Suprathermal ion transport theory and experiments in the simple magnetized torus

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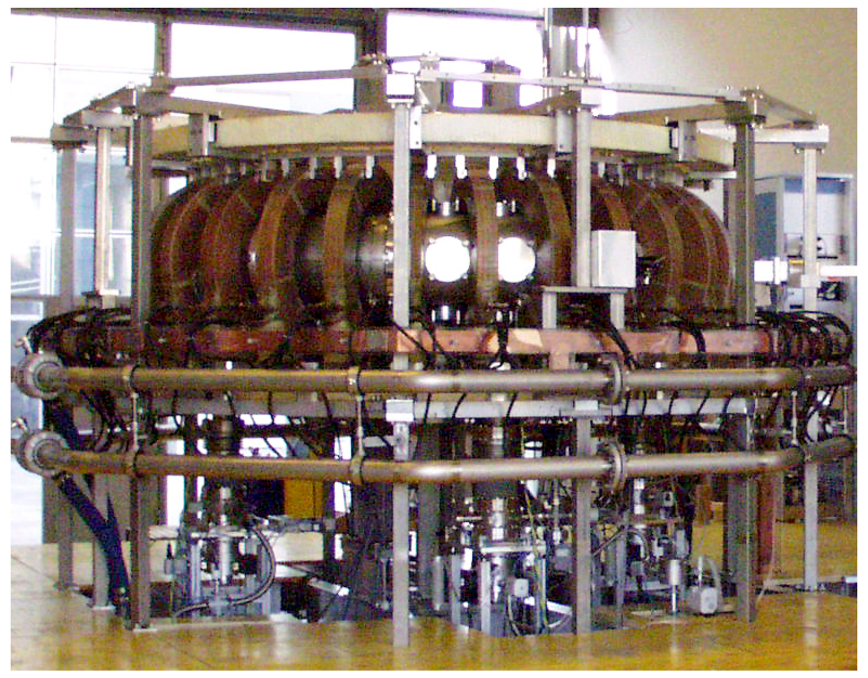
Motivation

