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IGNITION OF AN OVERHEATED, UNDERDENSE, FUSIONING TOKAMK PLASMA

BY

C. E. SINGER, D. L. JASSBY, J. HOVEY

PLASMA PHYSICS LABORATORY

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IGNITION OF AN OVERHEATED, UNDERDENSE, FUSIONING TOKAMAK PLASMA

C. E. SINGER, D. L. JASSBY, AND J. HOVEY

Plasma Physics Laboratory, Princeton University

Princeton, NJ 08544

ABSTRACT

Methods of igniting an "overheated" but "underdense" D-T plasma core with a cold plasma blanket are investigated using a simple two-zone model with a variety of transport scaling laws, and also using a one-dimensional transport code. The power consumption of neutral-beam injectors required to produce ignition can be reduced significantly if the underdense core plasma is heated to temperatures much higher than the final equilibrium ignition values, followed by fueling from a cold plasma blanket. It is also found that the allowed impurity concentration in the initial hot core can be greater than normally permitted for ignition provided that the blanket is free from impurities.

I. INTRODUCTION

Heating of a tokamak plasma directly to ignition with neutral beams may require a very large beam energy in order to penetrate the plasma. According to the "empirical scaling" of energy confinement [1,2] the required beam energy (in keV/deuteron) is

$$W_b = 1.8 \times 10^{-14} \langle n \rangle a, \tag{1}$$

where $\langle n \rangle$ is the volume-averaged electron density in cm^{-3} and a is the plasma radius in cm. For typical reactor parameters, this implies that W_b lies in the range of 200 to 400 keV [1], an energy range where positive-ion-based beams are impractical. One method of reducing the W_b required for ignition is to heat a low-density plasma, followed by major-radius compression to form an ignited core [1]. The ignited core can then be fueled from a dense cold plasma blanket [3] formed by addition of neutral gas during compression. The cold plasma blanket may have the additional function of decreasing impurity generation by protecting the containment vessel from the hot fusioning plasma core [4].

Here we show that ignition can eventually occur in a fusioning core surrounded by a dense cold plasma blanket even if the core is not initially ignited. [Ignition is defined here as the condition where power deposition of fusion alpha particles (and ohmic heating) can maintain or increase the plasma thermal energy against transport and radiation losses.] Eventual ignition occurs in a plasma with initially decreasing temperature if the fusioning core is fueled rapidly enough to enhance alpha-particle heating but slowly enough to avoid quenching the fusion reaction. We shall call this process "smouldering" to ignition.

Use of the smouldering technique extends the parameter range of fusioning cores which can be ignited, because it allows ignition of cores with lower initial density, albeit with higher initial temperature. It therefore allows good penetration of the core with lower energy neutral beams. However, more neutral beam power is generally required to produce the overheated core. In this paper we examine these conflicting requirements by computing the gross electrical power required for ignition of various starting plasmas. The gross electrical power is the injected power divided by the injector efficiency at energy W_b, which for simplicity is taken to be the efficiency with which the accelerated ions are neutralized in the injector [5]. (Power losses in beam transmission are assumed to be of the same magnitude as power returned to a direct recovery system.) The effects of the cold plasma blanket will be illustrated with a simple two-zone model of the plasma energy and particle balance for a variety of energy confinement scalings, and with a one-dimensional (1-D) model using "empirical" transport.

2. MODEL FOR EVOLUTION OF HOT PLASMA CORE

Figure 1 illustrates the core/blanket configuration. The arrows indicate the initial direction of evolution of the core density and temperature. The initial core electron density, typically $n_c \sim 10^{14}\text{cm}^{-3}$, rises due to *influx of gas from* the blanket, which has an electron density $n_b = 4 \times 10^{14}\text{cm}^{-3}$. [We take the ion density equal to the electron density, ignoring small effects due to dilution when considering impurities, and denote either density by the symbol n_c (core) or n_b (blanket).] Following beam heating, the initial core temperature $T_c(0)$ drops because of *dilution by inward diffusion of cold* particles from the blanket and because of radiative and transport losses. If the temperature does not fall too rapidly, the increase in n_c results in sufficient alpha heating to ignite the core (i.e., the core "smoulders" to ignition). If the core temperature drops too rapidly, ignition never occurs (i.e., the core "fizzles").

The equations used to follow the evolution of the core temperature and density are as follows:

$$\frac{dT_c}{dt} = \frac{n_c}{3}\Big(\underset{\substack{\text{alpha}\\\text{heating}}}{R_\alpha} - \underset{\text{Brem.}}{R_{Br}} - \underset{\substack{\text{impurity}\\\text{radiation}}}{R_{Fe}}\Big) - \underset{\substack{\text{Transport}\\\text{Losses}}}{T_c/\tau_E} - \underset{\text{dilution}}{\frac{T_c}{n_c}\frac{dn_c}{dt}} \tag{2}$$

$$\frac{dn_c}{dt} = \frac{n_b - n_c}{\tau_p} \tag{3}$$

with transport scaling laws:

$$\tau_E = r_{emp} K\, n_* a^2 \left(\frac{n_c}{n_*}\right)^{\nu} \left(\frac{T_c}{T_*}\right)^{\tau} \tag{4}$$

$K = 5 \times 10^{-19}\text{cm}\cdot\text{s}$ (empirical, or "Alcator," scaling [2])

$n_* = 10^{14}\text{cm}^{-3}$

$T_* = 1$ keV

$$\tau_p = r_p K n_* a^2 \left(\frac{n_c}{n_*}\right)^{\nu'} \left(\frac{T_c}{T_*}\right)^{\tau'} \tag{5}$$

and losses and heating:

$$R_{Br} = 3.3 \times 10^{-15} Z_{eff} T_c^{1/2} \qquad \text{keV}\cdot\text{cm}^3\cdot\text{s}^{-1} \text{ [4]} \tag{6}$$

$$R_{Fe} = 3.1 \times 10^{-11} \left(\frac{n_{Fe}}{n_c}\right) \qquad \text{keV}\cdot\text{cm}^3\cdot\text{s}^{-1} \text{ [6]} \tag{7}$$

$$R_\alpha = \frac{3500}{4} \tag{8}$$

$$\exp(-20.78\, T_c^{-0.30367} - 25.814 - 0.06625\, T_c + 0.00031\, T_c^2)$$

$$\text{keV}\cdot\text{cm}^3\cdot\text{s}^{-1} \text{ [7]}.$$

Here temperatures are in keV and other units are cgs. $Z_{eff} = 1 + 552(n_{Fe}/n_e)$ is the effective electric charge for a hydrogen plasma with Fe^{XXV} impurity. Plasma parameters are taken to be uniform through the core.

