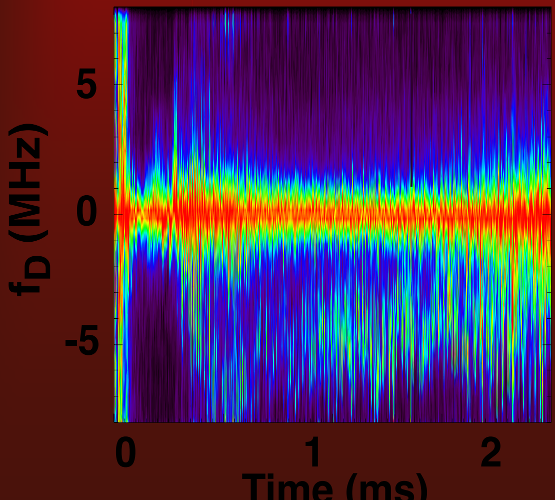
Suppressed Ion-Scale Turbulence in the C-2/C-2U FRC: Recent Experimental and Simulation Results

L. Schmitz (UCLA, TAE)

with

C. Lau, D. Fulton, I. Holod, Z. Lin (UCI), T. Tajima,
M. Binderbauer, H. Gota (TAE), and the TAE Team



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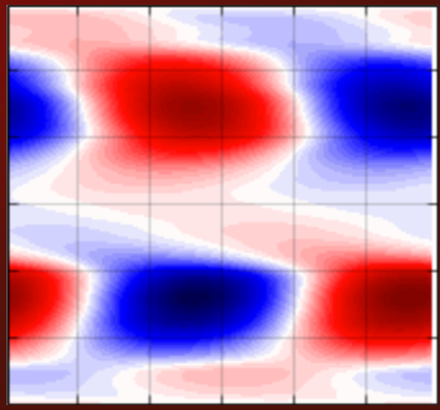
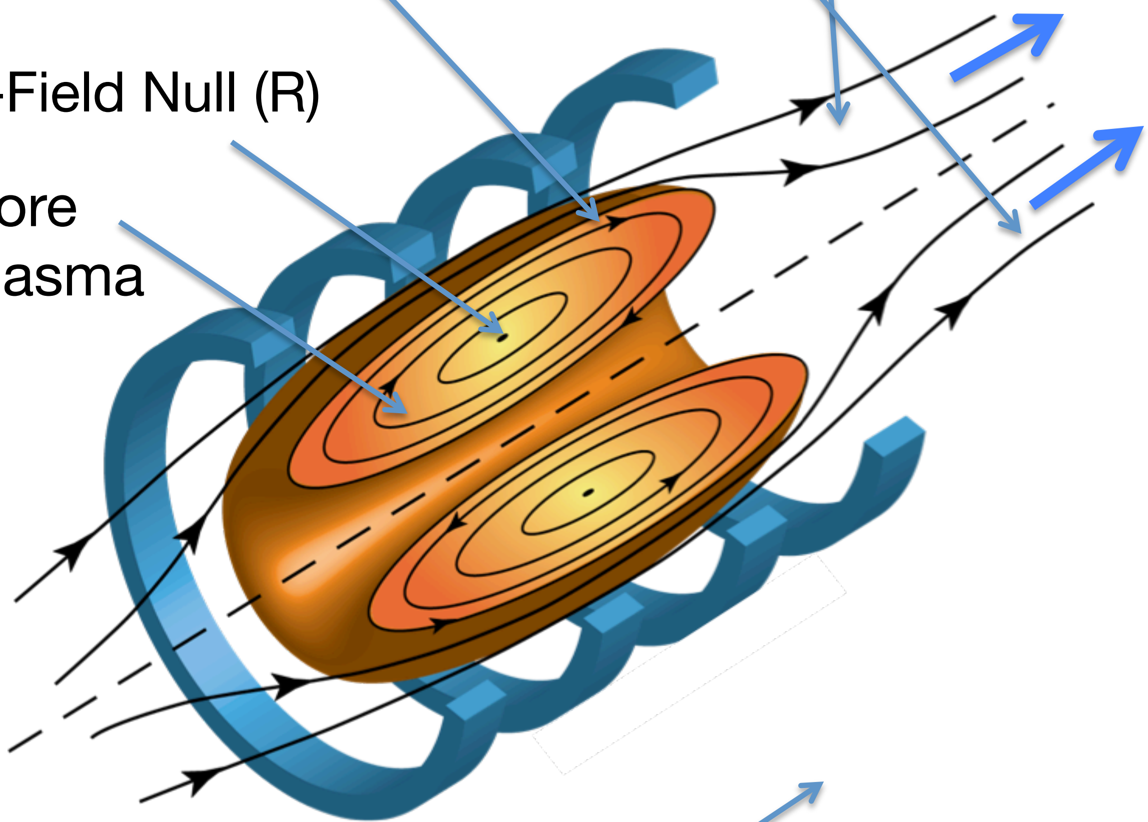
Irvine, CA



Outline

- Introduction
- Turbulence properties – experimental characterization
- Gyrokinetic simulations in the C-2 FRC Core and SOL
- Critical gradient, control of radial electric field via divertor biasing; radial transport barrier
- Summary

FRC Geometry / C-2 Parameters



Typical C-2/C-2U Parameters

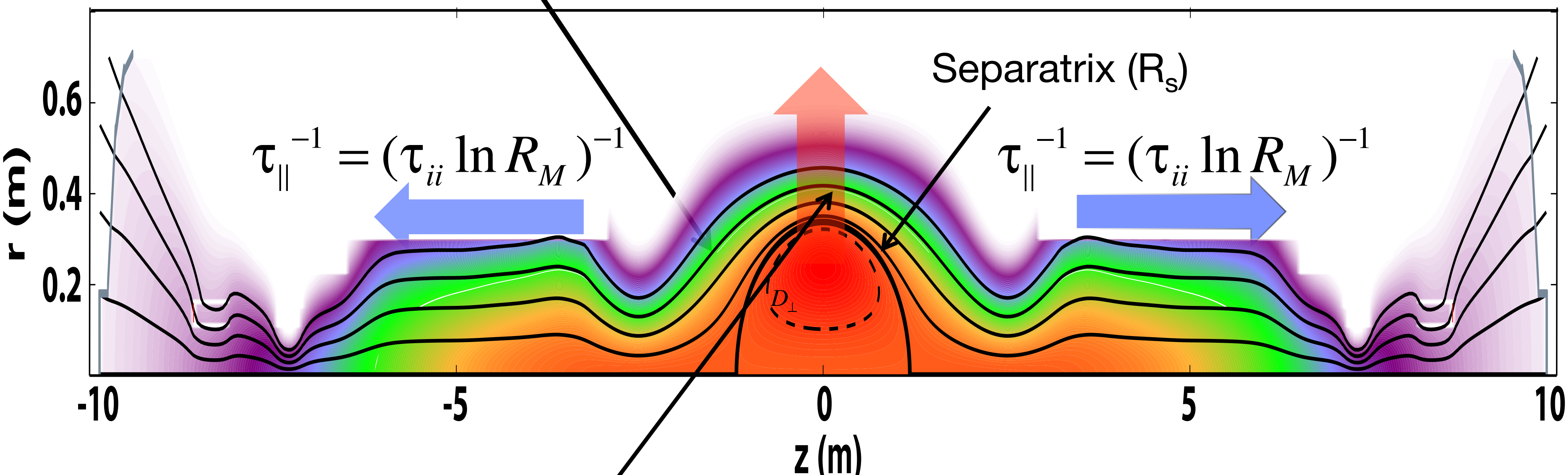
	FRC Core	SOL
Density (10^{19} m^{-3})	2-4	0.5-2
T_i (eV)	600-1000	≤ 250
T_e(eV)	≤ 150	30-80
B_e (Gauss)		≤ 1200
Sep. Radius (cm)	35-45	
Neutral Beam Power	≤ 10 MW (C-2U)	

FRC Radial and Parallel Transport

Scrape-off layer (SOL): Radial and parallel Transport (along z)

From continuity (particle conservation:)

$$\nabla_{\|}(n\mathbf{v}_i) = -\nabla_{\perp}(n\mathbf{v}_i)$$



Radial transport:

$$\tau_{\perp}^{-1} = \frac{1}{n_0}\frac{1}{r}\frac{\partial}{\partial r}\left(rD_r \frac{\partial n}{\partial r}\right)$$

Radial Gradient scale length :

$$L_{n\perp} = \sqrt{D_{\perp}\tau_{ii} \ln R_M}$$

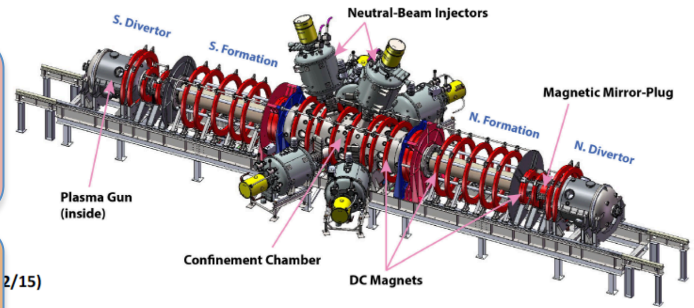
If $D_\perp$ depends on $L_{n\perp}$, parallel and perpendicular transport are coupled

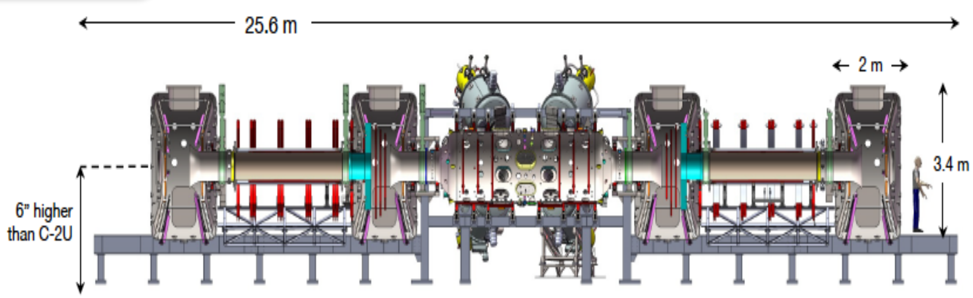
Turbulence/Transport Analysis Towards Predictive Capability

Advanced fluctuation Diagnostics:

- Doppler Backscattering ($k\rho_s < 50$)
- Far-Infrared Forward Scattering ($k\rho_s < 4$)
- Probes for ñ and ϕ, Transport fluxes (far SOL and JET)
- Toroidal/Axial Mirnov Coil Arrays (B)

C-2U





Transport Analysis

- 1-D Transport Analysis (Q-1D) Incl. Fast Ions
- 2-D Transport Analysis (Q-2D) Incl. Fast Ions

Gyrokinetic Turbulence Modeling

- Linear Flux-tube GTC Simulations (Core and SOL)
- Coupled Core-SOL Simulations
- Nonlinear/Global Simulations
- Fuilly Kinetic simulations (ANC)