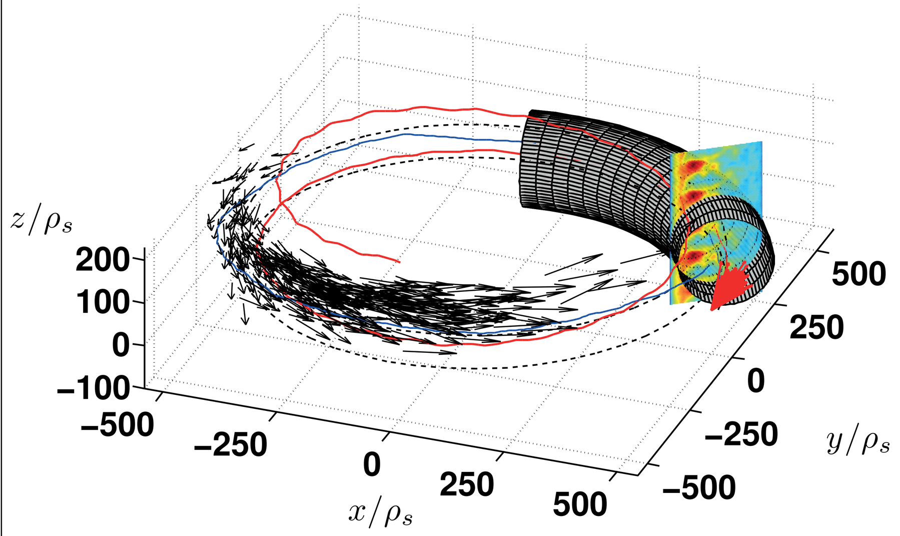


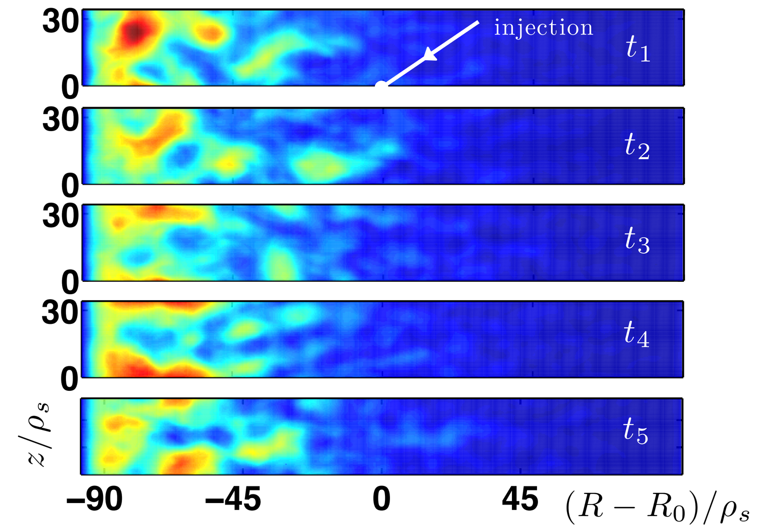
Suprathermal ions are created or introduced in both laboratory and astrophysical plasmas.

Their dynamics are influenced by electromagnetic fields, with interesting consequences.

An excellent testbed for careful theory-experiment comparisons of fundamental suprathermal ion behavior is the simple magnetized torus (SMT), of which TORPEX (see left) is a prime example.

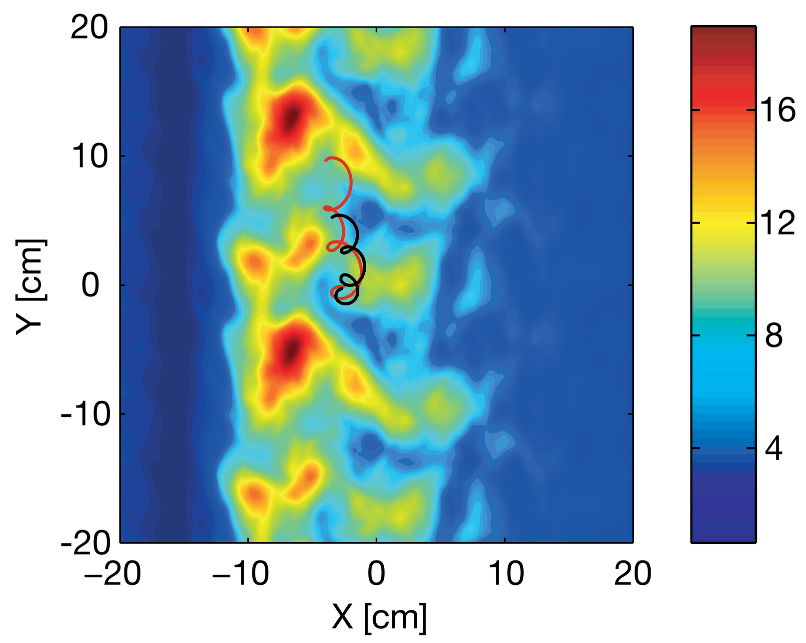
Simulating suprathermal ions in turbulence

