling using a seperatrix plasma model suggests [13] that values as low as q_{95} ~ 1.1 may be attainable assuming some wall stabilisation.

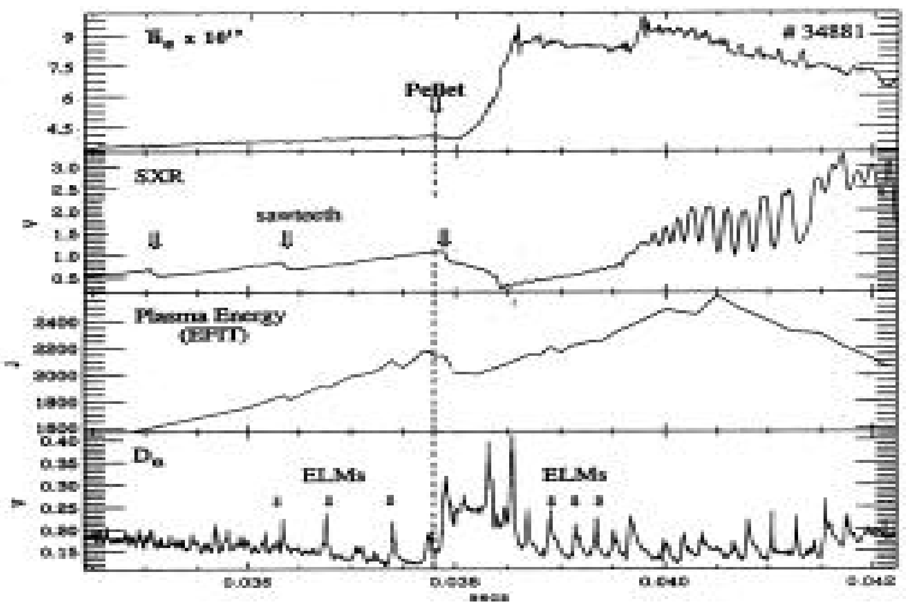


Fig 6 *Injection of a pellet into ELMing NBI heated 34881 in START; the density doubles, sawtoothing ceases but the ELMs continue*

2.4.3 Beta limit: Enhanced stability properties of the low aspect ratio configuration have been demonstrated at very high β values on START. In plasmas with $\beta_N > 4$ modelling suggests that the second stability regime for “ballooning” modes may have been accessed, with low central shear [14].

The values of β_N achieved in collisional plasmas on START significantly exceed the usual Troyon limit of $\beta_N = 3.5$ shown in Fig 2, in marked contrast to the situation in large, collisionless tokamaks of conventional aspect ratio, where neo-classical tearing modes limit β_N to approximately 2. Recent calculations [15] show that the (stabilising) Glasser term is relatively higher for a typical spherical tokamak equilibrium, so neo-classical tearing modes may not be such an issue. It remains to be seen from the next generation of larger, hotter and less collisional STs whether these favourable predictions are borne out experimentally to allow the high β_N operation observed in START.

2.5 The ‘Internal Reconnection Event’ (IRE)

At high density or low-q, operation in START is usually limited by ‘Internal Reconnection Events’ or IREs. These have several similarities to the ‘soft disruption’ seen in conventional tokamaks (including pre-cursors and an energy quench), occur typically once or twice in each discharge in START, and are also observed in CDX-U [16], Medusa [17] and HIST [18]. They appear to be associated with low m mode activity; for example, a small IRE sometimes occurs early in a START discharge when the central q value first falls below 2, and an m=2 instability can grow rapidly. Heavy gas puffing, or a reduction of toroidal field (and/or increase of plasma current), can also lead to a series of IREs.

An interesting non-linear simulation model of the IRE process has been proposed by Hayashi et al [19]. They show that at low aspect ratio, the m=2/n=2 and m=1/n=1 modes can couple (in agreement with experimental evidence from CDX-U) and, via magnetic reconnection between internal and external fields, exhibit the current spike, reduction in thermal energy, and helical deformation seen in experiment.

Equilibrium reconstructions based on magnetic data and kinetic profile measurements show that the current profile flattens as a consequence of the IRE in START. At low aspect ratio the plasma naturally has high elongation which increases further (as seen experimentally) when the internal inductance decreases; this increases q at the plasma edge and has a stabilising effect (Sec. 2.7).

