Absence of Ion-scale Core Turbulence, Transport Properties, and Transport Barrier Formation in the C-2U Field Reversed Configuration

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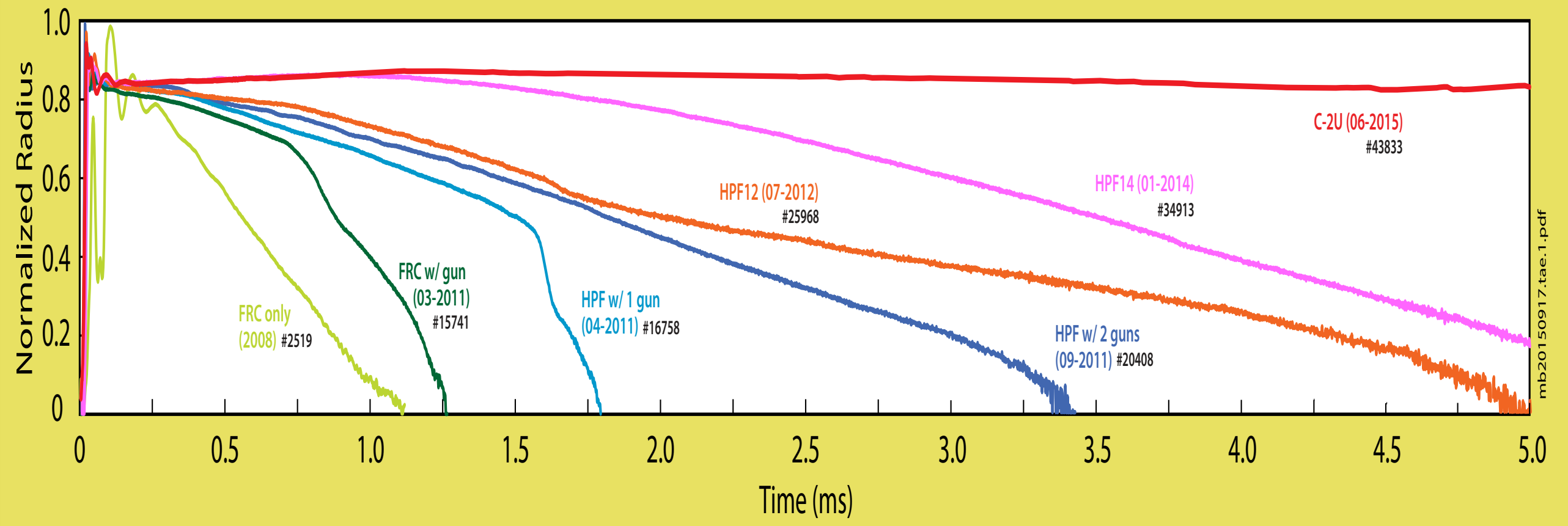
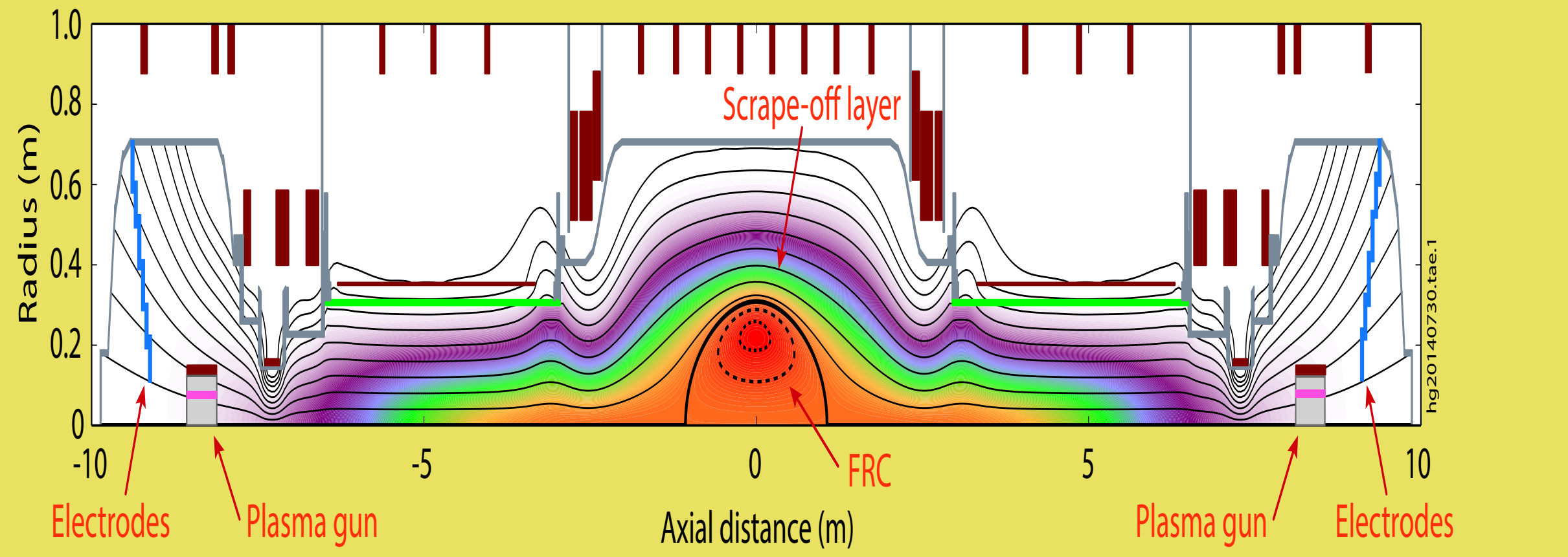
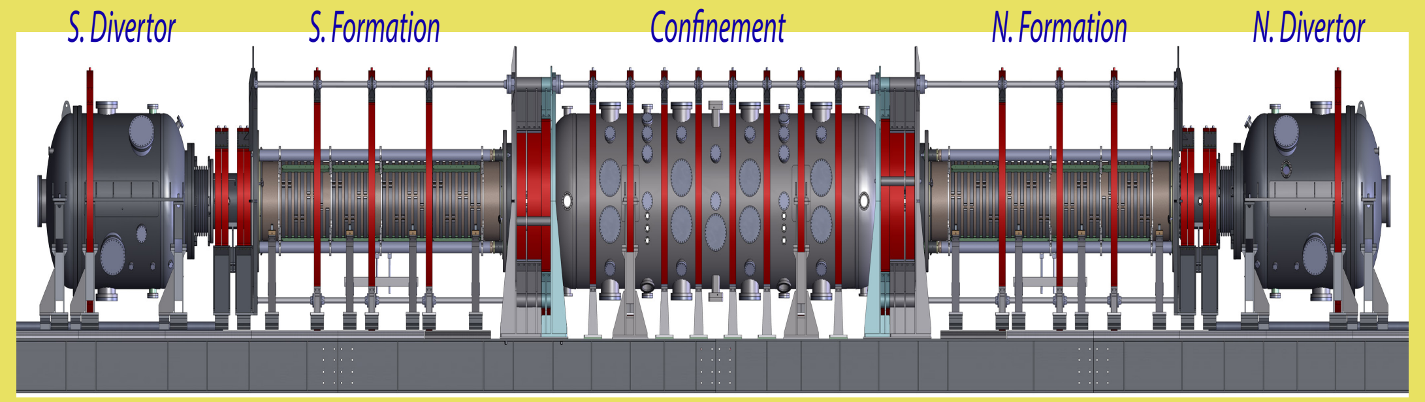
- Ion-scale modes have been shown to be stable in the C-2/C-2U FRC core, in agreement with initial gyrokinetic simulation results, and in contrast to tokamaks, with a characteristic inverted toroidal wavenumber spectrum confirmed via Doppler Backscattering (DBS) measurements. The ion/electron power balance shows near-classical ion confinement and anomalous electron thermal losses. Electron energy confinement scales positively with core electron temperature ($\tau_{Ee} \sim T_e^2$) in contrast to gyro-Bohm tokamak scaling ($\tau_{Ee} \sim T_e^{-1.5}$). Multi-scale turbulence is observed via DBS in the mirror-confined scrape-off layer plasma surrounding the FRC, in agreement with recent global gyrokinetic simulations which also indicate radial propagation into the outer layer of the FRC core (confirmed experimentally). The *E*×*B* flow shear (enhanced by axial plasma gun or divertor electrode biasing) is largest outside the FRC separatrix. The radial turbulence correlation length exhibits a pronounced minimum there, indicating radial transport barrier formation. Prospects for simultaneous measurements of density fluctuations (via DBS) and magnetic fluctuations via cross-polarization scattering (CPS) in C-2W are discussed.