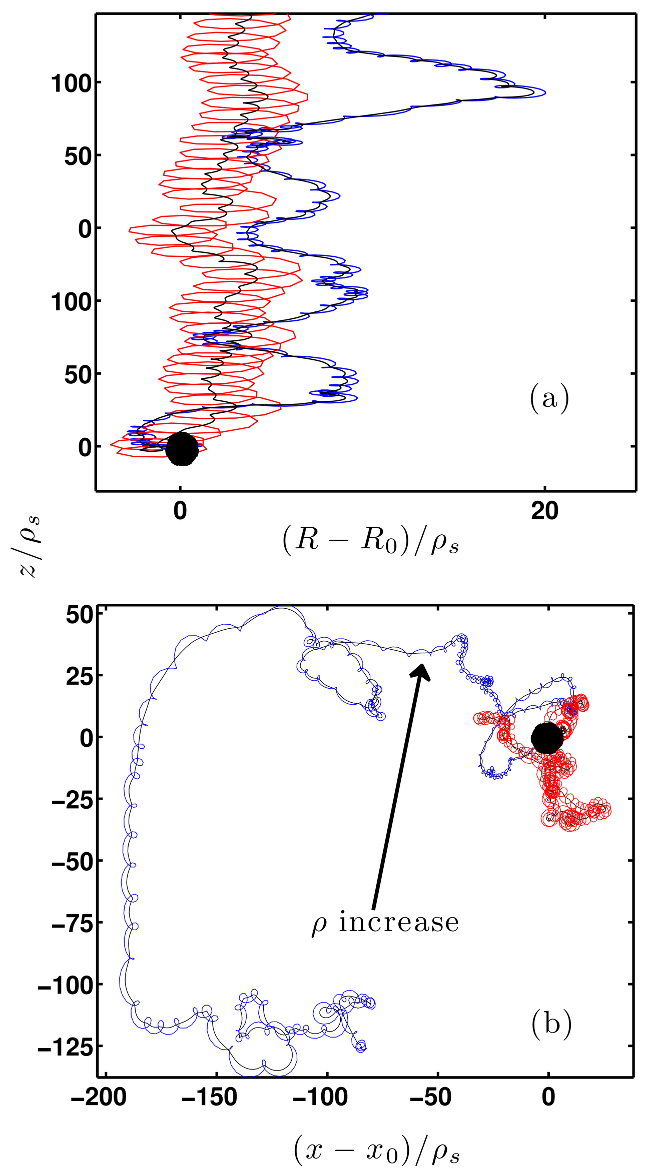




The TORPEX plasma (see above) is well-characterized by drift-reduced Braginskii simulations, which have been validated on experimental data.

Suprathermal ions are injected (see top right) as tracer particles influenced by the time-dependent turbulent electric field and the static helical magnetic field. Tracer ion motion can be approximated by ExB + gradB + curvature drifts and gyromotion (see right). Ion injection is designed to mimic the physical source of Li^{6+}.

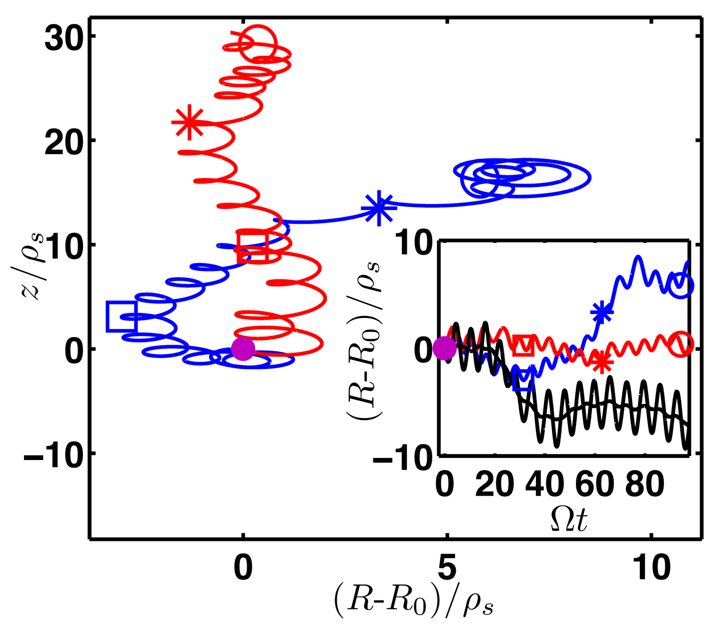




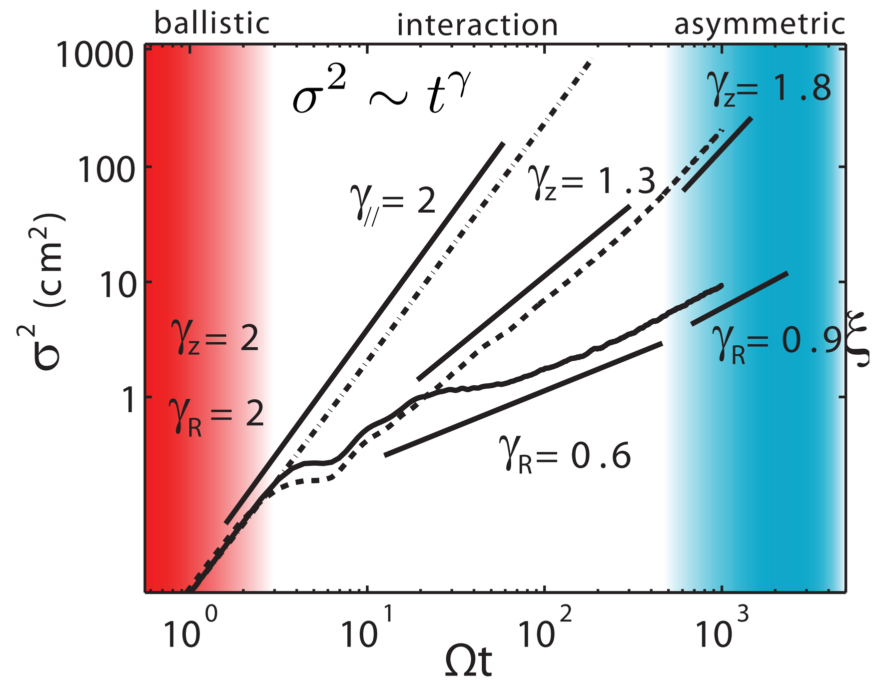
Tracer trajectories are solved with converged numerical methods using no drift or gyroaveraging approximations (shown for slab and SMT at left).

