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Authors

Heidbrink, WW
Carolipio, EM
La Haye, RJ
[et al.](#)

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The weak effect of static, externally imposed, helical fields on fusion product confinement in the DIII-D tokamak

W.W. Heidbrink^a, E.M. Carolipio^a, R.J. La Haye^b, J.T. Scoville^b

^a University of California, Irvine

^b General Atomics, San Diego

California, United States of America

Abstract. Stationary helical fields with toroidal mode numbers $n = 1$ and $n = 3$ are applied to beam heated DIII-D plasmas. Measurements of the 14 MeV neutron emission monitor the confinement of the 1 MeV tritium fusion product. To within $\sim 15\%$ uncertainty, static magnetic fields with vacuum amplitudes of $\delta B/B \sim O(10^{-3})$ have no impact on fusion product confinement.

1. Introduction

Ordinarily, energetic ions in tokamaks are better confined than thermal ions but, in the presence of long wavelength MHD modes, their confinement may be degraded (Ref. [1] and references therein). Modes that resonate with the characteristic frequency of the fast ion motion have the strongest effect [1], but low frequency helical modes can also be detrimental [1–5]. A likely mechanism for this enhanced transport is the process known as ‘intrinsic orbit stochasticity’ [6, 7]: the $n = 0$ orbit shift caused by ∇B and curvature drifts couples to the helical motion caused by the helical field perturbations, resulting in drift islands in the particle’s phase space. If these drift islands overlap, the orbits become ergodic. A recent comparison [5] of the beam ion losses induced by large tearing modes in the DIII-D tokamak found good agreement with the predictions of intrinsic orbit stochasticity theory.

The application of external helical fields to control the accumulation of thermalized alpha ‘ash’ in a tokamak reactor has been proposed. The basic idea is to manipulate the transport of a class of particles (e.g., ~ 200 keV alphas) by inducing intrinsic orbit stochasticity, with a negligible effect on the thermalized bulk population. Initially, the use of static fields with controlled phasing was proposed [7, 8], but it was quickly realized that frequency modulation provides additional selectivity in phase space [9, 10]. A conceptually related idea is to employ waves to extract energy from the alpha population prior to thermalization (called ‘alpha channelling’) [11]. The work reported here is also relevant to the confinement of alpha particles in compact stellarators [12], since some high beta stellarators combine the features of

a tokamak with the external helical windings characteristic of a stellarator.

This is not the first study of the effect of perturbation fields on the confinement of energetic ions. Because the field coils are discrete, the toroidal field in a tokamak is periodically corrugated or ‘rippled’; the perturbation has a large toroidal mode number (typically $n = 16$ – 24) and a vertically symmetric poloidal perturbation (predominately $m = 1$). There have been numerous studies of the effect of toroidal field ripple on energetic ion confinement [1, 13–19]. Another extensively studied perturbation is the helical field that is resonant in the tokamak edge plasma (such as an $n = 2$, $m = 7$ perturbation (Ref. [20] and references therein)), although separate measurements of the effect on energetic ion confinement have not been reported. In stellarators, the effect of rotating, externally imposed, magnetic perturbations on ion confinement was studied in the Auburn torsatron [21]; the results were consistent with the predictions of intrinsic orbit stochasticity theory.

This article describes the first study of the effect of low- q , externally imposed, magnetic perturbations on the confinement of fusion products in a tokamak. Coils that are normally used to *cancel* field errors are operated with their polarity reversed to produce stationary $n = 1$ or $n = 3$ field perturbations. The confinement of 1 MeV tritons is monitored by measuring the ratio of 14 MeV neutrons to 2.5 MeV neutrons (the triton ‘burnup’). The external perturbations have little effect on the triton confinement at experimentally achievable amplitudes (Section 2). Tailoring the energetic particle population with stationary perturbations appears impractical in a tokamak (Section 3).

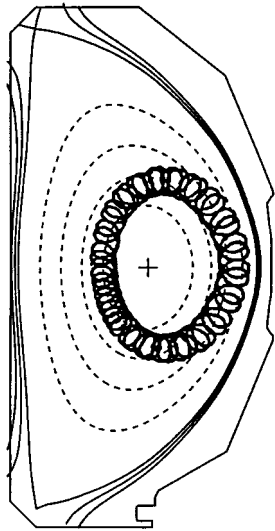


Figure 1. Elevation of DIII-D showing the flux surfaces for a typical discharge (82384) and the poloidal projection of the orbit of a centrally born, co-circulating, 1 MeV triton.

