Suprathermal ion transport in complex magnetic geometries on the TORoidal Plasma EXperiment (TORPEX)

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Motivation

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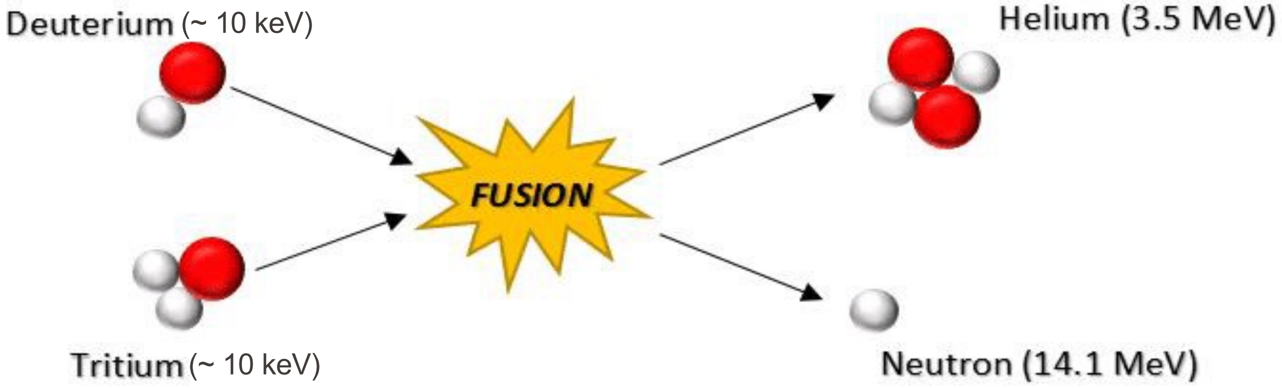
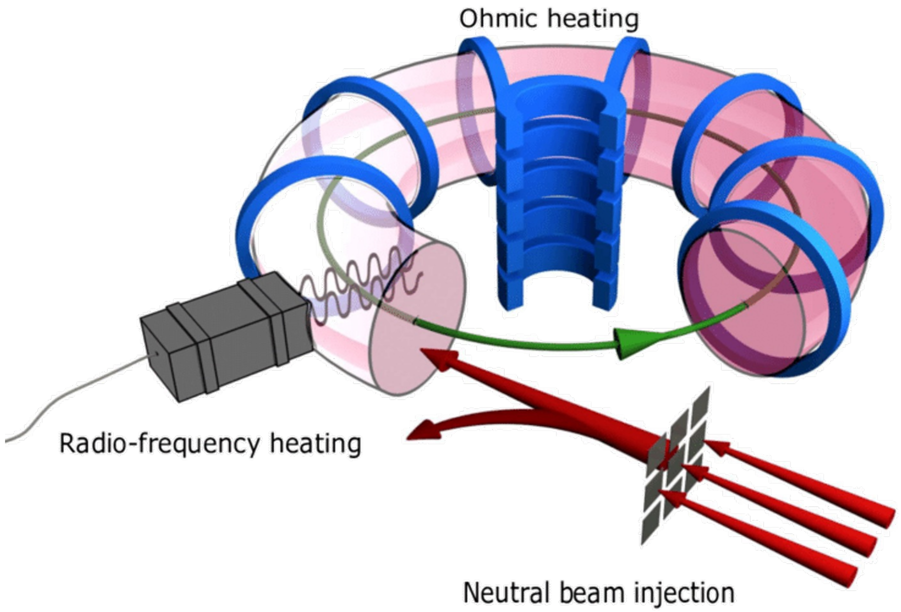
- Suprathermal ions ($E_{ion} \gg E_{e/i,plasma}$) in nuclear fusion research
  - → Product of the fusion reaction (3.5 MeV)
  - → Neutral Beam Injection (~ 1 MeV) and other heating systems

- Need to be confined to heat and sustain the main plasma

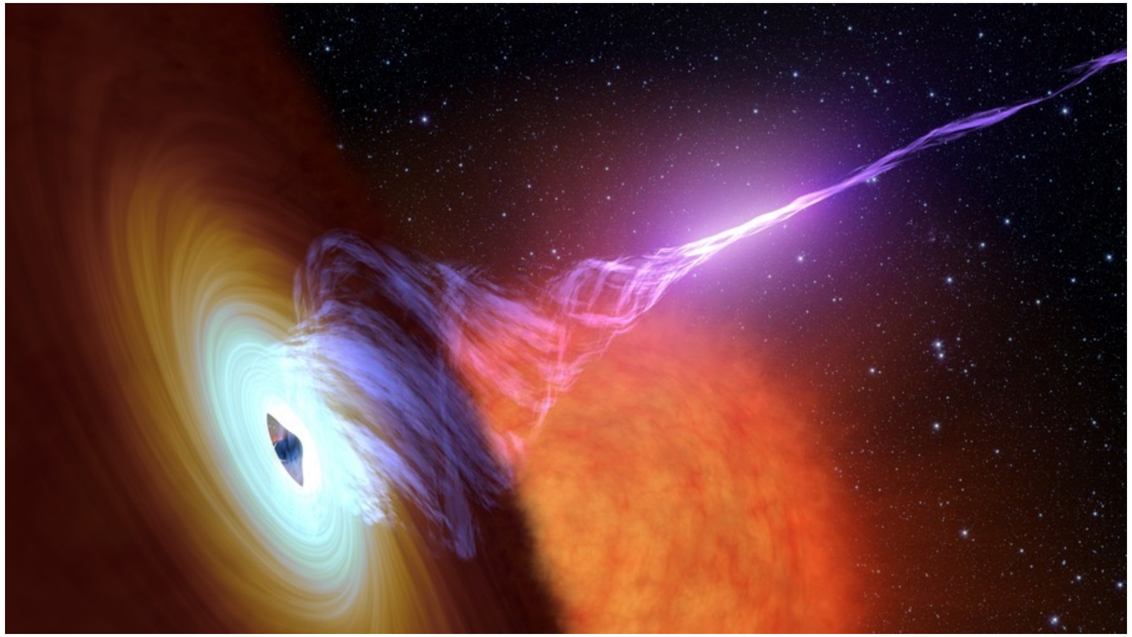


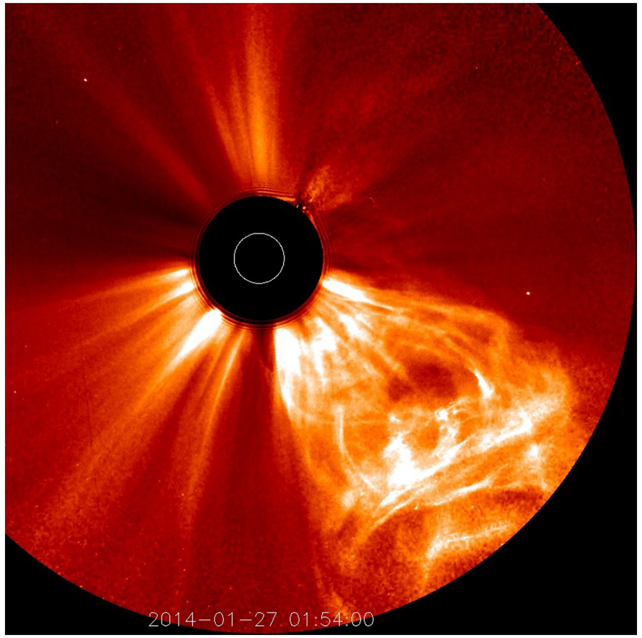


Motivation

- Suprathermal ions ($E_{ion} \gg E_{e/i,plasma}$) in astrophysics
  - → Supernovae explosions - cosmic rays ejection
  - → Solar flares (« Solar Energetic Particles »)

