Current Profile Control Issues

Advanced Tokamak Workshop

General Atomics, 3/9-11/99

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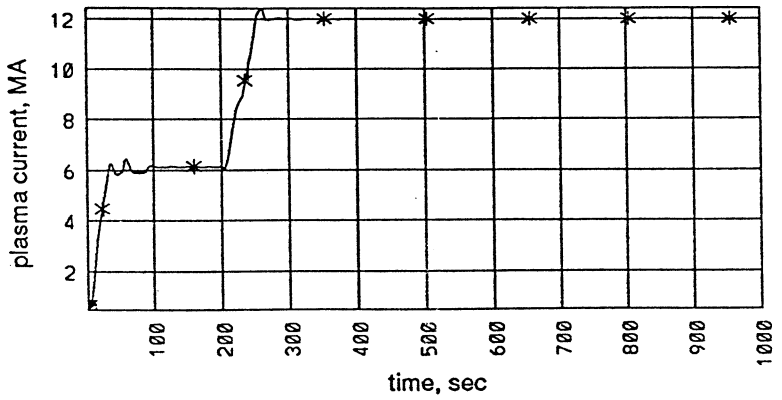
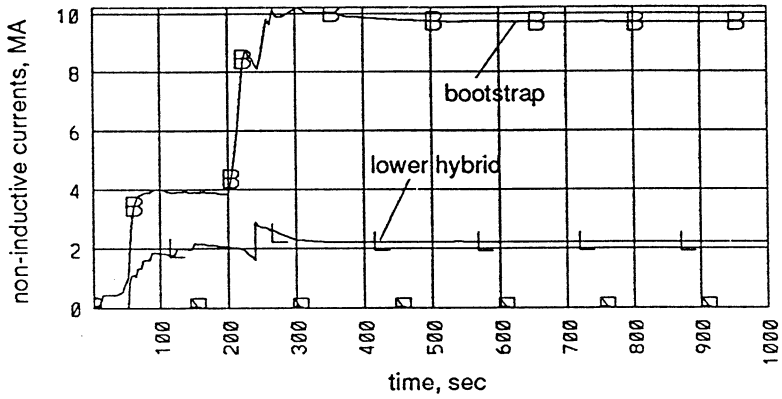
Introduction

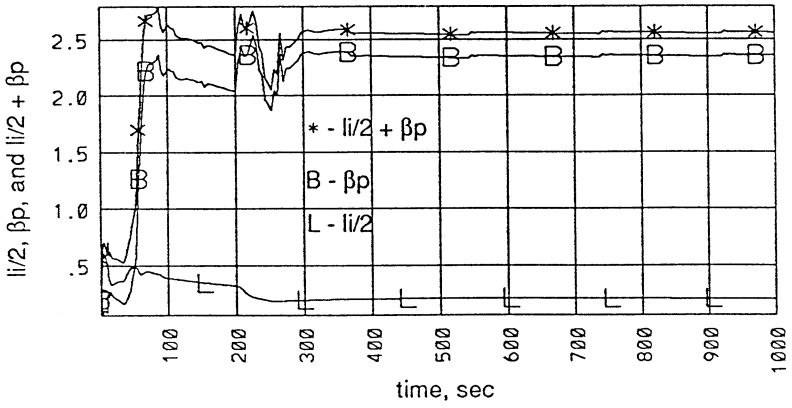
- the current profile control problem in tokamaks breaks into two distinct areas
  - controlling in the presence of significant inductive current
  - controlling fully non-inductive current
- these two areas further break down into
  - pre-programmed current profile control (open loop)
  - feedback current profile control (closed loop)
- present results of TSC simulations of the ITER reverse shear discharge
- present results of attempt to model CMOD evolution to a reverse shear plasma

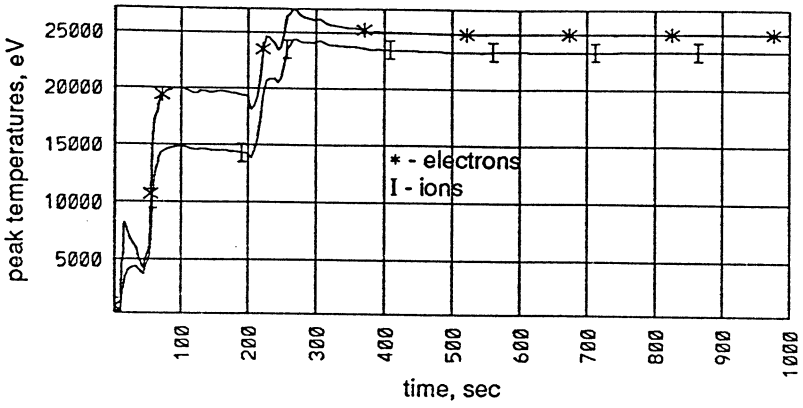
Simulation of ITER Reversed Shear Plasma

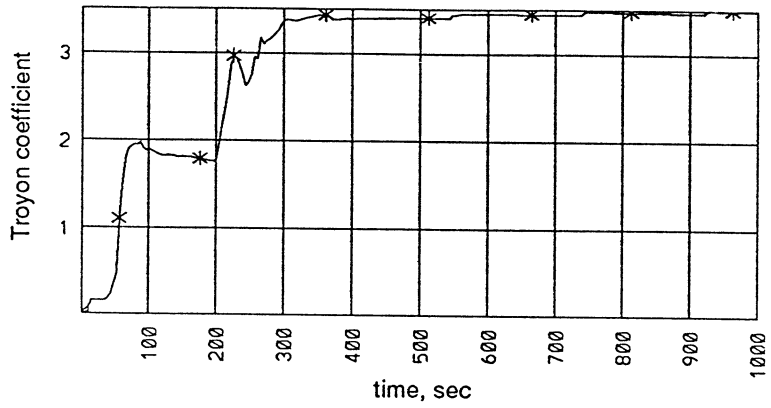
- this represents current profile control through pre-programming
- the discharge can be broken up into five phases
  - inductive plasma current rampup
  - transition to low β – low current non-inductive plasma
  - transition to high β – high current non-inductive plasma
  - flattop
  - rampdown (not modelled)

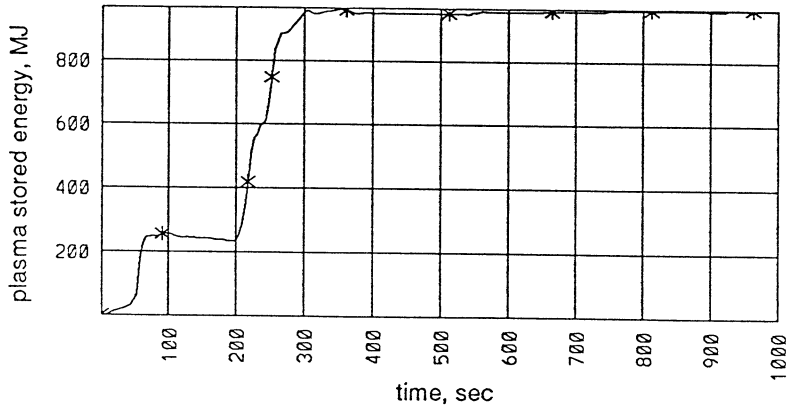

plasma current, MA
12
10
8
6
4
2
100
200
300
400
500
600
700
800
900
1000
time, sec

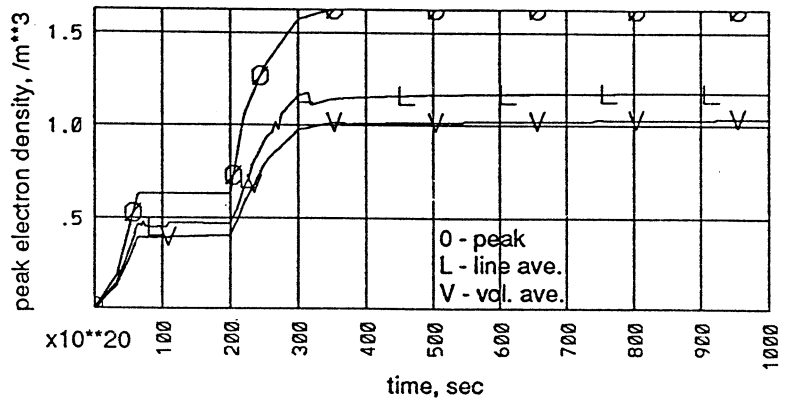

non-inductive currents, MA
10
8
6
4
2
0
bootstrap
lower hybrid
100
200
300
400
500
600
700
800
900
1000
time, sec

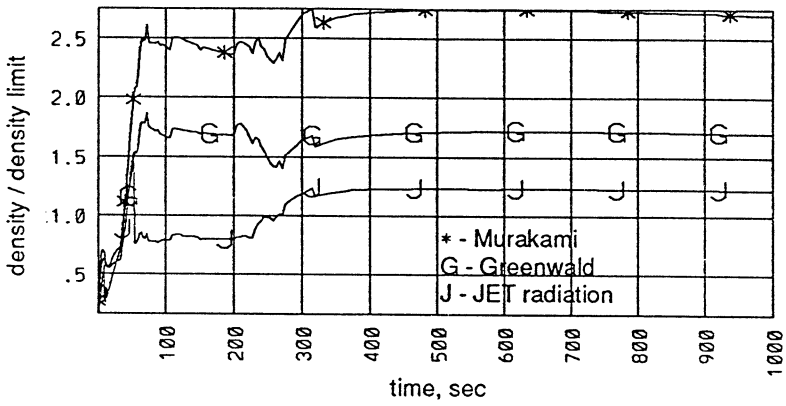

li/2, βp, and li/2 + βp
2.5
2.0
1.5
1.0
.5
* - li/2 + βp
B - βp
L - li/2
100
200
300
400
500
600
700
800
900
1000
time, sec

