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LOW-ASPECT-RATIO TORSATRON REACTORS AND ATF-II STUDIES

CONF-861175--3- Vugraphs

CONF-861175--3-Vugraphs

DE87 005506

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INTERNATIONAL STELLARATOR-
HELIOTRON WORKSHOP
KYOTO, JAPAN NOVEMBER 25-28, 1986

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MASTER

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TOPICS

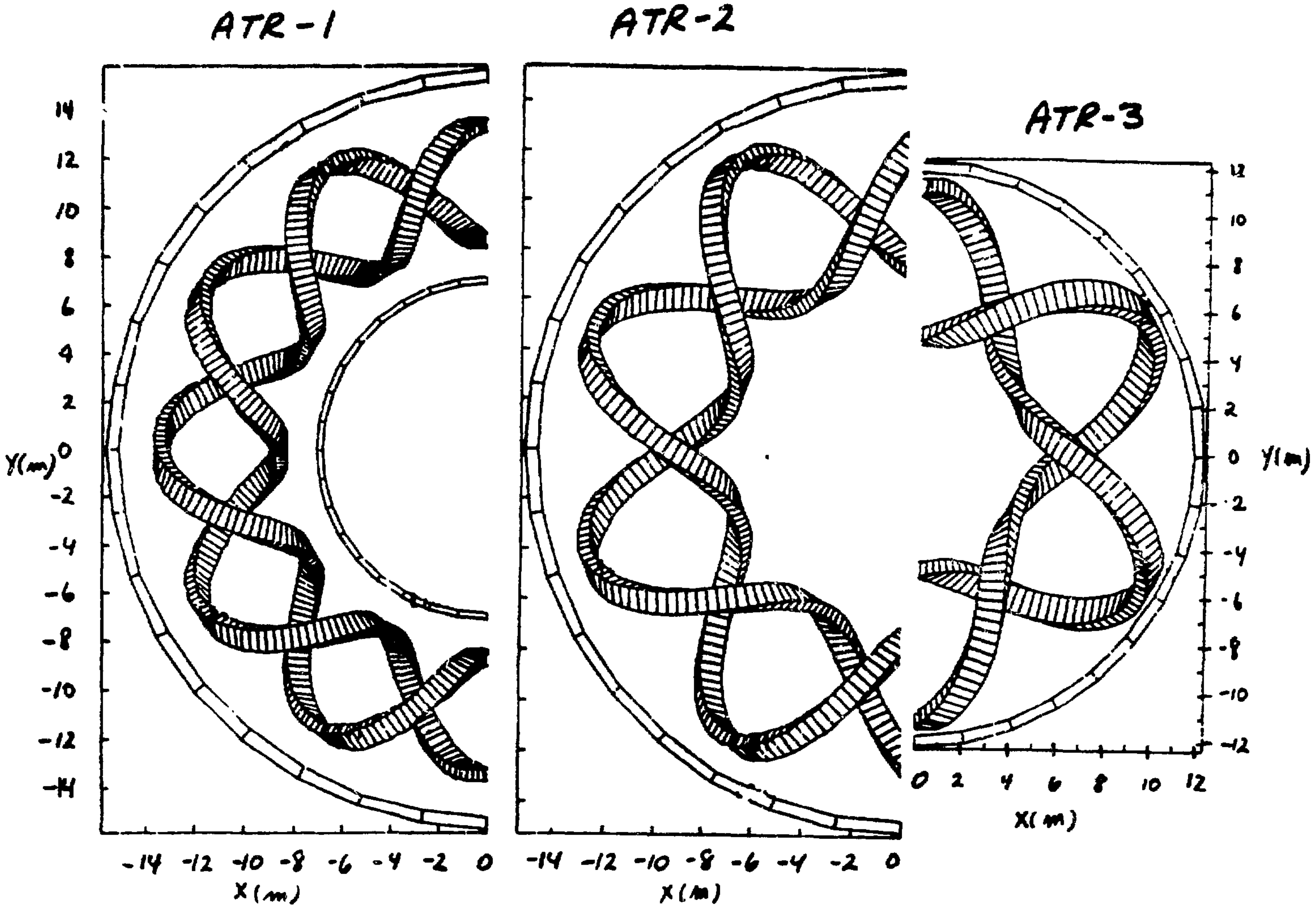
- Low R/a Approach
- Low R/a Torsatrons
- Reactor Configuration
- Key Physics Issues
- Reactor Performance
- D–T Burners
- ATF–II Studies

LOW $R/\bar{a}$ TORSATRON APPROACH

- The most developed reactor concepts (Heliotron–H, ASRA6C) have $R = 20 - 25\ m$, $R/\bar{a} \simeq 12.4$, and $R/r_c = 4.4 - 6.6$.
- ORNL studies have looked at reactors 1/2 – 1/3 this size in order to extent the options available for an attractive reactor.
- The cases considered have $R = 8 - 11\ m$. $R/\bar{a} = 3.9 - 7.8$, and $R/r_c = 2.5 - 4.5$.
- The potential advantages are
  - smaller size, weight, and cost
  - smaller size of components
  - better access for fabrication, assembly, and maintenance
  - higher power density

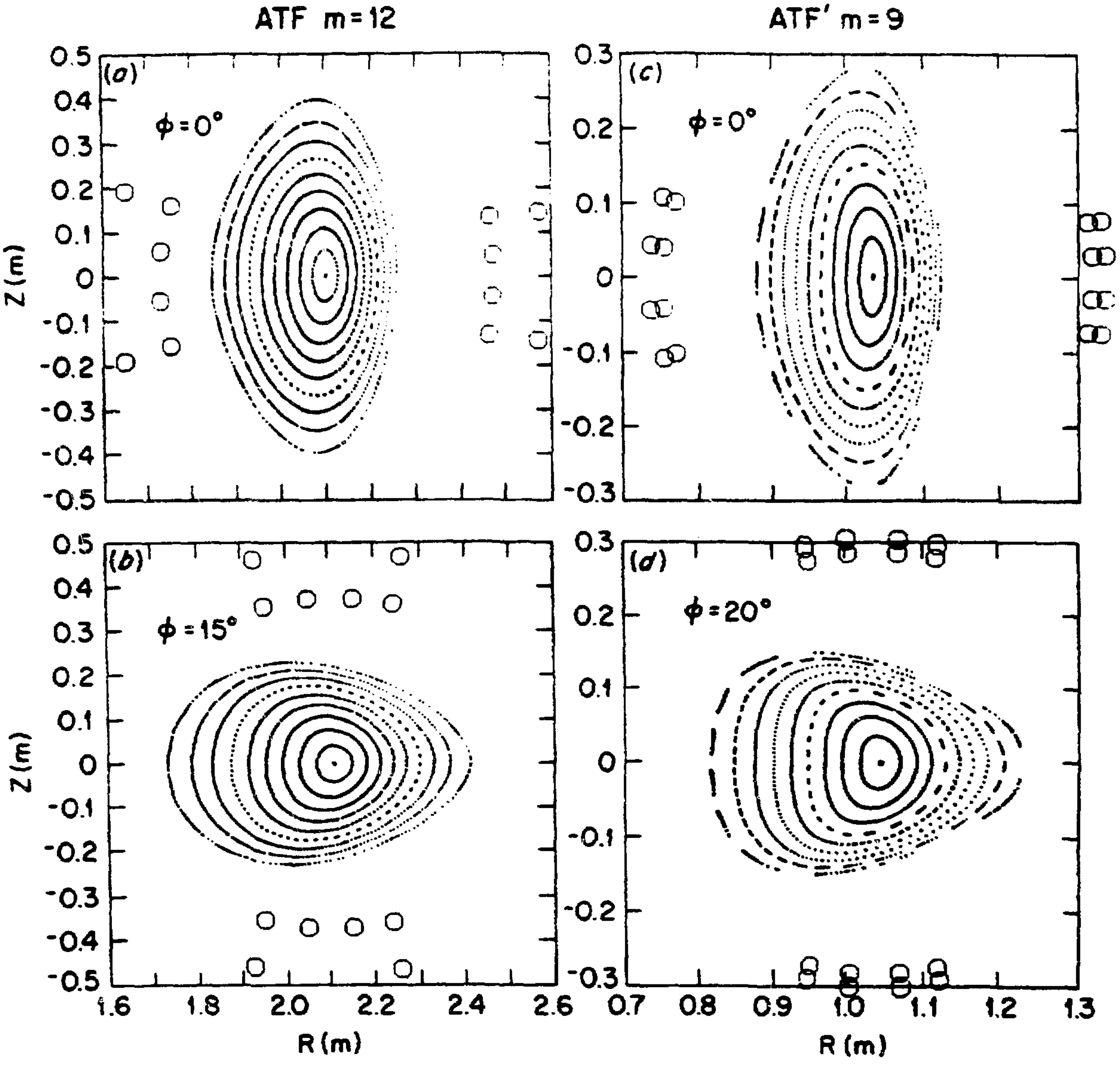
REACTOR SIZE REDUCTION MEASURES

- LOW PLASMA AND COIL ASPECT RATIOS (R/r)
- HIGH DENSITY (W) SHIELDING UNDER HELICAL FIELD COILS AT PLACES WHERE DISTANCE TO PLASMA EDGE IS SMALL
- ELIMINATION OF TRITIUM BREEDING BLANKET AT ABOVE LOCATIONS
- HELICAL FIELD COIL CROSS SECTION EXTENDED IN TOROIDAL DIRECTION
- HIGHER CURRENT DENSITY IN HELICAL COILS
- SHIELDING THICKNESS sh SETS SIZE SCALE
  - $sh = 0.57\ m\ (W) \rightarrow 2\%$ cooling for coils,
    3×10^{10} rads/30 years, 8 year anneal
  - $sh = 0.67\ m\ (W) \rightarrow 0.2\%$ cooling for coils,
    3×10^{9} rads/30 years, no anneal required
- SIZE DETERMINED BY $\sqrt{R} = 0.5\, \delta \left[\epsilon + (\epsilon^2 + 4x/\delta)^{1/2}\right]$ WHERE:
  - $\epsilon = \left[\pi B_o / 2\mu_o m j (w_c/d_c)\right]^{1/2}$
  - $x =$ plasma edge to coil edge distance
  - $\delta = R/\Delta$, $\Delta =$ plasma edge to coil center distance
- FOR CASES CONSIDERED, $B_o = 5\ T$, $w_c/d_c = 2$, $j = 5\ kA/cm^2$, $sh = 0.57\ m$, $x = 0.92\ m$



Coil configurations for ATR cases in aspect ratio scaling studies.

