HIGH β ACHIEVEMENT IN IMPROVED CONFINEMENT REGIMES AND ENERGETIC ION-DRIVEN INSTABILITIES IN START

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The low aspect ratio geometry of the START device at Culham makes it possible to test the tokamak pressure limit in a new environment [1], and the low magnetic fields (B_T ~ 0.15-0.4T) mean that (benign) Alfvénic instabilities are excited when neutral beams of relatively low energy (~ 30keV) are used to provide additional heating.

1. <u>High β achievement in improved confinement regime.</u> As in other high-β experiments, optimisation of current and pressure profiles and selection of the optimum plasma shape are key issues for the achievement of the best performance on START. The possibility of operation at shaping factor $S=I_N q_{95}$ ($I_N=I_p/aB_T$) significantly higher than that obtainable in conventional tokamaks is a fundamental advantage of spherical tokamaks. Values of $\boldsymbol{\beta_T}$ **~ 40 %,** which is a new record for tokamaks, and $\boldsymbol{\beta_N}$ **~ 6** have been obtained on START, Fig.1, in a NCS (Negative Central Shear) target regime [2] in a double-null divertor configuration without wall stabilisation. These were achieved by use of early NBH and delayed current ramp-up. The high β values could be sustained for several confinement times in discharges when toroidal field ramp-down was stopped at I_p/I_{rod} ~ 1 [1], where I_{rod} is the current in the central rod of the toroidal field system.

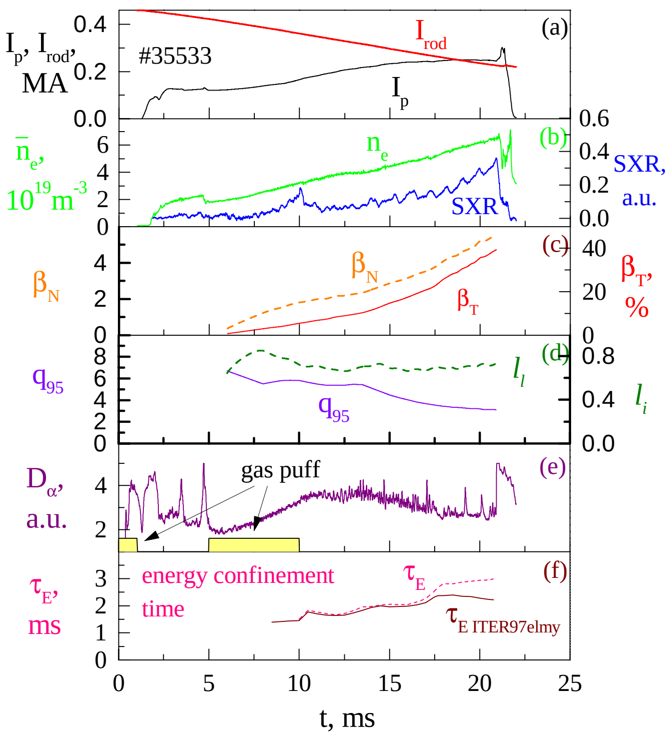

Fig. 1. *Traces of a high-β shot #35533. 30kV, ~ 0.9MW hydrogen neutral beam was applied from the beginning of the discharge into a deuterium plasma.*

Energy confinement has been studied at different heating powers using kinetic and magnetic methods and results are reported in [3]. The thermal ion and electron contributions to the stored energy have been found to be of similar magnitude with significant ion heating, and the peaked fast ion contribution of ~ 20% can double the central pressure in the high-β discharges [4]. An improvement in the energy confinement is often observed in these regimes, and confinement exceeds ITERH97-Elmy scaling even at the highest β, Fig.1f. Broad or hollow density profiles with a steep edge gradient have been measured. In some high-β shots a clear edge pedestal has been seen in the $T_e(R)$ profile with pedestal temperature ~ 100 eV. Large ELMs have been observed, Fig.1e, with inter-ELM periods of up to 3ms. The estimated energy loss during a single ELM on START is about $\Delta W/W \sim 5\%$, which is in good agreement with a $\Delta W/W = 1.81\ (P_{input}/S)^{-0.38} B_T^{-0.31}$ ITER scaling law [5]. A fast increase in the stored energy, observed during inter-ELM periods in some high-β discharges, suggests the possibility of a further significant improvement in confinement. The presence of ELM-like phenomena, with the observed reduction of turbulence, spontaneous increase in the plasma density, formation of edge pedestals in T_e and n_e, increase in poloidal rotation, reduction in the D_α emission and increase in confinement show that the improved confinement mode in this high-β regime has many characteristics of the H-mode [6].

