Predicting Performance in Ignition Experiments Using Transport Simulation

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Workshop on Physics Issues for FIRE
1–3 May 2000
PPPL

Summary

- Are there any unifying features of an (axisymmetric) magnetic confinement scheme that can help design a good fusion ignition/burning experiment?

  Fusion power and confinement

  Plasma stability

  Time-dependent evolution

- The most important parameter may be the plasma density — How to quantify it?

- Define an idealized "natural density" n_N for ignition of a clean (pure) plasma as a limiting minimum density of operation

  There is an approximate scaling for the minimum $n_N \simeq C_N I_p/(B_T a^2)$, over a large range of parameters.

- $C_N \sim 1$ plus Greenwald density limit $n < n_G = I_p/\pi a^2$ leads to a nontrivial limit on the toroidal magnetic field B_T for a practical ignition experiment.

  $B_T \gtrsim 6T$, if the energy confinement is limited by an H-mode τ_E.

Density, Z_{eff}, and Ignition

- There is a limited range of density that allows ignition for a given set of parameters.

  Radiation power and transport losses balanced by fusion power.

  Ideal ignition temperature, above which fusion power increases more strongly with T than bremsstrahlung radiation losses ($T_o \simeq 6$ keV or uniform $T \simeq 4$ keV)

  Lawson criterion for confinement

  Also, plasma stability — modes.

- Higher density is required for ignition under degraded conditions.

- Ignition is strongly sensitive to plasma purity (Z_{eff})
  Radiation increases with Z_{eff}
  Dilution of fusion fuel reduces fusion power

  Transport simulations show that ignition degrades strongly for $Z_{eff} \simeq 1.5$–1.6 (although $Z_{eff} \lesssim 1.2$ has little effect).

- Z_{eff} correlates inversely with density in all experiments to date, $Z_{eff} = C_Z/n_e$. (Coefficient C_Z may vary with local conditions, but is consistent within a given set of experiments.)

- The impurity contamination of a plasma is difficult to control, using present methods.

Natural Density for Ignition

- Define the natural density for ignition as the (range of) density that allows a pure plasma to ignite under a given set of assumptions.

- The natural density measures the best possible ignition performance of a given device under the assumptions. It is also the absolute minimum on the actual density of operation, since any real plasma will have $Z_{eff} \geq 1$.

  The minimum natural density is a useful parameter.

- The natural density cannot be too far below the actual density (e.g., a factor of 2), because of the sensitivity of ignition to Z_{eff}.

- Therefore, the natural density should be a good indicator of the actual performance of a machine.

Table 1: **Volume-averaged natural density ranges for several experiments**

	$\langle n_N \rangle$	T_{io}/T_{eo}	R/a	B_T	I_p	$\overline{n}_G$	P_{Aux}	H^*	$n_{eo}/\langle n_e \rangle$
Ignitor Ref 12MA	4.2	13.3/14.9	1.32/0.47	13	12	17.3	0	1.8	2.3
Ignitor Ref 12MA	5.5	11.6/12.8	1.32/0.47	13	12	17.3	0	1.7[a]	2.3
Ignitor Ref 12MA	4.2	17/19.5	1.32/0.47	13	12	17.3	0	1.6[b]	2.0
Ignitor Ref 12MA[c]	5–6	11-13	1.32/0.47	13	12	17.3	0	$\gtrsim 1$	1.1–2.9
Ignitor Ref 11MA	4.1	15/17	1.32/0.47	13	11	15.9	0	1.7	2.3
Ignitor Ref 11MA	5.5	17.5/21	1.32/0.47	13	11	15.9	0[d]	1.6	1.7
Ignitor RevShear[e]	2.6	32.7/32.1	1.32/0.47	12	7	10.1	8	(2.5)[e]	2.1
Ignitor RevShear	3.0	33.1/32.6	1.32/0.47	12	7	10.1	8	2.5	1.75
FIRE	4[f]	32/39	2.0/0.525	10	6.5	7.5	20[g]	2.1[h,i]	1.80
ITER-FEAT	0.6[j]	65/46[k]	6.2/2.0	5.3	15.1	1.2	24	2.0[i]	1.31
ITER EDA[l]	0.43	68/44[k]	8.14/2.80	5.7	21	0.73	24	2.0[i]	1.16
ITER EDA[l]	0.45	55/39[k]	8.14/2.80	5.7	21	0.73	24	1.8	1.65
ITER EDA[l]	0.65	70/40(45/40)[m]	8.14/2.80	5.7	21	0.73	24	1.7	1.17
ITER EDA[n]	0.63	71/53	8.14/2.80	5.7	21	0.85	24[o]	2.1	1.68
ITER EDA[n,p]	0.57	81/55	8.14/2.80	5.7	21	0.85	24[o]	2.0	1.16

