Abstract

The plasma edge region in the Pegasus ST exhibits: peeling modes at high $j_{||}/B$, broadband electrostatic turbulence, and strong deformation due to large-scale internal tearing modes. In addition, local helicity injection sources in the edge give rise to large current densities in the plasma scrape-off region, and potentially to a large non-axisymmetric edge current distribution. To address these issues, electrostatic and magnetic probes are deployed to measure the edge characteristics. A pair of scanning Langmuir probes measure edge n_e, T_e, and p_e in ohmic discharges. For an ohmically-driven plasma with I_p = 125 kA, B_T = 0.15 T, time-averaged profiles indicate $n_e = 7 \times 10^{18}$ m^{-3}, T_e = 9 eV at the radial location of the plasma limiter. A new 3-axis magnetic probe array is under consideration to measure $j_{||}/B$ in the edge of ohmic and helicity-driven discharges. This $j_{||}(R, t)$ is of special interest for quantifying helicity-driven Taylor relaxation states.

Supported by U.S. DOE Grant DE-FG02-96ER54375



Outline

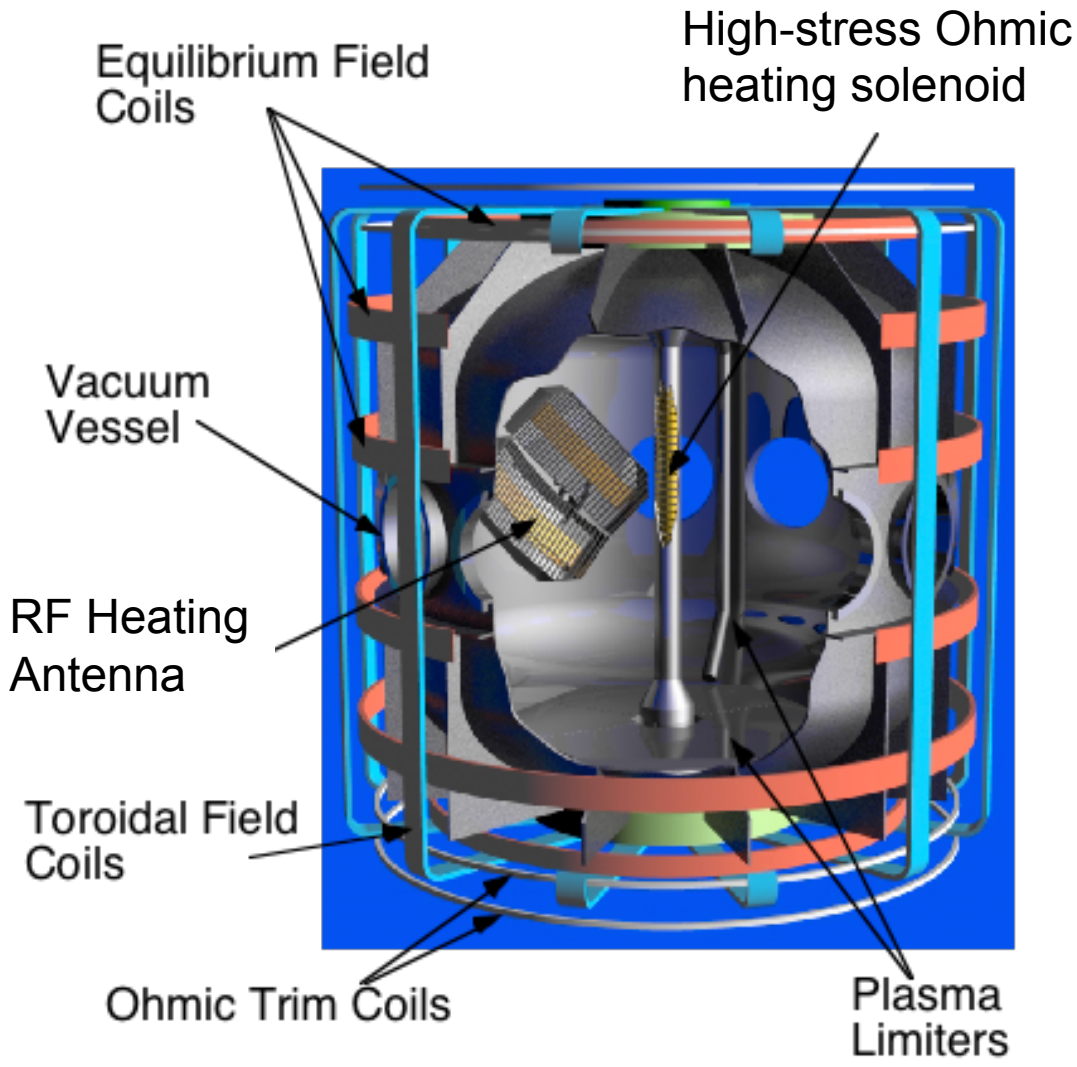
- Abstract
- Langmuir Probes
  - Theory
  - Setup
  - SOL scans (high/low TF)
  - Scale lengths
  - Bohm diffusion
  - Internal/Edge/SOL scan
  - Probe Perturbation
  - Edge fluctuations
  - Bohm SOL
- 3-axis Mirnov Probe Array
- Conclusion



Summary

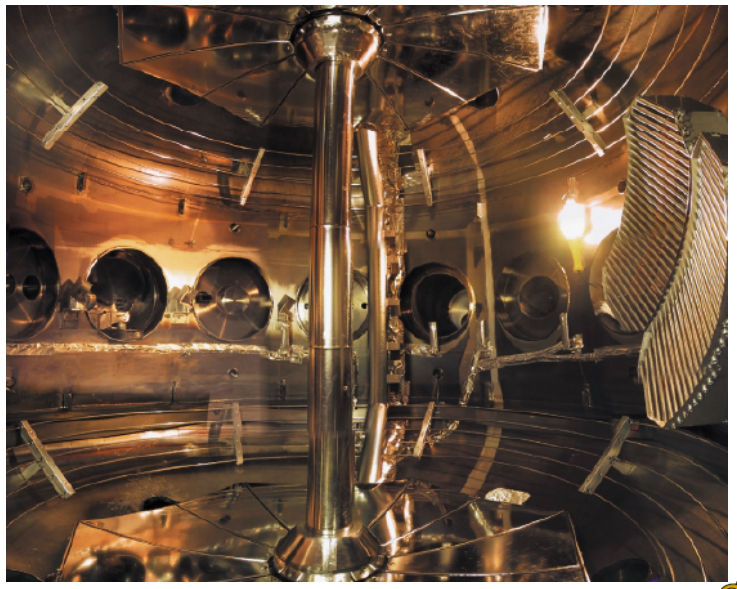
- A pair of Langmuir triple probes has been constructed for characterization of the edge and outer-half plasma regions for studies of
  - Peeling-mode behavior
  - EBW and HHFW feasibility
  - Turbulence
- First measurements of Pegasus' SOL region scale lengths are consistent with Bohm diffusion
- Studies conducted in large diffuse plasmas suggest in-plasma measurements with probe significantly perturb $T_e(R)$
  - A new design is needed for probing Pegasus plasmas, using non-conductive materials in far out-board region
- Pegasus' edge region shows significant fluctuations in T_e and n_e, consistent with high-speed imaging

PEGASUS: A University Scale, Ultralow-A ST



Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
I_N (MA/m-T)	6 – 12
ℓ_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2



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Langmuir Probe Theory*

- Measures T_e, n_e, and floating potential
- Biasing used to control collected fraction of $f_{Boltzmann}(v)$.
- Integrating ion and electron Maxwellian velocity distributions gives a general expression for probe current I_P:

$$I_P = -I_{sat}^{e} e^{\frac{e(V_{Bias}-V_P)}{kT}} + I_{sat}^{i} \quad \text{where}$$

$$I_{sat}^{e} = A_p n_e e \left(\frac{k_B T_e}{2\pi m_e}\right)^{\frac{1}{2}} \quad \text{and} \quad I_{sat}^{i} = \exp\left(-\frac{1}{2}\right) A_p n_e e \left(\frac{k_B T_e}{m_i}\right)^{\frac{1}{2}}$$

