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# Regime of Improved Confinement and High Beta in Neutral-Beam-Heated Divertor Discharges of the ASDEX Tokamak

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A new operational regime has been observed in neutral-injection–heated ASDEX divertor discharges. This regime is characterized by high $\beta_p$ values comparable to the aspect ratio $A$ ($\beta_p \leqslant 0.65A$) and by confinement times close to those of Ohmic discharges. The high-$\beta_p$ regime develops at an injection power $\geqslant 1.9$ MW, a mean density $\bar{n}_e \geqslant 3\times10^{13}$ cm$^{-3}$, and a $q(a)$ value $\geqslant 2.6$. Beyond these limits or in discharges with material limiter, low $\beta_p$ values and reduced particle and energy confinement times are obtained compared to the Ohmic heating phase.

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One of the main goals in fusion-oriented tokamak research is the production and investigation of high-temperature, high-$\beta$ plasmas. The stimulation for these efforts is the requirement of high $\beta$ values for a fusion reactor device in order to achieve high fusion power output at low investments of magnetic field energy. A significant portion of the research program of all major tokamaks is devoted to the investigation of the confinement properties of auxiliary-heated high-$\beta$ tokamak plasmas.[1] ASDEX ($R = 165$ cm, $a = 40$ cm, toroidal field $B_T \leqslant 2.8$ T, plasma current $I_p \leqslant 0.5$ MA) is a divertor tokamak with neutral-beam injection (NI) presently capable of delivering 3.1 MW to the plasma for 200 msec at a source voltage of 40 kV. The power is delivered by two beam lines both oriented tangentially in the direction of the plasma current. Hydrogen is injected into deuterium plasmas. The technical details of the ASDEX tokamak and the NI system are described by Keilhacker *et al.*[2] and Stäbler *et al.*[3] With NI an increase is seen in both the ion and electron temperatures $T_i$ and $T_e$. The increase in total energy content, however, is reduced by a decrease in global energy confinement time $\tau_E$ and in particle confinement time $\tau_p$.[4] Two different types of discharges, however, can develop.[5] In one case the reduction in confinement lasts throughout the NI pulse. Because of the low values of $\beta_p$ achieved during these discharges they are called L-type discharges. In the other case, particle and energy confinement suddenly improve during the NI pulse. As a higher value of $\beta_p$ is obtained, this discharge type is called H type.

The two types of discharges are compared in Fig. 1 (left column, L type; right column, H type) The only difference in the externally controlled parameters is an increase in injection power $P_{\rm NI}$ into the plasma vessel from 1.6 MW (L type) to 1.9 MW (H type).

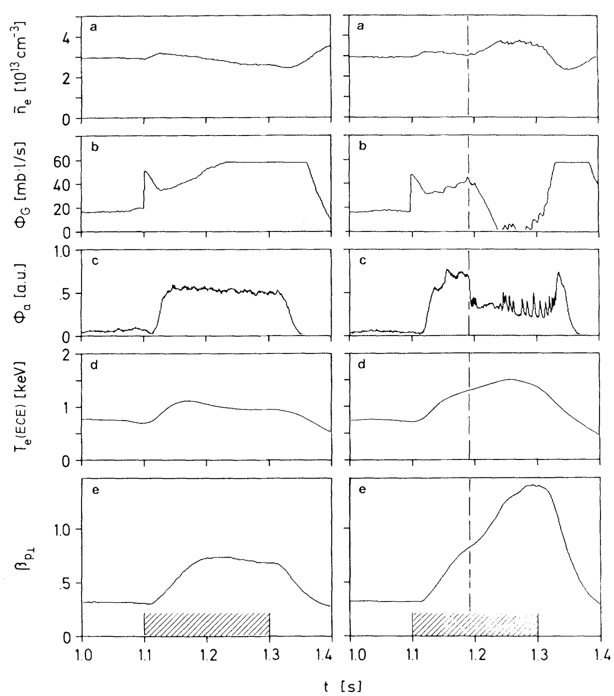


FIG. 1. Time dependence of various plasma parameters of L-type (left column) and H-type (right column) discharges: (a) line averaged density $\bar{n}_e$, (b) external gas flux $\varphi_G$, (c) atom flux $\varphi_a$ ($E$ =273 eV) reflected from the divertor neutralizer plate, (d) central electron temperature, and (e) beta poloidal. The neutral injection phase is indicated by the hatched time interval. The dashed vertical line indicates the transition from the L to the H regime (see text).

