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# PROCEEDINGS OF THE WORKSHOP OF THREE LARGE TOKAMAK COOPERATION ON ENERGY CONFINEMENT SCALING UNDER INTENSIVE AUXILIARY HEATING

May 18~20, 1992, Naka

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(ed.) Department of Fusion Plasma Research

日　本　原　子　力　研　究　所
Japan Atomic Energy Research Institute

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# Proceedings of the Workshop of Three Large Tokamak Cooperation on Energy Confinement Scaling under Intensive Auxiliary Heating May 18∿20, 1992, Naka

(ed.) Department of Fusion Plasma Research

Japan Atomic Energy Research Institute
Naka Fusion Research Establishment
Naka-machi, Naka-gun, Ibaraki-ken

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The workshop of three large tokamak cooperation W22 on "Energy confinement scaling under intensive auxiliary heating" was held 18-20 May, 1992, at Naka Fusion Research Establishment. This proceedings compiles 14 synopses of contributions (5 from JET, 4 from JT-60, 3 from TFTR, and 1 each from DIII-D and JFT-2M) and the summary of the workshop. Topic sections are ; (i) L-mode confinement and scaling, (ii) Confinement at high $\beta_p$ regimes, Supershots, High poloidal beta enhanced confinement mode etc., (iii) Confinement at various H-mode regimes and scaling (including the VH-mode), (iv) Characteristic time scales for present tokamak regimes, and (v) Theoretical comparison with experimental data.

Keywords : Tokamak, JET, JT-60U, TFTR, DIII-D, JFT-2M, Energy Confinement, Scaling Law, Auxiliary Heating, L-mode, H-mode, VH-mode, PEP-mode, High Poloidal Beta, High Normalized Beta, Supershots, Transport Model

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# 強加熱時のエネルギー閉じ込め比例則に関する
# 三大トカマク協力研究ワークショップ議事録
# 1992年5月18～20日，那珂町

日本原子力研究所那珂研究所
（編）炉心プラズマ研究部

（1992年8月6日受理）

「強加熱時のエネルギー閉じ込め比例則」に関する三大トカマク協力研究ワークショップW22が1992年5月18日－20日に那珂研究所で開催された。この議事録は，14の講演（JETから5件，JT－60から4件，TFTRから3件，DⅢ－Dから1件，JFT－2Mから1件）の概要およびワークショップのまとめを収録したものである。次の5つの話題に分類される講演が行われた；(1) Lモードの閉じ込めと比例則，(2) 高ポロイダルベータ領域での閉じ込め，スーパーショットや高ポロイダルベータ改善閉じ込めモードなど，(3) 各種Hモード（VHモードを含む）の閉じ込めと比例則，(4) 現トカマクにおける特徴的時間，および(5) 実験データと理論モデルとの比較。

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# 1. The Scaling of Energy Confinement and Equivalent $Q_{DT}$ in TFTR Supershots

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A database has been examined of some 1100 TFTR Supershots which have been run since 1990 when the main limiter was reinforced by the replacement of graphite tiles with carbon fiber composite material in the areas of high heat flux. This modification of the limiter has reduced the frequency and severity of "carbon blooms" which formerly occurred in most high-power supershots. The data span wide ranges in neutral beam heating power (5 - 33 MW) and plasma current (0.8 - 2 MA) and additionally limited ranges in plasma major radius and toroidal magnetic field. The factors influencing supershot confinement within this data set are discussed. Of particular importance is the state of "conditioning" of the limiter which involves both the level of recycling for hydrogenic species and also the rate of carbon influx into the ohmically heated phase of the discharge prior to the neutral beam heating pulse. A convenient characterization of this state of conditioning is developed in terms of the target plasma density and current. Restricting consideration to the subset of shots with well-coditioned limiters, high toroidal field and a major radius of 2.45m for which the most extensive data set is available, it is found that the confinement time for the total (thermal plus unthermalized beam) energy at the time of its peak ( $dW/dt \approx 0$ ) has only a very weak negative dependence on heating power, $P^{-0.06}$, and a weak negative dependence on plasma current, $I^{-0.24}$. Relative to this scaling, discharges which have had a lithium pellet injected into the ohmic phase before the neutral beams have confinement times up to 20% better than discharges without pellet pre-injection. When discharges at major radius 2.6m and at lower toroidal field are included, we find additional dependences $(BR)^{+1.1}$ and $R^{1.9}$for the total confinement time. It is not possible to separate the dependence of confinement time on major and minor radii in the data set.

The D-D neutron emission rate increases rapidly with power in the Supershot regime and it is found that there is a close relationship between this rate and the total stored energy, the rate varying as $W^{1.9}$ and almost inversely as the plasma volume. In addition to these dependences, there is a weak dependence on the edge $q$, $q^{0.3}$, which may be related to a systematic variation of the pressure profile with $q$. The strong dependence on total energy demonstrates the necessity to optimize both the confinement and the $\beta$-limit in Supershots. At present, most Supershots with high D-D fusion performance are degraded during the heating pulse by phenomena which appear to be related to the normalized plasma pressure, $\beta_N = \beta_T aB/I$. Modelling of deuterium Supershots with some of the neutral beam sources injecting tritium has shown that if the temperature profiles are maintained, $Q_{DT}$ of 0.25 - 0.3 should be achievable in planned experiments.

## 2. High βp Enhanced Confinement Mode in JT-60 and JT-60U

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The goal of high $\beta_p$ experiments in JT-60 & JT-60U is to find a realistic view of high $\beta_p$ tokamak concepts proposed as SSTR and ARIES-1 in order to determine whether such a reactor scenario is workable. Particular attention is paid to the establishment of experimental database under the reactor relevant conditions.

Succeeding the pioneering work on JT-60 (IAEA Washington D.C. '90), high $\beta_p$ experiment has been recently carried out in JT-60U, in which greatly enhanced confinement of high $\beta_p$ plasmas has been observed; here we call it high $\beta_p$ enhanced confinement mode. The aim of the paper presented here is to show power and beta dependence of the enhanced confinement observed in JT-60U. Furthermore, in terms of the isotope effects, the deuterium high $\beta_p$ plasmas in JT-60U are compared with the hydrogen high $\beta_p$ plasmas in JT-60.

High temperature ($T_i \sim$ 30keV, $T_e \sim$ 9keV) and significant enhancement in energy confinement time as three times L-mode scaling was attained in the high $\beta_p$ enhanced confinement mode at a low current region of $I_p \sim$ 1.1 - 1.3MA and the attainable diamagnetic stored energy reached 4.2 MJ at $I_p$ = 1.2MA.

The discharges were produced by central neutral beam injection (up to 22 MW) into a low-recycling low-density target plasma with a relatively small bore. The significant confinement enhancement of the discharges was obtained during the absence of frequent $H_\alpha$ spikes. While the energy confinement time is weakly dependent on absorption power, a strong tendency of degradation for the enhanced confinement with power emerges from the net-power dependence of the enhancement factor.

A beta limit determined by $\beta_p$ collapse for high $\beta_p$ discharges is found to be dependent on both Troyon factor, $g$, and $\varepsilon\beta_p$ substantially below the Troyon limit, as a product of $g\,\varepsilon\beta_p{}^{dia}$ is limited to less than ~ 1.3. Without degradation or saturation, the confinement enhancement is associated with increase in $\varepsilon\beta_p$ and Troyon factor up to the beta limit, near which the best confinement of the discharges is obtained.

The enhancement factors observed for hydrogen high $\beta_p$ plasmas in JT-60 are shown to be a factor of two lower than in JT-60U. This implies that isotope effects in the high $\beta_p$ plasmas would be more significant than in L-mode plasmas.

## 3. Confinement of Plasmas at High Poloidal Beta and High Normalized Beta in TFTR

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High poloidal beta plasmas ($\beta_{p\ dia} \leq 5.9$) exhibiting enhanced energy confinement ($2.2 \leq \tau_E / \tau_{E\ ITER\text{-}89\text{-}P} \leq 3.5$) have been produced in TFTR at relatively low current ($0.28 \leq I_p \leq 1.2$MA). Discharges attaining the largest values of $\tau_E/\tau_{E\ ITER\text{-}89\text{-}P}$ were obtained when neutral beam heating was applied after the completion of a fast decrease in $I_p$ at -2.5 MA/sec. This technique creates a plasma with a peaked (high $l_i$) current profile. In addition to the confinement enhancement, these plasmas simultaneously displayed improved stability. In particular, the Troyon normalized diamagnetic beta, $\beta_{N\,dia} \equiv 10^8 < \beta_{dia} > aB_0/I_p$, exceeded a value of 4 while also reaching $\tau_E/\tau_{E\ ITER\text{-}89\text{-}P} \sim 3$. A similar increase of both the confinement and stability is necessary to significantly reduce the size and cost of future tokamak reactors.

The scaling of $\tau_E$ with total injected beam power, $P_{beam}$, and plasma current has been examined in these discharges. In regard to these parameters, the behavior of $\tau_E$ varies as $I_p$ is increased. Specifically, at low $I_p$, $\tau_E \equiv W_E/P_{beam}$ ($W_E$ is the plasma stored energy) scales similarly to the ITER-89-P scaling relation, $\tau_E \sim P_{beam}^{-0.5} I_p^{0.85}$. At the lowest currents (0.4MA), $\tau_E$ actually degrades more strongly with $P_{beam}$ and increases more strongly with $I_p$. As the current increases, the dependence of $\tau_E$ on these parameters weakens. When $I_p \geq 1.0$ MA, there is essentially no dependence of $\tau_E$ on $I_p$ and $P_{beam}$, a result similar to that observed in TFTR supershot plasmas.