2.6 Energetic Particle-Driven Instabilities in Spherical Tokamaks

Several distinct classes of MHD instability have been observed during beam-heated discharges in START [14]. Although apparently benign in START, the excitation of Alfvenic instabilities by energetic ions may be a generic feature of STs since spherical tokamaks are characterised by low toroidal fields. It remains to be established, however, to what extent the instabilities in START arise from circumstances unique to that machine. Calculations of particle orbits show that significant numbers of beam ions in START cross the last closed flux surface and are neutralised. This effect, which gives rise to unstable distributions in velocity space, will be less important in MAST and negligible in ST power plants. Thus, one of the sources of instability drive in START is unlikely to be present in larger spherical tokamaks.

2.7 Resilience to major disruptions

Until October 1995, IREs in low aspect ratio START plasmas (for A < 1.8) were nearly always benign; a reduction in thermal energy content, a current spike and an increase in plasma elongation were the only consequences, and major (current-terminating) disruptions were very seldom seen (except when A > 1.8).

The explanation proposed [20] for this apparent immunity from the major disruption is that, following the flattening of the current profile associated with an IRE, low aspect ratio plasmas exhibit a significant increase in elongation which acts both to raise q_{95}, enhancing stability, and also (by reducing the plasma inductance, which leads to a significant increase in plasma current) to counteract the inward contraction of the plasma ring, thus avoiding heavy limiter interaction.

The close proximity of the X-point coils in START, as seen in Fig 7, inhibits this elongation, and indeed since installation of the X-point coils in 1995 disruptions at low q have occurred more frequently. It is hoped that the much greater clearance incorporated in the successor device, MAST, will restore the strong resilience to major disruptions initially demonstrated in START. Such a resilience would be a great advantage in future large, high current devices and is another key feature requiring study in the new generation of STs.

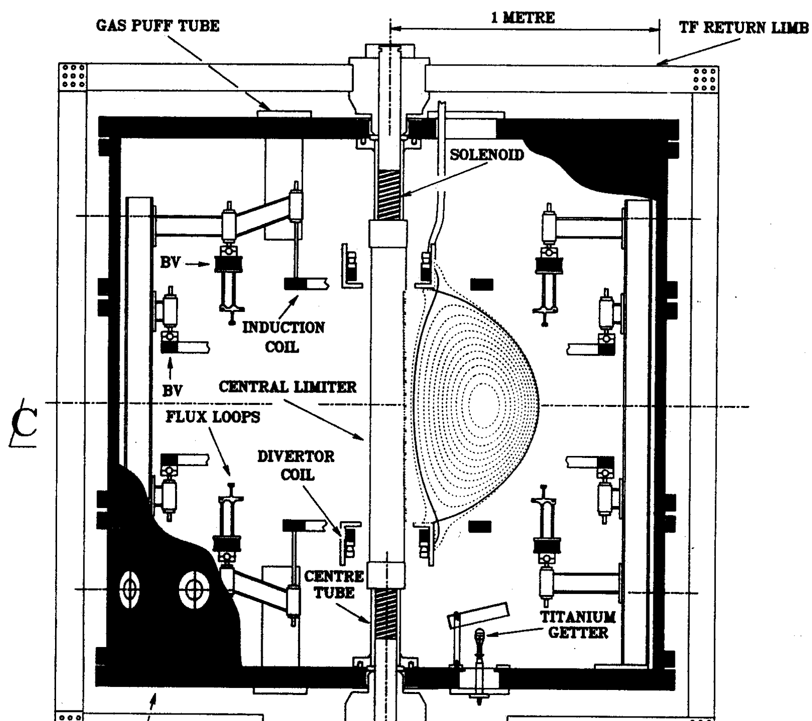


Fig 7 Layout of the START experiment, showing close proximity of X-point (divertor) coils to typical high performance plasmas

2.8 Energy Confinement in START

The accurate determination of energy confinement in START is difficult due to the transient nature of the discharges and the uncertainty in measurement of the beam power absorbed. To obtain the data, the total plasma energy is found from EFIT reconstructions based on carefully calibrated magnetic data, and then the fast ion component is estimated and subtracted in order to determine the plasma thermal energy. The input power P is here taken as the sum of the Ohmic input and the NBI power **absorbed**, i.e. the shine-through and first orbit losses (which together can be as high as 50% in START, because of the relatively low plasma current and small plasma size) are subtracted.