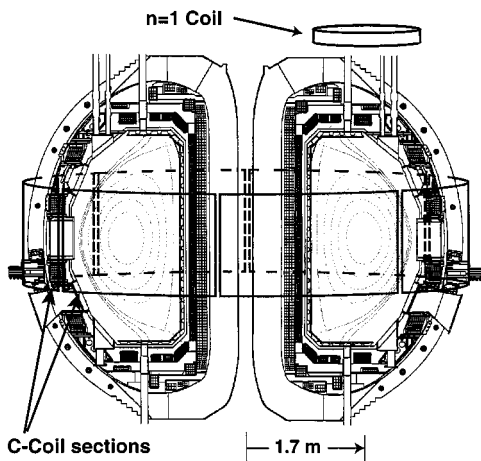


Figure 2. Illustration of the coils used to create helical magnetic fields.

2. Experimental results

The data in this article are from experiments conducted on the DIII-D tokamak [22]. DIII-D is a moderately sized tokamak with major radius $R_0 \approx 1.7$ m, minor radius $a \approx 0.6$ m and graphite walls. For these experiments, deuterium plasmas are heated by deuterium neutral beams in a double null divertor configuration (Fig. 1). The beams inject ~ 75 keV neutrals in the direction of the plasma current at tangency radii of 0.76 and 1.15 m.

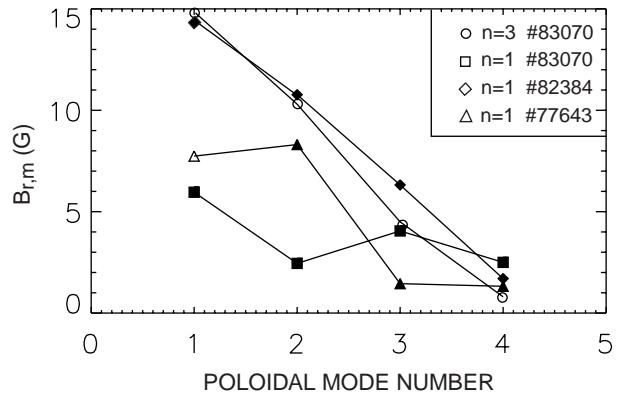


Figure 3. Fourier decomposition of the field perturbations for three typical discharges: predominately $n = 3$ perturbations produced by the C coil (discharge 83070), predominately $n = 1$ perturbations produced by the C coil (discharge 82384) and predominately $n = 1$ perturbations produced by the $n = 1$ coil (discharge 77643). The solid symbols represent harmonics that resonate with a rational q value in the plasma.

The field perturbations are produced by external coil sets that were designed to cancel intrinsic field errors. The ‘ $n = 1$ coil’ consists of a magnetic dipole placed above the machine (Fig. 2). The ‘C coil’ is actually six rectangular windings at the outer mid-plane.

The vacuum perturbations produced by the energized coils are calculated by a code that takes into account the measured field errors produced by the field shaping and toroidal field coils. The calculated vacuum field is then Fourier decomposed into toroidal and poloidal components. (The poloidal angle used as a co-ordinate is selected to give a ‘straight line’ field co-ordinate at the location of the $q = 2$ surface in a typical DIII-D double null divertor plasma.) Examples of the computed helical fields for several discharges in this study are shown in Fig. 3. The $m/n = 1/1$ and $2/1$ contributions generally predominate. On some discharges, the relative phasing of the C coil windings is adjusted to produce a large $n = 3$ component. For the $n = 3$ configuration, the largest perturbations are non-resonant, i.e. their helicities do not coincide with any of the rational- q surfaces in the plasma.

