Abstract

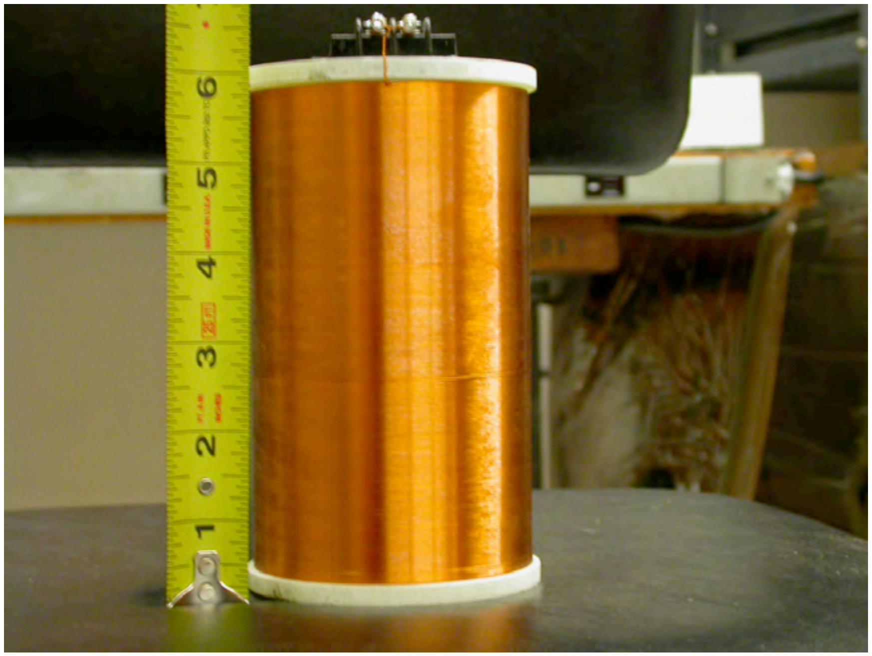
Magnetic diagnostics will serve as principal diagnostics to determine the equilibrium pressure profile of the LDX plasma and the nature of magnetic fluctuations induced by instabilities. Various magnetic sensors, including 18 Bp-coils, 18 Hall probes, 6 flux loops, and 1 Mirnov coil, have been installed and tested. The external diagnostics will measure the boundary magnetic field to be inputted into an equilibrium code. Specifically, the boundary field values will be used to constrain the free parameters associated with the pressure model. An internal diagnostic Mirnov coil will measure plasma fluctuations on the order of 100 kHz to a few MHz caused by MHD activities. The number of Mirnov coils will be increased to form a toroidal array in the near future. Data from the first plasma experiments will be presented here. The sensitivity of the pressure model on the final reconstructed equilibrium will also be discussed.

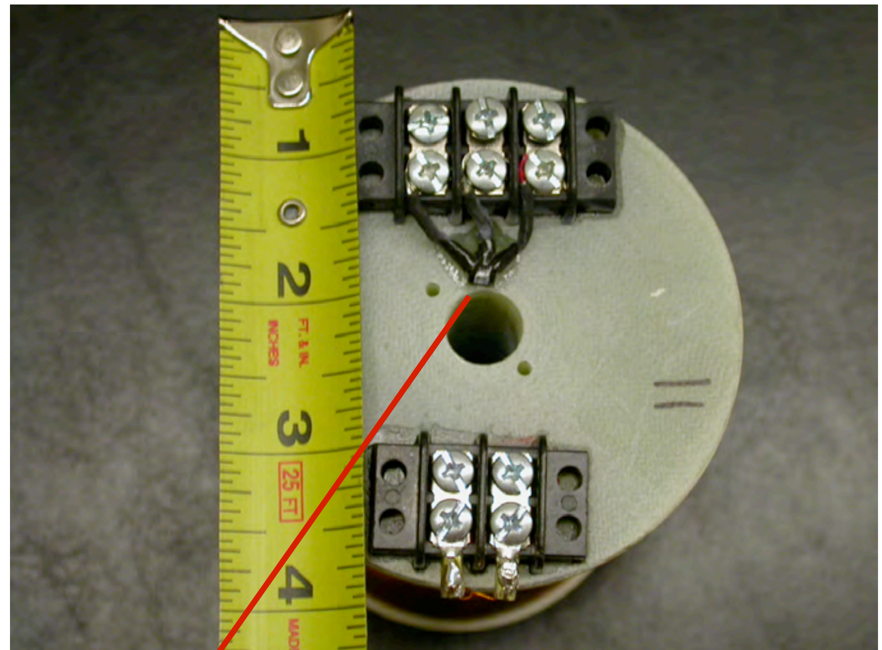
Outline

- Introduction
- Magnetic Diagnostics Basics
- Data Analysis
- Results
- Implications
- Summary / Future Work

What are magnetic diagnostics?

➡ Sensors that measure magnetic field and flux.





Hall Probe

B_p-Coil Specs:

- NA ~ 5 m^2
- Sensitivity: 500 mV/G
  (connected to a 1 ms RC integrator)

Hall Sensor Specs:

- Field Range: +/- 500 G
- Sensitivity: 5 mV/G

Flux Loop:

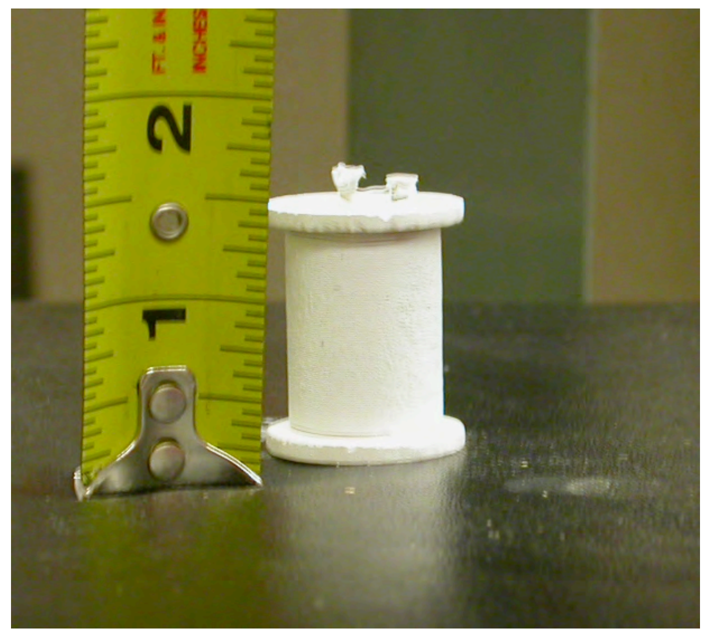
- Measures magnetic flux.
- Signal is integrated.

Mirnov Coil:

- Directly measures dB/dt to detect magnetic fluctuations.
- Must be placed inside the vessel to be able to measure fast activities.