Predictive Kinetic Transport Modeling to Guide Experiments

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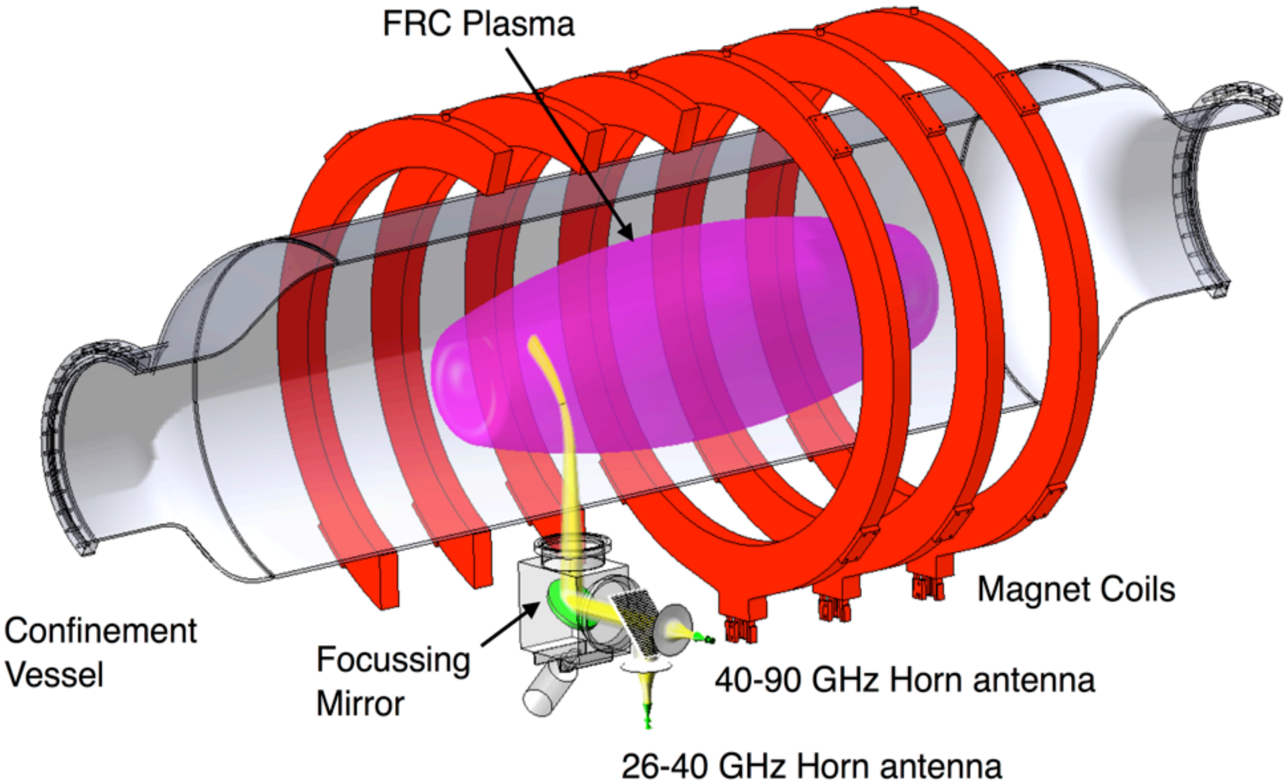
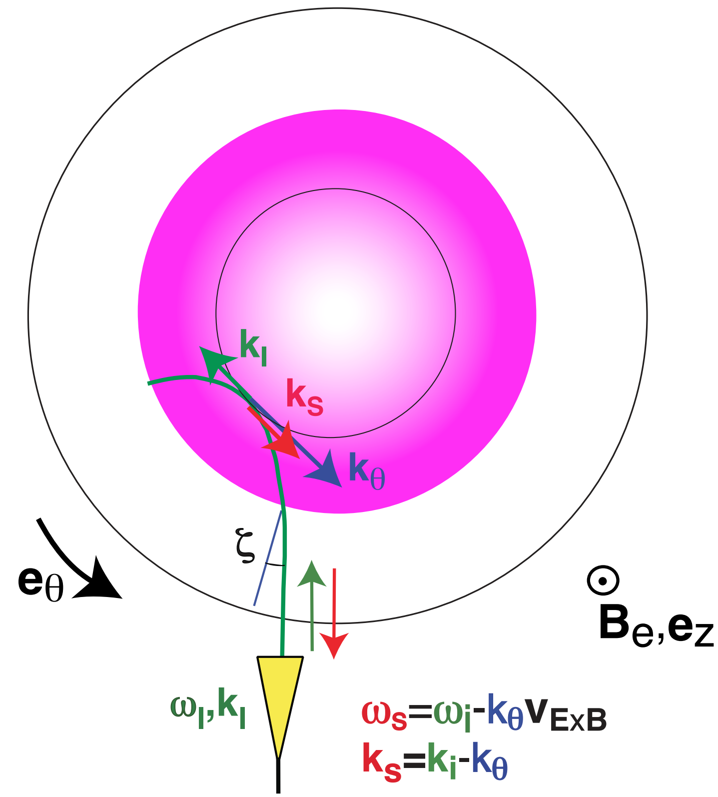
Schematic and Principle of Doppler Backscattering Diagnostic (DBS)





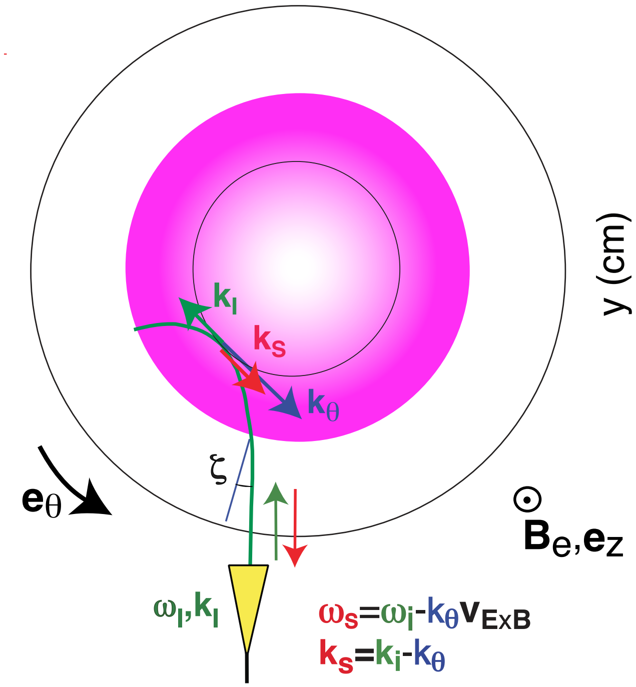
DBS provides local density fluctuation level $\tilde{n}(r)/n(r)$ vs. k_θ

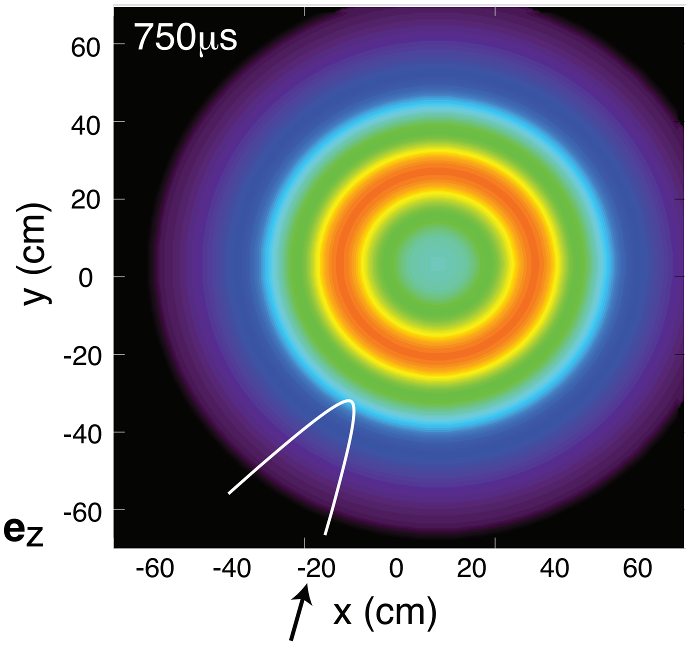
- here $k_\theta \sim 0.5\text{-}12\ cm^{-1}$ ($k_\theta \rho_s \sim 1\text{-}40$)

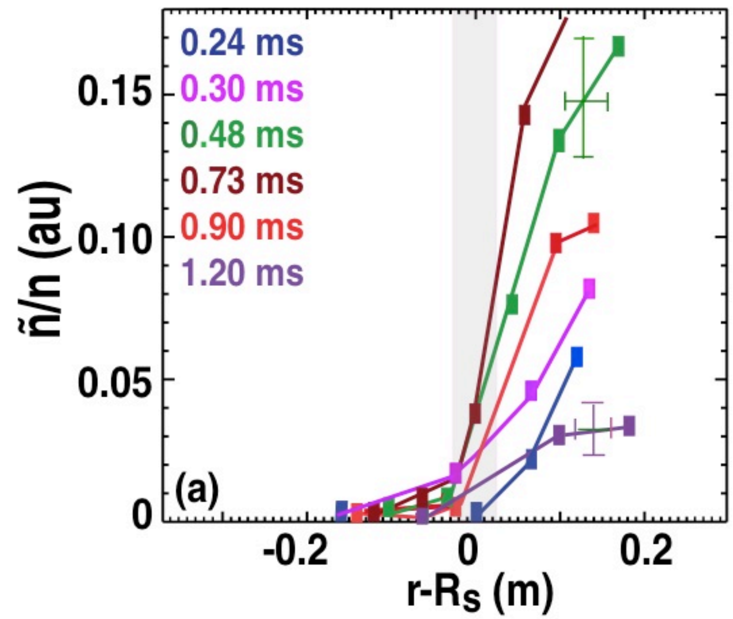
ExB velocity from Doppler shift of back-scattered signal: $\omega_{Doppler} = v_{turb} k_\theta \sim v_{ExB} k_\theta$

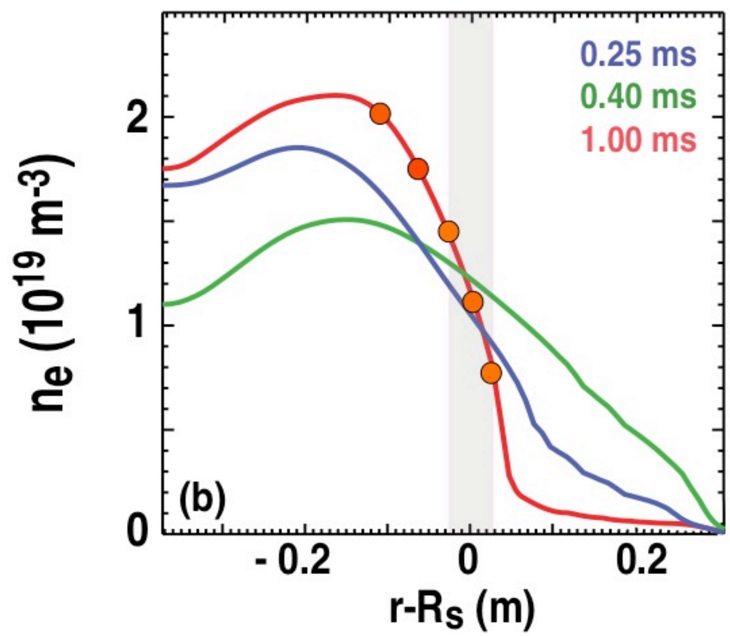
➔ $v_{ExB} \sim \omega_{Doppler} / 2k_i$