- Hard to diagnose and study in outer space…





TORPEX and the suprathermal ions

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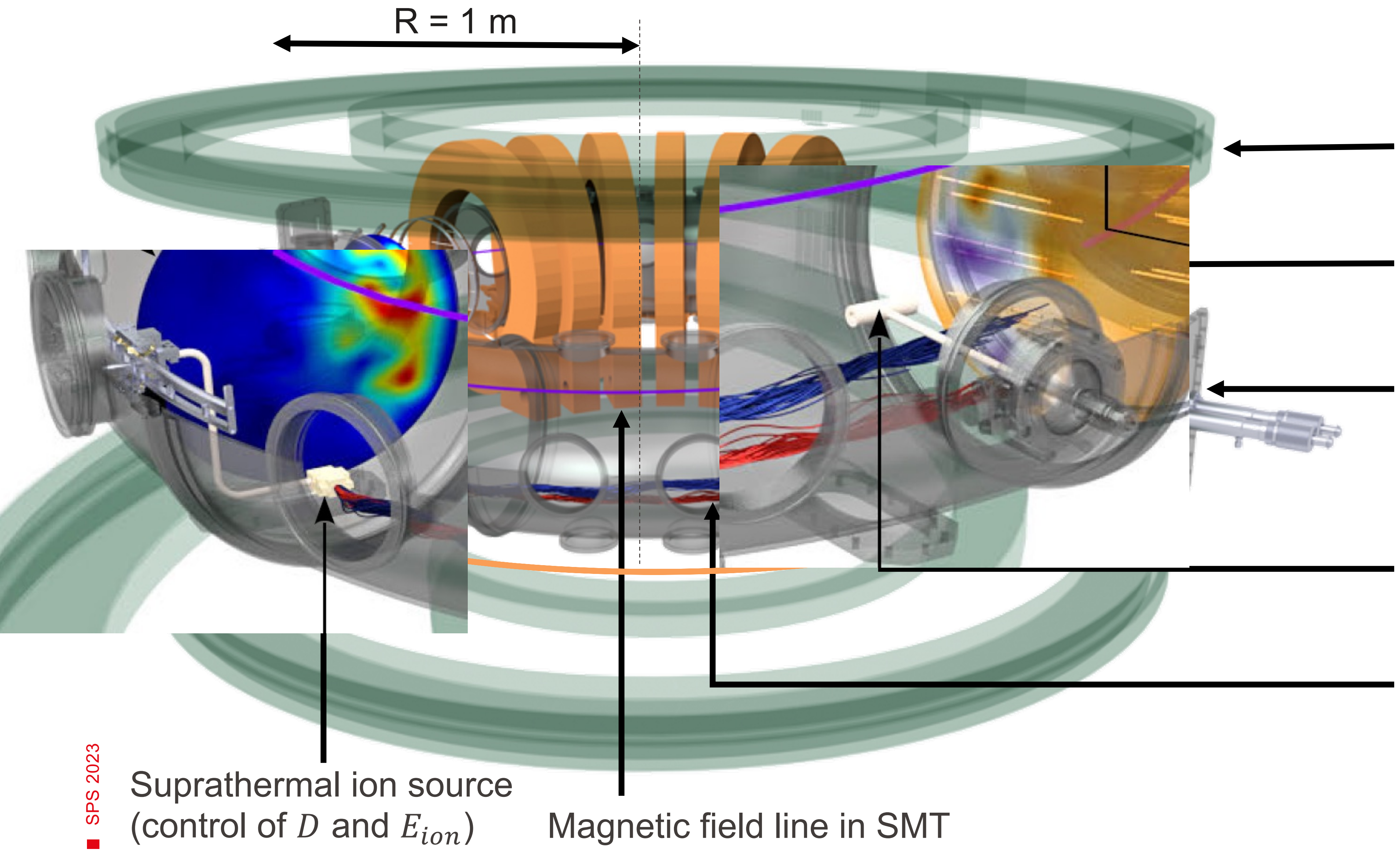
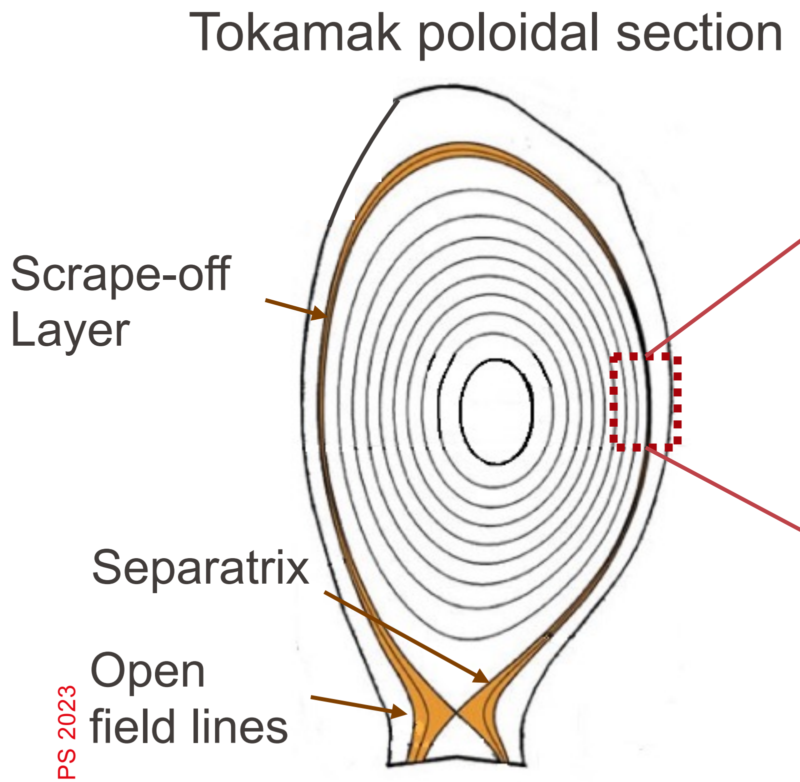
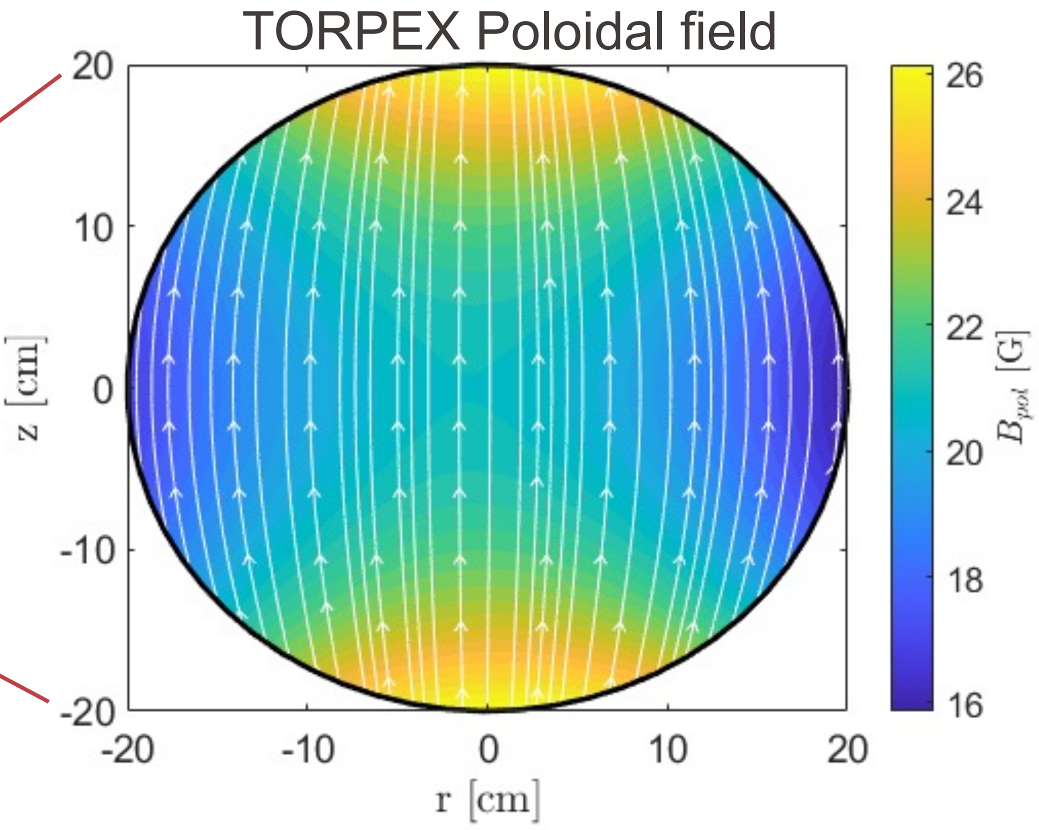


The SMT configuration in TORPEX

- Reproduces the scrape-off layer of tokamak
  - → Small vertical field on top of a main toroidal component
  - → Turbulent features widely characterized in the past years in TORPEX