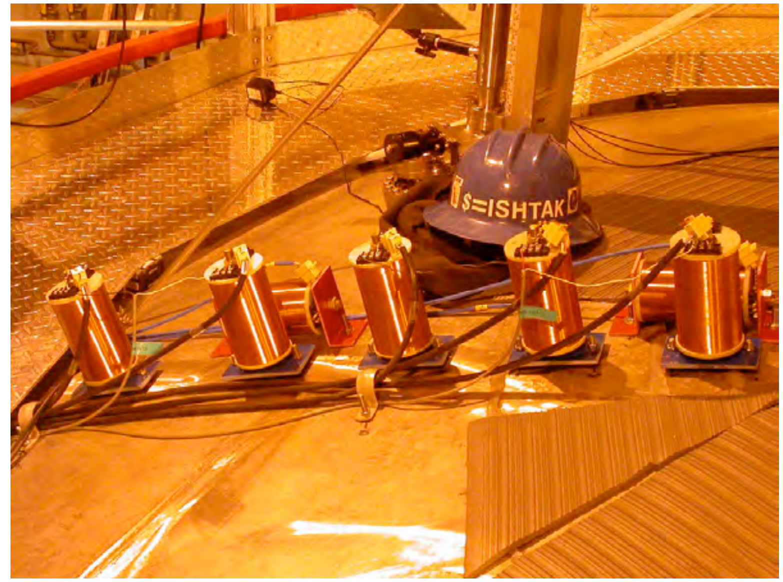
NA ~ 0.06 m^2

L ~ 0.3 mH

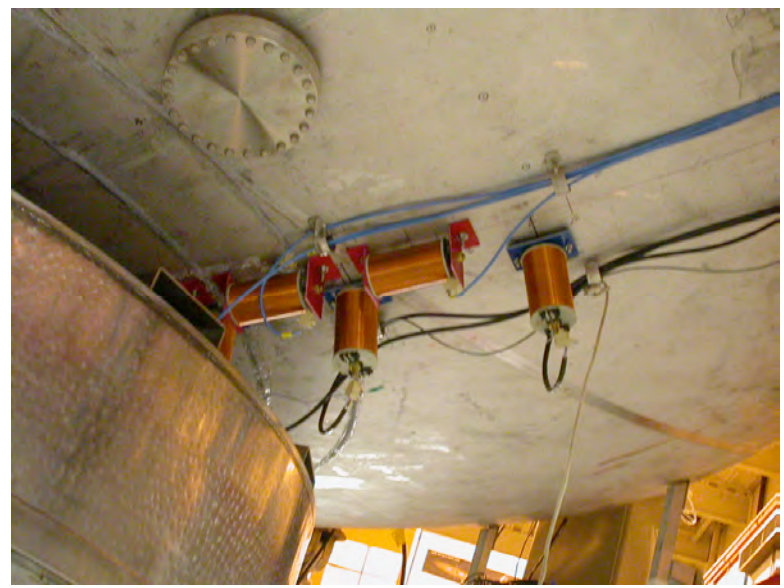


Chamber Side

Chamber Top



Chamber Bottom



Magnetics Overview:

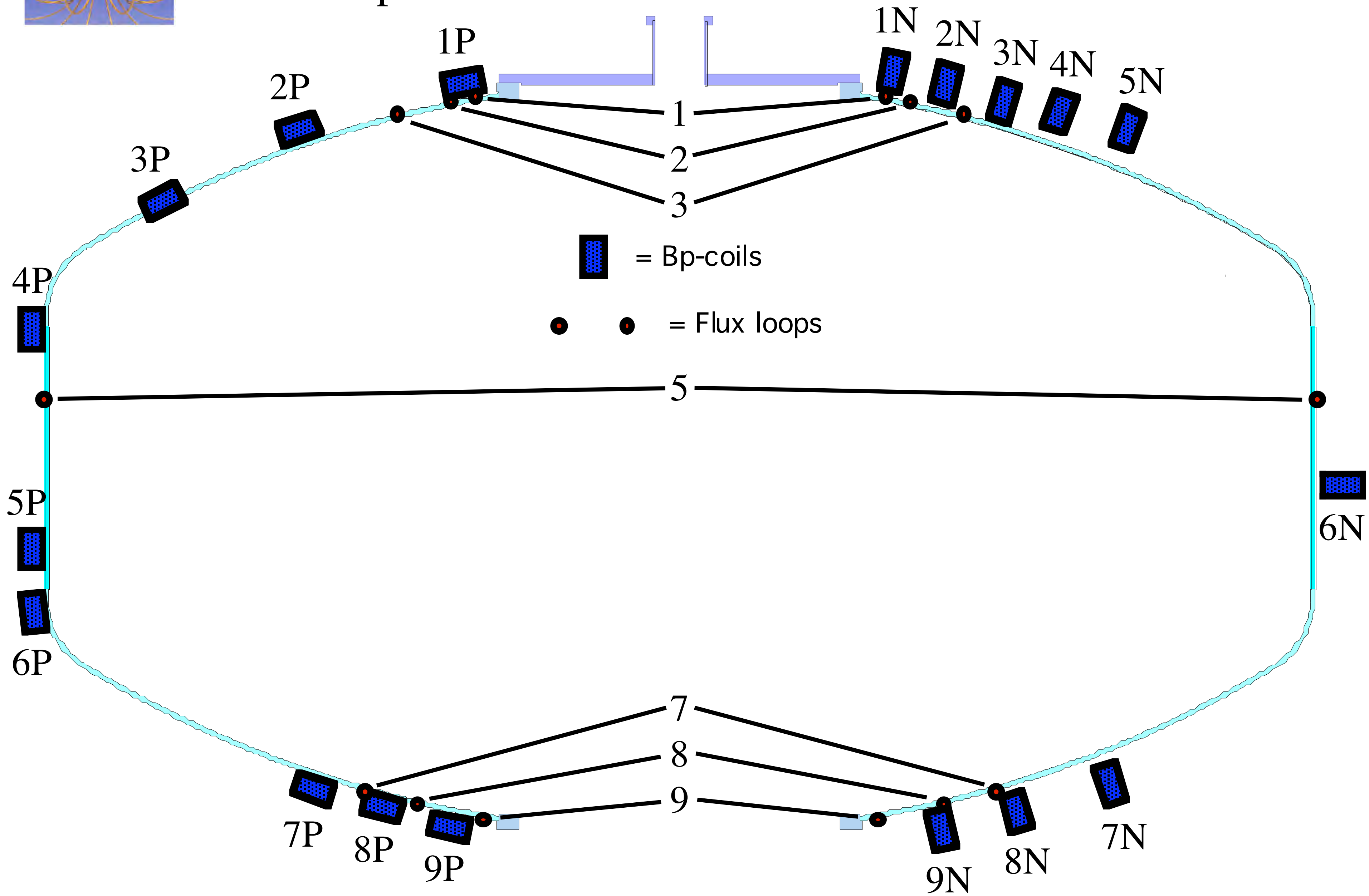
- 18 B_p-coils, half of which are oriented normal to the vacuum vessel and the other half oriented tangentially, to measure boundary diamagnetic field values.

- 7 flux loops to measure boundary diamagnetic flux values (total of 9 in the near future).

- 18 Hall probes, each mounted on a B_p-coil, to supplement the coil measurements.

- 2 toroidally separated Mirnov coils to measure fast plasma fluctuations (total of 8 in the near future).

Sensor positions:



Why are magnetic diagnostics so important?

➡ We can deduce the following plasma parameters through magnetic measurements:

- Current and pressure profiles
- Plasma shape and position
- Average and peak beta

Substantial analyses must be performed on the magnetic data to actually obtain the above mentioned parameters.

