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A Consistency Analysis on the Tokamak Reactor Plasmas

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Abstract

The parameter regime which simultaneously fulfills the various physics constraints are looked for in the case of ITER grade tokamaks. The consistency analysis code is applied. It is found that, if the energy confinement time reaches 1.6 times of the prediction of the L-mode scaling law, the Q-value of about 4 is possible for the full current drive operation at the input power P_{in} of 100MW (Q is the ratio of fusion output and P_{in}). In the ignition mode, where half of the current is inductively sustained, Q approaches to 15 for this circulating power. If only the L-mode is realized, Q is about 1.5 for $P_{in} \simeq 100$MW.

Keywords: Tokamak, Reactor design, plasma conditions, consistency analysis

§1 Introduction

Efforts have been made in the design of the fusion experimental device such as NET[1), FER[2) and ITER[3). ITER activity is most detailed among them in the sense that the database is carefully and widely examined. Many physics and engineering constraints and scaling laws have been counted for. It is, however, not clear what are the most critical elements in the list of constraints for the achievement of the projection (such as Q-value, stationarity, fluence of output). In addition to it, there is divergence of the accuracy in the listed constraints. If there is a large uncertainty in the scaling law or constraints, which are most strongly limiting the projection, then the first priority of the future physics R&D must be put on the reduction of this uncertainty. Another problem we should note is whether the constraints are considered consistently with others or not.

To answer these questions we study the regime of parameters which satisfy various constraints simultaneously. Numerical code TASK/CA (Transport Analysis and Simulation for tokamaK/ Consistency Analysis) has been developed[4). The region clearing all conditions is obtained in the space of the controllable parameters such as the heating power and density. This plot is called "CATS Plot" (Consistency Analysys for Tokamak System). Influence of the plasma size on the expected Q-value was studied. Which one of the constraints is the most significant depends on the choice of the target plasma size. We apply this analysisto the ITER-grade tokamak, by updating the scaling law of the energy confinement time.

As the missions of the present analysis, we choose two options. One is the steady state condition with full current drive. The other is the ignition mode, where some part of the plasma current is driven inductively. Both cases are studied under the assumption of the L-mode scaling of the energy confinement time τ_E and that of the enhancement factor h for τ_E. It is found that the current drive efficiency and the condition for the low temperature of the divertor plasma are the critical conditions for the steady state operation mode. The uncertainty in the particle confinement time leads to a large ambiguity in the prediction.

§2 Conditions for the Core Plasma

The conditions we use for the core plasma is discussed in Ref.[4]. The list is given as follows. The plasma current I_p is measured in [MA], minor and major radii a and R are given in [m], magnetic field is in [T], volume averaged density n in [$10^{20}/m^3$], density-weighted and volume-averaged temperature T in [keV], input power P_{in}, α heating power P_α, and total heating power P are in [MW], plasma volume V_p in [m^3], and the neutron wall loading P_N in [MW/m^2].

1. Beta Limit

$$\beta < \beta_c\ (\%) = g \frac{I_p}{aB} \quad , \quad g = 2.7 \tag{1}$$

2. q limit

$$q_{\psi 95\%} \geq 3 \tag{2}$$

3. Density limit

$$\bar{n}_e < \bar{n}_c = 0.4 \frac{I_p}{a^2} (0.1P)^{\alpha} \quad , \quad \alpha = 0.25 \tag{3}$$

4. Current drive efficiency

$$I_p < \frac{CT}{nR} P_{in} \quad , \quad C = 0.026 \tag{4}$$

5. Boot Strap Current

$$I_{BS} = \frac{10nT}{I_p} \left(\frac{a}{2}\right)^{2.5} \left(\frac{5.8}{R}\right)^{0.5} \tag{5}$$

6. Cold divertor plasma condition

$$T_{div} < 10\text{eV} \tag{6}$$

7. Ash exhaust (preliminary)

$$\frac{n_e V_p}{\tau_p} > 10^4 S_{\alpha} \tag{7}$$

8. Energy confinement time (L-mode)

$$\tau_E = 0.048 I_p^{0.85} R^{1.2} a^{0.3} \kappa^{0.5} \bar{n}^{0.1} B^{0.2} A^{0.5} P^{-0.5} \quad (8)$$