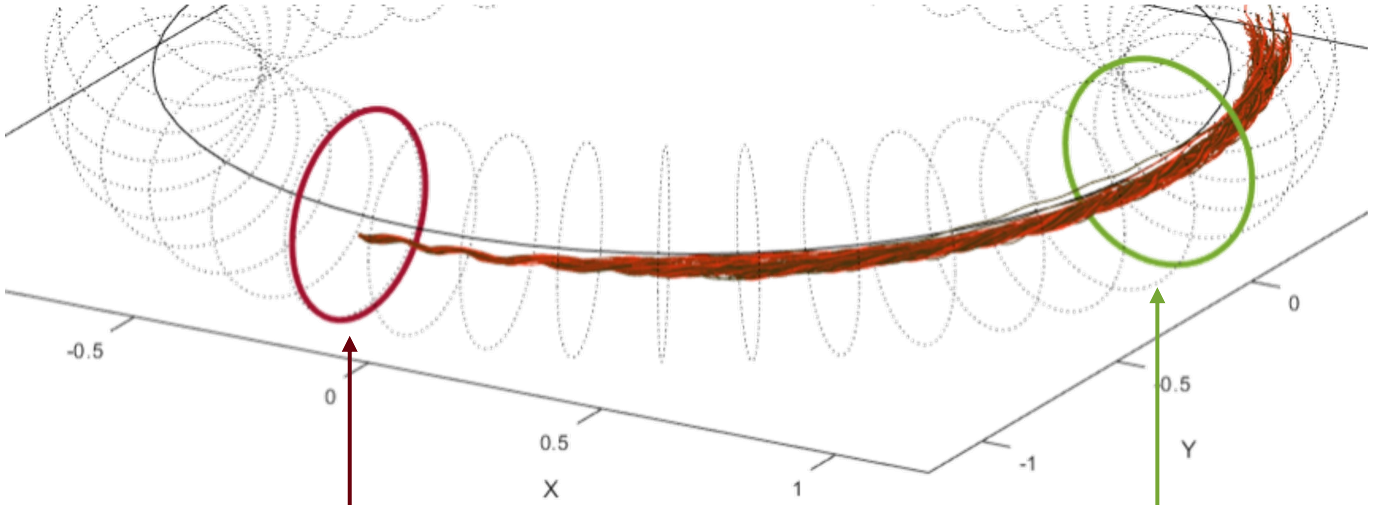




+ main B_{tor}

Suprathermal ion transport in SMT configuration [1,2]

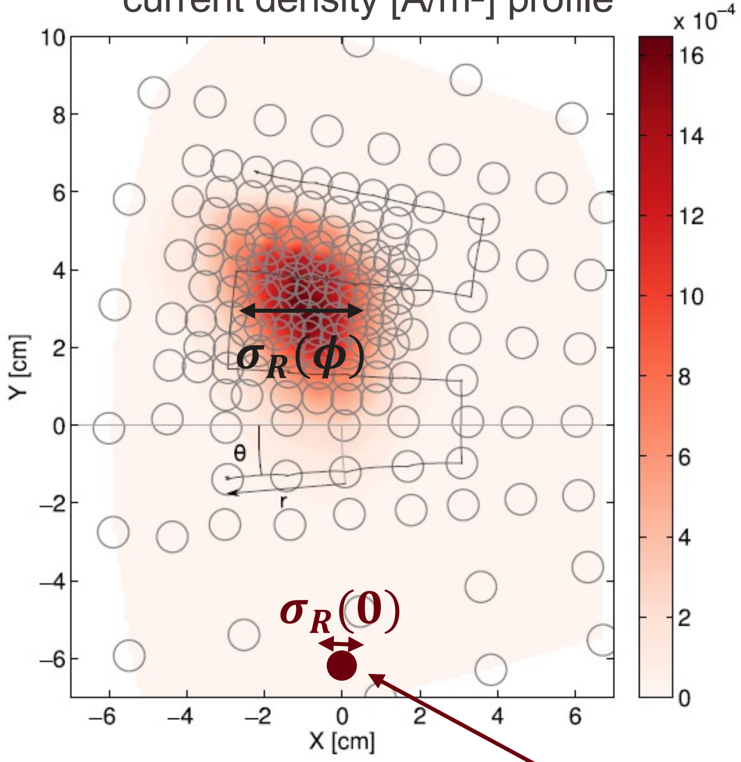
- Experimental 2D and 3D profiles
- Cross-field transport studies : $\sigma_R^2 \propto t^\gamma$



Injection plane

Detection plane

Poloidal suprathermal ion time-averaged current density [A/m²] profile



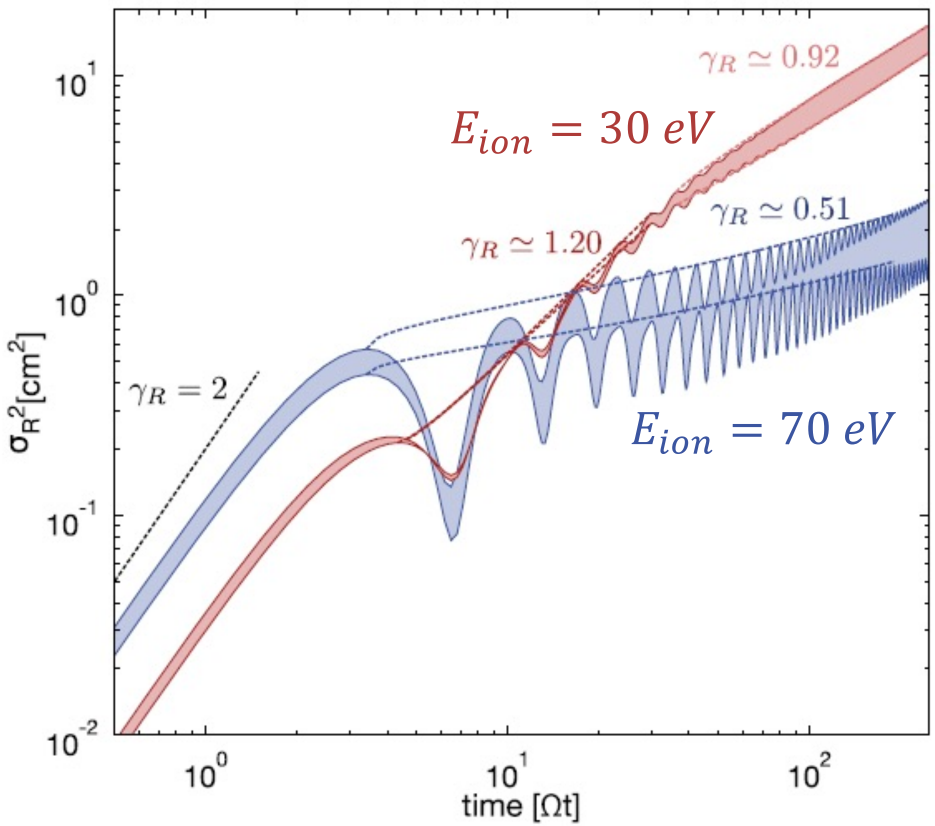
Suprathermal ion beam injection

[1] A. Bovet, EPFL PhD thesis n°6527, 2015
[2] F. Manke, EPFL PhD thesis n°10135, 2020

Suprathermal ion transport in SMT configuration [1, 2]

- Experimental 2D and 3D profiles
- Cross-field transport studies : $\sigma_R^2 \propto t^\gamma$
  - $\gamma > 1$ → super-diffusive transport
  - $\gamma = 1$ → diffusive transport (// random walk)
  - $\gamma < 1$ → sub-diffusive transport
- Development of statistical models

