Feedback controlled radiative edge cooling experiments in the Wendelstein 7-AS stellarator

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Introduction. Radiative edge cooling by seeded impurities with appropriate radiation characteristics is widely considered as an option to protect targets in fusion experiments from thermal overloading. In devices with active pumping capability (divertors, pump limiters), noble gases (e.g. Ne) are preferred as edge radiatiators due to both, their favourable radiation characteristics as well as their recycling properties [1, 2]. They are not pumped by plasma facing materials and, consequently, do not build up long-term reservoirs leading to uncontrollable release in particular during long-pulse or steady state discharges. In devices without active pumping capability as W7-AS, on the other hand, the seeded impurity has to be sufficiently pumped by the walls to allow control of the concentration. As was shown in Ref. [3], nitrogen is relatively well suited. It has favourable radiation characteristics, and its capability to be pumped by the walls enables feedback control of the radiation level over typical discharge durations ($\approx$1-2s) in W7-AS. A shot-to-shot build-up of an intrinsic nitrogen reservoir was found to settle at a very low, stationary background radiation level which could be completely removed by ECRH discharges without nitrogen puff. In continuing a previous study [3], this paper reports results from a nitrogen concentration scan with improved feedback control of the nitrogen radiation levels and with extended target diagnostics.

Experimental. The study in W7-AS (R = 2 m, a = 0.18 m) was performed at B = 2.5 T and ι = 0.34 with the configuration bounded by two horizontal graphite limiters at the top and bottom of an elliptic cross section. Nitrogen was injected into net current free ECRH (140 GHz, 430 kW) discharges with flat-top phases of 1.5 s at a line-averaged density $\bar{n}_e = 4\times10^{19}\mathrm{m}^{-3}$. Feedback control of the radiation levels was performed via VUV line emission (N IV, 765 Å). Compared to Ref. [3], the control spectrometer was now positioned further away from the nitrogen inlet thus actually enabling quasi-stationary radiation levels. In addition to the diagnostics mentioned in [3], limiter-integrated, poloidal Langmuir probe arrays allowed to study in particular downstream parameters in more detail. The limiters are poloidally segmented by ten tiles per limiter, each equipped with thermocouples allowing poloidally resolving target calorimetry.

Results and discussion. Stationarity within the injection phase of 0.7 s could be obtained up to a central nitrogen concentration of about 2.5% (estimated from CXRS) corresponding to a radiated power fraction of about 60% (from bolometer), Figs.1, 2. Attempts to exceed this limit lead to radiative instability and to feedback induced oscillations of the discharge parameters rather than to a complete collapse. CCD camera observations covering three of the five torus modules indicated strong shrinking of the hot plasma cross section, but did not give any evidence for MARFE formation during the radiative excursions. Decreasing the prescribed nitrogen radiation level and thus the nitrogen influx within the discharge duration to below this stability limit leads to re-establishment of stationary conditions. It was found that relatively small nitrogen concentrations (≈1%) already effectively suppress medium-Z radiation from the core which is primarily ascribed to lower impurity release from stainless steel components due to lower edge temperature.

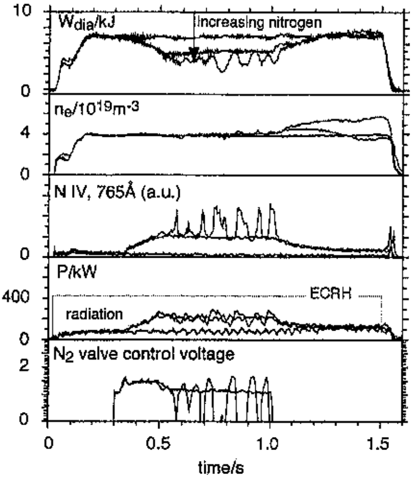

Fig.1: Stored energy, line-averaged density, nitrogen radiation intensity, total radiative power (bolometer) and N_2 valve control voltage versus time for a reference discharge without nitrogen and for nitrogen concentrations marginally below (≈ 2.5%) and above the thermal stability limit, respectively.

