JOINT EUROPEAN TORUS

JET-P(89)61

J. Jacquinot, D. Stork, A. Tanga and B.J.D. Tubbing

H-Mode in JET with Ion Cyclotron Resonance Heating Alone

H-Mode in JET with Ion Cyclotron Resonance Heating Alone

J. Jacquinot, D. Stork, A. Tanga and B.J.D. Tubbing

JET Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

Preprint of a paper to be submitted for publication in
Nuclear Fusion Letters

H MODE IN JET WITH ION CYCLOTRON RESONANCE HEATING ALONE

B.J.D. Tubbing, J. Jacquinot, D. Stork, A. Tanga
JET Joint Undertaking, Abingdon, OXON, OX14 3EA, United Kingdom

H mode discharges with ion cyclotron resonance heating alone have been achieved in JET, up to a power level of 12MW. These H modes, which have reached durations of up to 1.5s, have all the characteristics of H modes with neutral beam injection. In particular, the energy confinement is similar to that of neutral beam cases, and typically corresponds to two times Goldston L mode scaling. The ICRH heated H modes are characterized by long sawtooth free periods. Dipole antenna phasing and Beryllium gettering were the key factors in these experiments.

The discovery of the 'High' mode of tokamak confinement was made in Asdex[1]. The H mode was achieved in a magnetic separatrix configuration with a single X—point, and with neutral beam injection (NBI) heating. The most important characteristic is an increase of a factor of two to three in the global energy confinement time over the conventional L mode, and an even bigger increase of the global particle confinement time. The most common signature is a sharp reduction in the H_α light emission, indicating a reduction of the recycling all around the machine. Following it's discovery, the H mode was established in many tokamaks[2,3,4,5], initially only with NBI heating. The compatibility of the H mode with other heating systems became an issue of some uncertainty and, in fact, considerable urgency. Ion cyclotron resonance heating (ICRH) is the only scheme that allows efficient central ion heating in compact high field future tokamaks[6] with limited access for NBI. ICRH also remains the most efficient central heating scheme in medium field large tokamaks[7,8], where high NBI energies are required to penetrate to the axis (apr. 1MeV negative ion beams), or where off—axis NBI is favored for current drive[7]. The fact that the designs for these machines essentially rely on H mode like energy confinement, motivates the search for an H mode with ICRH alone, and with an energy confinement similar to that of NBI heated H modes.

The compatibility of H modes with electron cyclotron resonance heating (ECRH) was proven in DIII–D[9] and JFT2–M[10,11]. DIII–D also achieved the H mode with ohmic heating[12]. The coupling of ICRH to H modes was reported by Asdex[13]. H modes both with and without edge localized modes (ELMS) were achieved with ICRH alone[14,15], however, these were of very short duration. In JFT2–M[16], H modes lasting for about 2 energy confinement times were obtained with ICRH. The ICRH antennas in JFT2–M are situated on the high field side of the machine (in contrast to Asdex and JET, which have low field side antennas). H modes with combined NBI/ICRH heating were reported also by JT60[17] and JET[18]. Generating an H mode with ICRH alone, or the coupling of ICRH to H modes, generated by NBI, was invariably associated with enhanced influxes of impurities, in particular the metallic ones. In the H mode, with the strongly enhanced particle confinement time (for the main ion component and for impurities[19]) this leads to a rapid accumulation of impurities. The, consequently, high fraction of power radiated, leads to a degradation of the confinement and to a short duration of the H mode. Attempts at achieving an H mode with ICRH alone in JET were not successful[18].

In this paper the achievement of H modes in JET with ICRH alone, with confinement times similar to NBI only cases, and with a duration of over 1.5s, is reported. There are two important differences in experimental conditions between the present results and the earlier ones. First, the ICRH system was fitted with an automatic tuning system[20], which maintains the impedance matching to the generators despite a rapidly changing antenna coupling resistance. This allowed coupling of higher powers than before, in the more favorable dipole antenna phasing. Secondly, the interior of the JET machine is coated with a thin layer of beryllium, deposited by evaporation. The previous experiments were done with a carbon vessel interior, nickel faraday screens on the ICRH antennas and monopole phasing.