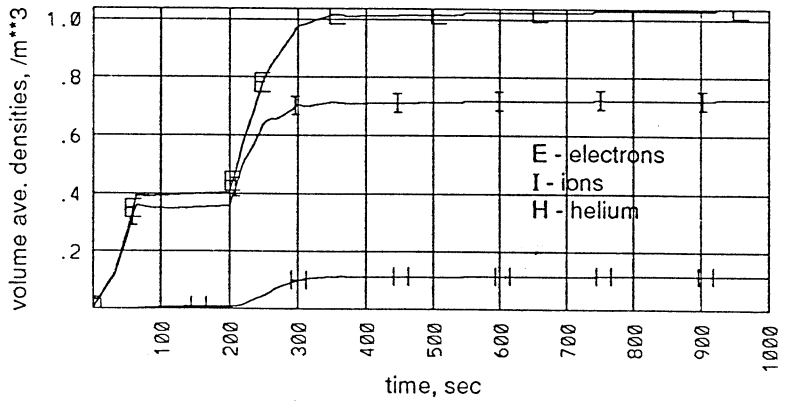

peak temperatures, eV
25000
20000
15000
10000
5000
* - electrons
I - ions
100
200
300
400
500
600
700
800
900
1000
time, sec


Troyon coefficient
3
2
1
100
200
300
400
500
600
700
800
900
1000
time, sec


plasma stored energy, MJ
800
600
400
200
100
200
300
400
500
600
700
800
900
1000
time, sec

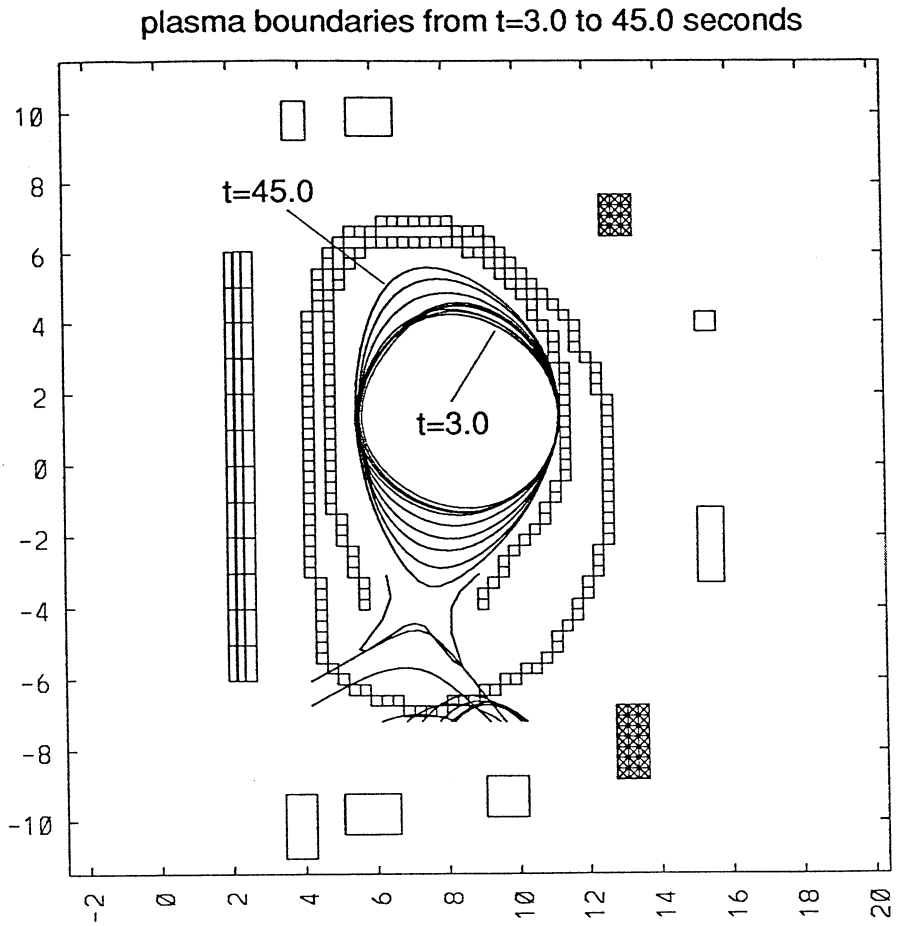

peak electron density, /m**3
1.5
1.0
.5
x10**20
100
200
300
400
500
600
700
800
900
1000
time, sec
0 - peak
L - line ave.
V - vol. ave.

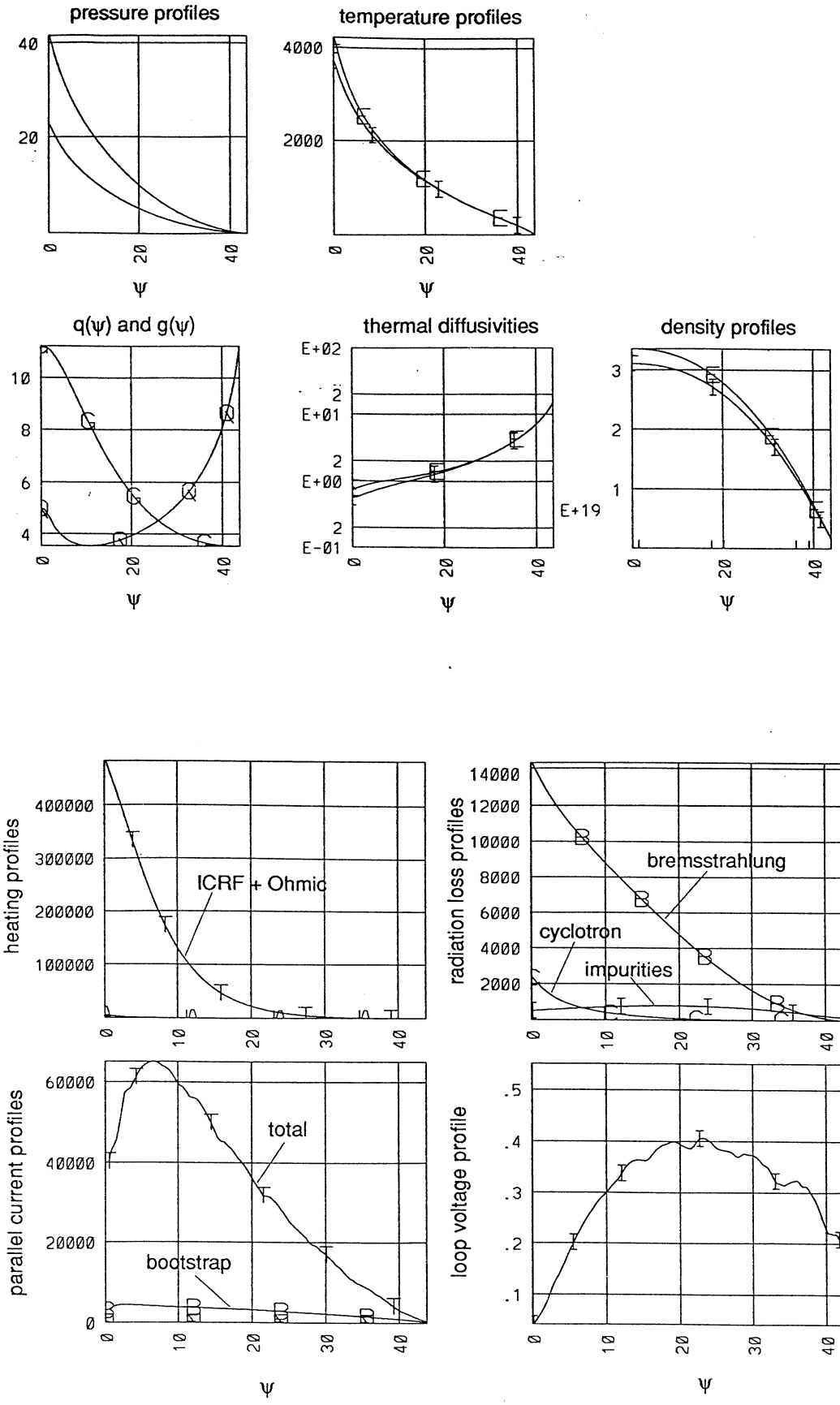

density / density limit
2.5
2.0
1.5
1.0
.5
100
200
300
400
500
600
700
800
900
1000
time, sec
* - Murakami
G - Greenwald
J - JET radiation

