Synchrotron and collisional damping effects on runaway electron distributions

by

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with

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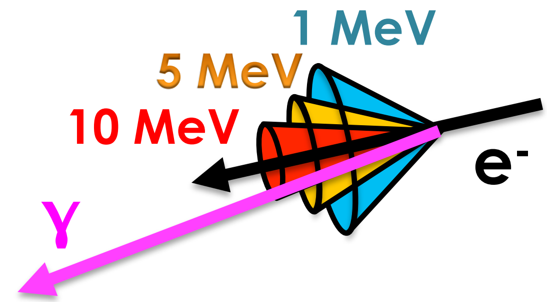
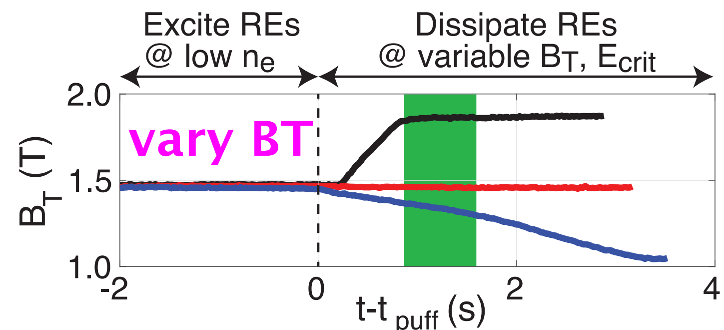
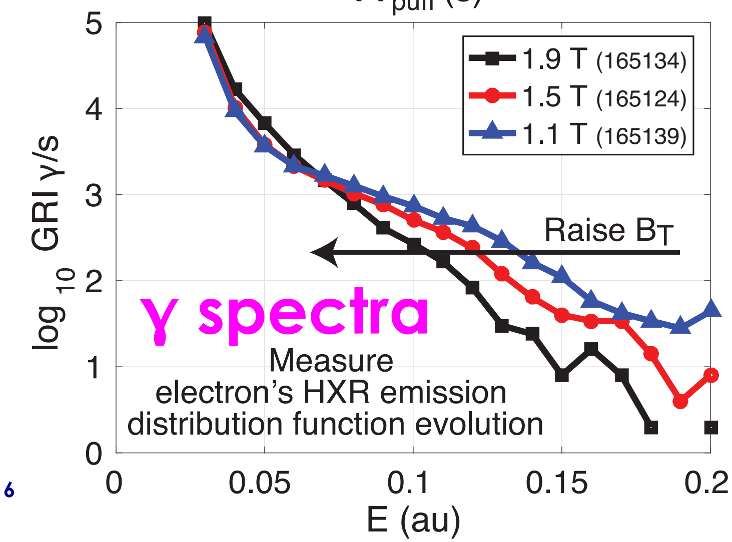
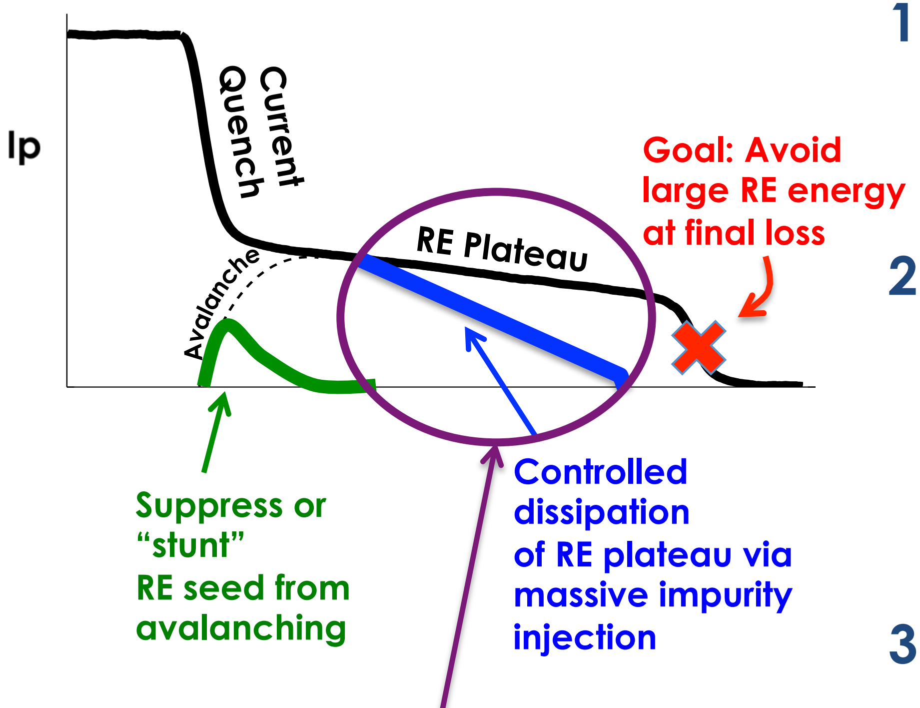