ORNL-DWG 86-2143 FED



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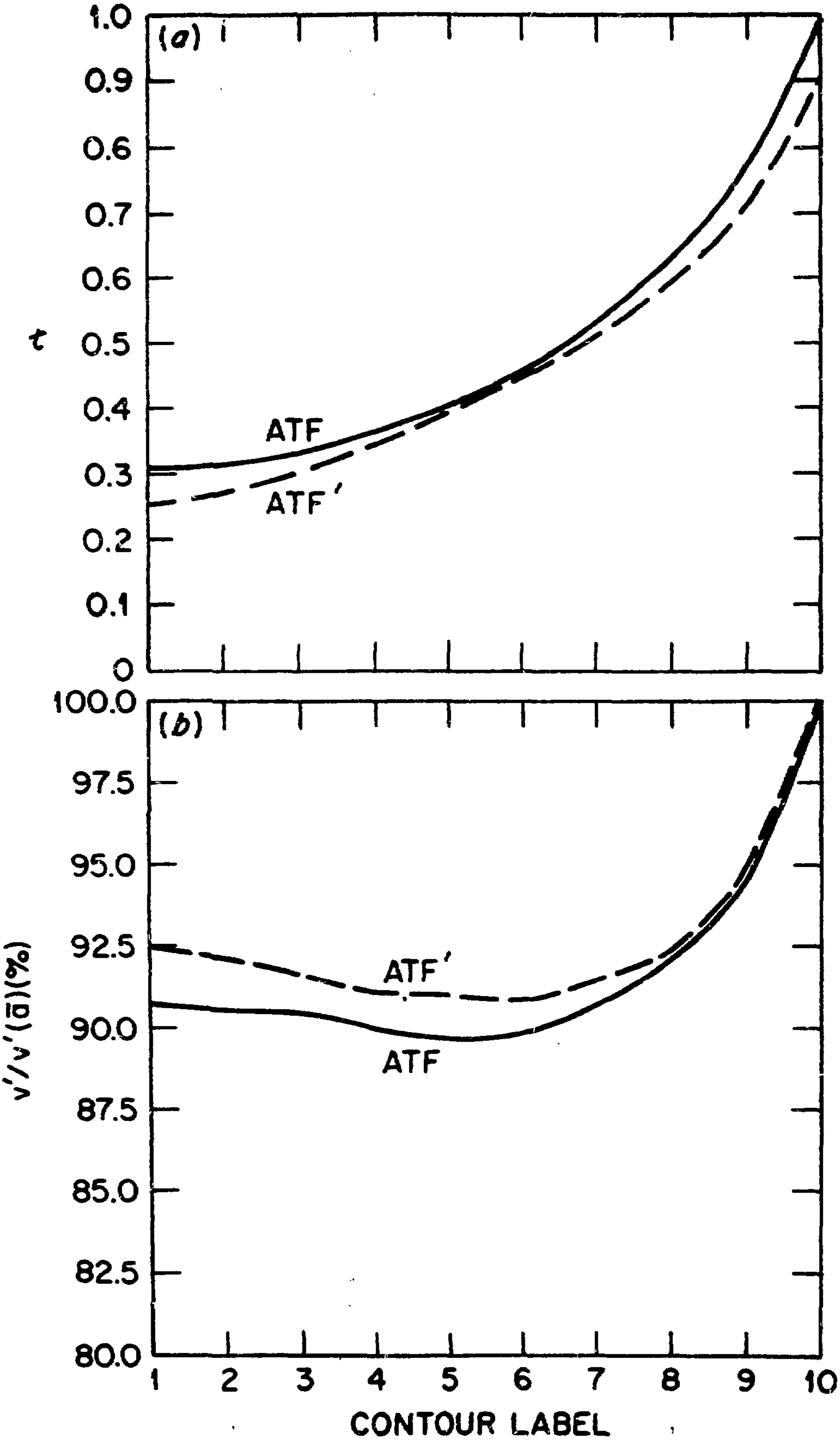
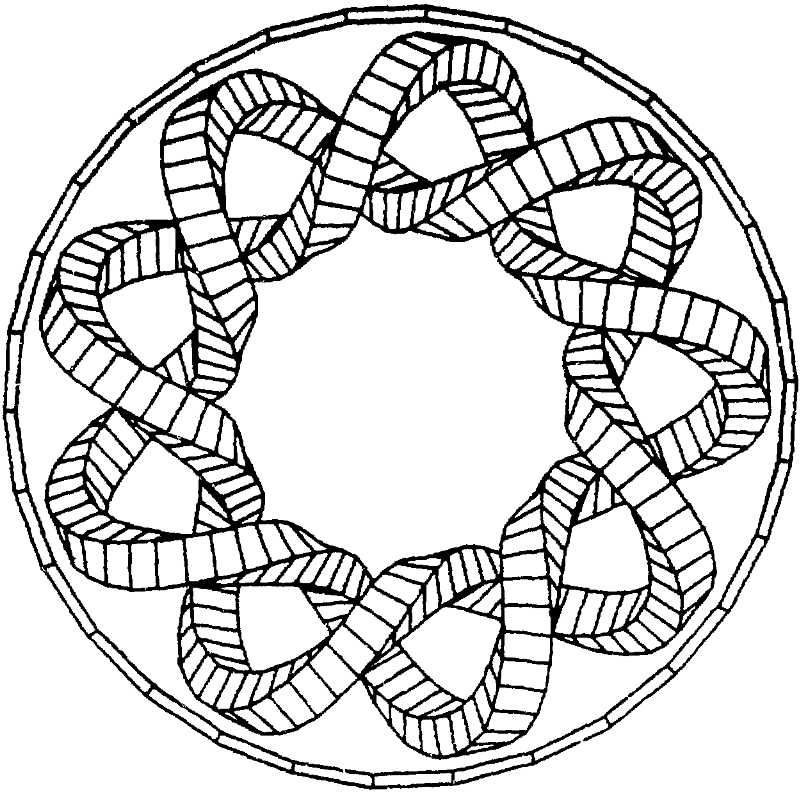
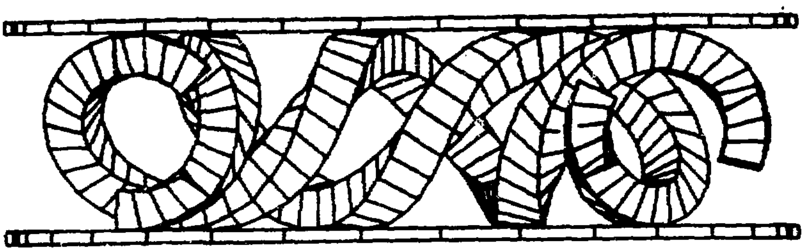
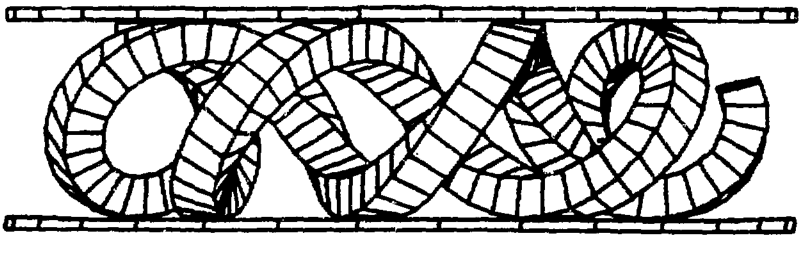


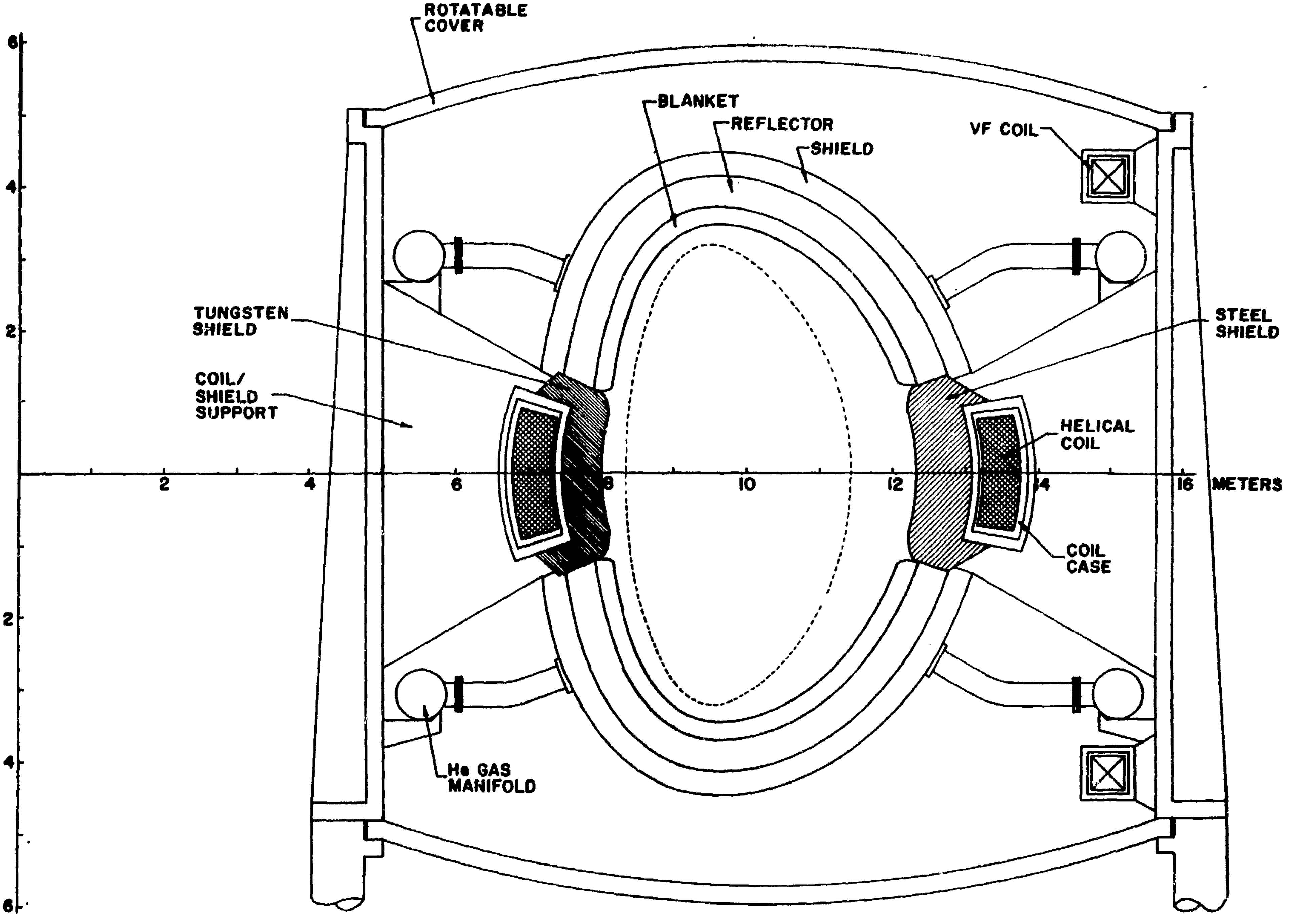
ATR Reactor Parameters

Parameter	ATF-1	ATR-2	ATR-3
<u>Configuration</u>			
m	12	9	6
R_o/r_{coil}	4.49	3.24	2.50
$R_o/\bar{a}$	7.78	4.66	3.87
R_o/Δ	9.50	8.64	6.62
<u>Coil</u>			
$R_o(m)$	11.02	10.25	8.01
$r_{coil}(m)$	2.45	3.16	3.20
no. of HF coils	2	1	2
I_{HF}(MA-turns)	23	28.5	33.4
$B_o(T)$	5	5	5
<u>Plasma</u>			
$\bar{a}(m)$	1.42	2.20	2.07
Volume(m^3)	440	980	680









CROSS SECTION OF ATR-2 POWER REACTOR

PRELIMINARY ENGINEERING PARAMETERS

	ATR-1	ATR-2	ATR-3
Major radius (m)	11.02	10.25	8.01
Minor coil radius (m)	2.45	3.16	3.20
Plasma radius (m)	1.42	2.20	2.07
Fusion power (MW)	4000	4000	4000
First wall area (m^2)	941	1321	1122
Neutron wall loading (MW/m^2)	3.4	2.42	2.85
Helical current (MA)	22.96	28.47	33.35
Coil dimensions (m^2)	0.48 × 0.96	0.53 × 0.96	0.58 × 1.16
Helical coil length (m)	231.4	217.1	151.5
W shielded length (m)	105.9	99	67.8
Fe shielded length (m)	125.5	118	83.7
W shield–			
front thickness (m)	0.57	0.55	0.56
side thickness (m)	0.25	0.24	0.25
front width (m)	1.72	1.70	1.92
Fe shield–			
front thickness (m)	0.77	0.74	0.75
side thickness (m)	0.34	0.33	0.33
front width (m)	1.90	1.88	2.10
Coil case–			
front thickness (m)	0.03	0.03	0.03
side thickness (m)	0.05	0.05	0.05
rear thickness (m)	0.07	0.11	0.17
Dewar thickness (includes vacuum wall and superinsulation) (m)	0.08	0.08	0.08
Mass of coil (Tonnes)	640	663	611
Mass of coil case (Tonnes)	278	341	366
Mass of W shield (Tonnes)	1718	1542	1190
Mass of Fe shield (Tonnes)	880	796	619
Area available for breeding			
No breeding under coils (%)	55.3	70	73
With breeding under Fe coils (%)	81	87	88

The average mass densities assumed are 13.8 g/cm^3 (W shield), 4.05 g/cm^3 (Fe shield), and 6 g/cm^3 (coil).

Preliminary Engineering Parameters

	ATR - 1	ATR - 2	ATR - 3
Major Radius (m)	11.02	10.25	8.01
Minor Coil Radius (m)	2.45	3.16	3.20
Plasma Radius (m)	1.42	2.20	2.07
Fusion Power (MW)	4000	4000	4000
First Wall Area (m^2)	941	1321	1122
Neutron Wall Load Γ (MW/m^2)	3.4	2.42	2.85
Helical Coil Current (MA)	22.96	28.48	33.35
Current Density (A/cm^2)	5000	5000	5000
Coil Cross Section (m x m)	0.48 x 0.96	0.53 x 0.96	0.58 x 1.16
Helical Coil Length (m)	231.4	217.1	151.5
W Shielded Length (m)	105.9	99.0	67.8
Fe Shielded Length (m)	125.5	113.0	83.7
Coil Shield			
W - Front Thickness (m)	0.57	0.55	0.56
(ρ_{avg} = 13.8) Side Thickness (m)	0.25	0.24	0.25
Front Width (m)	1.72	1.70	1.92
Fe - Front Thickness (m)	0.72	0.74	0.75
Side Thickness (m)	0.34	0.33	0.33
Front Width (m)	1.90	1.88	2.10
Max. Field on Conductor (T)	11.9	14.0	14.10
Max. Radial Body Force (MN/m)	30.9	58.0	79.0
Coil Case - Front Thickness (m)	0.03	0.03	0.03
Side Thickness (m)	0.05	0.05	0.05
Rear Thickness (m)	0.07	0.11	0.17
Vacuum Thickness (m)	0.08	0.08	0.08
Coil Case Design Stress (MPa)	340	340	340
Area Available for Breeding			
No Breeding under Coils (%)	55.3	70.0	73.0
Required Breeding Ratio	1.9	1.5	1.44
With Breeding under Coils (%)	81.0	87.0	88.0
Required Breeding Ratio	1.3	1.2	1.19
Need Breeding under Coils	Yes	No	No
Blanket Thickness (cm)	17.2	21.3	20.0
Reflector Thickness (cm)	47.8	43.7	45.0
Shield Thickness (cm)	32.0	29.0	30.0

Preliminary Engineering Parameters
(continued)

	ATR - 1	ATR - 2	ATR - 3
Masses			
Helical Coil (tonnes)	640	663	611
Helical Coil Case (tonnes)	278	341	366
W Coil Shield (tonnes)	1478	1310	1033
Fe Coil Shield (tonnes)	748	712	568
Blanket (tonnes)	407	632	521
Reflector (tonnes)	1719	2792	2547
Shield (tonnes)	674	1086	995
VF Coils & Coil Cases (tonnes)	430	353	286
Vacuum Chamber (tonnes)	2,070	2,794	2,233
Total Mass (tonnes)	8,444	10,683	9,160
Blanket Energy Mult.	1.59	1.57	1.58
Total Thermal Energy (MW_{th})	5,898	5,846	5,856
Net Elect. ($\eta = 0.36$)(MWe)	2,123	2,105	2,108
Mass Utiliz. (kWe/tonne)	251	197	230

KEY PHYSICS ISSUES

- BETA LIMITS
  - CONVENTIONAL WISDOM STATES EQUILIBRIUM BETA LIMIT β_c SCALES AS $\iota\!\!\!-(a)^2/A \propto A$ SINCE $\iota\!\!\!-(a) \propto A$
  - RECENT CALCULATIONS SHOW β_c HAS WEAKER DEPENDENCE ON $\iota\!\!\!-(a)^2/A$ AND IS ABOVE THIS VALUE AT LOW A

- TRANSPORT
  - IONS IN $\chi \propto \nu$ REGIME WHERE ELECTRIC FIELD IMPROVES CONFINEMENT
  - DOMINANT ENERGY LOSS IS ELECTRONS IN $\chi \propto 1/\nu$ REGIME WHERE ELECTRIC FIELD INEFFECTIVE
  - DENSITY PEAKING INCREASES ν AND REDUCES ELECTRON LOSSES