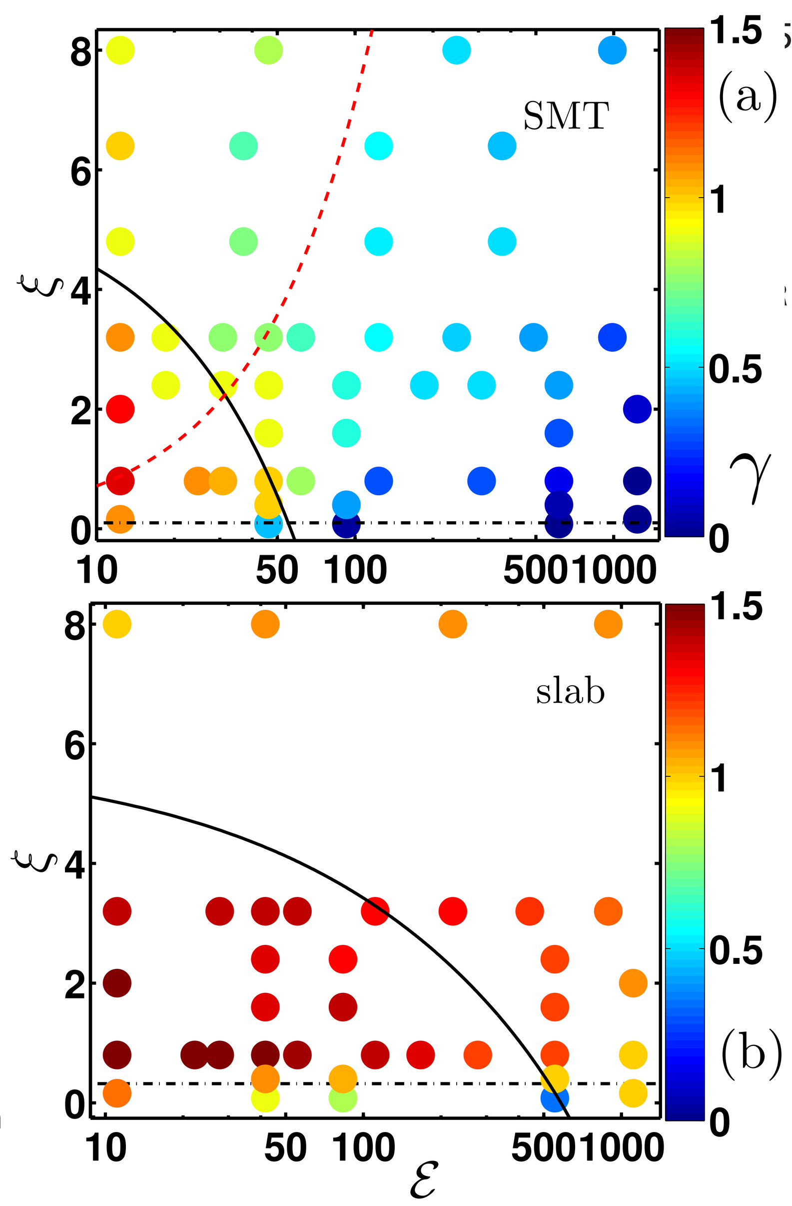
This technique reveals ion energization events due to sharp gradients in the electric potential in the frame of the ion motion.

These impulsive energization events tend to increase the Larmor radius of ions (shown left and below).



