POICOU: A Point Plasma Code Including Profile Effects for Tokamak Power Reactors

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FUSION TECHNOLOGY INSTITUTE

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I. Introduction

Although a point plasma model contains much less information than a fluid description, it is more convenient to use in carrying out preliminary fusion power reactor conceptual designs. Point computer codes require less computer time and are easier to manipulate, thus they can be used to survey over a large range of possible reactor operating parameters. The plasma density and temperature profiles assumed in getting the point kinetic equations can have an impact on the solutions obtained from solving those equations.[1] Physically, this is due to the fact that plasma energy balance depends on how the participating particles are distributed in configuration space as well as in velocity space. We report here a time independent point computer code for tokamak power reactors which includes effects of different particle density and temperature profiles. It was developed from a numerical model in our previous work.[2] As an illustration, we apply it to study the gas blanket power reactor[5] by assuming it has a flat density profile and a bell-shaped temperature distribution, and will see that while the average plasma density and temperature may remain the same compared with the one having both bell-shaped profiles, the thermal power output can drop by a factor of as high as 25%.

II. Numerical Model

The plasma density and temperature are assumed to vary radially according to

$$n(r) = n_o\left(1 - \frac{r^2}{a^2}\right)^x \qquad (1)$$

$$T(r) = T_o\left(1 - \frac{r^2}{a^2}\right)^y$$

the average plasma density and temperature are defined as

$$\bar{n} = \frac{2}{a^2} \int_o^a n(r)\, r\, dr$$

$$\bar{T} = \frac{\int_o^a n(r)T(r)\, r\, dr}{\int_o^a n(r)\, r\, dr}$$

The point energy balance equations are then obtained from plasma energy transport equations as follows:

(1) For the conduction and convection terms

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\, n(r) X \frac{\partial T(r)}{\partial r}\right) \rightarrow \frac{3}{2}\frac{\bar{n}\bar{T}}{\tau_c}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\, D \frac{\partial n(r)}{\partial r} \frac{3}{2} T(r)\right) \rightarrow \frac{3}{2}\frac{\bar{n}\bar{T}}{\tau_p}$$

where τ_c = energy conduction time = $\dfrac{L_c^{\,2}}{4X(\bar{n},\bar{T})}$ (2)

τ_p = particle confinement time = $\dfrac{L_p^{\,2}}{4D(\bar{n},\bar{T})}$

In these expressions, L_j is the characteristic length for the particular physical process j; for parabolic radial dependence it is taken to be the plasma minor radius a, and for non-parabolic profiles, since

$$< \frac{n}{\frac{dn}{dr}} > \propto \frac{a}{x}, \qquad < \frac{T}{\frac{dT}{dr}} > \propto \frac{a}{y}$$

L_p and L_c are taken to be $\frac{a}{x}$ and $\frac{a}{y}$. If the profile is flat, L is simply assumed to be some large distance. $X(\bar{n},\bar{T})$ and $D(\bar{n},\bar{T})$ are plasma thermal diffusivity and diffusion coefficient and are assumed to follow trapped particle scalings.[3]

(2) The equilibration, radiation and fusion terms are evaluated by integrating over the plasma volume with the assumed profiles.

(3) Alpha particles from fusion products are divided into two energy groups: fast and thermal with averaged energies given by (see ref. (4))

$$\bar{E}_{\alpha f} = \frac{\frac{3}{2} E_\alpha F_{\alpha e}}{\ln[1 + (\frac{E_\alpha}{E_{crit}})^{\frac{3}{2}}]}$$

$$\bar{E}_{\alpha t} = \frac{3}{2} \bar{T}_i$$

where E_α : alpha particle energy from D-T fusion = 3.52 MeV

$F_{\alpha e}$: fraction of alpha energy given to electrons

$$F_{\alpha e} = 1 - \frac{1}{3} \frac{E_{crit}}{E_\alpha} \{\ln [\frac{E_{crit} - E_{crit}^{1/2} E_\alpha^{1/2} + E_\alpha}{E_{crit} + 2E_{crit}^{1/2} E_\alpha^{1/2} + E_\alpha}] + 2\sqrt{3} \tan^{-1} [\frac{2E_\alpha^{1/2} - E_{crit}^{1/2}}{\sqrt{3}\, E_{crit}^{1/2}} + \frac{\sqrt{3}}{3} \pi]\} \qquad (3)$$

$$E_{crit} = 14.8\, A_\alpha\, \bar{T}_e \left(\frac{1}{\bar{n}_e \ell n\Lambda_e} \sum_j \frac{\bar{n}_j Z_j^2 \ell n\Lambda_j}{A_j}\right)^{2/3}$$

$\sum_j$ is over the plasma ion species, and

A_j, Z_j are atomic mass and atomic number for the j species respectively.

