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In this issue . . .

Small, stable plasmas, fully decoupled from the plasma-facing components in W7-X

We report on unusual discharges observed in Wendelstein 7-X (W7-X) in the OP1.2a and OP1.2b operation phases, exemplified by the discharge 20171207.021 obtained at the end of OP1.2a. These discharges displayed long, stable phases during which the plasma had shrunk to a smaller minor radius, with no contact with material components, and still remained relatively well confined for many confinement times – in some cases many seconds. The results in this report were presented as a poster at the APS-DPP virtual meeting in November 2020. A more complete description is being prepared for publication in the peer-reviewed literature.

Figure 1 shows snapshots from a video diagnostic camera from the discharge 20171207.021 for both the “full-size” and “small” phases of the discharge. This plasma shrank in minor radius to 0.62 times its original value, after having been full-size for several seconds (Figs. 1–3). The shrinkage was triggered by a strong hydrogen gas puff. The plasma stably remained in the small phase for several seconds, until it was terminated by the preprogrammed end of electron cyclotron resonant heating (ECRH). During the phase of reduced size, it had central T_e of ~ 2.5 keV and central n_e of 4 to 6 $\times 10^{19}$ m^{-3}. The plasma clearly had no

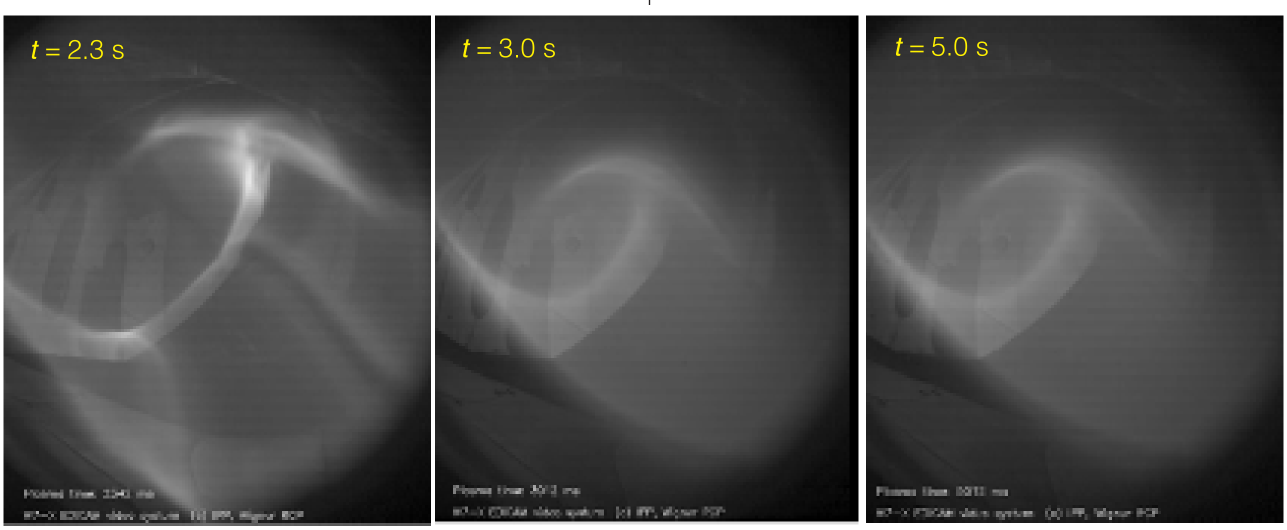

Fig. 1. Three snapshots of discharge 20171207.021. Left: The plasma is full-size for the first several seconds. Shown here is a video diagnostic image at t = 2.3 s, shortly before the plasma begins to shrink. Middle and right: Snapshots from t = 3.0 and 5.0 s. The visibly smaller plasma remains stable for several seconds.

direct contact with material objects (as confirmed convincingly by a number of diagnostics) and all the heating power (about 3 MW) was presumably dissipated in the clearly visible, several cm thick radiating mantle defining the edge of the plasma.