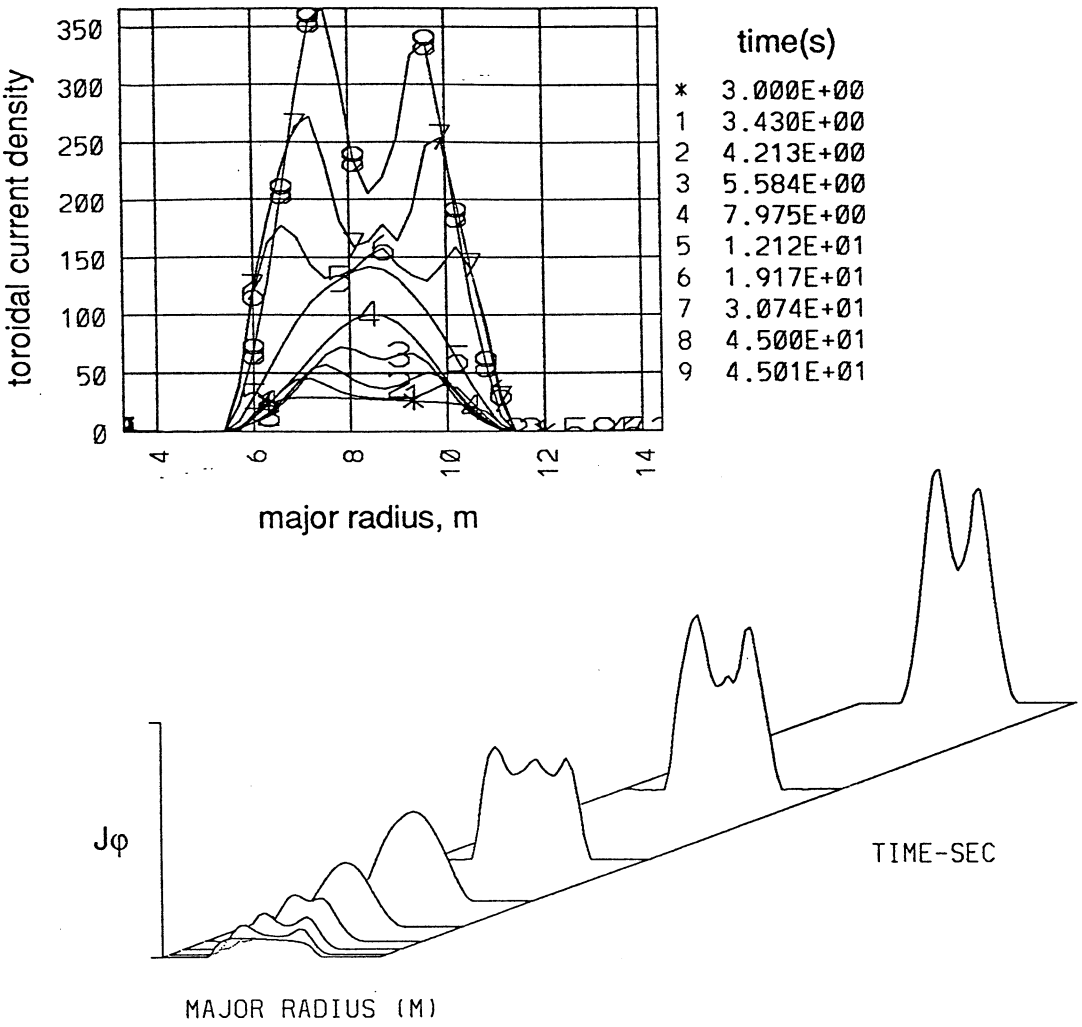

volume ave. densities, /m**3
1.0
.8
.6
.4
.2
100
200
300
400
500
600
700
800
900
1000
time, sec
E - electrons
I - ions
H - helium

Simulation of ITER Reversed Shear Plasma Inductive Plasma Current Rampup, t=0-45 s

- the plasma starts as a large circular plasma and is shaped during this phase
- the plasma current is ramped up to 6 MA, half its final value
  - the lower plasma current is to avoid large inductive current which will diffuse to the core and make hollow profile formation difficult
- between 5-15 MW of power is injected to slow current diffusion
- the electron density is ramped up to 0.5×10^{20} /m^3

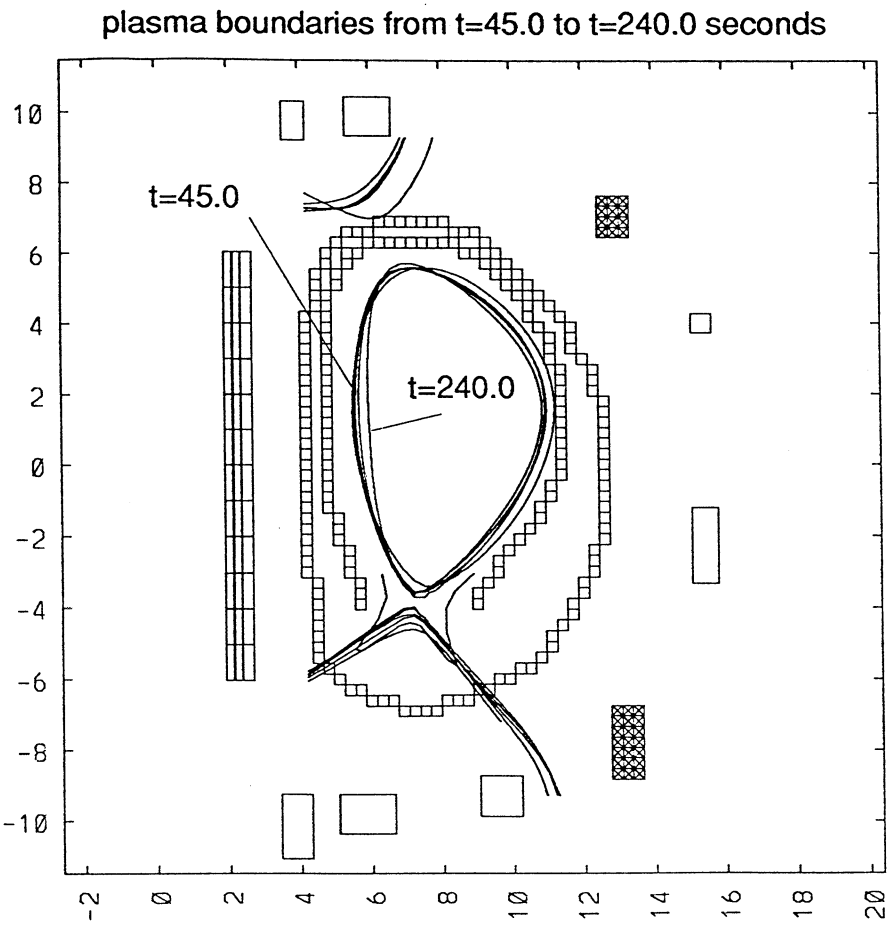


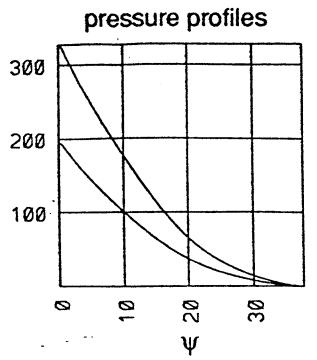

pressure profiles
temperature profiles
q(ψ) and g(ψ)
thermal diffusivities
density profiles
heating profiles
ICRF + Ohmic
radiation loss profiles
bremsstrahlung
cyclotron
impurities
parallel current profiles
total
bootstrap
loop voltage profile
ψ

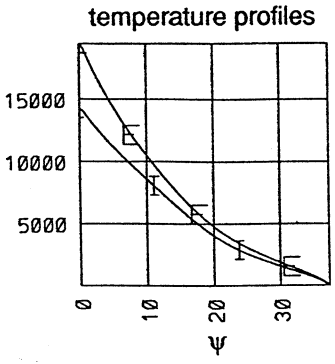

toroidal current density
350
300
250
200
150
100
50
0
4
6
8
10
12
14
major radius, m
time(s)
* 3.000E+00
1 3.430E+00
2 4.213E+00
3 5.584E+00
4 7.975E+00
5 1.212E+01
6 1.917E+01
7 3.074E+01
8 4.500E+01
9 4.501E+01
Jφ
TIME-SEC
MAJOR RADIUS (M)

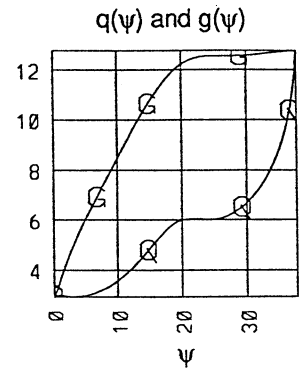
Simulation of ITER Reversed Shear Plasma Transition to Low-β – Low I_p, t=35-240 s

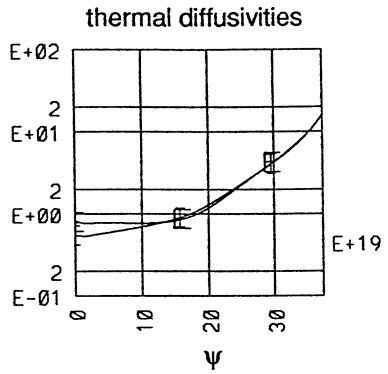
- the plasma current is held at 6 MA
- 50 MW of ICRF (FW) and 50 MW of LHCD are applied
- the peak electron density is fixed at 0.6×10^{20} /m^3
- β_p increases to 2.25 raising the bootstrap current to 4 MA
- the LHCD provides 2 MA
- the peak electron and ion temperatures become 20 and 15 keV
- l_i drops to 0.5 as the as the inductive current dissipates and the off-axis currents create a hollow profile
- the plasma minor radius drops and the plasma shaping is becoming more pronounced