The C-2U Beam-Driven Field-Reversed Configuration

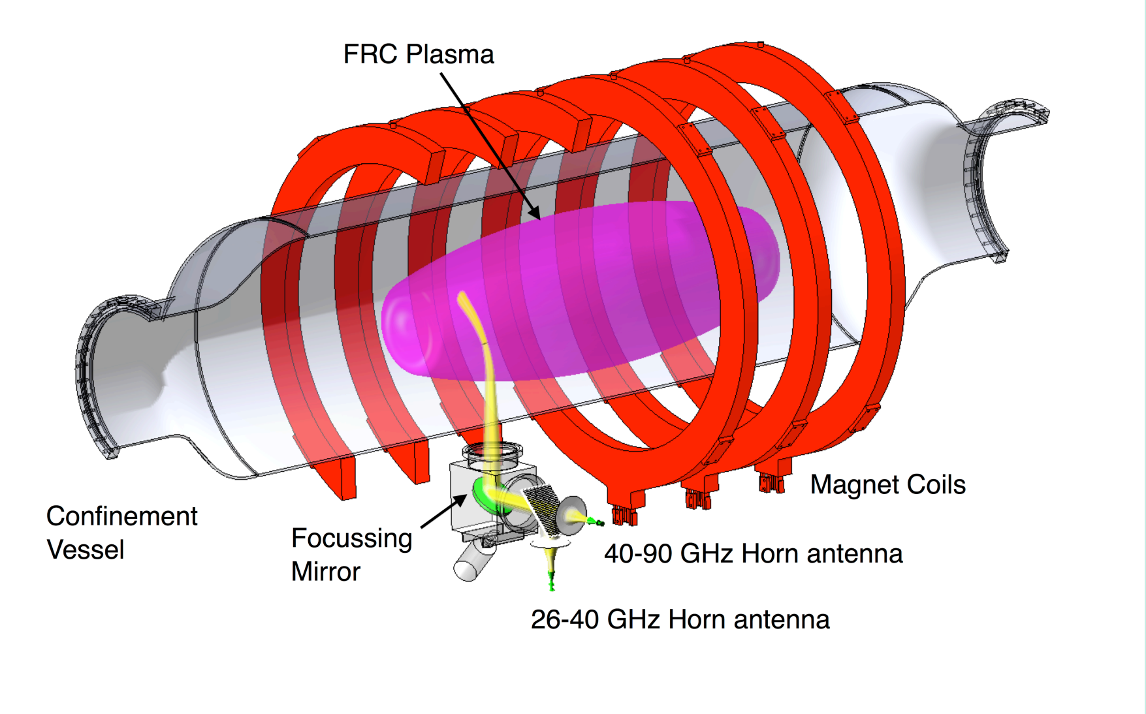
FRC Sustainment: C-2/C-2U History

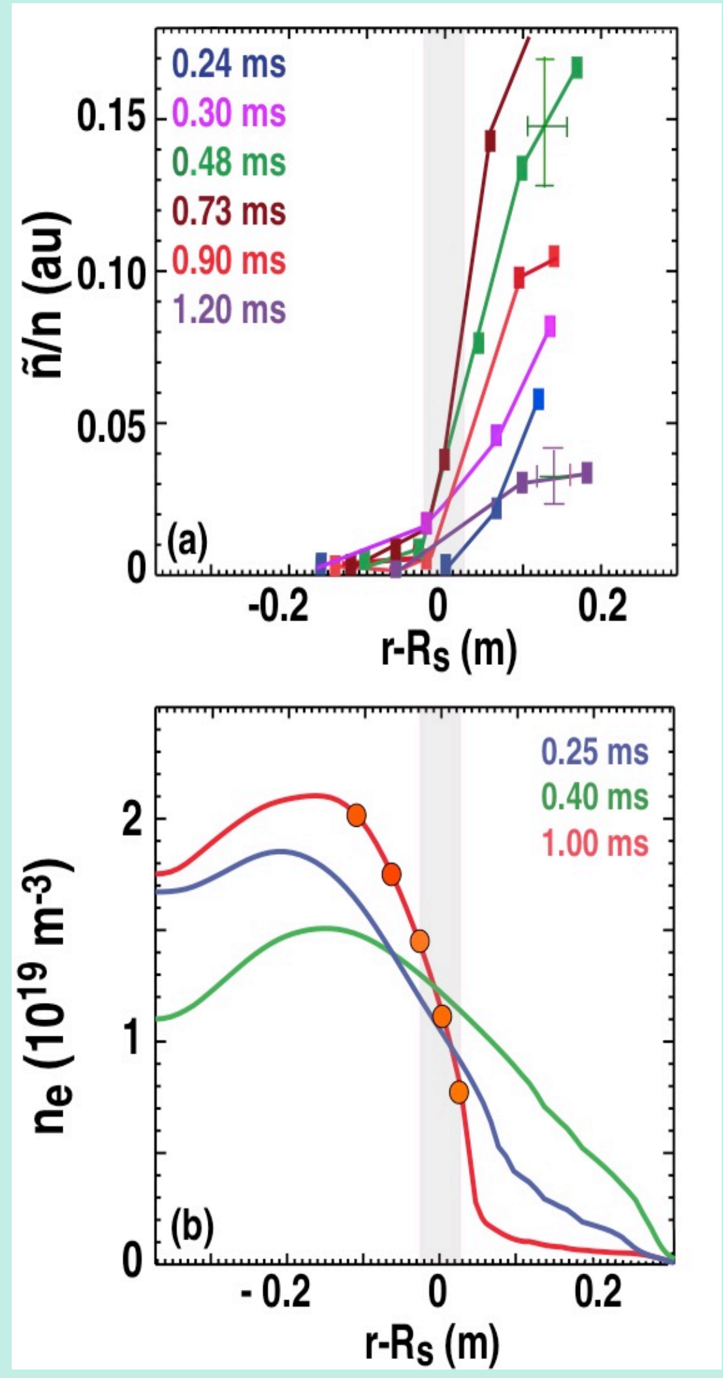




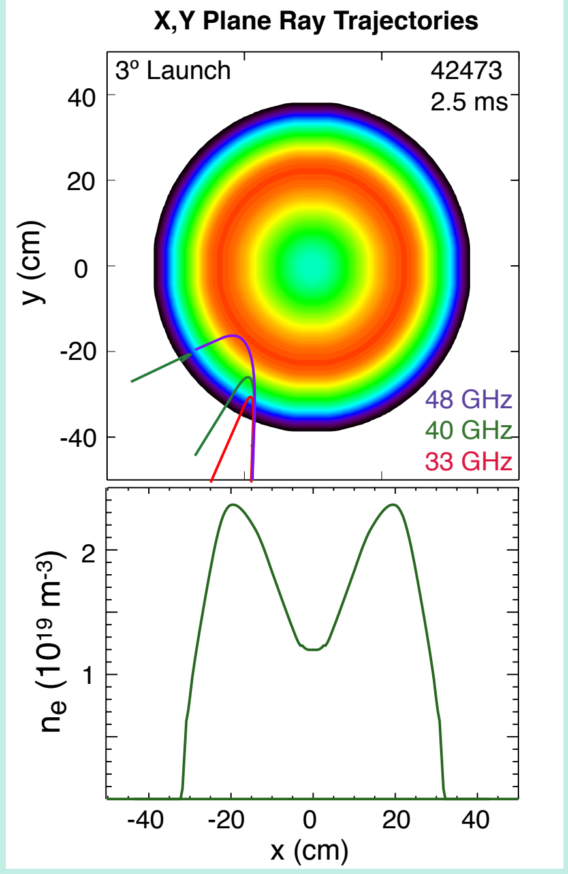


Doppler Backscattering (DBS) Provides Density Fluctuation Level, ExB Velocity, and Wavenumber Spectrum ñ(k$_\theta$)





DBS/CPS can probe toroidal wavenumbers k_θ=1-15 cm^{-1} (via adjusting the beam toroidal launching angle). GENRAY ray tracing is used to reconstruct the cutoff (scattering location and probed turbulence wavenumber).



