WHIST CODE CALCULATIONS OF IGNITION MARGIN IN AN IGNITION TOKAMAK*

PRESENTED AT THE
IGNITION DESIGN POINT WORKSHOP
PRINCETON PLASMA PHYSICS LABORATORY
MARCH 12, 1985

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A simple global model was developed to determine the ignition margin of tokamaks including electron and ion conduction losses - John Sheffield, ORNL/TM-8924, 1984 and updated by Nermin Uckan, January 1985.

- The model has now been compared for a reference ignition device,

\[ R = 1.5\text{m}, \ a = 0.5\text{m}, \ K = 1.6, \ \delta = 0.2 \]
\[ B_0 = 9\text{T}, \ \psi \approx 3, \ \text{Z}_{\text{eff}} = 1.5 \]

against results from Wayne Houlberg's 1 1/2 D-Whist code.

- Both calculations show that under the physics constraints presently imposed on the ignition tokamak ion confinement plays an important role

\[ \beta_{\text{crit}} = 3 \times 10^{-2} \left( \frac{I \text{(MA)}}{a \text{(m)} B_0 \text{(T)}} \right) \]

\[ \text{VOLUME} \]
\[ \text{AVERAGE} \]
\[ \text{VALUES} \]

and \( n_{20} \leq n_{\text{crit}} = 1.7 \frac{B_0}{a R_0} \)

- Therefore it is important to establish a criterion (\( Cx \)) for ion confinement

\[ \chi_i = C \times \chi_i \text{ (Chang-Hinton)} \]
FORMULA FOR IGNITION MARGIN (M)

\[ M \left[ \chi_e + \left( \frac{n_i}{n_e} \right) \frac{T_i}{T_e} \chi_i \right] \leq 0.162 F_\alpha \left[ 4 f_D (1 - f_D) f DT \right] n e20 T e10 \left( \frac{T_i}{T_e} \right)^2 a^2 \left( \frac{2 \kappa^2}{1 + \kappa^2} \right) \]

\[ F_\alpha \approx 0.8 \text{ fraction of alpha power to support conduction losses} \]

\[ f_D = \frac{n_d}{n DT} = 0.5, \quad f DT = \frac{n DT}{n e} \approx 0.84 \]

\[ \frac{n_\alpha}{n e} \approx 0.05, \quad \frac{n_\alpha}{n_e} \approx 0.007 (\alpha \approx 8), \quad \frac{n_i}{n e} \approx 0.9 \]

\[ n e20 T e10 \approx 1.15 \beta B_0^2 \text{ allowing for alpha pressure} \]

\[ M \left[ \chi_e + 0.9 \frac{T_i}{T_e} \chi_i \right] \approx 0.105 \beta B_0^2 a^2 \left( \frac{2 \kappa^2}{1 + \kappa^2} \right) \]
\[ \mathbf{\chi}_e = f_{\text{ex}} \mathbf{X}^\text{OH} \text{ Neo Alcator} = f_{\text{ex}} \frac{2.7a}{n_{e20} R_0^2 q} \left( \frac{2K^2}{1+K^2} \right) \text{ m}^2 \text{ s}^{-1} \]

\[ \mathbf{\chi}_i = f_{\text{ix}} \mathbf{X}_{\text{iCH}} = f_{\text{ix}} \left[ 2.06 \times 10^{-2} K^*_2 \frac{n_{e20} Z_{\text{eff}}}{T_{i10}^{1/2}} \left( \frac{q^2}{B_0^2 (1+K^2)} \right)^{3/2} \right] \text{ m}^2 \text{ s}^{-1} \]

\[ K^*_2 = (0.66 + 1.88 \epsilon^{1/2} - 1.54 \epsilon)(1 + 1.5 \epsilon^2) \]

\[ \epsilon = \frac{a}{R_0} \]

For \( Z_{\text{eff}} = 1.5, K = 1.6, F_\infty = 0.8, A = 3, \epsilon = 0.33, q = 5, T_e = T_i \)

\[ \frac{a B_0^2}{q} \geq M \left( 10.1 f_{\text{ex}} + \frac{4.5}{T_{i10}^{1/2}} f_{\text{ix}} \right) \]