Radial Density Profile and DBS Probing Radii



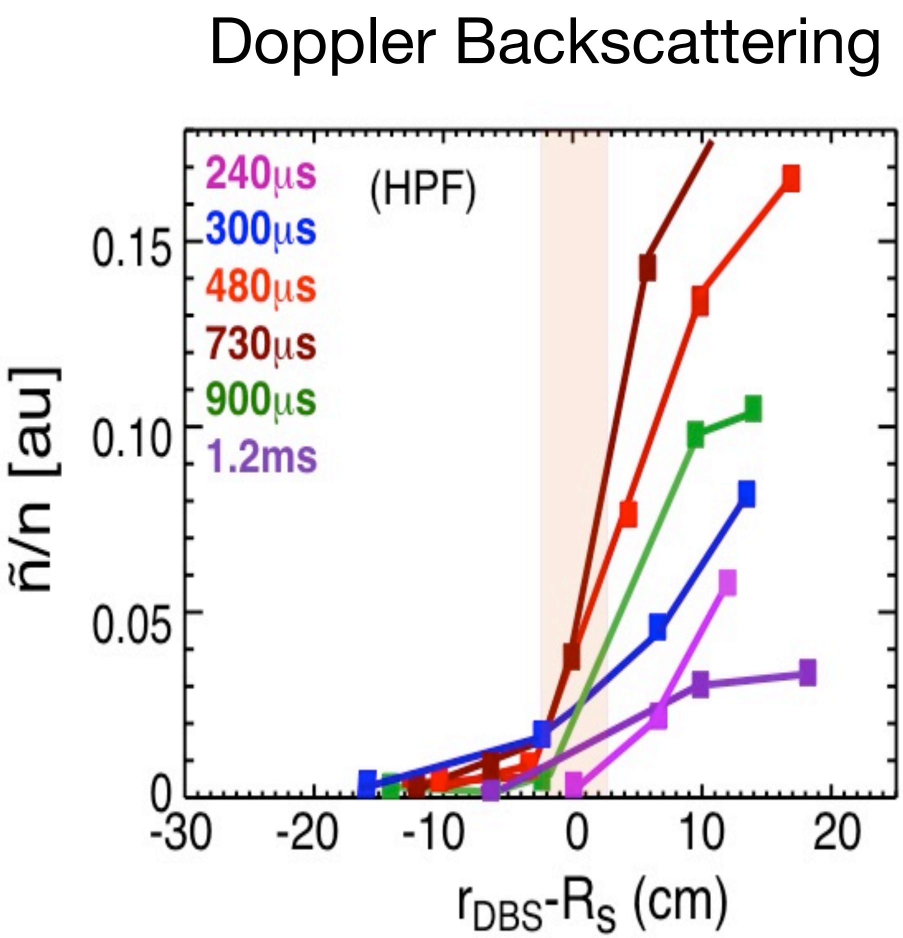


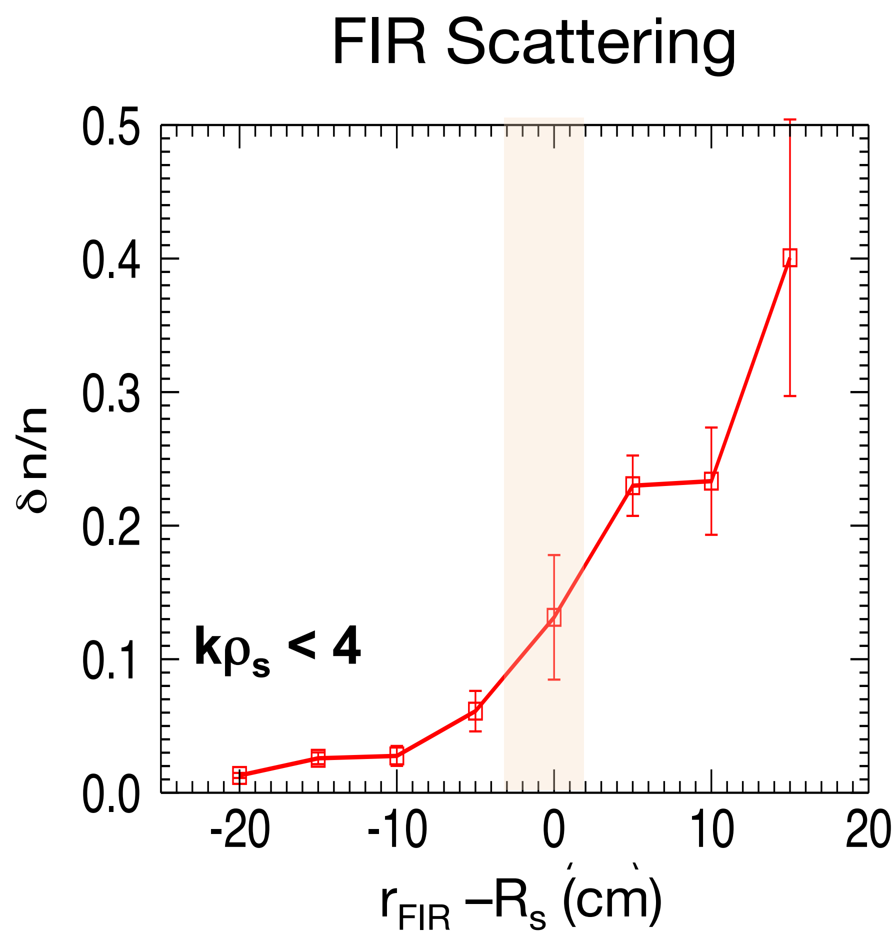




- **DBS: 6 remote-tunable channels (collinear beams), probing the FRC core (outside field null) and the SOL**
- **Beam path calculated via GENRAY ray/beam tracing, based on reconstructed (CO_2) density profiles**

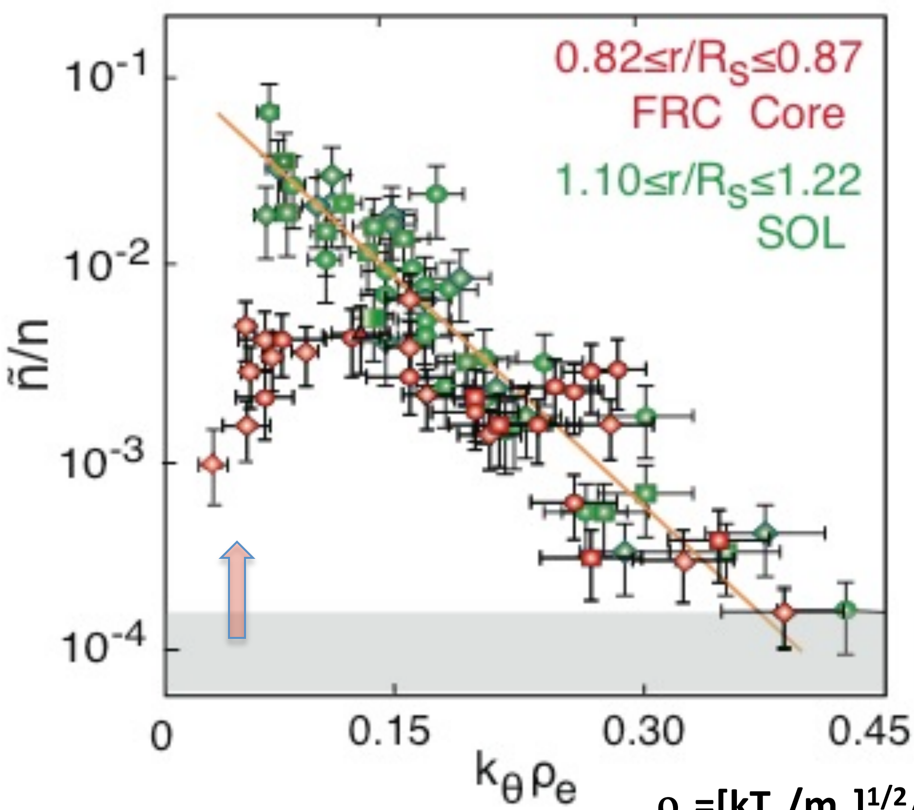
Density Fluctuations Peak Outside Separatrix
Very Low Fluctuations in FRC Core



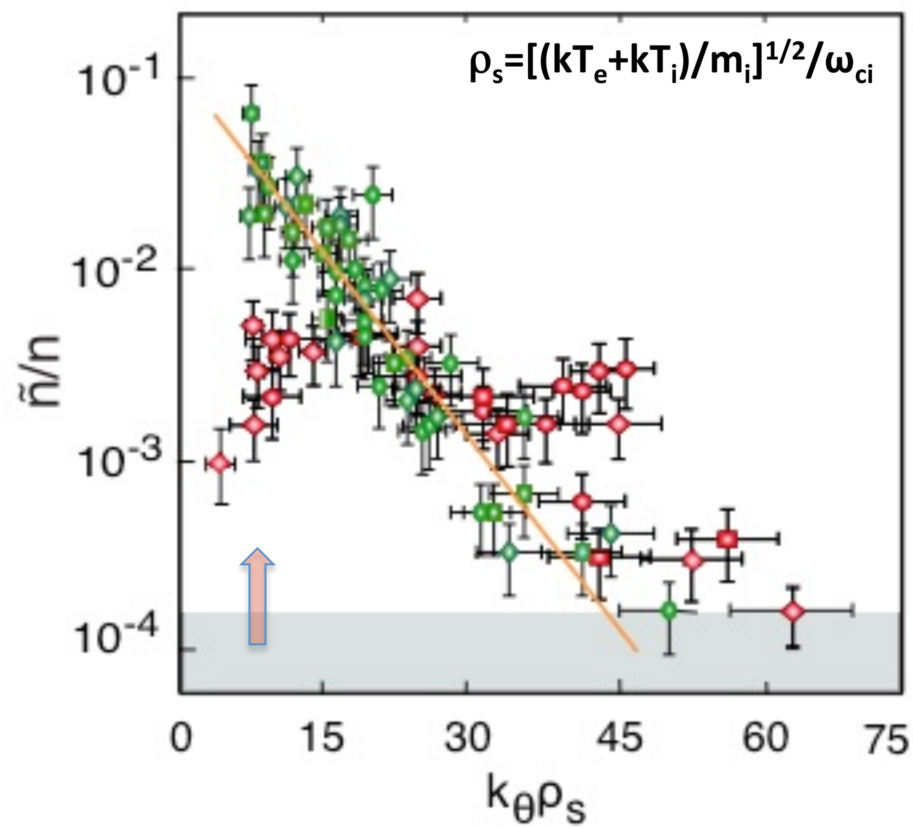


- Fluctuation levels peak outside the separatrix
- Very low fluctuation levels in the FRC core

FRC Core Plasma: Unique Inverted Wavenumber Spectrum; No Ion-range Modes



$\rho_e=[kT_e/m_e]^{1/2}/\omega_{ce}$



$\rho_s=[(kT_e+kT_i)/m_i]^{1/2}/\omega_{ci}$

- **FRC Core: Decreased Fluctuations; Inverted Spectrum at low $k\rho_e$**
- **Spectrum extends to $k\rho_e > 0.3$: Only unstable electron modes!**
- **SOL: Ion and electron-scale modes**
- **Broad exponential spectrum: $(\tilde{n}/n)^2 \sim \exp(-0.32\, k_\theta\rho_s)$**

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GTC (Gyrokinetic Toroidal Code) Simulations

First-principles, integrated microturbulence simulations; adapted for FRC geometry (Boozer coordinates)

Includes gyrokinetic or kinetic ions, fluid or drift-kinetic electrons; local/global simulations, electromagnetic effects Fokker-Planck-collisions

→ **Useful for testing reduced transport models and for predictive transport modeling**