- NEED DATA BASE AT HIGH β AND LOW ν FOR LOW ASPECT RATIO ($A = R/a$) TORSATRON: ATF

TRANSPORT MODELING

- WHIST 1-D TRANSPORT CODE

- ION LOSSES: 20x HINTON-HAZELTINE AXISYMMETRIC NEOCLASSICAL + SHAING RIPPLE TRANSPORT MODEL + 2x NEO-ALCATOR ANOMALOUS TRANSPORT

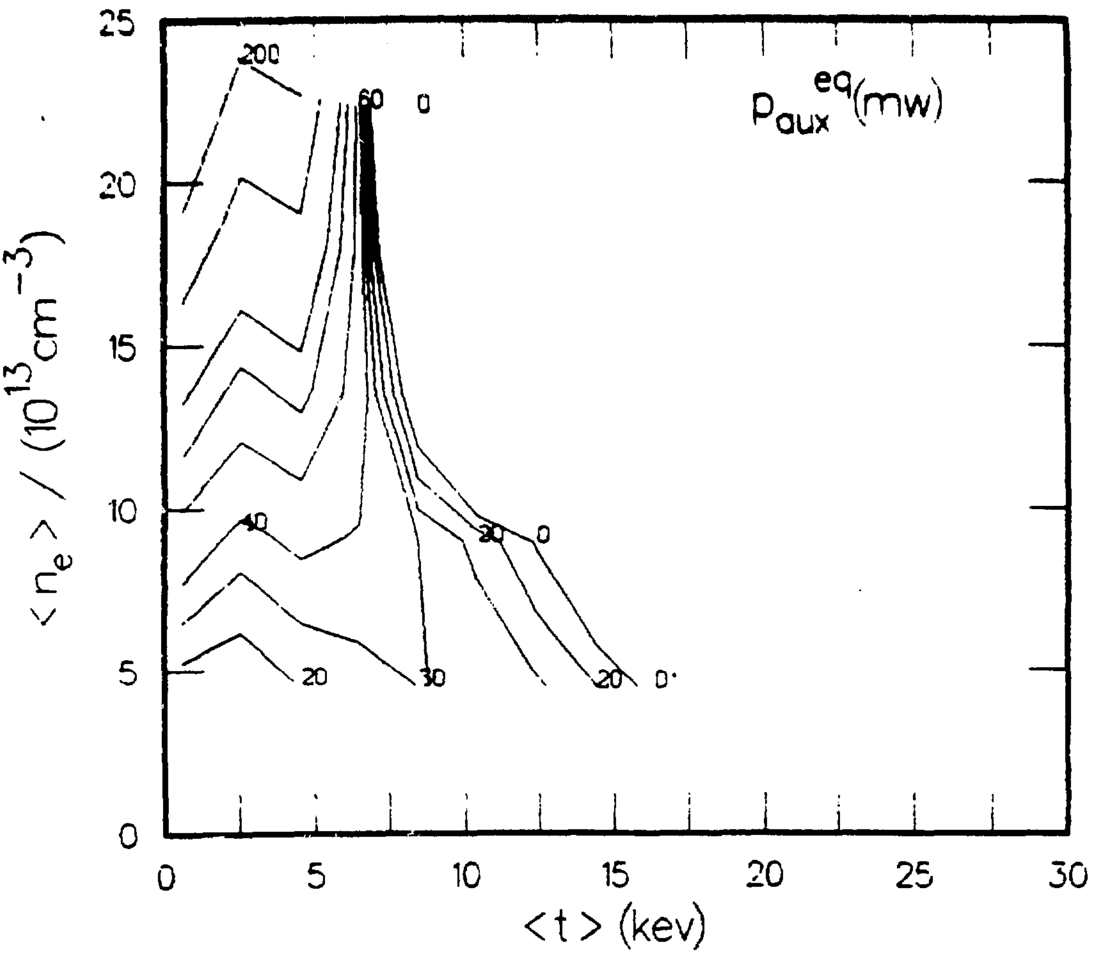
- ION LOSSES: 2x HINTON-HAZELTINE AXISYMMETRIC NEOCLASSICAL + SHAING RIPPLE TRANSPORT MODEL

- RADIAL ELECTRIC FIELD WITH $e\phi' = 2\ kT'$

- DENSITY: PINCH TERM CONVERGING TO $(\text{PARABOLIC})^P$
  RADIAL PROFILE
  : ALTERNATE MODEL D SIMILAR TO χ_e

- POWER DEPOSITION: ICRH WITH $e^{-(r/a)^2}$ PROFILE

- APPROACH: VARY ASSUMPTIONS TO DETERMINE SENSITIVITIES AND REQUIREMENTS



P_{aux}^{eq}(mw)
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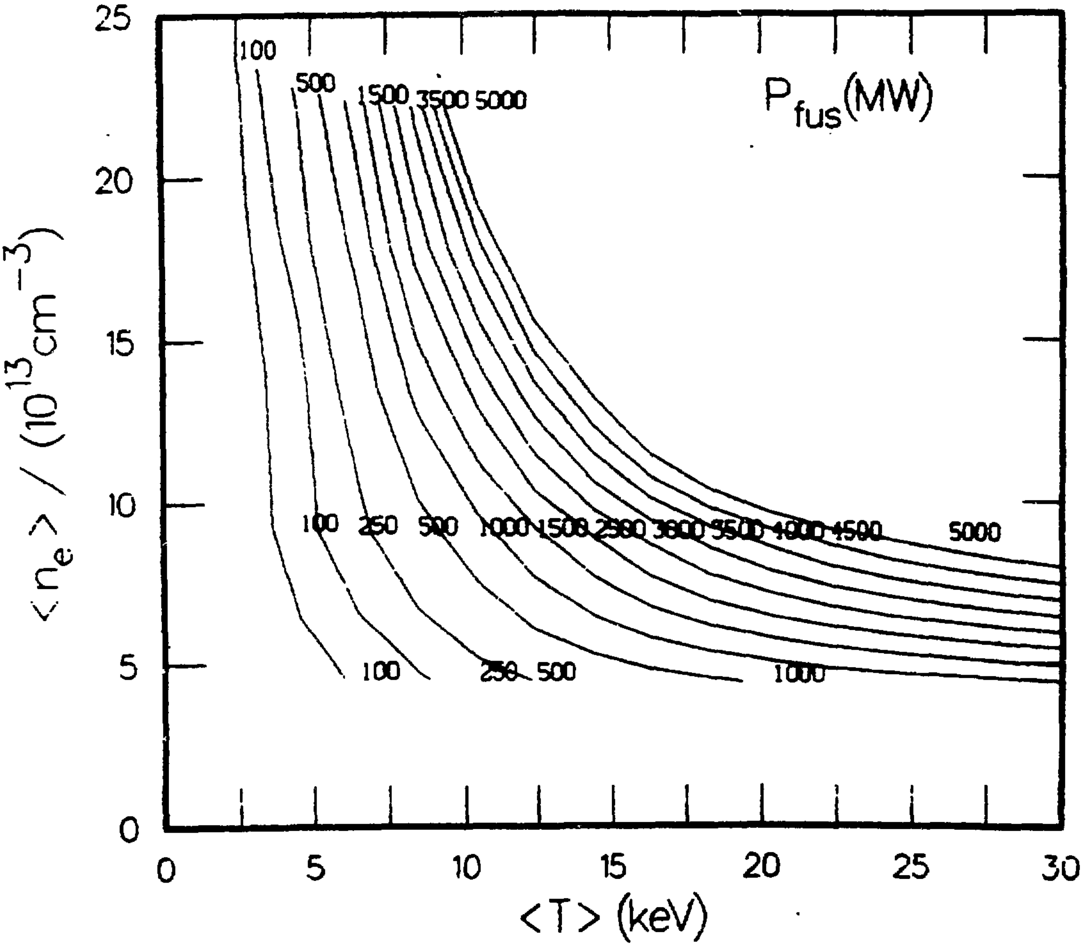
60
0
40
20
0
20
30
20
0
25
20
15
10
5
0
0
5
10
15
20
25
30
$\langle n_e \rangle$ / (10^{13}cm^{-3})
$\langle t \rangle$ (kev)



P_{fus}(MW)
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1500
3500
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1000
1500
2500
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3500
4000
4500
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250
500
1000
25
20
15
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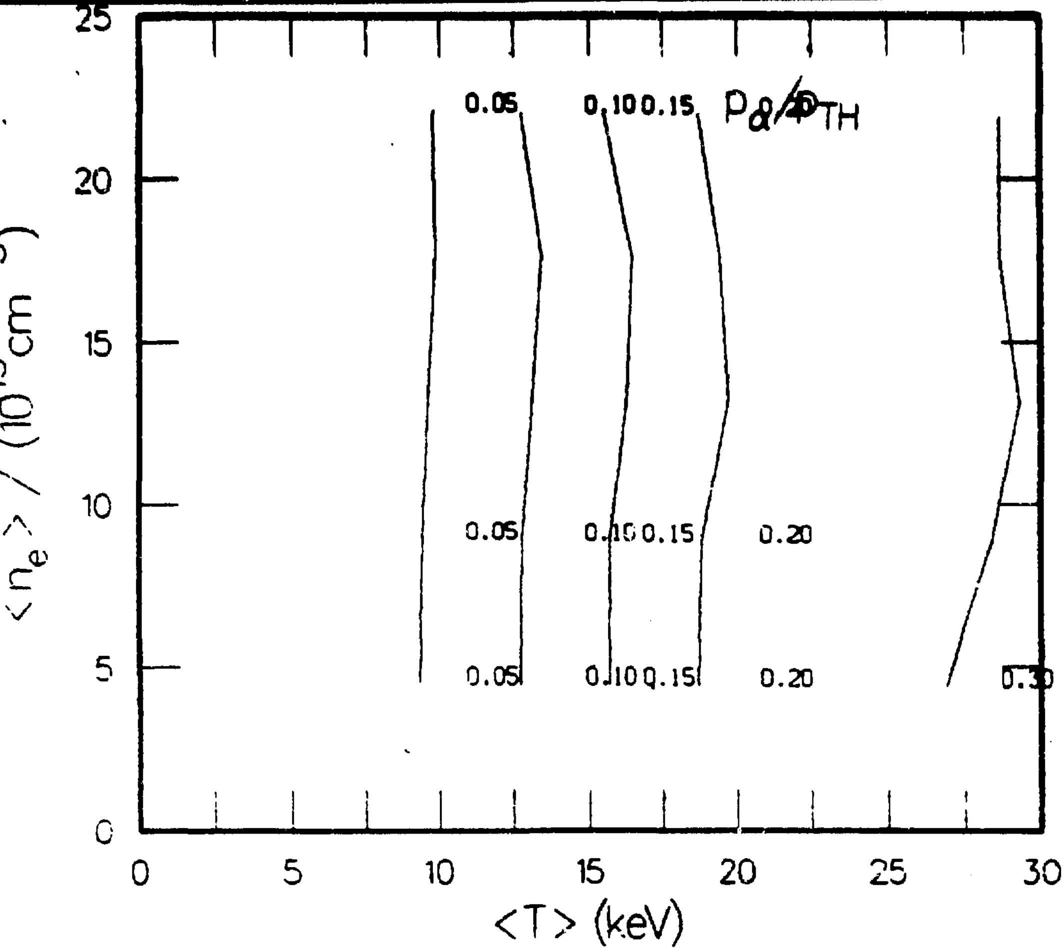
25
30
$\langle n_e \rangle$ / (10^{13}cm^{-3})
$\langle T \rangle$ (keV)


P_α / P_{TH}
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0.15
0.20
0.30
$\langle n_e \rangle / (10^{13} cm^{-3})$
$\langle T \rangle$ (keV)
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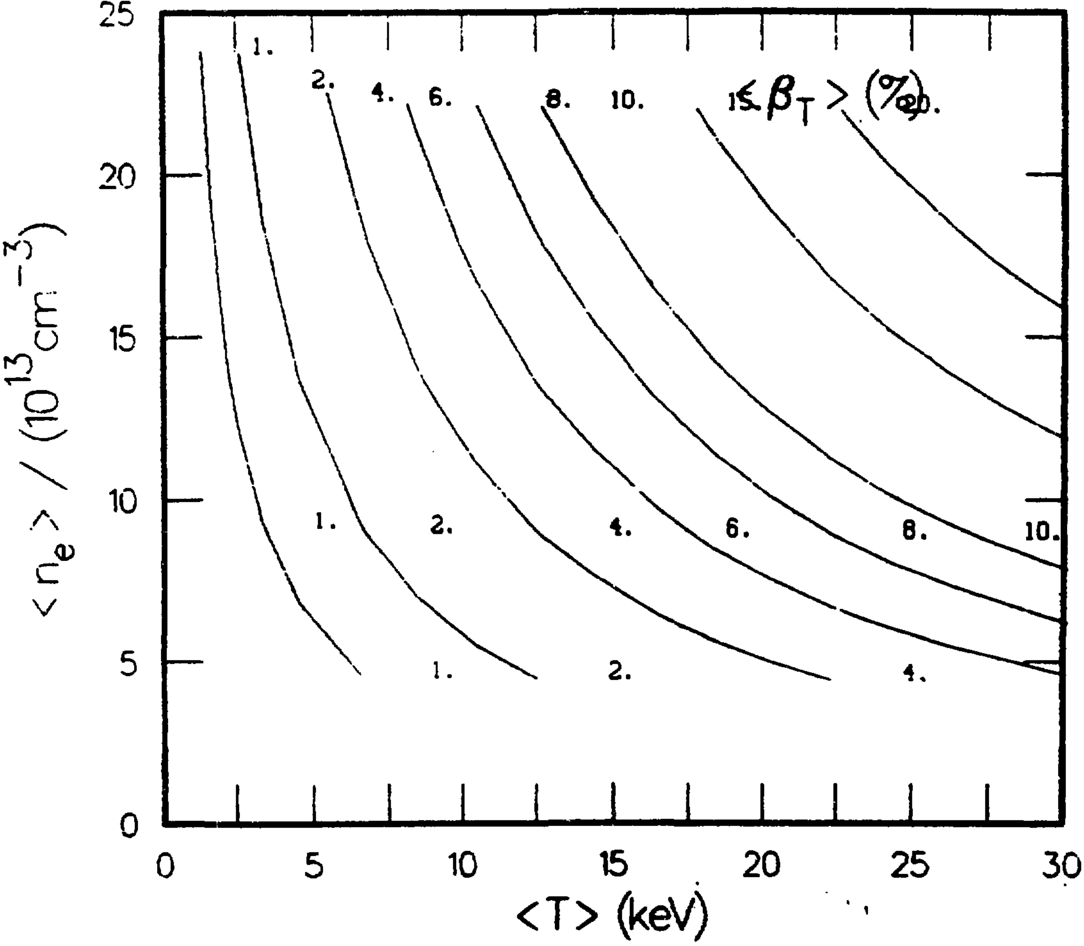
5
10
15
20
25
30