9. Particle confinement time (L-mode)

$$\tau_p = 0.05\, \bar{n}^{-1} (B/4.5)^{\delta} a\, P^{-0.5}, \quad \delta \simeq 1.5 \quad (9)$$

10. Neutron wall loading

$$P_N < 1 \quad (10)$$

The symbol q_ψ indicates the q value on the flux surface ψ = 0.95ψ(separatrix), κ is the elongation factor and M is the ion mass number. $T_e = T_i$ is assumed. $\bar{n}$ indicates the line averaged density. Scaling law (8) is updated according to the ITER activity (ITER-89P law is employed)[5]. Combining the particle confinement scaling law and the simulation results[6] of the divertor plasma, relation (6) is represented as

6'. Cold divertor plasma condition

$$T_{div}\ (\mathrm{eV}) = \frac{2.5\sqrt{P}}{n^2 \kappa a R} < 10 \quad (6')$$

These conditions are obtained for the L-mode. The scaling law for the H-mode is not yet clear, although the progress in constructing the database has been made very recently[7,8]. We here only introduce a parameter of enhancement h. τ_E is given as $h\times\tau_E$(L-mode). The improvement of τ_p is usually not identical to that of τ_E. However we in this article simply assume that $\tau_p = h_p\times\tau_p$(L-mode) holds. We further simply equate h and h_p in order to reduce the parameter in the analysis. In the case of the improved confinement mode, we use

6'H. Cold divertor plasma

$$\frac{h_p\sqrt{P}}{n^2\kappa aR} < 4 \tag{11}$$

8H. Energy confinement time

$$\tau_E = h\,\tau_E(\text{L-mode}) \tag{11}$$

9H. particle confinement time

$$\tau_p = h_p\,\tau_p(\text{L-mode}) \tag{12}$$

We have no detailed database on the H-mode correction to the other constraints. we here assume that the other conditions are unaffected even in the H-mode.

Throughout of this article we assume the profiles of the density and temperature as

$$n_e(r) \propto (1-r^2/a^2)^{0.3} \tag{13}$$

and

$$T(r) \propto (1-r^2/a^2)^{0.5} \tag{14}$$

The improved confinement mode with density peaking is not studied. This is because little is known about the parameter dependence of these discharge modes, and the applicability to the stationary operation is not clear. The formula to calculate P_α is given in Ref.[4].

§3 Operation Regime

The operation regime is looked for in a controllable parameter space, i.e., the average plasma density n and the total input power P_{in}. Namely we take a point model for the core plasma using Eqs.(1) to (14).

The plasma parameter is chosen according to the ITER design: R=6m, a=2.15m, B=4.85T, I_p=22MA, κ=2. The levels of impurity accumulation and the helium content are not known. We assume that the 10% helium is included, and neglect contribution of other impurities to fuel dilution.

3.1 L-mode Plasma

The database is abundant for the L-mode plasma, and the problems of the impurity accumulation seem to be less severe compared to other modes. We first study the case of L-mode as the basis of the analysis. The parameter h is chosen unity.

Consistency Analysis code is applied to this set of parameter. Figure 1 illustrates the result for the full current drive mode. Important constraints are shown by the solid line in Fig.1. They are the β-limit (left side of the line with "β_C" is permitted), low temperature divertor plasma (above the line with "T_{div}" is allowed), full current drive condition (right side of the line with "CD" is allowed) and the density limit (below the line with "n_C" is accessible). Thick broken lines indicate the condition of P_N=1MW/m^2 and 3MW/m^2. Contours of the Q-value and temperature are shown by the chained lines and dotted lines, respectively.

This graph shows that the consistent regime for the operation has a shape of triangle on this plane. At the point of the lowest power, P_{in} of about 130 MW is required, and the Q-value stays around 1.3. The maximum Q-value is about 2.2 with the input power of 0.9GW. In the latter case, the circulating power exceeds 1.4GW, and is, at present, beyond the controllable level.

The low expected Q-value is owing to the poor energy confinement time, not due to the request of the full current drive. In Fig.1, the lines of partial current drive condition are also shown. Even if we discard the current drive condition, the maximum Q-value is about 1.6 for the power input of P_{in} below 100MW.

It is noted that the plasma is stable against the thermal instability in the operation regime, regardless of the full current drive mode or the partially diven one.

