Development of the Quiescent Regime to Understand Runaway Electron Dissipation

By

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with

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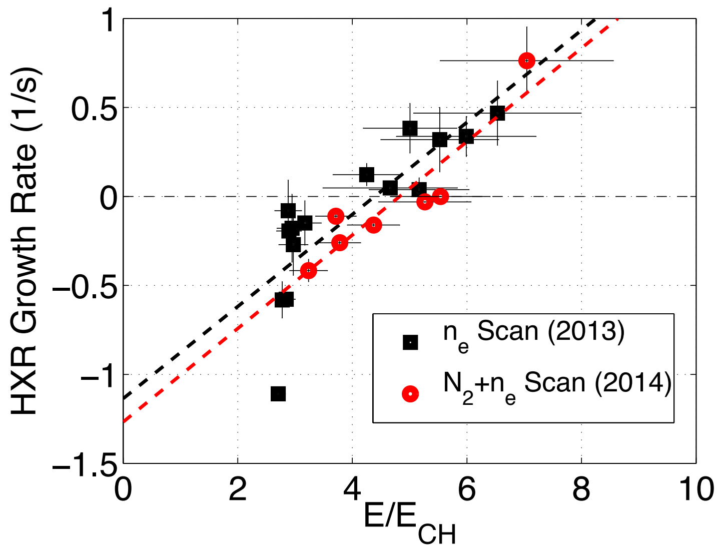
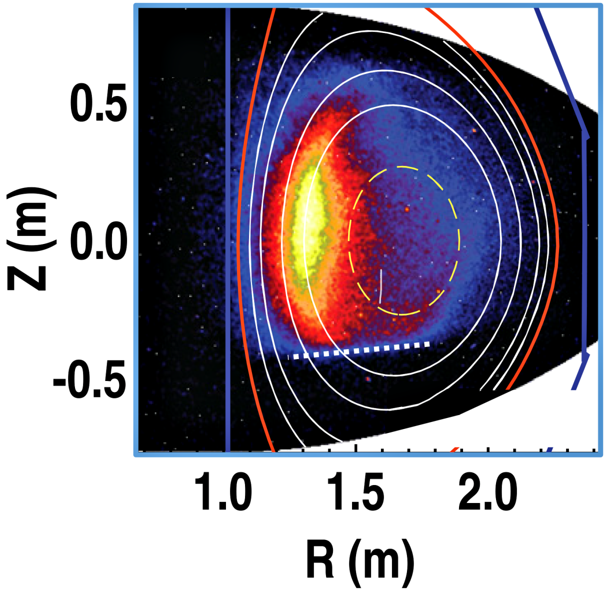




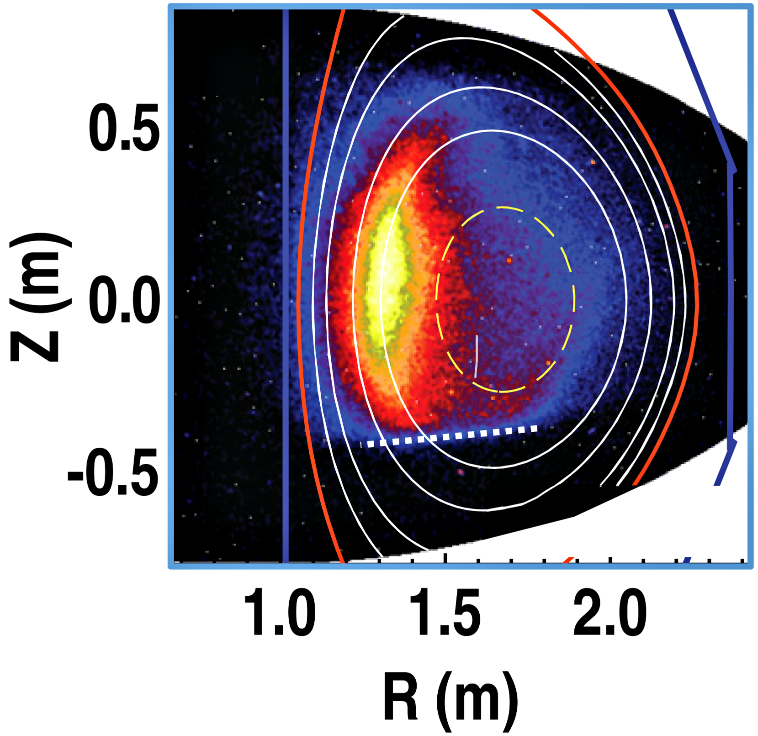
Presented at the

PPPL Disruption Workshop

July 14, 2015

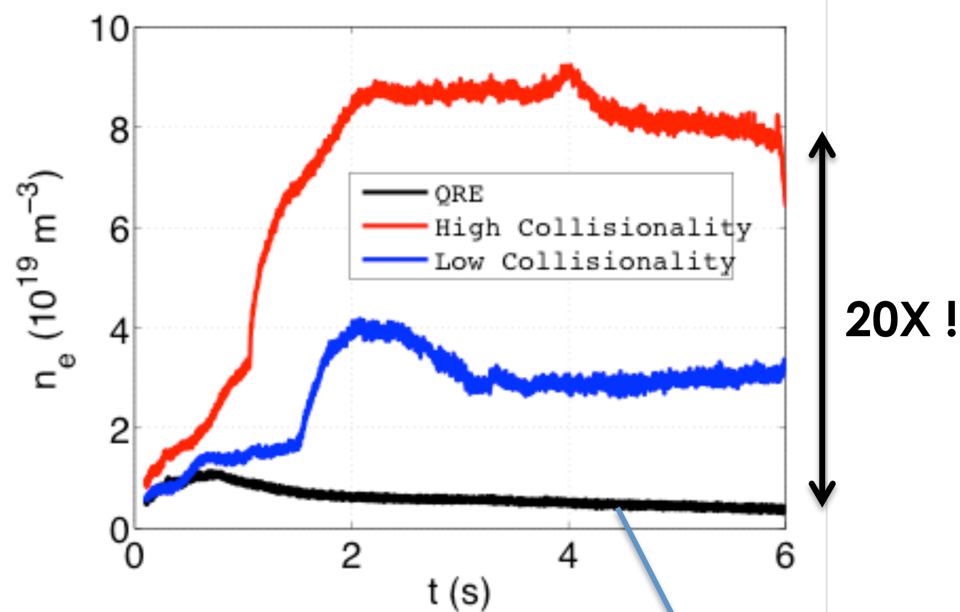
Outline

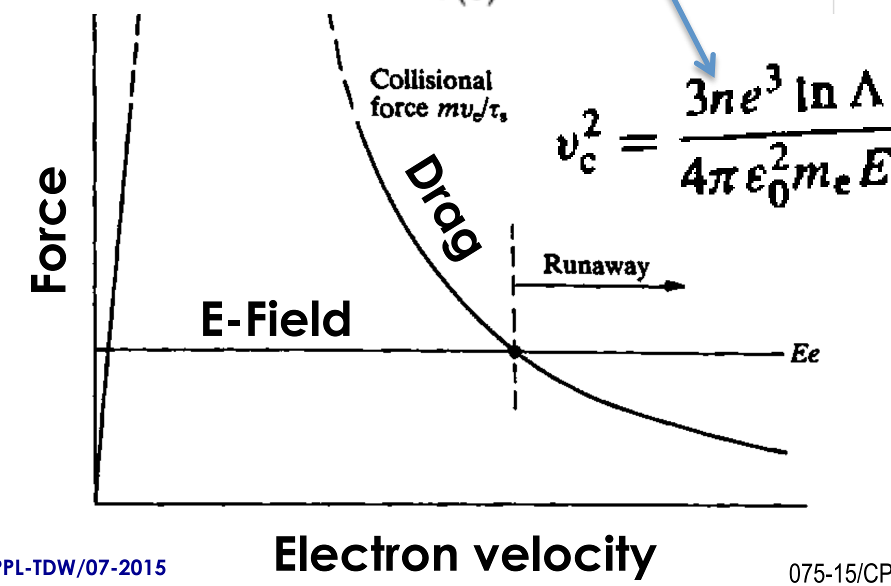
- **Quiescent runaway electron (QRE) regime and Dreicer growth**
- **Recap of QRE dissipation with Deuterium**
- **Extension to QRE decay with Nitrogen**
- **Progress towards constraining QRE energy distributions**
- **Non-thermal origin of the low density stability limit**



Very Low Density Operation on DIII-D Excites Runaway Electrons Through the Primary (Dreicer) Mechanism

- **QRE scenario execution:**
  - Ohmic plasma
  - Turn off gas and wait
  - Good error field correction avoids locked modes
- **Density is <u>way</u> below standard DIII-D scenarios**
- **Dreicer growth mechanism (thermal runaway) exponentially sensitive to density**
  - Linear ohmic confinement keeps T_e constant vs. n_e





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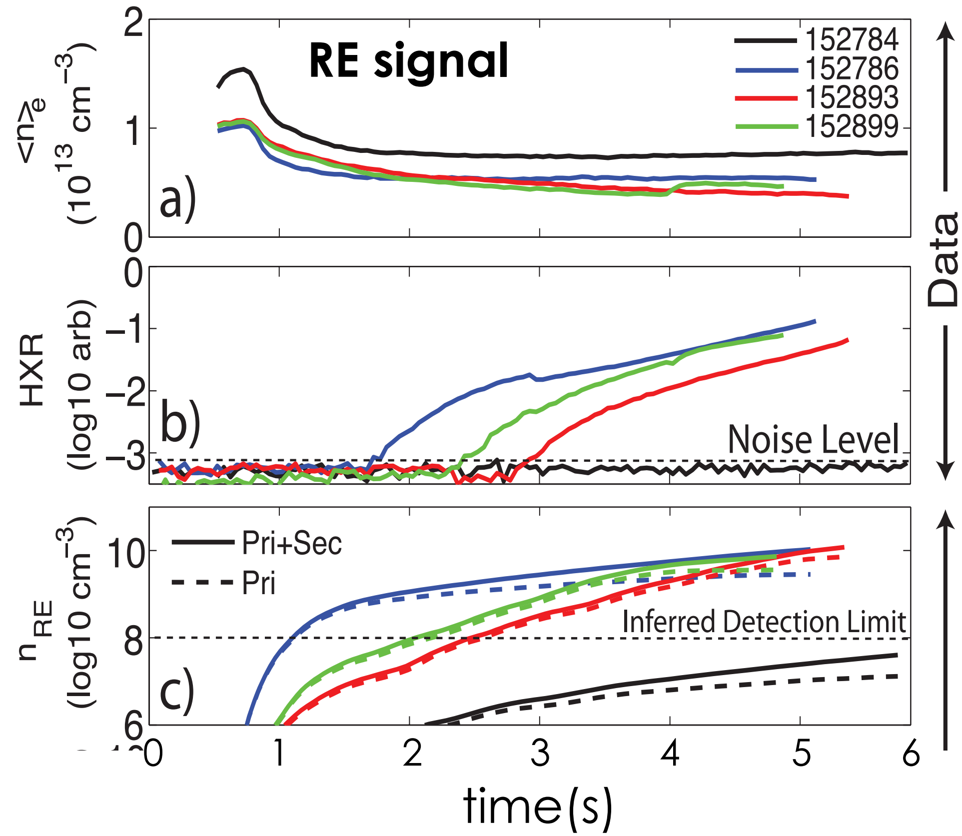
Density Must Be Below a Certain Level to Observe RE Signals — Primary Growth Rate is *Extremely* Sensitive

- **Has the appearance of a 'critical' density condition**
  - Slightly higher density case shows no RE HXR
  - Dropping density by ~25% yields ~1000x HXR increase
- **All parameters important to RE growth well measured:**
  - Contribution from primary and secondary mechanisms calculated
- **Extreme sensitivity consistent with Dreicer calculation**
  - RE onset is not anomalous



$$\frac{dn_{\mathrm{RE}}}{dt} = \underbrace{S_{\mathrm{pri}}}_{\text{primary}} + \underbrace{\gamma_{\mathrm{sec}} n_{\mathrm{RE}}}_{\text{secondary}}$$

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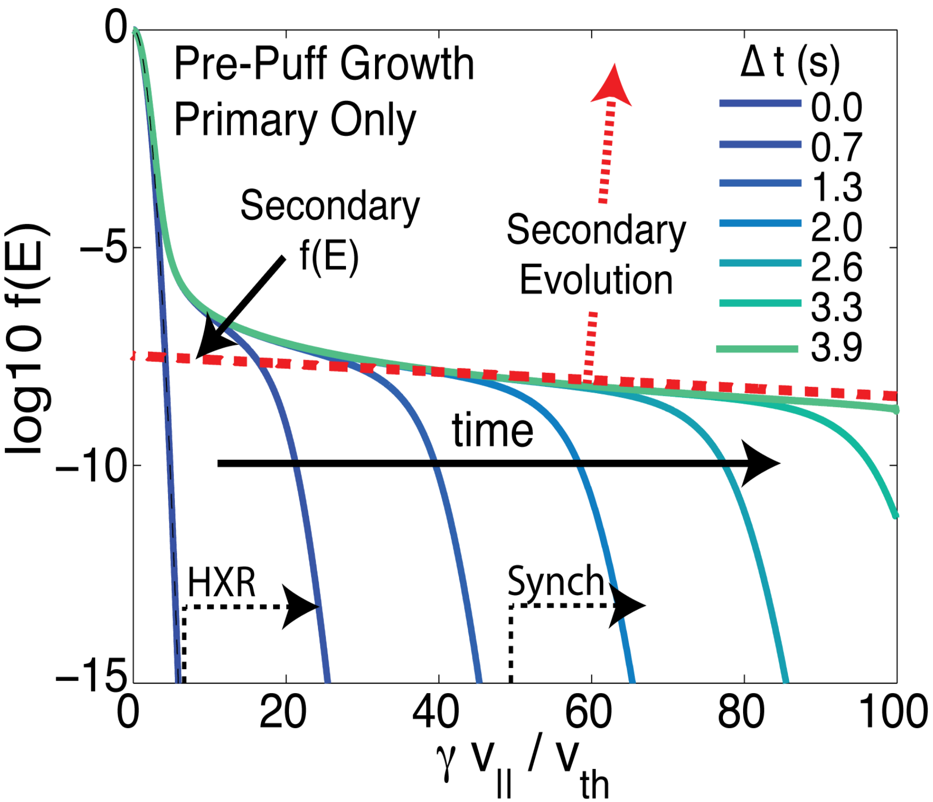
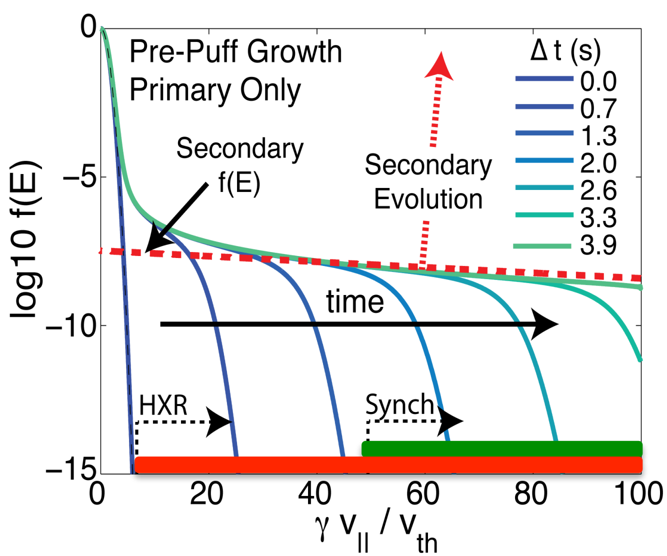
Modeling of Primary-only QRE Growth with Fokker-Planck CODE Shows Formation of High Energy Tail

