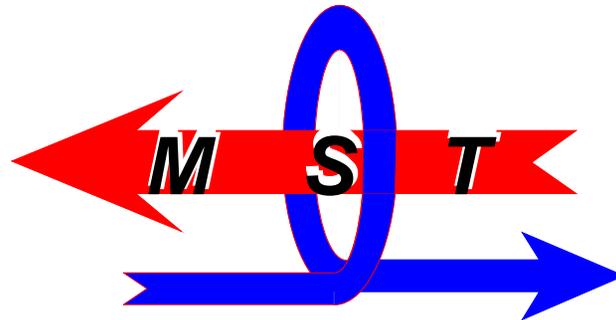


Particle Transport and Edge Dynamo in the MST RFP

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Velocity fluctuations play a critical role in particle and current transport in the RFP

Particle flux: $\Gamma = \langle \tilde{n} \tilde{v}_r \rangle = \gamma |\tilde{n}| |\tilde{v}_r| \cos \delta_{\tilde{n}\tilde{v}}$

- must simultaneously measure density fluctuations, radial velocity fluctuations, and relative phase
- \Rightarrow *density fluctuations result from core tearing modes and can cause substantial particle transport in the core, but cannot explain particle transport in the edge*

Dynamo emf: $\mathbf{E}_d = \langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle_{\parallel}$

- must measure all components of velocity and magnetic fluctuations, and relative phase
- \Rightarrow *edge dynamo results from $m = 0$ fluctuations and balances Ohm's law for $>0.85a$*

Outline



I. Particle transport

- character of density fluctuations
- phenomenology of \tilde{n} and \tilde{v}_r
- particle transport during standard and PPCD discharges
- summary

II. First direct measurement of $\langle \tilde{v} \cdot \mathbf{H} \tilde{\mathbf{B}} \rangle$ in the edge of an RFP

- the sawtooth cycle in MST (“dynamo events”)
- \tilde{v} , \tilde{B} , and $\langle \tilde{v} \cdot \mathbf{H} \tilde{\mathbf{B}} \rangle$ peak during a sawtooth crash
- MHD dynamo balances Ohm's law in the edge
- summary

Character of density fluctuations



- **Advective or compressional?**

Continuity equation:
$$\frac{\partial n}{\partial t} + \nabla \cdot n\mathbf{v} = S$$

assume

$$\tilde{S} \rightarrow 0, \nabla \cdot \mathbf{v}_0 \rightarrow 0, \text{ but } \nabla \cdot \tilde{\mathbf{v}} \neq 0, \text{ and } \tilde{n}, \tilde{v} \propto \tilde{f}(r)e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}$$

then

$$\tilde{n} = \frac{-i}{(\omega - kv_0)} \left[\tilde{v}_r \cdot \nabla_r n_0 + \frac{n_0}{r} \frac{\partial}{\partial r} (r\tilde{v}_r) \right] - \frac{n_0(\mathbf{k} \cdot \tilde{\mathbf{v}})}{(\omega - kv_0)} + \text{nonlinear}$$

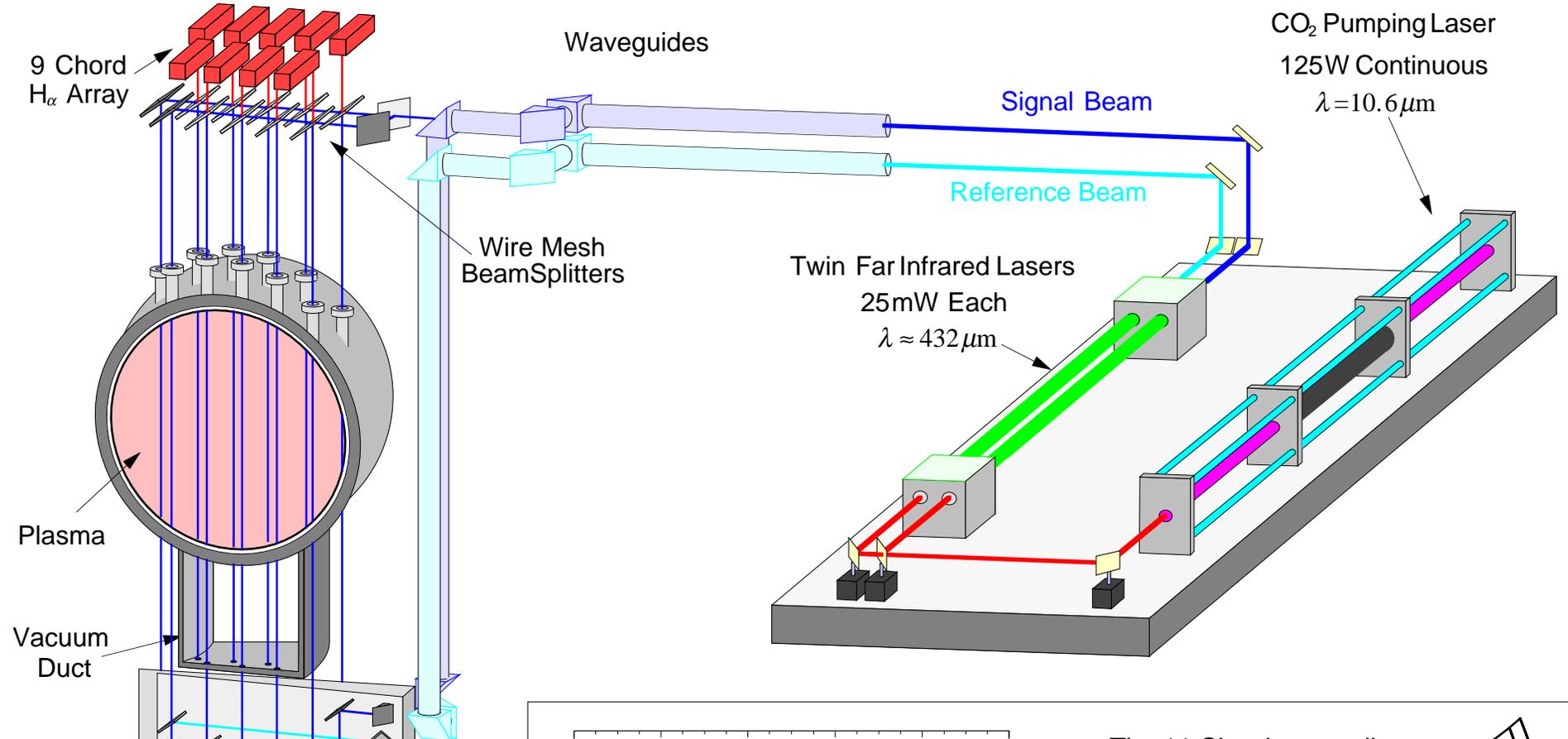
advection non-radial compression
⇓ ⇓
⇑
radial compression