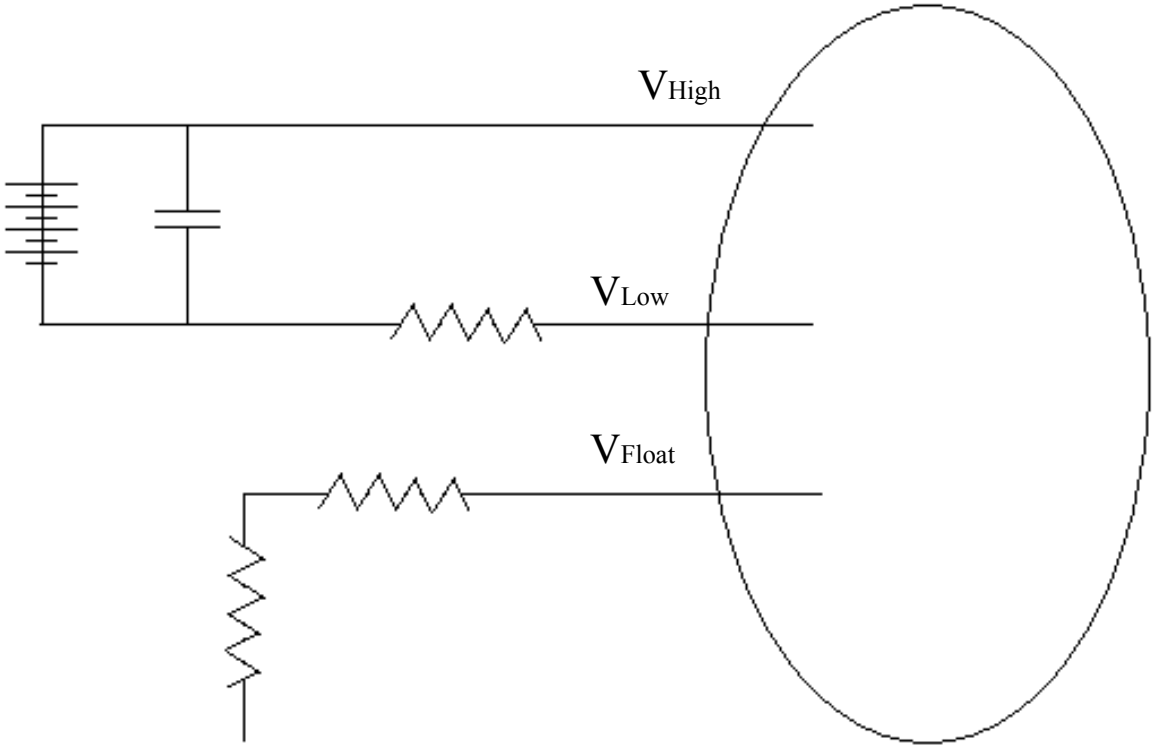
- The ion saturation current equation yields density immediately:

$$n_e = \left(\frac{m_i}{k_B T_e}\right)^{\frac{1}{2}} \frac{I_{sat}^{ion}}{Ae} \exp\left(\frac{1}{2}\right)$$

*Sin-Li Chen and T. Sekiguchi, J. Applied Phys. 36, 2363 (1965)

Triple Probe Theory

- The triple probe circuit topology places constraints on the current and voltages of each probe tip



$$V_H - V_L = V_{Bias}$$

$$I_H = -I_{sat}^{e} e^{\frac{e(V_H - V_P)}{kT}} + I_{sat}^{i}$$

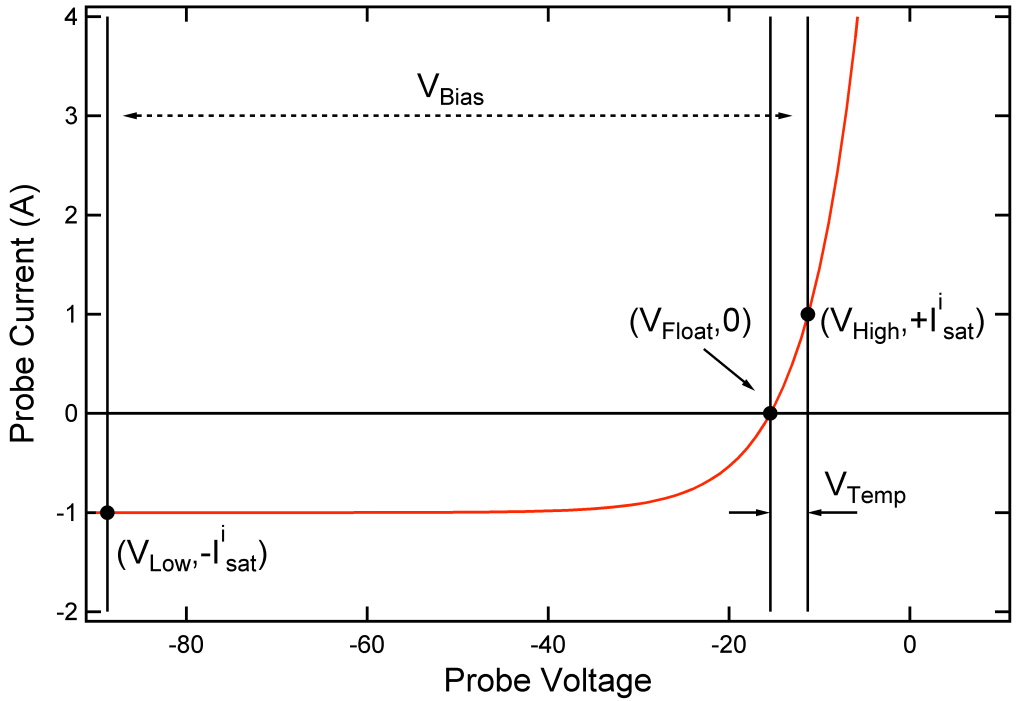
$$I_L = -I_{sat}^{e} e^{\frac{e(V_L - V_P)}{kT}} + I_{sat}^{i} = -I_H$$

$$I_F = -I_{sat}^{e} e^{\frac{e(V_F - V_P)}{kT}} + I_{sat}^{i} = 0$$

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Each Tip Samples Point on I(V) Curve

- 3 points on I(V) curve sampled by triple probe
- $V_H – V_L = V_{Bias} >> T_e$, $I_H = I_L$ and $I_F = 0$ constraints ensure sampling of well-defined points
- For $V_{Bias} >> T_e$, V_{Temp} is proportional to T_e
- Measuring I_{sat} yields n_e



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T_e is obtained from V_{High} - V_{Float}

- Making use of the expression for the current to each probe we consider the expression

$$\frac{I_H - I_F}{I_H - I_L}$$

- The simplification of this expression at right allows for a solution for Te.

$$\frac{I_H - I_F}{2I_H} = \frac{I_H - I_F}{I_H - I_L}$$

$$\frac{1 - I_F / I_H}{2} = \frac{1 - I_F / I_H}{1 - I_L / I_H}$$

$$\frac{1}{2} = \frac{1 - I_F / I_H}{1 - I_L / I_H}$$

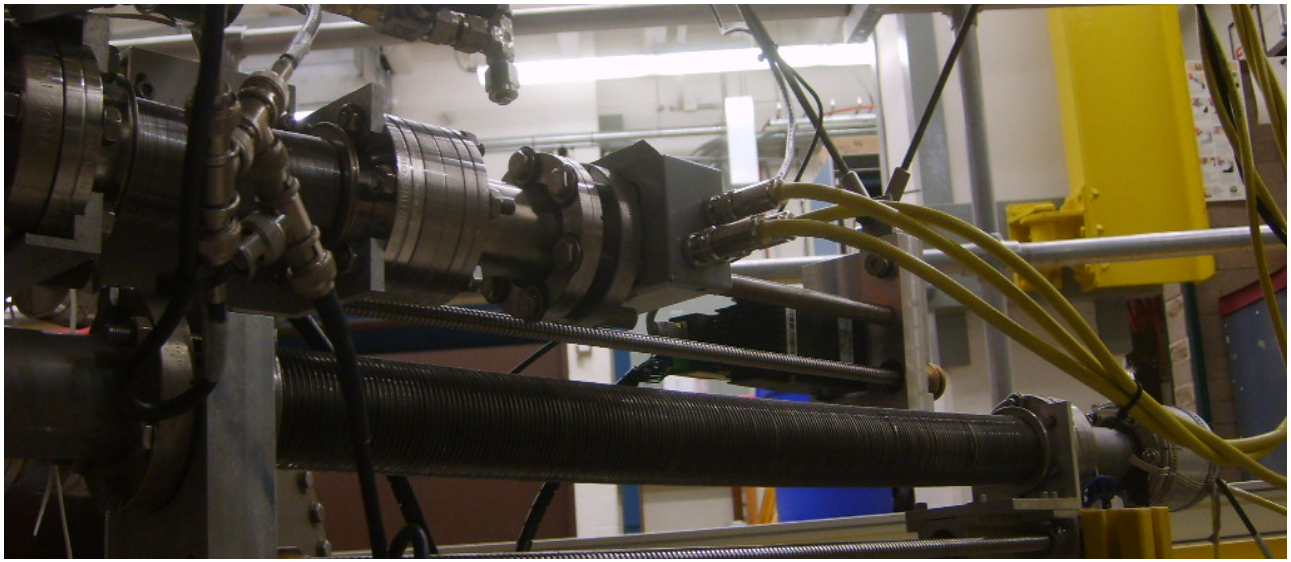
$$\frac{1 - e^{\frac{e(V_{Float} - V_{High})}{k_B T_e}}}{1 - e^{\frac{e(V_{Low} - V_{High})}{k_B T_e}}} = \frac{1}{2}$$

