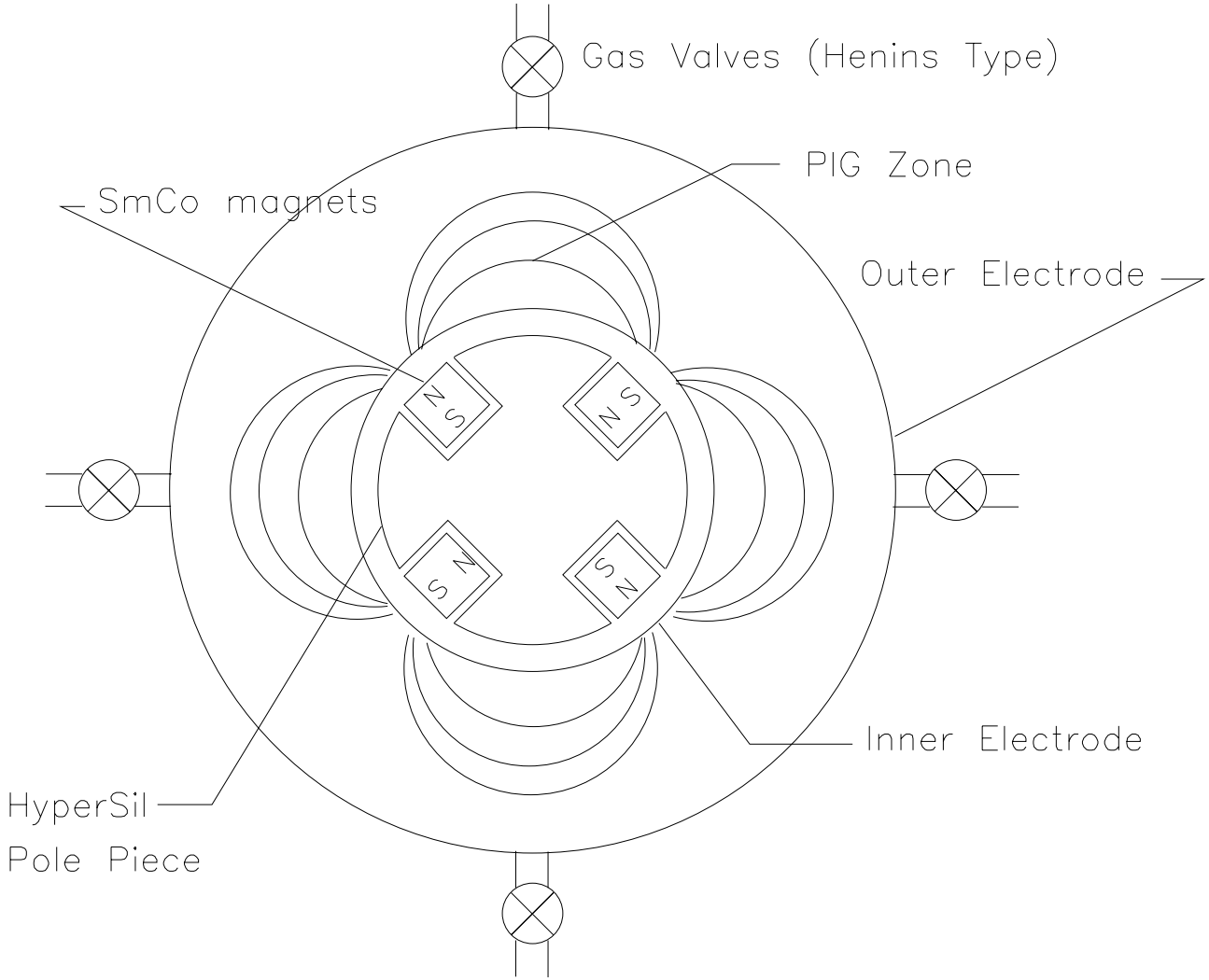
Experimental Studies of Spheromak Confinement and Heating on BCTX

Edward C. Morse and Charles W. Hartman
University of California, Berkeley

PIG Electrode Improves Breakdown



BCTX Features

- Fast Spheromak Formation with Marshall Gun
- 288 kJ Capacitor Bank
- B_{pol} to 4.0 kG observed
- 20 MW RF Heating System
- T_e to 200 eV observed

Stochastic Field Line Transport Model

- Electron Heat Balance: $U_m/\tau_B \sim B^2/T_e^{3/2}$
- Parallel Heat Conduction: $Q_e \sim T_e^{7/2}$
- Self-Similar Decay: $\vec{\nabla} \times \vec{B} = \lambda \vec{B}$, $\lambda = \text{const}$
- Gives $B \sim T_e^{5/2}$, $\qquad \tau_B \sim T_e^{3/2} \sim B^{3/5}$

0-D Model of Magnetic Decay

$$\frac{dB_p}{dt} = -\frac{\lambda^2 \eta}{\mu_0} B_p$$

$$\frac{dU_p}{dt} = \frac{dU_M}{dt} - Q^e_{cond}$$

$$Q^e_{cond} = \chi_{\parallel}(T_e/L) A_f$$

- $\chi_{\parallel}$ is Braginskii parallel electron value
- A_{fc} is area of stochastic magnetic flux
- L is equivalent length of flux line to wall

RF Heating Results

- Preionization Method obtained lower density $n_e \sim 1 - 2 \times 10^{14}\mathrm{cm}^{-3}$
- T_e to 200 eV with $t = 0$ RF On
- Enhanced MHD during RF Pulse
- Limited Improvement in τ_B

TRAC2 Modeling of Formation

- 2-D MHD Code
- Braginskii Resistivity, Ion Viscosity
- 16 Z $\times$ 48 R (FC) + 10 Z $\times$ 50 R (Gun)
- 3-D Effects NOT important during Formation
- 3-D Effects ARE important during Decay
- Close Agreement with Expt. for Formation

Figure Captions

Figure 1 (a) The Berkeley Compact Torus Experiment apparatus and diagnostics. (b) End-on view showing magnetic probe locations.

Figure 2 Initial magnetic fields in the gun. (a) Side view showing the initial poloidal fringe-field near the gun muzzle (from TRAC2 simulation) and the RB_θ contours and neutral density contours near the gas valves immediately after breakdown. (b) End-on view of the gun showing the quadrupolar PIG fields formed by four permanent bar magnets located inside the inner electrode near the gas valves.

Figure 3 B_{pol} (3a) and B_θ (3b) fields measured by probes 1-5, and circuit and gun current, and gun voltage (3c) shot 1880, $t = 0 - 300\mu$s. Insets on (3a) and (3b) show expanded view of times $t = 10 - 40\mu$s. TRAC2 simulations of poloidal field at Probe P5 (3a) and gun current (3c).

Figure Captions

Figure 4 (a) Multi-shot average of B_{pol} and B_θ vs time, with rms asymmetry of B_θ also shown. Zero-dimensional model of B_{pol} and T_e vs time. (b) Interferometer chord-averaged electron density for typical shot.

Figure 5 B_{pol} (5a) and B_θ (5b) fields measured by probes 1-5, and circuit and gun current, and gun voltage (c), shot 1855 ($I_{sol} = 0$), $t = 0 - 300\mu$s.

Figure 6 B_{pol} (6a) and B_θ (6b) fields measured by probes 1-5, and circuit and gun current, and gun voltage shot 1891, $t = 0 - 300\mu$s (flipped shot).

Figure 7 Current sheath position vs time obtained from calculation of instantaneous inductance from circuit current.

Figure 8 (a) "Ballooning" (ejection limit) current vs solenoid current, experimentally observed and theoretical prediction using Hammer's model.(b) Poloidal Field and poloidal flux in the flux conserver vs the initial poloidal flux in the gun ($\Phi = kI_{solenoid}$), shots 1852-1906, constant gun bank voltage = 10 kV.

