Investigation of fast ion transport in TORPEX

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Motivation

- Address fundamental aspects of the interaction between suprathermal ions and plasma fluctuations
  - Orbit averaging
  - Nature of ion transport
  - Role of semi-coherent waves, turbulence structures and turbulence

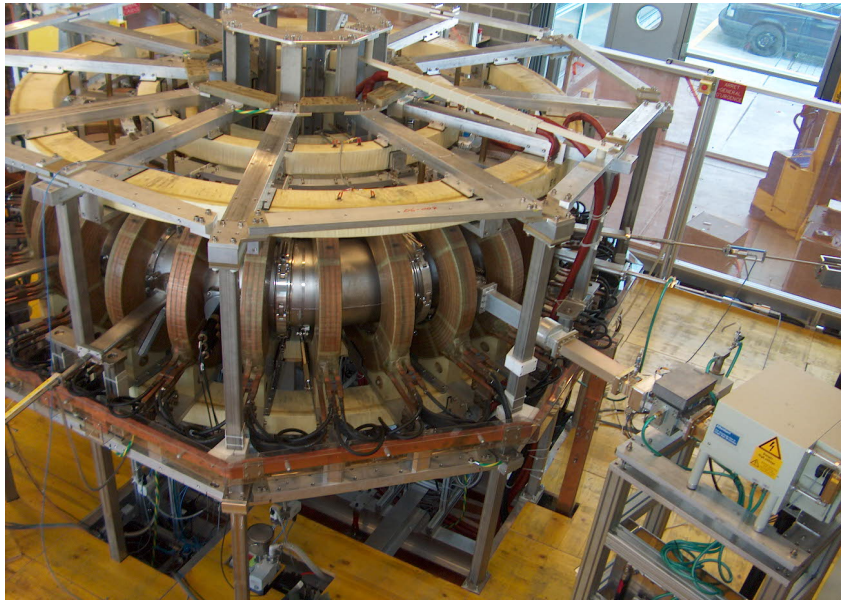
- Basic devices allow direct measurements of fast ion phase space evolution during their interaction with turbulence, and of waves, turbulence and plasma profiles

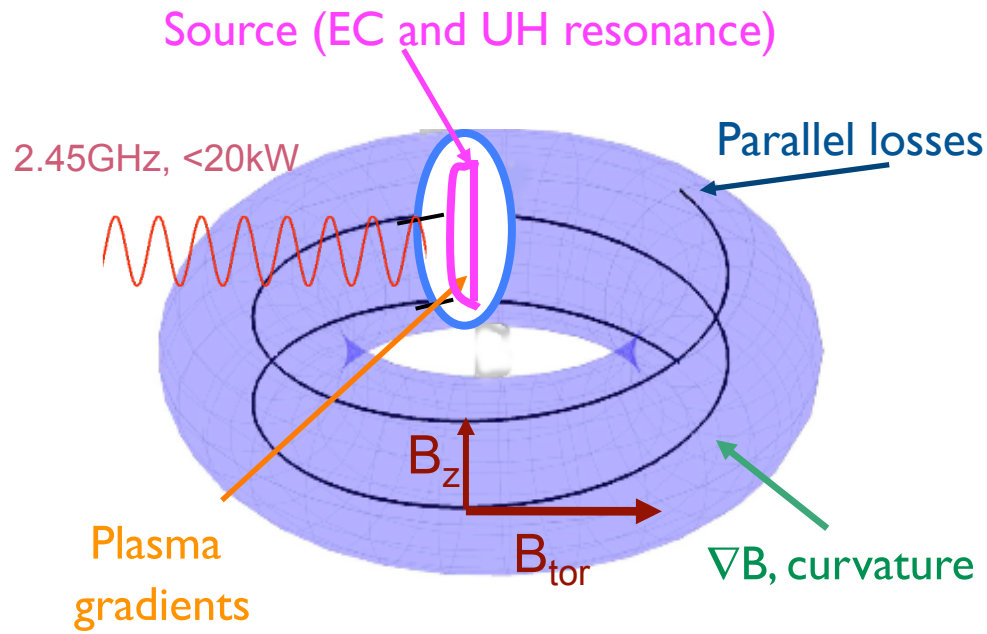
- Key experimental control parameters can be varied systematically
  - Ion energy, pitch angle, E_{ion}/T_e, Larmor radius, turbulence parameters, …

Outline

- The TORPEX device
- Fast ion generation and detection
- Experimental results in interchange-mode dominated plasmas
- Theoretical interpretation and experiment – simulation comparisons
- Summary and outlook

The TORPEX device





- Open field lines - no plasma current
- Plasma production by EC waves
- Extensive diagnostic coverage (electrostatic, magnetic, fast camera)
- ∇B, curvature, pressure gradients

