# Probe Measurements of Electrostatic Fluctuations in LDX

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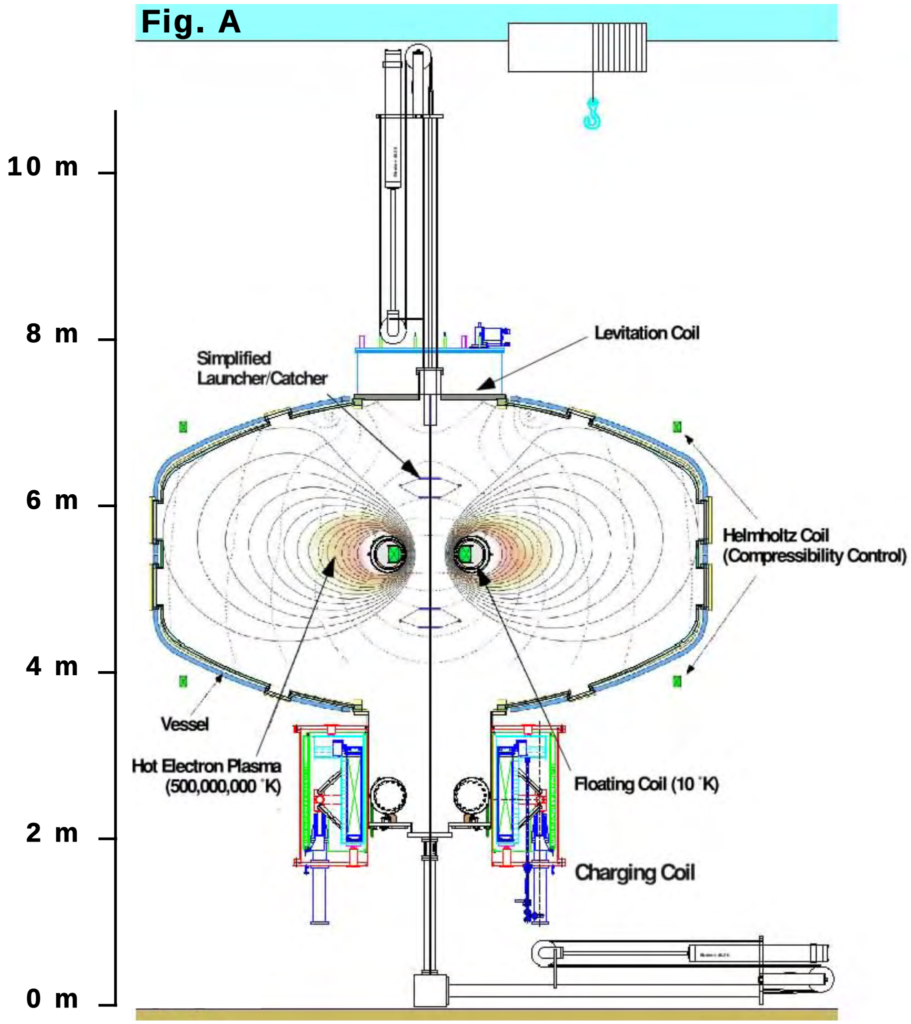
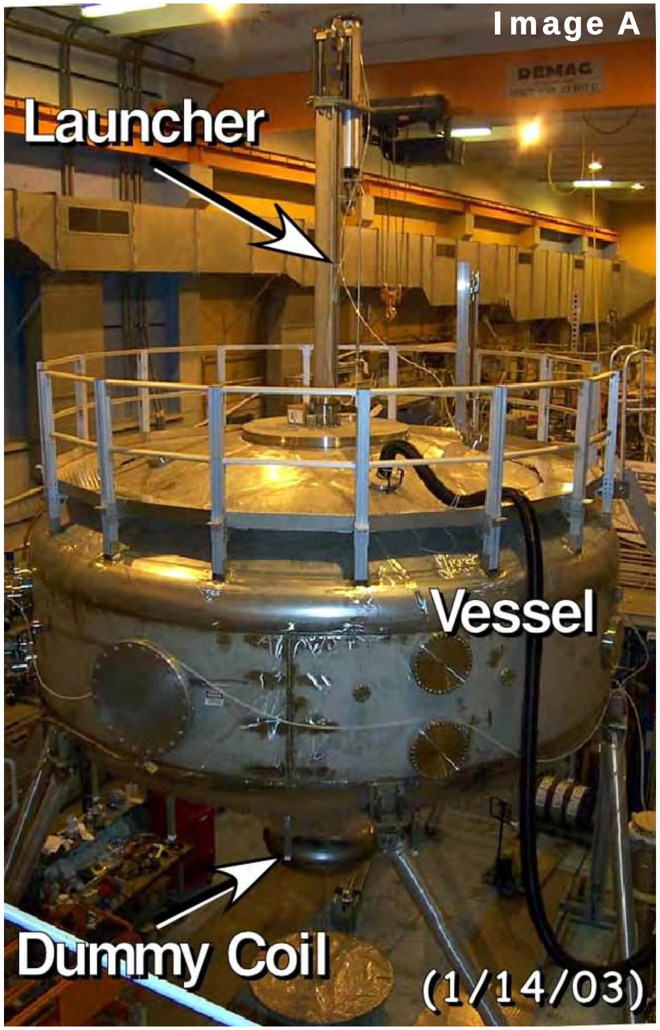
# Introduction

The first physics experiments were conducted on the Levitated Dipole Experiment (LDX). Two campaigns have been run, one on August 12-13 and the other on September 16-17, with the central floating coil suspended by a launcher/catcher system. The goals of these initial runs were to:

1. demonstrate successful operation of LDX in supported mode
2. create dipole-confined plasma and measure basic parameters using current diagnostics systems
3. investigate plasma heating with single and multiple-frequency ECRH
4. explore plasma response to varying magnetic field and gas pressure
5. identify interesting probe behavior and conditions leading to maximum beta

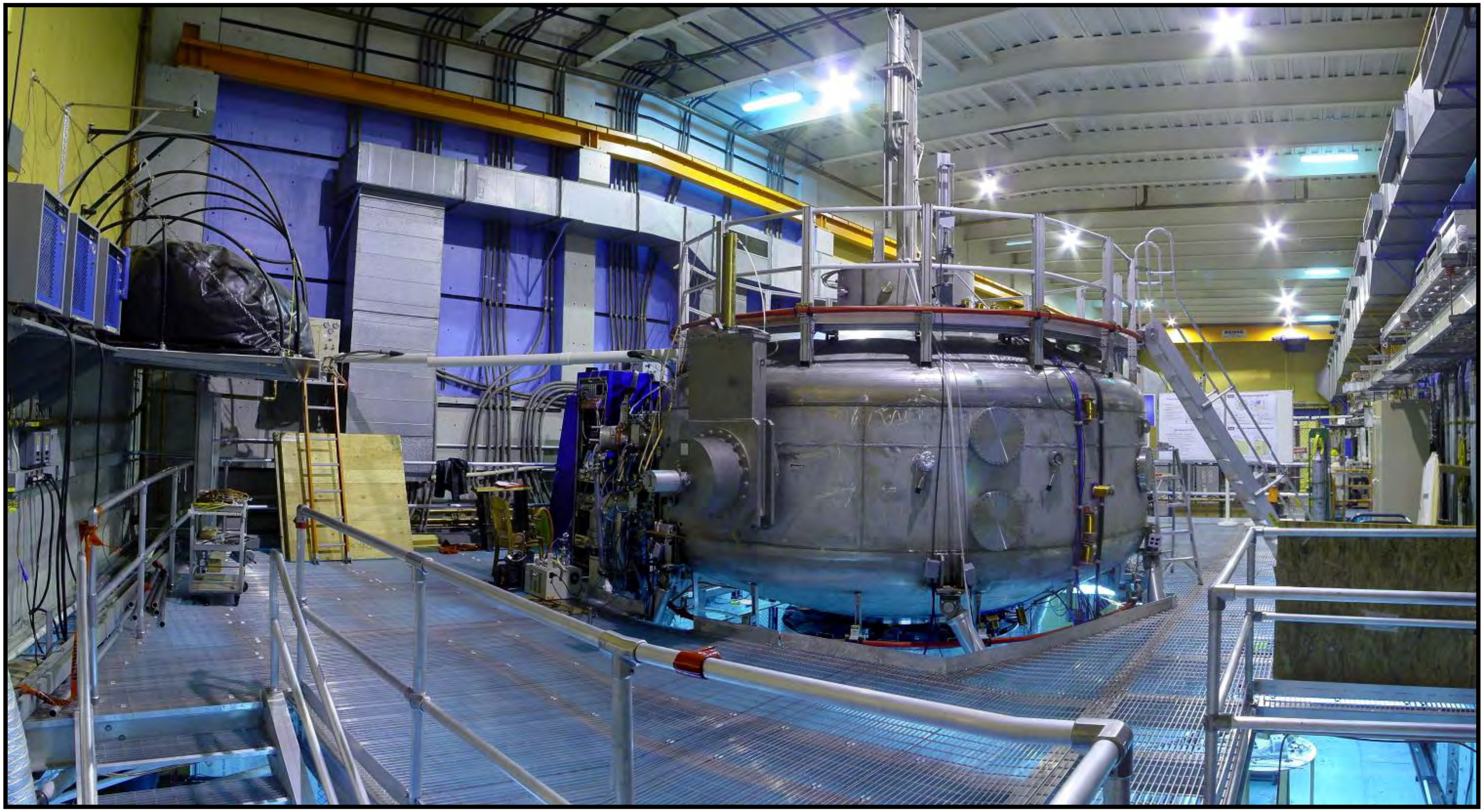
# The Big Picture




* Image and Figure by D. Garnier. Updated by E. Ortiz. October 2003.

# The Bigger Picture (latest picture)



* Image by E. Ortiz. Nov 12, 2004.

# LDX Parameters

| | EXPECTED** | AUG Run* | SEP Run* |
|---|---|---|---|
| **Current in Floating Coil (A)** | **1,190,000** | 750,000 | 900,000 |
| **Total Plasma Volume ($m^3$)** | **26** | - | - |
| **Core Volume ($m^3$)** | **0.5** | - | - |
| **B at Core (G)** | **47,600** | 30,000 | 36,000 |
| **B at Edge (G)** | **50** | 26 | 31 |
| **Core HOT electron density** | **3.60E+16** | - | - |
| **Core total electron density** | **7.60E+16** | - | - |
| **Core HOT Te (eV)** | **250,000** | 40,000 | 20,000 |
| **Core thermal Te (eV)** | **5,000** | - | - |
| **Core thermal Ti (eV)** | **50** | - | - |
| **Peak core Beta (%)** | **55** | 3+ | 8+ |
| **Edge Vf during Heating (V)** | **?** | [-28,-24] | [-28,-20] |
| **Edge Density ($m^{-3}$)** | **[7e14]** | [2e15,2e16] | [1e15,1e16] |
| **Edge thermal Te (eV)** | **5** | 8 | 10.5 |

* Robust data fitting.
\+ No shaping or Levitation coil.
** Table by D. Garnier. Updated by E. Ortiz. Nov 2004.

