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Density Limit Physics in Stellarators

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Abstract

Discharges in the W7-AS stellarator undergo a radiation collapse if the electron density is raised. This density limit was investigated in detail in discharges with constant line integrated density and a duration of up to 2 seconds. The central factor governing the physics of this density limit in stellarators was demonstrated to be the decreasing net power to the plasma core as the result of increasing radiated power.

The aim of producing steady state discharges at the highest possible density was best achieved in H-mode discharges where ELM's restricted the impurity in ux to the plasma and an equilibrium with suitably low radiation power levels was possible.

A simple model of bulk radiation predicted that the limiting density should depend on the squareroot of the heating power density. This was experimentally confirrmed for smaller stellarators (W7-A, Helitron-E, CHS and W7-AS) but a larger stellarator (LHD) performed better than predicted.

Keywords:

density limit, radiated power, impurity transport

1. Introduction

The parameter of interest in fusion is the triple product, $n_e \tau_E T_i$. The optimum value is expected near the operational density limit. From the international scaling law for the energy confinement time; ISS-95 [1], and the Lawson criterion the following expression at the density limit, n_c, can be obtained :

$$(n_e \tau_E)_{\max} \propto \bar{n}_c^{1.51} \quad (1)$$

for fixed plasma volume, V, and heating power, P_{in}. Thus the understanding of the density limit is a critical issue because it is ultimately closely related to stellarator reactor performance.

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2. Survey

W7-AS is a low-shear, modular stellarator with 5 periods, a major radius of 2 m and an effective minor radius smaller than 0.18 m. The rotational transform for most discharges was in the vicinity of 0.34, where the configuration is bounded by 10 poloidal limiters. In the H-mode discharge, the rotational transform is in the vicinity of 0.56, where the configuration is bounded by a separatrix.

The main results are briefly summarized. Firstly, different density limit mechanisms of the plasma in NBI discharges with B_0 = 0.8 T, 1.25 T and 2.5 T and power inputs of 0.5 MW and 1.0 MW were observed. Secondly, experiments with a ramp down in ECRH power were carried out. Thirdly, the oscillation in radiated power, P_{rad}, and diamagnetic energy, W_{dia}, in discharges at 1.25 T is discussed in detail. Fourthly, in a density scan for H-mode experiments with 0.5 MW ECRH, it is shown that ELM's are a way of achieving steady state operation. Fifthly, the maximum $\overline{n}_e$ reached as a function of P_{in} and B in W7-AS is compared to that deduced for Heliotron-E, CHS and LHD.

2.1 Magnetic field and power scan

The time evolution of W_{dia}, $\overline{n}_e$, central electron temperature and total P_{rad} for a magnetic field and power scan is shown in Fig. 1. These discharges share the common feature that initially W_{dia} decreases with time, even in discharges where $\overline{n}_e$ can be held at a constant value. The increase in P_{rad} during density plateau discharges was found to be caused by a steady increase in centrally peaked profiles of the radiation power density which in turn were due to a peaking of the impurity ion density [2]. This has also been observed previously in the W-VIIA stellarator [3] and Heliotron-E [4]. The radial profiles of the diffusion coefficient, D, and inward pinch velocity, v, of impurities needed for the simulations were calculated from measurements of the time evolution of soft X-ray emission and Al impurity lines after aluminium impurity injection by laser blow-off [5]. The plasma cooling and increasing P_{rad} is reinforced by the observed peaking of the electron density profiles so that the net heating power per particle was further decreased. The NBI radial profiles of deposited power in Fig. 2 are for a similar discharge at a time before density and temperature rapidly change as the density limit is reached. The net power to the plasma therefore decreases as the density limit is reached.

In these discharges it can be seen that at a particular value of $\overline{n}_e$, a dramatic decrease in W_{dia} and $\overline{n}_e$ occurs which may or may not lead to termination of the discharge. Extending the duration of operation of W7-AS plasmas with NBI heating alone at a power greater than 0.5 MW is diffcult because loss of density control and rising n_e causes the density limit to be reached.