Parameter scan reveals nondiffusive transport



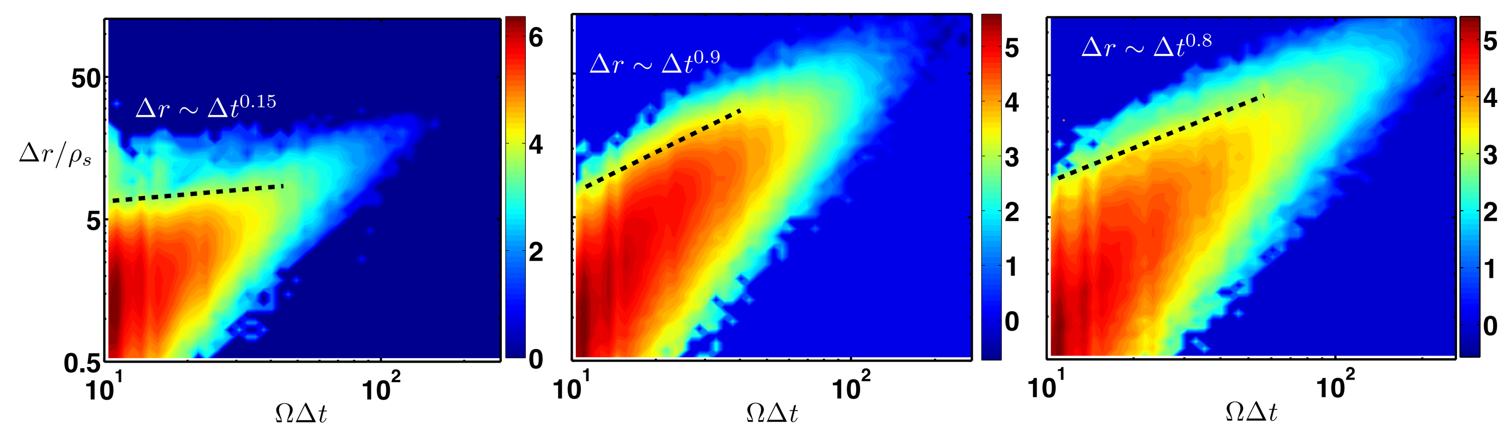


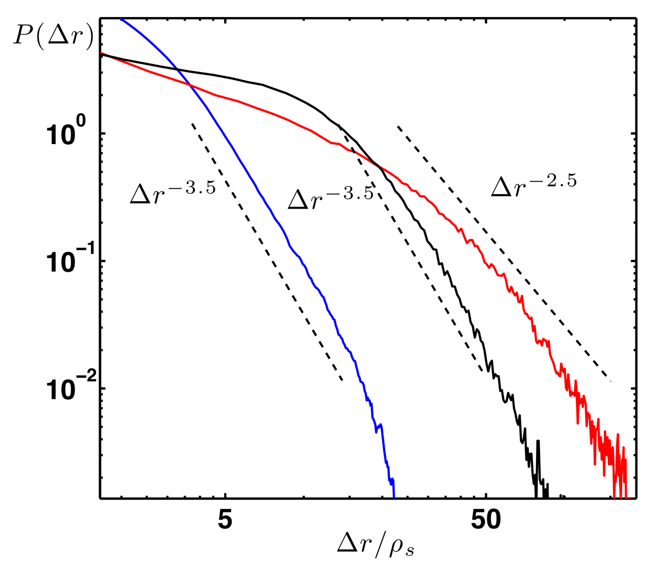
Suprathermal ion dispersion begins with a ballistic phase, followed by a turbulence-interaction phase with a steady value of γ, then an asymmetric phase manifests as the ions spread to the full cross-section (see above).

Varying the ion injection energy $\mathcal{E}$ and the intensity of the turbulent fluctuations in the electric field ξ, we demarcated a parameter range with several regimes for the interaction value of γ: superdiffusive, diffusive and subdiffusive (see right).

These regimes depend on the three ion drift terms, with a contrast apparent for a "slab" or non-curved field line approximation (see right). The slab behavior is due only to gyroaveraging. Disconnected topologies in low amplitude turbulence also lead to subdiffusion.

