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TEN YEARS OF RESULTS FROM THE TOSCA DEVICE

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ABSTRACT

The TOSCA device was built to investigate non-circular plasma cross-sections, minor radius compression and limiting values of β. A wide range of investigations on minor radius and minor/major radius compression have been conducted which show improved confinement on detachment from the limiter. The shaping studies have explored elliptical, D-shaped and triangular plasmas. Detailed comparisons between theory and experiment for positional instabilities in a variety of shapes were made. The investigations also demonstrated the failure of shaping to significantly decrease the MHD activity on a tokamak. Limiting β investigations both ohmically and using powerful electron cyclotron resonant heating have shown that the critical β is proportional to the plasma current, and reaches values very close to the predicted theoretical limits. A variety of studies have been made on MHD instabilities and attempts to control them using small resonant helical fields. Basic investigations into the influence of fluctuations on confinement have been made by a variety of techniques.

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Introduction

The TOSCA device (an acronym for Toroidal Shaping and Compression Assembly) first came into operation in 1974. It is a modest tokamak which was proposed originally to study the high β potential of tokamak geometry. It was built specifically to investigate:-

(1) predictions that the use of a non-circular plasma cross section will permit operation at much reduced values of the safety factor q leading to increased values of β,
(2) the limiting value of poloidal β in a tokamak with a circular plasma cross section compared with theory,
(3) the influence of limiters on stability and confinement by isolating the plasma from them and the walls in a controlled fashion by compression and by using a magnetic aperture.

These investigations were considered particularly important since for an economic reactor, values of total β in the region of 10% are required compared with values of much less than 1% obtained in tokamaks at that time. To study these problems the device contained two novel features: additional heating by adiabatic compression in minor radius, and the facility to change the shape of the plasma cross section in a controlled manner.

The first objective of the TOSCA device was to investigate the theoretical predictions that stable operation with the safety factor $q(o) < 1$, should be possible by changing the shape of the plasma from circular to a horizontal ellipse but with a substantial triangular component pointing inwards. Elliptical plasmas were also to be investigated. The third objective is just as relevant today as it was then.

At the time the device was a significant departure from other tokamaks. It is air-cored with a thin stainless steel bellows liner and no conducting shell.[1] The vacuum vessel time constant is short, 7 μs. The toroidal field coils consist of single turn conductors to provide rapidly varying toroidal fields. The major and minor radii are 30 and 10 cm, values similar to the well known Russian TM3 device. Values of longitudinal field of $\lesssim$ 1T, and plasma current $\lesssim$ 25 kA which are sustained for $\lesssim$ 10 msecs have been obtained on the device. Plasma parameters are typically:- central temperature $\sim$ 300 eV, density $0.4 \rightarrow 4 \times 10^{19} m^{-3}$ and confinement time $0.1 \rightarrow 1$ ms. Good tokamak operation was established and this clearly demonstrated that satisfactory tokamak behaviour could be obtained without the necessity for a thick vacuum vessel or a conducting wall.

The machine has operated reliably and reproduceably throughout its working life and the thin vacuum vessels have survived about a quarter of a million tokamak discharges. It is one of the smallest tokamaks currently in operation. It has piloted a number of important areas in tokamak physics as well as investigating a whole variety of basic phenomena. It has acted as a training ground for many key workers on tokamaks throughout the fusion community.

Compression

Compression experiments were conducted with a toroidal field increase of up to a factor of 2 in 150 μs. [2] The plasma current decreased as expected from flux conservation and the plasma displacement outwards associated with the compression increased substantially when the compression ratio reached 2, in close accord with theoretical predictions. The reduction in current as a function of compression ratio verified that the poloidal flux and toroidal flux conservation held during the compression. The initial increase in loop voltage was found to be in accord with the conservation of longitudinal flux. Edge Langmuir probes showed a marked reduction in the electron density near the wall indicating significant detachment of the plasma associated with the minor radius compression. The change in line average density was close to that expected for an adiabatic compression. In all cases the compression did not affect the gross stability as indicated by density or field fluctuations and the loop voltage fluctuations were reduced. The results were similar to those obtained on the Tuman 2 device [3].