Bootstrap current fractions of greater than 2/3 of $I_p$ have been calculated for these plasmas using the TRANSP code. During 1992 run, the beam heating pulse length of the high poloidal beta plasmas was increased to four seconds to study the long time scale behavior of the bootstrap effect on the plasma confinement and stability. As the initial current ramp-down perturbation relaxes and the bootstrap effect increases, $l_i$ decreases and reaches a value near or below that of the ohmic plasma. During this period, there is a slow decrease in $\tau_E$ and $\tau_E/\tau_{E\ ITER\text{-}89\text{-}P}$. However, the confinement enhancement is still large (~ 2) when $l_i$ has reached sub-ohmic values, indicating that $l_i$ may not be a good scaling parameter for confinement enhancement factor in plasmas with large fractions of bootstrap current. Energy confinement returns to near L-mode scaling predictions as the plasma stability decreases and MHD modes cause a beta collapse. Disruptions occur in these discharges at unusually low values of $\beta_{N\,dia} \sim 2$. This decrease in stability corresponds to a decrease in the n = 1 free boundary kink/ballooning mode stability for these discharges, which is shown to decrease significantly as $l_i$ is decreased.

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## 4. Confinement in High-$\beta_p$ and High-$\beta_T$ H-modes in JET

The JET Team, presented by D. Stork
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The range of operation in JET at high $\beta_{pol}$ and high normalized beta ($\beta_N = \beta_T a B_T / I_p$ ) has been extended, reaching $\beta_{pol}$ ~2 in low current (1.5MA) ICRF-heated H-modes and $\beta_N$ ~3.3 in low current (1.5-2.0MA) NBI-heated H-modes at low $q$ ($q_{95}$= 2.8).

High-$q$ ICRF-heated H-modes obtained significant bootstrap current in a reactor-relevant scenario with negligible central fuelling. In diverted plasmas with < 10MW ICRF heating, ELM-free H-modes up to 2 secs long were achieved with $I_{boot}/I_p$ ~ 0.7 at $\varepsilon\beta_{pol}$ values ~0.65 and confinement enhancement of 3-3.5 x Goldston L-mode scaling. Repetitive $\beta$ collapses occurred at the highest values of $\beta_{pol}$. Analysis shows the possible mechanisms are interaction with the RF antennae or the proximity of the edge plasma to the high-n ballooning limit.

The Pellet Enhanced Plasma (PEP) H-modes achieve high values of $\varepsilon\beta_{pol}$ (>0.6) in the inner 10% of the JET plasma. A high density core is created by injection of a pellet before the onset of sawteeth. Within this core the shear is reversed, due to the high off-axis bootstrap current created by the density gradient at $r/a$ = 0.4. The application of both NBI and ICRF produces the PEP phenomenon within this core, and in diverted plasmas this has been combined with the H-mode (PEP/H-mode). Transport analysis shows that the PEP/H-modes are ordinary H-modes with an enhanced core confinement where values of $\chi_{eff}$ ~ 0.5 $m^2s^{-1}$ and $D_e$ < 0.1 $m^2s^{-1}$ are attained. PEP H-modes are sustained for up to 1.2s. The collapse phase is complicated and the competing mechanisms put forward are low-n MHD (internal-kink); MHD activity leading to impurity accumulation in the core, and high-n ballooning modes, which analysis shows to be driven unstable by the high pressure gradient at the edge of the PEP core.

High-$\beta_N$ H-modes behaviour has been studied in the low current, low $q$ (<3.3) discharges and in the Hot Ion H-modes. The $\beta$-limit in the low-$q$ discharges is above the Troyon limit and is consistent with the $\beta_N = 4 \times l_i$ scaling proposed for DIII-D, but the high performance Hot Ion H-modes limit at $\beta_N$ = 2.3-2.5 (80-90% of $\beta_{Troyon}$ ). High frequency MHD fluctuations are seen above $\beta_N$ ~1 in the low-$q$, low current H-modes. A Ballooning analysis at the time of the $\beta$ collapse shows that the pressure profile exceeds the high-n Ideal Ballooning limit within $r/a$ < 0.45, suggesting this activity arises from high-n modes. At the $\beta$-limit the confinement enhancement over L-mode has deteriorated to ~1.8 for H-modes with $T_i$=$T_e$, but the Hot Ion confinement advantage is still seen with H values of 2.1-2.2 even near $\beta_N$ ~2.8. The confinement of 3.1MA Hot Ion H-modes with $\beta_N$ >2.0 shows a strong dependence on $B_T$ ($B_T{}^{0.7}$) with H values >3 being achieved above 2.8T. The collapse phase of the Hot Ion H-modes shows varied phenomena with the peak $\beta$ reached depending on target purity. For Hot Ion H-modes started after the onset of sawteeth, high frequency MHD activity is seen above a threshold which depends on the discharge purity and may be evidence for high-n ballooning modes. At the limiting $\beta$ there is either 'soft' limiting behaviour with enhanced conduction to the plasma edge being observed for >100ms before final collapse or a 'hard' limiting behaviour with collapse of the plasma temperature occurring rapidly across the profile within 100μs.

## 5. Isotope Dependence of Energy Confinement in JT-60U

presented by Hiroshi SHIRAI
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L-mode & H-mode confinement in JT-60U has been studied. The isotope dependence (H and D) of confinement has been also investigated in both ohmic and neutral beam heated plasmas. Plasma stored energy was measured by diamagnetic loop. These data were re-evaluated in February 1992, because Rogowsky coil overestimated plasma current by 1~2 % and poloidal beta value was hence overestimated by 2~4 %. We assumed that the electron density has a profile of $n_e(r) \propto (1-r^2)^m$. Putting two channels of interferometer data onto the equilibrium data, we calculated line averaged electron density. The electron temperature profiles were measured by ECE and Thomson scattering data. For the neutral beam heated plasmas, the ion temperature profiles were measured by CXRS. The effective charge number was calculated from visible Bremsstrahlung data.

The Energy Confinement time of L-mode plasmas have been improved by increasing the internal inductance $l_i$. Energy confinement time of H-mode plasma is 1.5 times (max.) larger than that of ITER power law scaling. Small minor radius plasmas ($R$ = 3.1 m, $a$ = 0.77 m) accompanied by central NBI deposition and low ripple loss show better energy confinement than that of Goldston scaling (1984 Aachen). Energy confinement time of JT-60 (hydrogen) and JT-60U (deuterium) data show agreement with ITER power low scaling.

The energy confinement time of hydrogen and deuterium plasmas were compared in both ohmic and neutral beam heated phases in JT-60U. H/D or D/H ratio was calculated by $H\alpha$ and $D\alpha$ intensities. The effective mass number of hydrogen was estimated 1.0 ~ 1.35 in ohmic and 1.2 ~ 1.35 in NBI plasmas. The effective mass number of deuterium was estimated 1.75 ~ 1.85 in both ohmic and NBI plasmas. Thus the square root of mass ratio is 1.1 ~ 1.3. The maximum stored energy of 3MA high elongated deuterium plasma reached up to 1.45 MJ in ohmic phase. The maximum energy confinement time of hydrogen plasma is 670 msec in standard configuration. The maximum energy confinement time of deuterium is 710 msec in high elongated configuration. Improvement of energy confinement time by isotope dependence is 1.1 and 1.2~1.3 in the high elongated and standard configuration, respectively. This difference comes from the difference in the effective mass ratio.

In the neutral beam heated plasma, stored energy of both hydrogen and deuterium plasmas increases linearly with internal inductance $l_i$. Let the stored energy has $l_i I_p^{0.8}$ dependence, the energy confinement time of deuterium plasma is larger than that of hydrogen plasma by 20 ~ 30 %. $\tau_E \propto M_i^{\alpha} l_i I_p^{0.8}$ indicates that $\alpha$ will be 0.5 ~1.0 maximum. with the same $n_e$, $T_e$ and $T_i$ profiles, the calculated beam stored energy in $H^0 \rightarrow H^+$ and $D^0 \rightarrow D^+$ plasma results in $W^D{}_{beam} \sim 1.9\ W^H{}_{beam}$. However, it results in only $W^D{}_{total} \sim 1.1\ W^H{}_{total}$. $W_{beam}$ alone cannot explain the mass dependence of total stored energy. The rest of stored energy comes from thermal component. The ambiguity of $Z_{eff}$ value, for example 2.5 ~ 3.5, may affect $W_i$. However, this variation is utmost 10 % of $W_{total}$.

## 6. Energy Confinement in High Current Limiter Discharges in JET

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In early 1992 limiter discharges with a plasma current of 7 MA were obtained in JET, with a current flat top duration of up to 8 seconds and auxiliary heating (NBI+ICRF) up to 25 MW for 4 seconds. The toroidal field on axis was 3.75 T, corresponding to an edge $q = 3.2$.
In these discharges the plasma energy content reached 10 MJ (nearly entirely thermal). The plasma density increased systematically with the input power, so that across the power scan the core temperature remained approximately unchanged at about 4 keV (for both electrons and ions). The plasmas were sawtoothing, with a corresponding wide central region of flattened profiles. Strong contact with the vessel walls limited the plasma purity, and $Z_{eff}$ was generally in the range 2.5-3.5.
The kinetic energy replacement time at 7 MA evaluated using the measured plasma profiles is approximately 0.45 seconds, nearly independent of the input power. The effect of sawteeth, in this low $q$ discharges, is estimated to be a loss of 30% of the plasma energy.
A comparison with steady-state L-mode data from JET discharges at 1, 3 and 5 MA shows that conventional scaling relationship fail to reproduce the observed general behaviour of the thermal energy replacement time. In particular, also at 3 and 5 MA the degradation with input power is not so clearcut as implied by, for example, Goldston's or the ITER-89P scaling. The current dependence in the JET L-mode data is certainly less than linear, even when the effect of sawteeth is taken into account.