The equation for (dT_c/dt) follows from considering the most important effects determining the rate of change of the energy density, $3n_cT_c$, in a dense plasma core, where $T_e \approx T_i \approx T_c$, and ohmic heating and charge exchange losses are minor contributors to the energy balance. The expression for R_α assumes 1:1 deuterium:tritium in the core. The equation for (dn_c/dt) is essentially a definition of the particle confinement time, τ_p.

The ratios r_{emp} $(= \tau_E/\tau_{E,emp}$ when $\nu = 1$, $\tau = 0)$ and r_p relate the energy and particle confinement times to "empirical" scaling at the reference plasma parameters $n_* = 10^{14}\text{cm}^{-3}$ and $T_* = 1$ keV. For the results presented here we take $r_p = 2$, $\nu' = 0$, and $\tau' = 0$ for simplicity. (The results obtained for the values of

n_c and T_c needed for ignition have been shown to be insensitive at least to the density scaling of τ_p. Changes in τ_p can be approximately compensated for by the appropriate changes in the blanket density n_b, to obtain, in the context of the present model, results identical to those presented here.)

3. RESULTS FOR "EMPIRICAL" SCALING

Figures 2a and 2b show the evolution of the core density and temperature from a variety of starting conditions. We can determine the evolution of the core from any given initial conditions $[n_c(0), T_c(0)]$ by eliminating the time t, and plotting T_c vs n_c. Figure 3 illustrates the division of (n, T) space into ignited cores, "fizzling" cores, and cores which "smoulder" to ignition as the density increases. The dashed line indicates plasmas which are just ignited in steady state. The bold solid line indicates the values of $[n_c(0), T_c(0)]$ for which the plasma just barely "smoulders" to ignition (i.e., the "smoulder fizzle/boundary").

4. INJECTOR ENERGY AND POWER

The above results illustrate the existence of plasmas which "smoulder" to ignition, but give little information about the usefulness of the "smoulder" technique. As a measure of the usefulness of the technique, we calculate the gross electrical power required for the neutral beam injectors to form a plasma which will smoulder to ignition. To calculate the gross electrical power we proceed as follows.

First, we compute the required injected beam power P_b to produce a plasma on the "smoulder-fizzle boundary." This power is plotted as a function of the initial core temperature in Fig. 4a. The value of P_b shown in Fig. 4a is the maximum power required to slowly heat a constant-density plasma to the indicated temperature, as computed from the steady-state, zero-dimensional energy balance for the core. For high n, low T plasmas, the maximum P_b is required to heat the plasma to a temperature (5 to 10 keV) where *alpha heating becomes important. For low n, high T plasma cores,* the maximum P_b is required to maintain a high T plasma against transport losses. Also shown in Fig. 4a is the maximum P_b required to produce an ignited core at the indicated temperature.

Second, we compute the beam energy $W_b = 1.8 \times 10^{-14} n_c a$ required to penetrate each "smoulder-fizzle boundary" plasma core. At high densities, lower beam energies result in deposition of beam energy near the plasma edge, which is expected to result in inefficient heating and possible problems with increased impurity generation. In reality there is a continuous transition from the optimum utilization of beam power when $W_b \geq 1.8 \times 10^{-14} n_c a$, and inefficient utilization of beam power when $W_b \leq 1.8 \times 10^{-14} n_c a$. We choose the above cutoff value as a convenient synopsis of the beam penetration problem. The values of W_b required to form "smoulder-fizzle boundary" plasma cores are shown in Fig. 4b. Also shown are the W_b required to produce ignited cores.

Third, we compute the gross electrical power

$P_{gross} = P_b/\eta_{inj}$ for each smoulder-fizzle boundary plasma, using the values of W_b described above to determine the injector efficiency η_{inj}. $\eta_{inj}(W_b)$ is shown in Fig. 5a, taken from Ref. 5. The resulting P_{gross} for smoulder-fizzle boundary plasmas is compared to that for direct ignition in Fig. 5b. For empirical energy confinement, only a modest savings in gross electrical beam power is obtained by using the smoulder technique. However, the smoulder technique does make use of near-state-of-the-art (TFTR-type) beam technology.

5. TRANSPORT SCALING

Extrapolation of experimental confinement measurements to thermonuclear reactor plasmas requires a large "leap of faith." Therefore, any discussion of reactor plasmas should consider the possibility of transport scalings different from those currently fashionable [8]. For example, the gross beam power required for direct heating and "smouldering" to ignition are illustrated in Fig. 6 for models with $\tau_E \propto a^2$ and $\tau_E \propto n^{1/2}a^2$.

The influence of transport scaling parameters on the gross beam power required for ignition is shown in Fig. 7. Here we show the minimum values of P_{gross} for direct and "smoulder-fizzle boundary" ignition. The minimum values of P_{gross} are obtained from P_{gross}:$T_c(0)$ plots such as Figs. 5 and 6. It is evident from Fig. 7a that the smouldering core technique offers the most significant savings in gross beam power if the value of τ_E in high temperature reactor plasmas scales as $\tau_E \propto n_c^{\nu}$ where $0 < \nu < 1$.

The temperature dependence of τ_E evidently does not have much influence on the usefulness of the smoulder technique. However, the dependence of P_{gross} on the temperature scaling of τ_E, shown in Fig. 7b, does illustrate the extreme importance of maintaining good energy confinement as the plasma temperature is increased. For more optimistic scalings than $\tau_E = 5 \times 10^{-19} n^1 T^0 a^2$, the smoulder technique is unnecessary, and direct ignition becomes relatively easy. For much more pessimistic scaling, beam heating to ignition is impractical without additional schemes such as compression of a beam-heated plasma. Present experimental results indicate that while $\tau_{Ee} \propto n_e$, the gross confinement time $\tau_E \propto n_e^{\alpha}$ with $0 < \alpha < 1$, and τ_E increases somewhat less rapidly than linearly with plasma temperature (when $T_e \sim T_i$).

