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J J FIELD
E MINARDI

CULHAM LABORATORY
Abingdon Oxfordshire

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TRANSPORT CALCULATIONS FOR A HIGH DENSITY OHMICALLY HEATED D-T TOKAMAK

by

J.J. Field and E. Minardi

Culham Laboratory, Abingdon, Oxon, OX14 3DB, UK
(Euratom/UKAEA Fusion Association)

Abstract

We present the results of transport calculations for a high current and particle density Tokamak, like Ignitor. The transport equations used are averaged over prescribed temperature and density profiles, with an assumed electron energy confinement time given by Alcator scaling and an ion energy confinement time slightly worse than neoclassical. The trapping, slowing down, etc., of alpha particles is included on the basis of classical theory. The results indicate that with realisable technological parameters ignition is unlikely to be achieved without the use of additional heating, even for a $Z_{eff} = 1$ plasma.

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1. INTRODUCTION

Coppi has suggested [1,2,3] that it might be possible to reach ignition in a Tokamak with high particle and current densities, based on the Alcator scaling [4], that the energy confinement time increases linearly with the particle density and with the square of the minor radius. A large current, $I \simeq 3$ MA, is required to obtain appreciable ohmic heating and to contain most of the alpha particles produced during thermonuclear reactions so that the 3.5 MeV of alpha energy can be given up to the background plasma [5].

In this paper we present some results of a transport calculation, where the effect of profiles is taken into account by suitable volume averaging. Section 2 gives the six basic ordinary differential equations that we solve, together with our assumptions about the density and temperature profiles. Section 3 contains a consideration of alpha particle effects, including an estimate of the alpha particle non-escape probability, the slowing down time, and the distribution of energy between the electrons and ions. The various sources and sinks of energy and particles are described in Section 4. Some considerations of the profile averaging are introduced in Section 5, while the numerical results and a discussion of them are presented in Section 6. The machine parameters assumed are given in the Appendix. Mks units are used, with energies and temperatures in keV.

2. TRANSPORT EQUATIONS

The particle species presently included in the calculation are deuterium, tritium, electrons and alpha particles, with particle densities n_D, n_T, n_e and n_α. It is useful also to introduce the fuel density, $n_F = n_D + n_T$ and the tritium ratio, $\epsilon = n_T/(n_D + n_T) = n_T/n_F$. The total ion density is given by

$$n_x = n_F + n_\alpha \quad . \tag{2.1}$$

In computing the fraction of alpha energy delivered to the ions and electrons it is useful to introduce the density weighted by the Coulomb cross-section, normalised to the DT mixture,

$$n_Z = n_F + n_\alpha\,(2 + \epsilon) \quad . \tag{2.2}$$

The transport equations actually solved are for the electron and ion energy densities, the fuel and alpha particle particle densities, tritium ratio and the energy density of the fast alphas; the electron particle density is calculated assuming quasi-neutrality. The thermalized alpha particles, tritons and deuterons are all assumed to be at the same background temperature of T_i (keV).

Radial dependence is averaged out of the transport equations by integrating over assumed profiles for the density and temperature. We follow Mercier [6] by assuming the relation

$$n(r) = \xi T_e^c(r) \tag{2.3}$$

between the density and temperature profiles for Tokamaks, where $c \simeq \frac{1}{2}$. Specifically we take

$$n(r) = n_o(1 - r^2/a^2)^{\delta/2} \tag{2.4}$$

$$T(r) = T_o(1 - r^2/a^2)^{\delta} \quad . \tag{2.5}$$

With the assumption of Spitzer resistivity (2.5) implies a current density profile

$$j(r) = j_o(1 - r^2/a^2)^{3\delta/2} \quad . \tag{2.6}$$

We note that (2.6) is the form used by Wesson [10] in many of his stability calculations for tokamaks and will enable us to make some useful comments regarding mhd stability.

For the moment, for simplicity, we will take $\delta = 0$, so all profiles are flat. The various weighting factors introduced into the equations by taking $\delta > 0$ will be discussed in Section 5. The equations for the electron and ion energy densities are

$$\frac{d}{dt}\left(\frac{3}{2}\, n_e K\, T_e\right) = \sum_{\ell} S_{\ell}^{e} \tag{2.7}$$

$$\frac{d}{dt}\left(\frac{3}{2}\, n_x K\, T_i\right) = \sum_{\ell} S_{\ell}^{i} \tag{2.8}$$

where $K = 1.6 \times 10^{-16}$ joule/keV. The terms on the right hand sides of (2.7) and (2.8) represent the collection of energy sources and sinks for the electrons and ions respectively, particular contributions are considered in Section 4.