DIII-D Runaway Electron Research Seeks to Provide Reliable Extrapolation of RE Generation, Dissipation, and Termination for ITER



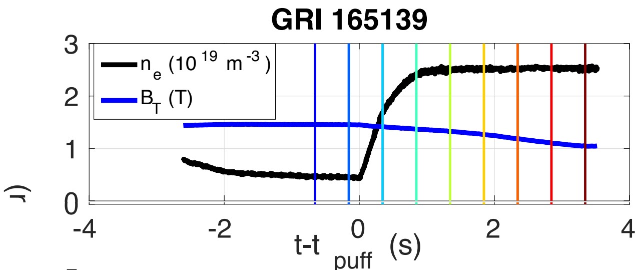
Experiments can help benchmark RE dissipation models

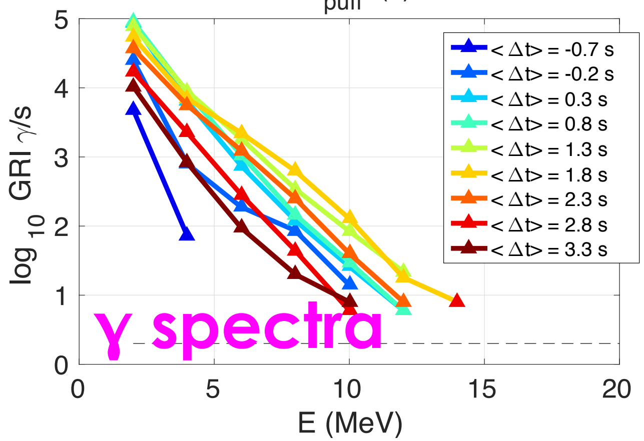
We divide RE problem into:

1. **RE generation physics and possibilities for suppression**
   – Difficult to study, since RE seeds are small/variable on DIII-D scale devices
2. **Dissipation of a fully formed RE plateau**
   - Model-based understanding necessary (**risk in ITER too great**)
   - Dissipation physics carries over to avalanche suppression
3. **RE termination physics determines requirements for dissipation**
   - Tolerable RE energy may be very low

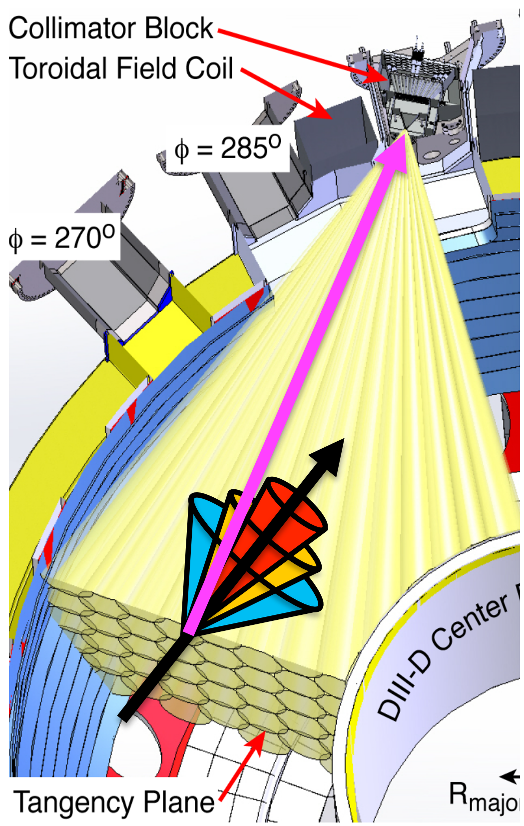
DIII-D low density “QRE” experiments provide “wind-tunnel” to validate theories of RE dissipation