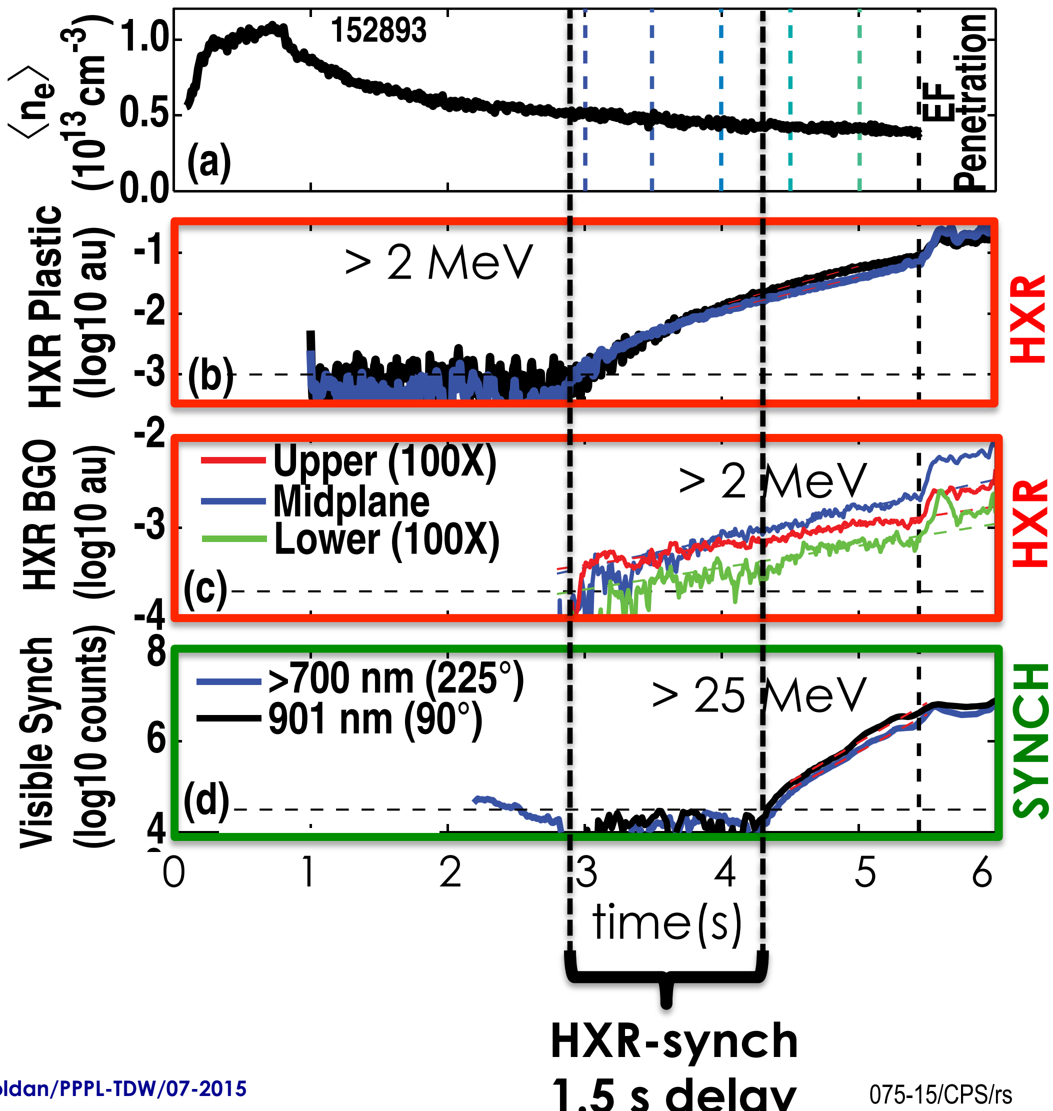
- **f(E) modeling done with 0D Fokker-Planck code (called CODE) [(old version)]**
  – Model QRE parameters
- **Confirms extension of canonical Dreicer tail**
  – Avalanche (secondaries) would raise level @ fixed slope



Time Delay Between Different RE Diagnostic Sensitivities Consistent with Free-fall Time

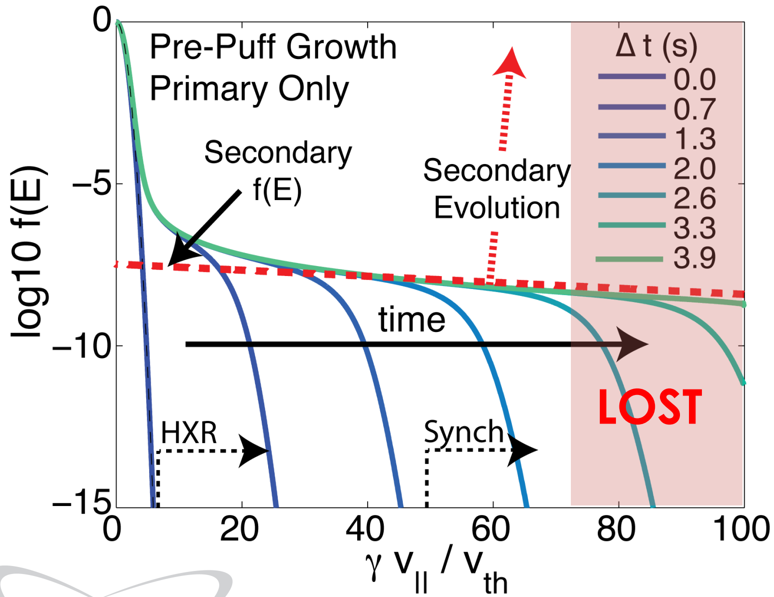
- **RE signature seen on many RE diagnostics**
  - We will return to this later
- **HXR ⇒ Synch. Time delay consistent with free-fall time from ~2 to 25 MeV**

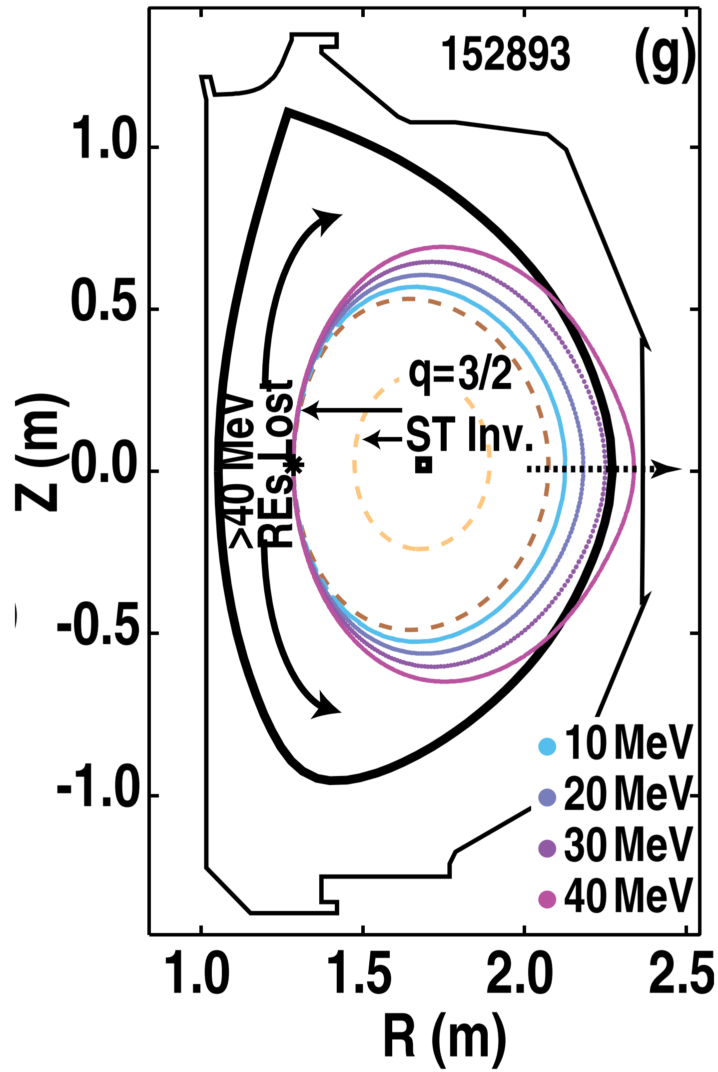




Drift Orbit Losses Set High-energy Limit in Outer Radius

- **Orbit sets max energy to ~40 MeV**
  - Larger orbits scrape off LFS wall

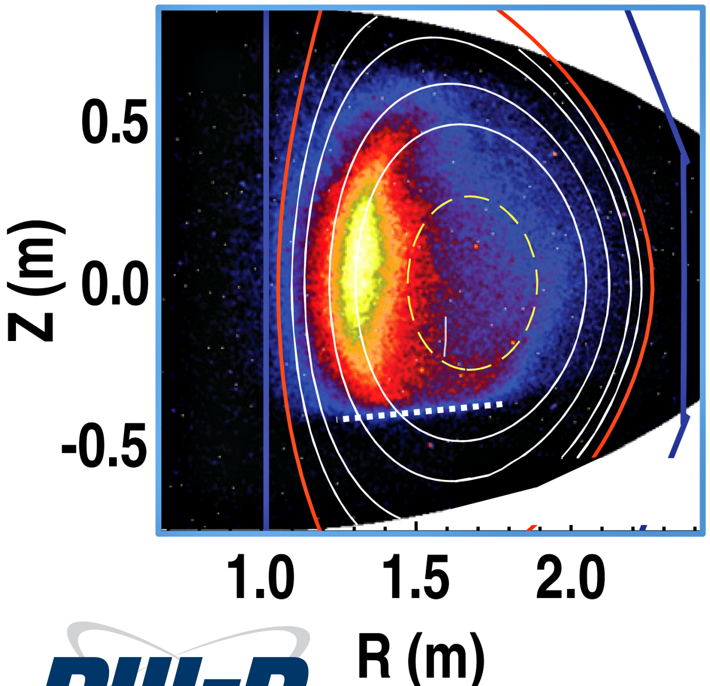


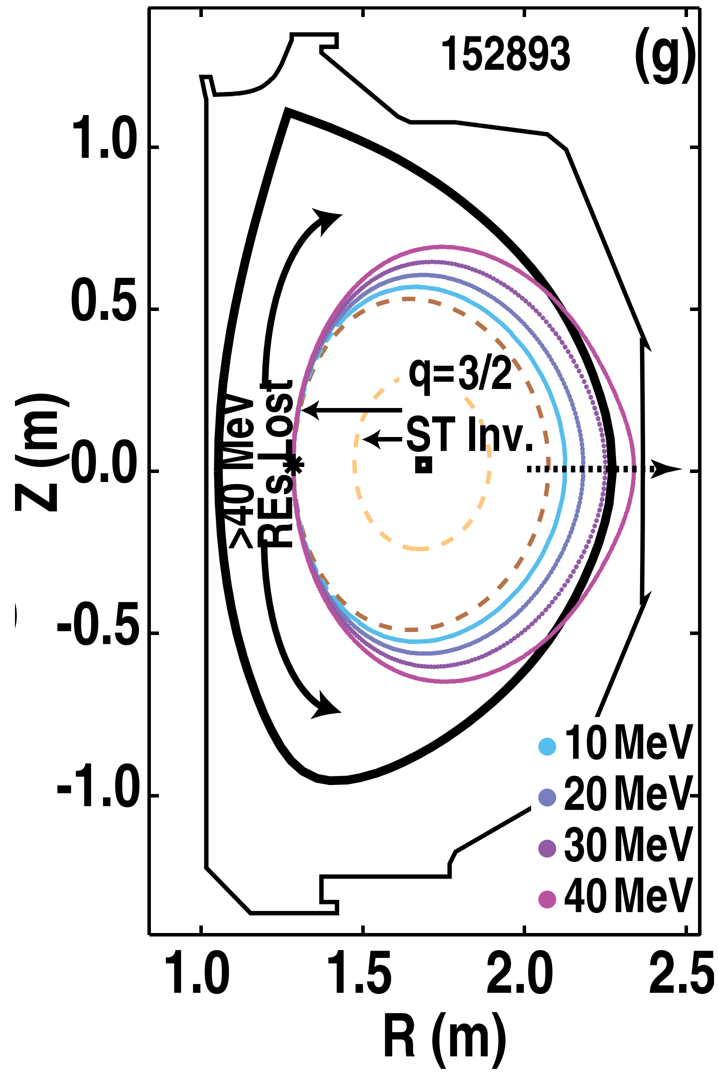


A. Wingen, ORNL

Drift Orbit Losses Set High-energy Limit in Outer Radius Consistent with HFS Synchrotron Emission Extent

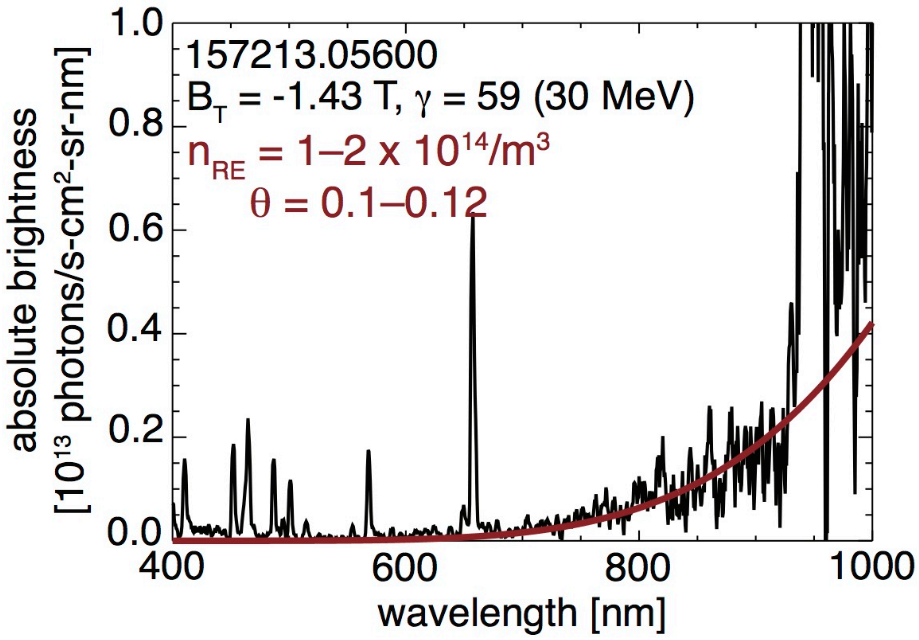
- **Orbit sets max energy to ~40 MeV**
  - Larger orbits scrape off LFS wall
- **Note relative absence of synch emission outside mid-radius**
  - REs must be >25 MeV to be detected by synchrotron





Synchrotron Spectrum Provides Second Check on Maximum RE Energy, Consistent with Orbit Loss Limit

- **Orbit sets max energy to ~40 MeV**
  - Larger orbits scrape off LFS wall
- **Note relative absence of synch emission outside mid-radius**
  - REs must be >25 MeV to be detected by synchrotron
- **Synchrotron spectrum consistent with drift orbit limit,**
  - max power at 30 MeV
  - confirms low pitch angle at highest energies



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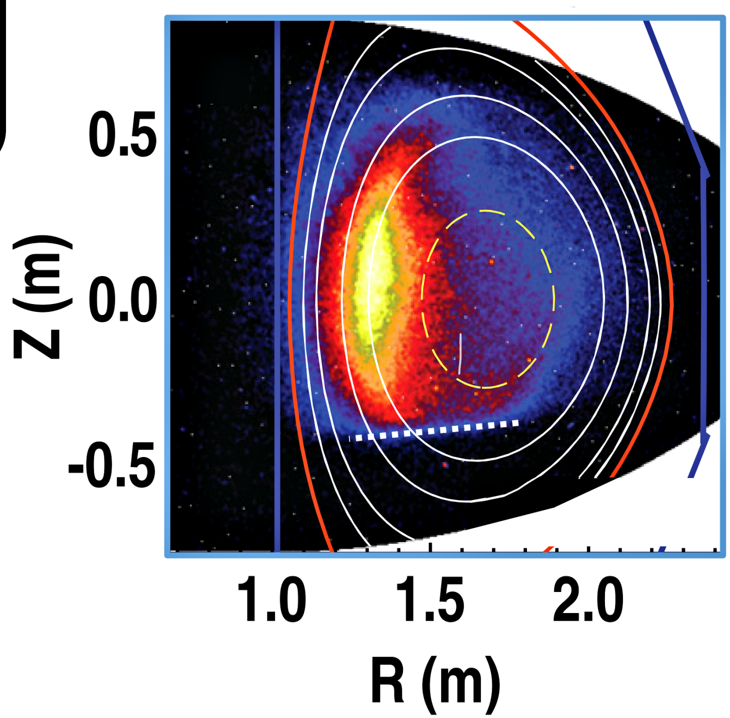
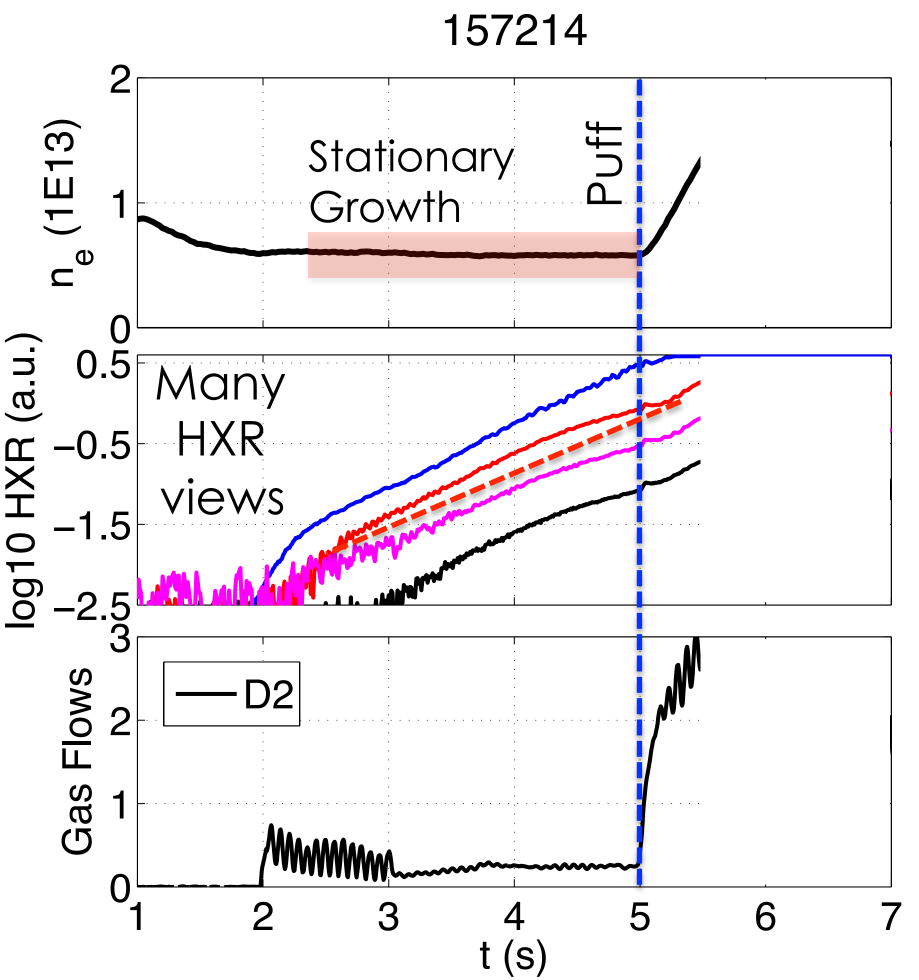