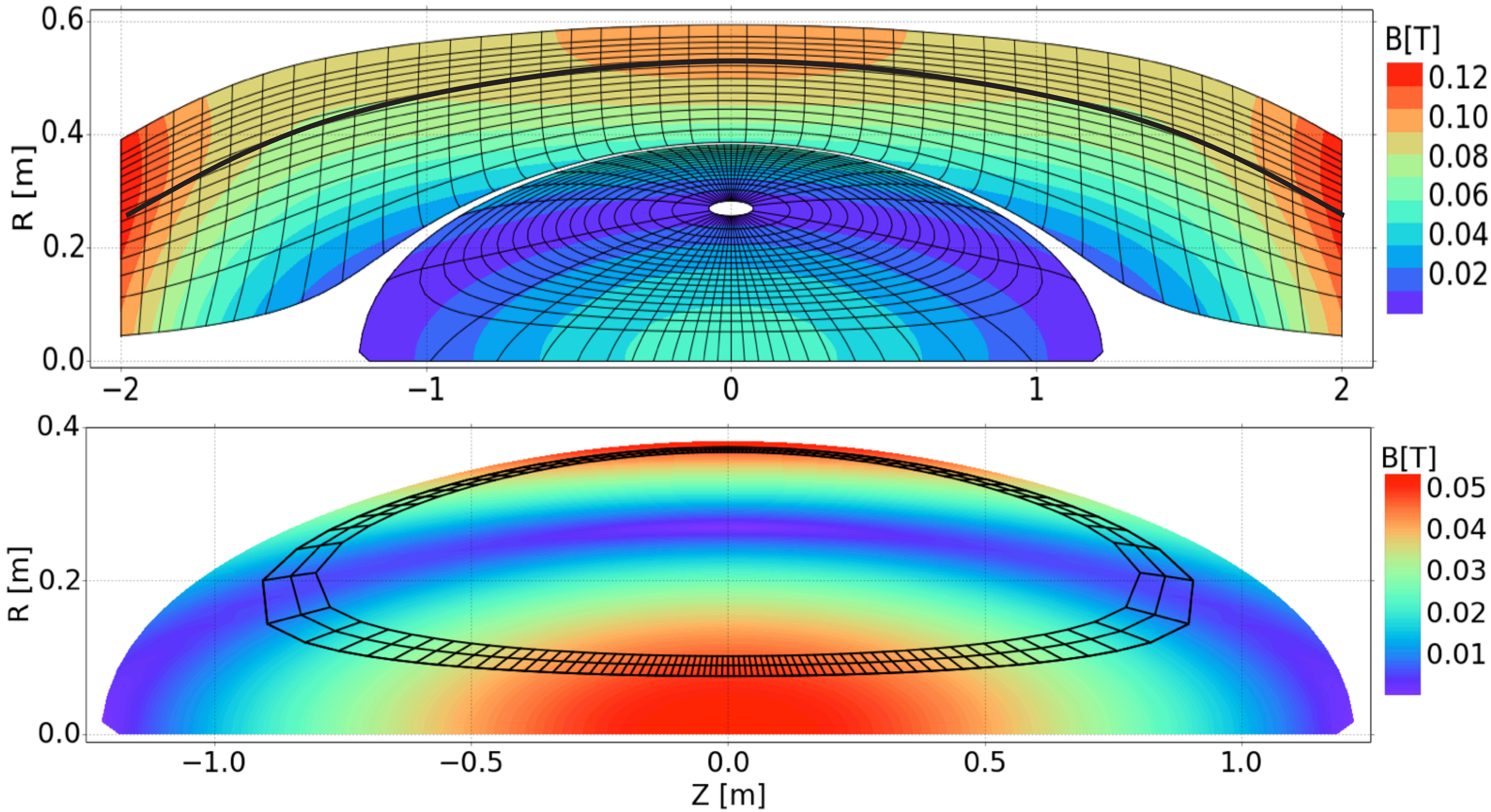
Input: Calculated FRC equilibria based on experimental parameters

Presented here: Results from linear, electrostatic flux-tube simulations, separate calculations for the FRC core and SOL

Upgrades in progress: Coupled SOL/core, kinetic ions, nonlinear runs:

→ **Much more detail in talk by C. Lau in this session**

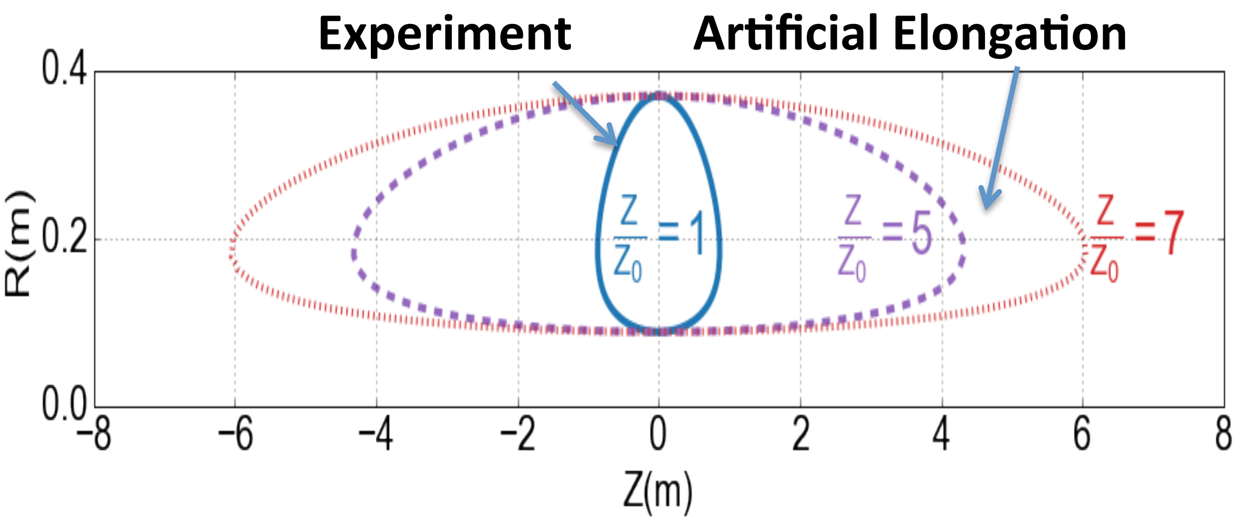
Simulation Geometry, Parameters

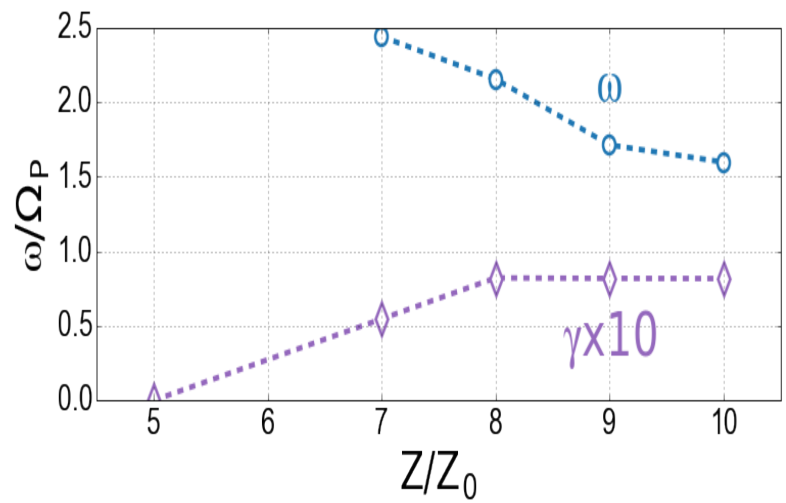


Core and SOL local simulation: Realistic C-2 Equilibrium
Periodic boundary conditions in z and θ
Gyrokinetic ions (D) and electrons, includes collisions $\nu_{e,i}^{*}=\nu_{e,i}/\nu_{transit}$ <<1 (>>1)

No Ion-Scale Instabilities Found in FRC Core by Local Electrostatic GTC Simulations

- No instabilities found for realistic $R/L_n < 5$ (limit of $L_n \sim \rho_i$)
- Instability found only by removing electron kinetic effects or by artificial elongation of core equilibrium:





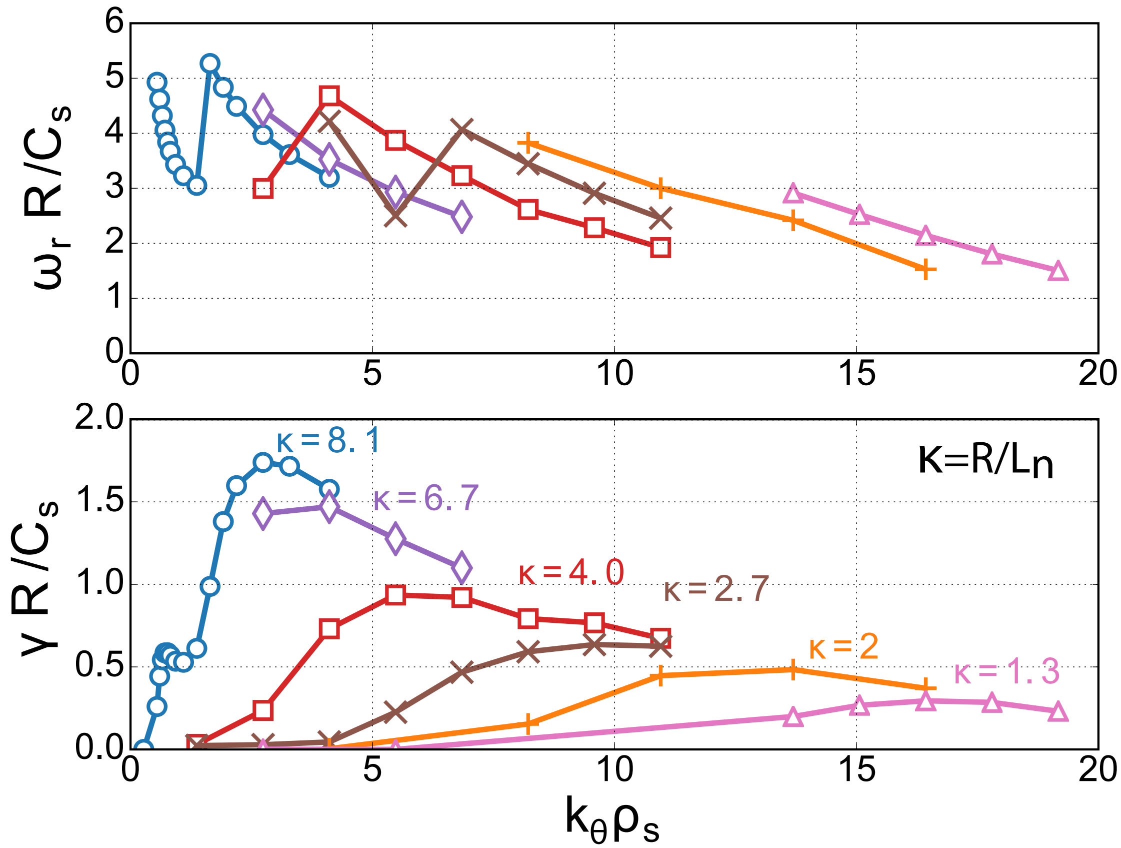
- Experiment detects small core fluctuations. Possible reasons…

  - Core is locally stable but turbulence can spread from SOL

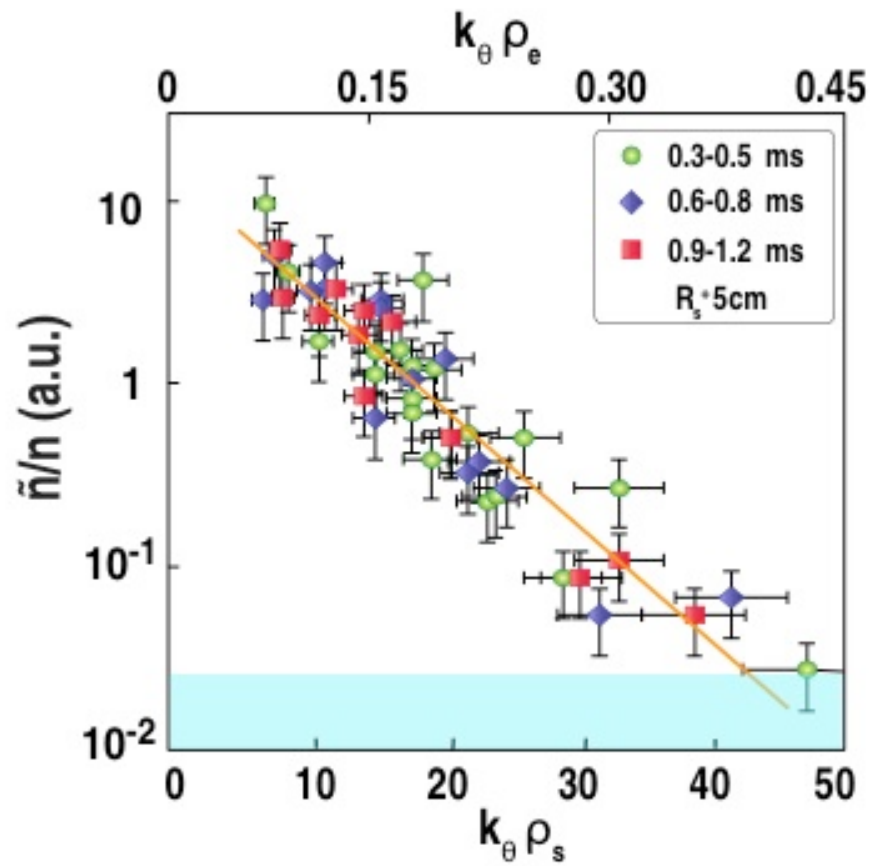
  - Important physics may be missing (by using gyrokinetic and/or electrostatic assumptions).