Minor radius adiabatic compression increases poloidal β but not toroidal β however the observed gain in poloidal β was greater than adiabatic and the total β value increased. Given the tight aspect ratio of TOSCA it was recognised that a combined compression in both minor and major radius could lead to further improvement in the plasma parameters [4]. Central β values as high as 3% were measured when a small major radius compression was superimposed on a minor radius compression [8]. Numerical code predictions of minor radius compression indicated that for anomalous electron thermal conductivity, the temperature scaling would be faster than that predicted for an adiabatic compression. This rise was attributed to detachment of the column and improved ohmic heating. In many of these experiments and those on Tuman 2, $\tau_E \lesssim \tau_{compression}$ but nevertheless significant current contraction and change in the plasma parameters was observed. All the experiments showed a clear improvement in the energy confinement time associated with the compression. The magnetic field fluctuations inside the vacuum vessel decreased by up to a factor of 5 for even quite small compressions. The magnetic field fluctuations due to tearing mode activity apparently moving in the electron diamagnetic drift direction, increased in frequency with compression. This was interpreted as a change in the diamagnetic drift frequency due to heating or as a change in the radial electric field. From probe measurements it was concluded that this reduction was not due to motion of the active region away from the coils but was ascribed to an improvement in the stability associated with a change in plasma current distribution.

The additional energy gains associated with minor radius compression are consistent with the reduction of thermal conduction losses. Additional ohmic heating power is then available to heat the plasma. Experiments with a gettered vacuum vessel wall confirmed that radiation and charge exchange do not play a dominant role in the process. The importance of the wall detachment is emphasised by experiments with a separatrix contained plasma [9]. If the initial energy confinement time is longer than the compression time then only the expected adiabatic increase in plasma energy content is observed, which is consistent with a model in which the conduction to walls is the dominant loss in the pre-compressed phase [8]. Present and past tokamak empirical scaling laws cannot explain the improved confinement.

The positive results obtained from small minor radius compression experiments, particularly the increase in energy confinement time and the rise in electron temperature being greater than that expected adiabatically, led to the construction of TUMAN 3. However it was recognised that power requirements for large devices where compression times should be comparable to τ_E are prohibitive unless compression is successful in reaching ignition conditions in which case some re-expansion of the plasma could be used to recover some of the compression power [4].

Shaping

Results on shaping experiments with non-circular cross-sections using elliptical plasmas with elongations between 0.75 and 1.5 were reported in 1976 [5]. The first studies were concerned with axisymmetric modes and comparisons with theoretical predictions. Full aperture plasmas which were stable for values of b/a of ~ 1.5 were obtained if the primary winding was used as a passive feedback system. This value is in agreement with stability calculations taking into account the currents induced in the windings by the shaped plasma. Equilibrium calculations also demonstrated plasma formation with a magnetic aperture. When the shaping current was increased up to some 10% of the plasma current, the growth time for the axisymmetric instability decreased to less than 50 μs, a value which is in close accord with that expected theoretically given the vacuum vessel time constant of 7 μs.

Marginal stability points for different combinations of passive feedback windings were demonstrated and also for different plasma apertures by using a limiter to restrict the size of the elliptical plasmas.

The stability and confinement properties of elliptic plasmas were investigated [6,7]. It was concluded that the observed tearing mode activity was unaffected by the shaping. From the onset of the m=4 mode it was possible to deduce the elongation for both vertically and horizontally elongated ellipses. Diamagnetic loop measurements showed that there was an increase in β poloidal with a vertically elongated cross-section. It was suggested that the improved confinement with a vertically elongated ellipse could be as a result of change in the current density or contact.

In 1977 the multipole moment method was used on the TOSCA device for determining the plasma position and the plasma shape [14]. Modified Rogowski saddle coils were used to determine the line integrals of poloidal field and then toroidal multipole moments of the plasma current density could be derived. This technique was used with plasmas of triangular cross section. Positional instabilities in triangular plasmas were also investigated [17,18].