# LDX Parameters

| | Diverted, No Shaping | Diverted, Maximum Beta | Diverted, Minimum Beta | Limited Plasma |
|---|---|---|---|---|
| **Top HelmHoltz (I_top)** | 0 | 1 | 50 | 3 |
| **Bottom HelmHoltz (I_bot)** | 0 | 12 | 50 | 12 |
| **Plasma Volume (m^3)** | 14 | 27 | 1.7 | 24 |
| **SOL Pressure (Pa)** | **0.25** | **0.25** | **0.25** | **0.1** |
| **Max Pressure (Pa)** | 136 | 1530 | 1530 | 472 |
| **Plasma Current (kA)** | 3.2 | 16.4 | 16.4 | 5.78 |
| **Stored Energy (J)** | 316 | 1450 | 1450 | 516 |
| **R(Pmax)(m)** | 0.76 | 0.76 | 0.77 | 0.79 |
| **B(Pmax)(T)** | 0.088 | 0.088 | 0.088 | 0.088 |
| **Beta(Pmax)** | **0.08** | **0.55** | 0.015 | 0.15 |

** Table by D. Garnier. Updated by E. Ortiz. Nov 2004.

# Overview of LDX Probes

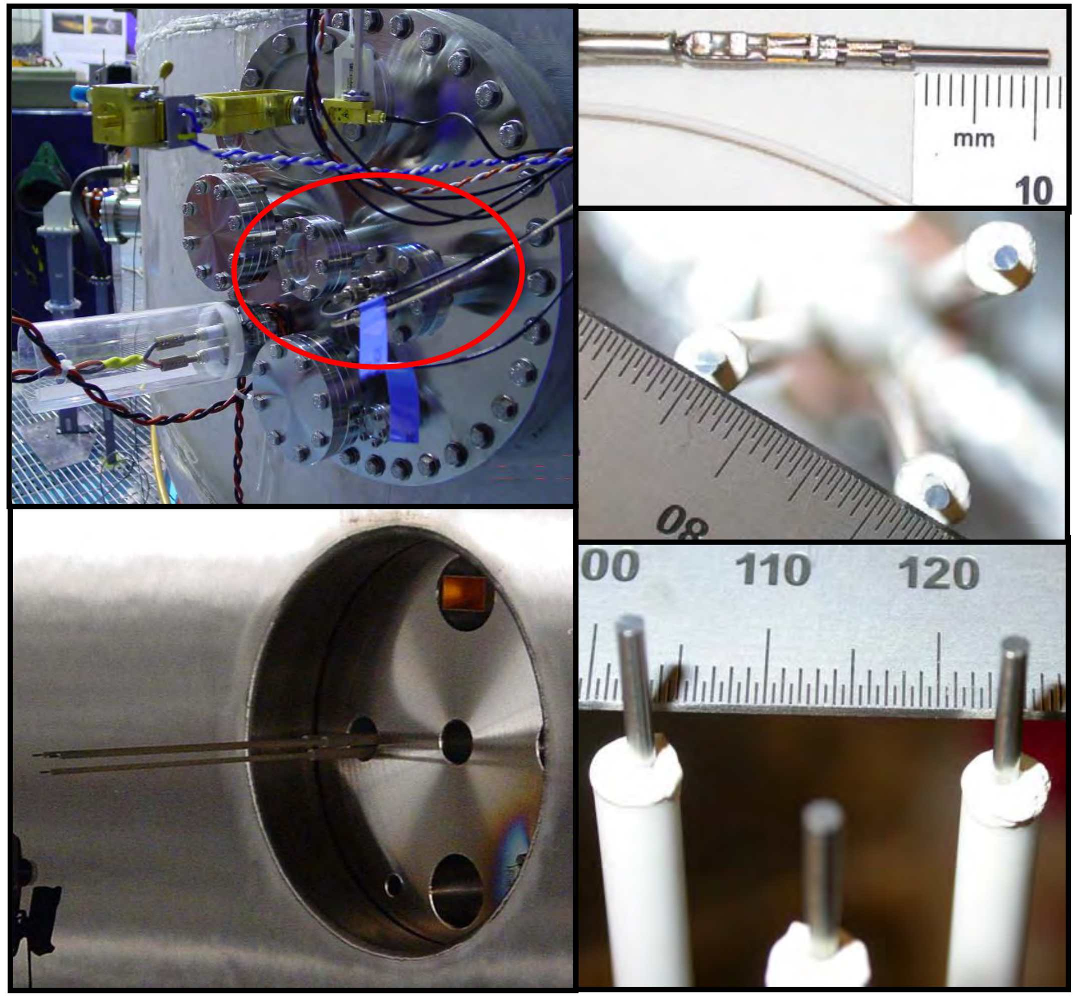
- Current Electric Probes
  - Isat, Vf, Single Swept, Mach
- Data Acquisition System
  - Probe Board Circuitry
  - Digitizers
  - Cabinet/Power Supplies
- Current Data Analysis
  - Swept probe analysis
    - Eliminating capacitive coupling
    - IV curve analysis (Single, Multi, Robust)
    - Multi-probe analysis (Mach probe)
  - Non Swept Probe Analysis
    - Floating & Isat probe considerations

# Overview of LDX Probes cont…

- Langmuir Results
  - Gas Scans
  - Modulated Runs
  - Varying Magnetic Field
  - Varying Gases
- A word on results
  - Vacuum Conditioning (GDC)
- Upgrades
  - New probe designs, layout, and circuitry
    - Triple probe
    - Emissive probe
    - Positioning system
    - Field array?

# Current Electric Probes (Lang)

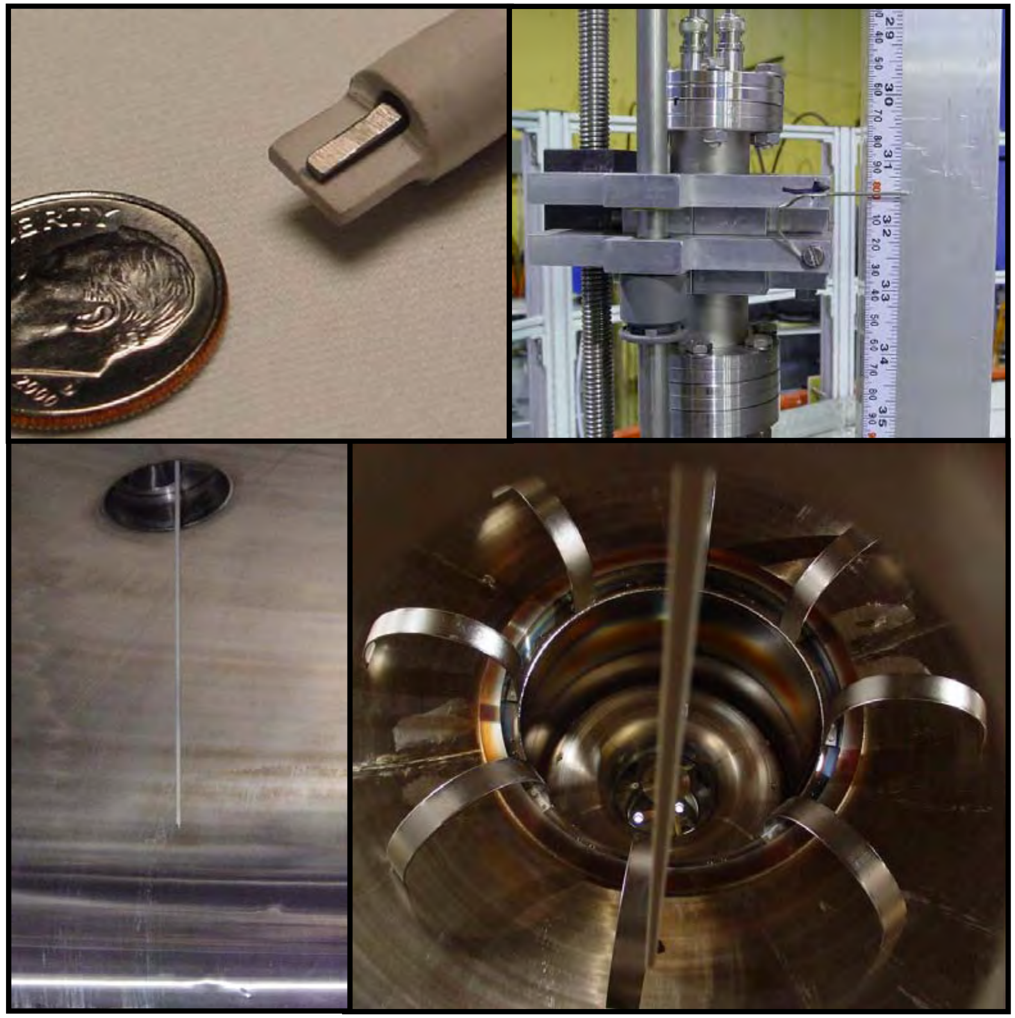
- Langmuir Probes
  - Three equally sized probes
  - Thoriated tungsten
    - $l$ = .9922 cm
    - d = .1588 cm
    - As = .4948 $cm^2$
  - Ceramic bond sealant
    - 904 ZIRCONIA, Ultra Hi-temp ceramic adhesive (Cotronics)
  - On mid-plane
    - LHS probe -> Isi
    - RHS probe -> Swept
  - Below mid-plane
    - MID probe -> Vf
  - All probes 1.27 cm apart on mid-plane




* Images by E. Ortiz. July 25, 2004. Aug 1..19, 2004. Nov 12, 2004.

# Current Electric Probes (Mach)

- Mach Probe
  - Two equally sized probes
  - Thoriated tungsten
    - $l$ = .6350 cm
    - d = .1588 cm
    - As = .1008 $cm^2$
  - // to Z-axis on 1 of 4 top diagnostics port
    - Probes Swept
  - Variable linear motion
  - Maximum penetration (~ 60 cm) for all experiments
    - See ‘Probe Location’ below for details
  - Aligned ⊥ to B-field



* Images by E. Ortiz. Oct 26, 2003. Aug 18-19, 2004. Nov 12, 2004.

# Probe Interface System

* Image by E. Ortiz. Nov 12, 2004.