Lévy walks





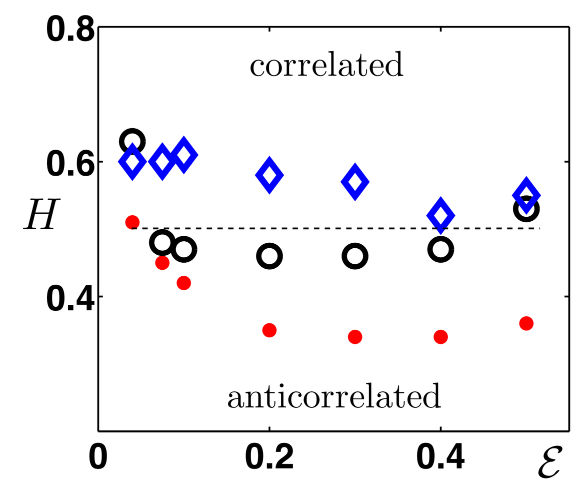
Using the distribution of "step sizes" (see left) and relationship to "waiting times," (see above) the analytic Lévy walk description of Klafter, Blumen and Shlesinger (1987) is found to be consistent with the suprathermal ion behavior (see Table below).

	γ_{SMT}	μ_{SMT}	ν_{SMT}	γ_{KBS}	γ_{RT}	γ_{AT}
superdiffusive	1.4	2.5	0.8	1.4	1.3	1.4
diffusive	1.0	3.5	0.9	1.0	1.0	1.0
subdiffusive	0.3	3.5	0.15	0.4	0.4	0.5

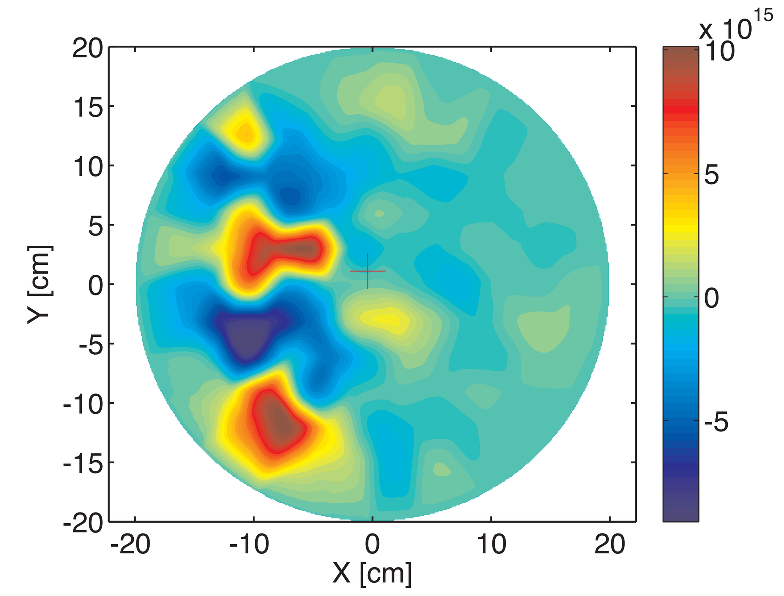
Hurst exponents from tracer velocity time series

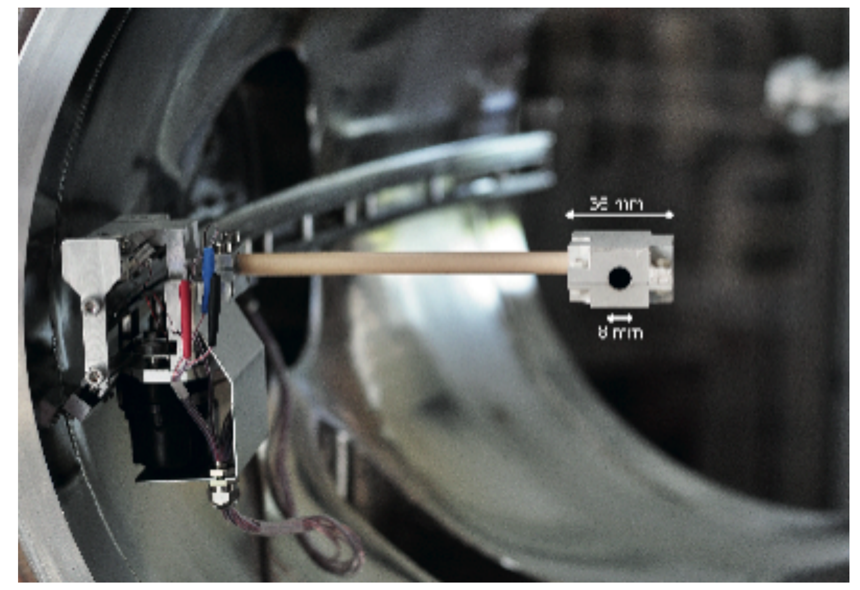
Hurst exponents, H, for different injection energies,(keV), computed with the structure function (SF) for the slab (blue diamonds) and with SF for TORPEX (red dots) and R/S for TORPEX (black circles), at intermediate-time lags (see right).

