hermal transport coefficient for high field experimen

Alcator C-Mod results (1994-95) suggested a non-power law dependenc
confinement time τ_E on plasma parameters:

OH: $\beta_p \simeq$ constant (0.25)

ICRH: β_p increases linearly with P_{ICRH}

A thermal transport coefficient with a similar dependence on β_p was constru
[Coppi-Daughton, EPS 1977; W. Daughton Ph.D. thesis, MIT 1997]

$$\chi_{eff}^{CD97} = \mathcal{V}_o^o \frac{I_\phi(\rho)}{n(\rho)T_e(\rho)} \mathcal{F}_D \frac{V_a}{\langle |\nabla V|^2 \rangle}$$

$$\mathcal{V}_o^o = \left[\frac{\nu_*}{1+\nu_*} + \left(\frac{n_o^o}{n} \right)^{1/3} \right] \alpha_V \frac{T_e}{e} \left(\omega_{pi} \frac{c^2}{\omega_{pe}^2} \frac{\nu_e}{v_{the}^2} \right)^{2/5} = \text{voltagescaling}$$

$$\mathcal{F}_D = C_2 \left(\frac{a}{d_i} \right)^{1/2} f_{C3}$$

$$f_{C3} = \begin{cases} C_3 \left[\frac{10\beta_{p*}}{q_E^{2/3}} \left(\frac{\Omega_{ce}}{\omega_{pe}} \right)^{1/3} - \frac{R}{4a} A_i^{1/2} \right] & \text{if} > D \\ D & \text{otherwise} \end{cases}$$

Fits to steady state experiments (Alcator C-Mod) gave coefficients $C_2 = 0.0$
$C_3 = 1.7$, $D = 0.25$, $\alpha_v = 0.18$.

The confinement time is not a power law,

$$\tau_E \simeq 0.031 R q_E^{2/3} I_p \left(1 + f_3 \frac{I_p \mathcal{V}_o}{P_H}\right) \left(\frac{d_i}{a}\right)^{1/2} \left(\frac{\omega_{pe}}{\Omega_{ce}}\right)^{1/3}$$

Fit to a restricted subset of the ITER OH and L-mode database (1997) t
was chosen to more closely resemble high field ignition conditions,

OH or L-mode

clean: $Z_{eff} < 2$

$T_i \simeq T_e$: $0.7 < W_i/W_e < 1.3$

mostly thermal: $W_{th}/W_{tot} > 0.7$

steady state: $(dW/dt)/P_H < 0.1$

gave excellent results, using an average β_{p*}.
RMS error (1088 cases) 13.1% compared to 23.6 % for the ITER89-P scal

Fit to Alcator C-Mod OH and ICRH steady states using a transport code s
ulation with good results, using $\beta_{p*} = 8\pi p_{e*}/\langle B_\theta^2 \rangle$, $p_{e*} = \max \frac{dp_e}{d(\rho/a)}$.