In W7-AS, density plateau discharges with constant n_e up to 2 s were considered. At sufficiently low densities, discharges of duration up to 2 s were possible. Increasing ne leads to a more rapid decrease in W_{dia}, so that the discharge length before collapse is in uenced by the choice of $\overline{n}_e$. The density limit in W7-AS therefore decreases as the required discharge length is increased. These density plateau discharges are closely related to the improved confinement scenario in W7-AS (H-NBI mode) but at densities in the vicinity of the density limit [6].

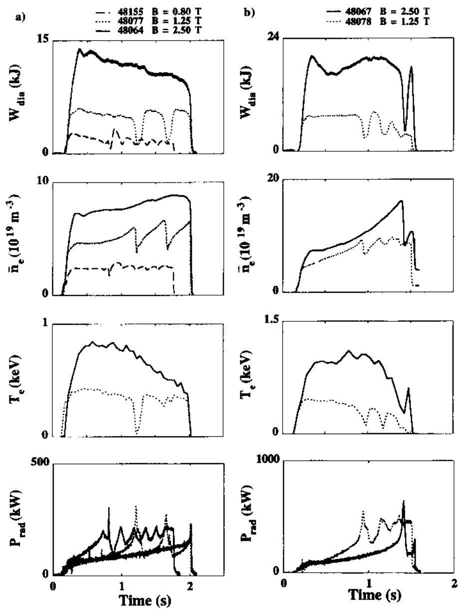

Fig. 1 Overview of density limit discharges at a rotational transform, ι, of 0.34 and with a) P_{NBI} = 0.5 MW and b) P_{NBI} = 1.0 MW.

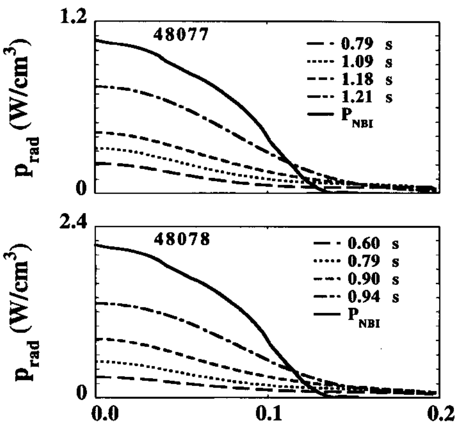

Fig. 2 The radial profile of radiated power density for the discharges at 1.25 T display the typical increase with time in the plasma core at the density limit in W7-AS.

2.2 ECRH power ramp

Details of the radiation collapse in the density limit were investigated by performing power ramp down experiments in ECRH plasmas. This study takes advantage of the feature of current disruption free operation in stellarators.

From an initial ECRH power of 0.5 MW, the deposited power was ramped down to 50 kW over a period of 0.7 s as shown in Fig. 3. At a central electron density of 6×10^{19} m^{-3} and B = 2.5 T, the power is centrally deposited with a typical FWHM of 4 cm. As expected, a decrease in W_{dia} with time due to decreasing net power input to the plasma is observed. As the plasma core cools, a stage is eventually reached where P_{rad} rapidly increases.

Although the plasma at low heating power is only optically thick for ECE above about 300 eV for the central densities of 6×10^{19} m^{-3}, it is nevertheless interesting to view the time evolution of $T_e(r)$ with steps of 10 milliseconds. As shown in Fig. 4, towards the end of the discharge distinctly hollow electron temperature profiles can be measured. Furthermore, the plasma radius clearly contracts. In contrast to tokamaks, this plasma contraction does not lead to any sudden dramatic termination of the plasma. Indeed Fig. 1 shows the possibility that the plasma can recover if the plasma can be sustained long enough so that impurities are ejected.

