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ACCELERATION OF BEAM IONS DURING MAJOR RADIUS COMPRESSION IN TFTR

By

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Acceleration of Beam Ions During Major Radius Compression in TFTR

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ABSTRACT

Tangentially co-injected deuterium beam ions were accelerated from 82 keV up to 150 keV during a major radius compression experiment in TFTR. The ion energy spectra and the variation in fusion yield were in good agreement with Fokker-Planck code simulations. In addition, the plasma rotation velocity was observed to rise during compression.

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The Tokamak Fusion Test Reactor (TFTR) project was initiated to study tokamak physics near D-T break-even conditions ($Q = P_{fusion}/P_{heat} = 1$) in a two-component plasma,[1] because the $n_e \tau_E$ requirement for break-even was considerably less stringent than the conventional Lawson criterion. The practical implementation of the two-component approach is through neutral beam injection.[2] If W_0 denotes the injection energy of the deuterium beam, the optimum Q near break-even is expected to occur at W_0 = 150-300 keV. It was pointed out by Furth and Jassby[3] that substantial improvement in Q can be achieved by clamping the injected ions at the energy giving the maximal ratio of fusion-reaction rate to plasma drag, rather than injecting at higher energy and passing through the optimal region during deceleration. One proposed method was to inject tangential beams, accelerate the beam ions to the optimal energy by rapid magnetic compression in major radius,[4,5] and then maintain this energy by slow compression. Compressional acceleration of low-energy beam ions (~ 15 keV) was first observed in ATC.[5] In this letter, we present experimental results which demonstrate that magnetic compression in major radius can accelerate tangentially injected beam ions from 82 keV up to 150 keV, accompanied by enhanced fusion neutron emission. The evolution of the fast ion energy distribution function was investigated in detail and found to be in good agreement with a bounce-averaged Fokker-Planck simulation. Unlike the ATC experiment,[5] plasma rotation was also observed, and its change during compression was roughly consistent with conservation of angular momentum.

The experiment was performed in TFTR with the following plasma parameters before compression: plasma major radius R = 3.0 m, minor radius a = 0.57 m, plasma current I_p = 450 kA, toroidal magnetic field B_0 = 3.3 T at R = 3.0 m, central electron temperature $T_e(0)$ ~ 3.3 keV, central deuterium ion temperature $T_i(0)$ ~ 3.8 keV, and line-integrated electron density

$n_eL \sim 1.5 \times 10^{19}$ m^{-2}. 82 keV deuterium neutral beams at 2.1 MW were injected parallel to the toroidal plasma current from t = 2.3 to 2.5 seconds. At t = 2.5 sec, the plasma major radius was compressed to 2.17 m by raising the vertical magnetic field. Figure 1 shows the waveforms of I_p, n_eL, and R in a typical plasma shot. Data from the multi-channel Thomson scattering (TVTS) system and the electron cyclotron emission (ECE) diagnostic were used to determine the evolution of R, $n_e(r)$, and $T_e(r)$ during compression. A five-chord infrared interferometer (MIRI) was also used to determine the plasma density profile. The locations of maximum electron density were obtained by a standard five-point spline-fitting technique, and they are compared with TVTS results in Fig. 1b. The agreement is reasonably good throughout the compression duration of approximately 15 ms. The post-compression $T_e(0)$ and $n_e(0)$ were somewhat lower than expected from adiabatic scaling. This feature has been described in some detail previously,[6] and is outside the scope of this letter.