Planned: Cross-Polarization Scattering (CPS): Measuring Magnetic Fluctuations (B$_r$)

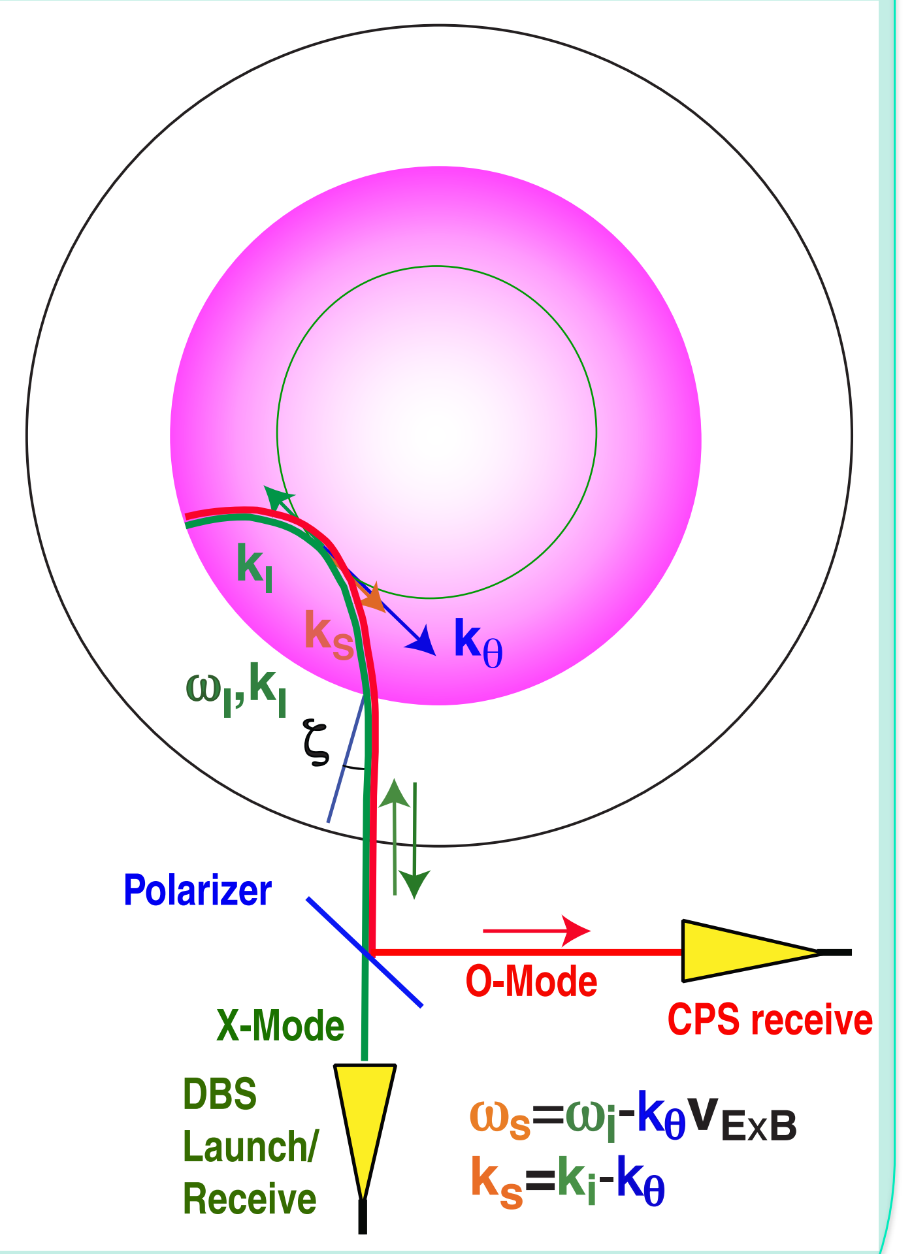
Incident/Scattered electric field $\boldsymbol{E}_{ii}$, $\boldsymbol{E}_s$:
Induced current $\boldsymbol{J}^{(i)}$:

$$-\nabla\times\left(\nabla\times \boldsymbol{E}_s\right)+\left(\frac{\omega_i}{c}\right)^2\left(1-\frac{\sigma}{i\varepsilon_0\omega_i}\right)\boldsymbol{E}_s=-i\mu_o\frac{\partial \boldsymbol{J}^{(i)}}{\partial t}$$

