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INTRODUCTION

In Current-Hole (CH) JET plasmas the toroidal current density falls to near-zero values over a significant central region, typically 1/3 of the minor radius [1]. Such plasmas exhibit a transport barrier at the border of the current hole. On JET these conditions are routinely achieved by the application of Lower Hybrid Current Drive in the early breakdown phase, but it has also been demonstrated on JET and other machines that current holes can be formed as a result of bootstrap current effects. Flat profiles of high temperature within the current hole make the regime interesting for tokamak physics in general and for quasi-steady state operation of ITER in particular. Current holes can be predicted to have both beneficial and adverse effects. The presence of a transport barrier offers the prospect of improved plasma energy confinement, but this has to be set against the poor confinement of fast ions inside a current hole due to the very low poloidal field in the plasma core [1, 2]. This can significantly affect a fast ion distribution due to a modification in the fast ion orbit topology. In a reactor, alpha particles born within the current hole have orbits with larger radial excursion than would occur in the current hole's absence, leading to enhanced collisional losses and overall reduction in alpha heating [3]. The distribution in both velocity and spatial coordinates of tritons injected by the neutral beam injection (NBI) heating system is also significantly affected by the presence of a current hole. To study these issues and to benchmark our simulation codes in the current hole regime, the injection of tritium beam ions into CH plasmas was carried out on JET.

1. EXPERIMENTAL OBSERVATIONS

The effect of the CH on beam ions was demonstrated during Trace Tritium Experiments as a result of measurements of the emission profiles of 14MeV neutrons from fusions of 105keV beam tritons with background deuterons. Note that due to the extremely fast decrease of the DT fusion reactivity $\sigma\upsilon_{TD}$ with decreasing triton energy, the neutron measurements provide information about confined beam tritons only in a rather narrow range E_b-E<<E_b (here E_b = 105keV). On-axis and off-axis co-injected beam tritons (see Fig.1) were used in these experiments. Figure 2 displays the neutron emission profiles measured by neutron cameras over horizontal (1-10) and vertical (11-19) channels in four JET shots with I/B=1.5MA/3.45T. The four cases include on-axis and off-axis beam injection into Monotonic Current (MC) and CH plasmas. For on-axis beam tritons, the measured profiles clearly demonstrate the CH induced outward shift of the maximum emission in Pulse No's: 61488 when compared to MC plasma (Pulse No: 61493). For off-axis tritons (Pulse No's: 61490 and 61492) the maximum neutron emission is shifted inwards with respect to the magnetic axis and is only weakly sensitive to the CH. Qualitative differences in measured neutron emission profiles in CH plasmas with on-axis and off-axis beam tritons become evident from the poloidal distribution of neutron emission in Fig.3, which is a tomographic reconstruction of neutron cameras data.

2. CURRENT HOLE EFFECT ON BEAM PARTICLE ORBITS

For an understanding of the CH shift of the maximum neutron emission from on-axis beam tritons the following observation is important: the maximum ion density corresponds to the major radius R

in the mid-plane where beam tritons execute near-stagnation orbits with $V_Z(=-V_d+V_{||}B_Z/B)\approx 0$ and $V_R(=V_{||}B_R/B)\approx 0$. As the pitch-angle cosine ξ_b (=$V_{||}/V$) of co-injected tritons ionized at $R=R_b$ is R_t/R_b (see Fig.1(b)) and increases along the beam path from ~0.5 at R_b=3.8m to 1 at $R_b=R_t$ (Fig.4(a)), the stagnation condition is always satisfied in the outer mid-plane at the point with $B_Z(R)=B_{\perp cr}(R)$. For 105keV tritons the critical poloidal field required for stagnation orbits is rather low, $B_{\perp cr} = 0.04(1+R_t^2/R^2)/R_t \sim 0.04$-0.05T. Therefore the stagnation orbits for beam tritons in MC JET plasmas are realized very close to the magnetic axis ($R_{stg}\approx$3m). However, in the CH case this stagnation point can be shifted outward to R_{stg}»(3.15÷3.20)m as shown in Figs.4(a),4(b). Note that the corresponding shift of the maximum neutron emission can be observed, as it is comparable to the distance between the channels 16 and 15 of the vertical neutron camera (Fig.4(b)). The transformation of the 105keV triton beam orbit shape with R_b in 1.5MA CH JET plasma (Pulse No: 61488) is illustrated in Fig.5.