Gas Puffing Introduced to Dissipate QRE Populations After Several Seconds of Growth

- **Electron density follows a target waveform**
- **Increase target at fixed time**
  - Gas puff enters



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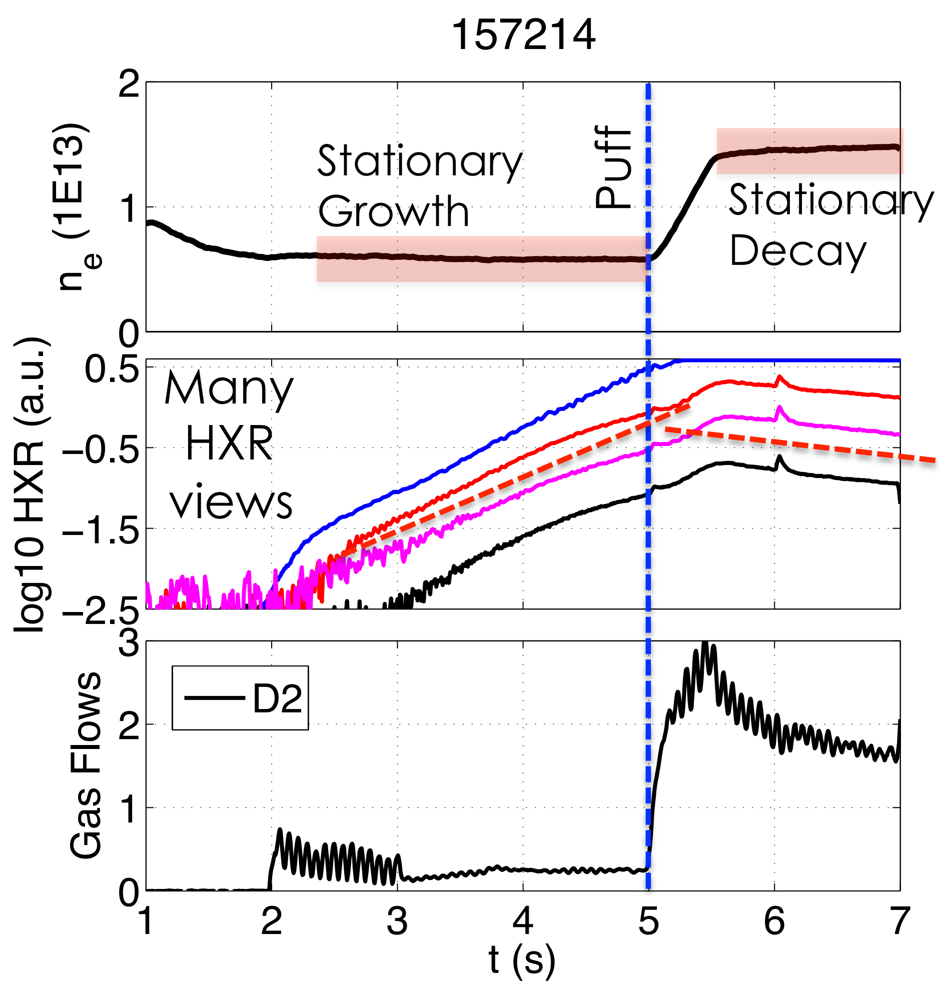
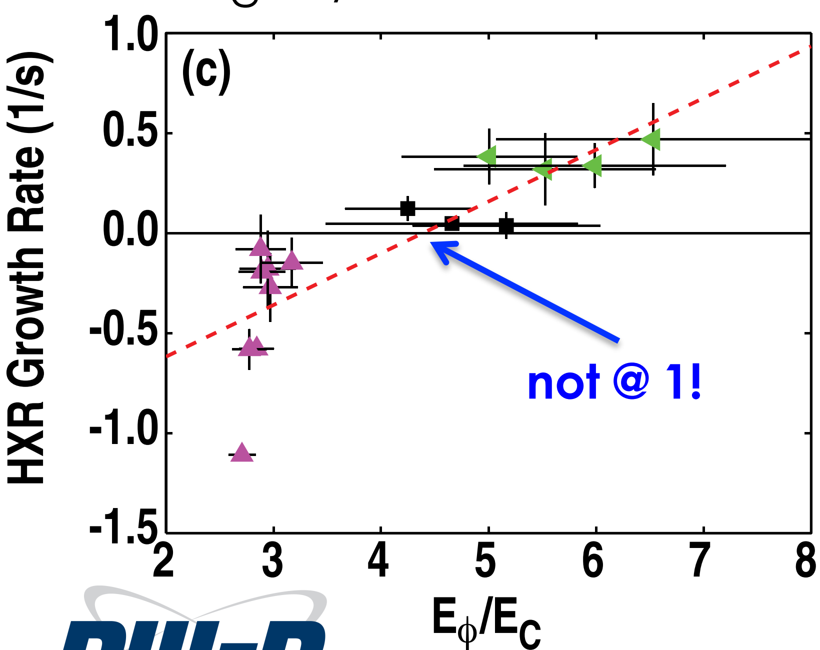
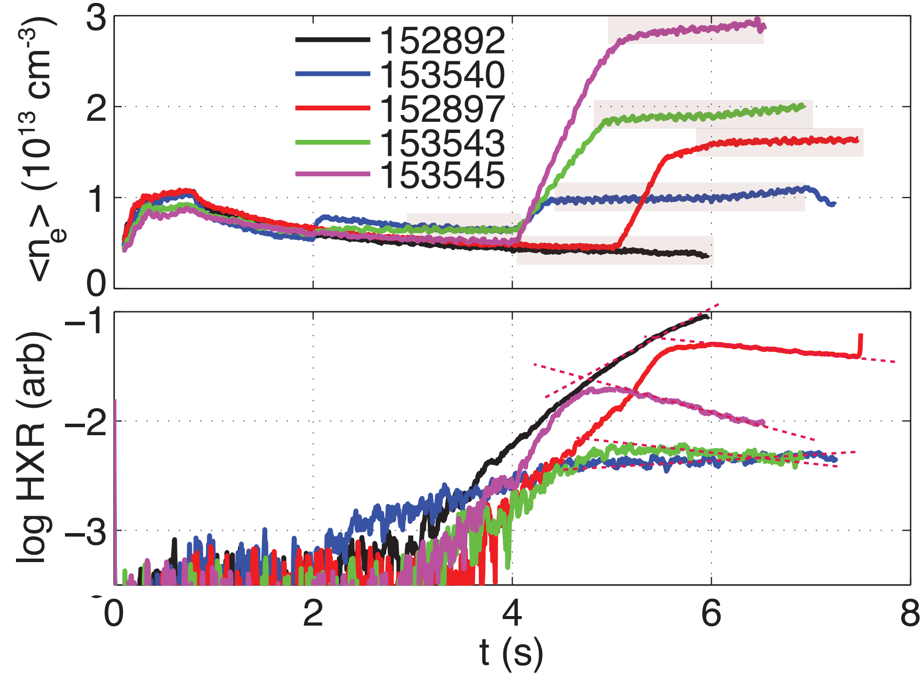
- **Electron density follows a target waveform**
- **Increase target at fixed time**
  - Gas puff enters
- **RE emission goes from growth to decay**
- **Analyze HXR growth rate during stationary phase**
  - Later we discuss other diagnostics



Transition from RE Growth to Decay Found to Occur ~4X Below Rosenbluth Density (Above E-crit)

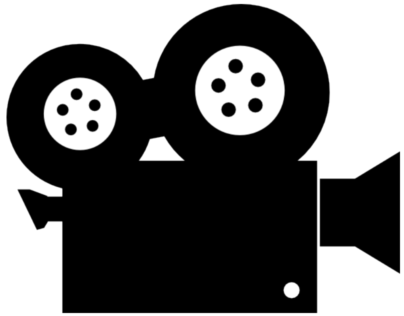
- **Stationary windows selected**
  - 1-2 second long slices
  - Equilibrium parameters stationary and measurable
- **HXR growth rate measured**
  - Transition at anomalously large E/Ecrit



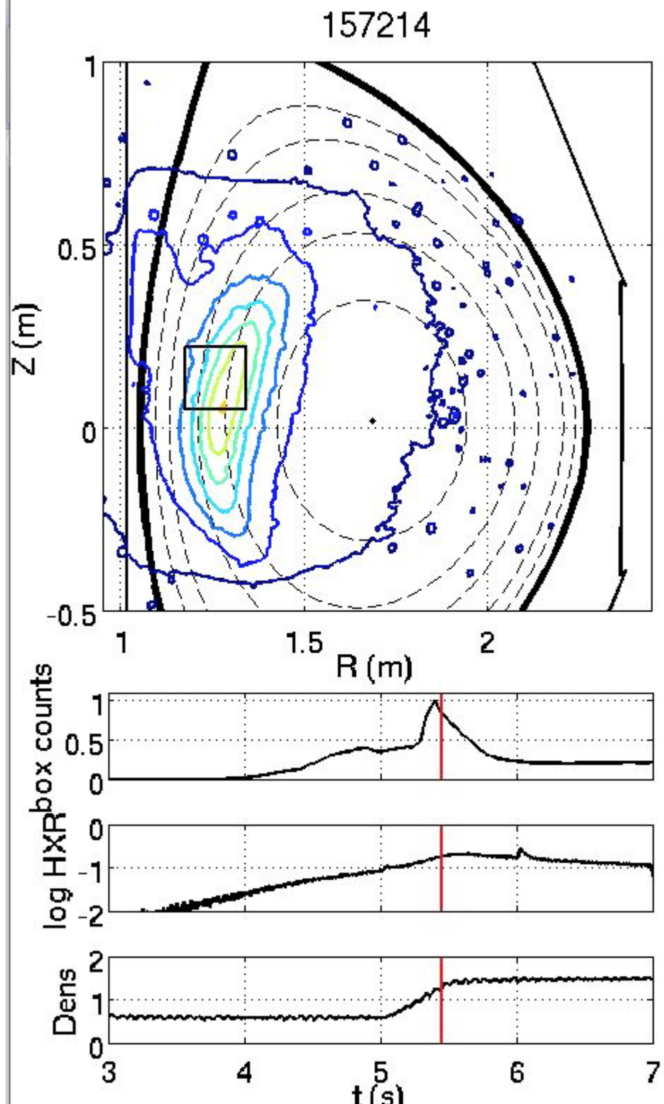


Paz-Soldan et al, PoP 2014
***reprinted in* Granetz et al, PoP 2014**
also Granetz invited IAEA, APS

Synchrotron Emission Movies Show Qrowth and Decay Process, As Well as Impact of Magnetic Islands



- [157214: D2 dissipation example]()
  - Note shape is not significantly affected through process
- [157209: RE population dumped when island opens]()
  - No longer quiescent!
  - Low density operation limited by error field penetration



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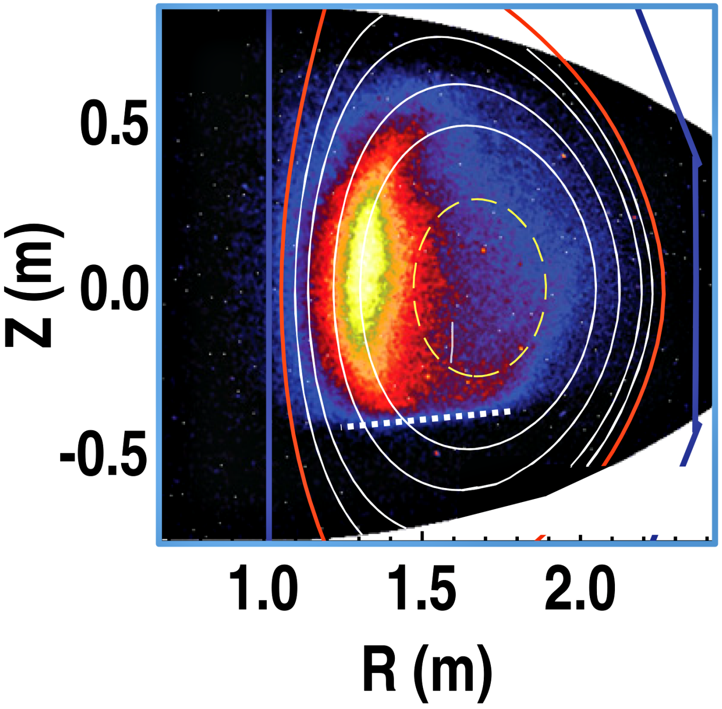
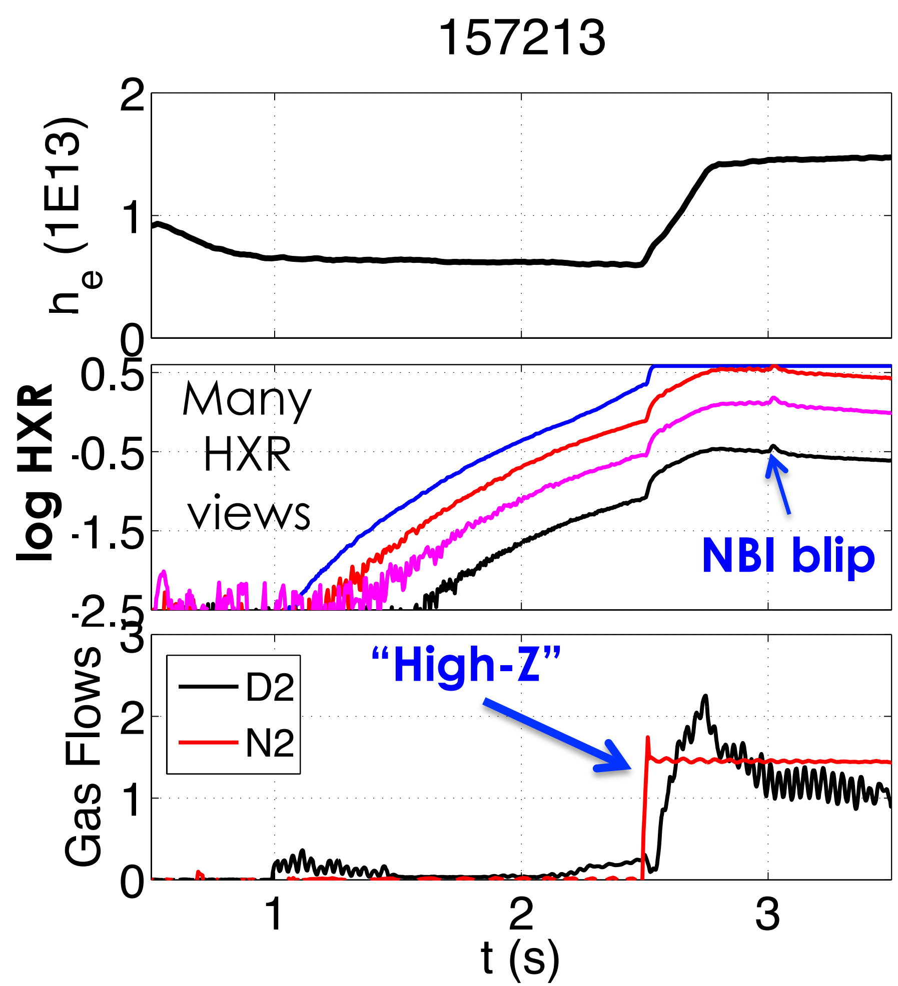


Discharge Setup Allows Easy Comparison of Low-Z and High-Z gas Dissipation — Controlling Electron Density

- **Feed-forward nitrogen puff**
  - D2 on density feedback
- **Nitrogen selected to ensure burn-through in low power Ohmic plasmas**
  - No bound electrons !
- **Diagnostic neutral beam (NBI) blip used for impurity CER**
- **Many shots in Nitrogen experiment lost to locked modes ☹ more on this at end**



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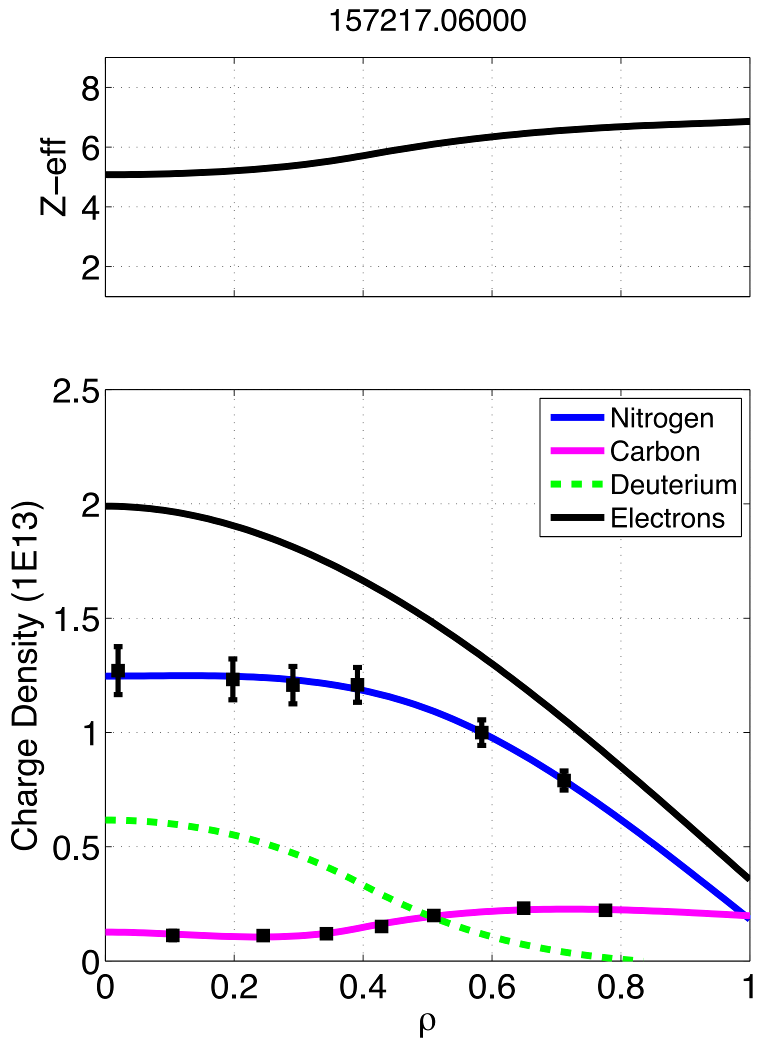
Multi-species CER Allows Precise Determination of "High-Z" Impurity Content and Z-effective

