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Abstract: The promises of low aspect ratio include the ability to run large plasma currents in compact devices, the possibility of very high β operation, and naturally elongated plasmas. START is the first tokamak to operate at low aspect ratio ($A \geq 1.2$) and to demonstrate the general features of tokamak-like discharges. START has a major radius $R \sim 0.2$ m, minor radius $a \sim 0.15$ m, and aspect ratio $A \sim 1.3$. In START, plasma currents up to 200 kA, electron temperatures $T_e \leq 1800$ eV, and line–averaged densities $n_e \leq 2X10^{20}$ m^{-3} have been achieved. This has led to central β_T values of ≤ 20 % and elongations of $\kappa > 2$.

I. INTRODUCTION

The initial low–aspect–ratio experiments were performed in 1987 in the Heidelberg Spheromak Experiment (HSE)[1], a spheromak which was fitted with a current–carrying central rod to provide tokamak–like discharges. The SPHEX[2] and Rotamak[3] experiments followed soon after. The START (Small Tight Aspect Ratio Tokamak) experiment began in 1991 and has the capability of producing larger hotter plasmas[4-8]. START plasmas have been shown to exhibit improved stability and confinement properties over conventional tokamaks, and to have a unique 'natural' particle exhaust. Improvements in diagnostic facilities and in operating conditions have led to a fuller understanding of the properties of plasmas at low aspect ratio, where the effects of particle trapping and toroidal coupling are expected to have important consequences.

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Work is continuing to extend the database of near-spherical plasmas, the results of which could have a significant impact on the design of future devices such as a Materials Test Facility/Volume Neutron Source[9], a Pilot Plant[10] a Divertor Test Facility[11], and a DEMO[12-14] power plant.

Table 1 lists machine and plasma parameters achieved by the end of 1993 in START.

Parameter	Achieved
R (m)	~0.2
a (m)	~0.15
Aspect Ratio R/a	1.3
I_p (kA)	≤200
B_T (Tesla)	0.5
Pulse length (ms)	≤30
Density n_e (m^{-3})	$\leq 2 \times 10^{20}$
Electron Temp T_e (eV)	300-1800
Shapes	Circle, D
Elongation	1.2-2.0
β_0(%)	≤20

Table 1. Parameters of START

II. PLASMA FORMATION IN START

A general layout of the START device is shown in Fig. 1. Plasmas are normally produced by an induction-compression technique[8] whereby breakdown is achieved around the induction coils (see P1 in Fig. 1). The plasma then coalesces at a magnetic field quadrupole null between the coils and is subsequently compressed into the final 'spherical tokamak' configuration shown in Fig. 2.

Recently, the introduction of 14 GHz klystron power has enabled conventional (in contrast to the original induction-compression) plasma induction in START, whereby a low–aspect–ratio plasma is 'grown' in place. In this way, 100 kA plasmas of aspect ratio 1.3 have been produced, using only 400 watts of ECR power and only 10 mVsec from the solenoid. The plasma can be initiated at loop voltages as low as 0.4 V.

III. EQUILIBRIUM AND NEO-CLASSICAL EFFECTS IN START

START plasmas exhibit a natural 'D'-shaping, as illustrated in Fig. 2, which is a photograph of a 100 kA plasma of major and minor radii of 23.5 cm and 18 cm, hence an aspect ratio of 1.3. This plasma has an elongation $\kappa \sim 1.9$ and is vertically stable without active feedback. This indicates a broad current profile.

One of the important parameters for proposed large scale spherical tokamaks is the ratio of the plasma current to the total current flowing in the central rod. This rod current produces the toroidal field. The ratio I_p/I_{rod} needs to be as high as possible for fusion power generation, because of ohmic losses in the central rod. Improvements to the operating techniques and plasma cleanliness have allowed this ratio to be increased in START from 0.30 to 0.55 over the last year, thus approaching the desired value of at least unity for reactor applications. It is found that there are no special stability problems with the plasmas that result, which have $q_{cyl} \approx 1.3$.

A small central solenoid has also been installed. This and other improvements, such as better gas control and optimization of the solenoid power supplies, have produced a three-fold increase in discharge duration, now up to 30 ms with a constant-current duration of up to 8 ms, as shown in Fig. 3.