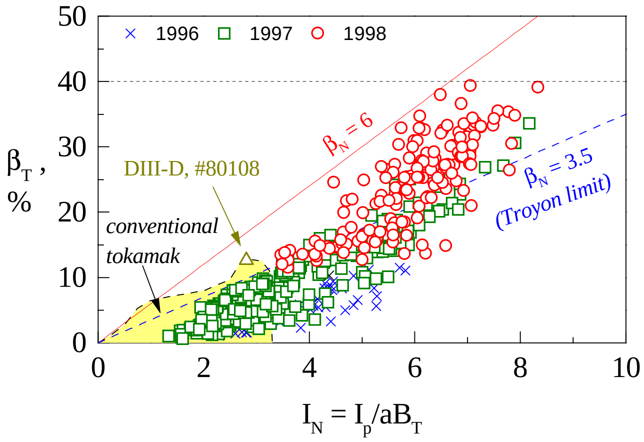

Fig. 2. *β_T vs I_N in START. Each point represents one shot*

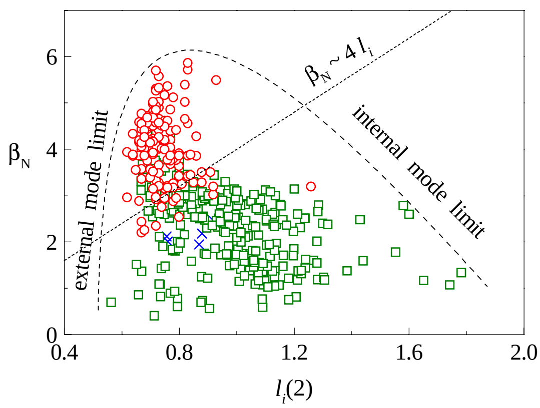

Fig. 3. *Stability diagram in β_N vs l_i space for START. Each point represents one shot. Stability limits (qualitatively) expected from conventional tokamak experience are shown.*

In this regime, the conventional limits [7] $\beta_T \sim 3.5\ I_p/aB_T$ and $\beta_N \sim 4\ l_i$ have been significantly exceeded, Figs.2,3. Ideal ballooning stability analysis suggests that to attain these high-β values, the plasma needs to be in the second stability regime. Stability simulations show that access to improved stability at low aspect ratio does not necessary require negative values of the central shear, as low positive central shear profiles, which are typical for spherical tokamak equilibria, can also provide second stability for these high pressure plasmas.

At the low q_a values (high I_N in Fig.2 and the top region in Fig.3), $q_{95} \sim 2$ - 4, it is difficult to separate internal and external modes in START to determine the cause of the operating limit. However, it is found that all high-β shots terminate through an IRE (Internal Reconnection Event), which can happen at any β-value on START, so there is no convincing evidence that a β-limit has been reached. Further increase in β was constrained by available beam power, and no β-saturation was observed.

2. <u>Energetic Ion-Driven Instabilities in START.</u> Several distinct classes of energetic particle-driven instability have been observed during beam-heated discharges in START. Bursts of MHD activity fall into four main categories: fixed frequency bursts at frequencies of typically $f \sim 100$ - 200 kHz, which resemble toroidal Alfvén eigenmodes (TAEs); modes at $f \leq 350$ kHz which sweep down rapidly in frequency during the course of bursts lasting for

≤ 0.2 ms; fishbone-like modes at f ~ 50 kHz, some of which also sweep down in frequency; and higher frequency bursts at f ~ 700-900 kHz.

We have used START plasma equilibrium reconstruction data to compute continuous spectra of Alfvén waves. Because the plasma β in these discharges is relatively high ($\beta_T \geq$ 10%), and the aspect ratio is low, the spectra have several gaps of finite width, extending up to frequencies of several times the Alfvén gap frequency $f_A \equiv c_A/4\pi q R_o$, where c_A, q are local values of the Alfvén speed and safety factor. Typically, f_A ~150 kHz in START. In each of the spectral gaps, Alfvén eigenmodes could be driven unstable by energetic beam ions.