Results from shaping the plasma cross section into triangular and D-shaped forms were presented [9]. By this means it was possible to obtain central values of β of $\sim$ 3%. Again it was found that axisymmetric instabilities limited the maximum distortion. The confinement time was found to increase when the plasma edge was defined by a separatrix for a triangular or elliptical plasma. Contrary to the ideal MHD theoretical predictions, sawtooth behaviour and m=1 oscillations observed on the soft X-ray detectors in triangularly distorted plasmas was similar to those observed in circular plasmas. Detailed observations showed that the m=1, n=1 instability was still present even when the conditions for ideal MHD stability were satisfied by more than a factor of 10. However, resistive calculations suggest that the m=1, n=1 instability may indeed occur and is not influenced strongly by the shaping, except possibly at high conductivity temperatures.

In these triangular plasmas the behaviour of the plasma edge density was monitored and it was shown that as the hexapole field increased so the edge density reduced sharply and the density gradient became much steeper, with the edge of the plasma corresponding closely to that calculated from free boundary equilibrium calculations. Once the plasma was detached from the limiter and vacuum vessel walls significant improvement in the poloidal β was observed (up to 75%) and this result was independent of whether the vacuum vessel was gettered or not. The increase in poloidal β and energy confinement time would not be expected to follow from a reduction in area which occurred in this type of experiment. It was also verified from bolometer measurements that the improved confinement was not due to a change in the radiation balance. This early observation of improved confinement with high shear and detachment of the plasma column is reminiscent of the H-mode, later observed with additional heating in larger separatrix-controlled devices [10]. It was possible to operate the triangular plasmas with q values down to 2 with mode activity dominated by the sawtooth behaviour. In this way it was possible to achieve discharges with average values of $\beta > 1\%$. Decompression of these triangular plasmas resulted in even higher values of β without disruption, approaching 2%. Such values are very close to the maximum value possible before the onset of ballooning modes occurs and are very similar to those given by the Troyon limit [11].

Magnetic islands and disruptions

Investigations were made on the TOSCA device [12] using magnetic probes, internal coils, and soft X-rays, of magnetic activity. The magnetic probe inserted into the plasma showed that the perturbed radial field signal does not change sign at the singular surface, indicating resistive mode activity. These observations revealed the presence of tearing modes with mode numbers, m, of 4, 3, 2 and toroidal numbers equal to 1. Typically the modes grow and rotate and saturate at levels of $\tilde{B}_r/B_\theta$ of about 3% which gives rise to magnetic islands with widths of about 1.5cm for m=3. The detailed form of the radial field and poloidal field perturbations is accurately predicted by a cylindrical initial value calculation for the instablities using the measured current distribution, saturation level and magnetic Reynolds number. If the m=3 mode exceeds the 3% level a minor disruption results. An m=2 mode can reach as high a level as 6% before giving rise to a major disruption. In these experiments high frequency fluctuations between 100-400 kHz with $\tilde{B}_r/B_\theta \sim 0.1\%$ were observed superimposed on the low frequency oscillations. These appear to have a cross field correlation length of about 1 cm. They appear to be rather too small to explain the observed confinement. It was also noted in these experiments that the mode structure and disruption was uncorrelated with any contact with the limiter.

During 1978 and 1979 several studies of sawtooth oscillations were made in the TOSCA tokamak [13]. Typically the period was 100-200 μs and the q=1 surface at a radius of 1-1.5 cm. By comparing results of this tokamak with those of larger devices an empirical scaling law for the repetition time was obtained and it was demonstrated that the scaling law was compatible with ohmic heating and a resistive instability whose growth rate is dependent on decreasing q below unity.

Instability control

Following on from the work on the Pulsator device [15,16] a variety of experiments have been conducted using external saddle coils to generate helical perturbations. Experiments with an external m=1,n=1 coil showed that sawtooth oscillations could be suppressed when the current in the coil exceeded about 1.5kA [17] with a plasma current of 15 kA. The suppression of the sawtooth oscillation occurred with a delay of 500 μs corresponding to the field penetration time.