Alpha particle density in each group is obtained by solving the steady state coupled equations:

$$\frac{d\bar{n}_{\alpha f}}{dt} = S_\alpha - \frac{\bar{n}_{\alpha f}}{\tau_{\alpha SD}} - \frac{\bar{n}_{\alpha f}}{\tau_{\alpha fP}}$$

$$\frac{d\bar{n}_{\alpha T}}{dt} = \frac{\bar{n}_{\alpha f}}{\tau_{\alpha SD}} - \frac{\bar{n}_{\alpha T}}{\tau_{\alpha TP}}$$

where S_α : fast alpha source from fusion

$\tau_{\alpha SD}$: fast alpha particle thermalization time

$$\tau_{\alpha SD} = \frac{6.67 \times 10^{12}\, \bar{T}_e^{3/2}}{\bar{n}_e\, \ell n\Lambda_e} \ell n\left(1 + \left(\frac{E_\alpha}{E_{crit}}\right)^{3/2}\right) \quad \text{(sec)}$$

$\bar{n}_e$ is in cm^{-3}, $\bar{T}_e$ is in KeV.

$\tau_{\alpha fP}$, $\tau_{\alpha TP}$: fast and thermal alpha particle confinement time; for simplicity they are taken to be equal to each other and equal to

$$\tau_{\alpha fP} = \tau_{\alpha TP} = C\, \tau_{Pi}$$

τ_{Pi} : plasma ion particle confinement time (see equation (2))

C : correction factor due to ion density and temperature profile effects

$$C = \begin{cases} 1 & \text{if} \quad x \geq y \\ \frac{x^2}{y^2} & \text{if} \quad x < y \end{cases} \qquad \text{(see equation (1))}$$

(4) If the reactor is operated in the driven mode, the injected beam particles are treated similarly as alphas by dividing them into fast and thermal groups.

We then obtain the ion and electron energy balance equations as follows:

$$\frac{d}{dt}\left(\frac{3}{2}(\bar{n}_i + \bar{n}_{\alpha t})\bar{T}_i\right) = \frac{P_{inj}\ F_b\ F_{bi}}{V} + \frac{P_{inj}\ F_{tct}}{E_b\ V}\ X_\alpha E_\alpha F_{\alpha i}$$

$$+ F_{tp}(1 - F_{tp})\ \overline{n_i^{\,2}<6V>_{dt}}\ X_\alpha E_\alpha F_{\alpha i} - \frac{3}{2}\bar{n}_i\bar{T}_i\left(\frac{1}{\tau_{pi}} + \frac{1}{\tau_{ci}}\right)$$

$$- \frac{3}{2}\bar{n}_{\alpha t}\bar{T}_i\left(\frac{1}{\tau_{P\alpha}} + \frac{1}{\tau_{c\alpha}}\right) - 4.38 \times 10^{-28}\ C_1\ \frac{(\bar{T}_i - \bar{T}_e)\ \bar{n}_i\bar{n}_e}{A_i\ \bar{T}_e^{\,3/2}}$$

$$+ \frac{3}{2}\frac{\bar{n}_{\alpha f}\bar{T}_i}{\tau_{\alpha SD}} \qquad (\text{watt/cm}^3) \qquad (4)$$

$$\frac{d}{dt}\left[\frac{3}{2}\bar{n}_e\bar{T}_e\right] = \frac{P_{inj}F_bF_{be}}{V} + \frac{P_{inj}F_{tct}}{E_bV}\ X_\alpha E_\alpha F_{\alpha e}$$

$$+ F_{tp}(1 - F_{tp})\overline{n_i^{\,2}<6V>_{dt}}\ X_\alpha E_\alpha F_{\alpha e} - \frac{3}{2}\bar{n}_e\bar{T}_e\left(\frac{1}{\tau_{pe}} + \frac{1}{\tau_{ce}}\right)$$

$$+ 4.38 \times 10^{-28}\ C_1\ \frac{(\bar{T}_i - \bar{T}_e)\ \bar{n}_i\bar{n}_e}{A_i\ \bar{T}_e^{\,3/2}} - 4.8 \times 10^{-31}\ C_2\bar{n}_e^{\,2}\bar{T}_e^{\,1/2}Z_{eff}$$

$$- 3.20 \times 10^{-13}\ C_3\ (1 - .0305\ A)^3\left(\frac{\bar{n}_e}{a}\right)^{.5} B_t^{\,2.5}\ \bar{T}_e^{\,2.1} \qquad (5)$$

$$- P_{zr} \qquad (\text{watt/cm}^3)$$

where

P_{inj} : injected beam power in watts

E_b : beam energy in KeV

$F_b = 1 - \frac{\bar{T}_i}{E_b}$

$E_\alpha = 3.52 \times 10^3$ KeV

F_{bi}, F_{be}: fraction of beam energy given to ions and electrons while slowing down (see equation (3))