The following equations describe the time evolution of the particle densities

$$\frac{d}{dt} n_F = \sum_{\ell} R_{\ell}^{F} \tag{2.9}$$

$$\frac{d}{dt} n_{\alpha} = \sum_{\ell} R_{\ell}^{\alpha} \tag{2.10}$$

$$\frac{d\epsilon}{dt} = \epsilon(1 - \epsilon)(2\epsilon - 1)n_F \overline{\sigma v} + (\epsilon_R - \epsilon)R_F/n_F \tag{2.11}$$

The sources and sinks for fuel and α-particles are described in Section 4. In (2.11) $\overline{\sigma v}$ is the cross section for the fusion reaction [7],

$$D + T \rightarrow He^4(3.5\ \text{MeV}) + n(14.1\ \text{MeV}) \ , \tag{2.12}$$

averaged over a Maxwellian distribution, ϵ_R is the tritium ratio of the refueling gas, which we set equal to 0.5 and R_F is the refueling coefficient.

Finally there is the equation for the time evolution of the energy density of the fast alpha particles,

$$\frac{dE_{\alpha}}{dt} = -\frac{E_{\alpha}}{\tau_{\alpha}} + \frac{S_{\alpha}}{P_{\alpha}} \tag{2.13}$$

where τ_{α} is the α-particle slowing down time, S_{α} is the thermal fusion energy density delivered to the plasma per unit time, and P_{α} is the alpha particle non-escape probability.

3. ALPHA PARTICLE EFFECTS

Apart from the generation of alpha particles due to the fusion reaction (2.12) there are two other important effects to be considered: the loss of energetic alpha particles because they are on orbits which intersect the plasma boundary, and the fact that the non-escaping alpha particles do not lose their energy to the background plasma immediately but have a finite slowing down time τ_{α}, during which they thermalise. Further, the way in which the alpha particle energy is shared between the background plasma ions and electrons is a function of the plasma temperature and density, and hence changes as the plasma evolves in time.

In considering the alpha particle non-escape probability two sources of particle loss have to be taken into account, the finite gyroradii of the high energy alpha particles and the width of their banana orbits. These two effects combined lead to the following estimate for the non-escape probability P_α [15],

$$P_\alpha = \exp\left[\frac{-(4\ K\ W_\alpha m_\alpha/3)^{\frac{1}{2}}(\tfrac{1}{2} + q_a)}{eB_T a}\right] , \tag{3.1}$$

where W_α is 3.52 MeV per alpha particle, m_α is the alpha particle mass, and e is the magnitude of the electronic charge, B_T the toroidal magnetic field, a the minor radius of the device and q_a the safety factor at the plasma boundary,

$$q_a = aB_T/RB_p\ . \tag{3.2}$$

In (3.2) R is the major radius of the plasma and B_p the poloidal magnetic field. We note that estimates using (3.1) appear to be in good agreement with more detailed calculations [5].

The source term S_α appearing in (2.13) is given by

$$S_\alpha = W_\alpha\ Kn_F^2\epsilon(1 - \epsilon)P_\alpha\ \overline{\sigma v} \tag{3.3}$$

where we take $\overline{\sigma v}$ to be [7],

$$\overline{\sigma v} = \frac{3.68 \times 10^{-18}}{T_i^{2/3}} \exp(-\ 19.94/T_i^{\frac{1}{3}}) \tag{3.4}$$

