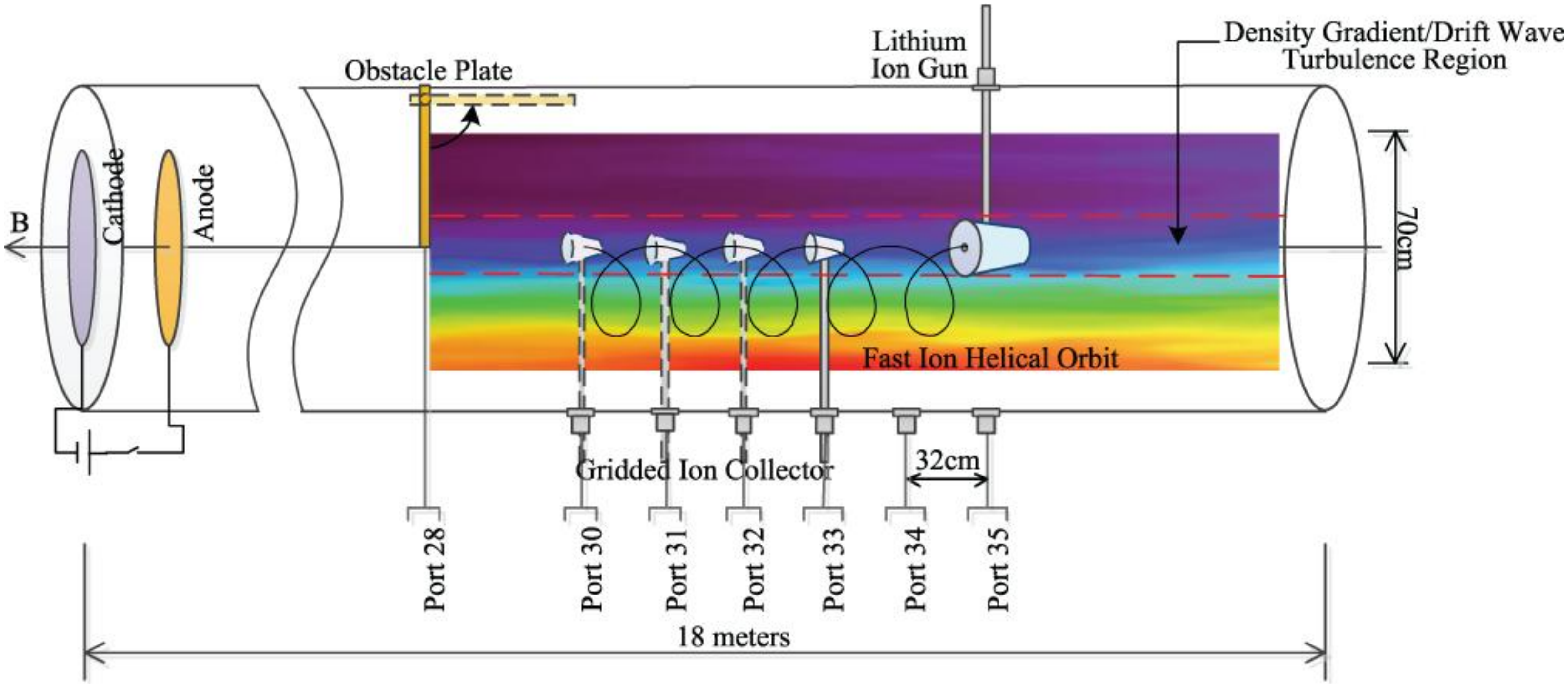
Turbulent Transport of Fast Ions in the Large Plasma Device

UCIrvine

UCLA



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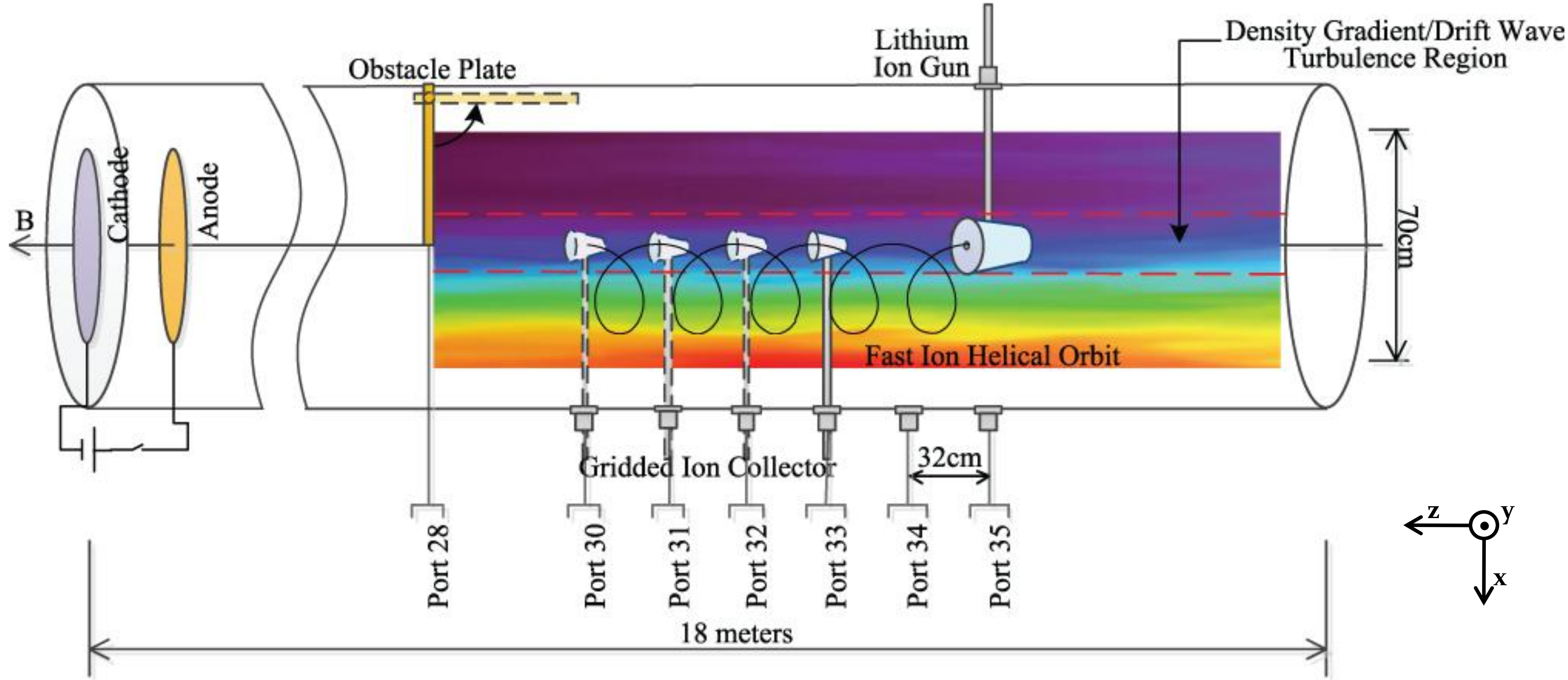
Energetic Ions are Confined Better than Thermal Ions in Electrostatic Microturbulence

- Large orbits of fast ions phase average over electrostatic microturbulence with decorrelation lengths on the scale of thermal ion gyroradius
- Transport reduces with higher fast ion energy due to phase averaging
- Effect of phase averaging depends on wave scale length (correlation length, L_{corr} and k_θ) and time scale ($\tau_{correlation}$)
- Direct, quantitative measurement of fast ion transport in turbulent wave is possible in LAPD

Outline

- **Fast Ion Diffusion In Waves : Energy Scaling**
- **Fast Ion Diffusion In Waves : L_{corr}, k_θ Dependence**
- **Time Dependence of Fast Ion Diffusivity**

Experimental Setup for Fast-ion Transport in Turbulent Waves



- Li^+ beam gyro-radius is adjusted by changing fast ion energy (400eV-1000eV, with background plasma T_e ~ 5eV) and pitch angle
- Li^+ beam orbit overlaps partially/fully with turbulent drift waves region
- Planar scan of collector measures beam spreading

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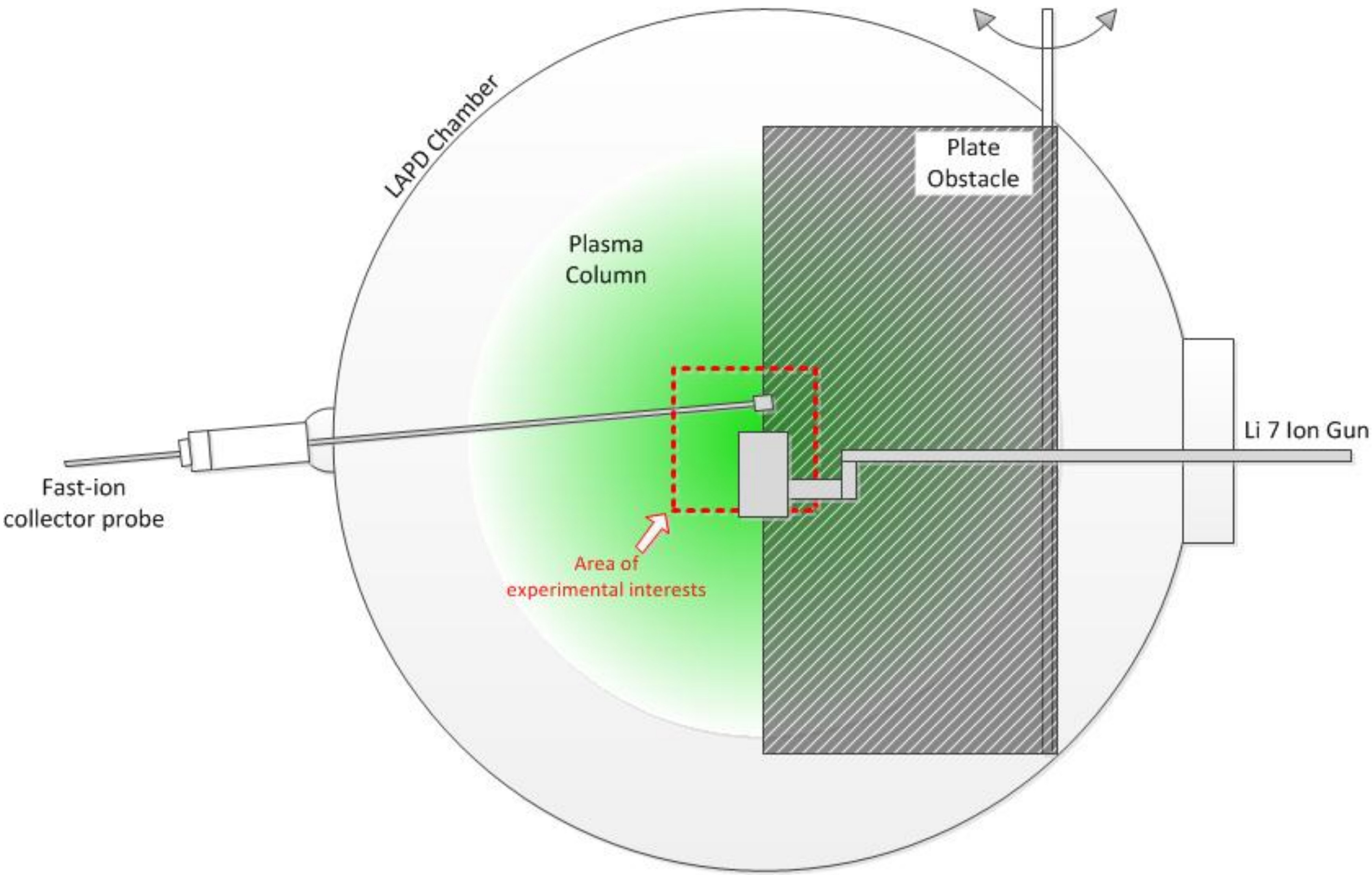
Broadband Drift Waves Induced at the Plate Obstacle Edge