3. MODELLING RESULTS

To calculate the effect of the CH on the neutron emission profile, 3D Fokker-Planck modelling of the distribution function of beam tritons $f_b(\mathbf{r},\mathbf{V})$ was performed assuming a source term $S(\mathbf{r},\mathbf{V})\sim\delta(E-E_b)\exp[(\xi-\xi_b)^2/\Delta\xi^2]\exp[(Z-Z_b)^2/a_{bZ}^2]$ with E_b = 105keV, $\xi_b = R_t/R$, $\Delta\xi = a_{bh}\xi_b/R_t$ and the transverse and vertical beam half-widths $a_{bh}\cong$6cm and $a_{bZ}\cong$11.5cm. Figure 6 displays the contours of the distribution function of tritons co-injected on-axis into a I/B=1.5MA/3.45T CH JET plasma in a phase-plane spanned by the normalized magnetic moment, λ, and the maximum radial coordinate along the orbit, rmax, for energies 105keV, 85keV and 42keV. It is important to note that triton distribution, originally strongly localised at both λ ~0.7 and r_{max}/a~0.2 in the vicinity of the stagnation orbit area (Fig.6(a)), remains localised in the radial coordinate (r_{max}/a~0.2-0.3) at least for high energies (E>40keV) dominantly contributing to the neutron emission. Consequently, one may expect maximum neutron emission from the outer midplane area of the plasma at flux surface radii r/a~0.2-0.3. Note that in the case of off-axis injection the beam tritons are deposited, as shown in Fig.7, in the phase space area distinctly apart from stagnation orbits. Nevertheless in this case, beam tritons with E>40keV are also localised in a rather narrow radial range r/a~0.4-0.5. Consequently, the neutron emission profile should be of hollow structure with a maximum at inner mid-plane where co-circulating tritons spend more time. This is seen from the neutron emission profiles in Fig.8 calculated via Fokker-Planck modelling of the beam triton distribution. Shown in this figure are modelled distributions of 14MeV neutron emission in R-Z plane for the reference Pulse No: 61488, 61490, 61492 and 61493. In agreement with measurements, the CH is seen to shift the maximum emission outward in the case of on-axis beam tritons (Figs. 8(a), 8(d)) and, in the case of off-axis injection (Figs.8(b), 8(c)) it results only in a marginal flattening of the hollow profile of neutron emission. The hollow structure of the modelled profiles in the off-axis case (Figs.8(b),8(c)) is not seen in the experimental tomographic reconstruction, Fig.3 (left), which may be due to the simplified T-beam model used and/or due to experimental errors and uncertainties. Fig.9 displays the line integrals of the modelled neutron emission along the lines-of-sight of horizontal and vertical channels of neutron cameras. The neutron emission profiles shown in this figure are normalized to the blip duration in order to account for the time variation of the emission rate in experiment. Note that modelling results of Fig.9 are in satisfactory agreement with measurements presented in Fig.2.

SUMMARY

The effect of the current hole on the beam ion distribution has been clearly demonstrated during the Trace Tritium Experiments at JET. A significant outward shift (comparable to the CH size) of the maximum DT neutron yield position is observed for on-axis co-injected tritons when compared to the maximum position in the absence of a CH. In the case of counter-injection the CH would result in a corresponding inward shift of the neutron emission maximum. These shifts are caused by the CH-induced relocation of the stagnation orbits of beam ions responsible for the maximum of $f_b(\mathbf{r},\mathbf{V})$. Conversely, for off-axis co-injected tritons, an inward shift of the maximum DT neutron emission was observed, again consistent with the expected orbital effects of beam tritons. However, due to the relatively small CH size compared to the flux surface radius where most of the beam tritons are deposited, the spatial profile of neutron emission is only weakly influenced by the current hole. Spatial profiles of neutron emission induced by NBI tritons where calculated and shown to satisfactorily agree with the measurements of 14 MeV neutrons using a multi-channel neutron camera.