Controlled Experiment

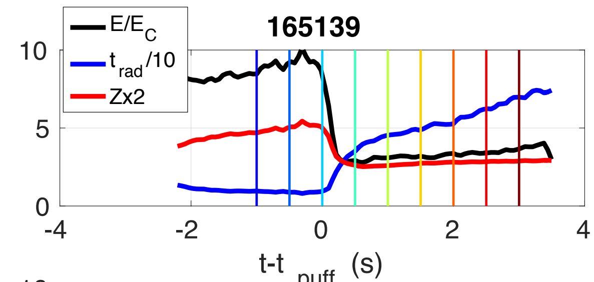


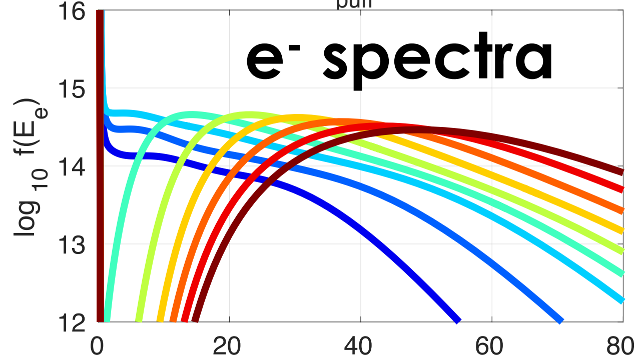


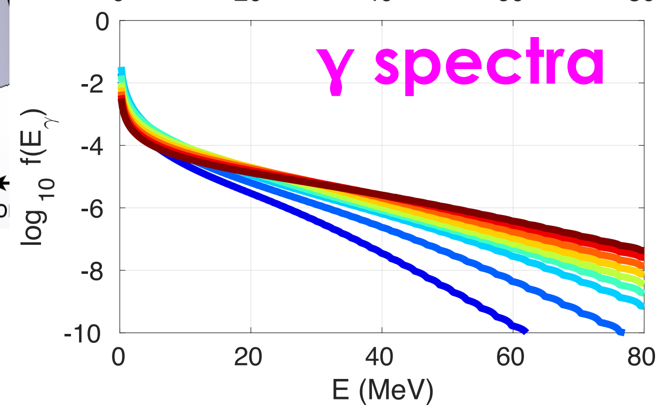
Novel Diagnostic



Detailed Modeling







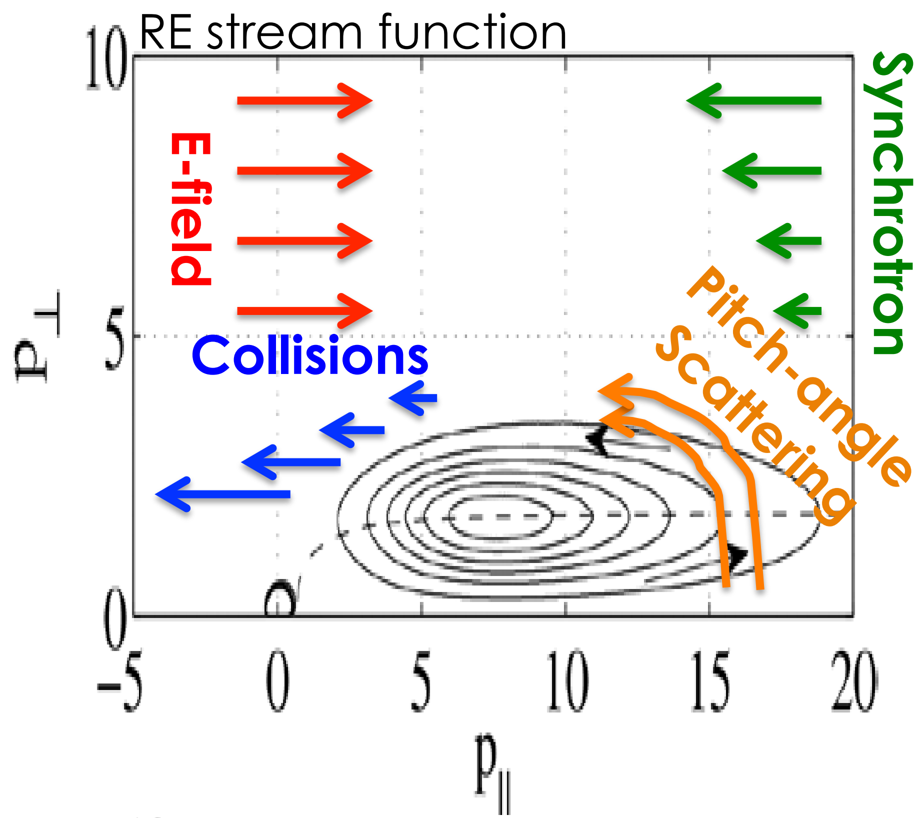
Outline:

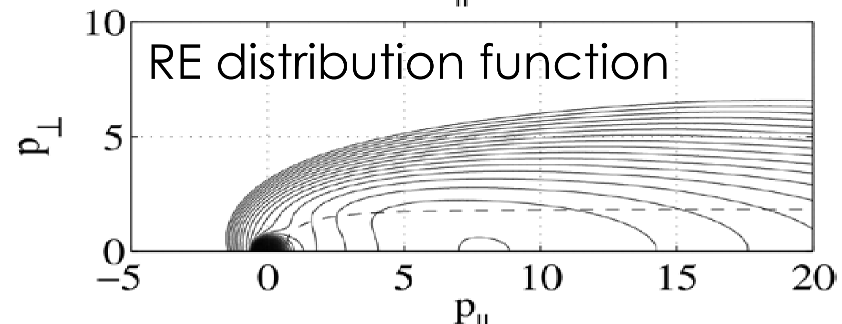
- **Recap of Theory Progress and Important Parameters**
- **Recap of QRE Regime to Study RE Dissipation**
- **Introduction to GRI Diagnostic and f(E) Inversion**
- **Spectrum Effect of Electron Density (Collisions)**
- **Spectrum Effect of Toroidal Field (Synchrotron)**
- **Conclusion and Future Directions**

Competition between physical effects gives complex phase space redistributions and "bump" formation