- **Causes transport?**

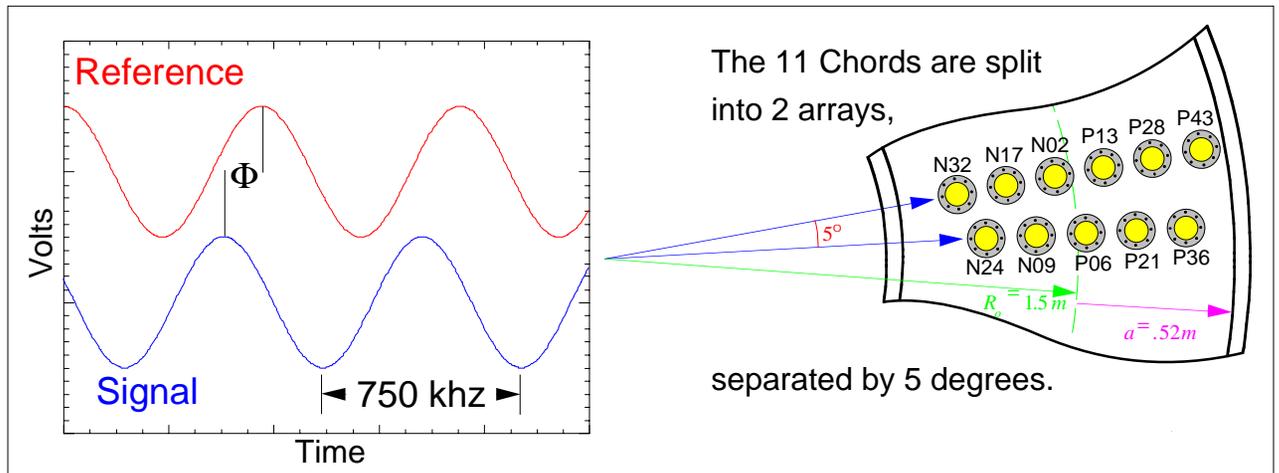
$$\Gamma = \langle \tilde{n}\tilde{v}_r \rangle = \gamma |\tilde{n}| |\tilde{v}_r| \cos \delta_{\tilde{n}\tilde{v}}$$

$$\delta_{\tilde{n}\tilde{v}} = \frac{\pi}{2} \Rightarrow \text{no transport, but } \delta_{\tilde{n}\tilde{v}} = 0, \pi \Rightarrow \text{transport}$$

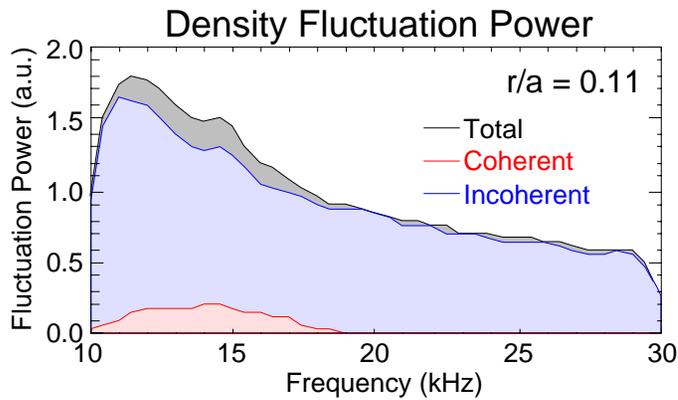
The Far-Infrared Interferometer* and H α array



* Developed with UCLA Plasma Diagnostics Group



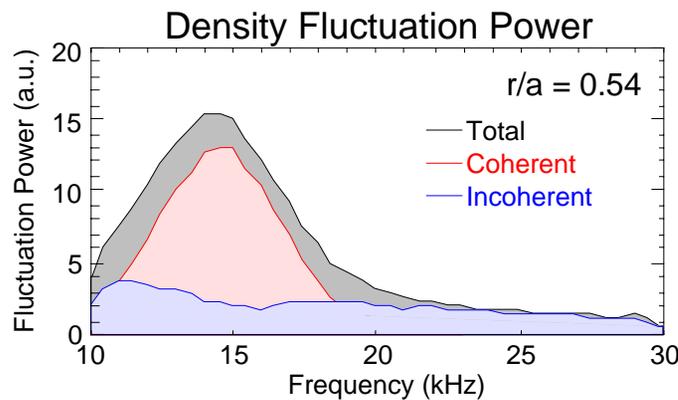
Core-Resonant Tearing Modes Drive Density Fluctuations



Correlation between core-resonant magnetic fluctuations and density fluctuations indicate:

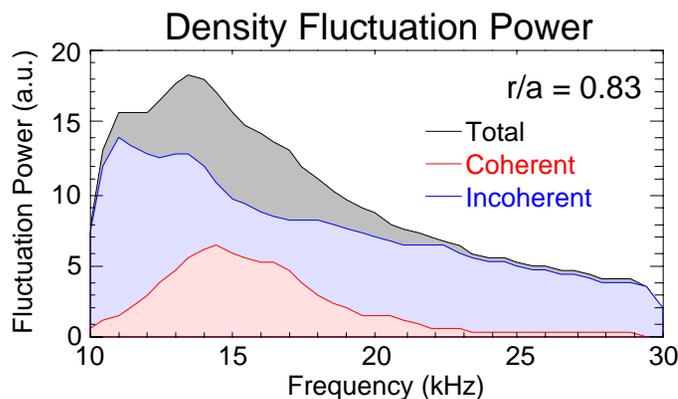
Core:

- density fluctuations are poorly coherent with the $m = 1$ magnetic fluctuations.



At larger impact parameters:

- virtually all the power between 10 and 20 kHz is coherent with the $n = 5$ to 15 modes.

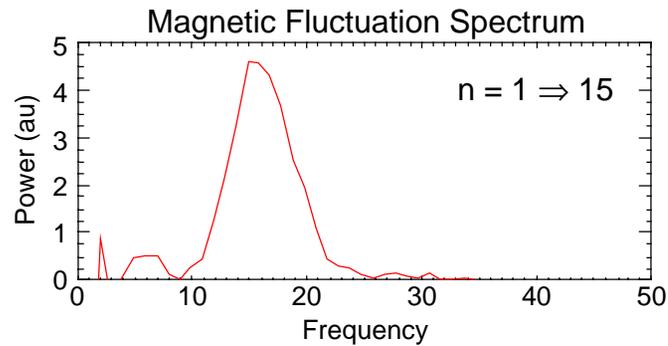


Edge:

- density fluctuations are less coherent with the core-resonant tearing modes
- relative contribution from smaller scale, higher frequency, fluctuations increase.

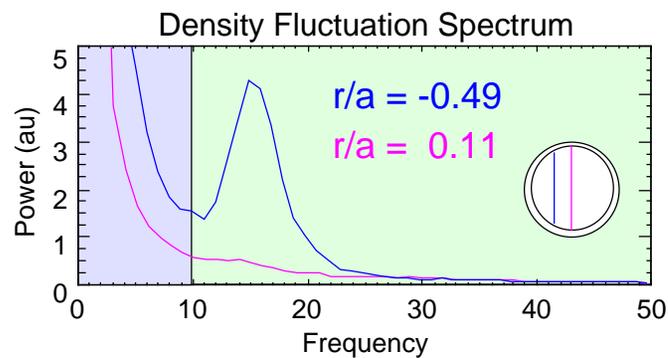


Density Fluctuations Display Both $m=0$ and $m=1$ Like Behavior



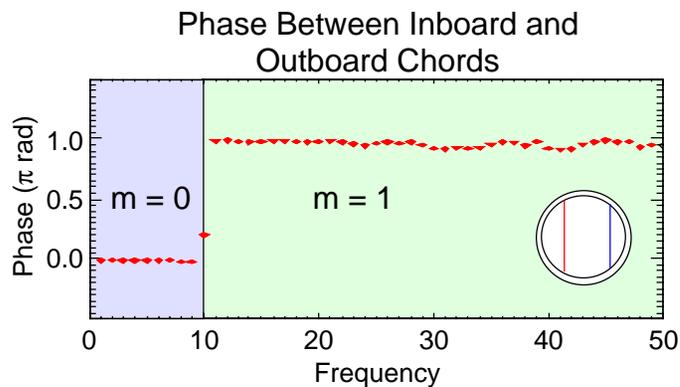
Magnetic fluctuation power

- shows a large peak between 10 \Rightarrow 20 kHz
- dominated by $m = 1$, $n = 6 \Rightarrow 10$ modes



Density fluctuation power

- displays similar 15 kHz peak in all but center chords.
- low frequency peak appears in all chords