The alpha particle slowing down time τ_α and the fractions of alpha energy that go to the electrons and ions, $f_{\alpha e}$ and $f_{\alpha i}$ $(= 1 - f_{\alpha e})$ respectively, are calculated on the basis of the classical theory for the slowing down of fast particles in a plasma [8]. The expressions we used in our computations were the following:

$$n_e\tau_\alpha = \frac{6.6 \times 10^{18} T_e^{3/2}}{\ell n\ \Lambda_e}\ \ell n\left\{1 + \frac{4.53 \times 10^2 n_e(2 + \epsilon)}{T_e^{3/2}\ n_z}\right\} , \tag{3.5}$$

where $\ell n \Lambda_e$ is the Coulomb logarithm and

$$f_{\alpha e} = 2x\left[\frac{1}{2x} - \frac{1}{6}\ell n\left\{\frac{1 - x^{-\frac{1}{2}} + x^{-1}}{(1 + x^{-\frac{1}{2}})^2}\right\} - \frac{1}{\sqrt{3}}\tan^{-1}[(2x^{-\frac{1}{2}} - 1)/\sqrt{3}] - \frac{1}{\sqrt{3}}\tan^{-1}(1/\sqrt{3})\right] \tag{3.6}$$

where

$$x = \frac{1.7 \times 10^{-2} T_e}{(2 + \epsilon)^{2/3}} \tag{3.7}$$

4. SOURCE FUNCTIONS FOR PLASMA ENERGY AND DENSITY

The functions that appear on the right-hand side of (2.7) are taken to be the following

S^e_Ω , ohmic heating

S^e_α , electron heating by alpha particles

S^e_Δ , electron-ion collisional transfer

S^e_{br} , bremsstrahlung radiation

S^e_{cy} , cyclotron radiation

S^e_{tr} , electron transport losses.

The ohmic heating term is taken to be

$$S^e_\Omega = 1.64 \times 10^{-10} \frac{\ell n\, \Lambda_e\, Z_{eff}\, I^2}{T_e^{3/2}\, a^4\, f_{tr}} \tag{4.1}$$

where $Z_{eff} = (n_F + 4n_\alpha)/n_e$, and the classical resistivity has been corrected to take account of the trapped particles [11],

$$f_{tr} = 1 - [1.9(r/R)^{\frac{1}{2}} - (r/R)]/(1 + \nu_e^*) \tag{4.2}$$

$$\nu_e^* = 0{\cdot}346 \times 10^{-23} (1 + Z_{eff}) (R/r)^{\frac{3}{2}} Rq\, n_e\, \ell n\, \Lambda_e / T_e^2 \ . \tag{4.3}$$

In estimating the fraction of trapped particles r is evaluated at a/2.

The source term for electron heating by alpha particles is taken as

$$S^e_\alpha = f_{\alpha e} E_\alpha (P_\alpha + \tfrac{1}{2}(1 - P_\alpha))/\tau_\alpha \,, \tag{4.4}$$

where E_α is given by (2.13) and the term $\frac{1}{2}(1 - P_\alpha)$ follows from the assumption that half the initial energy of particles escaping due to collisional diffusion during slowing down is lost to the plasma.

Electron-ion collisional transfer is taken to be

$$S^e_\Delta = \frac{2.48 \times 10^{-35} \ell n\Lambda \, n_e n_z e_i T_i (1 - T_e/T_i)}{(2 + \epsilon) T_e^{3/2}} \tag{4.5}$$

The bremsstrahlung losses are [7] ,

$$S^e_{br} = - 4.8 \times 10^{-37} Z_{eff} \, n_e^2 T_e^{\frac{1}{2}} \tag{4.6}$$

and the cyclotron radiation loss [9], [13]

$$S^e_{cy} = - 2.02 \times 10^{-10} B_T^{5/2} n_e^{\frac{1}{2}} T_e^2 R^{-\frac{1}{2}} \tag{4.7}$$

In (4.7) it is assumed that 90% of the radiation is reflected back into the plasma from the walls.

The energy losses due to electron transport are taken to be the combined effects of electron thermal conduction and convection. Introducing the electron energy confinement time τ_{Ee} we have

$$S^e_{tr} = - 1.5 \, n_e K T_e / \tau_{Ee} \,. \tag{4.8}$$

For τ_{Ee} we assume the empirical scaling of Alcator [4], specifically

$$\tau_{Ee} = C_\tau \, 10^{-21} q_a^{\frac{1}{2}} \, a^2 \, \bar{n}_e \tag{4.9}$$

where C_τ is a constant and $\bar{n}_e$ is the average electron density.