SOL: Ion-Range Modes Suppressed via FLR Effects, Spectrum Extends to Electron Mode Regime

Calculated Linear SOL Dispersion from GTC



Measured Saturated Spectrum



- Predicts no instability below $k_\theta \rho_s < 2$

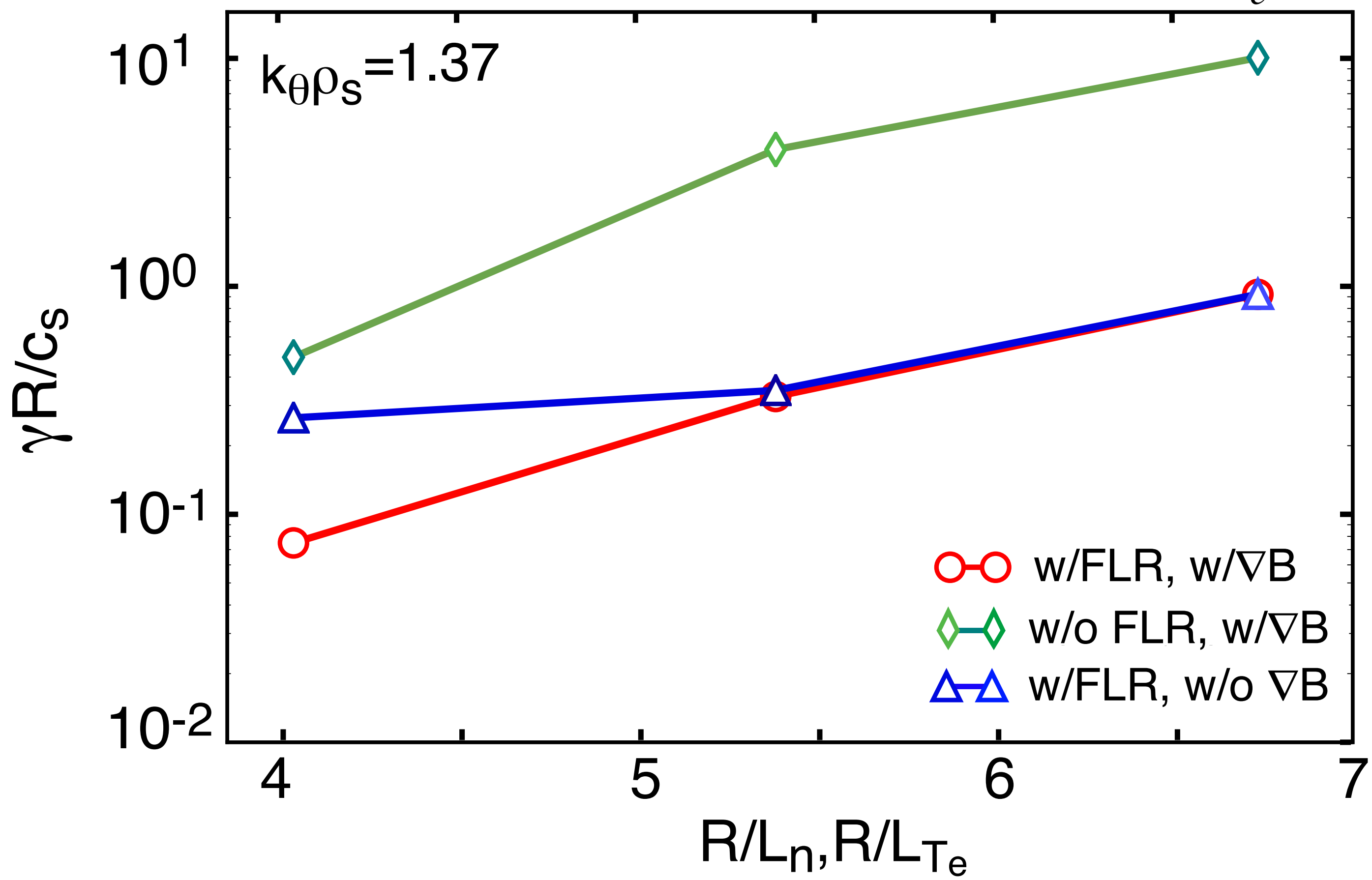
Spectrum extends to $k_\theta \rho_e > 0.3$

Low-k ion modes weak/absent due to FLR* effects*

*Rosenbluth, Kall and Rostoker, NF Suppl. pt1, 143 (1962)

FLR Effects Reduce the SOL Growth Rate Substantially

SOL modes are driven by $\nabla n,\ \nabla T_e$



TEM and Drift/Interchange Modes

Instability to $1/\eta_i$ =0

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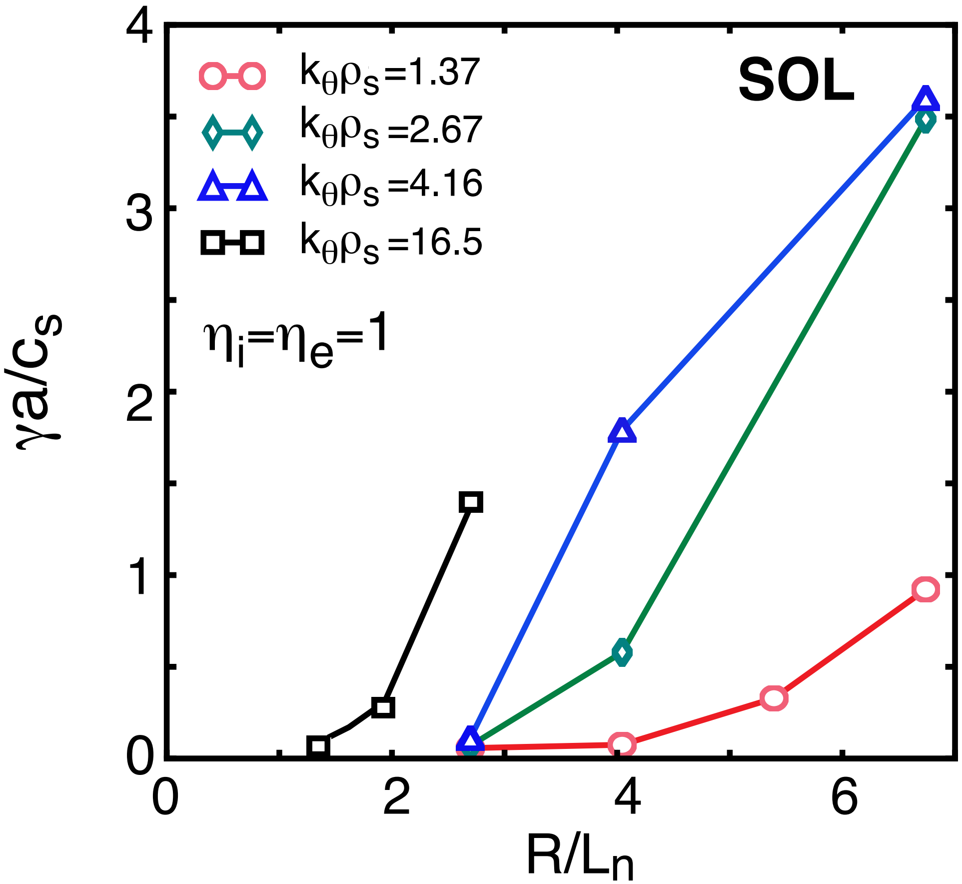
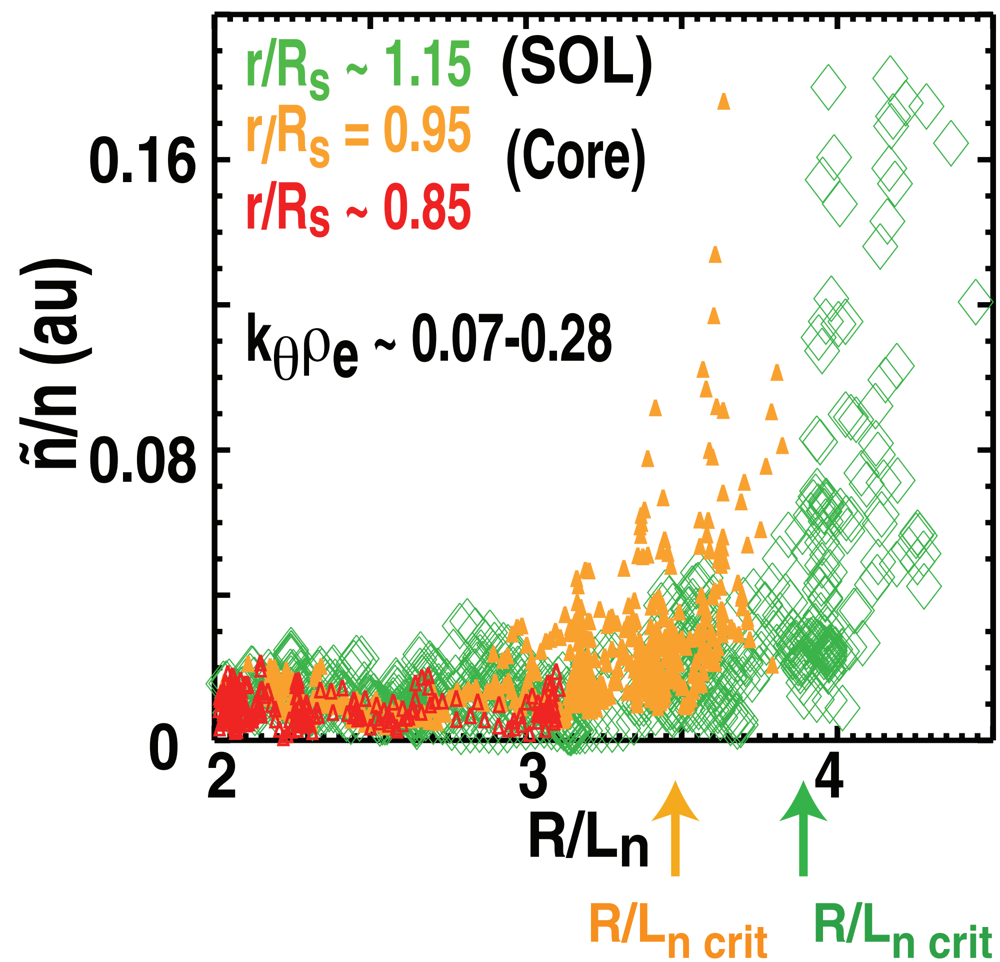
Measured SOL Critical Density Gradient Similar to Predicted Linear Instability Threshold