- Easy access via platform
  - Actual height ~ 4.5' (137 cm) from base flange
  - Four ports available
- Bellow stroke ~ 32.5" (83 cm)
  - Max length ~ 42.25" (108 cm)
  - Min length ~ 9.75" (25 cm)
- Linear incursion depth into chamber ~ 60 cm
- Remove probe w/out breaking main vacuum
- Remotely control linear motion with probe position system and air-motors
- Applications
  - Select specific magnetic field lines to probe or bias with emissive probe
  - Retractable GD anode

# Probe Location Relative to Plasma

- Magnetic Field Simulation
  - 40917018 @ t = 3.22 sec

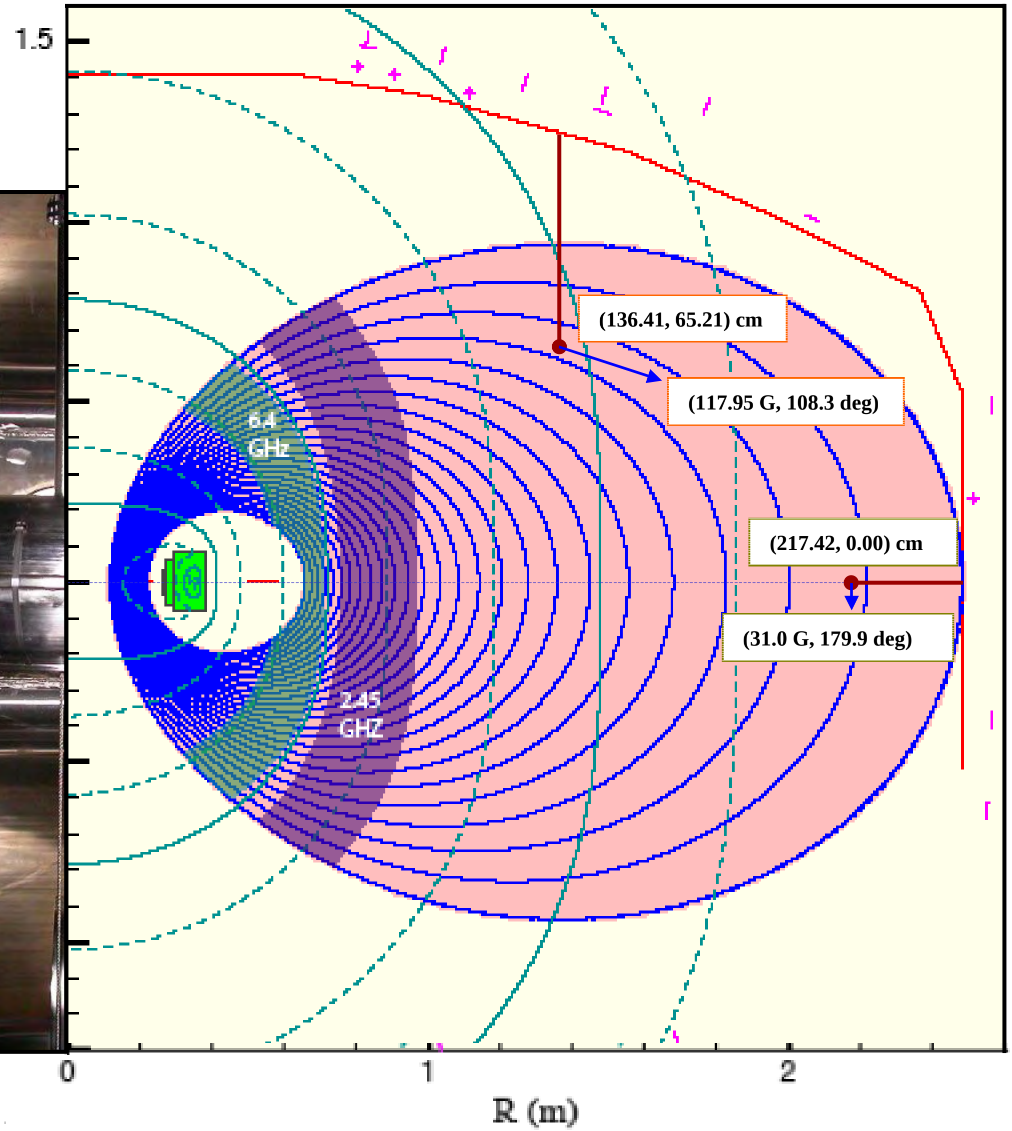



*Figure by A.K. Hansen. Edited by E. Ortiz. Nov 03, 2004. Image by E. Ortiz. July 24, 2004.

# Magnetic Field at Probe

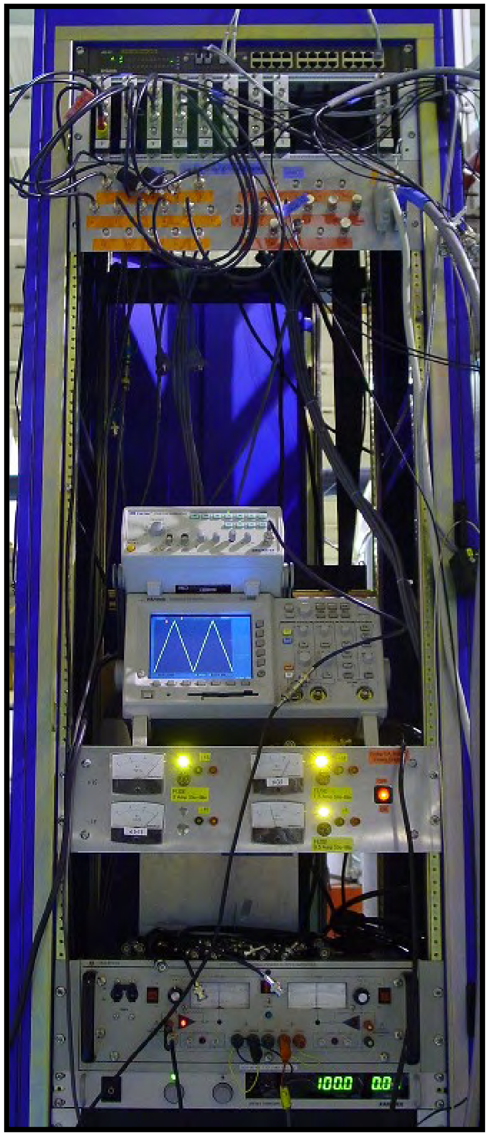
| | 40813032 Top | 40813032 Side | | 40917019 Top | 40917019 Side | |
|---|---|---|---|---|---|---|
| Te | 13.6 | 7.0 | | 10.1 | 9.8 | eV |
| Density | 3.69E+16 | 4.73E+15 | | 2.68E+16 | 2.92E+15 | m-3 |
| B-Field | 97.1 | 26.0 | | 118.0 | 31.0 | Gauss |
| B-Field Direction | 108.6 | 180.0 | | 108.3 | 180.0 | o from Vert |
| Cyclotron Freq. | 0.3 | 0.1 | | 0.3 | 0.1 | GHz |
| Thermal Velocity | 1548.2 | 1108.0 | | 1335.2 | 987.1 | km/s |
| Gyroradius | 5.7 | 15.2 | | 4.0 | 11.4 | mm |
| Debye Length | 0.143 | 0.285 | | 0.145 | 0.324 | mm |

Text talks about probe design gyro radius etc.

- Designed by [illegible] aBombard for ALCATOR plasmas
- Re-designed [illegible] rulke for LDX plasmas
- 50 boards built [illegible] front access, [Pin, Vout, Iout, $V_{sweep}$(3)]
- Flexible design amp[illegible] ffers and can be remotely controlled to adjust v[illegible] ttings
  - *Individually Select:* $V_{swe}$ [illegible] *libration, Float* settings

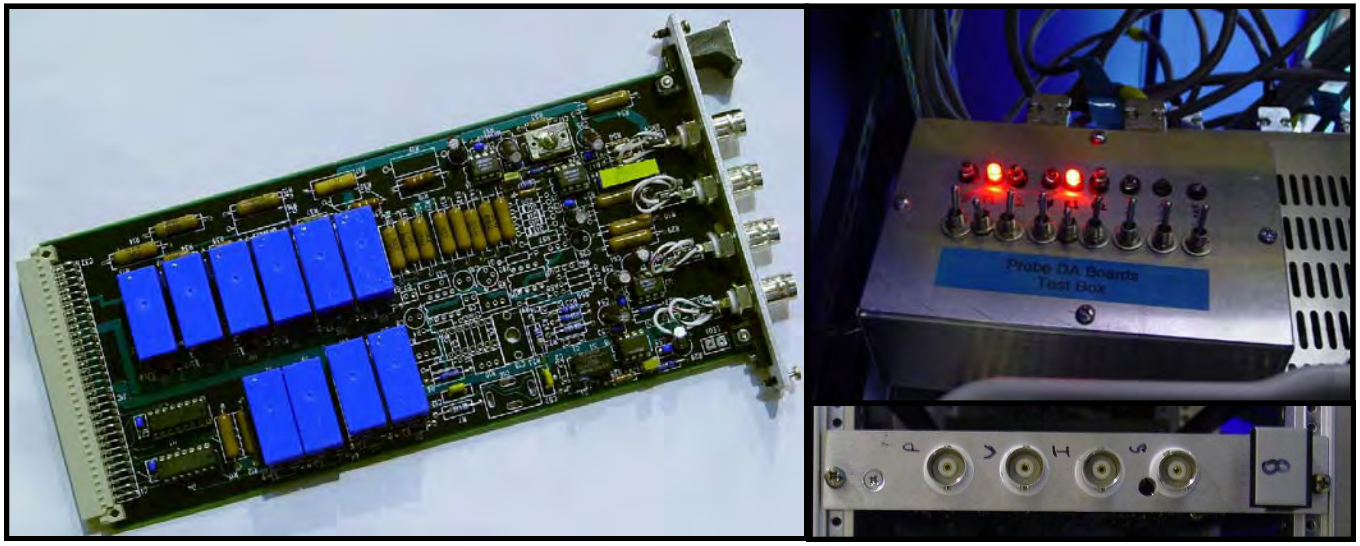
# Cabinet Setup

- New magnetically shielded
- Electrically Isolated
- Current Guests:
  - Front
    - Probe Ckt boards housing box
    - Digitizer breakout panel
      - Waveform Generator
      - Scope
    - Probe Ckt board PS
    - High Voltage Sweeping PS
    - Stable High Voltage PS
    - Probe board switch box (not visible)
    - RGA Controller
    - Interferometer control box
  - Rear
    - Probe positioning PLC
    - Optical encoder PS
- Future Guests:
  - Emissive PS
  - Triple probe Ckt Box



* Image by E. Ortiz. Nov 12, 2004.