$\langle \beta_T \rangle$ (%)
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2.
4.
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$\langle T \rangle$ (keV)
0
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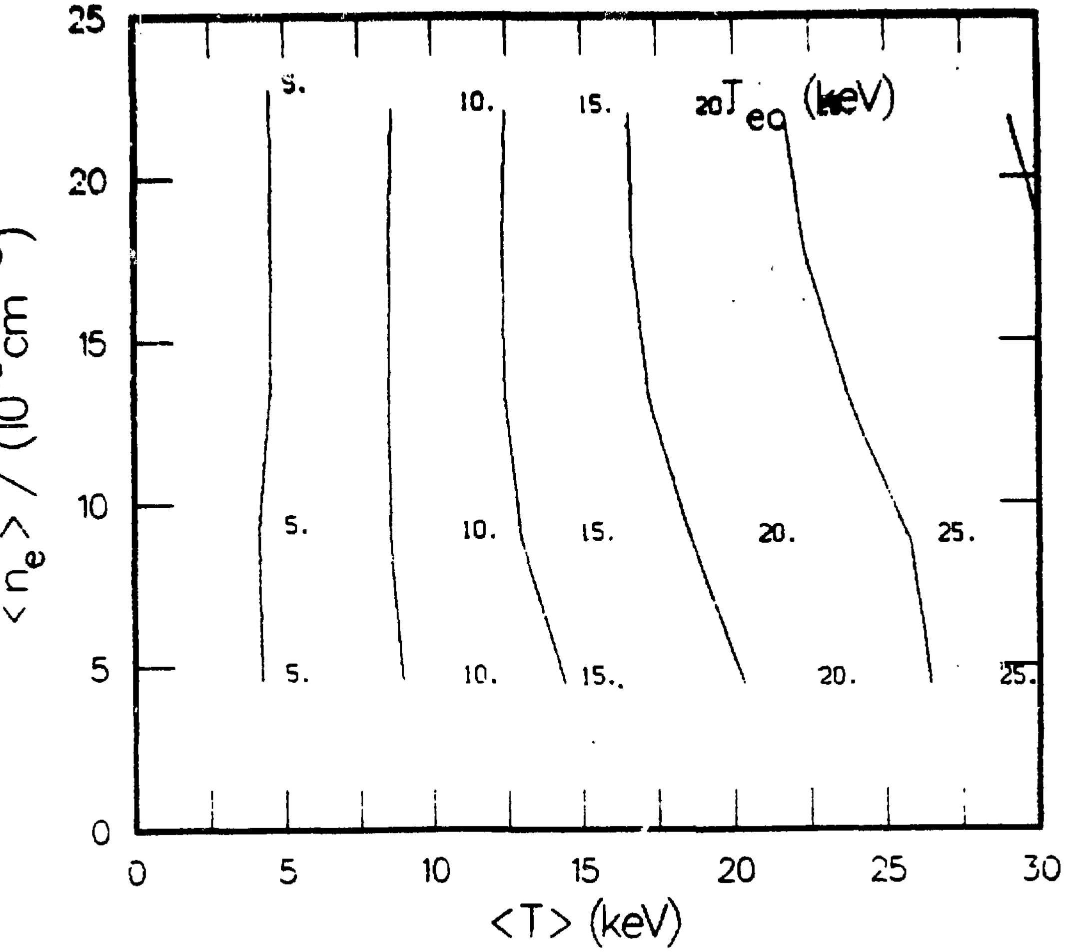

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15.
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25.
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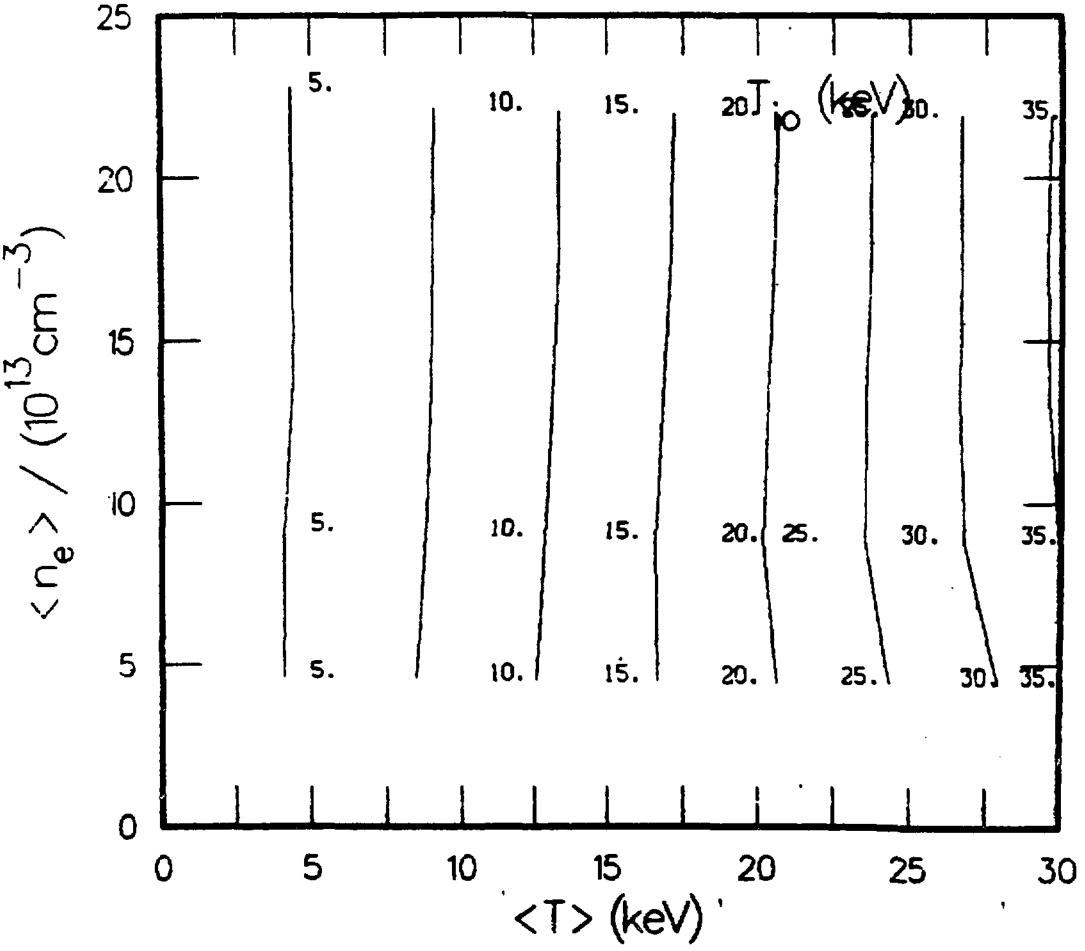
20
25
30