ACKNOWLEDGEMENT

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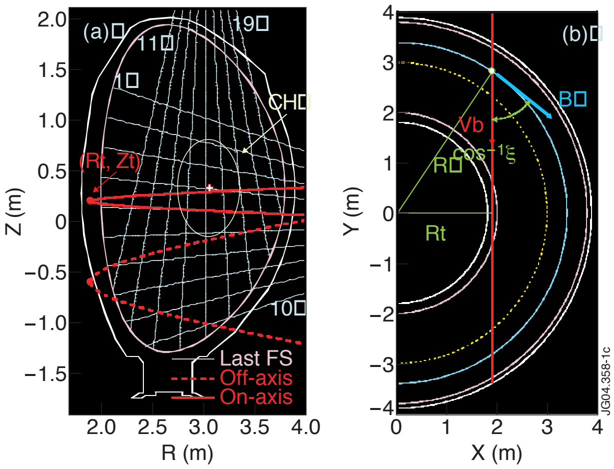
REFERENCES

[1]. N.C. Hawkes et al., Phys. Rev. Lett., **87**, 115001 (2001)

[2]. T. Fujita et al., Phys. Rev. Lett., **87**, 245001 (2001)

[3]. V.A. Yavorskij, et al., Nucl. Fusion **43**, 1077 (2003)



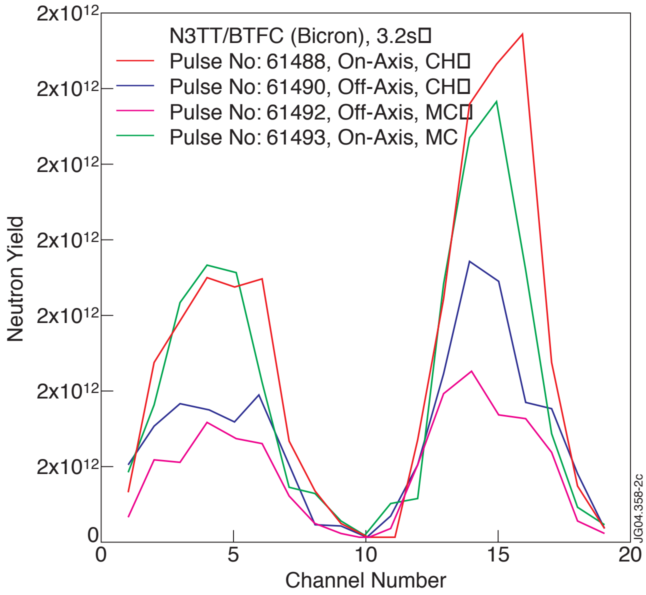


Figure 1: NBI (red lines in section and plan view) and neutron camera (blue lines in a) geometries in JET.