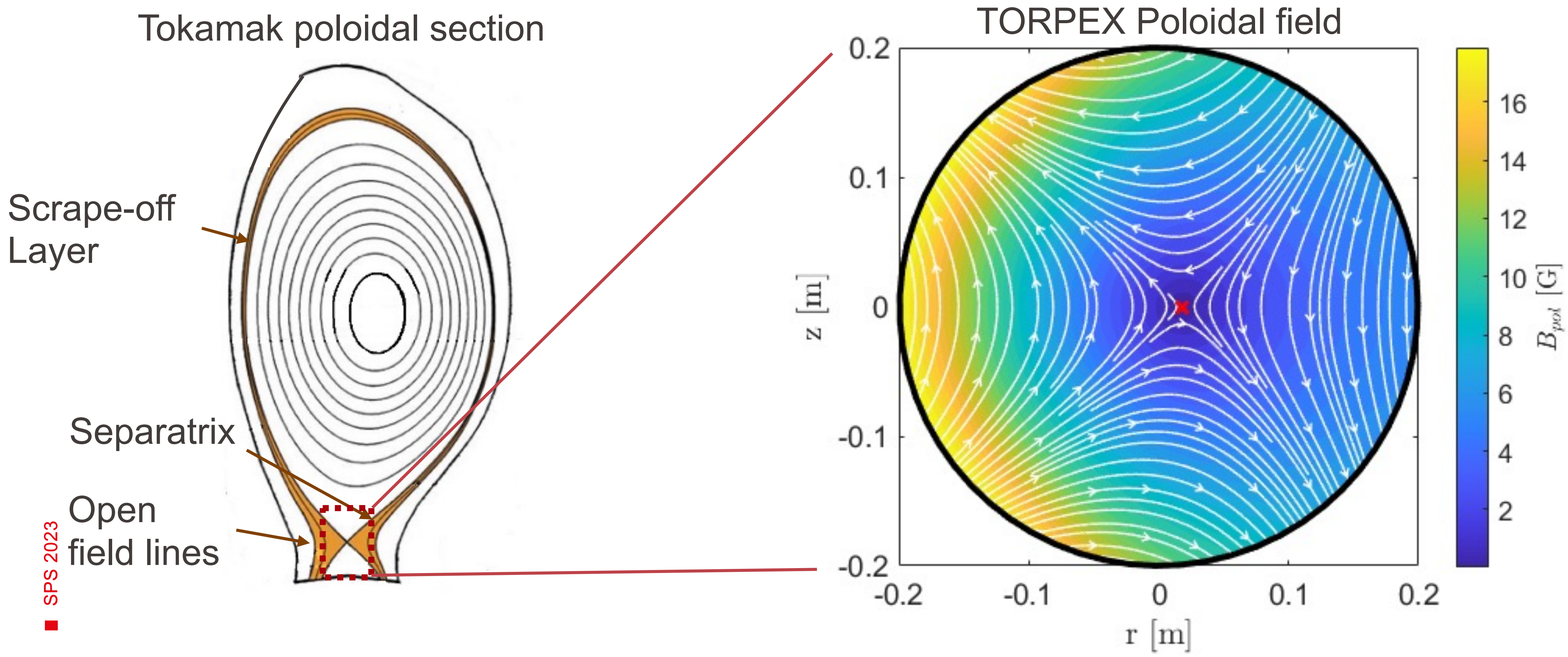
Variance of the ion radial positions as a function of time



[1] A. Bovet, EPFL PhD thesis n°6527, 2015
[2] F. Manke, EPFL PhD thesis n°10135, 2020

The X-point configuration in TORPEX

- Reproduces the X-point region of a tokamak
  - → Null-point close to the center of the poloidal section
  - → Challenging to diagnose plasma around the X-point in fusion devices
  - → Comparable setup w.r.t. tokamaks



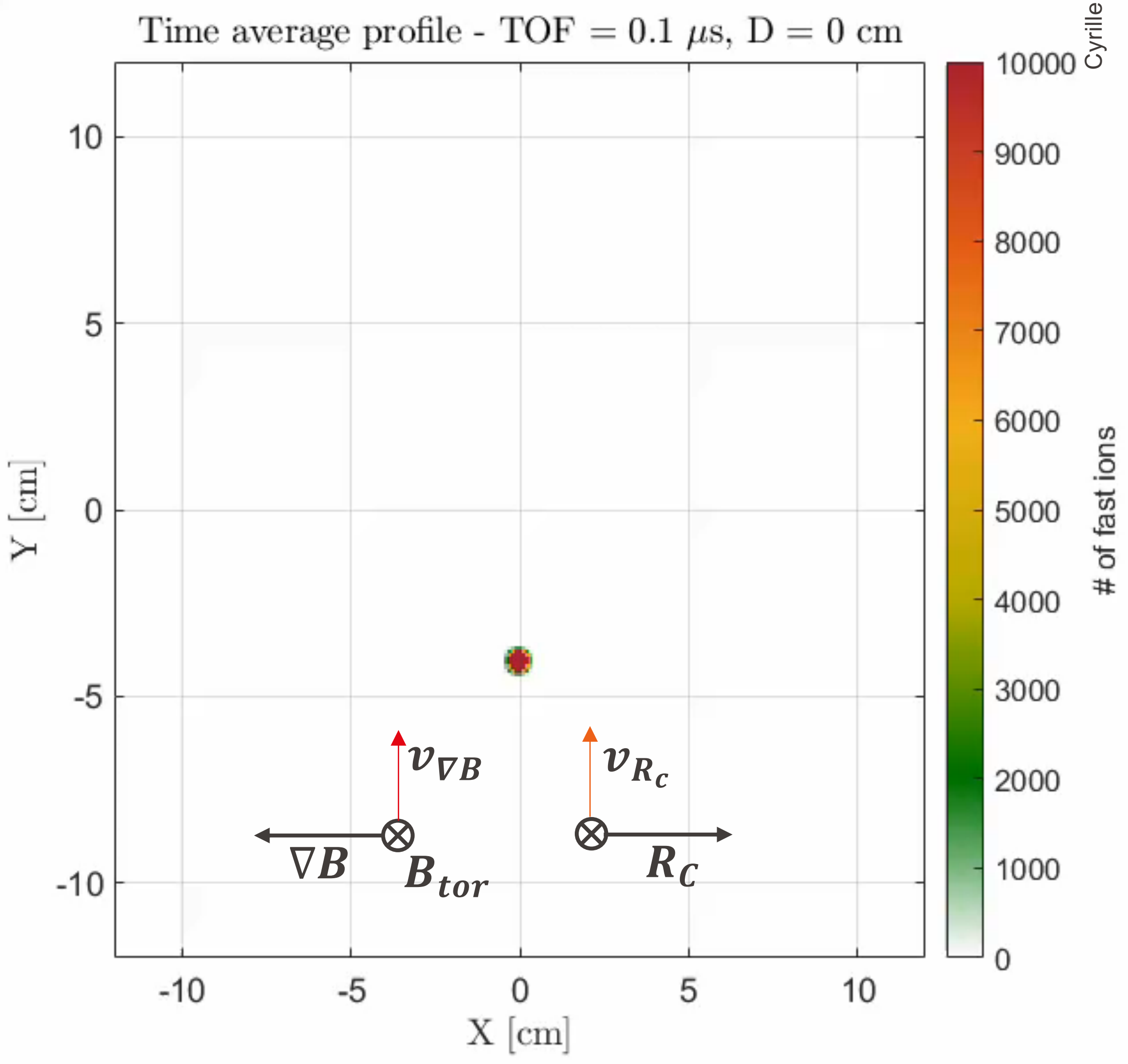
+ main B_{tor}

Suprathermal ion transport in X-point configuration

- **Simulations** under the X-point magnetic field only
- Cyclotron motion of the averaged beam
- Upward drift due to

$$v_{\nabla B} \propto \boldsymbol{B}\times\nabla B \qquad\qquad v_{R_c} \propto \boldsymbol{R_c}\times\boldsymbol{B}$$

- Small deviations caused by B_{pol} depending on
  - Injection position - Beam energy - Magnetic shear



