Mirror Langmuir Probe measurements of fluctuation-induced heat and particle transport in the Alcator C-Mod boundary plasma

B. LaBombard
D. Brunner, O.E. Garcia, M. Greenwald,
J.W. Hughes, R. Kube, J.L. Terry, S. Zweben

Contributed Oral BO7.00014
Presented at the 54th APS DPP Meeting, Providence, Rhode Island
October 29, 2012
A “Mirror Langmuir Probe” is being developed -- a powerful new technique to measure boundary $n$, $T_e$, $\Phi$ profiles and turbulence.

Motivation:

**Boundary plasma physics is the key to understanding:**
- SOL transport/profiles, extending to walls/antennas
- Heat flux channel width and its scalings
- Plasma/impurity flows, momentum coupling
- Transport bifurcations: L-H, L-I
- Tokamak density limit
A “Mirror Langmuir Probe” is being developed -- a powerful new technique to measure boundary $n$, $T_e$, $\Phi$ profiles and turbulence.

Motivation:

Boundary plasma physics is the key to understanding:
- SOL transport/profiles, extending to walls/antennas
- Heat flux channel width and its scalings
- Plasma/impurity flows, momentum coupling
- Transport bifurcations: L-H, L-I
- Tokamak density limit

Outline:

What is a ‘Mirror Langmuir Probe’?

Some exciting new observations:

High resolution $n$, $T_e$, and $\Phi$ profiles in L and H-mode
Fluctuation-induced heat and particle flux measurements
Quasi-Coherent Mode (QCM) $n$, $T_e$, $\Phi$ fluctuations, resolved at 100 kHz - unambiguously identifying mode type
Mirror Langmuir Probe\(^1\)

An electronic device that adjusts its I-V response in real time to match that of an actual Langmuir probe

Key Features:

- Outputs real-time signals of \(I_{sat}\), \(T_e\) and \(V_f\) that ‘mirror’ that of an actual Langmuir Probe

- High bandwidth system, updating \(I_{sat}\), \(T_e\) and \(V_f\) values at 1.1 MHz

- Also records probe current/voltage data at 10 MHz for post-processing data analysis

---

Working Example:
MLP waveforms from a C-Mod fast-scanning probe

Data from a probe scan to the separatrix in an ohmic L-mode plasma

Real-time signals of $I_{\text{sat}}$, $V_f$, and $T_e$ reported by Mirror Langmuir Probe

Fluctuations in signals are not noise!
These are plasma fluctuations.
Working Example: MLP waveforms from a C-Mod fast-scanning probe

Same data on expanded time scale

Real-time signals of $I_{\text{sat}}$, $V_f$, and $T_e$ reported by Mirror Langmuir Probe

Immediate physics result: $I_{\text{sat}}$ and $T_e$ fluctuations tend to track one another
Working Example:
MLP waveforms from a C-Mod fast-scanning probe

Same data on expanded time scale

1 μs time resolution adequate to resolve plasma dynamics
Working Example: MLP waveforms from a C-Mod fast-scanning probe

Same data on expanded time scale

1 µs time resolution adequate to resolve plasma dynamics

Post-processing computation of $I_{\text{sat}}$, $V_f$, and $T_e$ from I-V data yield nearly identical signals, but with no slew rate limitations

Use Fit data for remainder of talk

Compute local plasma potential from sheath drop: $\Phi = \alpha_{sh} T_e + V_f$

Compute local density from Bohm condition: $n = I_{\text{sat}} / (2q Area C_s)$
First experiments
MLP drive on high-heatflux, scanning Langmuir-Mach probe

Measurement capabilities:

Particle flux
\[ \Gamma_r = \langle \tilde{n} \tilde{E}_\theta \rangle / B \]

Heat fluxes
\[ Q_{er} = \left( \frac{5}{2} \right) \langle \tilde{P_e} \tilde{E}_\theta \rangle / B \]
\[ = \left( \frac{5}{2} \right) T_e \Gamma_r + \left( \frac{5}{2} \right) n \langle \tilde{T_e} \tilde{E}_\theta \rangle / B \]
  - convection
  - conduction

Turbulence drive (drift vs interchange)
\[ k_\theta - \text{resolved } \tilde{n}, \tilde{T_e}, \tilde{\Phi} \]
  - and relative phase angles