- **5 ms NBI blip / second**
  - ½ channels tuned to carbon
  - Other ½ tuned to nitrogen

- **CER analysis returns densities of each species and overall Z-effective**
  - Ignore higher-Z contributions



B. Grierson, PPPL

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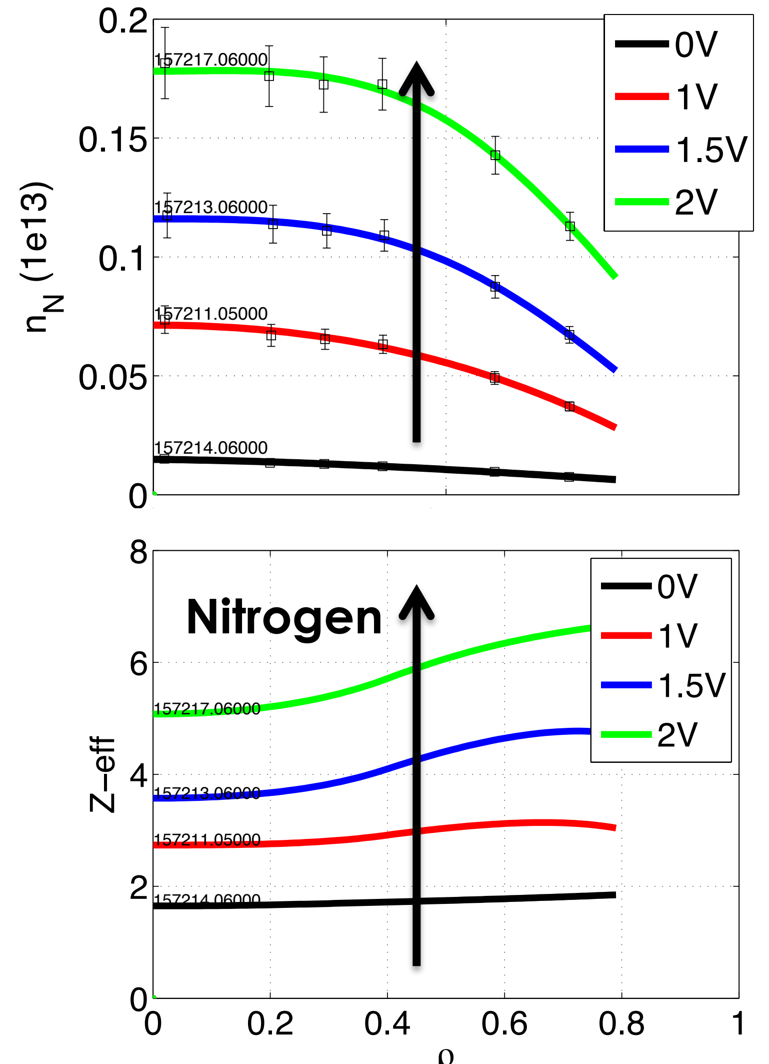
- **Increasing N2 puff indeed scanned nitrogen, Z-effective**

Nitrogen scan, constant Density



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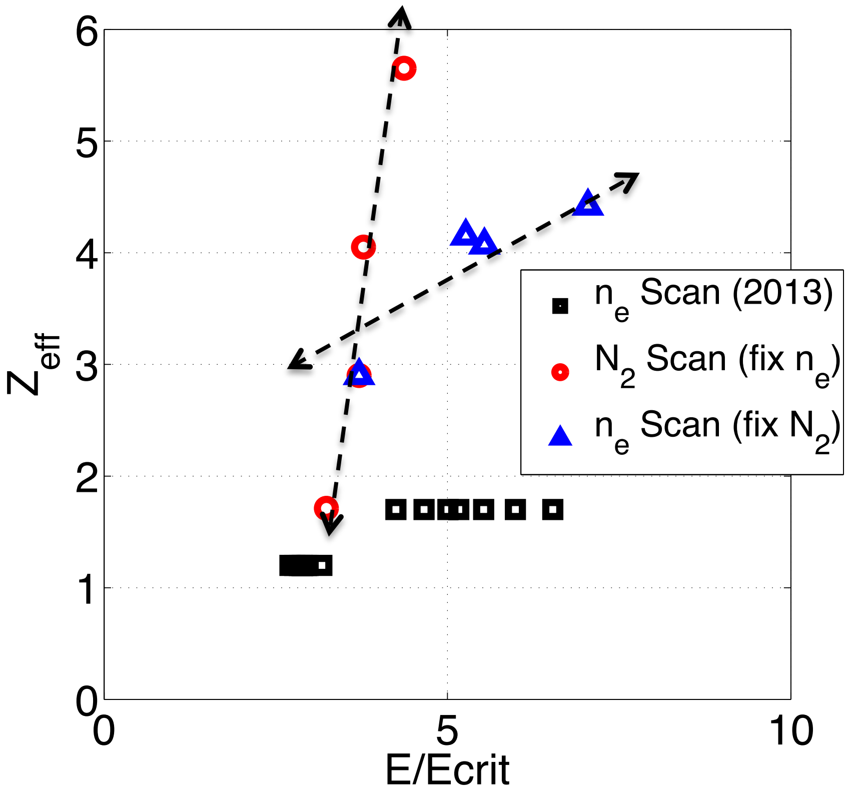
- **Changing ratio and quantity of D2 to N2 opens exploration of Z – Ecrit space**

Summary of accessed experimental parameters



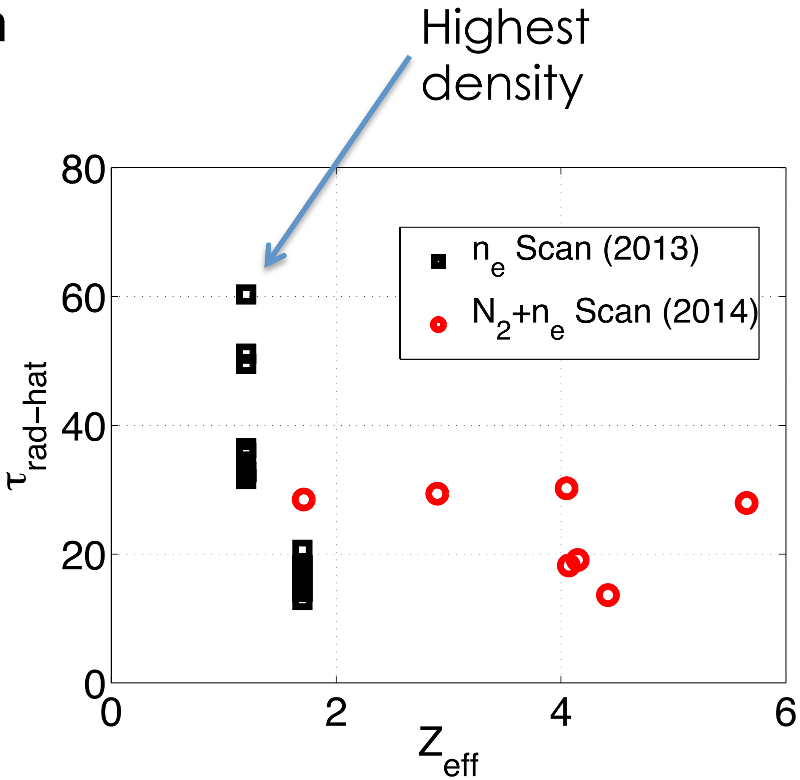
Interplay Between Collisional and Synchrotron time Scales Sets Non-dimensional RE Regime for Experiment

- **Critical ratio is effective electron density over B²**

$$\frac{\tau_{\text{rad}}}{\tau} \equiv \hat{\tau}_{\text{rad}} = \frac{3}{2}\left(\frac{m_e \ln\Lambda}{\epsilon_0}\right)\frac{n_{\text{eff}}}{B^2}$$

$$= 278 \cdot \frac{n_{\text{eff}}[10^{20}]}{(B[T])^2}$$

- **DIII-D plateau: tau-hat~700**
  - $n_{eff}[10^{20}]$=10, B[T]=2
- **DIII-D QRE: tau-hat~20**
  - $n_{eff}[10^{20}]$=0.1, B[T]=1.5
- **ITER plateau: tau-hat~70**
  - $n_{eff}[10^{20}]$~10*, B[T]=6
- **Surprisingly, DIII-D QREs are in correct RE regime for ITER !**



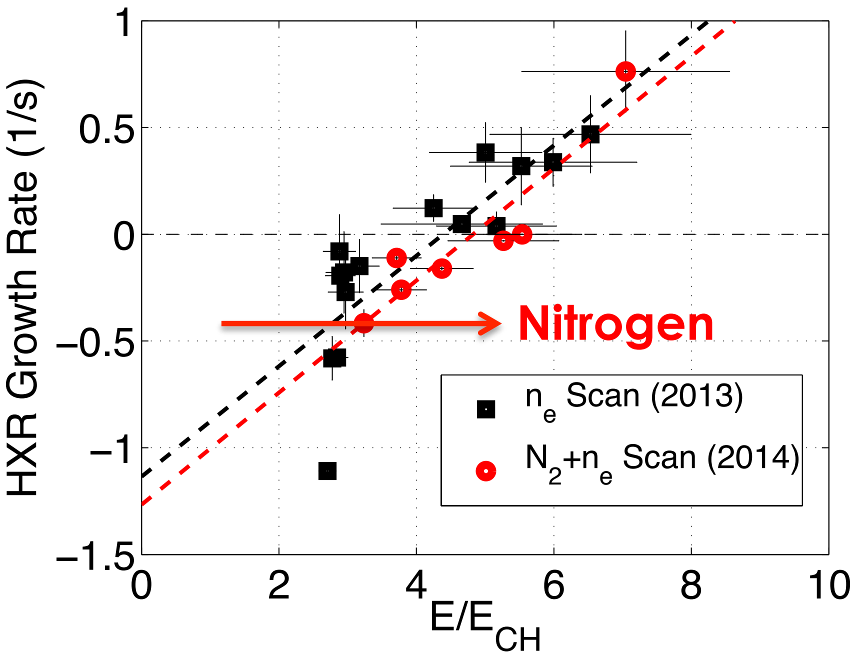
* M. Lehnen, J. Nucl. Mat. 2015

Nitrogen Dissipation Data vs. Ecrit Shows Modest but Measurable Increase in Zero-crossing (~1 Ecrit unit)

- **All red points are systemically lower than black points**
  - Possible exception at highest E/Ecrit

- **Nitrogen effect is thus measurable but relatively weak**

- **Opportunity to compare with theoretical prediction**

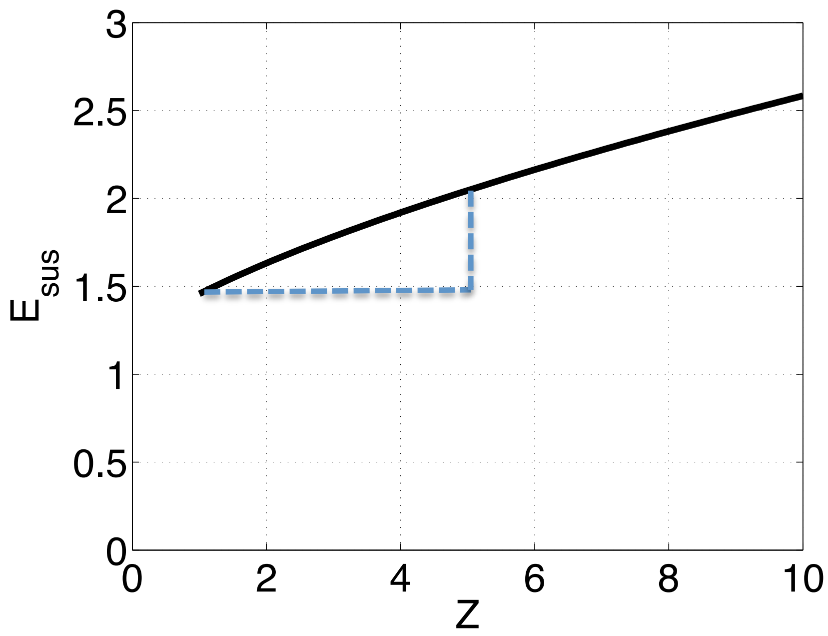


Shift in HXR Zero-crossing with Z Comparable to Recent Aleynikov Theory, but Offset

- **Increase of about 1 Ecrit unit in sustainment field and avalanche onset field as Z goes from 1 to 5**

- **Model says gets 1.5⇒2.5,**

- **We see ~4⇒5**

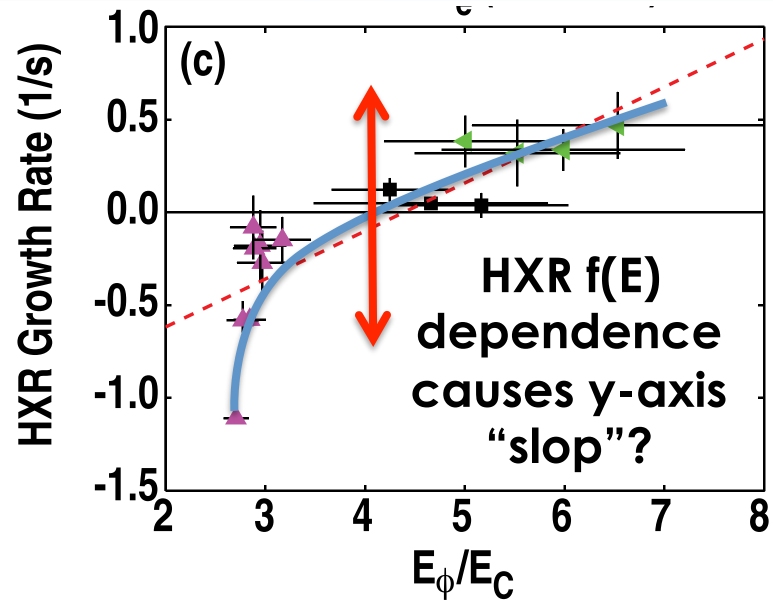


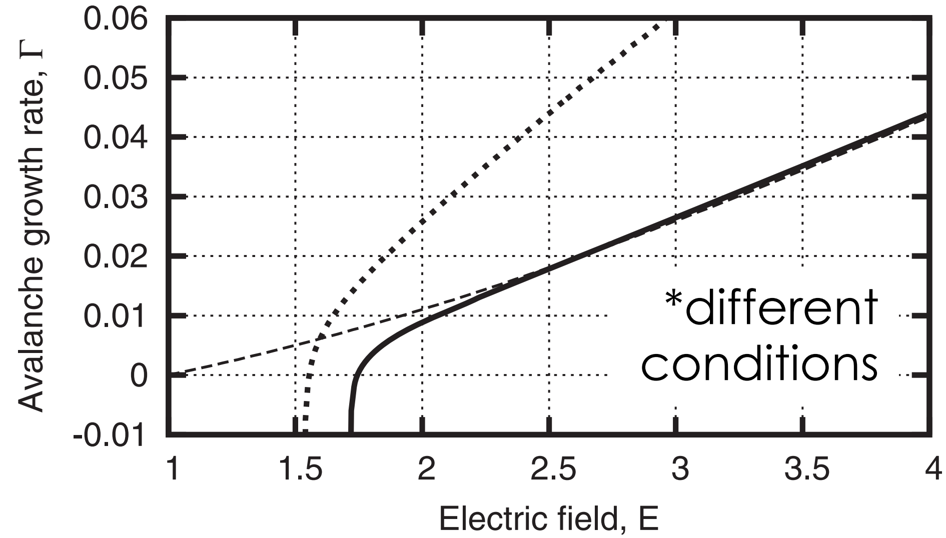
$$E_0 \approx 1 + \frac{\frac{(Z+1)}{\sqrt{\bar{\tau}_{rad}}}}{\sqrt[6]{\frac{1}{8} + \frac{(Z+1)^2}{\bar{\tau}_{rad}}}},$$

Aleynikov et al, PRL 2015

HXR Shows Hints of Growth Rate "Wall" at Lowest E/Ec, Similar Feature Found in Model

- **Baseline mismatch raises the question of energy sensitivity of HXR detectors**
- **Could distribution function re-arrangement mask an increasing number density with a decreasing signal?**
- **Note growth rate "wall" expected in model, hints are seen in the data**
  - More data at that E/Ec would help clarify