- **Acceleration due to E-field**
  - **E/E_{crit}**
- **Energy loss to synchrotron**
  - Depends on perp-energy
  - **t-rad-hat**
- **Pitch angle scattering on ions, from parallel to perp**
  - **Z_{eff}**
  - Energy is conserved

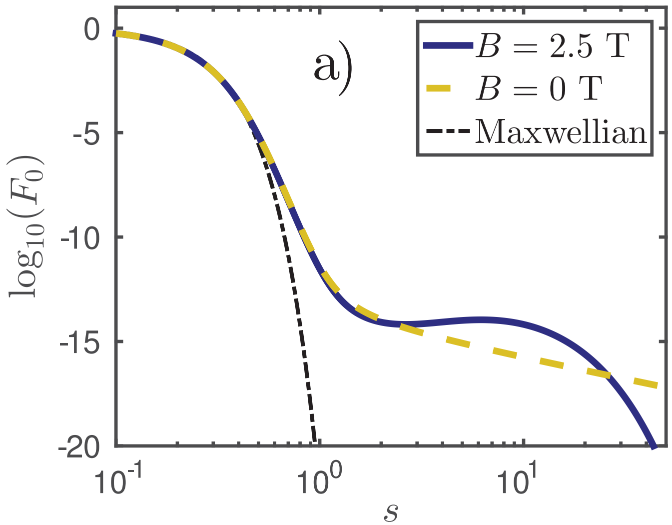
- **These effects give phase-space circulation that piles up electrons in a bump**



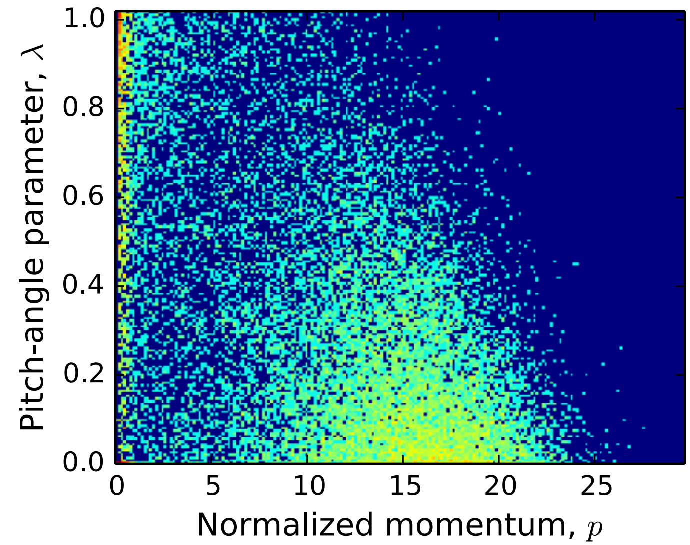


J. Decker et al, PPCF '16

Convergence of recent theoretical work on idea of phase-space attractors that pile up runaway electrons

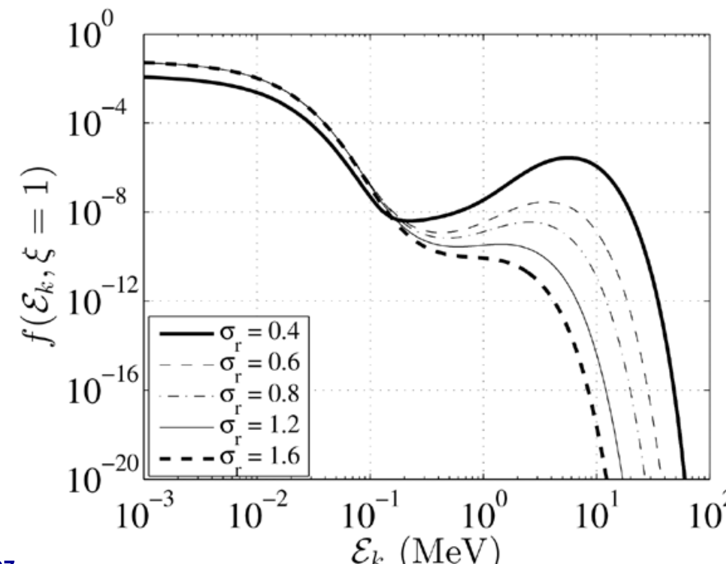


E. Hirvijoki et al, JPP 2015



P. Aleynikov et al, PRL 2015, IAEA 2014

- **Note important (?) effects are left out:**
  - Radial transport / losses
  - Kinetic instabilities