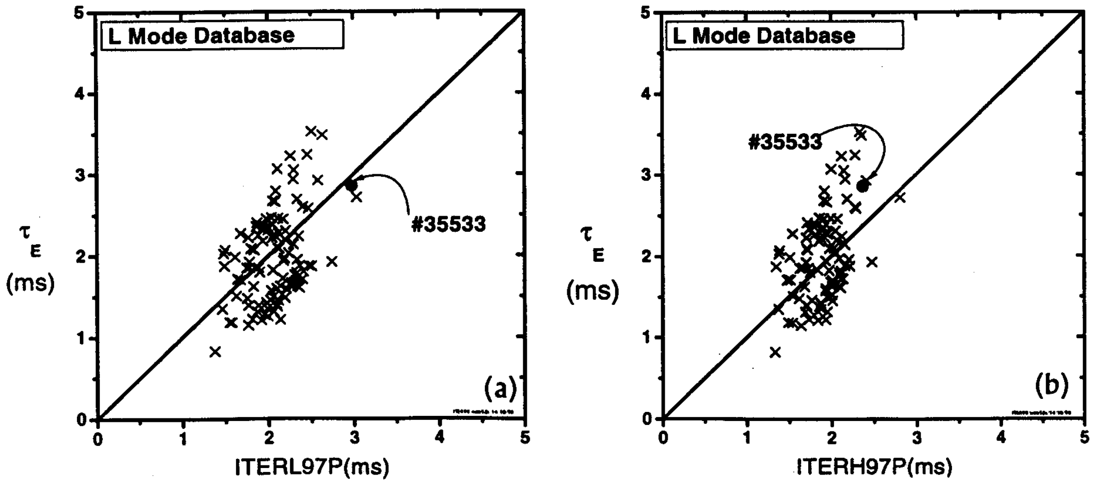


Fig 8 START L-mode data for NBI heated plasmas, compared to recent ITER L (Fig 8a) and H (Fig 8b) mode scalings. The high-β START shot 35533 is indicated by ·.

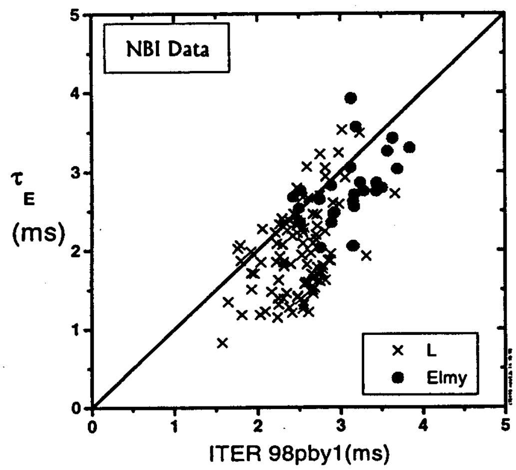
In fig 8 a comparison is made between the START results (for auxiliary heated L-mode data, i.e. showing no H-mode features) and the commonly-used ITER97 scaling laws produced to represent L-mode (Fig 8a) and H-mode (Fig 8b) confinement in conventional aspect ratio tokamaks. It is seen that the predictions of these empirical scaling laws for H- and L-mode confinement times are similar at the START aspect ratio; indeed the point indicated by · is below the prediction of the ITER L scaling (Fig 8a) but above the H-mode scaling (Fig 8b). Moreover, the experimental evidence (see section 2.2, and 2.9 below) indicates that improved confinement regimes very similar to H modes **can** exist on START, and indeed were observed in the high-beta shot 35533.

This anomaly may be resolved by a re-definition due to Kardaun [21] of the plasma elongation from κ_x = b/a to κ_a = (plasma area) / πa^2. This has a significant effect on the interpretation of the bean-shaped plasmas in PBX-M, and produces a change to the aspect ratio dependence of the H -mode ITER scaling which leaves the predictions for ITER unchanged but gives an increased prediction for START data. The new ITER 98Pby1scaling [21] is compared with the auxiliary-heated START confinement database in Fig 9a. It is seen that confinement in the ELMy discharges (solid symbols) is generally somewhat higher than in the L-mode (open symbols) and is quite well fitted by the new scaling, defined by

$$\tau_E \text{ (ITER98pby1)} = 0.0503*M^{0.13} * I^{0.91} * B^{0.15} * \kappa_a^{0.72} * R^{2.05} * \varepsilon^{0.57} * n_{19}^{0.44} / P^{0.65}.$$

Fig 9b shows a comparison of START Ohmic data with neo-Alcator scaling, using the definition $\tau_{n\text{-}A} = 0.07\ \bar{n}_e aR^2q^*$, where $q^* = 5\, a^2 B_T\, f / (R\, I_p)$, δ = triangularity, and f is the 'shape factor' $[1+\kappa^2 (1 + 2\delta^2 - 1.2\delta^3)] / 2$.