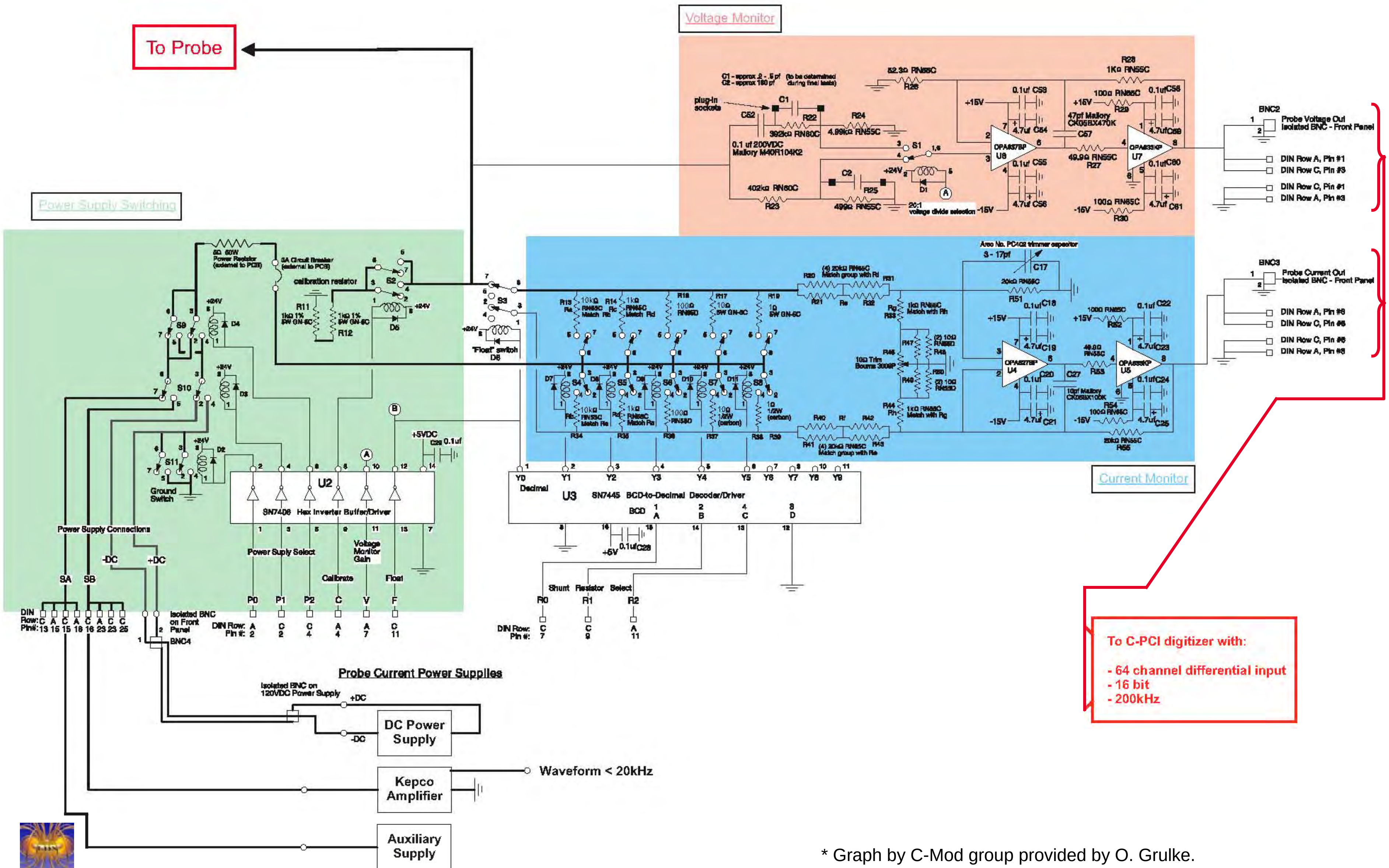
# Probe Ckt Boards and Control



* Images by E. Ortiz. Nov 12, 2004.

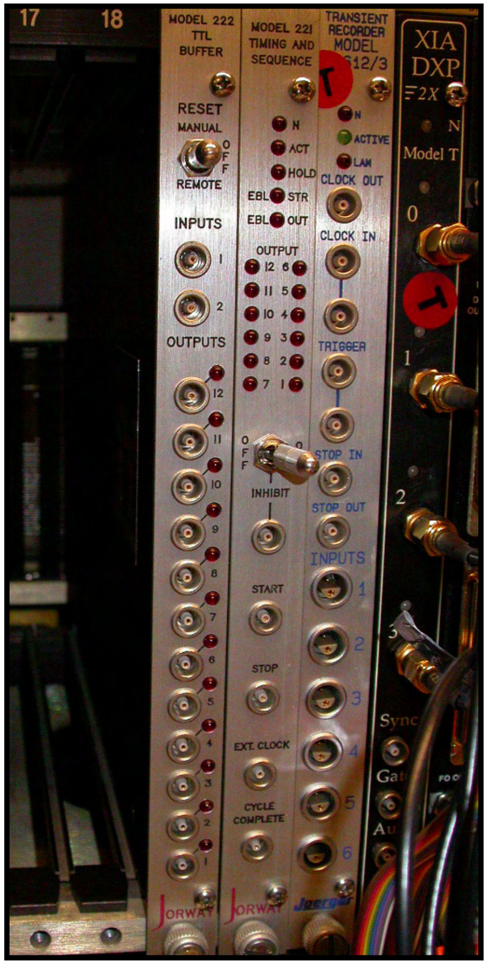
- Designed by Brian LaBombard for ALCATOR plasmas
- Re-designed by Olaf Grulke for LDX plasmas
- 50 boards built with easy front access, [Pin, Vout, Iout, $V_{sweep}$(3)]
- Flexible design amplifies, buffers and can be remotely controlled to adjust various settings
  - *Individually Select: $V_{sweep}$, $R_{load}$, Calibration, Float* settings

# Sweep Probe Board Circuit




* Graph by C-Mod group provided by O. Grulke.

# Digitizer Boards




* Image by E. Ortiz. June 6, 2004.

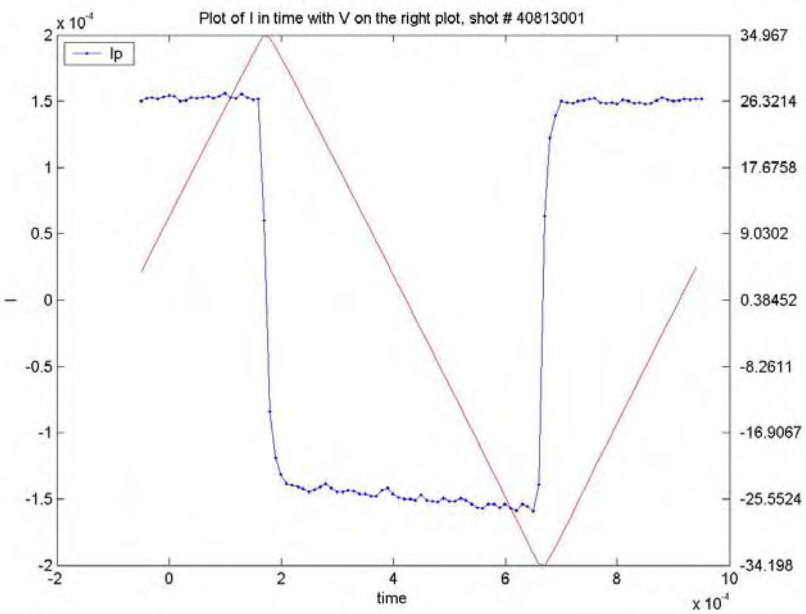
- (1)-Joerger 612/3 Transient Recorder/Digitizer
- 6 channels, 12 bit resolution, 3 MHz sample
- Input impedance ~ 1 MΩ differential, CAMAC
- Input range ± 5 V shipped, ± 10 switch able

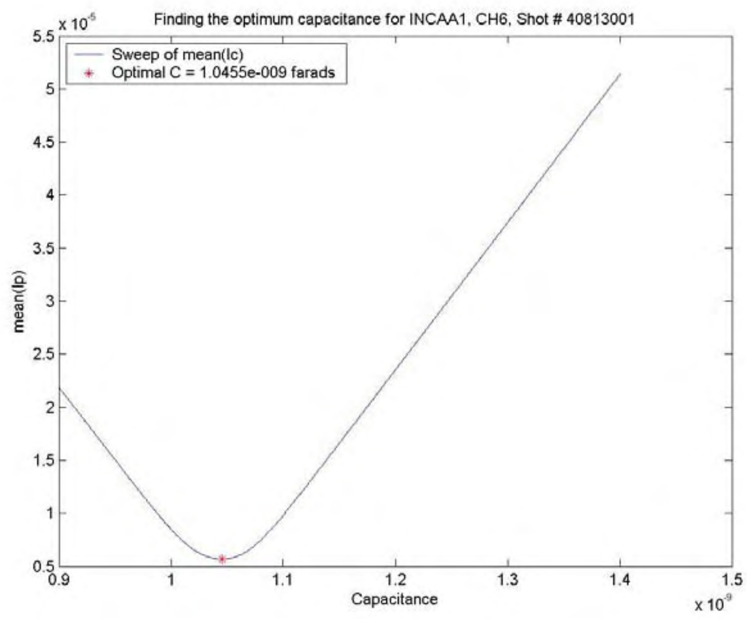
* Image by E. Ortiz. June 6, 2004.

- (4)-Incaa CP-TR10-5020 Isolated Transient Recorder, CPCI
- 16 channels,16 bits, 200 KS/s sample
- Input range ± 10 V
- Input impedance ~ 800 kΩ differential
- Accuracy ± .05% of full scale for both

# Data Analysis – Initial Considerations

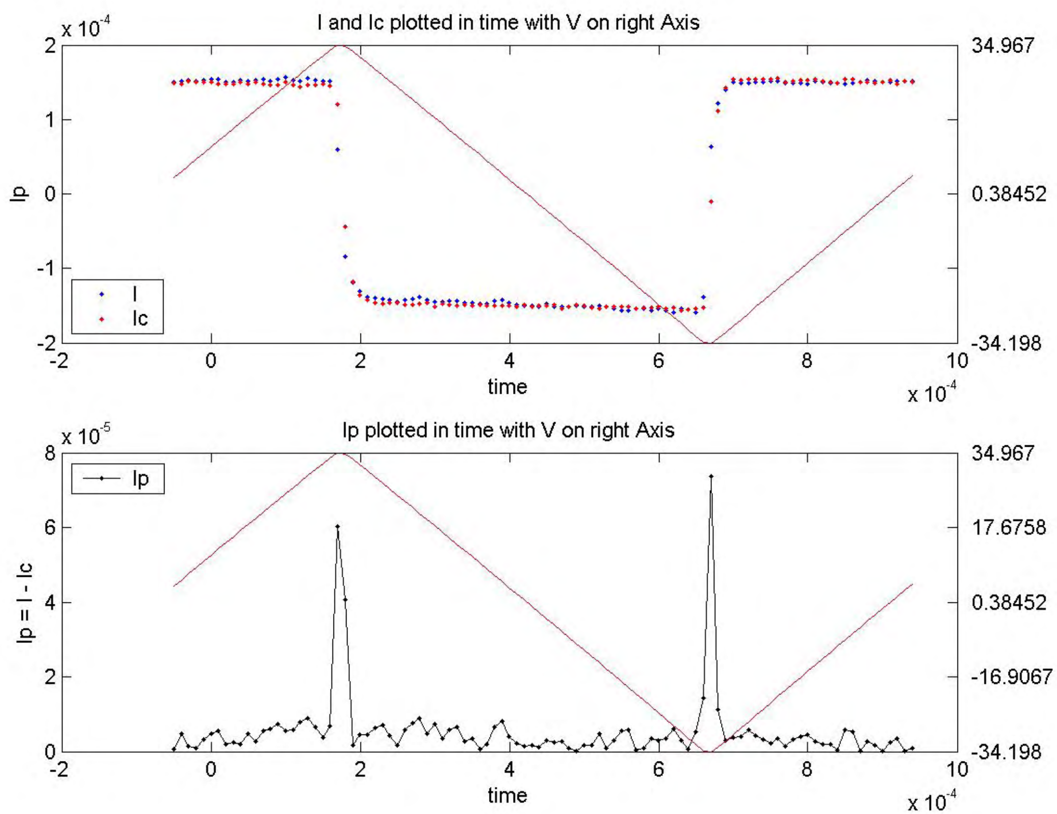
- Langmuir probes known for capacitive currents from the sweeping voltage
  - Important to subtract out this current
  - I = Ic + Ip, where Ic = c * dV/dt
  - Find c by recursive fitting