The m=1 coil was also observed to produce a stabilizing effect on the m=2, n=1 mode. This may be due to a side-band produced by the m=1 coil at the q=2 surface. An m=2, n=1 coil was also used on TOSCA and its position was corrected for the aspect ratio of the torus. The main effect of the coil was to stabilize the 2,1 mode [17]. Stabilization made it possible to operate at q values $\lesssim$ 2. If the 2,1 coil current was raised to large values then a major disruption was induced.

Some theories of the major disruption [20] indicate that it could be due to the destruction of magnetic surfaces by the interaction of magnetic islands of different helicity. An m=3, n=2 coil was constructed on the TOSCA device to produce an island which could interact with the 2,1 island. This coil was also used to detect the 3,2 mode. A clear growth of this mode was observed before disruption on the TOSCA device when the 2,1 amplitude reached a critical value [21]. Other modes were detected and are involved in the disruptive process, for example 5,3 and 8,3. The 3,2 mode was also observed when internal disruption occurs, particularly when operating at low q. The amplitude of the 2,1 mode at the rational surface, shortly before disruption, is calculated to be about 4% and the 3/2 mode amplitude about 4.5% (depending on the plasma response [24]) before a major disruption. The associated islands are close to overlapping. When the 2,1 and 3,2 coils were energised simultaneously at this amplitude then the probability of a disruption rises to 100%. It was also demonstrated that the 2,1 and 3,2 modes were observed before major disruptions on triangular and elliptical plasmas. The observations clearly show that these disruptions involve the internal interaction of modes of different helicity.

A flexible arrangement of saddle loops has been used on TOSCA to make variations in the harmonic structure of the fields. The broad spectrum of sidebands from the coils may produce properties similar to those of an ergodic magnetic limiter. Surprisingly quite large perturbations (several %) do not reduce the global energy confinement time but there is an influence on recycling and the pressure profile. A linear model has been used to calculate the effect of plasma response on island formation, [24] and depending on the current profile this may give a substantial reduction or enhancement in island size, as compared with vacuum fields.

The influence of resonant helical fields on tokamak confinement has been investigated in some detail [25]. Large applied m=2, n=1 fields stop the m=2, n=1 oscillations and reduce the amplitude of the broad band radial field perturbations. The size of the imposed magnetic island depends on the response of the plasma and measurements indicate that there is an enhancement of the applied field. The theoretical predictions depend critically on details of the current profile and with the inclusion of finite conductivity the results suggest that the current profile is near marginal stability for the 2,1 tearing mode. The magnetic power spectrum has been measured as a function of both radius and density and it is found that the global energy confinement time appears to be independent of the radial field fluctuations. The level inside the plasma is $\sim 10^{-4}$ of the toroidal field and there is no significant variation as the density and energy confinement time are varied by about a factor of 3. The radial field fluctuations increase as the radius decreases. Estimates of χ_e from the fluctuating fields are typically a factor of 10 lower than those required to explain the energy confinement time. The observed τ_E is a good fit to $\tau_E \sim 7 \times 10^{-22}$ $n\, a\, R^2\, q^{\frac{1}{2}}$ [32].

Critical β Experiments on TOSCA(ohmic)

Tokamak empirical scaling laws for an ohmically heated device show that maximum β is obtained in a small aspect ratio device with small major radius. The maximum central value of β obtained by a combination of gettering, gas puffing and shaping on TOSCA is about 5% which is very close to the maximum theoretical value for the onset of ideal MHD ballooning modes [19]. Using gas puffing together with feedback control of the plasma position and decompression of the plasma resulted in the highest values of $\langle\beta\rangle \sim 2\%$. Attempts to obtain high β at $q < 2$ showed that in low density plasmas using gettering it was possible to obtain current distributions which were sufficiently broad to sustain plasmas for times of several energy confinement times without a conducting shell, and the average value of $\beta \sim 1.5\%$

Attempts to look for ballooning modes were made on TOSCA. A number of coil systems were used to detect modes with m=8,n=4; m=8,n=3; m=5,n=3. Although such mode activity was detected at quite high frequencies (100-200 kHz compared with the 2,1 mode frequency of 35 kHz) the estimated amplitude in the plasma was less than 0.1% of the poloidal field and no significant correlation was found with the value of β. The internal soft X-ray activity was unchanged at high values of β so that with optimised ohmic heating there was no evidence for a change in the mode activity at central values of β as high as 5%.