Also shown, in Fig. 7c, is the dependence of P_{gross} on the coefficient r_{emp} of $n_c a^2$ in the usual empirical scaling law. Since $\tau_E \propto r_{emp} a^2$, an increase in r_{emp} is equivalent to an increase in a^2. The particular results shown in this paper correspond to an "equivalent circle model," with a = 110 cm, of the elongated hot plasma core in the Princeton Ignition Test Reactor (PITR) design [9]. With standard empirical scaling, $\tau_E = 5 \times 10^{-19} n_c a^2$, smaller cores in PITR require excessive beam power and larger cores are unnecessary.

6. COMPARISON WITH 1-D TRANSPORT CODE

Sophisticated transport codes are too cumbersome for the large parameter-range searches undertaken here. Such codes can, however, provide insight into the details of the burn process and provide a check on the accuracy of the assumptions used. Figures 8a to 8d show the evolution of T_e, T_i, n_e, and alpha heating profiles with a hot core and cold plasma blanket, as computed with the BALDUR transport code [10], which solves the 1-D plasma transport equations [4]. For computational convenience, the cold plasma blanket is formed by gas puffing during a moderate major radius compression by a factor $C = 1.14$. The transport coefficients used were $\chi_e = 5 \times 10^{17}/n_e$, χ_i = neoclassical, and $D = 2 \times 10^3 cm^2/s$. The corresponding confinement times are $\tau_{Ee} = a^2/(4\chi_e) = 5 \times 10^{-19} n_e a^2$ and $\tau_p = a^2/(4D) = 1 \times 10^{-4} a^2$, all in cgs units. The transport losses through the ion energy channel are smaller than, but comparable (about 60%) to those through the electron channel, so that $\tau_e \sim \tau_{Ee}$. The total energy and particle confinement times are very nearly equal to those in the "empirical" transport model used in the two-zone calculations above. Transport is enhanced to retain marginal MHD ballooning stability when the pressure gradient exceeds the MHD ballooning threshold [11], and resistivity is enhanced over neoclassical when needed to maintain a safety factor $q = 3$ at the edge of the plasma.

The validity of the simple two-zone mode is supported by the observation that the boundaries of the hot core and region of alpha heating stay nearly constant during the evolution of the burn. A comparison with the simpler core/blanket model of the values of $\langle T \rangle \equiv (\langle T_e \rangle + \langle T_i \rangle)/2$ and $\langle n_e \rangle$, averaged over the volume inside the radius $a = 110$ cm of the initial compressed plasma, is shown in Figs. 2 and 3.

7. EFFECTS OF IMPURITIES

It is well known that small concentrations of moderate-to-high Z impurities prevent ignition because of radiative losses [12]. The effect of a specified constant fraction of iron impurity on cores smouldering to ignition is shown in Fig. 9a. For example, the plasma starting with $T_c = 30$ keV, $n_c = 1.25 \times 10^{14} cm^{-3}$, and 0.4% iron, just fails to cross the dashed line in Fig. 9a, which is the ignition curve for 0.4% iron. If the cold plasma blanket is equally contaminated, there may be difficulty in preventing radiative collapse and recombination of the dense blanket plasma. This might be prevented by neutral beam heating of the blanket, but a detailed examination of such questions is beyond the scope of this paper.

However, one of the primary motivations for proposing the cold plasma blanket was the hope that it would be substantially free from impurities [4]. In this case, fueling of the core should dilute the original core impurity concentration. This leads to a much higher tolerable concentration of initial impurities in the core, as illustrated in Fig. 9b. The benefits of reduced impurity influx evidently can complement the benefits of the technique of smouldering to ignition in reducing the technological requirements for obtaining ignition in tokamaks.

8. CONCLUSIONS

The results discussed herein demonstrate the possibility of igniting a low density, high temperature plasma core by fueling from a cold plasma blanket. This technique allows ignition to be achieved from a wider range of starting plasmas. In particular, the lower density "smouldering" cores can be formed with lower energy (more efficient) neutral beams than are required to penetrate ignition-sized plasmas, resulting in a reduction in the gross electrical beam power required for ignition. Large reductions in the gross beam power requirement are obtained with the smoulder technique if energy confinement improves only weakly with plasma density. Finally, the cold plasma blanket can also allow significant increases in the initial impurity levels in the beam-heated core, provided that the blanket remains substantially pure.

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FIGURE CAPTIONS

Fig. 1 Core/blanket configuration.

Fig. 2 Evolution of (a) n_c and (b) T_c vs t from various starting densities. Curves of T_c evolution are labeled by starting values of n_c in units of $10^{14}cm^{-3}$.
$\tau_E = 1.3\ Kna^2$, $\tau_p = 2K\ n_* a^2$,
$K = 5 \times 10^{-19} cm \cdot s$, $a = 110$ cm.
Dot-dashed line is 1-D code result (c.f. Section 6).

Fig. 3 Evolution of T_c vs n_c as in Fig. 2. Dot-dashed Line is 1-D code result.

Fig. 4 (a) Beam power P_b and (b) energy W_b required to form ignited (---) and smoulder-fizzle boundary plasma cores (——). Confinement as in Fig. 2.

Fig. 5 (a) Injector efficiency vs beam energy.
(b) Injector electric power requirements for direct ignition and "smoulder-fizzle boundary" plasmas. Confinement as in Fig. 2.

Fig. 6 Injector electric power requirements for direct ignition with confinement scaling as in Fig. 2 but $\tau_E = 1.3\ Kn_* (n_c/n_*)^{\nu} a^2$ with $\nu = 1/2$ and $\nu = 0$.

Fig. 7 Minimum injector electric power required to form ignited (---) and "smoulder-fizzle boundary" plasma cores (——) as a function of confinement scaling parameters. $\tau_E = r_{emp}K\ (n_c/n_*)^{\nu}\ (T_c/T_*)^{\tau}\ a^2$, $\tau_p = 2Kn_*a^2$, $K = 5 \times 10^{-19}\mathrm{cm}^{-3}$, $n_* = 10^{14}\mathrm{cm}^{-3}$, $T_* = 1$ keV, $a = 110$ cm. $\nu = 1$, $\tau = 0$, $r_{emp} = 1.3$ when these parameters are not being varied as indicated.