An interesting feature of START Ohmic discharges is that, whereas standard Ohmic discharges (denoted by open circles in Fig 9b) have significant radiative losses, application of the NBI in the early stages of a discharge gives hotter discharges which, (evaluating confinement several slowing-down periods after the NBI is cut off), have good confinement. These 'assisted Ohmic' discharges, denoted by open triangles in Fig 9b, are evaluated at least 5ms after the beam



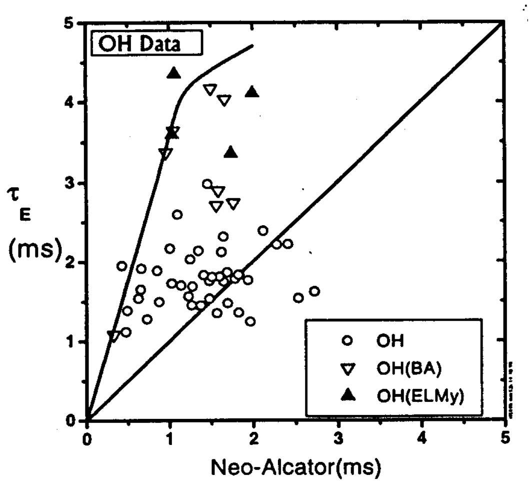


Fig 9a *START auxiliary-heated confinement database compared with ITER98PBy1 scaling*
Fig 9b *START Ohmic confinement database compared with neo-Alcator scaling*

cut - off (complete thermalisation of the beam ions is achieved in ~2ms). Indeed these 'beam-assisted Ohmic' discharges can exhibit improved confinement features (solid triangles), and yield some of the highest confinement data..

The START confinement data will, in conjunction with data from the next generation of STs, establish an ST confinement scaling which will enable the performance of futute applications of the ST (e.g. Volume Neutron Source, power plant) to be predicted; the data will also have a significant impact on the tokamak confinement scaling laws.

2.9 Features of Improved Confinement in START

Recent high performance START discharges have exhibited several of the characteristics of an H-mode type improved confinement regime [22]. These include: long ELMy periods; changes in poloidal rotation; a reduction in D_α intensity; a sharpening of the plasma edge in CCD images; an edge pedestal in density, and spontaneous increase in plasma density. A rapid rise in energy is observed between ELMs, representing a significant increase in the confinement. ELMing behaviour has not been observed in standard Ohmic discharges but can occur after the beam is cut-off, for example in shot 36429 (Fig 10).