H_2, D, He, Ne, Ar plasmas

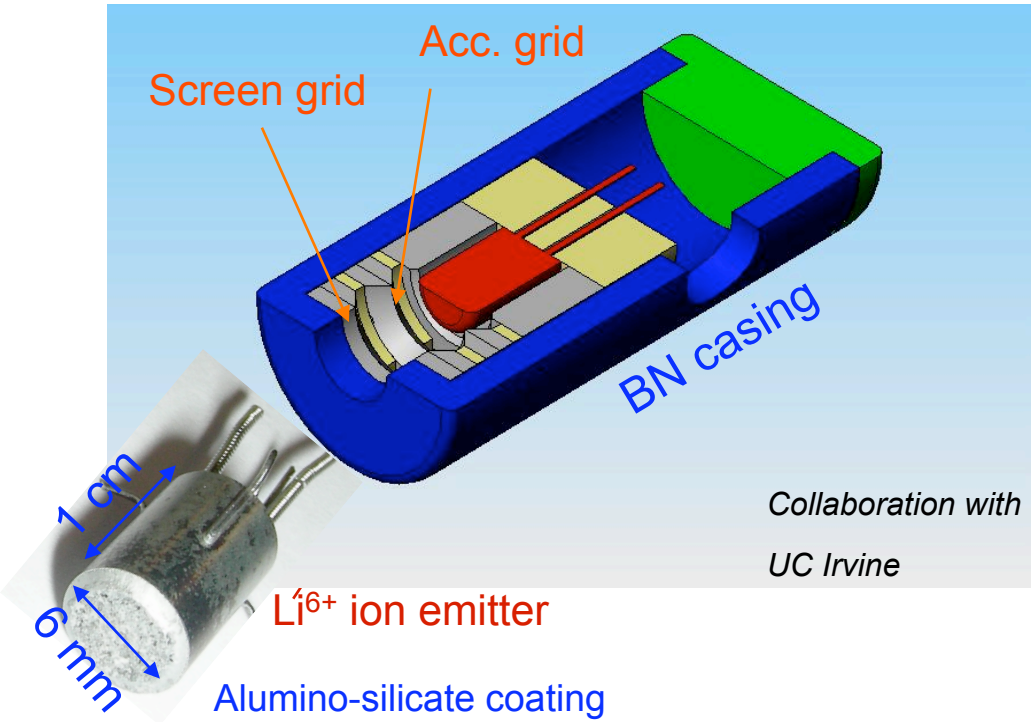
R = 1 m; a= 0.2 m

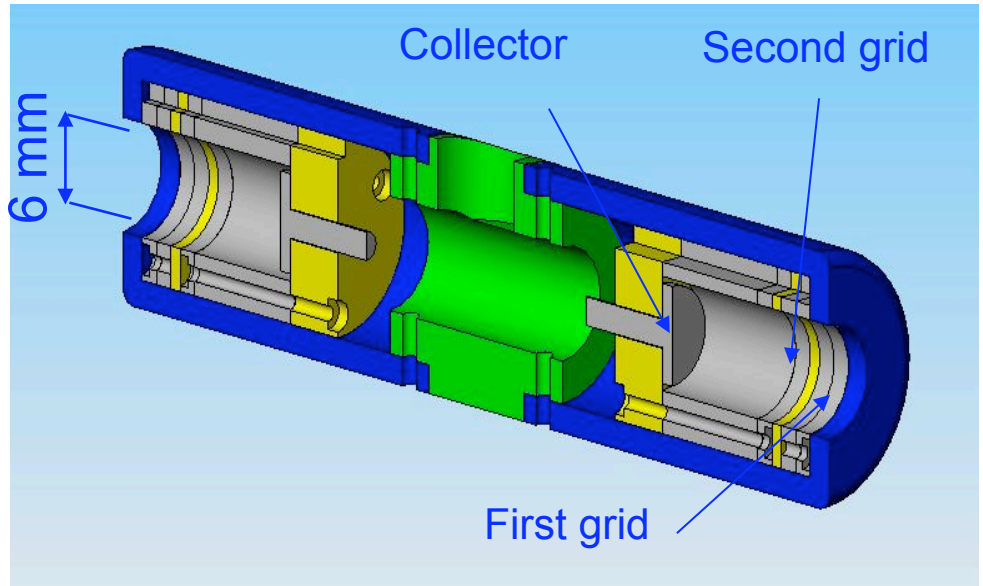
B_t = 76 mT; B_z= 0 - 6 mT

T_e = 2 – 20 eV

n_e = 0.1 – 5 x 10^{16} m^{-3}

The TORPEX fast ion source and detector

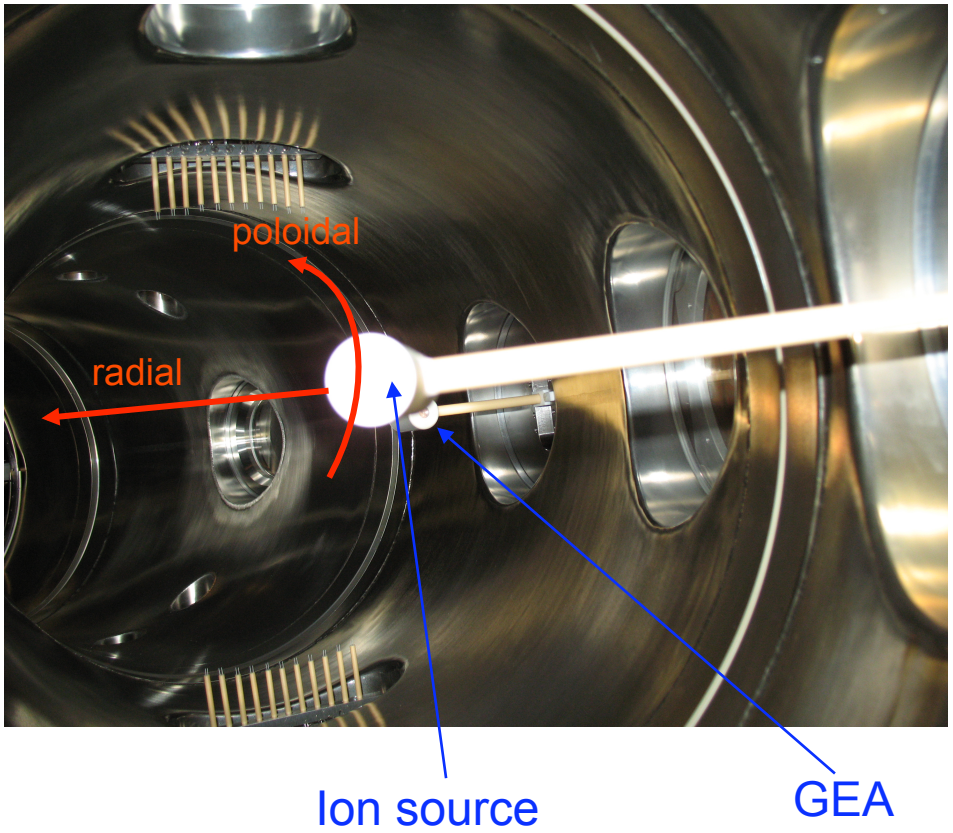


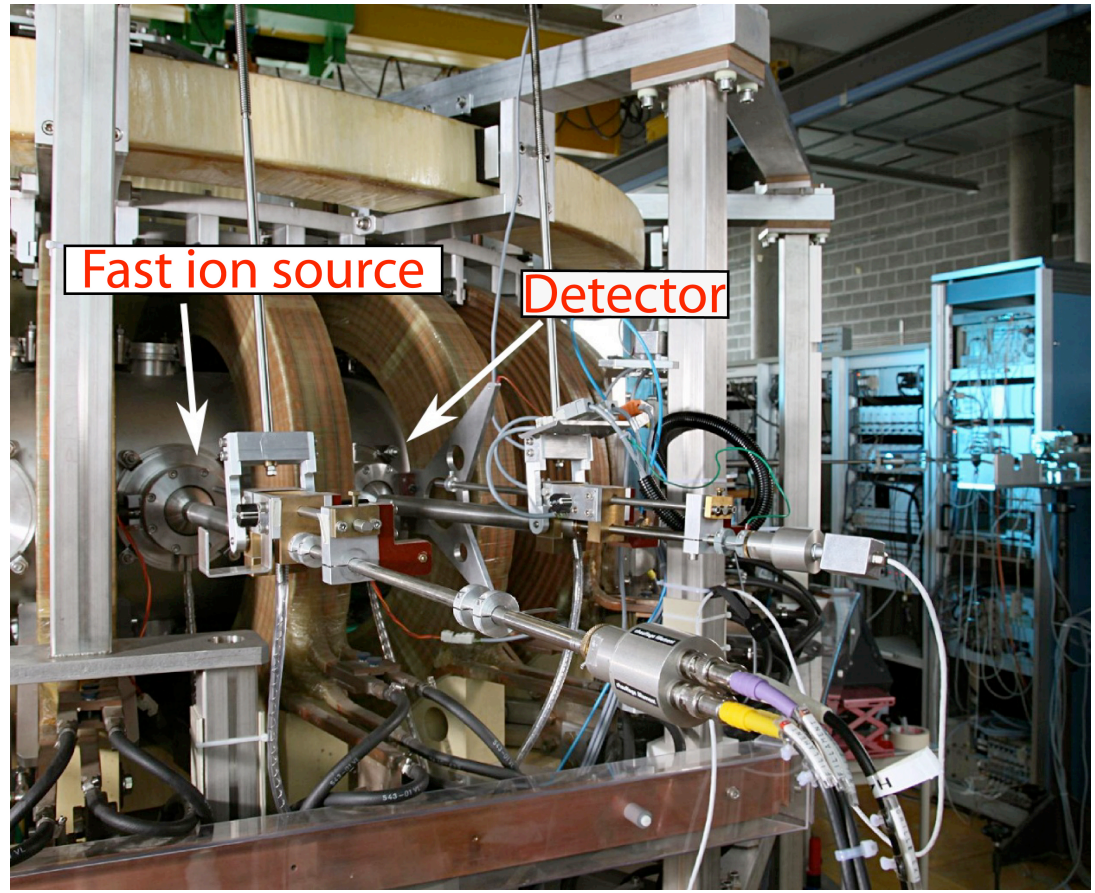


- Double grid for small beam divergence
- Thermo-ionic effect (~1200°; heating 30W)
- Extraction voltage: 0.1 – 1kV
- Ion current ~ 10μA

- Two identical Gridded Energy Analyzers for noise reduction
- 6mm spatial resolution

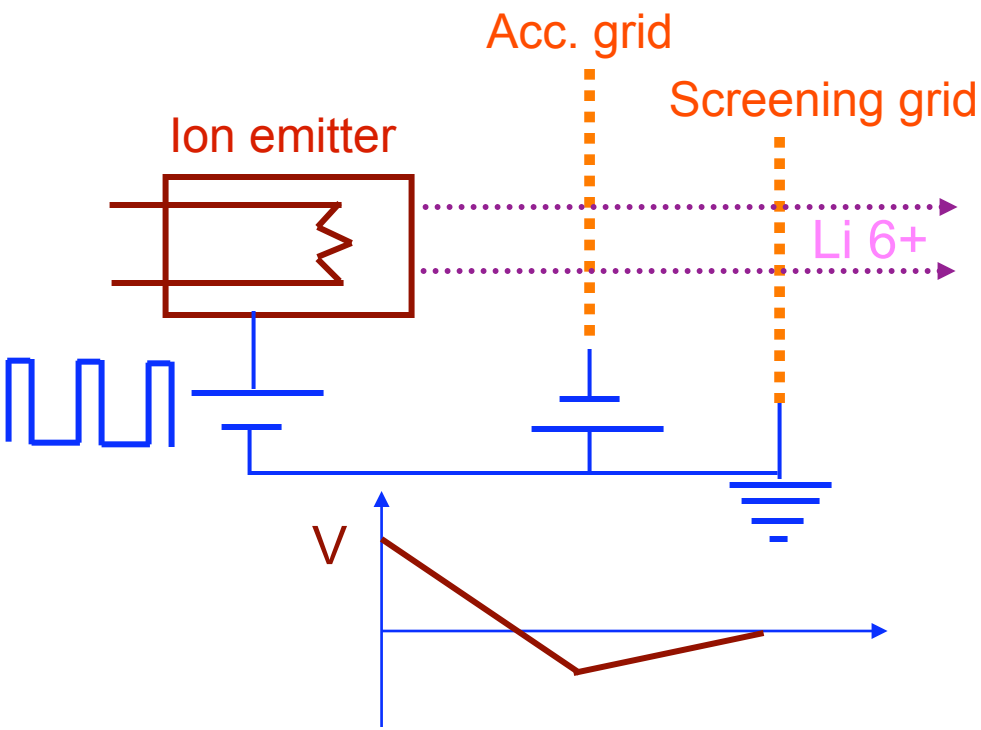
Fast ion source and detector arrangement

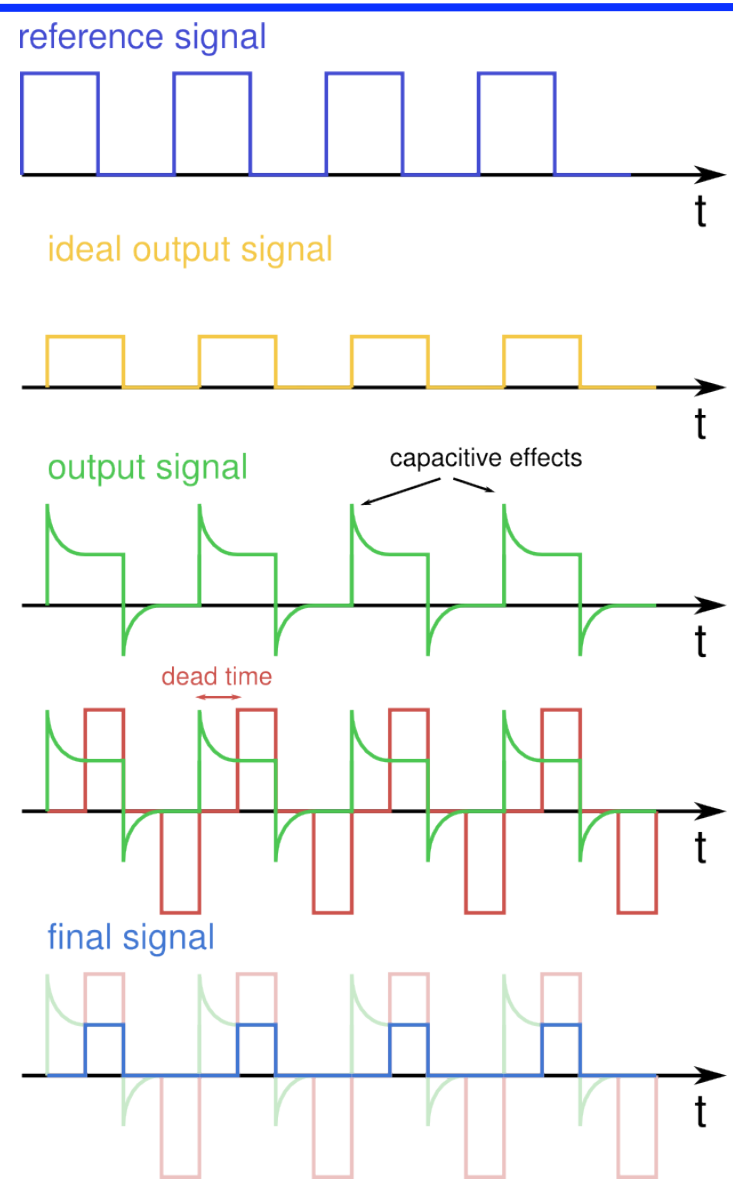




- Ion source and GEA on 2D movable systems ⇒ complete coverage of poloidal section
- Toroidal spacing ~ 10 cm - 5 m

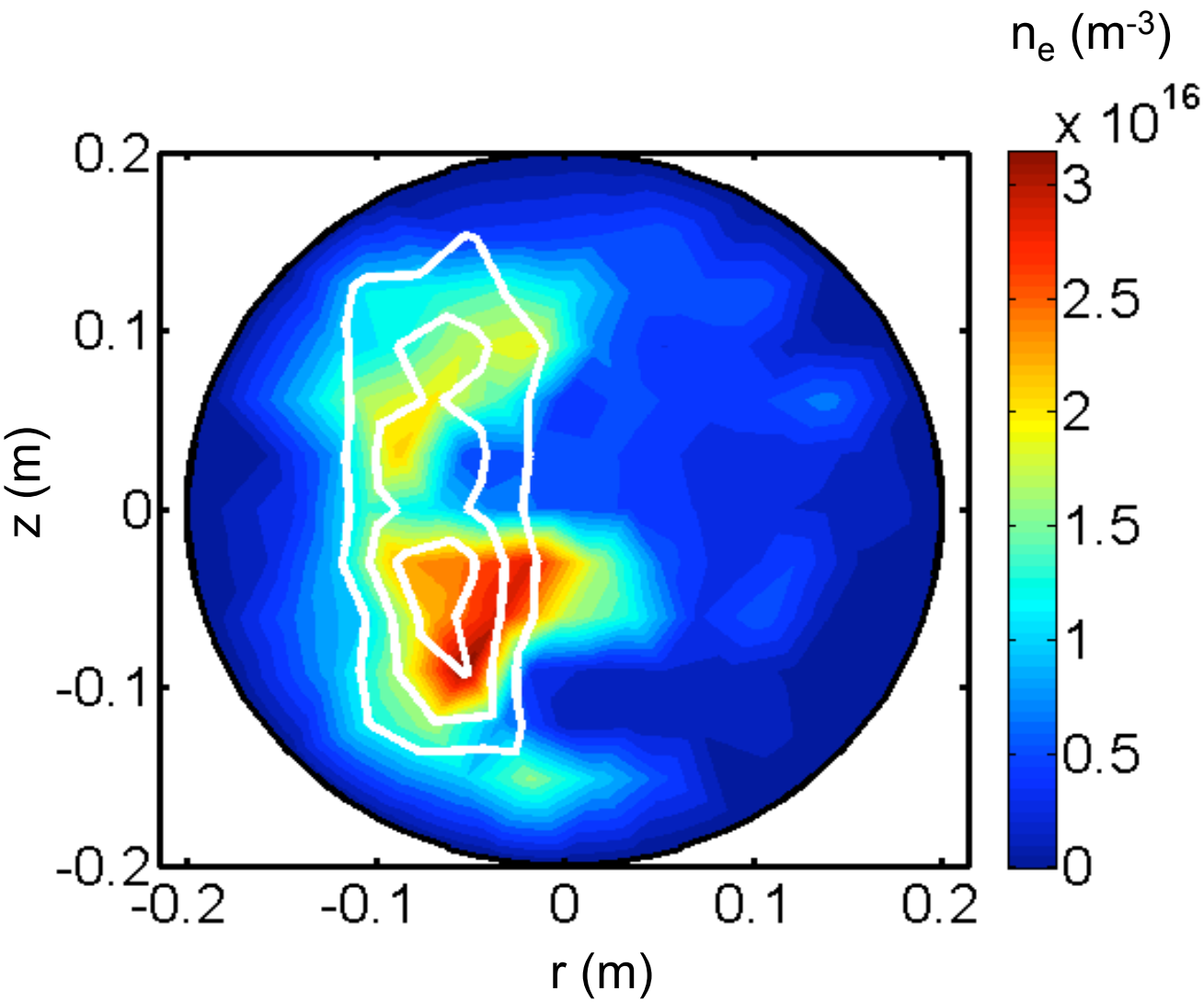
Fast ion beam modulation and detection scheme