Fig. 8 Evolution of plasma parameters, calculated by the BALDUR 1-D transport code [10]. Initial a = 120 cm plasma (e.g., formed by neutral beam heating) with parabolic $T_e(r)$, $T_i(r)$, and $\langle T_e \rangle = \langle T_i \rangle = 11$ keV is compressed from R = 320 cm to R = 280 cm during t = 0 to t = 80 ms, with gas puffing to form an a = 110 cm core surrounded by a cold blanket. After gas puffing, boundary conditions are 100% recycling, $T_e = T_i = 0.1$ keV, plasma current = 7.7 MA. $B_T = 4$ T. (a) T_e, (b) T_i, (c) n_e, (d) alpha-particle heating.

Fig. 9 (a) Evolution of T_c vs n_c for various constant iron impurity levels from 0.0% to 0.5%. Dashed line is ignition boundary for 0.4% iron. (b) Evolution of T_c vs n_c for various initial iron impurity levels in core. Impurity is diluted volumetrically by influx of pure blanket gas during the burn. Confinement scaling as in Fig. 2.

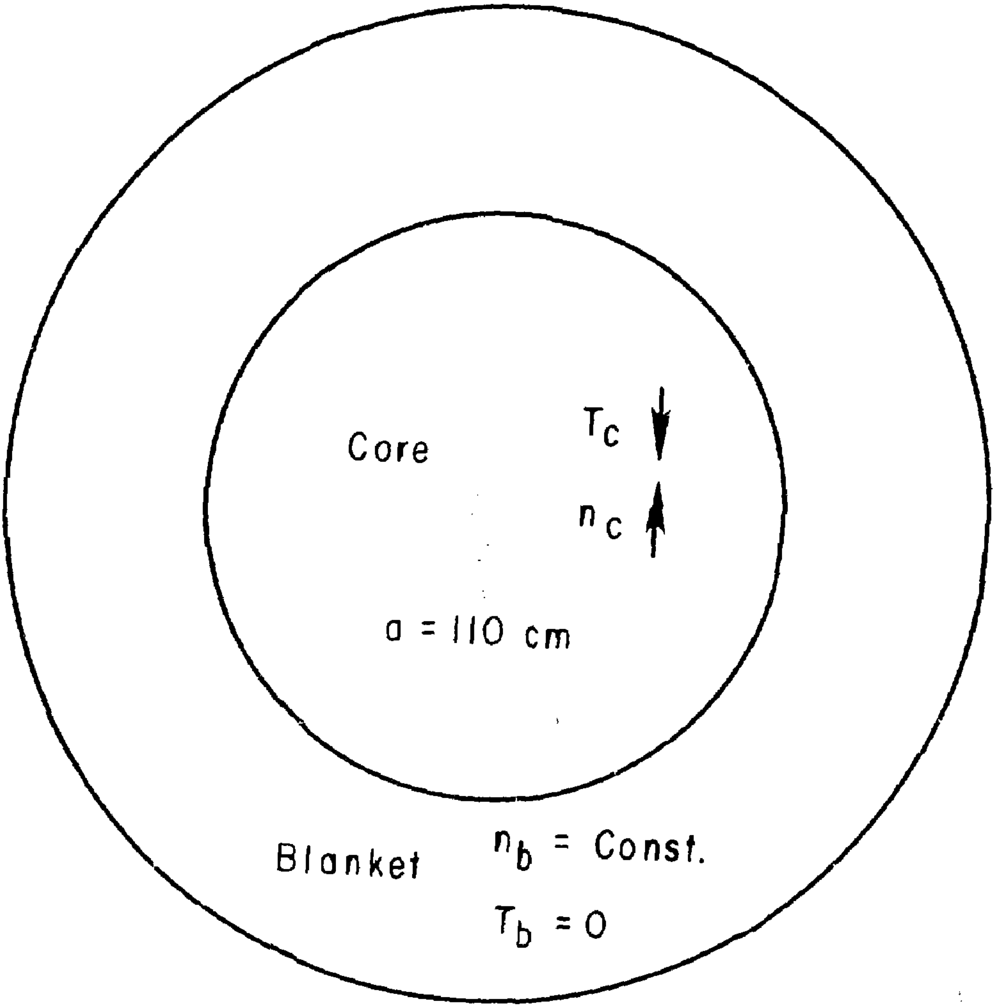
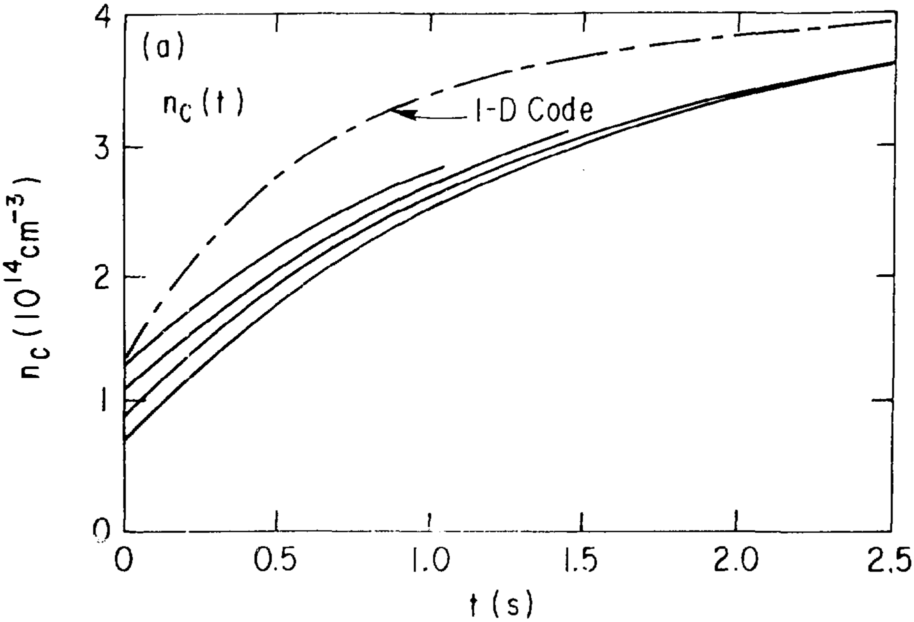
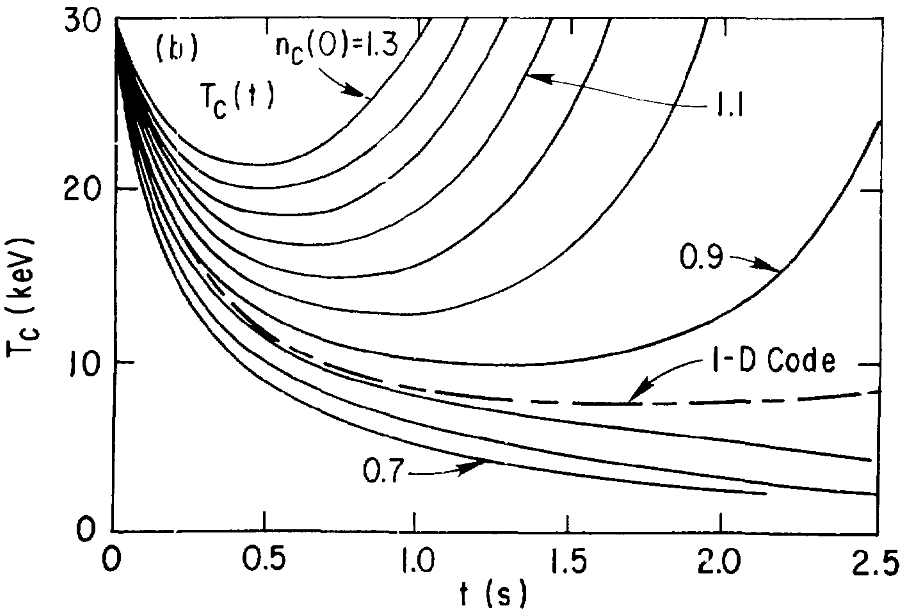