Figure 2: Measured neutron emission yield versus channel number

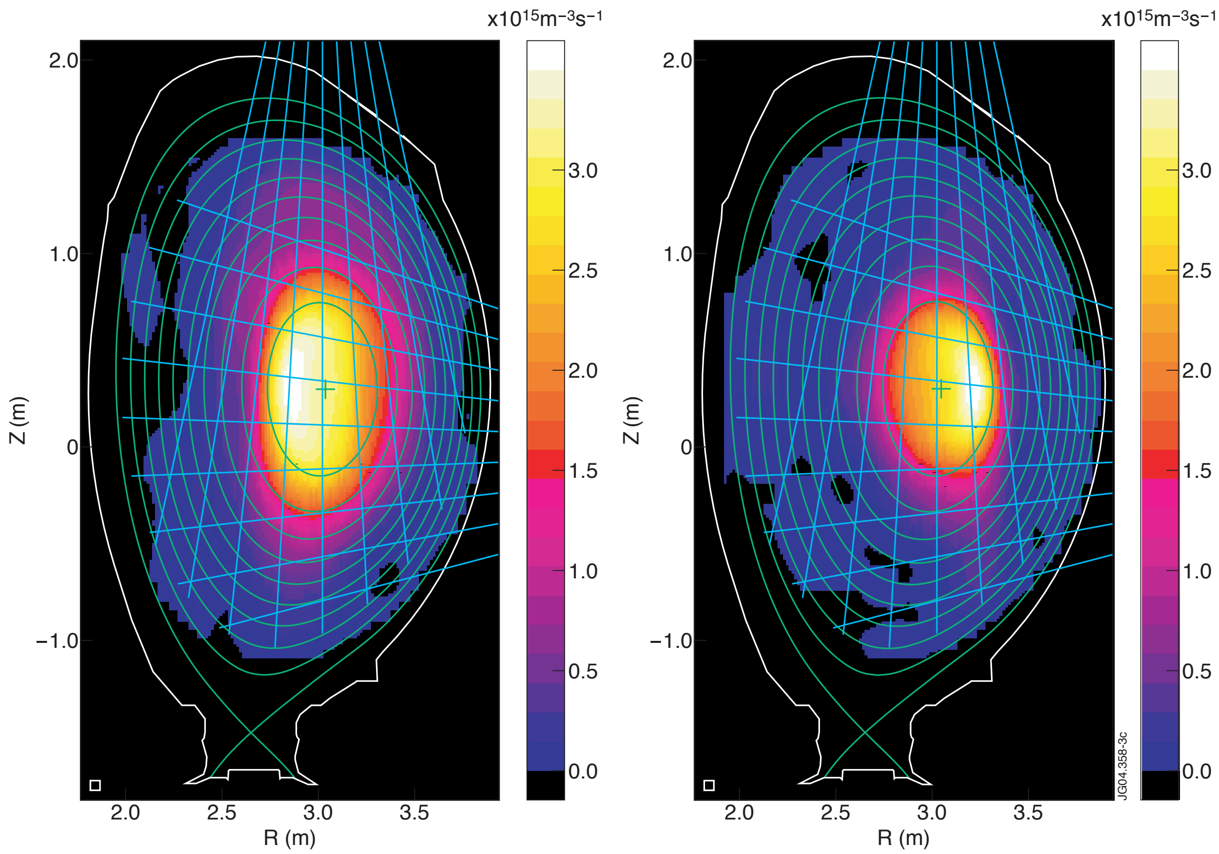


Figure 3: Poloidal distribution of neutron emission in CH plasmas with off- (left) and on-axis (right) beam tritons

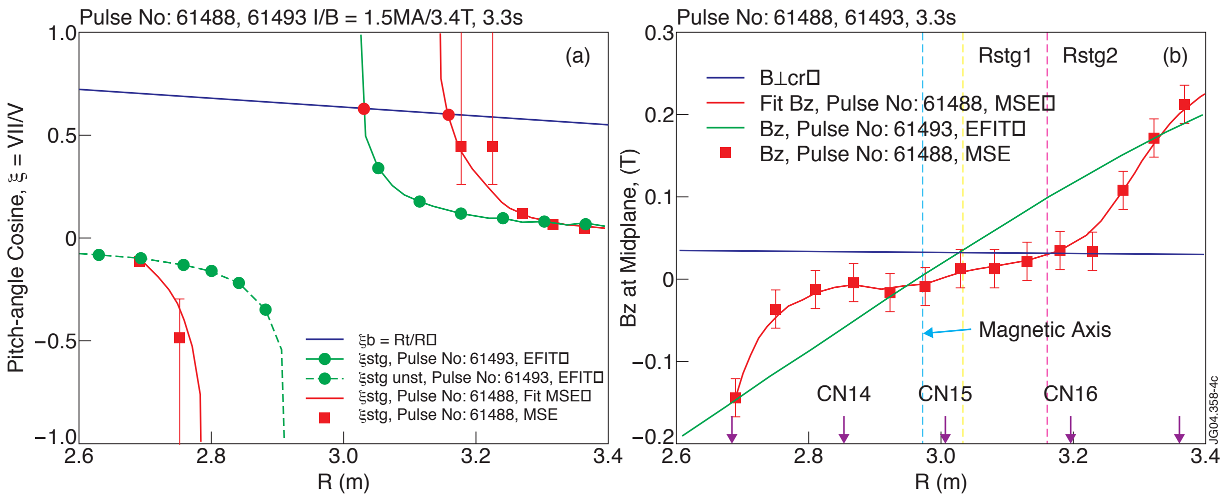


Figure 4: Mid-plane pitch-angle cosine (figure a) and BZ (figure b) required for stagnation orbits

