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PHYSICS PARAMETER SPACE OF TOKAMAK IGNITION DEVICES*

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..stract: This paper describes the results of a study to explore the physics parameter space of tokamak ignition experiments. A new physics systems code has been developed to perform the study. This code performs a global plasma analysis using steady-state, two-fluid, energy-transport models. In this paper, we discuss the models used in the code and their application to the analysis of compact ignition experiments.

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1. Introduction

An important step in the development of fusion energy is to demonstrate the feasibility of ignition. The design of a tokamak experiment which achieves ignition at minimal cost involves many physics and engineering trade-offs. In order to improve the preliminary design studies of ignition devices, a new physics systems code has been developed. It has been incorporated into the FEDC Tokamak Systems Code [1], thereby improving the interface between the physics and engineering analyses. Used in a stand-alone, it is used as an aid in exploring the physics design space and comparing the performance characteristics of several different machine configurations under various confinement and stability assumptions. This paper describes the code and presents specific applications to the plasma analysis of compact ignition experiments.

2. Methodology

Several studies have been performed to assess the global plasma requirements for tokamak systems, both under transient and steady-state conditions [2]. These have utilized theoretical and experimental models documented in the literature. In particular, we note recent work reported in Refs. [3,4]. The current use of global physics models, especially as part of a systems code, is important for the selection of an optimal set of both physics and engineering design parameters of an ignition experiment.

We now briefly describe the capabilities of the code analysis, with more detailed information on the specific assumptions and formulations incorporated given in Ref. [5]. The code performs a steady-state, two-fluid power balance for the ions and electrons subject to constraints imposed by the machine configuration and plasma equilibrium, stability, and confinement. The equations for steady-state power balance for the ions and electrons can be expressed as:

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$$0 = P_{alpi} - P_{ie} - P_{tri} \text{ [ions]} \quad (1)$$

$$0 = P_{alpe} + P_{oh} + P_{ie} - P_{tre} - P_{rad} \text{ [electrons]}$$

The power balance terms include the alpha power (P_{alp}), ohmic power (P_{oh}), rethermalization power (P_{ie}), radiation power (P_{rad}), transport power (P_{tr}), and the auxiliary power. In this analysis, we assume profile consistency and compute the plasma profiles in a manner consistent with specified density, temperature, and current density profiles [6]. All plasma quantities are volume averaged. Both uniform and nonuniform toroidal electric-field profiles may be modeled. The latter implies the presence of sawteeth with consequent profile flattening from the center of the plasma to the radius of the $q = 1$ surface. This is one characterization of stability in the code analysis; others are limits on the maximum achievable values of density and beta. Plasma equilibrium is described by the plasma current, vacuum toroidal field (TF) on axis, and the safety factor. Several models of plasma current are available based on different equilibrium data fits. The particle concentrations are fixed and include impurity species.

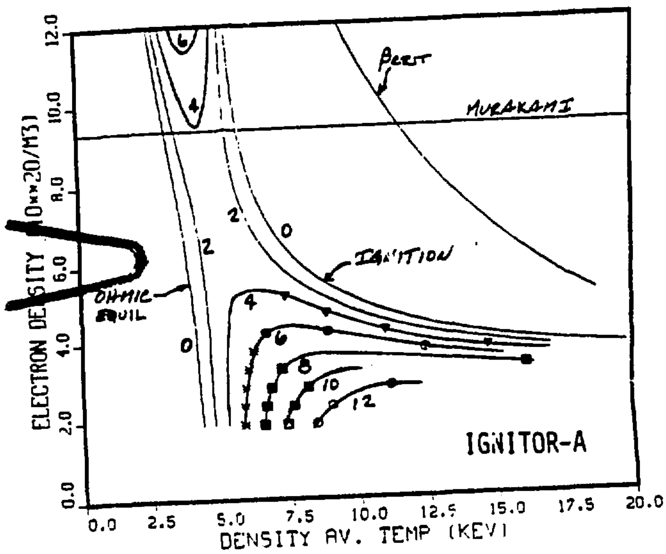
One of the most comprehensive sections of the code contains the energy transport models. The Chang-Hinton neoclassical formulation is included along with several empirical scalings, such as Neo-alcator, Mirnov, Kaye-Goldston, Perkins, Asdex, or Pfeiffer-Waltz. This provides flexibility for investigating the effects on system performance and design from considering different confinement models.

There are essentially two ways to use the physics code. It may be used to explore the physics design space and establish relationships between major radius, toroidal field, aspect ratio, elongation, triangularity, plasma current, neutron wall loading, fusion power, burn time, maximum ignition margin, and minimum auxiliary heating power requirements. The results contribute to the identification of favorable regions of design space. The code may also be used to compare the plasma performance of specific design concepts by generating Plasma Operating Contours (POPCONs). These are contours of steady-state auxiliary heating power plotted as a function of temperature and density showing the steady-state heating and operating windows, and minimum auxiliary heating power requirements for a given device. This representation was developed for the 1-1/2-dimensional WHIST code and is described in Ref. [7]. The POPCONs generated from the physics code compare well with those from the WHIST code [5]. We now use these contours as a basis to compare the performance of different compact ignition design concepts.