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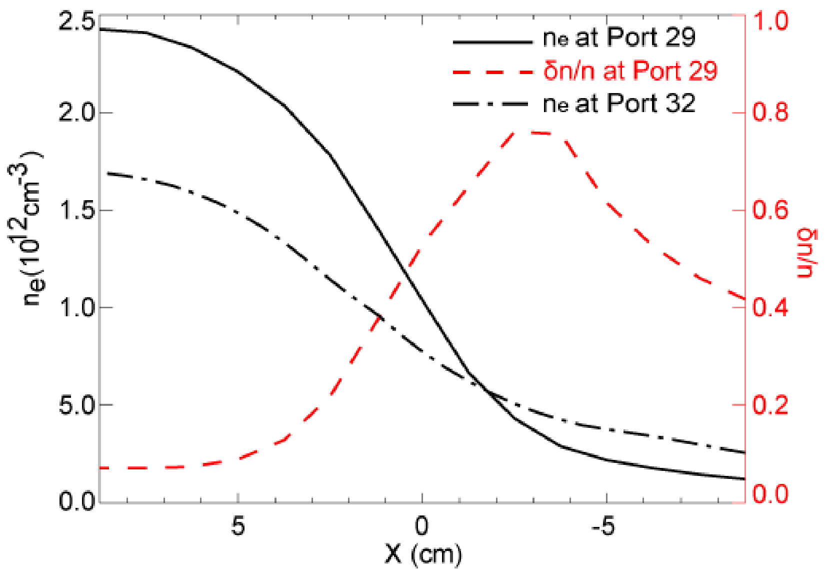
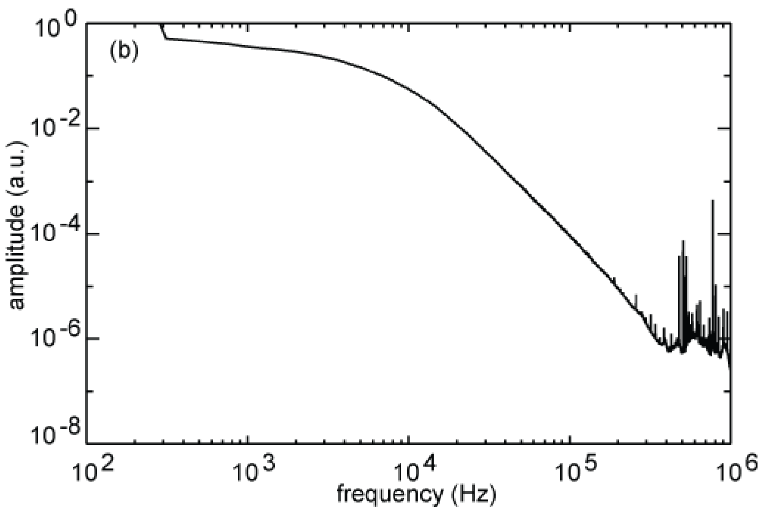
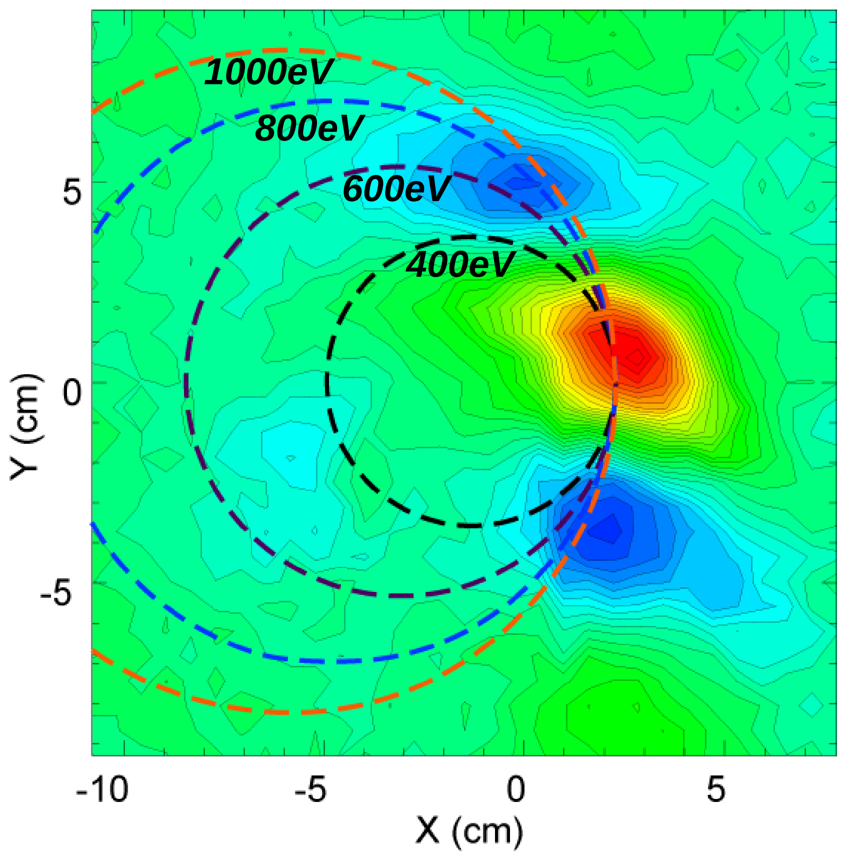
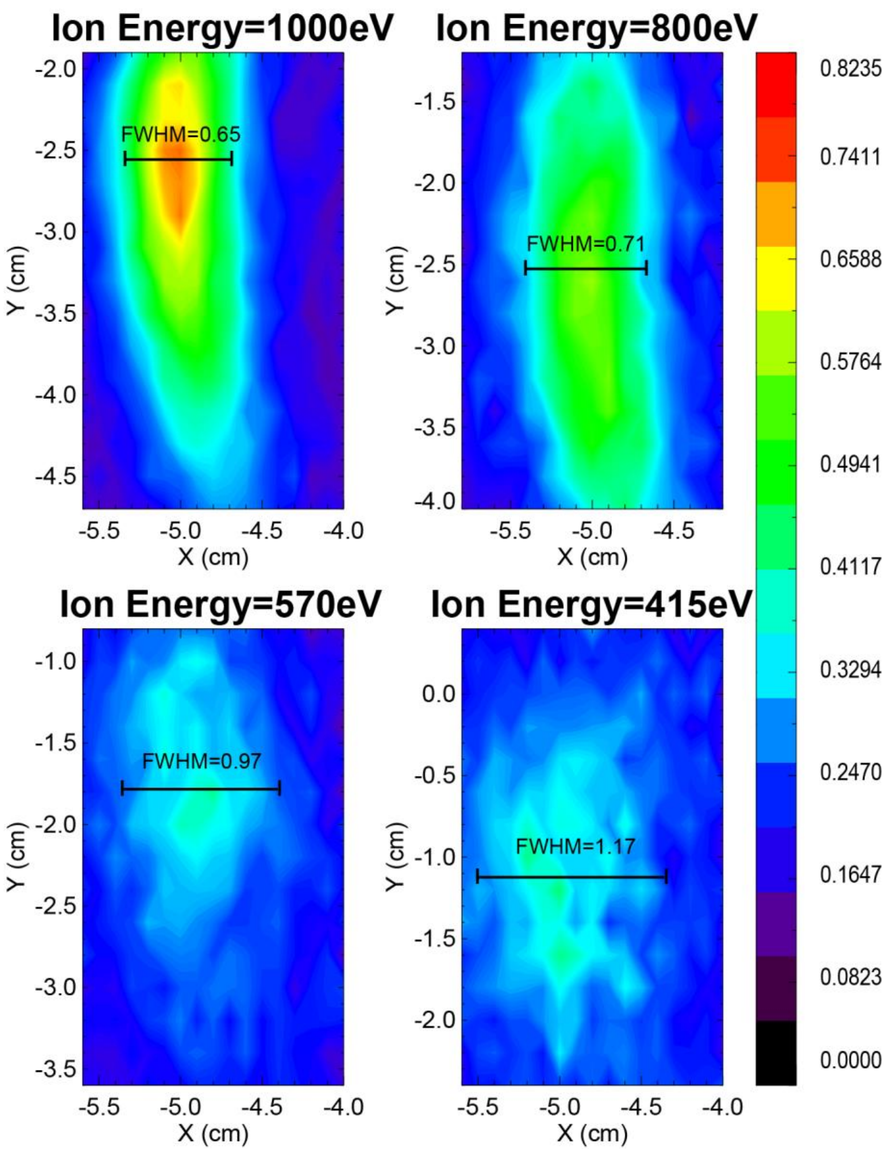


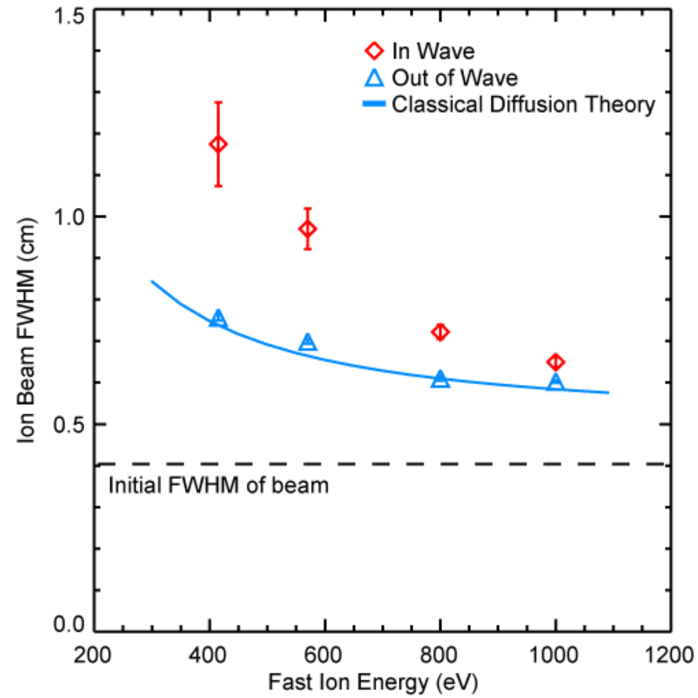


Cross-field correlation function for I_{sat}



Fast-Ion Transport Decreases with Increasing Fast-Ion Energy





•In quiet plasma, FWHM described by classical diffusion theory:

$$D_{\perp \mathrm{theor}} = \frac{\langle (\Delta r)^2 \rangle}{2t} = \frac{v^2 \cos^2 \theta}{4\Omega^2} \nu_{\mathrm{PAS}}$$

L. Zhao, W. W. Heidbrink, H. Boehmer, et al., Phys. Plasmas 12, 052108 (2005)

• Turbulent wave-induced fast-ion transport decreases with increasing fast-ion energy

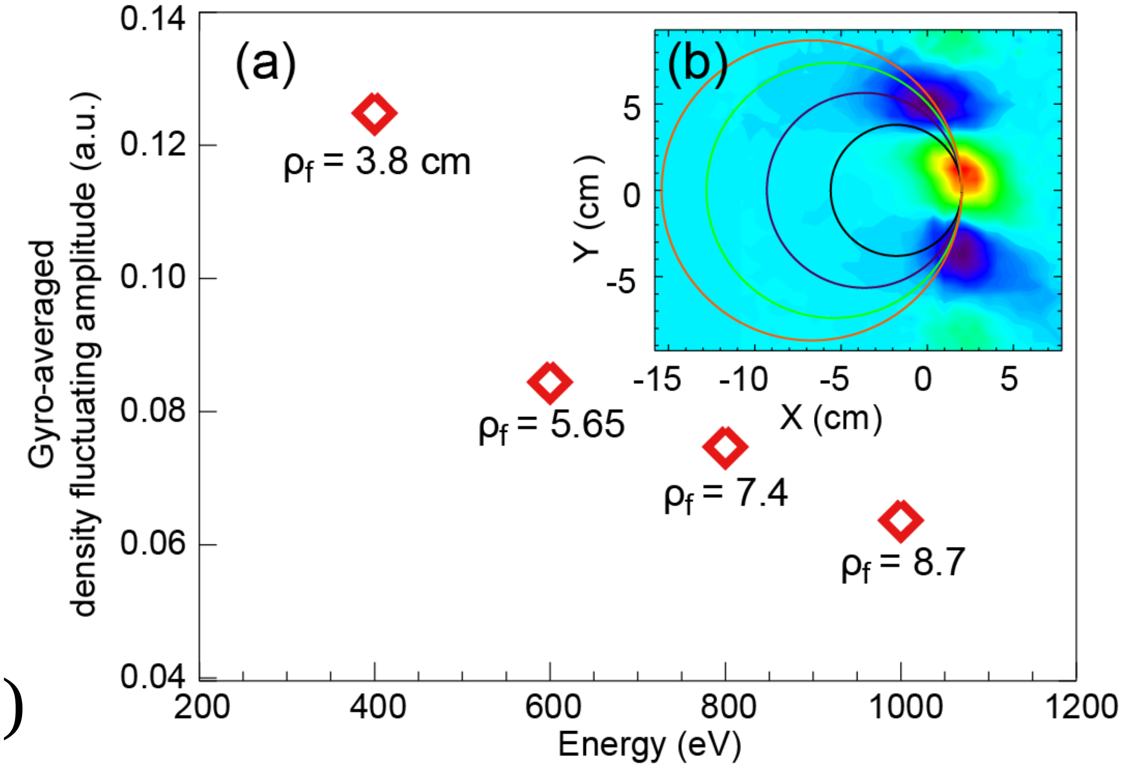
Gyro-Averaging Theory Explains Energy Dependence of Transport

Gyro-averaging requires:

- $\Omega_{ci} >> \omega_{drift}$
- $\mu = const$
- $\bar{\upsilon}_{ExB} \cdot \tau_{ci} << \rho_f$

Gyro-averaged potential is:

$$\bar{\phi}(x) = \sum_k \phi_k e^{ik\cdot x} \cdot J_0(k_\perp \rho_f)$$

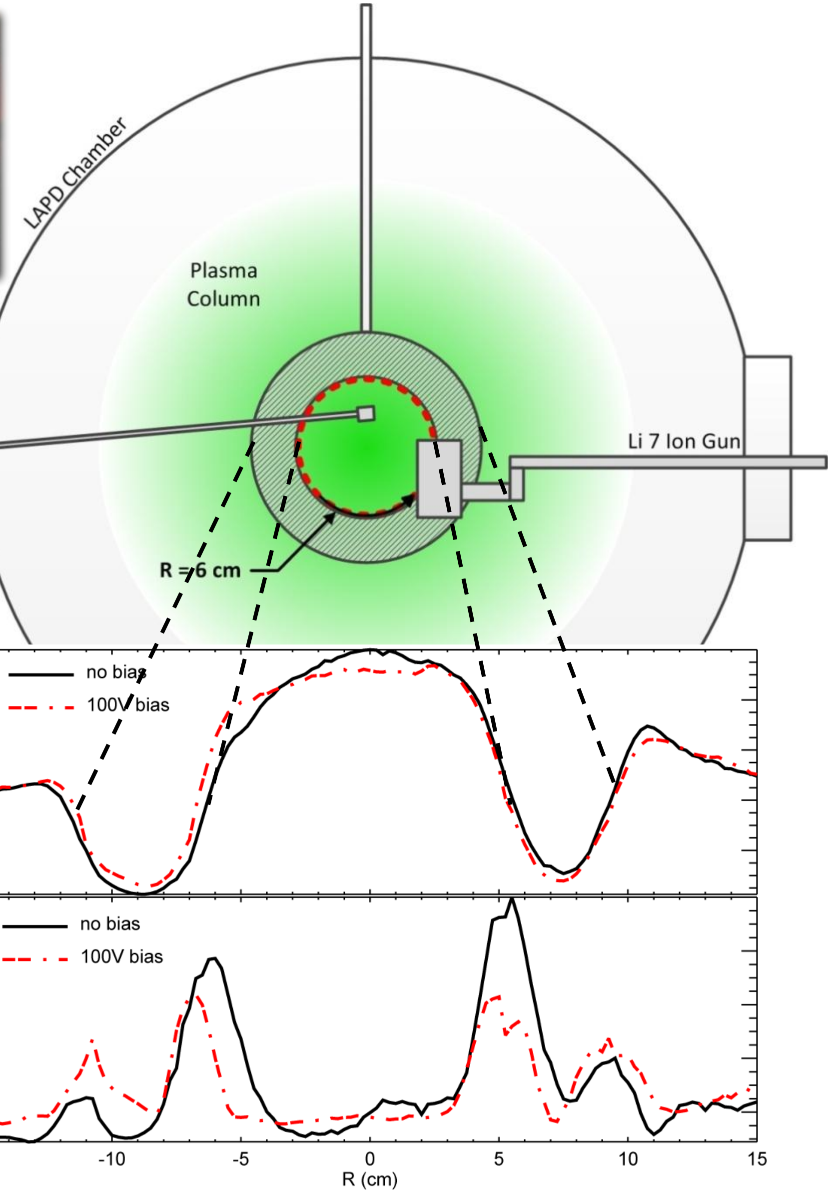


**Assuming L_{corr} scales the same for potential and density in drift wave turbulence*

Outline

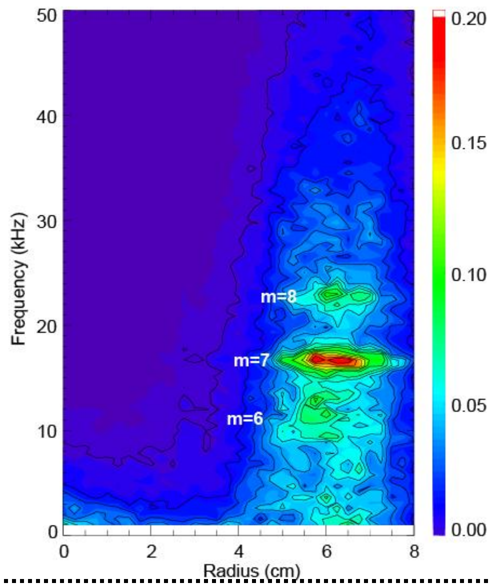
- Fast Ion Diffusion In Waves : Energy Scaling
- **Fast Ion Diffusion In Waves : L_{corr}, k_θ Dependence**
- Time Dependence of Fast Ion Diffusivity

