Boronization of ASDEX

U. Schneider, W. Poschenrieder,
M. Bessenrodt-Weberpals,J. Hofmann, A. Kallenbach, K. Krieger,
E. Müller, H. Niedermeyer, F. Ryter, J. Roth,F. Söldner,
A. Stäbler, K.H. Steuer, O. Vollmer,F. Wagner,
ASDEX-Team, ICRH-Team, LH-Team, NI-Team and PSI-Group

IPP III/166 September 1990

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

8046 GARCHING BEI MÜNCHEN

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

Boronization of ASDEX

U. Schneider, W. Poschenrieder,
M. Bessenrodt-Weberpals,J. Hofmann, A. Kallenbach, K. Krieger,
E. Müller, H. Niedermeyer, F. Ryter, J. Roth,F. Söldner,
A. Stäbler, K.H. Steuer, O. Vollmer,F. Wagner,
ASDEX-Team, ICRH-Team, LH-Team, NI-Team and PSI-Group

IPP III/166 September 1990

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

BORONIZATION OF ASDEX

U. SCHNEIDER, W. POSCHENRIEDER, M. BESSENRODT-WEBERPALS,
J. HOFMANN, A. KALLENBACH, K. KRIEGER, E. MÜLLER, H. NIEDERMEYER,
F. RYTER, J. ROTH, F. SÖLDNER, A. STÄBLER, K. H. STEUER, O. VOLLMER,
F. WAGNER, ASDEX-TEAM, ICRH-TEAM, LH-TEAM, NI-TEAM and PSI-GROUP

Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstrasse 2,
D-8046 Garching, Fed. Rep. Germany

Abstract

Boronization is the plasmachemical deposition of thin boron/carbon or pure boron films onto the inner wall of a tokamak device. Since mid-April 1989 the ASDEX vessel has been boronized seven times in glow discharges, first with a gas mixture of 10% B_2H_6+10% CH_4+80% He (A), once with 10% B_2H_6+90% H_2 (B) and once with 10% B_2H_6+90% He (C). All boronization runs were done at room temperature vessel walls. Local surface analysis of the deposited layers yielded thicknesses of up to 2000 Å. Boronization provided considerably improved plasma conditions. In ohmic discharges, reductions of CO by a factor of more than five in the divertor chamber and of two for H_2O were observed, in relation to a reduction of oxygen by a factor of more than five as measured by spectroscopy, but the reduction of hydrocarbons was only marginal. Iron disappeared from the spectra and even copper, the target plate material, was significantly reduced. As a consequence, Z_{eff} is < 1.5 for $\overline{n_e} > 3 \times 10^{19}$ m^{-3}. The density limit was improved by 25% (boronization A) and more (boronization B and C). The oxygen-diminishing effect of boron/carbon and pure boron layers was found to be longer lasting than the suppression of metal impurities. Deteriorated wall conditions occurred only after hundreds of discharges, including numerous additional heating shots with ICRH, NI, LH and combined scenarios, but pre-boronization conditions were never reached. The main emphasis of this paper is to describe the impact of boronization on aspects of plasma operation.

1. Introduction

Wall conditioning of the plasma vessel in a fusion device with thin hydrogenated carbon films applied in-situ during glow discharges in helium and methane to cover all plasma-facing surfaces (carbonization, [1]) yielded a reduction of the impurity release from limiters and walls during plasma discharges. In carbonized devices the release of metal and oxygen atoms during plasma-surface interaction is decreased, but oxygen is still the dominant plasma impurity together with the low-Z element carbon. For further reduction of the low-Z elements wall conditioning with boron [2] (boronization) was successfully accomplished on TEXTOR [3]. As compared with carbonization, the most significant advantage reported from TEXTOR [4] was a strong reduction of oxygen and carbon in the discharges and better density control. These results led to the realization of the boronization technique on ASDEX. Seven boronization cycles have been carried out since mid-April 1989, the first five with the original gas mixture applied in TEXTOR with B/C deposition, and then, in a second step, two boronizations with pure B deposition. Meanwhile boronization with B/C deposition is also used in TCA [5] and TFTR [6]. In the following the boronization technique on ASDEX is described and the improvements on ASDEX plasma parameters are discussed. First a short overview of the modifications to the ASDEX vessel in the last few years is given.

2. The boronization technique

2.1 Preliminary conditions

Since commissioning in 1980 plasma discharges in ASDEX have been studied under various wall conditions (stainless steel, carbonization, boronization) and with various divertors (pumping Ti-divertor and non-pumping Cu-divertor target plates). The most crucial change was the water-cooled "hardening" of the divertor installations for long-pulse operation in 1986/87 [7], yielding a more complex situation. This new divertor configuration originally had large bypasses ("open" divertor) resulting in a poor compression ratio. During shut-down in 1988 large areas of the ASDEX vacuum chamber were covered with graphite tiles and graphite mats to reduce high-Z impurities and the bypasses of the upper divertor chamber to the main chamber

were closed as far as possible [8]. During shut-down in 1989 also the lower divertor meanders were covered with graphite mats and the lower divertor chamber was closed in the same way as the upper one.