In order to obtain anything useful from the magnetic data, we must first solve the Grad-Shafranov equation and use the data to constrain the parameters of the pressure model:

$$\Delta^* \Psi^{k+1} = -\mu_0 R J_\phi^{k}(R, \Psi^k, \alpha_n^{k}) = -\mu_0 R^2 P'(\Psi^k, \alpha_n^{k})$$

We use the following pressure model for LDX plasma:

$$P(\Psi, \Theta_p, P_{edge}, g) = \begin{cases} P_{edge}[V(\Theta)/V_{edge}]^{-g} & \text{for } \Theta > \Theta_p \\ P_{edge}[V(\Theta)/V_{edge}]^{-g} \sin^2[(\pi/2)(\Theta/\Theta_p)^2] & \text{for } \Theta < \Theta_p \end{cases}$$

where

Θ_p is the normalized flux at the peak pressure position
P_{edge} is the edge pressure
g is the related to the slope of the pressure profile

These are the 3 parameters that get constrained to conform to the magnetic measurements.

- The equilibrium program not only solves the Grad-Shafranov equation but also minimizes the following merit function in order to constrain the free parameters associated with the pressure profile:

$$\chi^2 = \sum_{j=1}^{n_m} \frac{(M_j - C_j^k)^2}{\sigma_j^2}$$

M_j =	measurement value at the j^{th} detector
C_j^k =	calculated value from Ψ^k or J^k at the j^{th} detector position
σ_j =	measurement error

When the Grad-Shafranov equation is solved and χ^2 minimized, we will be left with $\Psi(R, Z)$ and $P(\Psi)$.

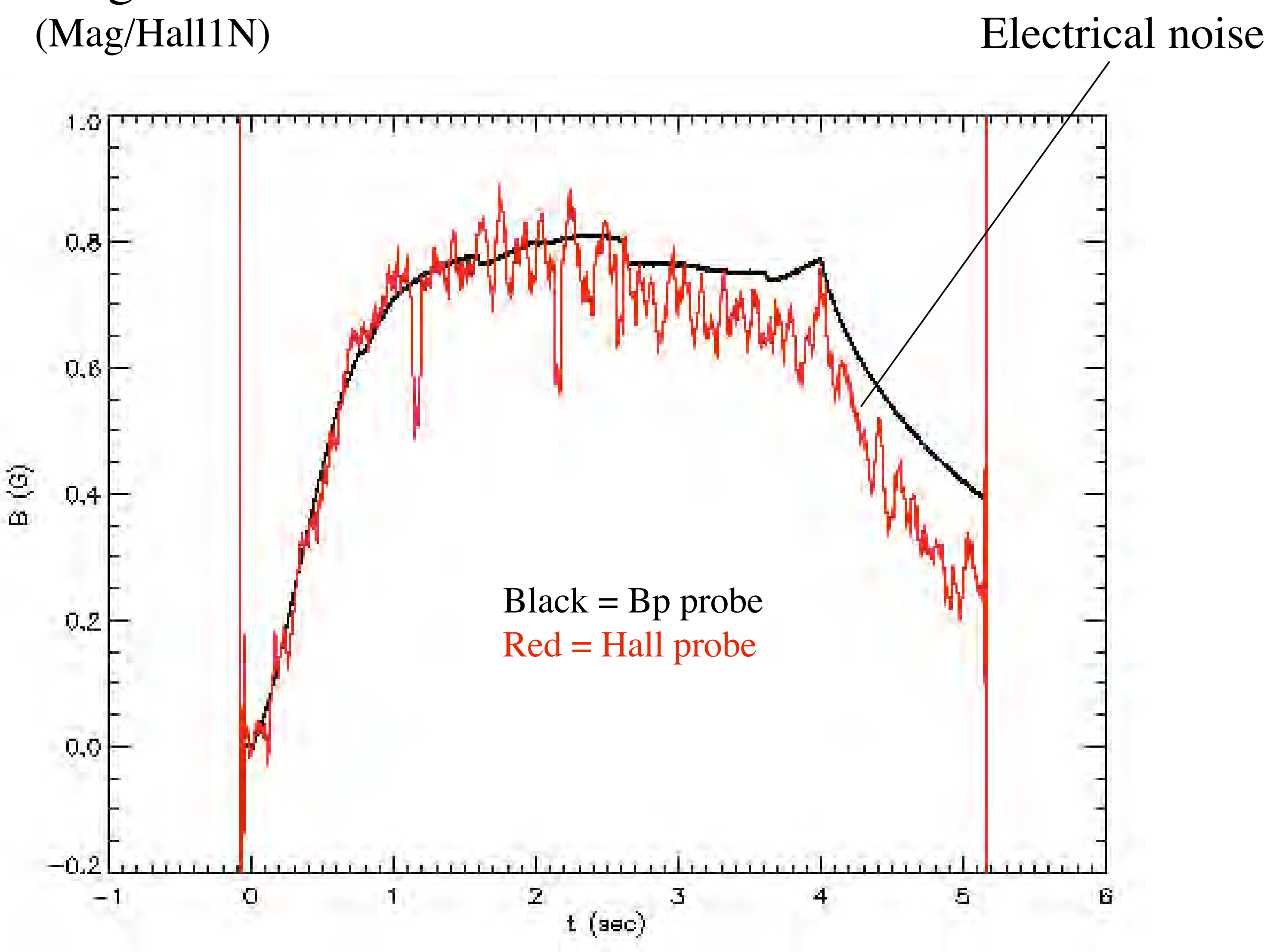
Then:

- $\Psi(R, Z)$ will directly give the plasma shape and position.
- Toroidal current, $J_\phi = R^*(dP/d\Psi)$
- Peak beta, $\beta_{peak} = (2\mu_0 P / B_\theta^2)_{peak}$
- Average beta, $\beta_{average} = 2\mu_0 \langle P \rangle / \langle B_\theta^2 \rangle$

Hence, the aforementioned parameters can be easily calculated from $\Psi(R, Z)$ and $P(\Psi)$.