# Data Analysis – Initial Considerations

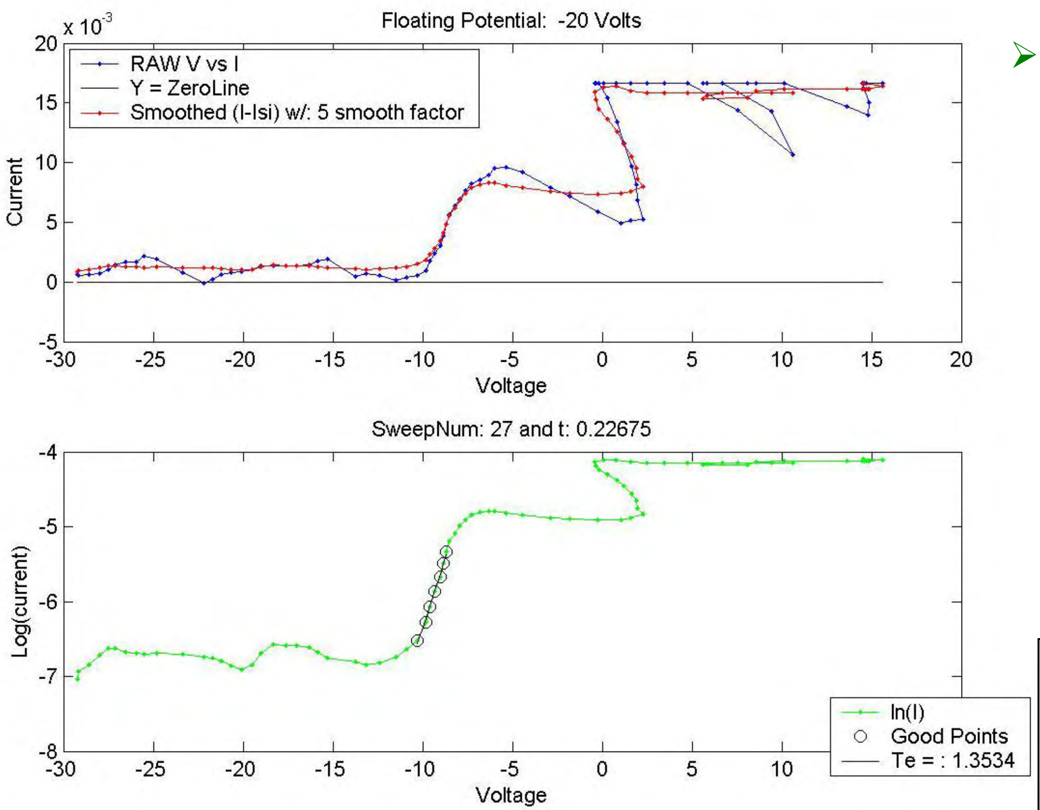
- ‘On the fly’ correction of Ip, independet of shot & channel
  - Take pre-trigger (ie pre-plasma) data and find $C_{shot,channel}$
  - Obtain Ip using analysis above
  - Ignore couple points on either side of $V_{sweep}$ peaks



# Data Analysis – Sweeping

## How to fit the best characteristic? – One by One

- Not all IV curves are created Equal!
  - Expect Ion Sat, Characteristic, and Electron Sat regions
  - Sweeping Frequency matters - # points per sweep
  - Assume Maxwellian distribution of electrons and obtain Te and from Transition region




- IV Analysis Formalism:
  - Take (1) sweep
  - Smooth (5) & choose Isi as min Ip
  - Subtract and take log
    - Ln(Ip-Isi)
  - Find "Good" points*
  - Slope ~ 1/Te
  - No ~ Isi/sqrt(Te)

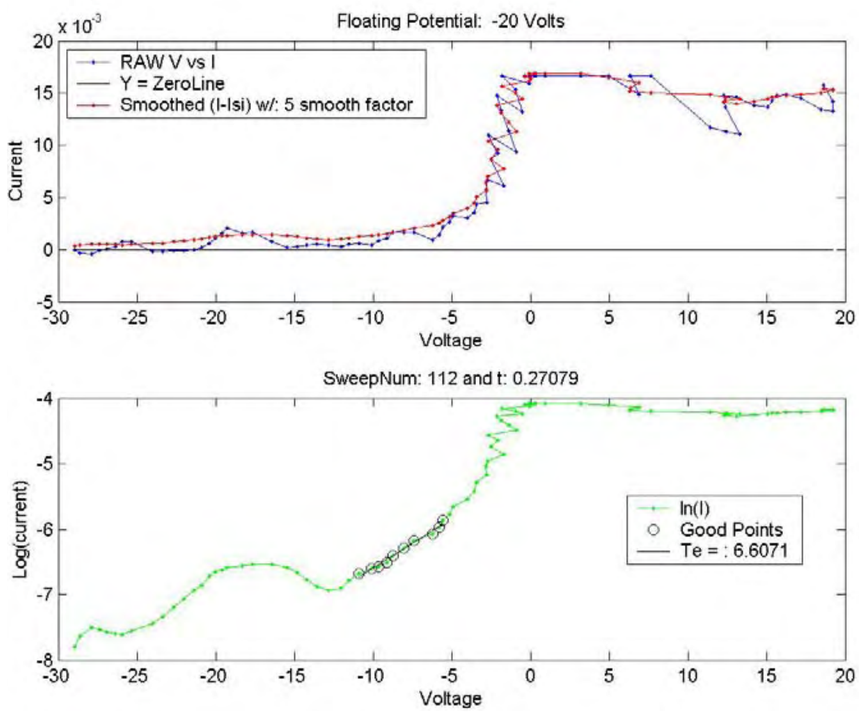
Shot # 40917013
Sweep Freq = 750 Hz
Time = .22675, Te = 1.4 eV

# Data Analysis – Sweeping

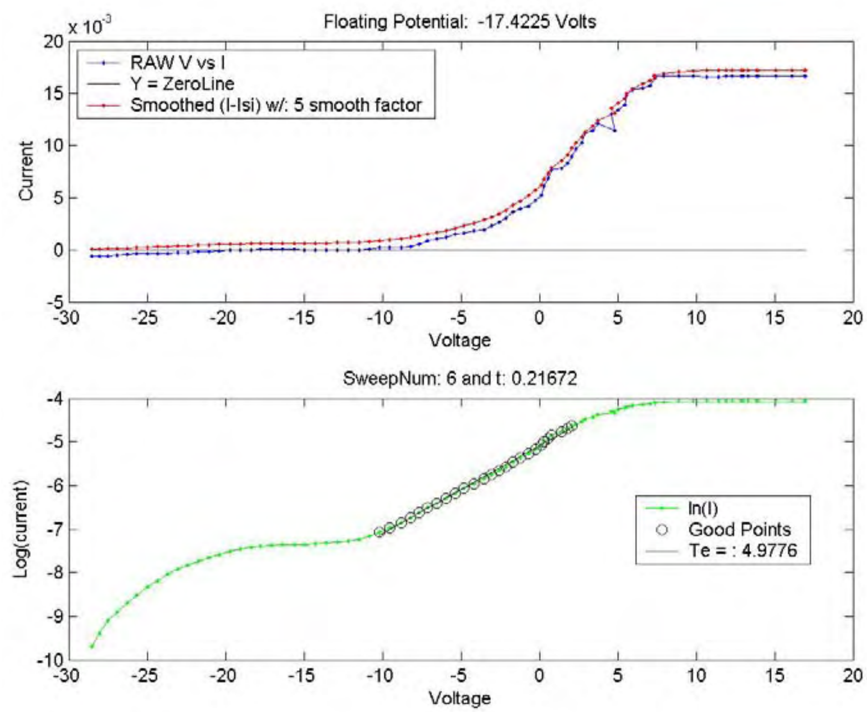
## How to fit the best characteristic? – One by One

- Smooth out the function and obtain Isi as smallest value of Ip of sweep
- Same Shot (40917013)
- LHS a complete mess, RHS as IV's are supposed to look