Figure Captions

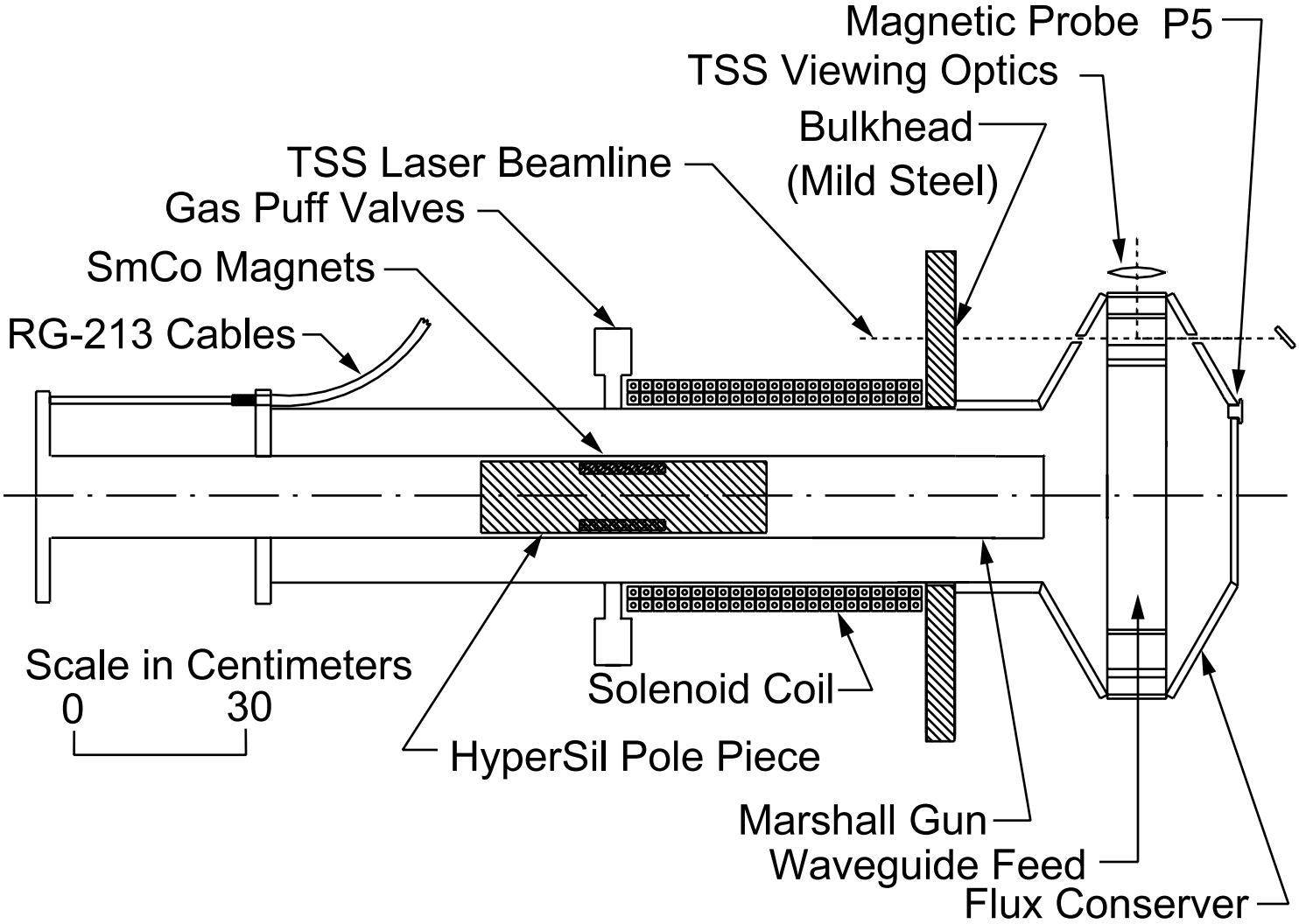
Figure 9 Poloidal field decay time vs Thomson scattering measurements of T_e for 34 shots at $t = 118\mu$s, all experimental parameters held constant.

Figure 10 Multi-shot average of magnetic decay time $\tau_B = B/(dB/dt)$ vs time, normal and flipped shots, and the same data divided by $(B/B_{peak})^{0.6}$.

Figure 11 Thomson scattering data for three shot types: (a) No RF heating,(b) RF-preionized (two-shot average), (c) RF heated shot (two-shot average). (d) Thomson T_e vs. $B/n_e^{0.5}$ for RF-heated shots (data) with 10% β limit shown.

Figure 12 TRAC2 simulation results for three times following discharge: (a) $t = 18.8\mu$s, (b) $t = 32.7\mu$s, (c) $t = 64.5\mu$s, and (d) Taylor state calculation for initial gun flux. Contours are RA_θ (poloidal flux) and vectors are flow velocities. The largest flow velocity shown is approx. 15 cm μs^{-1}.

Figure 1



Magnetic Probe Locations

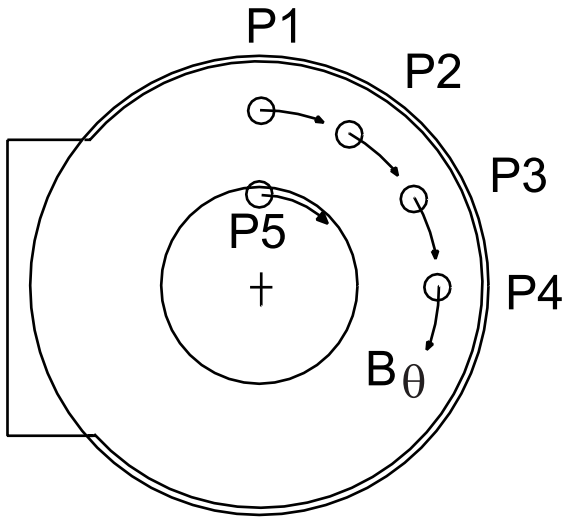
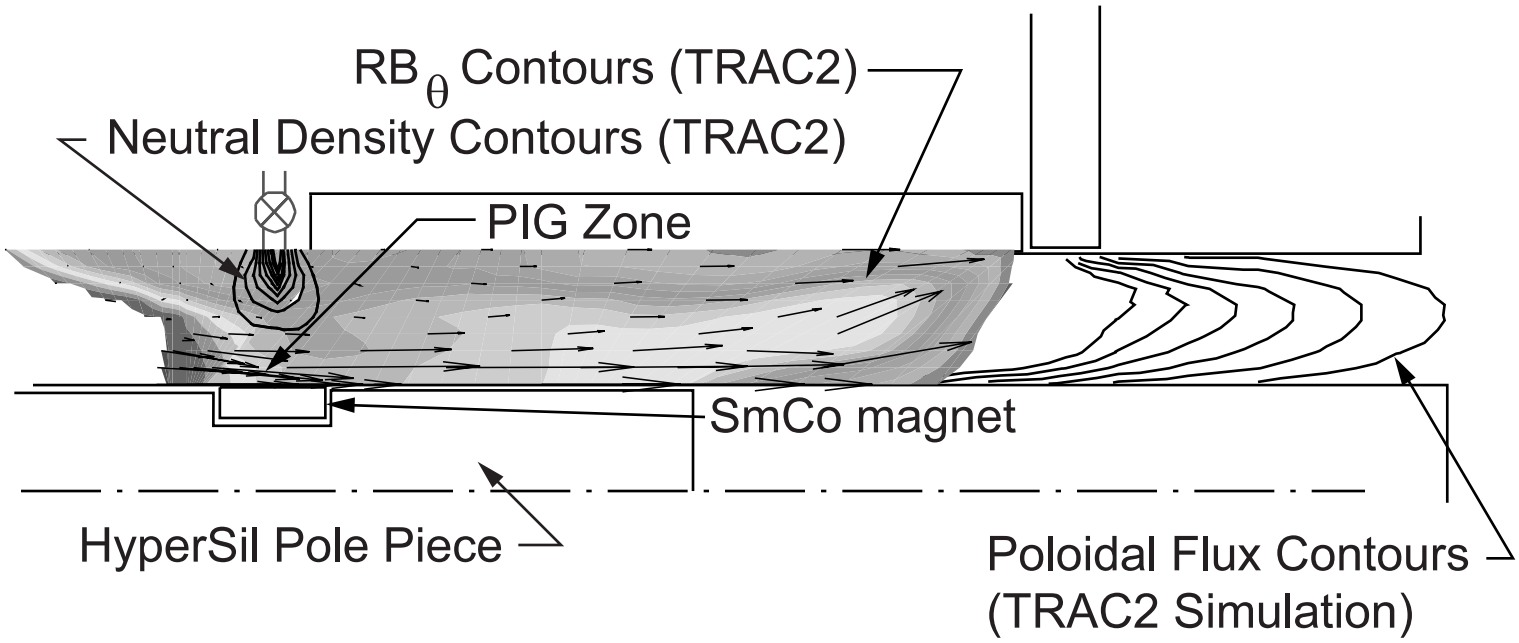