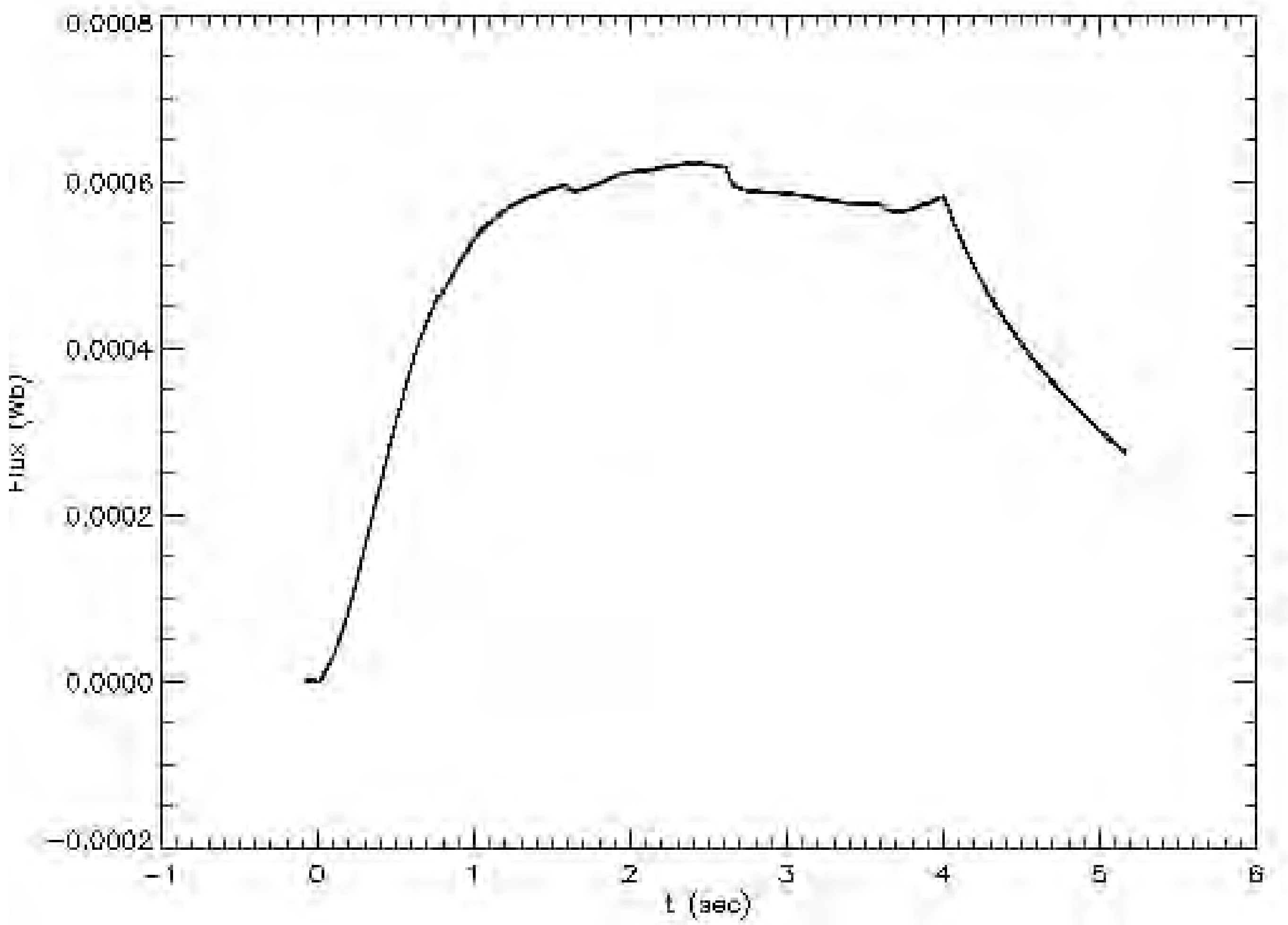
Magnetic data from shot 40813022:

(Mag/Hall1N)



Flux data from shot 40813022:

(Flux7)

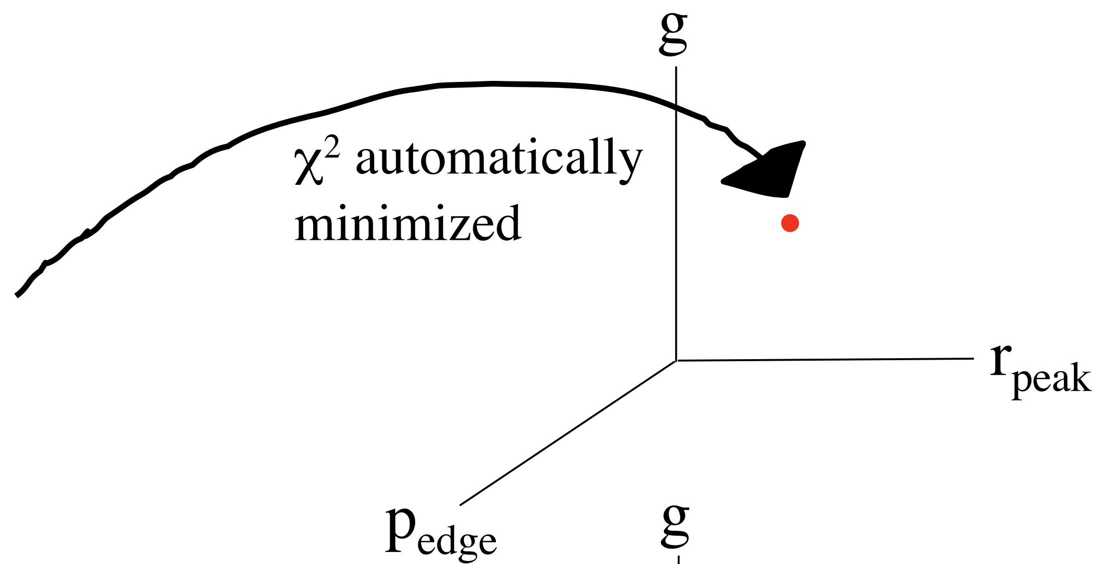


Analysis:

The code we have today does not have the fitting capability, hence a “poor man’s” fitting routine was performed.

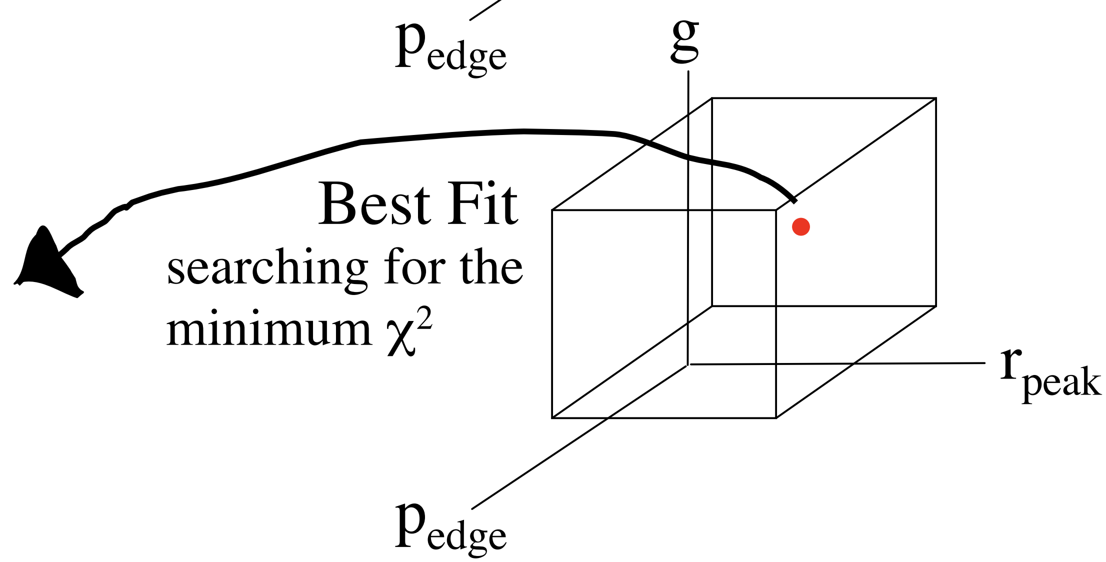
Ideal code operation:

$$[B_1, B_2, \ldots, B_{18}]$$
$$[\Psi_1, \Psi_2, \ldots, \Psi_9]$$



Current code operation:

$$[B_1, B_2, \ldots, B_{18}]$$
$$[\Psi_1, \Psi_2, \ldots, \Psi_9]$$



Results:

(t = 2 sec)

p_{edge}, r_{peak}, and g were varied over the parameter space; the upper bound on p_{edge} was set at 0.036 Pa, the pressure measured by a probe that was 30 cm into the plasma at the midplane.