The experiments were performed in a double null magnetic separatrix configuration. The dominant power load is on the top X point (there is a very slight upward vertical displacement), which has the grad B drift directed toward the target area. The X point target area consists of carbon tiles. The distance from the X point to the tiles is typically a few centimeters. A high triangularity of the equilibrium is required for the separatrix to match the curvature of the ICRH antenna. This is essential to obtain good ICRH coupling. For all experiments reported here, the toroidal field is 2.8T, the plasma current is 3MA, the elongation is 1.8 and the safety factor at the flux surface at 95% of the horizontal minor radius is 3.8.

There are 8 ICRH antennas, one in each octant of the machine[21], situated in the midplane at the low field side (only seven antennas were used in these experiments). The plasma facing element is a nickel faraday screen, surrounded by protective carbon tiles. The antennas can be operated in 'monopole' mode, with the currents in the active elements in phase, or 'dipole' mode, with the currents in anti–phase. The monopole mode is characterized by better (higher) values of the coupling resistance, but also by a higher level of plasma edge interaction and impurity generation than the dipole mode[21]. The dipole phasing was used for all the successful H modes reported here (it is not yet clear if the H mode can or can not be obtained with monopole phasing). The frequency of the ICRH is 42MHz, which implies power deposition in the plasma center, with a hydrogen minority in a deuterium plasma. The ICRH coupling resistance for the dipole antenna phasing varies between 2 and 6Ω, and is primarily related to the distance between the separatrix and the antenna. The distance between the separatrix and the protective carbon tiles varies between 1 and 3cm (from the magnetics data). The carbon tiles protrude 2cm with respect to the faraday screen. The variations in this distance are the result of changes in the equilibrium with the changes in plasma kinetic pressure, which are not always completely compensated for by the vertical field control. The effect of the distance appears more important than the effect of changing scrape–off layer parameters at the L to H transition, which causes the coupling resistance to drop by typically 1Ω.

The interior of the vacuum vessel, including the antenna faraday screens, is coated by a thin layer of beryllium, applied by evaporation. The nominal thickness of the layer at the time of these experiments, after multiple depositions, was about 250nm, in places not touched by the plasma. The beryllium deposit on the actual X point target areas erodes off in the first discharge after evaporation, leaving a carbon target area. The gettering effect of the beryllium on the vessel walls leads to a reduction of the oxygen concentration in the discharge by more than an order of magnitude with respect to situation with uncoated (mainly carbon) walls. Furthermore, there is an indication that the beryllium layer on the antennas leads to a reduction of the influx of nickel, especially just after a new evaporation.

In figure 1 the time evolution of relevant signals for an H mode with ICRH alone are shown. The variation of the ICRH power is due to a variation of the distance between the separatrix and the antenna screen. The event at 49.8s is the injection of a single 4mm pellet, which penetrates to the plasma center. Pellet injection (and/or gas puffing) is applied in order to maintain the density in the pre–heating X point phase; the X points have a large pumping capacity for deuterium. The D_{α} emission signal shown is from a detector with a vertical line of sight, viewing the emission in the vicinity of, but not at, the X point. The initial increase, (49.0 to 49.8s) is due to the formation of the X point equilibrium. The D_{α} signal shows a clear L to H transition at 50.4s, followed by an elm–free H mode until 52.0s. During the H mode, the density and the radiated power increase. The H mode is terminated when the radiated power becomes greater than the input power; this is a common observation for elm–free H modes with NBI. During the subsequent L phase, the density and the radiated power decrease, and at 52.5s there is a second L to H transition. The second H mode lasts until 53.3s. The maximum stored energy, measured by a diamagnetic loop, is 5.4MJ, at 6.3MW total input power, corresponding to a confinement time of 0.85s. This corresponds to approximately twice Goldston L mode scaling[22] for these discharges. The fast particle contribution to the energy content is negligible in the high density H mode phase, as observed by comparison of the stored energy from the diamagnetic loop and from the equilibrium analysis. The electron density at 51s is about $5.0\ 10^{19}\ m^{-3}$, and has a very flat profile, as measured by the LIDAR time of flight Thomson scattering system. The density increases throughout the H phase, without additional gas fueling, showing that there is a source of deuterium probably in the X point target tiles. The electron temperature, measured by electron cyclotron emission, is about 6keV, and the ion temperature, measured from the doppler broadening of a central nickel line, is about 5keV.