Figure 2


RB$_\theta$ Contours (TRAC2)
Neutral Density Contours (TRAC2)
PIG Zone
SmCo magnet
HyperSil Pole Piece
Poloidal Flux Contours
(TRAC2 Simulation)

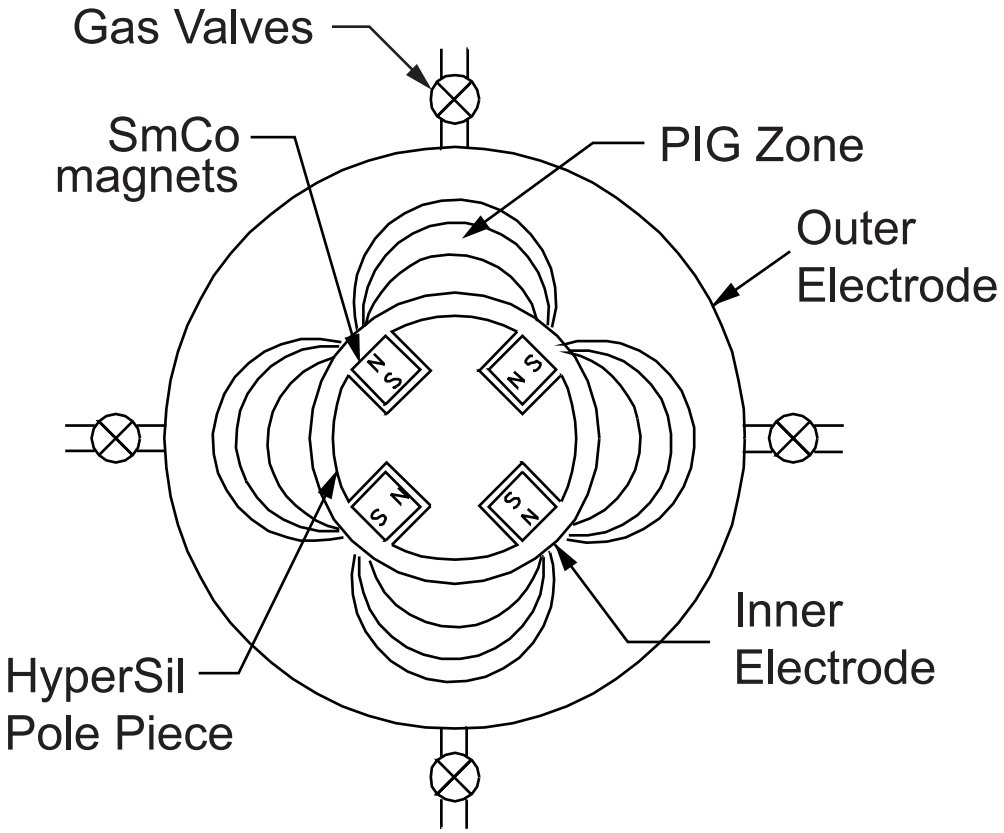

Gas Valves
SmCo
magnets
PIG Zone
Outer
Electrode
N
S
N
S
N
S
N
S
Inner
Electrode
HyperSil
Pole Piece

Figure 3

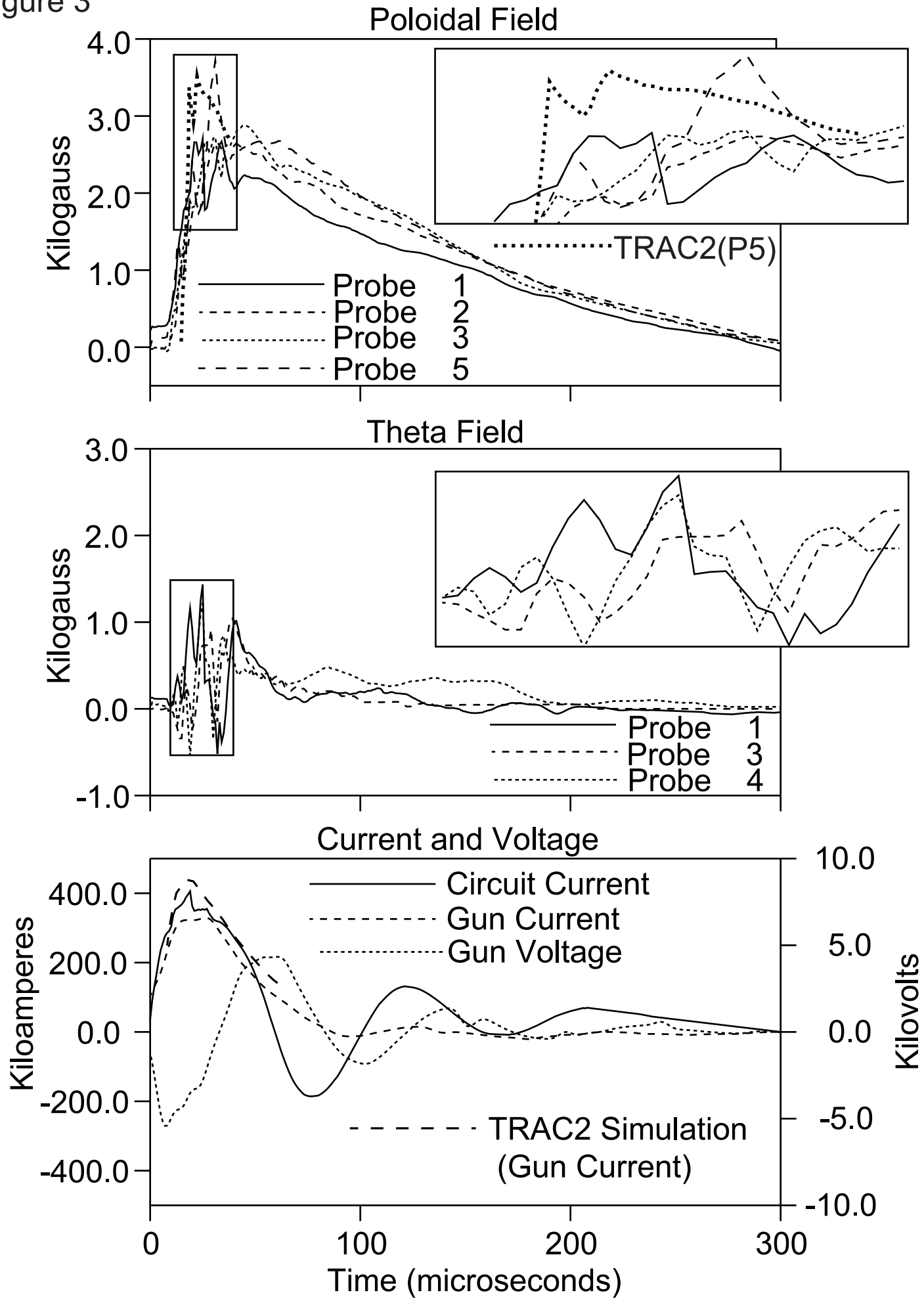

Poloidal Field
Kilogauss
4.0
3.0
2.0
1.0
0.0
TRAC2(P5)
Probe 1
Probe 2
Probe 3
Probe 5
Theta Field
Kilogauss
3.0
2.0
1.0
0.0
-1.0
Probe 1
Probe 3
Probe 4
Current and Voltage
Kiloamperes
400.0
200.0
0.0
-200.0
-400.0
Circuit Current
Gun Current
Gun Voltage
TRAC2 Simulation
(Gun Current)
Kilovolts
10.0
5.0
0.0
-5.0
-10.0
0
100
200
300
Time (microseconds)