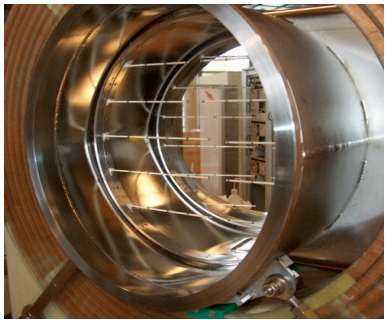




- Screen grid at plasma/ground potential ⇒ reduce plasma disturbance
- 0.1-1kV modulated (~1kHz) power supply ⇒ synchronous detection to increase SNR

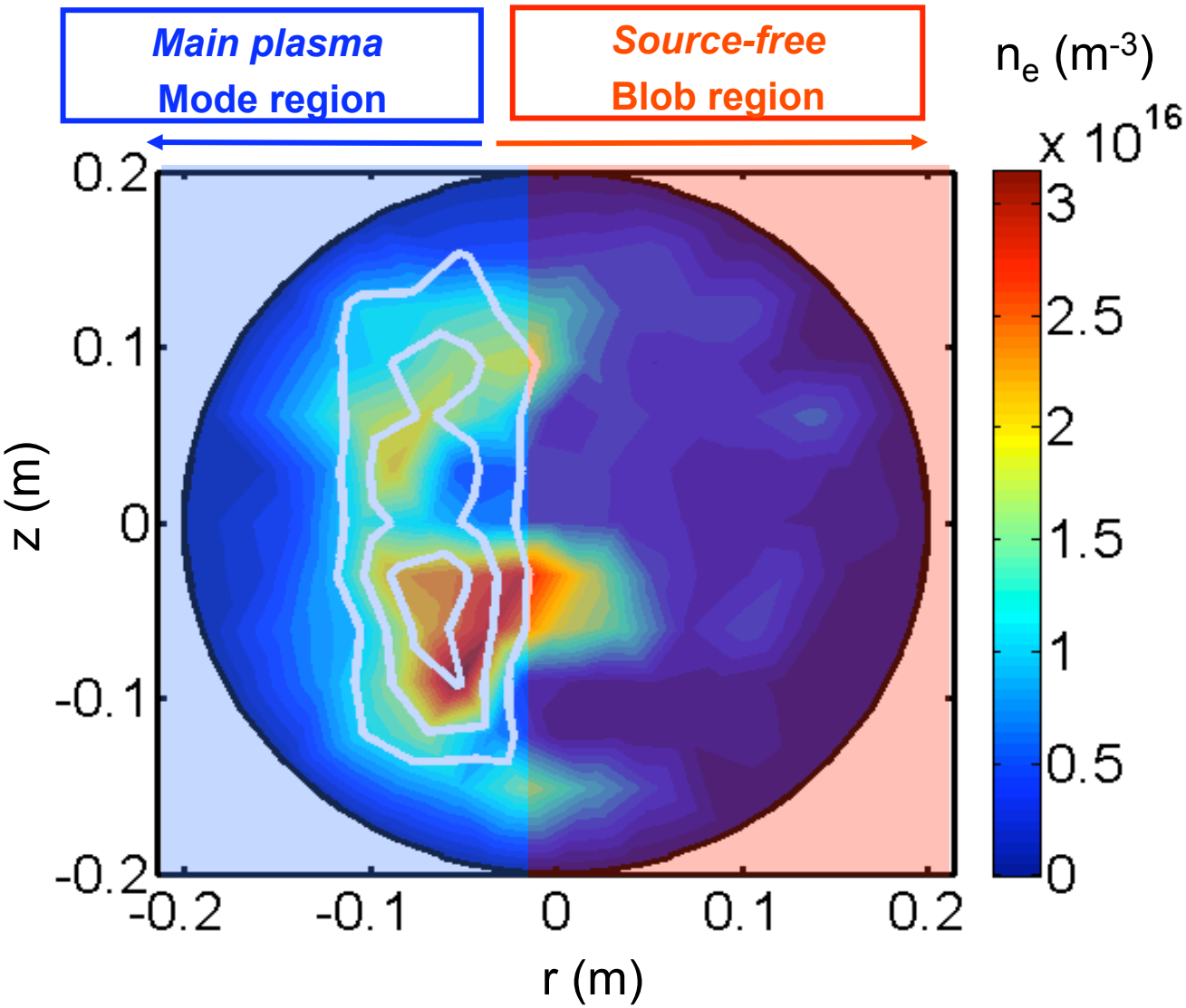
Target plasma

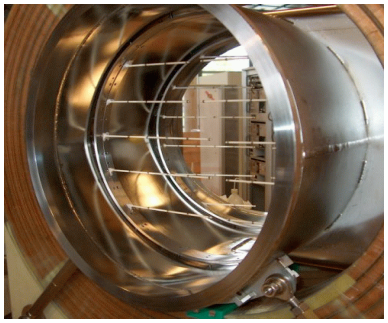




- H_2 plasma
  - P_{rf} = 150 W
  - B_{tor0}=76mT; B_z=2.1mT
  - p_{gas}= 6.0 x 10^{-5} mbar
- Elongated profiles with strongly sheared v_{ExB}
- Ion source and detector 42 cm toroidally apart

Target plasma





- H_2 plasma
  - P_{rf} = 400 W
  - B_{tor0}=76mT; B_z=2.1mT
  - p_{gas}= 6.0 x 10^{-5} mbar
- Elongated profiles with strongly sheared v_{ExB}
- Ion source and detector 42 cm toroidally apart

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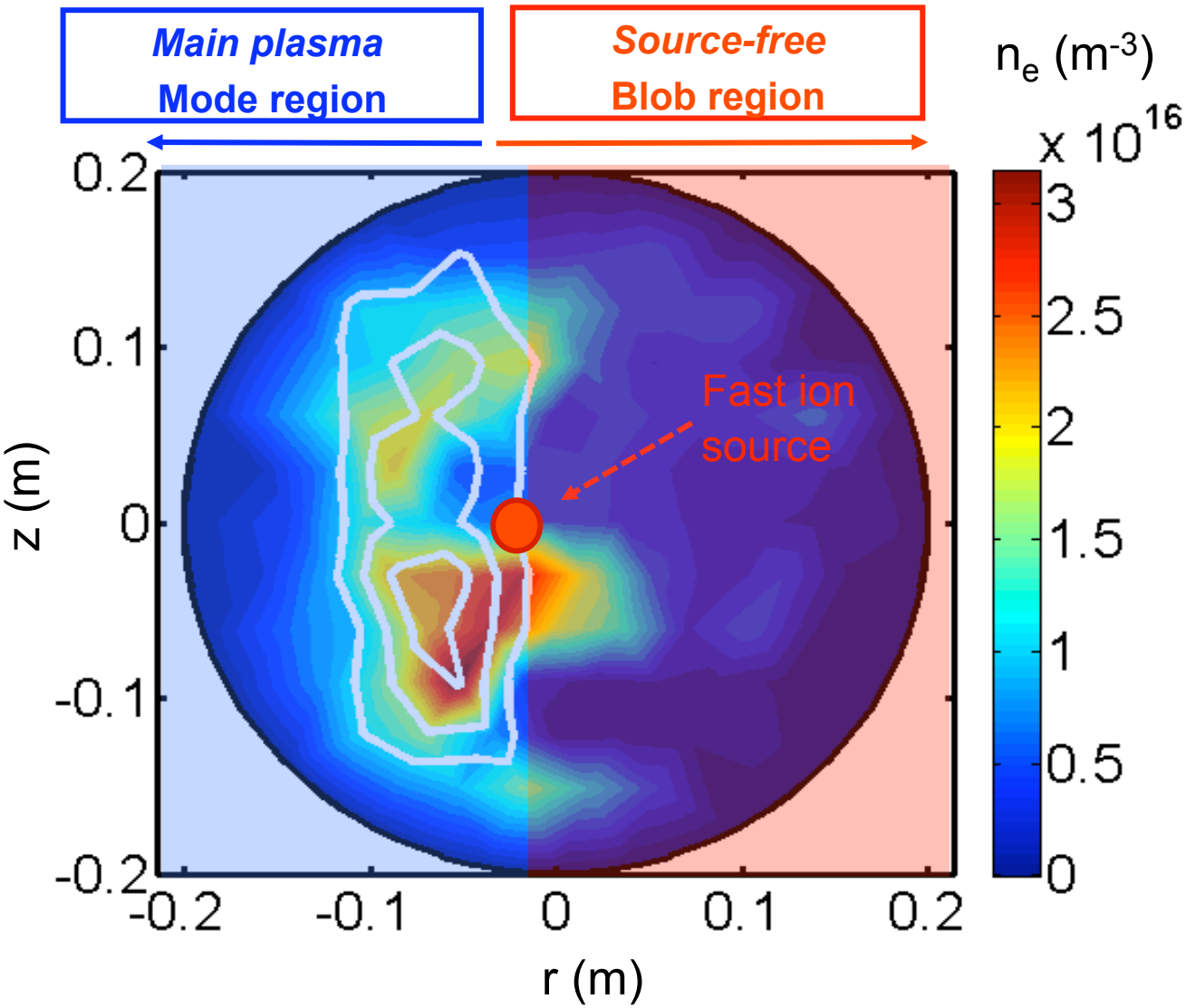