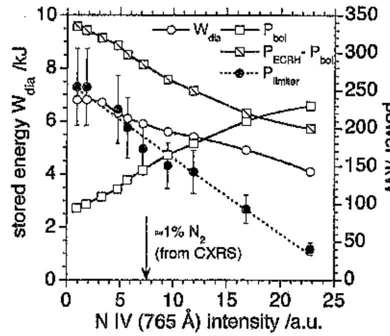

Fig.2: Stored energy from diamagnetic signal W_{dia}, total radiated power P_{bol} from bolometer, power flow P_{ECRH}-P_{bol} across the LCMS, and total power flow $P_{limiter}$ onto both limiters from calorimetry versus the NIV radiative intensity from SPRED spectrometer.

Under quasi-stationary conditions, the stored plasma energy degrades approximately linearly with the radiated power fraction (Fig. 2) because, due to the small size of W7-AS, the nitrogen radiation zone extends inward to $r/a \approx 0.4$ (Fig. 3). The electron temperature T_e is decreased only at the profile wings, whereas the value at the centre is not affected by the nitrogen radiation. A transport analysis (from power balance, Fig. 3c) indicates slightly improved confinement rather than a degradation. The density profiles (not shown) are flat inside $r/a \approx 0.7$ with steep gradients at the outside (from multi-channel interferometer and Li-beam). They are, within the error limits, not altered by the nitrogen radiation which means that the improvement of the central confinement does no coincide with density profile peaking as is often observed in tokamaks.

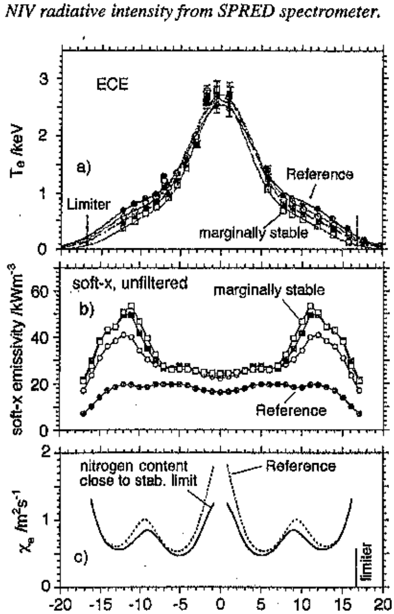

Fig. 3: Radial profiles of a) the elctron temperature T_e, b) the soft-x emissivity and c) the electron heat diffusivity χ_e (from power balance) for discharges with nitrogen concentrations from zero (reference) to slightly below the stability limit.

Calorimetric measurements at the two limiters (corrected for the injection phases being shorter than the pulse lengths) show much stronger reductions of the total power onto limiters than expected from bolometry, Fig. 2. The power accountability referred to P_{ECRH}-P_{bol} (with P_{ECRH} and P_{bol} being the heating and radiated power, respectively) is about 70 - 80% without nitrogen and decreases towards higher nitrogen content. This seems to indicate increasing toroidal asymmetry of the radiation shell not registered by the bolometers. CCD camera observations support this conjecture, but due to the lack of toroidally distributed bolometer cameras there is not yet direct quantitative evidence.

Data from the limiter-integrated Langmuir probe arrays show that the downstream electron temperature T_{ed} (measured at about 2 mm outside the last closed magnetic surface, LCMS) nearly linearly decreases fom about 90 eV without nitrogen to 20 eV slightly below the stability limit, whereas the downstream density n_{ed} stays approximately constant, Fig.4. The upstream temperature T_{eu} at the LCMS is decreased from about 90 to 40 eV (from a fast reciprocating Langmuir probe close to the stagnation plane). In order to check the consistency with calorimetric data, a simple two-point model of the scrape-off layer (SOL) power balance [4, 5, 6] was applied to estimate T_{eu}, T_{ed} and n_{ed} from the upstream density n_{eu} and the calorimetric power onto the central limiter tile which determines the LCMS. It includes parallel heat transport by classical parallel electron heat conduction, pressure constancy along field lines and the sheath boundary condition for the heat transfer to the target:

$$T_{eu} = \left(T_{ed}^{7/2} + \frac{7}{4\kappa_0} q_{\parallel} L_c \right)^{2/7}; \quad n_{ed} = n_{eu} T_{eu} / 2T_{ed}; \quad q_{\parallel} = n_{ed} c_s \gamma_s k T_{ed} \qquad (1)$$

k, c_s, γ_s, L_c and κ_0 are the Boltzmann factor, ion sound speed, heat transfer factor (≈8), connection length and parallel heat conductivity coefficient, respectively. The parallel power flux was derived from the fitted calorimetric power onto the central limiter tile, $q_{\parallel} = P_{target}/\lambda_q w$. For the power flux decay length λ_q an average value was inferred from the poloidal (representing also radial) power deposition profiles on the flat limiters, and w is the poloidal tile width (2.7 cm). The upstream density n_{eu} at the LCMS was kept fixed at 10^{19} m^{-3} (from upstream probe and Li-beam). The results (lines in Fig. 4) satisfactorily agree with the probe data thus indicating basic consistency.