Which in the limit $eV_{Bias} >> k_B T_e$ reduces to:

$$\boxed{\frac{(V_{High} - V_{Float})}{\ln(2)} = T_e (eV)}$$

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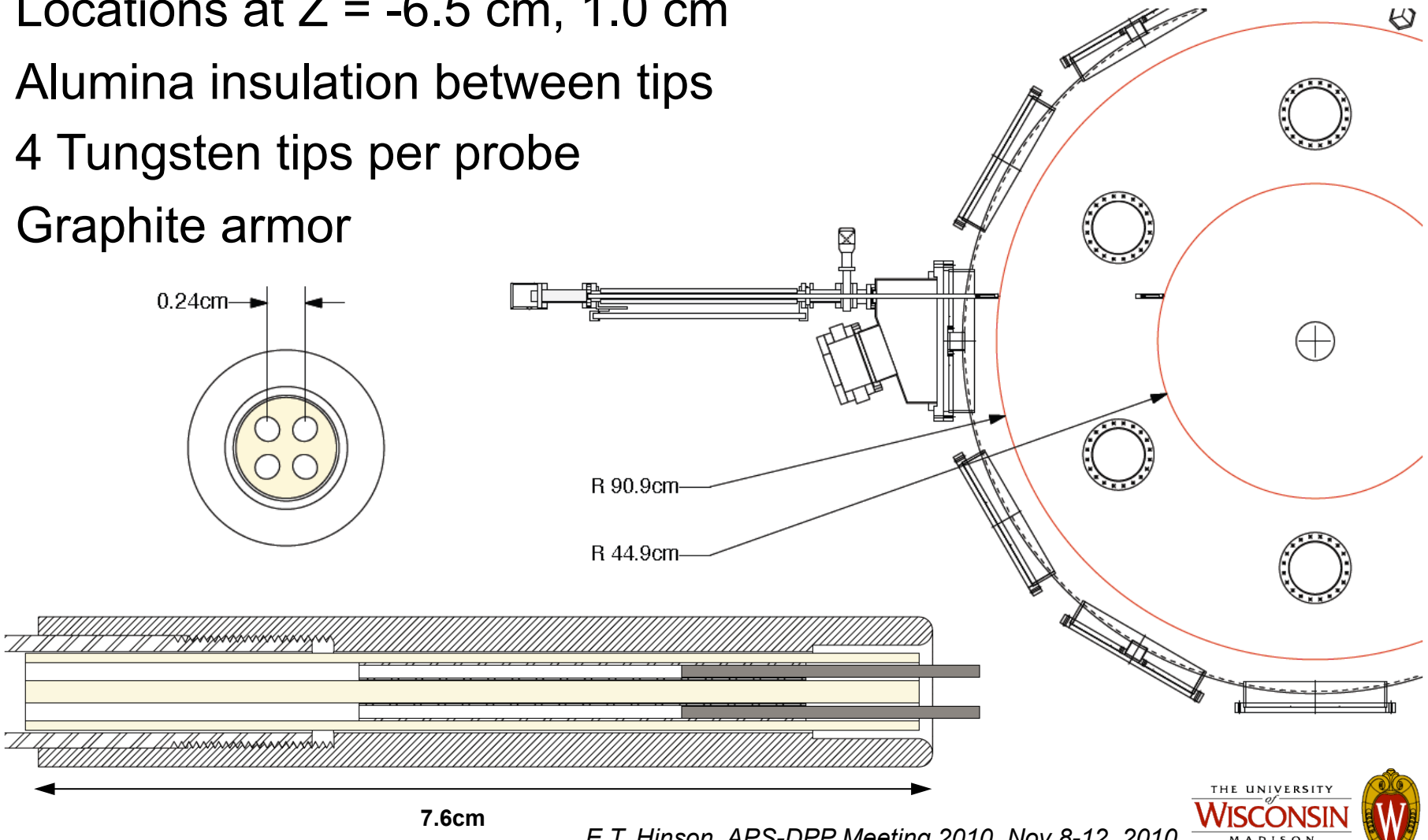
Langmuir Probes Deployed on Pegasus



- Dual radially-scanning probes
  - ~100kHz bandwidth
  - Local signal processing electronics
  - All power provided locally by 4 AA batteries

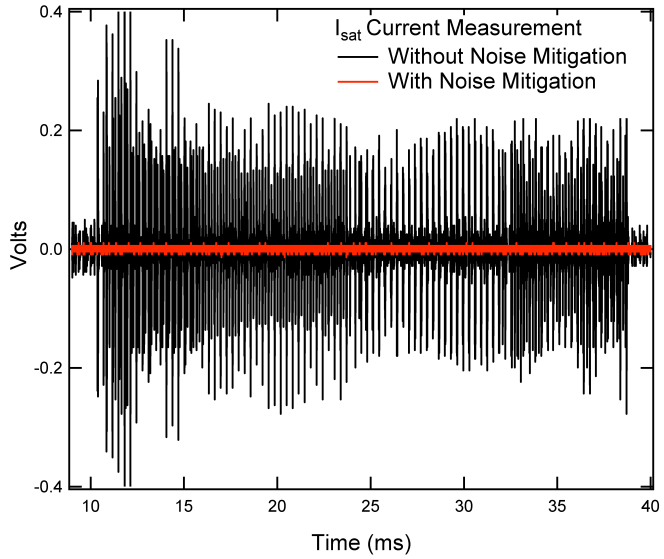
Dual Probes Configured for Scans

- Stepper-motor scanning for control room shot programming
- Locations at Z = -6.5 cm, 1.0 cm
- Alumina insulation between tips
- 4 Tungsten tips per probe
- Graphite armor



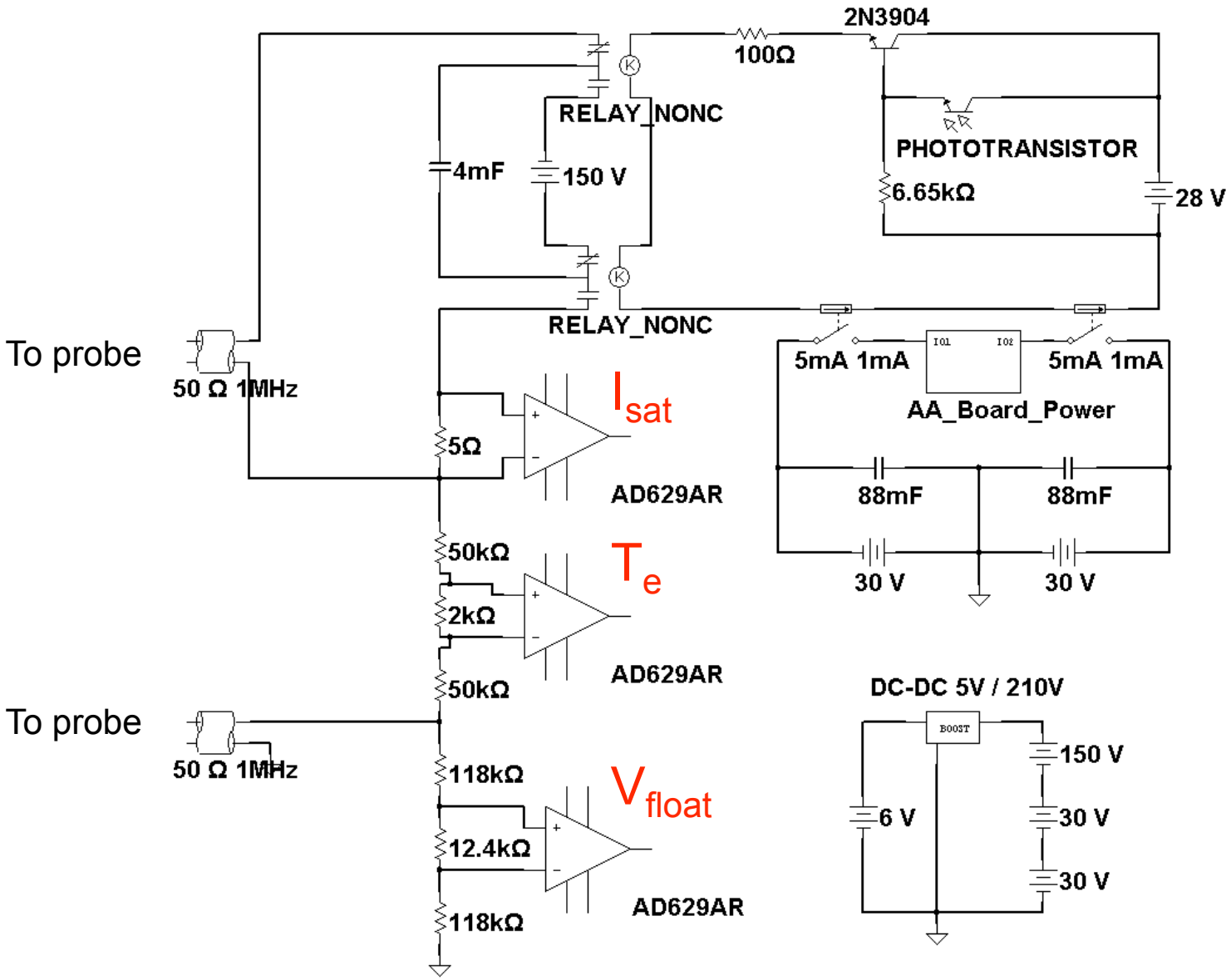
Switching Power Supplies Require Shielding Techniques