Characteristic of the ICRH H modes is the occurrence of long sawtooth free periods, the so–called monster sawteeth[23]. Sawtooth–free periods of over 1s, sometimes lasting as long as the H mode, have been obtained.

In figure 2 an overview of the confinement for H modes with ICRH alone is shown, in comparison to H modes with NBI alone, at the same (3MA) plasma current. Clearly the ICRH H modes have confinement times similar to those of the NBI H modes, typically corresponding to twice Goldston L mode scaling[22]. In comparison 3MA L mode discharges, limited on the belt limiter or on the inner–wall, are shown, which have a confinement of about once Goldston L mode scaling.

The effective ion charge Z_{eff} for the discharge shown is about 2.0 at the end of the H mode, corresponding to a dilution n_D/n_e of 0.8, if a flat profile of Z_{eff} is assumed. This value of n_D/n_e is consistent with the measured D—D reaction rate and the measured ion temperature.

The D—D reaction rate for the discharge shown is $2.5\ 10^{15} s^{-1}$, corresponding to a Q_{D-D} of $2.0\ 10^{-4}$. The $n_D\ \tau_E\ T_i$ product is $1.9\ 10^{23}\ m^{-3}$ s eV (at 51.0s, when the confinement time is 0.95s), giving an equivalent thermal Q_{D-T} of 0.06. This is lower than the Q_{D-T} achieved for NBI H modes in similar conditions and at the same input power, basically because the ion temperature is lower. This is due to two effects; the high densities we have operated the ICRH H modes at, and the higher fraction of direct electron heating by the ICRH.

The power threshold for the ICRH H modes is similar to that for NBI only H modes. With 7MW of ICRH power, in the 3MA, 2.8T discharge, no H mode was obtained, while with 9MW an H mode was triggered. There is a clear hysteresis effect, ie. lowering the input power after the start of the H mode to below the threshold power will not terminate the H mode, as long as the radiated power is lower than the input power.

The H mode signature,as a sharp drop of the vertical D_α signal, is not always observed. In particular for one discharge at 12MW ICRH power, with clear H confinement, there was no clear signature. This effect is most probably related to the distance between the separatrix and the antenna. For this H mode, in which the separatrix to antenna distance was about 1cm, no sharp decrease of the vertical D_α was observed, and a residual power deposition on the antenna tiles was observed (with an infra—red CCD camera viewing the machine interior, sensitive to the Be 825nm line and the thermal background). For other discharges, in which this distance was about 3cm, there was a sharp D_α decrease, and the residual interaction was reduced; Be light is observed, but no heating of the antenna tiles. In some discharges a transition in two steps (with as much as 250ms between them) was observed. For all discharges the main interaction is with the X point target area, as is evident from the CCD camera, after the X point is formed. It was already reported earlier[18] that an H mode was obtained with combined NBI/ICRH heating and with a small (about 1cm) distance between separatrix and antenna, which also did not show the usual signature on the vertical D_α.

Summarizing, H modes with ICRH only, of up to 1.5s duration, have been obtained in JET, at power levels up to 12MW. This shows that the H mode can be obtained with ICRH antennas on the large major radius side of the vacuum vessel. The edge phenomena, the confinement and the threshold power are similar to those of H modes with NBI alone. The density increases during the H mode, without external gas puffing. The radiated power and the effective ion charge also increase during the H mode, as is the case in NBI only H modes. In some discharges, H confinement is observed without a clear decrease of the vertical D_{α} signal; in that case, there is a residual interaction of the scrape—off layer with the antenna.

The authors are grateful for the support of the entire JET team. We wish to acknowledge in particular the director, Dr. P.H. Rebut, whose initiative resulted in the beryllium environment for this experiment, Dr. A. Gibson and Dr. M. Keilhacker for their support and interest, and the ICRH operating team.