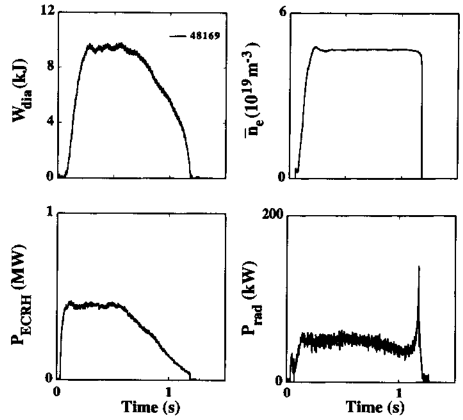

Fig. 3 Overview of ECRH power ramp down discharges, initially with P_{ECRH} = 0.5 MW, at a rotational transform, ι, of 0.34 and B = 2.5 T.

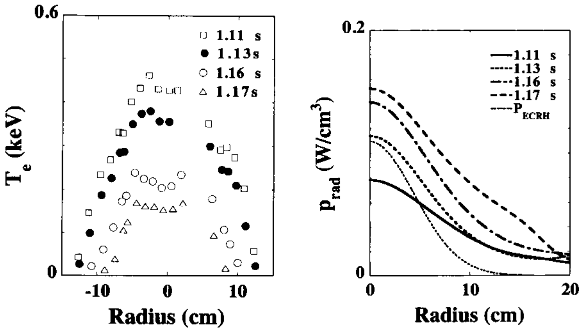

Fig. 4 Radial profile evolution of electron temperature from ECE measurements and radiated power from bolometer measurements in the collapsing phase. The ECRH deposition profile is calculated with FWHM = 4 cm at t = 1.15 s where P_{abs} = 50 kW.

2.3 Oscillation near density limit

In discharges at B = 1.25 T, the dramatic decrease of W_{dia} and recovery are most pronounced. By evaluating the experimental cooling curve of impurity ions, insight into the mechanisms of the oscillation near the density limit can be obtained.

The steady state cooling rates, L(Z,T), for low density, high temperature plasmas in a corona model with the absence of transport effects can be rewritten as:

$$\frac{P_Z}{n_e^2} = \frac{n_Z}{n_e} \mathrm{L}(\mathrm{Z},T) \tag{2}$$

where P_Z is the radiative loss rate from impurity ions of charge Z per unit volume, n_e is the electron density and n_Z is the impurity ion density. Experimentally, the following relation is of interest:

$$\frac{P_{rad}}{V_p\,(\bar{n}_e)^2} = \frac{n_Z}{n_e} \mathrm{L}(\mathrm{Z},T) \tag{3}$$

where variables with dependences on the local values of density and temperature are replaced with a volume average. In Fig. 5, $P_{rad}/\bar{n}_e^2$ and P_{rad} for the collapsing discharge at B = 1.25 T and P_{NBI} = 0.5 MW are plotted as a function of the derived mean plasma temperature, $\langle T_e(\mathrm{eV})\rangle$, for NBI plasmas, assuming $T_e \approx T_i$ so that:

$$\langle T_e(eV)\rangle = W_{dia}/(3e\bar{n}_e V_p). \tag{4}$$

In order to sustain the oscillatory evolution in the stored energy for fixed NBI power, there should be some non-linear (hysteresis) relation between the loss terms and W_{dia}.

It can be seen that the hysteresis in n_Z/n_e L(Z,T) is much smaller than in P_{rad}, as there is only a small difference in the phases where the plasma is collapsing or recovering. The hysteresis in P_{rad}(W) is attributed to the difference in electron density in the collapsing and recovering phase. The oscillation of P_{rad} is caused by a

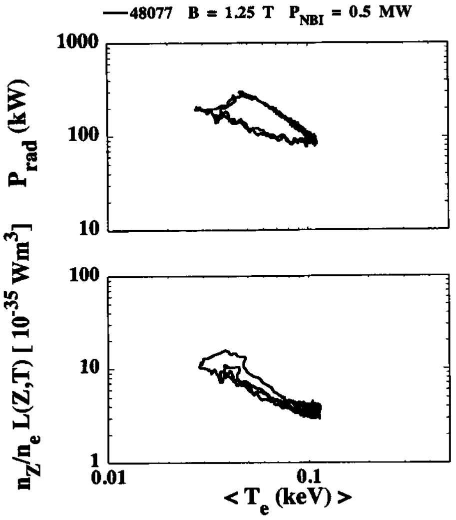

Fig. 5 Total radiated power and normalized radiated power plotted as a function of derived mean temperature.

rapid ejection of density when the plasma is cooled down.