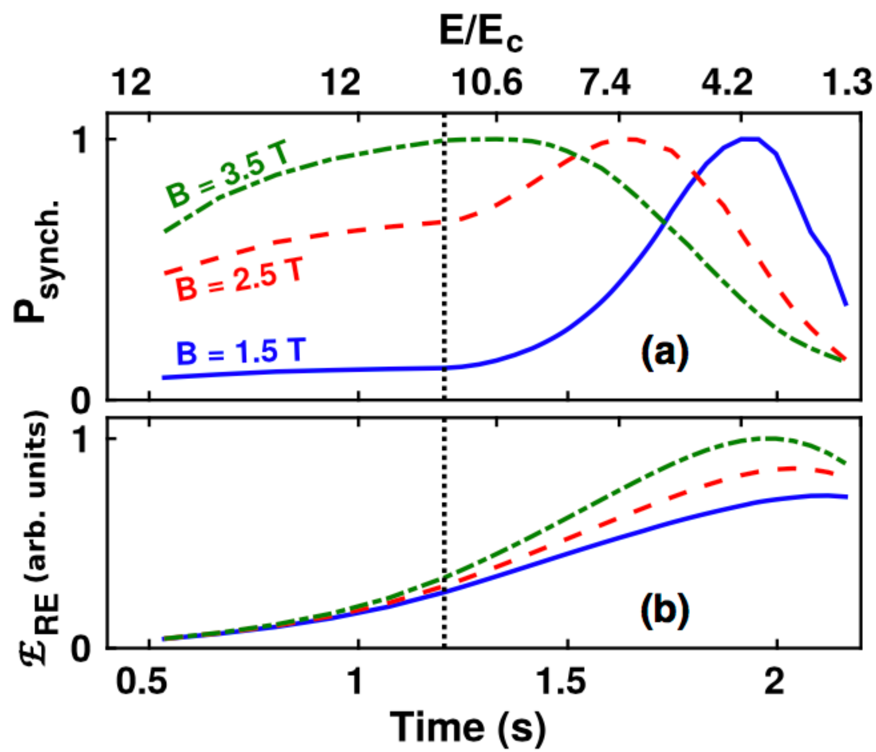




Aleynikov et al, PRL 2015

Stahl et al Finds Synch Emission can be Significantly Decreased While RE Energy Constant/Increases

- **Phase space re-arrangements can decrease synch emission (SE) at constant (or increasing) number density**
  - Synthetic SE diagnostic used based on CODE distribution functions
- **Could explain HXR?**
  - What is distribution function sensitivity of emissions



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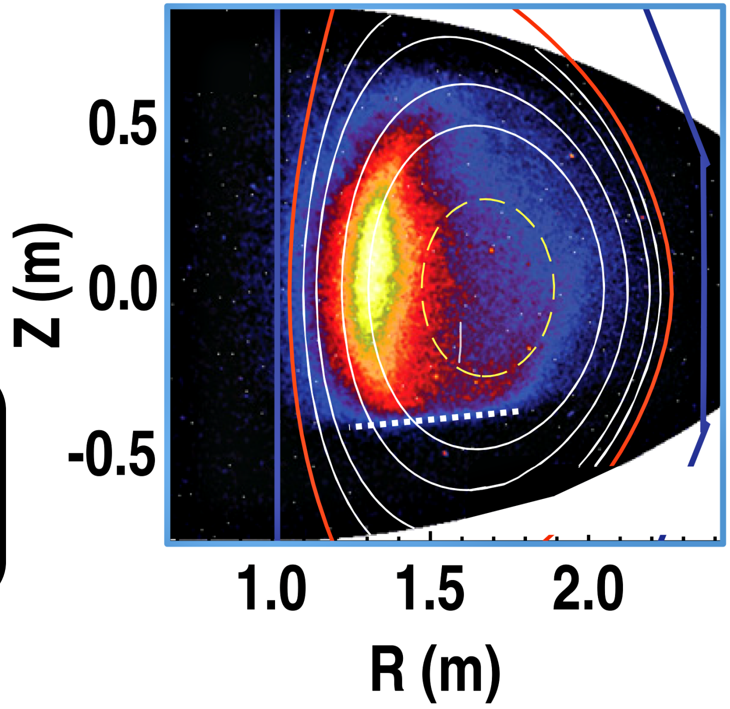
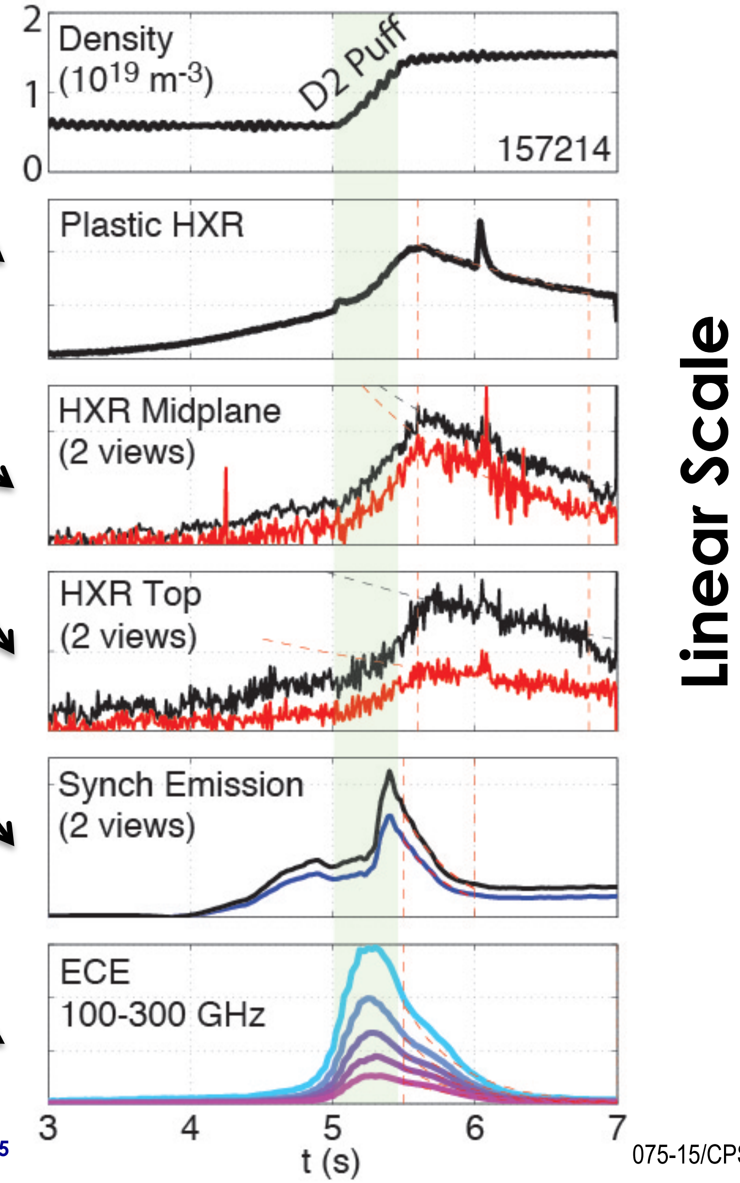


QRE Growth and Decay Visible on Many Diagnostics, all Signals Decrease (at Different Rates) After Puffing

- **Main diagnostic is plastic scintillator HXR**
  - most sensitive to QREs
- **Bismuth-germanium-oxide (BGO) HXR detectors also**
  - Above torus and at midplane
- **Visible synchrotron cameras and spectrometers @ midplane**
  - IR synch available for future
- **ECE interferometer for high frequency ECE emission**



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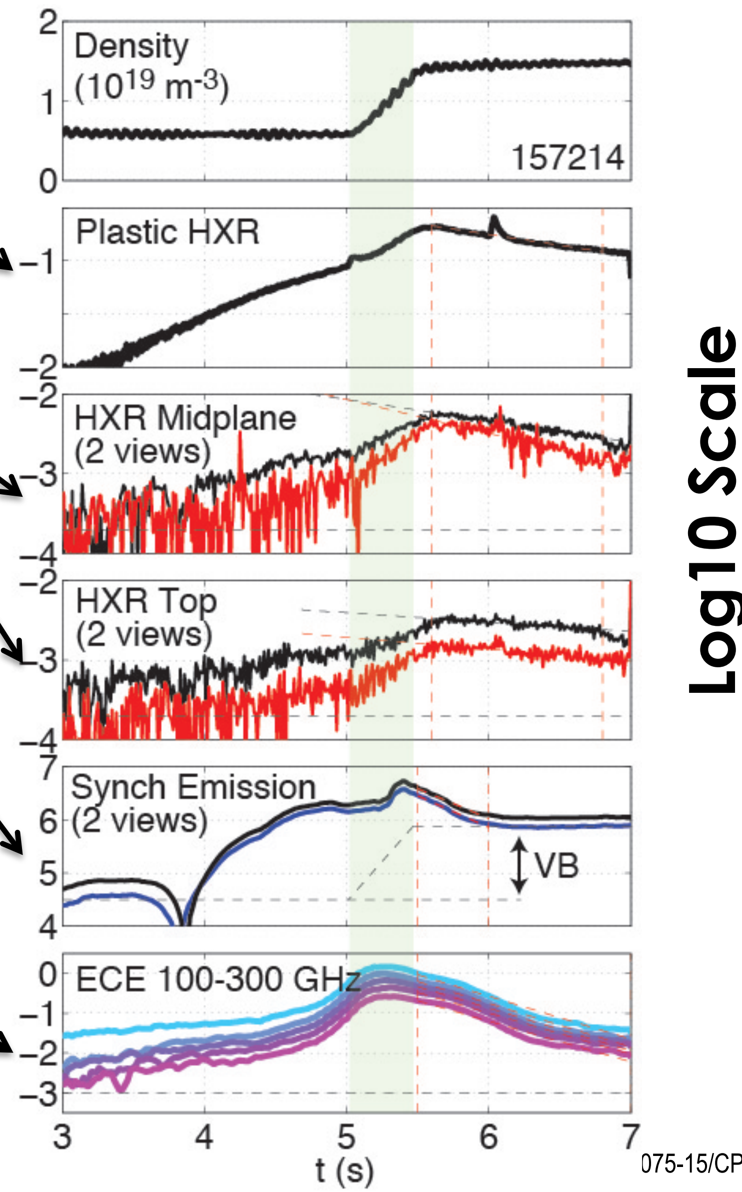

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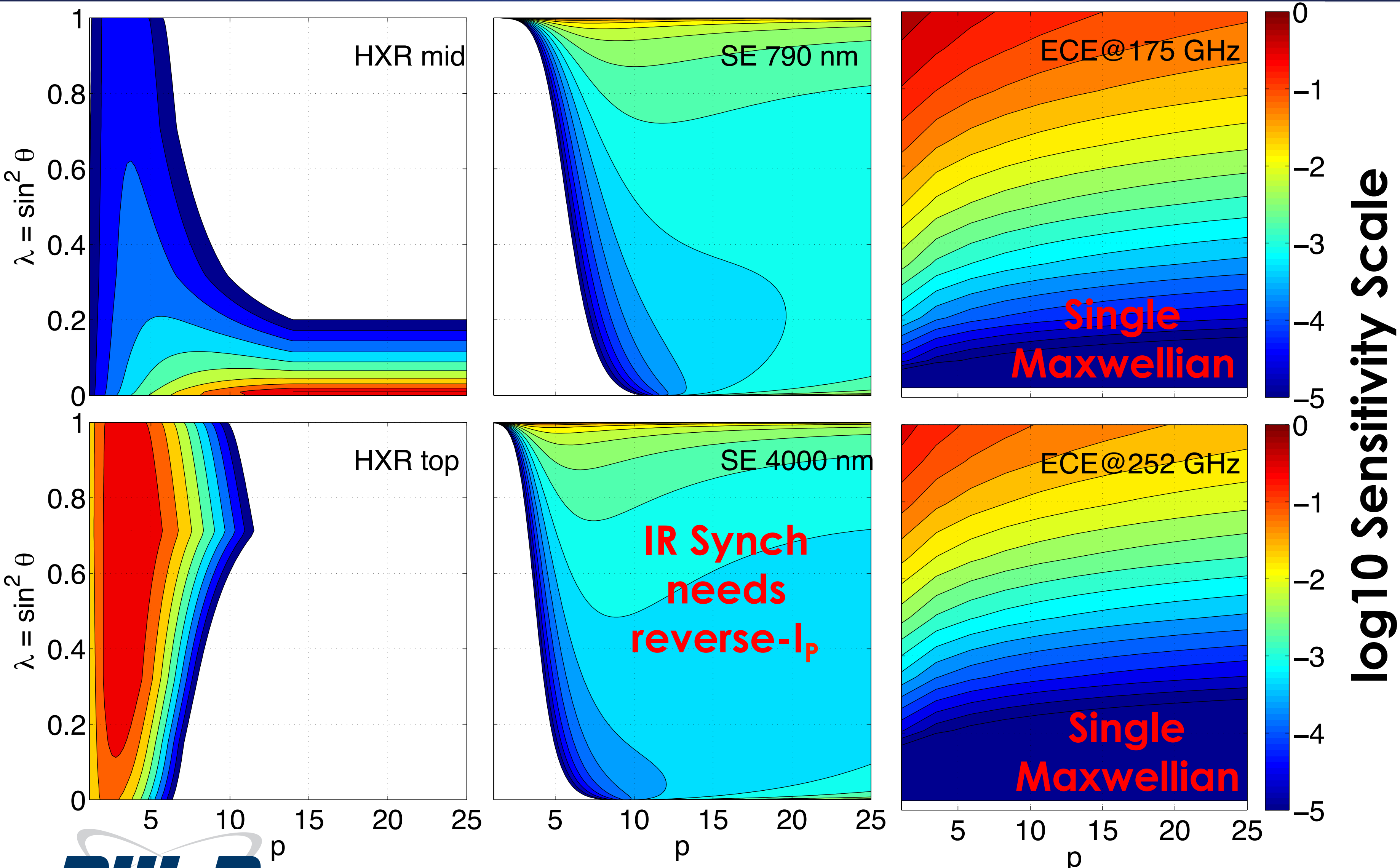
These Diagnostics Probe Different Parts of the QRE Distribution Function — Can Infer f(E) Properties



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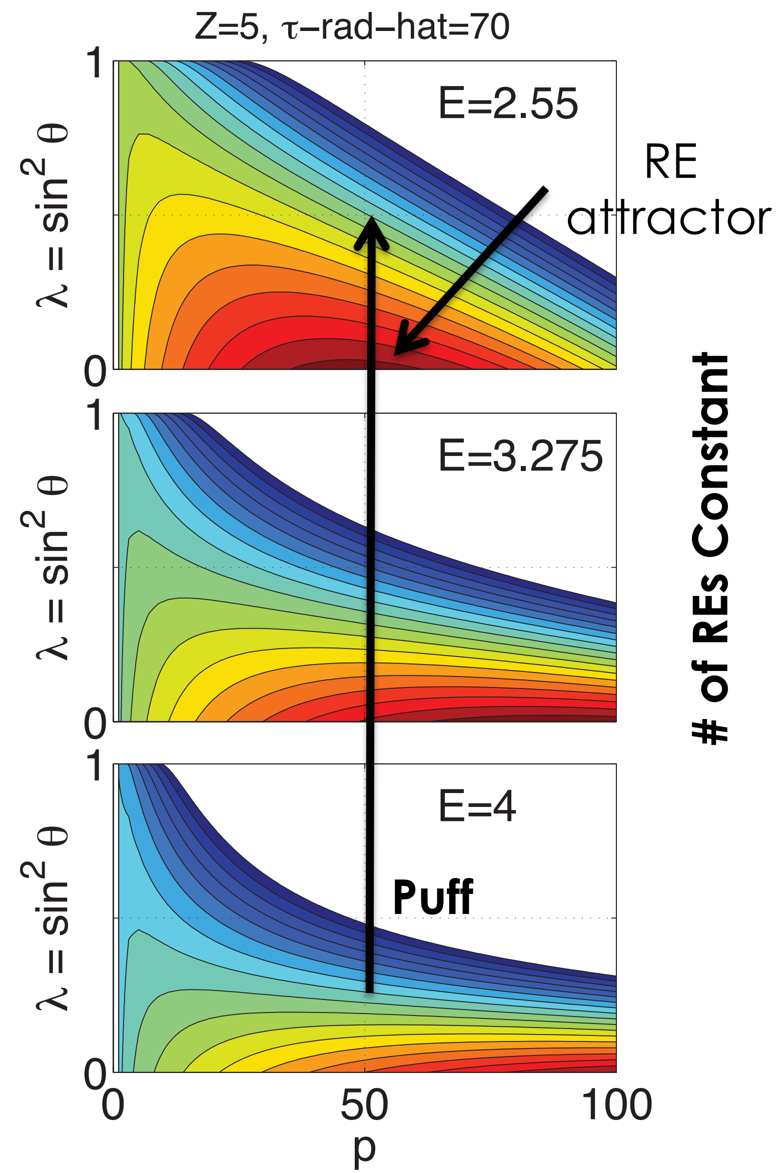
Example: Aleynikov's Distribution Functions Show Increased Pitch Angle at Low E/Ecrit

- **Aleynikov theory described in earlier talk**
- **Equal opportunity comparisons – I will study anyone's distributions!!**

YOUR DISTRIBUTION FUNCTION HERE

- **Example: Aleynikov theory shows increased pitch angle at low E/Ecrit ⇒ after gas puff**