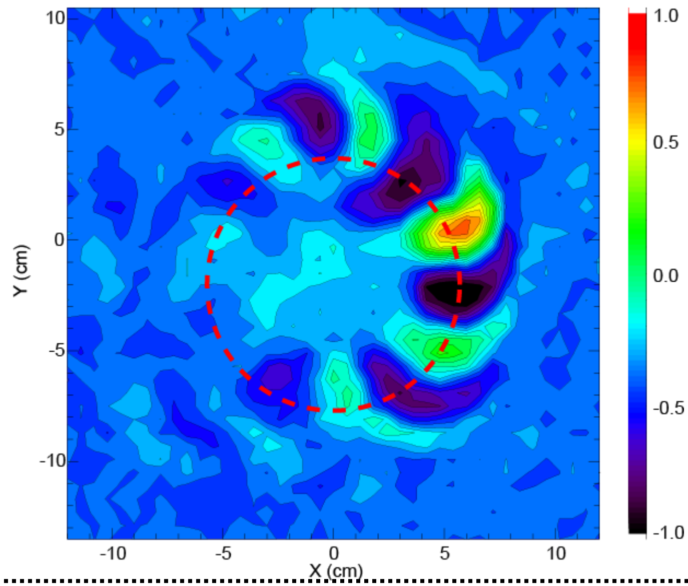
Drift Waves with Cylindrical Geometry Induced By Annulus Obstacle



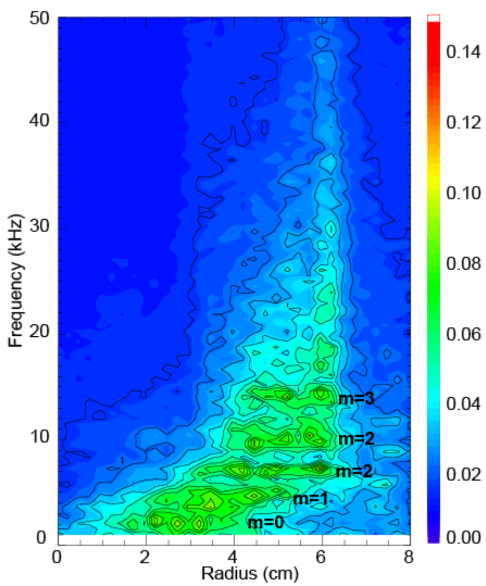
- ○ Large density gradient ($L_n \sim 2$ cm)
- ○ Large density fluctuation ($\delta n/n \sim 1$)
- ○ Cylindrical Geometry
- ○ Wave driven by ***density gradient*** and *drift velocity shear*
- ○ Wave modified by
  - • biasing the annulus
  - • changing plasma species

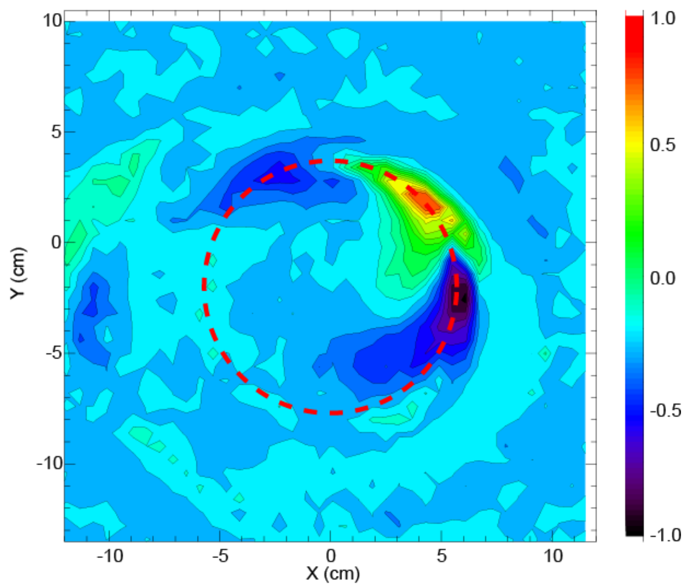
Drift Waves with Different Mode Numbers (k_θ) in Helium or Neon Plasmas





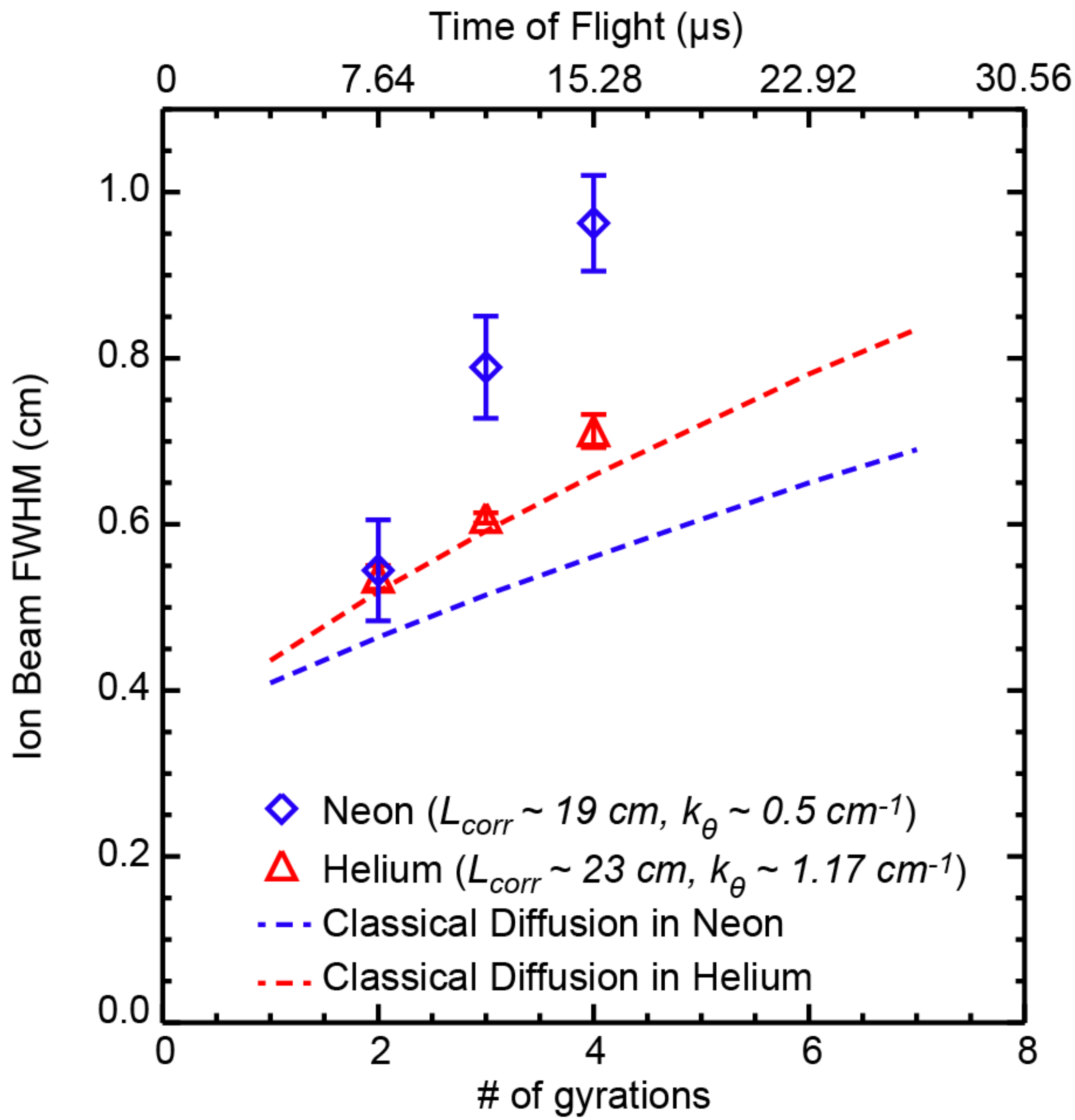
- Helium plasma (no bias on annulus @ Aug 2010)
- m = 6 ~ 8
- *Long* azimuthal correlation (L_{corr} ~ *23 cm*)
- *Small* azimuthal structure size ($k_\theta = m/\rho_f \sim 1.16\ cm^{-1}$)



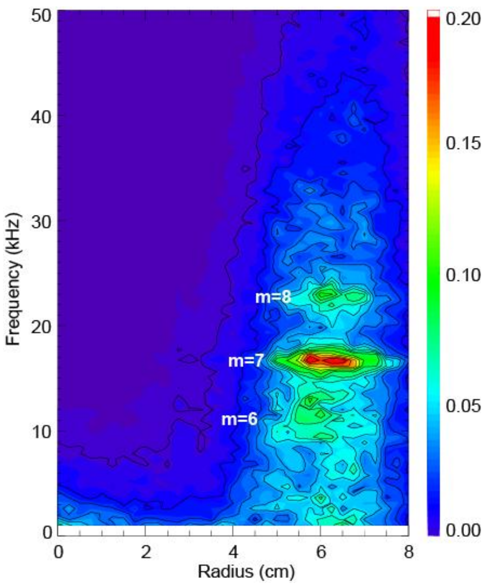


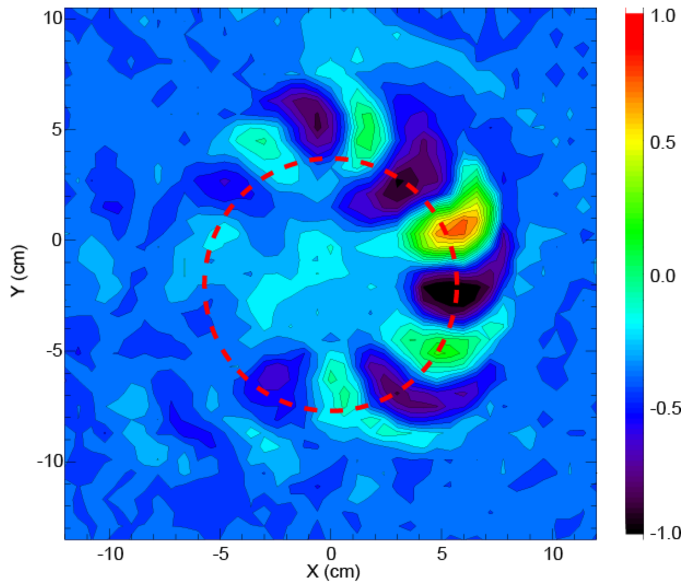
- Neon plasma (75V bias on annulus @ Oct 2010)
- m = 1 ~ 3
- *Long* azimuthal correlation (L_{corr} ~ *19 cm*)
- *Large* azimuthal structure size ($k_\theta = m/\rho_f \sim 0.5\ cm^{-1}$)

Drift Waves with Larger Scale Size Cause More Fast Ion Transport

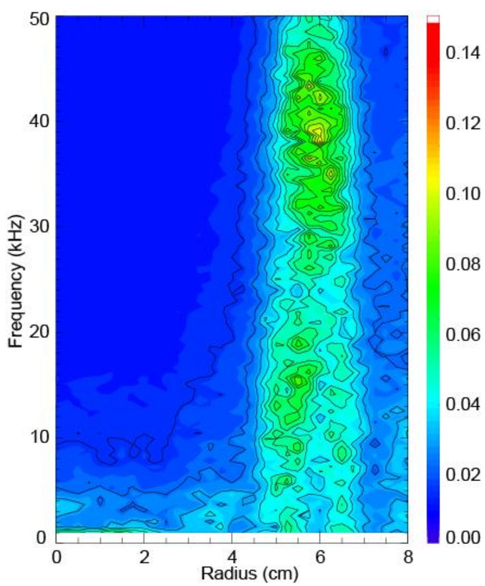


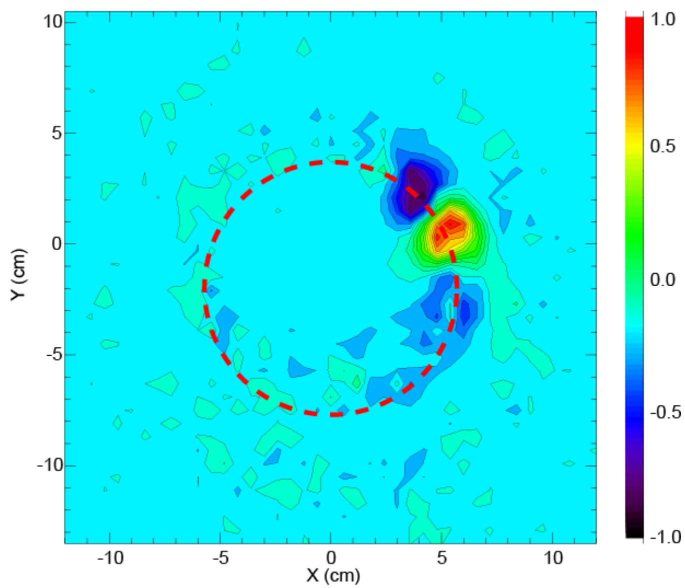
Two Wave Correlation Length Regimes were Made in Helium Plasma





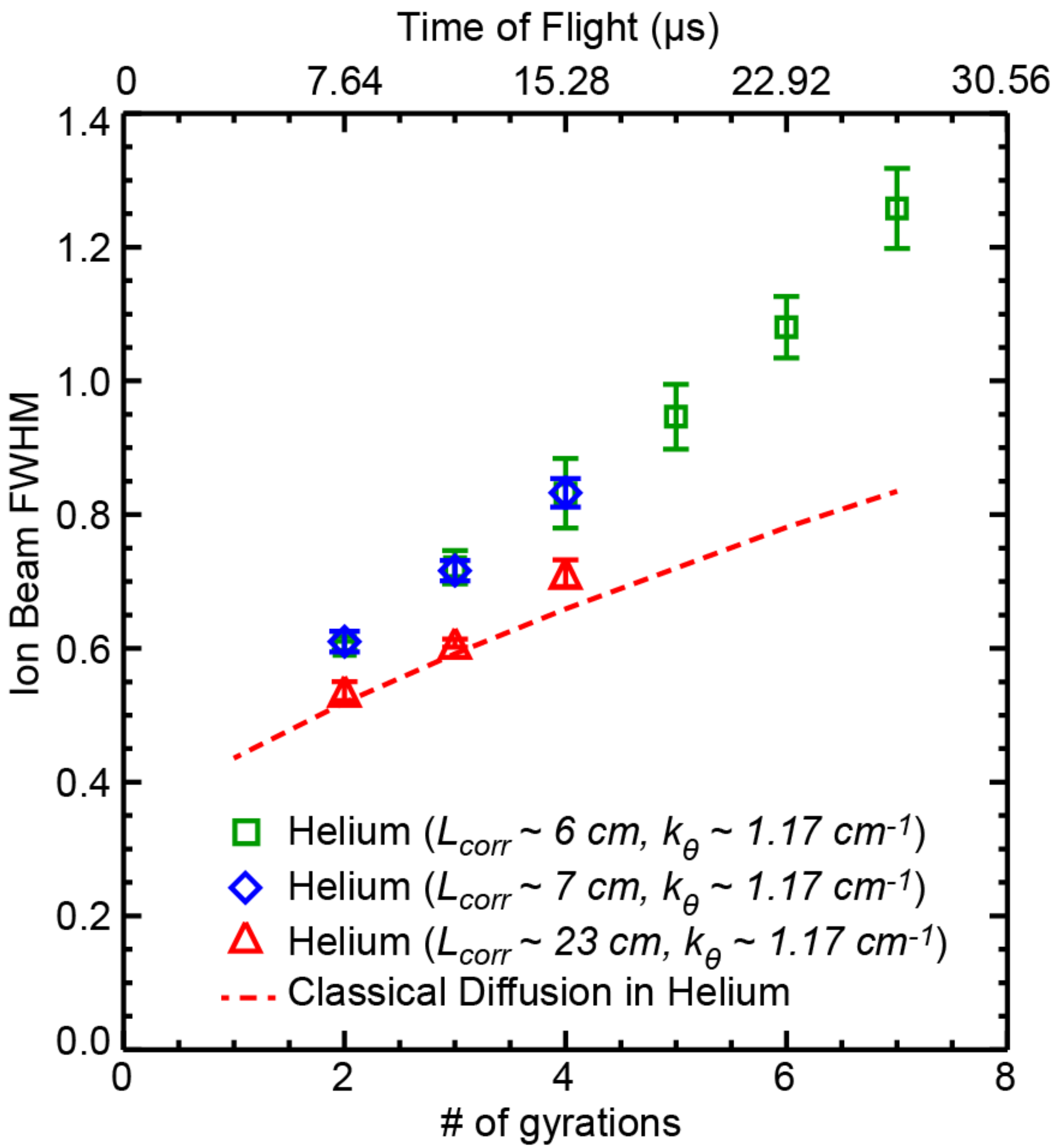
- Helium plasma (no bias on annulus @ Aug 2010)
- m = 6 ~ 8
- *Long* azimuthal correlation (L_{corr} ~ 23 cm)
- *Small* azimuthal structure size ($k_\theta = m/\rho_f \sim 1.16\ cm^{-1}$)