- Diagnostics in Pegasus require careful shielding and isolation techniques
  - Triaxial shielding
  - Local differential line drivers
  - Optical triggering



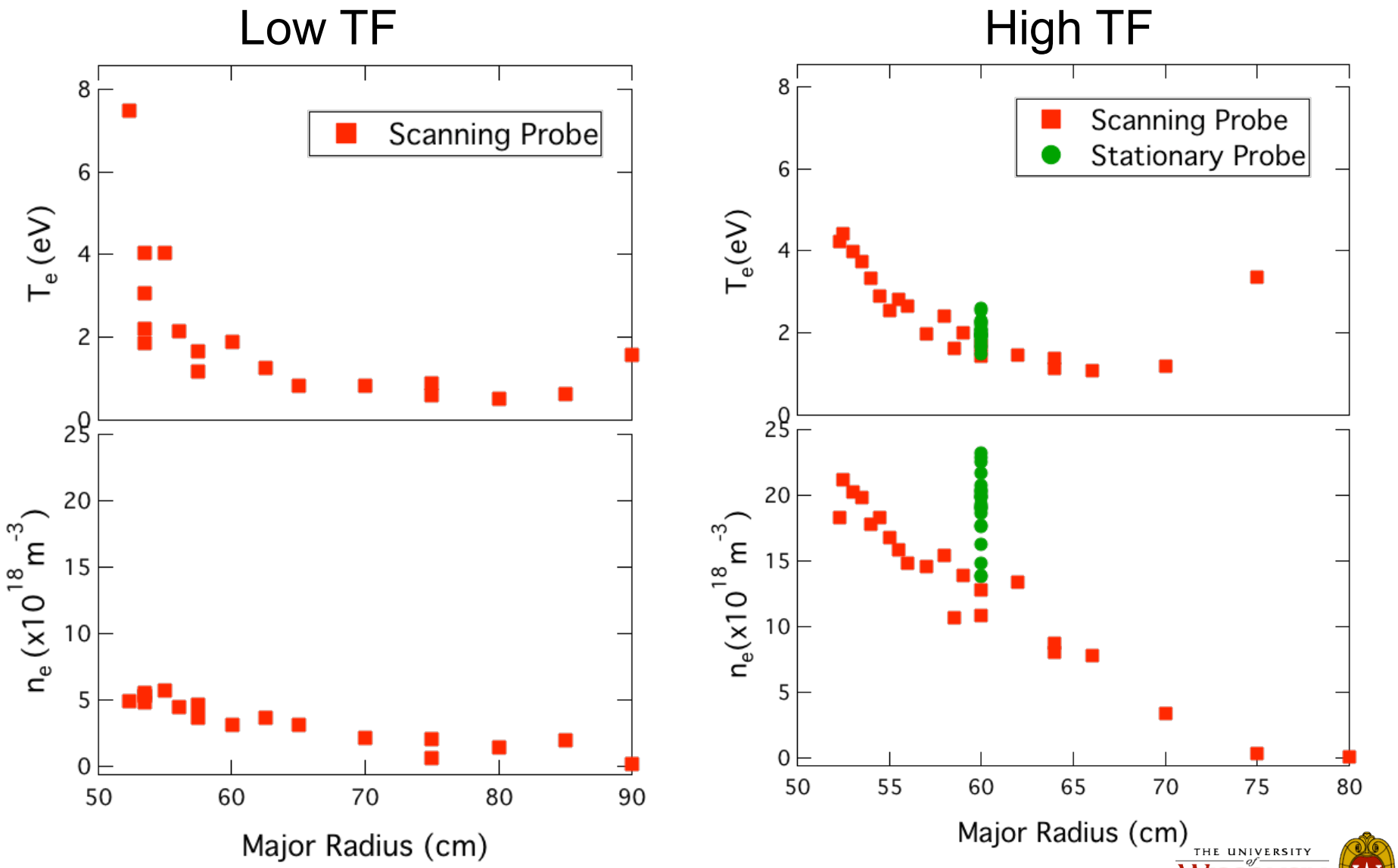
- Higher bandwidth requires local signal processing / power supplies
  - EMCO ULP05 DC-DC converter
  - Probe bias, optical triggering, and signal processing electronics accomplished with 4 AA batteries

Triple Probe Circuit



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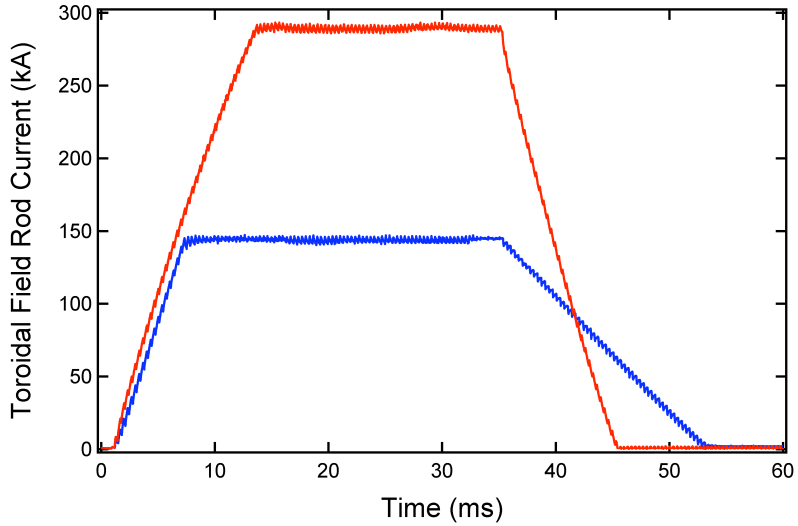
Edge Profiles Measured for Comparable High-Field and Low-Field Ohmic Plasmas

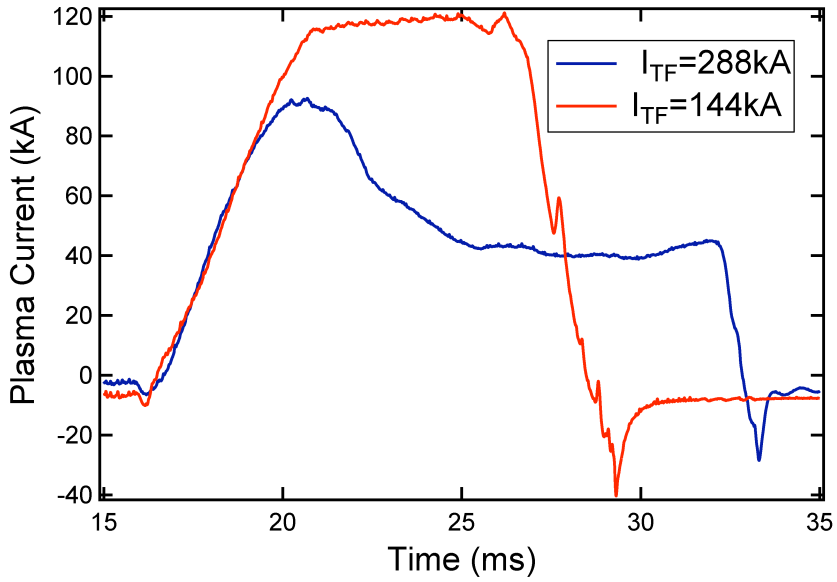


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SOL Probed with I_{TF}=144kA, I_{TF}=288kA

- Comparison undertaken to observe SOL length scale variation with discharge parameters
- Discharges with sizeable (x2) variation in toroidal field were selected $\propto$
- Compact discharges each with $R_0 \approx 55$ cm used