REFERENCES

1 WAGNER, F., BECKER, G., BEHRINGER, K., et al., Phys. Rev. Lett. 49 (1982) 1408.

2 KAYE, S., BELL, M.G., BOL, K., et al., J. Nucl. Mater. 121 (1984) 115.

3 SENGOKU, S., and JFT–2M TEAM, J. Nucl. Mater. 145/147 (1987) 556.

4 BURRELL, K.H., EJIMA, S., SCHISSEL, D.P., et al., Phys. Rev. Lett. 59 (1987) 1432.

5 TANGA, A., BARTLETT, D.V., BEHRINGER, K., et al., in Plasma Physics. and Controlled Nuclear Fusion Research 1986 (Proc. 11th Int. Conf. Kyoto, 1986), Vol.1, IAEA Vienna (1987) 65.

6 PARKER, R., and CIT GROUP, to be published in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 12th Int. Conf. Nice, 1988). Reference IAEA–CN–50/G–II–1–2.

7 SHIMOMURA, Y. and ITER TEAM, to be published in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 12th. Int. Conf. Nice, 1988). Reference IAEA–CN–50/F–II–4.

8 REBUT, P.H., LALLIA, P.P., Fus. Eng. and Design, 11 (1988) 1.

9 LOHR, J.M., STALLARD, B.W., PRATER, R., et al., Phys. Rev. Lett. 60 (1988) 2630.

10 HOSHINO, K., YAMAMOTO, T., SUZUKI, N., et al., Nucl. Fus. 28 (1988) 301.

11 HOSHINO, K., YAMAMOTO, T., KAWASHIMA, H., et al., Phys. Lett. A130, (1988) 26.

12 OSBORNE, T.H., BROOKS, N., BURRELL, K.H., et al.,
'Observation of H mode in Ohmically Heated Divertor Discharges on DIII–D', General Atomics Report, GA–A19362 (1988).

13 KEILHACKER, M., GIERKE, G. von, MULLER, E.R., et al.,
Plasma Physics and Controlled Fusion, 28 (1986) 29.

14 STEINMETZ, K., WAGNER, F., WESNER, F., et al.,
in Controlled Fusion and Plasma Physics (Proc. 13th Eur. Conf. Schliersee, 1986), Vol. 10C (II) (1986) 21.

15 STEINMETZ, K., NOTERDAEME, J.–M., WAGNER, F., et al.,
Phys. Rev. Lett. 58 (1987) 124.

16 MATSUMOTO, H., OGAWA, T., TAMAI, H., et al.,
Nucl. Fus. 27 (1987) 1181.

17 AKIBA, M., and JT60 TEAM,
Plasma Physics and Controlled Fusion, 30 (1988) 1405.

18 TUBBING, B.J.D., BHATNAGAR, V., BOYD, D., et al.,
in Controlled Fusion and Plasma Physics (Proc. 16th Eur. Conf. Venice, 1988) Vol. 13B (I) (1989) 237.

19 HAWKES, N., WANG, Z., BARNSLEY, R., et al.,
in Controlled Fusion and Plasma Physics (proc. 16th Eur. Conf. Venice, 1988) Vol. 13B (I) (1989) 79.