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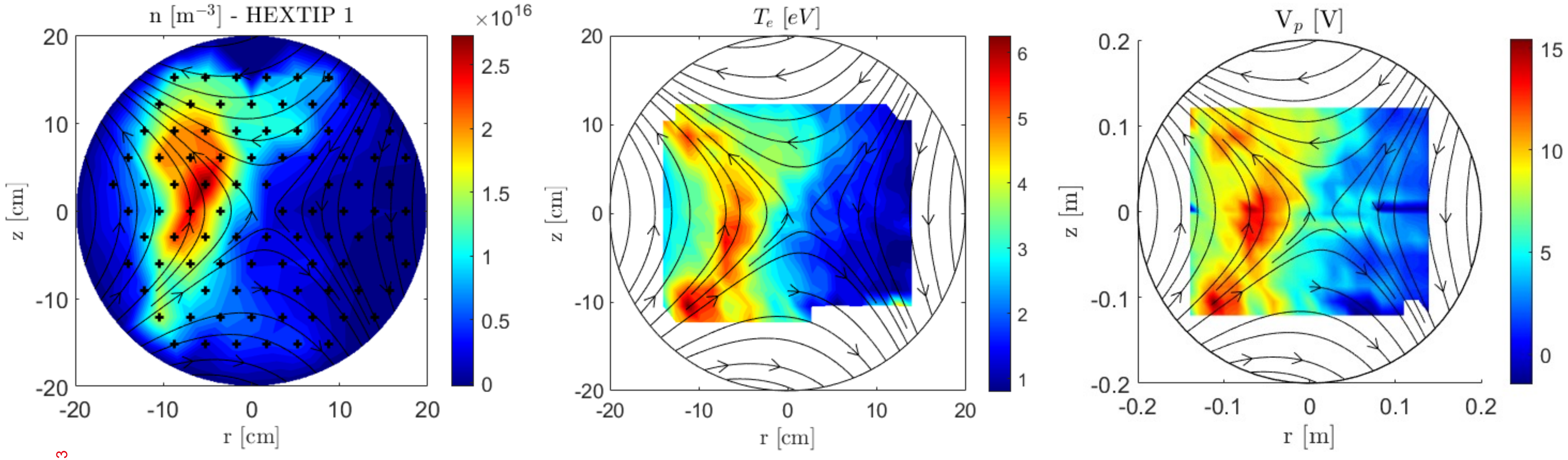
The X-point plasma scenario in TORPEX [3]

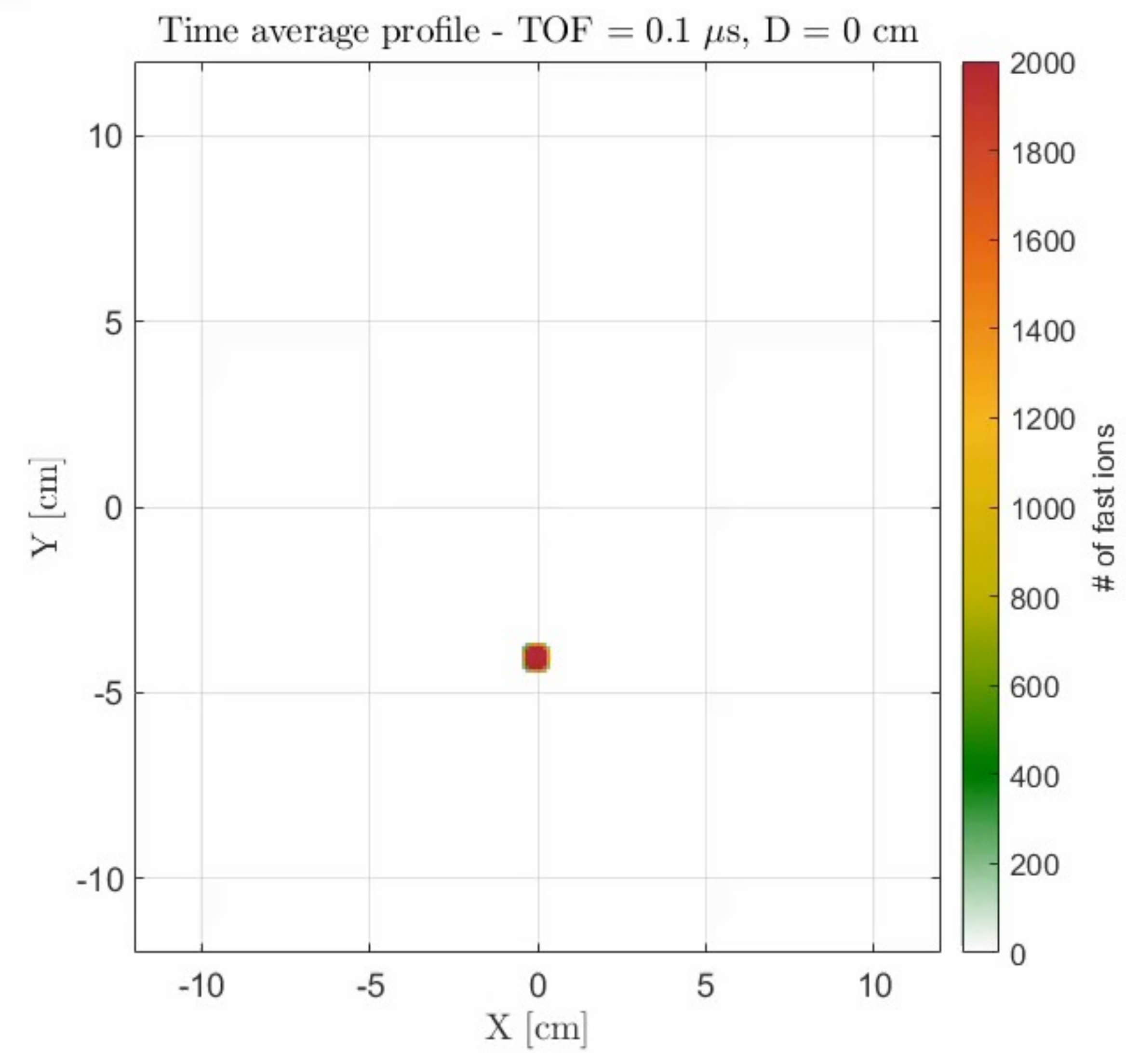
- Langmuir probe **measurements** leading to :
  - Time-averaged 2D n and V_{fl} profiles
  - 2D profiles of T_e
- Main plasma characteristics :
  - Asymmetric plasma density in the HFS region
  - V_p profile is dominated by T_e, along the separatrix



[3] D. Galassi *et al.*, Phys. Plasmas **29**, 012501 (2022)

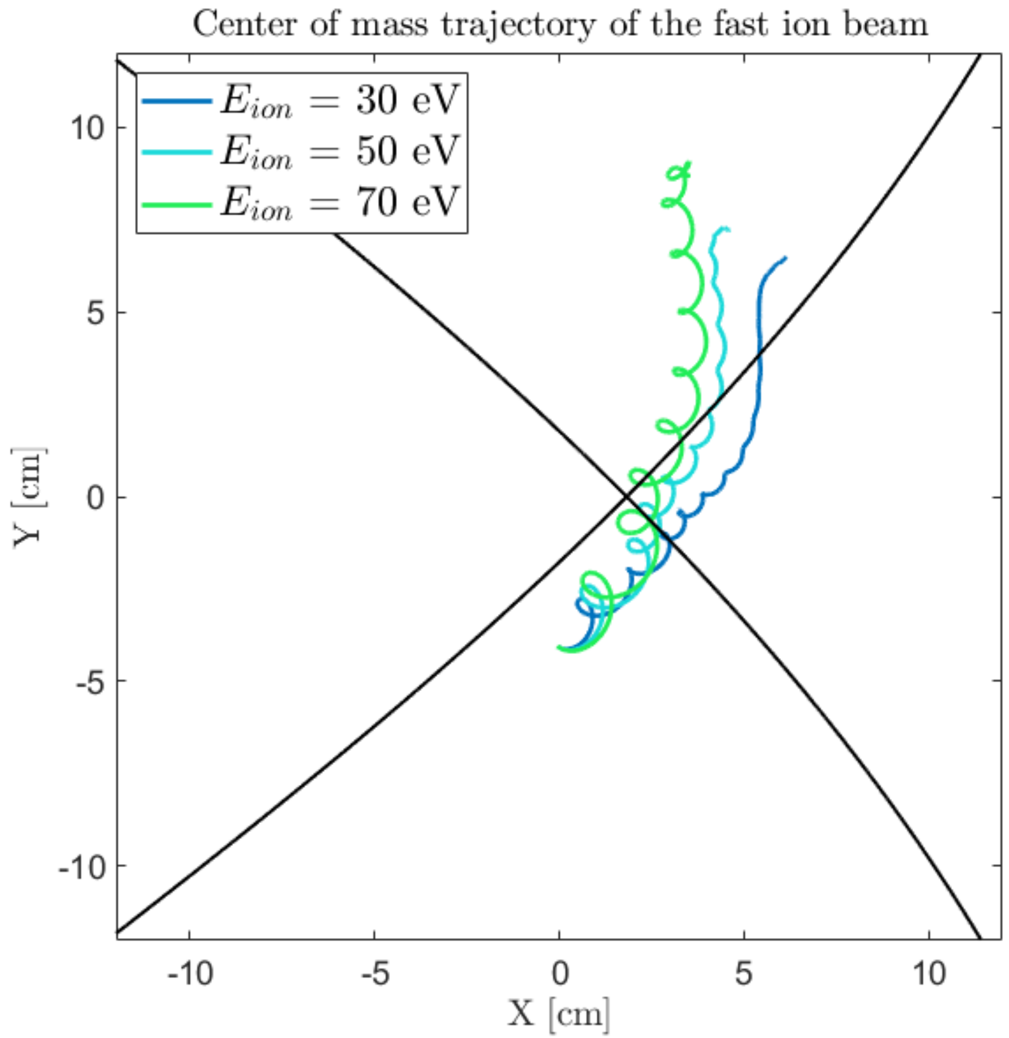
Suprathermal ion transport in X-point with plasma