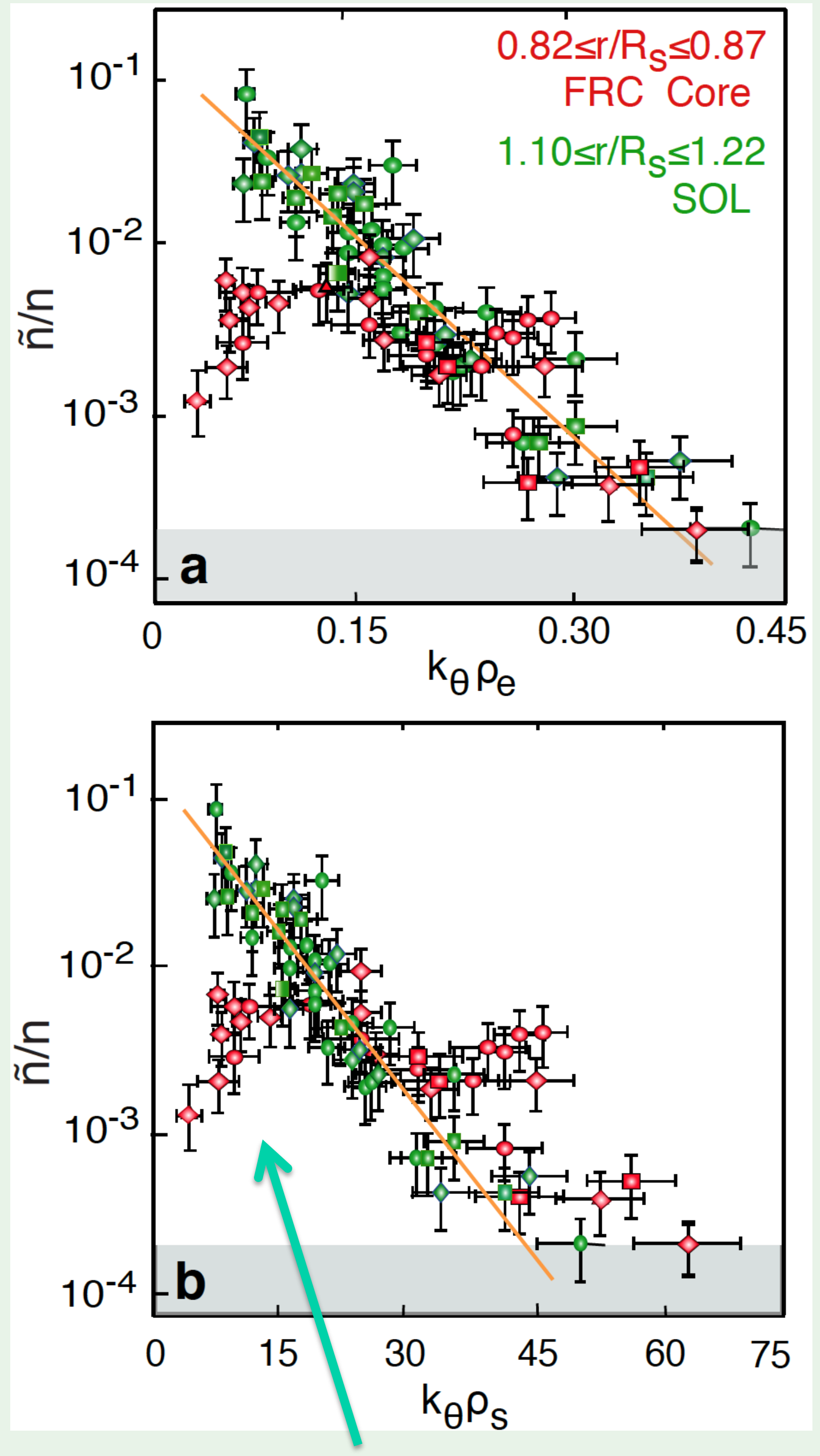
$$\boldsymbol{J}^{(i)}=\frac{i\varepsilon_0\omega_{pe}^2}{\omega_i}\frac{\tilde n}{n_e}\boldsymbol{E}_i+\boxed{\frac{\omega_i}{\varepsilon_o\omega_{pe}^2}\sigma\left[\sigma \boldsymbol{E}_i\times\tilde{\boldsymbol{B}}/B\right]}$$

The second (highlit) term describes the induced current in the opposite polarization and is proportional to B_r

In C-2W, the trajectories of launched and backscattered X-mode and O-mode nearly overlap (as $\omega_{pe} >> \omega_{ce}$). Hence the CPS (O-mode) component can be easily separated out via polarizers and detected via a dedicated receive horn