For the ion energy balance there are three terms to be considered on the right hand side of (2.8): ion heating by alpha particles, S^i_α, electron-ion collisional transfer, S^i_Δ , and ion transport losses due to thermal conduction and convection, S^i_{tr}. Explicitly we have

$$S^i_\alpha = f_{\alpha i} E_\alpha (P_\alpha + \tfrac{1}{2}(1 - P_\alpha))/\tau_\alpha \tag{4.10}$$

$$S^i_\Delta = - S^e_\Delta \tag{4.11}$$

$$S^i_{tr} = - 1.5\ n_x KT_i/\tau_{Ei} \ , \tag{4.12}$$

where we have taken the ion energy confinement time to be given by [12],

$$\tau_{Ei} = (T_e/T_i)\tau_{Ee} \ . \tag{4.13}$$

In discussing the source terms for the particle densities it is convenient to introduce the particle containment time τ_p, which we take to be given by

$$1/\tau_p = (1 - R_c)/\tau_{Ei} \tag{4.14}$$

where R_c is a recycling coefficient, $0 < R_c < 1$. Then for the diffusive loss of fuel particles we have

$$R^F_D = - n_F/\tau_p \tag{4.15}$$

In addition we must consider a source of fuel, for example by puffing in cold gas and the loss of fuel due to fusion reactions (2.12) ,

$$R^F_S = R_f - 2n_F^2 \epsilon(1 - \epsilon)\overline{\sigma v} \tag{4.16}$$

For the alpha particles there is also a loss due to diffusion which we take to be

$$R^\alpha_D = - n_\alpha/\tau_p \tag{4.17}$$

For simplicity we take the particle confinement time for alphas to be the same as for the fuel plasma, this is probably incorrect, but it is unimportant for our calculations because the density of alpha particles is so low that we are not concerned with problems of "alpha particle ash". The source of, non-escaping, alpha particles is given by

$$R^\alpha_s = n_F^2 \epsilon(1 - \epsilon)\overline{\sigma v}\ P_\alpha \tag{4.18}$$

5. THE EFFECTS OF AVERAGING OVER PROFILES

In the transport equations (2.7)-(2.11) and (2.13) n and T were taken to be homogeneous in space. It is to be expected that profile effects will be important and their consequences can be estimated by assuming reasonable profiles such as (2.4) and (2.5) and space averaging the transport equations. The equations are then formulated in terms of peak values with suitable weighting factors appearing. It can be shown that four weighting factors enter the equations,

$$C_1 = \int_0^1 (1 - y)^{3\delta/2}\, dy = 1/(3\delta/2 + 1) \tag{5.1}$$

$$C_2 = \int_0^1 (1 - y)^{\delta/2}\, dy = 1/(\delta/2 + 1) \tag{5.2}$$

$$C_3 = \int_0^1 (1 - y)^{5\delta/4}\, dy = 1/(5\delta/4 + 1) \tag{5.3}$$

$$C_4 = \int_0^1 (1 - y)^{\delta/3} \exp\{- 19.94[(1 - y)^{-\delta/3} - 1]/T_{i,o}^{\frac{1}{3}}\}dy \tag{5.4}$$

In (5.4) $T_{i,o}$ is the peak ion temperature; C_4 has to be evaluated numerically. The mean temperature, for example, is simply obtained,

$$\bar{T} = \frac{\int_0^a n(r)T(r)rdr}{\int_0^a n(r)rdr} = T_o \frac{C_1}{C_2} \cdot \tag{5.5}$$

6. NUMERICAL RESULTS AND DISCUSSION

Tables I - IV summarise the main plasma parameters in the steady state situation, which is typically achieved at about 800 ms, with a current rise time of 400 ms.

Table I for case A illustrates the effect of increasing the peakedness of the profiles and hence the current density and ohmic heating, while the electron energy confinement time is held fixed, $\tau_{Ee} = 179$ ms, and so is the mean electron density, $\bar{n}_e = 5 \times 10^{20}$. The safety factor on axis, q_o, is estimated using (2.6) and the relation of Wesson [10], that

$$\frac{q_a}{q_o} = \nu + 1 \qquad (6.1)$$

for

$$j(r) = j_o(1 - r^2/a^2)^{\nu} . \qquad (6.2)$$

q_a is fixed at 3.2. As δ is increased the alpha particle heating is increasing at a faster rate than the bremsstrahlung and transport energy losses; $C_\tau = 2.2$ was chosen for τ_{Ee} to fit the Alcator results quoted by Hugill and Sheffield, [14].