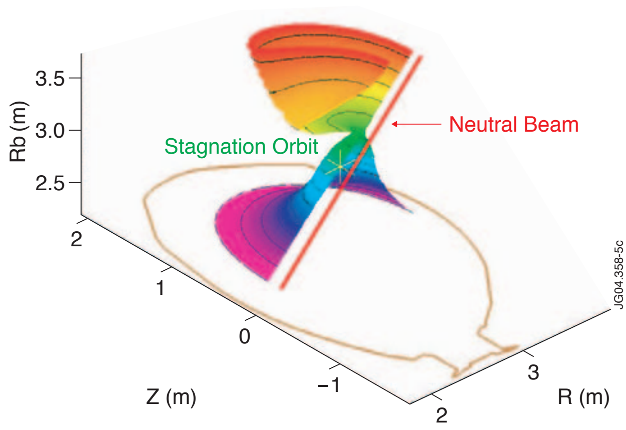


Figure 5: Transformation of 105keV triton beam shape with R_b in a CH JET plasma

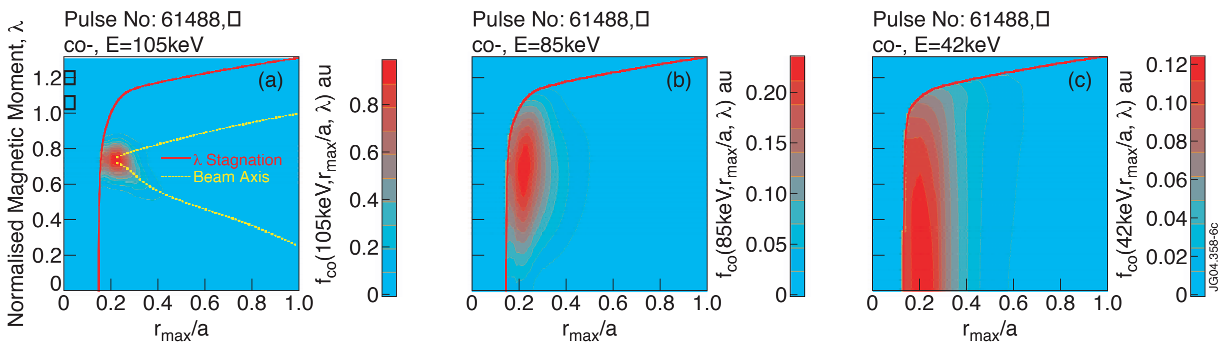


Figure 6: Distribution function of on-axis co-injected tritons in CH JET plasma in λ, r_{max} coordinates