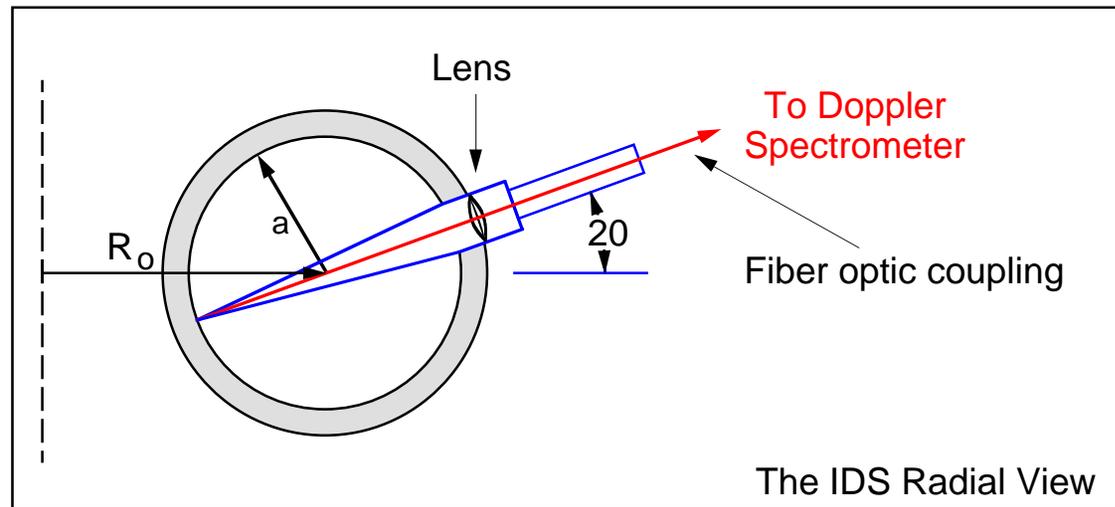


Density fluctuation m character

- low frequency peak has $m=0$ character
- ~ 15 kHz peak has $m=1$ character.



The Ion Dynamics Spectrometer (IDS) Radial Port



The IDS:

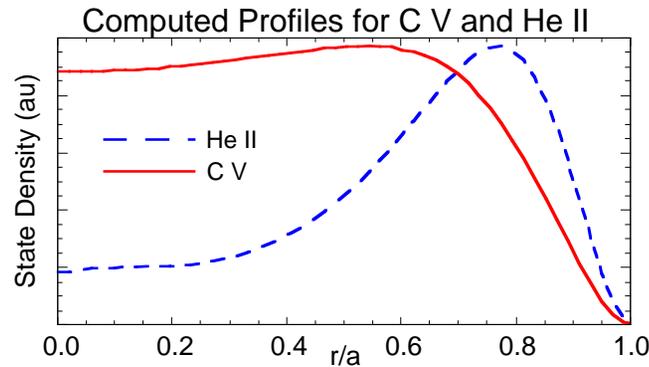
- custom designed Doppler Spectrometer
- fast time resolution $\rightarrow 10 \mu\text{s}$
- measures impurity ion flow fluctuations $\tilde{v}_i \rightarrow$ Doppler Shift

Radial View

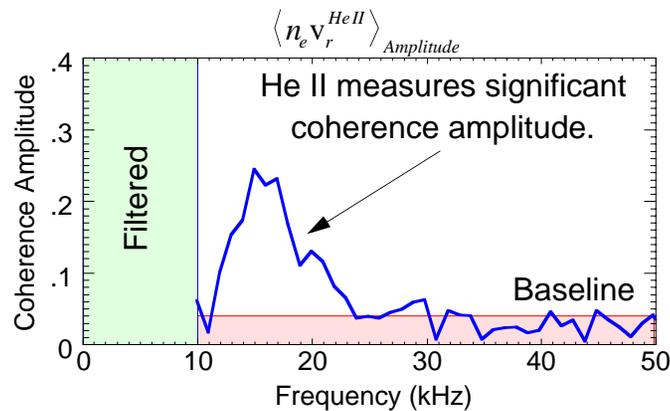
- high light throughput
- impurity choice can enhance localization



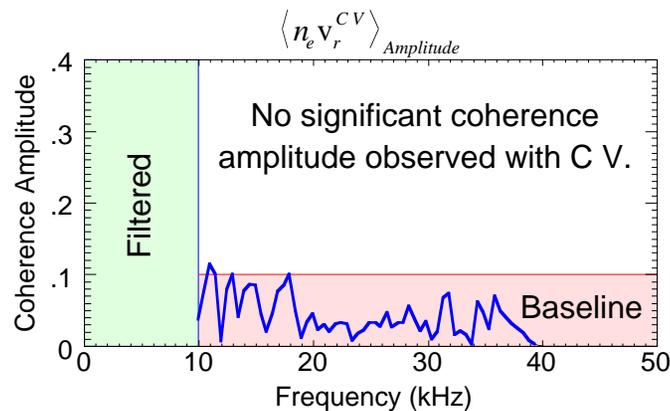
Measurements Indicate That \tilde{v}_r Flips Phase in the Core.



- The edge peaked profile of He II weights the edge more heavily.
- The broad C V profile provides a more even weighting over the plasma radius.



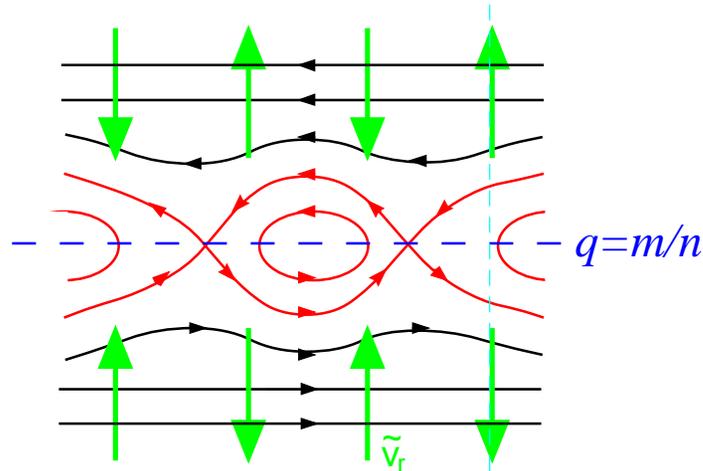
- Measurements with helium establish the existence radial velocity fluctuations in the plasma edge.



- Measurements of C V ions show no significant coherence - implying a phase flip in the radial velocity fluctuations.



Phase Flip in \tilde{v}_r is Consistent With Tearing Mode Picture

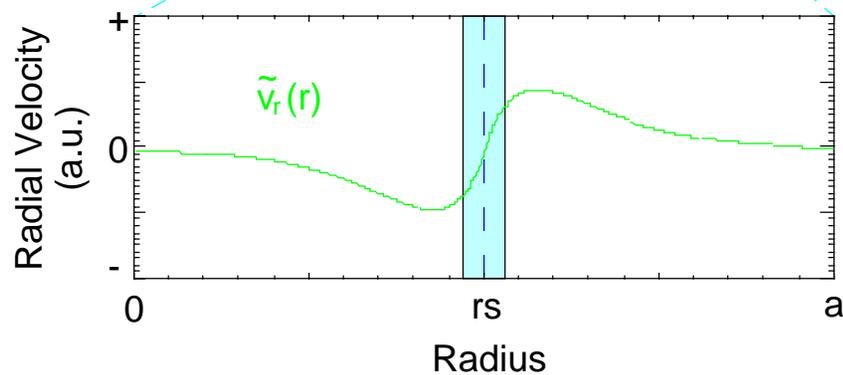


Tearing mode topology suggests that \tilde{v}_r should reverse across rational surface.