As low values of q could be obtained without a conducting shell a number of instability growth rate calculations were made by flattening the current distribution in the region of both the q = 2 and 3/2 surfaces [23]. It was possible to obtain completely stable current distributions for $q \geq 2$. It was also possible to obtain stable current distributions with $q \sim 1.6$ providing a conducting wall was situated within 1.4 plasma radii. However the vacuum vessel on TOSCA only has a time constant of < 7 μs for helical fields and so cannot act as a shell. It seems likely that the plasma motion or rotation makes the vacuum vessel act as a wall. This is possible for the m=2 modes if the frequency exceeds 25 kHz which is observed to be the case. It was concluded that the vacuum vessel probably has a stabilizing effect on these low q discharges.

Density and temperature fluctuations

Edge fluctuations have been investigated with several types of Langmuir probes, so that not only can density and temperature be measured but also the local flux of particles together with magnetic field fluctuations. The results have also been compared with CO_2 scattering experiments [26]. Floating potential measurements show that the m=2 tearing mode appears very strongly on the frequency spectrum, even though the probe is well outside the q=3 surface. The phase spectrum of the floating potential and density fluctuations from scattering show, for frequencies of 0-150 kHz, a phase velocity of around 3×10^5 cms^{-1} in the electron diamagnetic drift direction. For radii greater than the limiter radius this direction is reversed. The diffusion flux was investigated by concentrating the loss into the region of the probe by making the plasma elliptical in cross section. The diffusion co-efficient obtained from these measurements, both in the low and high frequency components is $\sim 10^5$ $cm^2 s^{-1}$ [22].

Experiments with biased limiters, variable aperture limiter arrays and novel split limiters show no clear influence on edge fluctuation levels [37]. Temperature fluctuations have been investigated by analysing double Langmuir probe current fluctuations. At frequencies greater than those of gross MHD instabilities, the temperature fluctuations are found to be much smaller than the density fluctuations. The dependence of global confinement time on the density fluctuations was investigated both with edge probes and laser scattering. However, only a weak dependence on the fluctuation levels was observed. Top to bottom asymmetry in the fluctuations is also observed on both the scattering and probe measurements. Quite large coherent oscillations in floating potential are observed on the limiters, ($\delta V_f \sim 3\ T_e$(limiter)) during large amplitude MHD activity.

Oscillations induced on the profile of a gaussian, CO_2, laser beam transmitted through the TOSCA plasma are confined within envelopes which are predicted by theory and which permit plasma fluctuation intensities and wavelengths to be deduced as functions of frequency [26]. The fluctuations are found to be mainly transverse to the magnetic field with the intensity maximum between 40 and 100 kHz and the density fluctuation decrease as $\tilde{n}(f) \propto f^{-2}$. The fluctuation level is a few %, and coherent oscillations are observed which are well correlated with rotating MHD structures. $\kappa_\perp \rho_s \sim 0.3$ and the phase velocities are observed to be similar to those observed with probes. Little change in the fluctuations is observed with intense electron cyclotron resonance heating.

Electron cyclotron resonant heating

In 1980 investigations [22] began on using electron cyclotron resonance heating and exploiting its potential for current profile control. Fast feedback control (40 μs) was used to assist in the ECRH experiments. These were conducted at 28 GHz with power levels ranging up to 150 kW at the second harmonic with pulse lengths up to 4 ms both in circular and elliptical plasmas. Substantial decreases in loop voltage, (~ 1.5V) could be obtained and distortions in the electron distribution function were observed. In general there was a decrease in the line average density. Bulk heating was observed below the cut-off density of $5 \times 10^{12} cm^{-3}$ but even some way above.