Figure 4

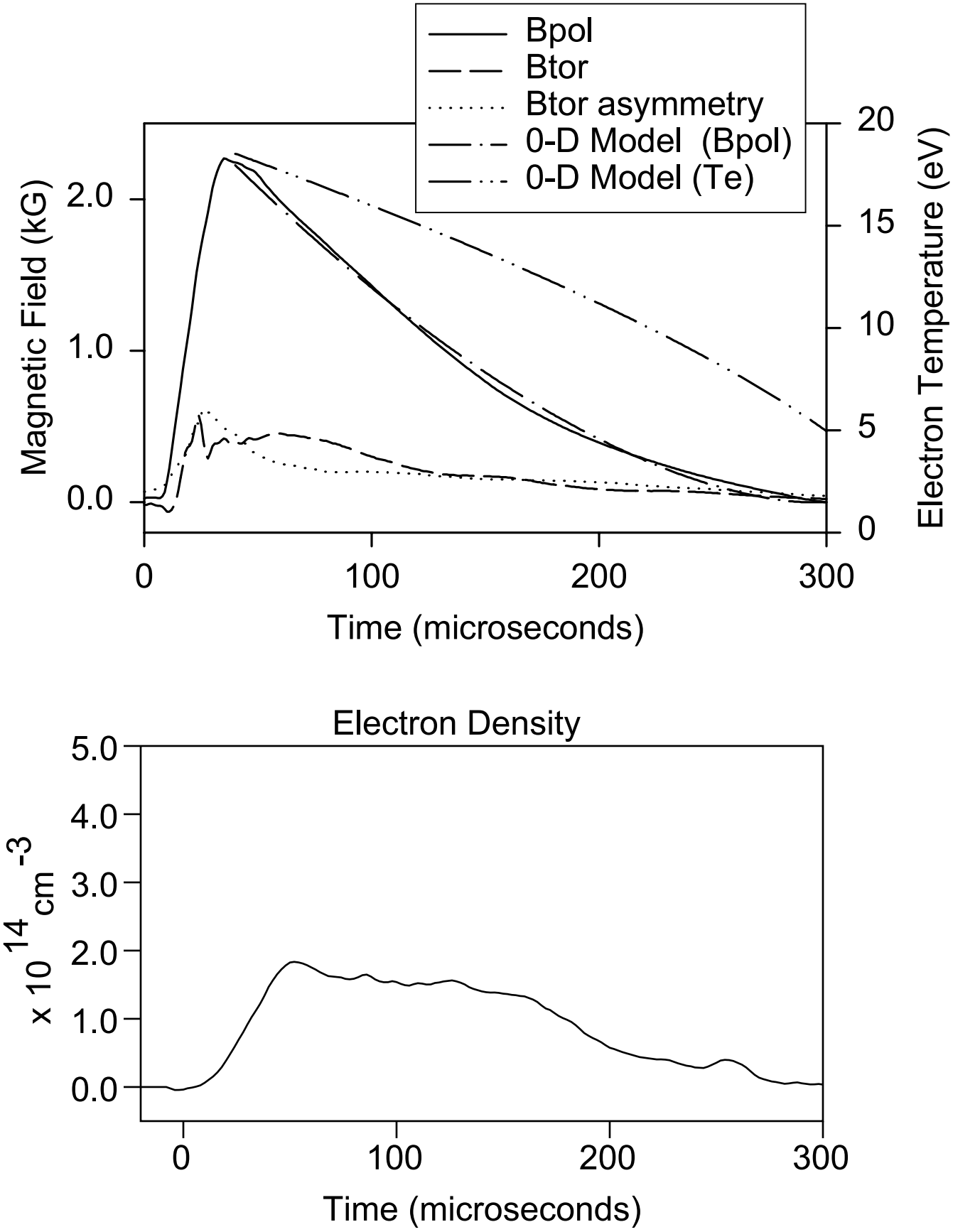

Bpol
Btor
Btor asymmetry
0-D Model (Bpol)
0-D Model (Te)
Magnetic Field (kG)
2.0
1.0
0.0
Electron Temperature (eV)
20
15
10
5
0
0
100
200
300
Time (microseconds)
Electron Density
5.0
4.0
3.0
2.0
1.0
0.0
x 10^14 cm^-3
0
100
200
300
Time (microseconds)

Figure 5

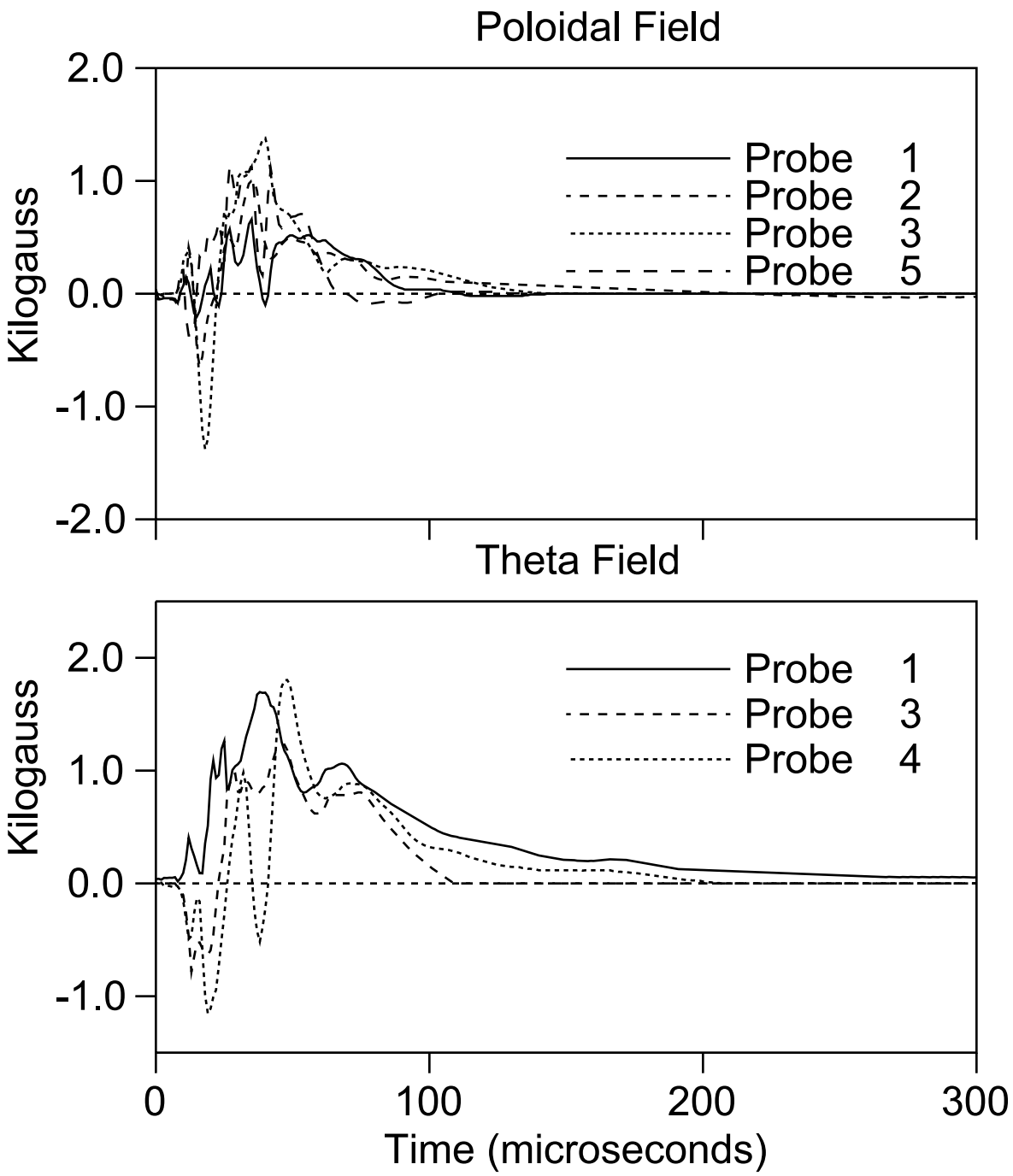

Poloidal Field
2.0
1.0
0.0
-1.0
-2.0
Kilogauss
Probe 1
Probe 2
Probe 3
Probe 5
Theta Field
2.0
1.0
0.0
-1.0
Kilogauss
Probe 1
Probe 3
Probe 4
0
100
200
300
Time (microseconds)