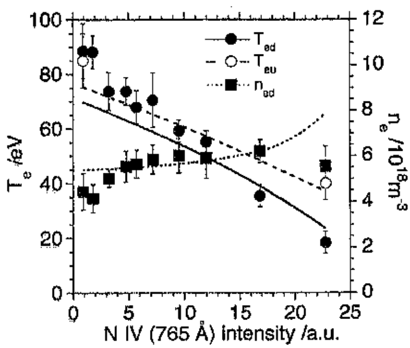

Fig.4: SOL upstream and downstream parameters close to the LCMS calculated by the two-point model (lines, see text) in comparison with probe data (symbols) versus the NIV radiation intensity from SPRED spectrometer. The upstream density n_{eu} is 10^{19}m^{-3}. Error bars are from statistics only.

In order to check the conditions near the stability limit towards smaller T_{ed} in somewhat more detail, the sheath boundary condition was extended to include energy losses to hydrogen, $q_{\parallel} = n_{ed} c_s k(\xi + \gamma_s T_{ed})$ with the temperature and density dependence of ξ fitted according to Ref. [7]. These losses could be neglected for calculating the results in Fig. 4, but become increasingly important towards smaller T_{ed}. The above model was then applied to calculate densities as functions of T_{ed} for calorimetric $q_{\parallel}$ values of the discharges without nitrogen and with the highest nitrogen

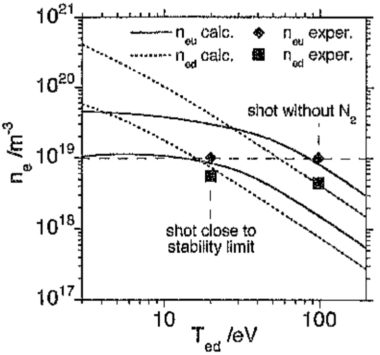

Fig.5: LCMS upstream and downstream n_e values calculated as functions of the downstream T_{ed} for $q_{\parallel}$ values from two shots, and probe data for comparison. The lower curve set indicates that further reduction of the power crossing the LCMS at fixed density would lead to thermal imbalance.

content below the stability limit (upper and lower curve set, respectively, in Fig. 5). Fig. 5 suggests that the marginally stable discharge closely approaches to the SOL thermal instability associated with the existence of a local maximum of n_{eu} versus T_{ed} [6]. Considering nitrogen radiative losses at coronal equilibrium from the SOL does not significantly affect this result. The deviation of the measured T_{ed} from the critical value at the maximum of the calculated upstream density is not too much of a concern because probe data generally tend to over-estimate T_{ed} in the presence of strong T_e parallel gradients. This SOL instability may destabilize the core radiative mantle with respect to radial shrinking as is seen in the experiments (see also Ref. [8]). However, to definitely confirm this interplay, a more refined analysis is needed which will be given elsewhere.

Summary and conclusions. Radiative edge cooling experiments have been performed in W7-AS by feedback controlled nitrogen injection into limiter-bounded, net current-free ECRH discharges. Within injection phases of 0.7s, quasi-stationarity was obtained up to central nitrogen concentrations of about 2.5%. Bolometer data indicate radiated power fractions up to about 60% whereas calorimetric data, together with downstream probe results, indicate target load reductions by up to factors of five to six. This discrepancy may indicate asymmetries of the radiation shell not registered by the bolometers. Though the plasma stored energy degrades with increasing nitrogen content due to the small machine size, the central T_e is not affected. A transport analysis shows improved confinement at $r/a < 0.3$. Exceeding the nitrogen level mentioned leads to radiative instability. Downstream data combined with model estimates suggest that this instability coincides with a SOL thermal instability. More detailed studies in particular on this latter issue including B2/EIRENE code analysis with selfconsistent treatment of impurity radiation are in preparation.

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