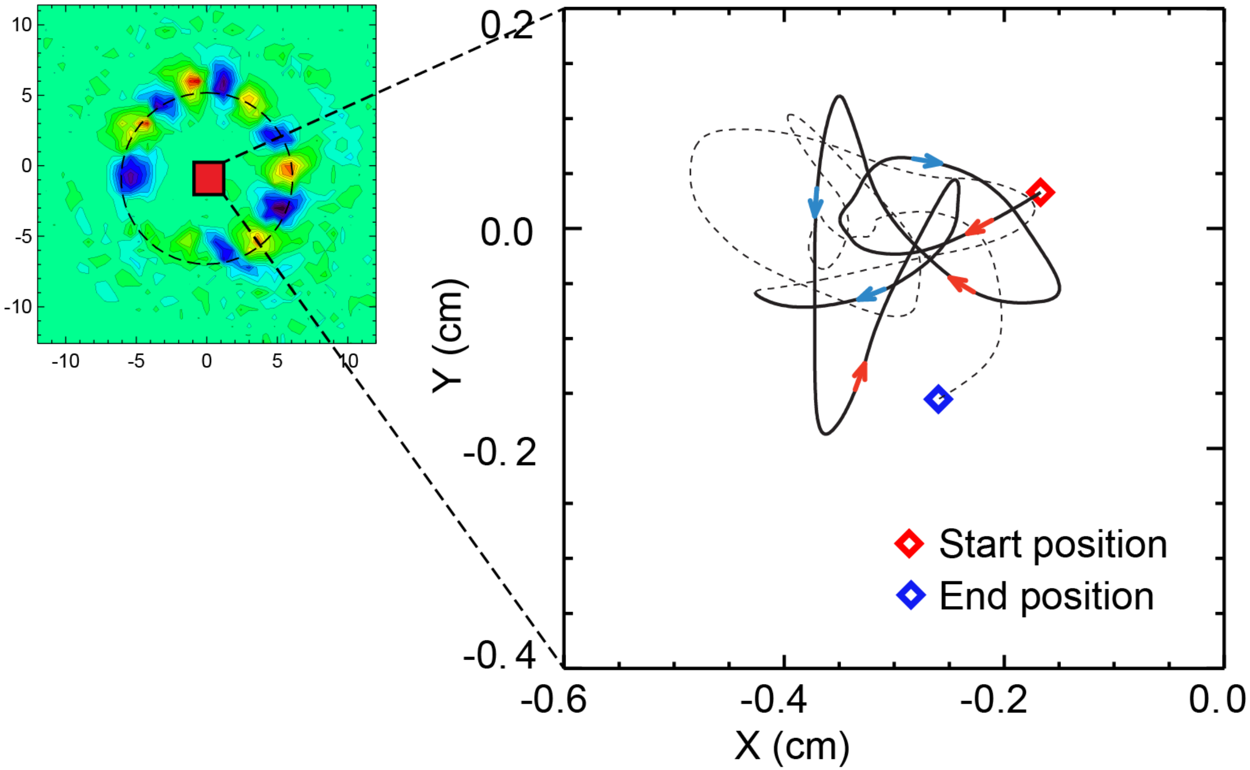


- Helium plasma (100V bias on annulus @ Aug 2010)
- broadband
- *Short* azimuthal correlation (L_{corr} ~ 6cm)
- *Small* azimuthal structure size ($k_\theta = m/\rho_f \sim 1.16\ cm^{-1}$)

Turbulent Waves Cause More Fast-Ion Diffusion Than Coherent Waves



Test Particle Gyro-Center Trajectory for Coherent Wave shows Gyroaveraging Effect

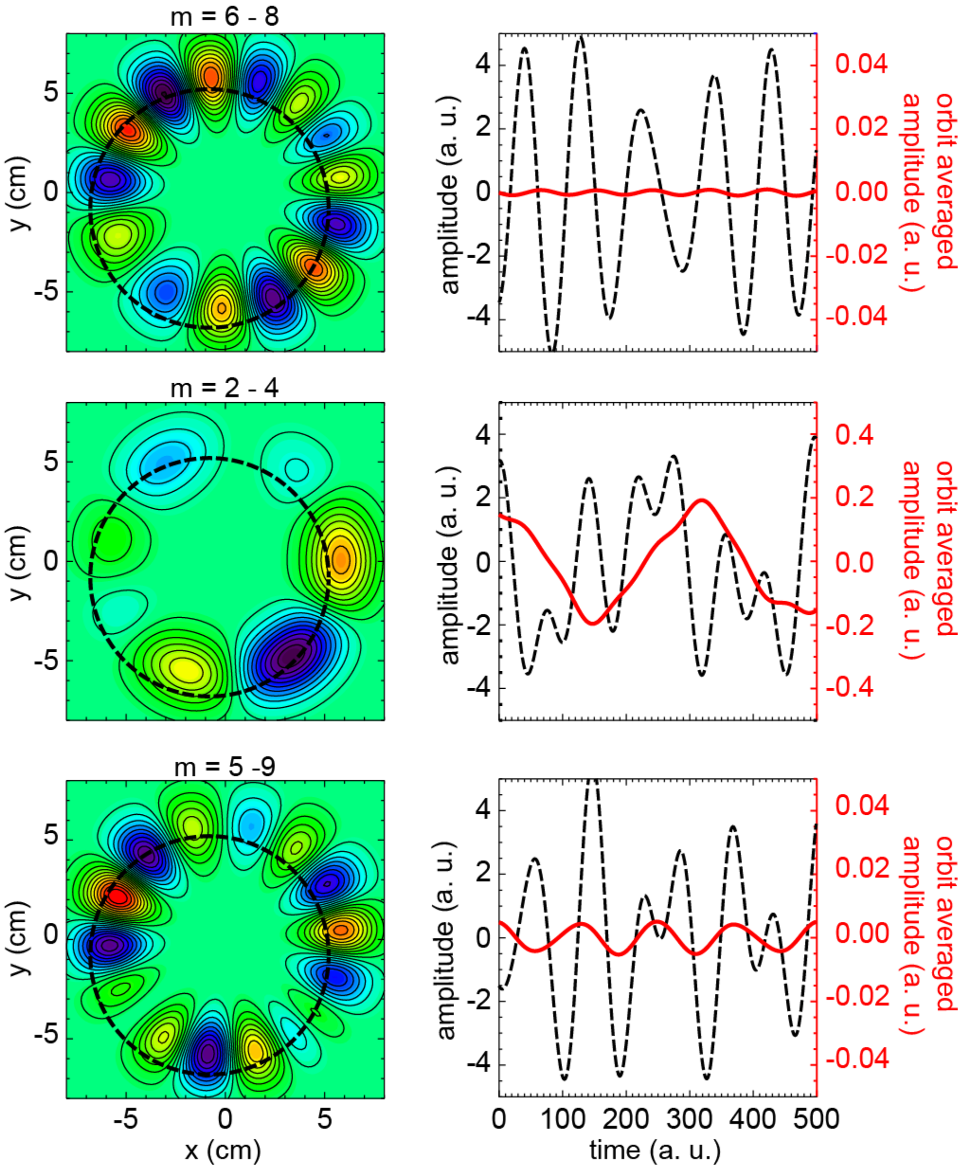


○ Gyro-Center (GC) E×B drift for each potential structure has ~0.2 cm scale

○ The E×B drifts are averaged over the whole fast-ion orbit.

○ The averaged GC drift during one orbit has a scale length of ~ 0.2cm

Transport-driving ϕ averaged over gyro orbits depends on L_{corr} and k_θ



○ Wave potential (amplitude) modeled by:

$$\phi(r,\theta,t) = \sum_m \phi_m \cdot \sin(m\theta + \omega t + \theta_0) e^{\left(-\frac{(r-r_0)^2}{a}\right)}$$

○ Gyro averaging is applied along an off-axis orbit:

$$\bar{\phi}(r,\theta) = \sum_k \phi_k e^{ik\cdot x} \cdot J_0(k\rho_f)$$

○ Gyro-averaged ϕ decreased with decreasing potential scale length

○ Gyro-averaged ϕ decreased with waves having less number of modes

Outline

- **Fast Ion Diffusion In Waves : Energy Scaling**
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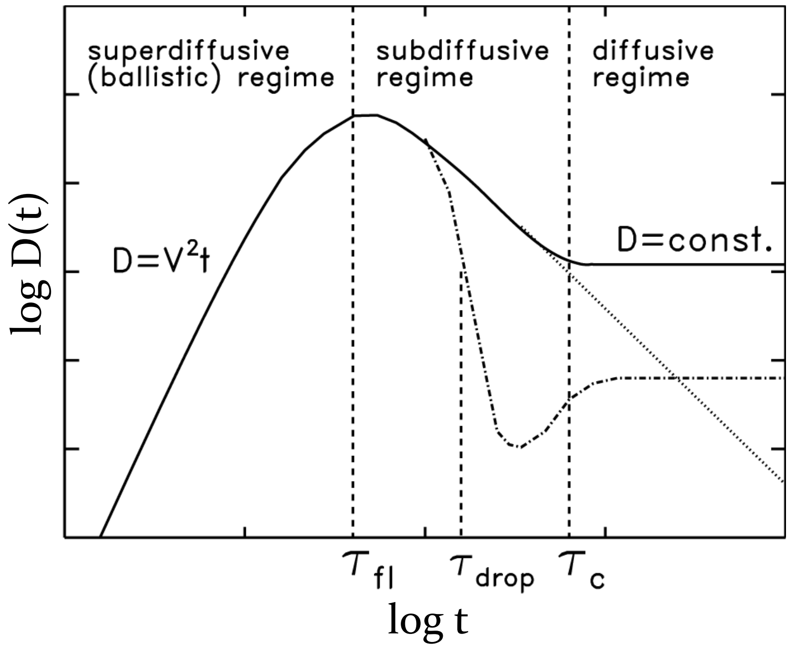
Wave-Particle Correlation Results in Super-Diffusive & Sub-Diffusive Transport

$$D(t) = \int_0^t d\tau \cdot L_{ii}(\tau),$$

$$\text{where } L_{ii}(t) = \langle v_i(0,0) v_i(x,t) \rangle = \left\langle (v_c + v_E)\big|_{(0,0)} \cdot (v_c + v_E)\big|_{(x,t)} \right\rangle$$

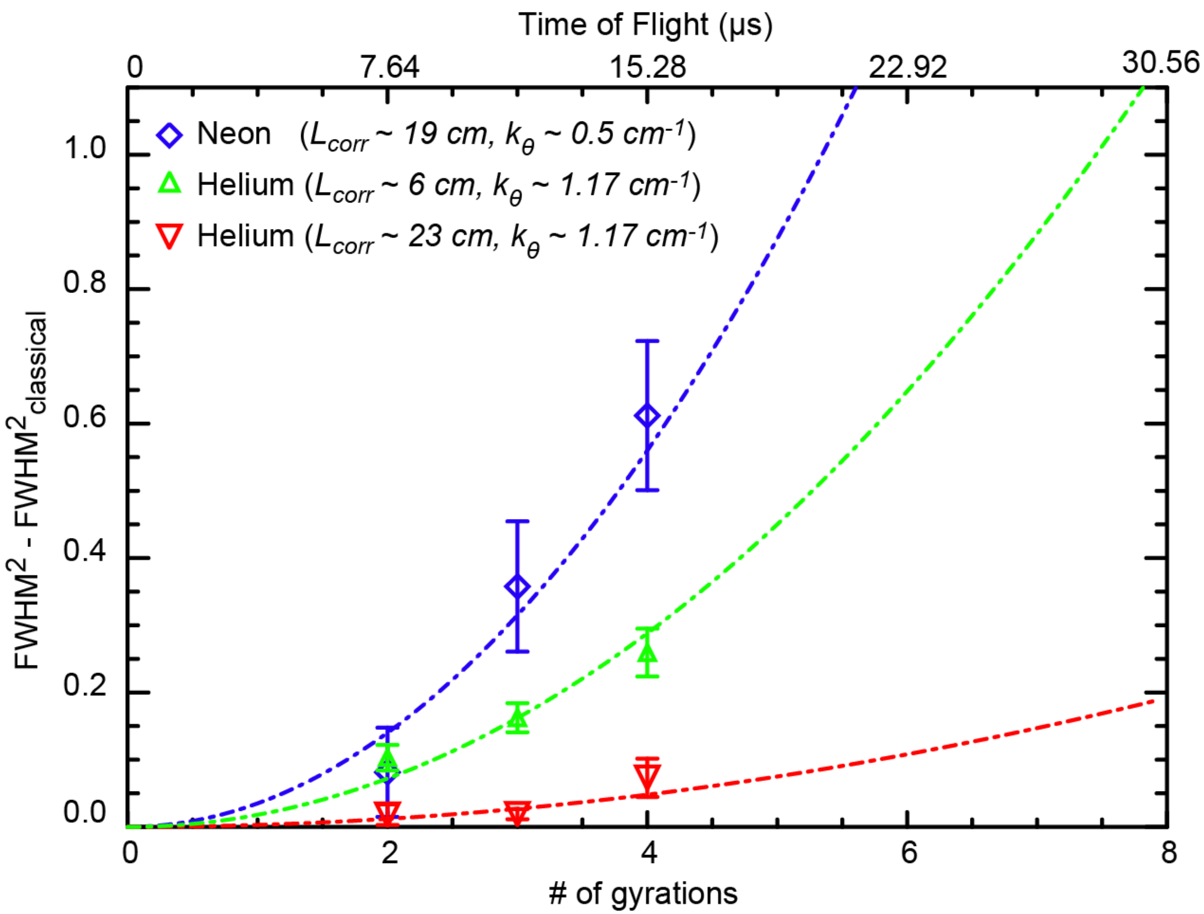
$$\cong \langle v_E(0,0) v_E(x,t) \rangle$$