2.2 The boronization system

For further reduction of the low-Z impurities carbon and oxygen it was decided to condition the ASDEX vacuum vessel walls with diborane (B_2H_6). As in carbonization already routinely employed [9], a DC glow discharge is used for boronization, with the essential difference that diborane is added to the working gas. Three gas mixtures were used: 10% B_2H_6+10% CH_4+80% He (boronization A), 10% B_2H_6+90% H_2 (boronization B) and 10% B_2H_6+90% He (boronization C). The use of diborane, which is both explosive and highly toxic, necessitated the following modifications to the gas inlet and vacuum system [10].

For safe handling of the diborane a separate gas inlet was installed in conjunction with an exhaust system opposite it, comprising one of the standard turbomolecular pumps of ASDEX backed originally by thermal decomposers (700° C) and followed by a special chemical pump and a $KMnO_4$ filter. During summer shut-down 1989 a Roots blower was installed in front of the thermal decomposer. Diborane in the exhaust system will be completely decomposed in the filters into undangerous products. Because of the toxicity and explosiveness of diborane special operating rules for boronization runs are necessary, e. g. helium leak analyzing of the whole system before and continuous monitoring for diborane during every boronization run.

2.3 Deposition of boron/carbon layers

The gas mixture for boronization runs is fed from a pressure bottle at a pressure of about 100 bar via a reduction valve to the low-pressure tube at 1.8 bar. The typical discharge pressure during boronization is about $5 \cdot 10^{-3}$ mbar. The burn conditions for the two electrodes fixed on the outer vessel wall and toroidally displaced by about 180° are 400 V - 600 V and 1.7 A - 2.2 A depending on the gas mixture. Unlike in other tokamak devices, boronization in ASDEX is performed on room temperature walls. Surface analysis of a removable collecting probe after boronization runs with gas mixture A yielded compositions of the deposited boron/carbon layers with a ratio of about 1:1. The thicknesses of the layers near the gas inlet were estimated

from interference colours [11] to be around 1000 Å, but probe data as well as visual inspections of the layer after opening of the vacuum vessel during shut-down 1989 revealed strong toroidal asymmetries. Near the exhaust system the thickness of the B-C layer was only about 100 Å. The inhomogeneity in deposition was improved by installing a Roots blower in front of the low-conductance thermal decomposer. The tripling of the throughput of the working gas and the use of gas mixture C (diborane in helium) resulted in the highest coverage and best homogeinity: about 2000 Å near the gas inlet and about 1000 Å, respectively, near the exhaust system. As is also the case with carbonization on ASDEX, the divertor chambers are not accessible to the glow discharge and are not directly coated, and the divertor throats, owing to their geometry, show decreasing coverage towards the divertor chambers.

3. Plasma discharge improvements

3.1 Residual gas analysis after boronization

The residual gas analysis after boronizations shows a transient reduction of the residual pressure of H_2O by a factor of two. In the course of the following day the water vapour pressure reverts to its previous value, but can be repeatedly restored to the improved condition by glow discharges in hydrogen or helium as well as by plasma discharges. It was also found that the boron layer did not pump molecular oxygen if not activated shortly before by plasma discharges. The conditioning in a 15-minute He glow discharge is a standard procedure prior to a run-day. This helps to preserve the beneficial effects of boronization for a long period, even in the case of venting the vessel.

3.2 Impurity composition in ohmic discharges

Residual gas analysis. Boronization results in significantly improved plasma conditions. Figure 1 shows the partial pressures in the upper divertor chamber measured by a quadrupole gas analyzer in a pumping port during the flat top of standard ohmic discharges ($\overline{n_e} = 3 \cdot 10^{19}$ m^{-3}, $I_P = 0.32$ MA, $B_t = 2.17$ T). Compared are discharges with typical conditions before and directly after fresh boronizations. A remarkable decrease of CO in the divertor chamber is observed. For boronization A a reduction of CO at least a factor of five and of the water vapour

pressure by a factor of more than two is measured, but the reduction of methane is only marginal [12]. Boronization B and especially boronization C resulted in a further decrease of CO and now also a decrease of methane is found. In addition, the partial pressures of the hydrogen isotopes in the divertors are increased by a factor of ≥2 (Fig. 1) in relation to typical values of a well-conditioned uncovered machine. This change in divertor conditions can be explained by increased energy flux onto the target plates by a factor of 2 owing to reduced impurity radiation from the main plasma. The same mechanism gave rise to an increase of the plasma edge density in the scrape-off layer.

Z_{eff}. As a consequence of the reduction of light impurities Z_{eff}, obtained by bremsstrahlung [13], is strongly reduced. Z_{eff} decreases at $2 \cdot 10^{19}$ m^{-3} from 3.8 to 1.8 and at $4.5 \cdot 10^{19}$ m^{-3} from 2 to close to 1. The plasma edge values of Z_{eff} were strongly decreased, especially with boronization B and C, leading to broad radial profiles with low Z_{eff} values. The reduction of Z_{eff} with increasing density is consistent with the observation of a decrease of CO in relation to hydrogen within the divertors, the light impurities are more diluted. The increase of Z_{eff} from the low values (Fig. 2) after boronization in course of machine operation depends on the specific heating scenarios during different experimental phases. The overall tendency, however, is a general increase of Z_{eff} intersperced by strong reduction after each boronization run as shown for ASDEX fiducial shots (I_p = 0.32 MA, B_t = 2.17 T, q_a = 3.3) in Fig. 2.