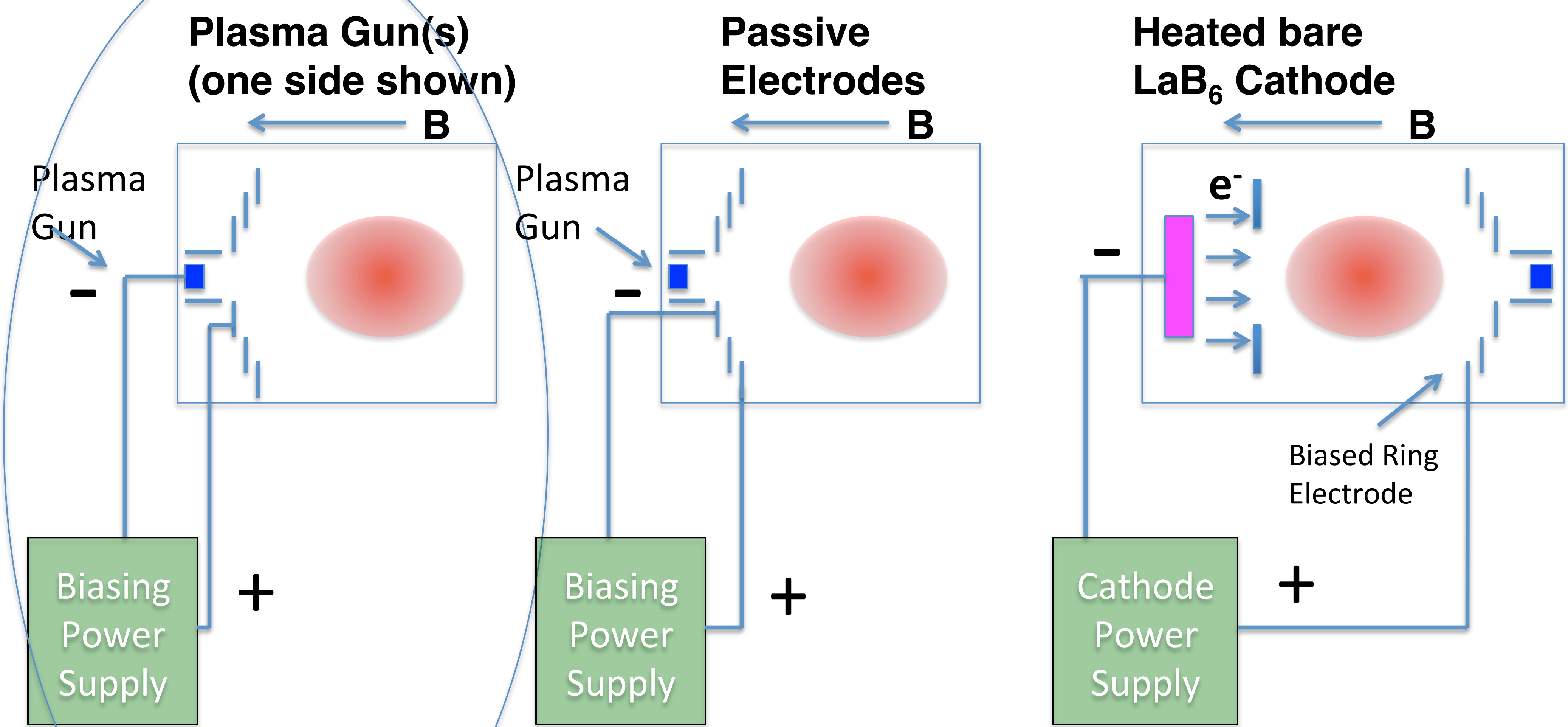
FRC core growth rate vs. R/L_n from linear GTC simulation



Measured R/$L_{n\ crit}$ (FRC core/SOL)



Passive/Active Biasing Schemes Explored



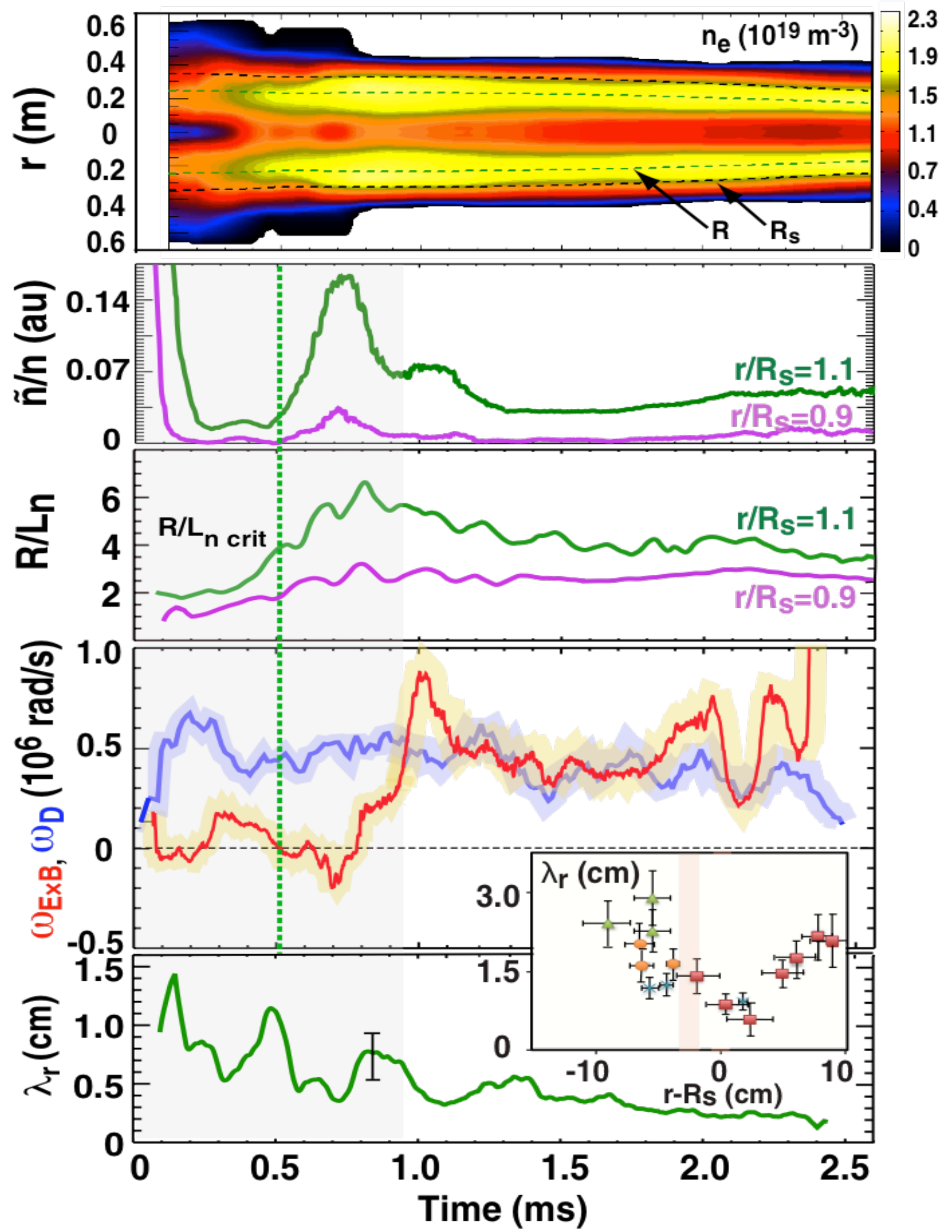
Change plasma potential/E_r
Current limited to $I_{sat\ i}$

Change plasma potential/E_r
Current limited to $I_{sat\ i}$

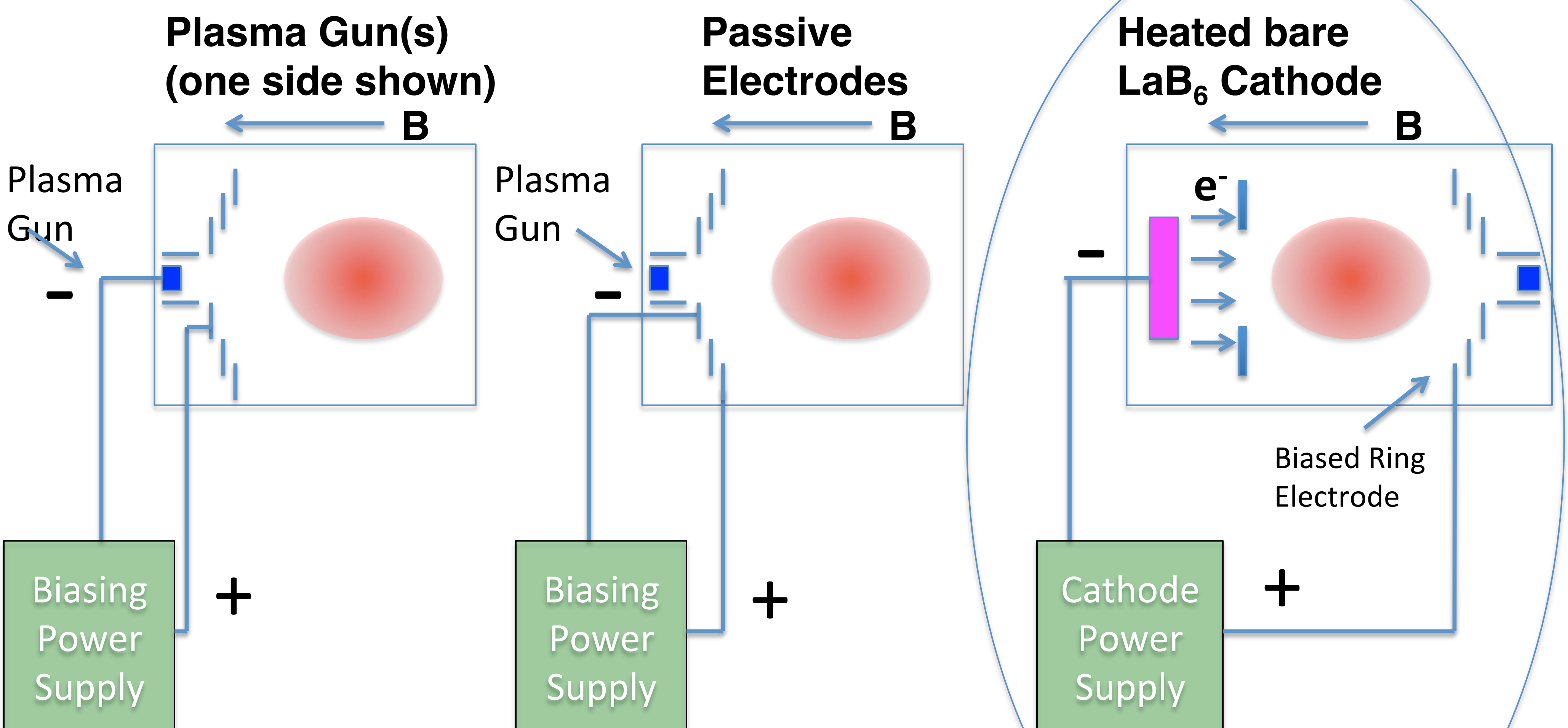
Change plasma potential/E_r
Max. current $I_{th\ e}$
Changes $f(v_e)$

E×B Shear Increases the SOL Critical Gradient

- Density profile time history
- SOL fluctuations increase once critical density gradient is exceeded
- Radial density gradient increases after ~0.5 ms (SOL is depleted)
- Fluctuation decrease once E×B shearing rate increases and exceeds the turbulence decorrelation rate:
  $\omega_{E\times B} > \Delta\omega_{\Delta}$ (Biglari, Diamond, Terry, Phys. Fluids B1,1989)
- The radial correlation length de-ceases with increasing E×B shear