Two charge-exchange neutral particle analyzers were used to measure the ion energy spectra before and after compression. One analyzer was aimed approximately along the post-compression magnetic axis, while the second analyzer was aimed for tangency at R = 0.52 m. The change in the ion energy spectra due to compression is depicted in Fig. 2. The charge exchange spectra were averaged over 10 ms, and all the spectra shown in this figure were taken during the same shot. Before compression, the ion energy distribution function showed a cut-off near the injection energy (82 keV). This cut-off energy was raised to 150 keV immediately after compression. This was expected for the compression ratio C = 1.38, since the energy of particles moving along magnetic field lines increases by a factor of C^2. In order to interpret these data quantitatively, a bounce-averaged Fokker-Planck code[7,8] was used to follow the ion distribution function $f(E, \xi, r, t)$ in time as a function of energy, pitch angle, and minor radius. Since the equipartition time for the beam ions is much longer than the compression time (~ 15 ms), we can treat the beam-ion angular momentum about the major axis, $v_\phi R \simeq v_\parallel R$, and the magnetic moment, $\mu = 1/2\ m\ v_\perp^2/B$, as invariant quantities. This means that $\frac{dv_\parallel}{dt} \simeq -\frac{v_\parallel}{R}\frac{dR}{dt}$ and $\frac{dv_\perp}{dt} \simeq -\frac{v_\perp}{2R}\frac{dR}{dt}$. Utilizing these results together with the usual effects of classical collisional slowing down, energy diffusion, pitch angle scattering, neutral beam injection, and charge exchange losses, we solve for f, and the charge exchange spectra can then be calculated along different sightlines at various times. The results are shown by the dashed lines in Fig. 2. The shapes of the predicted spectra are in good agreement with experimental data, providing further evidence that the energy gained by fast ions during compression is consistent with classical expectations. Since the neutral density variation during compression is not known, we cannot calculate the absolute magnitude of the charge exchange signal. After compression, $dR/dt = 0$, and the decay of the fast ions is also observed to behave classically.

The fusion neutron yield was observed to increase during compression because of the density rise and beam-ion acceleration. The measured neutron yield is compared with that calculated from the Fokker-Planck code in Fig. 3a. The dotted line represents the calculated neutron yield rescaled to fit the experimental data, which is about half of the value expected if the $Z = 1$ plasma ions are assumed to be 100% deuterium. However, the fractional increase due to compression and the decay time due to Coulomb relaxation are in good agreement with the experiment. Considering the uncertainties in the neutron detector calibration, deuterium concentration, neutral beam species mix, and deposition profile, a factor two discrepancy in absolute magnitude is within experimental error.[8] In this experiment, the neutron emission mainly comes from beam-target interactions. The agreement in neutron yield indicates that the absolute magnitude, as well as the shape of the energetic ion distribution function, is not far from the Fokker-Planck code simulation. With 4 MW of neutral beam power, a peak neutron yield of 5×10^{14}/sec was observed, which is the highest so far achieved in TFTR.

The $d(d,n)^3He$ cross section increases by a factor 3.2 when the deuteron energy goes from 80 keV to 150 keV. Since the $^3He(d,p)\alpha$ cross section increases 14 times over this energy range, a more dramatic increase in this reaction rate is expected, which would reinforce the neutron measurement. A small amount of ^3He gas was puffed into the vacuum vessel 250 ms before compression (at t = 2.25 sec), just before injection of the 82 keV D° beams. The 15 MeV protons produced by d-^{3}He reactions were unconfined in this experiment, and were detected by surface barrier detectors situated at the bottom of the vacuum vessel. Fig. 3b shows that the proton detector signal increases over an order of magnitude by the compression, and the decay time correlates with the slowing-down time of the energetic ions. It should be noted that the proton detector efficiency has considerable uncertainty and varies during compression because the 15 MeV proton orbits which reach the detector depend upon the plasma position. Orbit code calculations[9] indicate that the efficiency for the post-compression plasma is about one half the value for the pre-compression plasma. Thus, the d-^{3}He rate increased by about 25 times when the beam ions were accelerated up the steep cross section.

The co-injecting neutral beams in this experiment caused the toroidal plasma to rotate about its major axis.[10] Since the momentum confinement time (~ 80 ms with neutral beams) was significantly longer than the compression time (~ 15 ms), the plasma angular momentum was approximately conserved during compression, and the rotation velocity v_ϕ was expected to increase by the compression ratio ($v_\phi \rightarrow C\ v_\phi$), provided that the radial profile of v_ϕ was unchanged. In the experiment, v_ϕ was measured by the Doppler shift of the K_α-line from helium-like titanium ions. As the excitation energy is 4.75 keV for this line, emission mainly comes from the center of the plasma. Fig. 4 shows the variation of rotation velocity in a typical compression shot; v_ϕ went up by a factor 1.28, somewhat lower than the compression ratio ($C = 1.38$). The accuracy of this measurement (~ ± 10%) is limited by mechanical vibration, as well as by the low counts associated with the high temporal resolution. Detailed analysis of these data, including the effects of the finite momentum confinement time, beam slowing down, and sawtooth acitivties will be published later.