Momentum fluxes
\[ \langle \tilde{V}_r \tilde{V}_\parallel \rangle \quad \langle \tilde{n} \tilde{V}_r \tilde{V}_\parallel \rangle \quad \langle \tilde{V}_r \tilde{V}_\theta \rangle \quad \langle \tilde{n} \tilde{V}_r \tilde{V}_\theta \rangle \]
First experiments
MLP drive on high-heatflux, scanning Langmuir-Mach probe

Measurement capabilities:

**Particle flux**
\[ \Gamma_r = \langle \tilde{n} \tilde{E}_\theta \rangle / B \]

**Heat fluxes**
\[ Q_{er} = (5/2) \langle \tilde{P}_e \tilde{E}_\theta \rangle / B \]
\[ = (5/2) T_e \Gamma_r + (5/2) n \langle \tilde{T}_e \tilde{E}_\theta \rangle / B \]
convection conduction

**Turbulence drive (drift vs interchange)**
\[ k_\theta \text{- resolved } \tilde{n}, \tilde{T}_e, \tilde{\Phi} \]
and relative phase angles

**Momentum fluxes**
\[ \langle \tilde{V}_r \tilde{V}_{\parallel} \rangle \quad \langle \tilde{n} \tilde{V}_r \tilde{V}_{\parallel} \rangle \quad \langle \tilde{V}_r \tilde{V}_\theta \rangle \quad \langle \tilde{n} \tilde{V}_r \tilde{V}_\theta \rangle \]

Examine Ohmic H and L-modes
First experiments ~ ELM-free H and L mode plasmas
Fluctuations and profiles resolved with unprecedented detail

- Each profile contains 18,000 measurement points (in + out scan, 16 ms)
First experiments ~ ELM-free H and L mode plasmas

- Each profile contains 18,000 measurement points (in + out scan, 16 ms)
- Smoothing over 200 μs window yields high resolution, ‘time-averaged’ profiles
First experiments ~ ELM-free H and L mode plasmas
Fluctuations and profiles resolved with unprecedented detail

- Each profile contains 18,000 measurement points (in + out scan, 16 ms)
- Smoothing over 200 $\mu$s window yields high resolution, ‘time-averaged’ profiles

ExB shear layer resolved

ELM-free H-mode: $E_r$ changes from +25 kV/m to -25 kV/m
L-mode: very weak shear layer

B. LaBombard APS2012
First experiments ~ ELM-free H and L mode plasmas
Measurements of fluctuation-induced heat and particle transport

$$\Gamma_r = \frac{\langle \tilde{n}\tilde{E}_\theta \rangle}{B}$$

$$V_r = \frac{\langle \tilde{n}\tilde{E}_\theta \rangle}{\langle n \rangle B}$$

$$\left( \frac{5}{2} \right) \frac{\langle \tilde{p}_e \tilde{E}_\theta \rangle}{B}$$

$$\left( \frac{5}{2} \right) n \frac{\langle \tilde{T}_e \tilde{E}_\theta \rangle}{B}$$

$$\left( \frac{5}{2} \right) T_e \Gamma_r$$

$$V_r = \frac{5\langle \tilde{p}_e \tilde{E}_\theta \rangle}{2\langle T \rangle \langle n \rangle B}$$

- Results from heat and particle flux computation look reasonable
First experiments ~ ELM-free H and L mode plasmas
Measurements of fluctuation-induced heat and particle transport

- Results from heat and particle flux computation look reasonable

**L-Mode:** Heat flux (0.25 MW m⁻²) roughly accounts for $P_{sol}$ (~ 1 MW)
Conduction is 2× higher than convection
First experiments ~ ELM-free H and L mode plasmas
Measurements of fluctuation-induced heat and particle transport

ELM-free H-mode

\[ \langle \rangle = 200 \mu \text{s average} \]
\[ \Gamma_r = \frac{\langle \tilde{n} \tilde{E}_\theta \rangle}{B} \]
\[ V_r = \frac{\langle \tilde{n} \tilde{E}_\theta \rangle}{\langle n \rangle B} \]

L-mode

\[ \left( \frac{5}{2} \right) \frac{\tilde{P}_e \tilde{E}_\theta}{B} \]
\[ \left( \frac{5}{2} \right) n \langle \tilde{r} \tilde{E}_\theta \rangle / B \]
\[ \left( \frac{5}{2} \right) T_e \Gamma_r \]
\[ V_r = \frac{5 \langle \tilde{P}_e \tilde{E}_\theta \rangle}{2 \langle T \rangle \langle n \rangle B} \]