Since passive doppler spectroscopy measures

$$\int_{\text{Chord}} I_Z(r) \tilde{v}_r(r) dr,$$

a ' π ' phase shift would explain how



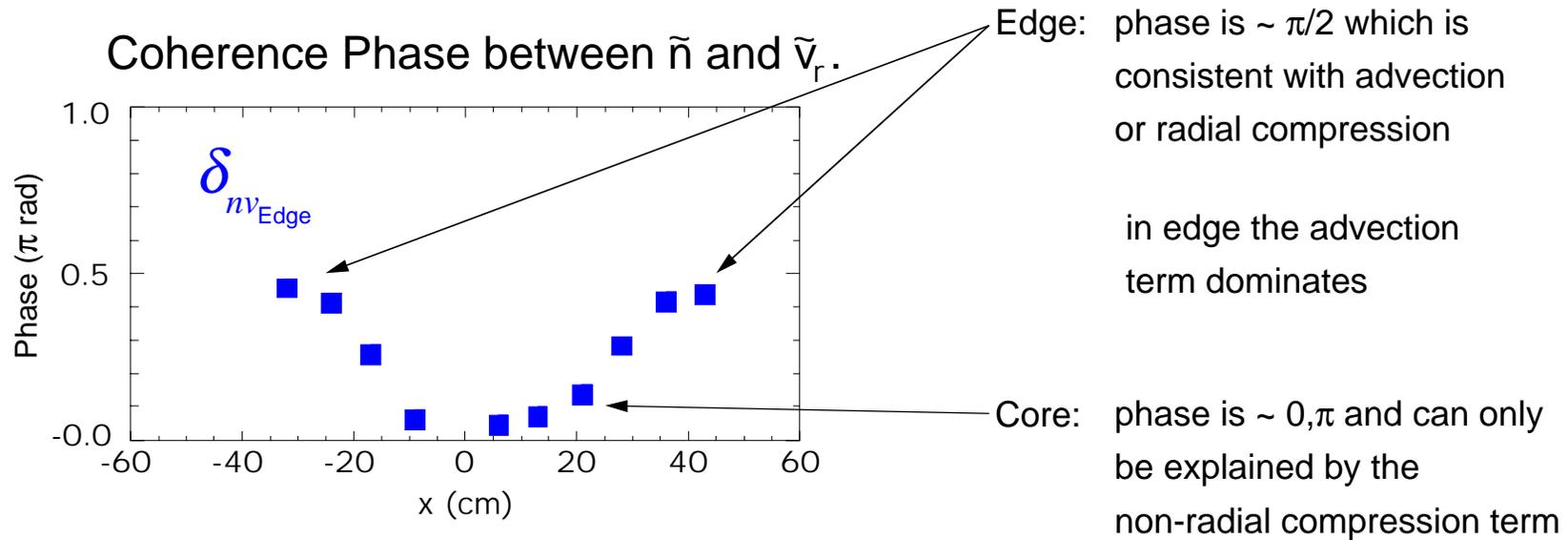
$$\tilde{v}_r(r) \rightarrow \text{finite}$$

but

$$\int_{\text{Chord}} I_Z(r) \tilde{v}_r(r) dr \rightarrow 0.$$



Density Fluctuations in the Edge are Primarily Advective While in the Core are Compressional



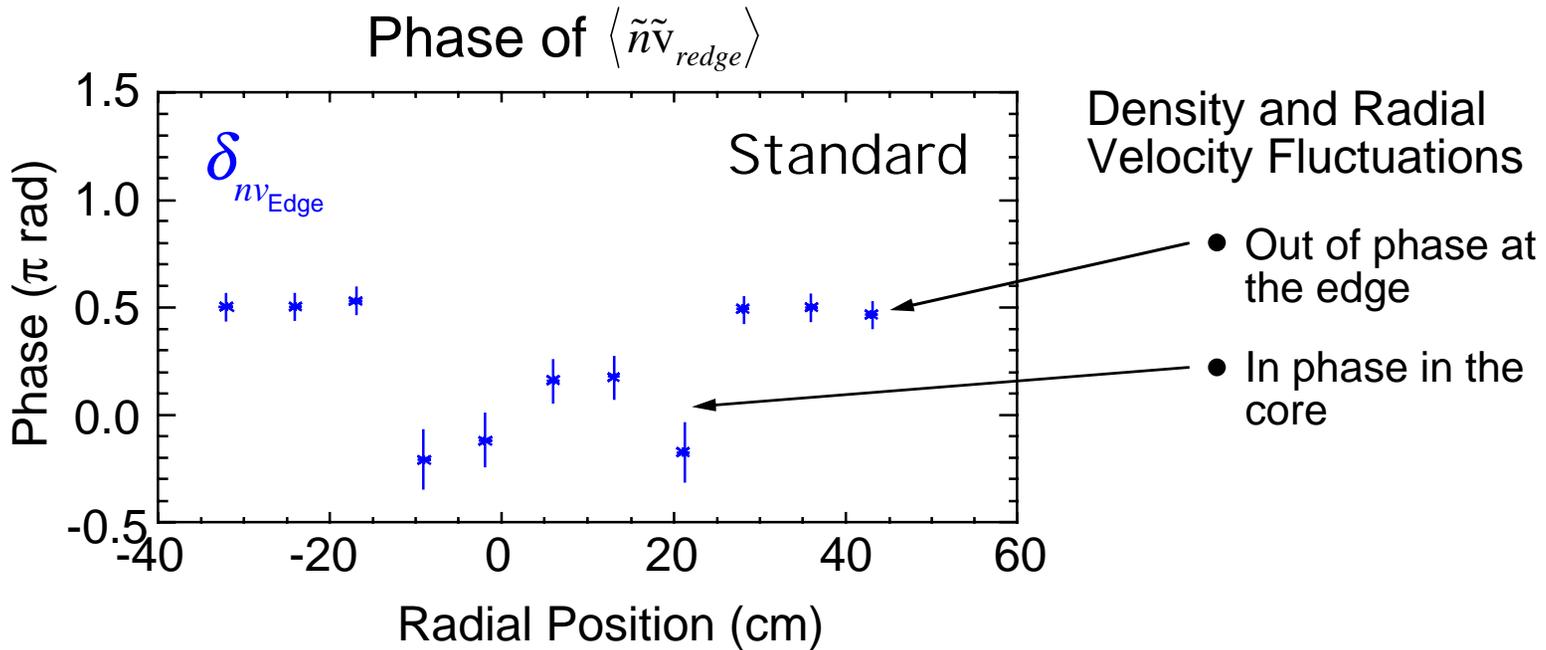
Measurements show:

- In the edge, density and velocity fluctuations are $\pi/2$ out of phase.
- Density fluctuation phase in the core is shifted by $\pi/2$ from that in the edge.
- Velocity fluctuation phase in the core is shifted by π from that in the edge.

Therefore: we deduce that the density and velocity fluctuations are in phase in the plasma core.