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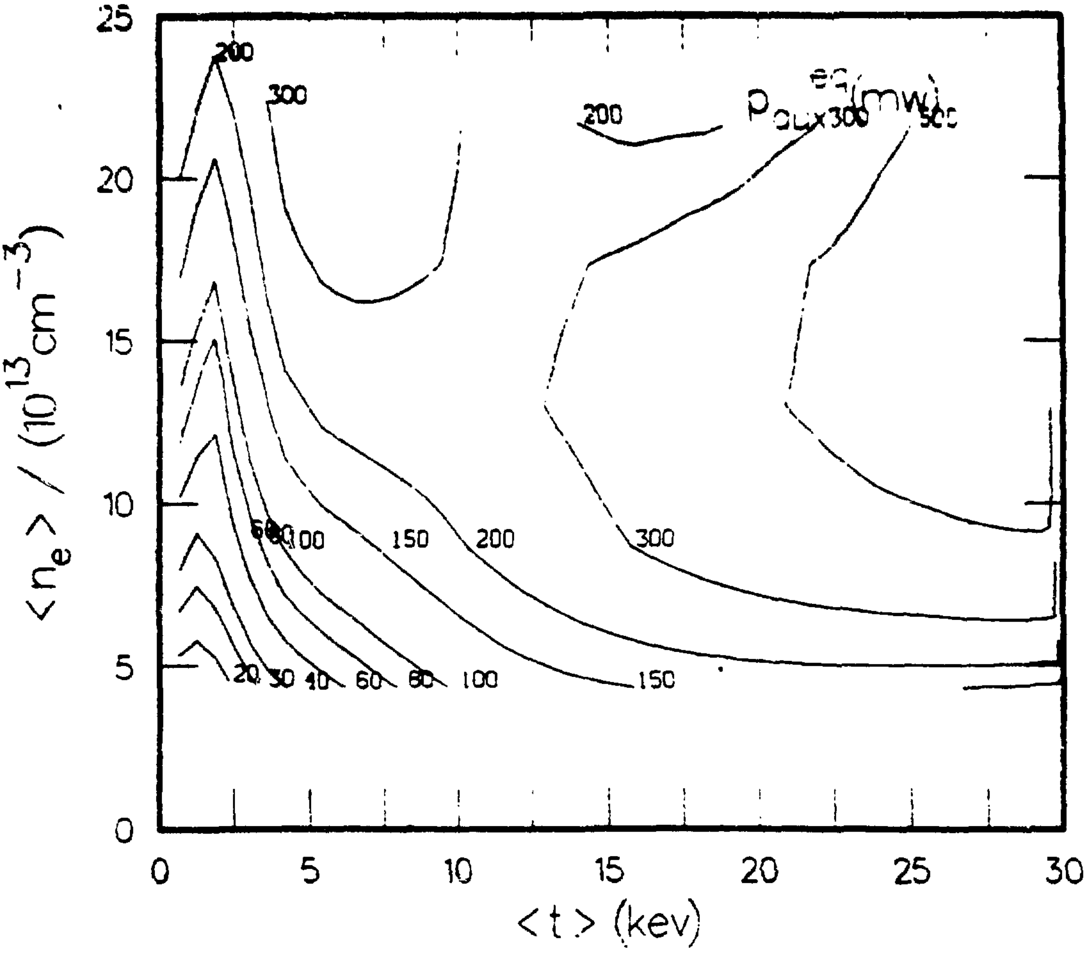
30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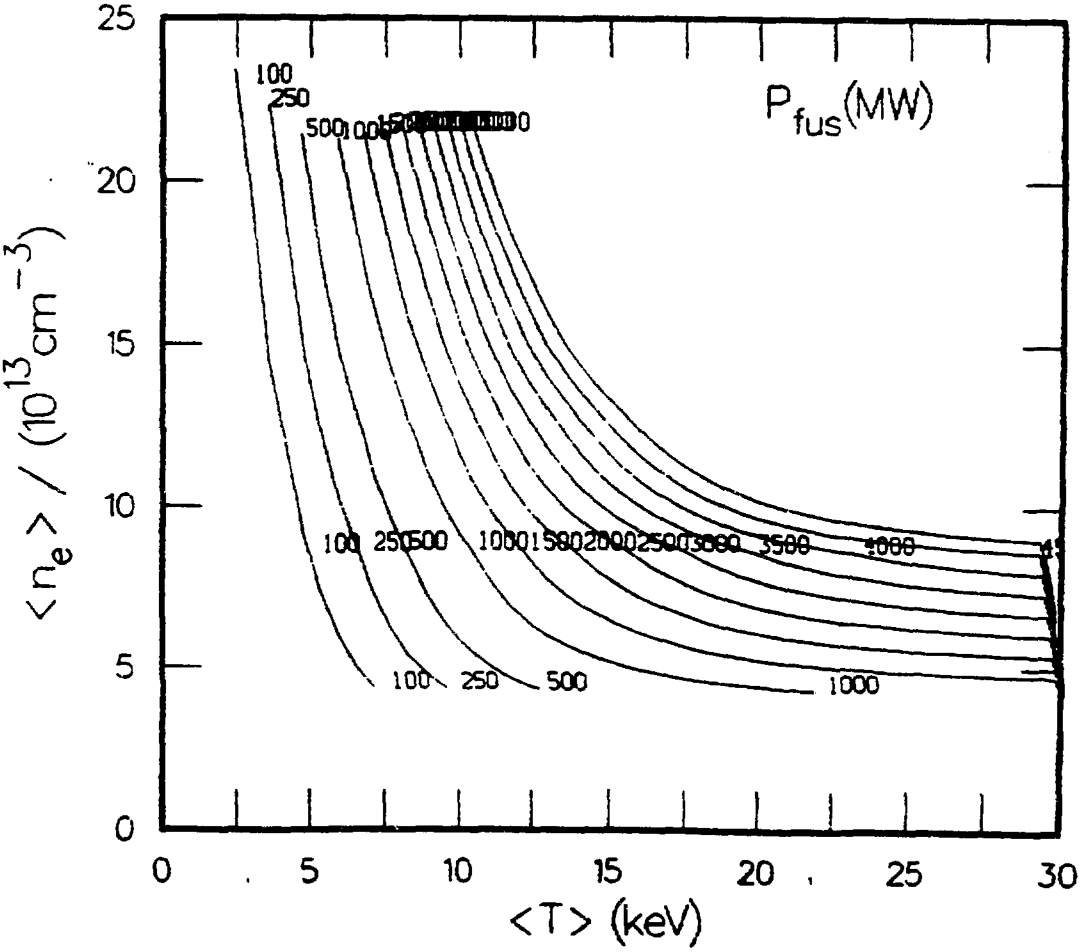
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10
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20
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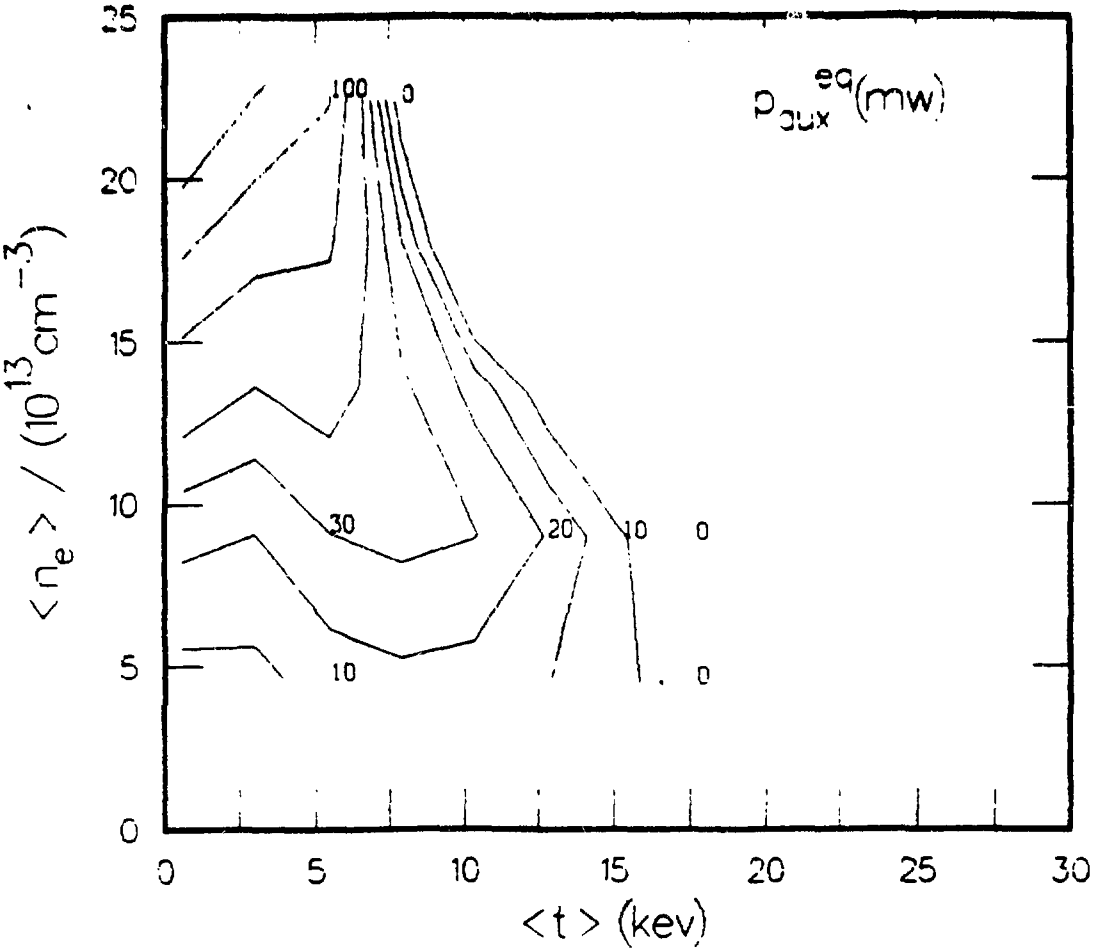
2500
3000
3500
4000
100
250
500
1000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<t> (kev)
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20
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0
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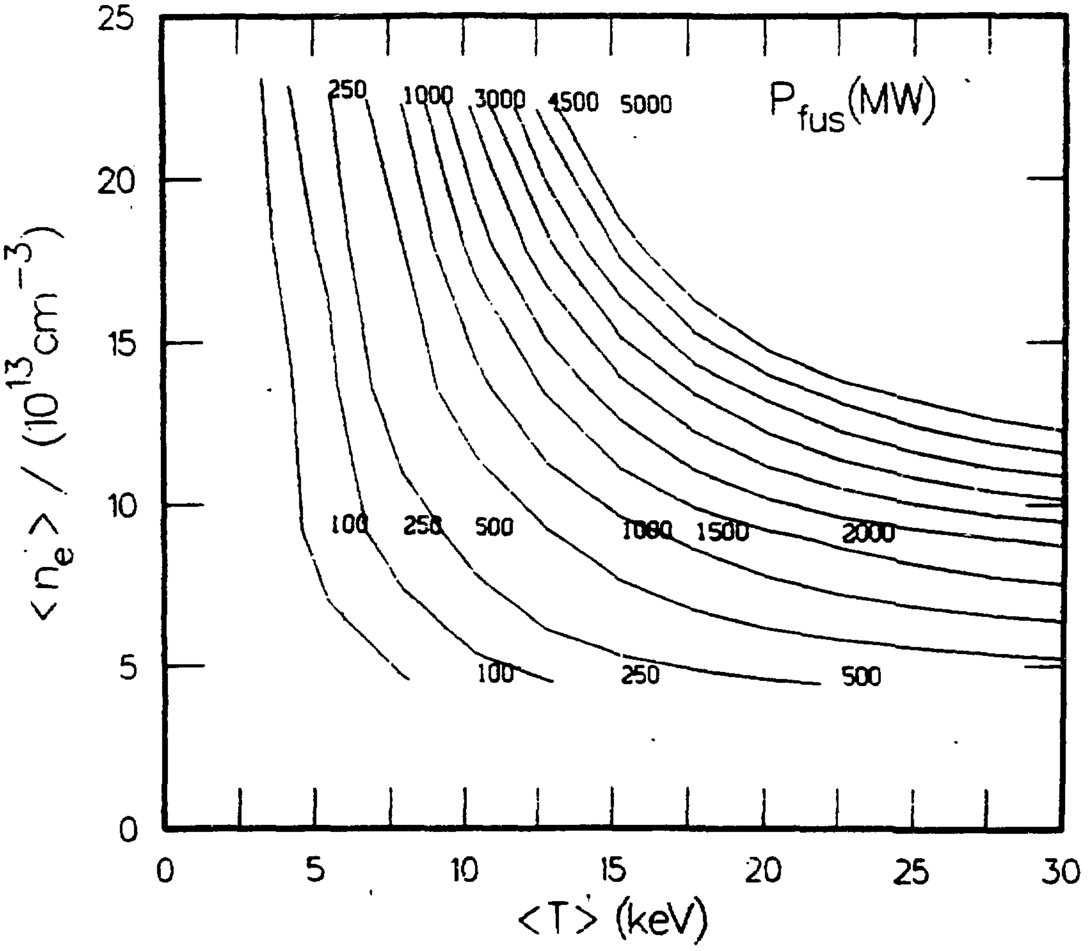
0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<T> (keV)
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2000
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250
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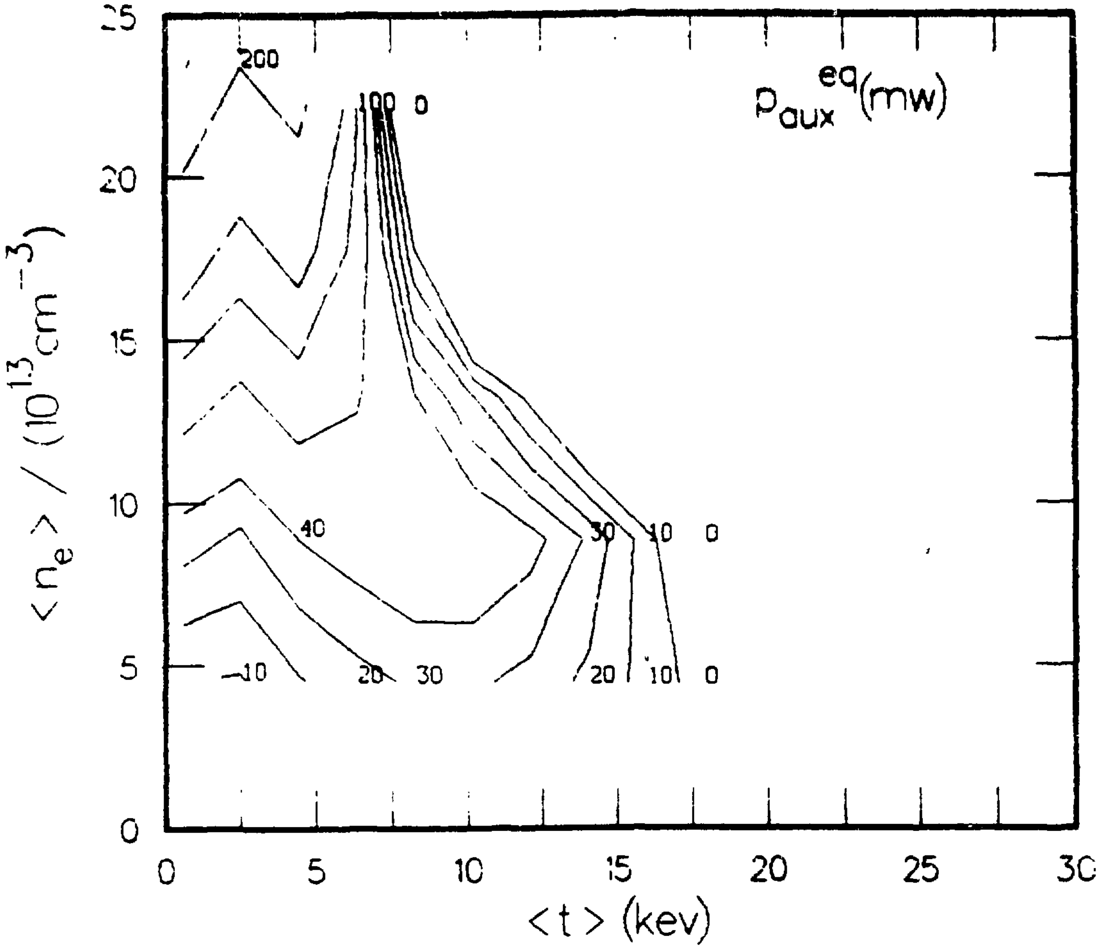
P_{aux}^{eq}(mw)
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-10
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20
10
0
$\langle n_e \rangle$ / (10^{13}cm^{-3})
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10
15
20
25
0
5
10
15
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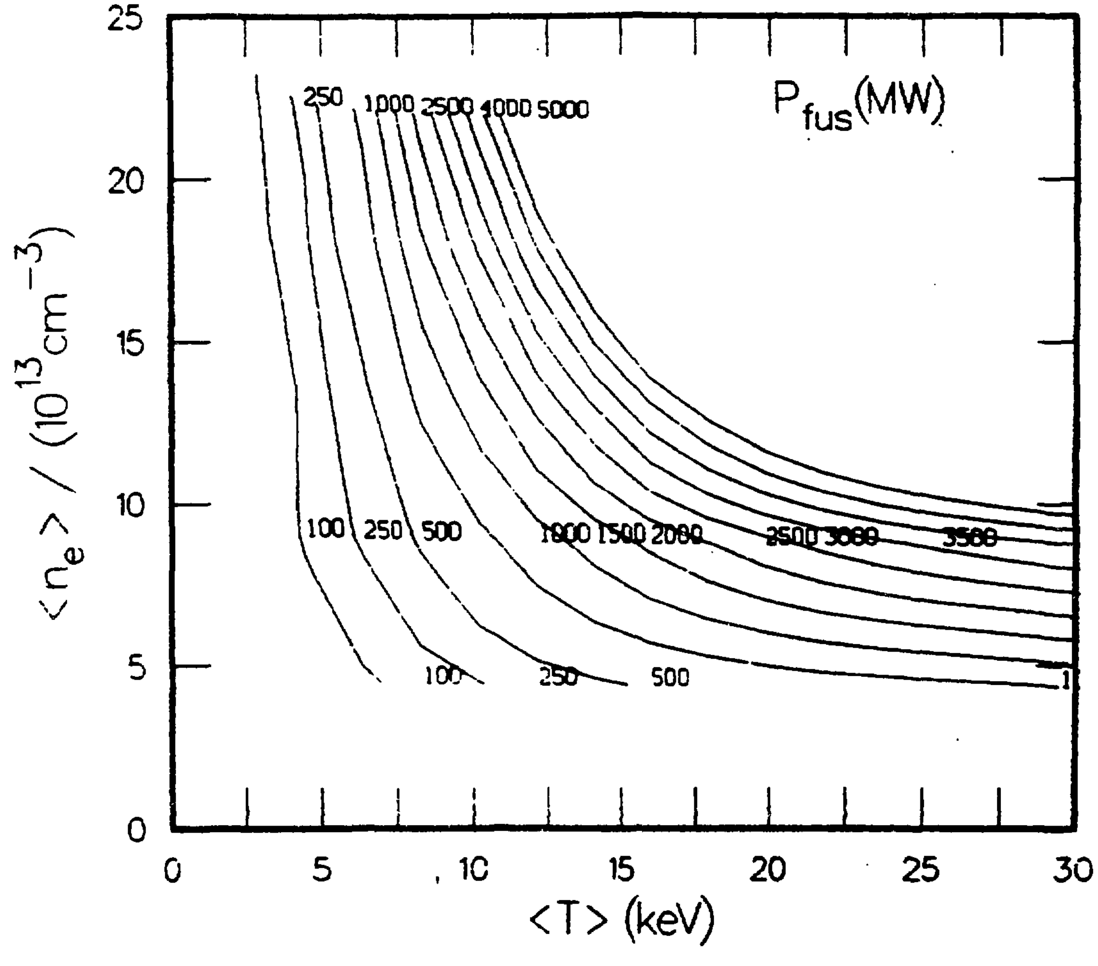
25
30
<t> (kev)


