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In magnetically confined fusion plasma science, the tokamak – a toroidal plasma confining device - has the potential to provide confinement sufficiently high to sustain thermonuclear fusion reactions. As such, the tokamak may be the basis for electricity production based on the fusion of the isotopes of hydrogen. However, in the standard tokamak configuration (see Figure 1b), in order to achieve sufficiently high energy-confinement the edge plasma pressure must be very high. As a result, the edge pressure gradient is also large, and this leads to instability that repetitively ejects particles and energy, which can potentially damage the plasma facing wall in a fusion reactor [1]. There may be a very simple solution to the problem. By inverting the geometry of the magnetic configuration, going from (b) to (a) in Figure 1, we change triangularity (δ) from positive to negative and in so doing the energy confinement time typically doubles; a discovery made on the TCV tokamak. At the same time, the edge pressure gradient remains sufficiently low that the instabilities, mentioned above, become much smaller or do not appear at all [2]. This article, very briefly, describes the work, performed on the Tokamak à Configuration Variable (TCV) at the Ecole Polytechnique Fédérale de Lausanne, in the field of negative triangularity tokamak. Some attempt will be made to put TCV's results in relation to observations on other machines and in the context of a reactor device.

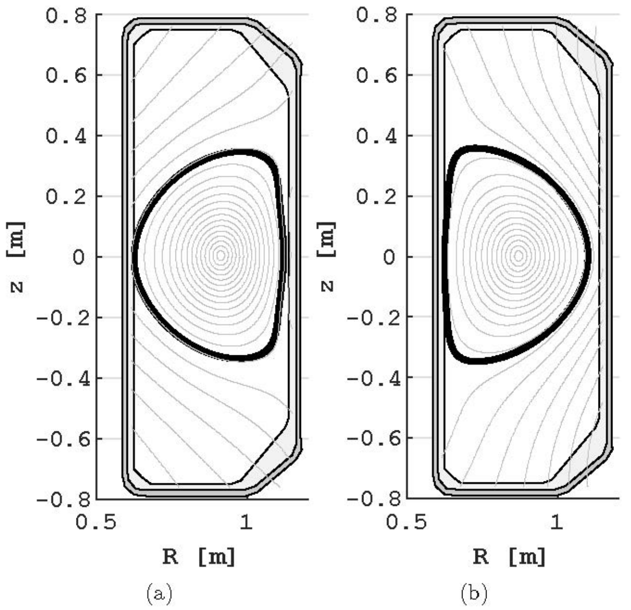

Figure 1: Two cross-sections of TCV, torus axis on the left, showing the plasma inside the TCV vacuum vessel, for two similar discharges, (a) has negative triangularity while (b) exhibits positive triangularity – the standard plasma shape in tokamaks. Apart from this difference in geometry, the discharges are very similar in terms of plasma current, vertical elongation, density etc.

TCV was conceived as a machine for testing the effect of plasma shape on energy/particle confinement and on plasma stability. As such it was endowed with many independently controlled shaping coils allowing for a myriad of exotically shaped plasmas to be created in the device – most of them having never been explored. In addition to this shaping flexibility, TCV has electron and ion heating capabilities that allow the study of transport in different regimes of plasma collisionality and ratio of electron to ion temperature T_e / T_i. These two parameters are decisive in determining the type of unstable modes and growth rate underlying turbulence, therefore, the amount of heat and particles that the plasma loses by transport.

TCV has much greater plasma shaping capability than any other existing machine. Making use of this advantage, a great deal of effort has gone into characterising the effects of triangularity, which has been found to play an important role in plasma confinement and in plasma stability [3, 4, 5]. It may, in principle, be used to actively control both confinement and stability.

