Non-diffusive transport of suprathermal ions in toroidally magnetized plasmas

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Why suprathermal ions? Why in basic devices?

In fusion plasmas, suprathermal ions are created by
- Fusion reactions (alpha particles) and additional heating (NBI, ICRH)
- Crucial for burning plasmas (heating, non-inductive current drive)

In space and astrophysical plasmas, suprathermal ions are ubiquitous
- Cosmic rays and solar energetic particles
- Can be harmful to spacecraft and are essential for Space Weather

Measurements in fusion devices or space plasmas are difficult

Basic plasma physics devices allow simpler investigations
- Many details of turbulence and suprathermal ions are directly measured
- Key experimental physics parameters can be varied systematically
- Direct comparison with numerical simulations ➔ code validation
Diffusive and non-diffusive transport

Spreading in time of the particle positions to extract an exponent:

\[ \sigma^2 \propto t^\gamma \]

- \( \gamma > 1 \) “super-diffusive”
- \( \gamma = 1 \) “diffusive”
- \( \gamma < 1 \) “sub-diffusive”

Are all these regimes accessible to suprathermal ions?
Which key elements determine the regime?
How can we identify them?
Outline

- The TORPEX device, experimental setup and diagnostics
  - ideal interchange turbulence
  - suprathermal ions source and detector
- Experimental measurements
  - energy dependence of suprathermal ion transport
- Comparison experiments-simulations
  - evidence for super- and sub-diffusive regimes
- Time-resolved measurements
- Conclusions
TORPEX (TORoidal Plasma EXperiment) at CRPP

major radius = 1m, minor radius = 20cm

4 vertical field coils

Magnetron for plasma production

28 toroidal field coils
TORPEX and the simple magnetized torus (SMT)

Toroidal coils

$B_t \sim 800$ Gauss
TORPEX and the simple magnetized torus (SMT)

- **Toroidal coils**
  - Magnetic field: $B_t \approx 800$ Gauss

- **Vertical coils**
  - Magnetic field: $B_v \approx 10$ Gauss
TORPEX and the simple magnetized torus (SMT)

Helical field lines winding N times around the torus
$\nabla B$ and curvature $\Rightarrow$ interchange drive
SMTs have similarities with tokamak SOLs

Scrape-Off Layer
open field lines
$\nabla B$ and curvature

Last Closed Flux Surface
magnetic topology change

Perpendicular turbulent transport
SOL parallel flow
Open field lines and sheath physics
At low N, SMTs are dominated by field-aligned turbulence.

- Ideal Interchange
- Resistive Interchange

\[ k_{||} = 0 \]

Hydrogen
\[ N \sim 2 \]
\[ T_e \sim 2-5 \text{eV}, \quad T_i < 1 \text{eV} \]
\[ n_e \sim 3 \times 10^{16} \text{m}^{-3} \]

Field-aligned turbulence

- Drift

P. Ricci and B. Rogers, PRL 2010
Ideal interchange regime: waves and blobs

I. Furno, PRL 2008
Ideal interchange regime: waves and blobs
Suprathermal ion source and detector

Three-dimensional profile of the suprathermal ion beam

Time-averaged meas.
Time-resolved meas.

Suprathermal ion source
Gridded energy analyzer
Tracer Li$^+$ ions 10eV-1keV

x
y
z
Distance from the source = 0.2 m

E = 70 eV
E/Te ≈ 46

Fast ion injection location

3D time-averaged profile at two ion energies
3D time-averaged profile at two ion energies

$E = 70 \text{ eV}$
$E/T_e \approx 46$

$E = 30 \text{ eV}$
$E/T_e \approx 20$

Distance from the source = 0.2 m
3D time-averaged profile at two ion energies

E = 70 eV  
$E/T_e \approx 46$

E = 30 eV  
$E/T_e \approx 20$

Distance from the source = 2.2 m
The beam spreading is different for different energies

Exp. $E = 70$ eV
Exp. $E = 30$ eV

![Graph showing the radial variance of the beam for different energies.](image)
Ion tracers in simulated turbulent fields

GBS 3D fluid code
Electrostatic, Drift-reduced Braginskii equations
Tracer trajectory solver

P. Ricci, PoP 2009
Particle spreading in time $\Rightarrow$ transport regime

- **Ballistic** $\gamma_R = 2$
- **Interaction** $\gamma_R < 2$

![Graph showing particle spreading in time and transport regime](image_url)
Phase space for suprathermal ion transport

Normalized energy ($E/T_e$)

Normalized fluctuations amplitude ($e/T_e$)

$\gamma_R$
Phase space for suprathermal ion transport

Gyro-averaging

Drift-averaging

Normalized energy ($E/T_e$)

Normalized fluctuations amplitude ($e/T_e$)

Drift-averaging condition

Gyro-averaging condition

$\gamma_R$
Comparison with simulations: synthetic diagnostics

Toroidal position: $\phi = 0.016\, \text{rad}$

![Diagram 1](image1)

![Diagram 2](image2)
Two regimes for fast ion transport

30eV: $\gamma=1.2$ superdiffusive

$\gamma=0.92 \sim$ diffusive

$\gamma=0.51$ subdiffusive
The TORPEX device, experimental setup and diagnostics
- ideal interchange turbulence
- fast ions source and detector
Experimental measurements
- fast ion transport: energy dependence
Comparison experiments-simulations
- Evidence for super and subdiffusive regimes
Time-resolved measurements
Conclusions
Time-resolved measurements in super- and sub-diffusive regimes

- Time traces of the detector at 40 cm
  - \( E = 30 \text{ eV} \): superdiffusive
  - \( E = 70 \text{ eV} \): subdiffusive

- Probability density functions

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Different statistics in different transport regimes

Poloidal cross sections at 40 cm from the source

Time-averaged Current density [A/m²]

«Crown» of high skewness

Skewness profile

E = 30 eV
superdiffusive

E = 70 eV
subdiffusive
The ion intermittency is causally related to turbulence

\[ \text{Transfer Entropy} \]

\[ \text{HEX} \rightarrow \text{GEA} \]
The ion intermittency is causally related to turbulence
The ion intermittency is causally related to turbulence.
The entropy transfer is mediated by blobs

Conditionally averaged suprathermal ion current density [A/m^2]

$E = 30 \text{ eV}$  
superdiffusive

$E = 70 \text{ eV}$  
subdiffusive

A. Bovet, PRL 2014
Conclusions

Simple plasma devices offer great possibilities to investigate the fundamentals of suprathermal ion – turbulence physics.

On TORPEX, experiments and numerical simulations reveal different non-diffusive regimes for suprathermal ions depending on their energy and turbulence amplitude.

Time-resolved measurements reveal the effect of blob transport.

Link between Eulerian time-resolved measurements (tokamaks, spacecrafts) and 3D time-averaged measurements.