Fig. 1. 793716

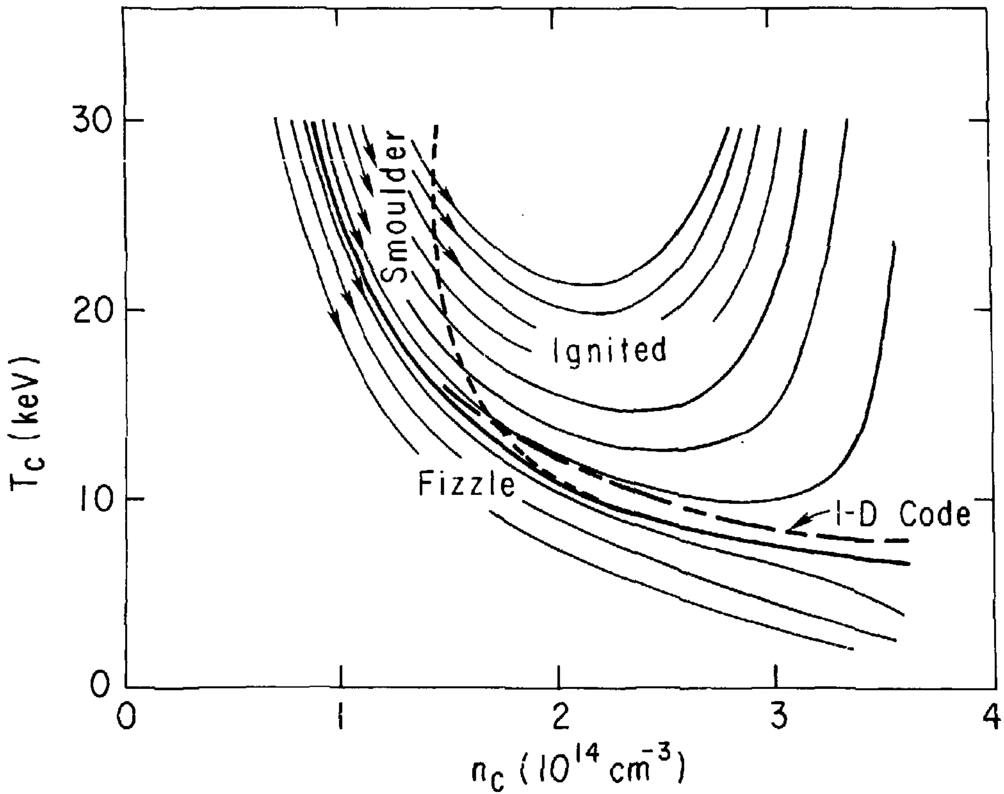


(a)
$n_c(t)$
1-D Code
$n_c\ (10^{14}cm^{-3})$
t (s)
0
1
2
3
4
0.5
1.0
1.5
2.0
2.5



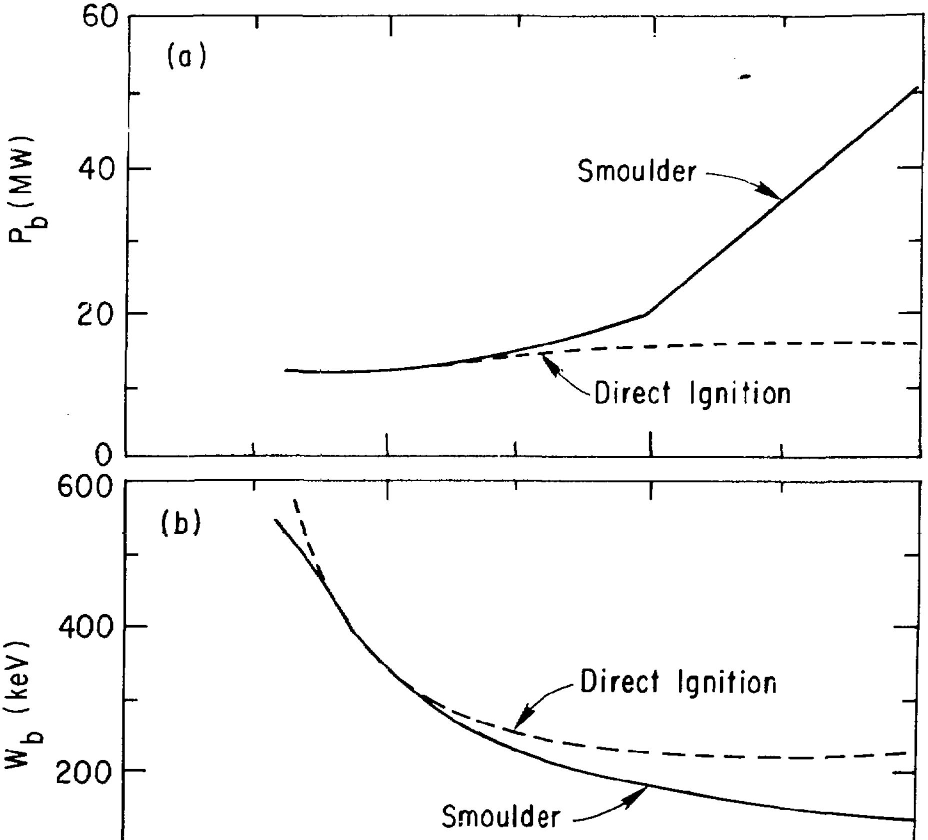
(b)
$T_c(t)$
$n_c(0)=1.3$
1.1
0.9
1-D Code
0.7
T_c (keV)
t (s)
0
10
20
30
0.5
1.0
1.5
2.0
2.5