The parallel speed $v_{b||}$ of newly-born beam ions is greater than c_A, and so it is possible for passing beam ions to interact with Alfvén waves via the resonance $v_{b||} = c_A$. Beam ions provide free energy to drive Alfvén eigenmodes not only through pressure gradients (as in conventional tokamaks), but also because they are generally anisotropic ($T_\perp \neq T_{||}$), and, in some cases, have a non-monotonic velocity distribution, Fig.4. The non-monotonic property, observed in both neutral particle analyzer measurements and Monte Carlo simulations, is a consequence of energy-dependent charge exchange losses, which can prevent the formation of monotonic slowing-down distributions [4]. The existence of a bump-on-tail in the beam ion distribution may also have important implications for plasma heating: ion temperatures in START are often higher than neoclassical predictions.

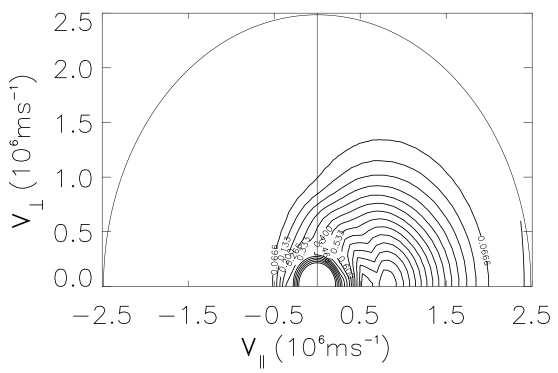

Fig. 4. *Contours of velocity distribution, $F_b(v)$ of fast NBI ions sampled at plasma core determined by the LOCUST NBI Monte Carlo code [4]. Non-monotonic $\partial F_b/\partial v$ is generated at the plasma centre by virtue of large poloidal flux excursion and high propensity for charge exchange in the plasma periphery.*

Linear stability analysis is used to interpret the START observations of wave excitation at f ~ 0.7 - 0.9 MHz, see Fig. 5. The frequency of this emission is below the beam ion gyrofrequency f_b ~ 2 - 3 MHz, although in some cases there appears to be weak, harmonically-structured secondary emission at frequencies up to ~ 2 MHz. Most beam ions have initial energies of E_{ib} ~ 30 keV, and those born in the outer midplane have oblique pitch

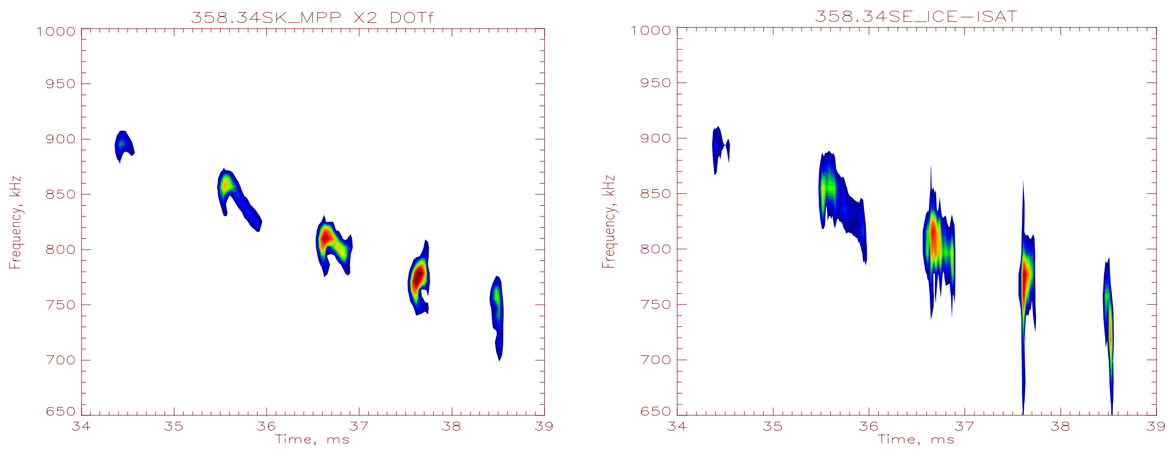

Fig. 5. *Outer midplane Mirnov coil and Langmuir probe spectrogram from shot #35834.*