J. Decker et al, PPCF 2016

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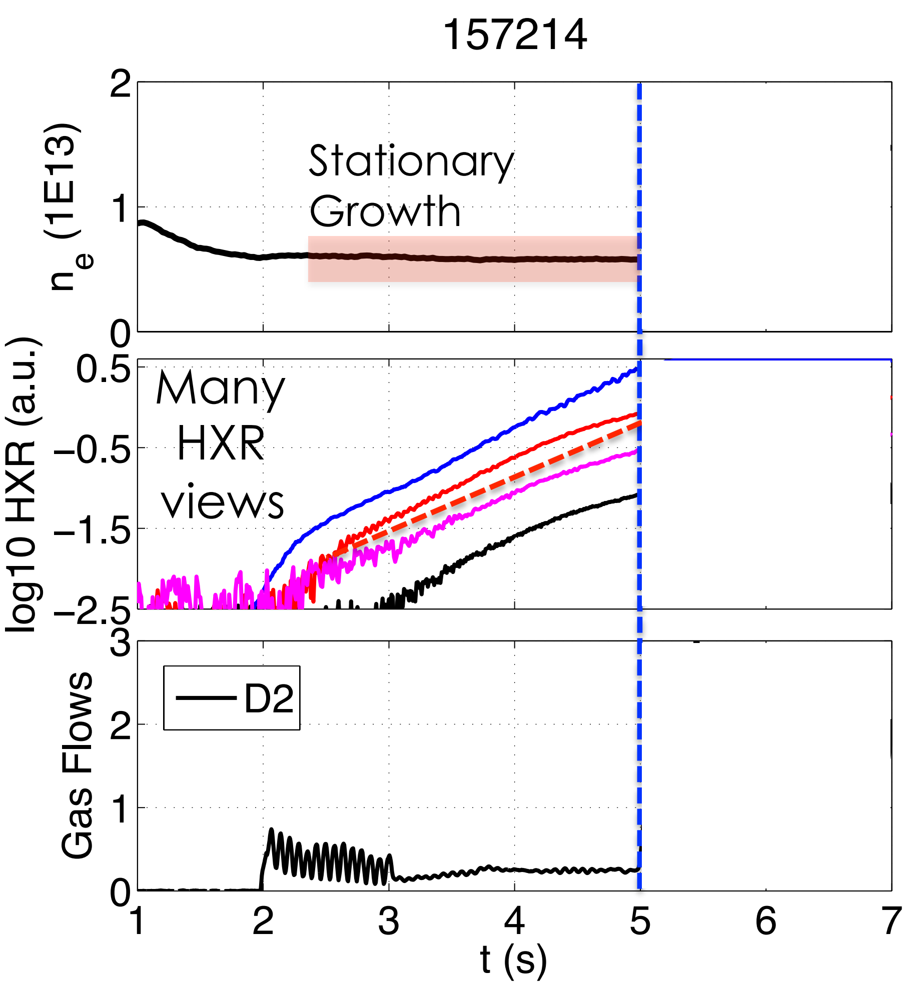
Low density yields long-timescale growth of QREs

- **Either turn off gas or feedback to low level**
- **Await buildup of REs until a control system alarm is tripped**