The confinement of fusion products is assessed by a standard technique known as ‘triton burnup’ [1]. Tritium fusion products are created in the $d(d,p)t$ branch of the $d-d$ fusion reaction. The reaction rate for the $d(d,p)t$ branch is nearly equal to the rate for the $d(d,n)^3\text{He}$ branch, so measurements of 2.5 MeV

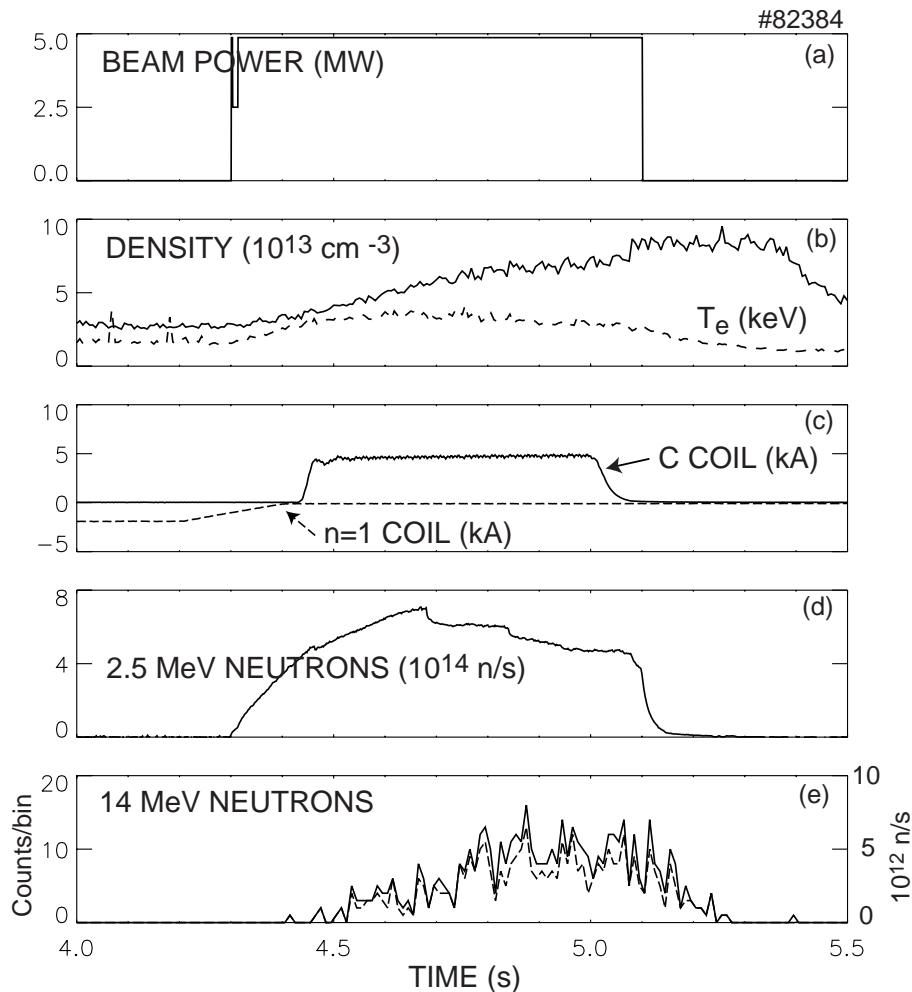


Figure 4. Time evolution in a typical discharge of (a) the neutral beam power, (b) the central ($r/a \simeq 0.3$) electron density and temperature from Thomson scattering, (c) the $n = 1$ and C coil currents, (d) the 2.5 MeV neutron rate and (e) the 14 MeV neutron rate measured by two different channels of the silicon diode detector with different energy thresholds. $B_T = 1.9$ T, $I_p = 1.0$ MA. The negative $n = 1$ coil current indicates an applied field that partially cancels intrinsic error fields. The accuracy of the absolute calibration of the 14 MeV neutron signal is no better than 45% [23].

neutron emission are used to monitor the production of energetic tritons. Some of the confined tritons undergo subsequent $d(t,n)^4\text{He}$ reactions; the number of reactions depends on the confinement and thermalization rate of the energetic tritons. Thus, the ratio of the flux of 14 MeV neutrons to the flux of 2.5 MeV neutrons is sensitive to the triton confinement. The 14 MeV neutron rate is measured with a silicon diode [23], while the 2.5 MeV neutron rate is measured by scintillators and counters [24]. Previous studies using these diagnostics showed that the

time evolution and magnitude of the triton burnup are consistent with classical predictions in quiescent DIII-D plasmas with minimal MHD activity [23].