Spectroscopic data. Comparison of spectroscopic data shows a significant decrease of the line radiation from the plasma after fresh boronization (Fig. 3). Spectroscopic measurements yield a reduction of oxygen by a factor of more than 5, which is also confirmed by charge exchange spectroscopy and which is in agreement with the residual pressure in the divertor. Basically iron disappears almost totally from the spectra but is replaced by boron, which however, does not seem to affect the discharges. Even copper, originating mainly from the divertor plates, is reduced by a factor of 2. With increasing number of discharges iron reappears, but pre-boronization values were never reached. The oxygen-diminishing effect of the boron-carbon and pure boron layers is found to be longer lasting than the suppression of metal impurities.

Density limit. Investigations of the density limit as a function of wall conditioning are based on specially dedicated density limit shots where the density is slowly ramped up by feedback

control until the plasma disrupts. The density limit in standard ohmic density limit discharges (I_p = 0.32 MA, B_t = 2.17 T, q_a = 3.3) was $5 \cdot 10^{19}$ m^{-3} before boronization, which is typical of a clean metal or carbon machine. After boronization A the density limit resulted in $6.2 \cdot 10^{19}$ m^{-3}, further increased to $6.7 \cdot 10^{19}$ m^{-3} (boronization B) and $7.3 \cdot 10^{19}$ m^{-3} (boronization C), respectively. The close correlation between the partial pressure of mainly CO in the divertor and the density limit strongly supports the assumption that the density limit in ohmic discharges is most strongly influenced by the light impurities C and O, and that oxygen recycling is mainly via CO. Two series of ohmically heated D^+ plasmas are compared in the Hugill diagram (Fig. 4) for boronized and non-boronized walls. The absolute value of the Murakami parameter $\overline{n}_e R/B_t$ strongly depends on the contamination of the plasma. Because of the significant reduction of Z_{eff} at high densities to values <1.5 a linear increase of $\overline{n}_e R/B_t$ for $q_a > 2.5$ by a factor of roughly 1.5 is observed. For $q_a \leq 2.5$ the qualitative behaviour of the density limit is rather different: under boronized conditions D^+ plasmas show a minimum of $\overline{n}_e R/B_t$ at $q_a \approx 2.15$, which agrees with earlier results under clean plasma conditions (e.g. in the old ASDEX divertor configuration together with Ti evaporation in the divertor region [14]). For $q_a < 2$ boronized wall conditions lead to appreciably higher Murakami parameters.

Radiated power. For boronized wall conditions the fraction of radiated power compared with the input power P_{rad}/P_{tot} was about 25%. This is an important difference to carbonization with $P_{rad}/P_{tot} \approx 50\%$. A comparison of radiation profiles shows, for carbonization as well as for boronization, a highly depressed central radiation in relation to a clean metal machine. For the carbonized case, however, the radiation profiles show slightly increased boundary radiation as compared with the clean metal case. With boronization however, the radiation from the plasma edge is significantly decreased to values below that of a metal machine.

3.3 Impact on confinement aspects

IOC. In ohmic discharges on ASDEX a new regime, improved ohmic confinement (IOC), was obtained [15] after modifications to the divertor chambers (see 2.1, "open" divertor). IOC conditions are reached for $\overline{n}_e > 3 \cdot 10^{19}$ m^{-3} at the end of the n_e ramp-up phase when the external gas puff rate is reduced. Simultaneously, the global particle confinement time rises by approximately the same amount as the energy confinement. The density profile peaks along the

slow time scale of improving confinement. During the transition to the IOC phase the intensity of soft X-ray emission increases. The power influx into the scrape-off layer (SOL) drops in the IOC regime, causing the edge density to decrease.

After closing the divertors and with boronization, when the radiation is strongly reduced and the power fluxes across the separatrix are high, IOC conditions do not develop any more. It seems that IOC conditions need a certain amount of edge impurity radiation to sustain a low power influx into the SOL with the consequence of low edge density [16]. It is now evident why IOC conditions do not develop spontaneously with boronized walls, where the radiation is strongly reduced, giving rise to high power fluxes across the separatrix. On the other hand, impurity addition (e.g. Ne gas puffing) can initiate the IOC regime with boronized walls too [16].

H - mode. During neutral beam injection no significant increase of the relative impurity concentrations of CO and H_2O in the divertor is observed, in accordance with the rather constant behaviour of Z_{eff}. The boronization provides very good conditions for the H-mode which could be obtained over a wide range of plasma current, magnetic field and injection power [17]. After boronization B and C (no methane in the working gas) the power threshold for the H-mode is significantly reduced (e.g. P_{NI} = 1.05 MW, I_P = 0.45 MA, B_t = 1.8 T, double null). For quiescent H-phases (lasting up to 190 ms) the plasma energy increase is terminated by the occurrence of Edge Localized Modes (ELM) and not by excessive radiation losses. The previously observed beta limit values were reproduced, however, at lower power. Long (2 sec, limited by the NI pulse) and very stationary H-phases with ELMs could be achieved [18]. The ELMs were extremely regular (200 Hz with less than 10% variation over 1.8 s) which is probably an effect of the stable and reproducible edge conditions provided by the boronization.