Figure 6

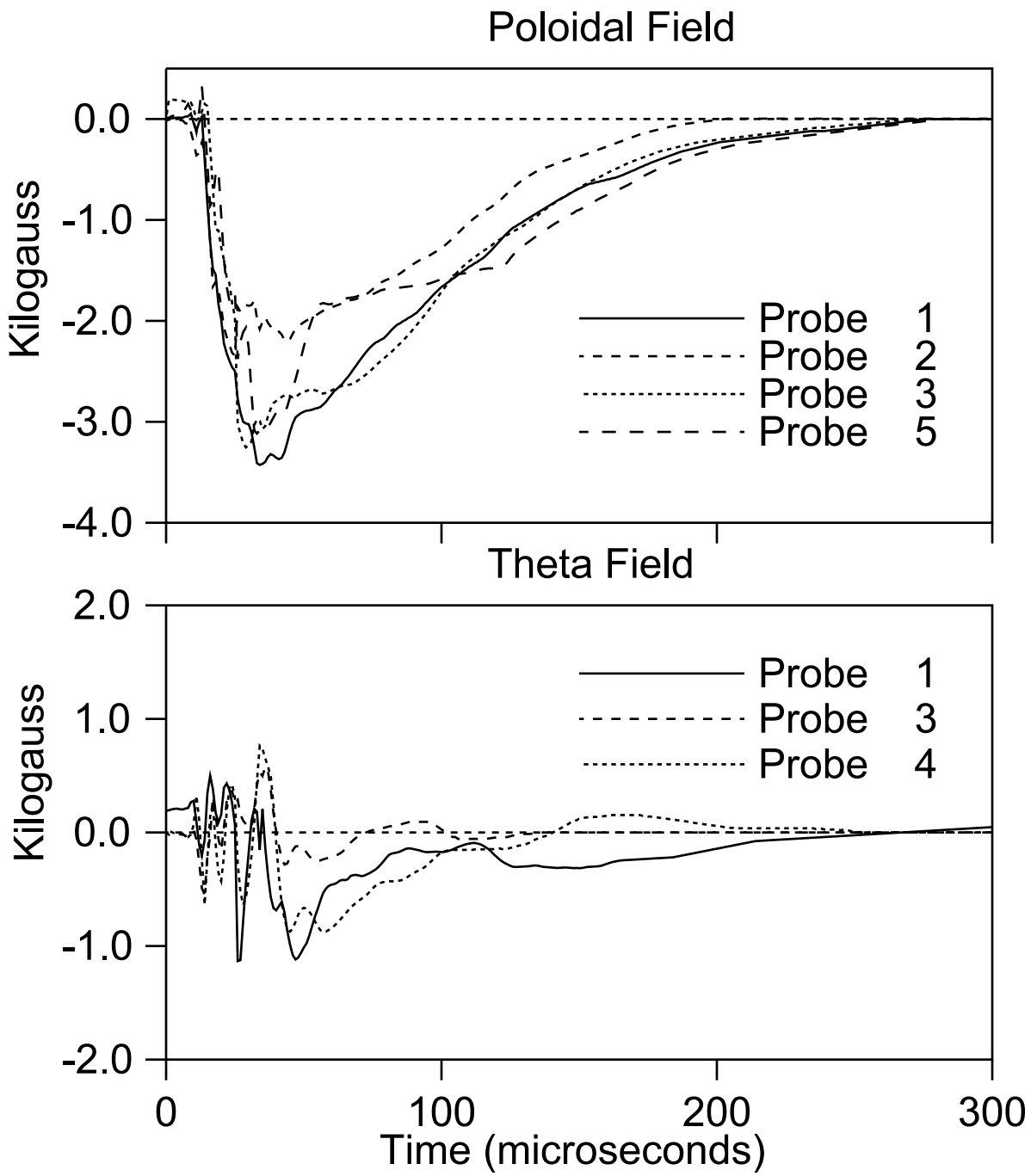

Poloidal Field
Kilogauss
0.0
-1.0
-2.0
-3.0
-4.0
Probe 1
Probe 2
Probe 3
Probe 5
Theta Field
Kilogauss
2.0
1.0
0.0
-1.0
-2.0
Probe 1
Probe 3
Probe 4
0
100
200
300
Time (microseconds)

Figure 7

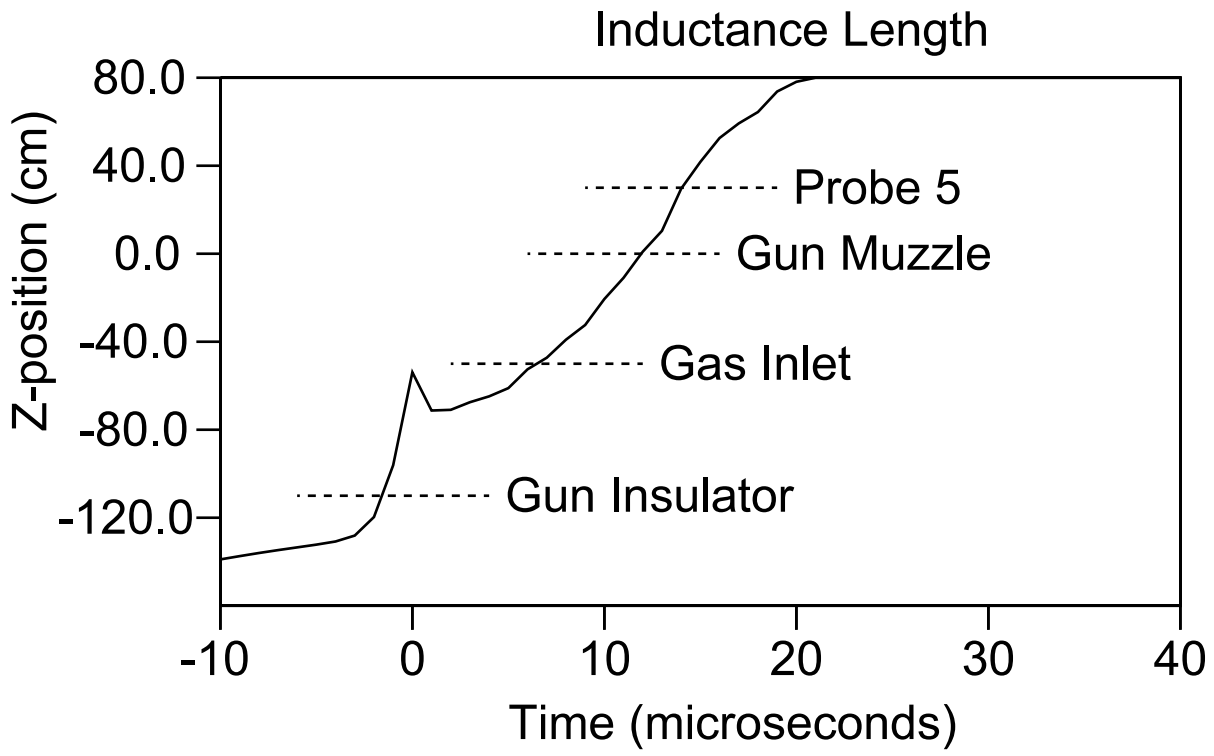
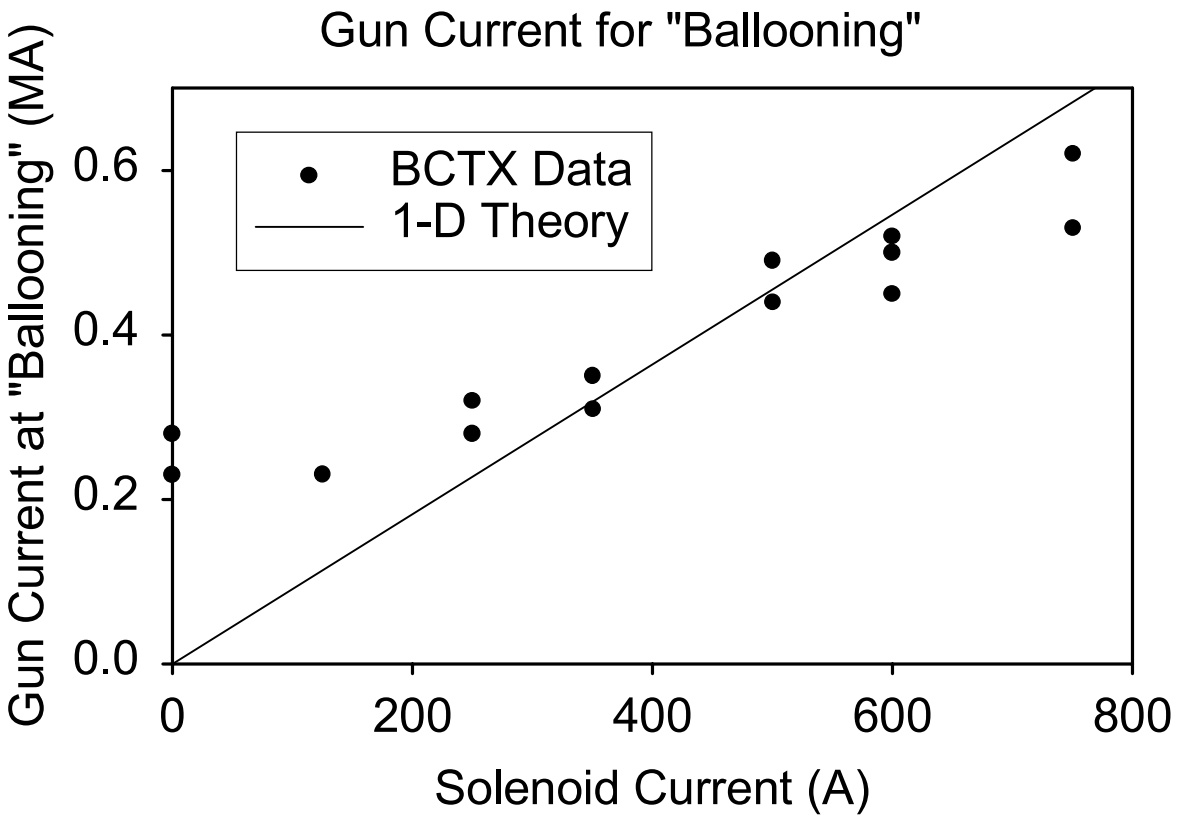