Fluctuation-Induced Transport is Small at Edge, Large in Core



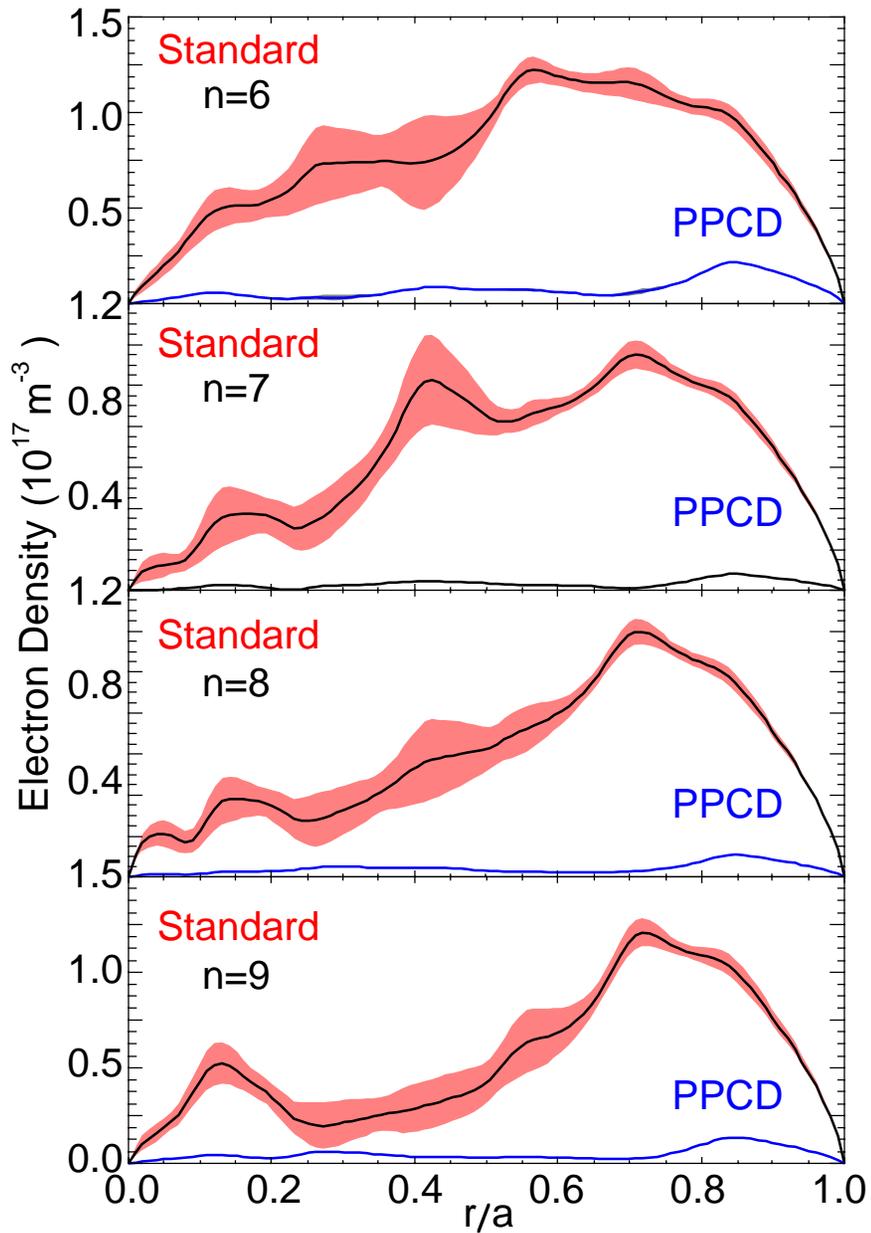
Standard Discharges

- Fluctuation-Induced Transport small in the edge.
- Fluctuation-Induced Transport large in the core.



Local Fluctuation Amplitudes Decrease During PPCD

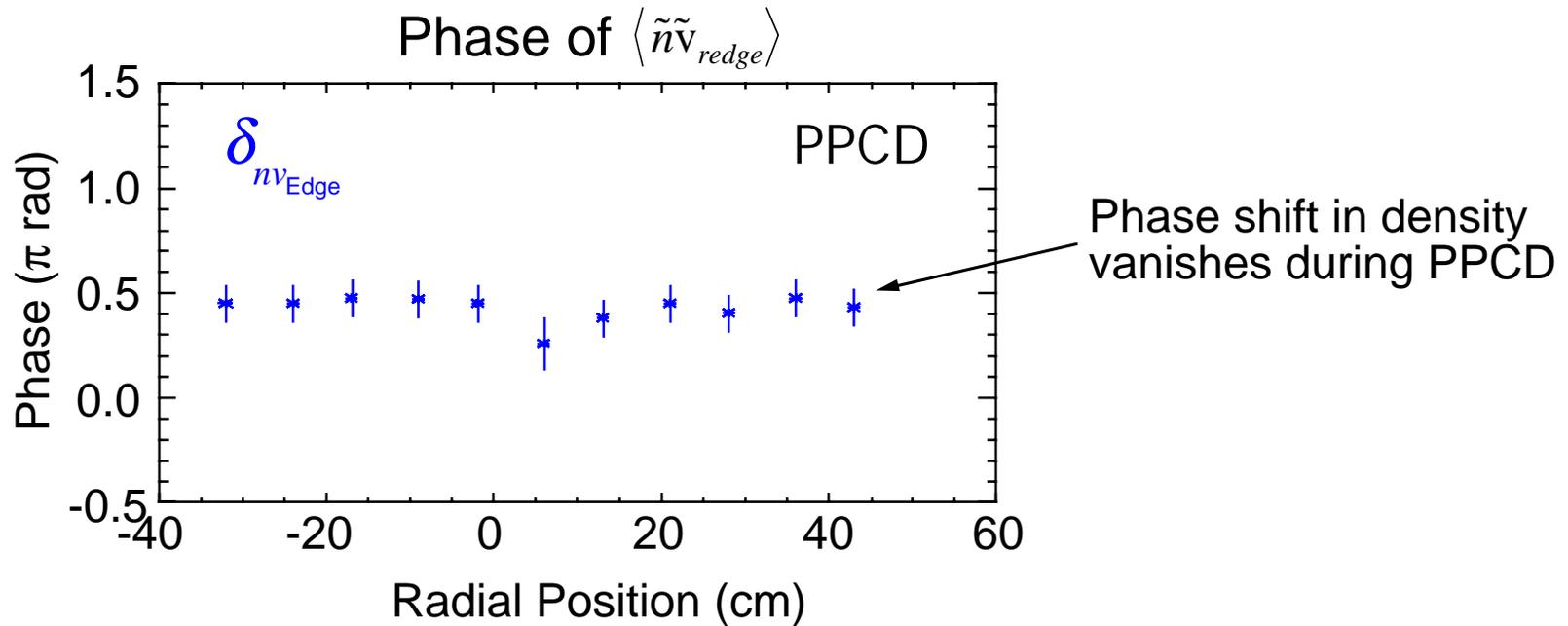
Local Fluctuation Profiles for $m=1$, $n=6-9$ Perturbations.



- Profile peaks farther out as n increases
- Fluctuation amplitudes are
 - ~ 1.0 % Standard
 - ~ 0.1 % PPCD



PPCD Reduces Fluctuation-Induced Transport in the Core

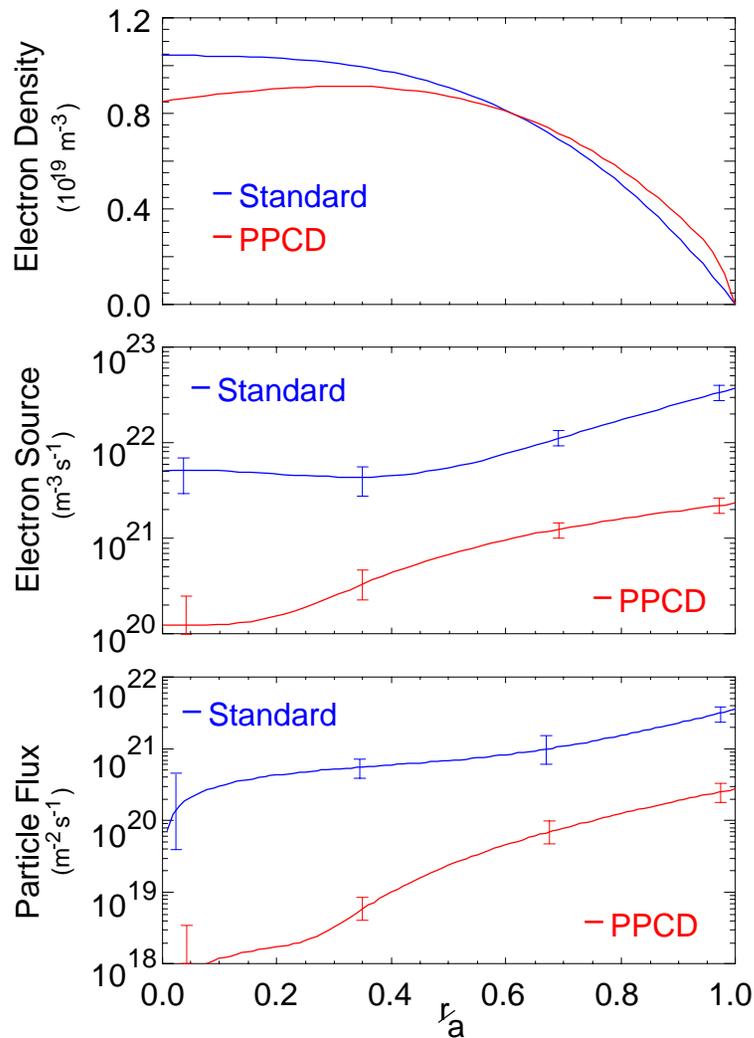


PPCD Discharges

- Density and velocity fluctuations remain out of phase deeper into the plasma.
- Fluctuation-Induced Transport reduced in the core.