The first experiments of 20 s duration on LHD with 0.5 MW NBI heating at 1.5 T for $\bar{n}_e$ above 5×10^{19} m^{-3} also show oscillations with a period of 1 to 3 seconds in the plasma temperature, plasma density and impurity radiation [7]. At densities of 3×10^{19} m^{-3} such phenomena were not observed.

2.4 H-mode

Discharges with 0.5 MW NBI heating at 2.5 T and at an edge iota value, $\iota(a)$, of 0.553 and 0.557 were compared. The transition into a H-mode in W7-AS has been shown to be a sensitive function of $\iota(a)$ [8]. The discharge with $\iota(a) = 0.557$ makes a transition to the H-mode but with $\iota(a) = 0.553$ it does not. The rapid rise of P_{rad} and the soft X-ray power from a camera with a 12.5 μm Be filter reflects the improvement in confinement of impurity ions in addition to the improvement for deuterium ions. Effectively, a density limit in the H-mode discharge occurs as P_{rad} reaches values greater than the nominal input power. A comparison of 2 discharges with a density ramp dramatically emphasizes that the maximum in W_{dia} is observed at a lower density in the discharge with a H-mode because of its higher impurity concentration.

The path to steady state confinement in W7-AS therefore cannot be found in ELM free H-mode discharges. Shown in Fig. 6 is a $\bar{n}_e$ scan in 1.0 MW

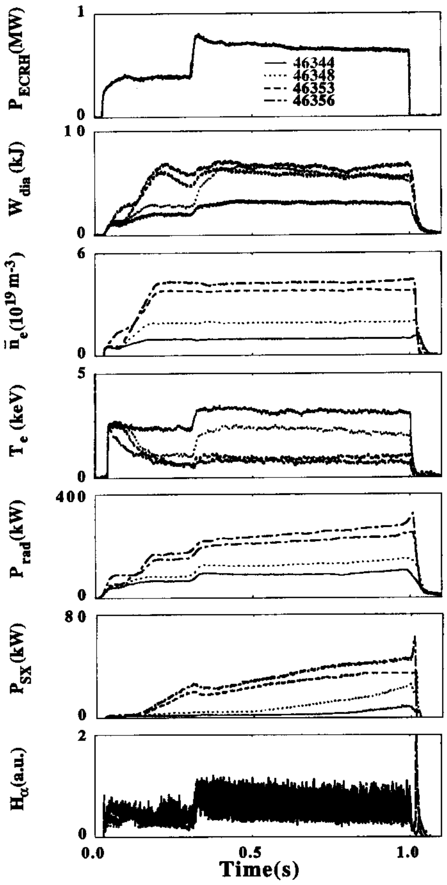

Fig. 6 Overview of a density scan in ECRH discharges at $B_0 = 2.5$ T and $\iota(a) = 0.564$ with $P_{ECRH} = 1.0$ MW.

ECRH plasmas at 2.5 T and $\iota(a) = 0.564$. As indicated by H_α measurements, the two highest densities make the transition to the H-mode [9], have considerable ELM activity and the radiated soft X-ray power have reached equilibrium. It is evident that without a transition to the H-mode, the soft X-ray radiated power does not reach equilibrium. The radial profiles of P_{rad} rises continuously with a peaked profile in the discharges at the lower densities while at the higher densities the peaked profiles appear to have almost reached a steady state. Therefore the path to steady state confinement in W7-AS will be, like tokamaks, through such H-mode discharges with strong ELM activity. This assumes that such a scenario is compatible with machine operation in the presence of powerflux bursts on the plasma facing components.