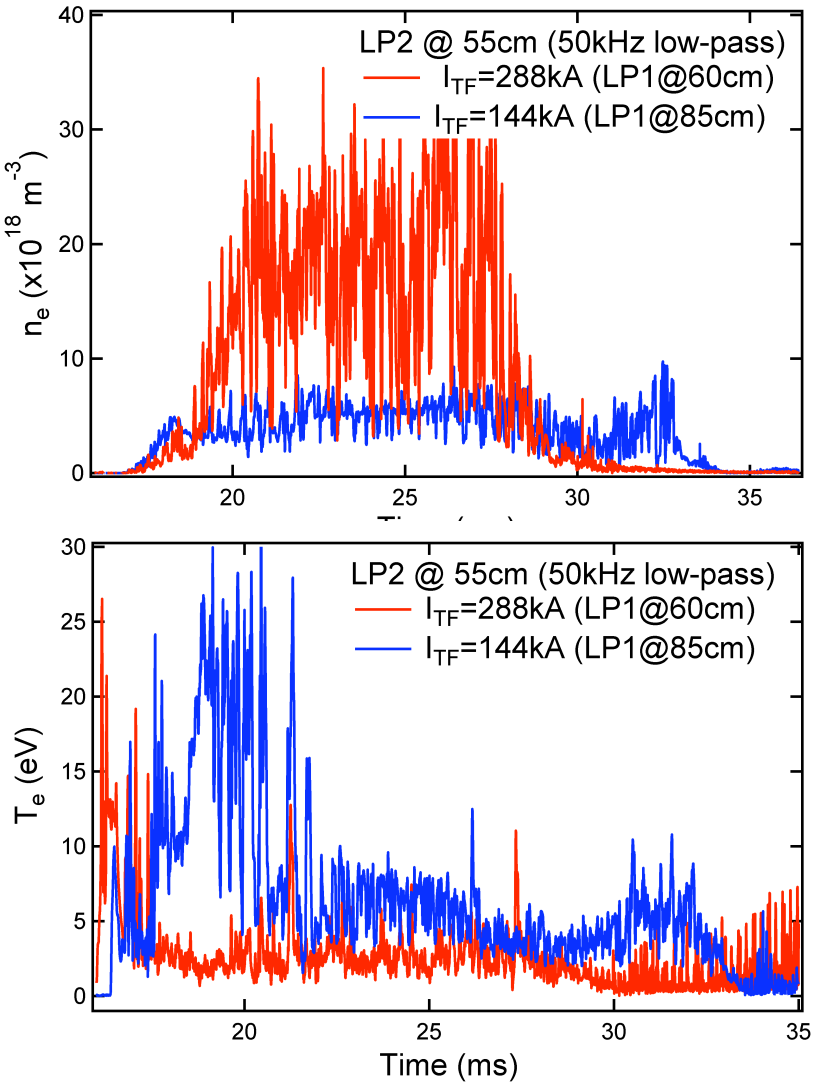




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n_e and T_e Measurements Obtained

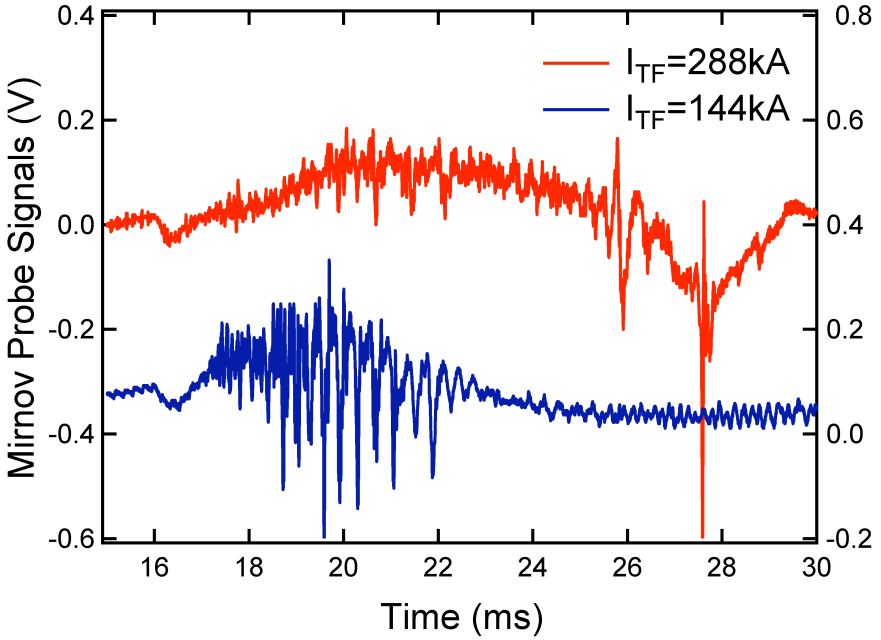
- T_e data suggest probe in low I_{TF} discharge is close to edge
- In high I_{TF} case, measured edge and internal n_e are of same order as line-averaged n_e ~ 1-2 x10^{19} m^{-3}
- Higher-than-expected edge/ SOL n_e measured in some discharges could be related to proximity of gas valve
  - Gassing duty cycle at 95% in high-TF case



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λ_n, λ_T Measurements Taken from Profiles Measured During Quiescent Period

- MHD quiescence necessary to avoid time-average over bulk displacements
- 1ms of time-averaging during quiescent period of obtained profiles
- Data at 24 ms (High I_{TF}) and 27 ms (Low I_{TF}) used for scale length calculations



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Ratio of density Scale Lengths is Consistent with Bohm Diffusion

- At a Bohm-like edge,

$$\lambda_{nBohm} = \sqrt{\frac{D_{\perp 0 Bohm} 2L_c}{c_{S0}}} \quad \text{with} \quad D_{\perp 0 Bohm} = \frac{T_{e0}(eV)}{16 \cdot B_T(T)}$$

- For two discharges with similar L_c ($\propto B_T/I_p$) and edge T_{e0}, and for $B_2=2B_1$, Bohm diffusion predicts

$$\frac{\lambda_{n1}}{\lambda_{n2}} \propto \sqrt{\frac{D_{\perp 01}}{D_{\perp 02}}} \propto \sqrt{\frac{T_{e1}}{B_1}\frac{B_2}{T_{e2}}} \propto \sqrt{\frac{B_2}{B_1}} \propto \sqrt{\frac{288kA}{144kA}} \propto \sqrt{2} \approx \frac{22cm}{15cm}$$

- Observations are in agreement with this ratio

Bohm Diffusion Predicts $(B_2/B_1)^{1/2}$ Scaling for Similar Discharges

- Density scale lengths in a Bohm-like scrape-off layer are assumed to be given by:

$$\lambda_{nBohm} = \sqrt{\frac{D_{\perp 0 Bohm} 2L_c}{c_{S0}}}$$

where $D_{\perp 0 Bohm}$ and c_{so} are values of diffusion and sound speed at the edge, and L_c is the connection length to the limiter

- Assuming edge temperature T_{e0} and L_c is similar for both discharges

$$\frac{\lambda_{n1}}{\lambda_{n2}} \propto \sqrt{\frac{D_{\perp 01}}{D_{\perp 02}}} \propto \sqrt{\frac{T_{e01}}{T_{e02}}\frac{B_2}{B_1}} \propto \sqrt{\frac{B_2}{B_1}}$$

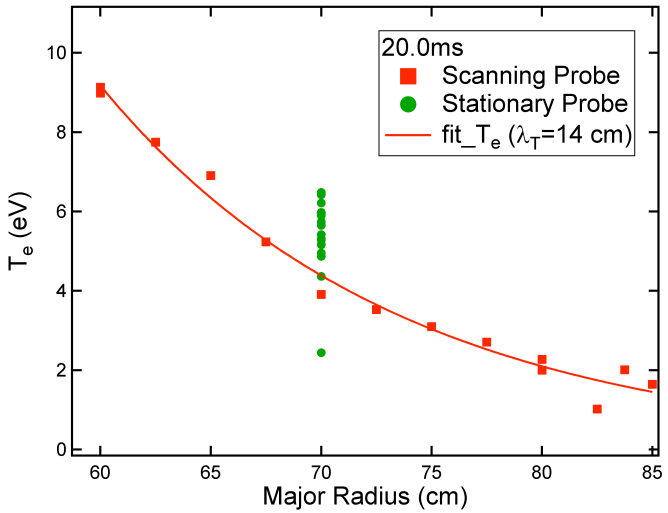
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Scale lengths calculated over time domain

- Shifted-exponential model assumed

$$n_{eSOL} = n_0 \exp\left(\frac{-(r-R)}{\lambda_n}\right) \qquad T_{eSOL} = T_0 \exp\left(\frac{-(r-R)}{\lambda_T}\right)$$