Inductance Length
80.0
40.0
0.0
-40.0
-80.0
-120.0
Z-position (cm)
Probe 5
Gun Muzzle
Gas Inlet
Gun Insulator
-10
0
10
20
30
40
Time (microseconds)

Figure 8


Gun Current for "Ballooning"
Gun Current at "Ballooning" (MA)
0.0
0.2
0.4
0.6
BCTX Data
1-D Theory
0
200
400
600
800
Solenoid Current (A)

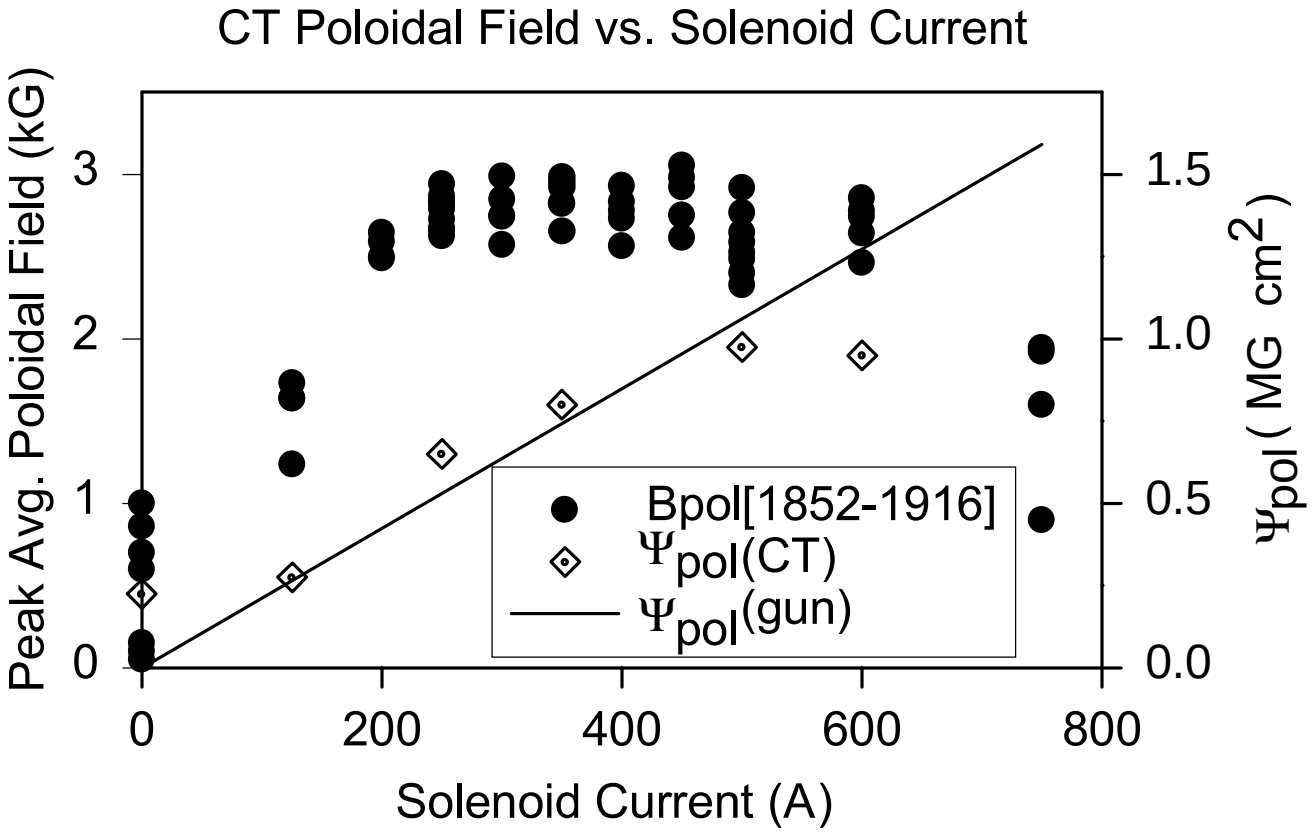

CT Poloidal Field vs. Solenoid Current
Peak Avg. Poloidal Field (kG)
0
1
2
3
Bpol[1852-1916]
Ψpol(CT)
Ψpol(gun)
0.0
0.5
1.0
1.5
Ψpol (MG cm2)
0
200
400
600
800
Solenoid Current (A)