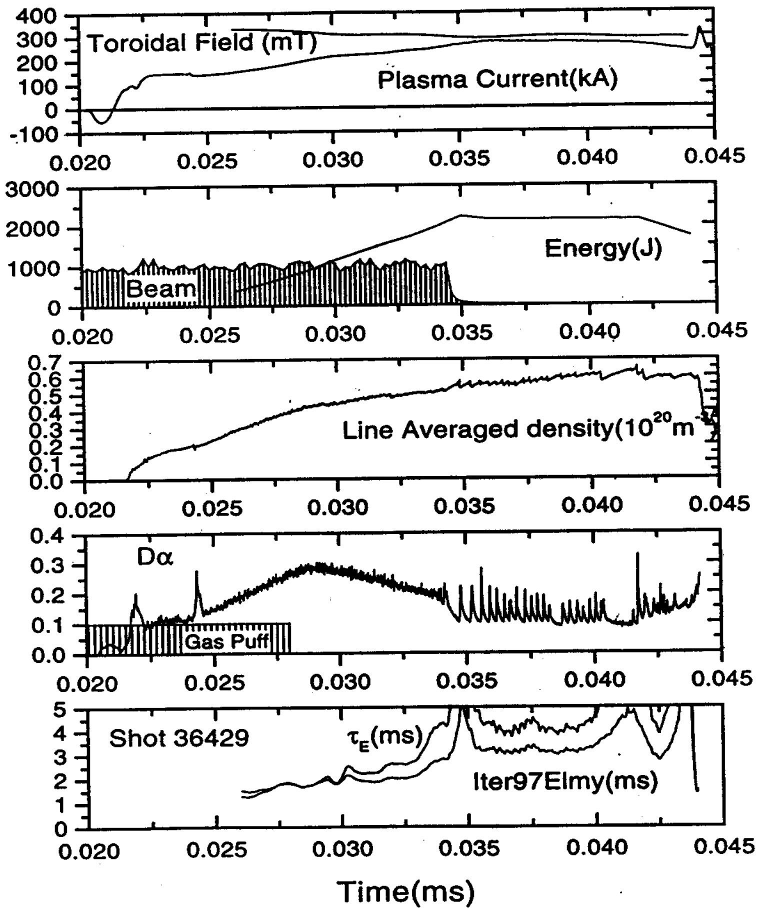


Fig 10.In Shot 36429 the beam is cut off just as ELMs appear. ELMing continues, with some ELM-free periods. From t~ 39ms this can be regarded as an Ohmic plasma, as the beam ions will have fully thermalised

The ELMing discharges observed in START are the first indications that an improved confinement regime, displaying a transport barrier, can be accessed in a spherical tokamak. Although typical START discharges are well above the usual power threshold for access to H-mode [23], H-mode like behaviour was only achieved in certain START discharges under the best vacuum conditions and in specific parameter regimes. This may be due to the relatively poor vacuum conditions on START and / or the high edge neutral density, exacerbated by the high ratio of tank volume to plasma volume (about 20:1) in START. Physics of the access to H-mode for the ST is hence another feature awaiting further study.

2.10 Edge Physics in START

The power loading onto plasma -facing surfaces is an important issue at tight aspect ratio, because the power exhausted from the confined plasma may be distributed over a smaller area. A detailed study of power deposition to the four strike points of the START standard double null divertor configuration (Fig 11) has revealed a strong in-out asymmetry and an up-down asymmetry on the inboard side [26].

The strike zones are typically narrow (~0.5-1.5cm) and, considering the significant poloidal flux expansion from the mid-plane (by a factor of ~8-12), this indicates the presence of large gradients across the scrape-off layer (SOL), [27]. The observed up-down asymmetry would appear to be related to particle drifts due to the electric field in the SOL, which may dominate the magnetic curvature drifts in START . The in-out asymmetry however is probably not due to particle drift effects.

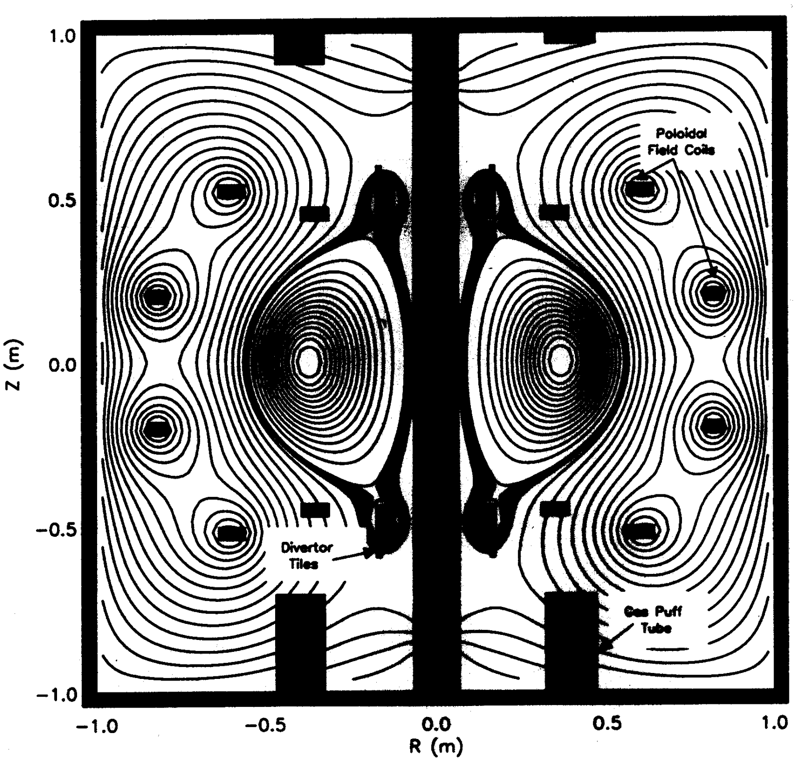


Fig 11 *Flux surfaces, SOL and location of strike points in a typical DND discharge in START*

It is observed that more power flows into the outboard SOL than would be predicted based on the relative surface areas, and indeed the highest power densities (of about 4 - 8 MW / m^2 in NBI-heated START discharges) were found to be at the **outboard** strike point.