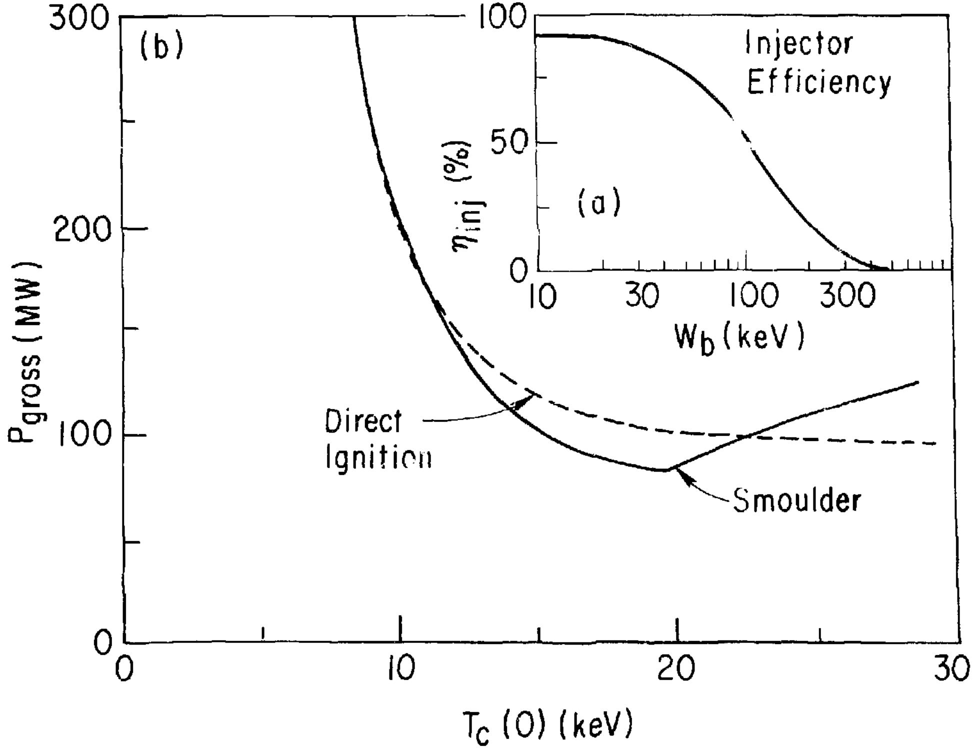
Fig. 2. 793722



30
20
10
0
T_c (keV)
Smoulder
Ignited
Fizzle
1-D Code
0
1
2
3
4
n_c (10^{14} cm^{-3})

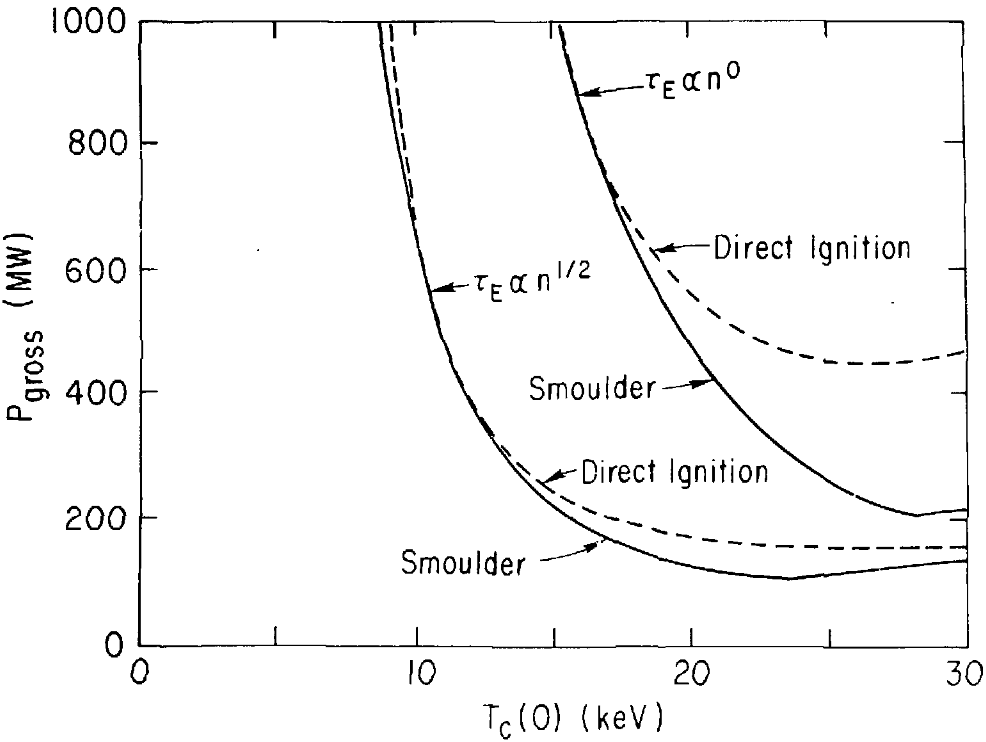
Fig. 3. 793720


60
(a)
40
P_b (MW)
Smoulder
20
Direct Ignition
0
600
(b)
400
W_b (keV)
Direct Ignition
200
Smoulder