T. Hauff and F. Jenko, Phys. Plasmas 15, 112307(2008)

$$\tau_{ci} < \tau_{drift} < \tau_{corr}$$

Fast Ion Radial Diffusivity in Super-Diffusive Regime is Observed



- In Super-Diffusive regime ($\tau_f << \tau_{drift}$, $D_{drift} = \alpha t$), fast ion FWHM satisfies:

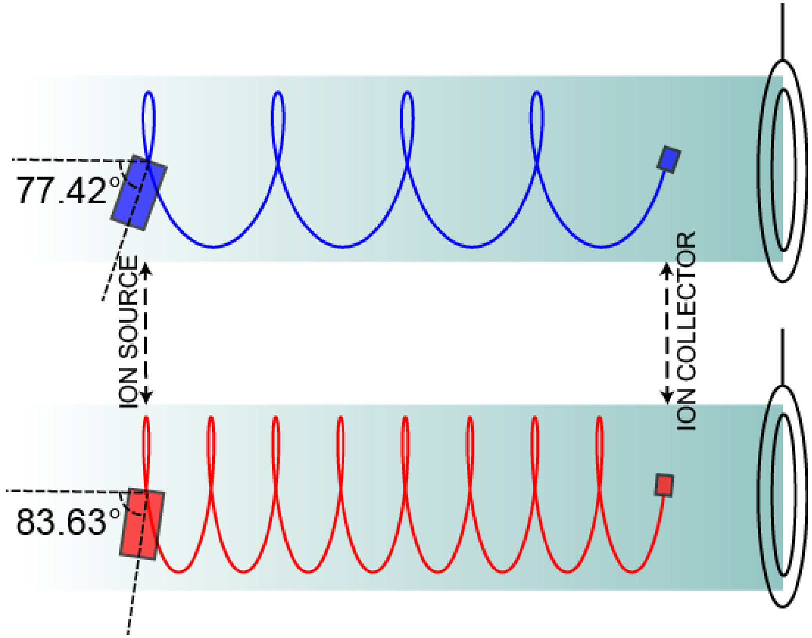
$$W_{FWHM}^2 - W_{Classical}^2$$

$$= (16 \ln 2)\,(D_{drift}\, t)$$

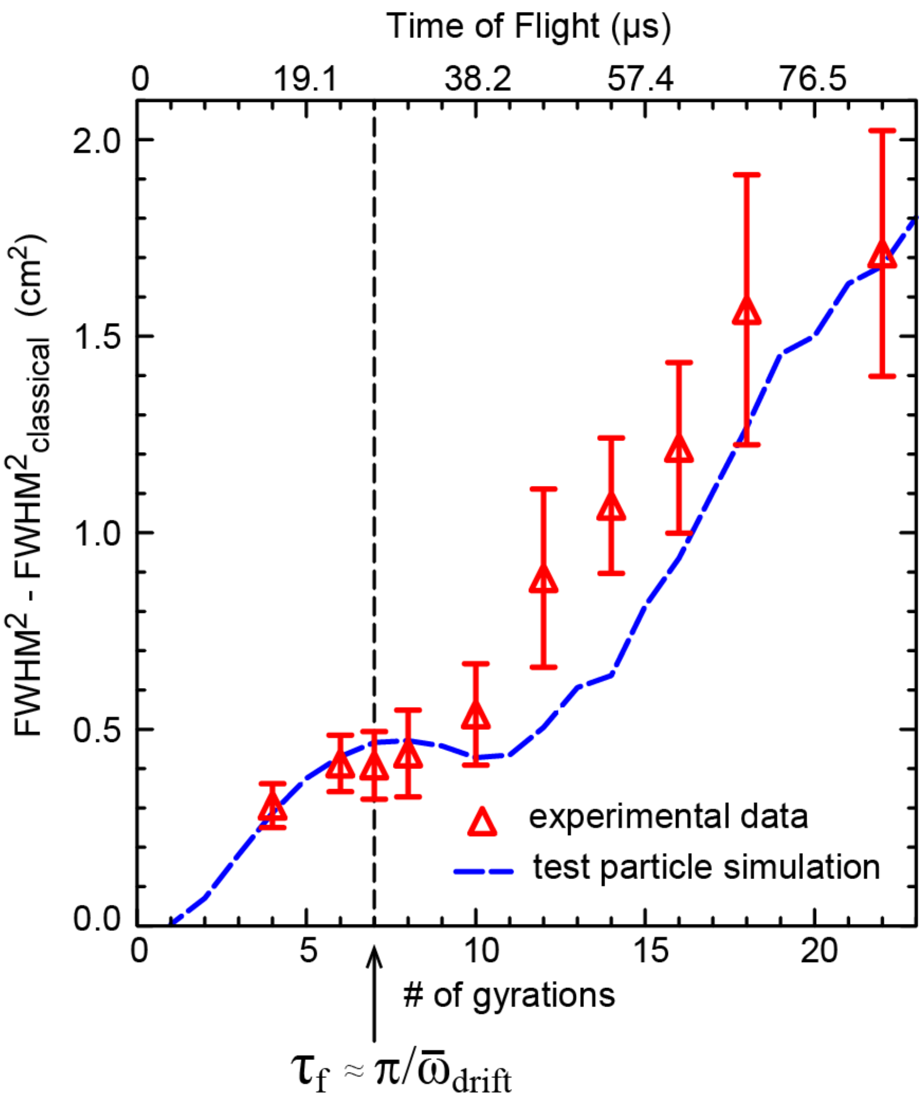
$$= 5.545 (2 \overline{V}_E^{\,2} t^2) \propto t^2$$

- $D_{drift\ waves}$ agrees with the gyro-averaging prediction

Sub-Diffusive Regime is Observed when Fast Ion Time-of-Flight Exceeds Wave Half Period



Avg # of Cyls	4	10	16	22
pitch angle (degree)	48.2	70.4	77.4	80.8
Gyro Radius (cm)	5.7	5.7	5.7	5.7
Time-of-Flight (μs)	15.3	38.2	61.1	84.0



Conclusions

<u>*In experiment with plate obstacle:*</u>

○ Fast ion transport decreased with increasing fast ion energy

S. Zhou et al., Phys. Plasmas ***17****, 092103 (2010)*

<u>*In experiment with annulus obstacle:*</u>

○ Waves with larger spatial scale size caused more fast-ion transport

○ Turbulent waves caused more fast-ion transport than coherent waves

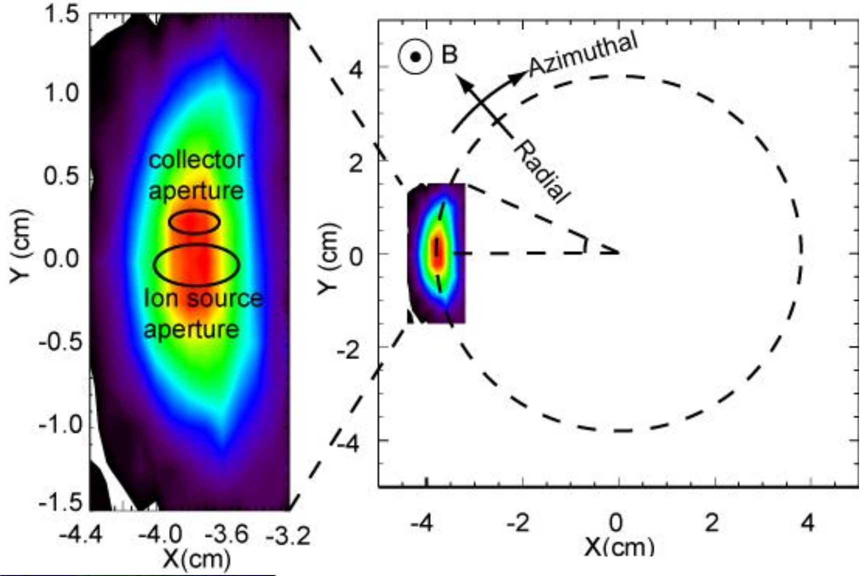
<u>*Beam diffusivity versus time*</u>

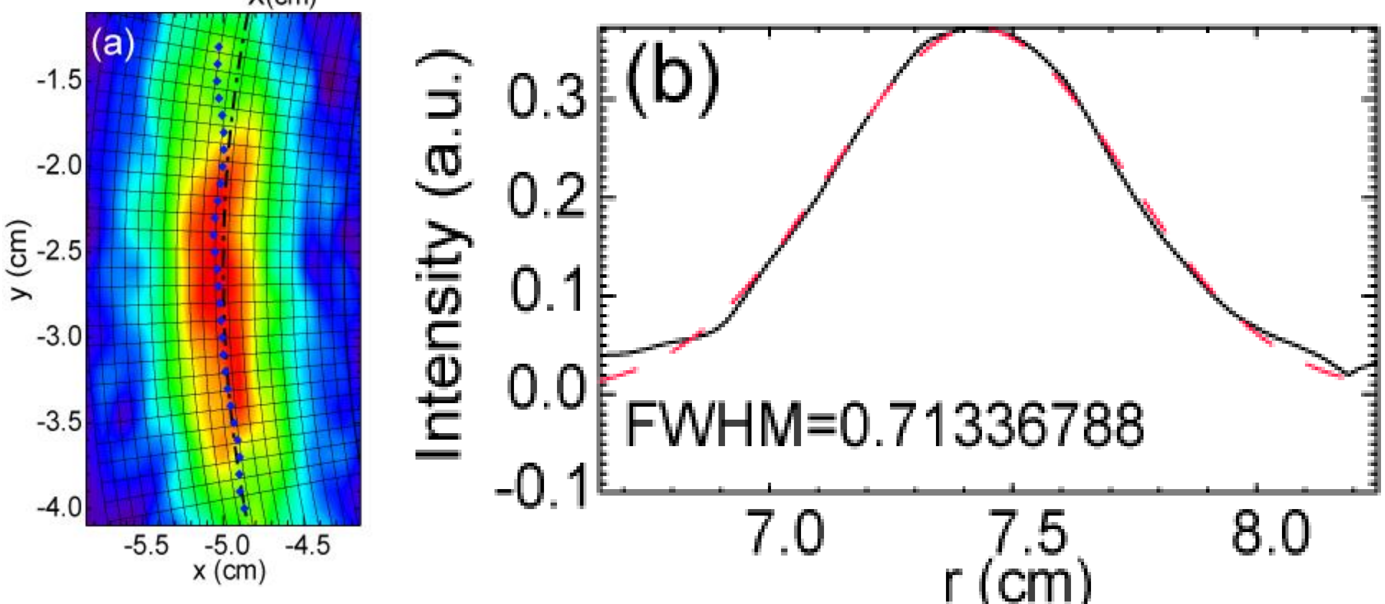
○ Transport is super-diffusive when fast ion time-of-flight << wave period

○ Transport is sub-diffusive when fast ion time-of-flight exceeds half the wave period

Backup Slides

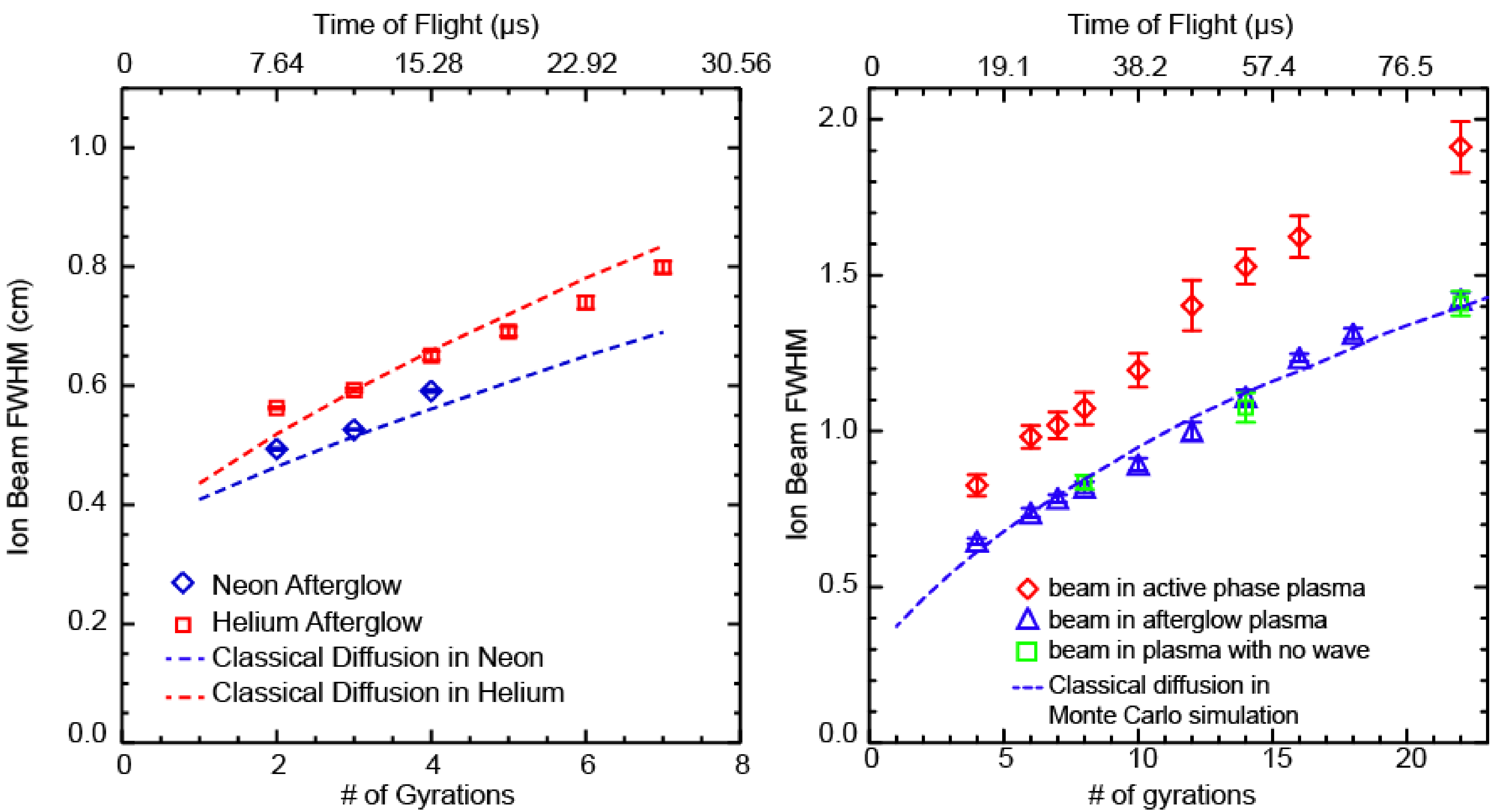
Radial Fast Ion Beam Profile is Analyzed to Determine Transport