Interest in using the second harmonic stems from the very strong absorption which occurs in the extraordinary mode at this harmonic (six times higher than for any other mode) and the fact that it allows much higher β plasmas to be produced consistent with accessibility. Even in low temperature initial target plasmas very strong absorption is predicted to occur if wall reflections are taken into account [29]. Soft X-ray emission measurements show strong local heating close to the cyclotron resonance [27,28,30]. This may occur at central densities even above the X mode cut-off and the local rise in soft X-ray emission on the outer flux surfaces is associated with the build-up in the population of trapped electrons. Attempts to detect a wave-driven current using a variable angled antenna indicate that the current drive is ~ 20 A/kW dependent upon resonance position. There is a strong decrease in current when the resonance is on the outer flux surfaces where the trapped electrons are present. Second harmonic preionisation experiments were also performed [30] using the 28 GHz radiation and this reduced the initial applied voltage substantially (eg 20→5V) and the volt-second consumption. A particular result of preionisation at power levels of typically 20-40 kW was the very marked reduction in the electron cyclotron emission signal at 33 GHz. The most effective preionisation system used on TOSCA was an 18 GHz source producing up to 700 W at the fundamental.

Very strong heating was observed giving $\Delta\beta_p \sim 4$ [31]. The efficiency of heating was deduced to be very high (50 - 100%). High diamagnetic temperatures were obtained ~ 1-2 keV and the loop voltage decreased to ~ 0.15 volts corresponding to a Spitzer conductivity temperature in the region of 1 keV. The energy content decayed after heating approximately in an energy confinement time. Efficient heating could still be maintained for line average densities up to about $2.5 \times 10^{18} m^{-3}$ but then the efficiency decreased. The distribution of soft X-ray emission is sensitive to the position of the resonance zone producing peaked distributions on axis and broad distributions with an off-axis resonance, particularly on the inside of the plasma. The plasma energy content does not increase linearly at the highest powers and some form of saturation is present. No significant increase in impurity radiation or recycling was observed associated with the strong electron cyclotron resonance heating.

The attainable value of poloidal β is found to decrease as the current increases, [31] (as I^{-1}) and thus the average value of β is found to scale linearly as plasma current. [35] This observation, Fig 1, is in close correspondence with that obtained in other additionally heated tokamaks at high densities [32]. Since the ECR heating produces $\beta_\perp/\beta_\parallel > 1$ then ballooning modes are more unstable with the resonance in the bad curvature region though the two component electron energy distribution may enhance the stability. In many of these plasmas the poloidal β value is comparable to the aspect ratio $R/a_p \sim 5$. No sawtooth activity was observed and at the maximum β achieved no disruptions occur. When the plasma current is increased to about 9 kA an m=2 mode was observed to appear during the heating pulse. Significant heating with the resonance on the outside (r = +1.1 cms) would lead to small disruptions. These plasmas at high poloidal β come close to challenging optimised β limits but significant pressure anisotropy is present [33] and this affects the stability limits. The heating efficiency was explored by examining in detail the time

dependent behaviour of the diamagnetic loop signal [34].
The confinement time falls at high β_p, or the absorbed power is not proportional to injected power.

During strong electron cyclotron resonance heating on the TOSCA device when the value of poloidal β is large and the β limit close to that expected for a tokamak device there is an increase in the amplitude of radial magnetic field fluctuations (100-300 kHz) and the amplitude reaches a level of about 0.2% [35]. These fluctuations are composed of a broad frequency spectrum with specific features superimposed associated with low number mode activity. The enhanced activity has a substantial ballooning nature. The rise in activity is related to the resonance position but most of the activity is found to have relatively low toroidal mode number (< 3).

Measurements of the vertical field required for plasma equilibrium when combined with the measurement of plasma diamagnetism show that the electron pressure at lower densities can become strongly anisotropic with $\beta_\perp/\beta_\parallel > 1$ [33]. It is likely that the enhanced confinement may not be purely related to the anisotropy but to the distortion in the electron distribution function as both the two effects are marked at low densities.