Fluctuation Reduction During PPCD is Accompanied by Similar Reductions in Equilibrium Radial Electron Flux



In standard discharges:

Density profiles are flat in the core with a steep edge gradient.

Electron source is dominated by ionization of neutral hydrogen and is quite broad with substantial sourcing in the core.

Radial Particle flux ranges from $\sim 2\text{E}+20$ to about $3\text{E}+21$ at the edge.

During PPCD discharges:

Density profile hollows slightly in the core and gradient at the edge steepens.

Electron source drops over an order of magnitude.

Radial particle flux also decreases with the most dramatic reduction seen in the core.



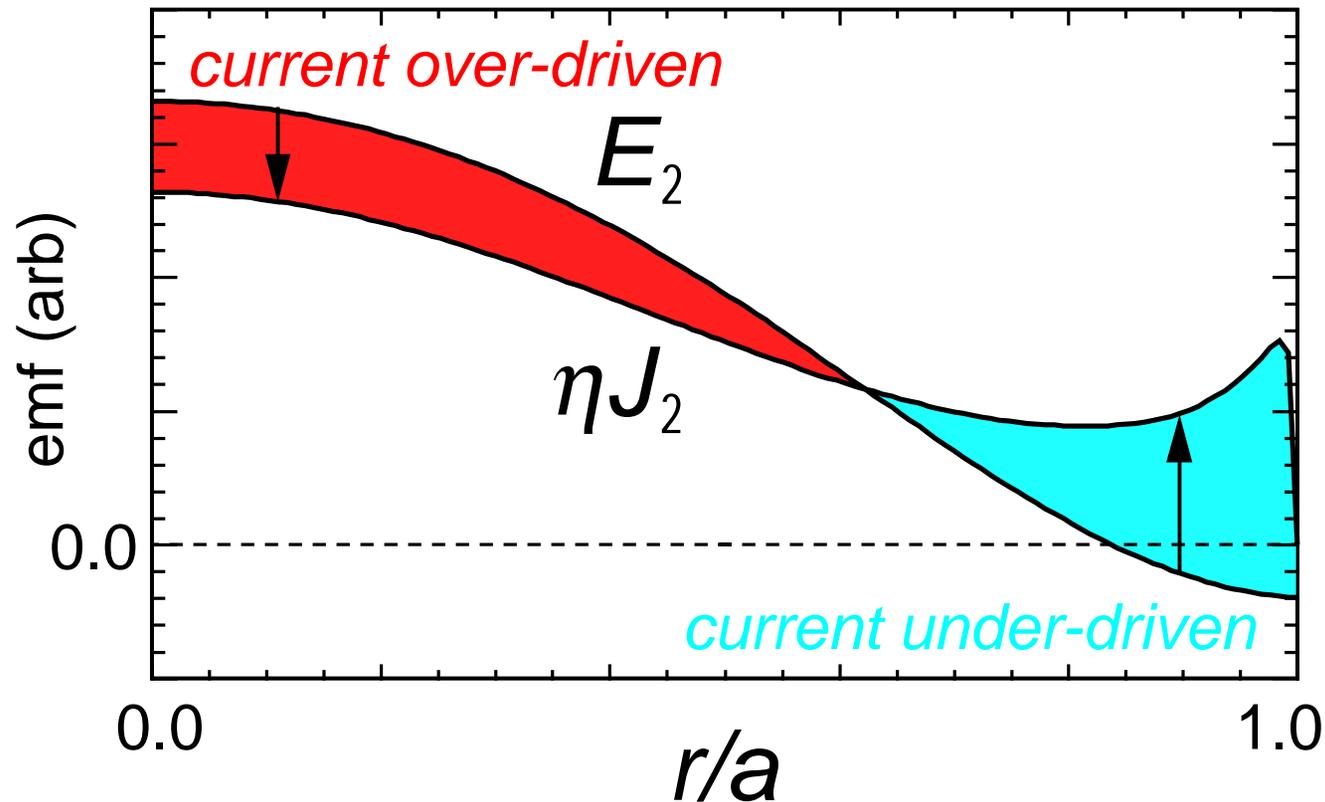
Density fluctuation and particle transport summary

- Density fluctuations result mainly from the core-resonant tearing modes ($m = 1, n = 6 \Rightarrow 10$), and are advective in the edge and compressional in the core.
- Although large in the outer region of the plasma, the density fluctuations from core modes do not cause transport there.
- During PPCD, the measured radial particle flux decreases dramatically concurrent with similar reductions in density fluctuations.
- Phase measurements of density and radial velocity fluctuations indicate, that during PPCD, the region of vanishing fluctuation-induced transport extends deeper into the core.



Ohm's law requires the RFP to have a dynamo

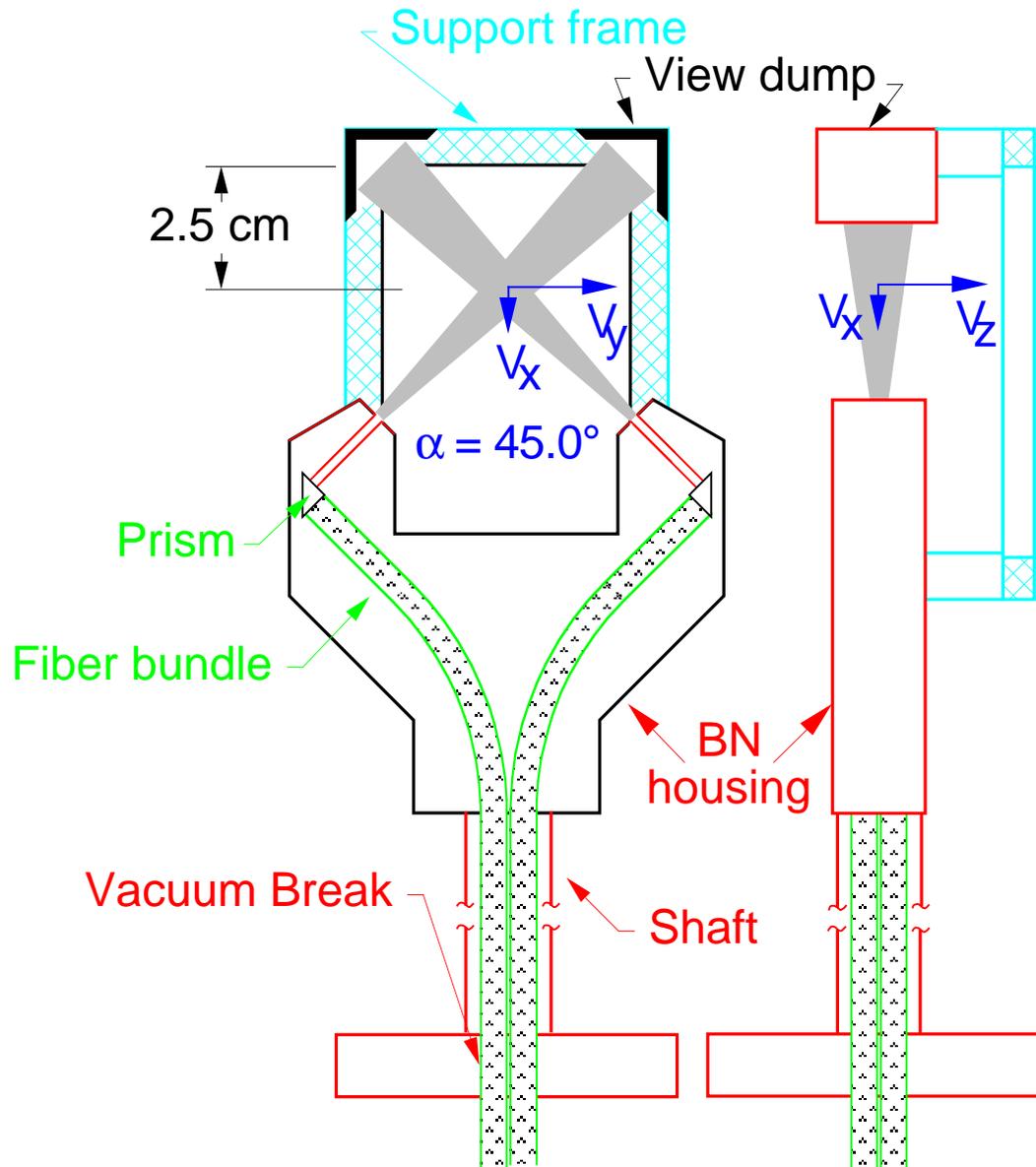
$E_2 \neq \eta J_2$ both in the core and edge