2.11 Halo Currents in STs

Shaped tokamak plasmas at conventional aspect ratio are naturally unstable to vertical displacements, and in the event of feedback control failure during a plasma disruption the resulting vertical motion and current quench is often accompanied by the establishment of "halo" currents, flowing in a composite circuit completed between the plasma and surrounding conductors. Toroidal asymmetries in the halo current give rise to a net lateral or tilt force on the vessel. Results from conventional tokamaks such as COMPASS-D [28] indicate that the total halo current can approach 40% of the plasma current, and that toroidal asymmetries are significant, with toroidal peaking factors up to ~3.5.

Although plasmas on START can be vertically stable for high elongations (depending on current profile), vertical displacements can occur at still higher elongations and/or during a disruption. Measurements of halo currents have been performed on START, confirming results from CDX-U [16] that for the Spherical Tokamak, the symmetric halo currents on the central column appear to be very small (< 3%) with small asymmetry currents (< 5%), and therefore should not be a problem for the next generation of devices.

These results are consistent with recent models which describe the toroidal asymmetry in terms of inductively linked plasma-wall circuit elements [29,30]. The mechanism depends on the composite circuit `linking' the torus both poloidally and toroidally. At low aspect ratio the relatively short connection length around the centre tube allows eddy currents to flow in the toroidal direction, providing a stabilising effect which hinders the development of halo asymmetry.

3. NEXT GENERATION ST EXPERIMENTS

As described in Section 2, results from the first prototype ST experiments appear to be very promising. It remains both to verify these results (high beta, good confinement, large operating space, resilience to disruptions, etc.) in larger, less collisional, better controlled plasmas with longer pulses, and also to explore the advanced features now predicted by modelling. These include reduced turbulence due to the high ExB shearing rate, and (for high beta plasmas) the appearance of a true magnetic well; and self-consistent stable, high beta configurations with very high bootstrap fraction which may avoid limitations due to neo-classical tearing modes.

3.1 The MAST device now nearing completion at Culham [31] is essentially a scaled-up version of the successful START experiment but with good vacuum conditions, controlled (rather than capacitor bank) power supplies, and having a plasma cross-section comparable to ASDEX-U and DIII-D. Key parameters of START and MAST are compared in Table 1.

	MAST	*START*
R	0.7m	0.32m
a	0.5m	0.25m
κ(elongation)	≤ 3	≤ 4
R/a	≥ 1.3	≥ 1.2
I_p	≤ 2MA	≤ 0.31MA
I_{rod}	≤ 2.2MA	≤ 0.5MA
$B_T(R)$	≤ 0.63T	≤ 0.31T
P_{NBI}	5MW	1MW
P_{ECRH}	1.5MW	≤ 0.2MW
pulse length	1 - 5s	≤ 0.06s
Bakeout temp	200°C	50°C
plasma volume	~5m^3	~0.5m^3

Table 1 Comparison of key parameters for START and MAST

3.2 NBI programme on MAST . The ORNL injector used on START at up to 40keV and 1MW power was remarkably successful at producing plasma heating but was not suitable for current drive on the relatively small START plasma due to high shine-through at low plasma densities. This injector is being augmented by a further beam line, and the ion sources are being upgraded for MAST to higher energies and for pulse lengths of up to 5s. The total power obtainable should be up to 5MW. Deuterium injection will be used and the installation will be co-injection. Beam energies of 60 - 70keV and tangency radius of 70cm are optimal for both plasma heating and current drive.