3.4 Aspects of RF - Heating

Ion Cyclotron Resonance Heating. The effects of boronized walls with ICRH were studied in two scenarios : hydrogen second-harmonic and hydrogen minority ion cyclotron resonance heating (ICRH), alone or combined with neutral beam injection (NI). The boronization does not

affect the confinement and heating properties, but it is very efficient against difficulties encountered with ICRH, such as impurity production [19] and power limitation. For both ICRH scenarios with boronization A, the maximum RF power which could be applied to an ohmic plasma without causing disruption was considerably improved: 2.4 MW instead of 1.5 MW with carbonization. This is attributed to the reduced density increase and cooling in the divertor with ICRH and is related to the higher density limit generally observed under boronized conditions. The impurity production is reduced, as illustrated in Fig. 5, which shows the total radiated power as a function of the plasma energy content for a combination of ICRH with NI. For comparison, data for carbonization are also reported. The important feature is that, for a fresh layer, the points ICRH+NI are aligned with the data for NI alone. As the layers degrade with time, the iron concentration increases [20] and the slope of the radiation power versus ICRH power (reported in Fig. 5) becomes steeper. The term "older" applied to the layers mentioned in Fig. 5 denotes the situation after ≈400 discharges with boronization and after ≈130 discharges with carbonization. The discharges performed in the meantime were not comparable and a quantitative comparison of the long-term protection against iron is not possible. It seems, however, that with ICRH boronization lasts longer than carbonization.

Lower hybrid. The improving effects of boronization were also studied in LH-heated plasmas. During LH operation Z_{eff} increased before boronization typically from 2 to 5 because of the low-density operation. After boronization Z_{eff} was reduced by a factor of 2 and increased typically by $\Delta Z_{eff} \approx 1$ to 2.5. Because of the detrimental effects of Z_{eff} on the current drive efficiency, η_{CD}, the highest η_{CD} values were achieved with boronized walls. Moreover, better power coupling was achieved with much fewer HF-induced disruptions.

4. Conclusions

Boronization was found to be superior to carbonization since it does not pose any problem with density control. The effective particle confinement τ_p is high, as is typical of metallic walls. The depression of high-Z impurities is very similar for pure carbon, boron/carbon and pure boron layers. Essential differences are observed for the concentration of the light impurities

oxygen and carbon as well as for the long-term aspects of the protection against metallic impurities. The reduction of the low-Z materials, primarily oxygen (boronization A) and oxygen and carbon (boronization B and C), which are still the dominant impurities after carbonization, is significantly higher with boronization. The density limit is durably improved in all boronization cases. With boronization B and C (wihout methane) the plasma conditions are generally more improved than with boronization A, e.g. the density limit is increased by additional ≈10% to $\overline{n_e} \approx 6.7 \cdot 10^{19}$ m^{-3} (boronization B) and ≈20% to $\overline{n_e} \approx 7.3 \cdot 10^{19}$ m^{-3} (boronization C), respectively.

The oxygen-diminishing effect of boronization remains over a long period (> 500 discharges) and older layers can be partly reactivated by plasma discharges even after venting of the vessel and mainteinance work inside it. Boron/carbon and pure boron layers are more durable than pure carbon layers because boron is resistant to chemical erosion. Improved conditions are maintained even after hundreds of discharges. Boron, supposedly removed by sputtering, is partly transported into the divertors, as indicated by collection probe data, and might also yield favourable action there. Even the vacuum vessel was vented in March 1990 and operation was resumed in April 1990 there was still some residual activity of the old boron layer. After just one day of operation good conditions for plasma discharges were reached (e.g. Murakami parameter $= 4.3 \cdot 10^{19}$ m^{-2} T^{-1} at $q_a = 3.3$ or e.g. H-mode conditions).

All observations on ASDEX support the assumption, that the effect of boronization is not simply based on a reduction of H_2O in the vacuum vessel. More likely, the reaction of boron with atomic oxygen from the plasma, forming boron/oxygen compounds, and an activation of the layer by the plasma itself is the true reason. By avoiding carbon in the deposited layers (boronization B and C without methane) and removing the oxygen from the plasma the vicious circle of CO recycling is suppressed.

The improving effects on plasma discharges will be further investigated in the Wendelstein VII-AS stellarator, where a boronization device is in preparation.

Acknowledgement

The authors are grateful to the plasma surface interacting group at TEXTOR, Jülich, for helpful discussions on the concept definition of the boronization system. They also acknowledge the technical contributions of J. Stadlbauer in system design and his assistance during boronization.

References

[1] J. Winter, J. Nucl. Mater. 145 - 147 (1987) 131 - 144

[2] S. Veprek et al., J. Nucl. Mater. 63 (1976) 405 and S. Veprek et al., J. Nucl. Mater. 162 - 164 (1989) 724 - 731

[3] H. G. Esser, H. B. Reimer, J. Winter and D. Ringer in: Proc. of the 15th Symposium on Fusion Technology (Utrecht, The Netherlands, Sept. 19 - 23, 1988) p. 791

[4] J. Winter et al., J. Nucl. Mater. 162 - 164 (1989) 713 - 723

[5] C. Hollenstein et al., this confrence

[6] H. F. Dylla et al., this conference

[7] H.Niedermeyer et al., Plasma Physics and Controlled Fusion, Vol. 30, No. 11 (1988) pp. 1443 - 1453,

[8] Annual Report 1988, Max-Planck-Institut für Plasmaphysik, 8046 Garching, Fed. Rep. Germany

[9] W. P. Poschenrieder et al. in: Proc. of the 13th European Confference on Controlled Fusion and Plasma Heating (Schliersee, Fed. Rep. Germany, April 14 - 18, 1986) p.196