The work of Moret [3], finding confinement increasing by diminishing δ in the positive triangularity range, could be prolonged to negative triangularity with stable discharges in additional heating conditions by Pochelon [6]. With his student Camenen [7], they studied the effect of triangularity on transport, comparing positive and negative δ. They, in turn, stimulated more recent work concentrating on the effect of triangularity on turbulence: the main drive for energy loss in magnetically confined fusion plasmas. Turbulence measurements culminated in the work of De Meijere [8], Huang [9] and Fontana [10]. At the same time Sauter [11] and Merle [12] studied the edge plasma properties showing, clearly, its important role. In parallel with the experiments a significant

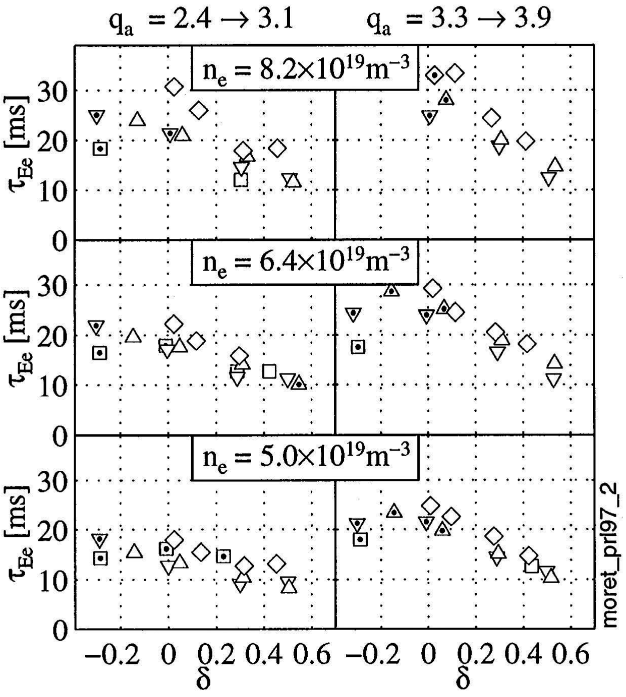

Figure 2: For various values of electron density and q_a, energy confinement time is seen to increase as delta decreases in the positive delta range. q_a is proportional to plasma current and is linked to stability of the plasma.

effort has been made to model these discharges on a microscopic, turbulence scale using fully electromagnetic, fluid and kinetic codes. The simulations are at least in qualitative agreement with experimental findings [13, 14].

Moret [3] first observed an improvement of confinement towards small positive triangularity with less clear behaviour at negative triangularity, see Figure 2, and ascribed the improvement to purely geometric effects. Pochelon [6] pursued these studies with electron cyclotron resonance heating (ECRH), enabling more stable discharges.

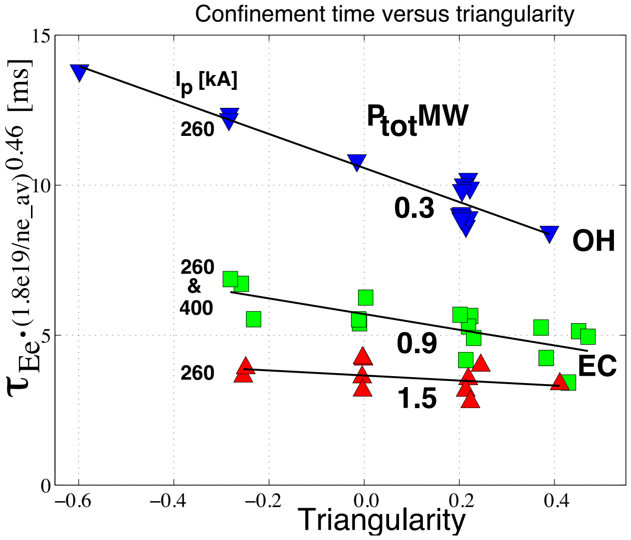

Figure 3: Linear increase in confinement extending to the negative triangularity range at low density, in Ohmic and with ECR heating.