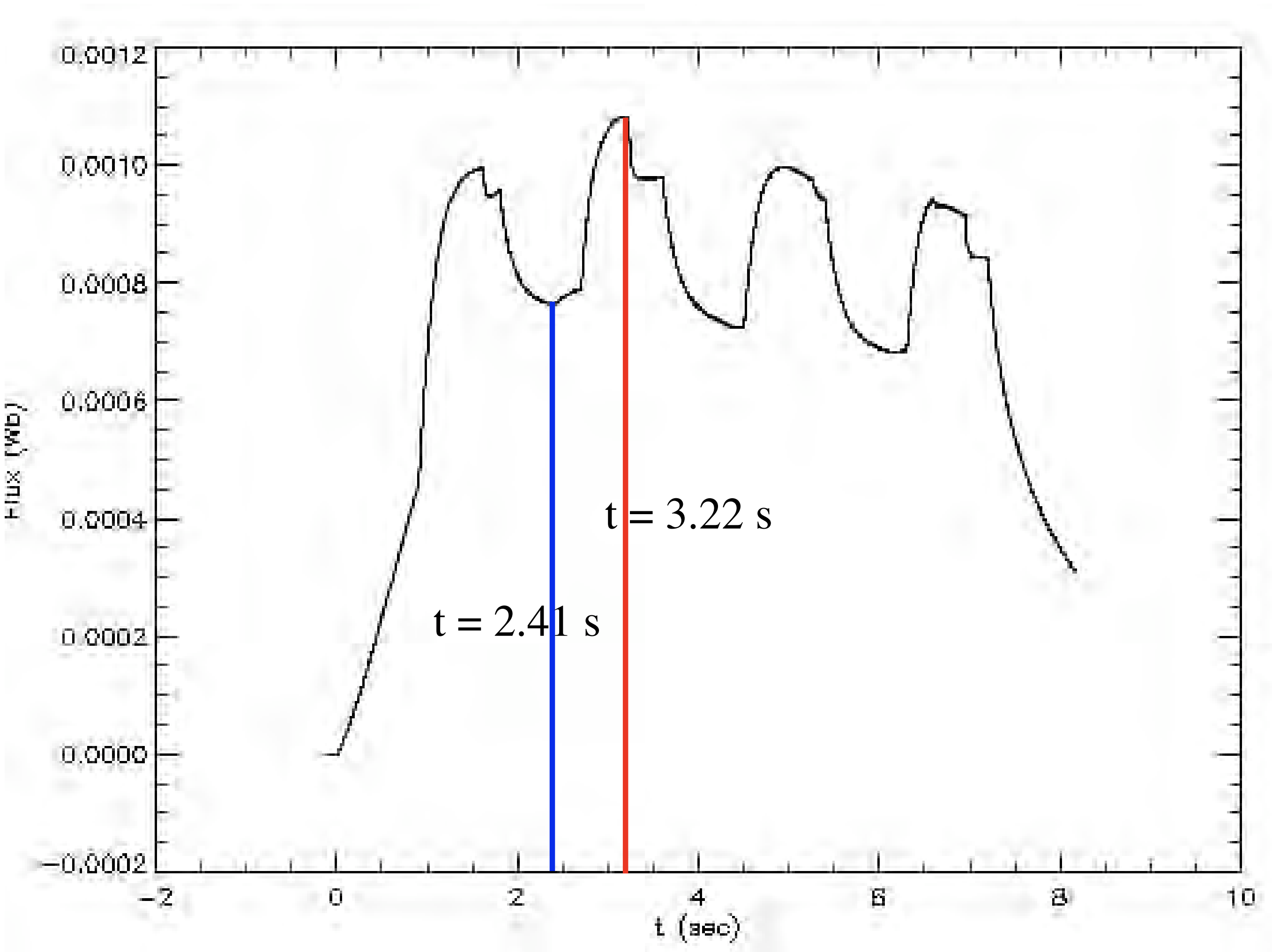
$p_{edge} = 0.010$ Pa
$g = 1.10 * (5/3)$
$r_{peak} = 0.75$ m

$\chi^2 \approx 19$

- $I_p = 1225$ A
- Total Stored Kinetic Energy = 55 J
- $\beta_{avg} = 0.7\%$
- $\beta_{peak} = 4.6\%$

Flux data from shot 40917019:
(Flux7)

ECRH heating with 6.4 GHz while 2.45 GHz power was being modulated.