Altogether, an assessment of the dependences of local transport appears to be a more appropriate way of characterizing energy confinement than the derivation of scalings for the global energy replacement time.
Initial work in this direction indicates - for this extensive set of limiter discharges- that the thermal conductivity in the confinement region correlates with the average input power per particle. This is true at all currents (with the value of the "effective" thermal conductivity increasing, in average, as the current decreases) and it seems to indicate that transport is more favourably dependent on the plasma density than implied by conventional L-mode scalings.
At 7 MA, the local transport analysis confirms the lack of power degradation observed globally ($\chi_{eff}$ is found to be approximately the same for all discharges). at this current a very limited range in $P/n$ has been explored.
No clear correlation is observed in the current scan data between $\chi_{eff}$ and the local temperature or the local temperature gradient. Conversely, it appears that at all currents the local heat flux predicted by the RLW "critical temperature gradient model" provides a reasonable fit (to within 50% for all data) to the heat flux inferred from the measurements. Since the model is highly non-linear, however, transport code simulations at the extremes of the JET current range will be required in order to conclusively demonstrate this agreement.

# 7. Effects of Current Profile on Energy Confinement in JT-60U

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Based on the ohmic and neutral beam heating experiments in JT-60U, discharge regions in the tokamak are categorized by internal inductance $l_i$ and the effective safety factor at the edge $q_{eff}$ in the low $\beta$ region. Stable discharges have medium $l_i$ values and disruptive discharges appear both in higher $l_i$ and lower $l_i$ regions for a given $q_{eff}$. There also exists a clear boundary of $l_i$ below which sawtooth activity disappears. In the sawtooth region, there is another boundary of a kind of profile consistency corresponding to the quasi-stationary current distribution profiles, along which the maximum value of $r_{inv}/a$ (sawtooth inversion radius / minor radius) is almost proportional to $1/q_{eff}$. At a given $q_{eff}$, $r_{inv}/a$ increases with increasing $l_i$. Concerning L-mode confinement, H-factor ( $H = \tau_E / \tau_E^{ITER89P}$ ) is almost proportional to $l_i$ in the wide range of $q_{eff}$ : $q_{eff}$ = 2-11. The degradation of confinement in the low-$q$ region ( $q_{eff} < 4\sim5$ ) in L-mode is caused by effects of $l_i$ and sawtooth activity. The maximum value of $H/l_i$ is almost constant in the whole region of $q_{eff}$. In the low-$q$ region, $H/l_i$ is reduced as sawtooth frequency $\tau_{sw}^{-1}$ becomes high and the degradation due to $\tau_{sw}^{-1}$ is stronger at lower $q_{eff}$.

# 8. Thermal Confinement in TFTR L-Mode Plasmas and Supershots

Presented by Larry Grisham
for
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High recycling TFTR plasmas follow traditional L-mode scaling with total stored energy confinement degrading as roughly $P^{-0.5}$. SNAP analyses to obtain local transport characteristics indicate that $\chi_i$ is the dominant loss channel in the L-mode, typically being a factor 2 or so larger than $\chi_e$ across most of the profile. Both $\chi_i$ and $\chi_e$ show an unfavorable temperature correlation, with the value at $a/2$ increasing as approximately $T_e^{1.5\text{-}2}$. The density dependence of confinement in L-mode is found to be weak. A set of size scaling experiments in L-mode across wide range of aspect ratio (2.8 - 8) have found a strong favorable scaling of confinement with major radius, but only a weak or negative dependence upon minor radius. These same experiments found that the profile dependence of $\chi_i$ is better ordered by the inverse local aspect ratio, $r/R$, than by $r/a$, suggesting that toroidicity plays a significant role in confinement. A set of scans in which the plasma current and the aspect ratio were varied while their product was kept constant found that the fusion performance factor $< nT > \tau_E$ is approximately constant for a given value of $I_pR/a$. Only weak species dependence has been found in experiments with H and D. Supershots in TFTR differ from L-mode discharges in that the transport within the core is reduced even though the ion temperature there is much higher than in L-mode. A set of current ramp experiments in L-mode plasmas showed that by controlling the current profile, confinement can be made to substantially exceed or undershoot L-mode scaling. These experiments also suggest that $I_p$ scaling of $\tau_E$ does not originate in the outer half of the plasma, but that $\tau_E$ is related to the current in the core of the plasma. Comparison of the ramping experiments with theory shows that the electron thermal transport (at least for $r > a/2$) does not agree with models having a strong local dependence on plasma current, $q$, or shear. TFTR has also carried out nondimensional scaling scans which found little dependence of transport upon $\nu_*$, while $\rho_*$ scans found transport to scale more like Bohm than gyroBohm, implying that long wavelength fluctuations are important.

## 9. Kinetic Energy Confinement in JT-60 L-Mode Plasmas

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The detailed analysis of the kinetic database of the JT-60 tokamak during 1985-1987 experiments (M. Kikuchi et al., JAERI-M 91-057, 1991) has been done to obtain a kinetic energy confinement scaling for JT-60 L-mode plasmas.

For the present database, the global energy confinement time $\tau_E$ is roughly proportional to $n_e^{0.25}/P^{0.5}$ ($n_e$ ; electron density, $P$ ; heating power), which is almost the same as ITER89-P scaling. In the total stored energy $W_{tot}$, however, contains sometimes more than 30% fraction of the beam stored energy $W_b$. It is very important to obtain a scaling for the thermal energy component $W_{th}$.

By using 73 data points with almost the same values of $I_p \approx 1.5$MA and $B_t \approx 4$T, we search for the dependence of $W_{th}$ on $P$ and $n_e$, and find the standard deviation minimum and no remained tendency at the relation $W_{th} \propto P^{1/3} n_e^{1/2}$. This relation is not of the form given by the Bohm transport ($W_{th} \propto P^{1/2} n_e^{1/2}$) nor by the gyro-Bohm transport ($W_{th} \propto P^{2/5} n_e^{3/5}$). The correlation between $P$ and $n_e$ is small in the database, which consists of TiC/Mo wall discharges and graphite wall discharges, though this correlation is strong for the graphite wall discharges. For each set of the different $I_p$ value, above relation holds well, and $I_p$ dependence of $W_{th}$ can be determined. Finally we have a following scaling of $W_{th}$ ; $W_{th} \propto (I_p B_t n_e)^{1/2} P^{1/3}$. $Bt$ dependence of this scaling is not so accurately determined because of the narrow range of $Bt$ values in the database.

Beam stored energy $W_b$ is described by the classical formula using average electron temperature $Te^* = W_e / (1.5 n_e V)$; $W_b = 0.5P \ \tau_s(Te^*) f(E_b/Te^*)$, and $W_{tot}$ is then given by $W_{tot} = W_{th} + W_b$. Experimental values are well reproduced by this scaling expression.

Beam acceleration energy $E_b$ (30keV< $E_b$ <75keV) affects little the confinement performance, which suggests the weak dependence on the heating profile. Ohmic confinement with high density regime (saturated ohmic confinement) can be also described by using the same scaling of $W_{th}$. The confinement properties for limiter discharges and for divertor are essentially the same. For divertor discharges in graphite wall, density cannot become high compared with limiter case (especially in high $I_p$ region) and stored energy becomes lower.

From the present scaling, we presume that a collisionless or weak-collisional high $\beta$ transport dominates the L-mode confinement, and that the thermal diffusivity takes the form
$\chi \propto (T/B)(\rho/a)\,\beta^{0.5}$.

## 10. Probing the Details of a Transport Model

M. L. Watkins
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Understanding heat and particle transport in a tokamak plasma is a major aim of the fusion programme. The critical electron temperature gradient model of transport confronts this aim and the progress made in comparing model and experiment over the last year is reported in this Workshop contribution.

The results of numerical tokamak experiments using this model show very good agreement with the power law scalings (such as ITER89-P) commonly in use. Furthermore, a detailed comparison with TFTR experiments on the scaling of confinement with major and minor radius shows that as $R/a$ is varied, the total stored plasma energy and the magnitude and spatial dependence of the effective thermal diffusivity vary as predicted by the model.

Moving to high performance plasmas, the PEP H-mode on JET is used to illustrate the dependence of confinement on the safety factor, $q$. The model predicts neoclassical transport for both electrons and ions in regions of negative magnetic shear and this is shown to occur in the central plasma under conditions with central ICRF and central pellet fuelling. Further out, the transport is found to be consistent with the anomalous transport predicted. This regime is identified with the JET PEP-modes which have good central confinement and MHD characteristics that are consistent with a central region of negative magnetic shear. Plasma confinement during current ramp experiments is also consistent with the model. In this case, the $q$-profile is modified transiently in the edge and the resulting change in magnetic shear partly compensates the dependence of confinement on current.

The dependence of confinement on $\nabla T_e$ is tested rigorously in experiments with off-axis ICRF heating and central pellet deposition which allow the study of hollow, flat and peaked temperature profiles. The transient behaviour of these profiles is found to be fully consistent with the predictions of the model, namely that the transport is anomalous only for $|\nabla T_e| > |(\nabla T_e)_{crit}|$, with $(\nabla T_e)_{crit}$ being the critical electron temperature gradient. Since transport is determined by electrons, the ions can be heated well above the electrons when electron heating is low and ion heating is high. These conditions pertain in the hot-ion H-mode discharges employed for the preliminary tritium experiment on JET and it is shown that these discharges can also be well simulated by the model.

# 11. Limits on High Power Heating in JET and Their Implication on Confinement

A. Tanga
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The plasma regimes which are characterized by best plasma performances in JET are obtained with high additional power. The time duration of such regimes is time limited by several factors. The PEP mode (Pellet Enhanced Performance) is limited in time by the MHD instability, probably a double tearing mode, due to the double value q profile. The Hot ion H mode which has better confinement than the "normal" H mode is limited in time by two different phenomena: First the high heat load of the x point dump plates produces large carbon influxes. Secondly and in the best cases, the plasma becomes MHD unstable and the energy is lost on MHD time scale of less than 1 ms. Consequently in these two regimes the plasma energy never reaches equilibrium. In the best cases the time variation of the stored energy is more than 30% of the input power. The situation is somewhat better for the ELMy H modes where a transport steady state is reached albeit with confinement time sensibly deteriorated if compared with "normal" ELM-free H modes. Long limiter L mode pulses reach current diffusion relaxation with characteristically narrow values of the internal inductance of about 1.0, which is probably linked to plasma MHD stability.