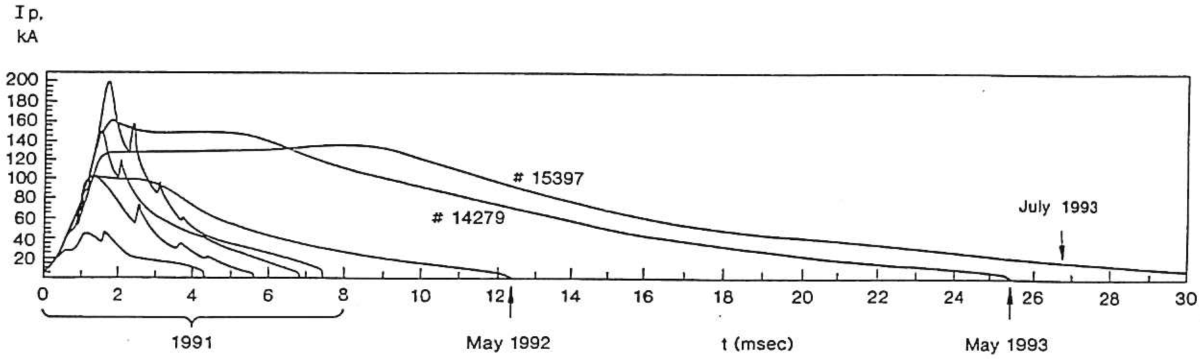

Figure 3 .Variation of plasma current with time for typical START discharges from March 1991 to July 1993

Experimental results, primarily using the Thomson scattering diagnostic to determine the plasma pressure profile, together with numerical simulations using a self-consistent 2-D steady–state neo-classical equilibrium code[7], support the theoretical predictions of an overall 3-4 fold increase in resistivity over the value predicted by Spitzer resistivity. The presence of sawteeth, implying q=1 near the centre (while the edge q value $q_\Psi \sim 12$), is also consistent with current peaking due to enhanced trapped-particle-induced resistivity[7].

The high densities obtained on START, as shown in Fig. 4, correspond to very high values of the plasma β, with $\beta_o = 20\%$ achieved ($\beta_o \equiv 2\mu_o p_o / B_o^2$, where B_o is the vacuum toroidal field at the plasma centre and p_o the central pressure). Modeling shows that low aspect ratio tokamaks can support much higher β values[14] (up to volume averaged betas of 40%) than conventional devices, and this is one of the major attractions of the concept.

IV. ENERGY CONFINEMENT TIME

Energy confinement in tokamaks is not fully understood and is described by various empirical scalings. For low aspect ratio devices, such as START, predictions of these scalings vary widely and information from START provides an important extension of the existing database.

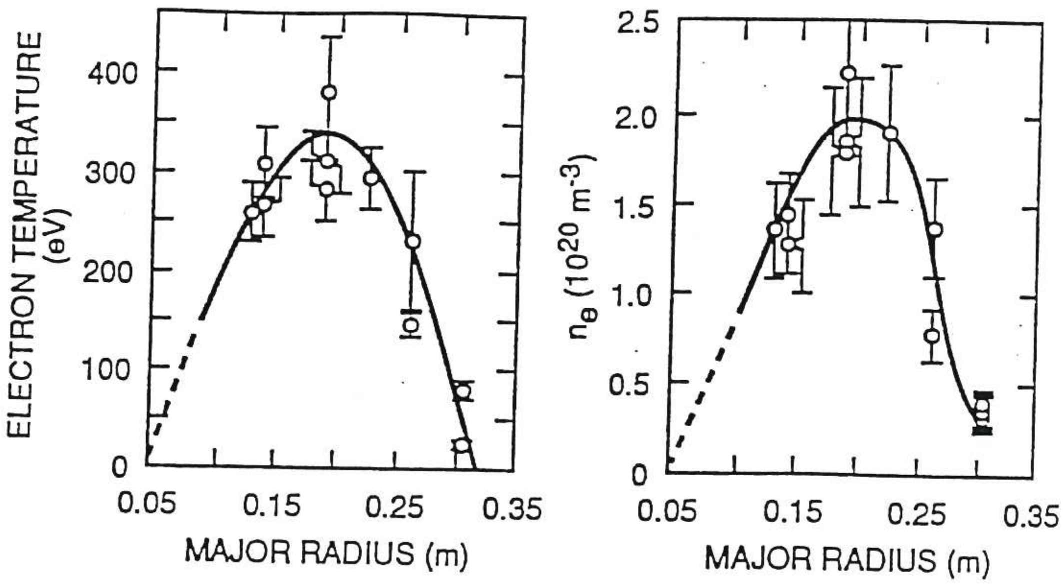

Figure 4. Electron temperature and density profiles in 100kA START discharge, measured by Thomson scattering diagnostic

Neo-Alcator scaling is widely used for ohmically heated tokamaks and the results from START are compared with this in Fig. 5. Although there is considerable scatter in the data from START, the energy confinement time consistently exceeds the neo-Alcator prediction and, moreover, shows no sign of the saturation[15] at high density which conventionally would have restricted values to the dashed line on the graph. Energy confinement in START is therefore between two and ten times greater than might have been expected[6]. Comparisons with other scaling laws give best fits[5,7,16] with the Rebut-Lallia[17] and the Lackner-Gottardi[18] scalings.