These experiments revealed for the first time a clear continuous improvement of confinement time far in the negative triangularity range down to δ = -0.6 [6], as shown in Figure 3. This showed how existing scaling laws were improved by decreasing triangularity δ. The negative triangularity results indicated also that there was a more fundamental confinement improvement, beyond purely geometrical effects.

Camenen [7] completed a thorough and exhaustive study of the effect of triangularity on heat transport using modulated ECRH power. He produced the, now famous, figure relating electron thermal diffusivity (χ_e), effective collisionality (υ_{eff}) and δ. Figure 4 reproduces Camenen's figure, showing the factor of 2 decrease of the electron thermal diffusion coefficient over a large range of υ_{eff} between discharges at $\delta \approx +0.4$ and $\delta \approx -0.4$ with the improvement diminishing at high υ_{eff}. The reduction of the relative superiority of negative δ discharges at high collisionalty may explain the relatively weak effect at negative δ seen by Moret.

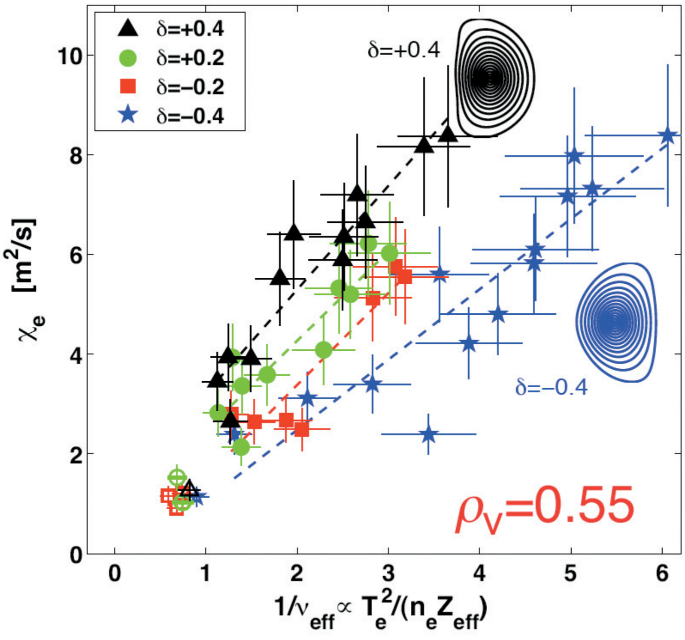

Figure 4: Decrease in the experimental χ_e with decreasing δ in ECR heated plasmas.

Camenen's work was performed in conditions where $T_e >> T_i$ and a specific type of plasma instabilty, the trapped electron mode (TEM), was the dominant unstable mode and driver of transport. Marinoni [13] modelled these discharges using both linear and non-linear local gyrokinetic simulations using state of the art modelling tools [15]. He was able to reproduce the trend of diminishing χ_e as δ decreased. The physical mechanism for the confinement improvement was postulated to be a complex interplay between particle motion in the non-homogeneous magnetic field of a tokamak that leads to particles being trapped in magnetic wells or being free to propagate along the field lines. The change in the curvature introduced by negative δ modifies the toroidal precession drift of the trapped particles. As the TEM is intrinsically linked to the resonance with the toroidal precession drift, this modification affects the radial transport.

So, it had been shown that, over a wide range of υ_{eff} , by inverting the triangularity, the energy confinement was improved by up to a factor 2 when $T_e >> T_i$ and when a particular type of instability was driving plasma turbulence and diffusion of energy. Theory had been able to, at least qualitatively, offer some explanation for the improvement of energy confinement at reduced or negative triangularity.

It is assumed that plasma turbulence drives energy and particle diffusion, since transport in tokamaks is at least an order of magnitude higher than calculated from particule trajectories and collisions, so-called neoclassical transport.