Time = .27029, Te = 6.6 eV



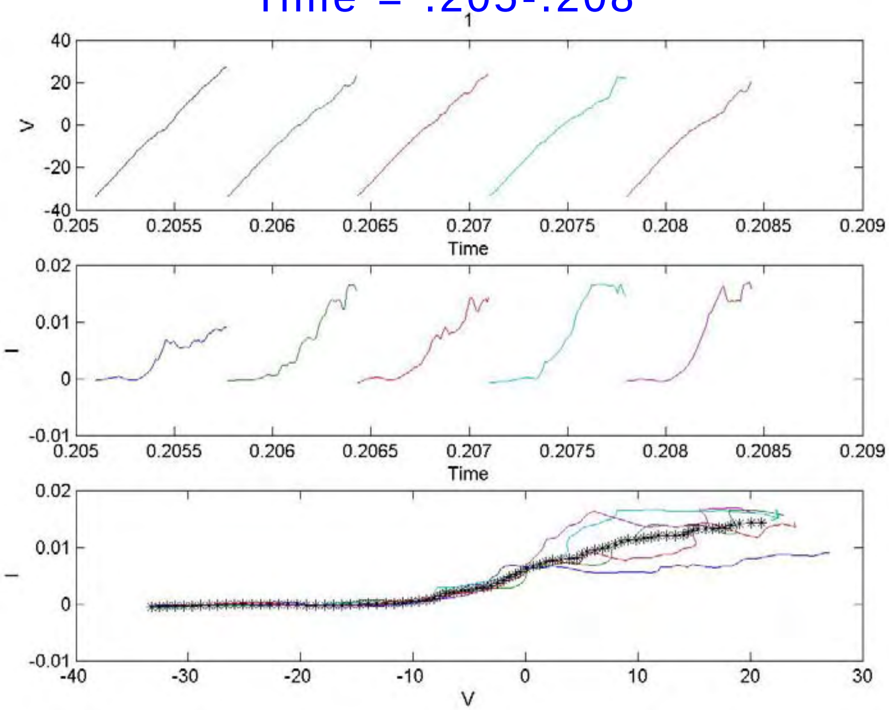

Time = .21672, Te = 4.9 eV

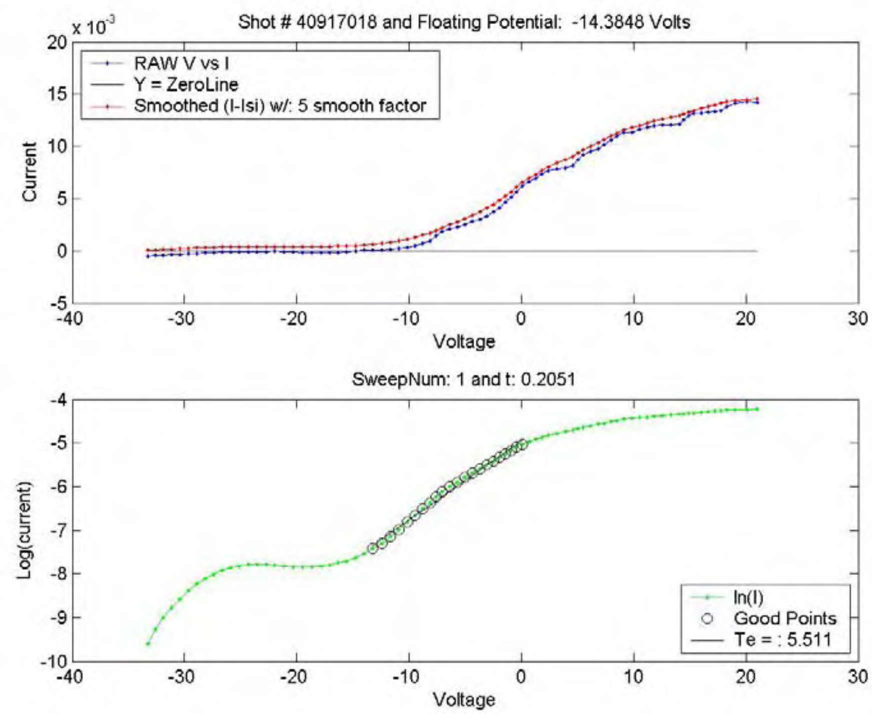


# Data Analysis – Sweeping
## How to fit the best characteristic? – Five at a Time?

- We can also try fitting sets or multiple sweeps (Multi)
  - Take a series (say five) consecutive IV plots
  - Take an average of them
  - Then find the slope as before

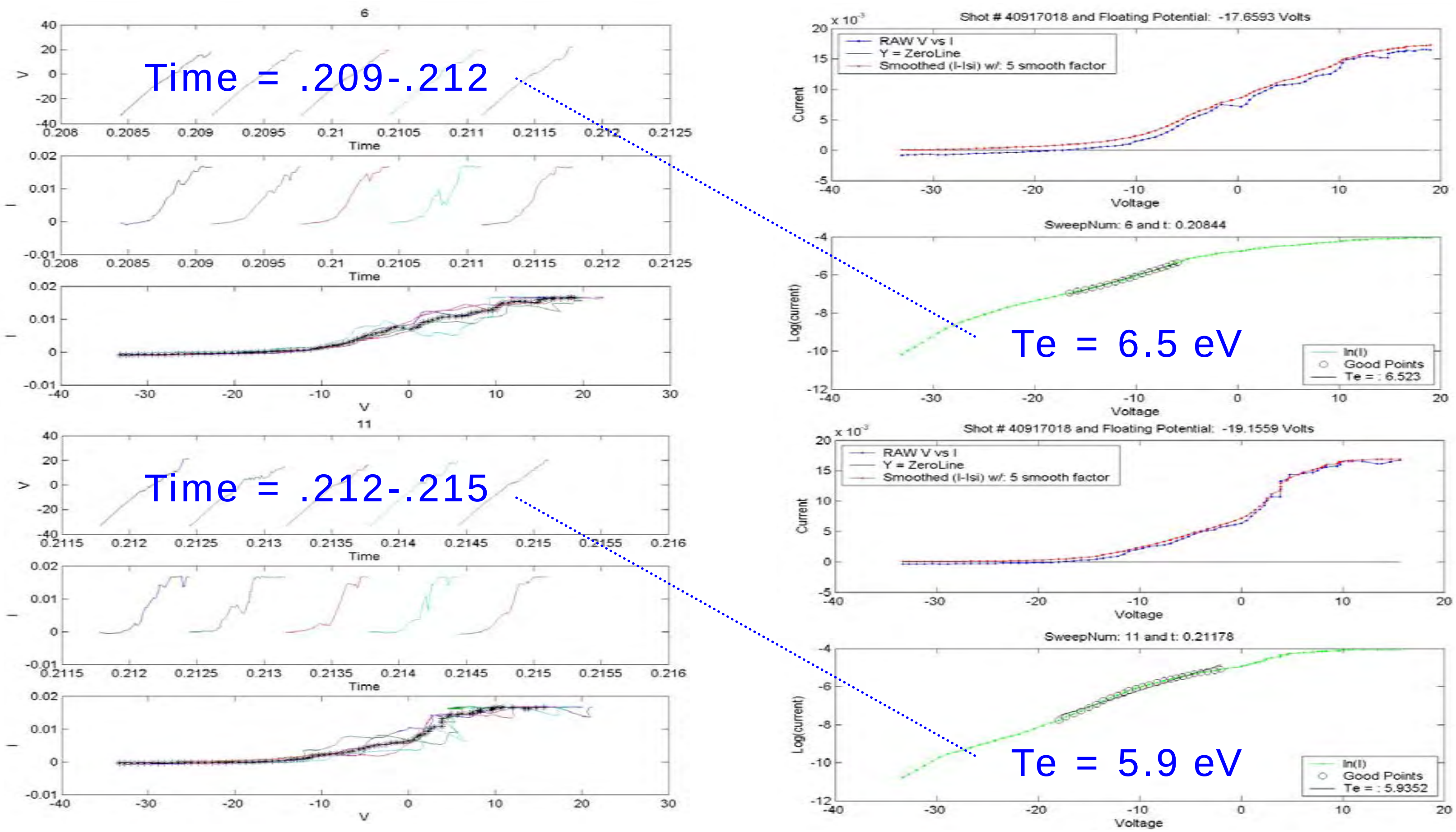
Time = .205-.208 Te = 5.5 eV




- A couple more examples…

# Data Analysis – Sweeping
## How to fit the best characteristic? – Five at a Time?

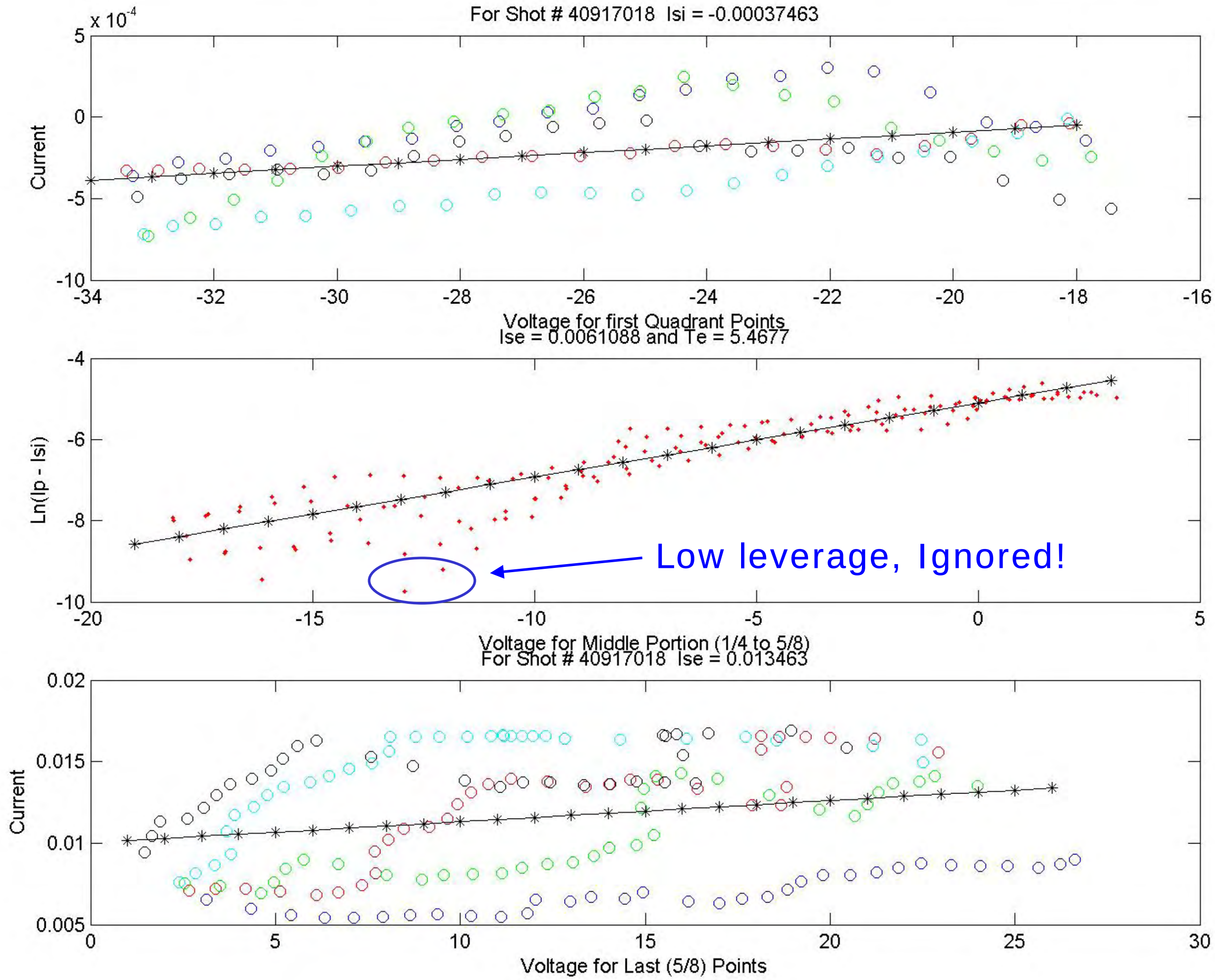



- Results show/prove that taking multiple sweeps helps
  - Why not take more? ... in fact for 750 Hz, 25X arrived trial/error
  - Not exact science since Vsp changes in time – should shift in time
  - What about outliers? ...S/N ratio reduced but is it real?

# Data Analysis – Sweeping

## How to fit the best characteristic? – Robust Fitting

- Robust fitting gives us the best of both worlds…
  - Filter out outliers and average over multiple sweeps!