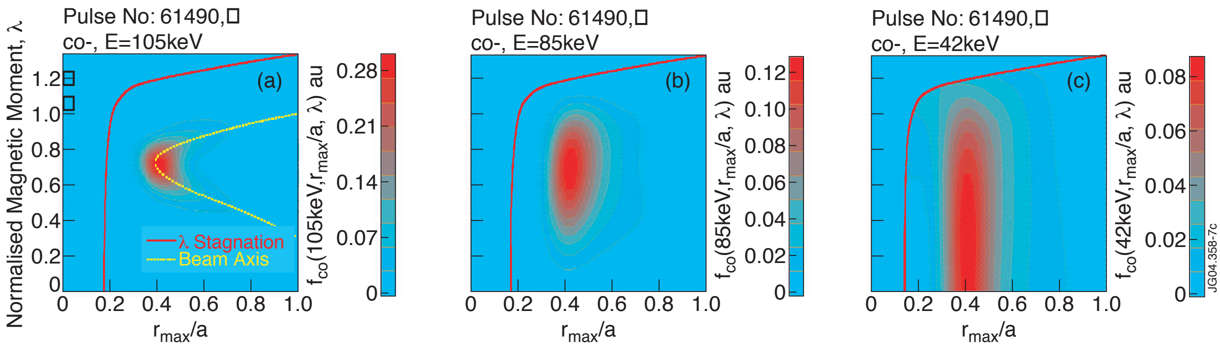


Figure 7: Distribution function of off-axis co-injected tritons in CH JET plasma in λ, r_{max} coordinates

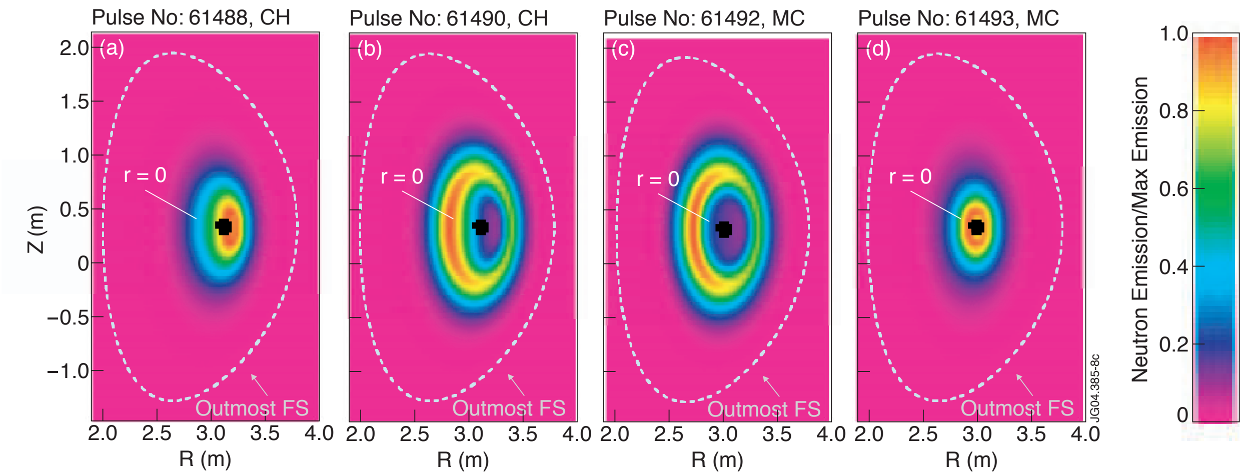


Figure 8: Calculated poloidal distributions of neutron emission in I/B=1.5MA/3.45T JET plasmas for on-axis (figures a, d) and off-axis (figures b, c) triton injection

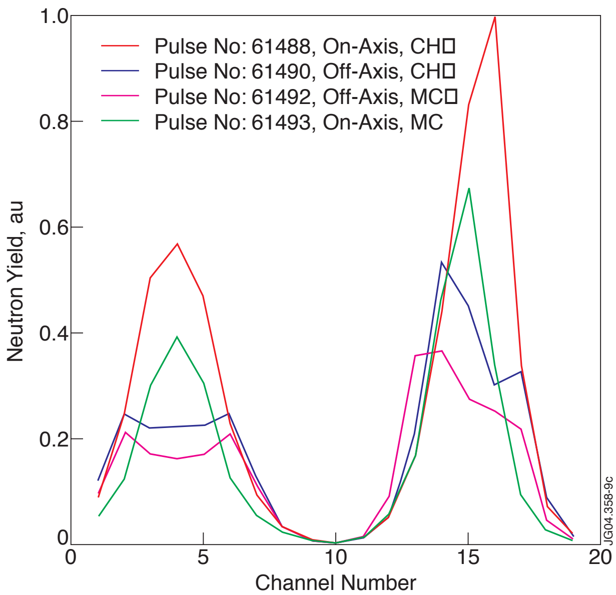


Figure 9: Modeled neutron emission profiles for reference shots of Fig.2.