Further, in a fusion reactor it is necessary that $T_i \approx T_e$. In this circumstance different plasma instabilities are excited and the transport properties of plasma change. It is not obvious

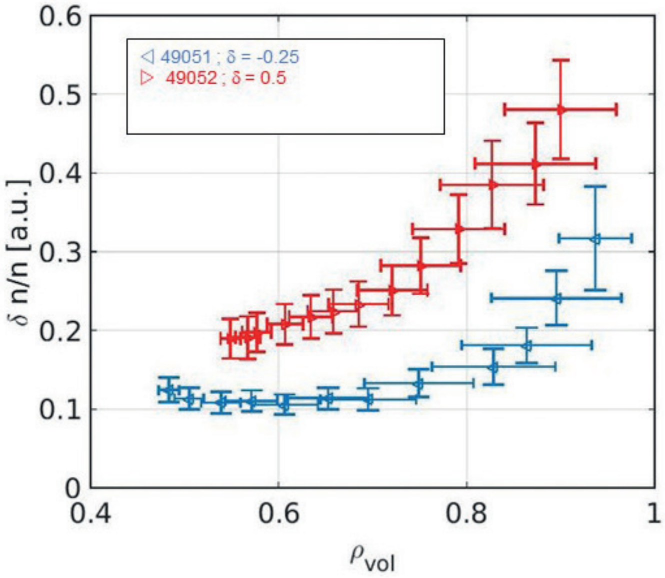

Figure 5: Relative density fluctuation amplitude $\tilde{n}/n$ as a function of radial position in a δ = 0.5 (blue) and a δ = −0.25 (red) TCV discharge; both discharges have 0.45 MW EC heating at the plasma center (ρ_{vol} = 0: plasma center, ρ_{vol} = 1: plasma edge).

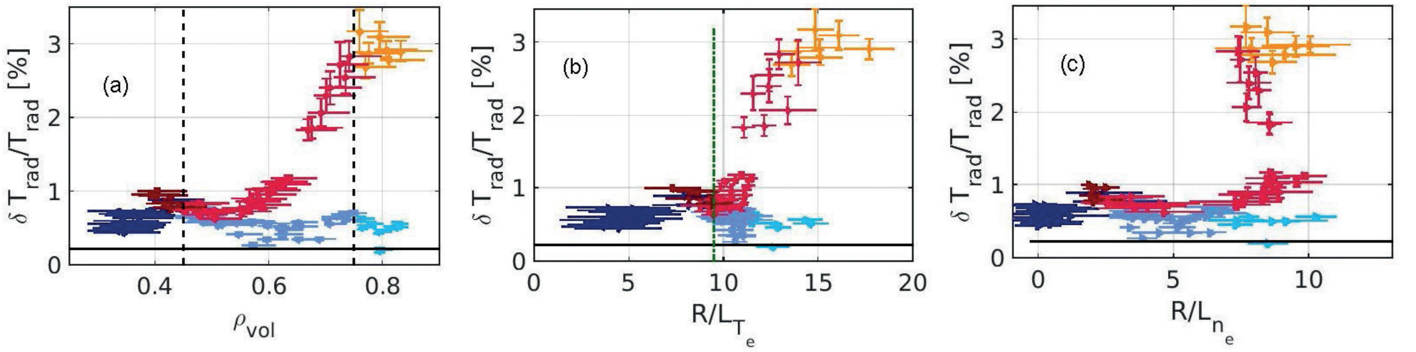

Figure 6: a) Radial profiles of relative radiative temperature fluctuations amplitude for different triangularity values. (red/yellow δ ≈ 0.5: blue δ ≈ -0.4) The fluctuations amplitude is reduced changing shape from positive to negative triangularity and the effects extend up to ρ_{vol} = 0.5. The same data are plotted against the normalized inverse temperature (b) and density (c) scale lengths. Notice that these data points combine measurements taken over a wide fraction of the radius.

that negative δ will maintain its advantage in reactor relevant conditions.

These two observations lead immediately to two questions concerning negative δ:

(i) Is there a connection between the improved confinement at negative δ and the measured turbulence?
(ii) Does the improvement of energy confinement at negative δ persist when $T_i \approx T_e$?