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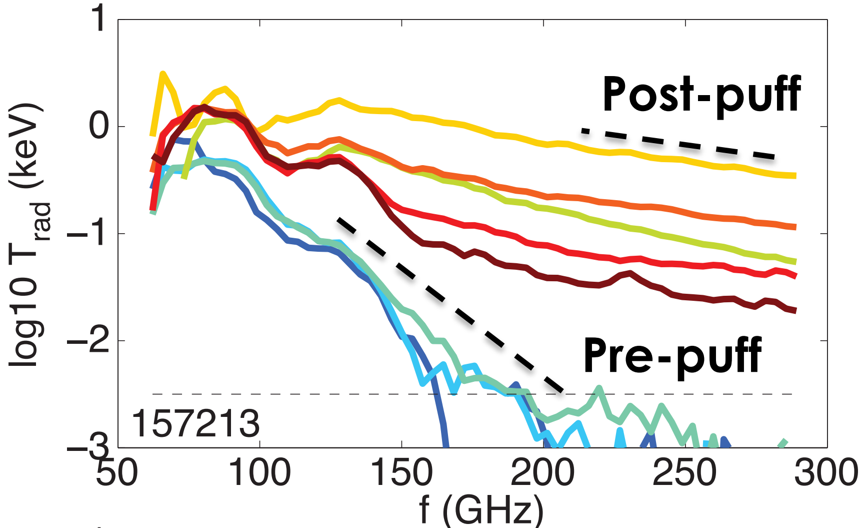
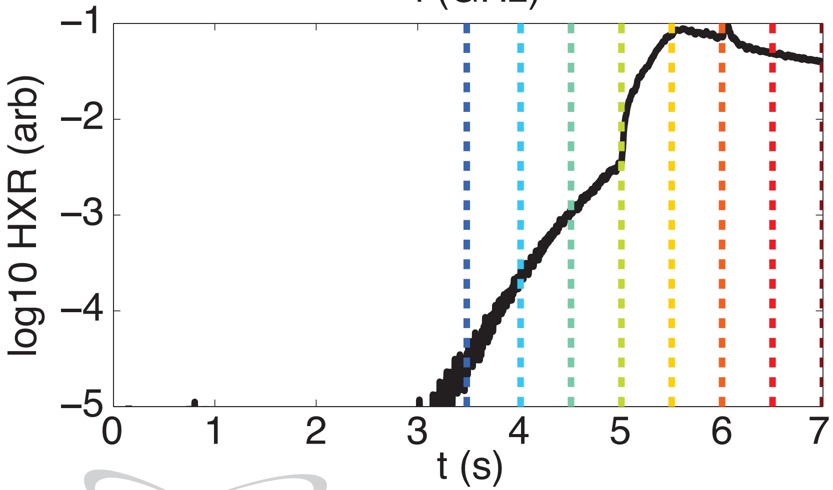
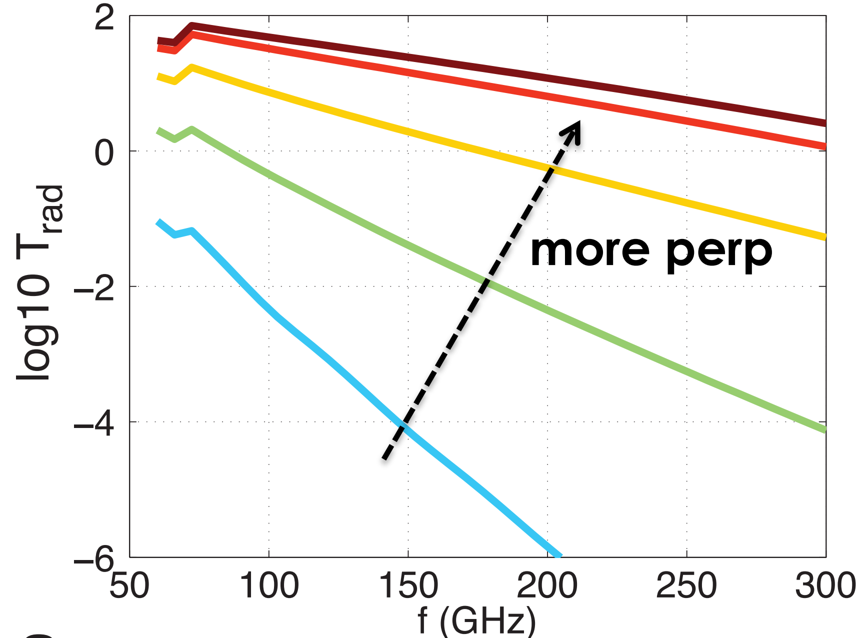
ECE Spectrum "Hardening" Provides Evidence for Pitch Angle Change After Gas Puff

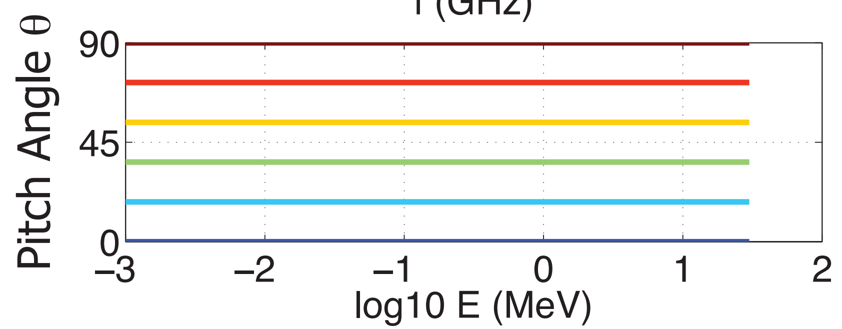
Data





Model





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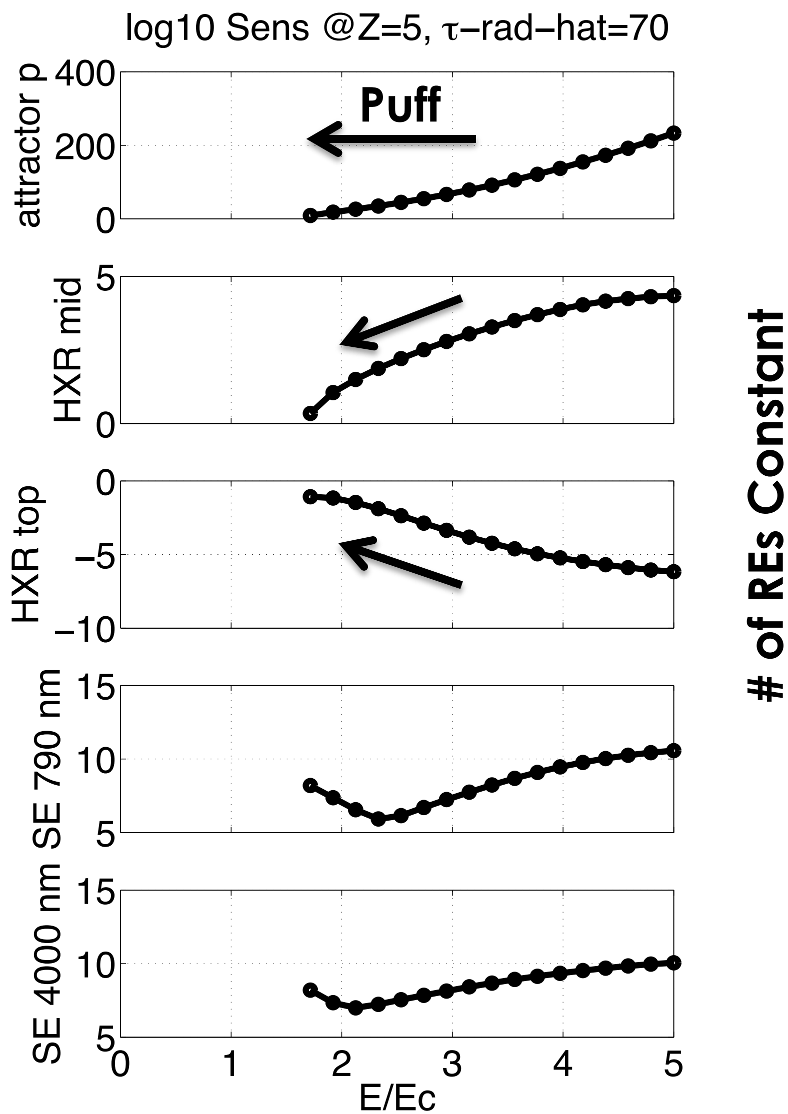
Distribution Function Predictions Allows Convolution with Diagnostic Sensitivity Functions

- **Scan E/Ecrit, but assuming:**
  - Steady-state f(E)
  - # of REs constant
  - Neither is true!

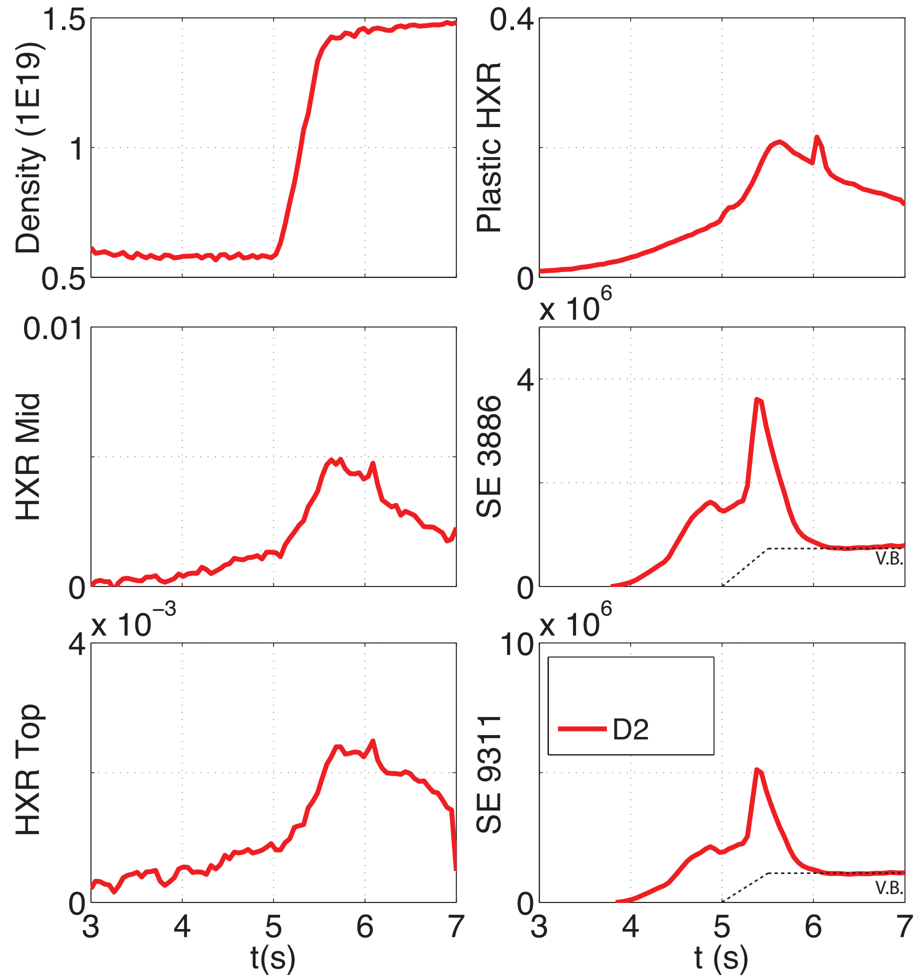
- **We see very strong f(E) sensitivity on all diagnostics even at constant # of REs**

- **Notice HXR @ top of torus actually predicted to decrease with increasing E**



Experimental Data Shows all HXR Diagnostics Behave Similarly, While SE Decays More Quickly

- **HXR decays slowly after gas puff, but all do the same**
  - MAYBE top is slower
  - No evidence for large pitch re-arrangement, unlike ECE
- **Synch is quickly growing, quickly decaying**
  - Emission is very sensitive to energy
  - Final value is vis. Brems, a baseline to subtract out



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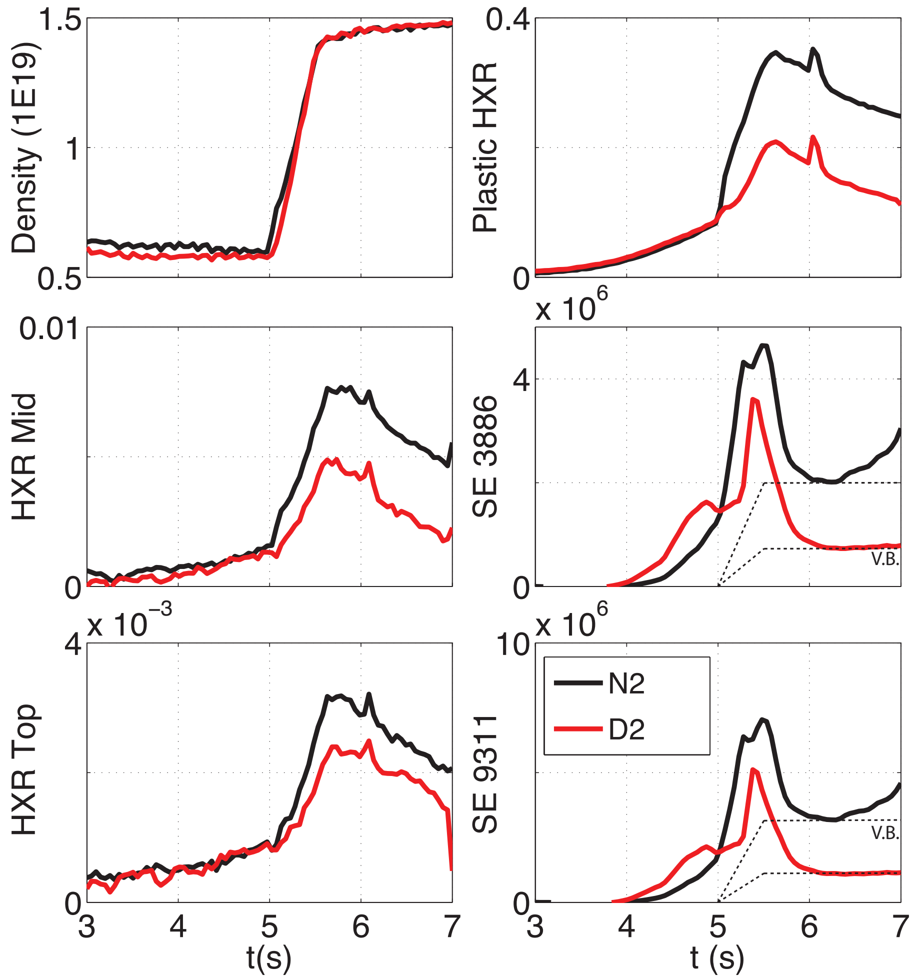
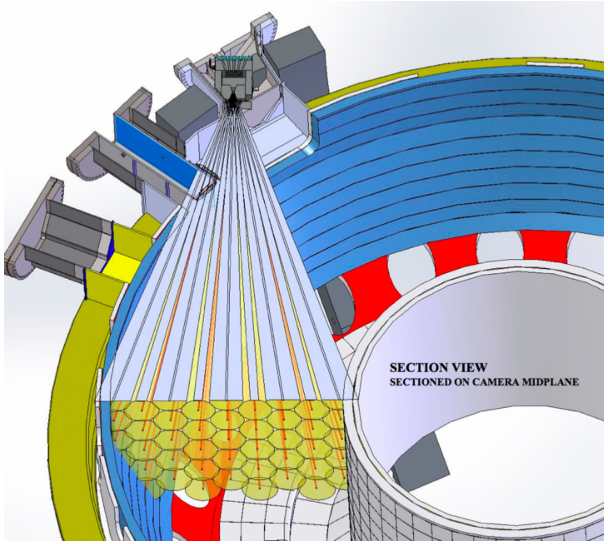
Comparison of all Diagnostics with Nitrogen vs. Deuterium Shows Mainly More Absolute Emission

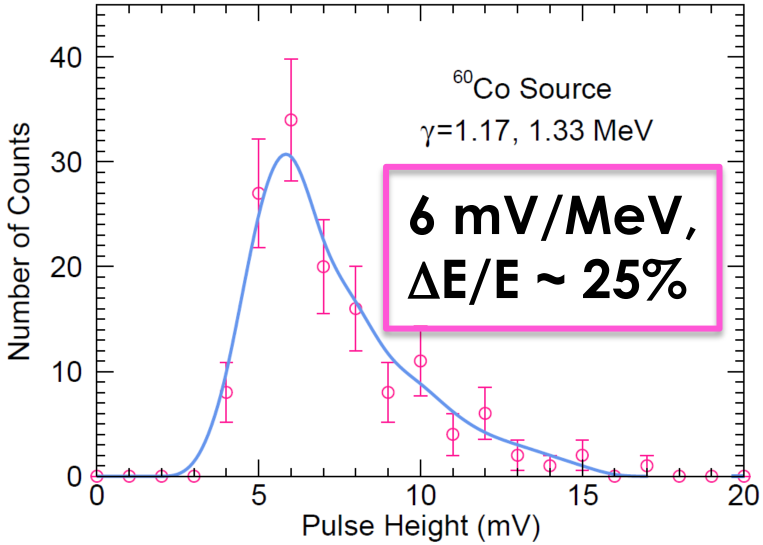
- **Big change is large signal intensity after the puff**
  - Brems depends on Z
- **HXR decay rates again similar**
- **SE decay appears faster with Nitrogen**
- **Larger VB baseline in SE signals with Nitrogen**



New HXR Diagnostic ("Gamma Ray Imager" = GRI) Being Deployed to Measure RE Distribution Functions

- **Can directly measure HXR energy spectrum selecting from 121 spatial chords**
  - 30 detectors for now
- **Pulse height counting gives 0.5 MeV resolution at 1 kHz**
  - On each channel!
- **Current limit mode gives MHz time resolution, but no energy resolution**
- **First measurements in 2015**