The measured triton burnup is compared with calculations of the expected d - t : d - d burnup ratio. Thomson scattering measurements [25] of the electron temperature T_e and density n_e and visible bremsstrahlung measurements of Z_{eff} are inputs to the calculations. Three separate calculations are employed. The simplest, the steady state MIS code [26], ignores spatial and velocity space diffusion;

these approximations are accurate for temperatures $\lesssim 10$ keV [27]. The fraction of tritons that are confined and undergo subsequent d-t reactions is calculated at various locations using an analytical formula for the prompt losses and classical formulas for the slowing down rate. The second code (TIMEEV) makes similar approximations but includes temporal variations in the plasma parameters [27]. Calculations with TIMEEV indicate that the expected temporal variations are generally small for the discharges in this study. The third code (TRANSP) (Ref. [28] and references therein) provides a complete description of the classically expected burnup in an axisymmetric torus but is computationally expensive. Comparison of TIMEEV and TRANSP for one discharge in this study (No. 77643) yields similar predictions.

The classical, axisymmetric triton confinement is relatively poor in these DIII-D plasmas. Figure 1 shows the orbit of a centrally born triton that is circulating in the direction of the plasma current in a representative plasma with current $I_p = 1.0$ MA and toroidal field $B_T = 1.9$ T. The large orbit shift and gyroradius are evident. Approximately 30% of the tritons are lost on their first orbit.

Signals from a typical discharge are shown in Fig. 4. Prior to the portion of the discharge devoted to this study, the polarity of the $n = 1$ coil current is selected to partially cancel intrinsic field errors (in order to avoid locked modes [29]), but this current is turned off beginning at 4.2 s. The current in the legs of the C coil are energized at 4.5 s to produce helical field perturbations. Meanwhile, deuterium neutral beam injection commences, which produces a gradual increase in density, temperature and 2.5 MeV neutron rate. Finally, the 14 MeV neutron signal begins to rise with a delay of ~ 0.2 s with respect to the 2.5 MeV neutron emission; the emission also persists for ~ 0.2 s after beam injection. This delay is an expected classical effect: it takes ~ 0.2 s for Coulomb collisions to decelerate 1.0 MeV tritons to the peak of the d(t,n) fusion cross-section.

In this study, relative measurements of triton burnup in steady state plasmas are employed. (This eliminates uncertainties associated with the absolute calibration of the 14 MeV neutron detector and also minimizes uncertainties associated with systematic errors in the Z_{eff} and T_e measurements.) The measured burnup is the ratio of the 14 MeV neutron fluence to the 2.5 MeV neutron fluence, typically summed for 0.5 s. Transient discharges that did not reach a steady state for $\gtrsim 0.3$ s are excluded from the study. The measured burnup is compared with the

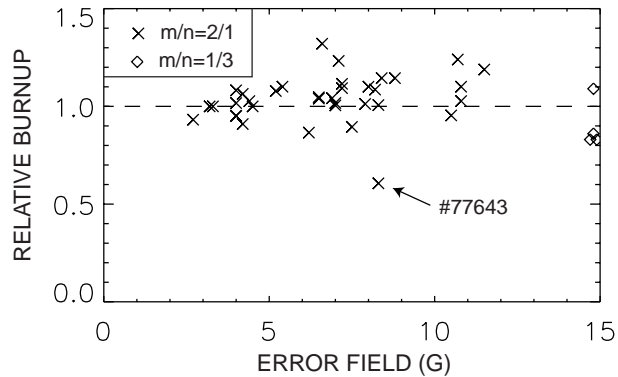


Figure 5. Relative burnup versus the magnitude of the $m/n = 2/1$ error field (crosses) or the $m/n = 1/3$ error field (diamonds). The relative burnup is the measured burnup (14 MeV fluence:2.5 MeV fluence) divided by the expected steady state burnup; all burnup ratios are normalized to the ratio observed in a control discharge from the same sequence. The expected steady state burnup is calculated by the MIS code [26] using measured values of T_e . The applied error fields also contain other Fourier components (cf. Fig. 3).

expected steady state burnup as calculated by the MIS code. This ‘burnup ratio’ is then normalized to the measured ratio in a nominally identical ‘control’ discharge (in which the $n = 1$ and C coils are off) to give a relative measure of triton confinement.