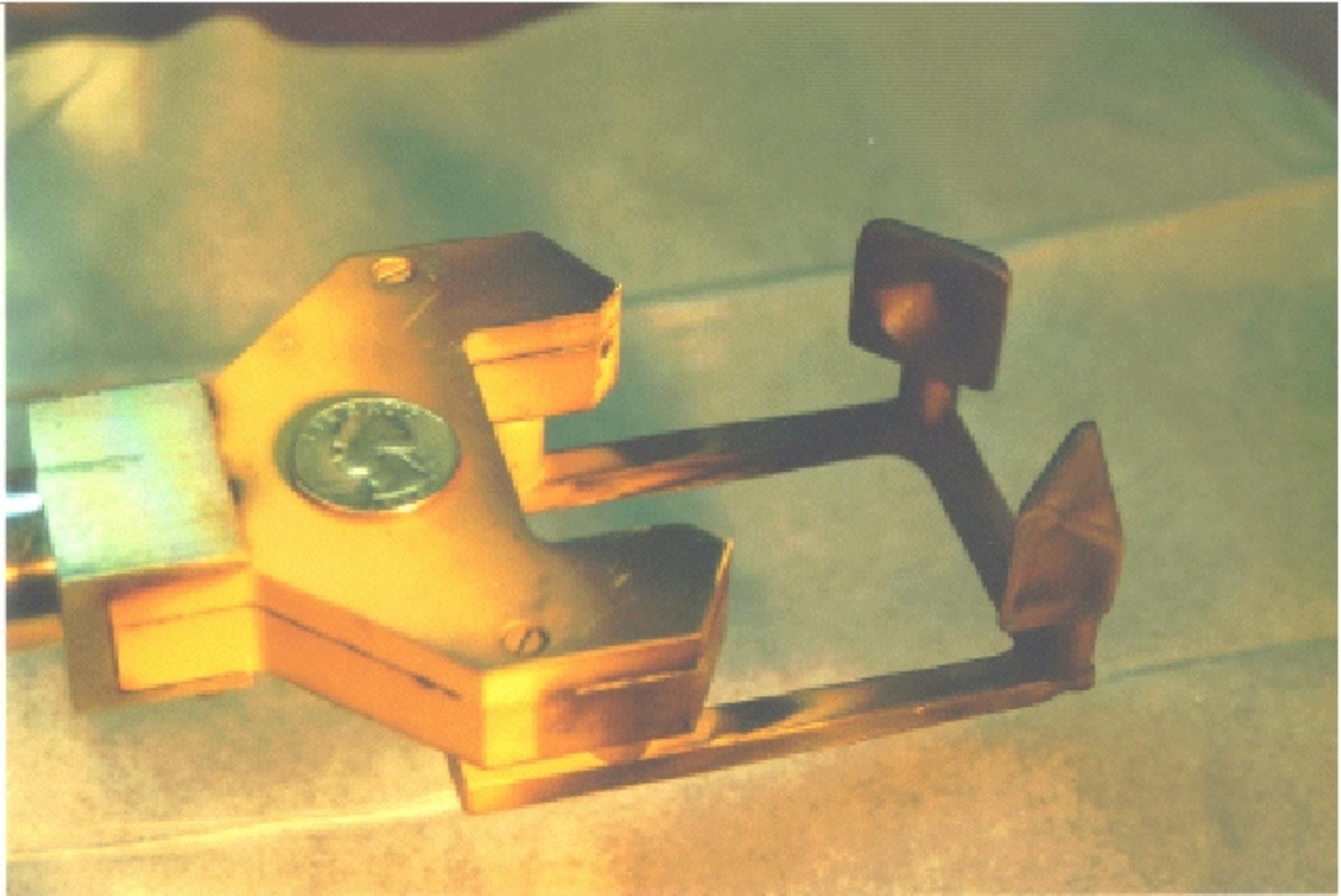
- need noninductive current drive to balance Ohm's law:

$$2 + \langle \tilde{\mathbf{v}} \cdot \mathbf{H} \tilde{\mathbf{B}} \rangle_2 = \eta J_2$$