V : plasma volume in cm^3

F_{tct} : fraction of beam particles undergoing fusion while slowing down

X_α : fraction of born fast alphas which are retained in the plasma

F_{tp} : tritium fraction in plasma

$F_{\alpha i}$, $F_{\alpha e}$: fraction of alpha energy given to ions and electrons (see equation (3))

$\overline{n_i^2 \langle 6V \rangle_{dt}}$: profile average of n_i^2 and $\langle 6V \rangle_{dt}$

For 7. KeV < T < 30. KeV

$$\langle 6V \rangle_{dt} = (-2.06 + .314T) \times 10^{-16} \frac{cm^3}{sec}$$

$$\overline{n_i^2 \langle 6V \rangle_{dt}} = (-2.06\, U_1 + .314\, U_2 \bar{T}_i)\bar{n}_i^2 \times 10^{-16}$$

U_1, U_2 : correction factors due to profile effects

A_i : atomic mass of ions

A : aspect ratio

B_t : on axis toroidal magnetic field in Tesla

a : plasma minor radius in meter

C_1, C_2, C_3 : correction due to profile effects

$\bar{n}$, $\bar{T}$: average plasma density and temperature in cm^{-3} and KeV respectively

τ_p, τ_c : particle confinement time and energy conduction time in sec (see equation (2))

$$Z_{eff} = \frac{\bar{n}_i}{\bar{n}_e} + \frac{\bar{n}_z}{\bar{n}_e} Z^2$$

$\bar{n}_z$, Z : impurity density and atomic number

P_{zr} : impurity line and recombination radiation loss term

$$P_{zr} = 1.82 \times 10^{-32} C_4 Z^4 \bar{n}_z \bar{n}_e \bar{T}_e^{-1/2} + 4.13 \times 10^{-34} C_5 Z^6 \bar{n}_z \bar{n}_e \bar{T}_e^{-3/2}$$

At low temperature, it is replaced by Hinnov's formula

$$P_{zr} = 1.2 \times 10^{-26}\ C_6 \bar{n}_z \bar{n}_e$$

C_4, C_5, C_6 : profile correction factors

Ion and electron density are then obtained by fixing poloidal β_p and assuming plasma is quasi-neutral.

$$\beta_p = 1.602 \times 10^{-10} \frac{\left(\frac{2}{3}\bar{n}_{bf}\bar{E}_{bf} + \frac{2}{3}\bar{n}_{\alpha f}\bar{E}_{\alpha f} + \bar{n}_{\alpha t}\bar{T}_i + \bar{n}_i\bar{T}_i + \bar{n}_e\bar{T}_e\right)}{\frac{B_p^2}{2\mu_o}} \qquad (6)$$

where $\bar{n}_{bf}$: average beam particle density in fast group

$\bar{E}_{bf}$: average beam particle energy in fast group

B_p : poloidal magnetic field in Tesla

$$\bar{n}_e = \bar{n}_i + 2\bar{n}_\alpha + Z\bar{n}_z \qquad (7)$$

Our steady state point kinetic model is based on these four coupled equations (4-7). They are used to solve for $\bar{T}_i$, $\bar{T}_e$, $\bar{n}_i$, $\bar{n}_e$ for a given input set of parameters using implicit looping newton's method.

III. An Application

In this section we use the previously developed point model to study the gas blanket reactor. In Table 1 we compare the solution obtained from assuming a uniform density distribution with one assuming a parabolic density distribution, both are having same parabolic temperature profiles and identical other input parameters. Since the solution for flat density distribution is not very sensitive to the particle confinement time, τ_p, for simplicity it is taken to be ten times that of the parabolic density distribution case. First, we note that although the machine size is relatively small (R = 5 m, A = 4) comparing with UWMAK I, II and III,

Table 1: Comparison Between Solutions Obtained for Flat Density Profile and Parabolic Density Profile