## 12. Comparison of Confinement in Different H-Mode Regimes in JET

The JET team, presented by D.J. Campbell
JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK

Extensive experiments in JET have explored a range of H-mode confinement regimes. At the highest currents and powers, H-mode plasmas with up to 23MW of auxiliary heating (NBI and ICRF) have been established in the double-null configuration at plasma current of up to 5MA. Analysis of global energy confinement, using diamagnetic energy measurement, indicates that confinement does not scale linearly with plasma current. While 3MA plasmas have confinement times which are in good agreement with common scaling laws (e.g. ITER90H-P), a smaller proportion of 4-4.5MA plasmas are consistent with such scalings and the 5MA H-modes are not improved relative to the 4-4.5MA cases (although the range of experiments at 5MA was not extensive).

Comparison of plasmas with and without sawteeth indicates that sawtooth effects are not responsible. Moreover, comparison of NBI and ICRF heated plasmas shows that heating profiles do not have a significant influence. One possible explanation for the observed trend is the progressive reduction in edge shear as the plasma current is increased and the X-point moves gradually outside the target (by up to 8cm in the 5MA case). This may also contribute to the high $Z_{eff}$ values observed. In spite of extensive gas-puffing, which is effective in delaying carbon 'blooms', $Z_{eff}$ can rise to values ~4-5 and it is found that, for fixed values of $P_{tot}/\langle n_e \rangle$, plasma purity decreases with increasing plasma current. This is responsible for the observation that the projected $Q_{DT}$ does not increase with plasma current over the range 3-5MA. If hot-ion modes are excluded, the best fusion performance achieved in this regime corresponds to an equivalent $Q_{DT} \sim 0.2$-0.3.

High fusion yield (with equivalent $Q_{DT} \sim 1$) is obtained in hot-ion H-modes produced by high power NBI in both double and single null configurations at plasma current of 3-4MA with $q_{95} \sim$ 3.3-3.8. Many such hot-ion H-modes show evidence of enhanced thermal confinement. Analysis using the TRANSP code and experimentally determined plasma profiles indicates a substantial reduction in $\chi_i$ across the plasma. Moreover, in the central plasma, $\chi_i$ is consistent with neoclassical values. As a result, the best such discharges exhibit a considerable enhancement in thermal energy confinement (up to a factor of 2 greater than the JET/DIII-D H-mode scaling). Recently NBI and ICRF heating have been combined in these discharges for the first time. The major result was a significant increase in the rate of rise in the neutron production. Analysis suggests that the increased electron temperature is insufficient to explain this effect and that acceleration of deuterons by second harmonic ICRF absorption makes an important contribution.

H-modes in JET are generally ELM-free and the density and radiated power rise continuously, leading to a termination of the H-mode after 3-5s when the bulk radiation is ~60% of the input power. A variety of techniques have been investigated for the production of ELM's and, recently, significant progress has been made. In 2-2.5MA double-null X-point plasmas at 2.3T, steady-state H-modes, in which plasma parameters were held constant by ELM's, have been produced using gas-puffing into the lower X-point. The longest duration achieved was 18s and the limits were set by stresses in the shaping field circuit rather than by plasma properties. A preliminary analysis of the thermal energy content indicates that the thermal energy confinement is degraded relative to ELM-free H-modes, with confinement times in the range 75-90% of those predicted by the JET/DIII-D scaling law.

# 13. Confinement Characteristics in JFT-2M

presented by Y. Miura
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## I. Rapid Change of Hydrogen Neutral Energy Distribution at L/H-Transition in JFT-2M H-mode

Y.Miura, F.Okano, N.Suzuki, M.Mori, K.Hoshino, H. Maeda, T. Takizuka, and JFT-2M Group (JAERI) S.-I.Itoh, K.Itoh (NIFS)

Rapid changes of the main ion energy distribution at transitions from L-to-H, H-to-L and during ELMs are studied with the time of flight neutral measurement on the JFT-2M tokamak. At the L to H transition, 200-400μs prior to the start of $H_\alpha$ drop, an increase of the high energy out flux above an energy of 200eV is observed. An energy of more than 200eV for hydrogen corresponds to the collisionless condition $\nu_{*i} < 1$ just inside the separatrix. The change of the energy distribution precedes that of the $H_\alpha$ signal and is also found for ELMs and the H to L transition.

## II. Offset Linear Scaling for H-mode Confinement

Y.Miura, H.Tamai, N.Suzuki, M.Mori, T.Matsuda, H.Maeda, T.Takizuka (JAERI)
S.-I.Itoh, K.Itoh (NIFS)

An offset linear scaling for the H-mode confinement time is examined based on single parameter scans on the JFT-2M experiment. Regression study is done for various devices with open divertor configuration such as JET, DIII-D, JFT-2M. The scaling law of the thermal energy is given in the MKSA unit as

$$W_{th} = 0.0046\, R^{1.9}\, I_p^{1.1}\, B_T^{0.91}\, A^{0.5} + 2.9 \times 10^{-8}\, I_p^{1.0}\, R^{0.87}\, A^{0.5}\, P\ ,$$

where $R$ is the major radius, $I_p$ is the plasma current, $B_T$ is the toroidal magnetic field, $A$ is the average mass number of plasma and neutral beam particles, and $P$ is the heating power. This fitting has a similar root mean square error (RMSE) compared to the power law scaling. The result is also compared with the H-mode in other configurations. The $W_{th}$ of closed divertor H-mode on ASDEX shows a little better values than that of open divertor H-mode.

## III. Geometric Dependence of the Energy Confinement Time Scaling for H-mode Discharges

Y.Miura, T.Takizuka, H.Tamai, T.Matsuda, N.Suzuki, M.Mori, H.Maeda (JAERI)
K.Itoh, S.-I.Itoh (NIFS) O.J.W.F.Kardaun (IPP Garching)

The dependence of the energy confinement time $\tau_E$ in the H-mode discharges on the plasma elongation and divertor configurations is studied. Regression analysis is made on the H-mode database, while the dependence on the closed/open divertor is introduced according to the ASDEX experiments. The dependence of $\tau_E$ on the elongation factor $\kappa$ was found to be positive (approximately $\kappa^{0.6}$) for the ELM free H-mode, confirming the experiments on $\kappa$-dependence in JFT-2M tokamak. The influence of the single/double null divertor configuration is also discussed.

## IV. Steady State H-mode by Ergodic Field on JFT-2M

Y.Miura, T.Shoji, M.Mori, T.Fujita, N.Suzuki, H.Ogawa, T.Yamamoto , and JFT-2M Group (JAERI)
N.Ohyabu, K.Ida (NIFS) A.W.Leonard, A.M.Howald, A.W.Hyatt (GA)

H-mode has little controllability from the view point of a steady state operation. By applying a high-m ergodic magnetic field, the suppression in density and radiation increase is observed with $H_\alpha$ bursts and a steady state H-mode can be realized in JFT-2M. The total stored energy of the steady state H-mode shows some loss compared with that of the burst free H-mode. But it is only less than 10% due to the suppression of density increase. The profiles of the core plasma density and temperature are almost the same with and without the ergodic field. The controlled region of the steady state H-mode can be seen as a belt above L/H threshold in neutral beam power versus ergodic field graph. That region increases with incresing the ergodic field. This demonstrates an active controllability of the H-mode.

# 14. VH-mode Discharges in DIII-D* Confinement and Transport

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Following boronization of the DIII-D vessel, very high confinement discharges (VH-mode) have been obtained in DIII-D with thermal energy confinement times up to 2 times the JET/DIII-D ELM free H-mode scaling and nearly 4 times above the ITER89-P L-mode scaling. This high confinement regime is characterized by a continually rising energy content and continually rising thermal confinement during constant deuterium neutral beam power injection, until the high confinement regime is terminated by a global MHD event near the expected beta limit for these discharges. These VH-mode discharges are obtained with low target density and low recycling and have low $Z_{eff}$ and low radiated power ($P_{RAD}/P_{NBI} < 30\%$), with neutral injection power up to 15 MW.

The increased energy content in the VH-mode discharges, compared to H-mode discharges, is a consequence of the change in the temperature profiles: the density profiles of the VH-mode and H-mode are very similar. The region of high temperature gradients and high pressure gradient observed in H-mode discharges broadens in VH-mode discharges, extending from the edge inward to $r/a \cong 0.8$. Time dependent transport analysis shows a significant decrease in the thermal diffusivity in the outer portion of the plasma, $r/a > 0.6$, with the largest decrease occurring approximately at $r/a$ of 0.8:
$\chi_{eff,VH}\ (r/a=0.8) \cong 1/3\ \chi_{eff,H}\ (r/a=0.8)$, where $\chi_{eff} = -q/(n_e\nabla T_e + n_i\nabla T_i)$.

We are evaluating two possible causes of the reduced transport in VH-mode, broadening of the region of strong radial electric field shear, and increasing fraction of the plasma volume entering the second stable regime. The region of strong shear in the radial electric field is observed to broaden from the H-mode to the VH-mode, extending inward from the plasma edge to approximately $r/a = 0.8$, consistent with the region of reduced transport. The edge region of the VH-mode discharges is calculated to be in the second regime of stability to ideal ballooning modes and the volume of plasma entering the second regime increases with increasing edge current density. The edge bootstrap current is calculated to increase throughout the VH-mode phase.

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# 15. Summary of the Workshop

D.Stork
(JET Joint Undertaking)

## 1.Introduction

The workshop comprised 14 contributions; 5 from JET; 4 from JT-60U; 3 from TFTR and 1 each from DIIID and JFT-2M. The material is divided into 5 areas in this summary, based on the topics covered. Contents of a talk thus often appear in more than one area. This will ease the comparison between different machines.

Topic sections are; i) L-mode confinement and scaling.; ii) High $\beta_{pol}$ regimes, especially confinement at high-$\beta_{pol}$; iii) H-mode regimes (including the VH mode); iv) Characteristic timescales for present Tokamak regimes; v) Theoretical comparison with experimental data.