3. Plasma Performance Analysis of Compact Ignition Tokamak Designs

The plasma performance of two concepts (the IGNITOR-A and ISP-0424) was evaluated under several confinement models. The specific design parameters for these concepts is shown in Table 1. Figure 1 shows POPCONs for the two design concepts under the neo-Alcator electron confinement model. The ions are treated with the neoclassical theory and an anomaly factor of 1. The IGNITOR-A POPCON is characterized by a smaller heating window (3.1 MW vs 5.4 MW) and a larger operating window than that for the ISP-0424. The corresponding *maximum* ignition margins for this optimistic confinement model are 2.3 and 1.7, respectively. A more pessimistic model, shown in Fig. 2, considers the degradation of confinement with the addition of auxiliary power and alpha power. In this model, proposed by Kaye and Goldston [8], the ions and electrons are modeled globally as:

$$\frac{1}{\tau_E^2} = \frac{1}{\tau_{aux}^2} + \frac{1}{\tau_{OH}^2} \qquad (2)$$



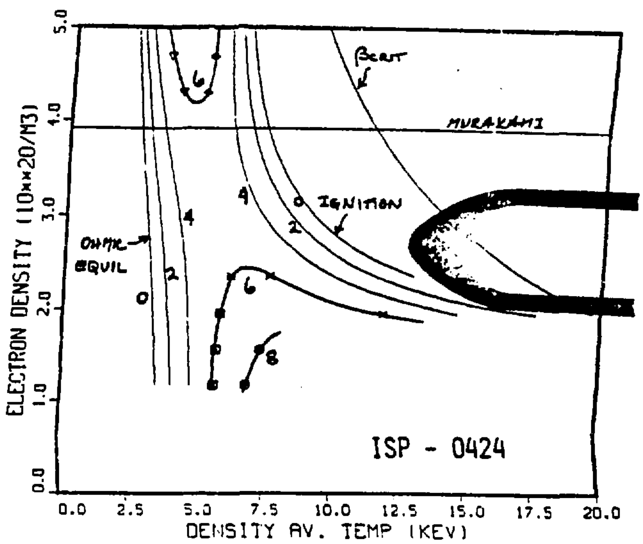
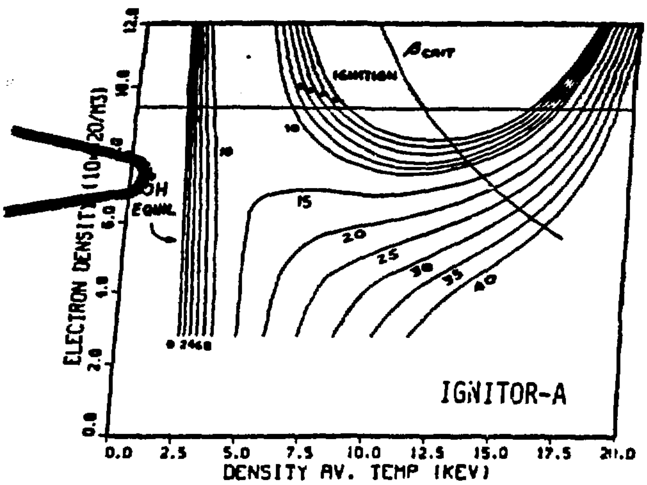


Fig. 1. Contours of auxiliary power



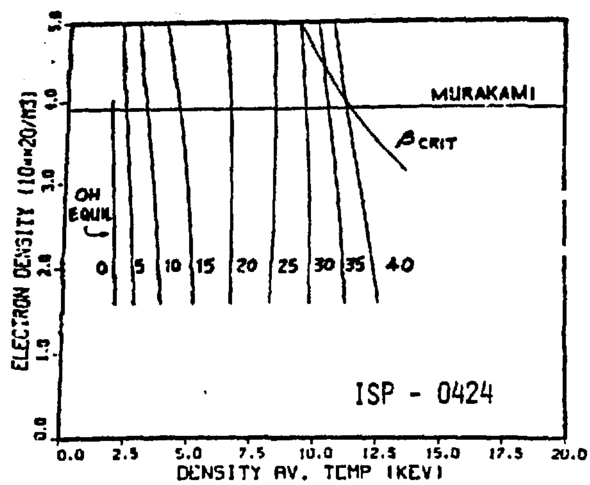


Fig. 2. Contours of auxiliary power

where

τ_{aux} = Kaye-Goldston L-mode confinement time,

τ_{OH} = Neo-Alcator . confinement time .