Free boundary equilibrium calculations have been made to model the TOSCA plasma at very high values of poloidal beta and these reveal a significant error in the use of the equilibrium vertical field to deduce $\beta_p + \ell_i/2$ [36]. The multipole moments of the current distribution were shown to provide information on the current profile. The accuracy of the simple cylindrical formula for deducing the poloidal β from the diamagnetic flux was good.

Conclusions

A wide range of pioneering compression, shaping, ECRH, β limit and basic studies including investigations into the effect of instabilities, fluctuations and disruptions on tokamak confinement have been pursued on the TOSCA device. Many of these investigations have been conducted in collaboration with universities.

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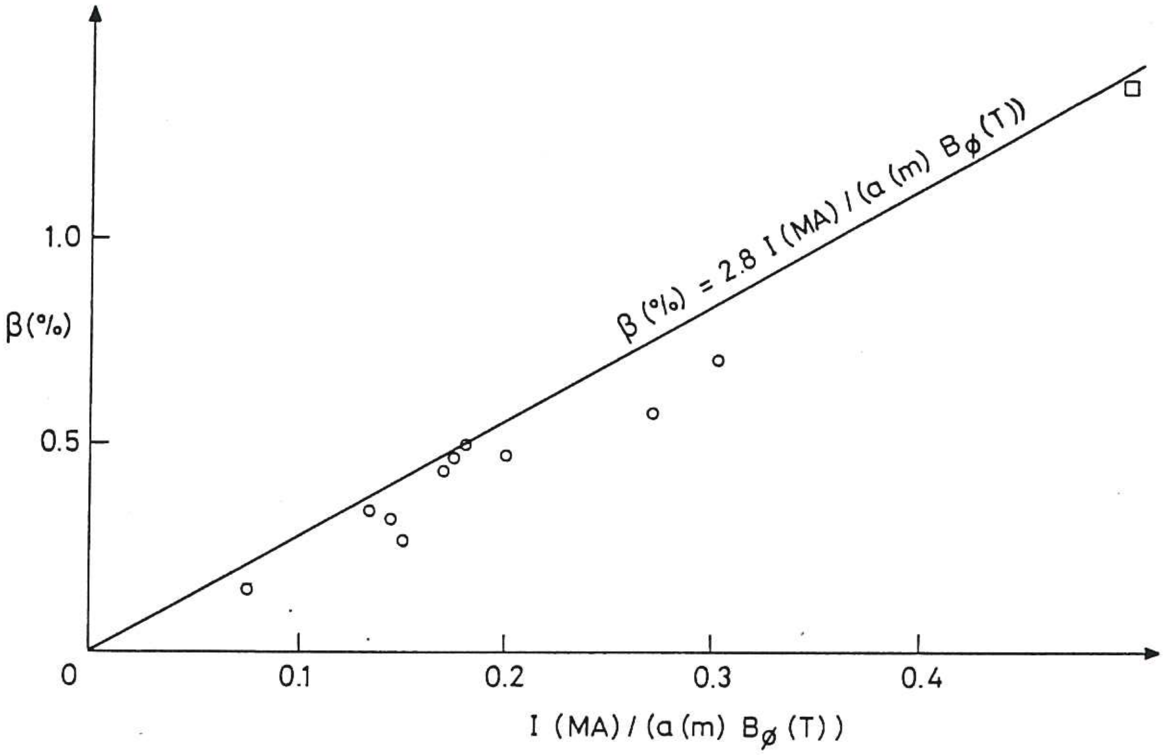

Fig. 1 Average β-value as a function of $I/(aB_{\phi})$ for ECRH on TOSCA. The theoretical limit β_C (%)=2.8I(MA)/(a(m)B_{ϕ}(T)) is shown. The box point was obtained by decompressing an ohmically heated plasma, thus obtaining a higher value of $I/(aB_{\phi})$.

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