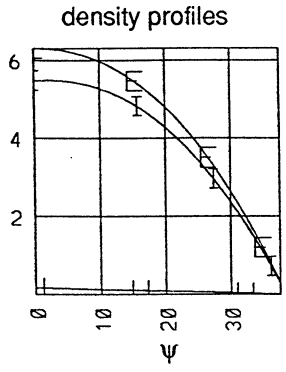


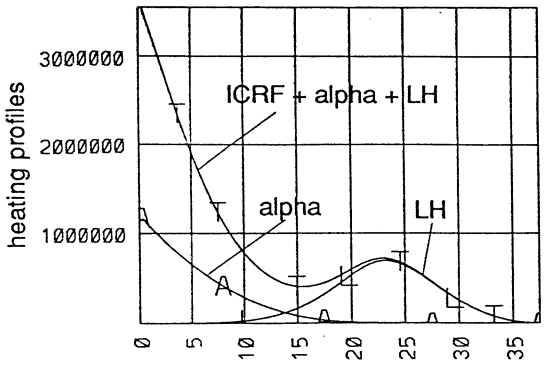

pressure profiles
300
200
100
0
10
20
30
ψ

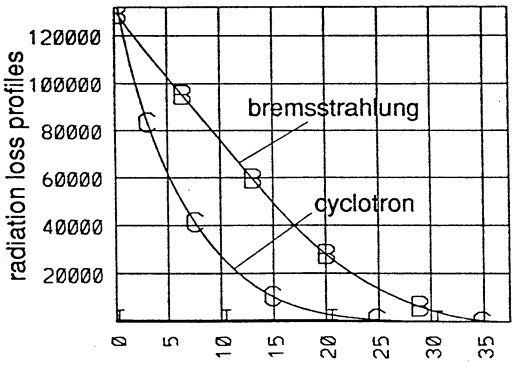

temperature profiles
15000
10000
5000
0
10
20
30
ψ

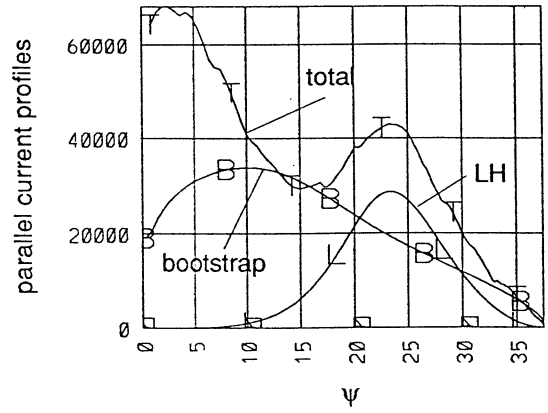

q(ψ) and g(ψ)
12
10
8
6
4
0
10
20
30
ψ

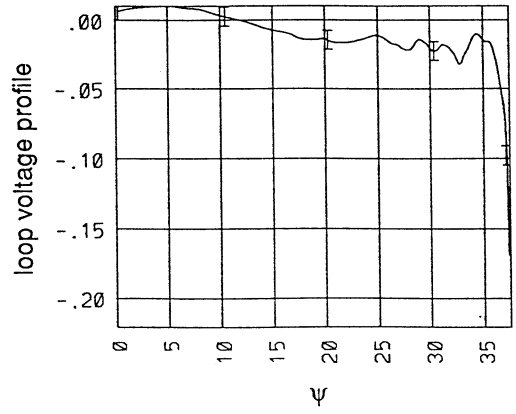

thermal diffusivities
E+02
2
E+01
2
E+00
2
E-01
E+19
0
10
20
30
ψ

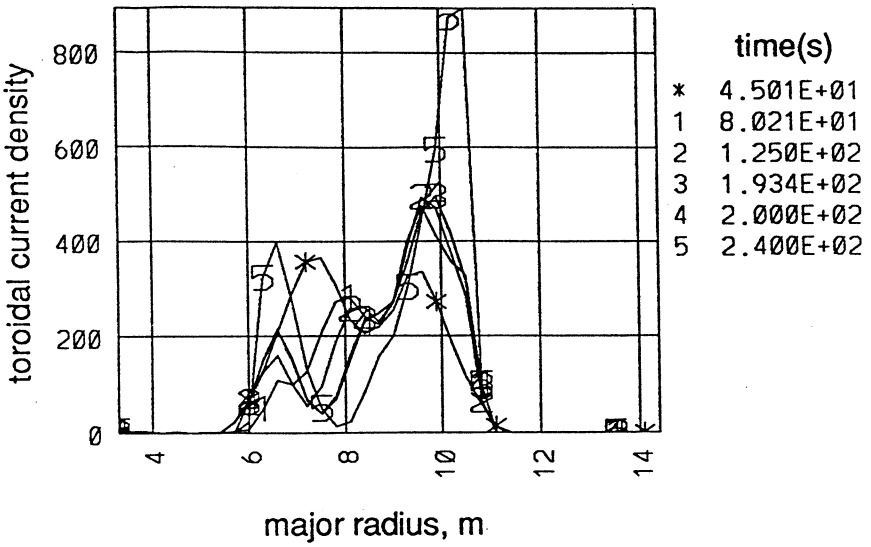

density profiles
6
4
2
0
10
20
30
ψ

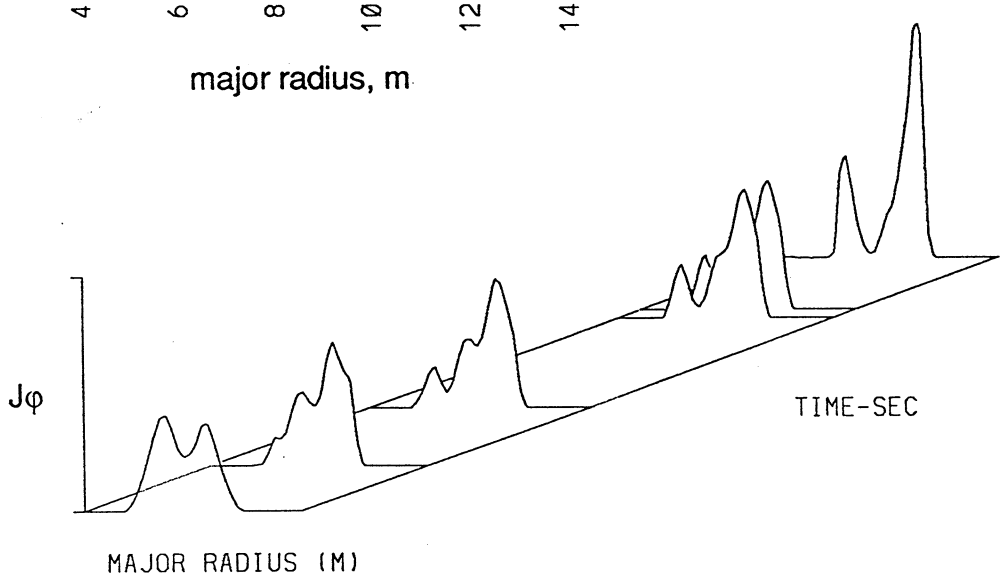

heating profiles
3000000
2000000
1000000
ICRF + alpha + LH
alpha
LH
0
5
10
15
20
25
30
35


radiation loss profiles
120000
100000
80000
60000
40000
20000
bremsstrahlung
cyclotron
0
5
10
15
20
25
30
35


parallel current profiles
60000
40000
20000
0
total
LH
bootstrap
0
5
10
15
20
25
30
35
ψ