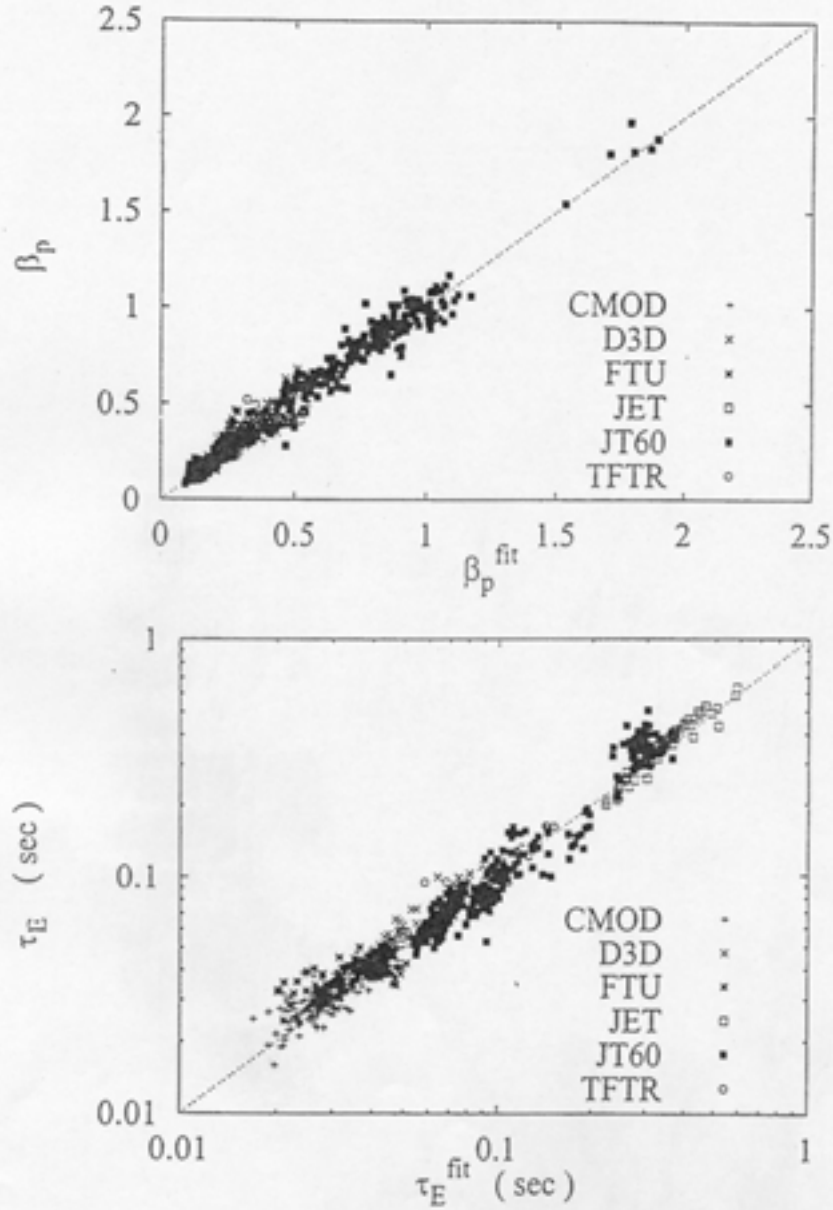

Figure 1: Comparison of β_p scaling in Eq. (3) and τ_E scaling in Eq. (8) with ITER L-mode database

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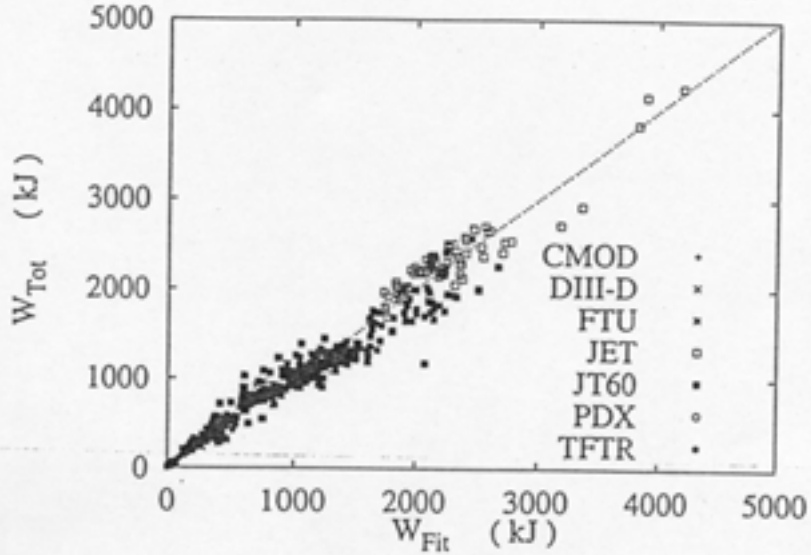

Figure 4-3: Comparison of W scaling in Eq. (4.22) with selected discharges from the ITER L-mode database