V. MHD IN START

Major disruptions, which cause the abrupt termination of the plasma current in conventional tokamak, have not been observed on START in over 17,000 discharges, as long as the plasma remains at the low-aspect ratio. However, an internal reconnection is frequently observed and Figure 6 compares a major disruption in JET with a typical internal reconnection in START.

A possible explanation for the absence of the current termination in START is that, because the external inductance of the plasma column is very small at low aspect ratio, a decrease in the internal plasma inductance during an internal reconnection causes a relatively large (up to 50%) increase in the plasma current. This increases the outward force on the plasma, moving it away from material surfaces[19]. This is in contrast to conventional tokamaks, where reconnections may act to reduce the major radius and thus increase contact with inner limiters, producing an influx of impurities that can lead to a rapid cooling of the plasma and the termination of the current.

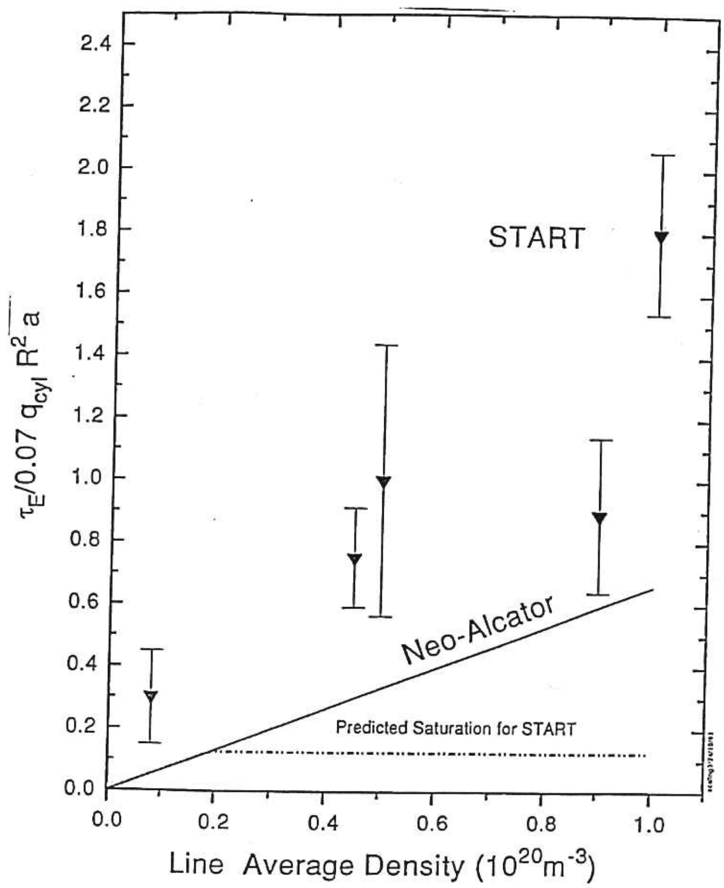

Figure 5. Comparison between confinement time measurements from START and those predicted by neo-Alcator scaling

It is also possible that the very high edge shear and increased toroidal coupling inherent at tight aspect ratio[5,20] play a role in preventing hard disruptions in START. In some discharges, stability code simulations of soft x-ray observations suggest an n=1, predominantly m=2 mode is present, but this mode does not universally occur before an internal reconnection. There is evidence for high frequency MHD (≥100 kHz) and increased CIII radiation before internal reconnection events, but the instability causing this behaviour remains unclear.

VI. PLASMA EXHAUST

The scrape-off layer in START has the potential to provide a test bed for several new concepts relevant to present generation and future large tokamaks. An array of fixed single Langmuir probes embedded in one of the bottom target plates and a moveable double probe at the outboard mid-plane have been installed so that the effect of this configuration on the plasma boundary and exhaust mechanisms can be investigated. These measurements have already confirmed the existence of an exhaust plume extending up and down the central rod[6,21]. This result could in fact be expected from the pattern of magnetic flux surfaces shown in Fig. 7.