These results indicate that the IGNITOR-A concept ignites with a maximum ignition margin of 1.1, while the ISP-0424 concept does not ignite (maximum ignition margin = 0.6). The latter suggests the need for possible design modifications for the ISP. The higher value of the plasma current in the IGNITOR favors this device for ignition under the Kaye-Goldston scaling.

Table 1. Design parameters

	IGNITOR-A	ISP-0424
Major radius, (m)	1.01	1.62
Minor radius, (m)	0.39	0.53
Aspect ratio	2.61	3.06
Elongation	1.67	1.6
Triangularity	0.3	0.4
Field on axis, (T)	12.56	8.95
Plasma current, (MA)	10.0	7.83
Edge safety factor	2.6	2.6
Critical beta, (%)	6.1	4.9
Murakami density, ($10^{20}/m^3$)	9.3	3.9

A systematic study of the physics design space for the Compact Ignition Tokamak (CIT) devices was performed to investigate the relationship between major plasma parameters such as major radius, field on axis, aspect ratio, elongation, and ignition margin. This design space is characterized by major radii of 1 to 1.7 m, fields of 8 to 13 T, aspect ratios of 2.5 to 3.5, and elongations of 1.6 to 2.0. Three confinement models were used: neo-Alcator scaling for the electrons and neocalssical for the ions (with an anomaly factor of 1); Mirnov for the electrons and neoclassical for the ions; and the Kaye-Goldston global model [Eq. (2)]. It is noted that this Mirnov model is more optimistic than the neo-Alcator model and is shown here only as a point of comparison. The current physics design guidelines indicate that the neo-Alcator confinement time can be more optimistic than the Mirnov confinement time in some regimes of the design space.

The results of these calculations, plotted in Figs. 3-6, indicate that lower aspect ratios (2.5-3.0) and higher elongations (>1.6) are attractive characteristics for the CIT experiments. Also shown in Figs. 3-6 are values of the figure-of-merit parameter "aB^2/q^*." The functional dependence of this parameter on aspect ratio, ignition margin, and elongation are given below.

For a given ignition margin (based on a given confinement scaling) and elongation, we find that:

- If the aspect ratio is held constant, then aB^2/q^* increases by approximately 25% under the neo-Alcator and Mirnov models when the field is increased from 9 to 13 T. It remains relatively constant under the Kaye-Goldston model.

- As the aspect ratio is increased from 2.5 to 3.5:

  - For a given field, aB^2/q^* is approximately constant under neo-Alcator and increases by approximately 15-30% under Mirnov and Kaye-Goldston.

  - For a given major radius, aB^2/q^* is increasing by approximately 20% under neo-Alcator, approximately 45% under Mirnov, and approximately 15% under Kaye-Goldston.

For a given aspect ratio and elongation, aB^2/q^* increases by approximately 30% under neo-Alcator and Mirnov as the ignition margin is increased from 1.0 and 2.0. It increases by approximately 30% under Kaye-Goldston as the ignitionmargin is increased from 1.0 to 1.5. For a given aspect ratio and ignition margin, increasing the elongation from 1.6 to 2.0 reduces the size and field requirements and results in lower values of aB^2/q^*. The reductions in aB^2/q^* are approximately 18% under neo-Alcator, approximately 28% under Mirnov, and approximately 30% under Kaye-Goldston.

These results show that the figure-of-merit parameter has a different functional dependence on aspect ratio and elongation for each confinement model considered (see Figs. 7 and 8). This suggests that "aB^2/q^*" may be a good figure of merit for CIT plasma performance only under a limited range of design parameters, but not for the entire CIT physics design space of interest.

4. Conclusions

In summary, a new physics code has been developed for system modeling, and extensive parameter surveys. The results ~~forming~~ from the code have been found to be consistent with those from the 1-1/2-D *WHIST* code.

The code has been applied to the analysis of the Compact Ignition Tokamak devices. Comparisons of the plasma performance of the IGNITOR-A and ISP-0424 concepts under optimistic and pessimistic confinement models indicate that design modifications may be needed for the ISP concept to ensure ignition under conservative confinement models. Exploration of the broad CIT physics design space has shown that the parameter "aB^2/q^*" should not be the only figure of merit for plasma performance over the entire CIT physics design space. Ignition margins based on various confinement models should also be used.