[10] U. Schneider, IPP-Report August 1990, Max-Planck-Institut für Plasmaphysik, 8046 Garching, Fed. Rep. Germany, to be published

[11] J. Winter , KFA - Report Jül-2207, June 1988, Kernforschungsanlage Jülich GmbH, D-5170 Jülich, Fed. Rep. Germany

[12] W. Poschenrieder and K. Desinger, this conference

[13] H. Röhr, K. H. Steuer, and the ASDEX Team, Rev. Sci. Instrum. 59 (8), Aug. 1988, p.1875

[14] A. Stäbler et al., 17th European Conference on Controlled Fusion and Plasma Physics (Amsterdam, The Netherlands, June 25 - 29, 1990)

[15] Söldner, F.X., E.R. Müller, F. Wagner, et al., Phys. Rev. Lett. 61 (1988) p.1105

[16] M. Bessenrodt-Weberpals et al., The multiple facets of ohmic confinement in ASDEX, Nucl. Fusion (submitted)

[17] F. Ryter et al., 17th European Conference on Controlled Fusion and Plasma Physics (Amsterdam, The Netherlands, June 25 - 29, 1990)

[18] O. Vollmer et al., 17th European Conference on Controlled Fusion and Plasma Physics (Amsterdam, The Netherlands, June 25 - 29, 1990)

[19] J.-M. Noterdaeme et al., Fusion Eng. Des. 12 (1990) 127

[20] F. Ryter et al., Fusion Eng. Des. 12 (1990) 267

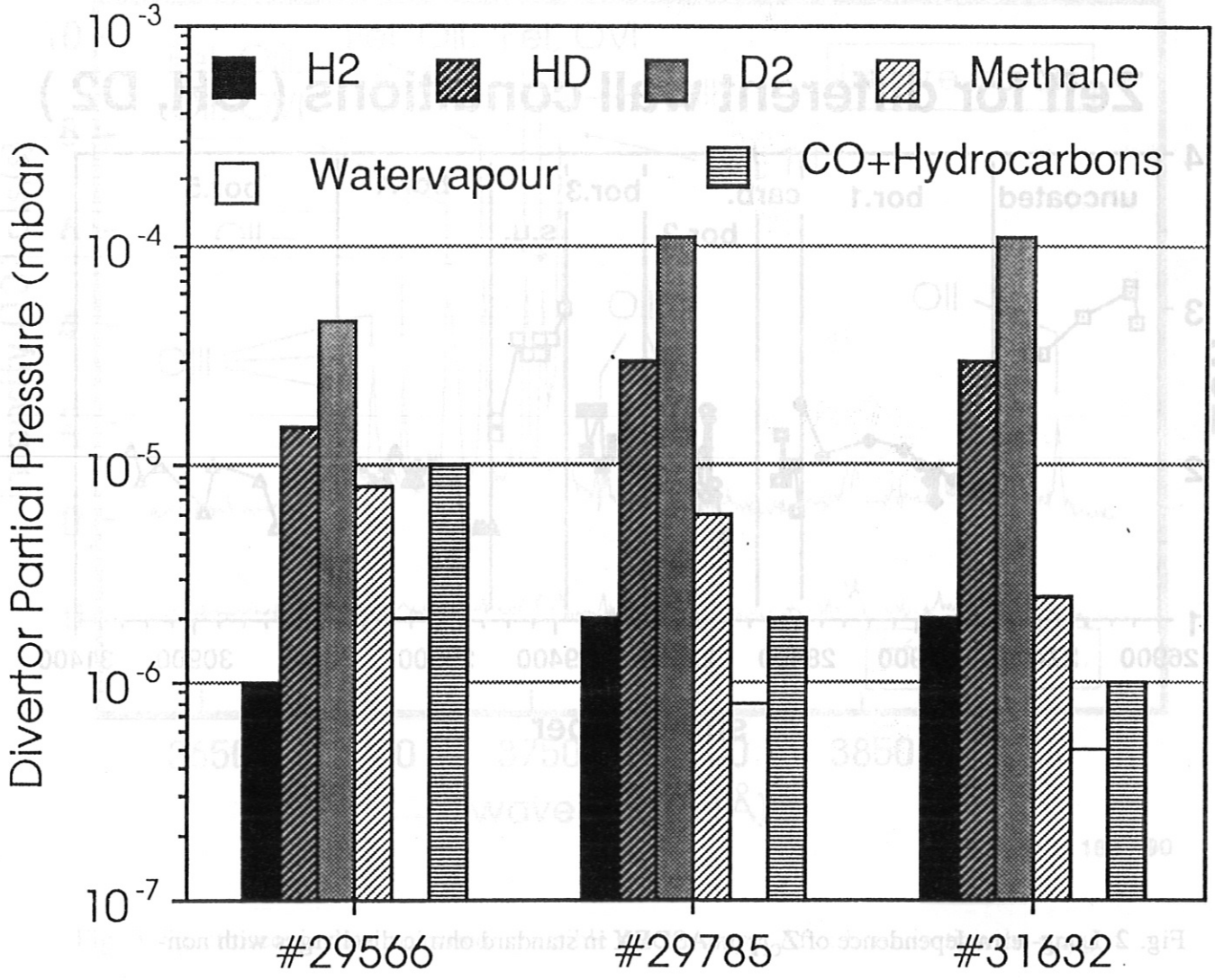

Fig. 1 The partial pressures in the upper divertor chamber during standard ohmic discharges (I_p = 0.32 MA, B_t = 2.17 T, $\overline{n_e} = 3 \cdot 10^{19}$ m^{-3}) before (# 29 566) and after boronization A and B (in 10% B_2H_6 + 10% CH_4 + 80% He (# 29 785) and 10% B_2H_6 + 90% H_2 (# 31 632), respectively). Mainly CO is significantly reduced after boronizations, especially after boronization B (#31 632).