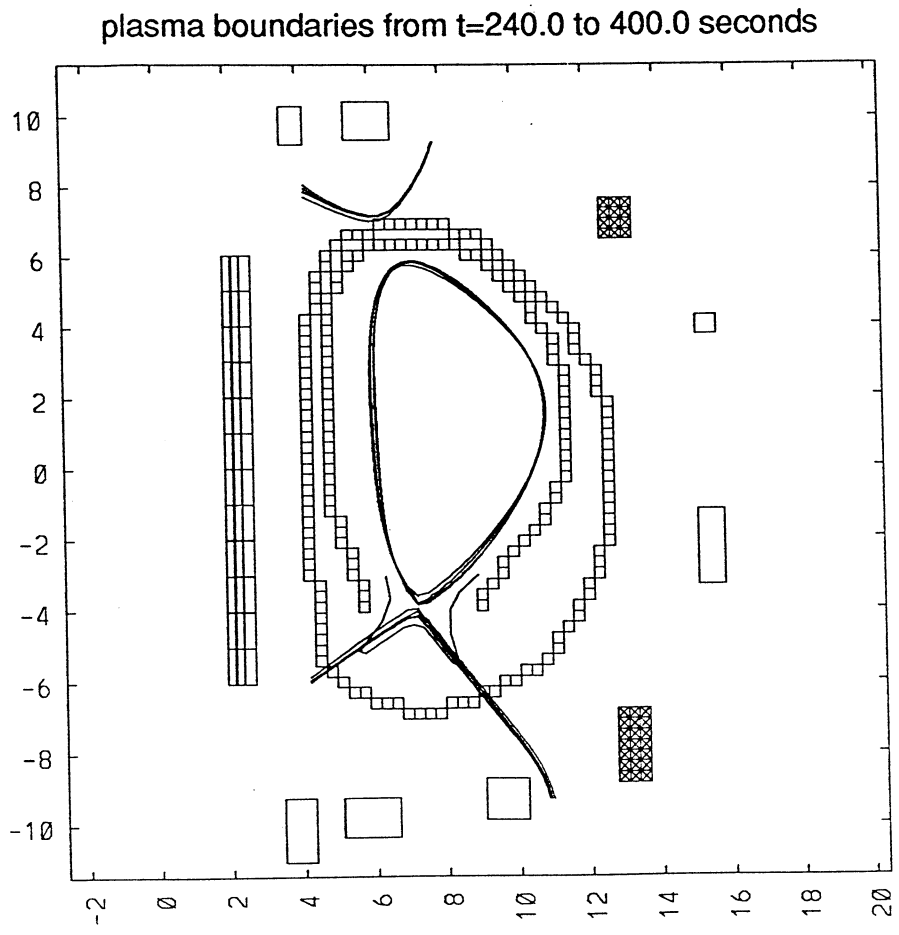

loop voltage profile
.00
-.05
-.10
-.15
-.20
0
5
10
15
20
25
30
35
ψ

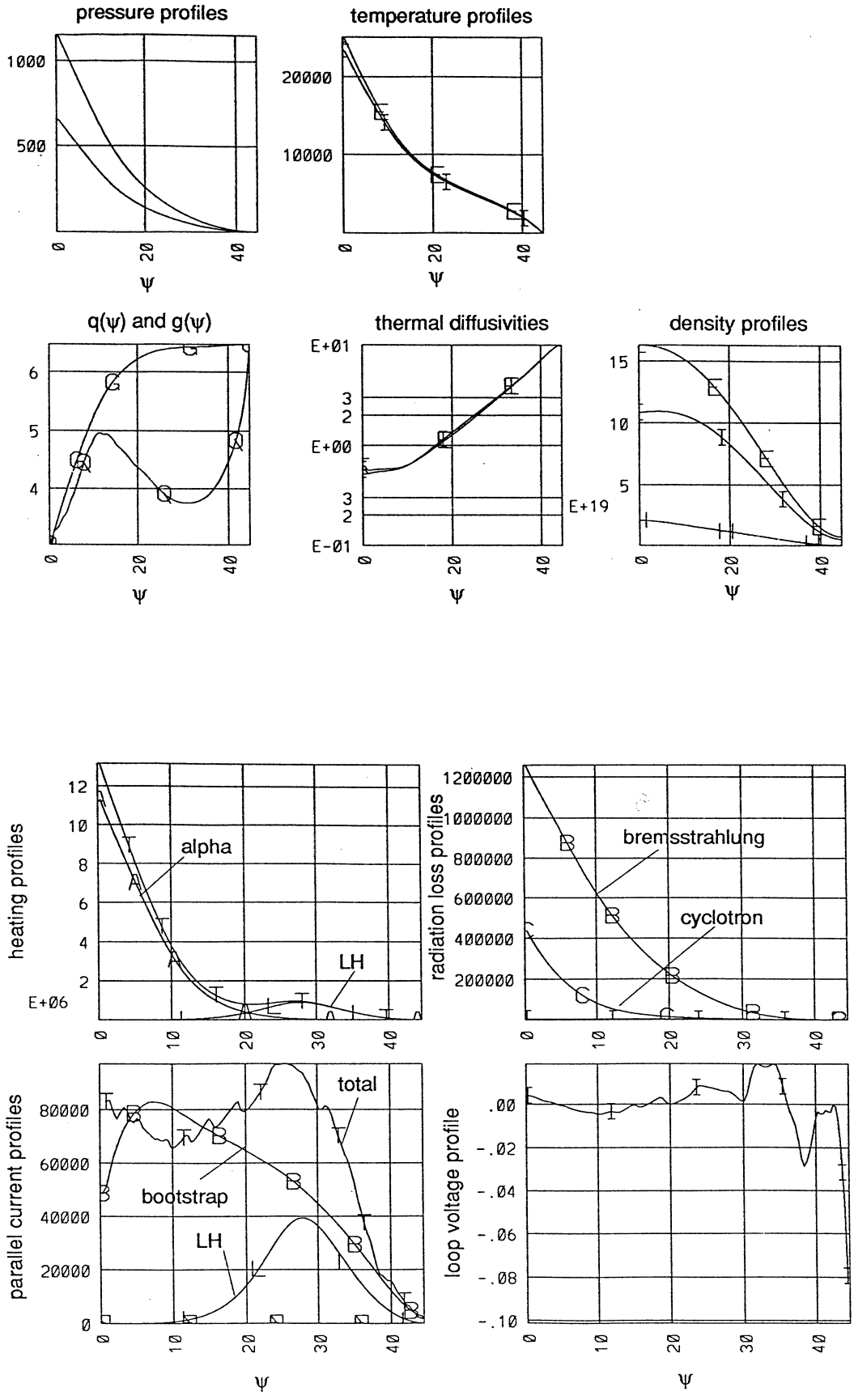

toroidal current density
800
600
400
200
0
4
6
8
10
12
14
major radius, m
time(s)
* 4.501E+01
1 8.021E+01
2 1.250E+02
3 1.934E+02
4 2.000E+02
5 2.400E+02

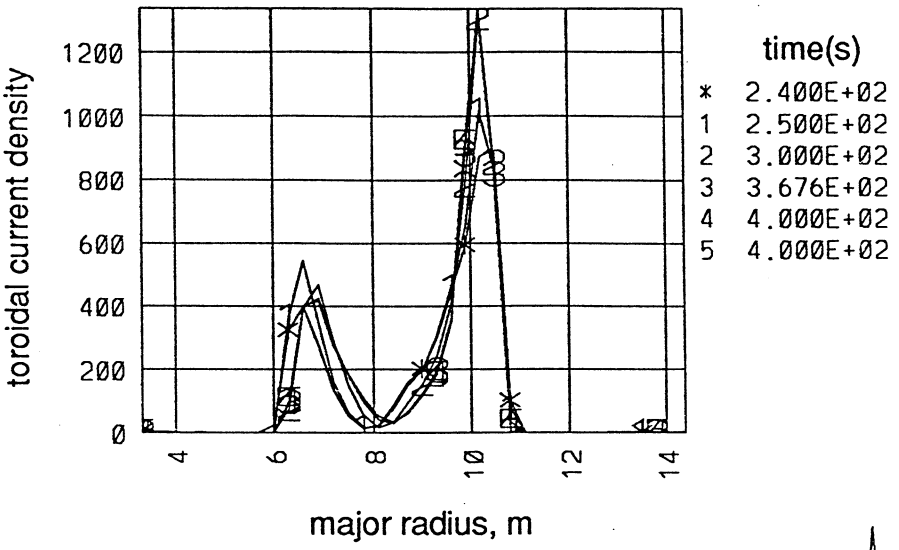

Jφ
TIME-SEC
MAJOR RADIUS (M)

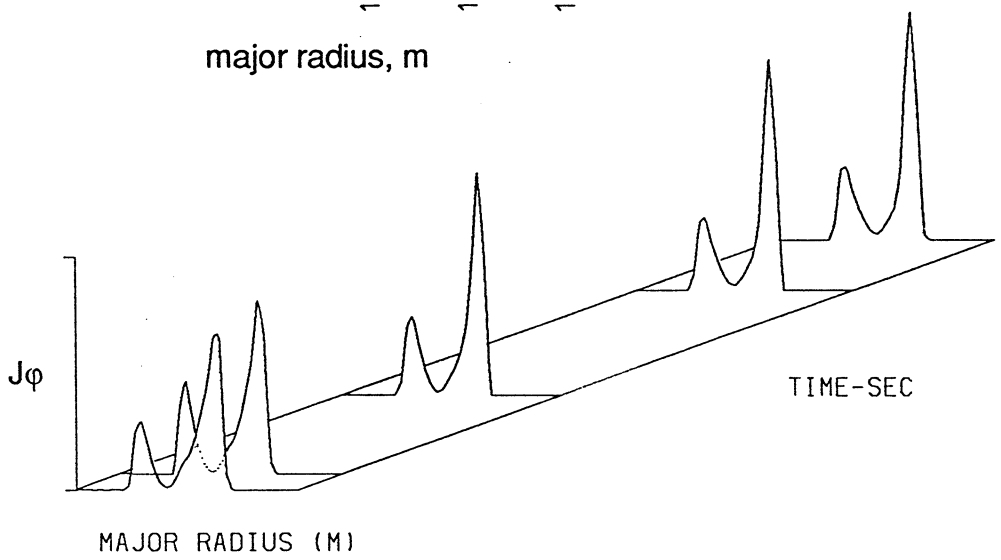
Simulation of ITER Reversed Shear Plasma Transition to High-β – High I_p, t=240-400 s

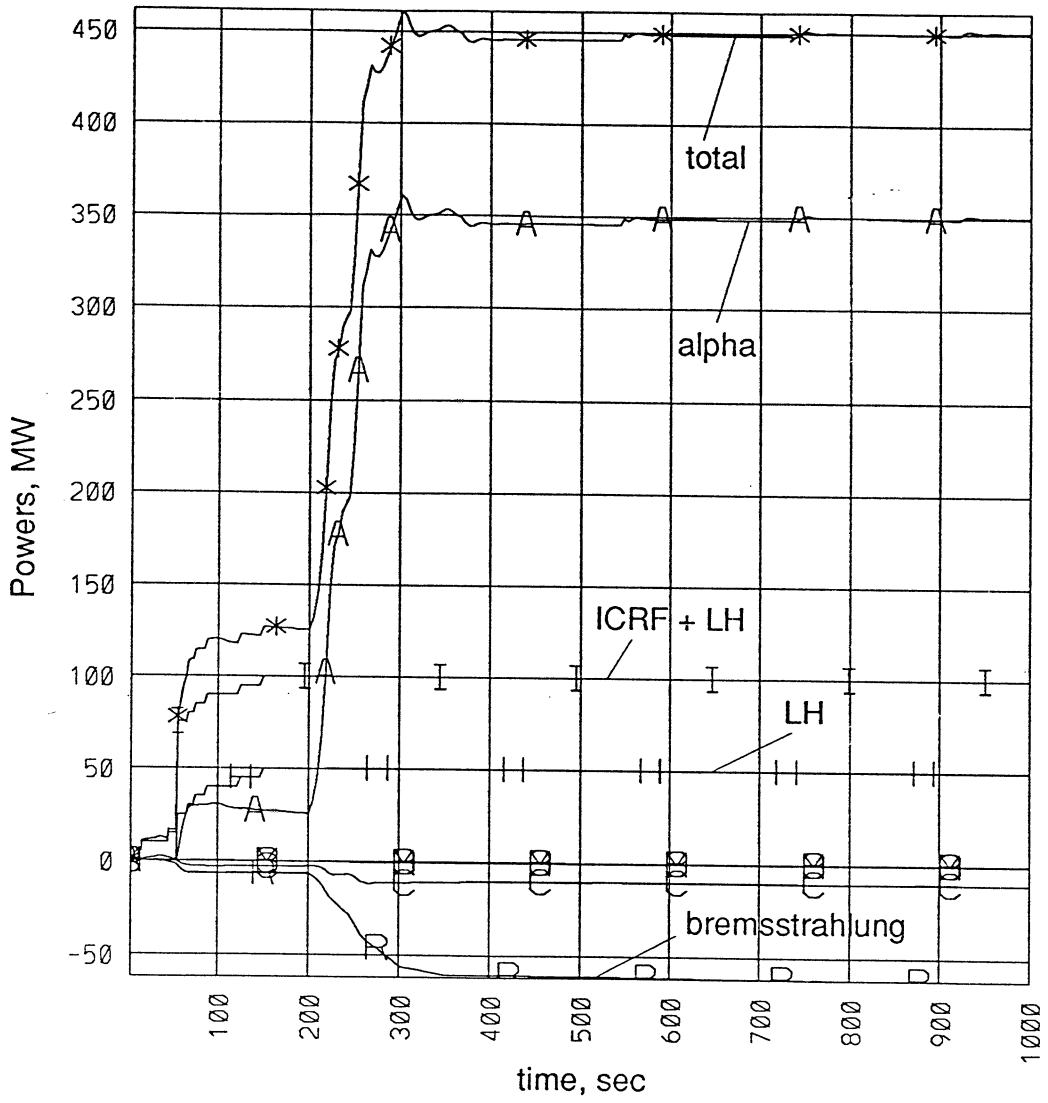
- in this phase the density is increased and the formation of an internal transport barrier is assumed, leading to a more peaked density profile
- strong fusion heating follows
- the electron density increases to 1.6×10^{20} /m^3
- β_N increases to 3.5
- the bootstrap current increases to 10 MA, while the LH current remains at 2 MA
- the plasma becomes even more strongly shaped with κ=2.0 and δ=0.5
- the peak ion and electron temperatures reach 25 keV