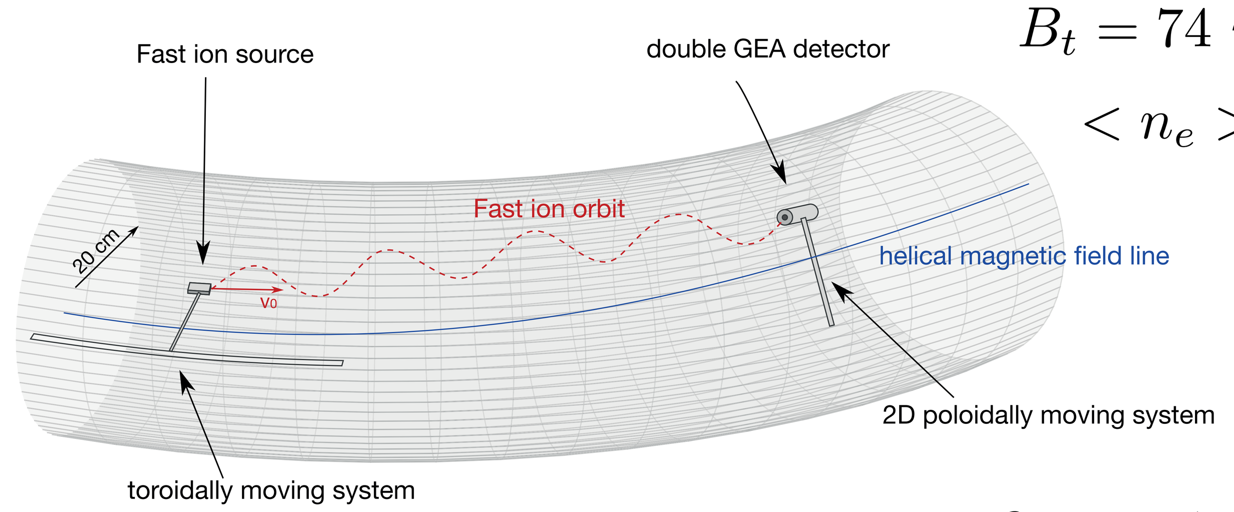
The structure function confirms anti-correlated trajectories for TORPEX at larger $\mathcal{E}$ and correlated trajectories for the slab at small $\mathcal{E}$, consistent with the appearance of subdiffusion and superdiffusion in γ. The R/S diagnostic is unable to distinguish the anticorrelated trajectories for the TORPEX cases.