In summary, we have experimentally demonstrated that major radius compression can accelerate deuterium beam ions up to the energy range where optimal Q is expected to occur. Increase in plasma rotation velocity was also observed.

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Figure Captions

Fig. 1. (a) Experimental wave forms for plasma current, line-integrated density, and plasma major radius. (b) Plasma major radius on expanded time scale, the dots being Thomson scattering data and the open circles being results from the five-chord infrared interferometer. Compression starts at 2.5 sec.

Fig. 2. Comparison of charge exchange spectra with simulation by Fokker-Planck code (dashed line). (a) Charge exchange analyzer viewing approximately tangential to the toroidal field at R = 2.19 m. (b) Charge exchange analyzer viewing at R = 0.52 m.

Fig. 3. Fusion product measurements. (a) Neutron yield from $d(d,n)^3He$ reaction. (b) Proton count rate from $^3He(d,p)\alpha$ reaction. The dashed lines indicate the Fokker-Planck code simulations, including the detector efficiency.

Fig. 4. Change of rotation speed due to compression. The dashed lines bracket the signal oscillations (caused by mechanical vibration) which are eliminated by averaging over the oscillation period.

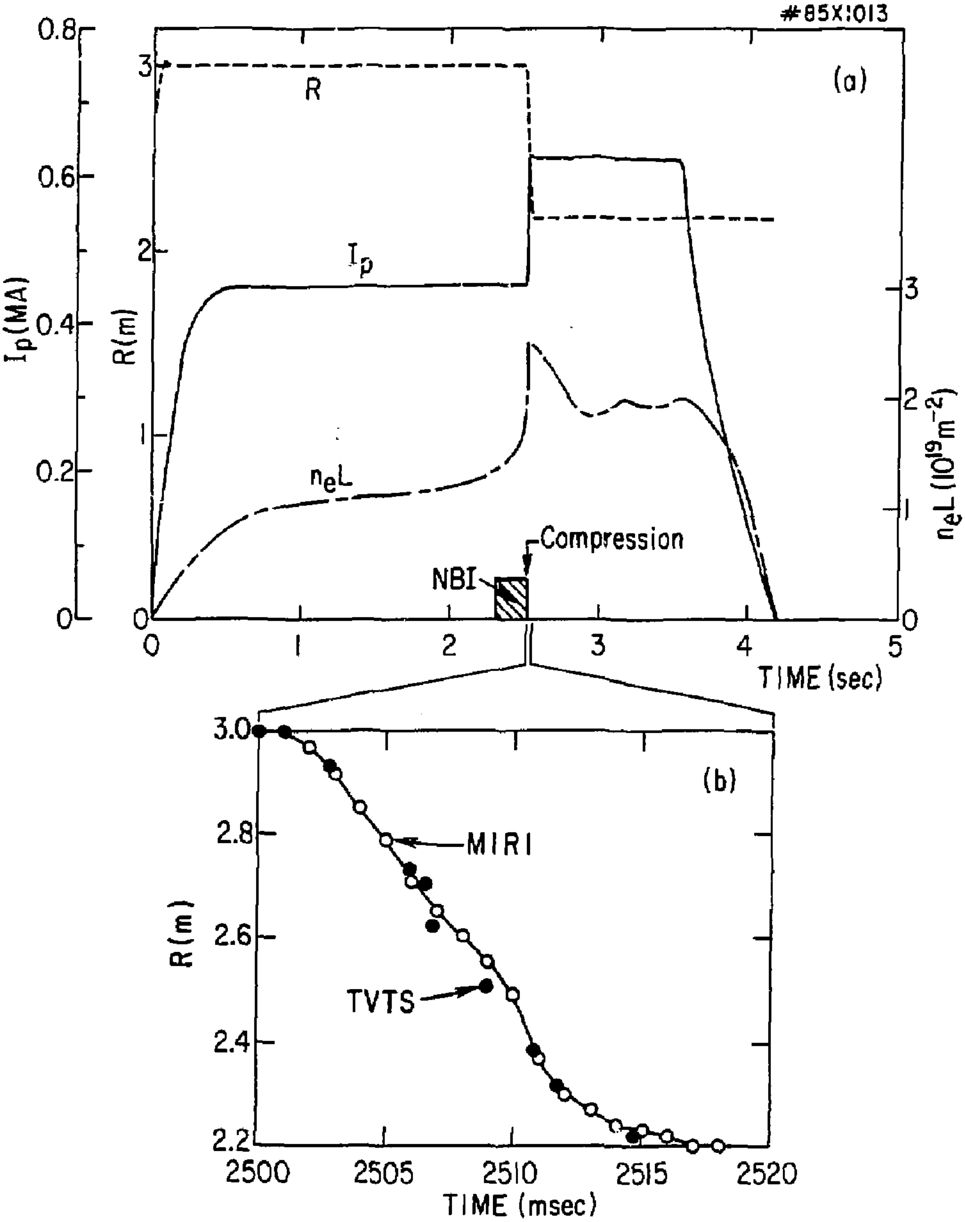
#85X1013
(a)
R
I_p
n_eL
I_p(MA)
R(m)
$n_eL\ (10^{19}m^{-2})$
0.8
0.6
0.4
0.2
0
3
2
1
0
3
2
1
0
Compression
NBI
0
1
2
3
4
5
TIME (sec)
(b)
MIRI
TVTS
R(m)
3.0
2.8
2.6
2.4
2.2
2500
2505
2510
2515
2520
TIME (msec)