pressure profiles
1000
500
0
20
40
ψ
temperature profiles
20000
10000
0
20
40
ψ
q(ψ) and g(ψ)
6
5
4
0
20
40
ψ
thermal diffusivities
E+01
3
2
E+00
3
2
E-01
E+19
0
20
40
ψ
density profiles
15
10
5
0
20
40
ψ
heating profiles
12
10
8
6
4
2
E+06
alpha
LH
0
10
20
30
40
radiation loss profiles
1200000
1000000
800000
600000
400000
200000
bremsstrahlung
cyclotron
0
10
20
30
40
parallel current profiles
80000
60000
40000
20000
0
total
bootstrap
LH
0
10
20
30
40
ψ
loop voltage profile
.00
-.02
-.04
-.06
-.08
-.10
0
10
20
30
40
ψ


toroidal current density
1200
1000
800
600
400
200
0
4
6
8
10
12
14
major radius, m
time(s)
* 2.400E+02
1 2.500E+02
2 3.000E+02
3 3.676E+02
4 4.000E+02
5 4.000E+02


Jφ
TIME-SEC
MAJOR RADIUS (M)

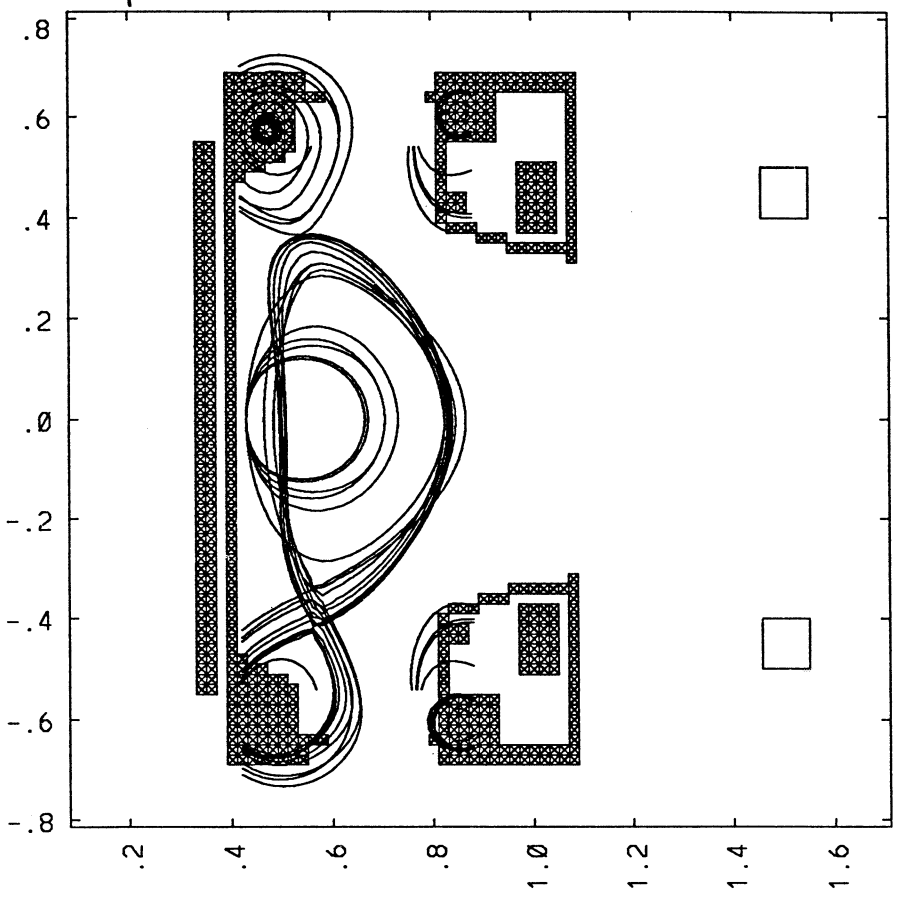

450
400
350
300
250
200
150
100
50
0
-50
Powers, MW
total
alpha
ICRF + LH
LH
bremsstrahlung
100
200
300
400
500
600
700
800
900
1000
time, sec

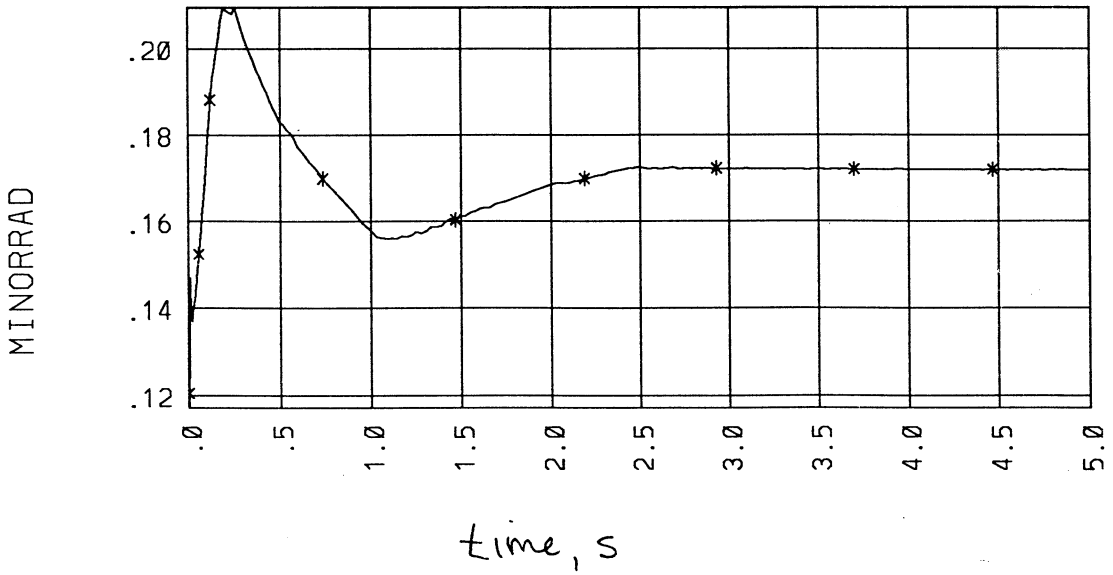
Simulation of CMOD Reversed Shear Evolution

- using 3 MW of LHCD and 2.5 MW of ICRH, at B_T=4.3-4.5 T
- with minimization of inductive current and sufficient CD/heating power we have obtained a nearly 100% non-inductive state in CMOD
- amount of CD/heating required depends primarily on the amount of bootstrap current obtained, which is uncertain
- we have used prescribed LH current deposition profiles based on CD calculations from Bonoli
- future work includes
  - improve PF coil current waveforms
  - use LSC for CD calculations in TSC
  - get better alignment with CMOD parameters