Huang [9] and Fontana [10] addressed these two questions experimentally making very detailed measurements over a wide range of plasma conditions allowing a large database to be constructed.

Figure 5 shows the reduction in relative density fluctuation amplitude across a large section of the plasma minor radius in discharges that are similar apart from δ [9]. In Figure 6 are plotted profiles of $\widetilde{T_{rad}}/T_{rad}$ plotted against normalised radius (a), and normalised density- (b) and temperature- (c) -scale lengths. Red/yellow is for positive δ while blue is negative δ. So we see a clear reduction of both density and temperature fluctuations across a substantial portion of the plasma radius in negative δ. At the same time there is the suggestion that in positive triangularity, there may be a critical gradient in either temperature or density above which the instability and fluctuations can grow [10]. There is no such critical gradient in the negative δ data; it may be that the critical gradient for the onset of instability is much higher in negative δ than in positive δ. Similar observations were made in the density fluctuation data [9]. Merlo [14], using the GENE code, was able to qualitatively reproduce these observations using local, non-linear simulations of theses discharges. He observed a global reduction of the growth rate of instability and a significant increase of the critical gradient for the onset of instability at negative δ compared to positive δ, and that the critical gradients increased even further the closer to the plasma edge. The reduction in fluctuation level going from postive to negative δ are consistent with the observed improvement in energy confinement in the same circumstance.

Fontana was able to extend the database to cases where $T_i \approx T_e$. He observed that the reduction in fluctuation level was preserved even at elevated T_i; this is to say in fusion relevant conditions.

It is clear that negative triangularity can improve confinement over a wide range of plasma conditions including conditions approaching reactor relevance. Why is confinement improving and where is confinement improved?

Sauter [11] has completed an extensive study of profile stiffness, which is the tendance of a magnetised plasma to resist temperature peaking in the presence of central heating. Sauter's work has shown that the core of a magnetised plasma exhibits stiff profiles meaning that the transport gradients of magnetised plasma remain similar irrespective of the plasma heating regime. Sauter's startling observation was that the confinement properties of tokamak discharges are governed by the plasma edge and it is the change to the edge profiles and transport characteristics induced by negative δ that drive the confinement improvement.

The confinement improvement localised to the plasma edge is, in fact, a phenomenon already observed in tokamak physics and is usually associated with high edge plasma pressure gradients as mentioned at the beginning of this article. In the case of high edge pressure the improved confinement is called H-mode (H for high) and is observed in both positive and negative δ. The question then is, in H-mode does negative δ display improved characteristics compared to positive δ? More to the point, are the instabilities, associated with H-mode, less harmful in negative δ

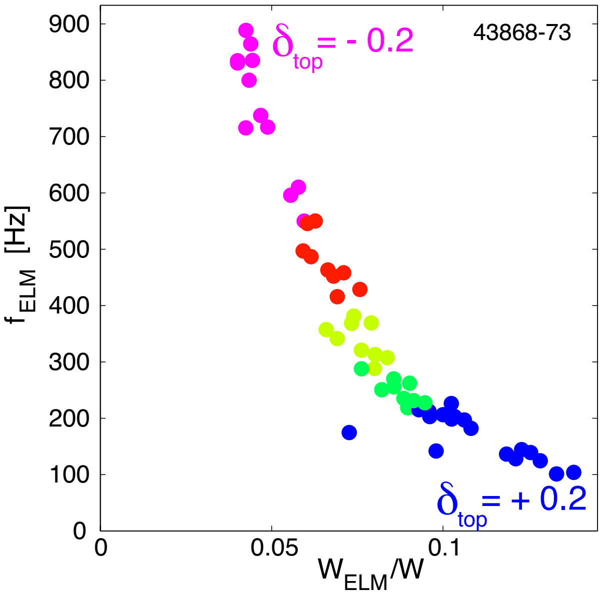

Figure 7: Plot of ELM frequency against energy loss per ELM. There is a clear reduction of the relative energy loss per ELM in negative δ associated to a frequency increase.

than in positive δ? Pochelon [2] was the first to study this issue. He showed that, for similar conditions, the frequency of the instabilities (Edge Localised Modes: ELMs) was increased and that the energy loss per ELM was significantly reduced in negative δ. The result is shown in Figure 7.