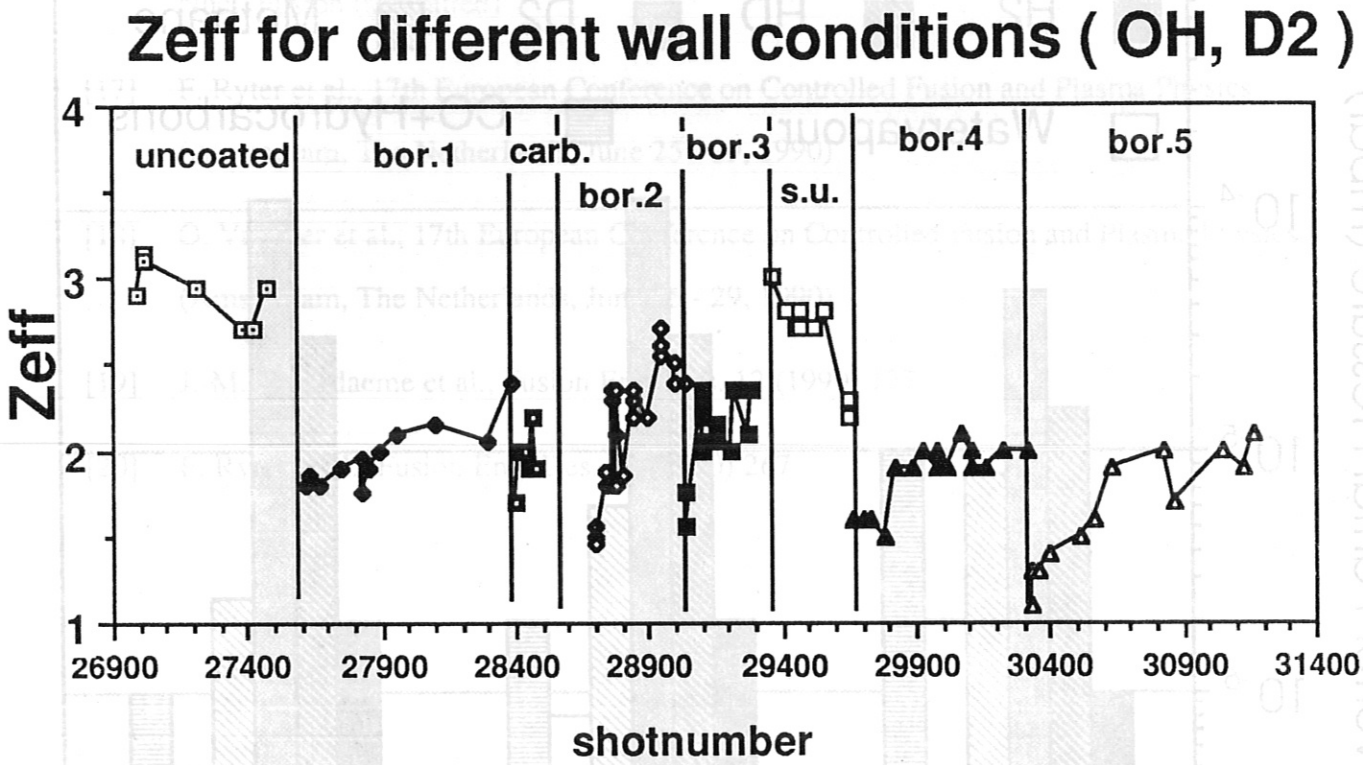

Fig. 2 Long-term dependence of Z_{eff} on ASDEX in standard ohmic discharges with non-boronized (uncoated), boronized (bor. 1 - 5) and carbonized (carb.) walls and in start-up phases (s.u.) after venting of the vacuum vessel.