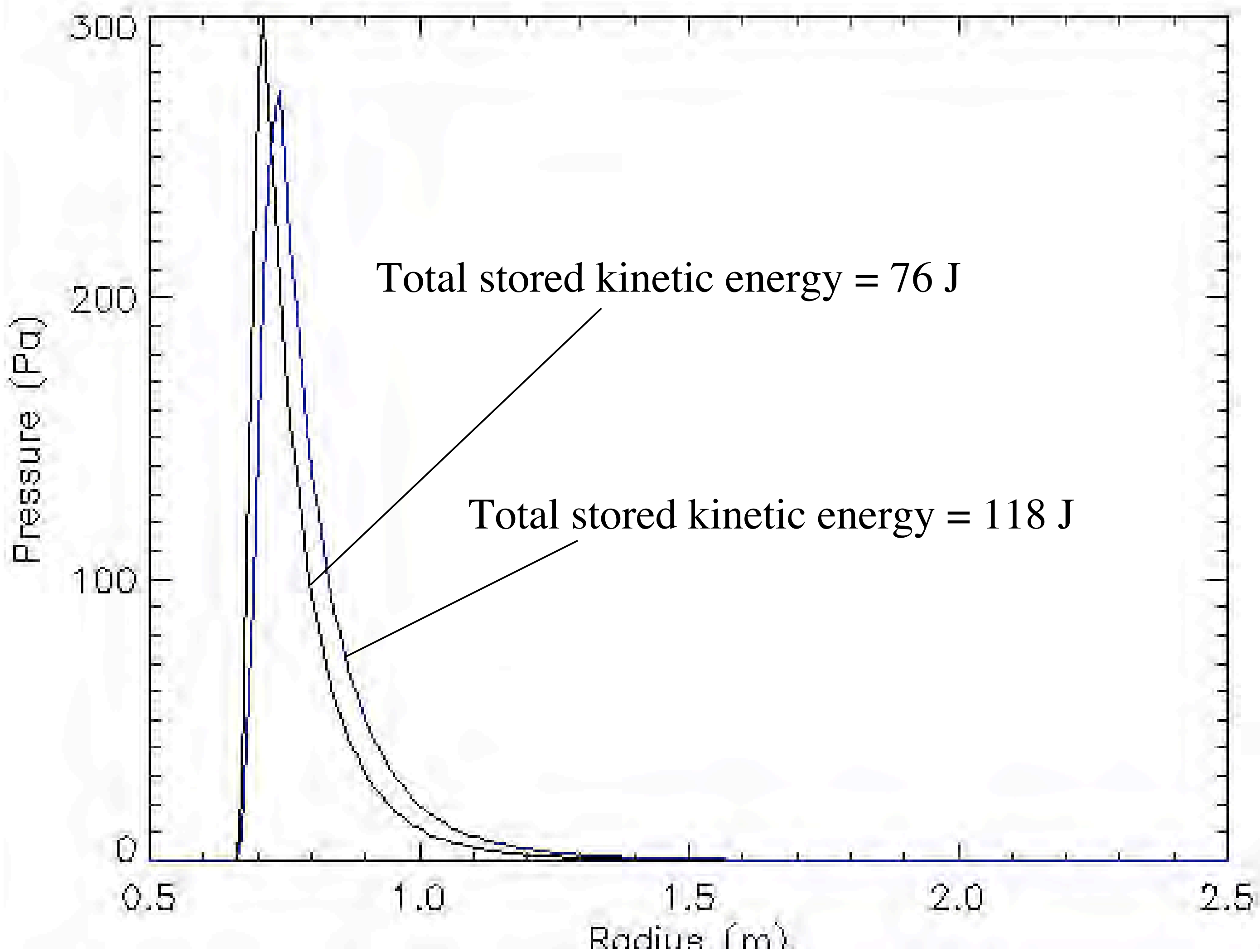


Pressure profiles:

Results:

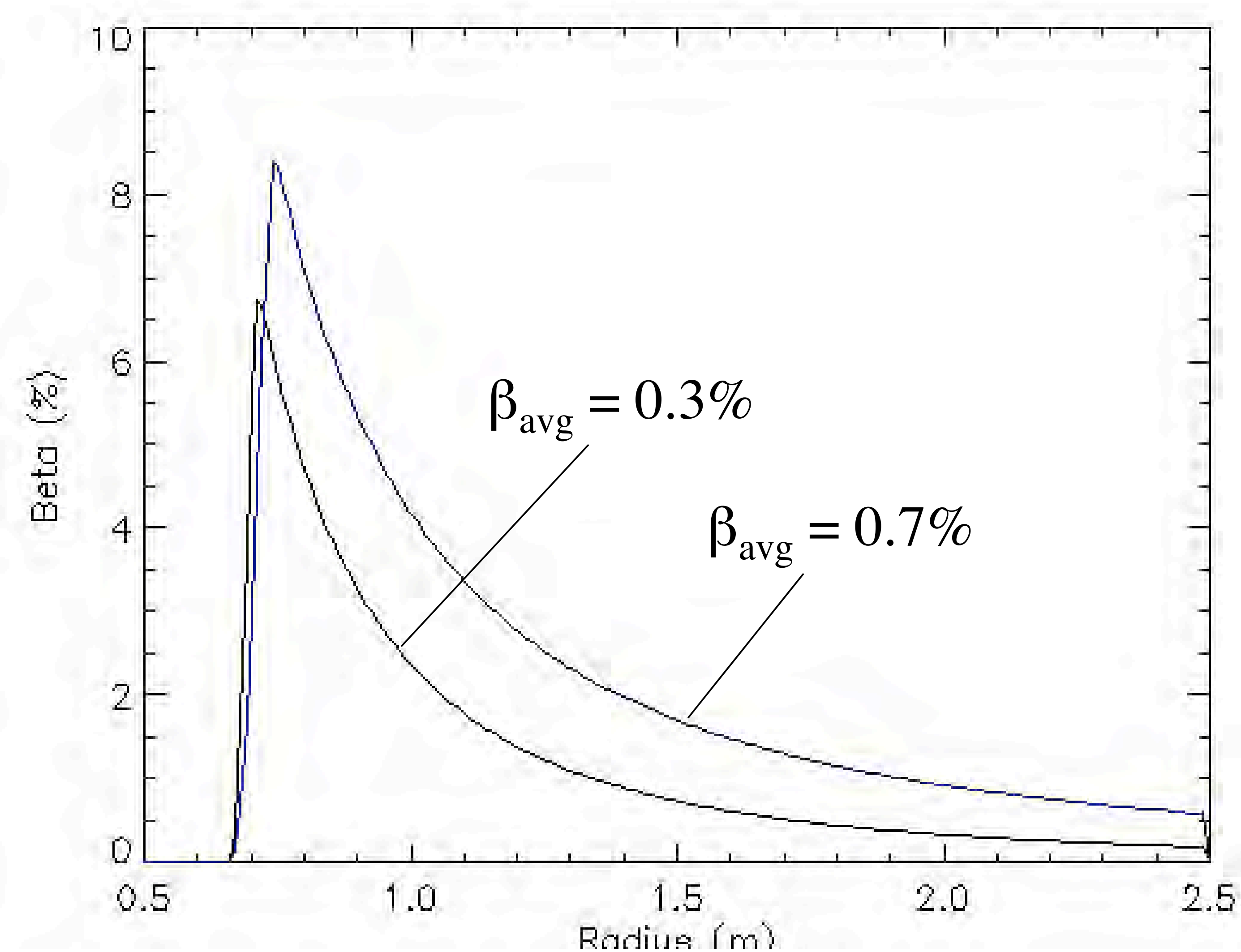
t = 2.41 sec: (black)
p_{edge} = 0.003 Pa
g = 1.31 * (5/3)
r_{peak} = 0.71 m

t = 3.22 sec: (blue)
p_{edge} = 0.010 Pa
g = 1.21 * (5/3)
r_{peak} = 0.74 m



- The pressure peak can be seen to move out as the 2.45 GHz power turns on.
- This is consistent with our expectation that the average heating region moves out since the 2.45 GHz resonant layer is farther out than that of 6.4 GHz.

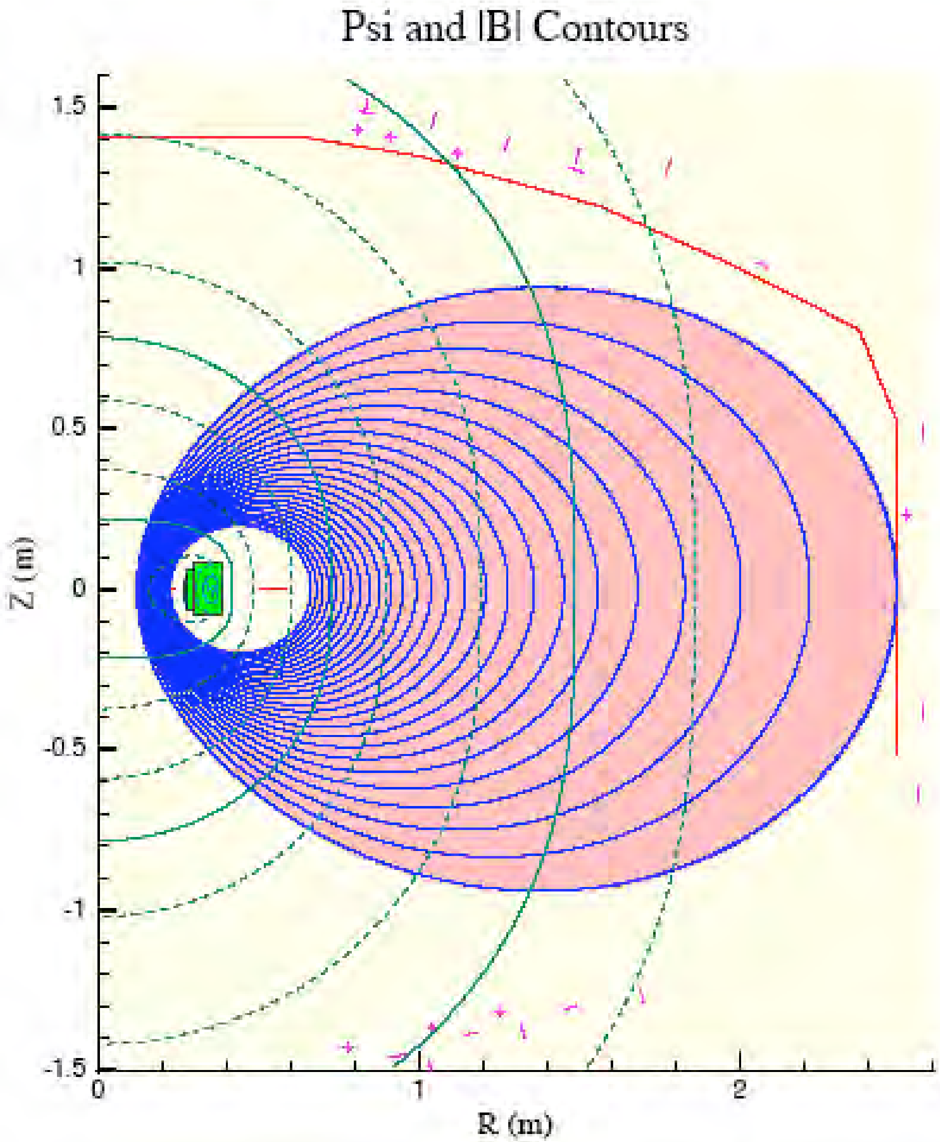
Beta profiles:



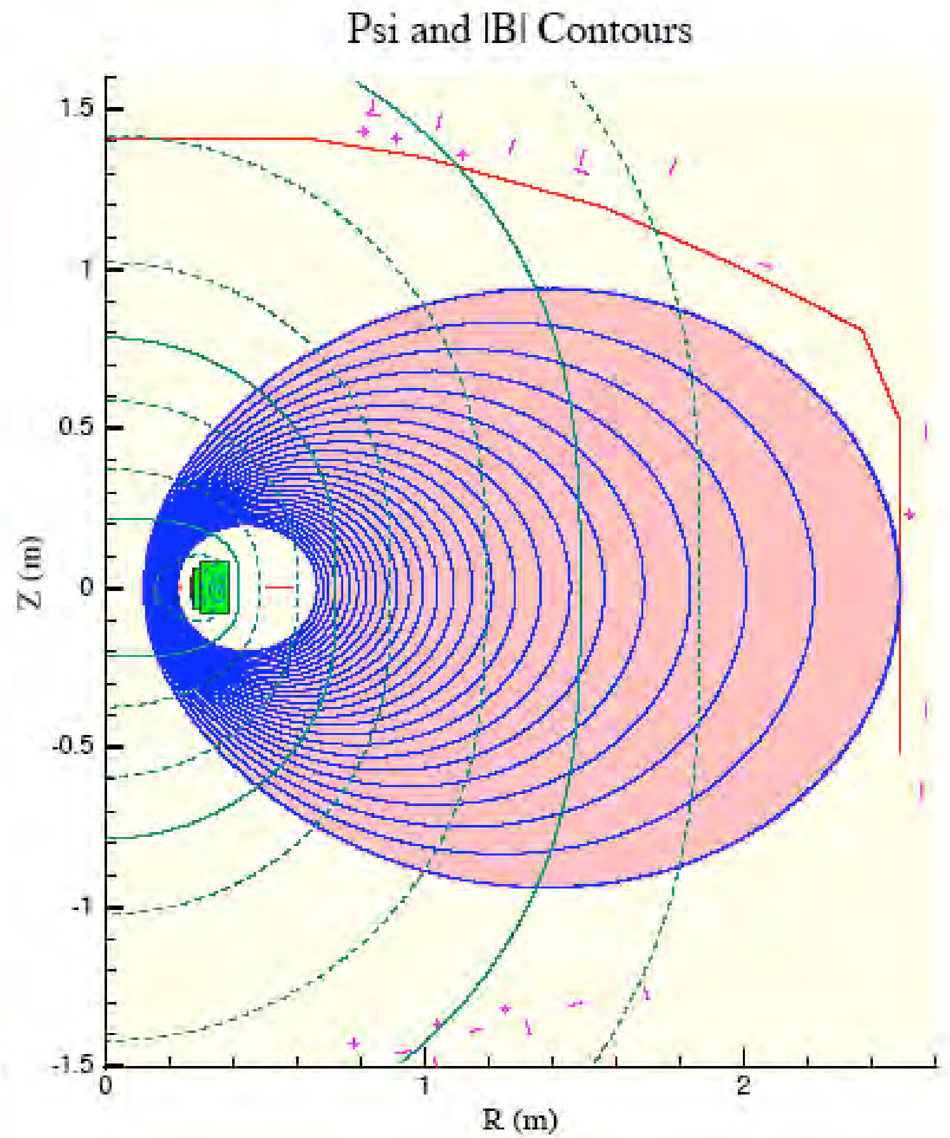
black = 2.41 sec: peak beta ~ 7%
blue = 3.22 sec: peak beta ~ 8.5%

- Although the previous graph shows a higher peak pressure when the 2.45 GHz is turned off, this graph confirms that the peak beta is higher when both sources are turned on.

Flux contours:



t = 2.41 sec



t = 3.22 sec

Sensitivity of χ^2 to the input parameters:

(shot 40917019 @ 3.22 sec)