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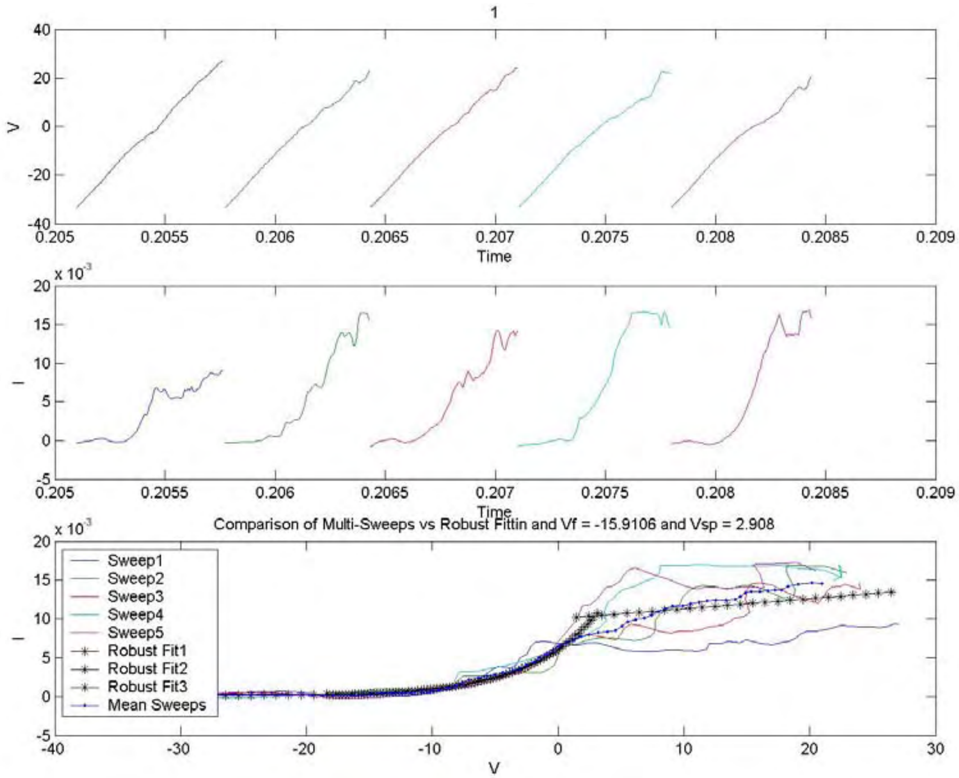
# Data Analysis – Sweeping

## How to fit the best characteristic? – Robust Fitting

- Robust fitting tends to report higher values of Te than other methods
  - For Same Shot (40917018)
  - Te(Single) = 3.3 eV, Te(Multi) = 5.5 eV, Te(Robust) = 8.3 eV

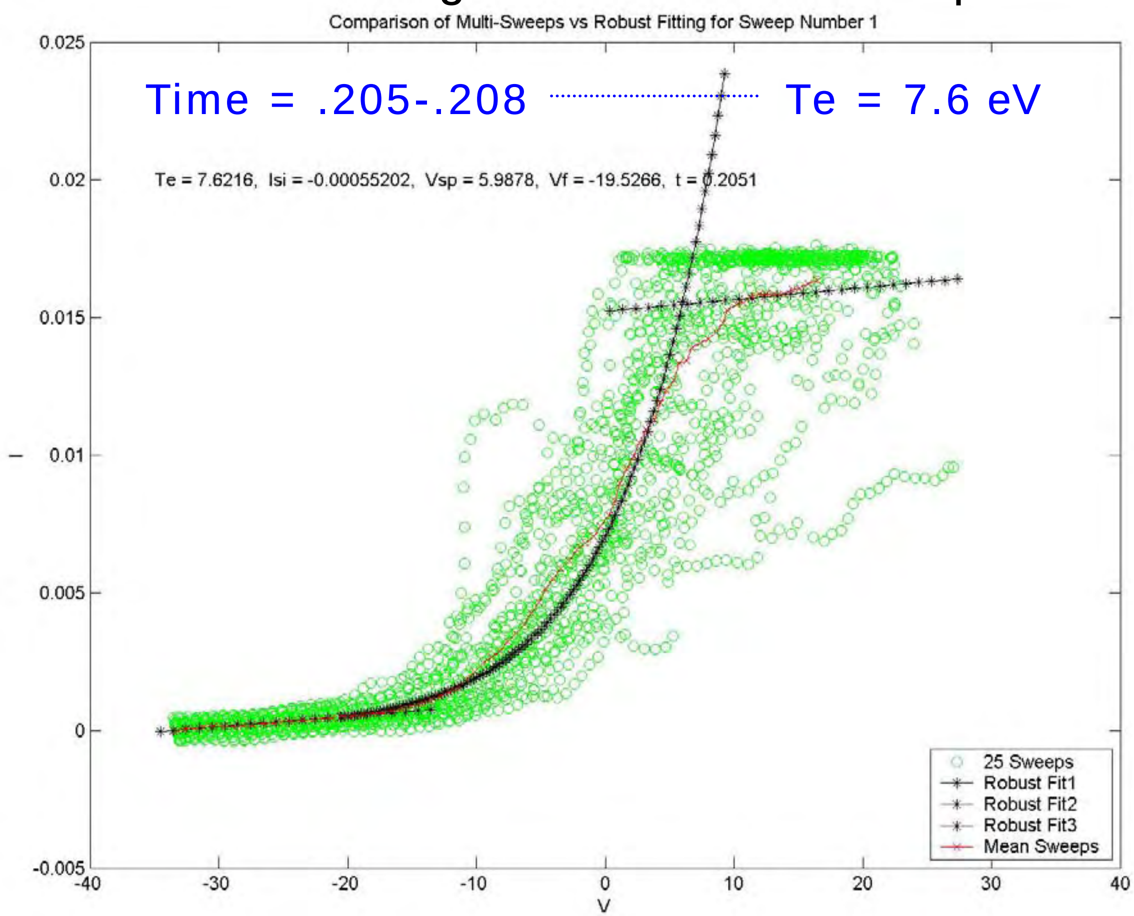
Time = .205-.208 ........................ Te = 8.3 eV




- Robust Analysis Formalism:
  - Determine IV regions
  - Robust fit *Isi* region
    - Isi = $I_{fit}(V_{min})$
  - Subtract Isi and take log in *Transition* region
    - Obtain Vf,Te
  - Robust fit *Ise* region
    - Obtain Vsp from log of both *Transition* & *Ise* regions
  - Find No using Te,Isi

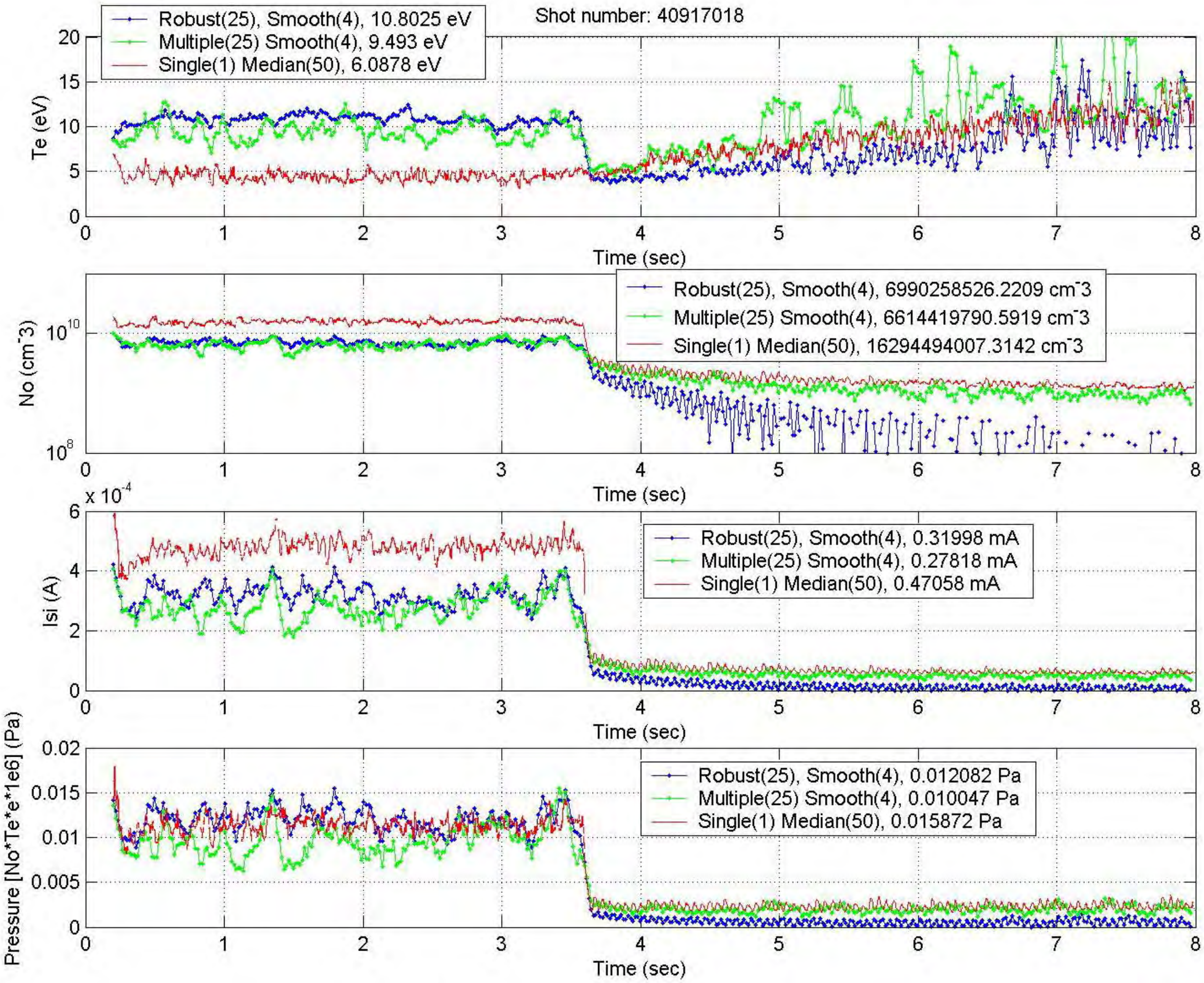
# Data Analysis – Sweeping
## How to fit the best characteristic? – Robust Fitting

- Robust fitting using 25X
  - Distinction between three regions
  - Notice how Robust avoids outliers and how Multi(red) is pulled up by them in Transition region
  - Even lower Te with higher number of sweeps



# Data Analysis – Sweeping

## What is the best method to analyze IV characteristics?



# Data Analysis – Sweeping

## What is the best method to analyze IV characteristics?

- Summary of Behavior
  - Multiple [illegible]eep Fitting returns higher Te during ECRH heating & lower T[illegible]he afterglow region
  - MSF gives [illegible] Isi (& No) in both regions, since No ~ Isi/sqrt(Te)
  - Yet, MSF Pressu[illegible]re not very different in heating region but lower in afterglow [illegible]ns
- Discussion

Fill in later

# Data Analysis - NonSwept

IF ENOUGH TIME INCLUDE

Floating and Isat Probe considerations

Isi, Vf, fft Spectrum of most interesting CASE

(40917018?)

Can do spectral fft

# Results - Gas Scan

Analysis Done,
Past Graphs Saturday

# Results - Modulated Runs

Analysis Done,
Past Graphs Saturday

# Results - Varying Magnetic Field

Analysis Done,
Past Graphs Saturday

EO_APS_DPP_11-04

# Results - Varying Gases

Analysis Done,
Past Graphs Saturday

# A word on results…

Analysis Done,
Past Graphs Saturday

# Vacuum Chamber Condition

Discuss Quality of Vacuum during first exp.