3.2 Improved-mode Plasma

The predicted performance of the L-mode plasma is not enough to test burning plasma phenomena. The improved confinement mode is inevitable.

We study the case of enhancement factor of h=1.6. In H-mode plasmas, better enhancement factor has been obtained[7,8]. However, the discharges with good enhancement factor are often associated with strong impurity accumulation and are not suitable for extrapolation to reactor plasmas. Recently, discharges with small grassy ELMs (Edge Localized Modes) have been found[9]. The duration time of them can be long, though the enhancement factor is not so large. Standing on these situations, we choose a moderate value for h, and assume that such a mode can be sustained long enough.

Figure 2 shows the operation regime. The definition of lines are the same as in Fig.1.

The steady state operation point with minimum power (A) shifts to the higher-density and lower-power region. Q-value increases to 4.2. If the power of 130MW is available, which corresponds to the minimum power in the case of Fig.1, the Q-value reaches 5.

If the operation of the partial-current-drive mode, which should be long enough, is chosen, the Q-value can be much higher. (Hybrid drive mode.) In the case where 50% of the plasma current is driven inductively, Q of 12 would be possible at the input power of 100MW. The neutron wall loading reaches to $1MW/m^2$ at this working point. The Q-value of 20 is obtained with small increment of the affordable neutron wall loading from the calculation.

Figure 2 shows that higher Q-value is possible. The sudden change of the output will take place due to the chracteristic temperature dependence of the fusion crosssection. In the region of [n>3, and $n>\sqrt{P_{in}}/5$], the solution becomes multi-valued. There are three branches; the low Q and low T branch, which is shown in this graph, the high Q and high T branch, and the third is an unstable one. If the density is increased to just below the density limit at low power (say 50MW), and then the power and density are increased along the line of n_c (path I in Fig.3), then the sudden jump of the output occurs at the crossing of the line n_c and the jagged line in Fig.2. The Q-value increases from 5 to over 50. The jump of Q in the reverse direction occurs, if we hit the bifurcation line from the reverse side (path II in Fig.3). Both cases are avoidable by carefully controlling the plasma density and input power.

The operation region in Fig.2 also indicate the importance of the particle confinement time. If τ_p is much more improved than τ_E, the estimation of the minimum power would be too optimistic. In the case h_p is larger than h, then the line T_{div} in Fig.2 moves to higher density region by the factor $\sqrt{h_p/h}$. As a result of this shift, the crossing of the line denoted by T_{div} and the one with CD (i.e., point A) moves to higher power and density region for the fixed ratio of the driven current. The triangle of the consistent working regime shrinks. In other words, the fraction of the driven current reduces for the fixed maximum input power. This change in evaluation affects the plausibility of the steady state operation.

Compared to the steady state operation, the ignition mode is not affected much. For instance, for the fixed value of P_{in} =100MW, n can be increased to $1.6\times10^{20}/m^3$, without hitting the β-limit and free from the threat of thermal instability. This indicates that the line of T_{div} is allowed to move to the higher density direction by the factor of 4. This means that h_p can be as high as 25. In the case that the neutron wall loading is limited to $1MW/m^2$, then n can be increased to $10^{20}/m^3$, i.e., h_p up to 10 is permissible.

§4 Summary and Discussion

We have analysed the consistent operation regime for the burning plasma. Both the steady state mode and ignition mode are investigated. The consistency analysis code is applied to the ITER grade tokamak. The effect of the confinement enhancement is studied. As the energy confinement time, we employ the ITER-89P model. The particle confinement time is assumed to be the extended JT-60 law. The working region is limited by the conditions of the beta limit, the low divertor plasma temperature and the current drive. If the neutron wall loading of $1MW/m^2$ is a matter of consern, this also limits the working region.

For the L-mode plasma, the expected Q-value is very low in the range of $P_{in} \simeq 100MW$. The ignition mode also has low Q-value. The confinement improvement is inevitable to have the burning core plasma.

As an example of the improved mode, we simply multiply the factor h to τ_E and τ_p. The case of h=1.6 is studied. It is shown that the Q of 5 would be possible for the input power of 130MW. In the hybrid drive mode, where 50% of the plasma current is driven by the induction, the Q-value of 12 is possible with the heating power of 100MW.