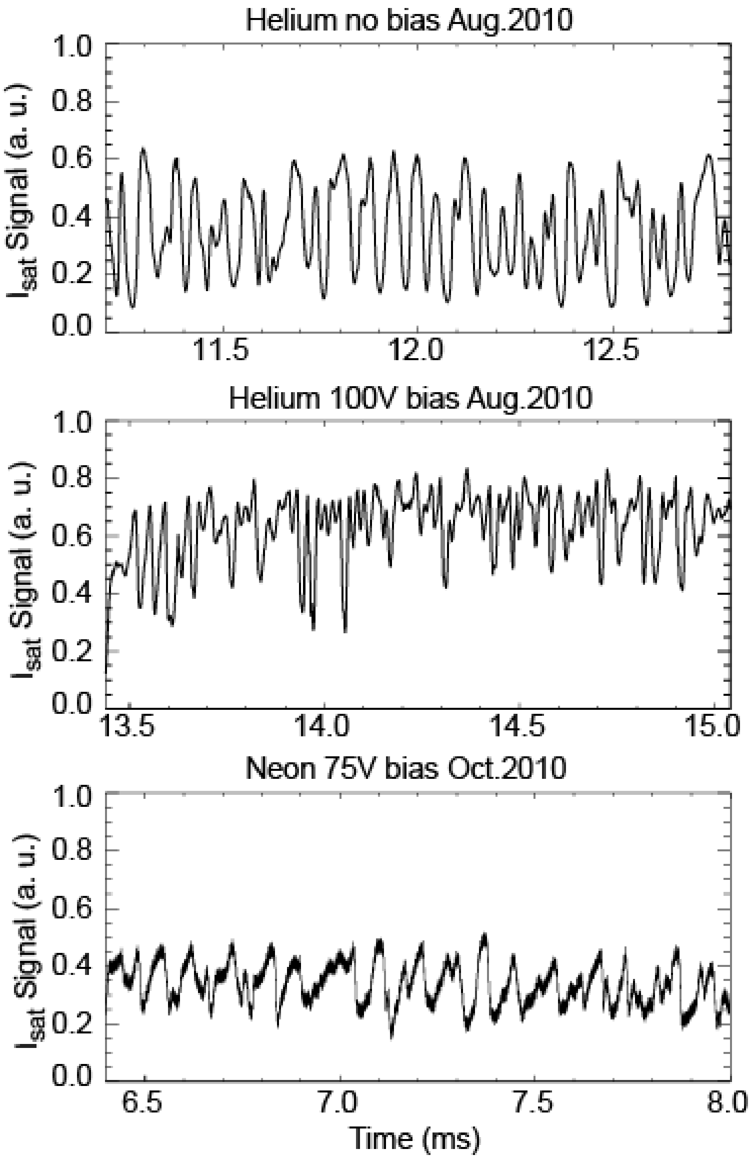
- Beam radial full-width at half-maximum indicates transport

Sub-Diffusion Regime is Observed when Fast Ion Time-of-Flight Exceeds the Wave Correlation Time

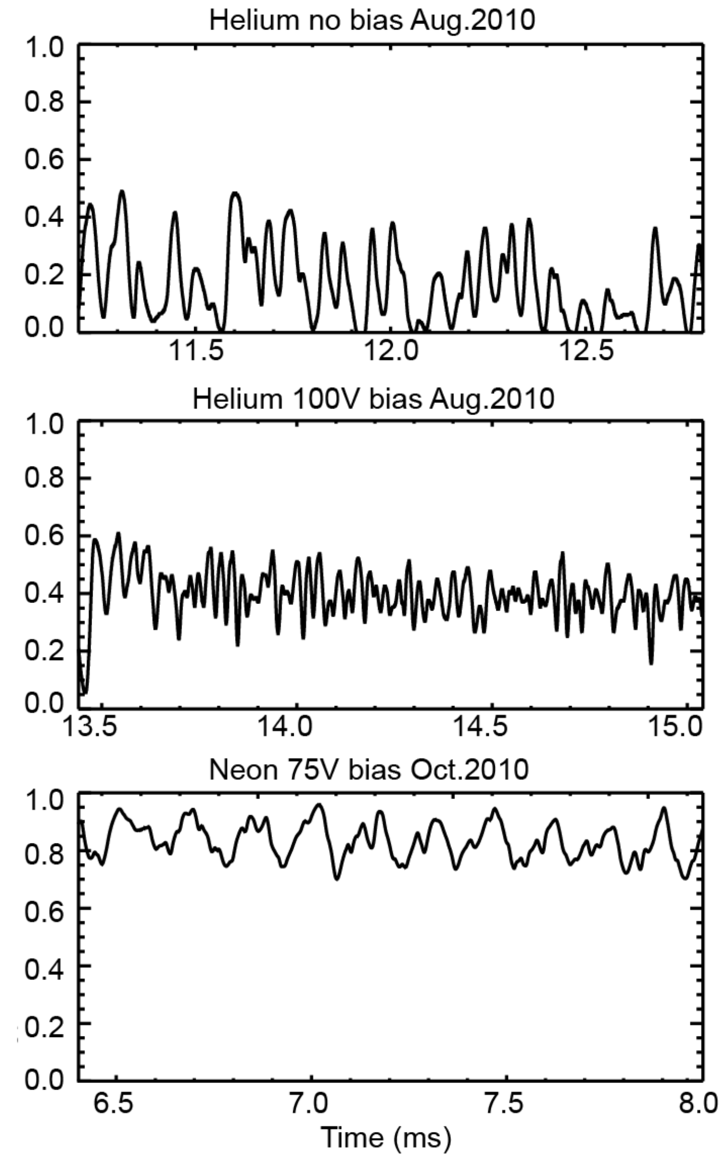


Sample I_{sat} & V_{float} Signals

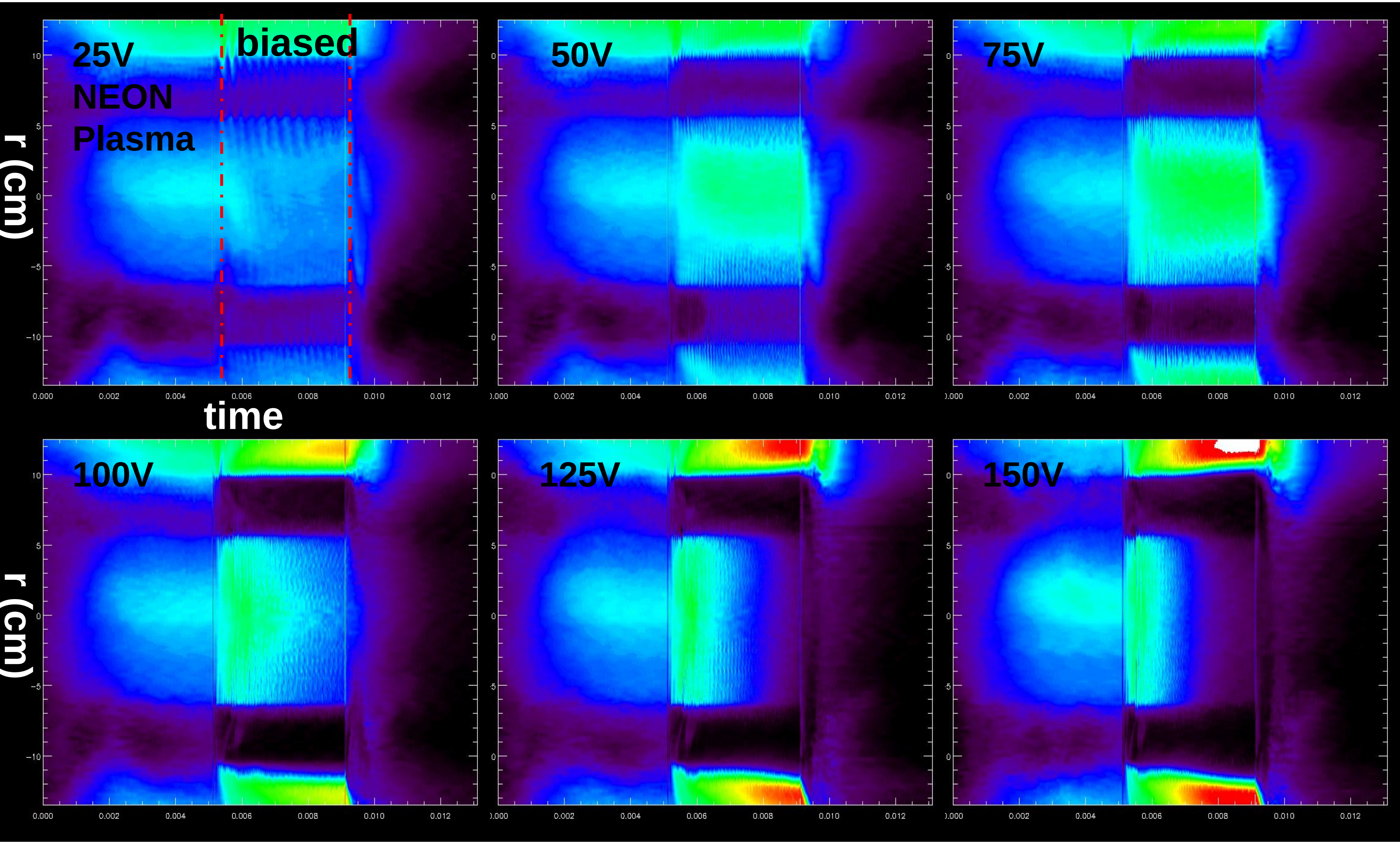
I_{sat}



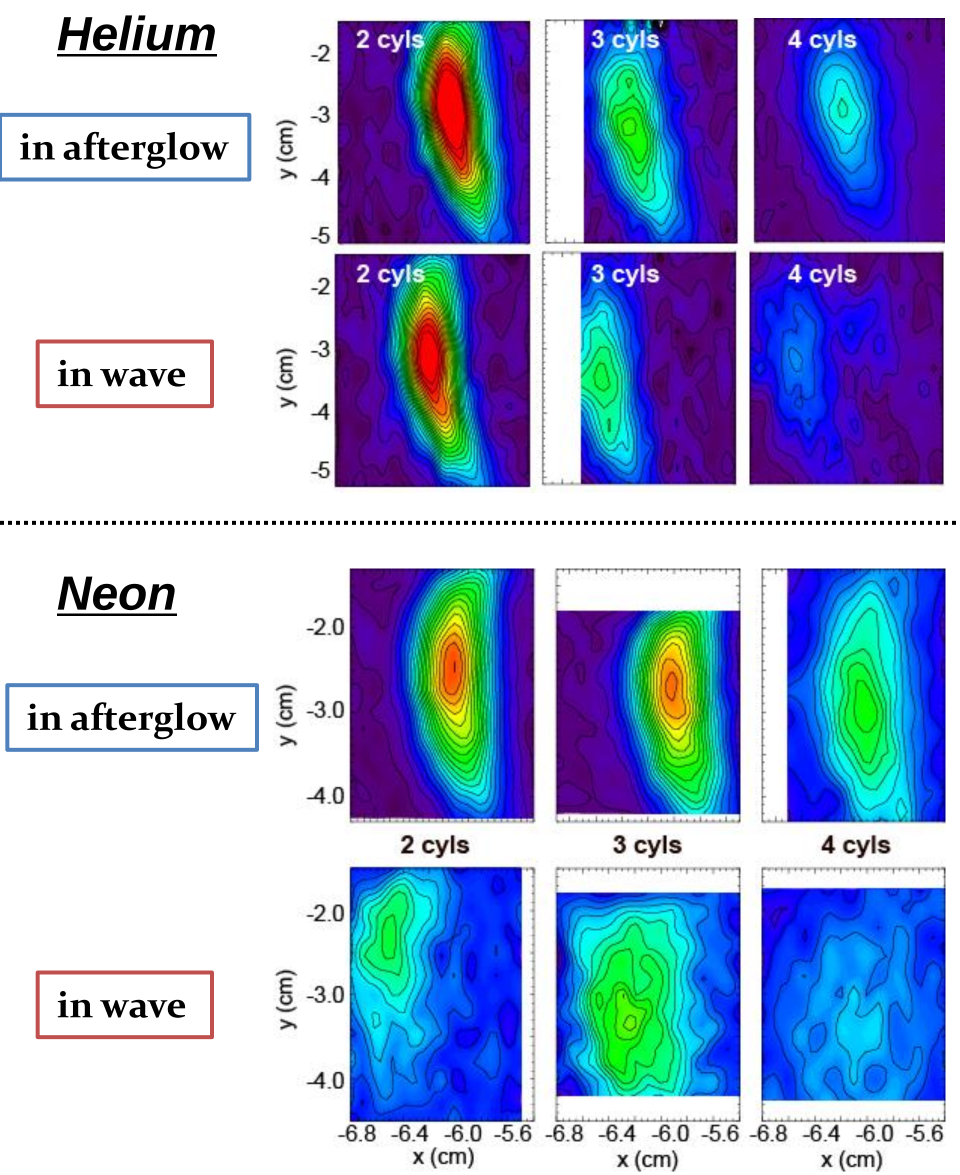
V_{float}

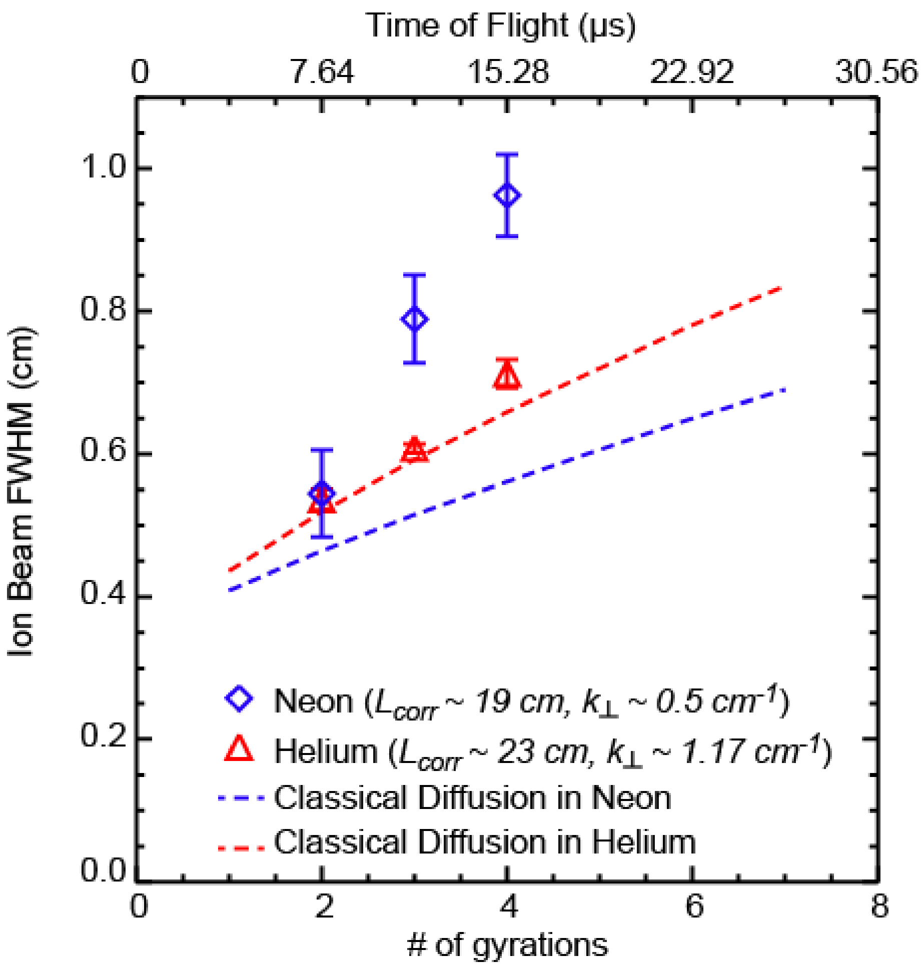


Isat Profile: Large cross field Transport Observed in several cases with large bias/small B field