	Flat Density Profile	Parabolic Case
P_T	1819 MW	2596 MW
$\bar{n}e$, $\frac{\bar{n}_{D+T}}{\bar{n}_e}$	2.16×10^{14} cm^{-3}, .97	2.20×10^{14}, .95
$\bar{T}i$, $\bar{T}e$	14.2 KeV, 15.6 KeV	13.1 KeV, 15.2 KeV
βt, βp	7.7%, 4.0	7.7%, 4.0
Ip, q(a)	6.94 MA, 2.40	6.94 MA, 2.40
BT	6.0 T	6.0 T
R, a, S	5 m, 1.25 m, 1.33	5 m, 1.25 m, 1.33

it can be ignited without much difficulty even with trapped-particle transport scaling laws using a moderate on axis toroidal magnetic field of 6 Tesla. Secondly, although the temperature and density in the two cases are roughly equal, the output thermal power for flat density case is dropped by a factor of almost 30%.Comparing with the parabolic case, this is due mostly to the profile effect because $\int_{vol} ni^2 <6v> d\bar{r} \propto c_1 \int_{vol} ni^2 d\bar{r} + c_2 \int_{vol} ni^2 Ti\, d\bar{r}, c_1 = - 2.06,\ c_2 = .314$, for flat density profile $<ni^2> = \bar{n}i^2,\ <ni^2Ti> = \bar{n}i^2\ \bar{T}i$ while for the parabolic density distribution case $<ni^2> = \frac{4}{3}\bar{n}i^2,\ <ni^2Ti> = \frac{3}{2}\bar{n}i^2\ \bar{T}i$.

In Figure 1 we plot $\beta p = \frac{\sum_j \bar{n}_j \bar{T}_j}{\frac{Bp^2}{2\mu o}}$ as a function of electron density for equilibrium ion and electron temperature $\bar{T}_i = 14.2$ KeV, $\bar{T}_e = 15.6$ KeV. The lower curve gives the contribution of alpha particles to plasma pressure which is roughly 10% of the total plasma pressure. In Figure 2 we show the ion energy balance varying as function of ion temperature for a fixed ion to electron temperature ratio $\frac{Ti}{Te} = .91$ corresponding to that at equilibrium. The intersection between the ion energy gain and ion energy loss curves gives the solution; as can be seen from the graph, the equilibrium is thermally stable. In Figure 3 we show electron energy balance varying as function of electron temperature, also for the same equilibrium ion temperature to electron temperature ratio $\frac{Ti}{Te} = .91$.

There are two intersecting points but only the upper one at T_e = 15.6 KeV satisfying both ion and electron energy balance equations corresponds to the real solution, as is shown; it is also thermally stable. In both Figures 2 and 3, the average electron density is $\bar{n}_e = 2.16 \times 10^{14} cm^{-3}$. In all three figures, the plasma density profile and temperature profile are flat and parabolic respectively; other parameters are as given in Table 1. Finally, we note that this solution lies closely to the ion temperature range approximately 15 KeV which has optimim power density for a βt limited D-T reactor.

Acknowledgement

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References

1. J. Kesner, R. W. Conn, Nuclear Fusion 16 (1976), 397.

2. J. Kesner, "Space and Time Code," (unpublished); J. Kesner, R. W. Conn, Nuclear Fusion 15 (1975), 775.

3. S. O. Dean, et al., "Status and Objective of Tokamak System for Fusion Research."

4. W. Houlberg, UWFDM-103.

5. F. Engelmann, et al., Comments on Plasma Physics, 3 (77), 63.

Appendix

Structure, Input and Output Format of POICOU

1. Structure

There are eight major routines in POICOU and these are discussed briefly below:

PMAIN: inputing and outputing, solve electron energy balance equation using Newton's method.

PBETAP, PTIEQT, TEQTN: evaluate terms in poloidal beta equation, ion energy equation and electron energy equation.

TIEQTN, BETAEQ: solve ion energy equation and poloidal beta equation by Newton's method.

SCALE: calculate particle confinement time, electron and ion energy conduction time using trapped-particles scalings.

TCT: calculate fraction of injected beam undergoing fusion while slowing down.

2. Input and Output

Inputs to POICOU are free format of the following form:

DBM TAN ITRANP EDGET EDGED FATDTP

KSET MTCT BCONV TCONV

RMAJ RMIN XHIWID BETAP BETAT

BT FTB FTP Z XZ AZ

XALPH EFUS WB PINJ

DENGES TGES TSTEP NSTEP

These terms are explained below:

DBM: $n_j = n_{jo} \left(1 - \frac{r^2}{a^2}\right)^{DBM}$

TAN: $T_j = T_{jo} \left(1 - \frac{r^2}{a^2}\right)^{TAN}$

ITRANP: 0 or 1 for using average or edge temperature and density when evaluating transport coefficients.

EDGET, EDGED: no effect if ITRANP = 0, if ITRANP = 1 then evaluate transport coefficients using edge temperature = average temperature x EDGET, edge density = average density x EDGED.

FATDTP: if DBM = 0, τp = FATDTP x τp of parabolic.