For this improved mode, the sudden change of Q-value, i.e., thermal instability, could take place in the high density region. The steady state operation regime with full current drive is free from this unstable region. The instability is eluded by the careful control of the plasma density.

The analysis indicates the importance of the condition of the low temperature plasma at divertor plate. This determines the lower limit of the input power. The temperature strongly depends on the particle outflux to the scrape-off-layer plasma. Thus the estimation of minimum power depends on the scaling law of the particle confinement time τ_p. The present analysis uses somewhat lower value of h compared to the achieved value of h, compromising the stationarity of the discharge. The simple assumption of $h=h_p$ may be too optimistic. Recently developments are made on τ_p scaling. However, the knowledge of those in the improved mode is sparse and limited. The further development of the physics R&D is inevitable for the progress of the dependable scenario of the fusion experimental reactor.

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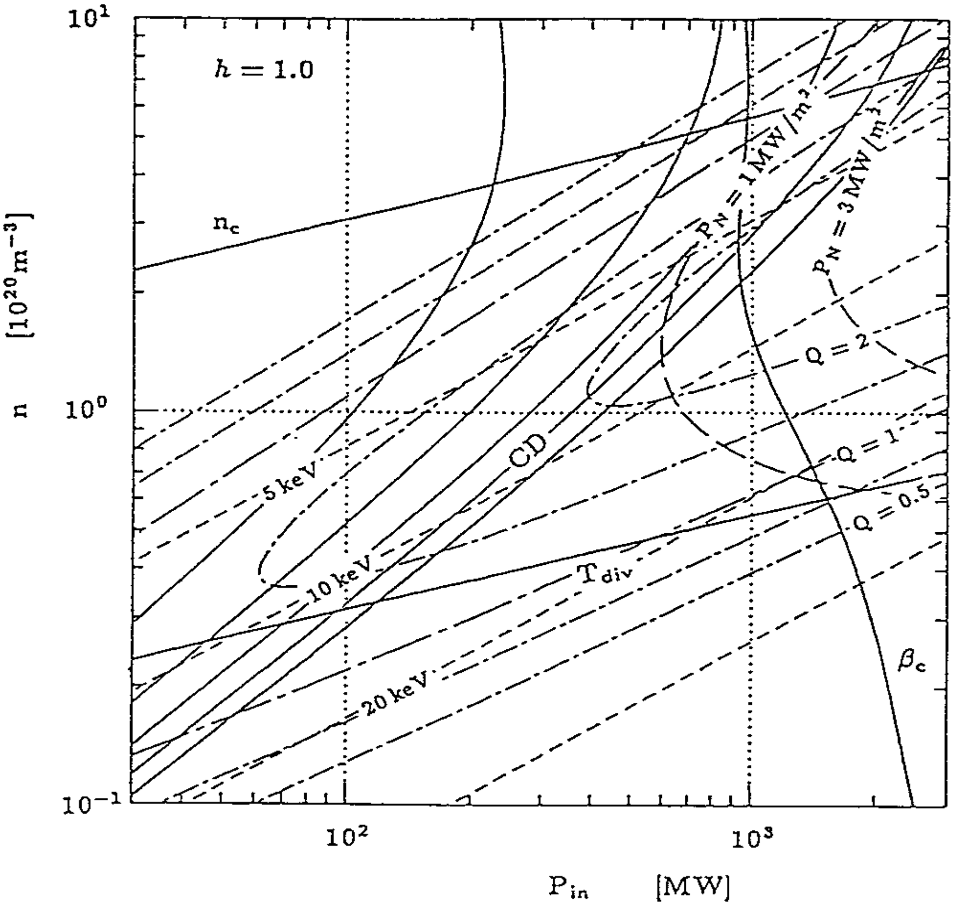
Figure Captions

Fig.1 Plasma performance on the plane of the average density n and in put power P_{in} for the ITER grade plasma. The line with n_c denote the density limit, β_c the beta limit, CD full current drive condition, T_{div} divertor plasma temperature of 10eV, respectively, and P_N is the neutral wall loading. Dashed lines are for the temperature contours, and the dashed-dotted lines for the Q contours. L-mode plasma and $h=h_p=1.0$. Lines for partial current drive (80%, 60%, 40% and 20%) are also plotted.