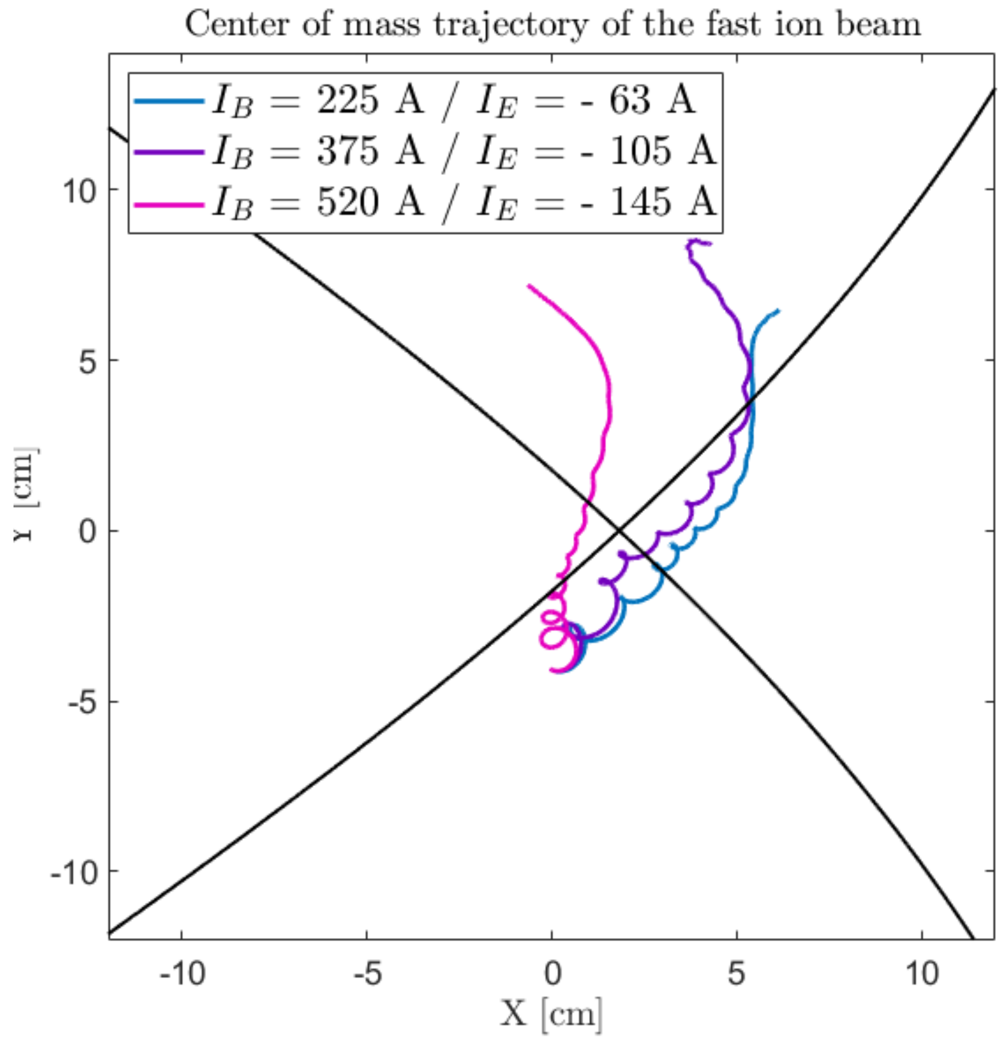
- **Simulations** with both $\boldsymbol{B}$ and $\boldsymbol{E}$
  - With $\boldsymbol{E} = -\boldsymbol{\nabla} V_p$ and $V_p = V_{fl} + 3.1\, T_e$ taken directly from TORPEX diagnostics



Suprathermal ion transport in X-point with plasma

- Focus on E_{ion} and $shear$ effects
  - Cyclotron motion averages out with beam spreading
  - $\boldsymbol{v}_{ion} \approx \boldsymbol{v}_{E\times B} + \boldsymbol{v}_{\nabla B} + \boldsymbol{v}_{R_c} \sim \boldsymbol{v}_{E\times B}$ → /!\ scaling with experimental results