### 1.1 Attainment of enhanced confinement regimes

One constant theme of the workshop, was that the attainment of enhanced confinement regimes is frequently viewed in terms of surface conditioning of the Tokamak vessel or in terms of enhanced MHD stability. It was felt that local transport improvement in the inner part of the plasma ($r/a \leq 0.8$) often resulted from improved interactions at the plasma edge or from the manipulation (controlled or otherwise) of the magnetic configuration of the discharge. The maintenance of the condition of such improvement against the tendencies of wall de-conditioning and/or current diffusion in long term discharges represents a major challenge for Tokamak research. It is thus appropriate that this confinement workshop spent so much of its time discussing surface conditioning and MHD physics effects.

## 2 L-mode confinement properties and scaling

| | | |
|---|---|---|
| Contributions from ; | Kamada, Shirai, Takizuka | :JT-60 |
| | Tibone | :JET |
| | Grisham | :TFTR |

### 2.1 Global Confinement Scaling of L-mode

Data was reported from JT-60 (Takizuka) showing the scaling of L-mode kinetic energy obeys the relationship;

$$\tau_k \sim (I_p B_t n_e)^{1/2} / P_t^{2/3} \qquad (1)$$

and that the (preliminary) lower X-point data from JT-60 shows good agreement with this. Also the exact transport properties at the edge of JT-60 plasmas are not a good global confinement indicator (i.e high $\chi_{edge}$/low $P_{rad}$ and low $\chi_{edge}$/high $P_{rad}$ give similar confinement). The indicator giving the best correlation to global confinement is $\chi_{eff}$ at mid radius ($\tau_k \sim <0.2/\chi_{eff}(r/a=0.5)>$). $\chi_{eff}$ is parametrised as $\sim (T/eB)(r/a)\beta^{0.5}$.

Data from TFTR (Grisham) shows strong positive $I_p$ scaling, negative $P_t$ scaling and virtually no $B_t$ dependence for the L-mode scaling viz.

$$\tau_E^{th} \sim I_p P_t^{-0.71} \qquad (2)$$

Also, in contradiction to previously reported papers at the EPS [1], the dependence of $\tau_E^{th}$ on density is negligible.

The JET data reported (Tibone) concentrated on the extension of global confinement scaling up to 7MA. (from 1MA) at total powers >20MW. Many global scalings have been tried but do **not** fit the data well. Neo-Alcator scaling is a poor description of the OH phase; Goldston, ITER-89P and Rebut-Lallia are all poor descriptions for the high-power phase. The simple confinement scaling with current ($\tau_E \propto I_p$) is **not** maintained up to 7MA. The 7MA L-mode global confinement does not degrade with power, but nevertheless lies below the L-mode scaling.

## 2.2 Confinement Scaling with particular parameters

### 2.2.1 Plasma Ion Mass

There is still variation between the results obtained on the different machines regarding the mass dependence of confinement scaling. The JT-60U data (Shirai) shows scaling with mass both in the OH and high power NBI phases. The database does not contain either pure H or pure D plasmas (due to isotope-exchange problems with the vessel walls) so the effective mass changes only form ~1.25 to ~1.8. A 20-30% change in confinement is seen of which only ~10% can be explained from extra fast ions in the 'D' case. The confinement scaling $\tau_E \sim I_p^{0.8} l_i A_{eff}^{\alpha}$ is inferred with $\alpha$=0.5-0.7.

TFTR (Grisham) see a smaller variation of stored energy between pure D plasmas with $D^o$ injection, and H plasmas with $D^o$ injection where the H/(H+D) ratio is well below unity. From this data they infer a $\sim A_i^{0.2-0.3}$ dependence in $\tau_E$.This is weaker than the exponent inferred from dedicated 'mass scaling' experimental runs with Ohmic plasmas where $\tau_E \sim A_i^{0.36}$.

JET data was not reported, but the forthcoming paper (1992 ICPP Innsbruck - Tibone et al.) shows a weaker scaling than either JT-60 or TFTR. Contamination of the minority isotope was <10% in these discharges.

### 2.2.2 Aspect ratio

Both JT-60U and TFTR contributors emphasised the favourable behaviour of confinement with increased aspect ratio.

On JT-60U (Shirai) the small $a_p$ plasmas have improved confinement relative to $\tau_E^{ITER-89P}$ by a factor ~1.3. It was not clear whether an improvement of this size could be attributed to more central beam deposition or the reduced ripple-loss which occur in such plasmas rather than to aspect ratio scaling *per se*.

Much clearer was the TFTR data (Grisham) presented and discussed at length. In this previously reported [2] study, comparison of confinement for pairs of inboard and outboard limited TFTR plasmas, with other parameters ($I_p$, q, $\langle n_e \rangle$, $a_p$, $P_{in}$) kept constant, showed a strong R scaling ($R^{1.57-1.72}$). Over the whole database (fitting all plasmas in this set) there emerged strong positive R scaling and weak negative $a_p$ scaling, eg. the kinetic energy scaling

$$W_{kin} \sim R^{1.77} I_p^{1.12} a_p^{-0.242} P_t^{0.344} \qquad (3)$$

Clearly there is a limit to how far this scaling can be pursued ($a_p$=0 clearly not desirable). Also, for a given $I_p$, to keep q at reasonable values $B_t \propto A/a$, (A=R/a); unless a strong favourable $B_t$ scaling is seen (not seen so far in L-mode) then the cost and stored energy in TF becomes prohibitive. The **local** transport analysis of the aspect ratio scaling shows that toroidicity (r/R) is a good scaling parameter, but not r/a. The results indicate that the $\chi_{avg}$ in small plasmas is similar (vs r/R) to the inner part of larger plasmas. Small plasmas behave as the inner part of large plasmas (see also section 6). This result is true at the +/- 20-30% level.

### 2.2.3 Current profile, $l_i$, sawteeth

An examination of JT-60U L-mode data (Kamada) showed that enhancement factor H ($\tau_E/\tau_E^{ITER\text{-}89P}$) varied almost linearly with $l_i$ over a wide range of q (2-14). At high values of $l_i$ (~2), enhancement factors of ~1.6 are seen. The usefulness of this result should be balanced against the JET observations (Tibone) that $l_i$ in the current flat-top is inversely proportional to $I_p$, indicating that a 'poor' value of $l_i$ will be obtained at the top end of any given machine's operating range.

JT-60U find an important effect of sawteeth on the H parameter ($H/l_i \propto \tau_{saw}$), but the dependence becomes less marked at high $q_{eff}$. The confinement degradation in the low-q regime can be explained by the combined effects of $l_i$ and sawteeth. JT60 experiments have stabilised sawteeth with pellets at low $T_e$, and improved $\tau_E$, indicating that the dependence of H is **not** simply due to a high H→high $T_e$→long $\tau_{saw}$ causal chain. More pellet experiments are planned soon.

In the JET 7MA data (Tibone) the effect of large values of the sawtooth radius explains some of the lower than predicted energy confinement. Also, $l_i$ is lower. The JET current-ramp data (not presented at the meeting, but submitted to Nuclear Fusion) indicate that $\tau_E \propto I_p^{4/3} l_i^{2/3}$. When applied to the 7MA data, this scaling is a worse predictor than a simple $I_p$ scaling however. The decrease in $l_i$ is insufficient to outweigh the increase in $I_p$ when scaling from low to high currents..

TFTR data on heating during current ramps was briefly reported (Grisham). The ramps are shorter (~5 times) than the current diffusion time. Significant changes in the shear in the outer region are achieved and $\tau_E$ loses its proportionality to $I_p$ for many (>15) confinement times. The transient confinement is seen to be enhanced relative to L-mode as the $l_i$ peaks (in a ramp down). The team report $\chi_i$ and $\chi_e$ stay approximately constant during the ramps and that the electron heat flux values are not compatible with predictions of resistive ballooning theory or some $\eta_e$ models.

## 2.3 Local Transport

JET results (Tibone) show that $\chi_{eff}(r/a{=}0.75)$ has a strong correlation with **power per particle deposited** within this radius for the range $1.0 \le I_p \le 7.0$MA. No correlation is apparent between $\chi_{eff}$ and local $T_e$ or $\nabla T_e$. The Rebut-Lallia-Watkins expression for the conducted power agrees fairly well with the data at this radius over the current range, usually getting the correct trend.

TFTR results which have been around for some time were summarise by Grisham showing that **Ion conduction** is the dominant loss channel in the L-mode; that $\chi_i$ and $\chi_e$ improve with $I_p$ across the profile; that they have little dependence on density and that $\chi_i$ and $\chi_e$ correlate strongly with temperature at the r/a=0.5 radius.

## 3 High $\beta_{pol}$ regimes

| | | |
|---|---|---|
| Contributions from; | Ishida | JT60 |
| | Stork | JET |
| | Bell, Sabbagh | TFTR |

The high $\varepsilon\beta_{pol}$ regime underpins 'advanced reactor concepts ' such as SSTR and ARIES and holds out the prospect of efficient current drive through the Bootstrap mechanism.

### 3.1 High $\varepsilon\beta_{pol}$ arising from strong, transient profile manipulation

Two regimes were discussed here ; the current ramp experiments to low Ip with inboard separatrix-limited plasma (TFTR) and the JET Pellet Enhanced Performance (PEP) H-modes.

With the highly-transient nature of the profile changes concerned, it is **uncertain that these modes can ever be translated to a reactor scenario.** This remains a formidable experimental challenge. In view of the extremely large size of present L-mode reactor scenarios however, it seems worthwhile to pursue study of these high confinement modes to the point where the database can really be helpful in establishing their reactor relevance.

#### 3.1.1 Current ramp plasmas (TFTR)

Sabbagh reported the attainment of some impressive parameters at the low currents.

| | |
|---|---|
| $2.2 \leq \tau_E/\tau_{E,L} \leq 3.5$ | $\beta_{pol} \leq 5.9$ |
| $\varepsilon\beta_{pol} \leq 1.6$ | $\beta_{N,DIA} \leq 4$ |

There are virtually no non-disruptive shots with $\beta_N>3.6$ and about 25% of shots disrupt if $\beta_N>3.0$. This should not be viewed as a 'reliability study' of these discharges however. Most of the plasmas at high $\beta_N$ disrupt on the timescale of the current profile relaxation at the edge. With steady state current profile control the stability of the discharges might be maintained.