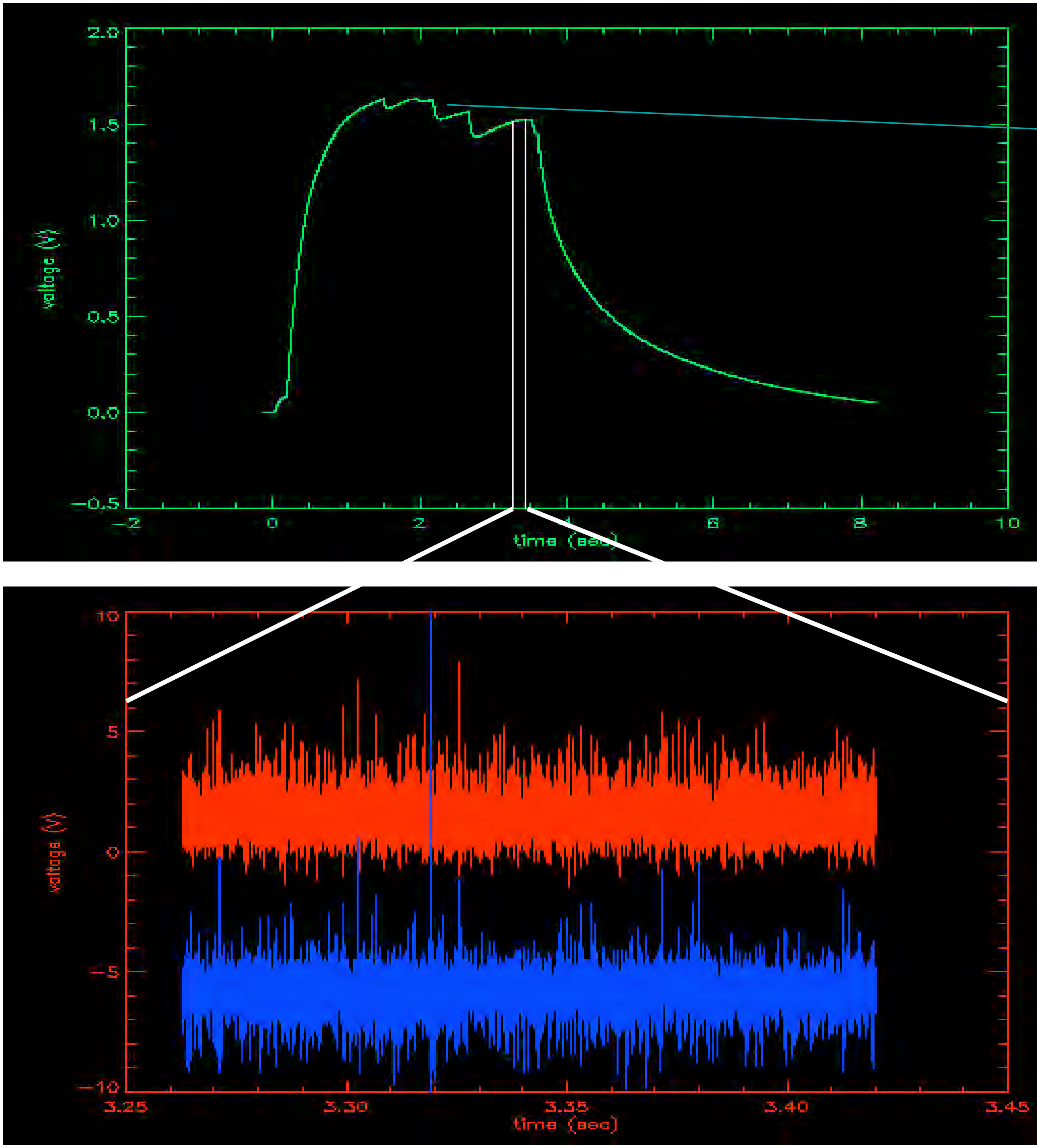
$$\chi^2_{min} \approx 25$$

δp_{edge} = +/- 0.001 Pa → $\delta\chi^2$ = +17 / +20

δr_{peak} = +/- 0.01 m → $\delta\chi^2$ = +2 / +1

$\delta f_{crit} = (3/5)\delta g$ = +/- 0.01 → $\delta\chi^2$ = +8 / +9

Shot 40917012



Sawtooth like structure

Flux5

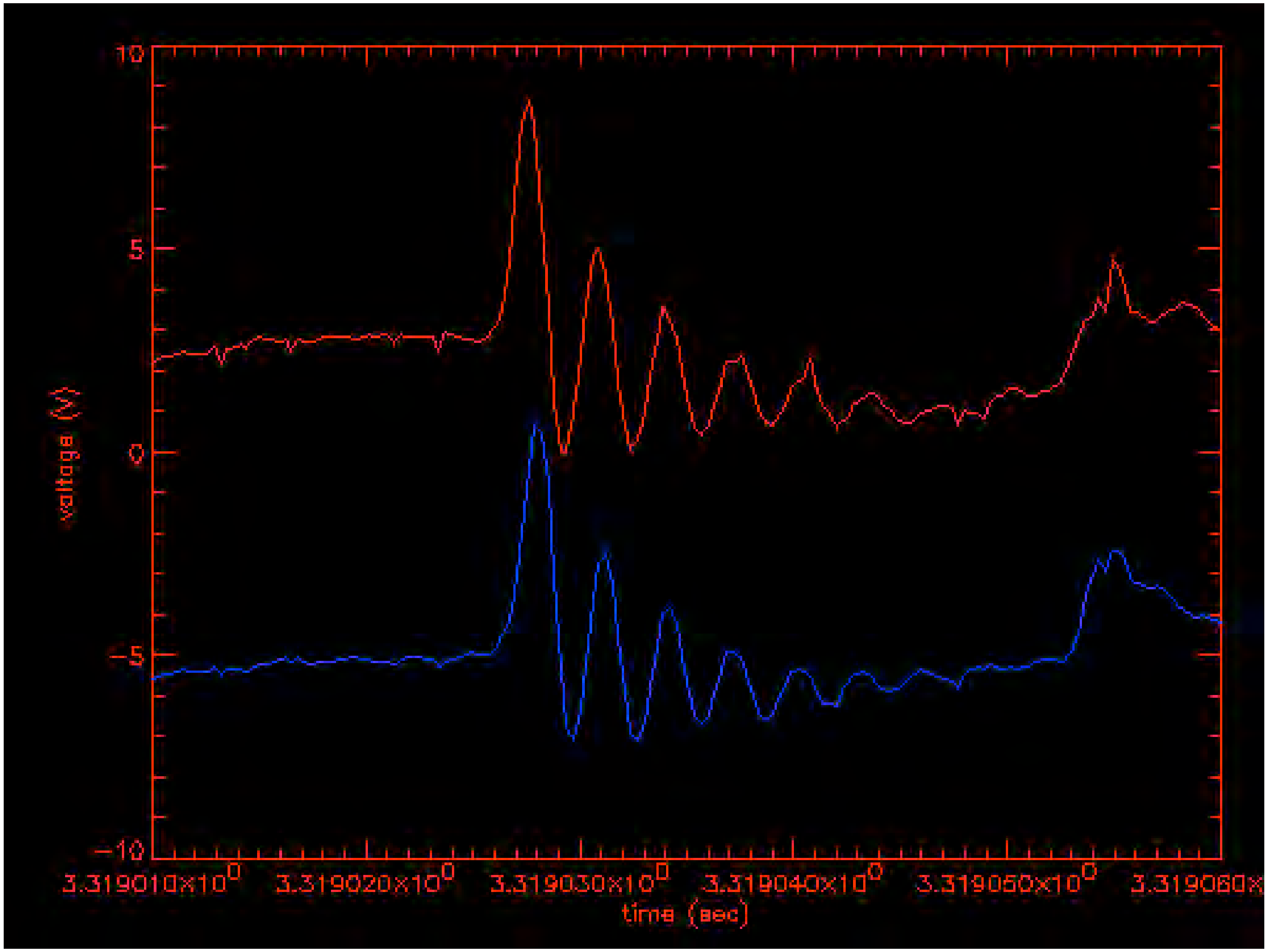
- Observe the sawtooth like oscillation on the flux-loop signal.

- At the bottom, a magnified view of the Mirnov signals is shown.

Mirnov2

Mirnov3

More magnified:



Mirnov2

Mirnov3

$\omega \sim 330$ kHz

$v_{ph} \sim 4000$ km/s

This oscillation doesn't seem to coincide temporally with the sawtooth-like phenomenon seen in the flux trace. Is this an external mode that doesn't manifest itself in global measurements?

Summary/ Future Work

- The magnetic diagnostics successfully recorded data from first LDX plasma.
- Magnetic data was successfully used to reconstruct plasma equilibrium.
- Certain modes were observed on both the flux loops and Mirnov coils.
- These modes will be studied more carefully in order to identify their origin.
- The equilibrium code will be upgraded to be able to run in the fitting mode.