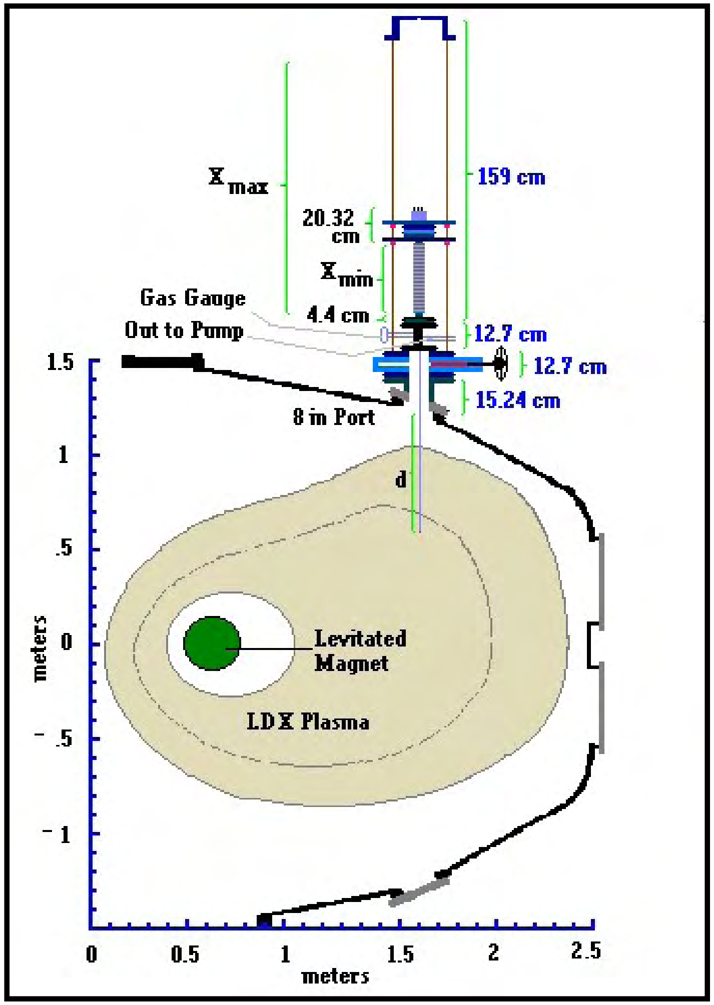
Again, Analyis done, paste graphs Sunday

(LAST IF TIME)

Point out need to have clean environment

For next run, refer to GDC slides/presentation

# Future Plans & Upgrades (Emissive Probe)




* Fig. by E. Ortiz. May 15, 2001.

- Measure edge plasma phenomena
  - Fluctuations in local potential, ie. **E**-field
- Switch application to emitting filament and bias single magnetic field line
  - Pin point injection of hot electrons
  - Attempt to 'stir' plasma and create vortex motion
  - Expect density profile evolution (local flattening) - product of particle transport by convective cells [8]

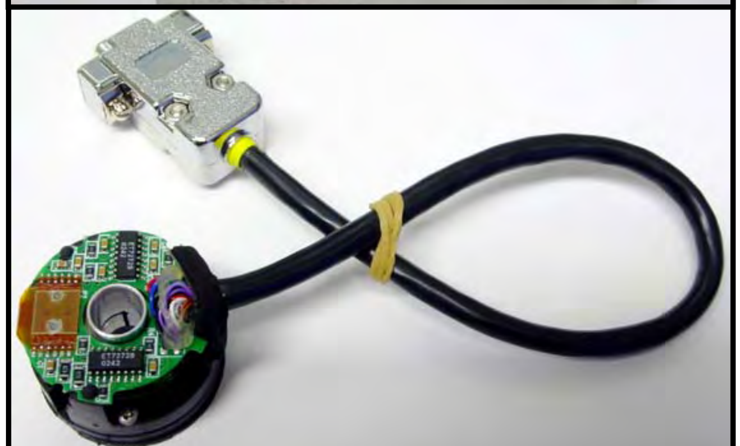
# Future Plans & Upgrades (Triple Probe)

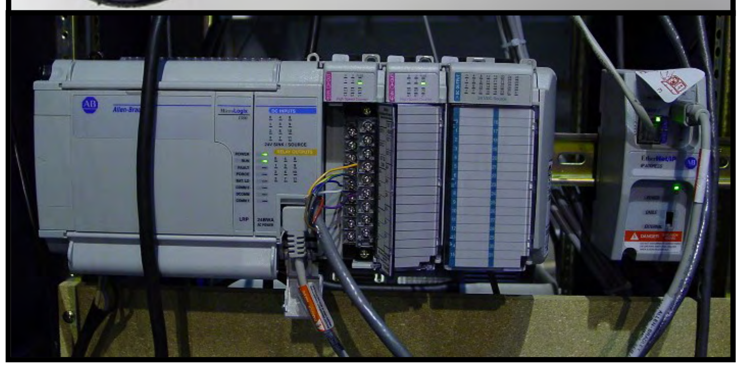
- Triple probe
  - Allo[illegible] the instantaneous measurement of electron tem[illegible] and density
  - Three [illegible] wires aligned with plasma flow
  - Essential [illegible] three probes as identical as possible and free of c[illegible]tion

Talk failure, New design and attach Ckt diagram Saturday

# Future Plans & Upgrades (Positioning System)

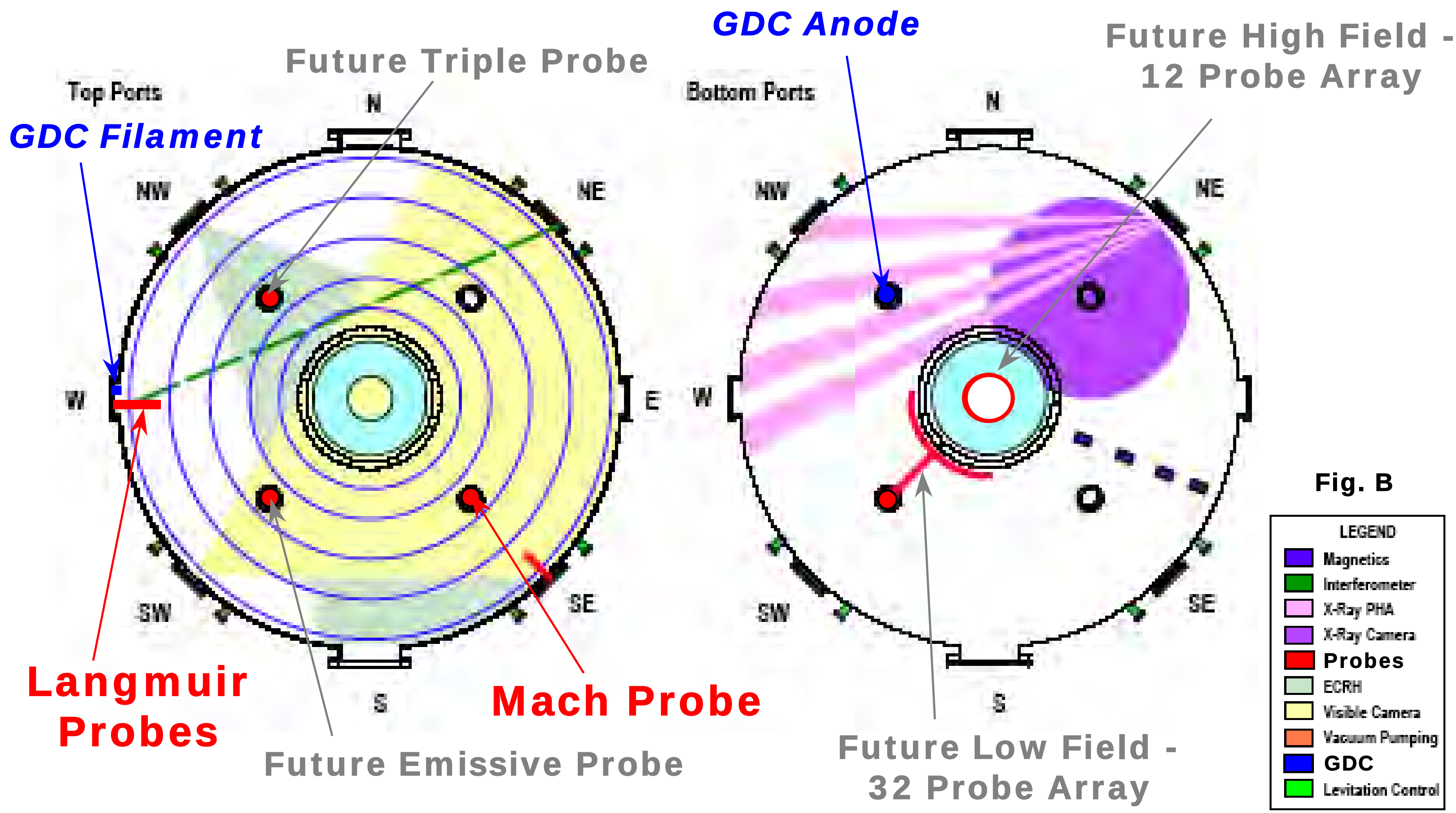
- Dynapar Series M15 1000 PPR modular encoder
- MicroLogix 1500 PLC
  - Compact High Speed Counter module
  - Monitors number of turns of lead screw
- Air motor controlled with PLC feedback loop and solenoid valves
- Will integrate this system into the shot initialization procedure
  - Probes repositioned before each shot





* Images by E. Ortiz. Nov 12-13, 2004.

# Future Plans & Upgrades (Multi-Probe Array)




* Figure by D. Garnier. Update by E. Ortiz. Nov 12, 2004.

# Summary

- Future plans
- Somet[illegible]g about Results
- CONC[illegible]ON PROBE TYPE, SIZE, include errors i[illegible]g too small

Once entire presentation complete
ADD new TEXT

# Abstract (updated)

Electrostatic fluctuations play an important role in the equilibrium and stability of a high-beta plasma confined in a dipolar magnetic field. Initial plasma experiments in LDX will use movable edge probes to measure plasma potential, plasma characteristics, and plasma mass flow. Three different probes have been built out of 2 % thoriated tungsten wire and installed: a set of three Langmuir probes [*l* = 1.00 cm, *d* = 0.16 cm], an emissive probe [*l* = 1.00 cm, *d* = 0.02 cm], and a Mach probe [*l* = 0.64 cm, *d* = 0.16 cm]. The emissive and Mach probes are mounted on an adjustable feedthroughs capable of scanning for plasma parameters along a 20-40 cm cord at the plasma edge, but were fixed at a position of (136 cm, 65 cm) relative to the center of the chamber . The Langmuir probes are fixed on the mid-plane penetrating 31 cm from the wall. Initial measurements and interpretations from first plasma experiments will be presented as well as a discussion on the performance of the various probes.