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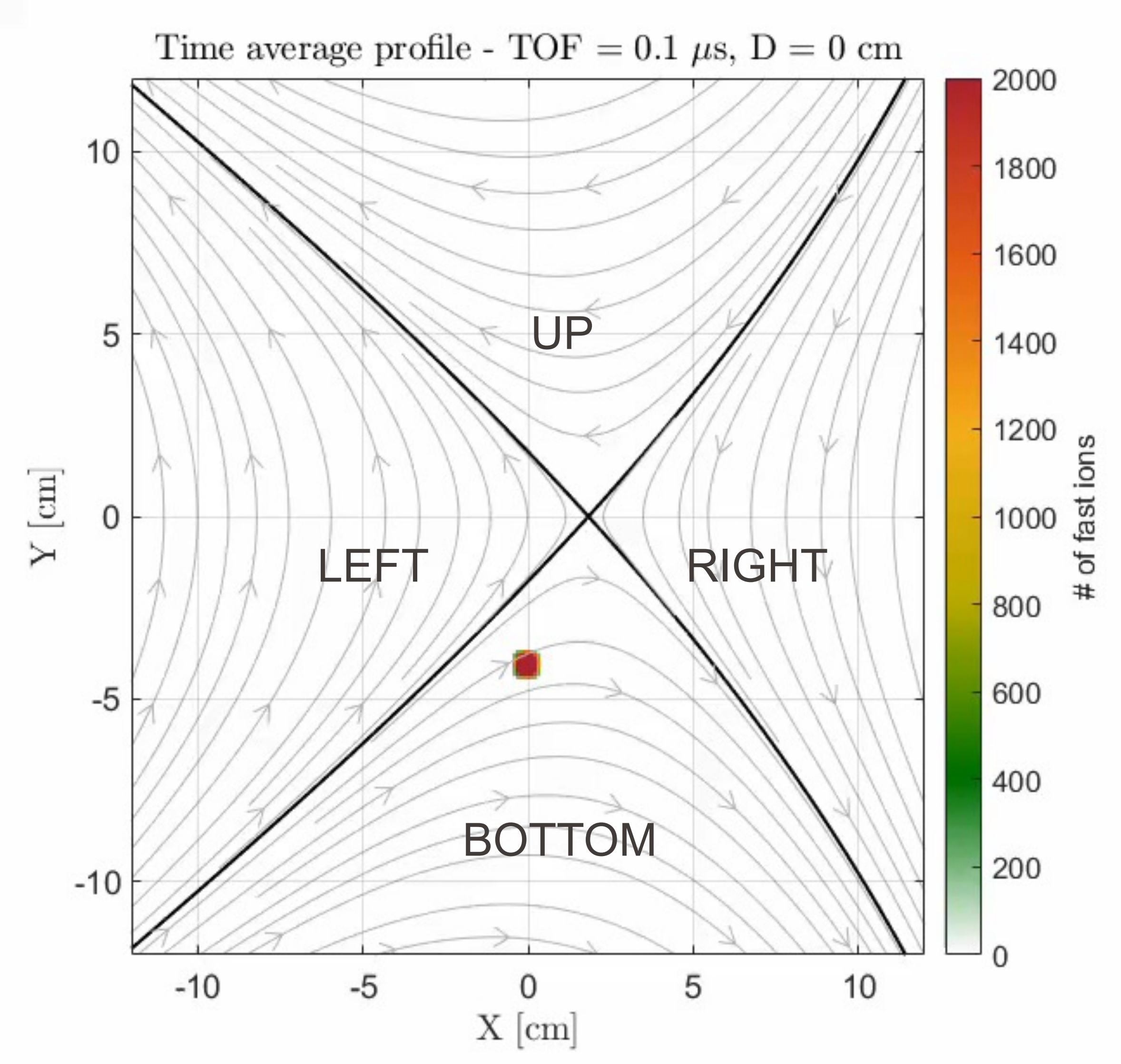
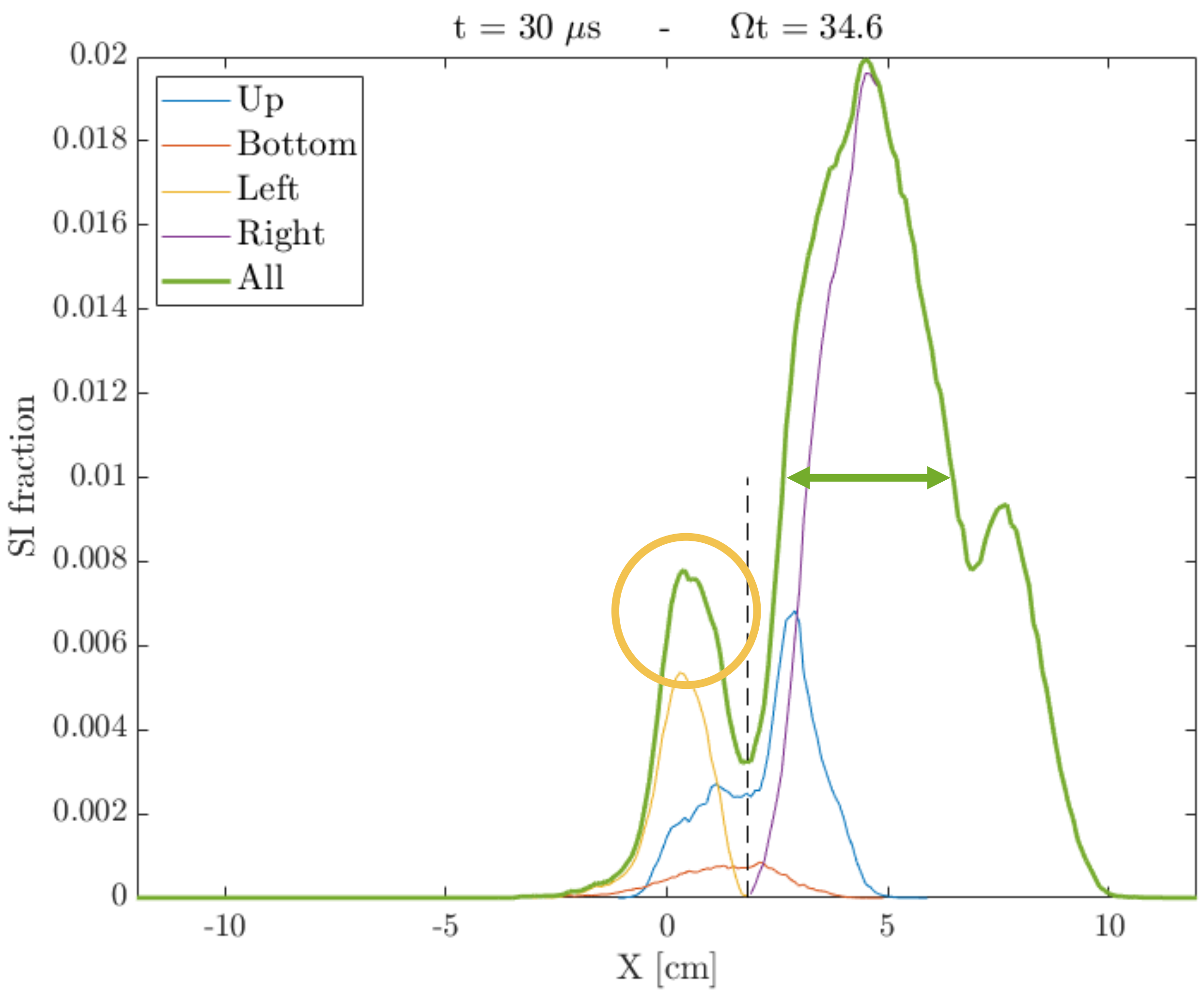
Suprathermal ion transport in X-point with plasma

- Interaction with the X-point (from **simulations**) :
  - A fraction of suprathermal ions is « stuck » at the X-point



Suprathermal ion transport in X-point with plasma

- Interaction with the X-point (from **simulations**) :
  - Transport studies must account for plasma interactions in different « regions » of the X-point



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Suprathermal ion transport in X-point with plasma