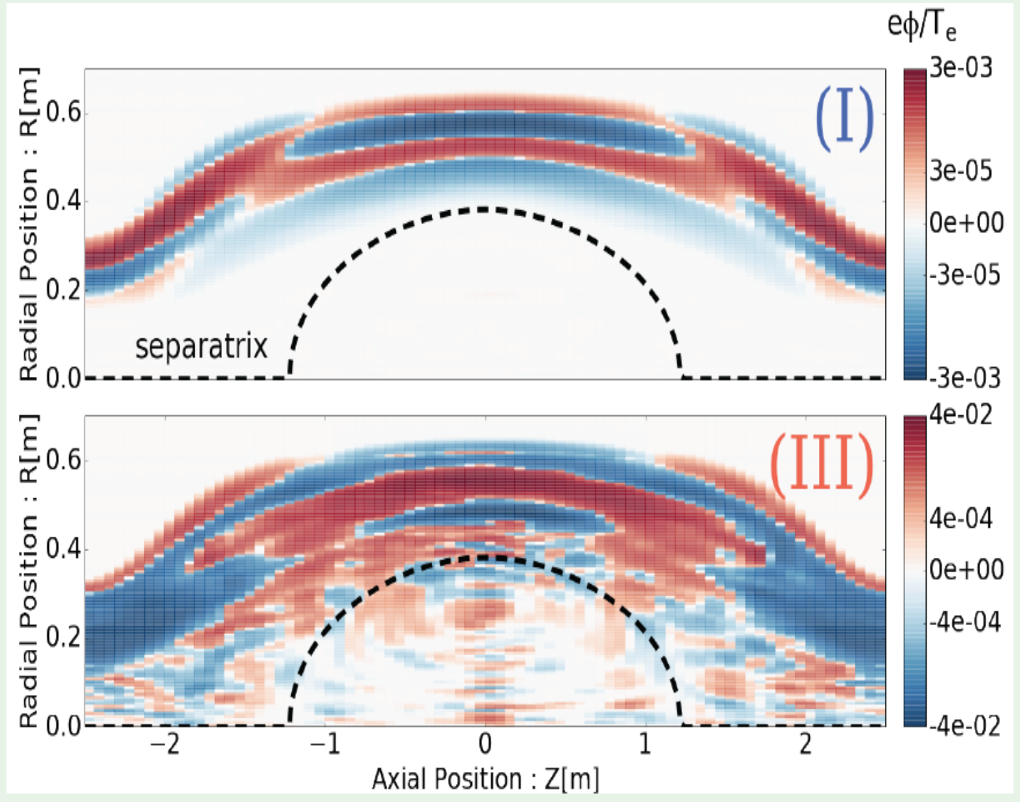


Wavenumber Spectrum of FRC core and Edge Fluctuations: Decreased core fluctuation level at low kρ_s



Low-k ion modes reduced by almost two orders of magnitude in the FRC core

A gyrokinetic simulation of the FRC core and SOL shows a quiescent core and inward turbulence propagation from the SOL past the FRC separatrix (dashed line)