P_{fus}(MW)
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1000
2500
4000
5000
100
250
500
1000
1500
2000
2500
3000
3500
100
250
500
$\langle n_e \rangle$ / (10^{13}cm^{-3})
0
5
10
15
20
25
0
5
10
15
20
25
30
<T> (keV)

ATR Reactor Parameters

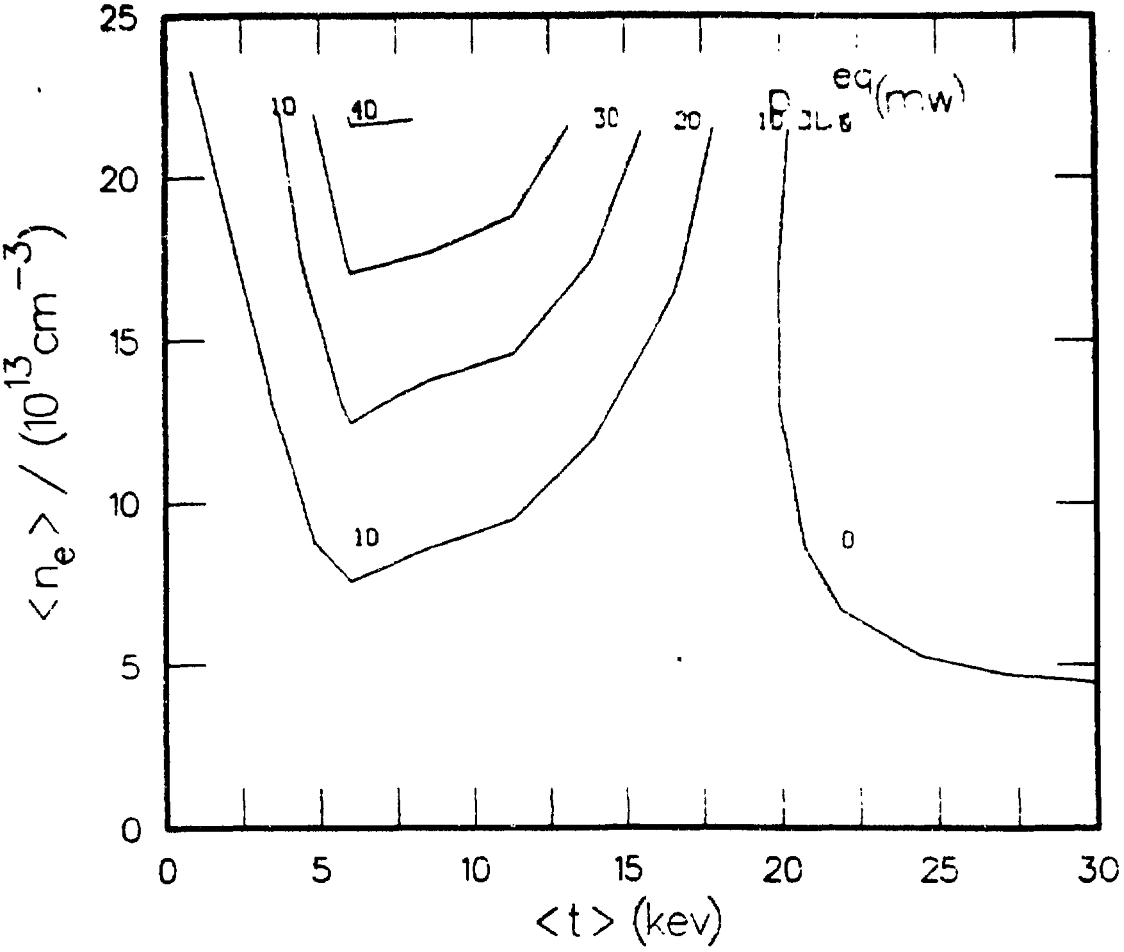
Parameter	ATF-1	ATR-2	ATR-3
Plasma			
$R_o(m)$	11.02	10.25	8.01
$\bar{a}(m)$	1.42	2.20	2.07
$B_o(T)$	5	5	5
Volume(m^3)	440	980	680
$P_{thermal}(GW)$	4	4	4
$P_{neutron}(MW/m^2)$	3.4	2.4	2.85
$\langle n_e \rangle$, $10^{20}\ m^{-3}$	2	2	2
$T_{io}(keV)$	14.4	10.5	11.9
$T_{eo}(keV)$	14.4	11.1	12.7
$\langle \beta \rangle$, %	9	6.3	7.2

D–T BURNERS

- SAME COIL CONFIGURATIONS AS ATR–1,2,3
- SAME TRANSPORT MODEL IN WHIST 1–D CALCULATIONS
- ASSUME COPPER COILS TO AVOID THICK SHIELDING OF HELICAL FIELD COILS
- VARY PLASMA RADIUS AND DENSITY PROFILE FOR MINIMUM SIZE D–T BURNER

ATB D–T BURNER PARAMETERS

Parameter	ATB–1		ATB–2		ATB–3	
Configuration						
m	12		9		6	
$R_o/\bar{a}$	7.78		4.66		3.87	
Coil						
$R_o(m)$	3	4	3	4	3	4
$r_{coil}(m)$	0.67	0.89	0.93	1.23	1.2	1.6
no. of HF coils	2		1		2	
I_{HF}(MA–turns)	6.25	8.33	8.33	11.1	12.5	16.7
$B_o(T)$	5		5		5	
coil depth (m)	0.25	0.29	0.29	0.33	0.35	0.41
Plasma						
$\bar{a}(m)$	0.39	0.51	0.64	0.86	0.78	1.03
Volume(m^3)	8.81	20.9	24.5	58.2	35.6	84.4


Paux eq(mw)
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0
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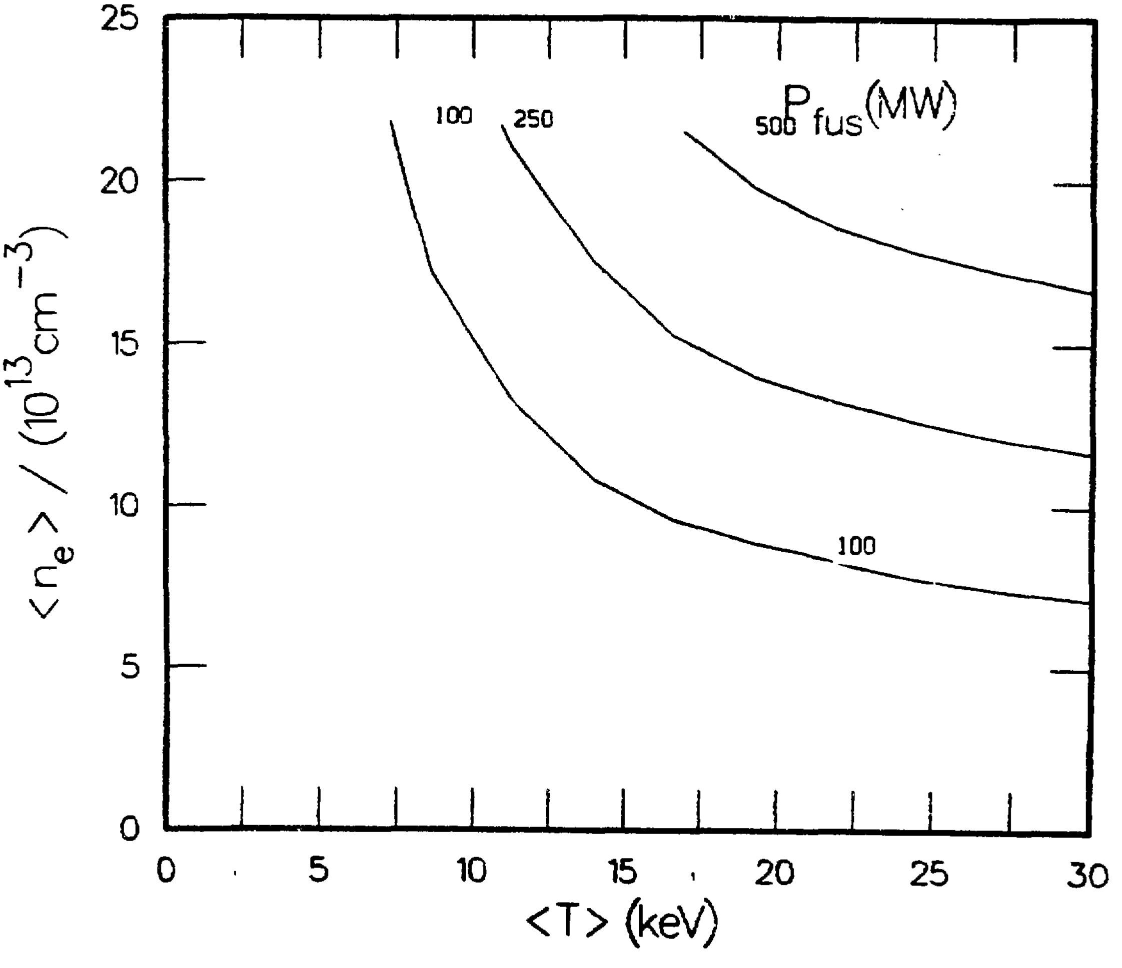
30
< t > (kev)
< ne > / (10^13 cm^-3)