KSET: number of retrials for driven reactor, for each new trial Pinj = 1.1 x Pinj old.

MTCT: 1 or 0, corresponding to whether or not tritium ion fraction is to be readjusted due to deuterium beam injected on cold tritium target. This is for driven reactors.

BCONV, TCONV: poloidal beta and particle energy equations converging criteria.

RMAJ, RMIN: plasma major and minor radius in m.

XHIWID: plasma height to width ratio (1 corresponding to circular plasma).

BETAP, BETAT: poloidal and toroidal beta.

BT: on axis toroidal magnetic field in Tesla.

FTB, FTP: fraction of tritium in beam and plasma.

Z, XZ, AZ: impurity atomic number, fraction and atomic weight.

XALPH: fraction of born alphas contained within the plasma chamber.

EFUS: energy released per fusion event in MEV.

WB, PINJ: injected beam particle energy in KEV and beam power in watts, respectively.

DENGES, TGES: initial particle density and temperature guess in cm^{-3} and KEV, respectively.

TSTEP, NSTEP: if the initial guess is bad, the code will retry NSTEP times with each new initial temperature guess = old temperature guess + TSTEP (KEV).

A typical input and output stream of POICOU is shown at the end. POICOU first summarized the input data, then gives various parameters corresponding to the found solution. Some of the major terms are explained below:

TAUSDA, TAUPA: alpha slowing down time and confinement time.

TAVENG: plasma energy confinement time = $\frac{\sum_j \bar{n}_j \bar{T}_j}{Pinj+P\alpha}$.

TAUP: particle confinement time.

TAUXE, TAUXI: electron and ion energy conduction time.

MODE: 1 pseudo-classical scaling.

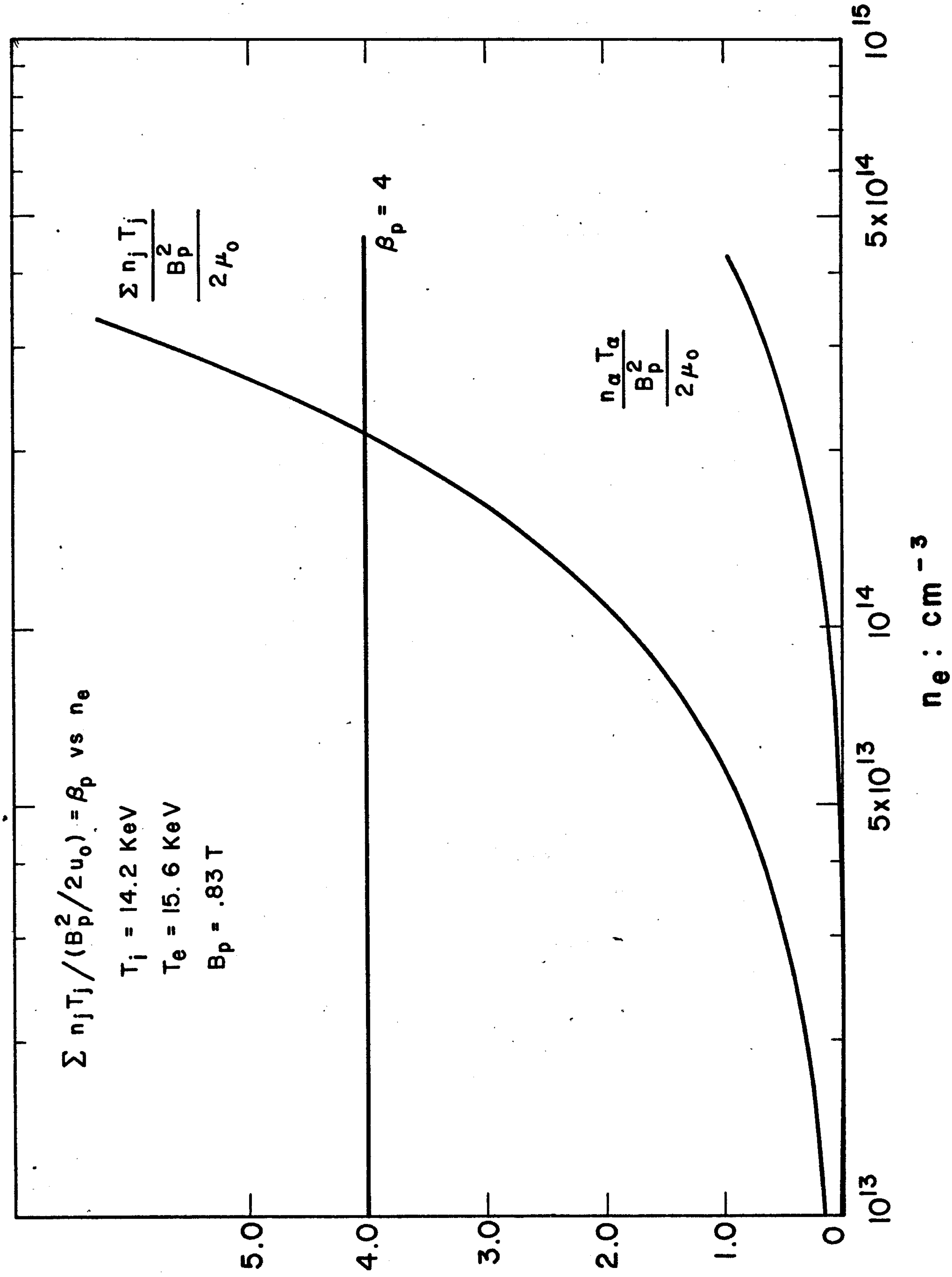
2,3 high and low collisionality trapped-electrons scaling.