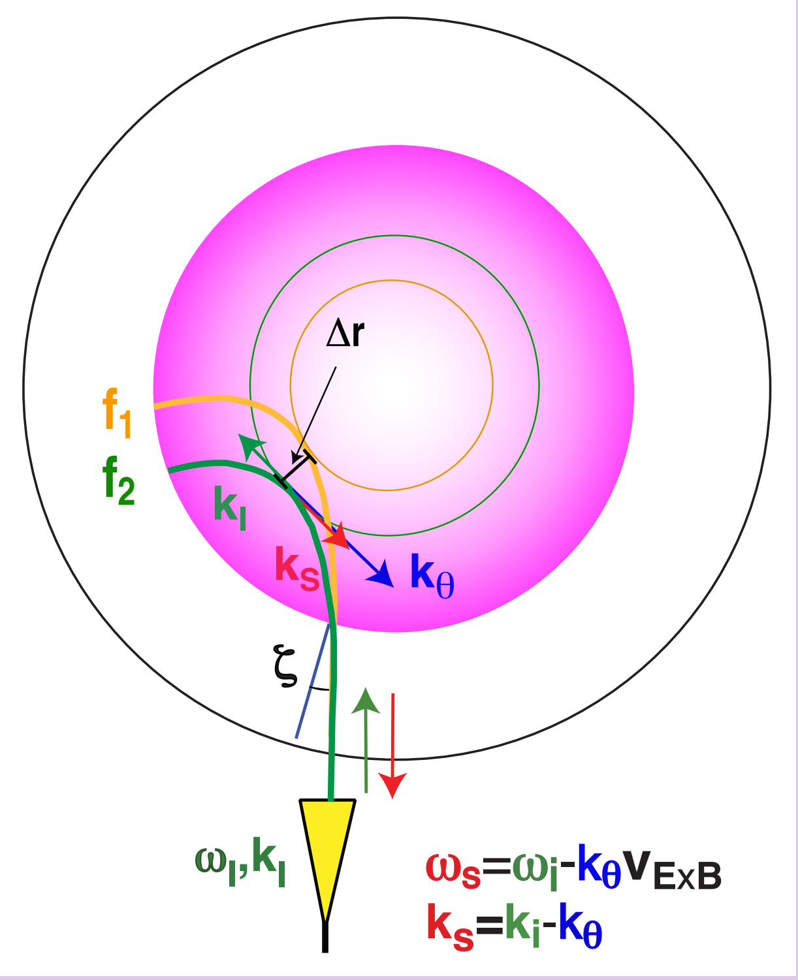


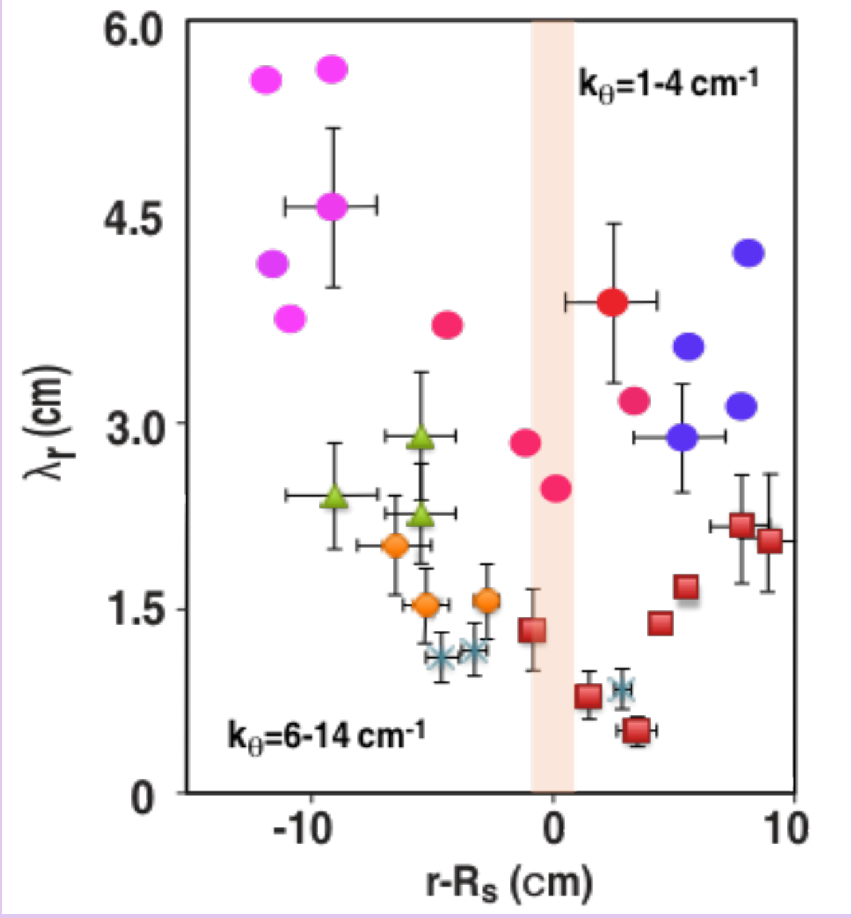
Radial Transport Barrier Formation: Radial Correlation- and *E*×*B* Shear Measurements

Launch two tunable frequencies f_1,f_2 (radially separated turning points/cut-off layers): Construct the radial correlation function by varying Δr.

The same measurement principle provides ***E*x*B*** flow measurements at different radii, and allows ***E*x*B*** shear to be determined.

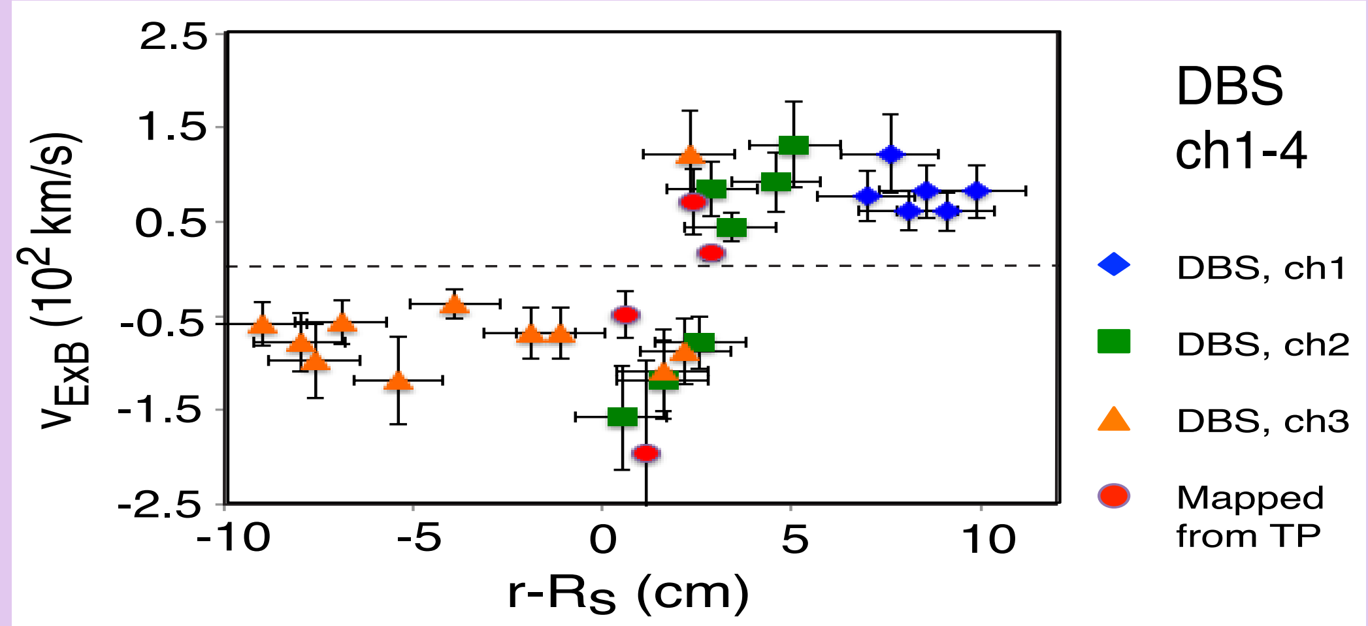
The measured radial turbulence correlation length has a pronounced minimum at the excluded flux radius R_s: this is the location of maximum ***E*x*B*** shear [1,2] and indicates radial transport barrier formation.