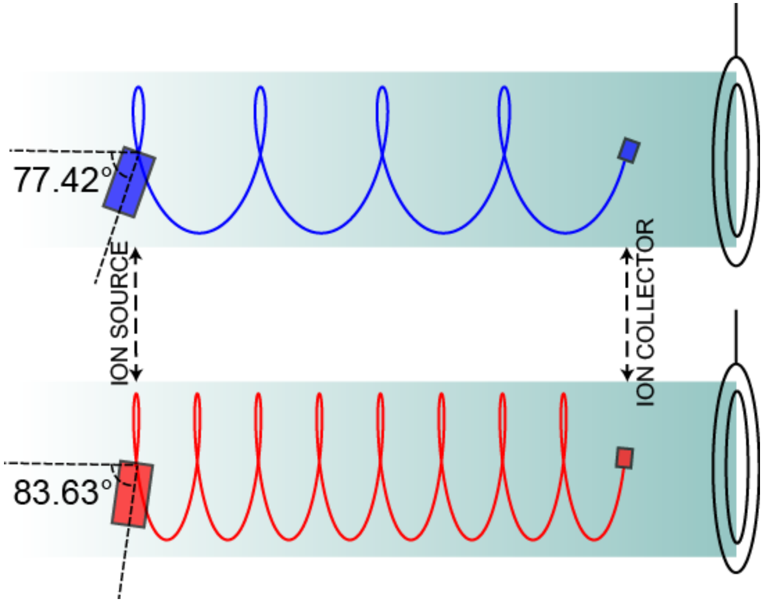


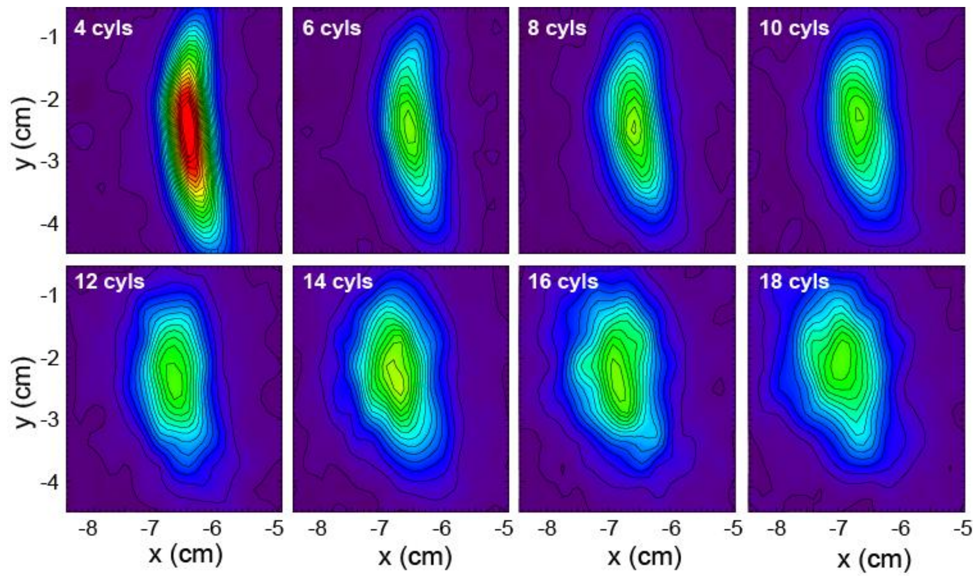
Drift Wave with Larger Scale Size Cause More Fast Ion Transport





Fast Ion Transport in Long Time Scale is Studied by Operating the Source at Various Pitch Angle





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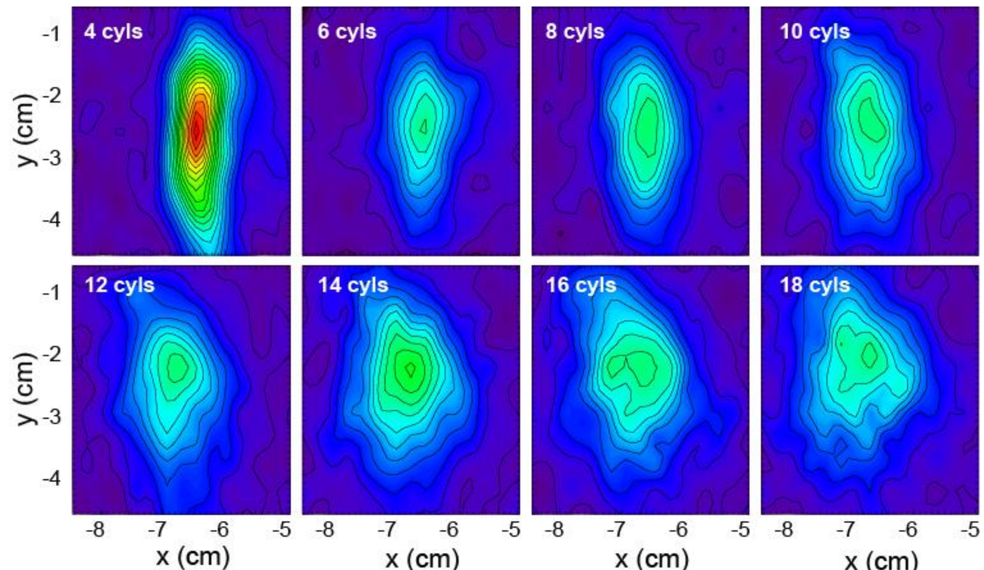

- *Wave Half Period~ 25µs*

Wave-Particle Correlation Results in Super-Diffusive & Sub-Diffusive Transport

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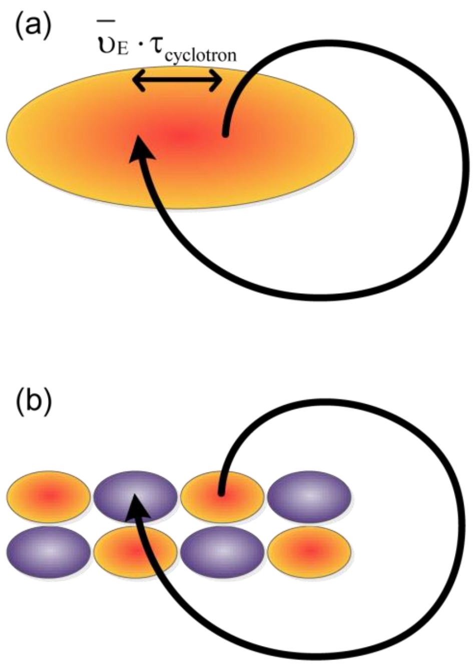
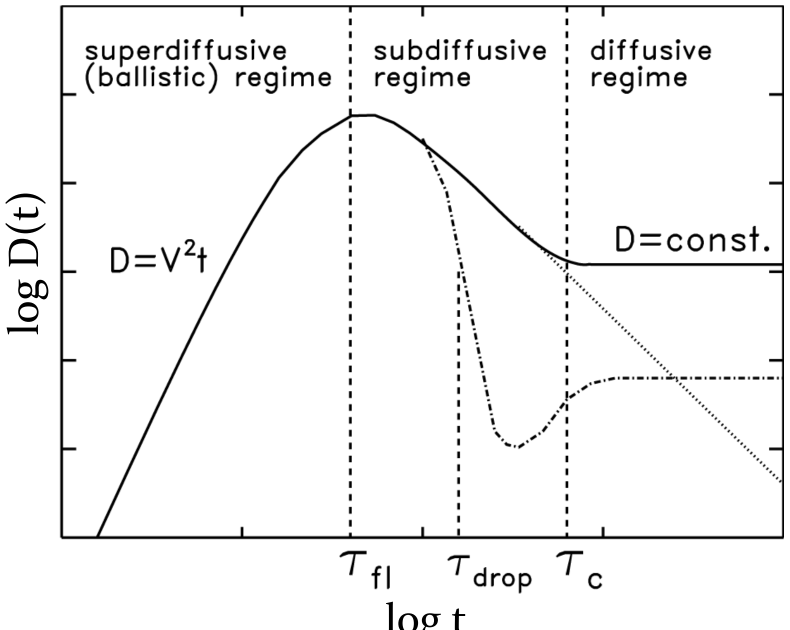
$$\text{where } L_{ii}(t) = \langle v_i(0,0) v_i(x,t) \rangle = \left\langle (v_c + v_E)\big|_{(0,0)} \cdot (v_c + v_E)\big|_{(x,t)} \right\rangle$$

$$\cong \langle v_E(0,0) v_E(x,t) \rangle$$



- *leads to* ***non-diffusive*** *transport*

- *leads to* ***diffusive*** *transport*

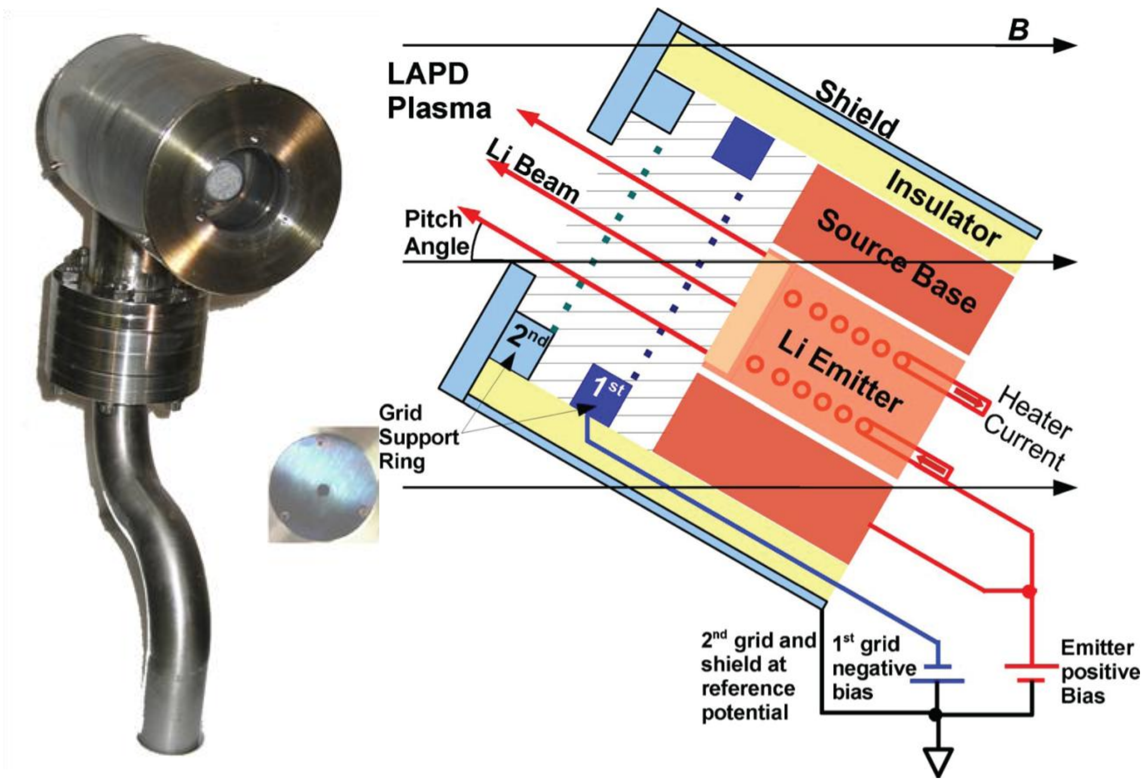


T. Hauff and F. Jenko, Phys. Plasmas 15, 112307(2008)

$$\bar{v}_E \cdot \tau_{ci} << L_{corr}$$

$$\tau_{ci} < \tau_{drift} < \tau_{corr}$$

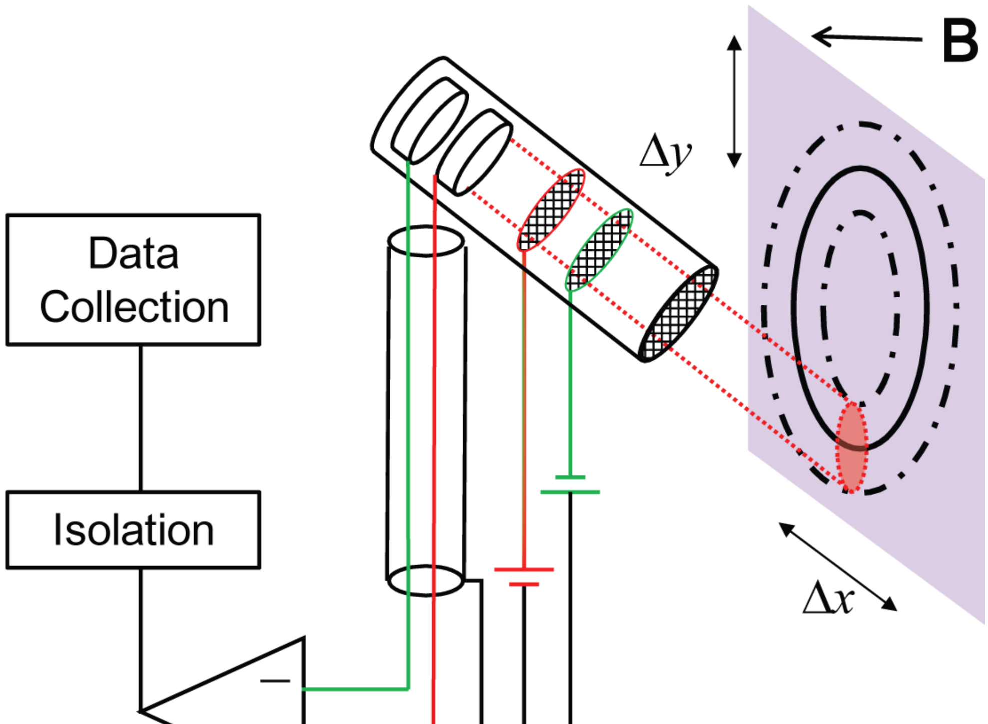
Lithium Ion Source Developed by UC Irvine Fast-ion Group

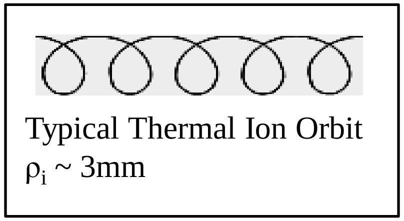


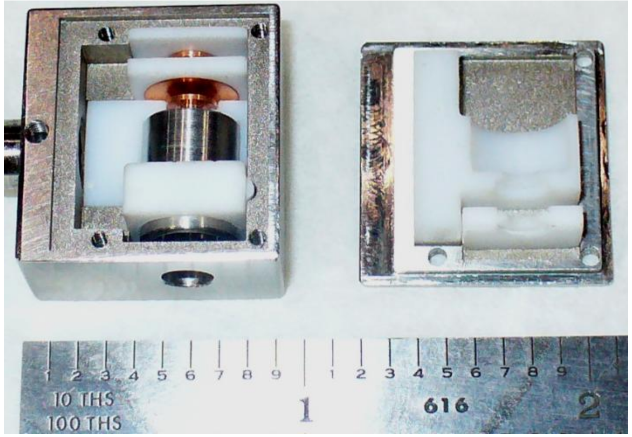
- Alkali ion emitter is heated to ~1200 K for Li^7 ion emission.
- Double grids form a accelerate - decelerate configuration
- Emitter is biased to 400V ~ 1000V to control the energy of the Li^7 ion beam
- Front aperture controls the Li^7 beam initial width
- Typical beam current density ~ 300 μA/cm^2, initial width ~ 5mm

H. Boehmer, et al, Rev. Sci. Instrum. , Vol. 75, 1013 (2002)
G. Plyushchev, et al, Rev. Sci. Instrum. 77, 10F503 (2006)
Y. Zhang, et al, Rev. Sci. Instrum. , Vol. 78, 013302 (2007)

Collimated Fast Ion Collector measures wave-modulated Fast Ion Signal







- Ion Collector can be rotated to match the pitch angle of the beam
- Negatively biased (-9V) 1st grid and Positively biased (+46V) 2nd grid effectively repel thermal electrons and ions
- The collimation design of the collector avoid thermal particle collection geometrically
- The collector has an acceptance angle of ~ 15 degree.