Table II illustrates the effect of arbitrarily increasing the confinement time τ_{Ee}, for case A, by increasing the numerical constant in (4.9), while the mean density is held fixed at $\bar{n}_e = 5 \times 10^{20}$ and δ is fixed at 2. The temperature naturally increases with confinement time, but the losses are still dominated by energy transport, rather than bremsstrahlung.

Table III illustrates the dependence on mean density, with $C_\tau = 2.2$ and three values of the parameter δ. The point to note here is that if the density becomes too high, $\bar{n}_e = 10 \times 10^{20}$, the temperature actually decreases due to enhanced bremsstrahlung.

Table IV gives the steady state results for the more optimistic scaling $C_\tau = 5$ and more extreme technological parameters, case B. At low densities and confinement times the losses are mainly due to conduction, which at high densities the bremsstrahlung loss is very considerable.

These results indicate that ignition is unlikely to be achieved without the use of additional heating.

APPENDIX

MACHINE PARAMETERS

CASE A

$R = 0.7$ m

$a = 0.3$ m

$I = 3$ MA

$B_T = 15$ T

With scaling parameter, C_τ specified in tables.

CASE B

$R = 0.57$ m

$a = 0.22$ m

$I = 3.3$ MA

$B_T = 15.75$ T

$C_\tau = 5.0$

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TABLE I

STEADY STATE PLASMA PARAMETERS WITH A FIXED τ_{Ee} AND VARYING PROFILE PARAMETER δ, FOR CASE A. $q_a \cong 3.2$

C_τ	2.2	2.2	2.2	2.2	2.2
δ	0	0.5	1	1.3	2
$T_{e,o}$, keV	2.08	2.98	3.69	4.05	4.79
$T_{e,o}$, keV	2.00	2.85	3.53	3.88	4.60
$\bar{n}_e \tau_E$, $10^{20} m^{-3} s$	0.938	0.939	0.937	0.936	0.934
τ_{Ee}, ms	179	179	179	179	179
q_o	3.20	1.83	1.28	1.09	0.80
β_p	0.205	0.210	0.220	0.224	0.237
β, %	0.365	0.37	0.39	0.40	0.422
S^e_{br}, MW m^{-3}	- 0.173	- 0.185	- 0.207	- 0.223	- 0.263
S^e_α, MW m^{-3}	0.008	0.012	0.025	0.035	0.0695
S^e_{tr}, MW m^{-3}	- 1.395	- 1.425	- 1.478	- 1.515	- 1.605
S^i_{tr}, MW m^{-3}	- 1.334	- 1.364	- 1.418	- 1.455	- 1.545
S^e_{cy}, MW m^{-3}	- 0.024	- 0.028	- 0.035	- 0.038	- 0.044
S_Ω, MW m^{-3}	2.86	2.93	3.05	3.14	3.32
P_α	0.695	0.695	0.695	0.695	0.695
τ_α, ms	14.70	15.00	15.80	16.30	17.40
$n_{e,o}$, 10^{20} m^{-3}	5.00	6.25	7.50	8.25	10.00
$\bar{n}_e$, 10^{20} m^{-3}	5.0	5.0	5.0	5.0	5.0

TABLE II

STEADY STATE PLASMA PARAMETERS WITH C_τ VARYING AND δ FIXED, FOR CASE A. $q_a = 3.2$

C_τ	2.2	3.2	3.73
τ_{Ee}, ms	179	254	300
$T_{e,o}$, keV	4.79	5.49	5.86
$T_{i,o}$, keV	4.60	5.30	5.66
$\bar{n}_e \tau_E$, $10^{20} m^{-3} s$	0.934	1.31	1.55
q_o	0.80	0.80	0.80
β_p	0.237	0.273	0.292
β , %	0.422	0.486	0.520
S^e_{br} , MW m^{-3}	- 0.263	- 0.281	- 0.291
S^e_α , MW m^{-3}	0.0695	0.111	0.137
S^e_{tr} , MW m^{-3}	- 1.605	- 1.29	- 1.17
S^i_{tr} , MW m^{-3}	- 1.545	- 1.253	- 1.131
S^e_{cy} , MW m^{-3}	- 0.044	- 0.057	- 0.065
S_Ω , MW m^{-3}	3.32	2.74	2.50
τ_α , ms	17.4	20.4	22.00
$n_{e,o}$, 10^{20} m^{-3}	10	10	10
$\bar{n}_e$, 10^{20} m^{-3}	5	5	5
δ	2	2	2