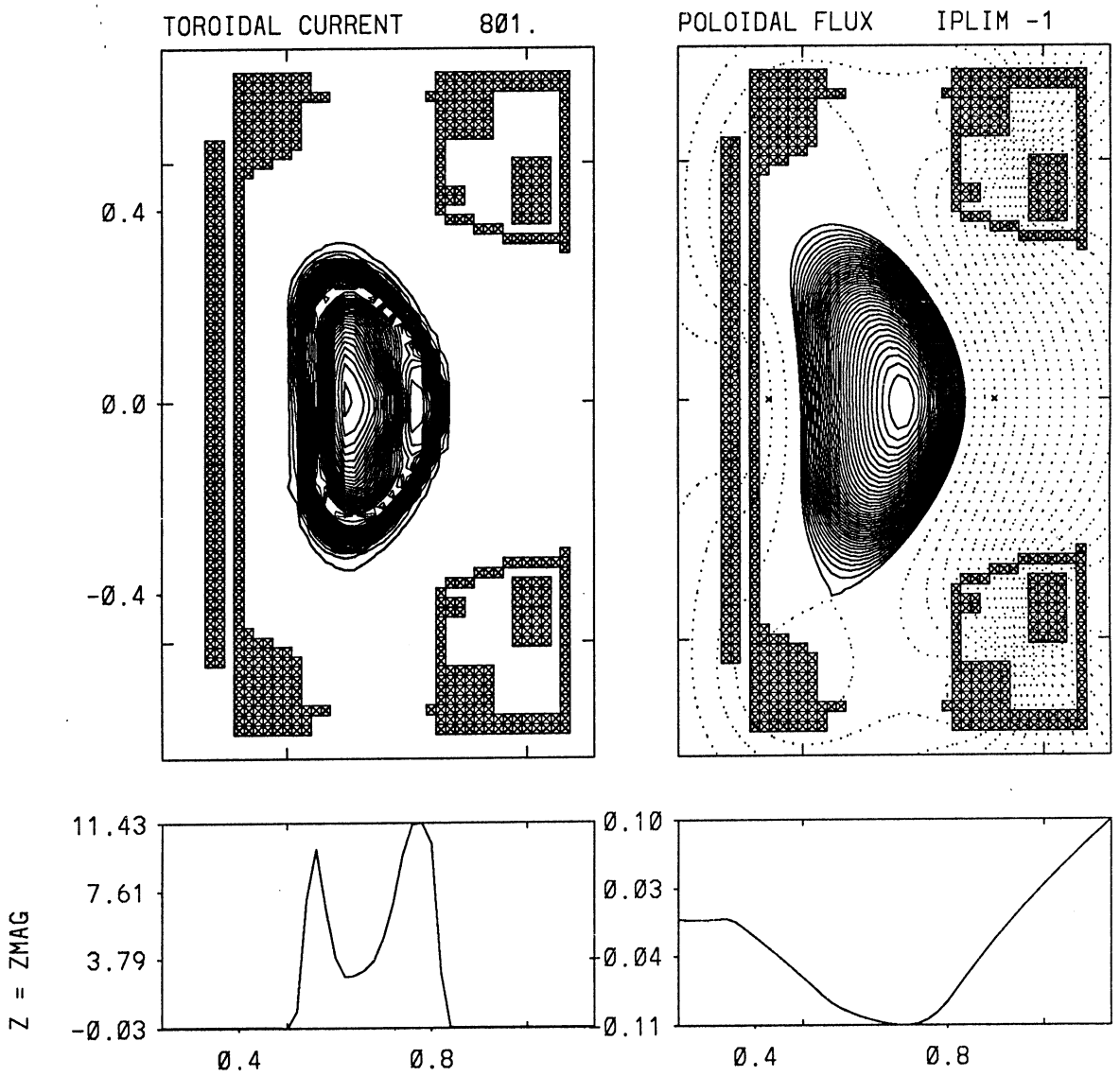
CMOD Simulation with TSC

plasma boundaries $t = 0 \rightarrow 5$ s

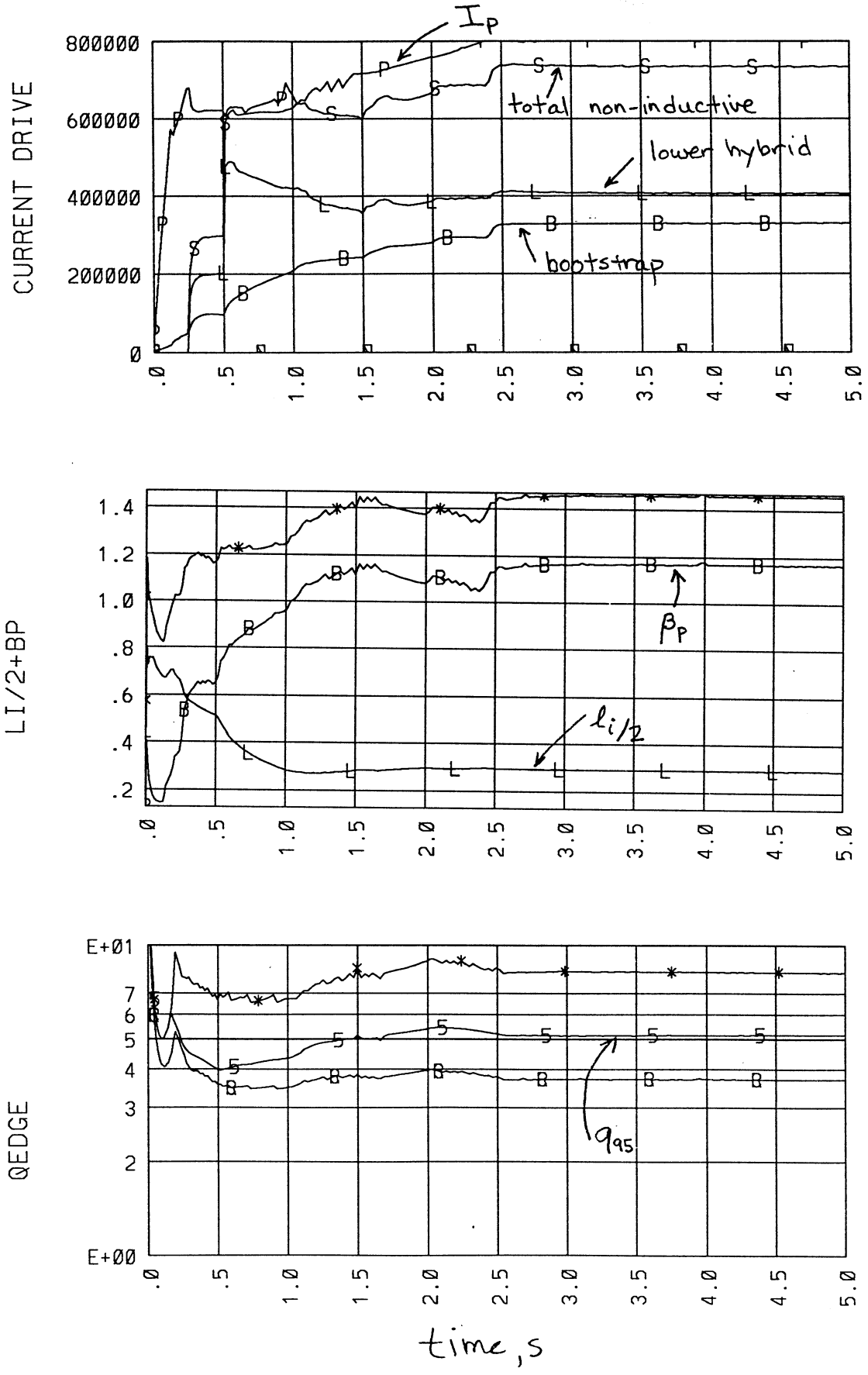




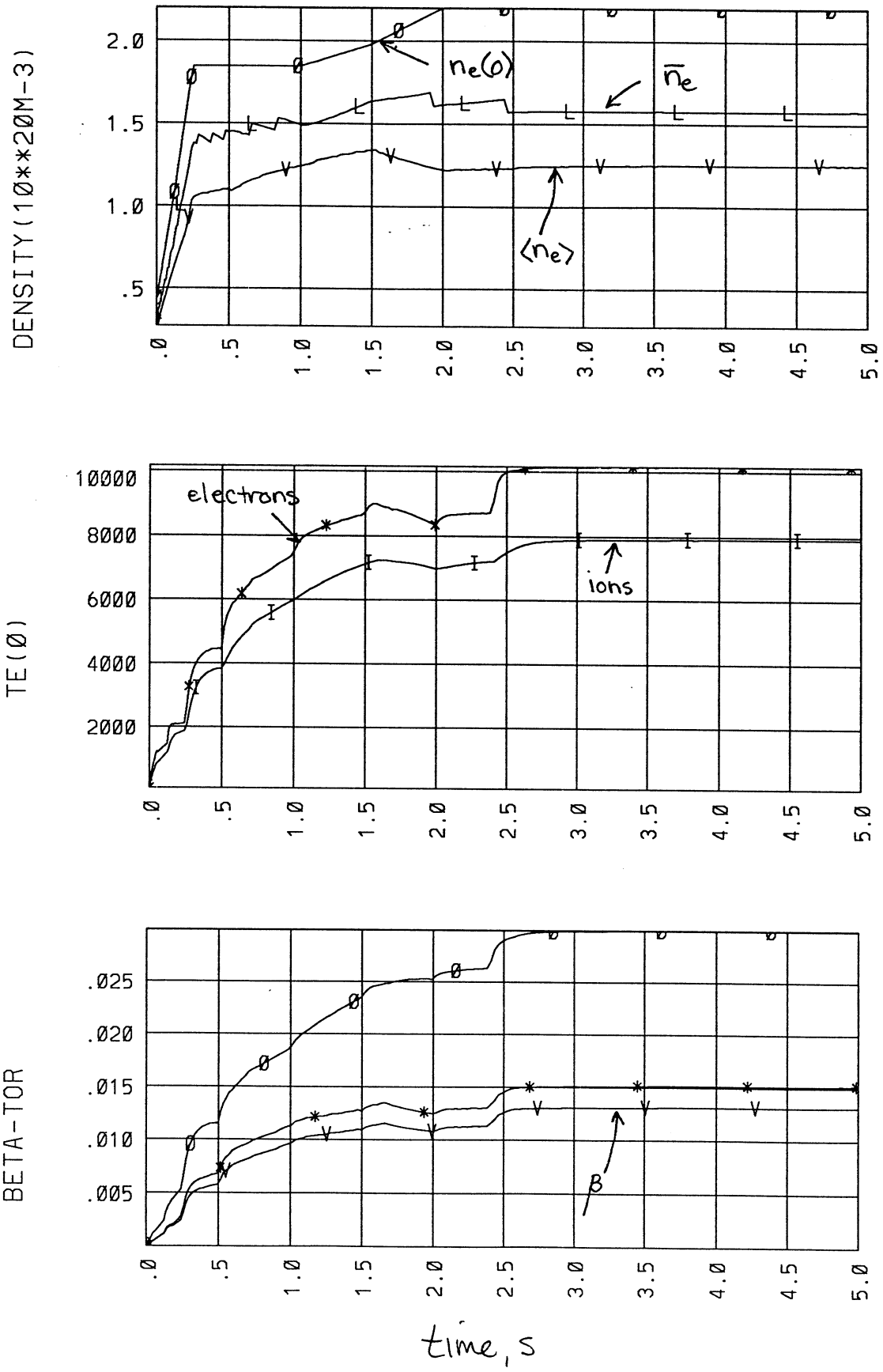
CMOD Simulation with TSC



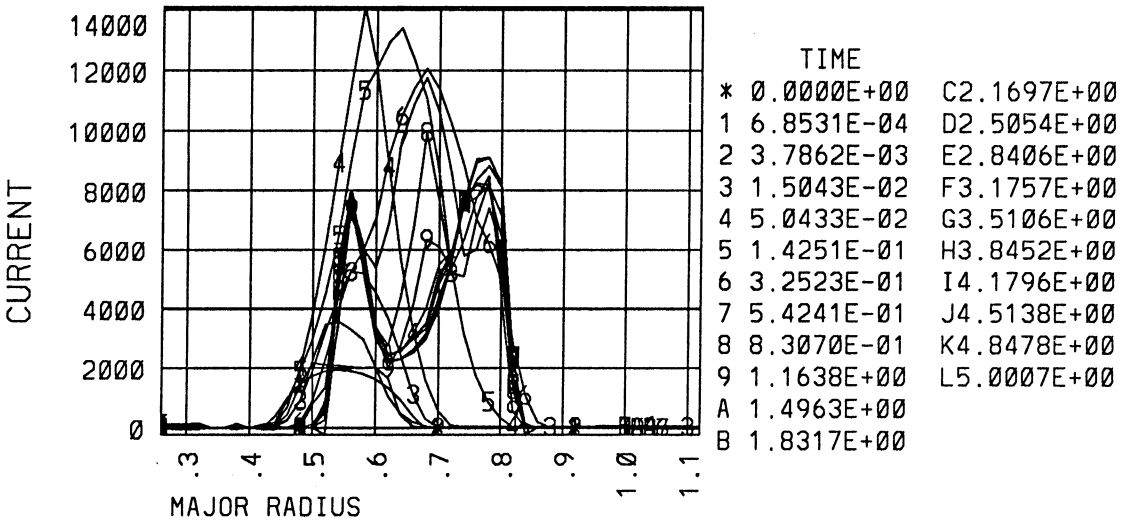
CMOD Simulation with TSC



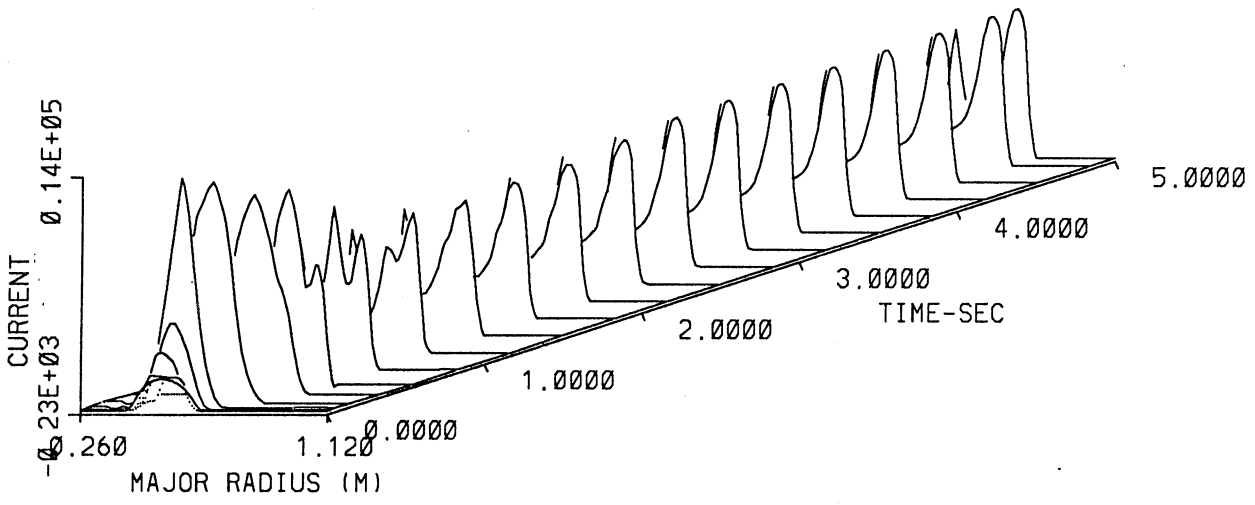
CMOD Simulation with TSC



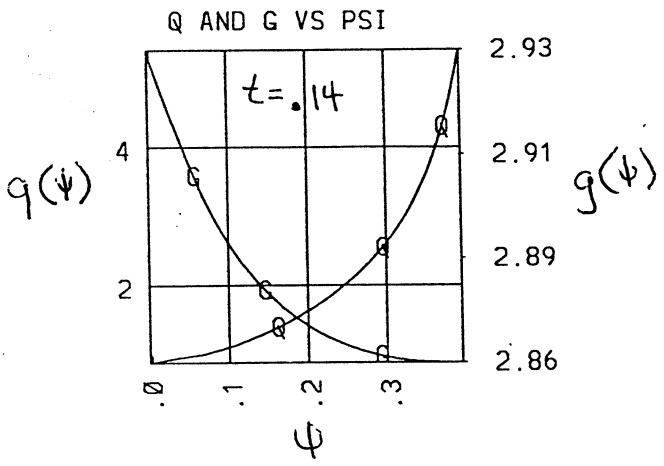
CMOD Simulation with TSC

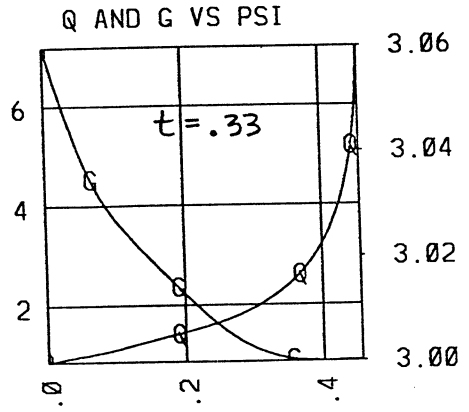


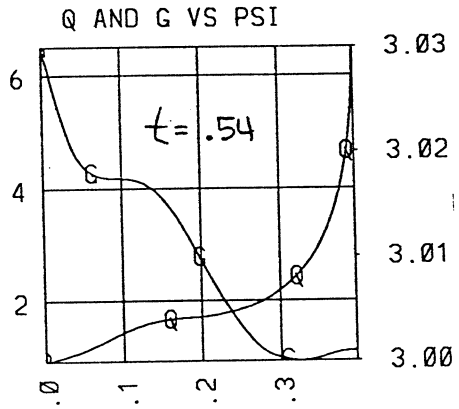
j_φ

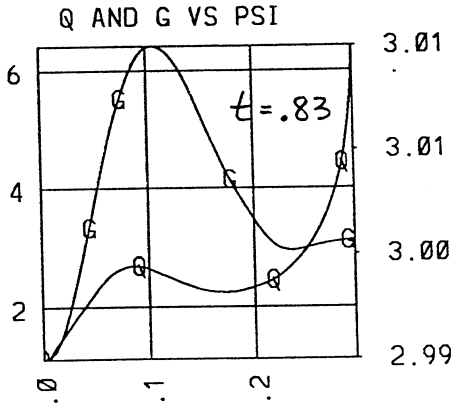


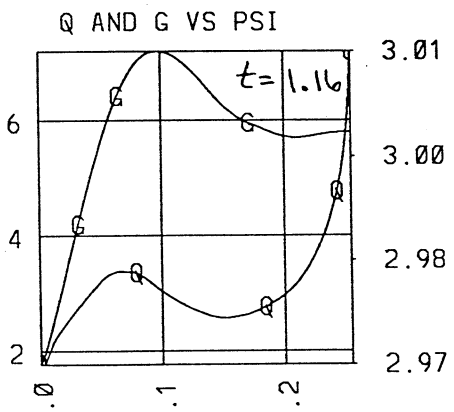
CURR DENS (AMPS/W-TOR FLX)
LOOP VOLTAGE VS PSI
t=.14
t=.33
t=.54