Figure 9

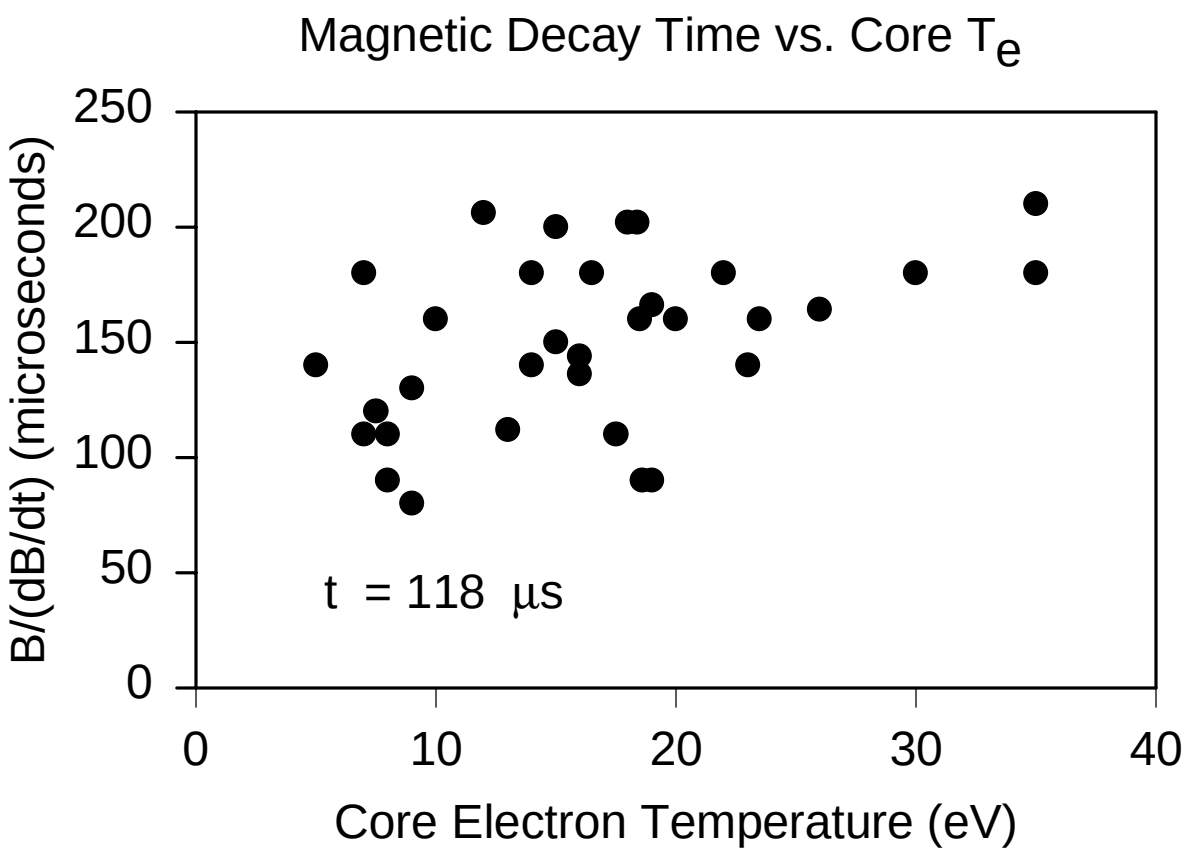

Magnetic Decay Time vs. Core T_e
B/(dB/dt) (microseconds)
250
200
150
100
50
0
t = 118 μs
0
10
20
30
40
Core Electron Temperature (eV)

Figure 10

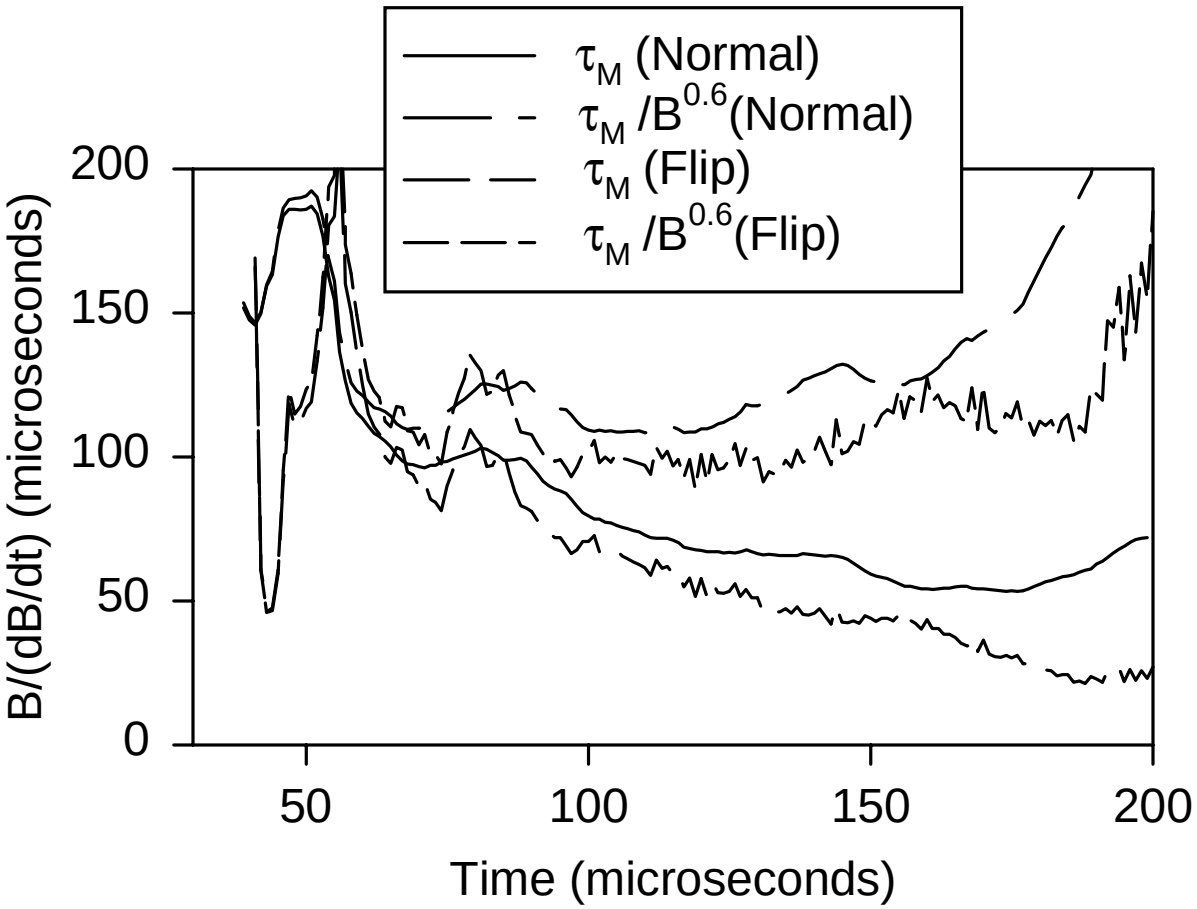
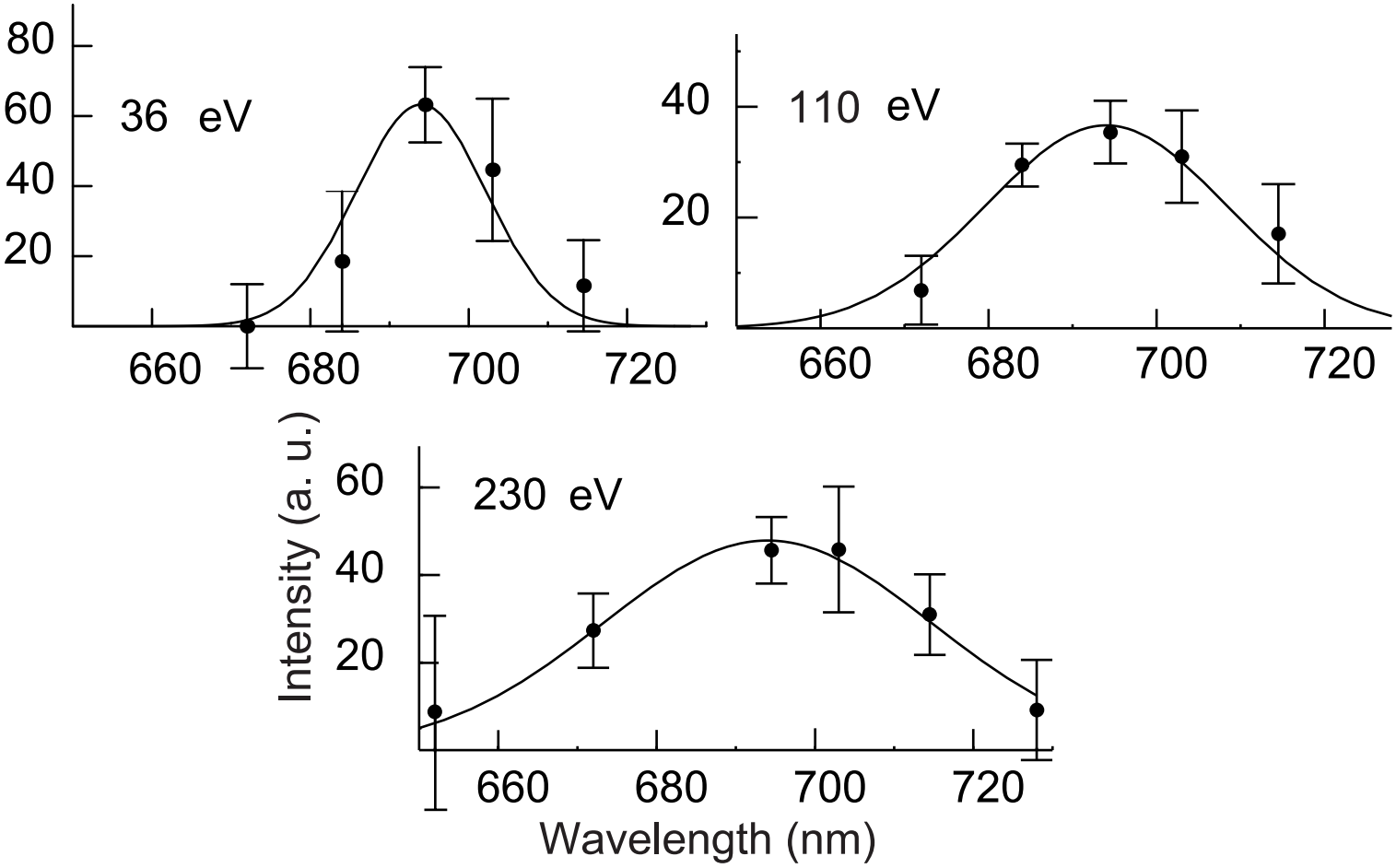
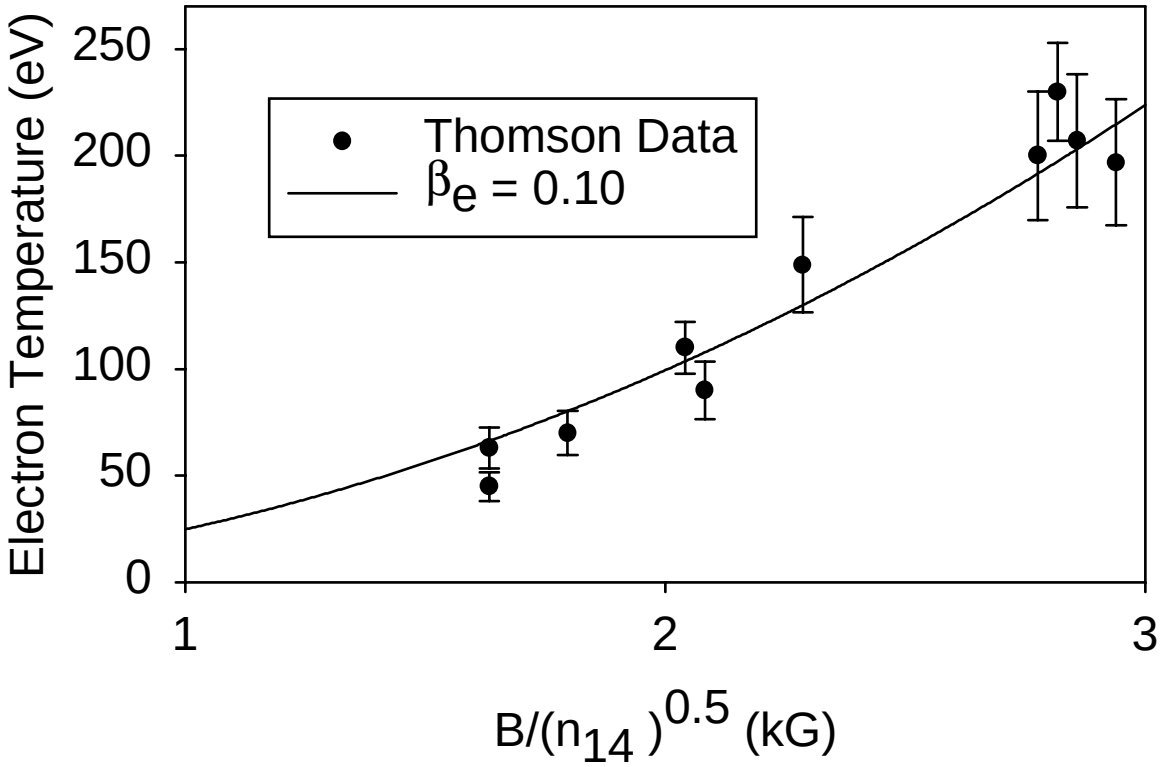