- Model fit to measured profiles for each time point in region of interest



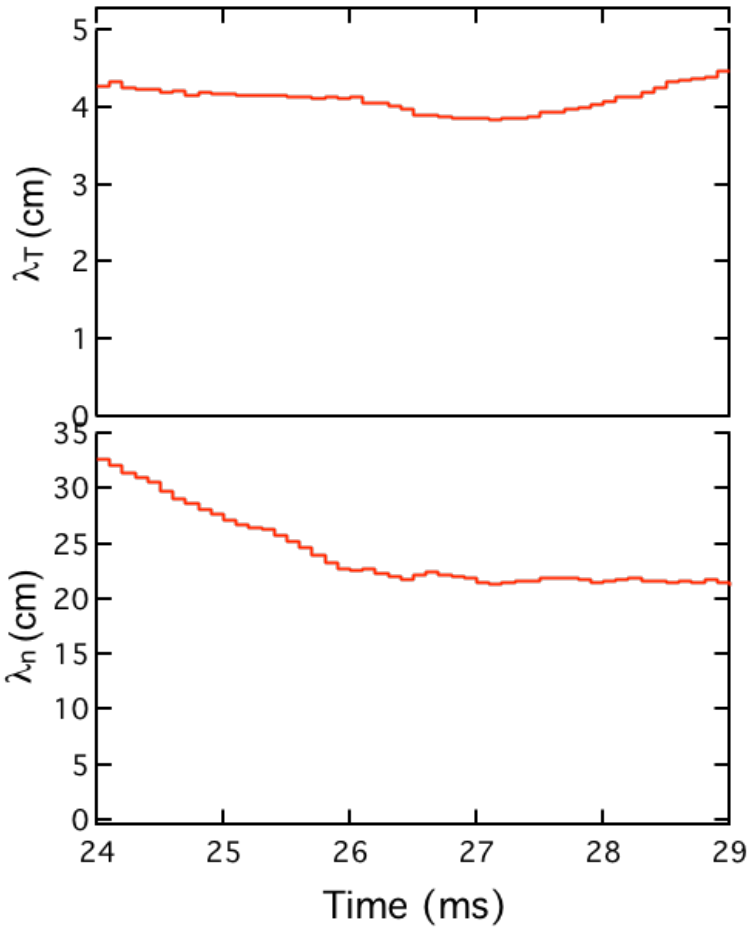
- Model applied repeatedly to obtain scale lengths as a function of time

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T_e, n_e scale lengths obtained

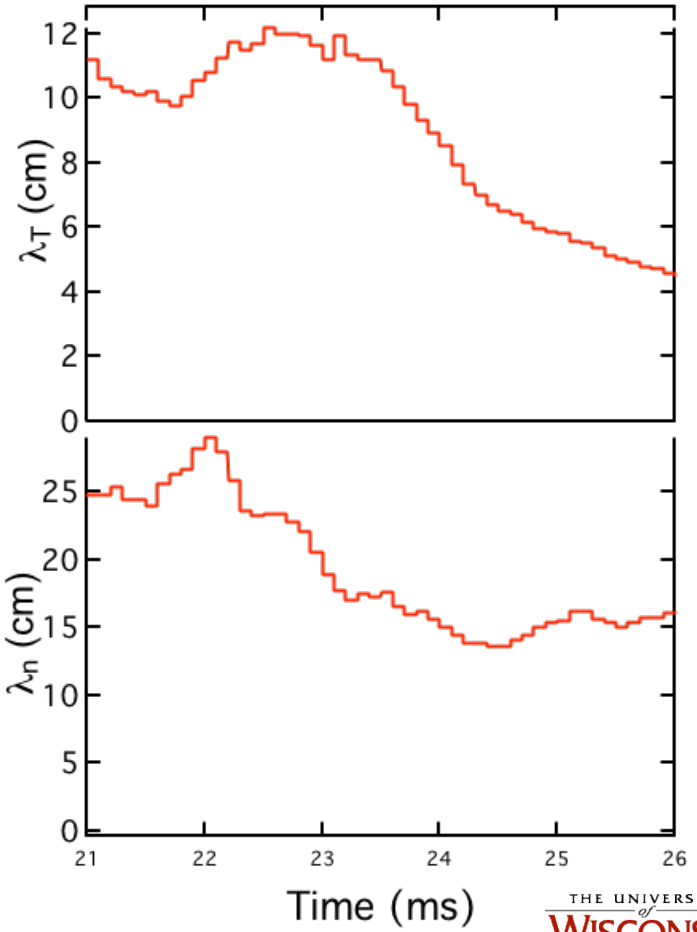
Low TF (144kA, 27ms)

λ_{n_e} = 22 cm, λ_{T_e} = 4 cm



High TF (288kA, 24ms)

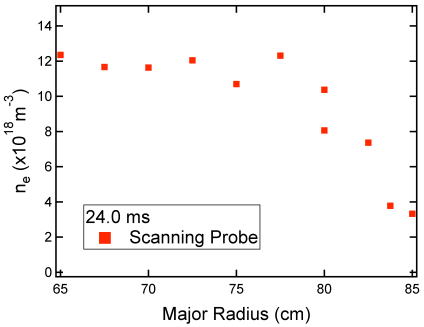
λ_{n_e} = 15 cm, λ_{T_e} = 8 cm

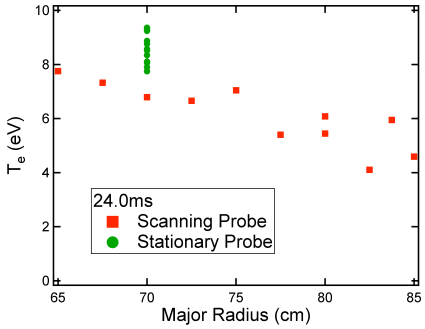


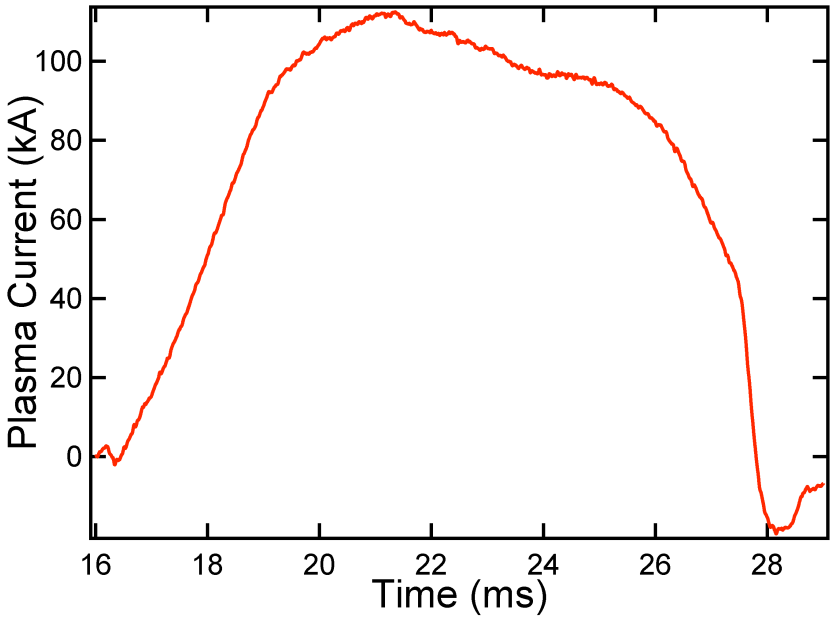
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Profiles Measured in Large, Diffuse Ohmic Discharge

- Equilibrium field coils used to sweep plasma edge over probes, allowing internal, edge, and SOL quantities to be probed at all radial locations





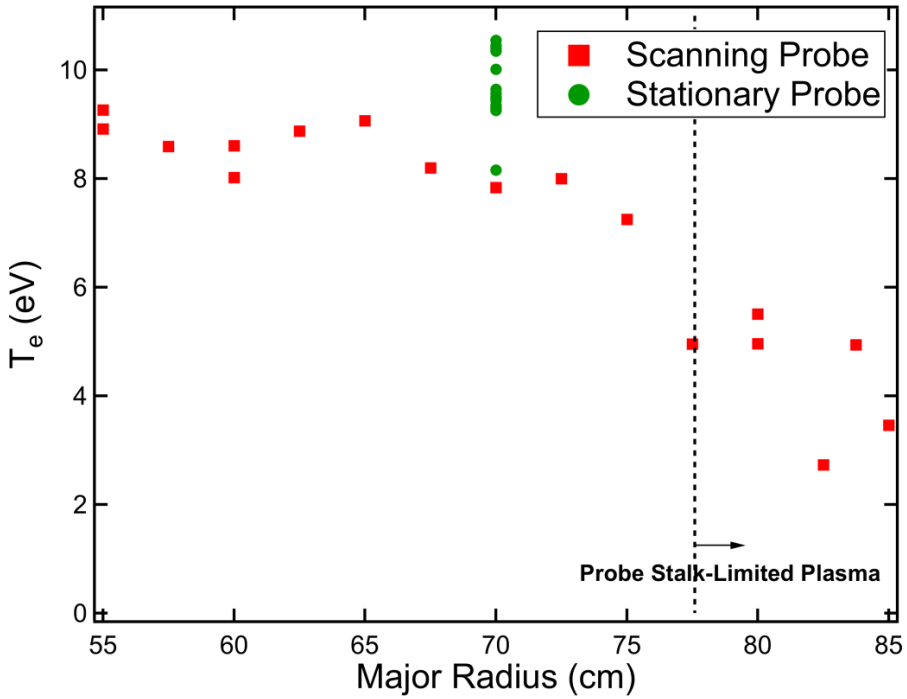


- Internal scans showed perturbation by probe
- Edge measurements revealed turbulent edge fluctuations
- SOL scaling was again consistent with Bohm diffusion