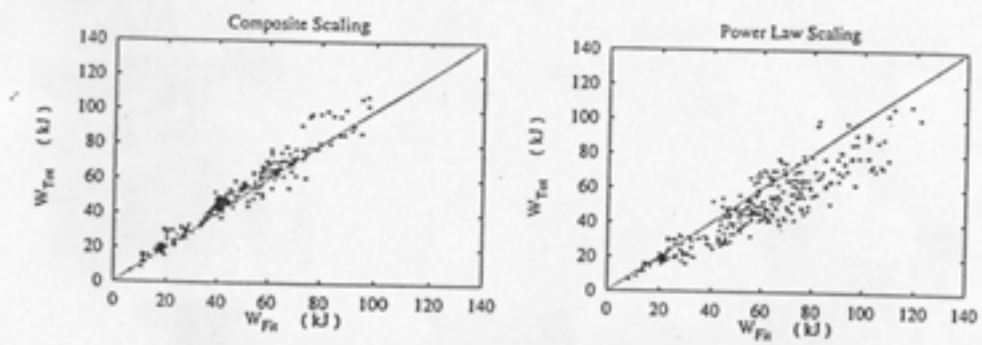

Figure 4-5: Comparison of composite and power law scalings for the stored energy of Alcator C-Mod discharges

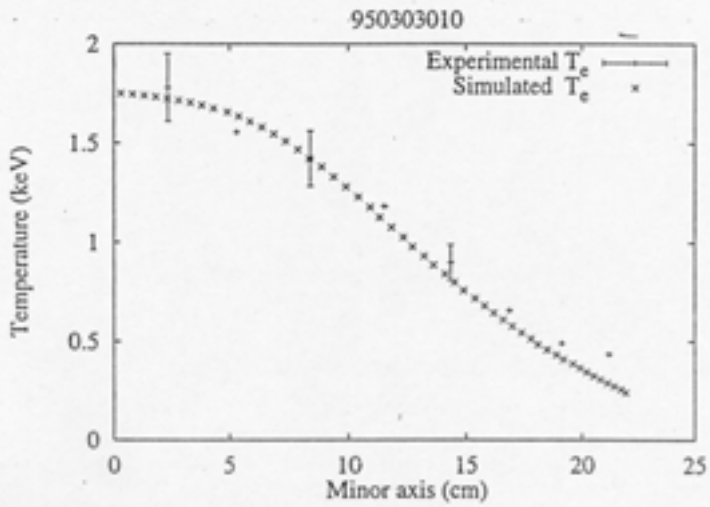

Figure B-5: Comparison of simulated and experimental ECE temperature profiles $I_p = 1.02$ MA, $\bar{n}_e = 2.7 \times 10^{14}$ cm^{-3}, $P_{rf} = 1.4$ MW

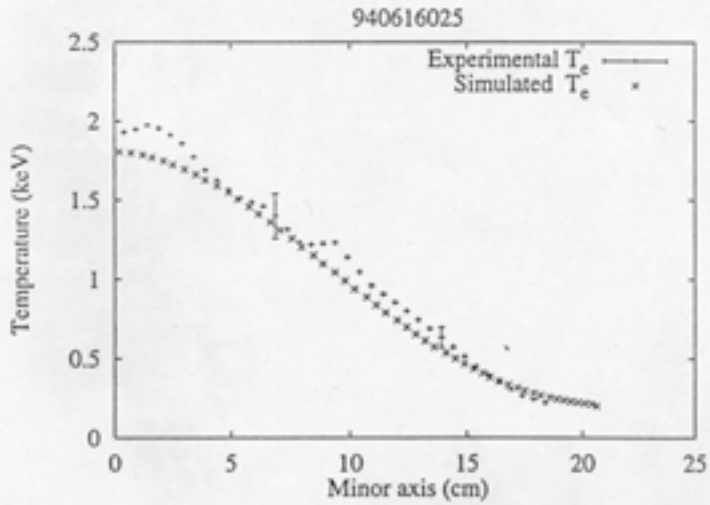

Figure B-6: Comparison of simulated and experimental ECE temperature profiles $I_p = 0.44$ MA, $\bar{n}_e = 0.9 \times 10^{14}$ cm^{-3}, $P_{rf} = 1.5$ MW

Critical Physics Issues for Ignition Experiments: Ignitor

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7 Confinement issues

7.1 Confinement and transport models

The difficulty of predicting even the global level of plasma transport (energy and particle confinement) for a given plasma configuration with a good degree of reliability is one of the main problems encountered in choosing the parameters for an ignition experiment. High field experiments at high density require the least extrapolation from the available experimental database, but still lie outside the range of existing experimental data.