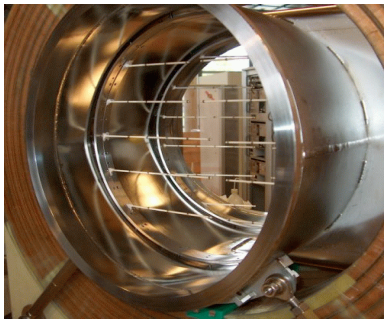

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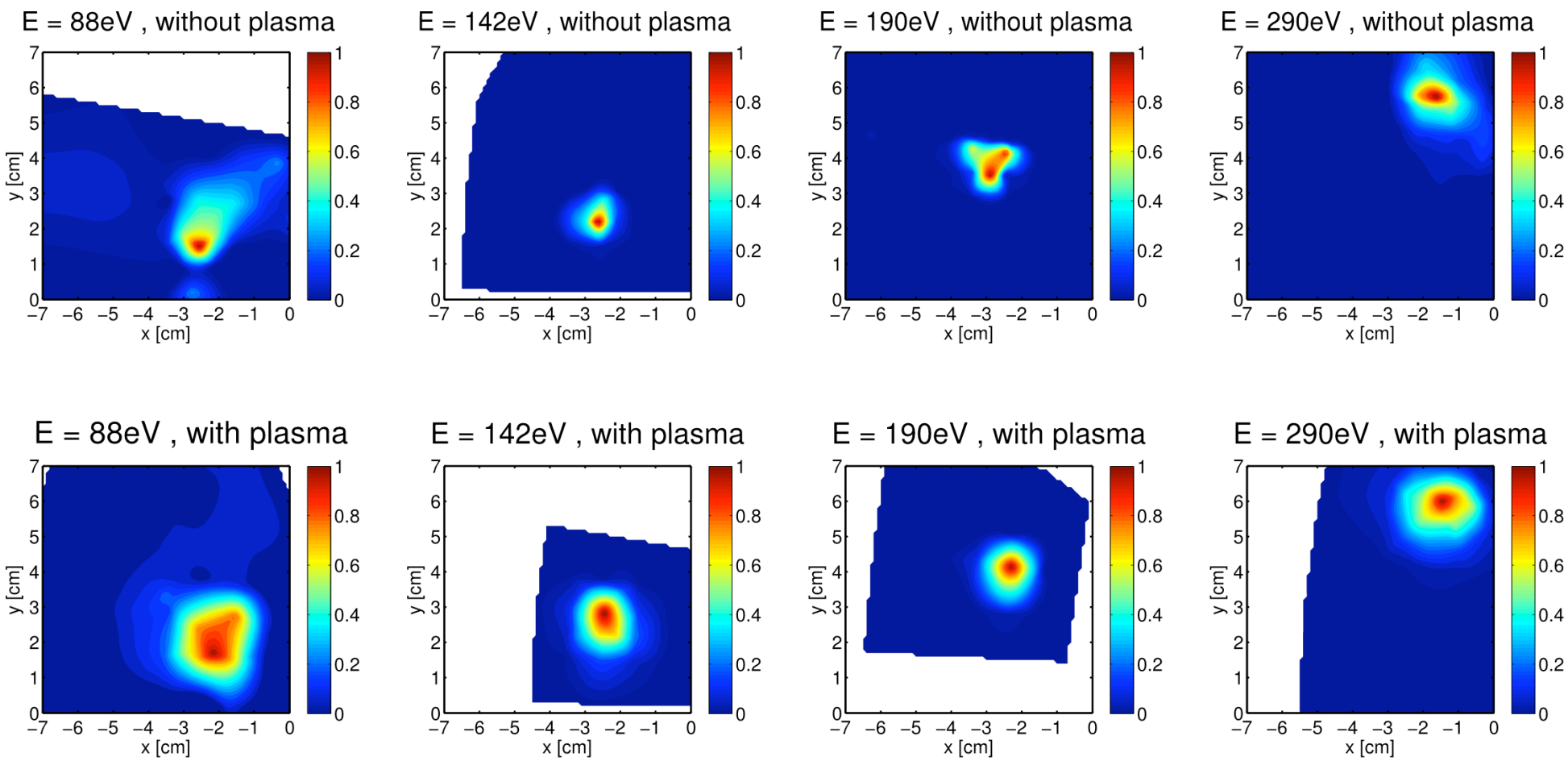
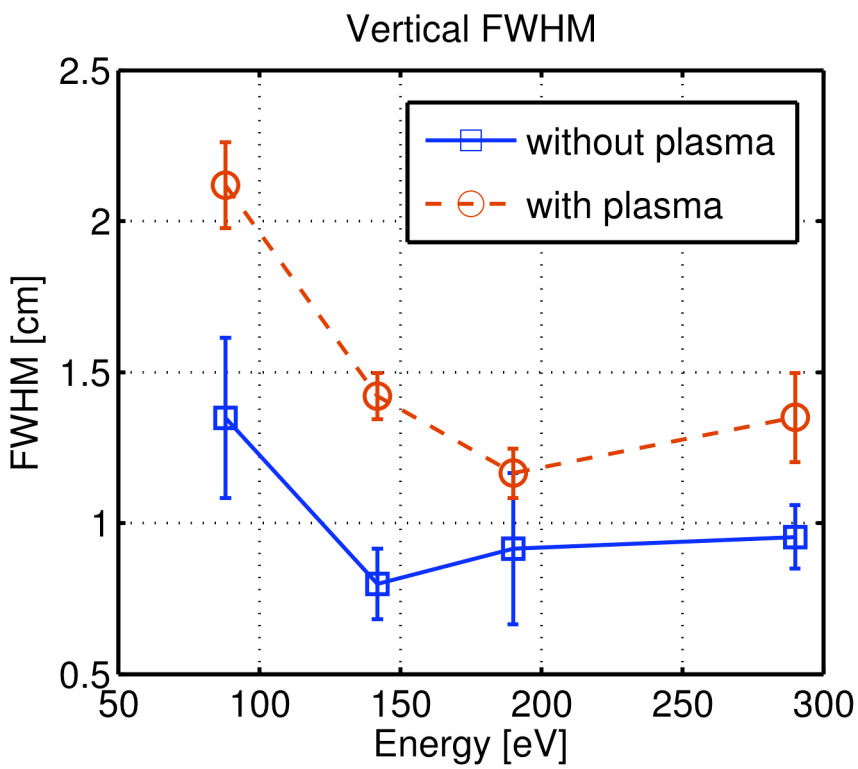
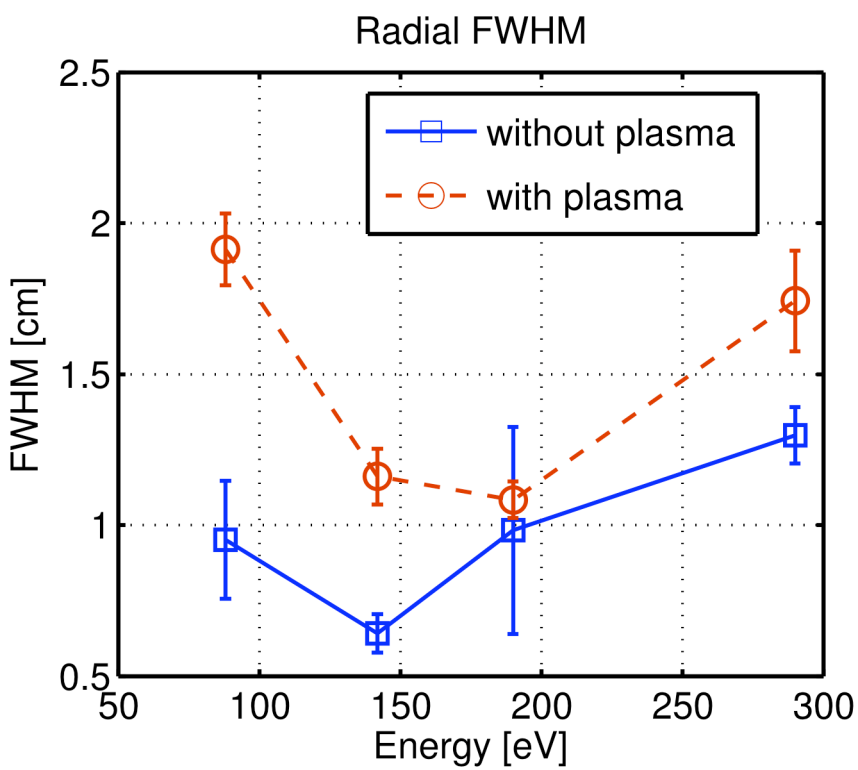
Experimental fast ion current density profiles, $\Delta\phi$=42cm



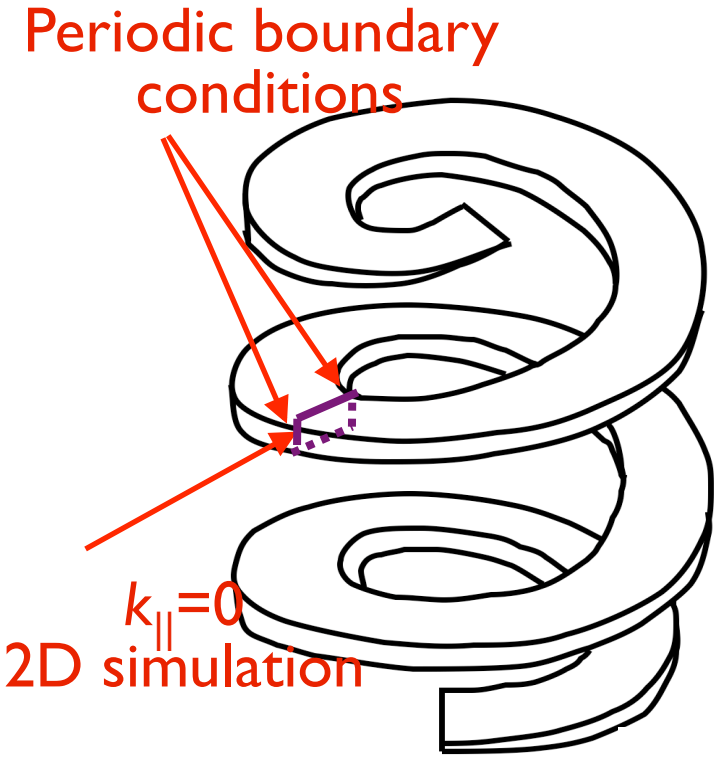
Measured spreading of fast ion beam at $\Delta\phi$=42cm

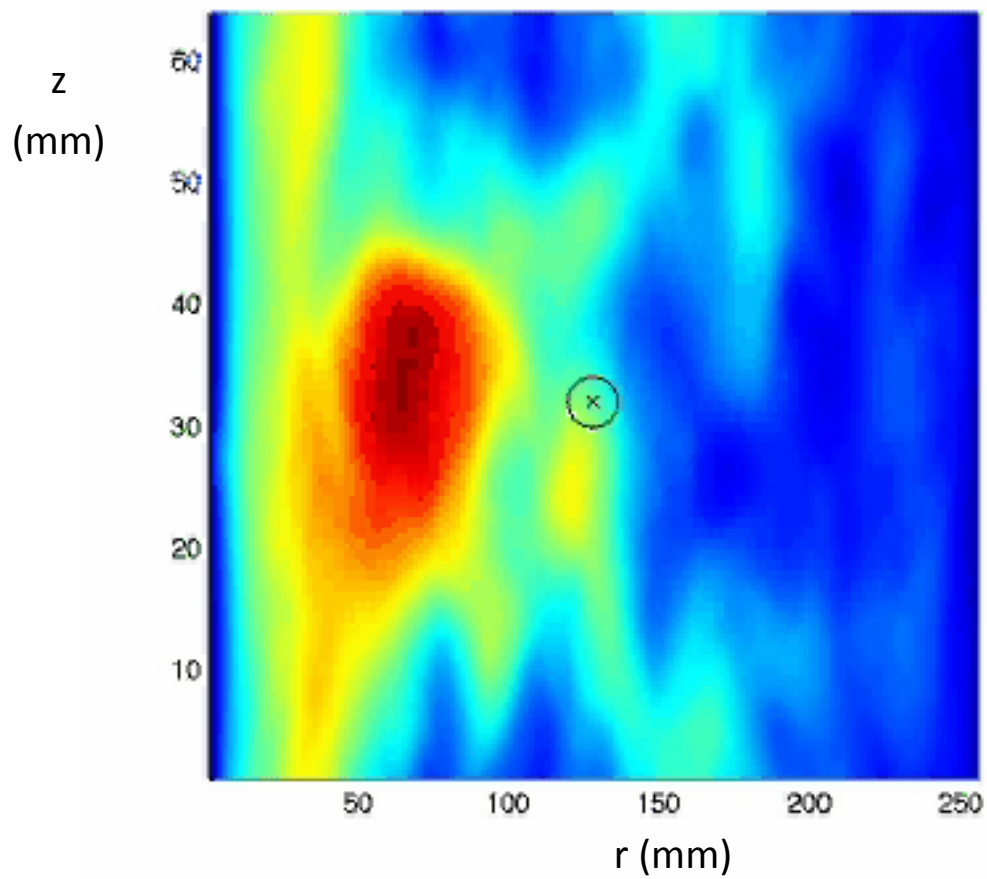


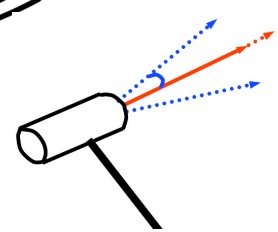


Simulated fast ion motion in turbulent E-field

- Motion of tracer particles in turbulence calculated by 2D fluid simulations

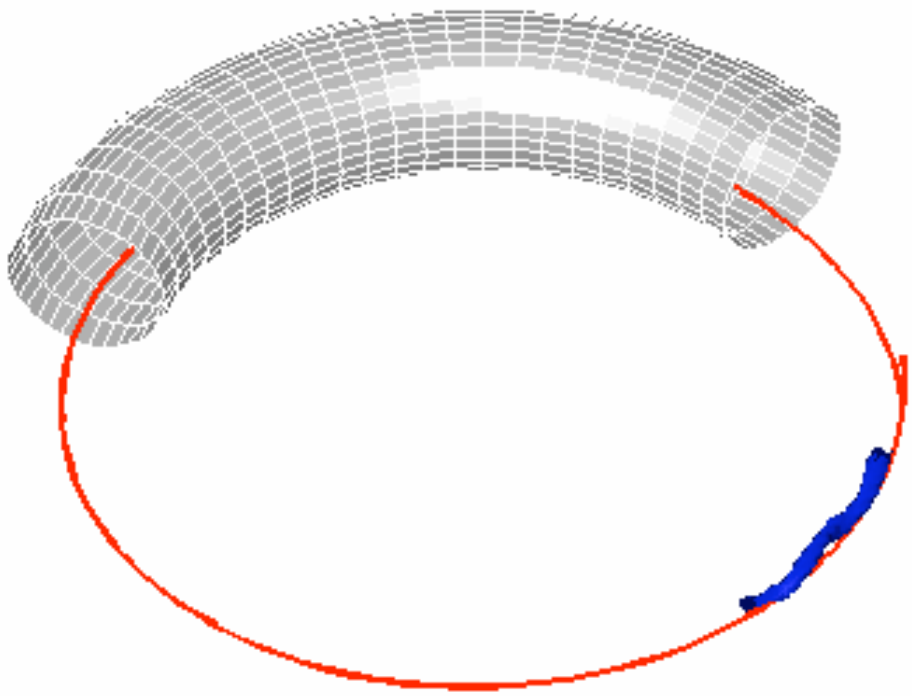






Source with spread in energies ($\Delta E/E=10\%$) and in angular distribution (0.2rad)