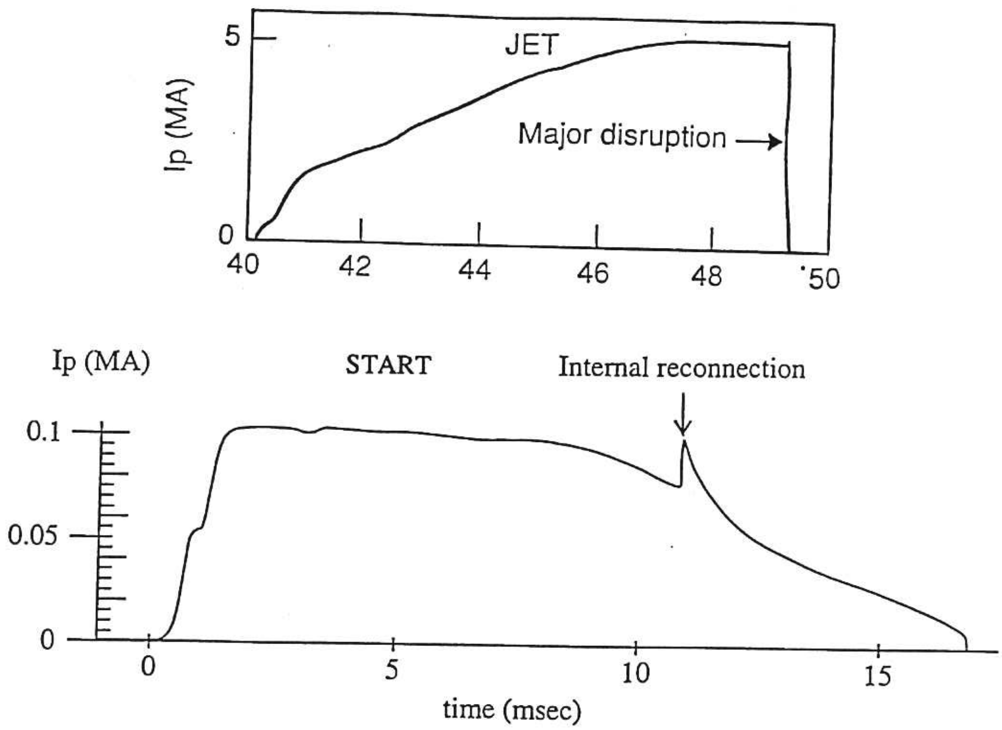

Figure 6. Comparison of a major disruption on JET with a typical internal reconnection event on START

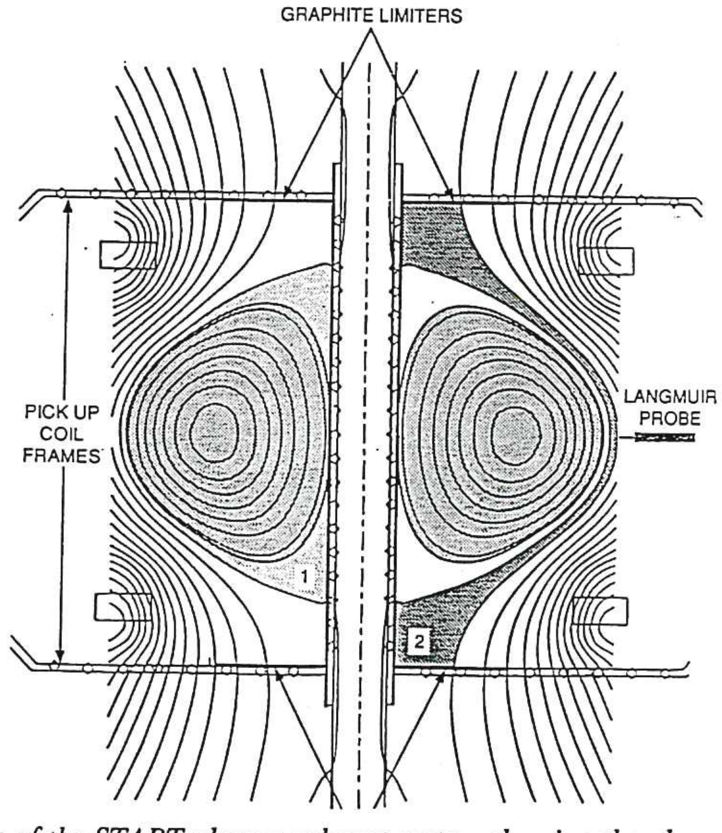

Figure 7. Schematic of the START plasma exhaust system showing the plasma, the exhaust region inside the separatrix (labeled "1" in the figure), and the plasma exhaust outside the separatrix (labeled "2" in the figure).