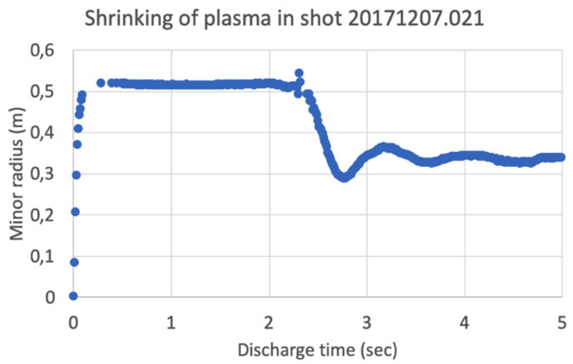

Fig. 2. Based on the video diagnostic images, the minor radius of the plasma can be estimated. The plasma clearly shrinks and settles into a reduced minor radius of ~0.32 m after some small, damped oscillations. This is about 0.62 times its original minor radius.

The plasma in this shot had parameters typical for W7-X before it shrank. During the phase of decreased size, its parameters and confinement times were roughly as one would expect, when taking the reduced minor radius into account.

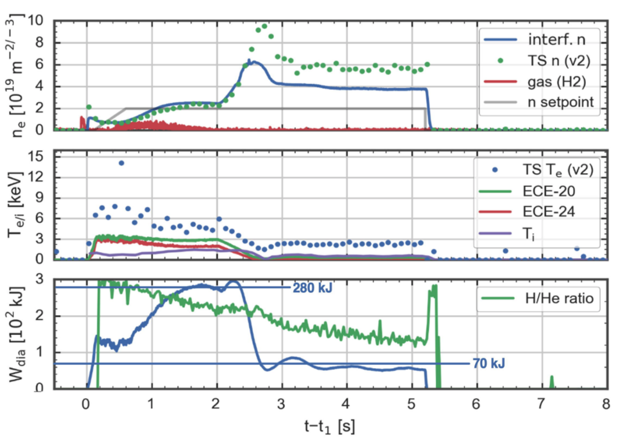

Fig. 3. Time traces of a few key quantities for the plasma discharge 20171207.021 also shown in Figs. 1 and 2. The lower trace shows the stored energy dropping by about a factor of 4.

The confinement time (about 23 ms) is commensurate with that for the full-size plasma, when adjusted for its smaller minor radius. The ISS04 scaling for energy confinement time has a strong scaling with minor radius, $\sim a^{2.28}$, so τ_E would therefore be predicted to be reduced by a factor $0.62^{2.28} = 0.34$, which is close to the observed factor of ~0.25 (stored energy decreasing from 280 kJ to 70 kJ, τ_E decreasing from 93 ms to 23 ms). The slightly larger reduction of the energy confinement time seen experimentally may be due to the relatively larger reduction of ion temperature (Fig. 3) due to charge-exchange neutrals. The small-plasma phase lasts for approximately 2.4 seconds, i.e., approximately 100 confinement times, and was terminated as preprogrammed.

Further "small" plasma discharges have since been identified, not only from the OP1.2a phase but also from the OP1.2b phase. These plasmas can be thought of as extreme versions of the power-detached radiating-mantle plasmas seen in W7-X before boronization [1], some of which were visibly smaller than detached plasmas obtained after boronization [2].

In the following, we provide a simple argument for why plasmas with smaller radii should be stable, rather than collapse, or grow back to full size, at least under the following simplifying assumptions: We assume that the plasma is surrounded by a radiating mantle of finite but small and constant thickness δ, with a radiated power per unit volume σ, also assumed constant over time and across the radiating mantle. The mantle is located at a distance r from the magnetic axis. Then the total radiated power from the radiating mantle can be estimated as $P_{loss} = 4\pi^2 Rr\delta\sigma$.

If we ignore core radiation losses, this relation trivially determines the radius r_r for which the plasma radiates all its power in the radiating-mantle layer ($P_{loss} = P_{heat}$):

$r_r = P_{heat}/(4\pi^2 R\delta\sigma)$.