20 BOSIA, G., et al., to be published.

21 JACQUINOT, J., and JET TEAM, Plasma Physics and Controlled Fusion, 30 (1988) 1467.

22 GOLDSTON, R., Plasma Physics and Controlled Fusion, 26 (1984) 87.

23 CAMPBELL, D.J., START, D.F.H., WESSON, J.A., et al.,
Phys. Rev. Lett. 60 (1988) 2148.

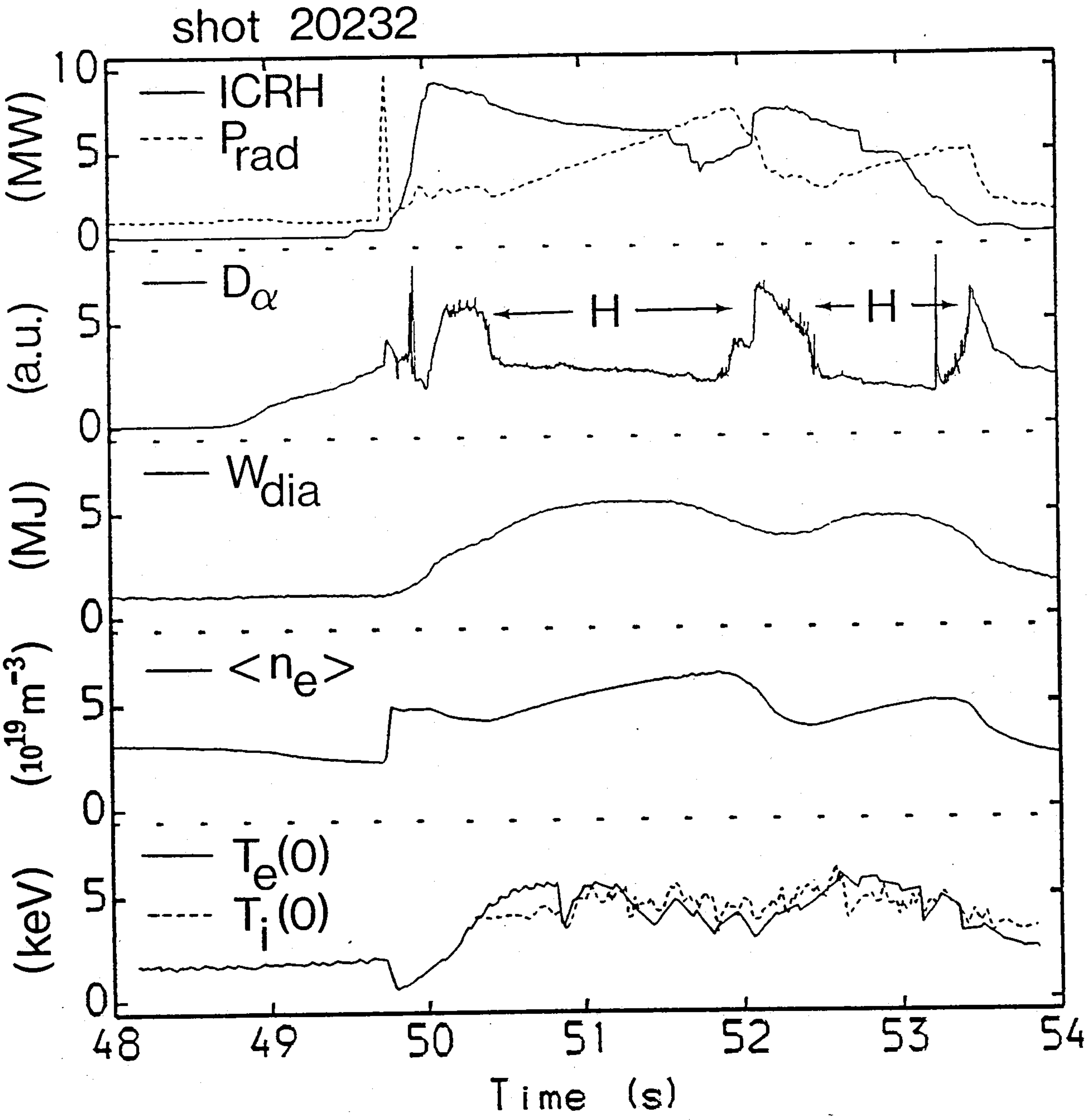

Figure 1: time traces of relevant signals for an H mode with ICRH alone. Shown are: the ICRH power, the radiated power, the vertical D_α emission signal, the kinetic stored energy from the diamagnetic loop, the volume—average density, the central electron temperature and the central ion temperature.