Pfus(MW)
100
250
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30
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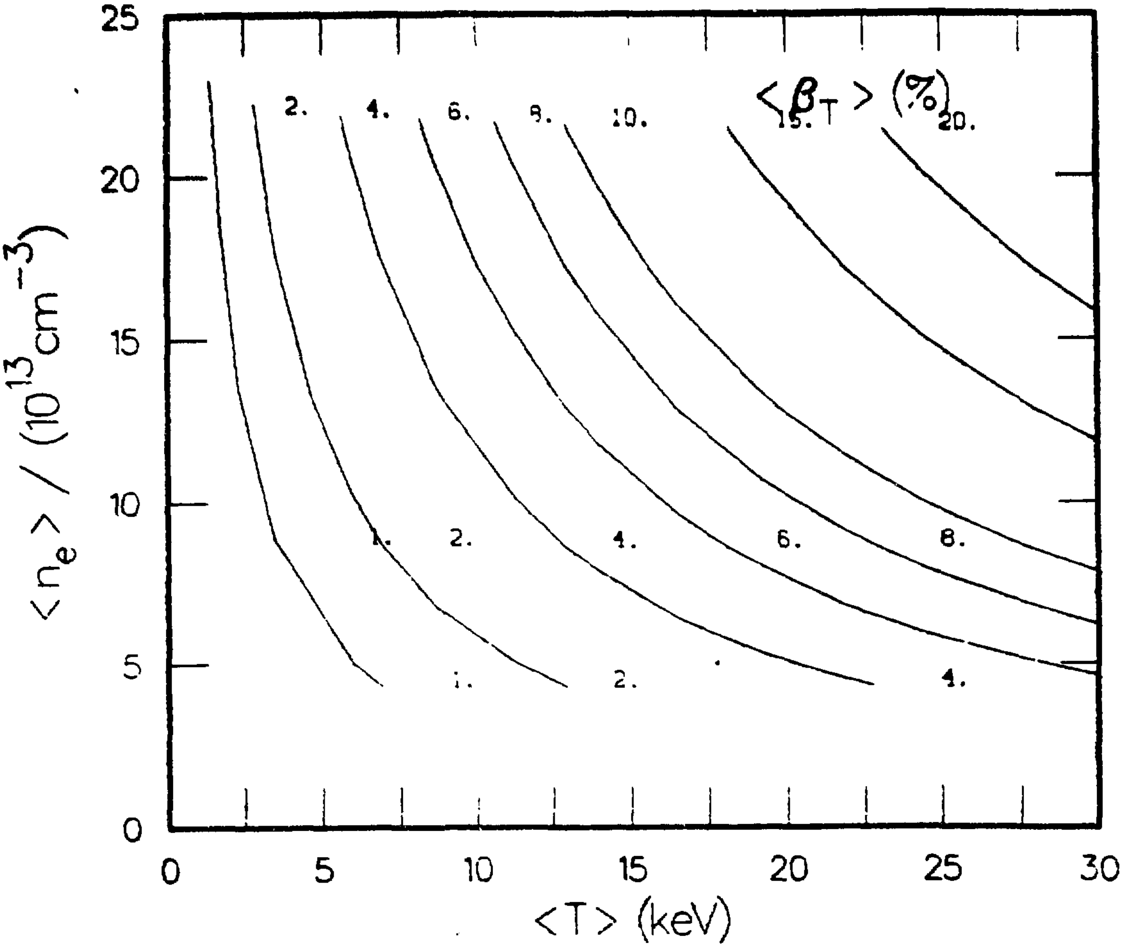
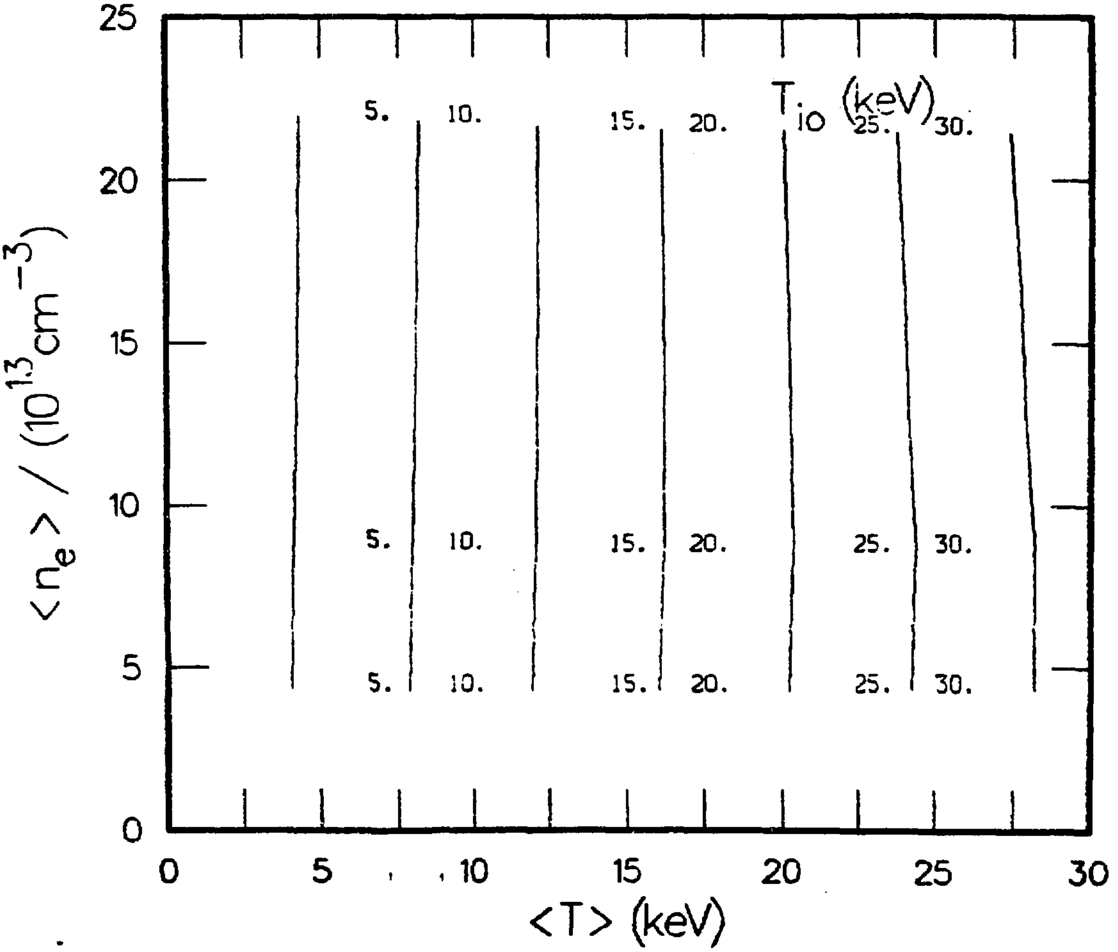
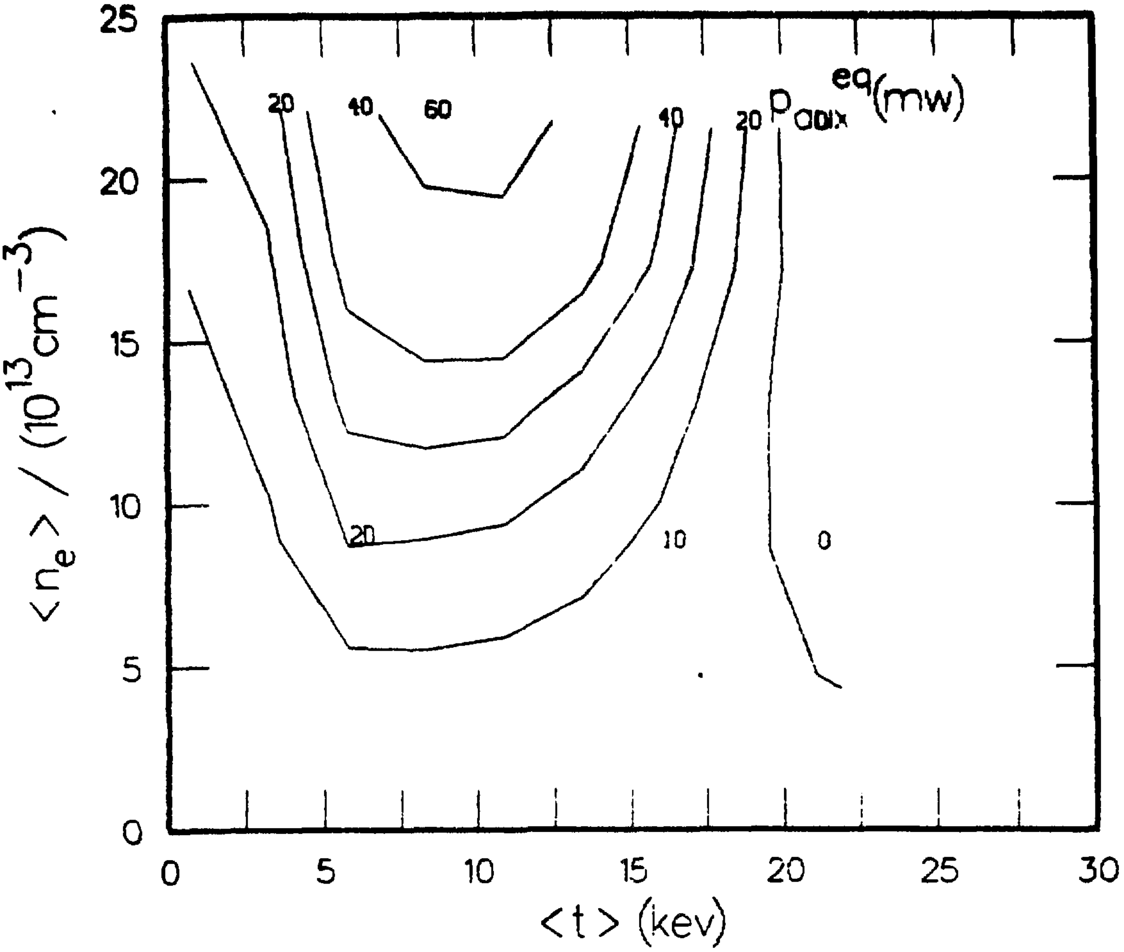
< ne > / (10^13 cm^-3)

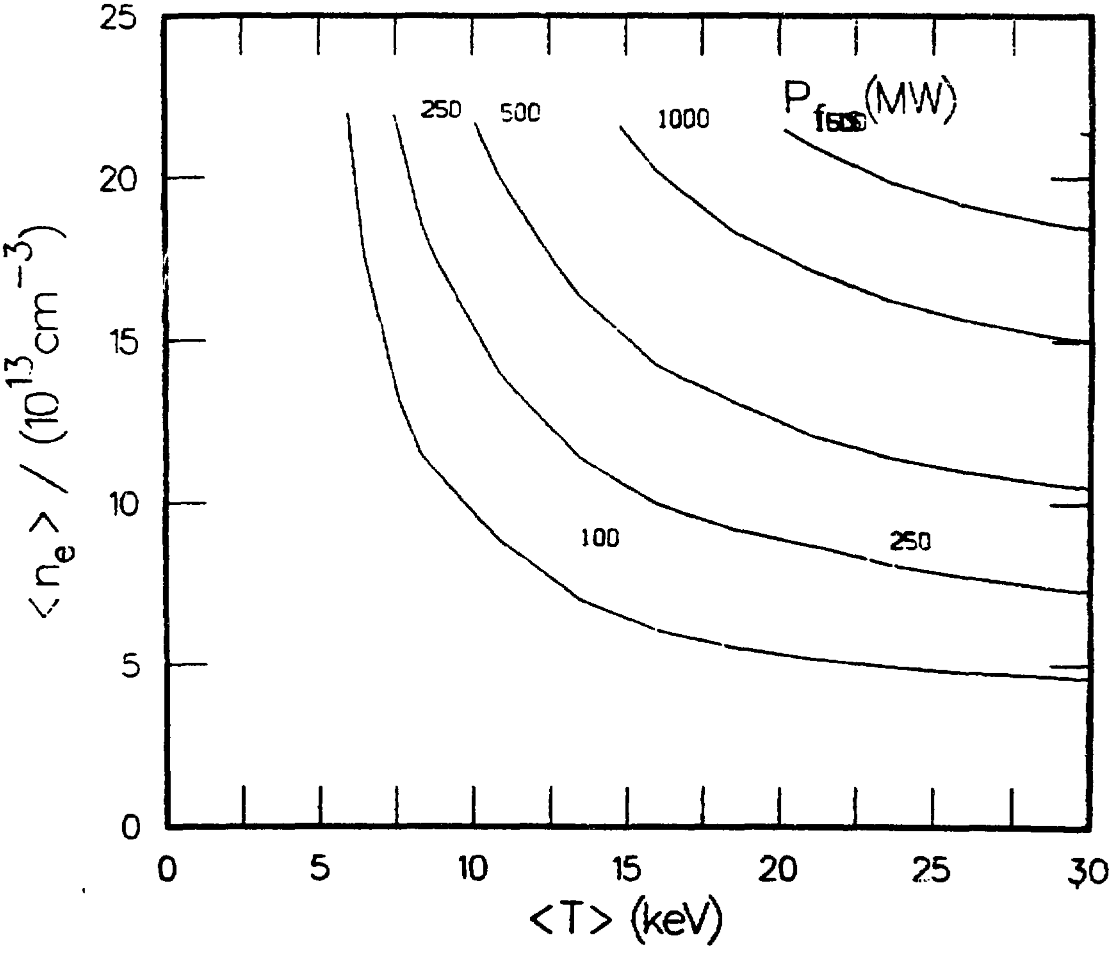


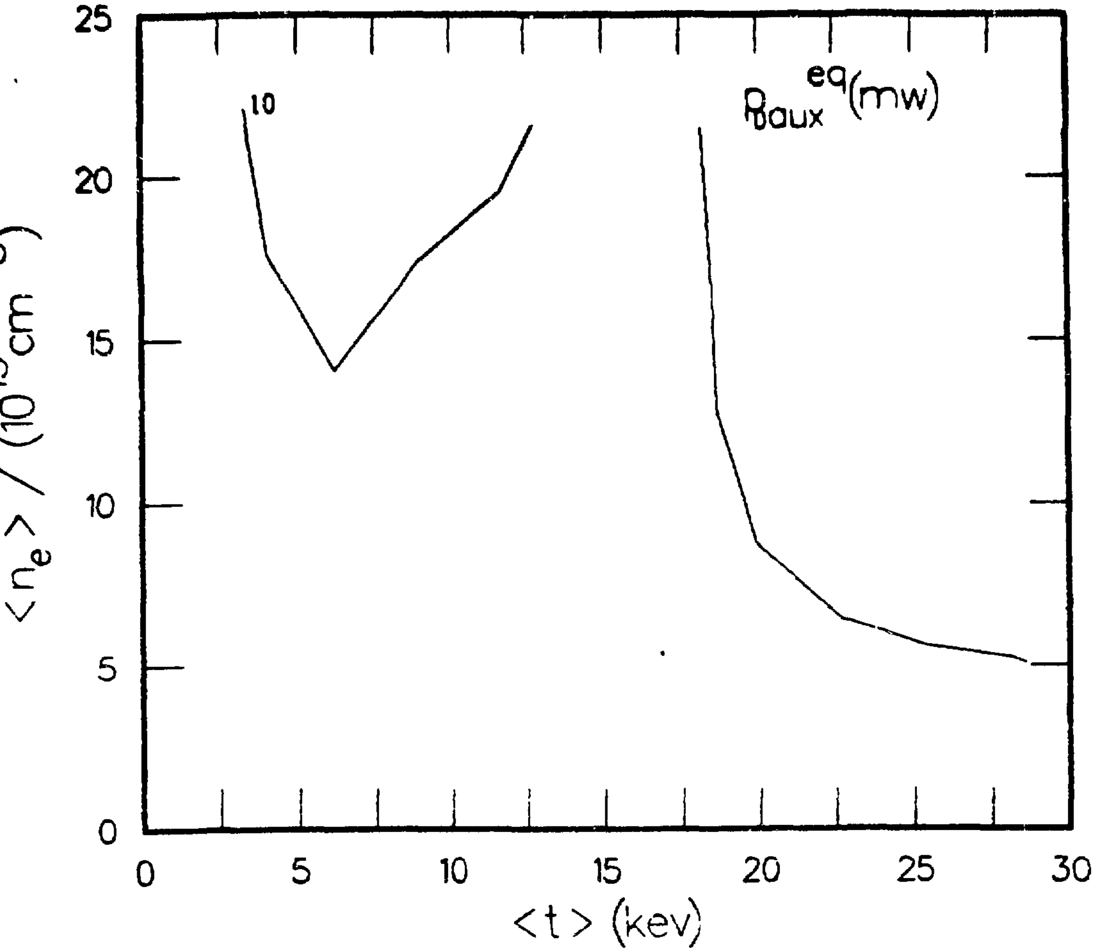
<β_T> (%)
2.
4.
6.
8.
10.
15.
20.
1.
2.
4.
6.
8.
1.
2.
4.
<n_e> / (10^13 cm^-3)
25
20
15
10
5
0
0
5
10
15
20
25
30
<T> (keV)