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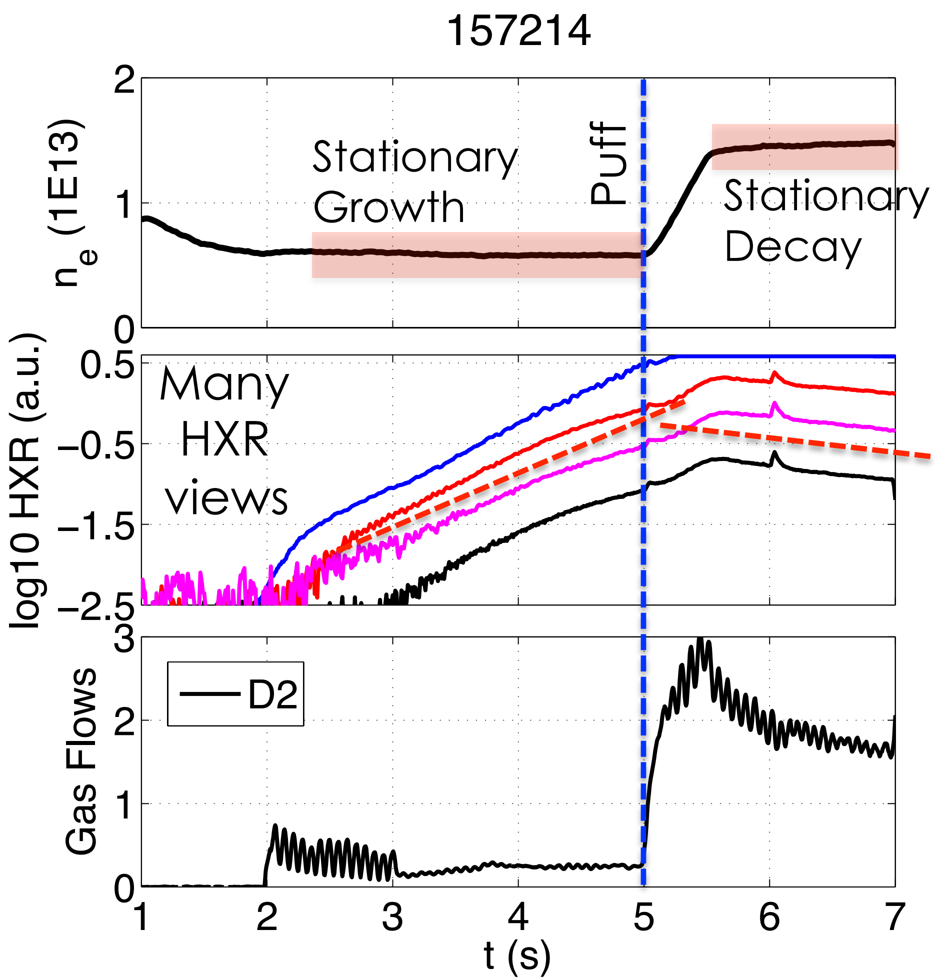
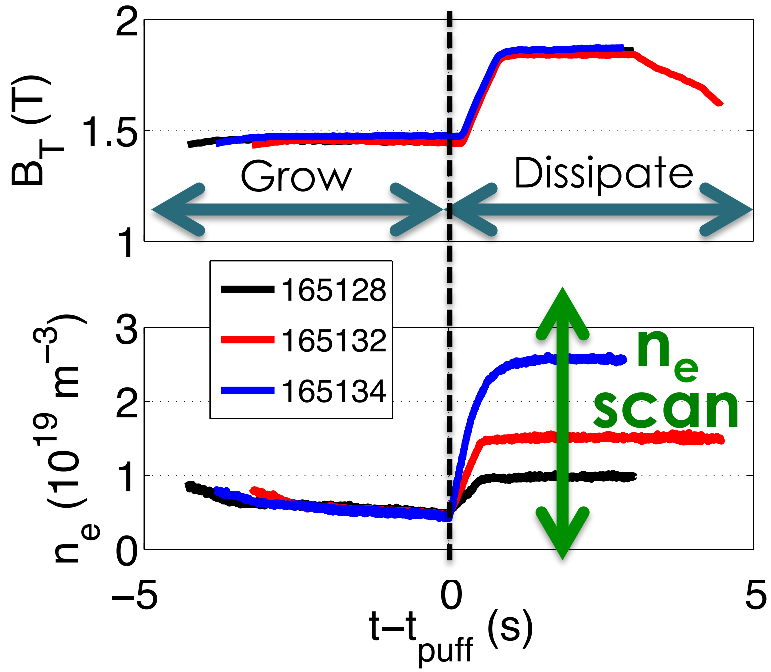
Low density yields long-timescale growth of QREs … dissipation phase is then triggered

- **Either turn off gas or feedback to low level**
- **Await buildup of REs until a control system alarm is tripped**
  - Trip level ensures similar RE populations pre-dissipation
- **Vary experimental actuators only in dissipation phase:**
  - **Density (E/E_{crit})**
  - **B_T (t-rad-hat)**
  - **Z_{eff} (pitch-angle scattering)**

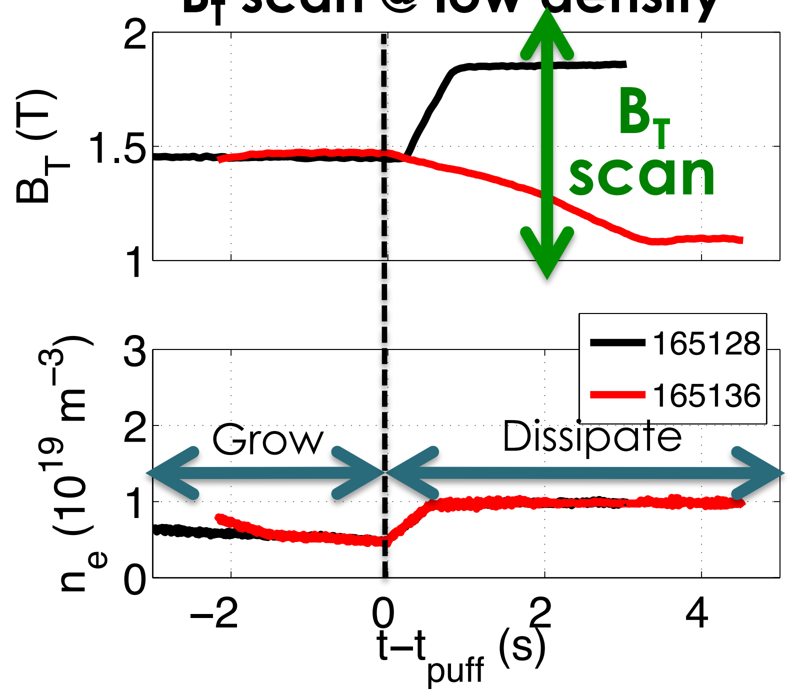


New experiments in 2016 varied B_T, density, Z_{eff}
➔ Thanks to this community for support to get D3D time