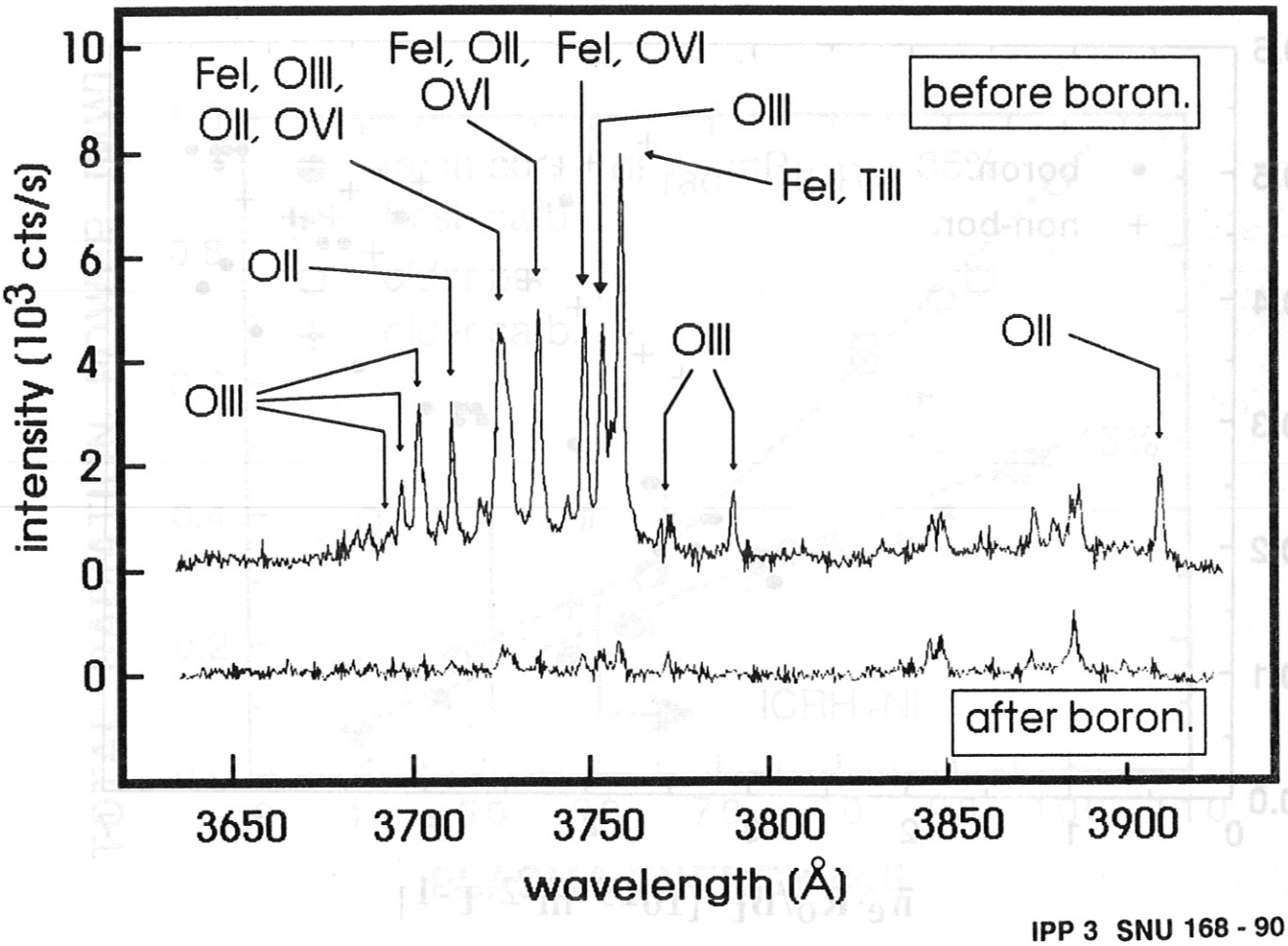

Fig. 3 Spectroscopic data measured by visible spectroscopy. After boronization the oxygen and iron line radiation disappears from the spectra.