(1) \( f_{\text{ix}} = 0, M = 1.5 \) need \( \frac{a B_0^2}{q} \geq 15 \)

\( f_{\text{ex}} = 1 \)

(2) \( f_{\text{ix}} = 1, M = 1.5 \) need \( \frac{a B_0^2}{q} \geq 22 \)

\( f_{\text{ex}} = 1, T_{i10} = 1 \)

(3) \( f_{\text{ix}} = 2, M = 1.5 \) need \( \frac{a B_0^2}{q} \geq 29 \)

\( f_{\text{ex}} = 1, T_{i10} = 1 \)

(4) \( f_{\text{ix}} = 2, M = 1.0 \) need \( \frac{a B_0^2}{q} \geq 29 \)

\( f_{\text{ex}} = 2, T_{i10} = 1 \)

At the Murakami and \( \beta_{\text{crit}} \) limit, for \( T_i \sim T_e, T_{i10} \sim T_{i1}, n_{e20} \sim 3.9 \)

\[ \mathbf{\chi}_e \text{ Neo Alcator} \sim 0.085 \text{ m}^2 \text{ s}^{-1}, \mathbf{X}_{\text{iCH}} \sim 0.032 \text{ m}^2 \text{ s}^{-1} \]

\( (r = 0.5, Z_{\text{eff}} = 1.5) \)
WHIST CODE CALCULATIONS

- CASES WERE RUN WITH:
  \[ R = 1.5\text{m}, \quad a = 0.5\text{m}, \quad K = 1.6, \]
  \[ B_0 = 9\text{T}, \quad q_\psi = 3, \quad \text{NO RIPPLE LOSSES}, \]
  \[ \text{NO THERMAL ALPHAS} \]
  \[ \text{FAST ALPHA PRESSURE, } Z_{\text{eff}} = 1.5 \]
  \[ X_e = f_{\text{ex}} X_{\text{Neo Alcator}}, \quad f_{\text{ex}} = 1, 2 \]
  \[ \text{Higher losses inside } q = 1 \]
  \[ X_i = f_{\text{ix}} X_{\text{i Chang-Hinton}}, \quad f_{\text{ix}} = 1, 2 \]
  \[ \text{surface.} \]

- THE RESULTS ARE SLIGHTLY MORE FAVORABLE THAN THE GLOBAL MODEL BUT THE SAME TREND SHOWS THAT
  - GOING FROM \( f_{\text{ix}} = 1 \rightarrow 2 \) SUBSTANTIALLY REDUCES \( M \).
  - GOING FROM \( f_{\text{ex}} = 1 \rightarrow 2 \) ELIMINATES IGNITION.

- A RECENT TFTR/JET WORKSHOP SUGGESTED USING \( f_{\text{ix}} = 3 \) !

- REMOVAL OF THE HIGHER LOSSES FOR \( q < 1 \) DOES NOT CHANGE \( P_\alpha \) MUCH AT THE \( \beta \)-LIMIT.
WHY IS ION CONFINEMENT IMPORTANT?

1. IGNITION MARGIN IS SENSITIVE TO $T_i$ and $T_i \geq 1$ 
   \[ \frac{T_i}{T_e} \]

2. THE BULK OF THE ALPHA POWER GOES TO THE ELECTRONS, 
   TO ACHIEVE $T_i \geq 1$ REQUIRES THAT $\chi_i \frac{P_{\alpha i}}{P_{\alpha e}} \chi_e$.

3. FOR THE HIGH FIELD IGNITION DEVICES THE MAXIMUM IGNITION MARGIN IS FOR $n_{20} \sim 4$ and $T_{i10} \sim 1$ AND 
   
   \[ \chi_i \approx \frac{P_{\alpha i}}{P_{\alpha e}} \chi_e \]

CONCLUSION

BOTH $\chi_e$ AND $\chi_i$ CRITERIA SHOULD BE GIVEN.