Experimental setup and results



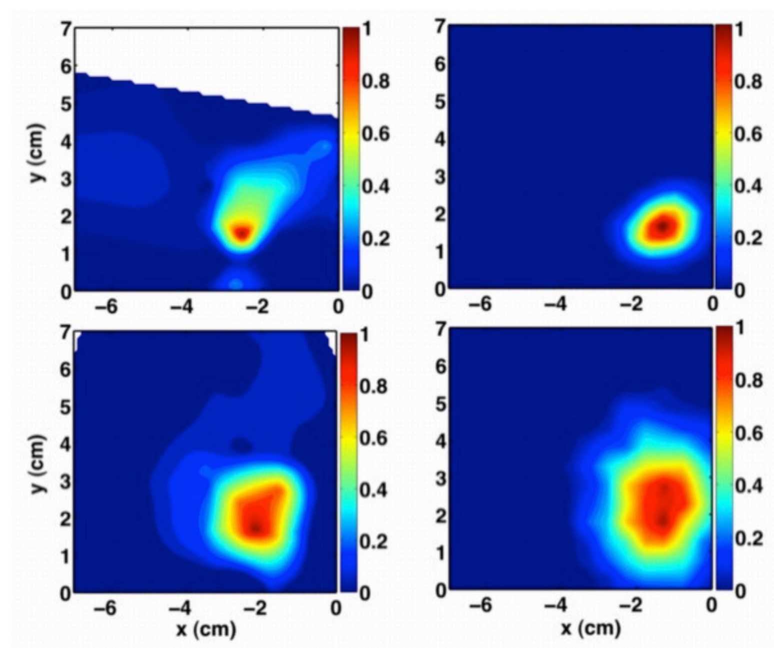




$B_t = 74\ mT; B_v = 2\ mT$

$< n_e > \sim 5 \times 10^{15} m^{-3}$

$\mathcal{E} \sim 40; \xi \sim 0.6\ at\ 40cm$

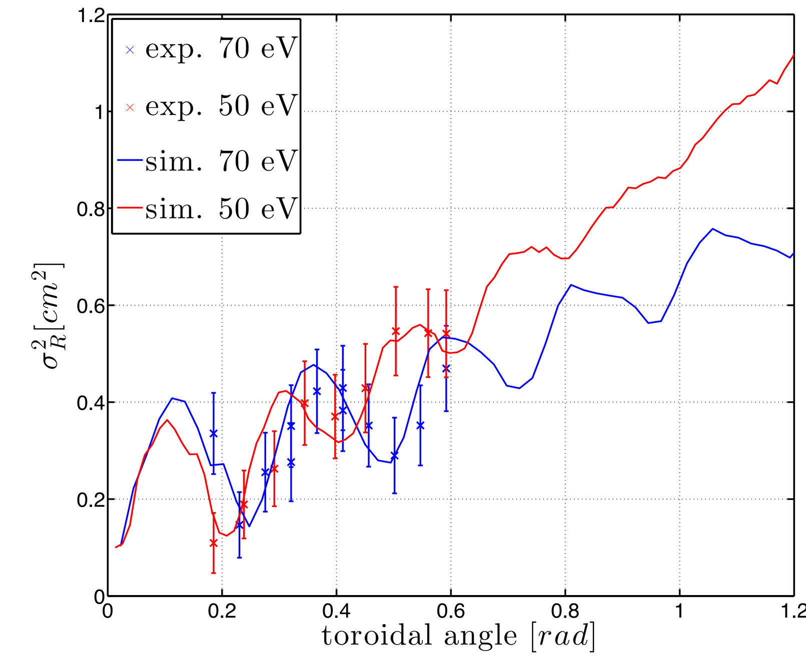


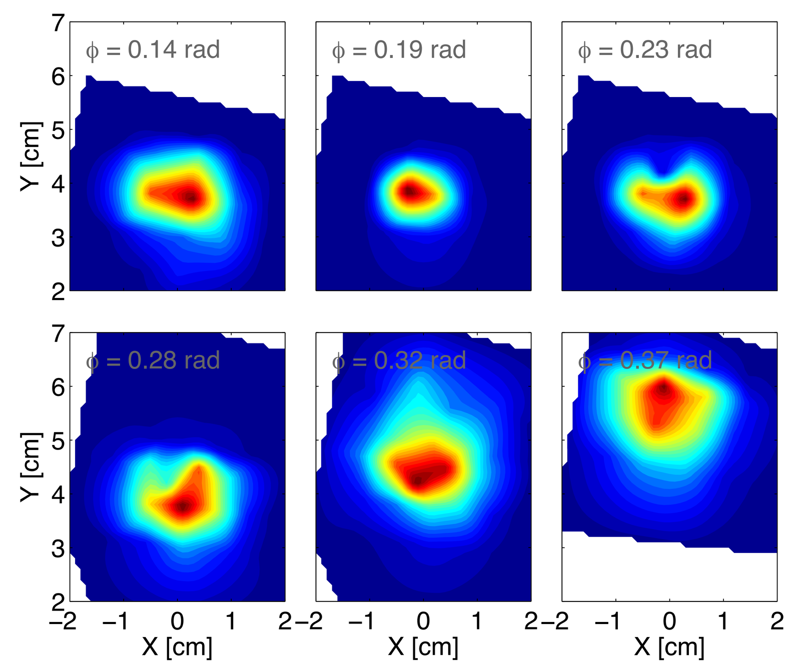
Suprathermal ion source and detector are moveable in 3D (above).

Synthetic diagnostic for ion current agrees well with measurements (top right). Measured profiles show effect of vertical drift and Larmor oscillation.

Spreading of the profiles in time (distance to source) agrees well with the simulations – for a superdiffusive and subdiffusive case (below).

Feedback on source from plasma should be incorporated for better agreement.





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