$^*H$ does not include $-dW/dt$ or $-P_{BREM}$ in P_H for L-mode scaling. $-dW/dt$ significantly lowers Ignitor Ref values. Units of keV, m, T, MA, MW, densities in $10^{20}\mathrm{m}^{-3}$.

- **The minimum natural density satisfies an empirical scaling with the device parameters,**

$$n_N \simeq C_N I_p/(B_T a^2).$$

Over a wide range of parameters, $C_N \lesssim 1$. (FIRE is higher.)

- **Since aspect ratio is similar, $R/a \simeq 3$ (FIRE 3.85), scaling with aspect ratio is not well determined, e.g., $n_N = C_N(R/a)I_p/(B_T a^2)$ gives similar results.**

Table 2: **Scaling of the natural density $n_N \simeq C_N I_p/(B_T a^2)$**

	$\langle n_N \rangle$	$I_p/(B_T a^2)$	C_N	$\overline{n}_N{}^a$	$\overline{C}_N{}^a$	$M_G{}^b$	$\beta_p{}^c$
Ignitor 11 MA	4.1–5.5	3.83	1.1	5.6–6.6	1.46–1.74	0.74	0.26
Ignitor 12 MA	4.2–5.5	4.18	1.0	5.8–7.4	1.39–1.78	0.66	0.22
Ignitor RS	2.6–3.5	2.64	1.0–1.1^d	3.3–4.4	1.25–1.68	0.73	0.82
FIRE	4	2.36	1.7	4.9	2.07	0.35	1.79
ITER-FEAT^d	0.6	0.71 (0.64)	0.85 (0.95)	0.67	0.94 (1.05)	0.44	0.59
ITER EDA^d	0.43–0.64	0.47 (0.38)	0.91 (1.13)	0.52–0.71	1.11–1.50(1.37)	0.39	0.78

[a]Line-averaged density.

[b]Density margin for operation, $M_G \equiv 1 - (\overline{n}_N/n_G)$.

[c]Volume-averaged poloidal beta.

[d]Values in parentheses based on actual I_p at ignition. ITER EDA used full current $I_p = 18$ MA.

The natural density is defined by transport simulation.

- **Given plasma size and shape R, a, κ, δ, magnetic field B_T and plasma current I_p, available heating power P_{Aux}, intended ignition scenario.**
- **Assumptions on thermal and particle transport (here, that the energy confinement time follows an L- or H- mode like power scaling scaling, defined by a factor H times τ_L, a given L-mode scaling, such as ITER89-P. Particle transport is defined separately.)**
- **Full time dependent ignition sequence is followed, starting from initial current and density ramp. If necessary, determine the length of a current rise phase.**
- **Impose stability conditions, such as a mostly monotonic q-profile with $q_{min} > 1$ or only a small radius where $q < 1$.**
- **Start from an initially pure D-T plasma. (Let fusion ^{4}He ash accumulate.)**

Simulations were carried out for a number of different designs, covering a wide range of parameters.