Simulated 3D fast ion current density profile



Synthetic diagnostic of fast ion current profile evolution

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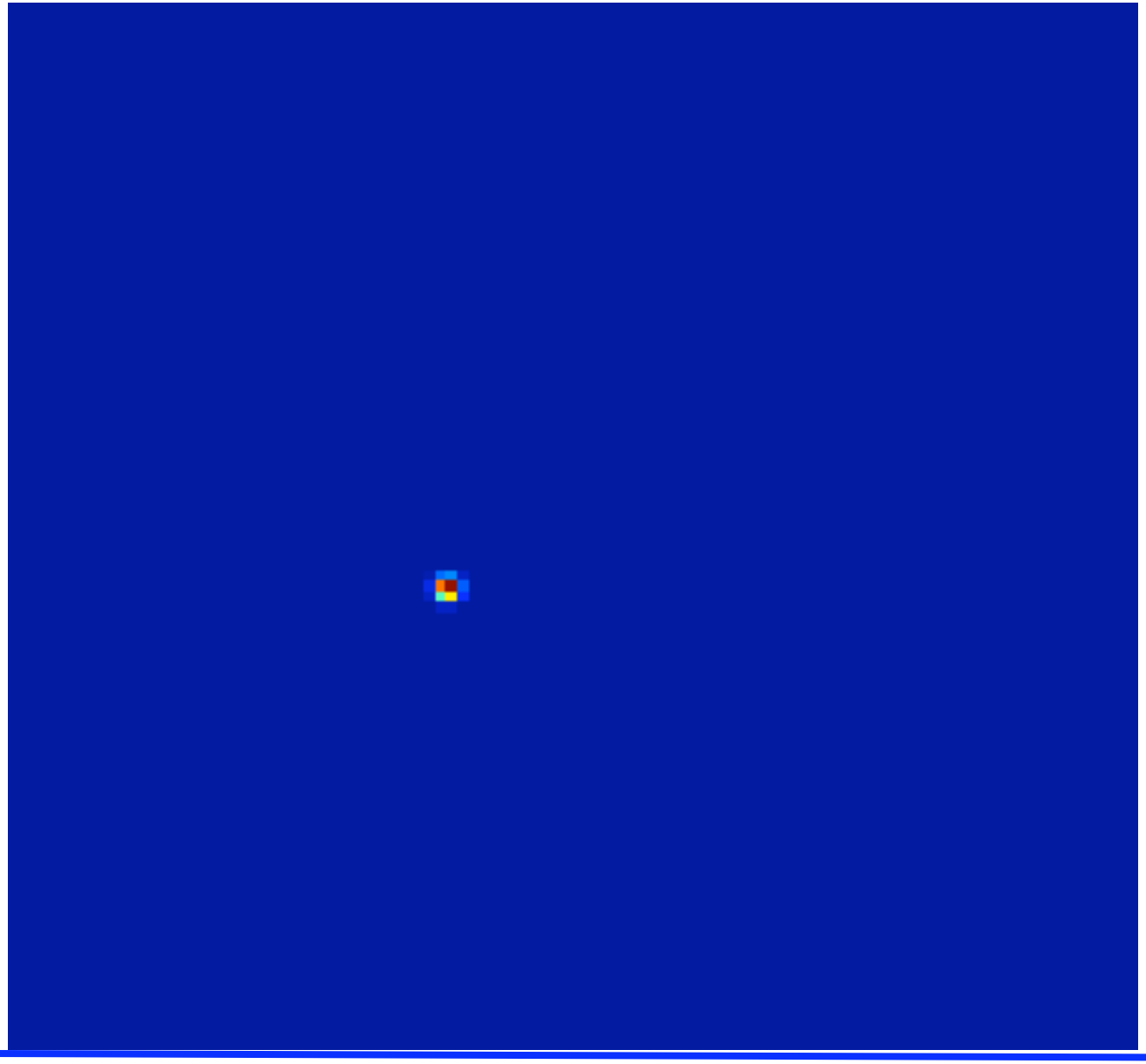
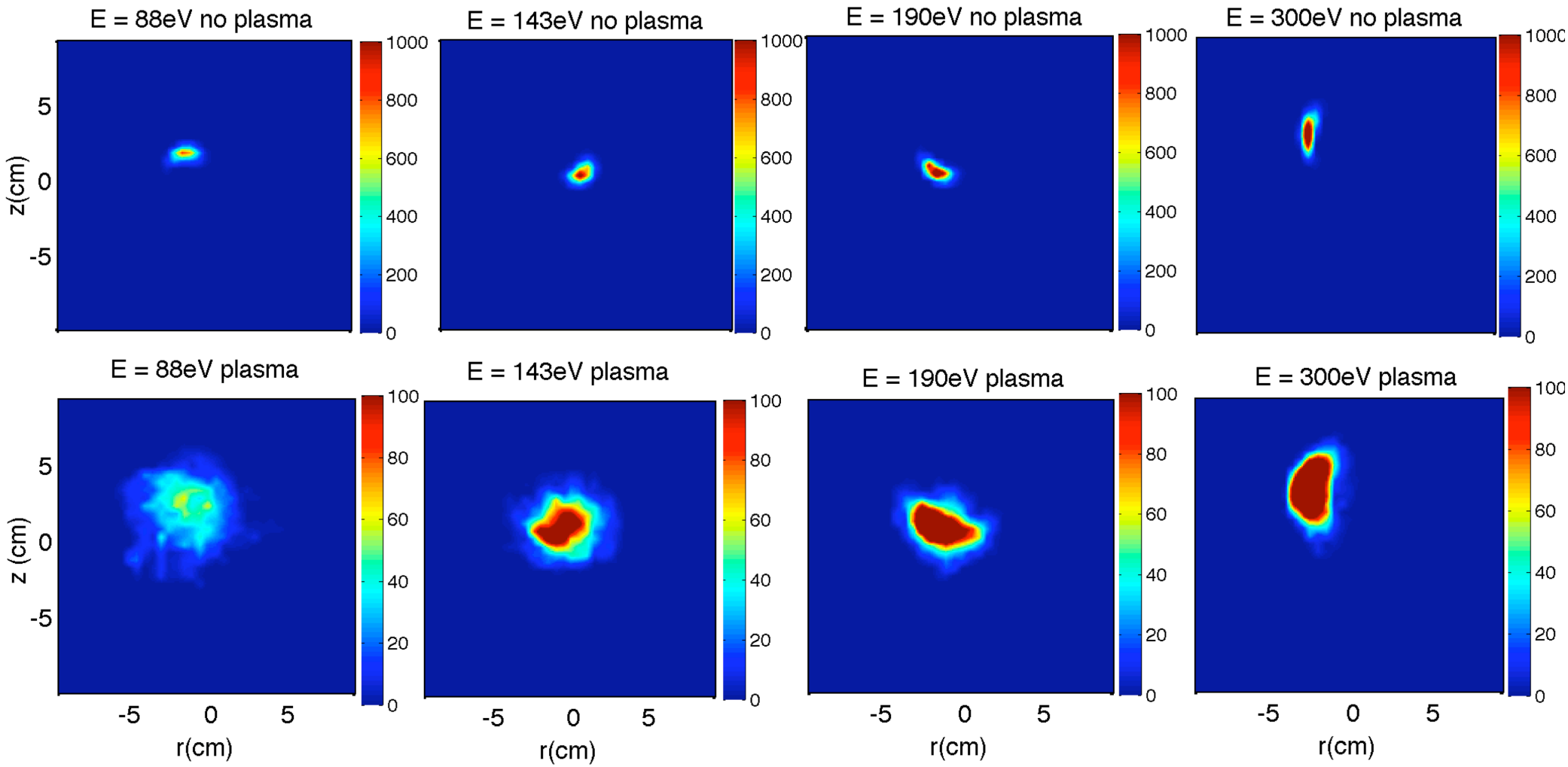