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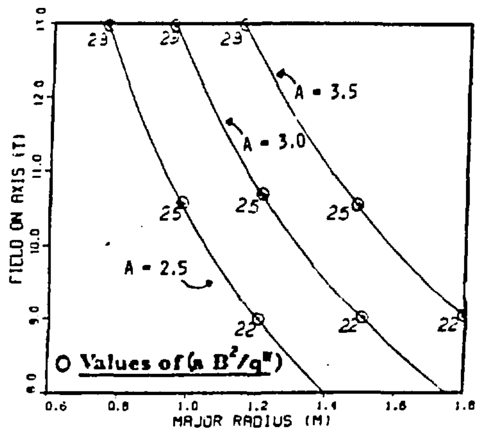

Fig. 3. Variation of major radius and field with aspect ratio for a maximum ignition margin of 1.5 (neo-Alcator; 1.6 elongation).

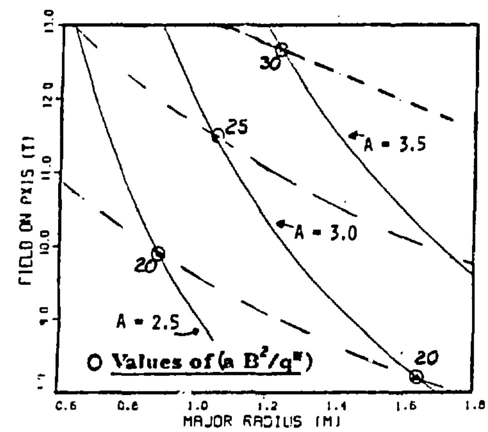

Fig. 4. Variation of major radius and field with aspect ratio for a maximum ignition margin of 1.5 (Mirnov, 1.6 elongation).

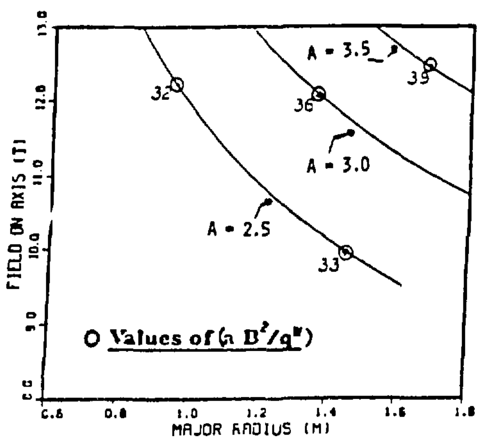

Fig. 5. Variation of major radius and field with aspect ratio for a maximum ignition margin of 1.0 (Kaye-Goldston; 1.6 elongation).

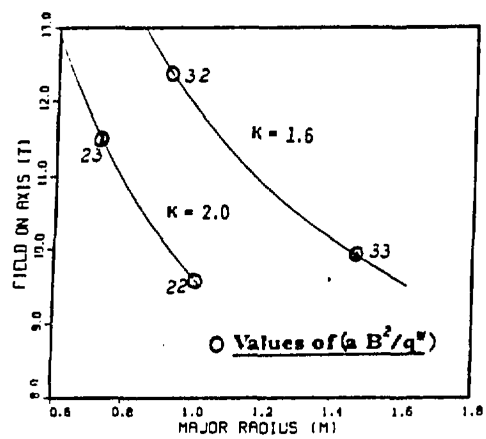

Fig. 6. Variation of major radius and field with elongation for a maximum ignition margin of 1.0 (Kaye-Goldston; 2.5 aspect ratio).

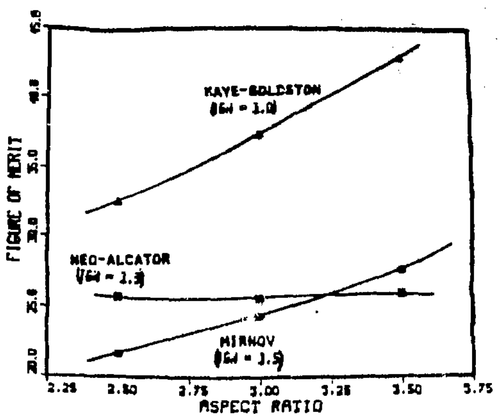

Fig. 7. Variation of figure of merit with aspect ratio (11-T field; 1.6 elongation).

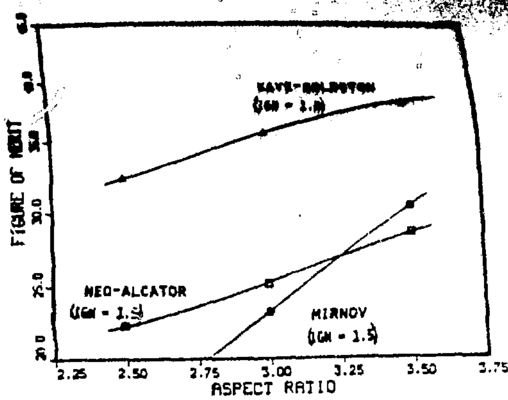

Fig. 8. Variation of figure of merit with aspect ratio (1.2-m major radius; 1.6 elongation).

[Uniform assumptions: 0.3 triangularity; 2.6 safety factor]