Fig.2 Plasma performance of the improved confinement mode. $h = h_p = 1.6$. Same definitions of lines as in Fig.1. The point A indicates the point with minimum input power. Multiple solution appears in the high density region [$n > 3$ and $n > \sqrt{P_{in}}/5$].

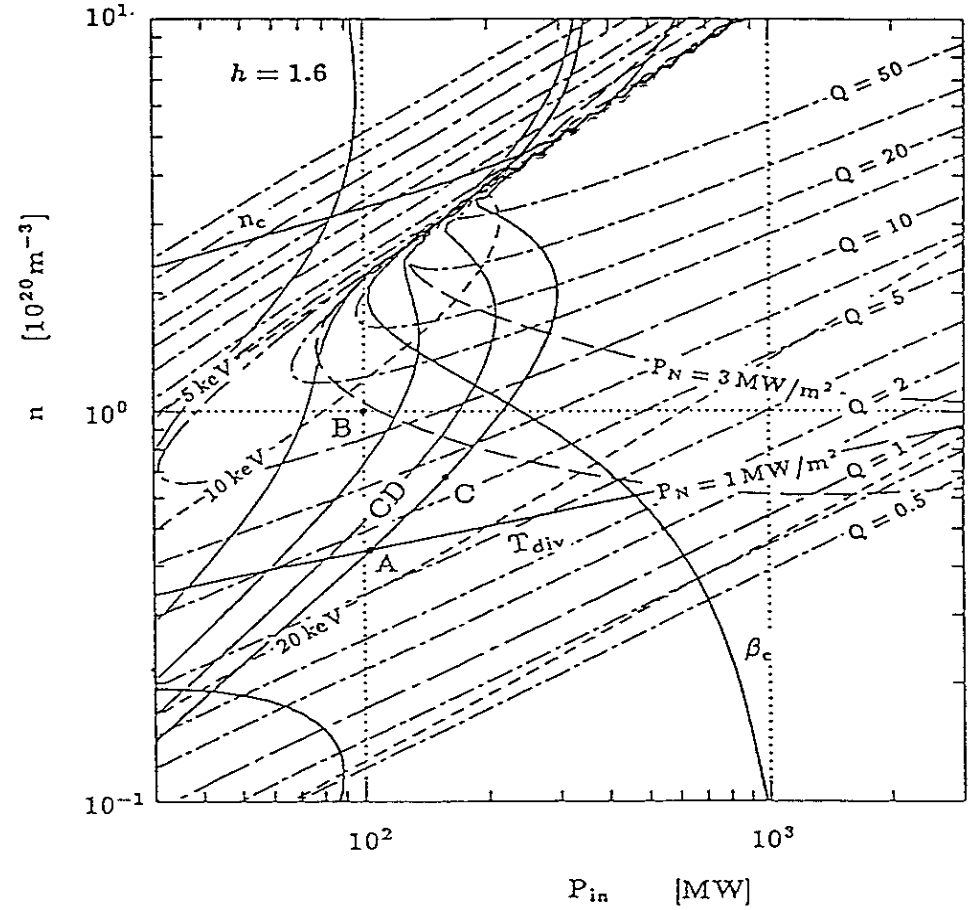
Fig.3 Paths encountering the thermal instabilities are indicated. Bold dotted lines indicate the critical condition for the bifurcation. The Q-value jumps up at the end of the path I. Q-value decays at the end of path II. Control of the density is a key for the stationary and stable operation.