Passive/Active Biasing Schemes Explored

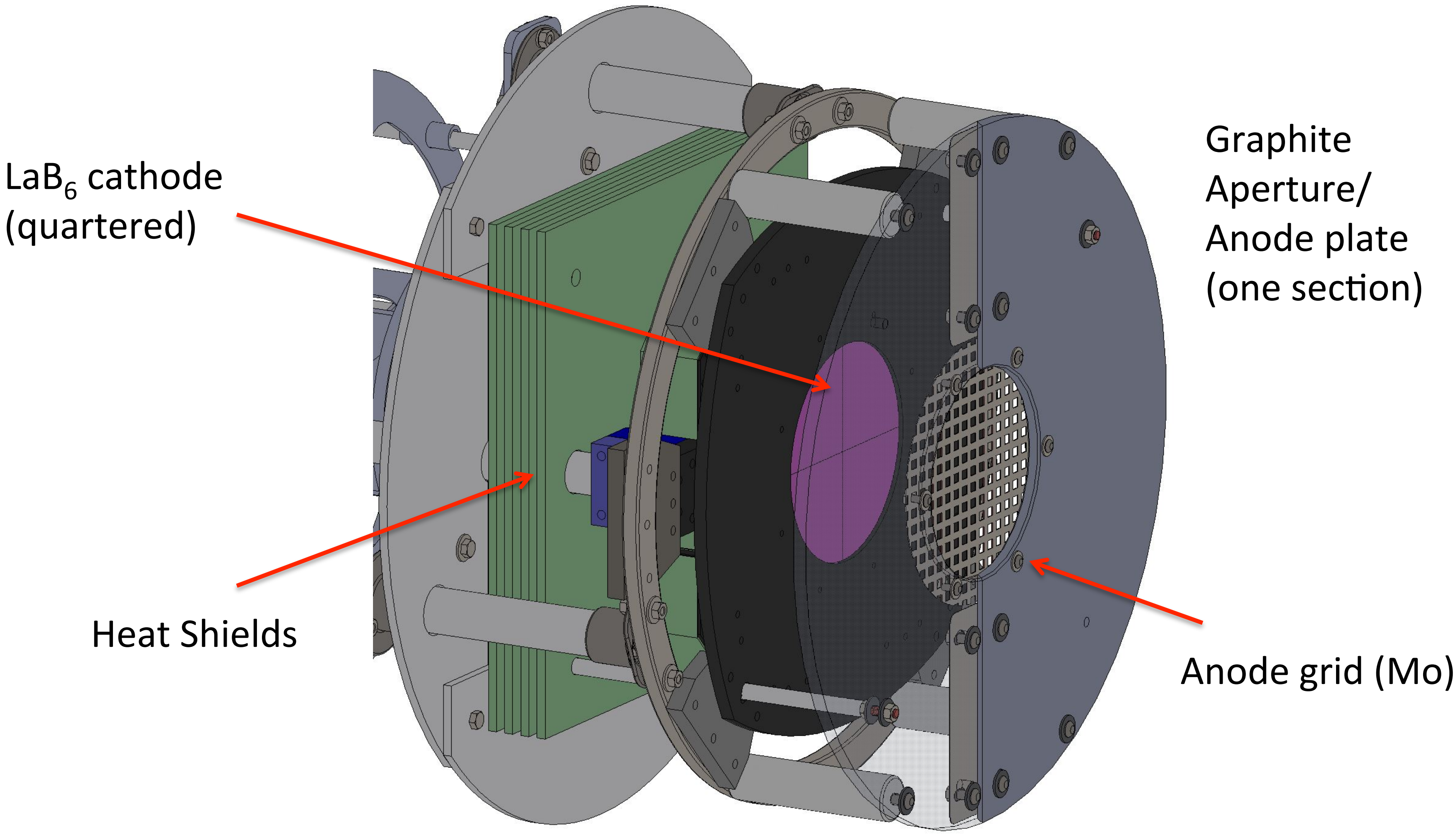


Change plasma potential/E_r
Current limited to $I_{sat\ i}$

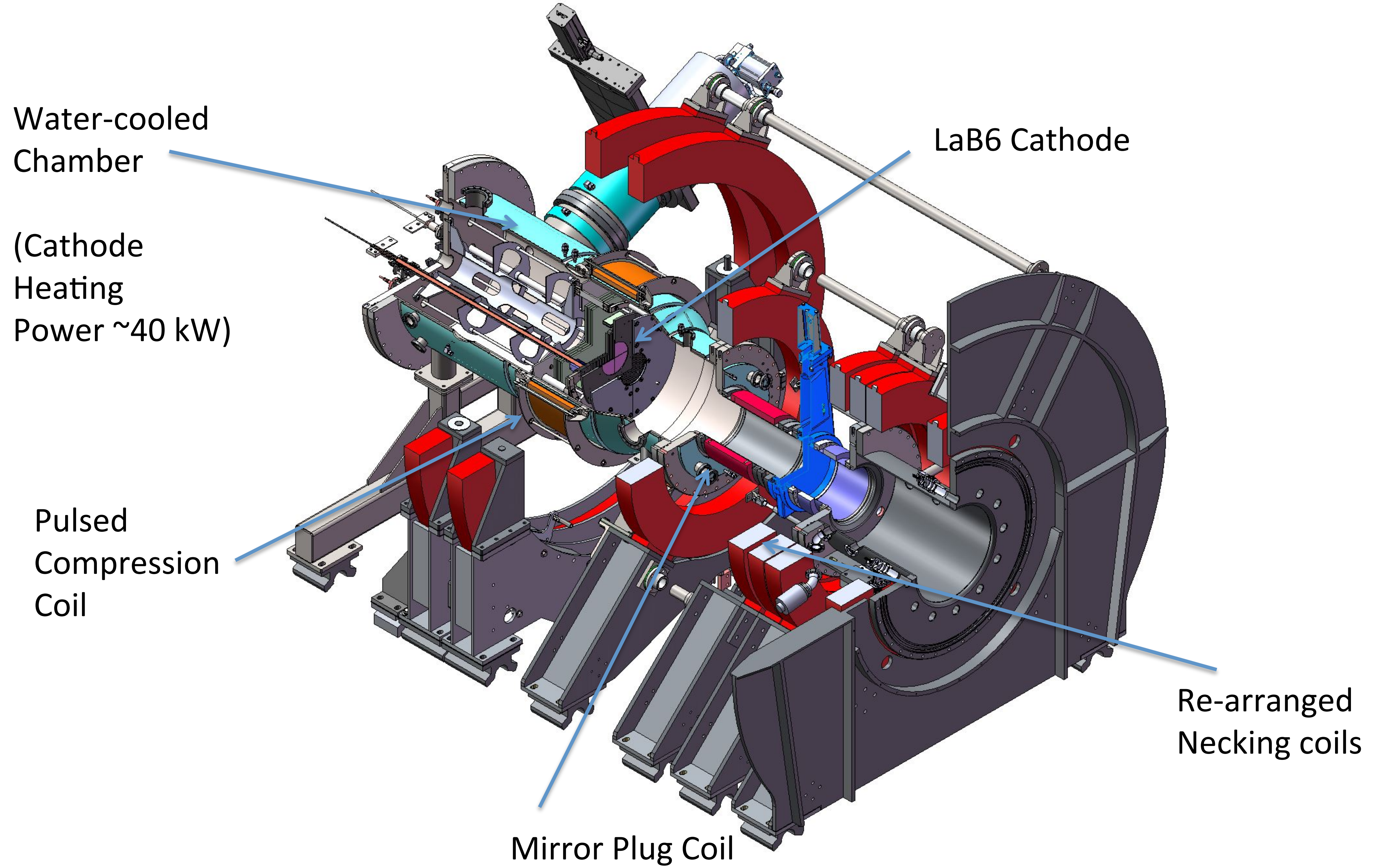
Change plasma potential/E_r
Current limited to $I_{sat\ i}$

Change plasma potential/E_r
Max. current $I_{th\ e}$
Changes $f(v_e)$

LaB_6 Cathode-Anode assembly



LaB_6 Chamber and cathode assembly



Cathode Electron Emission Current Substantially Exceeds Ion Saturation Current

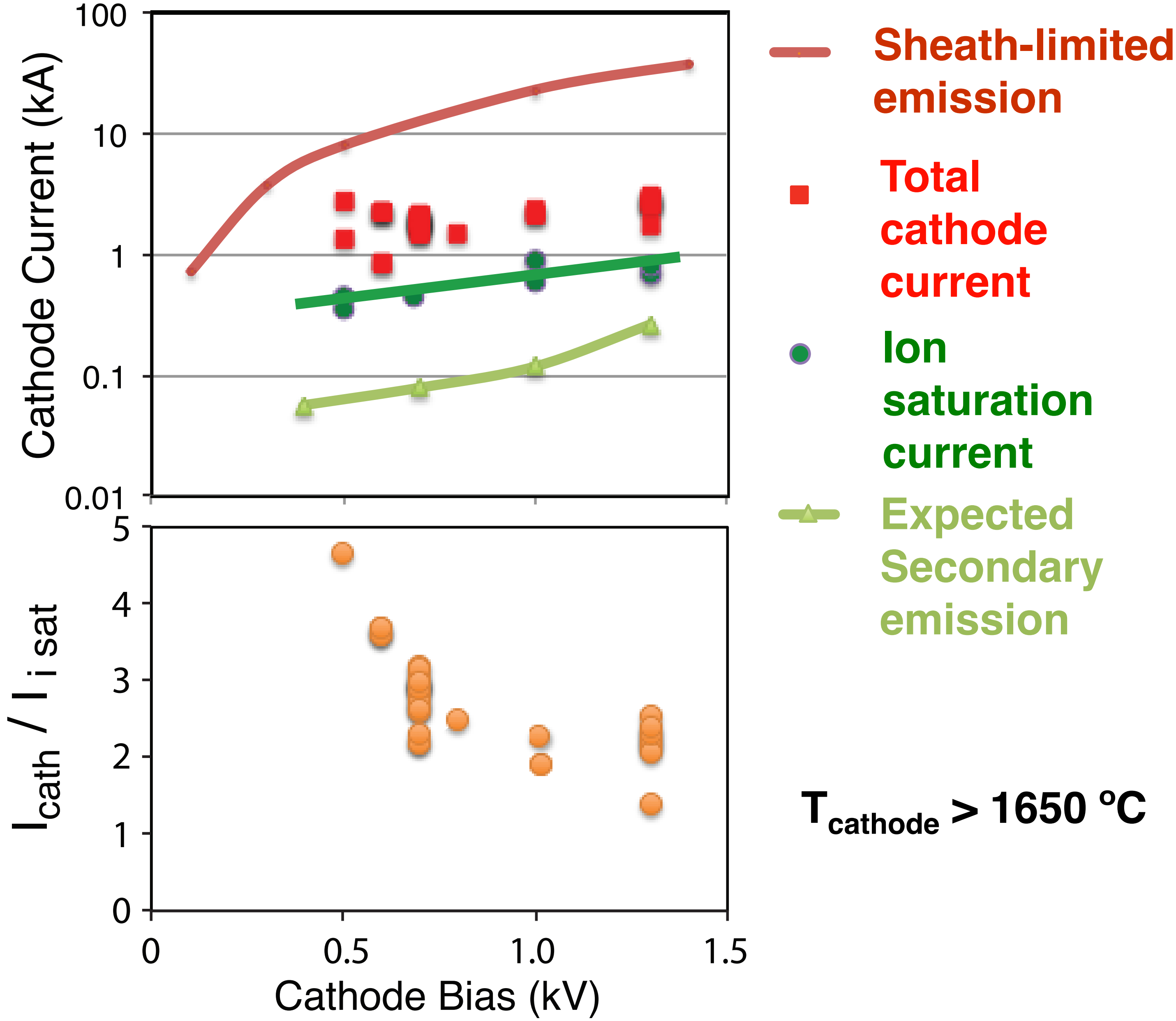
Sheath-limited emission current:

$$j_{esh} = \frac{1}{9\pi}\left(\frac{2e}{m_e}\right)^{1/2}\frac{U^{3/2}}{d^2}$$

$$d \sim 4\lambda_{Debye}$$

Ion saturation current:

$$j_{is} = 0.3nec_s$$



$T_{cathode}$ > 1650 ºC

Radial Potential / Density Profiles Clearly Show that E_r (Shear) Reduces Radial Transport