For constant $I_p$ $\tau_E/\tau_{E,L}$ increases slowly with $\varepsilon\beta_{pol}$, but stronger confinement enhancement occurs with ramped currents. At the higher currents (1.75MA ramped to 1.2MA) there is no confinement degradation with power increase. Long pulse operation (up to 4 sec with NBI) shows well the development of the mode after the ramp. $\beta_{pol}$ declines from 4 to 3 and then suffers a collapse after ~ 2.5 sec. This again emphasises the need to combine this scenario with a method of maintaining the current profile near the edge. A MHD (3,1 mode) appears to be implicated. By the time the collapse occurs the current profile has significantly broadened with $l_i$ decreased. This combination has been shown to be unstable to the low-n kink. The drop in $l_i$ whilst confinement enhancement is largely maintained has effectively decoupled these parameters in this experiment.

The high $\beta_{pol}$ current ramp discharges have a high fraction (around 70%) of the total current driven by the Bootstrap mechanism, comparable to results on other large Tokamaks.

#### 3.1.2 PEP and PEP/H-modes

Stork reported on the latest JET experiments in this area. From the injection of the pellet plus high power heating (**before** the onset of sawteeth), values of $\varepsilon\beta_{pol}$ ~0.6-1.2 are reached within the PEP core region ($r/a \leq 0.4$). Density profiles are very steep at the core edge, and the shear is clearly reversed within the core (effects of the off-axis Bootstrap current).

PEP H-modes are shown (from local transport analysis) to be ordinary H-modes with enhanced core confinement ($\chi_{eff}^{core} \sim 0.5\ m^2s^{-1}$; $D_e^{core} < 0.1\ m^2s^{-1}$). Operationally, there are no disruptions with the PEP once established, but termination occurs (at most) about 1.5sec after the start of the high power heating. PEPs with dominant NBI heating tend to last longer. The termination phase shows wide variability. Candidates for the PEP termination are low-n MHD (though difficulties exist with identifying this as an internal kink which should be unstable with an off-axis $q_{min}$~1); impurity accumulation due to a combination of MHD activity in the rise phase of the PEP plus the enhanced core confinement; high-n ballooning modes with the PEP pressure profile expanding into the gap between the 1st and 2nd stable regions. A preliminary analysis shows that p' at r/a~0.4 comes close to the ballooning limit.

Note that so far, no $I_p$ or $B_t$ scaling is available for the PEP/H-mode.

### 3.2 JT-60U High $\beta_{pol}$ regime and TFTR Supershots

These occupy similar regions of $\varepsilon\beta_{pol}$ and normalised beta ($\beta_N=\beta_T aB_T/I_p$). They are very similar regimes, with similarity in the recipes required for their attainment.These recipes emphasise surface conditioning (to achieve low recycling); strong central fuelling and power deposition by NBI (to ensure that the centre of the discharge further dominates over the edge); in the case of JT-60U the plasmas are also relatively small volume and on the inboard side (although still diverted). This latter gets away from TF ripple effects, but also removes the influence of the wall of the vessel on the bad-curvature side.

The q range for these modes is similar (q* ~ 3-11 on TFTR, ~ 5-11 on JT-60U) and since they are achieved at different aspect ratio (~4.3 on JT-60U, ~3.3 on TFTR) there is clearly some scope for scaling between the 2 machines.

#### 3.2.1 JT-60U High $\beta_{pol}$

Ishida reported on the high $\beta_{pol}$ regime. This is a hot-ion type regime with $T_i>2*T_e$. The maximum enhancement factor $\tau_E/\tau_{E,L}$ is obtained at $P_{loss}=(P_{abs}\text{-}dW/dt) \sim 8MW$ and then drops rapidly with increased power. At any given value of $P_{loss}$, the best discharges suffer $\beta_{pol}$ collapse.

The fusion neutron rate $S_n \propto W_{dia}^{1.99}$ (very similar to the Supershots reported by Bell).

At high values of $\varepsilon\beta_{pol}^{dia}$ (>0.5) the discharges which show $\beta_{pol}$ collapses are consistent with a limit at $g\varepsilon\beta_{pol}^{dia} \sim 1.3$ ($g=\beta_T aB_T/I_p$), as shown in fig1. This is compatible with a simple Troyon-like theory. The enhancement factor over ITER-89P L-mode of the best discharges is $\propto$ $\varepsilon\beta_{pol}^{dia}$ up to $\varepsilon\beta_{pol}^{dia} \sim 0.6$, where it reaches H ~ 3-3.5.

The mode has been achieved at toroidal fields up to 4.4T in JT-60U and with similar aspect ratio to the similar discharges on JT-60. The plasma volume in the JT-60U case is ~47m$^3$ (compared to 30m$^3$ in JT-60). As yet, the current scaling is not clarified.

#### 3.2.2 Supershots.

Bell reported the results of an extensive and very careful documentation of Supershot performance. The current range for Supershots now extends up to 2MA and values of $\beta_N$ ~2.1

have been attained. Careful elimination of the carbon bloom has enabled discharges to be pushed to what seems now to be an MHD limit at $\beta_N \sim 2.1$.

Regarding confinement scaling, the mode exhibits a weak $P_t$ degradation ($P_t^{-0.06}$) and a weak $I_p$ degradation ($I_p^{-0.24}$). This is a scaling for the **total diamagnetic energy,** including the fast particles, which the TFTR team say are not dominant.# One question which arises concerns whether or not the surface interactions become more important in the large plasmas and degrade the confinement. There is a strong $B_t$ scaling of Supershot confinement ($\sim B_t^{1.0}$) and an R scaling similar to the TFTR L-mode.

Low recycling was emphasised as being important to obtain the mode (Lithium and boron pellets aid this also) but the key is probably the ratio of edge:central fuelling (shown in the $n_e(0)/<n_e>$ correlation of the $\tau$ enhancement), the maintenance of this in the face of a first wall gradually charging up with deuterium is an important issue here. Whether or not the density peaking **causes** the enhanced confinement or both phenomena are the result of a further underlying cause is not clear.

The best Supershots have $\tau_{E,dia}{}^S/\tau_{E,dia}{}^L \sim 3\text{-}3.5$ at $n_e(0)/<n_e> \sim 3$. The best Supershots show the effect of MHD limitations with degraded fusion yield (after a peak has been reached) setting in at $\beta_N \sim 2.0$. Sometimes this is accompanied by strong low-n activity.

### 3.3 High Bootstrap-fraction H-modes

Stork reported the results from JET ICRF H-modes at low $I_p$ ($\leq$1.5MA) which have succeeded in driving $I_{boot}/I_p \sim 0.7$ at high q ($q_{95} > 12$). The configuration is aimed at generating high $\varepsilon\beta_{pol}$ in a reactor relevant scenario with high edge fuelling, negligible central fuelling and flat density profiles. This contrasts strongly with all the other high $\varepsilon\beta_{pol}$ regimes.

Due to the high edge density gradients, the Bootstrap current is located at the edge (cf. DIIID VH modes- section 4, but lower values than on DIIID). In the region $\varepsilon\beta_{pol} \sim 0.48 - 0.65$, $\beta_{pol}$ collapses are seen. These are not catastrophic and can be repetitive with the time averaged $\beta_{pol}$ remaining at ~90% of the peak value. The confinement enhancement factor is high, with $\tau_E \sim 3.5 * \tau_{E,L}$(Goldston) being achieved. (~1.7*JET/DIIID scaling).

Analysis shows that the edge ballooning limit may be exceeded at the collapse. A competing mechanism is interaction of the edge plasma with the RF antenna, and the data are not sufficient to distinguish between these at the present time.

### 3.4 Comparative $\beta_{pol}$ regimes

To aid the comparison between different machines, figure 1 plots the regimes of some of the high $\beta_{pol}$ plasmas on JT-60, JET and TFTR.

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-# **Comment**; Notwithstanding the various comments about the size of the fast ion contribution to the stored energy, it would be preferable if teams would adopt the same quantity to scale. Thermal stored energy seems to be the most relevant option. The comparison with eg; Goldston scaling would then be a problem as this scaling was developed from Tokamak data including fast particle content. Perhaps the time is right for a new look at **thermal** L-mode scaling to provide a baseline for comparison?

## 4 H-mode regimes (including the VH mode)

| | | |
|---|---|---|
| Contributions from; | Taylor | DIIID |
| | Miura | JFT-2M |
| | Campbell, Stork | JET |

### 4.1 JET H-modes at high $\beta_N$

Stork reported on the beta limit experience with JET H-modes.

Values of $\beta_N \sim 3.3$ (20% above $\beta_{TROYON}$) have been reached in JET low $B_t$, low q ($q_{95}<3$) H-modes. ($\varepsilon\beta_{pol}$ values ~ 0.18-0.26). The JET limit appears consistent with peak $\beta_N \sim 4l_i$, but no systematic test of this has been done. At the highest $\beta_N$ values, high frequency noise is seen on magnetics, B (evidence of ballooning modes?). A numerical ballooning analysis shows that the plasmas exceeding $\beta_N \sim 2.8$ are reaching the ideal high-n limit at $0.4 \leq r/a \leq 0.5$. Confinement in these high $\beta$ shots has a H factor over Goldston L-mode ~ 1.7-1.9 for discharges with $T_i \sim T_e$, and slightly above 2 for the high $T_i$, high $\beta$ shots. (See also section on JET Hot Ion H-modes).

### 4.2 High performance H-modes

#### 4.2.1 'VH' modes on DIIID

Taylor reported on the occurrence and characteristics of the 'VH' mode on DIIID.