C. Cooper, ORAU

Concluding Remarks About Distribution Function Modeling

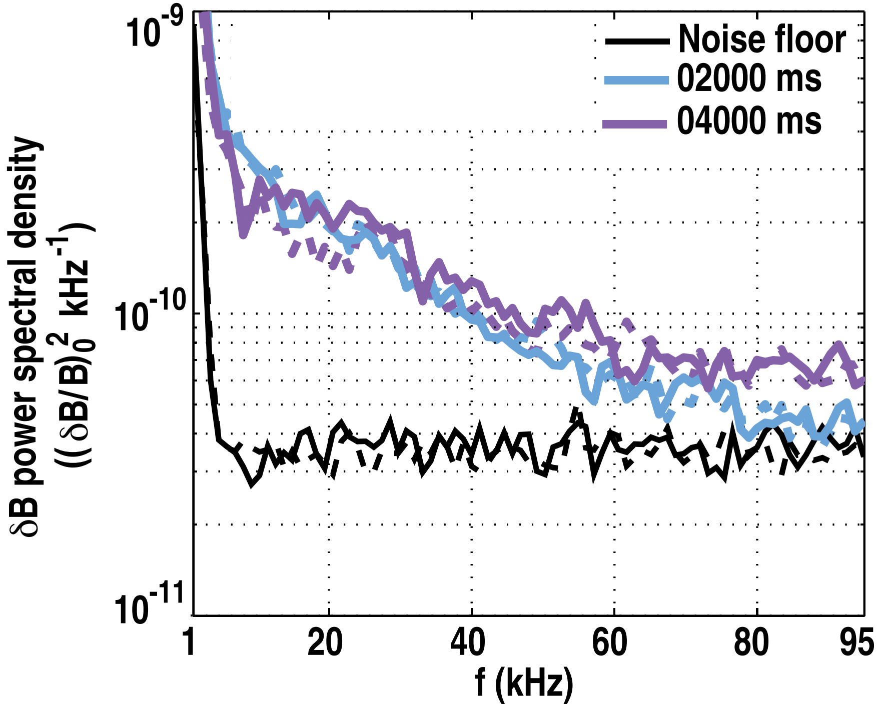
- **Many (and more soon) diagnostics deployed to sense different parts of distribution function**
  - Example: HXR diagnostics above the midplane do not see strong increase after gas puffing
  - Example: SE decays much faster than HXR

- **Multiple diagnostics allow treatment of forward problem:**
  - What is expected measurement, given distribution X function

- **Inverse problem is very difficult, likely impossible for arbitrary energy and pitch angle distributions**
  - Possible exception is truly energy resolved diagnostics
  - Existing attempts have only allowed single pitch angle per energy

Finally: We Should Not Forget Broadband Magnetic Fluctuations are Present Even in Quiescent Plasmas

- **Internal magnetic fluctuation levels directly measured with UCLA polarimeter instrument**
  - Uses faraday rotation effect to measure line-averaged <n **δB**> on midplane
  - First-time measurement?
- **Dimensionless scaling arguments say δB/B ~1E-4 may impact RE loss**
  - Correlation lengths un-measured
- **Opportunity for modeling**

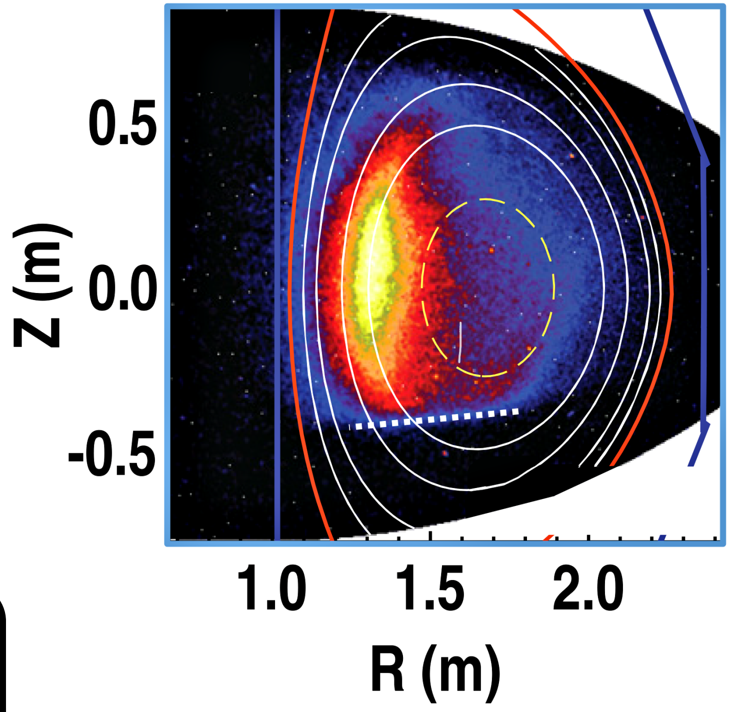


Total ~kHz fluctuations: δB/B ~ 1E-4

J. Zhang, UCLA

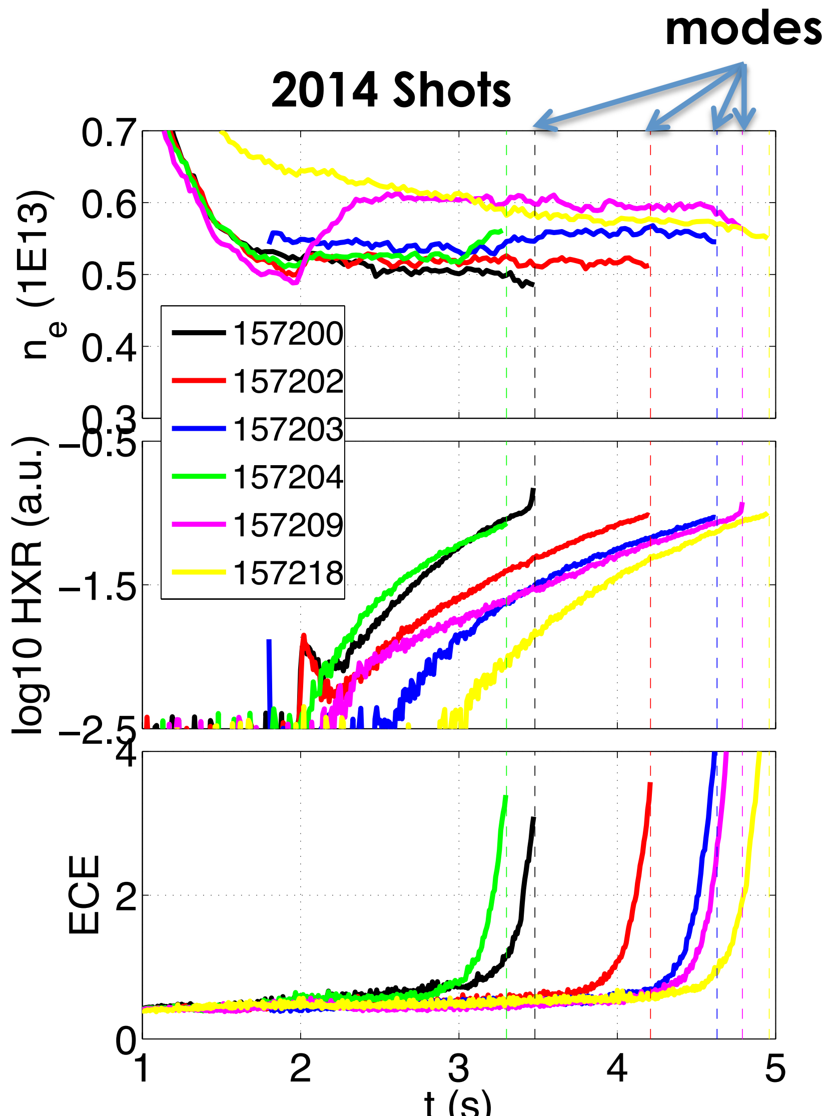
Outline

- Quiescent runaway electron (QRE) regime and Dreicer growth
- Recap of QRE dissipation with deuterium
- Extension to QRE decay with Nitrogen
- Progress towards constraining QRE energy distributions
- **Non-thermal origin of the low density stability limit**



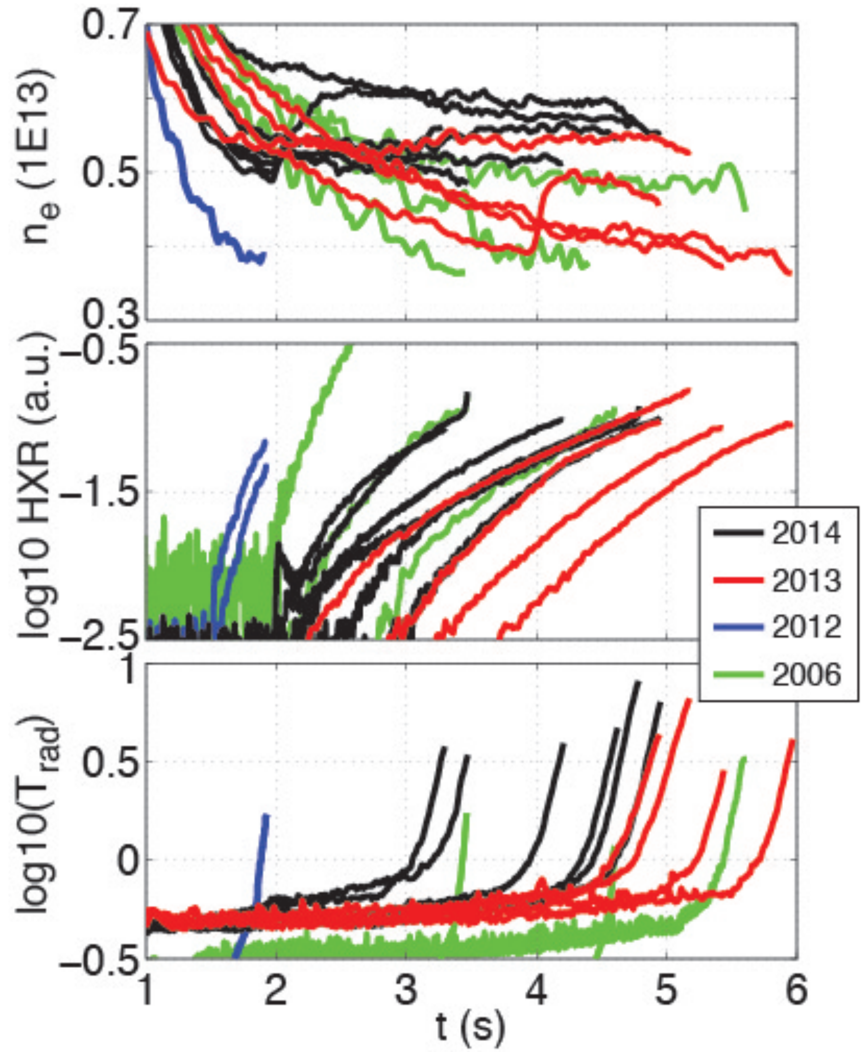
LM Onset Occurs at Various Densities but Similar Levels of HXR Emission, all Preceded by ECE Blow-up

- **Nearly ½ of shots in 2014 were lost to locked modes**
- **Density feedback or density increase did not avoid the locked mode (!)**
- **ECE gives LM warning ~500 ms before LM onset (!!)**



LM Onset Occurs at Various Densities but Similar Levels of HXR Emission, all Preceded by ECE Blow-up

- **Nearly ½ of shots in 2014 were lost to locked modes**
- **Density feedback or density increase did not avoid the locked mode (!)**
- **ECE gives LM warning ~500 ms before LM onset (!!)**
- **Same thing found in historic low density record discharges**
  - Robust instability prediction by ECE non-thermalization



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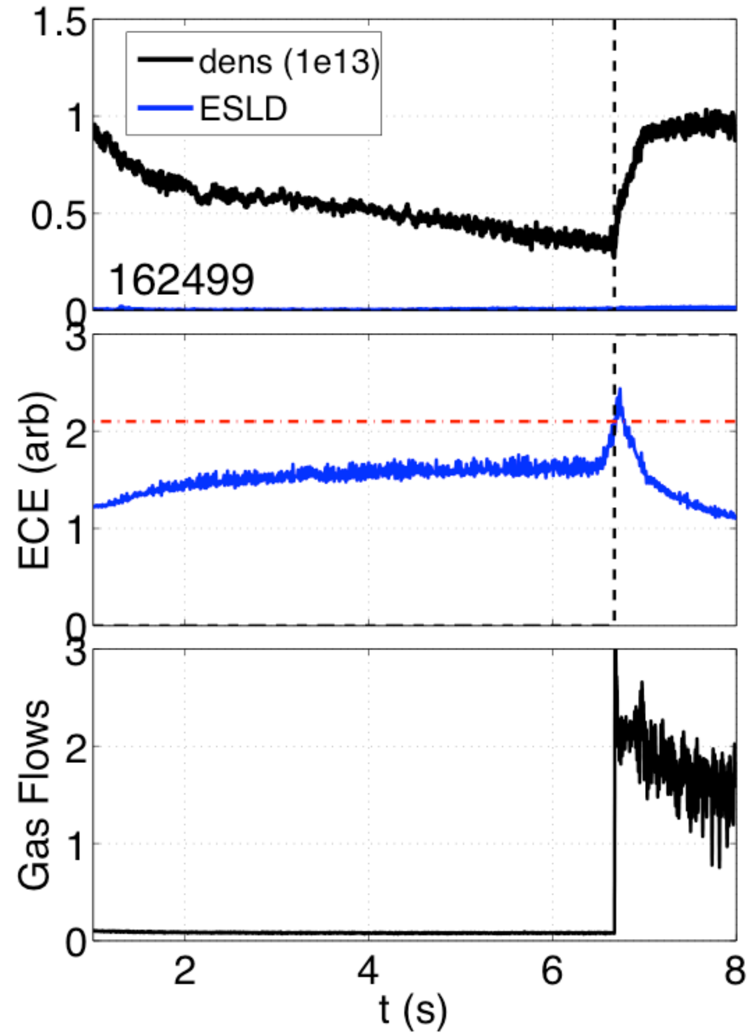
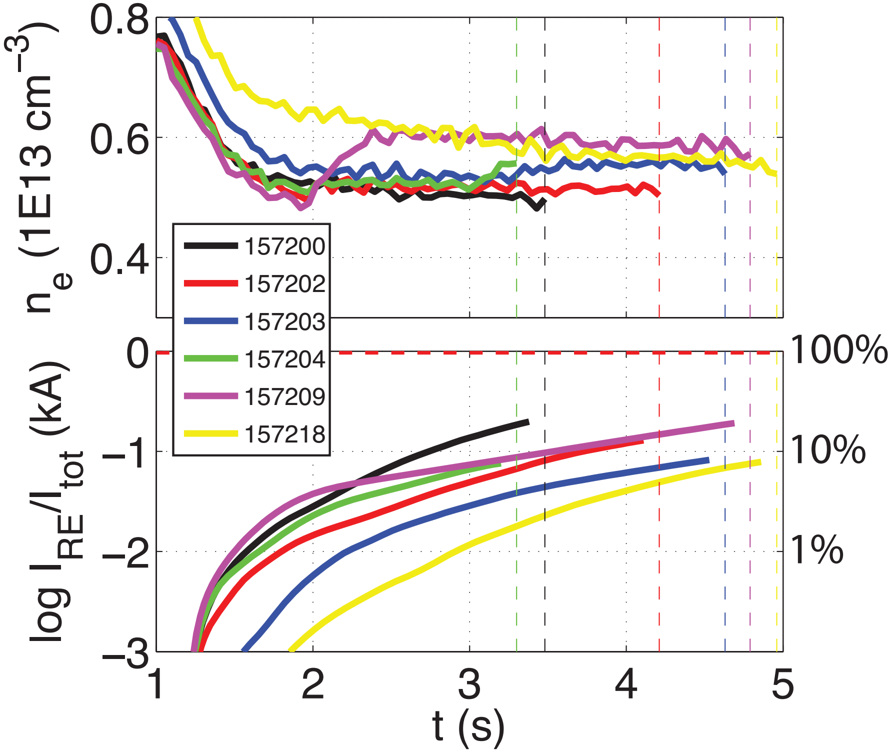
DIII-D Plasma Control System Can Now Trigger Gas Puffing Based on ECE Signal to Avoid Locked Mode

- **Ensures "goldilocks" QRE population ☺**
  - Large enough to diagnose accurately
  - Small enough that locked mode avoided
- **Significantly improves future experimental efficiency**
- **Allows examination of dissipation effect vs. "RE maturity" through time-delay and trip-level setting**



Calculations of Runaway Excitation Indicate RE Could Carry "Appreciable" Current Prior to LM

- **Calculation uses measurements of ne, Te, Vloop, Zeff**
  - Solves primary + secondary RE generation ODE
  - See Paz-Soldan et al, PoP 2014 for details on calculation
- **Finds RE current can be appreciable (~10%) prior to LM**
  - May be larger locally (in core)
- **Internal inductance is not found to significantly vary**
  - Conjecture thermal replaced by RE current, with similar profile