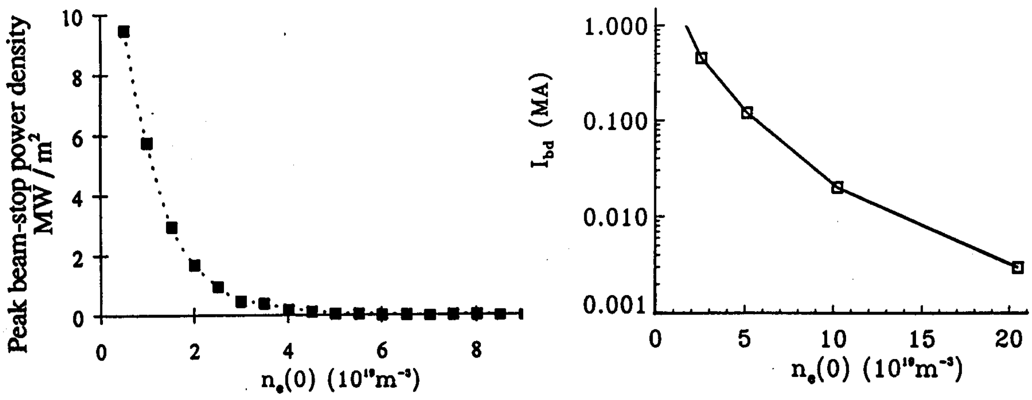


Fig 13 *(a) shine-through (and beam-stop loading) becomes small for* $n_{eo} \geq 1 \times 10^{19}m^{-3}$
(b) high current drive efficiency achieved; beam-driven current I_{bd} *~ 0.5MA for* $n_{eo} = 2 \times 10^{19}m^{-3}$

Calculations show that injection at these energies and tangency radius into a typical MAST plasma of R_o=0.7m, a=0.5m will produce low shine-through for $n_{eo} > 1\times10^{19}m^{-3}$ (Fig 13a) and injection of a 60keV, 3.8MW beam into a 1MA plasma of $n_{eo} = 2\times10^{19}\ m^{-3}$ will drive a substantial plasma current of ~0.5MA (Fig 13b), the remaining current being largely self-driven. This demonstration of significant bootstrap current (predicted by modelling) is also a key part of the ST programme at Culham. An advantage of operation at these relatively low densities is that the existing 1.5MW, 60GHz ECRH facility can be used to provide substantial plasma heating at the same time as the NBI, giving additional flexibility. Installation of the first beamline is planned for early 1999.

4. FUTURE APPLICATIONS

DT fuelled larger STs of ~10MA [32] and Volume Neutron Source designs [33] based on the ST appear extremely promising and may provide an important low-cost step on the route to a fusion power plant. However DT devices with an unshielded centre-post cannot use a conventional solenoid for induction and ramp-up. Several schemes are under consideration; MAST will use the ‘induction-compression’ scheme used so successfully in START for current initiation, and the application of NBI in 1999 will test the favourable current drive properties predicted by modelling and reviewed in the previous section.

Power plant designs based on an ST [33], [34] demonstrate the economic viability of this route to fusion power and have attractive featrures (e.g. simple normal conducting coils, no inboard blanket) which lend themselves to novel maintenance methods [34]. The evaluation of the ST Power Plant concept of course requires considerable input from the next generation of purpose-built STs.

5. CONCLUSIONS

As indicated in the previous sections, there are many features observed in START and other prototype STs which appear to be very promising (β_T ~ 40%, β_o ~ 100%, a magnetic well, improved confinement regime, disruption resilience etc.) and results from these experiments are providing new insights into toroidal confinement physics and reducing uncertainties in the application of scaling laws, applicable to all types of tokamak. Important objectives of the next generation of hot, low collisionality MA-level devices such as MAST, PEGASUS, NSTX, TS-4, GLOBUS-M and ETE will be to verify these results in less collisional plasma regimes, and to increase the tokamak database through developing the aspect ratio and size scaling. Potentially, the Spherical Tokamak offers a low cost route to fusion for both volume neutron source and power plant applications but first it is important to demonstrate steady state operation (as theoretically predicted) via efficient current drive with high bootstrap current fraction, and to demonstrate operation at the high beta and high plasma elongations required for an efficient ST power plant.

ACKNOWLEDGEMENTS

The work is jointly funded by Euratom and the United Kingdom Department of Trade and Industry. The NBI equipment on START is loaned by the US DoE, the Pellet Injector experiments were in collaboration with Ris and ENEA Frascati, and the EFIT reconstruction code is supplied by General Atomics.

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