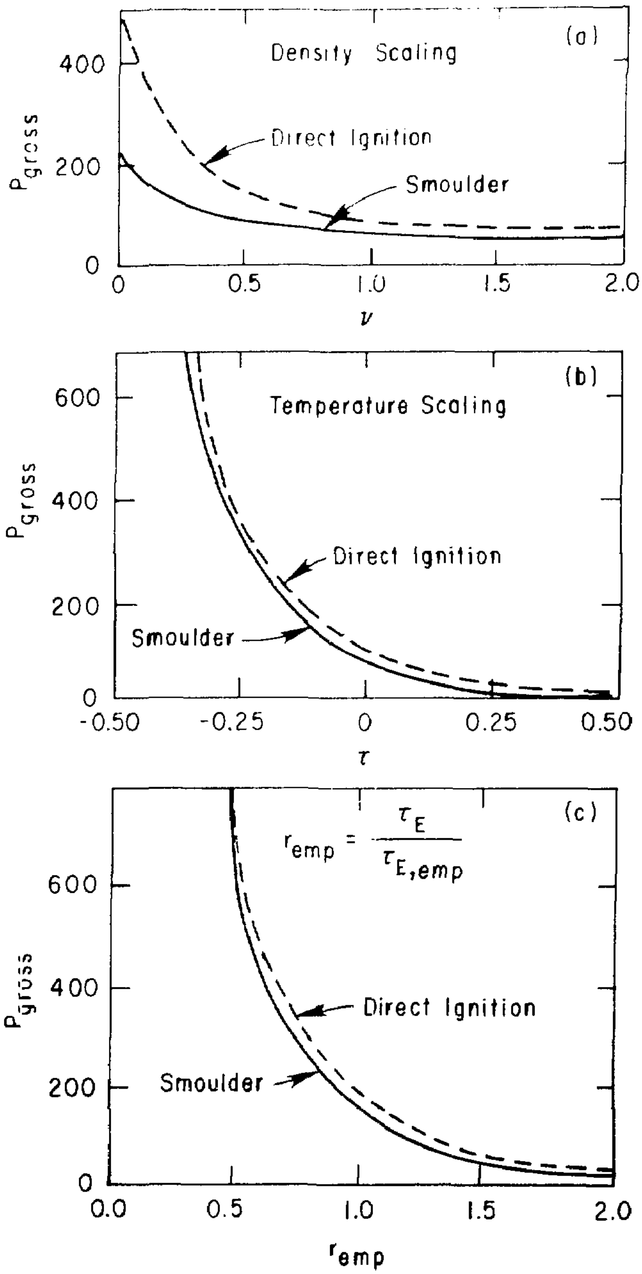
300
200
100
0
(b)
P_{gross} (MW)
0
10
20
30
T_c (0) (keV)
Direct Ignition
Smoulder
100
50
0
η_{inj} (%)
(a)
Injector Efficiency
10
30
100
300
W_b (keV)

Fig. 5. 793719



1000
800
600
400
200
0
0
10
20
30
P_{gross} (MW)
$T_c(0)$ (keV)
$\tau_E \propto n^0$
Direct Ignition
$\tau_E \propto n^{1/2}$
Smoulder
Direct Ignition
Smoulder

Fig. 6. 793721



(a)
Density Scaling
Direct Ignition
Smoulder
P_{gross}
ν
0
200
400
0
0.5
1.0
1.5
2.0
(b)
Temperature Scaling
Direct Ignition
Smoulder
P_{gross}
τ
0
200
400
600
-0.50
-0.25
0
0.25
0.50
(c)
$r_{emp} = \frac{\tau_E}{\tau_{E,emp}}$
Direct Ignition
Smoulder
P_{gross}
r_{emp}
0
200
400
600
0.0
0.5
1.0
1.5
2.0