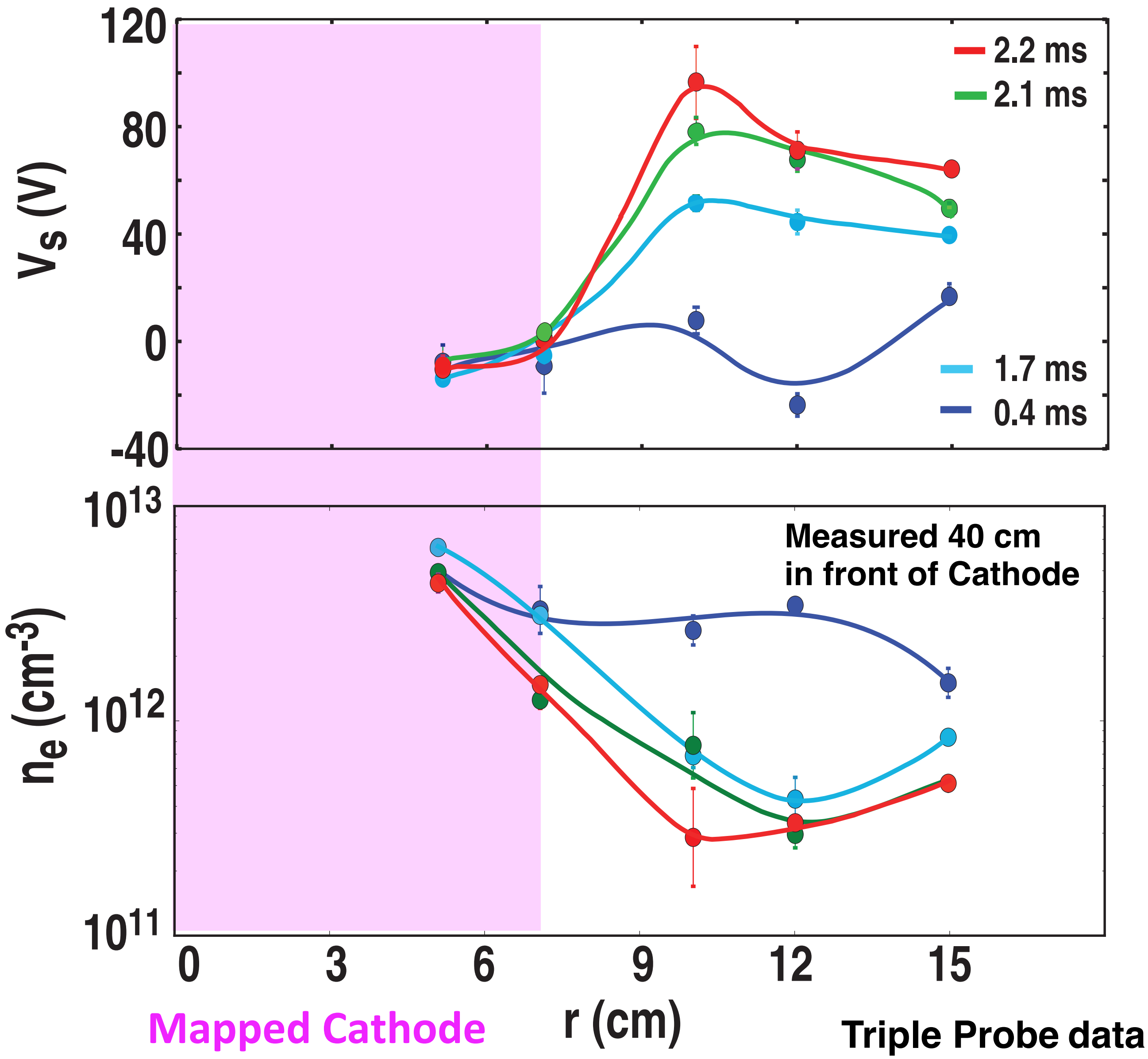
- **Strongest radial electric field outside cathode radius:**

  $E_r \leq 9.5$ kV/m

  (mapped to C-2U midplane)

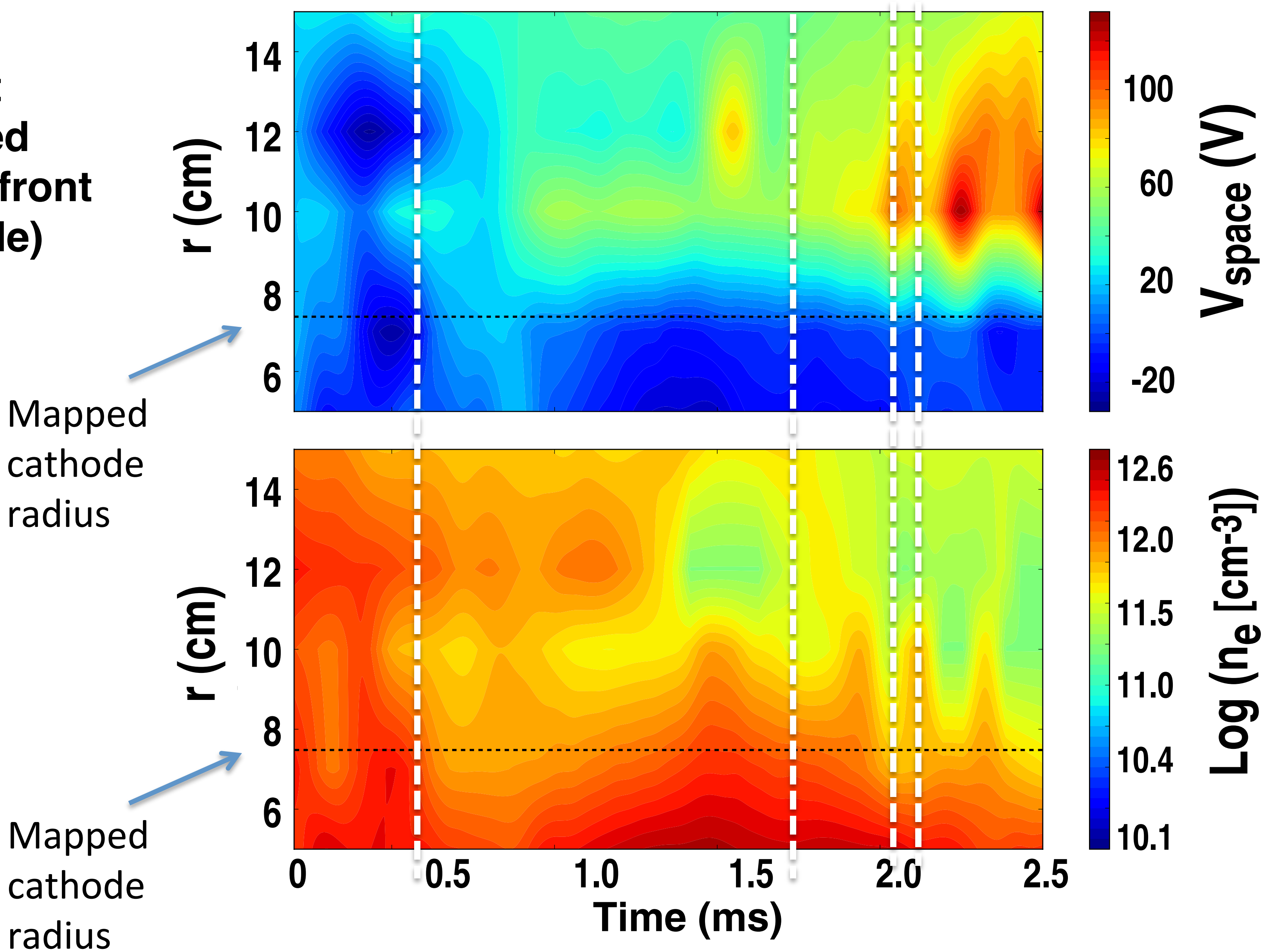
- **Active biasing dramatically reduces outer SOL density**

- **Active biasing increases SOL density gradient**



Radial Potential Well and Increased Density Gradient Develop 0.5-1 ms into Discharge

North Jet (measured 40 cm in front of cathode)



Mapped E×B Velocity Radial Profile with Active Biasing: High Mach number, Large Flow Shear

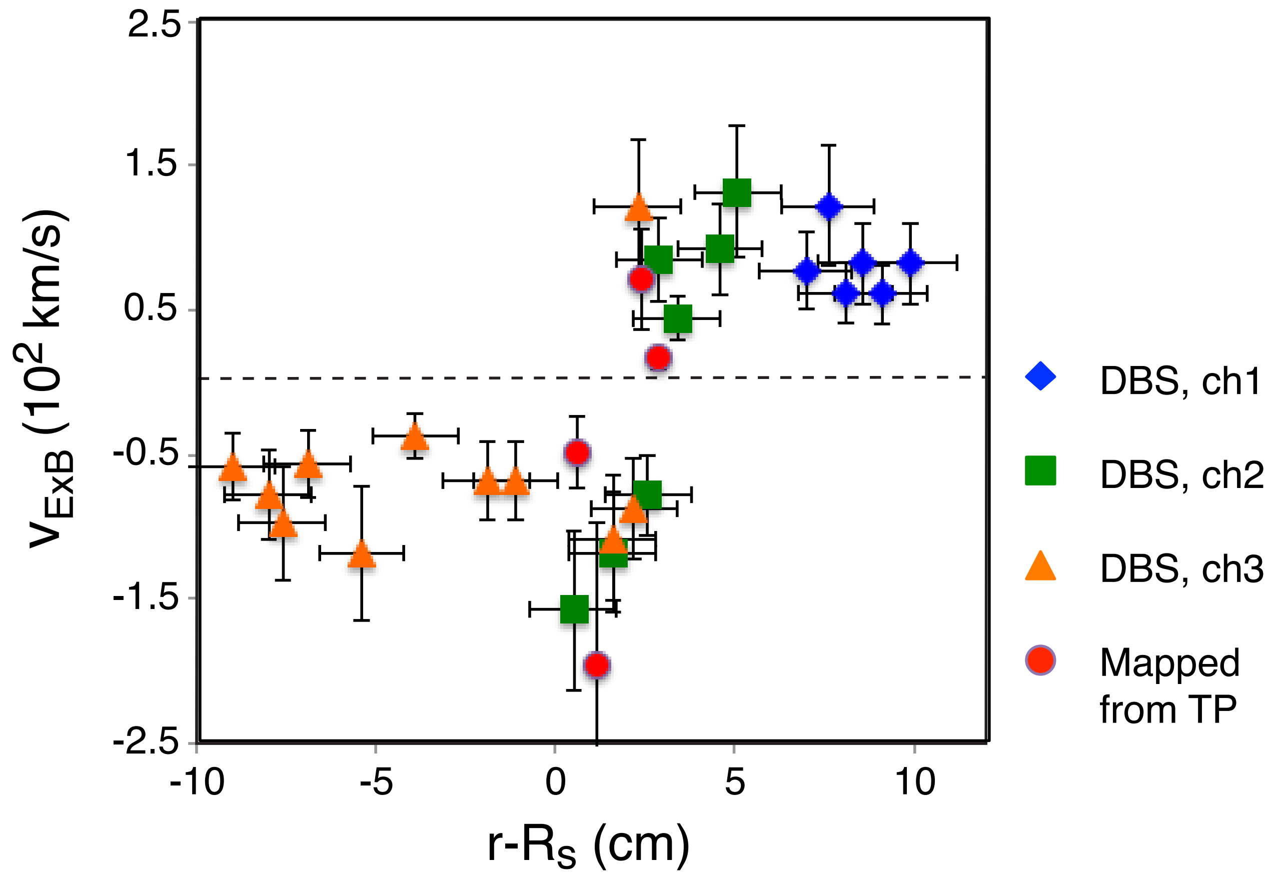
- **Mapped Triple Probe (TP) data matches Doppler Backscattering (DBS) midplane data (within error margins)**

- **Maximum E×B shearing rate just outside R_s (excluded flux radius):**

$$\omega_{E\times B} \leq 5\times10^{6}\,\mathrm{rad/s}$$

- **Mach number M ≤ 1**
  for electron E×B flow
  Ion E×B velocity perhaps lower due to FLR effects

E×B velocity Mapped to C-2U Midplane



T_{cath} ~ 1650°C I_{cath} ~ 2.5 kA

Summary

- C-2 FRC core: Ion-range modes stable due to FLR effects
- GTC simulations reveal unstable FRC Core modes only for unrealistically large gradients or for artificially elongated plasmas (θ-pinch equilibrium)
- Multi-scale SOL turbulence observed/predicted (TEM and Resistive drift waves); driven by $\nabla n, \nabla T_e$
- Strong evidence of SOL radial transport barrier with passive and active biasing. No evidence of sustained large-scale radial streamers (radial corr. length $\lambda_r < \rho_i$)
- Observed critical SOL density gradient compares well with predicted linear instability threshold; compatible with required reactor SOL width

Thank you for your attention!

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