t=.83
t=1.16
t=1.5
t=1.83
t=2.5
ψ
ψ
V_L

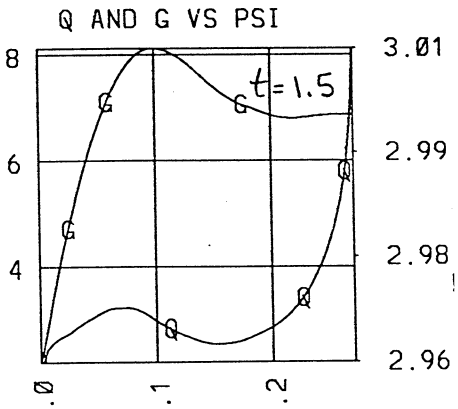

Q AND G VS PSI
t=.14
q(ψ)
g(ψ)
ψ
2.93
2.91
2.89
2.86
.0
.1
.2
.3
2
4

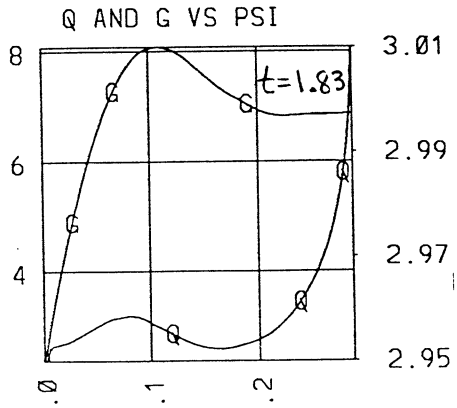

Q AND G VS PSI
t=.33
3.06
3.04
3.02
3.00
.0
.2
.4
2
4
6

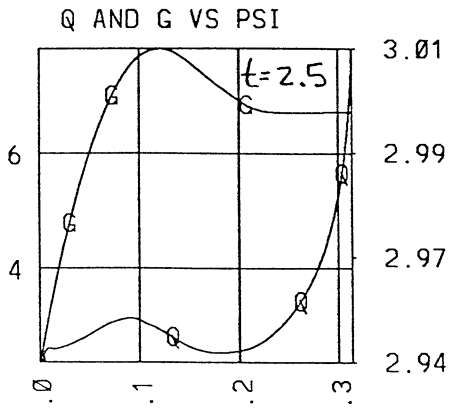

Q AND G VS PSI
t=.54
3.03
3.02
3.01
3.00
.0
.1
.2
.3
2
4
6


Q AND G VS PSI
t=.83
3.01
3.01
3.00
2.99
.0
.1
.2
2
4
6


Q AND G VS PSI
t=1.16
3.01
3.00
2.98
2.97
.0
.1
.2
2
4
6


Q AND G VS PSI
t=1.5
3.01
2.99
2.98
2.96
.0
.1
.2
4
6
8


Q AND G VS PSI
t=1.83
3.01
2.99
2.97
2.95
.0
.1
.2
4
6
8


Q AND G VS PSI
t=2.5
3.01
2.99
2.97
2.94
.0
.1
.2
.3
4
6

CMOD Simulation with TSC