- **Ignitor, Ignitor with reversed shear, FIRE, ITER-FEAT, ITER EDA**
- **Models were chosen more for consistency rather than for optimizing ignition performance in a given device. Limiting H was varied to reflect the intended mode of operation.**
- **The natural density range is a well defined function of the device parameters. The range is not too broad.**

The normalized natural density C_N measures the relative lengths of the density and current ramps, or the magnitude of the minimum density required for ignition compared to the current capacity of the experiment.

- **The density ramp time t_N is closely related to the ignition time t_{IGN} for the natural density.**
- **Current capacity is expensive, so the minimum $t_N \geq t_R$ and $t_{IGN} > t_R$ in practice.**
  Current drive is expensive and often difficult, so the desirable t_N and t_{IGN} are not too much longer than t_R.
- **Ignitor Ref and RS have $C_N \simeq 1$ and $t_N \gtrsim t_R$ for ohmic ignition at confinement significantly less than H-mode.**
  Actual operating densities are similar to n_N.
  The near equality t_N,$t_{IGN} \simeq t_R$ is by design.
- **ITER-FEAT and ITER EDA have $C_N \lesssim 1$ and $t_N < t_R$.**
  They are intended to operate at significantly higher Z_{eff} and density, where the extra current is needed.
- **FIRE has higher $C_N = 1.7$ and $t_N > t_R$. It has a relatively high ignition density for its current and requires fuelling and heating for a significant time after the current ramp to reach ignition. (The natural density is similar to expected operating density.)**

FIRE ignition/burning operation could be improved by

- **Higher H factor**
- **Higher P_{Aux}, especially during current ramp**
- **Use of current drive**
- **Raising $I_p/B_T a^2$.**
  Since edge safety factor $q_{95} \geq 3$ is strongly desirable for plasma stability and $q \sim a^2 B_T/(R I_p)$, keeping $q_{95} \simeq 3.3$ at similar shaping would require decreasing the major radius R.

The natural density scaling implies an (empirical) limit on the minimum magnetic field for a practical ignition experiment.

- Assuming that the Greenwald density limit for tokamak operation, $n \leq n_G = I_p/\pi a^2$ holds (and the earlier Murakami limit for ohmic plasmas, $n_M \sim B_T/(Rq_a) \sim J_\phi$), implies

  $$\frac{\pi C_N}{B_T}\frac{\overline{n}_N}{\langle n_N \rangle} \leq \frac{\overline{n}_e}{n_G} \leq 1.$$

  Then taking $\overline{C}_N = C_N \overline{n}_N/\langle n_N \rangle \simeq 1$ as a lower limit, based on the simulation results,

  $$B_T^{MIN} \simeq \pi \overline{C}_N \simeq 3T.$$

- An adequate range of operation requires a smaller density $\overline{n}_N \leq 0.5 n_G$, or at least

  $$B_T \geq 2B_T^{MIN} \simeq 6T.$$

- This is not an absolute limit on operation, but it becomes increasingly difficult and expensive to operate below it. The exact value depends on the assumptions made for determining n_N, in particular on confinement.

Conclusions

- **A "natural density" for ignition can be defined as an idealized parameter for ignition of a clean plasma, using transport simulation.**
- **It predicts properties of actual ignition performance based on a small set of fundamental device properties (size, shape, field, current, heating power, etc), under limited assumptions on confinement and ignition path.**
- **A normalized natural density C_N, defined by $n_N = C_N I_p / B_T a^2$, measures the relative "size" of the density and current in an experiment, where $C_N \sim 1$ for current and density ramps of approximately the same length and $C_N > 1$ for ignition that requires substantial fuelling after the end of the current ramp.**
  (Aspect ratio dependence not determined.)
  C_N is a useful parameter for 0D ignition studies.
- **If the Greenwald density n_G poses an operational limit for fusion plasmas as it does for present ones, a minimum magnetic field is required for a practical ignition experiment.**