*L-type discharge.*—The left-hand column of Fig. 1 shows the line-averaged density during the NI pulse (indicated by the hatched time interval) as it develops during a discharge with feedback-controlled density. The density tends to decrease although the external gas flux $\varphi_G$, plotted in Fig. 1(b) (left column), increases up to the maximum, and an additional 5 mb • L/s • MW are deposited by the beams. From the total ionization rate (deduced from toroidal $H_\alpha$-$D_\alpha$ measurements), which rises while the density decreases, it is concluded that $\tau_p$ deteriorates during NI. Another indication of the change in particle confinement is the outflux of plasma ions measured at energies $\geq$100 eV as a flux $\varphi_a$ of back-reflected atoms from the divertor neutralizer plates by a charge exchange analyzer. $\varphi_a$ increases during NI as shown in Fig. 1(c) (left column). The increase in atom flux is caused by a reduction in particle confinement and to a lesser extent by an increase in the plasma-edge ion temperature. Another indication of a degradation in confinement is an increase in hard x-ray radiation caused by an enhanced outflux of runaway electrons produced during the initial phase of the discharge. The deterioration in $\tau_p$ is accompanied by a decrease in energy confinement time $\tau_E$ during NI into L-type discharges which is a common feature of NI-heated tokamak plasmas.[1] The value of $\tau_E$ during an Ohmically heated deuterium discharge with $\bar{n}_e = 3 \times 10^{13}$ cm$^{-3}$ and $I_p$ =0.3 MA is between 50 and 70 msec. Figure 2 shows $\tau_E$ (deduced from temperature and density profiles) and $\tau_E^+$ (deduced from the diamagnetically measured $\beta_{p\perp}$) during NI versus $\bar{n}_e$ at $I_p$=0.3 MA and for $P_{\rm NI} \geq 2$ MW. $\tau_E$ and $\tau_E^+$ are determined from the absorbed power (shine-through, orbit, and primary charge-exchange losses are subtracted). There is good agreement between thermally and magnetically measured energy confinement times. In L-type discharges $\tau_E$ and $\tau_E^+$ decrease to 20–30 msec. A beam power of 2 times the power input during the Ohmic phase is sufficient to affect the confinement deleteriously.[5] In addition to the observed decrease in global energy confinement, the favorable $\tau_E \propto \bar{n}_e$ scaling of Ohmically heated plasmas is not seen with NI into L-type discharges. A numerical transport-code analysis of this discharge type[6] shows that the degradation of confinement with NI results from enhanced electron heat conduction and particle diffusion. The ion heat conduction continues to be approximately neoclassical.

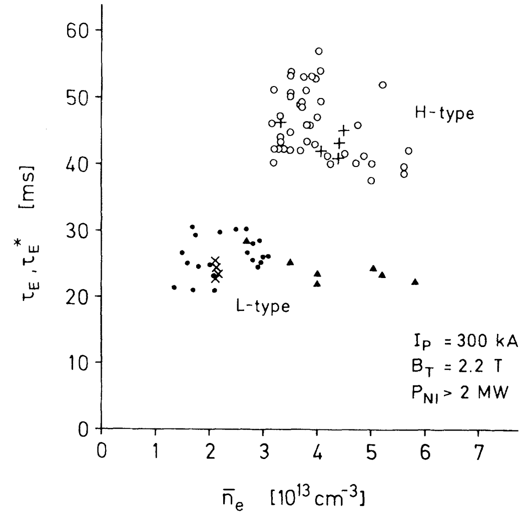


FIG. 2. Global energy confinement time vs average line density for toroidal limiter (triangles) and divertor discharges (other symbols). $\tau_E$ (plusses and crosses) is deduced from thermal profiles and $\tau_E^+$ (open circles, solid circles, and triangles) is determined from the diamagnetically measured $\beta_{p\perp}$.

*H-type discharge.*—Some of the discharge characteristics are plotted in the right-hand column of Fig. 1. The discharge begins as L type. The line density tends to decrease with the beginning of NI [Fig. 1(a) (right column)], and the external gas valve counteracts by increasing its throughput [Fig. 1(b) (right column)]. At $t = 1.18$ sec, however, as indicated by the dotted line, the density suddenly increases without modifications from the external controls. The gas valve closes, but nevertheless the density continues to rise and exceeds the value obtained during the plateau of the Ohmic phase. From bolometric measurements and from the intensity of O VI and Fe XVI radiation (O and Fe are intrinsic impurities), it can be excluded that the density rise is caused by an enhanced impurity influx. All three signals, normalized with respect to the plasma density, decrease at the transition into the H regime.

The increase in density is caused by a sudden improvement in particle confinement. This can be seen from the variation of the back-reflected atom flux from the neutralizer plates [see Fig. 1(c) (right column)]. At the transition into the H regime the back-reflected flux drops suddenly as a consequence of a corresponding reduction in plasma ion outflux. The improvement in particle confinement is also indicated by $H_\alpha$-$D_\alpha$ and hard x-ray radiation measurements. At the transition both signals decrease approximately to the values obtained during the Ohmic phase.