Many of the plasmas contain sawteeth. For example, sudden drops in the 2.5 MeV neutron rate in Fig. 4 occur at sawtooth crashes. Although large sawteeth can reduce the triton burnup [1], the sawtooth instability is barely altered when the helical field coils are energized, so the sawteeth should not affect the relative measurements.

With the exception of one discharge (discussed in detail later), the application of external helical perturbations has no detectable effect on the triton confinement (Fig. 5). Several different coil configurations are employed, including the $n = 1$ coil alone, the C coils phased to produce large $n = 1$ perturbations and the C coils phased to produce large $n = 3$ perturbations. Discharges with toroidal fields in the range $B_T = 1.4$ – 1.9 T, plasma currents in the range $I_p = 1.0$ – 1.3 MA, electron densities in the range $(3$ – $7) \times 10^{13}$ cm^{-3} and beam powers in the range $P_B = 2$ – 8 MW are studied. None of these configurations produce statistically significant effects on triton confinement. For the entire ensemble of discharges with $m/n = 2/1$ amplitudes greater than 6 G, the relative burnup is 1.06 ± 0.14 ; similarly, the

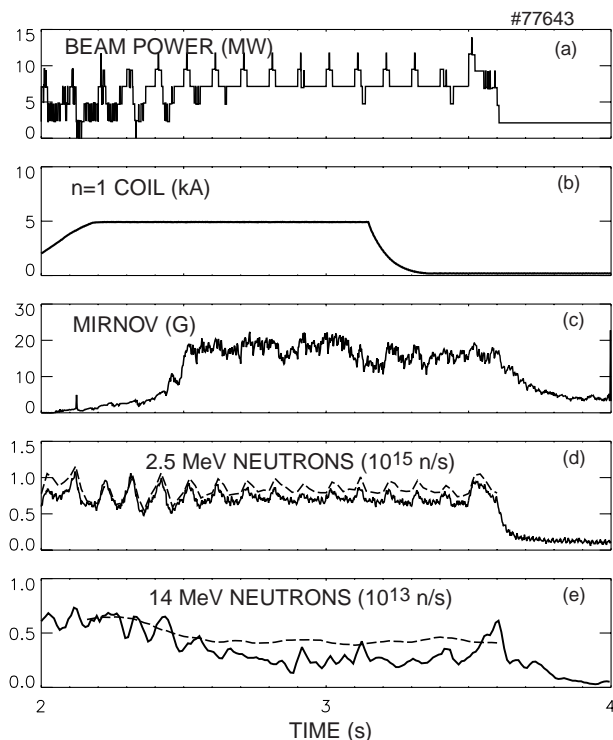


Figure 6. Time evolution of (a) the neutral beam power, (b) the $n = 1$ coil current, (c) the amplitude of the rotating Mirnov mode \tilde{B}_θ near the outer vessel wall, (d) the measured (solid line) and calculated (dashed line) 2.5 MeV neutron rate and (e) the measured (solid line) and calculated (dashed line) 14 MeV neutron rate in the discharge with anomalous triton burnup. The expected neutron rates are calculated by the TRANSP code [28]. Parameters at 3.0 s: $B_T = 1.7$ T, $I_p = 1.3$ MA, $T_e(0) \simeq 3.1$ keV, $T_i(0) \simeq 4.3$ keV, $n_e(0) \simeq 7.5 \times 10^{13}$ cm $^{-3}$, double null divertor. The rotation frequency of the Mirnov mode is ~ 5 kHz. The beam power is modulated for diagnostic purposes.

discharges with $n = 3$ perturbations larger than 10 G have a relative burnup of 0.90 ± 0.12 .

On discharge 77643, a measurable reduction in triton burnup is observed when the $n = 1$ coil is energized to produce helical perturbations (Fig. 6). In this discharge, one beam source injects from 0.5–1.6 s, then the power is increased to ~ 5 MW. The external helical field is applied beginning at 1.9 s. Initially no impact on the 14 MeV neutron rate is observed but, with the onset of a large $m/n = 2/1$ rotating mode at 2.5 s, the 14 MeV neutron rate falls to approximately half of the expected level. Since the reduction correlates temporally with the Mirnov signal, we conclude that the plasma 2/1 mode is responsible for the degradation in triton confinement.