High density values have been measured by the probes in the lower exhaust plume, which acts as a natural divertor to carry particles away from positions just outside the last closed flux surfaces. Correlations between signals of the probe array and the moveable probe have been used to accurately map out the shape of the flux surfaces, which agree with those calculated by an equilibrium code (Fig. 7). Further confirmation of the flux–surface shape comes from the distribution of light emission seen in CCD pictures.

Recently, biased divertor experiments have been conducted in START. In these experiments, the upper divertor target was removed, and the lower divertor target was biased to 350 V. The aim of these experiments was to produce a change in the radial electric field in the plasma. The biased plasmas exhibited a reduction in edge fluctuations and H_α emission, and an increase in density (Fig. 8), implying an improvement in particle confinement. Similar effects have been observed in TEXTOR[22] and in other devices[23].

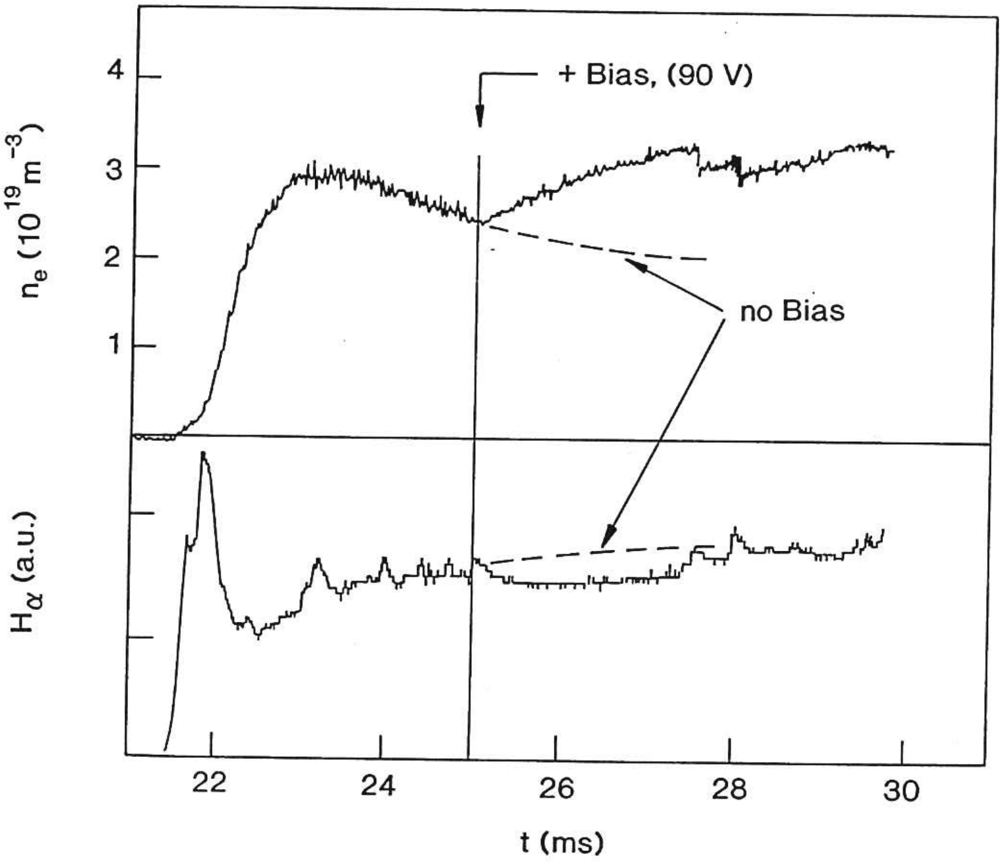

Figure 8. Density increase and H_α decrease seen on application of bias voltage at time t=25 ms

VII. FUTURE PROGRAMME ON START

START has been modified (Dec. 1993) to include a more powerful central solenoid, and the internal poloidal field coils have been re-positioned. This should enable the achievement of larger plasmas and higher plasma currents. Installation of 60 GHz ECRH for auxiliary heating, X-point

coils for improved confinement modes (as seen with ohmic heating on COMPASS-D[24] and on other tokamaks) as well as for active field shaping, and a vertical position feedback control system are also planned for 1994.

VIII. CONCLUSION

In addition to its success in the study of physical processes in tokamaks and in extending the tokamak database at low aspect ratio, results from START show that spherical tokamaks appear to have significant advantages over conventional (higher aspect ratio) tokamaks. These results encourage the further investigation of this novel concept.

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