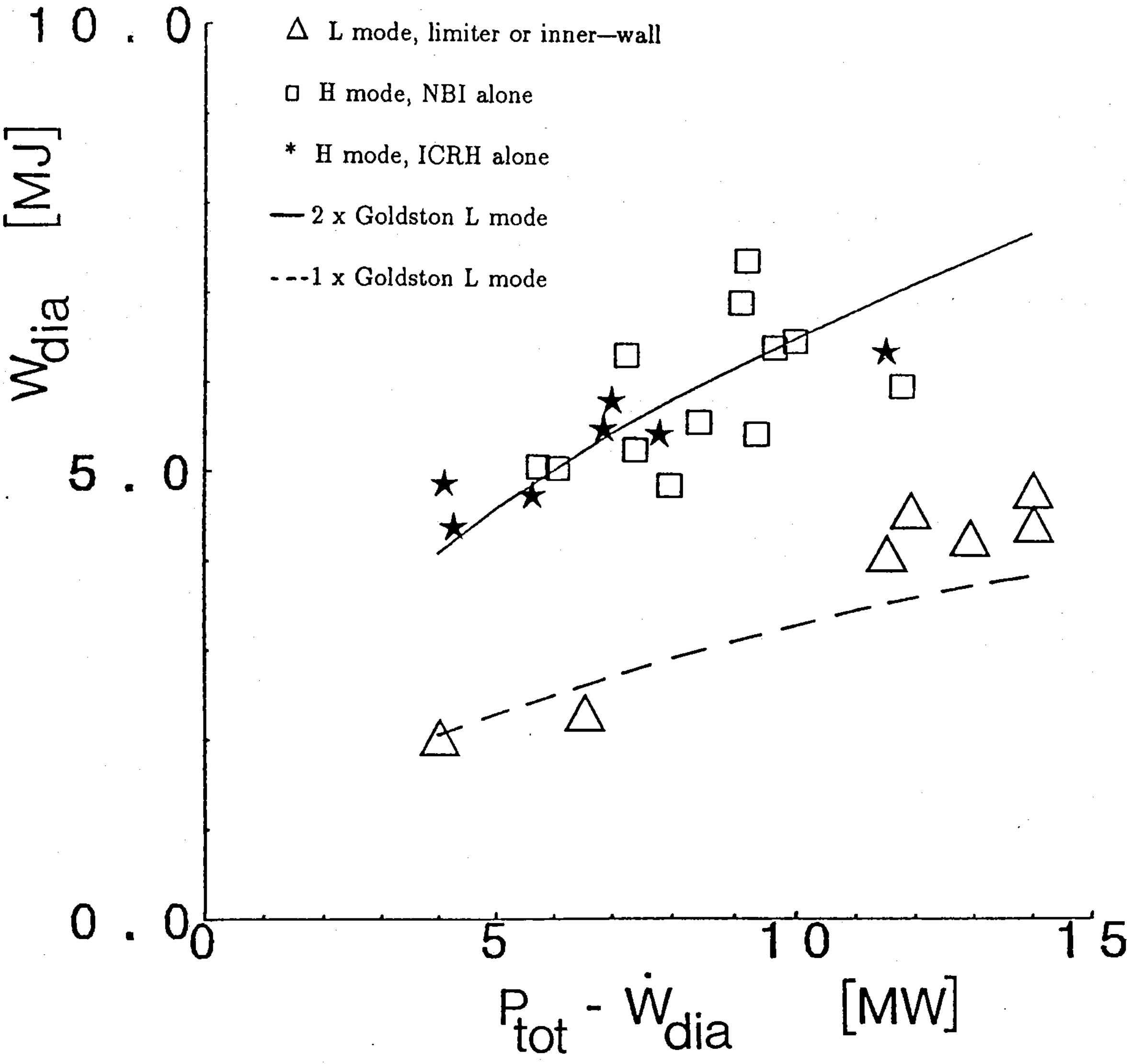

Figure 2: the confinement of H modes with ICRH alone in comparison to H modes with neutral beam injection and with L mode discharges, resting on the belt limiter, or on the inner—wall. The plot shows the kinetic stored energy from the diamagnetic loop, versus the net input power $P_{total} - dW_{dia}/dt$. All discharges shown have a plasma current of 3MA, and all are obtained after beryllium evaporation in the vacuum vessel. The solid line indicates two times Goldston L mode scaling for the 3MA discharges, the dashed line indicates once Goldston scaling for 3MA discharges.