4 trapped-ions scaling.

FRTBRN: fractional burn-up of plasma.

PALPMW: alpha particles power.

```
0. 1. 0 1. 1. 10.
0 0 1.E-3 1.E-3
5. 1.25 1.6 4. .077
6. .5 .5 26. 0. 55.
1. 20. 0. 0.
1.E14 30. 2. 1
 DENSITY=DENMAX*(1.-(R/RMIN)**2)**DBM,     DBM=   .0000
 TJ      =TJMAX *(1.-(R/RMIN)**2)**TAN,     TAN=  1.0000
 MTCT        =          0          KSET         =          0          ITRANP      =          0
 EDGED       =     1.0000          EDGET        =     1.0000          FAIDTP      =    10.0000
 RMIN(M)     =     1.2500          RMAJ(M)      =     5.0000          XHIWID      =     1.6000
 S           =     1.3342          AREA(M2)     =   329.1924          VOLUME(M3)=   246.7401
 A           =     4.0000          BT(T)        =     6.0000          BP(T)       =      .8325
 BETAT       =      .0770          BETAP        =     4.0000          Q           =     2.4040
 CUR(MA)     =     6.9416          AP           =     2.5000          NI/NE       =     1.0000
 PINJ(W)     =   .0000             WB(KEV)      =      .0000          AB          =     2.5000
 Z           =    26.0000          NZ/NE        =      .0000          AZ          =    55.0000
 ***** THIS IS AN IGNITION MACHINE *****
      FUSION ENERGY          NEUTRON WALL LOADING        THERMAL POWER            POWER DENSITY
           KEV                     MW/M2                      MW                       MW/M3
      17600.000                    4.025                  1819.279                     7.373
      20000.000                    4.025                  2067.363                     8.379
 TI(KEV)     =    14.1768          TE(KEV)      =    15.5643          NE(CM-3)   =  .2160+15
 BETAP       =     4.0007          BETAT        =      .0770          NTAU(S-CM-3)=  .2572+15
 TAUSDA(S)   =      .2632          TAUENG(S)    =     1.0310          MODE        =          4
 TAUP(S)     =    13.1018          TAUXE(S)     =     1.3102          TAUXI(S)    =     1.3102
 NI/NE       =      .9683          XALPHA       =     1.0000          NA/NE       =      .0159
 FTP         =      .5000          FTB          =      .5000          FRTBRN      =      .0328
 FALPMW(MW)=   363.8558            TAUPA(S)     =     1.3102          XLOGLM      =    21.4395
 TERMS OF ION ENERGY EQUATION IN WATT/CM3:
 BEAM INJ    =      .0000          BIM FUSION=        .0000          PASMA FUS =       .3461
 THERMAL     =    -.6064           ELN-ION      =      .2529          TERMA ALPA=        .0074
 THERMA BIM=        .0000          TISUM        =      .0000
 TERMS OF ELECTRON ENERGY EQUATION IN WATT/CM3 :
 BIM INJ     =      .0000          BIM FUSION=        .0000          PASMA FUS =      1.1285
 THERMAL     =    -.6793           ION-ELN      =    -.2529          BREMSS      =    -.0859
 SYNC RAD    =    -.1105           Z RECB       =      .0000          Z RAD       =      .0000
 Z LINE RAD=        .0000          TESUM        =      .0009
 TERMS OF BETAP EQUATION :
 BEAM ALPHA=        .0000          FAST BEAM =        .0000          ION-ELN     =     3.6760
 PASMA ALPA=        .3248
 %%%%%%%%%%%%%%%      DONE      %%%%%%%%%%%%%%%%%%
 %%%%%%%%%%%%%%%      BYE, BYE   ------------
```