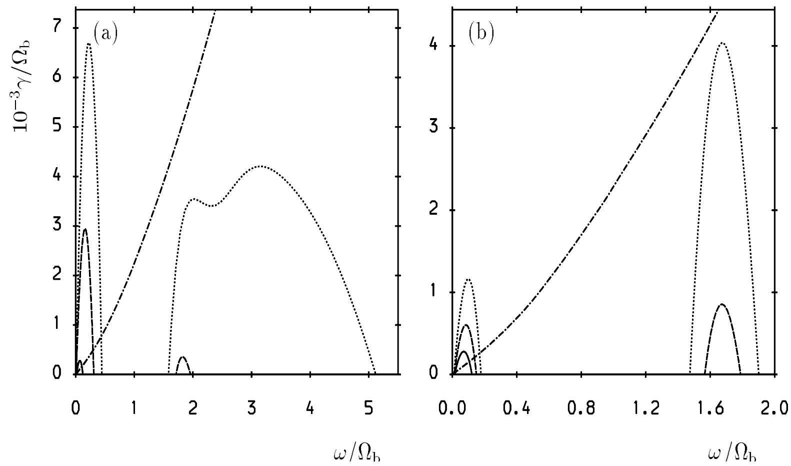

Fig. 6. *Computed growth rates of fast Alfven waves in START, showing the effect of varying (a) $v_{\perp b}/c_A$ and (b) $\delta v_{\perp b}/v_{\perp b}$. In (a) $\delta v_{\perp b}/v_{\perp b}$=0.3 and $v_{\perp b}/c_A$=3 (solid curve), 3.25 (dashed curve), 3.5 (dotted curve). In (b) $v_{\perp b}/c_A$=3 and $\delta v_{\perp b}/v_{\perp b}$=0.3 (solid curve), 0.28 (dashed curve) and 0.26 (dotted curve). The dashed-dotted curves show electron damping.*

angles. Because of the low B_T, both velocity components, $v_\perp$ and $v_{||}$, exceed c_A. This allows waves be excited on the fast Alfvén branch, via the Landau resonance $\omega = k_{||}v_{b||}$. Fig. 6 shows growth and damping rates of obliquely-propagating fast Alfvén waves, on the assumption that

$$F_b(v) \sim \exp[-\frac{(v_\perp - v_{\perp b})^2}{\delta v_{\perp b}^{\ 2}}]\exp[-\frac{(v_{||} - v_{||b})^2}{\delta v_{||b}^{\ 2}}]$$

calculated using these parameters: β_i = 0.04, n_b/n_i = 1%, $v_{||b} = 0.5v_{\perp b}$,. $\delta v_{||b} = \delta v_{\perp b}$. The waves are assumed to have $E_{||}$ = 0, with $k_{||}/k$ = 0.64, and the plasma is assumed to be uniform.

The beam ion concentration can be very high, giving rise to strong instability drive even when the beam ions have a broad spread of velocities. However, the growth rate is sensitive to the beam parameters: this may partially explain the cessation of emission at a sawtooth crash. A broad spread of beam velocities also implies a rapid fall-off in the instability drive with increasing frequency in the ion cyclotron range: measurements have not revealed any clear coherent emission at 2 MHz $\leq f \leq$ 20 MHz. Other possible explanations of the high frequency emission include the existence of wide high order gaps in the continuous Alfvén spectra, noted above, which implies that shear Alfvén waves may be excited in the 700-900 kHz range.

3. <u>Conclusions.</u> The combination of high β-values and good confinement demonstrated on START is very encouraging and will be further investigated on the much larger MAST device now under construction at Culham. Benign instabilities have been observed across a wide range of $f \leq 1MHz$ during beam heating in START. Sources of instability drive include strong beam pressure gradients and non-monotonic beam velocity distributions. A combination of high β and low aspect ratio implies the possibility of shear Alfvén eigenmode excitation at $f >> f_A$, but instability in the 0.7 - 0.9 MHz range may also be due to fast wave exitation.

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