Some basic considerations for predicting transport and performance in ignition experiments can be made. First, 0D (global, volume-integrated) steady-state models are not sufficient to predict ignition, as they give only a rough idea of global power requirements. They provide a functional relationship between input power and loss for a given burning level, but do not predict the optimal point for operation, and say little about the possibility to achieve a given operating point in practice. At a minimum, time-dependent, 1 1/2D transport simulations are needed for performance prediction and to envision the relevant control systems, because the energy balance is intimately tied to the plasma profiles (including $q(\psi)$ and current density) and therefore to plasma stability [1,2,3,4].

Second, frequently considered global scalings for energy confinement time are based on a set of criteria and an experimental database [5] that have been chosen in view of a particular design, the ITER EDA [6], whose requirements are different from those of high field designs. One result is the ITER89-P scaling for the L-mode confinement time for which the energy confinement time, τ_E, degrades with the total heating power roughly as $\tau_{E,L} \propto 1/P_H^{1/2}$, or even more strongly [5,6]. An important question is whether different selection criteria, more suited to high field ignition conditions, would yield different results. In fact, as pointed out in Ref. [7], if we apply the so-called "Kaye-All-Complex" scaling to high field ignition experiments, this gives drastically better values for τ_E than the ITER89-P scaling. Since the database used to propose both of these

scalings include experiments involving a large diversity of plasma regimes and conditions, it is not surprising that they should not be unique nor give the same extrapolations.

In fact, such criteria can lead to different confinement predictions. A case can be made that the degradation of τ_E with the heating power P_H ceases above a certain power level [8]. This is the prediction of the Coppi-Daughton effective thermal diffusion coefficient [9,10] suggested by a relevant series of experiments carried out by the Alcator C-Mod machine. The corresponding scaling for τ_E was in fact derived from the experimentally observed behavior of β_p in ohmic and RF-heated discharges [8], where $\beta_p \approx$ constant ($\approx$0.25) for OH heating, while with additional ICRH, β_p increases linearly with P_{ICRH}. Thus, the resulting τ_E does not have a power law dependence on the plasma parameters, but an offset relation that suggests that the confinement ceases to degrade with heating power above a certain power level,

$$\tau_E \approx 0.031 R q_E^{2/3} I_p \left(1 + f_3 \frac{I_p V_0}{P_H}\right)\left(\frac{d_i}{a}\right)^{1/2}\left(\frac{\omega_{pe}}{\Omega_{ce}}\right)^{1/3} \qquad (1)$$

in MA, MW, and mks units. Here the coefficient is $f_3 \approx 1.4(R_0/5a)^{1/2}(R_0/20d_i)^{1/2}$, where $d_i = c/\omega_{pi}$, ω_{pj} is the plasma frequency for species j, Ω_{cj} the gyrofrequency, q_E the "engineering" safety factor, $q_E = 2\pi a^2 \kappa B_T / (\mu_0 I_p R_0)$. The characteristic voltage $V_0 = 0.18 \frac{T_e}{e}\left(\omega_{pi} \frac{c^2}{\omega_{pe}^2} \frac{\nu_e}{v_{the}^2}\right)^{2/3} \approx 1$ for typical tokamak parameters, is a weakly increasing function of density. All numerical coefficients were determined from Alcator C-Mod data. The resulting expression for τ_E was then shown to fit the global energy confinement times of a specific subset of the ITER L-mode and OH database (as it existed in 1997), with no additional free parameters. The subset was chosen to be more applicable to high density, high field experiments than the general ITER database. It consisted of all the data points satisfying

- OH or L-mode
- clean: $Z_{eff} < 2$

- $T_i \approx T_e$: $0.7 < W_i/W_e < 1.3$
- mostly thermal: $W_{th}/W_{tot} > 0.7$
- steady state: $(dW/dt)/P_H < 0.1$.