Let a be the usual—in this context maximum—plasma size for a particular W7-X configuration. For regular island divertor operation, this is set by the edge island chain whose field lines are intersected by the divertor. If $r_r > a$, the plasma will not radiate its full power in the radiating mantle but will be expected to touch the divertor and deposit the leftover (nonradiated) energy there, and the plasma minor radius will be equal to a.

If conditions change such that r_r becomes smaller than a, the plasma will shrink to the minor radius r_r since it would otherwise be radiating more heat than it is receiving. It follows that if one changes P_{heat}, σ, or δ, the plasma will adjust its minor radius accordingly until $r_r = a$. Changing P_{heat} is easily done experimentally, and σ can be increased by increasing the plasma density or adding impurity seeding. Changing δ is also possible but this is not easily captured by a simple model. Additionally, the W7-X density feedback system may also influence the stability of these plasmas. The effect of this system on the stability of these plasmas could well be important. Since the line-integrated density from interferometry is being used for feedback control of the divertor gas fueling, this feedback system will attempt to impose an inverse proportionality between plasma minor radius and plasma density. At the same time, since the smaller plasmas recede from the divertor plates, the fueling efficiency goes down for smaller plasmas, possibly negating this effect. These dynamics are not yet fully understood.

Working from these assumptions, one would expect to be able to create stable, small plasmas at any reduced minor radius, for example by changing the heating power. There are, however, discharges that are observed to shrink until full collapse after a large density increase or impurity injection. This is because our implicit assumption that the absorbed heating power is independent of the plasma size will fail for cases where the above-calculated size is very small. For such very small plasmas, the absorbed power will decrease as the plasma shrinks, even if the injected heating power remains constant.

This is related to the details of the absorption characteristics of second-harmonic ECRH, which is the main heating mechanism in W7-X and was the only one available in early operation. The X2 (second harmonic, extraordinary polarization) ECRH is poorly absorbed for T_e below ~150 eV. The radiating mantle layer is characterized by temperatures in the 5–50 eV range, and the radial transport is driven by gradients, so the core temperature is bound to drop when the plasma minor radius shrinks, unless one increases the heating power. Therefore, the plasma collapses entirely if r_r is very small—the lower absorbed power leads to further shrinkage of the plasma, which leads to lower temperatures and even further loss of absorption, until the plasma collapses. A collapse is even more likely when using second harmonic, ordinary polarization (O2) ECRH, since in this case T_e must be above ~1 keV for efficient absorption.

Neutral beam injection (NBI)-heated discharges may also suffer from reduced absorbed heating at small sizes and collapse rather than be stable: As the plasma gets smaller and colder, it will increasingly suffer from beam shine-through and therefore lowered plasma absorption.

Furthermore, the part of the W7-X interlock system meant to protect the device against damage due to nonabsorbed heating power can also be activated and trigger the termination of a discharge that might have been stably sustainable at small size.

These plasmas warrant further study for several reasons: They are, as far as we are aware, the first laboratory examples of keV-level, stably confined plasmas without any contact with material objects and are in that sense novel laboratory plasmas. Moreover, within the fusion context, such plasmas would have strongly reduced plasma-wall interactions and could therefore eliminate the risk of the plasma-wall-lifetime problem, and spread out the heat flux rather uniformly on the entire first wall in the form of photons and charge-exchange neutrals, allowing for much lower peak heat fluxes onto the plasma-facing components than experienced by divertors or limiters. Finally, as far as we understand these plasmas today, they are not associated with the magnetic topologies of edge island chains or stochastic regions. The edge of the plasma is determined by a power balance and can be located in a region of nested magnetic surfaces. This means that these plasmas can be expected to be stable even for configurations that have substantial bootstrap currents or high beta values.

However, there are several drawbacks: Given that these plasmas are fully decoupled from the divertor, there will be no significant divertor compression of neutrals. Therefore, much larger pumping or absorbing areas would need to be present to ensure the exhaust of particles from the plasma. Also, adequate impurity screening and compatibility with high overall fusion performance are still open questions.

References

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