Fig. 1

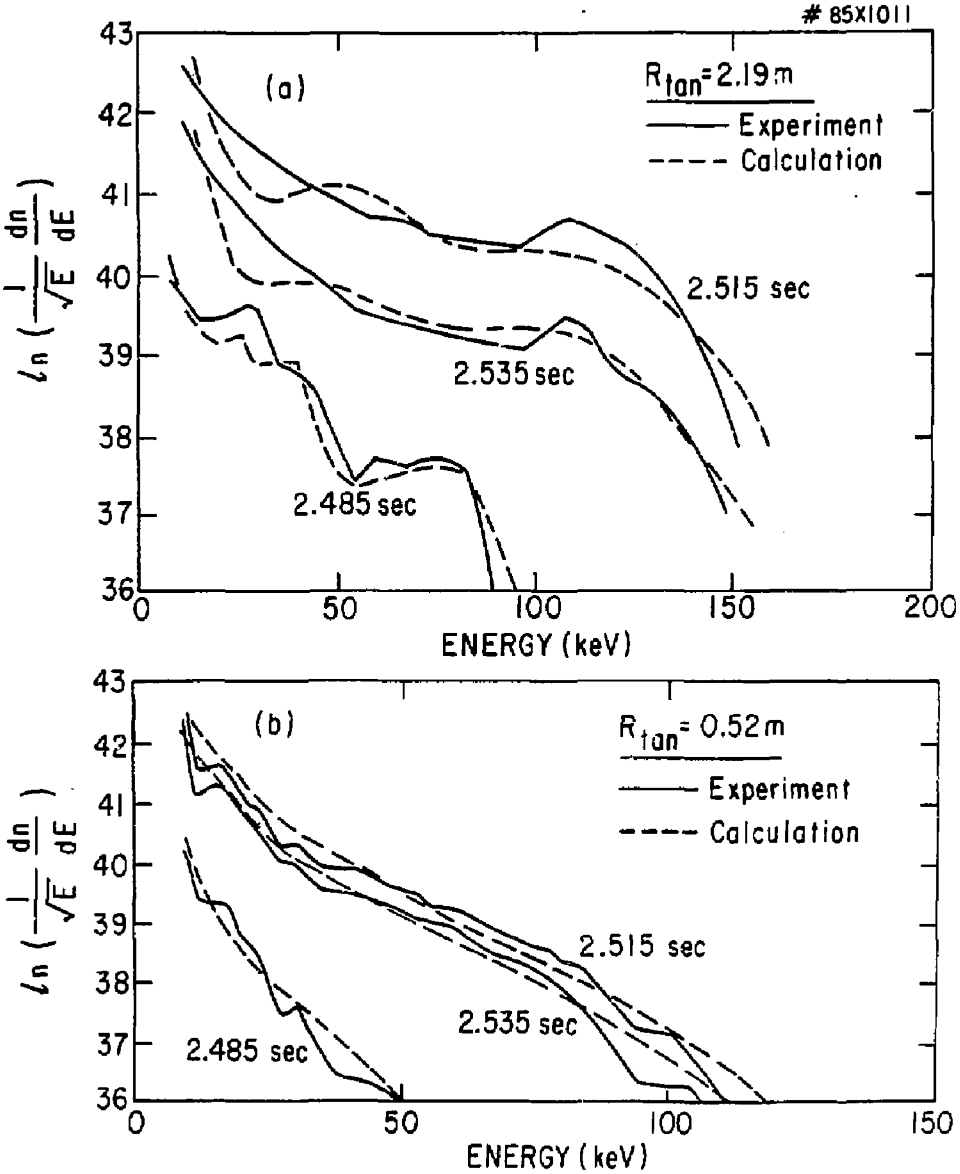
85X1011
(a)
R tan=2.19m
Experiment
Calculation
ln (1/√E dn/dE)
43
42
41
40
39
38
37
36
2.515 sec
2.535 sec
2.485 sec
0
50
100
150
200
ENERGY (keV)
(b)
R tan= 0.52m
Experiment
Calculation
ln (1/√E dn/dE)
43
42
41
40
39
38
37
36
2.515 sec
2.535 sec
2.485 sec
0
50
100
150
ENERGY (keV)