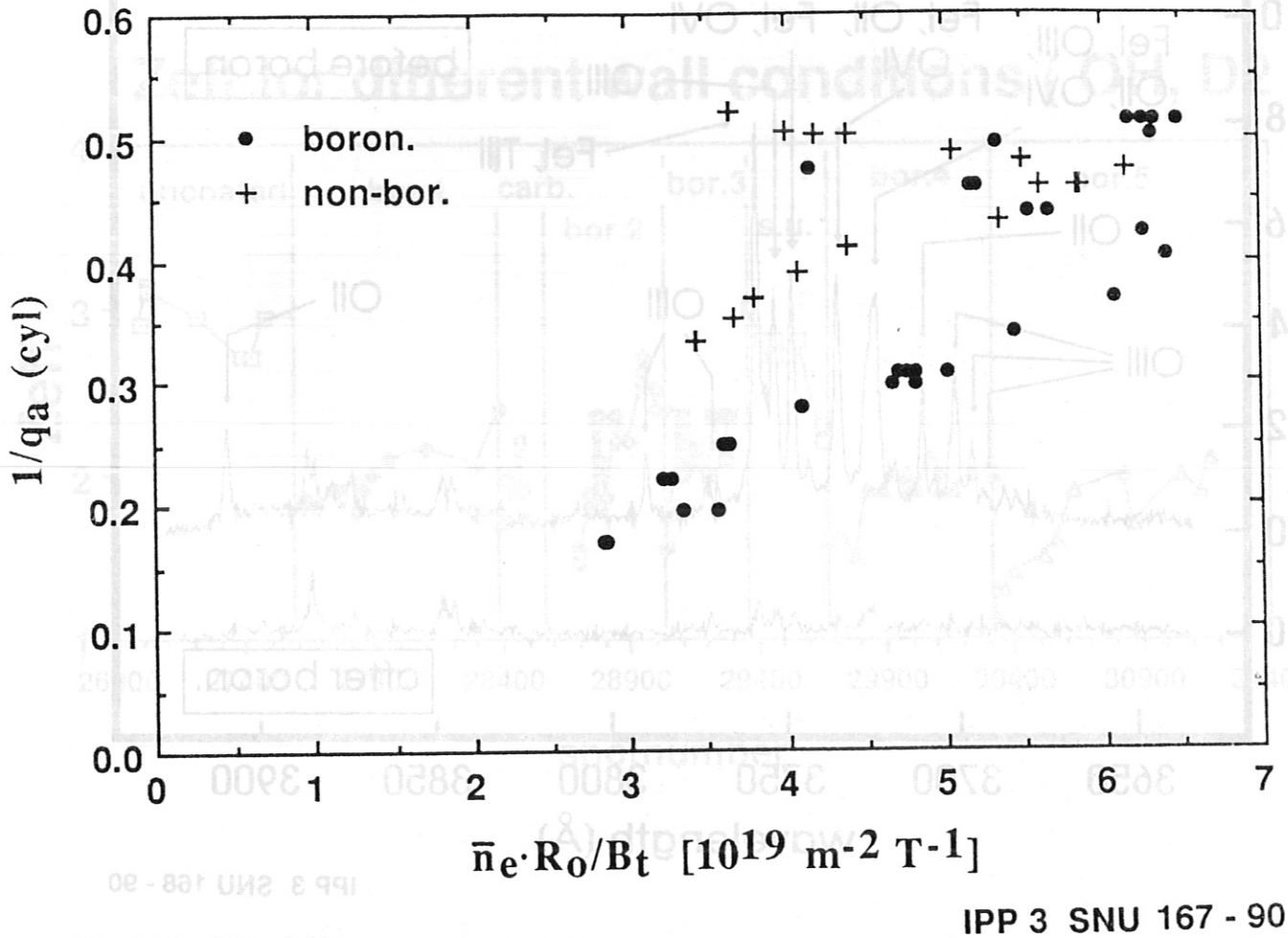

Fig. 4 The Hugill diagram ($1/q_a$ versus $\bar{n}_e R/B_t$, cylindrical definition for q_a) shows a substantial increase in the density limit after boronization.

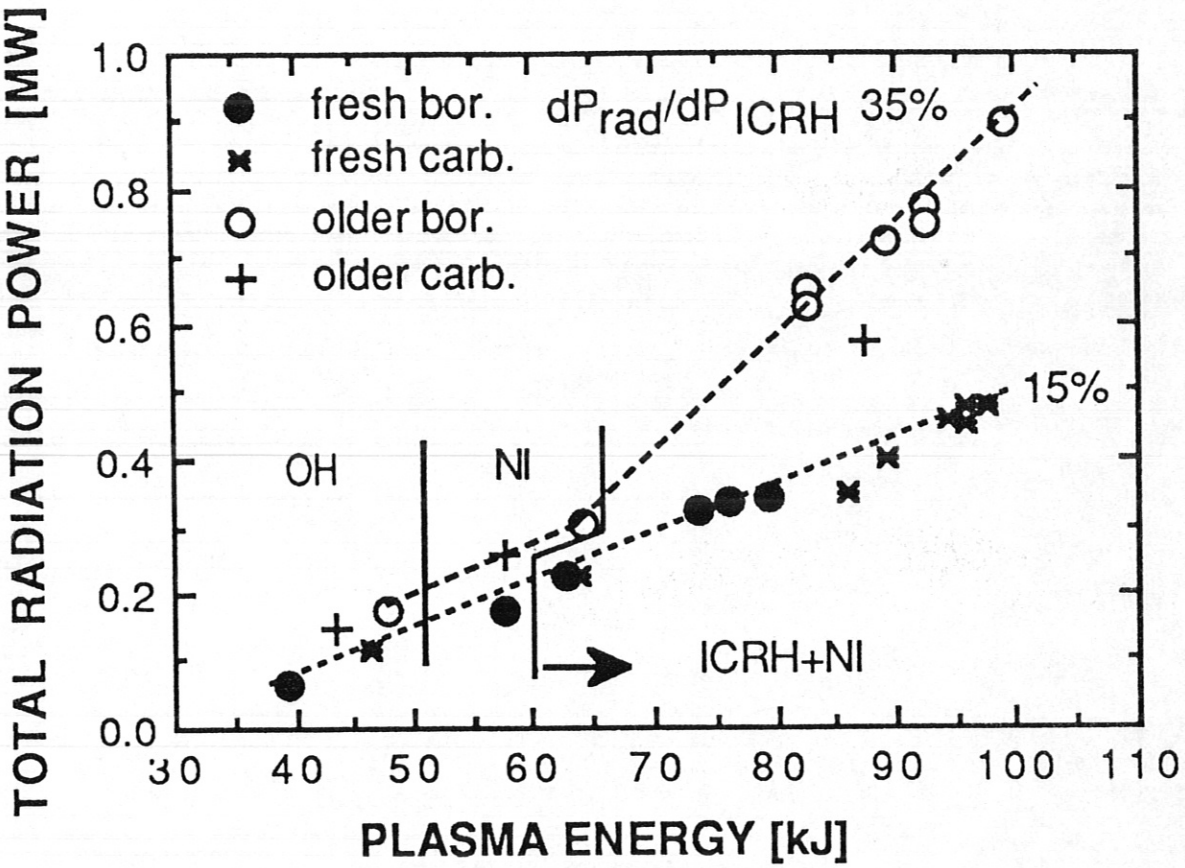

Fig. 5 Total radiated power versus plasma energy for different layers and different heating scenarios. Hydrogen harmonic heating (ICRH) combined with hydrogen neutral injection (NI) for similar plasma parameters: $B_t = 2.36$ T, Ip = 0.46 MA, line-integrated density around $5.5 \cdot 10^{19}$ m^{-3}.