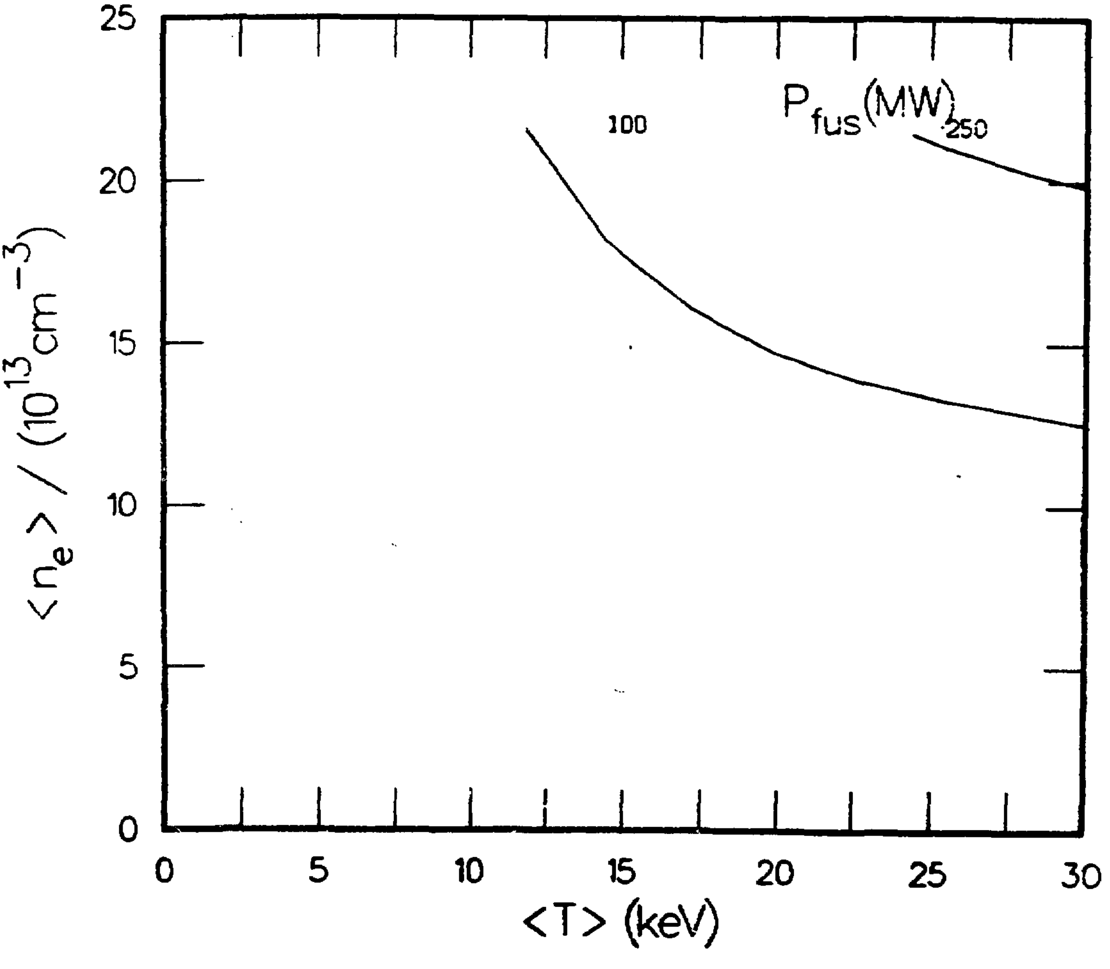
T_io (keV)
5.
10.
15.
20.
25.
30.
5.
10.
15.
20.
25.
30.
5.
10.
15.
20.
25.
30.
<n_e> / (10^13 cm^-3)
25
20
15
10
5
0
0
5
10
15
20
25
30
<T> (keV)


P_{aux}^{eq}(mw)
20
40
60
40
20
20
10
0
$\langle n_e \rangle$ / (10^{13}cm^{-3})
0
5
10
15
20
25
$\langle t \rangle$ (kev)
0
5
10
15
20
25
30

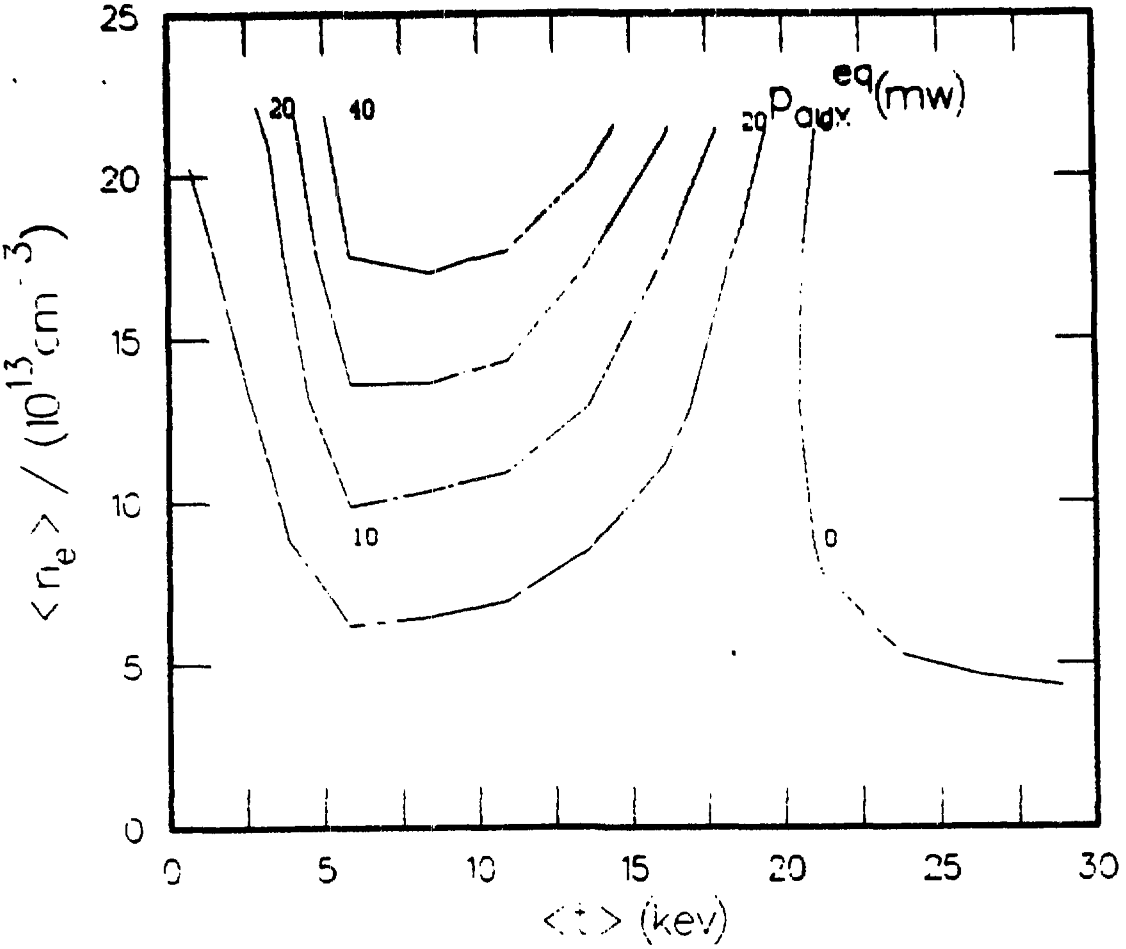

P_{fus}(MW)
250
500
1000
100
250
$\langle n_e \rangle$ / (10^{13}cm^{-3})
0
5
10
15
20
25
$\langle T \rangle$ (keV)
0
5
10
15
20
25
30

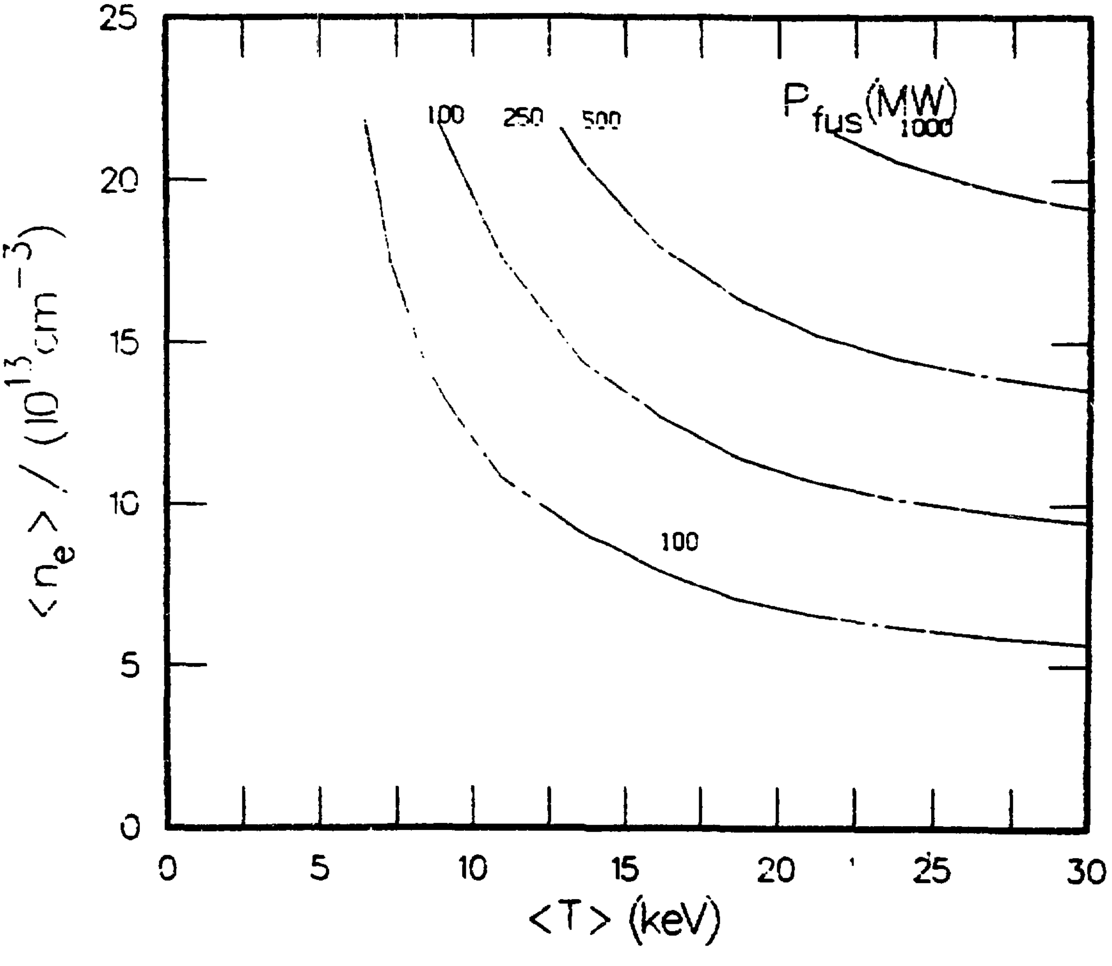


P_{aux}^{eq}(mw)
10
100
<n_e> / (10^{13}cm^{-3})
0
5
10
15
20
25
<t> (kev)
0
5
10
15
20
25
30



P_{fus}(MW)
100
250
<n_e> / (10^{13}cm^{-3})
0
5
10
15
20
25
<T> (keV)
0
5
10
15
20
25
30


Paux eq (mw)
20
40
20
10
0
<ne> / (10^13 cm^-3)
25
20
15
10
5
0
0
5
10
15
20
25
30
<T> (keV)


Pfus (MW)
100
250
500
1000
100
<ne> / (10^13 cm^-3)
25
20
15
10
5
0
0
5
10
15
20
25
30
<T> (keV)

ATF–II STUDIES

- ATF–II MISSION: DEMONSTRATE CLEAN, HIGH–BETA LONG-PULSE TO STEADY–STATE OPERATION AT REACTOR-RELEVANT PLASMA PARAMETERS IN AN OPTIMIZED TOROIDAL CONFIGURATION
- COST CONSTRAINT
  - CONSTRUCTION $\lesssim$300 M$
  - OPERATING $\lesssim$ 50 M$/YEAR
- SHOULD COMPLEMENT SIMILAR STUDIES IN JAPAN, GERMANY, ETC.
- TWO MAIN OPTIONS
  - HYDROGEN FEASIBILITY EXPERIMENT WITH SUPERCONDUCTING COILS
  - HIGH Q (OR IGNITION) D–T EXPERIMENT WITH COPPER COILS

ATF–II A: HYDROGEN FEASIBILITY EXPERIMENT WITH SUPERCONDUCTING COILS

ADVANTAGES

- COIL CAPABLE OF STEADY-STATE OPERATION AT MODEST COST
- NO SHIELDING, TRITIUM HANDLING, REMOTE MAINTENANCE, ETC.
- PHYSICS GOALS FLEXIBLE (HIGH T_i, $n\tau_E$, $\langle\beta\rangle$, etc.)

DISADVANTAGES

- NO D–T OPERATION, RESTRICTED D–D OPERATION
- NO ALPHA HEATING SO HIGHER AUXILIARY HEATING POWER REQUIRED
- LONGER PULSE TO STEADY-STATE HEATING REQUIRED
- HIGHER INITIAL COST
- SUPERCONDUCTING COIL CONSTRUCTION

ATF–II B: HIGH Q (OR IGNITION) D–T EXPERIMENT WITH COPPER COILS

ADVANTAGES

- CAN STUDY DOMINANT ALPHA HEATING EFFECTS ON STELLARATORS
- REQUIRES SHORTER-PULSE, LOWER AUXILIARY HEATING POWER
- COIL CONSTRUCTION SIMPLE

DISADVANTAGES

- TRITIUM HANDLING, REMOTE MAINTENANCE, PERSONNEL SHIELDING, ETC.
- HIGH OPERATING COST FOR STEADY-STATE OPERATION
- INFLEXIBLE PHYSICS GOALS – $Q \gtrsim 10$

RATIONALE FOR D–T STELLARATOR

- CAN STELLARATOR–SPECIFIC ALPHA–PARTICLE PHYSICS BE EXTRAPOLATED FROM SHORT PULSE TOKAMAK EXPERIMENTS?

- NEED STEP BETWEEN “LARGE” ($\bar{a} \sim 0.4\ m$) HYDROGEN EXPERIMENT AND IGNITED D–T DEMO ($\bar{a} \sim 2\ m$)?

- THERE ARE STELLARATOR–SPECIFIC ISSUES WITH AN IGNITED D–T PLASMA
  - CONFINEMENT (P_α DETERIORATION?)
  - MHD EQUILIBRIUM AND STABILITY (p_α)
  - ELECTRIC FIELDS (ALPHA LOSSES)
  - VELOCITY–SPACE INSTABILITIES (f_α)
  - TEMPERATURE CONTROL
  - ASH REMOVAL

CONCLUSIONS

- LOW-ASPECT-RATIO TORSATRONS COULD LEAD TO COMPACT REACTORS ONE-HALF TO ONE-THIRD THE SIZE OF MORE CONVENTIONAL STELLARATOR REACTORS

- ELECTRON RIPPLE-INDUCED TRANSPORT MAIN LOSS MECHANISM, DENSITY PEAKING HELPS