TABLE III

STEADY STATE PLASMA PARAMETERS WITH VARYING DENSITY AND δ, FOR CASE A. $C_\tau = 2.2$

$q_a = 3.2$

	$\delta = 1$			$\delta = 1.3$			$\delta = 2$		
$\bar{n}_e$, $10^{20} m^{-3}$	2.5	5	10	2.5	5	10	2.5	5	10
$T_{e,o}$, keV	3.97	3.69	3.32	4.36	4.05	3.65	5.14	4.79	4.31
$T_{i,o}$, keV	3.37	3.53	3.28	3.72	3.88	3.61	4.42	4.60	4.28
$\bar{n}_e \tau_E$, $10^{20} m^{-3} s$	0.264	0.937	3.62	0.263	0.936	3.62	0.260	0.934	3.61
τ_{Ee} , ms	89.6	179	359	89.6	179	359	89.6	179	359
q_o	1.28	1.28	1.28	1.09	1.09	1.09	0.80	0.80	0.80
β_p	0.11	0.22	0.40	0.114	0.224	0.409	0.121	0.237	0.434
β , %	0.20	0.39	0.70	0.202	0.398	0.728	0.220	0.422	0.77
S^e_{br} , MW m^{-3}	- 0.0538	- 0.207	- 0.707	- 0.0578	- 0.223	- 0.846	- 0.068	- 0.263	- 0.997
S^e_α , MW m^{-3}	0.0052	- 0.025	0.0758	0.0076	0.035	0.109	0.015	0.0695	0.216
S^e_{tr} , MW m^{-3}	- 1.590	- 1.484	- 1.320	- 1.635	- 1.515	- 1.370	- 1.725	- 1.605	- 1.401
S^i_{tr} , MW m^{-3}	- 1.35	- 1.418	- 1.316	- 1.425	- 1.455	- 1.353	- 1.485	- 1.545	- 1.392
S^i_{cy} , MW m^{-3}	- 0.028	- 0.035	- 0.040	- 0.031	- 0.038	- 0.043	- 0.035	- 0.044	- 0.050
S_Ω , MW m^{-3}	2.83	3.05	3.41	2.90	3.14	3.51	3.08	3.32	3.72
P_α	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695
τ_α , ms	33.0	15.8	7.00	34.7	16.3	7.3	37.00	17.4	7.9
$n_{e,o}$, $10^{20} m^{-3}$	3.75	7.5	15	4.13	8.25	16.5	5.20	10.00	20.00

TABLE IV

STEADY STATE PLASMA PARAMETERS CORRESPONDING TO THE MACHINE PARAMETERS FOR CASE B, FOR VARYING DENSITY, $C_\tau = 5$ AND $\delta = 1$

$\bar{n}_e$, 10^{20} m^{-3}	3.33	6.67	13.3	26.7
$n_{e,o}$, 10^{20} m^{-3}	5	10	20	40
$T_{e,o}$, keV	6.87	6.40	5.93	4.42
$T_{i,o}$, keV	5.63	6.05	5.85	4.41
$\bar{n}_e\tau_E$, 10^{20} $m^{-3}s$	0.467	1.62	6.2	24.5
τ_{Ee} , ms	115	230	460	920
q_o, q_a	0.8, 2.03	0.8, 2.03	0.8, 2.03	0.8, 2.03
β_{pol}	0.113	0.225	0.426	0.629
β , %	0.4	0.8	1.54	2.3
S^e_{br} , MW m^{-3}	- 0.126	- 0.486	- 1.88	- 6.48
S^e_α , MW m^{-3}	0.057	0.285	1.03	1.64
S^i_α , MW m^{-3}	0.004	0.017	0.06	0.07
S^e_{tr} , MW m^{-3}	- 2.87	- 2.68	- 2.48	- 1.85
S^i_{tr} , MW m^{-3}	- 1.93	- 2.39	- 2.41	- 1.84
S^i_{cy} , MW m^{-3}	- 0.123	- 0.152	- 0.184	- 0.145
S_Ω , MW m^{-3}	4.99	5.41	5.88	8.62
P_α , MW m^{-3}	0.725	0.725	0.725	0.725
τ_α , ms	48.3	22.8	11.0	3.87

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