Advantages & Limitations of Current Experimental Setup

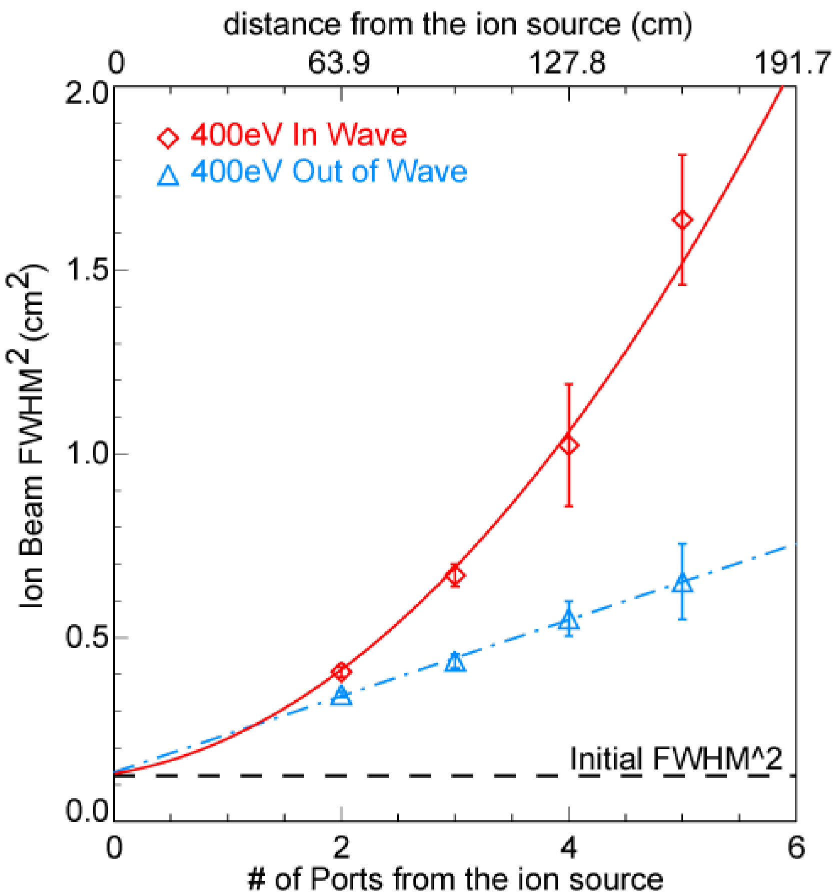
Advantages:

- Probe accessible, high density plasma environment
- Good visualizing ability, 2D probe drive with ~1mm radial resolution
- Tunable drift wave instability by density and temperature gradient
- similar scale of dimensionless parameters related to Tokamak: $\frac{E}{T_{i,e}}, \frac{\delta n}{n}, \frac{\tau_c}{\tau_f}$

Limitations:

- Wave-particle interaction time is limited by source-collector distance (< 2 meter)
- Small Fast-ion beam signal (~ 10nA), signal/noise drop with beam diffusion.
- Fast-ion orbit has only gyro averaging, no drift orbit averaging

Wave - Particle Correlation Results in Non-Diffusive (Ballistic) Transport



- Classical diffusion:

$$D_{cl} = \text{const}$$

$$W_{FWHM}^2 = 8\ln 2[\langle(\Delta r_0)^2\rangle + 2D_{cl}t]$$

- Turbulent wave induced diffusion:

$$D_{dr}(t) = \overline{\upsilon_E}^2 t$$

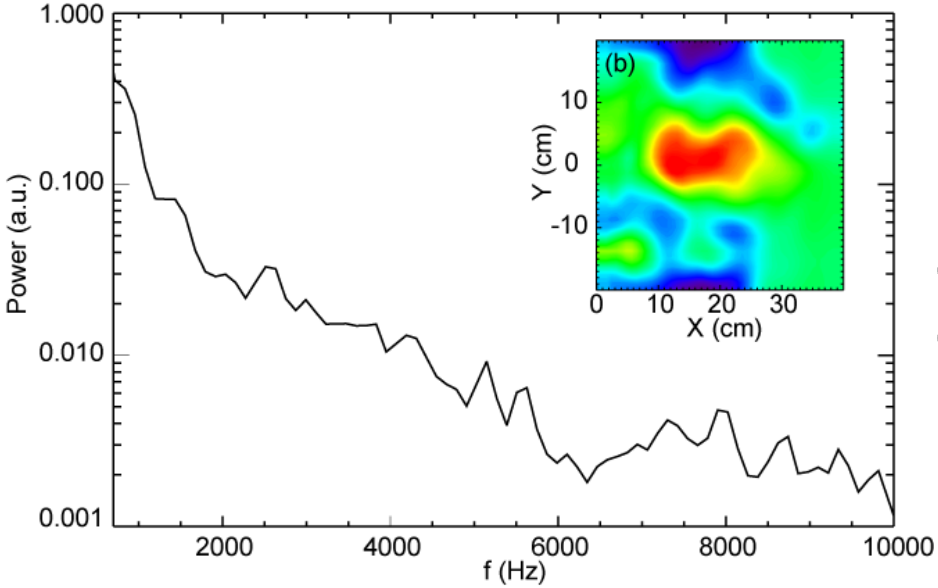
$$W_{FWHM}^2 = 8\ln 2[\langle(\Delta r_0)^2\rangle + 2(D_{cl} + D_{dr})t]$$

$$= 5.545[\langle(\Delta r_0)^2\rangle + 2D_{cl}t + 2\overline{\upsilon_E}^2 t^2]$$

- Observed spreading in wave combines *classical diffusion* and *ballistic transport*

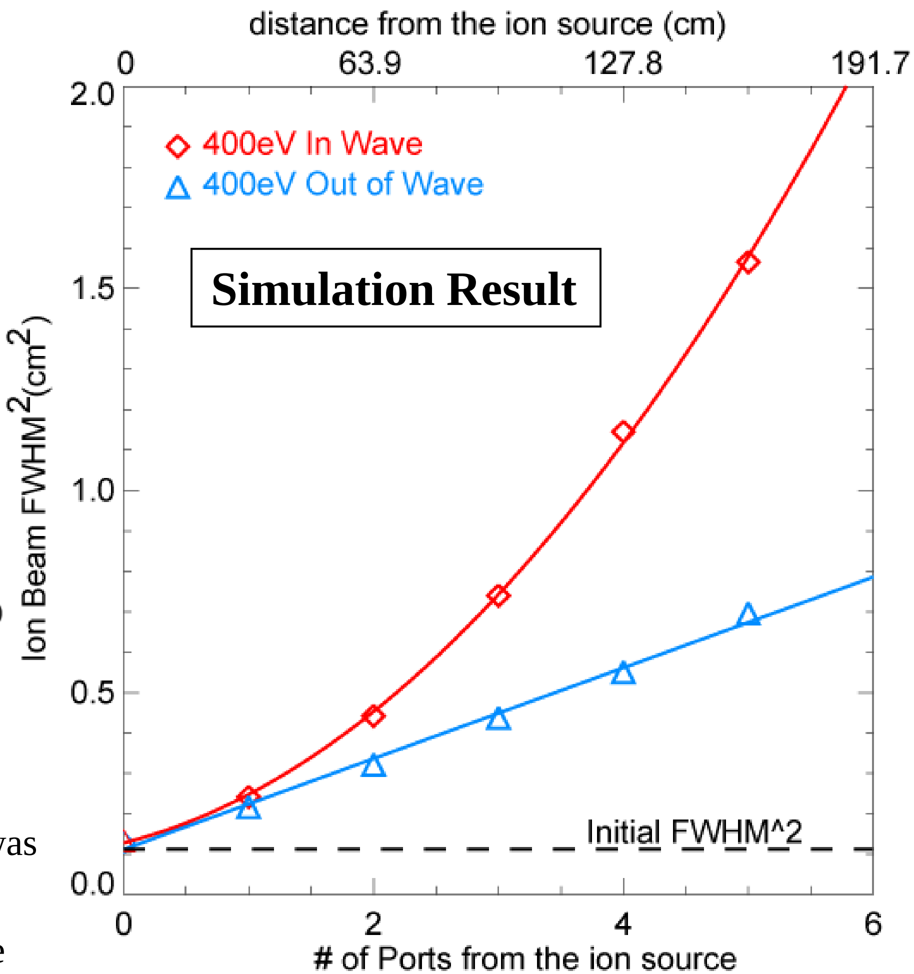
- Analytical model is well fitted into observed data

Monte Carlo Test-Particle Simulation in a BOUT Simulated Wave Field confirms the Analytical Model



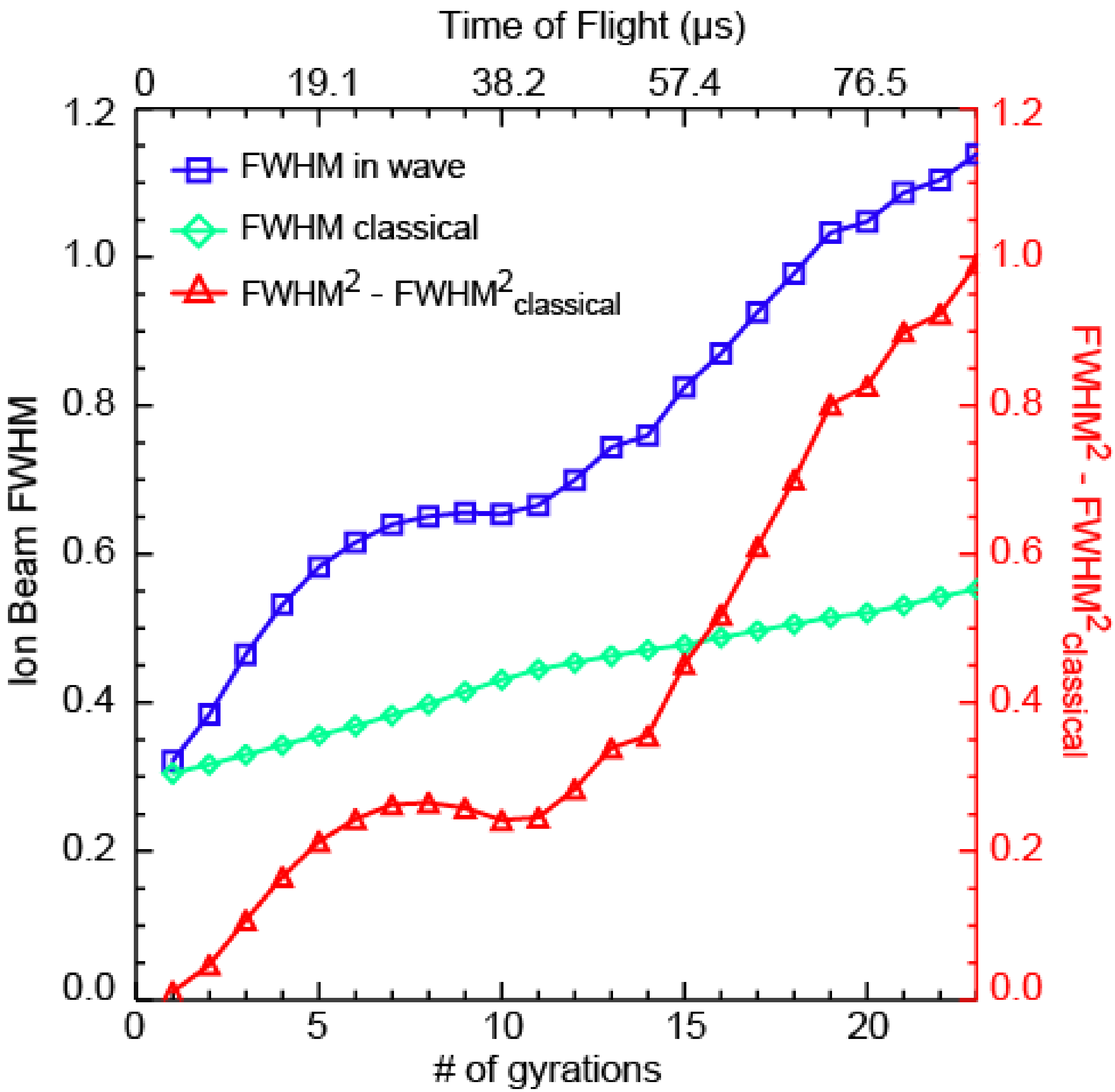
The characteristics of drift wave turbulence simulated by the BOUT code. (a) Fluctuation power spectrum. (b) Cross correlation of the potential fluctuation.

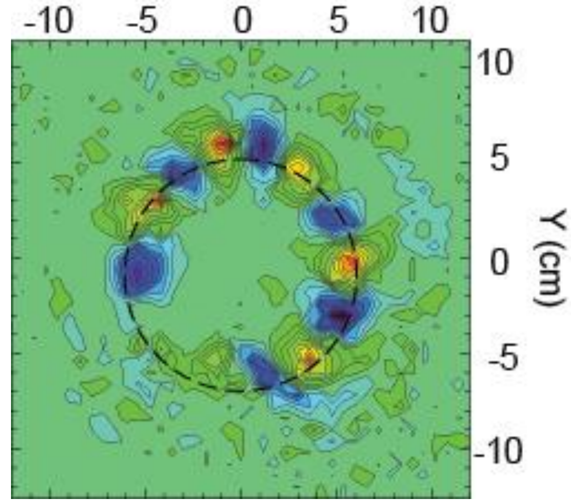
- A shallower gradient than the actual experimental profile was used in the simulations.
- The wave electric field is derived from the potential profile
- The amplitude of the field is multiplied by a factor to match the experimental measurement.



- Simulated beam FWHM has the same scaling as experimental results

Test Particle Simulation in Experimental Wave Field Shows Consistent Sub-Diffusion Effect





○ Experimentally measured wave pattern by 2-point correlation scan is used to model the background wave potential.

○ Fast ion transport simulated by a test particle beam in such wave field shows very similar sub-diffusion effect when τ_f exceeds (T_{drift} / 2)