Under conditions with high $P_{aux}$ (>8MW NBI), at high $B_t$ (>2.1T) or high q ($\geq 4$), with a low density target and predominantly boronised walls, the H-mode on DIIID is further enhanced to produce plasmas with $\tau_E \sim 1.5\text{-}2$* JET/DIIID scaling values (3-4* Goldston L-mode). This has been dubbed the 'VH-mode'. The mode will last for many confinement times and is generally terminated by global MHD at $\beta_N > 2.8$. In the termination phase a rapid loss of energy occurs across the profile in 100-300$\mu$s. Internal n=1 mode and higher n modes near the edge are seen. This leads the team to conclude that this mode is limited by stability

Local transport analysis shows that after the propose H-VH transition, the $\chi_{eff}$ at $r \sim 0.8$ is reduced by a factor > 2. $T_i \sim T_e$ and so the analysis does not distinguish which loss channel is improved. As the VH mode progresses, the power deposition becomes more off-axis. The edge fluctuations become quiescent over a broader edge range than in the H-mode. The region of shear in the edge electric field is widened. $E_r$ is much lower from $0.7 \leq \rho \leq 0.9$ in the VH mode. The confinement still degrades with power ( ~ $P_{loss}^{-0.5}$) and a scaling with current ( ~$I_p^{1.0}$) is still seen. Energy confinement appears to improve with triangularity.

The effect of the boronisation is postulated to lie in the reduction of edge density, leading to high $T_e$ at the edge, low collisionality and high $\nabla p$ and causing a high Bootstrap current (>50 $Acm^{-2}$ at $\rho \sim 0.85$). This edge current is shown in a ballooning analysis to place the outer 30% of the plasma volume in the 2nd stable region.

#### 4.2.2 JET Hot Ion H-modes

The Hot Ion H-mode on JET was described (Campbell). A low density target is needed, although the best of these discharges at the higher end of this range ($\langle n_e \rangle \sim 2\ 10^{19}\ m^{-3}$).

Beryllium gettering assures the best performance, although the separatrix interacts with the carbon tiles for the high performance discharges. NBI remains the heating scheme for the discharges with the highest $R_{DD}$ and highest $Q_{DD}$, but ICRF has now been coupled into these discharges in significant amounts. ICRF increases the initial rise of $dR_{DD}/dt$. In NBI heated discharges, the thermal neutron production is ~60% of the total for the best performance shots. For the NBI/ICRF discharges the acceleration of NBI deuterons by $2\omega_{CD}$ damping is required to explain the neutron yield.

Local transport analysis shows that $\chi_i$ is significantly lower (~50-60%) for the Hot Ion H-mode across the entire plasma profile, when compared to ordinary H-modes. Central values are commensurate with neoclassical values ($<0.5m^2s^{-1}$). The termination phase is associated with a change in $\chi_i$ across.the plasma The Hot Ion H-modes show enhanced thermal confinement before the collapse with H factors ~2*JET/DIIID scaling.

The behaviour of JET Hot-Ion H-modes at high $\beta$ and low $B_t$ (low q), was described (Stork). Recent JET operation has extended the Hot Ion domain down to 1.8T at 3.1MA ($q_{95}$ ~2.8). The Hot Ion H-modes performance is limited at $\beta_N \sim 2.3$. Sometimes this appears to be associated with a variety of MHD activity, on other occasions **no** clear MHD cause appears is seen. High frequency MHD activity is seen at a threshold value ($\beta_N^{HF}$) which is inversely dependent on $Z_{eff.}$ The collapse phase at high $\beta$ sometimes shows a 'soft' limiting across the profile before collapse, at other times a rapid collapse (~100μs timescale) is seen across the plasma, accompanied by a giant ELM.

The confinement enhancement shows a strong $B_t$ scaling ($B_t^{0.7}$) in these discharges, dropping to ~2.1* Goldston at 1.8T. The scaling of confinement with $l_i$ in such discharges is uncertain and does not follow the $l_i^{0.68}$ scaling which has been postulated for the JET current ramp (L-mode) data.

## 4.3 H-mode confinement scaling

### 4.3.1 Data from JFT-2M

Miura reported on an exercise to apply offset-linear scaling to H-mode data from JFT-2M, DIIID and JET. This was motivated by the behaviour of data in single parameter scans in JFT-2M. A scaling law for the thermal energy was given as follows;

$$W_{th} = 0.0046\, R^{1.9}\, I_p^{1.1}\, B_t^{0.91}\, A_i^{0.5} + 2.9\; 10^{-8}\, I_p^{1.0}\, R^{0.87}\, A_i^{0.5}\, P \qquad (4)$$

This scaling has a similar fit quality to the power law scaling.

### 4.3.2 Confinement scaling for JET H-modes at high current

JET data was presented (Campbell) up to $I_p$=5MA, now achieved on JET in the DNX configuration. The scaling of confinement with $I_p$, which applies in the JET H-modes up to 4MA, is not continued in these highest current discharges, which have confinement considerably below the ITER 90HP scaling. The best of these high current discharges achieve a projected $Q_{DT}$ ~0.2-0.3, which is largely thermal.

The reasons for the degraded performance at 5MA were discussed. The X-point has to be outside the tiles in these discharges, making them effectively limiter H-modes. There is hence a reduction in edge shear at the highest currents. Also the $z_{eff}$ deteriorates (at fixed value of $P/<n_e>$) for the highest currents, due to surface interactions.

## 4.4 Steady state H-modes

### 4.4.1 Use of Ergodic field on JFT-2M

Miura reported on a very interesting development on ELM stimulation using an EML (Ergodic Magnetic Limiter). The coils used are n=2 and have a high m spectrum which is dependent on minor radius. Their application is seen to suppress density and radiation rise and to provoke Hα bursts in an ELM-like manner. Using this a steady-state H-mode has been obtained on JFT-2M with only ~10% deterioration in energy confinement below ELM-free periods. Central profiles are almost unaffected by the EML operation. Increasing the magnetic field increases the frequency of the ELMs. Increasing the NBI power at fixed ergodic field generally gives an improved ELM-free H-mode.

### 4.4.2 JET Steady-state H-modes

The development of JET ELMy H-modes with steady state up to 18s. length was presented by Campbell.

Medium and high power H modes in JET are usually ELM-free (unless near the β-limit ) and the density and radiation rise continuously in the H phase. ELM free H-modes in JET terminate in 3-5 s when bulk radiation is ~60% of the input power. In the 18s H-mode, an ELMy phase of ~16 s occurred. No carbon bloom occurred in spite of 75MJ energy being delivered to the X-point tiles. The H-mode enhancement factor lies between 1.6*Goldston (thermal profile integration) and 2*Goldston (diamagnetic), these differences are still to be resolved. Gas puffing occurs throughout the discharge. The ELMy plasmas show a reduction in the pressure profile in the outer part of the plasma. A preliminary local transport analysis shows that $\chi_{eff}$ is $\sim 2^*\chi_{eff}^{ELMfree}$ at the ρ>0.6 region.

## 5 Timescales in Tokamak plasmas

Tanga presented a discussion on the requirements which a meaningful experiment would need to have in order to be relevant to the timescales for a reactor, and then discussed how far present generation experiments fall short of this, especially with respect to JET.

For a particular mode, one wants the plasma duration in that configuration ($\tau_{mode}$) to be long relative to Energy confinement, wall residence and particle diffusion times viz.

$$\tau_{mode}/\tau_E >> 1 \qquad \tau_{mode}/\tau_w >> 1 \qquad \tau_{mode}/\tau_d >> 1$$

This is not generally true in the discharges obtained at the highest power. On JET;

| | | |
|---|---|---|
| **Hot Ion H and PEP H modes** | $\tau_{mode} \sim \tau_E$ | $\tau_{mode} \sim 0.1\ \tau_w$ |
| | $\tau_{mode} \sim 0.01\ \tau_d$ | |
| **ELM-free H-mode** | $\tau_{mode} \sim 5\text{-}10\ \tau_E$ | $\tau_{mode} \sim 0.5\text{-}1.0\ \tau_w$ |
| | $\tau_{mode} \sim 0.1\text{-}0.5\ \tau_d$ | |
| **ELMy H-mode** | $\tau_{mode} \sim 10\text{-}30\ \tau_E$ | $\tau_{mode} \sim 2\text{-}5\ \tau_w$ |
| | $\tau_{mode} \sim 0.5\text{-}1.0\ \tau_d$ | |
| **Limiter long pulses/ Ohmic** | $\tau_{mode} \sim 10\text{-}50\ \tau_E$ | $\tau_{mode} \sim 2\text{-}5\ \tau_w$ |

$$\tau_{mode} \sim 1\text{-}4\ \tau_d$$

Thus as we approach the conditions we want, we are progressively confronted with steadily degraded performance.

## 6 Comparison with theoretical models

Only one theoretical model was discussed in any detail, the Rebut-Lallia-Watkins (RLW) model, presented by Watkins. Most of the talk aimed at presenting tests of the model against high performance JET plasma results. There was some discussion of the model's success in describing the scaling in the TFTR aspect ratio experiment (see section 2.2.2). This has caused some surprise that a **local** transport model should have success in describing a result where the toroidicity seemed so important. The crucial reasons for the agreement were not fully explained at the meeting but terms with q, $\nabla q$, $T_e$, $\nabla T_e$ in the model may conspire to produce the result.

The main features of the model tested in the JET simulations were;

**Shear dependence** * $H(\nabla q)$ dependence of $\chi_{an,e}$ in the model was tested by simulating a JET PEP/H-mode where the shear in the inner core is reversed. Agreement was obtained.

* $q^2/\nabla q$ dependence of $\chi_{an,e}$ in the model was also tested against the results of the JET current ramp data (where shear in the outer plasma is changed significantly during the ramps). Again the model is able to explain the data.

**$\nabla T_e$ - $(\nabla T_e)_{cr}$ dependence**

*The critical temp. gradient ( one of the main features of the model) was tested in simulating the off-axis heating by ICRF following small pellet injection. The evolution of the $T_e$ profile is fitted adequately.