Density scan @ High B_T

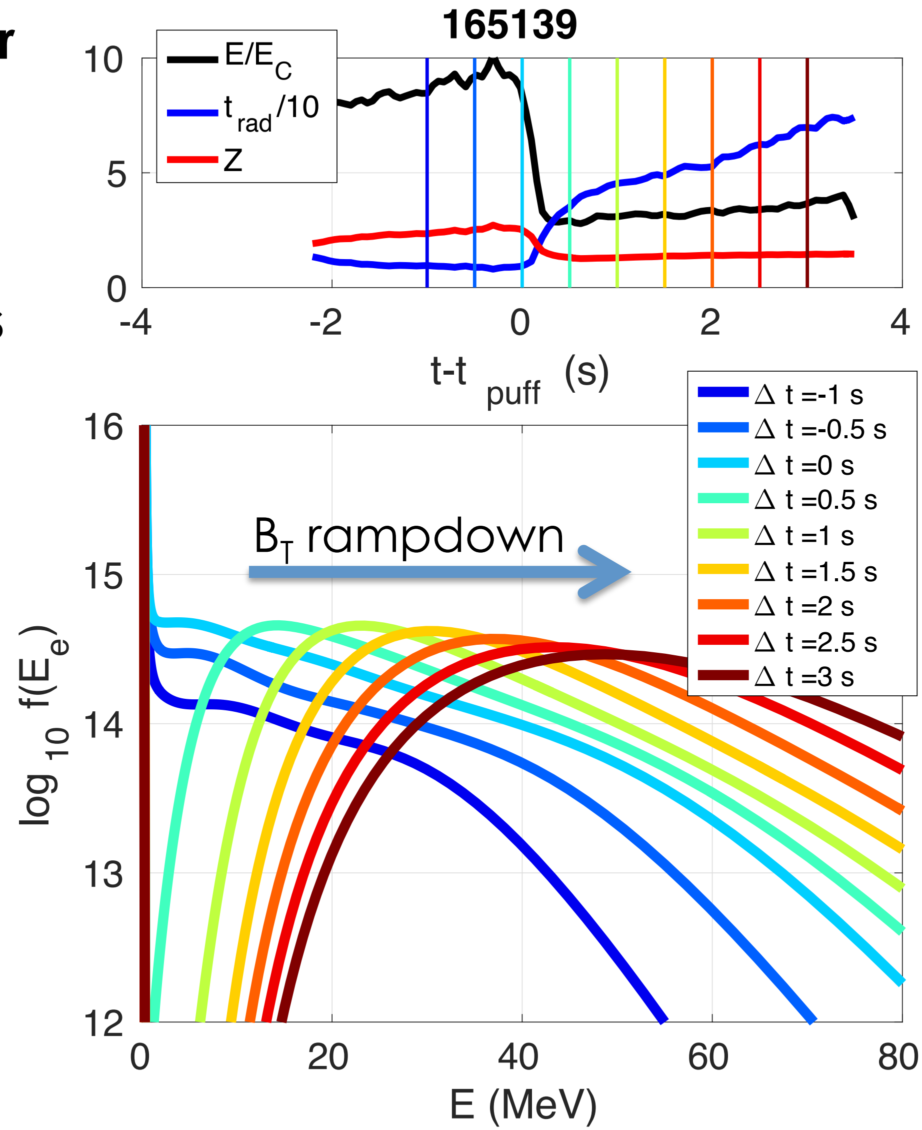


B_T scan @ low density



Well-diagnosed plasmas allow complete simulation of RE distribution function evolution during shot

- **f(E) equation solved in time for continuously varying inputs**
- **Demonstrates formation of phase-space attractor and its evolution in time as t-rad-hat (B_T) ramped**
  - Initial simulations had avalanche term turned off
  - More on this later