τM (Normal)
τM /B0.6(Normal)
τM (Flip)
τM /B0.6(Flip)
200
150
100
50
0
B/(dB/dt) (microseconds)
50
100
150
200
Time (microseconds)

Figure 11


36 eV
110 eV
230 eV
Intensity (a. u.)
Wavelength (nm)
660
680
700
720


Thomson Data
β_e = 0.10
Electron Temperature (eV)
$B/(n_{14})^{0.5}$ (kG)

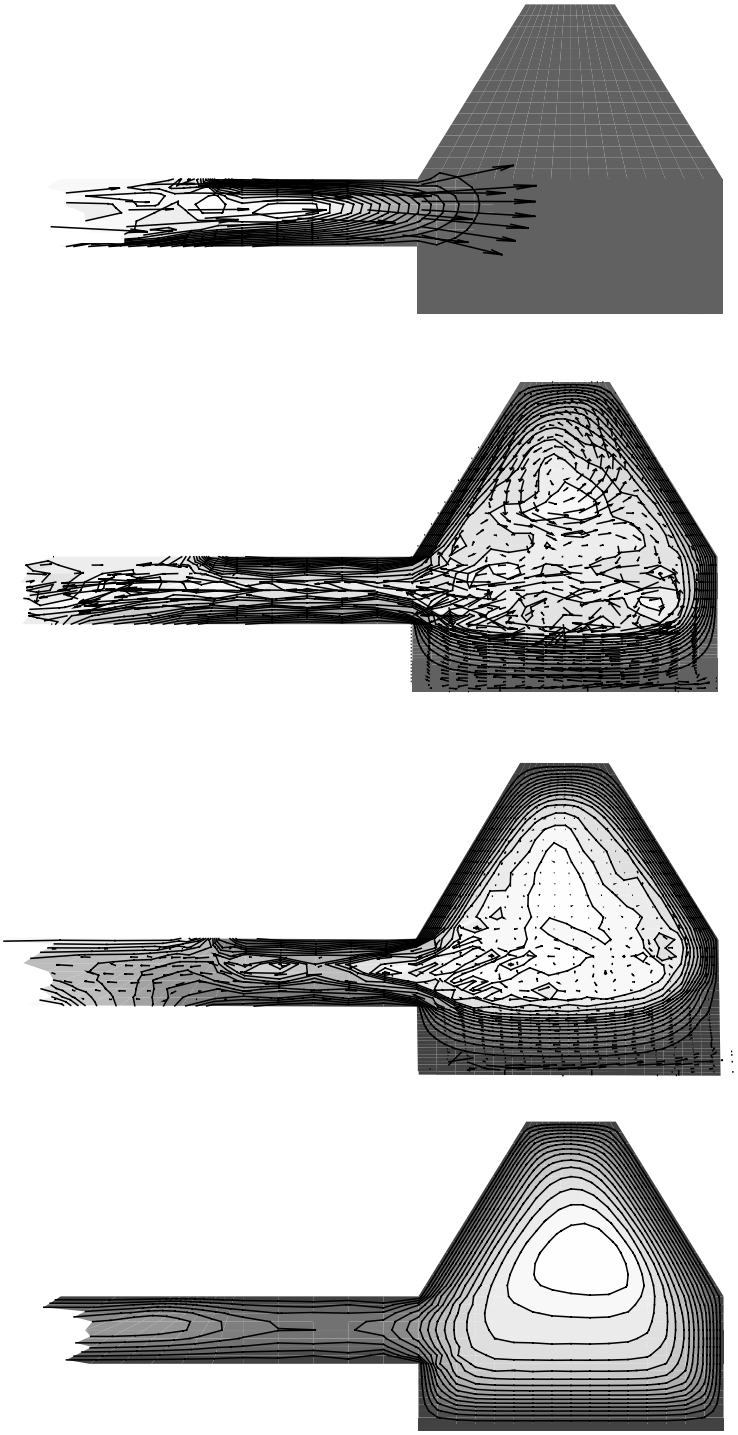



Figure 12