Fig. 2

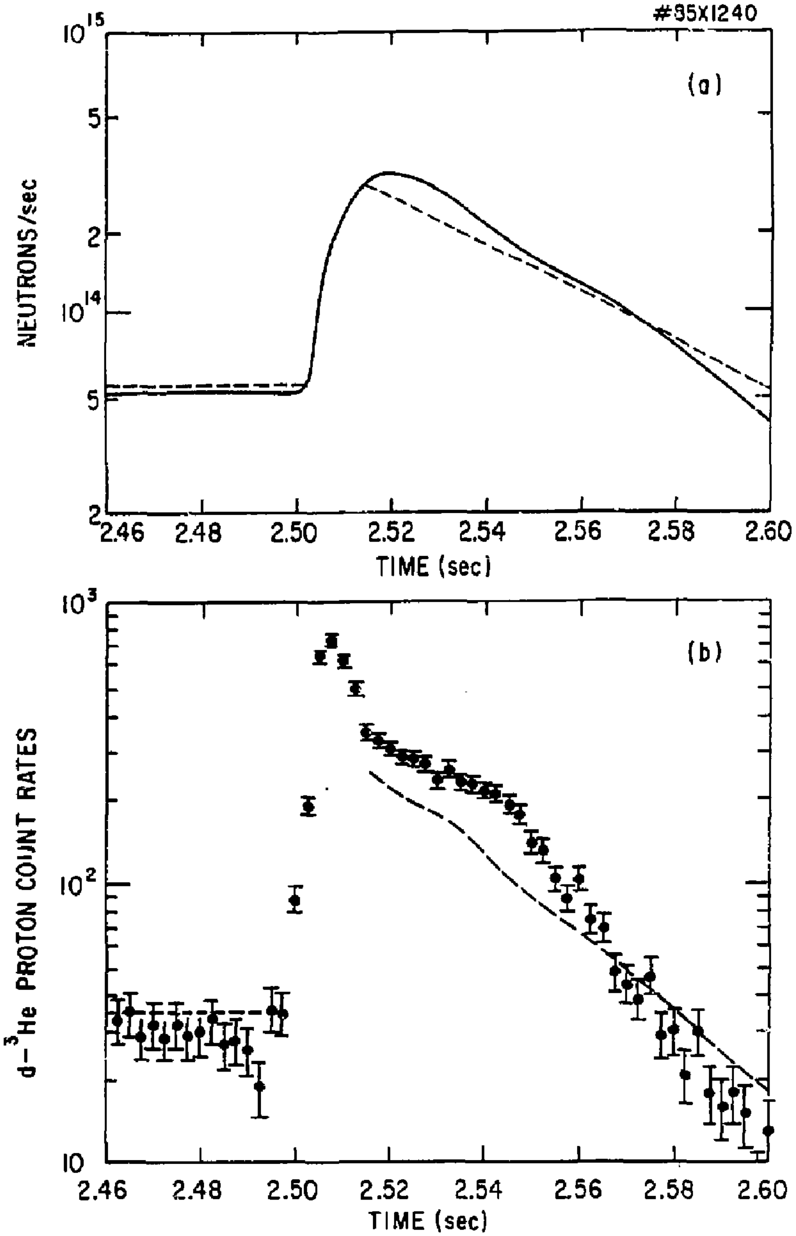
#85X1240
(a)
10^{15}
5
2
10^{14}
5
2
NEUTRONS/sec
2.46
2.48
2.50
2.52
2.54
2.56
2.58
2.60
TIME (sec)
(b)
10^{3}
10^{2}
10
d-^{3}He PROTON COUNT RATES
2.46
2.48
2.50
2.52
2.54
2.56
2.58
2.60
TIME (sec)