- Results from heat and particle flux computation look reasonable
L-Mode: Heat flux (0.25 MW m\(^{-2}\)) roughly accounts for Psol (~ 1 MW)
Conduction is 2x higher than convection

B. LaBombard  APS2012
First experiments ~ ELM-free H and L mode plasmas
Measurements of fluctuation-induced heat and particle transport

ELM-free H-mode

- Results from heat and particle flux computation look reasonable
  - L-Mode: Heat flux (0.25 MW m$^{-2}$) roughly accounts for $P_{sol}$ (~ 1 MW)
  - Conduction is 2x higher than convection

H-mode: Transport velocities drop near separatrix
  - Very low heat fluxes, difficult to resolve - shear layer effect?
First experiments ~ ELM observations
Density, temperature and potential evolution easily resolved

H-mode with a few ELMs

- Multiple ELM events, ~25 µs evolution timescale, easily resolved
First experiments ~ ELM observations
Density, temperature and potential evolution easily resolved

H-mode with a few ELMs

- Multiple ELM events, ~25 μs evolution timescale, easily resolved
First experiments ~ Quasi-Coherent Mode observations
Mode structure resolved -- indicates electron drift-Alfven wave

- Data obtained from probe scanning deep into ohmic EDA H-mode
- **QCM (110kHz)** exists in region of positive $E_T$ (i.e. ExB in ion diamag. dir.)
- Probe perturbs plasma/QCM deeper into plasma - not reliable there
First experiments ~ Quasi-Coherent Mode observations
Mode structure resolved -- indicates electron drift-Alfven wave

- Snapshot of QCM reveals large amplitude, in-phase $n$, $T_e$, $\Phi$ fluctuations

\[
\frac{\Delta n}{\left< n \right>} \sim 30\% \quad \frac{\Delta T_e}{\left< T_e \right>} \sim 33\% \quad \frac{\Delta \Phi}{\left< T_e \right>} \sim 37\% 
\]
First experiments ~ Quasi-Coherent Mode observations
Mode structure resolved -- indicates electron drift-Alfven wave

Cross Power Spectrum: Density and Potential

$$V_r = \frac{\langle \tilde{n} \tilde{E}_\theta \rangle}{\langle n \rangle} B \sim 10 \text{ m/s}$$

Potential is in phase or slightly lags Density

=> Drift wave
First experiments ~ Quasi-Coherent Mode observations
Mode structure resolved -- indicates electron drift-Alfven wave

Cross Power Spectrum: Density and Potential

Potential is in phase or slightly lags Density
=> Drift wave

Simple Boltzmann electron response?
Compute $\tilde{\Phi}_B$ required to satisfy

$$\tilde{n} = \langle n \rangle \exp \left[ \left( \tilde{\Phi}_B - \langle \Phi \rangle \right) / \tilde{T}_e \right]$$

Measured $\tilde{\Phi}$ is ~1.5x larger than $\tilde{\Phi}_B$

Possible inductive voltage contribution

$$\tilde{B}_\theta \sim 1 \text{ mTesla}$$
=> Drift-Alfven wave
First experiments ~ Quasi-Coherent Mode observations
Mode structure resolved -- indicates electron drift-Alfven wave

Density

Cross Power Spectrum - North and South electrodes

Poloidal Wavenumber (radians/cm)

-1.0
-0.5
0.0

Electron Temperature

Poloidal wavenumber ~ 1.5 rad./cm

Propagation in electron diamagnetic direction

=> Electron drift-Alfven wave

See T. Golfinopoulos, Poster JP8.00087, Tues 2:00 PM
Excitation of QCM waves using a 'shoelace' antenna
Mirror Langmuir Probe technique is an exciting new tool for investigating boundary layer turbulence and transport

*Real-time, simultaneous* measurements of $n$, $T_e$, $\Phi$ with 1 $\mu$s time resolution

- High resolution $n$, $T_e$, $\Phi$ profiles
- Fluctuation-induced heat and particle transport
- ELM dynamics
- Fluctuation and coherent mode identification
  
  **New result:** QCM is a electron drift-Alfven mode
- Parallel and perpendicular flows and dynamics (not presented)

A world of boundary plasma physics phenomena awaits to be explored...