**Form of $\chi_i$ in Hot Ion H-modes**

*The model has $\chi_i = 2\chi_e Z_i(T_e/T_i)^{1/2}(1/(1+Z_{eff}))^{1/2}$ with $\chi_e < (\nabla T_e-(\nabla T_e)_{cr})\chi_{an,e}$.
This has been tested on the JET Hot Ion H-mode data from the Preliminary Tritium Experiment. The model needs an imposed narrow edge region with neoclassical transport to simulate the L to H transition. The final simulations agree fairly well with the data, giving low values of $\chi_i$ ( ~ $0.4 m^2 s^{-1}$) in the centre and simulating the temperature profiles well except in the very centre of the discharge.

The general conclusion would be that the model is bearing up well in comparison with data.

## References

[1] Johnson D.W., et al., 17th.EPS Conf. Contr. Fus. and Plasma Htg., Amsterdam (1990). Europhys. Conf. Abstracts 14B(I), 114-117.
[2] Grisham L., et al., Phys. Rev. Letts. **67**(1) (1991), 66.

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I would like to thank the other participants for the provision of their transparencies, and for many useful discussions.

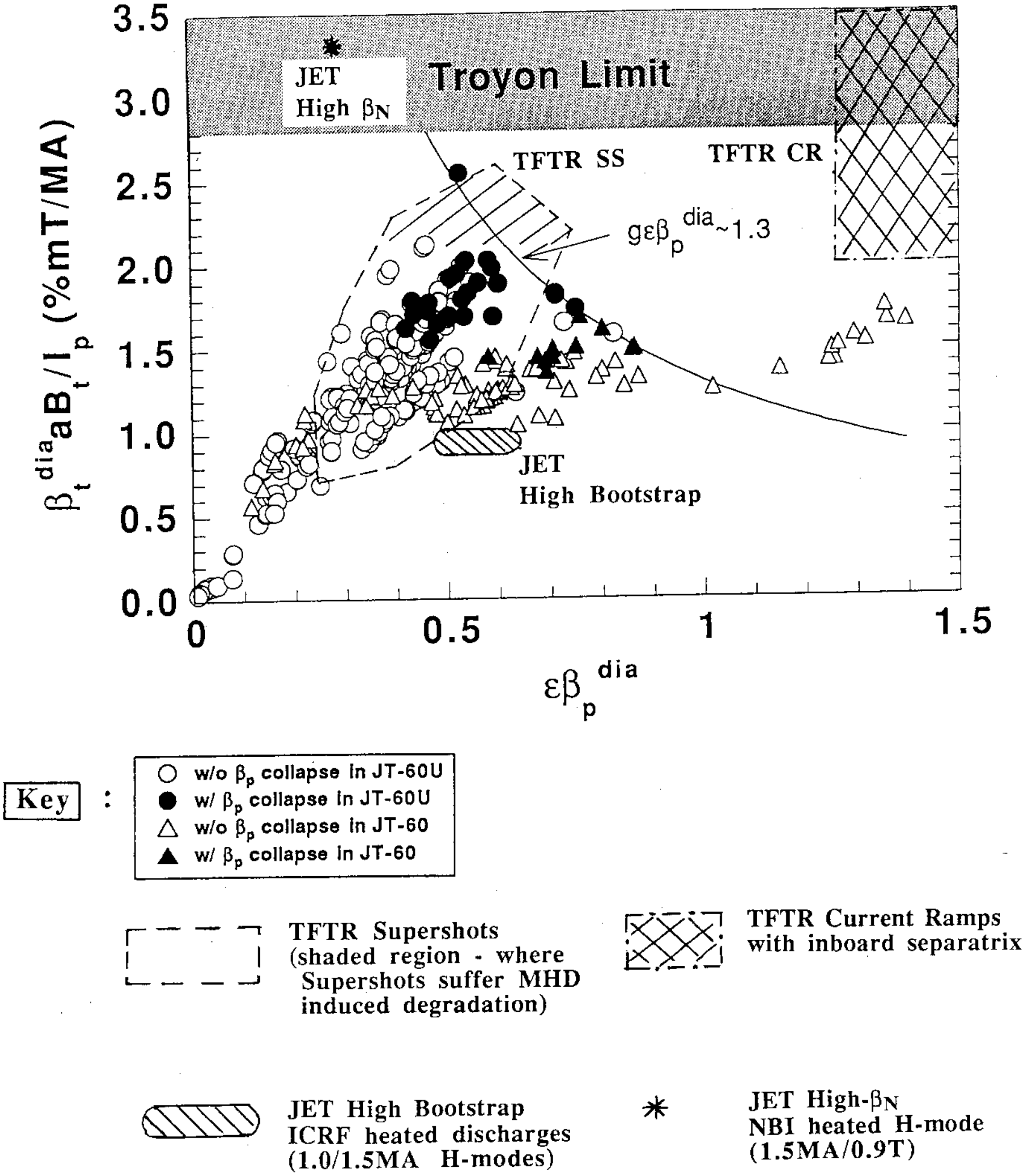


FIG. 1. Comparison of the $\varepsilon\beta_{pol}$ regimes on various Tokamaks (note the JET PEP/H-modes where the high $\varepsilon\beta_{pol}$ values are only achieved in the plasma core are not shown). The JT-60 data which exists beyond the limit line is all at low plasma current (280kA), and dominated by non-thermals with consequent anisotropic pressure.

# Appendix 1 Agenda

**Workshop of Three Large Tokamak Co-operation W22**

**"Energy Confinement Scaling under Intensive Auxiliary Heating"**

**18-20 May 1992, JAERI, Naka, Japan**
**( Room 204+208, Control Building )**

**18 May (Monday)**

| | | | |
|---|---|---|---|
| *Chairman* | | M. Kikuchi | |
| 13:30-14:30 | The Scaling of Energy Confinement and Equivalent $Q_{DT}$ in TFTR Supershots | M. Bell | (TFTR) |
| 14:30-15:30 | High $\beta_p$ Enhanced Confinement Mode in JT-60 and JT60-U | S. Ishida | (JT-60) |
| | *coffee break* | | |
| 15:40-16:40 | Confinement of Plasmas at High $\beta_p$ and Normalized $\beta$ in TFTR | S. Sabbagh | (TFTR) |
| 16:40-17:40 | Confinement in High-$\beta_p$ and High-$\beta_T$ H-Modes in JET | D. Stork | (JET) |
| 18:30- | *Welcome party at Keisei Hotel* | | |

**19 May (Tuesday)**

| | | | |
|---|---|---|---|
| *Chairman* | | M. Bell | |
| 09:30-10:20 | Isotope Dependence of L-mode Energy Confinement in JT-60U | H. Shirai | (JT-60) |
| 10:20-11:20 | Energy Confinement in High Current Limiter discharges in JET | F. Tibone | (JET) |
| 11:20-12:20 | Effects of Current Profile on Energy Confinement in JT-60U | Y. Kamada | (JT-60) |
| | *lunch* | | |
| *Chairman* | | D.J. Campbell | |
| 13:40-14:40 | Thermal Confinement in L-mode Discharges and Supershots on TFTR | L. Grisham | (TFTR) |
| 14:40-15:30 | Kinetic Energy Confinement in JT-60 L-mode Plasmas | T. Takizuka | (JT-60) |
| | *coffee break* | | |
| 15:50-16:50 | Probing the Details of a Transport Model: Intensely Heated Plasmas | M.L. Watkins | (JET) |
| 16:50-17:40 | Limits on High Power Heating in JET and Their Implication on Confinement | A. Tanga | (JET) |

**20 May (Wednesday)**

| | | | |
|---|---|---|---|
| *Chairman* | | L. Grisham | |
| 09:30-10:30 | Comparison of Confinement in Different H-mode Regimes in JET | D.J. Campbell | (JET) |
| 10:30-11:30 | Confinement Characteristics in JFT-2M | Y. Miura | (JFT-2M) |
| 11:30-12:30 | VH-mode Discharges in DIII-D: Confinement and Transport | T. Taylor | (GA) |
| | *lunch* | | |
| *Chairman* | | T. Takizuka | |
| 13:45-14:30 | Summary and Comments | D. Stork | |
| 14:30-16:00 | ***JT-60U tour*** | | |
| 16:00-17:00 | Discussion | | |

## Appendix 2 List of Participants

| | |
|---|---|
| **D.J. Campbell** | (JET) |
| **D. Stork*** | (JET) |
| **A. Tanga** | (JET) |
| **F. Tibone** | (JET) |
| **M.L.Watkins** | (JET) |
| | |
| **M. Bell*** | (TFTR) |
| **L. Grisham** | (TFTR) |
| **S. Sabbagh** | (Columbia University, TFTR) |
| **T. Taylor** | (GA) |
| | |
| M. Azumi | (JT-60) |
| A. Van Blokland | (JT-60) |
| N. Fujisawa | (ITER Project) |
| T. Fukuda | (JT-60) |
| A. Funahashi | (JT-60) |
| T. Hirayama | (JT-60) |
| **S. Ishida** | (JT-60) |
| **Y. Kamada** | (JT-60) |
| M. Kikuchi | (JT-60) |
| A. Kitsunezaki | (JT-60) |
| S. Konoshima | (JT-60) |
| **Y. Miura** | (JFT-2M) |
| M. Mori | (JFT-2M) |
| Y. Murakami | (ITER Project) |
| H. Nakamura | (JT-60) |
| K. Nagashima | (JT-60) |
| H. Ninomiya | (JT-60) |
| T. Nishitani | (JT-60 |
| T. Ozeki | (JT-60) |
| M. Sato | (JT-60) |
| M. Shimada | (JT-60) |
| **H. Shirai** | (JT-60) |
| M. Sugihara | (ITER Project) |
| H. Takeuchi | (JT-60) |
| **T. Takizuka*** | (JT-60) |
| S. Tamura | (Director, JT-60) |
| T. Tsunematsu | (ITER Project) |
| S. Wolfe | (JT-60) |
| M. Yagi | (JT-60) |
| S. Yamamoto | (ITER Project) |
| R. Yoshino | (JT-60) |

( **bold:** contributors, * : key persons)