The improvement in particle confinement in H-type discharges is accompanied by an improvement in global energy confinement. In Fig. 1(d) (both columns) the time variation of the central electron temperature $T_e$ (measured by electron cyclotron emission) of the two discharge types is compared. In the H regime $T_e$ increases to a value 540 eV above $T_e$ of the L-type discharge despite the increase in electron density. The overall improvement in plasma energy content and confinement time is illustrated in Fig. 1(e) (right column), which shows $\beta_{p\perp}$ (with tangential injection, this signal contains only a minor beam contribution). Compared to the L-type discharge [Fig. 1(e) (left column)], $\beta_{p\perp}$ increases by a factor of 2, although the injection power is only 18% larger. The energy confinement time of the H type is 40–50 msec at $I_p = 0.3$ MA (see Fig. 2) and increases linearly with plasma current. At $I_p = 0.38$ MA, $\tau_E^+$ is between 50 and 70 msec. In the H regime the values of $\tau_E$ and $\tau_p$ attained during Ohmic discharges are approximately recovered. This result holds up to the highest injection power of 3.1 MW.

$\Delta[\beta_p + \frac{1}{2} l_i]$, the increase in the measured signal $\beta_p + \frac{1}{2} l_i$ due to NI, is plotted in Fig. 3 versus the power, $P_{NI}$, injected into the vessel, both for L-type (solid symbols) and H-type (open symbols) discharges. The plasma current is 0.3 MA. There are experimental indications that the internal inductance $l_i$ does not change much during NI (a slight reduction cannot be excluded). $\beta_p + \frac{1}{2} l_i$ is deduced from the plasma equilibrium by use of either the applied vertical field or measurements of the poloidal magnetic flux and field near the plasma boundary. The values for $\beta_p + \frac{1}{2} l_i$ obtained from the two measurements agree within 10%. $\Delta[\beta_p + \frac{1}{2} l_i]$ of L-type discharges increases linearly with injection power. No saturation or $\beta_p$ limit is observed. Above 1.9 MW the $\Delta[\beta_p + \frac{1}{2} l_i]$ curve of the H-type discharge branches off. Although there is a larger scatter in the data points, there seems to be no saturation in $\beta_p + \frac{1}{2} l_i$ of the H-type discharges either.

So far, the highest $\beta_p$ value measured at a plasma current of 0.2 MA is 2.65 (~0.3 is the beam contribution). This value corresponds to 65% of the aspect ratio $A$ ($A = 4.1$). The highest observed value of the volume-averaged toroidal beta is $\langle\beta\rangle = 1.06\%$ at a $q(a)$ value of 2.8.

In the following, the experimental conditions and the range of plasma parameters which allow

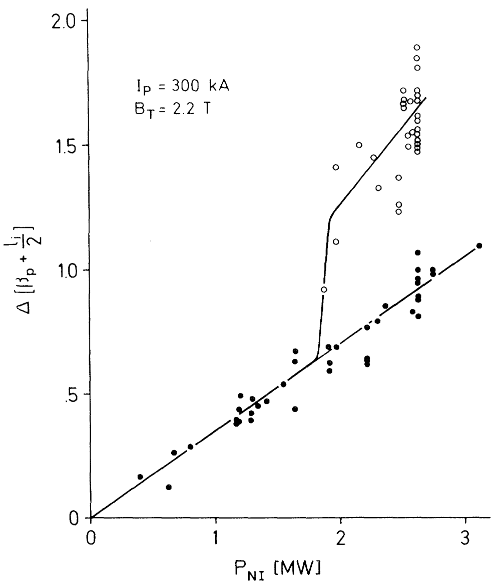


FIG. 3. Increase in $\beta_p + \frac{1}{2}l_i$ with respect to the Ohmic phase vs the power $P_{\rm NI}$ injected into the vessel in the L regime (solid symbols) and the H regime (open symbols).

the development of the H regime are described. Figure 3 reveals that there are only L-type discharges at an injection-power level $P_{\rm NI} < 1.9$ MW. Above this power level both discharge types are encountered depending on $\bar{n}_e$ and $B_T$. Figure 2 reveals that the H phase develops above $\bar{n}_e = 3 \times 10^{13}$ cm$^{-3}$. In the density range $(3-3.5)\times 10^{13}$ cm$^{-3}$ there is a transition region where either an L-type or an H-type discharge can develop without external modifications. At high density at $I_p = 0.38$ MA the achieved $\beta_p$ values of the H regime decrease again, possibly because of the limitation in available injection power or deposition depth, and L-type discharges can develop.

H-type discharges have been obtained at plasma currents between 0.2 and 0.4 MA. A decrease of the toroidal magnetic field resulting in a lower $q(a)$ value can lead to a transition into the L regime. H-type discharges have not been observed for cylindrical values of $q(a) < 2.6$ [$q(a) \equiv 2\pi a^2 B_T/\mu_0 R I_p$].