Merle [12] completed a theoretical study of the edge pressure in H-mode and, reassuringly, predicted that the edge pressure, and therefore the energy release per ELM, would be reduced by factor 4 in negative δ compared to positive δ. At the same time he stated that the reduced pressure made any large ELM event impossible.

Recent work performed at DIII-D, a conventional tokamak in America, showed that in negative triangularity it was possible to achieve high confinement and performance in discharges where in positive triangularity, the performance would have been a factor of 2 poorer (see Figure 8). This without degradation of energy confinement with additional heating power. It is a very significant result as it points to the possibility of creating high power, high confinement fusion plasma without the need for very high edge pressure and edge pressure gradient.

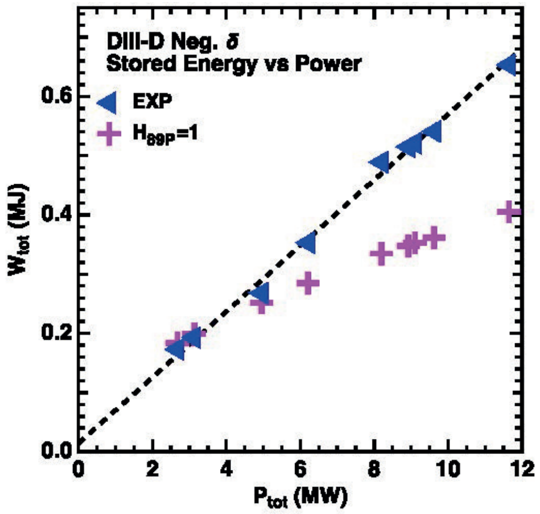

Figure 8: Confined thermal energy against additional heating power showing the absence of degradation with heating power. Confinement is comparable with H-mode confinement but with an L-mode edge (L for low confinement). The blue triangles represent the experimentally measured stored energy while the magenta crosses show the expected stored energy from empirical scaling laws with standard positive triangularity. Negative triangularity clearly exhibits superior confinement properties.

So we see that negative triangularity has some specific benefits for magnetic confinement fusion: high energy confinement with a low pressure and so with no ELMs.

Besides these important physics benefits, there are several potential engineering advantages to using negative triangularity. The part of the chamber wall which would be exposed to the most particle and energy flux, the so-called divertor can be placed at large major radius. Therefore its surface area is large, compared to positive triangularity, and the exhaust can in principle be deposited over larger surface (~2πR). At the same time the engineering problems associated with a low field side divertor as compared to a high field side divertor are much reduced. It is much easier to design a low field side divertor and the means to remove it and replace it when needed as compared to a high field side divertor.

It sounds as if negative triangularity is the long sought panacea for magnetic fusion: low edge pressure with, at the same time, high energy confinement and no edge instalibilities and reduced tendence to generate internal perturbations. There are, of course, many questions that remain to be answered and there may be drawbacks.

We know that it is difficult to control the vertical position of negative triangularity discharges in the vacuum vessel. In fact they are notoriously unstable [16]. To date it has proven extremely difficult to achieve high performance negative triangularity discharges with a divertor. In cases where diverted discharges have been produced, measurements show that the area over which energy is deposited on the divertor tiles is substantially reduced and may negate any advantage of having a divertor at larger major radius [17]. The design of magnetic coils for a negative triangularity machine may be very difficult and may require use of coils that will have a reduced lifetime as compared to a normal tokamak.

All of these issues are being addressed in Switzerland and all over Europe. Only time and extensive experimentation will tell if negative triangularity will lead to a robust solution for magnetic fusion. Switzerland is leading the way in these studies.

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