Synthetic diagnostic of fast ion current profile, $\Delta\phi$=42cm



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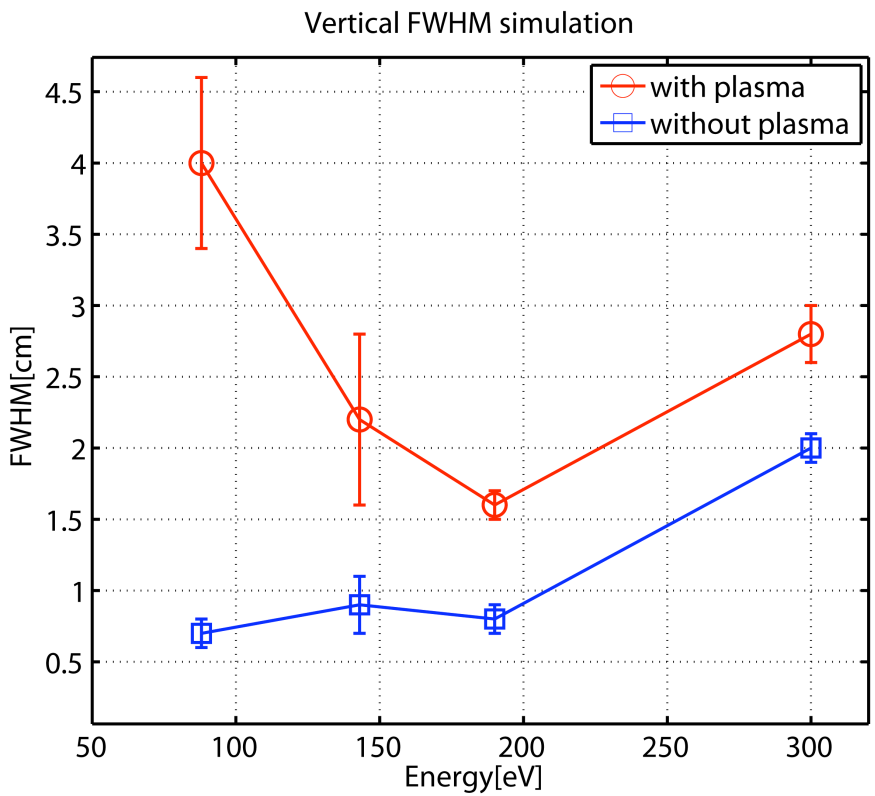
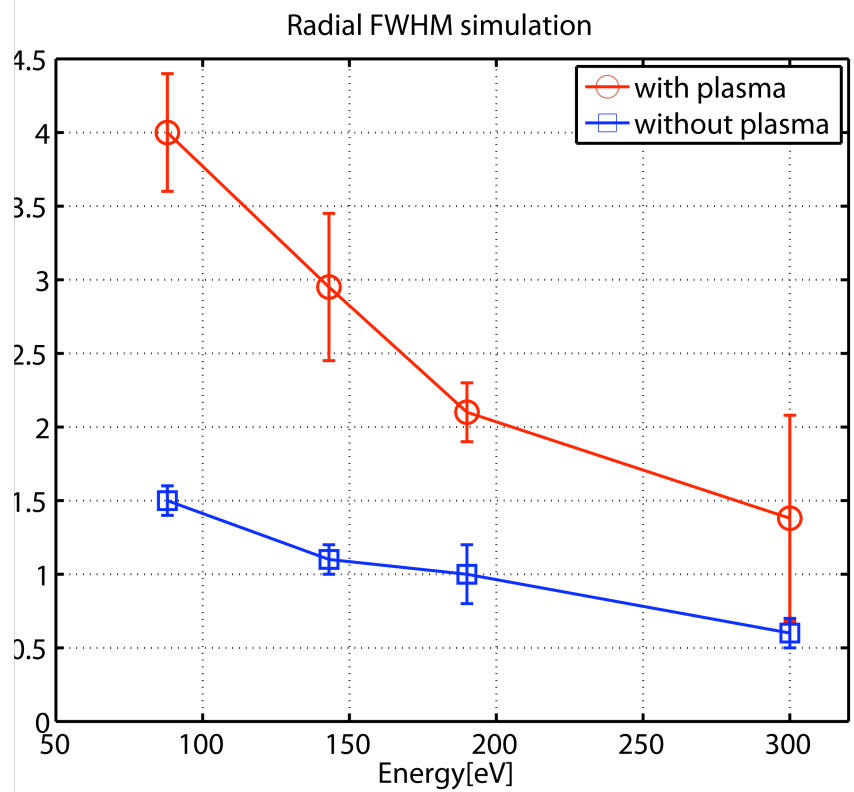
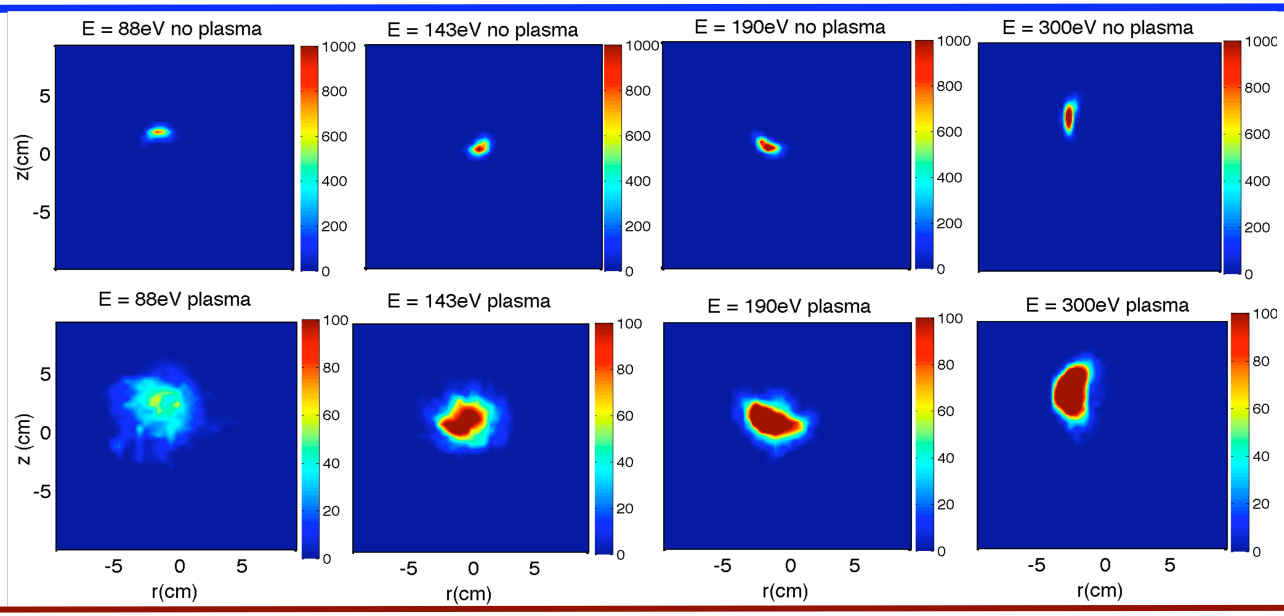
Beam spreading from synthetic diagnostic at Δϕ=42cm





Fast ion current profile – theory vs. experiment, Δϕ=42cm

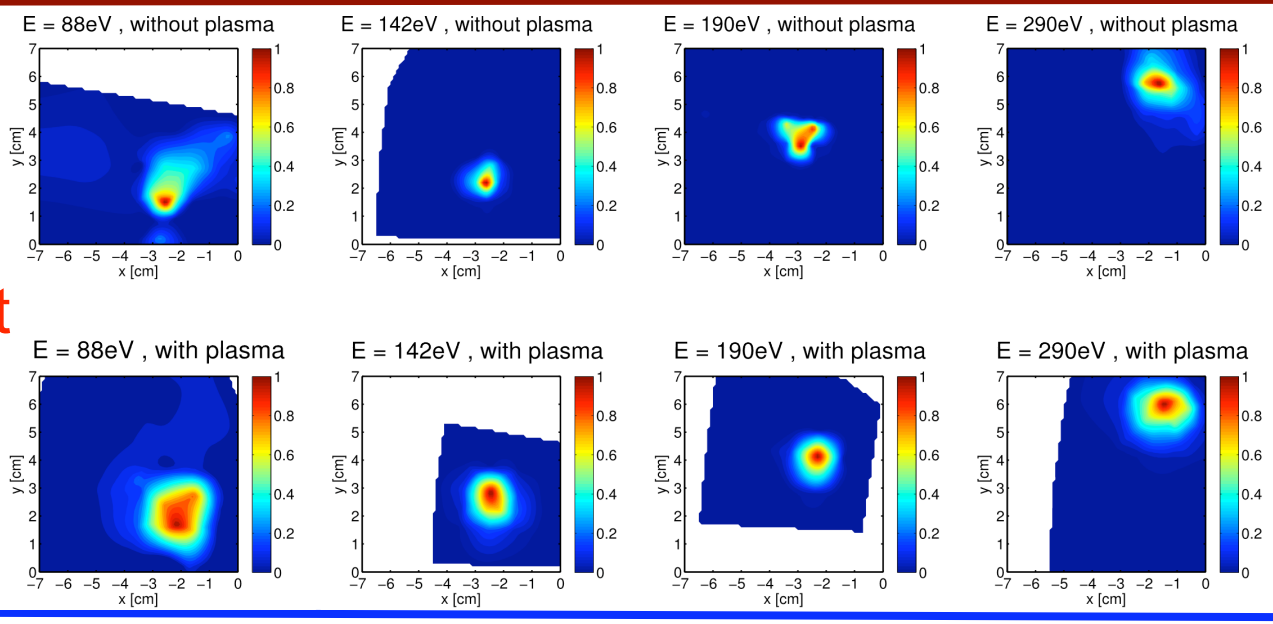
Theory



Without plasma

With plasma

Experiment

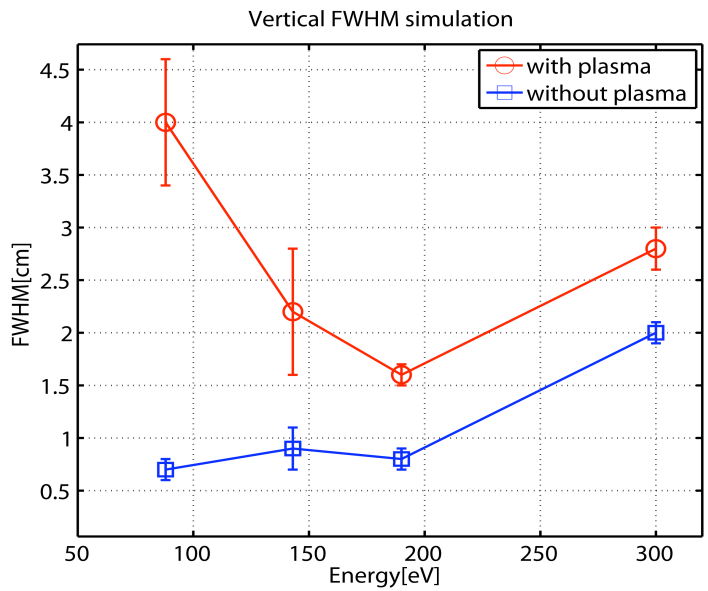


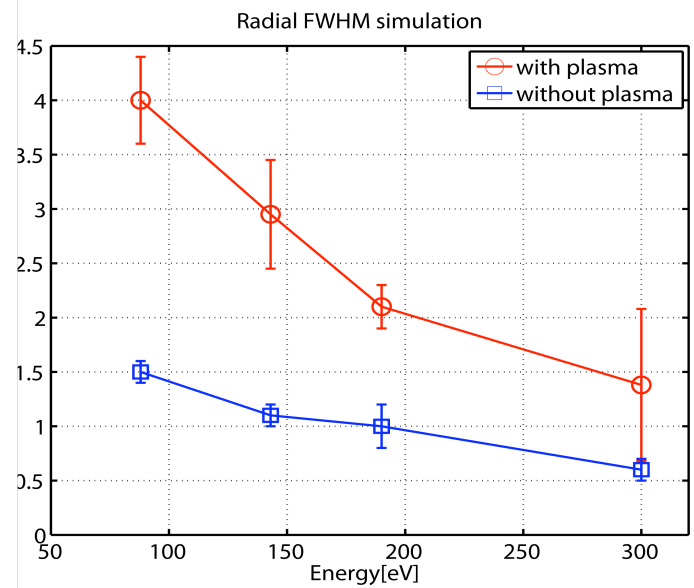
Without plasma

With plasma

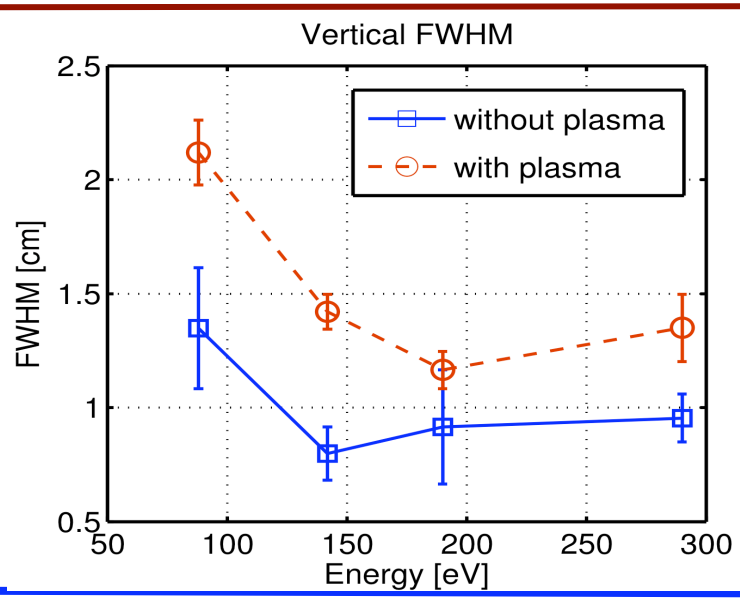
Fast ion beam spreading – theory vs. exp. at Δϕ=42cm