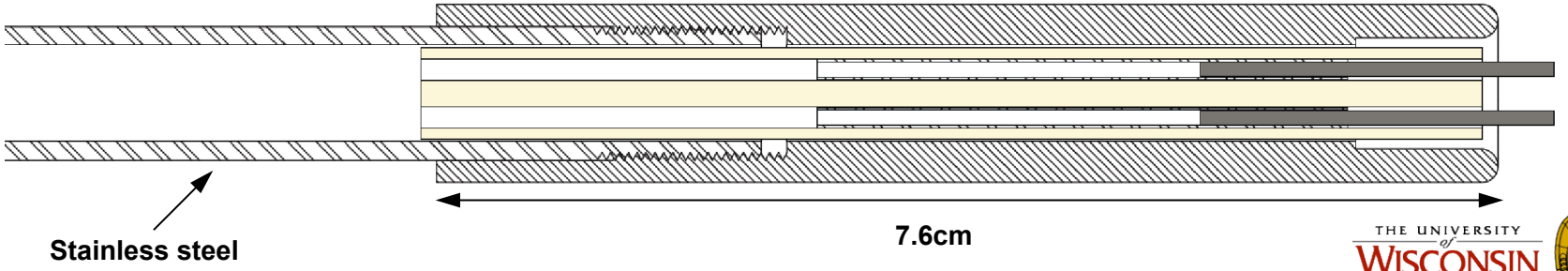
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Internal measurements suggest perturbation by probe

- Flat low-valued T_e profile suggests strong perturbation of plasma
- Stainless steel probe stalk of control probe appears to work as a local limiter
  - R_0 of probe tip at 70 cm
  - Steel tube R_0=77.6cm



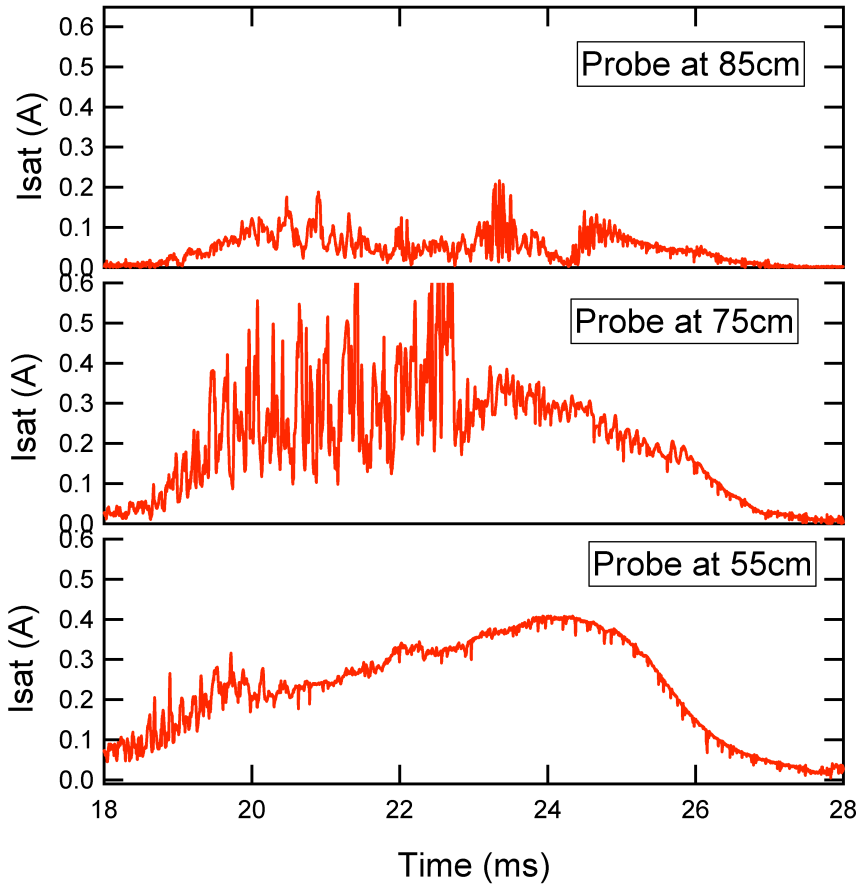
- Phaedrus-T era probe to be replaced with new design having longer graphite shield

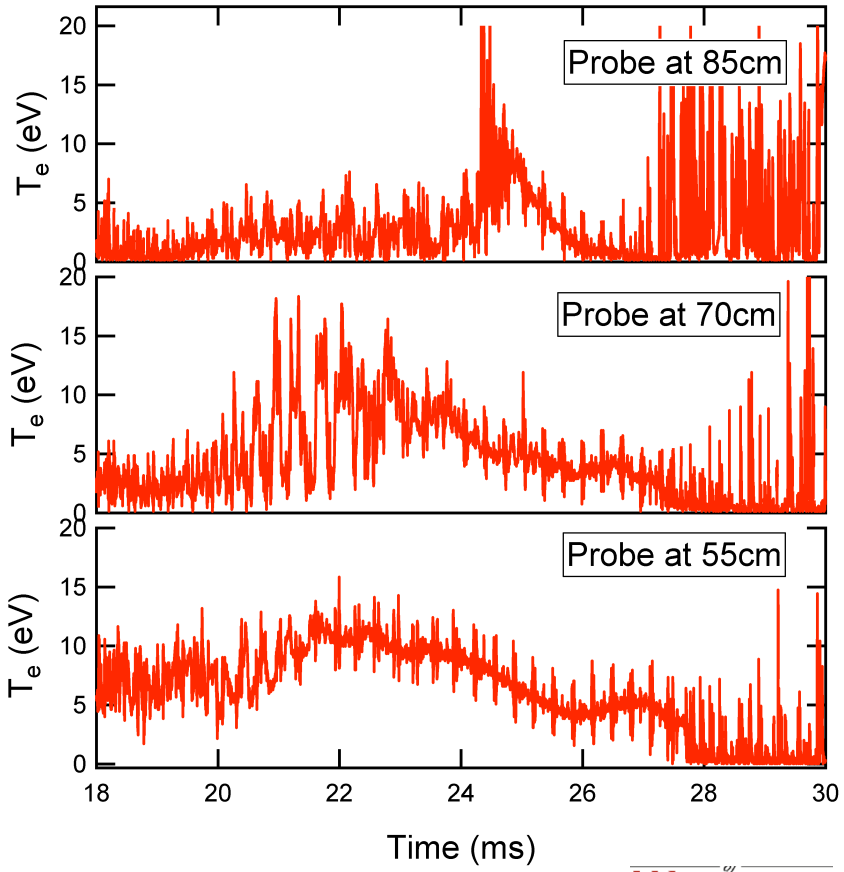


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Large edge fluctuations observed

- Plasma edge swept over probes, revealing large edge fluctuations and in-plasma behavior
- Fluctuations observed in T_e and I_{sat} (200kHz smooth)





Bohm diffusion-governed SOL hypothesized

- Edge T_e was measured to be 4eV. Expected diffusion is

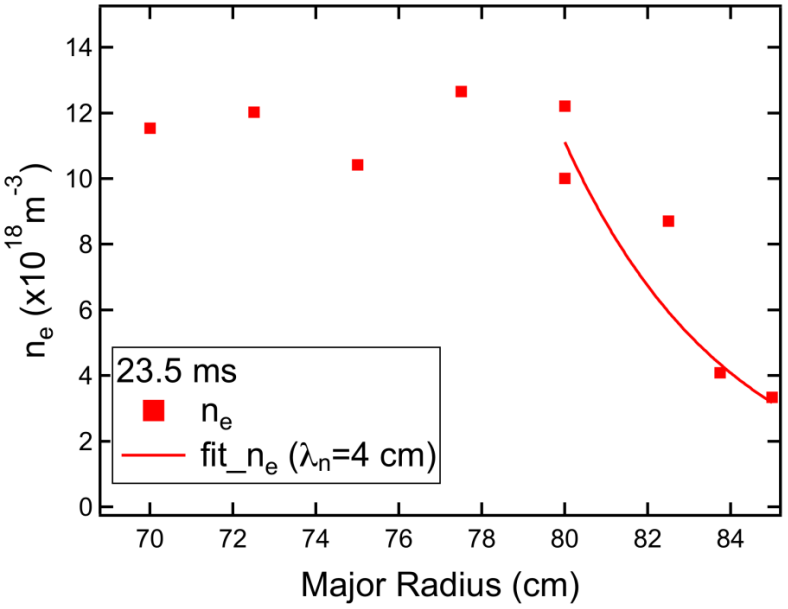
$$D_{\perp 0 Bohm} = \frac{T_{e0}(eV)}{16 \cdot B_T(T)} = \frac{4(eV)}{16 \cdot 0.1(T)} \approx 3\frac{m^2}{s}$$