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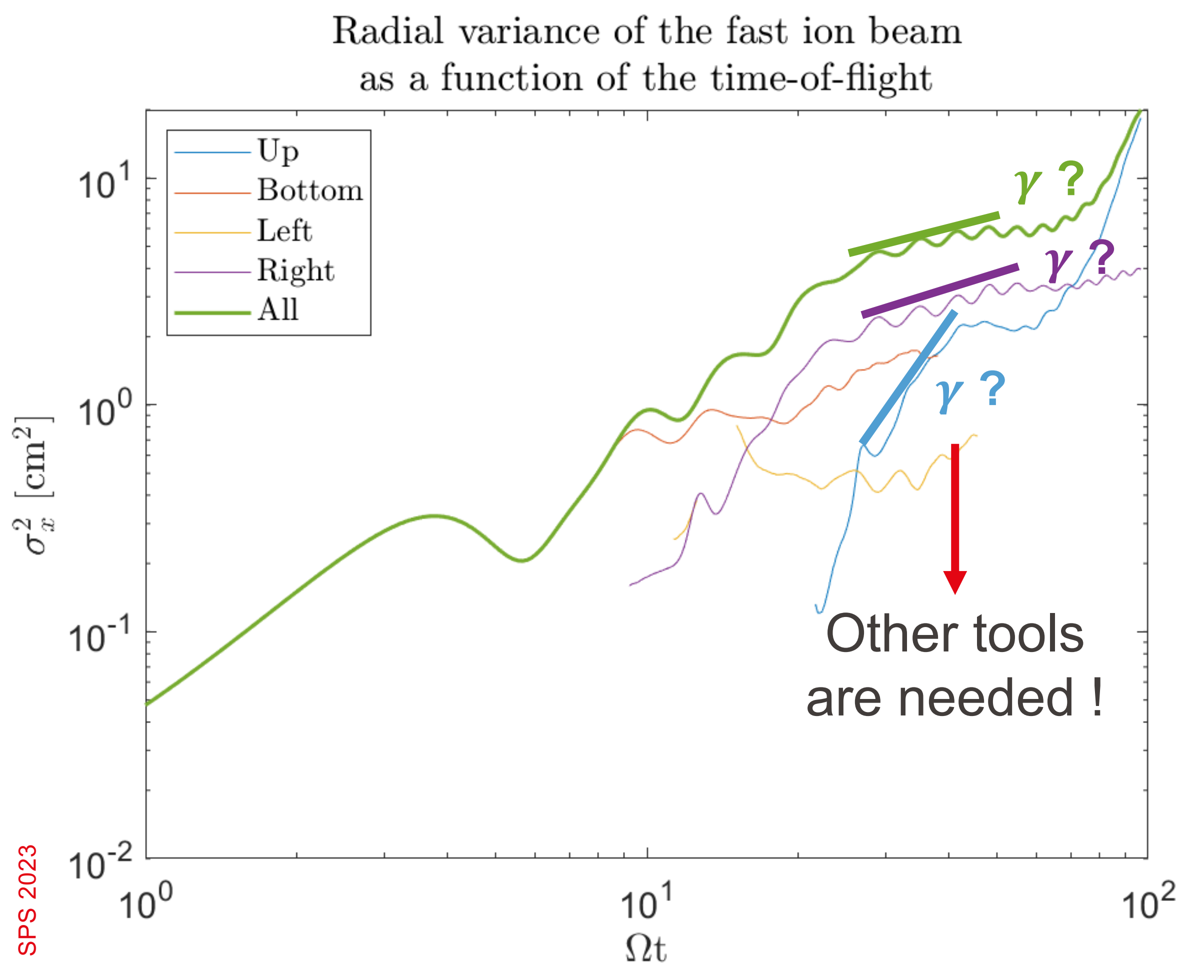
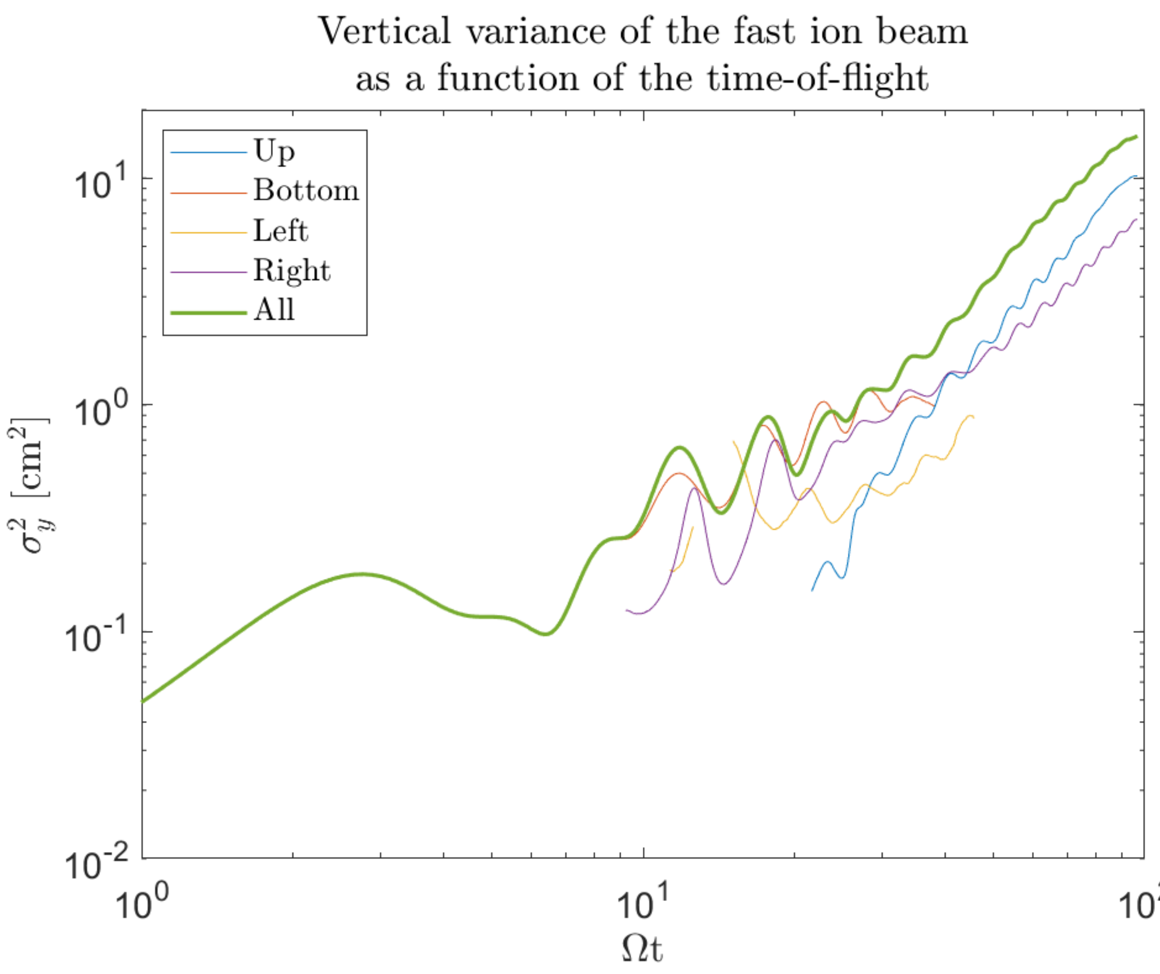
- Interaction with the X-point (from simulations) :
  - Transport needs to be understood for each region and in both spatial directions





Conclusion and outlook

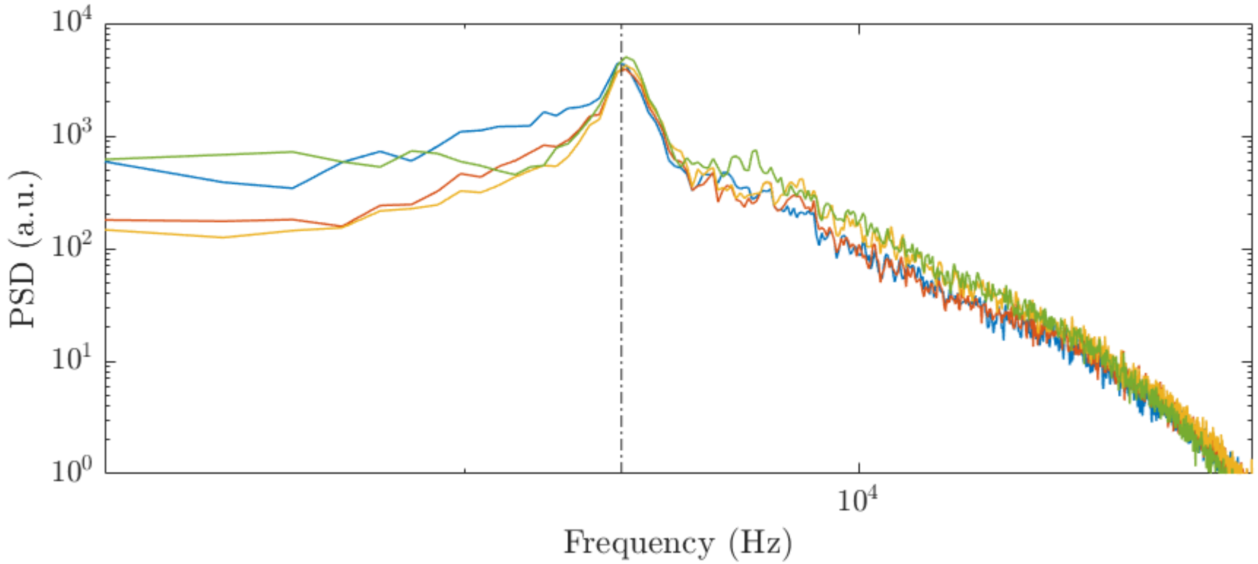
- What has been done :

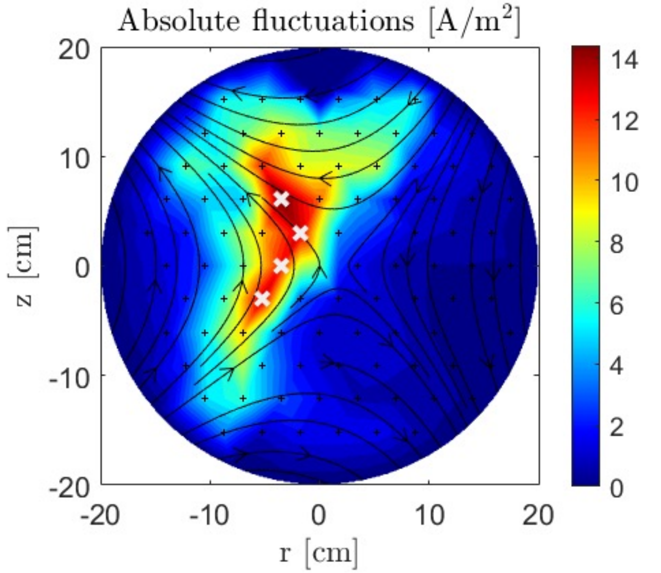
  1. Simulations of suprathermal ions with the X-point magnetic field only
     - Expected gyromotion and drift
  2. Understanding of the X-point plasma scenario in TORPEX
  3. Suprathermal ions with the X-point and the plasma
     - Radial transport due to $\boldsymbol{E}\times\boldsymbol{B}$, depending on E_{ion} and plasma scenario (shear)
     - A non-negligible fraction of suprathermal ions is "stuck" at the X-point
       → transport studies need to be adapted

- What will be done :
  - Experimental validation without and with the plasma
  - Statistical quantitative analysis

The X-point plasma scenario in TORPEX

- Main plasma drifting mode in the ~kHz range





- Turbulent transport measurements (S. Vincent and P. Quigley)