3. Discussion and conclusion

The helical fields applied by the external coils are too weak to perturb significantly the triton orbits. Because the neutral beams apply a torque to the plasma, DIII-D plasmas rotate in the direction of beam injection. Two factors associated with the plasma rotation affect the amplitude of the perturbations. First, for resonant perturbations, the flowing plasma alters the vacuum field at the resonant surface, resulting in a magnetic island of greatly reduced width [30]. The field perturbations experienced by the tritons consist of the superposition of stationary vacuum perturbations and the perturbations associated with the plasma response. Both of these perturbations can, in principle, generate island chains in the phase space that describes the triton orbits. In practice, neither resonant nor non-resonant perturbations have an effect on triton confinement (Fig. 5).

In addition to shielding the resonant perturbations, the plasma rotation governs the maximum amplitude of the applied vacuum perturbation. The applied helical field exerts a torque on the plasma which tends to slow the plasma rotation [30]. If the torque is too large, rotation ceases. Without plasma rotation, tearing modes often grow large and cause a disruption. For these experiments, the amplitude of the applied perturbations is near the empirical limit. In several discharges, application of the external fields slows the rotation frequency of Mirnov modes 50% during the beam pulse, while the rotation frequency in subsequent control discharges changes $\lesssim 10\%$. Indeed, in approximately 15% of discharges the external coils trigger disruptions. Thus, it is impractical to increase the magnitude of the external perturbation further.

The unshielded vacuum perturbations are not expected to induce intrinsic orbit stochasticity in the triton orbits. For example, in discharge 77643 (Fig. 6), the vacuum amplitude of the $m/n = 2/1$ component of the external perturbation is 9 G. In contrast, the amplitude of the 2/1 tearing mode produced by the plasma is much larger: $\tilde{B}_\theta \simeq 21$ G at the Mirnov coil and approximately 80 G in the plasma. It is little wonder that the Mirnov mode has a stronger effect on triton burnup than the external perturbation.

Quantitatively, the analytical island overlap theory [7] that successfully explained beam ion losses induced by large tearing modes in DIII-D [5] is consistent with the results of this experiment.

Stochasticity is expected when the width of the triton $m = 2$ and $m = 3$ islands, $\frac{1}{2}\delta\rho(\sqrt{|G_0|} + \sqrt{|G_1|})$, exceeds the spacing between the $q = 2$ and $q = 3$ surfaces. (Here $\delta\rho$ is the island width normalized to the minor radius and G_0 and G_1 are coefficients that depend on the size of the orbit.) For the large $m/n = 2/1$ tearing mode in discharge 77643, the triton orbits exceed the Chirikov criterion by 20%, while the vacuum perturbation produced by the $n = 1$ coil produces triton islands that only span 40% of the spacing between the $q = 2$ and $q = 3$ surfaces. Thus, these calculations are consistent with the observation that the $m/n = 2/1$ tearing mode produced a reduction in triton confinement of about 50% but that the $n = 1$ coil had no detectable effect on triton burnup. Similar calculations apply to the other discharges in this study.

In conclusion, application of static 10 G helical fields in the DIII-D tokamak causes no measurable deterioration in fusion product confinement. Neither resonant fields ($m/n = 2/1$) nor non-resonant fields ($m/n = 1/3$) cause reductions in triton burnup. If the perturbations were an order of magnitude larger (comparable to the large $2/1$ tearing modes) they might have an effect, but static perturbations of this amplitude trigger disruptions.

Control of the alpha population with static perturbations is probably more difficult in a reactor than in DIII-D, since the difference between the fusion product orbits and the thermal orbits is smaller, while the lower rotation frequency increases the sensitivity to disruptions [30]. Although static perturbations are impractical, rapidly rotating helical perturbations that resonate with the energetic ions remain promising for control of the energetic particle population. Rotating fields were not employed in this study because the relatively long skin time of the metallic vessel wall prevents application of rapidly rotating fields by external field coils. A test of the effect of rotating helical fields on fusion product confinement must be performed on a tokamak with internal field coils.

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E-mail address of W.W. Heidbrink:

wwheidbr@uci.edu

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