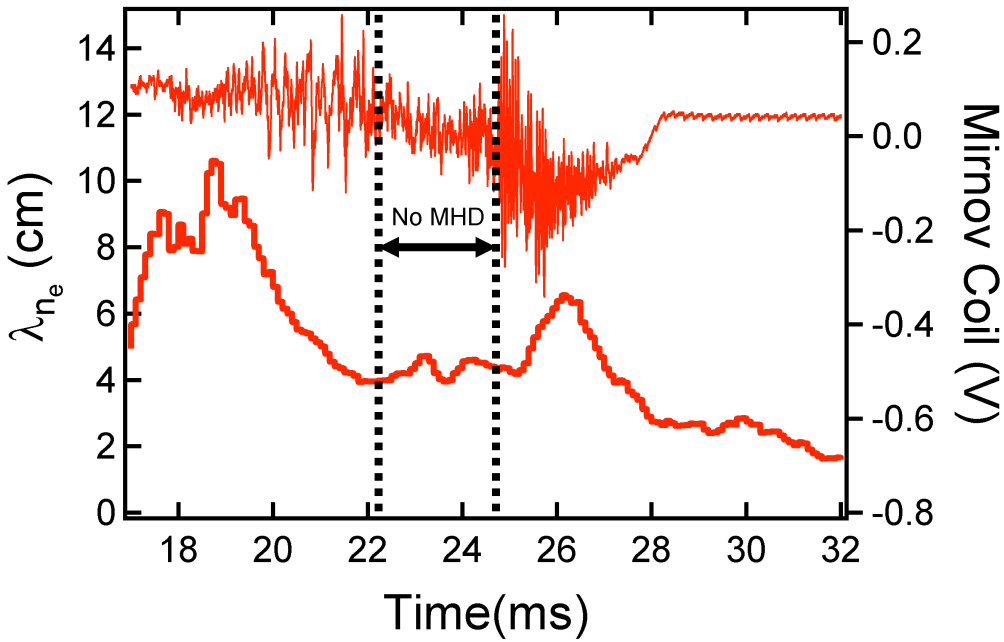
- Expected n_e scale length is

$$\lambda_{nBohm} = \sqrt{\frac{D_{\perp 0 Bohm} 2L_c}{c_{S0}}} = \sqrt{\frac{4V \cdot 2 \cdot 5m}{16 \cdot 0.1T \cdot \sqrt{\frac{4eV}{2m_p}}}} \approx 4cm$$

- These values are close to those observed

Measured λ_n again matches Bohm values



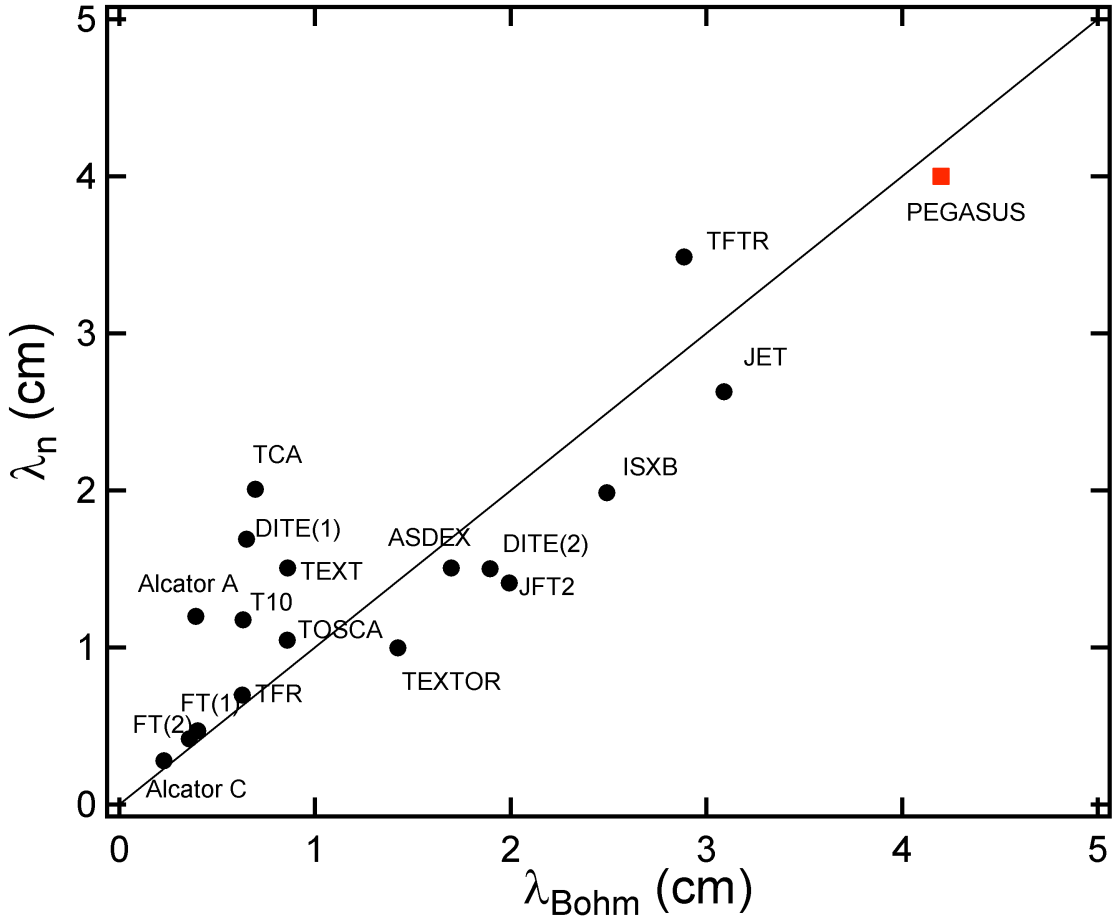


- Density scale length observed to drop in absence of MHD
- During MHD quiescence, $\lambda_n \approx 4$cm, matching expectations
- Cross-field diffusion value calculated with measured λ_n and T_{e0} is close to Bohm value:

$$D_{\perp 0} = \frac{\lambda_n^2 c_{S0}}{2L_c} \approx 2\frac{m^2}{s}$$

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Broad n_e profiles observed in Pegasus SOL



P.C. Stangeby, G.M. McCracken, Nuclear Fusion, Vol.30, No.7 (1990)

- Low field in Pegasus leads to extended SOL scale lengths

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3-axis Mirnov Probe Array Planned

- Taylor relaxation I_p limits scale with injected current I_{inj} in gun-driven discharges in Pegasus:

$$I_p \propto \sqrt{\frac{I_{TF} I_{INJ}}{w}}$$

I_{inj}: Injected Current

I_{TF}: TF Current

w: Width of Driven Layer

- New diagnostics planned for measurement of edge plasma and current properties with helicity injection
  - 3-axis Mirnov probe array to measure edge current density
  - Modified Langmuir probe in gun discharges to measure local plasma properties
  - These diagnostics will enable study of currents in the driven layer during gun discharges and plasma properties in the driven SOL region

Summary

- A pair of Langmuir triple probes has been constructed for characterization of the edge and outer-half plasma regions for studies of
  - Peeling-mode behavior
  - EBW and HHFW feasibility
  - Turbulence
- First measurements of Pegasus' SOL region scale lengths are consistent with Bohm diffusion
- Studies conducted in large diffuse plasmas suggest in-plasma measurements with probe significantly perturb $T_e(R)$
  - A new design is needed for probing Pegasus plasmas, using non-conductive materials in far out-board region
- Pegasus' edge region shows significant fluctuations in T_e and n_e, consistent with high-speed imaging

Conclusions

- Langmuir probe implemented on PEGASUS for investigation of edge fluctuation/equilibrium properties
  - Turbulent behavior observed in edge and SOL
  - Less-perturbative probe design planned for systematic internal studies

- 3-axis Mirnov probe array in design for edge measurements of non-axisymmetric current profiles in ohmic and gun-driven discharges

Reprints

Contact: ehinson@wisc.edu

Reprints of this and other PEGASUS presentations are available at

http://pegasus.ep.wisc.edu/Technical_Reports

Camera images reveal edge fluctuations