Fig. 7. 793715

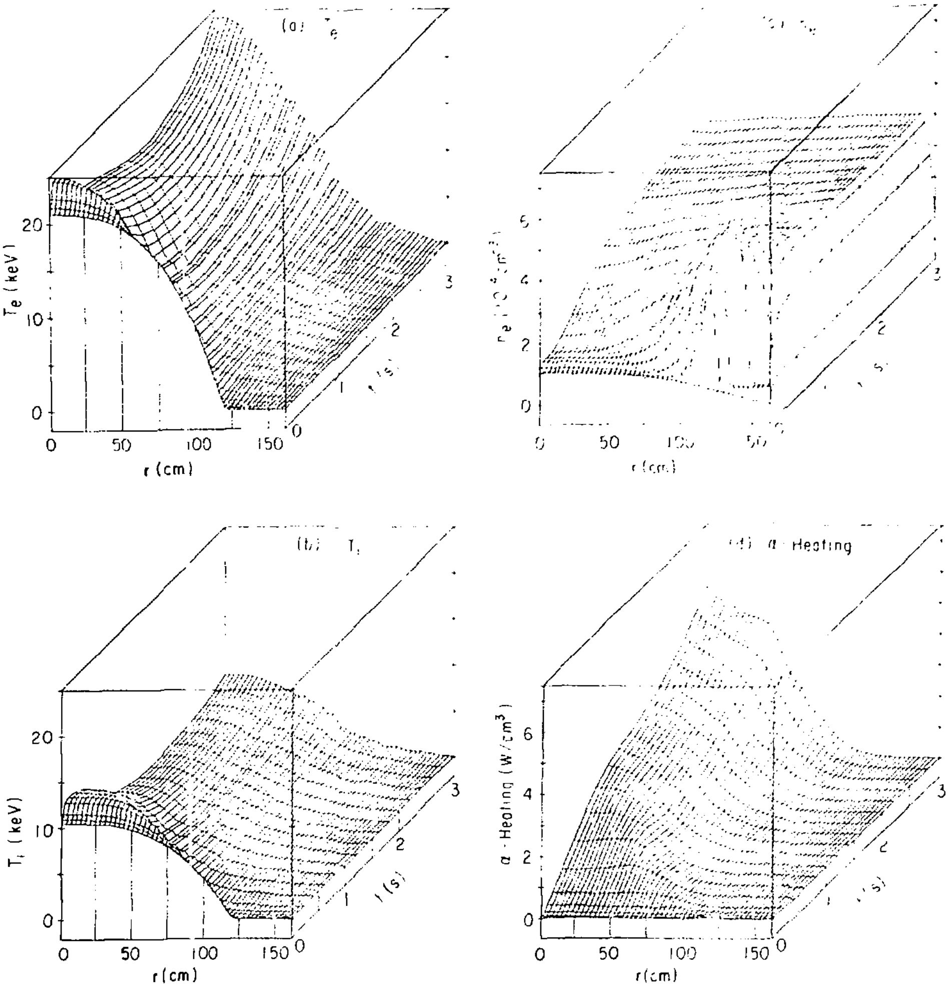


Fig. 8. 793714

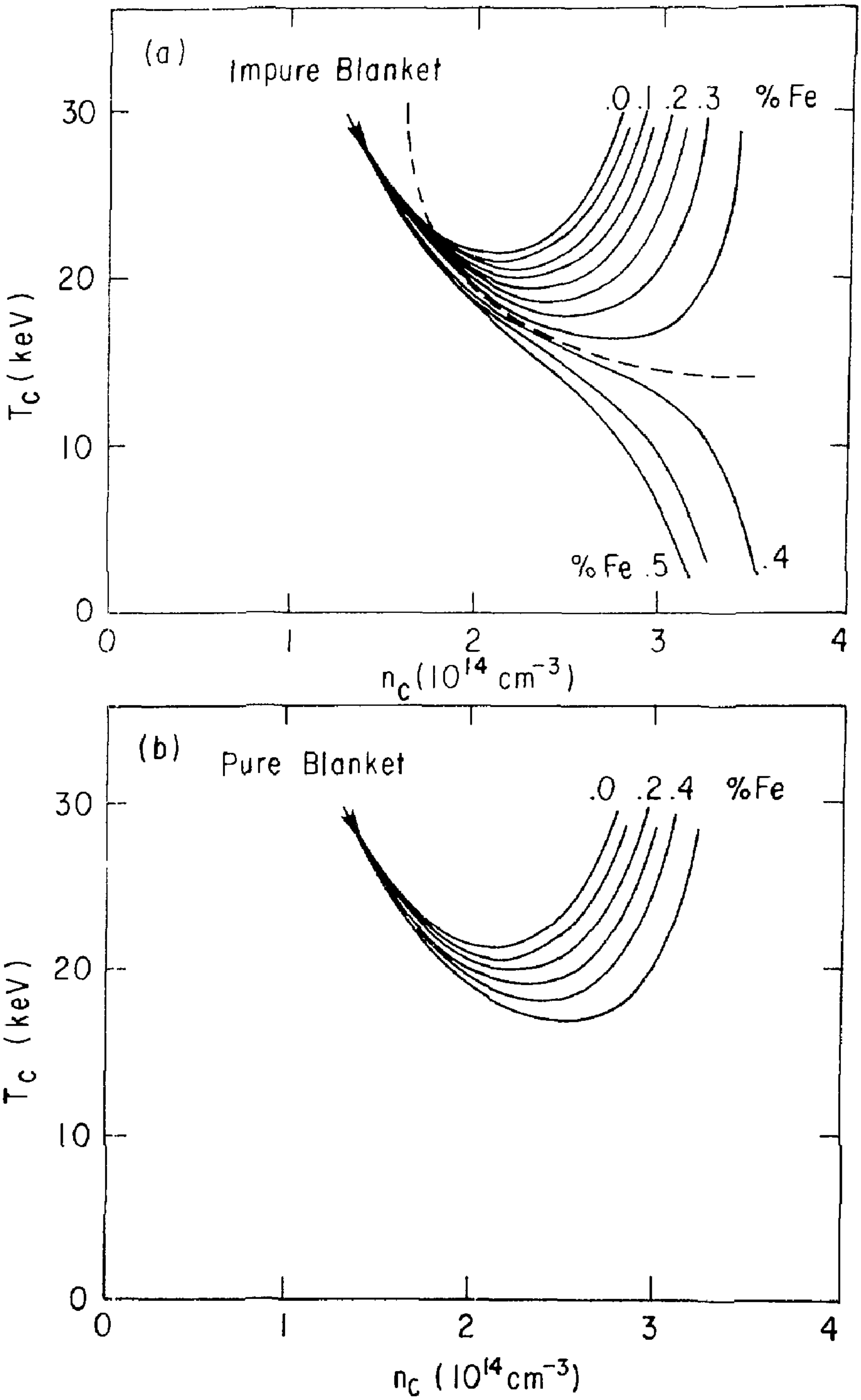

(a)
Impure Blanket
.0 .1 .2 .3 %Fe
%Fe .5
.4
30
20
10
0
0
1
2
3
4
T_c (keV)
$n_c (10^{14} cm^{-3})$
(b)
Pure Blanket
.0 .2 .4 %Fe
30
20
10
0
0
1
2
3
4
T_c (keV)
$n_c (10^{14} cm^{-3})$

Fig. 9. 793717

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D. Palumbo, C. European Comm. B-1049-Brussels
P.H. Sakanaka, Instituto de Fisica, Campinas, Brazil
M.P. Bachynski, MPB Tech., Ste. Anne de Bellevue, Quebec, Canada
C. R. James, University of Alberta, Canada
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Max-Planck-Inst. fur Plasmaphysik, W. Germany
Nucl. Res. Estab., Julich, West Germany
K. Schindler, Inst. Fur Theo. Physik, W. Germany

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THEORETICAL

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B. Buti, Physical Res. Lab., India
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Int'l. Center for Theo. Physics, Trieste, Italy
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M.A. Hellberg, Univ. of Natal, South Africa
H. Wilhelmson, Chalmers Univ. of Tech., Sweden
Astro. Inst., Sonnenborgh Obs., The Netherlands
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T. J. Boyd, Univ. College of North Wales
K. Hubner, Univ. Heidelberg, W.Germany
H. J. Kaeppeler, Univ. of Stuttgart, West Germany
K. H. Spatschek, Univ. Essen, West Germany

EXPERIMENTAL
ENGINEERING

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P. Lukac, Komenskeho Univ., Czechoslovakia
G. Horikoshi, Nat'l Lab for High Energy Physics, Tsukuba-Gun, Japan
V. A. Glukhikh, D.V. Efremov Sci. Res. Instit.of Elect. App., USSR

EXPERIMENTAL

F. J. Paoloni, Univ. of Wollongong, Australia
J. Kistemaker, Fom Inst. for Atomic & Molec. Physics, The Netherlands

THEORETICAL

F. Verheest, Inst. Vor Theo. Mech., Belgium
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Korea Atomic Energy Res. Inst., Korea
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