2.5 Scaling

Theoretically, assuming a simplified radiation model and one dimensional transport to describe the energy balance, it is possible to predict the scaling of n_c with respect to the volume averaged absorbed power in stellarators [10].

$$\bar{n}_e^2 < KP_{abs} / V_p \qquad (5)$$

where the coecient K is given as:

$$K^{-1} = 2\int_0^1 L(Z,T)\left(\frac{n_Z}{n_e}\right)\left(\frac{n_e}{\bar{n}_e}\right)^2 xdx. \qquad (6)$$

In this model it is assumed that the plasma is core radiation dominated and L(Z,T) increases strongly when the temperature becomes lower than some critical temperature. In this simplified situation, the density limit scales with $P^{0.5}$. This model is consistent with density limit experiments over the last four years of operation in W7-AS and published results from other stellarators which are summarized in Fig. 7. In contrast to Fig. 7, a number of discharges in LHD lie above the density limit scaling law predicted on the basis of data from smaller stellarators. This suggests that a theoretical basis for a density limit scaling law to include such parameters as machine size is needed [12].

The addition of a divertor to W7-AS is planned and should lead to a reduction in the impurity fluxes to the plasma. Density limit experiments with a divertor then should achieve sustainable discharges at higher values of density as the onset of plasma cooling may not lead to P_{rad} levels that are comparable to the input power.

3. Conclusions

Two types of density limit phenomena were identified. These were a simple density limit, which is characterized by the monotonous increase of radiation loss in time, and a self-sustained oscillation of radiation loss. In the latter, the rapid ejection of electrons in the cooled plasma rather than the selective loss or accumulation of impurities is a feature.

From ECRH power ramp down experiments it could be inferred that the density limit in stellarators is determined by the power balance of P_{in} and P_{rad}.

When $P_{rad} \approx P_{in}$, the plasma undergoes disruption free contraction. When impurity ion concentration is reduced by bulk plasma density ejection, the discharge is able to recover. The cyclic behavior of W_{dia} versus net P_{in} is an interesting feature that highlights the interdependence of the density limit, P_{rad} and impurity transport.

The observation that H-mode discharges with strong ELM activity reach equilibrium with respect to the radial profiles of P_{rad} within the 2 s duration of the discharge, suggests that this scenario, like tokamaks, will be the path to steady state confinement.

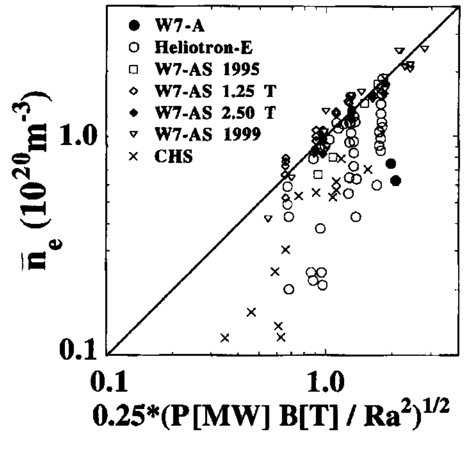

Fig. 7 Comparison of the empirical stellarator scaling law [11] and density limit discharges in W7-A, Heliotron-E, CHS and W7-AS.

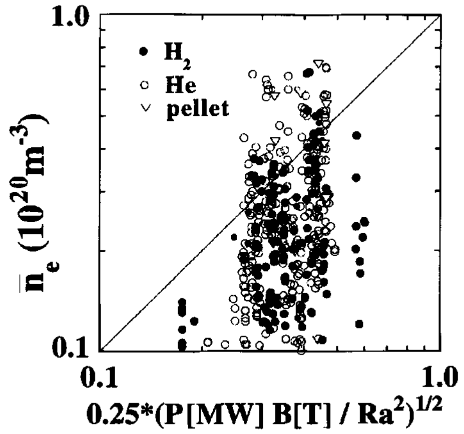

Fig. 8 Comparison of the empirical stel-larator scaling law [11] and density limit discharges in LHD.

Scaling studies confirm the square root dependence on P_{in} predicted for the bulk radiation dominated density limit discharges in small stellarators [10]. The density limit in LHD is above that predicted by this scaling law and suggests that further theoretical work is necessary.

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