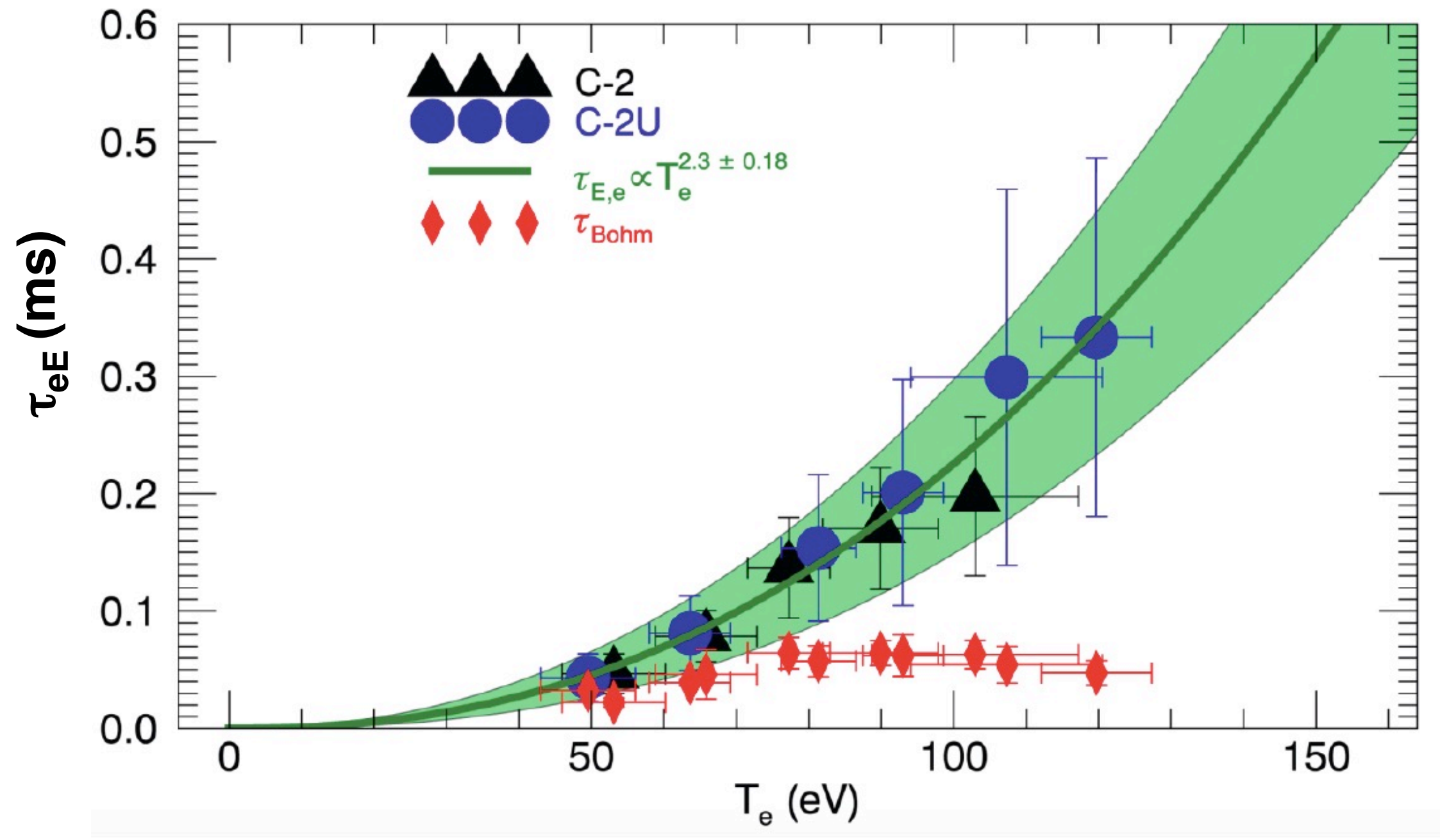
Strong ***E*x*B*** shear is observed outside the separatrix in the scrape-off layer. Shear is obtained via biased plasma guns in the divertor or via biased concentric electrodes. ***E*x*B*** flow shear is most pronounced with a biased LaB$_6$ active electron emitter (instead of a second plasma gun) placed in one of the divertors.

LaB$_6$ Emitter + Plasma Gun



[1] M. Tuszewski et al. PRL 2012
[2] L. Schmitz et al., Nature Comm. 2016

Electron Thermal Confinement is Strongly Correlated with Electron Temperature T_e



C-2 and C-2U data show good agreement; only major change: Increased beam power

TAE electron confinement scaling is similar to Spherical Tokamak (ST) scaling: τ_{Ee}~1/ν^*B

Summary

- C-2/C-2U FRC core: Ion modes are stable due to FLR effects (large particle orbits), short connection length and grad-B drift reversal; only electron modes are weakly unstable.
- SOL: Moderate, multi-scale SOL turbulence observed/predicted by gyrokinetic simulations (driven by the radial density/electron temperature gradients).
- Turbulence is generated near the separatrix and propagates inwards into the core as well as outwards into the SOL. Radial correlation is reduced near R_{sep} due to E_r shear, consistent with radial transport barrier formation.
- Electron thermal confinement time increases with $T_e \sim T_e^2$: Favorable T_e scaling, opposite to $T_e^{-1.5}$ Gyro-Bohm confinement scaling.
- Magnetic fluctuations measurements via CPS have great potential (planned for C-2W).