$\Sigma\, n_j T_j / (B_p^2 / 2u_o) = \beta_p$ vs n_e
T_i = 14.2 KeV
T_e = 15.6 KeV
B_p = .83 T
$\frac{\Sigma\, n_j T_j}{B_p^2 / 2\mu_o}$
$\beta_p = 4$
$\frac{n_\alpha T_\alpha}{B_p^2 / 2\mu_o}$
5.0
4.0
3.0
2.0
1.0
0
10^{13}
5×10^{13}
10^{14}
5×10^{14}
10^{15}
n_e : cm^{-3}

FIG. I

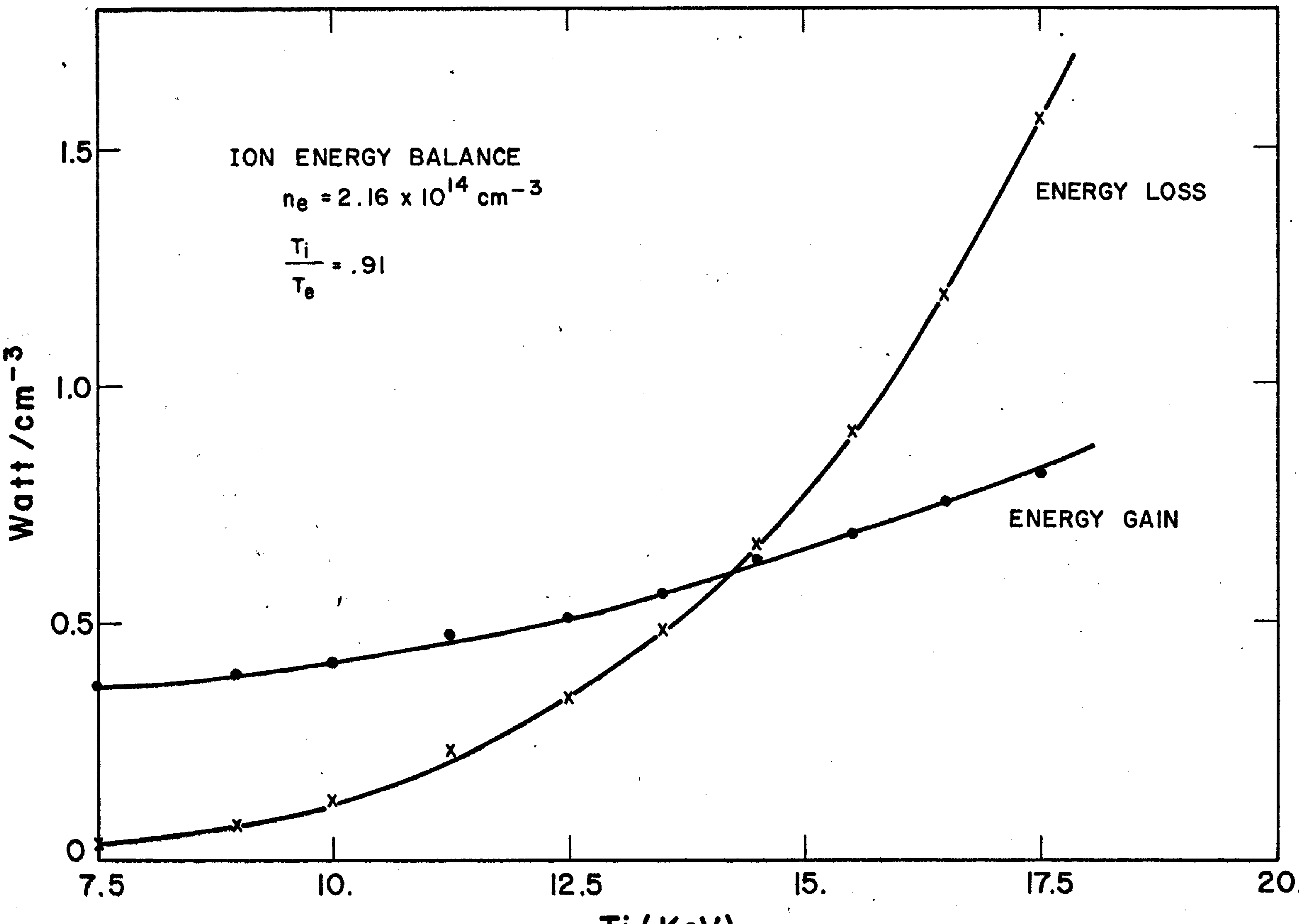

ION ENERGY BALANCE
$n_e = 2.16 \times 10^{14}\ cm^{-3}$
$\frac{T_i}{T_e} = .91$
ENERGY LOSS
ENERGY GAIN
Watt /cm^{-3}
1.5
1.0
0.5
0
7.5
10.
12.5
15.
17.5
20.
Ti (KeV)