The Ion Dynamics Spectroscopy Probe

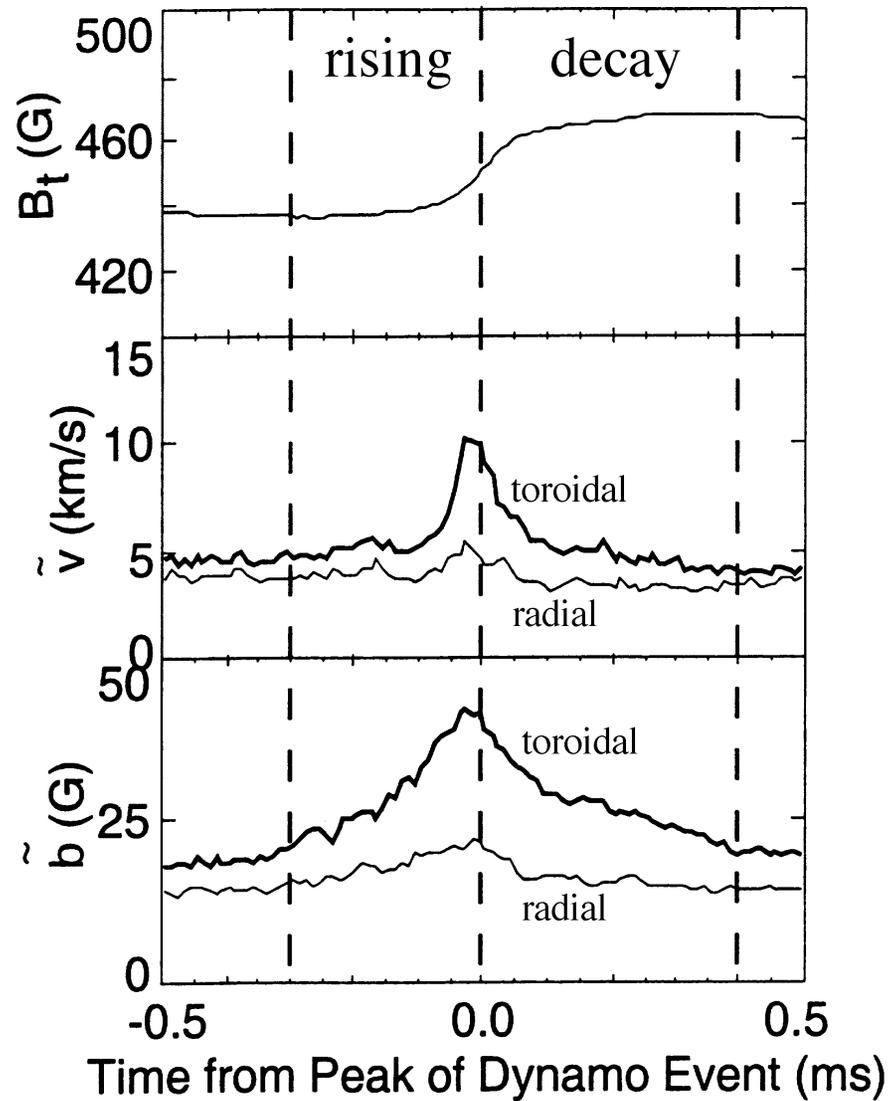


IDSP proof-of-existence

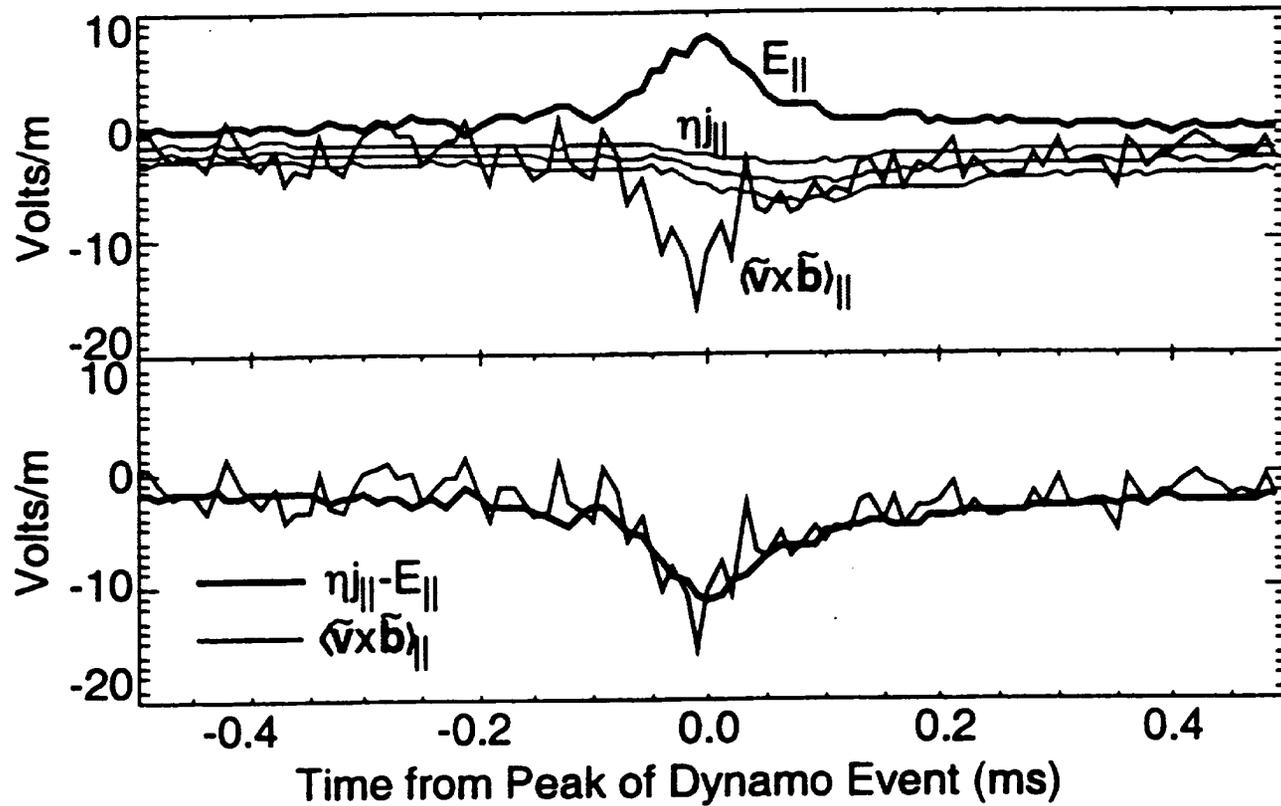


RFP dynamo events

Regular discrete bursts of dynamo activity occur in MST

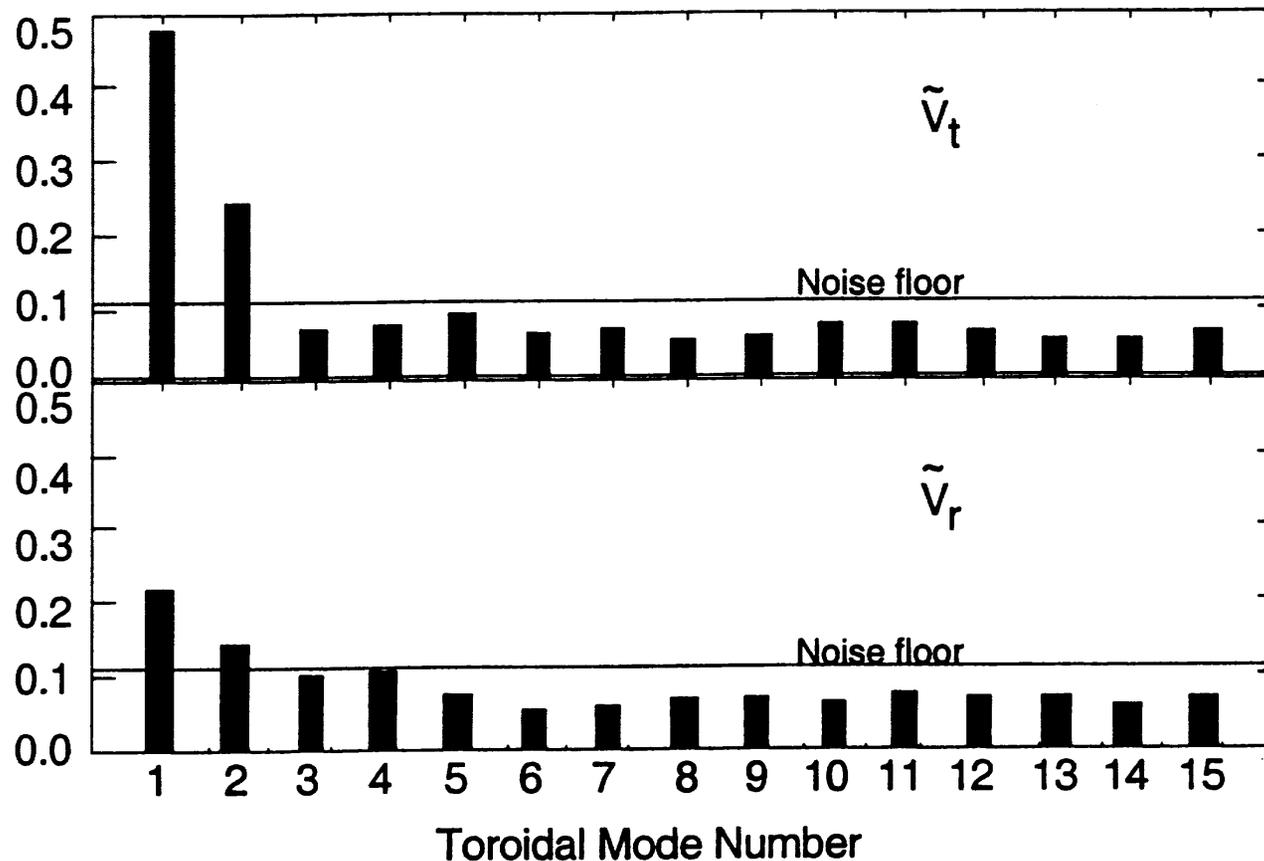


The MHD dynamo balances Ohm's law



- Ohm's law balance is good at $>0.85a$
 - deteriorates for $\leq 0.85a$

Velocity fluctuation spectra are dominated by $n = 1$ and 2, implying $m = 0$ dynamo in edge



- Numerical values represent the correlation (from 0 to 1) of the fluctuation with each mode resolved by the B_t array

Summary of edge dynamo measurements

- The MHD dynamo term balances mean-field Ohm's law in the edge of MST
- The edge dynamo is driven by $m = 0$ fluctuations which resonate at the reversal ($q = 0$) surface
 - dynamo in MST is a superposition of relatively localized reconnection events
- May be a different current drive mechanism active inside $0.85a$