Fig. 1



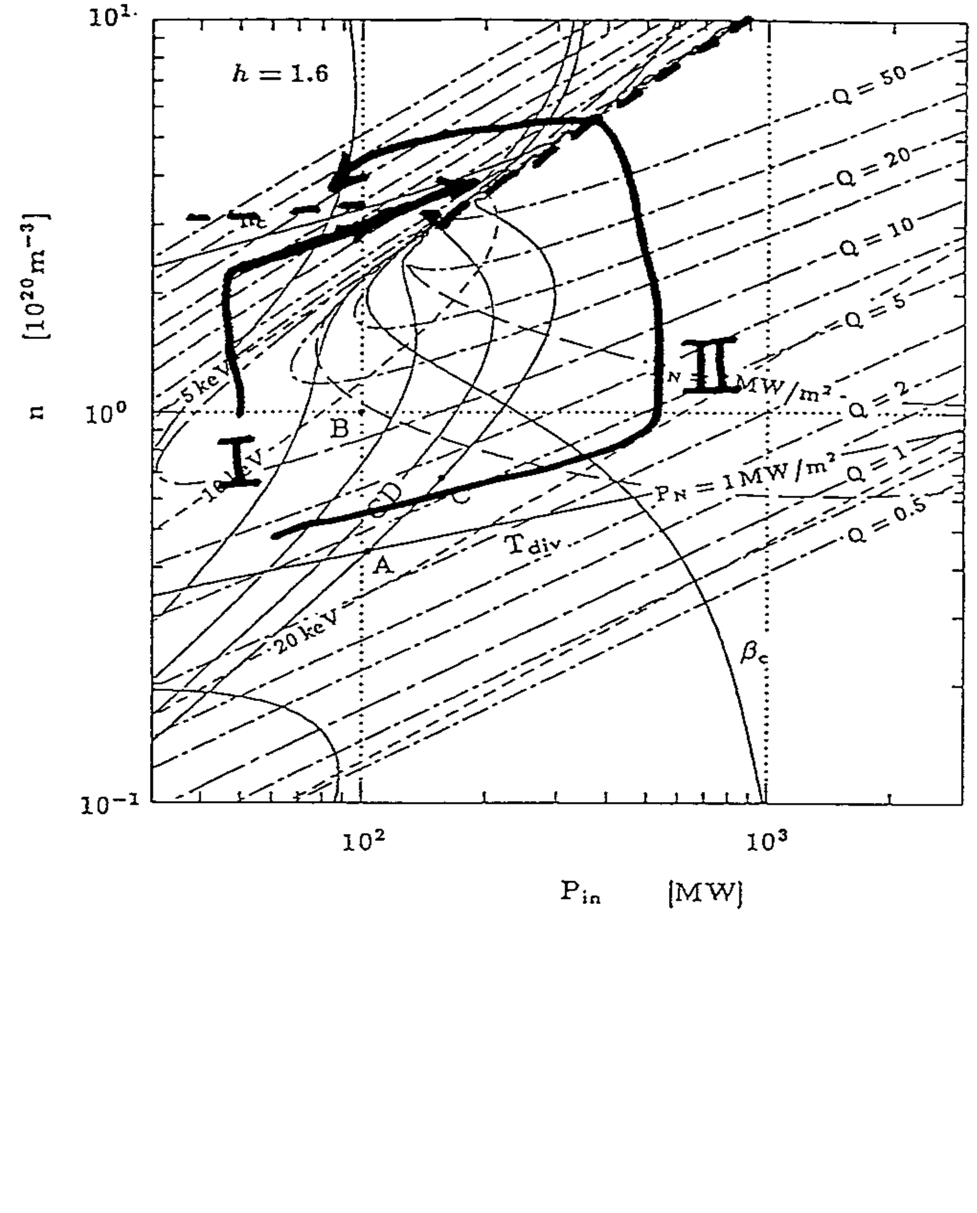
10^1
$h = 1.0$
n_c
$P_N = 1\,MW/m^2$
$P_N = 3\,MW/m^2$
$Q = 2$
$Q = 1$
$Q = 0.5$
5 keV
10 keV
20 keV
CD
T_{div}
β_c
n $[10^{20} m^{-3}]$
10^0
10^{-1}
10^2
10^3
P_{in} [MW]

Fig. 2



h = 1.6
10^{1}
10^{0}
10^{-1}
10^{2}
10^{3}
n [10^{20} m^{-3}]
P_{in} [MW]
n_c
5 keV
10 keV
20 keV
B
C
CD
A
T_{div}
β_c
P_N = 3 MW/m²
P_N = 1 MW/m²
Q = 50
Q = 20
Q = 10
Q = 5
Q = 2
Q = 1
Q = 0.5

Fig. 3



h = 1.6
Q = 50
Q = 20
Q = 10
Q = 5
Q = 2
Q = 1
Q = 0.5
5 keV
10 keV
20 keV
B
A
C
D
I
II
P_N = 1 MW/m²
T_{div}
β_c
n_c
10^1
10^0
10^{-1}
10^2
10^3
n [10^{20} m^{-3}]
P_{in} [MW]

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