Using a volume-averaged β_p gave excellent results, with a RMS error of 13.1%, compared to 23.6% for the 1996 ITER96 L-mode scaling [8] restricted to these cases. (The ITER96 scaling had a lower error than the original ITER89-P scaling.) Only 7 of the 14 machines represented in the full ITER database appear under these criteria. A thermal diffusion coefficient with an appropriate dependence on the flux surface was also derived and shown to fit a wide variety of steady state ohmic and RF-heated L-mode discharges from Alcator C-Mod.

We note that, as was clearly shown by the series of experiments carried out with the Alcator C machine, the quality of confinement in ohmic heating discharges is not unique. For instance, peaked density profiles resulting from the injection of pellets have been observed to produce considerably higher energy confinement times. The Alcator C-Mod ohmic discharges on which the scaling (1) is based were non-optimized. No attempt was made to improve the confinement time by any means. Therefore, Eq. (1) should be considered too pessimistic in trying to assess the confinement time in Ignitor.

The radial form of a transport coefficient is important for predicting ignition, which is a strongly dynamic and non-local process. Then we observe that, even if nearly stationary conditions are accurately described by a given transport coefficient, this may give poor results under dynamic conditions. In fact, numerical transport simulation consistently indicates that a coefficient that nearly preserves the temperature profile shape ("profile consistency" [11]) is required to fit many present-day experiments, especially their transient phases, as well as having a strong effect on ignition predictions. For example, the CD97 coefficient described in Refs. [9,10] does not work as well for transient conditions, including Alcator C-Mod current ramps and ignition simulations, because its strong dependence on the plasma pressure gradient tends to produce an artificially steep gradient at mid-radius. In particular, a simple profile-consistent coefficient, such as the original CMG (Coppi-Mazzucato-Gruber [12]) scaled to match a desired global confinement, has been shown to be quite adequate [3,4].

The numerical transport codes that have been employed mostly are BALDUR (fixed boundary) [13], TSC (free boundary) [14], and JETTO (free boundary) [15].

7.2 Effective Thermal Diffusivity

As indicated earlier, the possibility to reach ignition conditions depends on, among other factors, the *radial* profiles of both the electron and the ion effective thermal diffusivity. The models of these parameters that appear to simulate best existing experiments, both under stationary and dynamic conditions, have in common the fact that they increase toward the edge of the plasma column. This circumstance is, in fact, an aspect of the "profile consistency" argument [12,16]. Thus one of the problems on which an ignition experiment will have to shed light is whether the fusion reaction products will be scattered by collective modes to deposit their energy in the outer region where the thermal conductivity is relatively high.

High magnetic field and plasma density experiments have shown that extremely low thermal diffusivities can be produced in the central part of the plasma column. In particular, we refer to the experiments carried out by the Alcator C machine where confinement times slightly exceeding 50 msec were obtained with a plasma radius of 16 cm, peak plasma densities $\approx 2 \times 10^{21}$ m^{-3}, $T_e \approx T_i$, and $Z_{eff} \approx 1$. For these plasmas we may estimate a corresponding mean effective thermal diffusivity as

$$\overline{\chi}_E \approx \frac{a^2}{4\tau_E} \approx 0.13\,\mathrm{m^2/sec}$$

We note that the poloidal magnetic field corresponding to a current of about 750 kA in this case is slightly below 1 T.

The mean effective thermal diffusivity that in Ignitor would correspond to a confinement time $\tau_E \approx 0.5$ sec can be estimated as

$$\overline{\chi}_E \approx \frac{\overline{a}^2}{4\tau_E} = \frac{0.47^2 \times 1.83}{4 \times 0.5} \approx 0.2\,\mathrm{m^2/sec}\,.$$