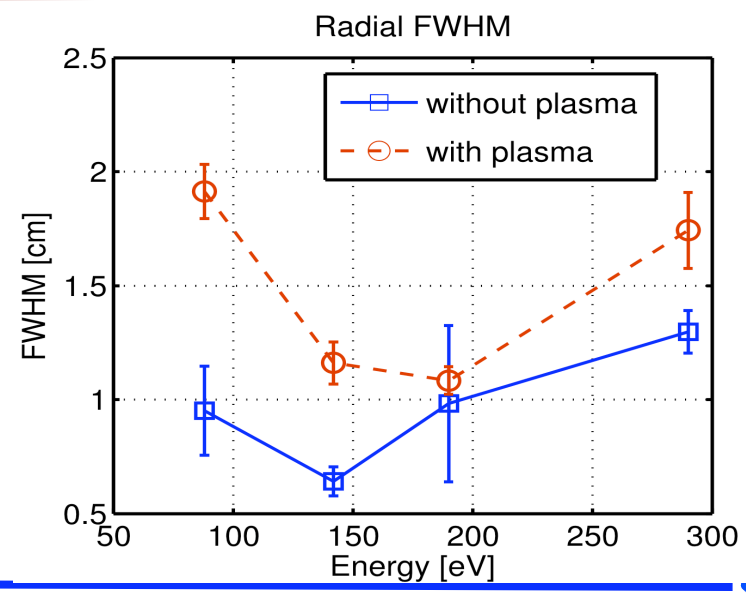
Theory





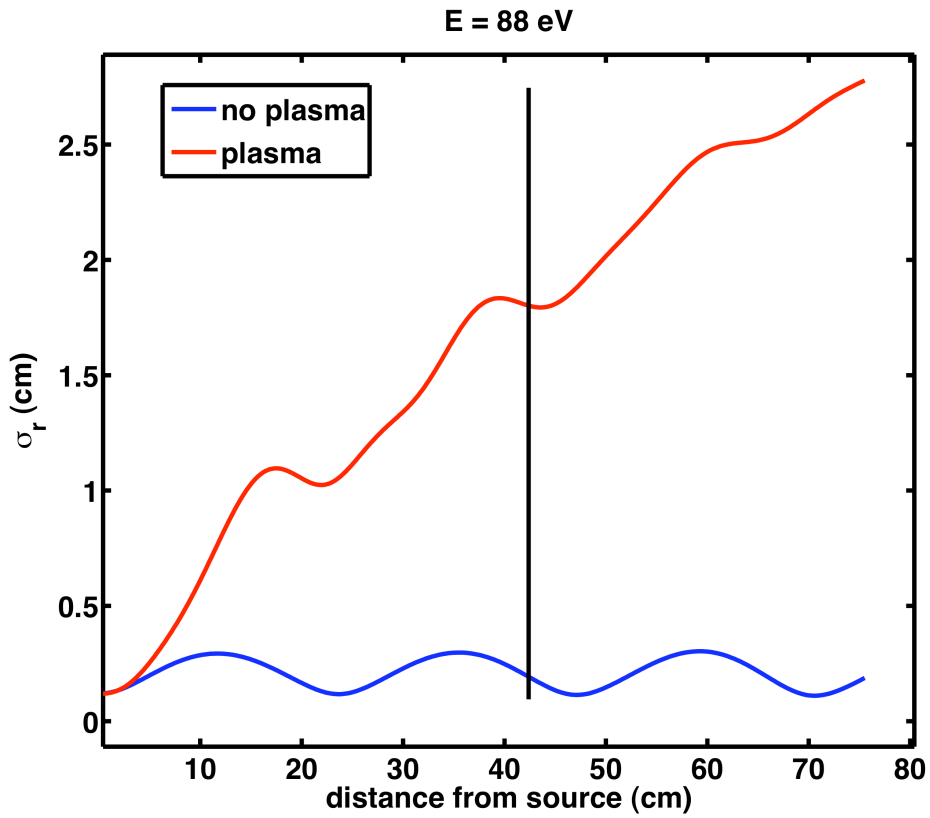
Experiment

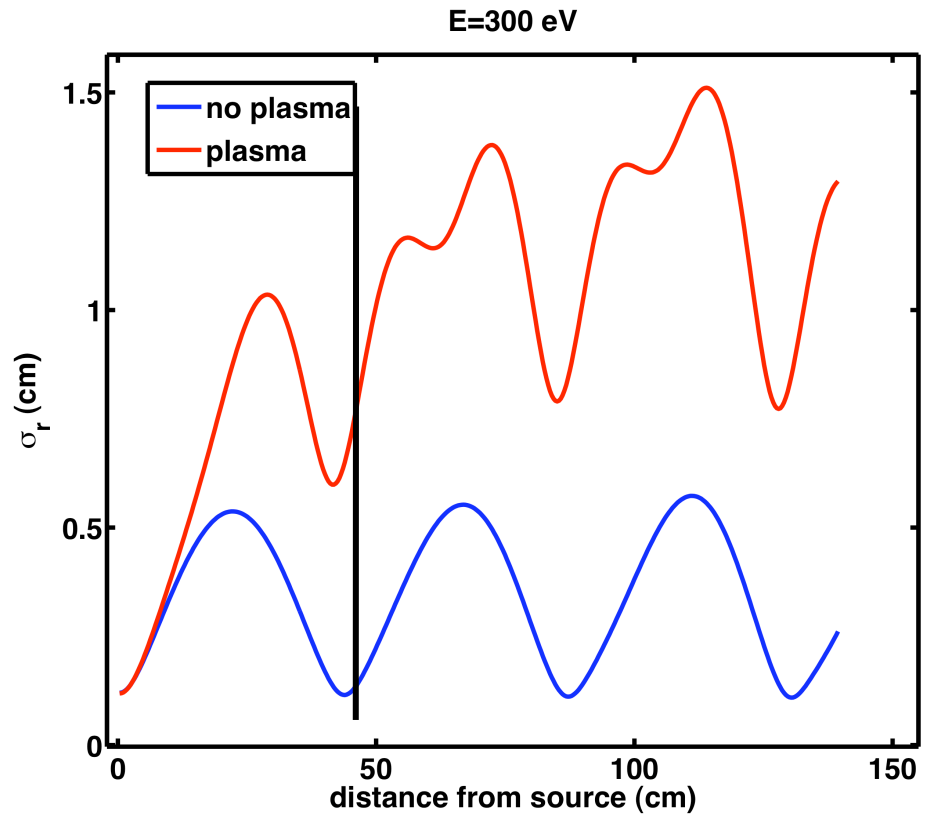




Simulation reveals complex 3D beam evolution

Standard deviation of particle distance from mean position





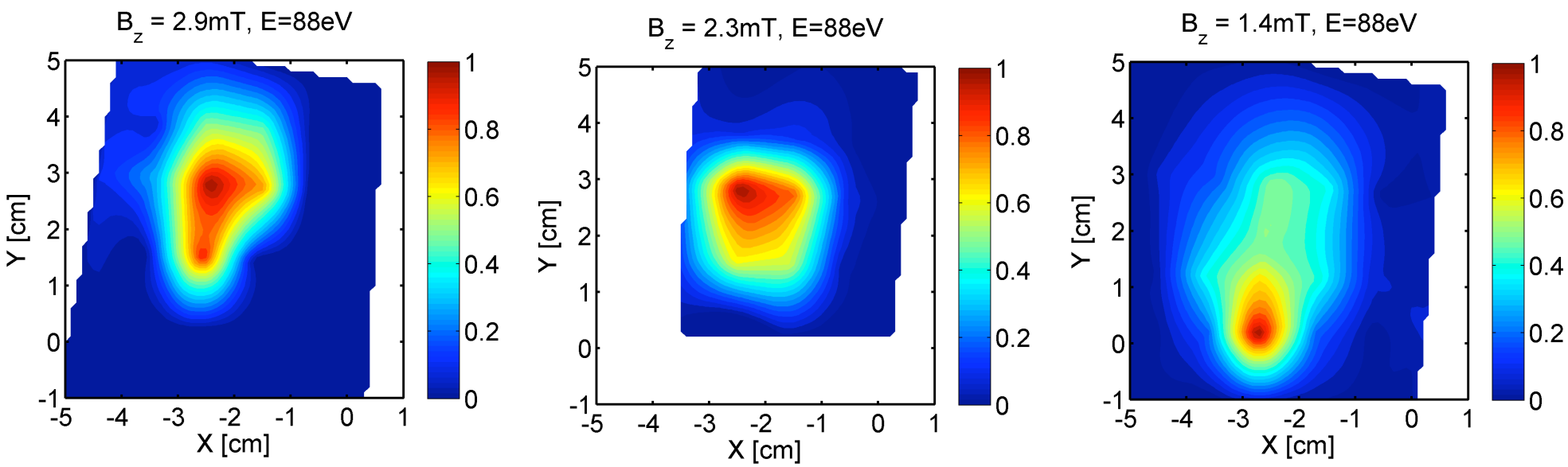
Gyro-motion influence on 3D dynamics is stronger for higher ion energies

Summary

- Miniaturized fast ion source and detector have been developed for TORPEX simple magnetized plasmas
- First experiments reveal effects of plasma turbulence on fast ion profiles: small but systematic broadening detected in the presence of plasma with interchange modes/turbulence
- Simulation qualitatively explains the shape of the experimental profiles: radial broadening due to turbulence
- Complex 3D nature of fast ion orbits and beam spreading

Outlook

- Transport of fast ions in the presence of well diagnosed waves and turbulence will be investigated in different magnetic configurations, from the SMP described here to one with rotational transform induced by an internal wire, varying
  - E_{ion}/T_e (varying both E_{ion} and T_e), pitch angle, turbulence characteristics
    - Ex. measured fast ion spreading due to interchange modes with different k_z obtained in SMP by varying vertical B-field



Small k_z (~20m^{-1}) Medium k_z (~30m^{-1}) Large k_z (~40m^{-1})

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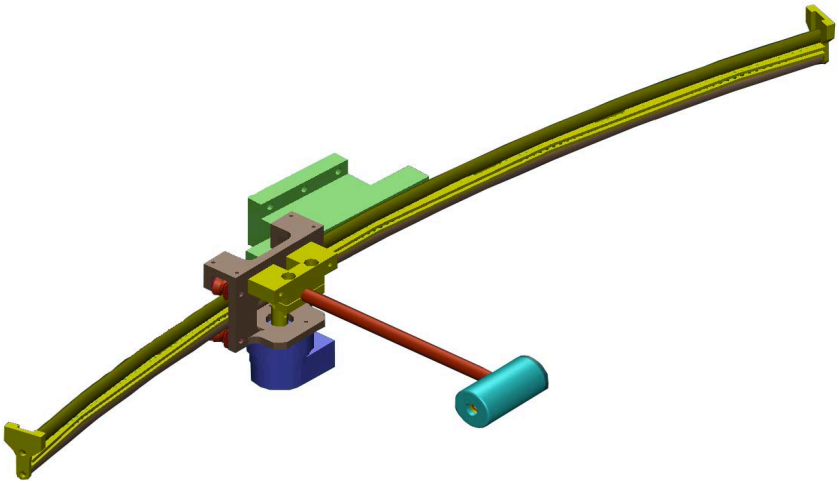
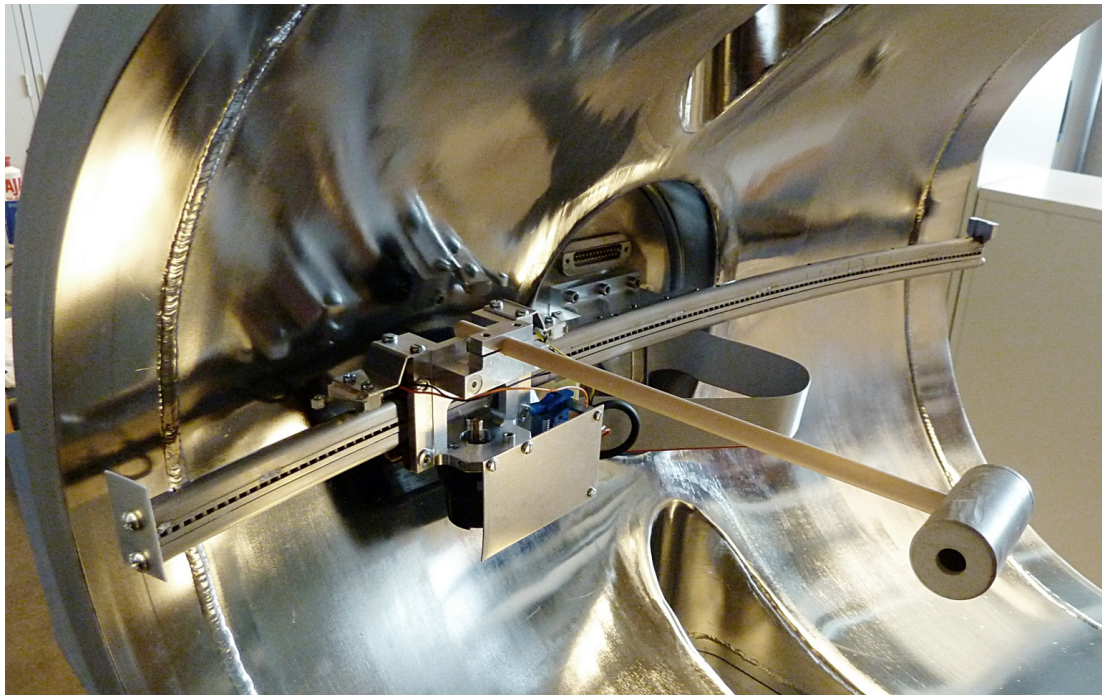
Outlook

- Transport of fast ions in the presence of well diagnosed waves and turbulence will be investigated in different magnetic configurations, from the SMP described here to one with rotational transform induced by an internal wire, varying
  - E/T (varying both E and T), pitch angle, turbulence characteristics
  - Distance between source and detectors (continuously)
    - Discriminate sub-, super-diffusion according to ion energy





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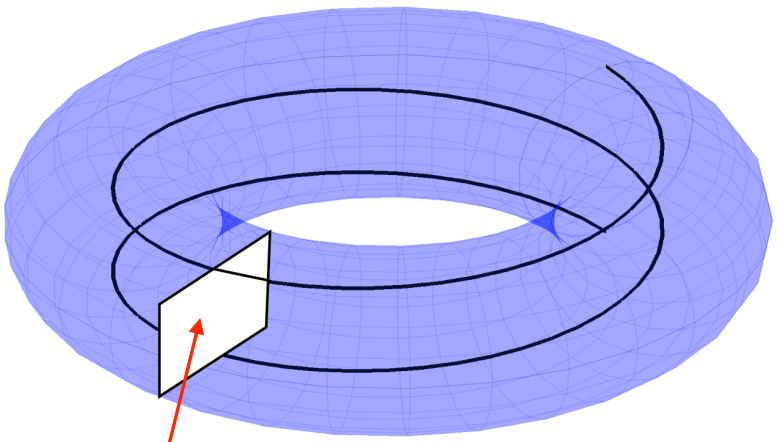
Theory development: fluid model



2D domain

- 2-Fluid model, evolving N, ϕ, T_e.
- ∇B and curvature taken into account.
- 2D geometry with dissipation in the parallel direction.
- Diffusion coefficients from Braginskii equations.
- Source terms from the experiment.