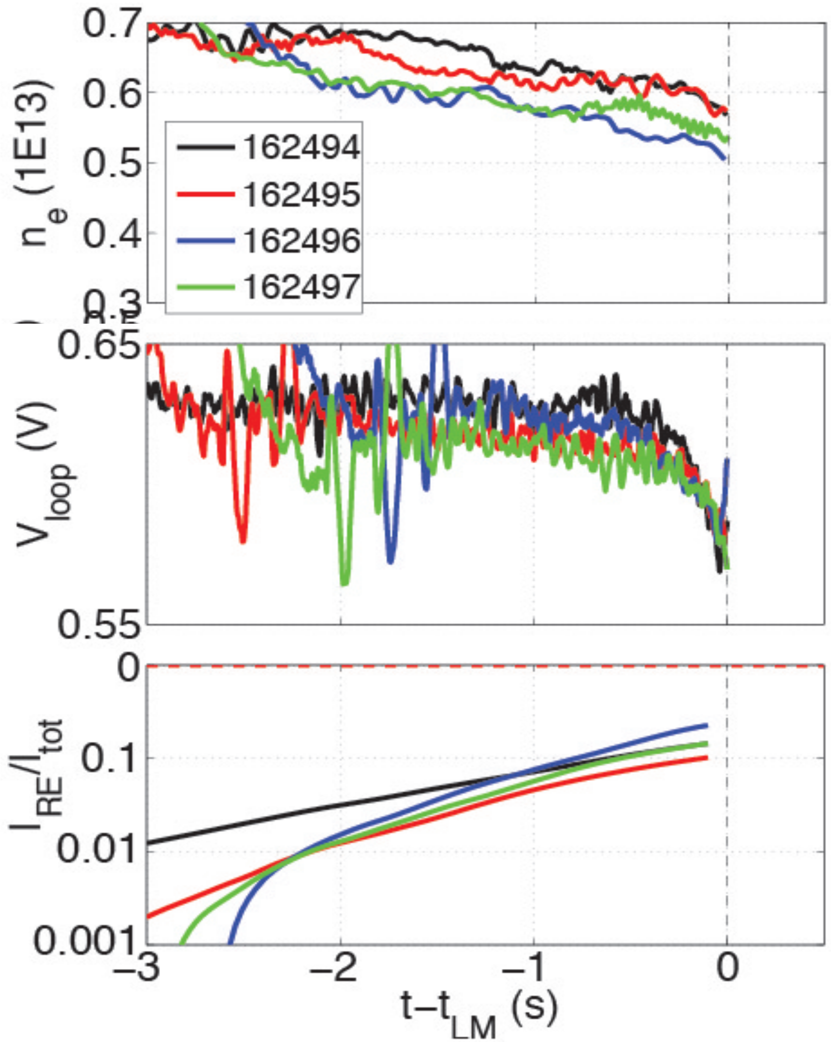
$$\frac{d(n_{\rm RE})}{dt} = \underbrace{S_{\rm pri}}_{\rm primary} + \underbrace{\gamma_{\rm sec} n_{\rm RE}}_{\rm secondary}$$

$$I_{\rm RE} = n_{\rm RE}(\pi a^2)ce$$

Concurrent Drop in Loop Voltage Indicates RE Current Fraction is Becoming Appreciable

- **Recent dataset shows dropping Vloop as resistivity decreases**
- **Indicates REs carrying significant current**

$$E_{\text{loop}} = \eta J$$
$$E_{\text{loop}} = \eta_{\text{th}}(J_{\text{tot}} - J_{\text{RE}}) + \eta_{RE} J_{\text{RE}}$$

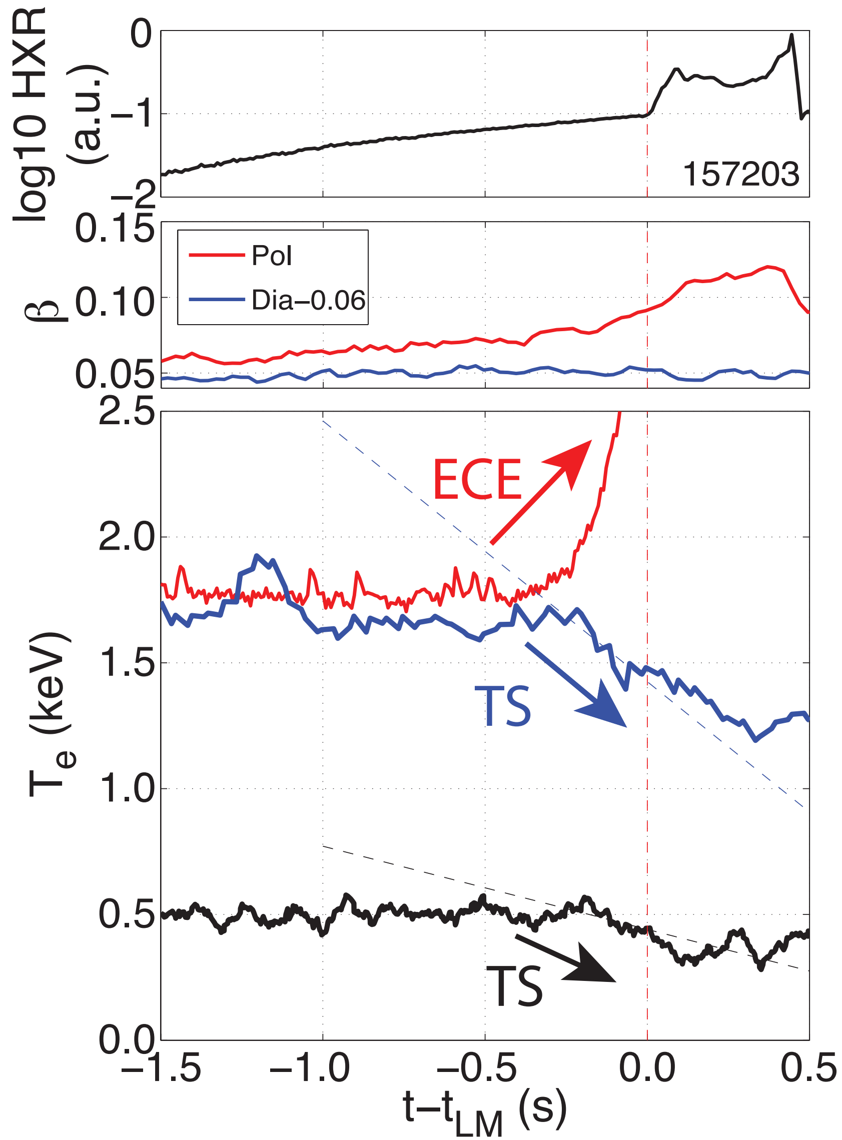


Divergence of ECE and TS Electron Temperature is Also Observed Prior to LM Formation

- **TS cooling appears concurrent with ECE non-thermalization**
- **Expect Ohmic power to thermal electrons to be reduced by square of RE current fraction:**

$$P_{\text{ohm}} = \eta J^2$$
$$P_{\text{ohm}} = \eta_{\text{th}}(J_{\text{tot}} - J_{\text{RE}})^2 + \eta_{RE} J_{\text{RE}}^2$$

- **Scaling laws indicate it is easier to penetrate into cold plasmas**



Conclusion: We Are Developing the Quiescent Regime to Understand Runaway Dissipation

- **RE onset is well characterized by primary (Dreicer) model**
  - There is nothing anomalous in RE onset

- **2013 experiments scanned D2 density, 2014 used nitrogen**
  - Great diagnosis of impurity profiles possible
  - Good range in Z and E/Ecrit accessible
  - HXR zero crossing significantly above E/Ecrit with all gases
  - Nitrogen increased HXR zero-crossing consistent with models

- **Varied diagnostic sensitivity probes RE distribution functions**
  - Preliminary work shows unexpected trends, much more to do
  - All possible distribution functions can be studied

- **Locked modes at lowest density related to RE population itself**
  - DIII-D control upgraded to avoid mode, improve future experiments

Much Scope for Further Experiments in this Regime Exist

- **Comparison of high and low toroidal field @ similar densities**
  - Synchrotron vs. collision rate greatly affected ((changes t-rad-hat))
- **New control capabilities allow time-delay gas puff scan**
  - Puff into “mature” and “immature” RE populations
- **Extension of high-Z dissipation to lower E/Ecrit**
  - Can we see Aleynikov’s dissipation ‘wall’ shift with nitrogen ?
- **Improved diagnostic coverage by reversing IP**
  - Some diagnostics look the other way
- **No DIII-D run-time given for these experiments in FY15-16**
  - Vocalized interest from community would help make the case

Bonus Slides

Kinetic Equation for REs is Complex, Only Input Parameters are E, Z, t-rad-hat:

The distribution function F satisfies the relativistic Fokker-Planck equation

$$\frac{\partial F}{\partial s} + \frac{\partial}{\partial p}\left[E\cos\theta - 1 - \frac{1}{p^2} - \frac{p\sqrt{1+p^2}}{\bar{\tau}_{\rm rad}}\sin^2\theta\right]F$$

$$= \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\left[E\frac{\sin\theta}{p}F + \frac{(Z+1)}{2}\frac{\sqrt{p^2+1}}{p^3}\frac{\partial F}{\partial\theta}\right.$$

$$\left. + \frac{1}{\bar{\tau}_{\rm rad}}\frac{\cos\theta\sin\theta}{\sqrt{1+p^2}}F\right], \qquad (2)$$

- **Relevant parameters are E = E/Ecrit, Z-eff, and tau-rad-hat**

Aleynikov PRL 2015

Two Versions of Beta from EFIT Gives an Integral Measure of RE Pressure and Energy

- **EFIT provides two pressures:**

$$\beta_{\rm pol} = 2\mu_0 \langle p \rangle / B^2_{\theta a}$$

$$\beta_{\rm dia} = 2\mu_0 \langle p_\perp \rangle / B^2_{\theta a}$$
$$\beta_{\rm dia} = 1 + \frac{E^2+1}{2E}\frac{B_{t0}\Delta\phi}{20\pi I_p^2}$$

- **Beta_dia is based only on diamag loop and shape:**

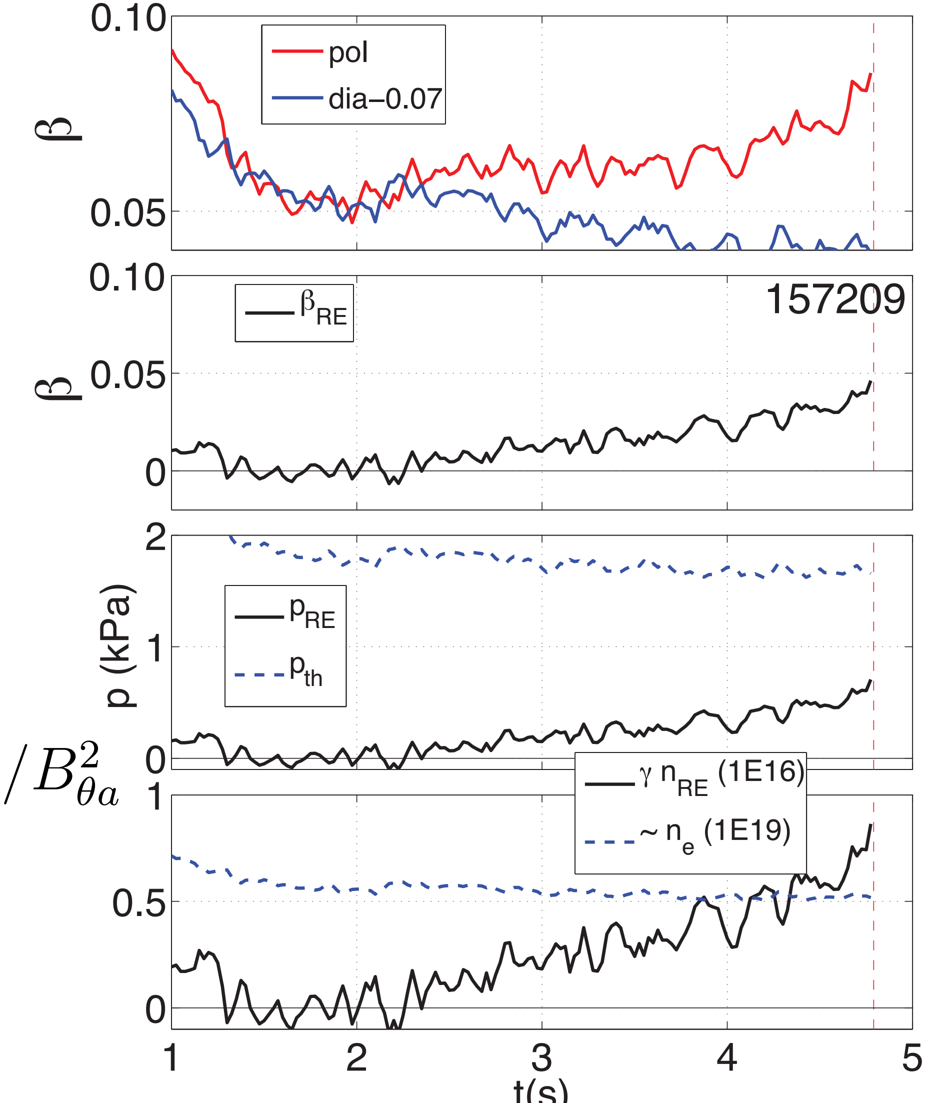
$$\Delta\phi = -\int_\Omega dS_t (B_t - B_{t0})$$

- **Take difference as RE grows as RE parallel pressure:**

$$\beta_{\rm dia} - \beta_{\rm pol} = 2\mu_0(\langle p \rangle - \langle p_\perp \rangle)/B^2_{\theta a}$$
$$\Delta_{\rm RE,onset}(\beta_{\rm dia} - \beta_{\rm pol}) = 2\mu_0 \left\langle p_{||,\rm RE} \right\rangle / B^2_{\theta a}$$

- **Gives mean RE energy:**

$$p_{\rm th} = n_e(T_e + T_i)$$
$$p_{\rm RE} = \langle n_{\rm RE}\gamma \rangle (m_e c^2)$$



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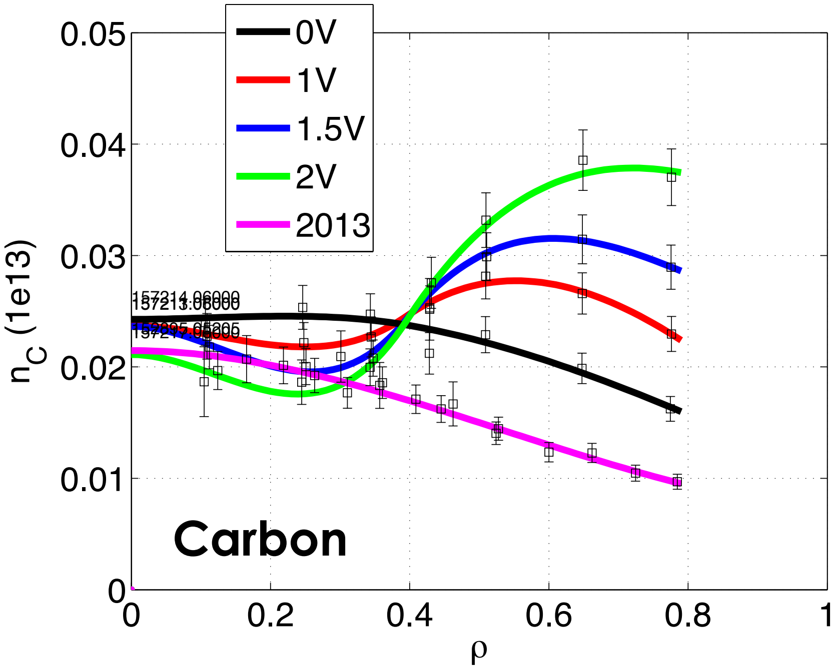
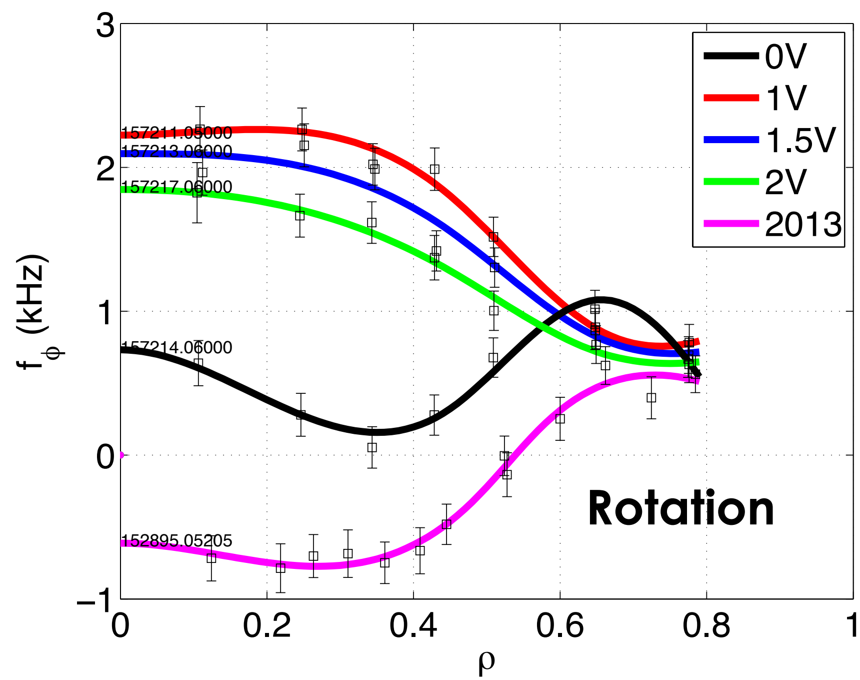
Experiment Also Revealed Interesting Changes in Rotation Reversal Behavior – Nitrogen Turned It Off!

- **Needs to be revisited for changes in turbulence vs. neoclassical components**
  - We certainly changed collisionality by going to nitrogen…





Puffing Quickly Kills off Dreicer Source Term, Leaving Dynamics to be Dominated by the Avalanche

- **Takes advantage of extreme density sensitivity of primary source**
  - Cases shown from now on have "negligible" primary growth
  - Primary growth rates: $d(n_{RE})/dt < 10^5\ cm^{-3}/s$
- **Gas puffing is critical to isolate the avalanche from Dreicer growth in these discharges**