FIG. 2

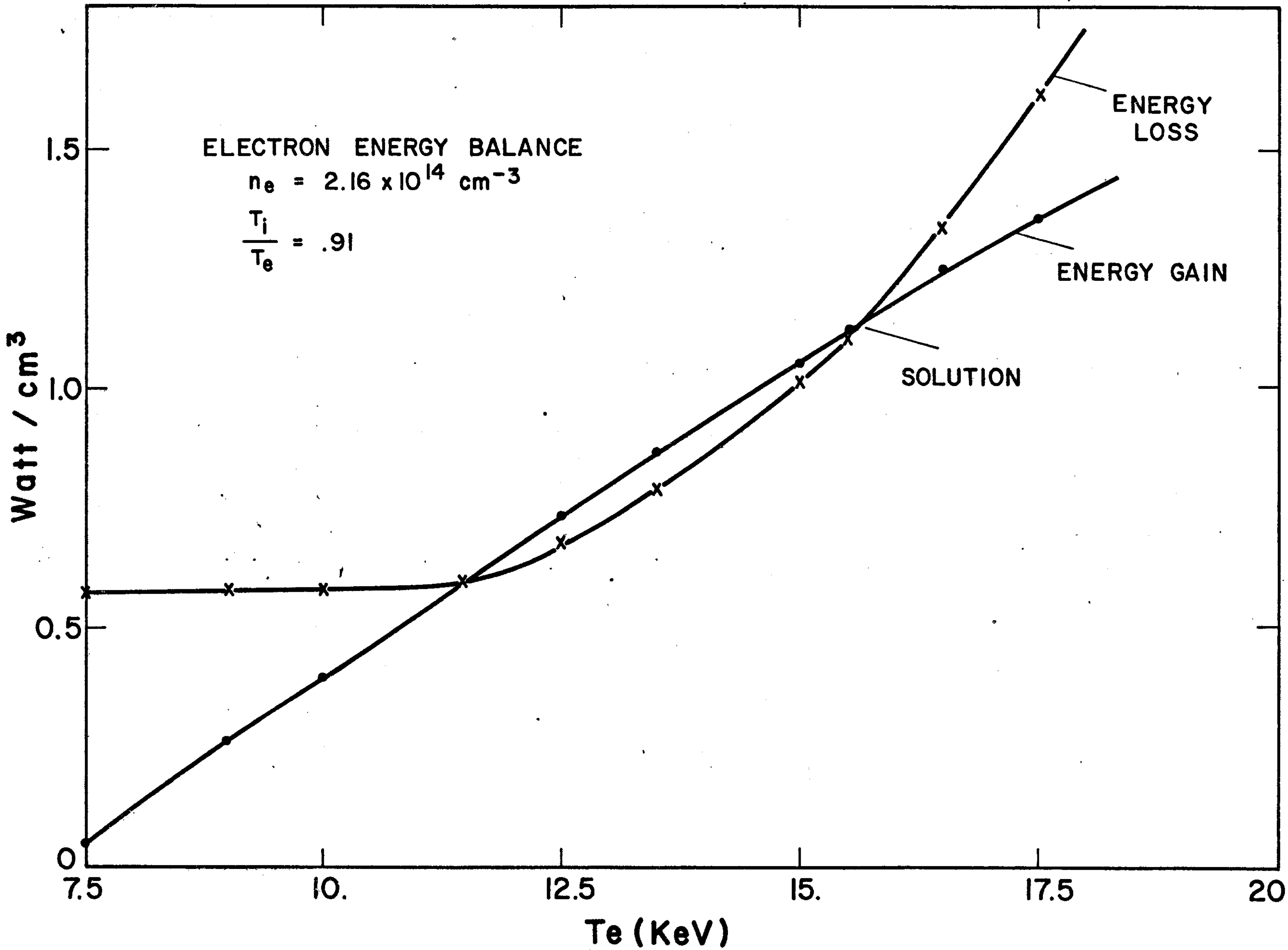

ELECTRON ENERGY BALANCE
$n_e = 2.16 \times 10^{14}\ cm^{-3}$
$\frac{T_i}{T_e} = .91$
ENERGY LOSS
ENERGY GAIN
SOLUTION
1.5
1.0
0.5
0
Watt / cm^3
7.5
10.
12.5
15.
17.5
20.
Te (KeV)

FIG. 3