Fig. 3

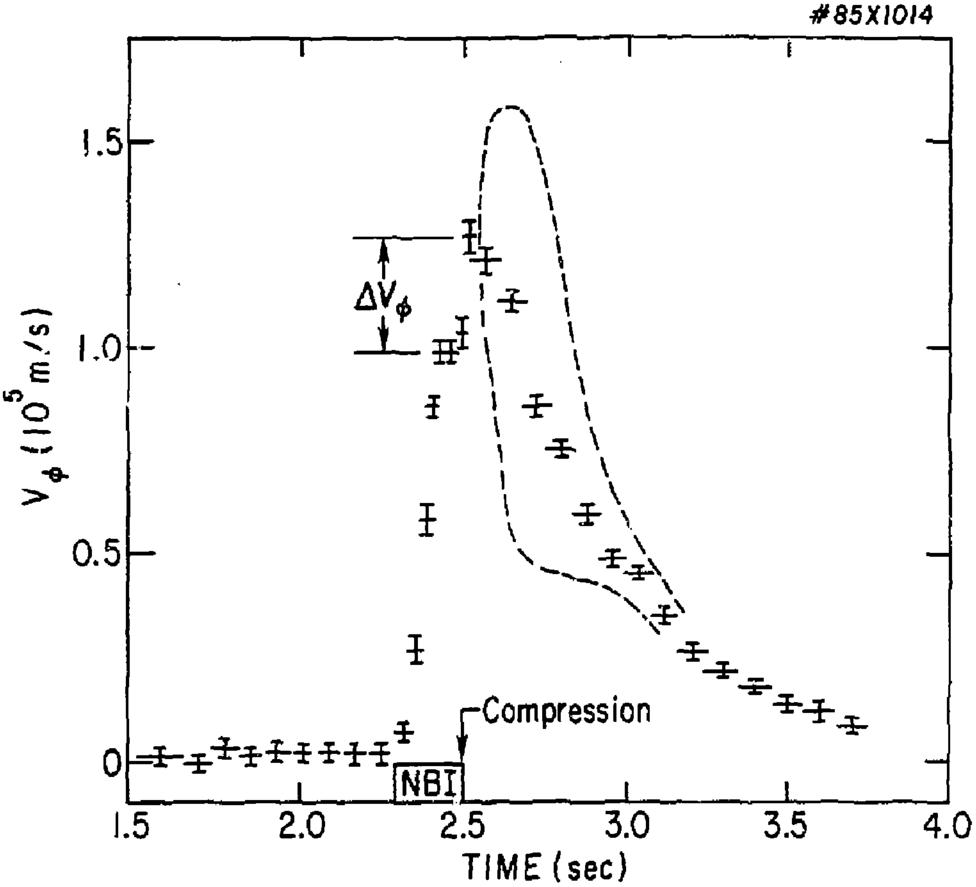
#85X1014
V_ϕ (10^5 m/s)
1.5
1.0
0.5
0
ΔV_ϕ
Compression
NBI
1.5
2.0
2.5
3.0
3.5
4.0
TIME (sec)

Fig. 4

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