The H regime is characteristic of divertor discharges in ASDEX. It has never been obtained in ASDEX limiter discharges. $\tau_E^+$ values of toroidal limiter discharges are plotted in Fig. 2. Given a limited number of shots with material limiters, the accuracy of this statement is mainly based on the observation that the H regime disappears at the transition from divertor to limiter discharges. In sequential discharges, both divertor and limiter behavior could be compared. The H-type characteristics of the divertor discharges with NI always disappeared in the limiter discharge which followed.

The observation that the H type does not develop in limiter discharges may be the result of the higher impurity content of these discharges. The role of impurities in the formation of the H-type discharges was empirically studied by puffing small amounts of low-$Z$ ($CH_4$) and high-$Z$ (Kr) gases into the discharges. The addition of impurities deteriorates an H-type discharge or prevents its formation. As a result of radiation, particularly from the plasma edge, added impurities or those released from the limiter may suppress the formation of very broad, nearly circular, temperature and density profiles, which are characteristic of H-type discharges.

The achieved $\beta_p$ values and confinement times in H-type discharges are affected by short bursts, detected by Mirnov coils and soft-x-ray diodes, which lead to periodic density and temperature reductions in the outer plasma zones. The gross plasma parameters remain unaffected in the plasma center. In particular, these discharges show no sawtooth activity. Bursts are also observed in the back-reflected flux from the neutralizer plate [see Fig. 1(c) (right column)] as thermal particles are expelled from the main plasma into the boundary layer. There are indications that these bursts can cause the transition back into the low confinement regime which, however, is not maintained as long as enough beam power is available. Figure 1(c) (right column) shows that the H regime is sustained until 20 msec after termination of the beams. Then the discharge changes to an L-type discharge as indicated by a sudden increase in flux, $\varphi_a$. The transition back into the L regime occurs simultaneously with, or is triggered by, a burst. Possibly as a result of the decaying beam, the plasma does not return to the H regime, but transforms into the Ohmic heating phase as an L-type discharge.

In summary, a new operational regime in neutral-injection–heated discharges of ASDEX is discovered with high $\beta_p$ values. It is documented that NI-heated discharges can have confinement properties close to those of Ohmic discharges. The new regime extends over a wide range of $q$ values, plasma currents, and densities, but—so far—has only been obtained in divertor discharges.

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# Atomic-Scale Structure of Random Solid Solutions: Extended X-Ray-Absorption Fine-Structure Study of $Ga_{1-x}In_xAs$

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In random solid solutions of $Ga_{1-x}In_xAs$, the Ga-As and In-As near-neighbor distances change by only 0.04 Å as $x$ varies from 0.01 to 0.99, despite the fact that this alloy accurately follows Vegard's law, with a change in average near-neighbor spacing of 0.17 Å. This result contradicts the underlying assumption of the virtual-crystal approximation. Nonetheless, the cation sublattice approaches a virtual crystal with a broadened single distribution of second-neighbor distances, whereas the anion sublattice exhibits a bimodal anion-anion second-neighbor distribution.

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In random solid solutions the atomic-scale structure, i.e., the nature of the near-neighbor (nn) environment, is not well understood because of the fact that standard diffraction techniques average the structure over distances which are large on the scale of a lattice constant. One consequence of this lack of microscopic information is that calculations of the properties of solid solutions have often relied on simple approximations. One of the most used of these models is the virtual-crystal approximation (VCA)[1] which assumes that all atoms occupy the average lattice positions defined by the x-ray lattice constants. With use of the VCA, properties of the alloy, such as the electronic band structure, can be calculated whether or not the alloy lattice constant varies linearly with composition between those of the end members, i.e., follows Vegard's Law.[2] Similarly for dilute alloys, the assumption that the impurity-host distance is equal to the host-host distance is often used to calculate alloy properties, even those which may depend very sensitively on distance, e.g., the magnetic properties and the NMR and ESR spectra. However, the validity of this assumption, namely, an average distance or equal impurity and host distances, has never been systematically addressed with experimental measurements.

We have used extended x-ray-absorption fine structure (EXAFS) to address these issues in random solid solutions since this technique is well suited to the study of local bonding, especially the determination of nn distances relative to a well-defined standard. As a result EXAFS has been used successfully to study other issues in alloys. These include studies of dilute binary metal alloy systems[3] where the main issues addressed were local clustering or chemical order, such as Guinier-Preston zones, and deviations from the continuum elastic theory. Other EXAFS studies of ternary alloys[4-6] have indicated that the nn distances do differ from the average, but the main emphasis was on other issues and so these studies were not performed over a wide

 