Density →

$$\frac{dN}{dt} = D_n \nabla^2 N + \frac{2}{R}\left(N \frac{\partial T_e}{\partial z} + T_e \frac{\partial n}{\partial z} - n \frac{\partial \phi}{\partial z} \right) - \sigma N \sqrt{T_e} e^{\Lambda - \phi / T_e} + S_n$$

Temperature →

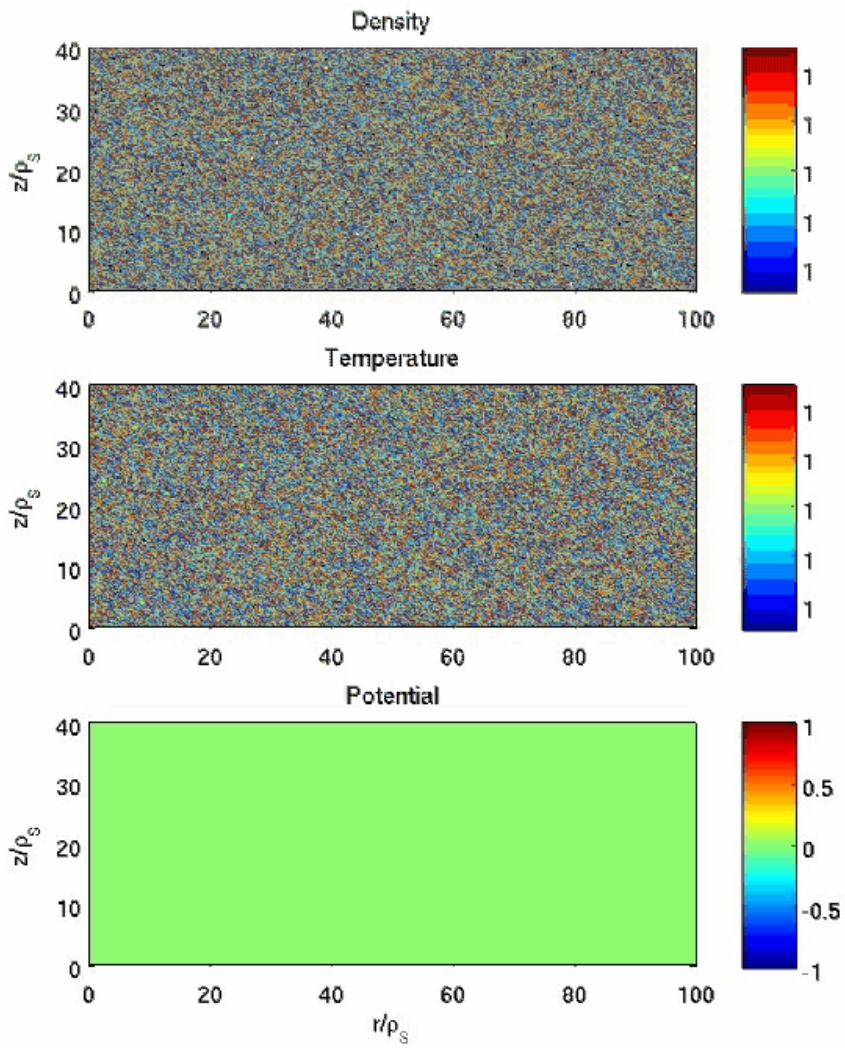
$$\frac{dT_e}{dt} = D_T \nabla^2 T_e + \frac{4}{3R}\left(\frac{7}{2} T_e \frac{\partial T_e}{\partial z} + \frac{T_e^2}{n} \frac{\partial n}{\partial z} - T_e \frac{\partial \phi}{\partial z} \right) - \sigma \sqrt{T_e^3} e^{\Lambda - \phi / T_e} + S_T$$

Potential →

$$\frac{d\nabla^2 \phi}{dt} = D_\phi \nabla^4 \phi + \frac{2}{R}\left(\frac{T_e}{n} \frac{\partial n}{\partial z} + \frac{\partial T_e}{\partial z} \right) + \sigma \sqrt{T_e} \left(1 - e^{\Lambda - \phi / T_e} \right)$$

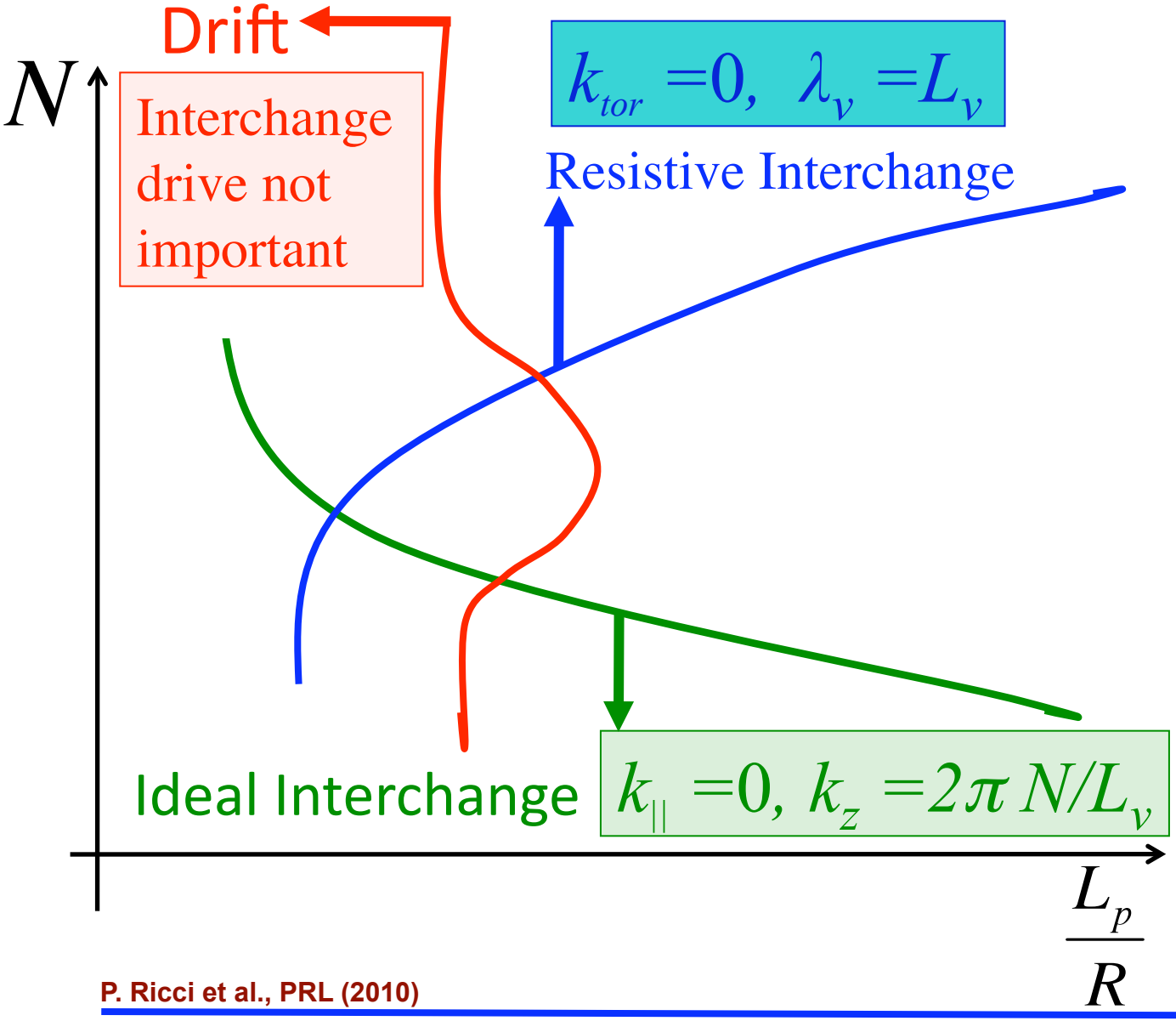
Advection | Diffusion | Interchange drive | Parallel losses | Source

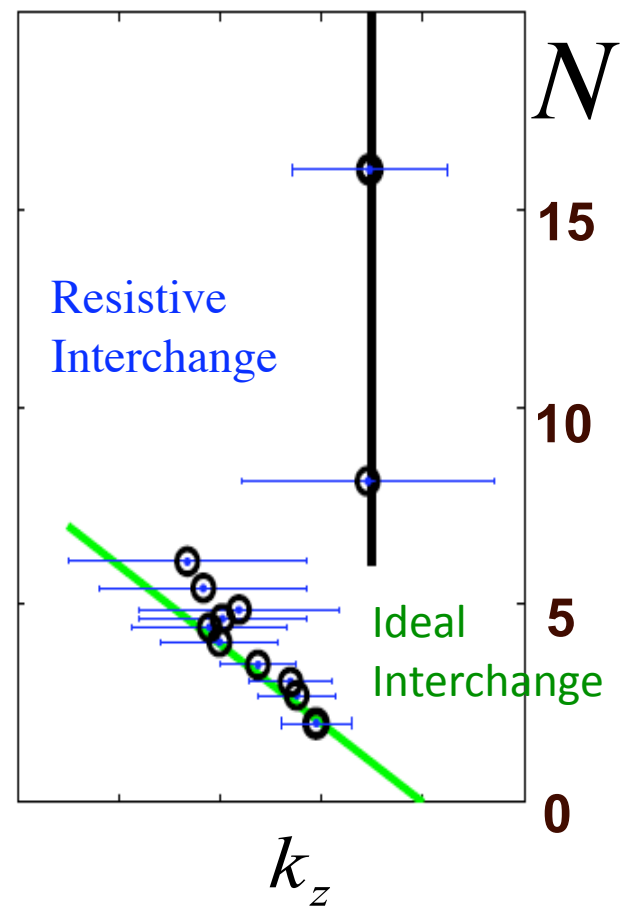
Simulation of interchange-dominated plasmas



- Numerical code based on 2D-ADS code by O.E. Garcia, numerical schemes in V. Naulin, J. Sci. Comput. **25**, 104, 2003.
- The simulation is started from constant values and energy and particles increase during first phase.
- An interchange mode is destabilized. During the non linear stage, the generation of blobs is observed.
- A framework for experiment-simulation comparison has been developed ⇒ definition of observables [P. Ricci, et al., Phys Plasmas (2008)]

Phase space diagram for SMT instabilities





P. Ricci et al., PRL (2010)