P. Aleynikov model

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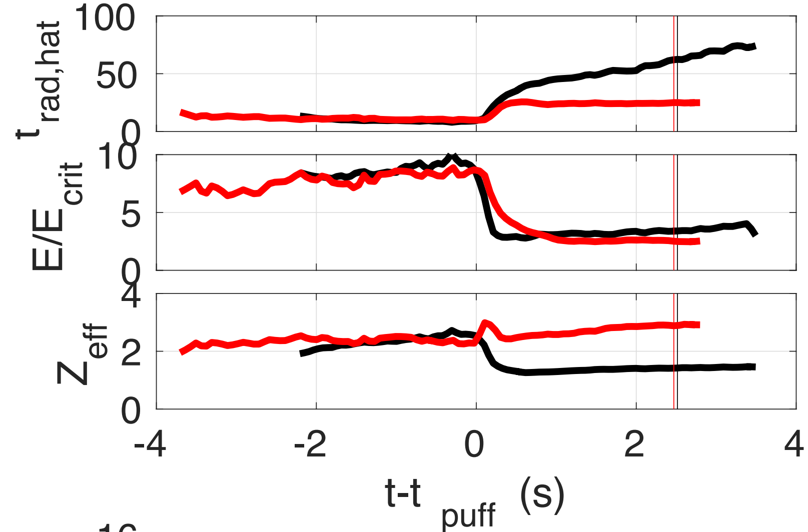
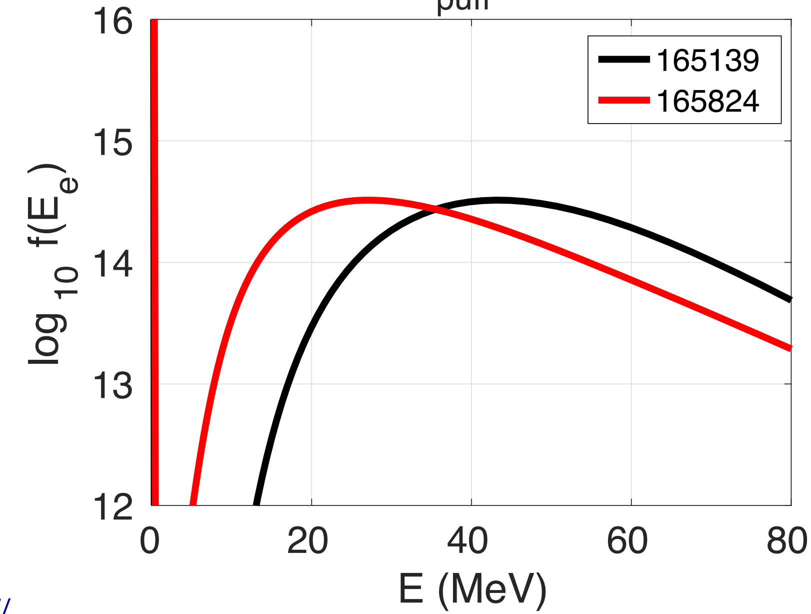
- **Demonstrates formation of phase-space attractor and its evolution in time as t-rad-hat (B_T) ramped**
  - Initial simulations had avalanche term turned off
  - More on this later
- **Changes in experimental parameters map to changes in predicted distribution functions**





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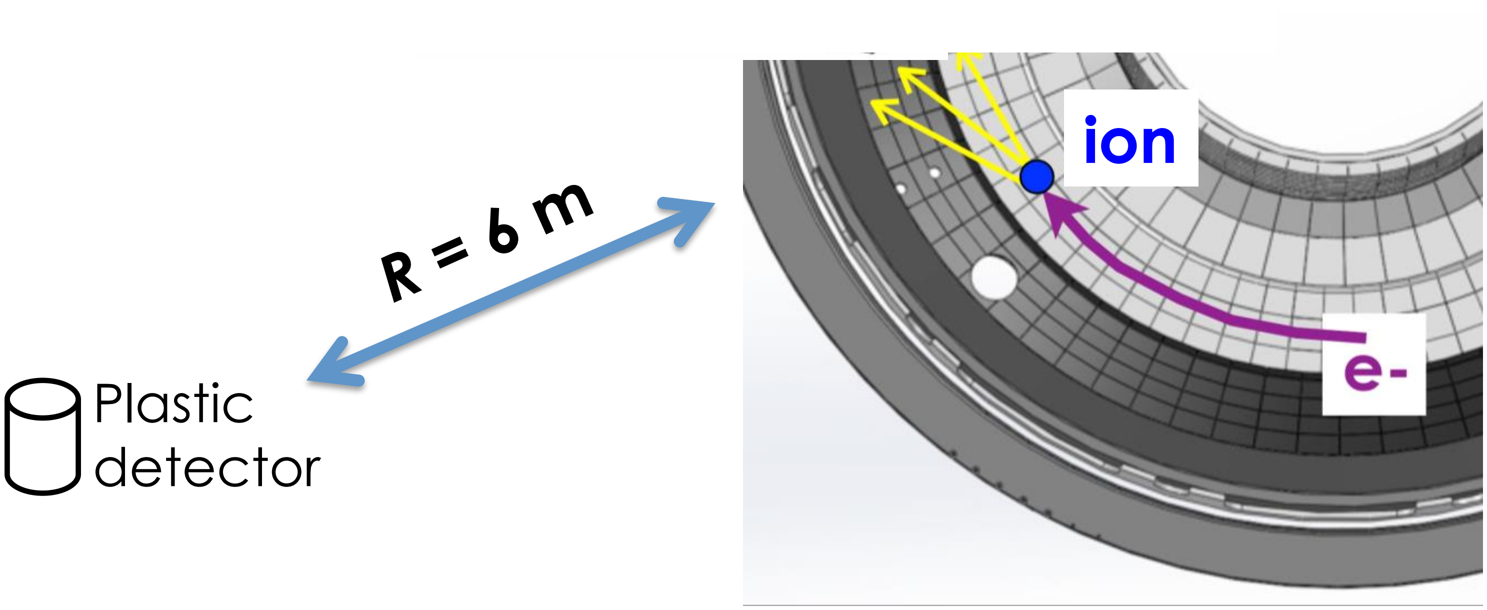
Previous studies relied on distant hard X-ray flux detector (HXR) for majority of analysis



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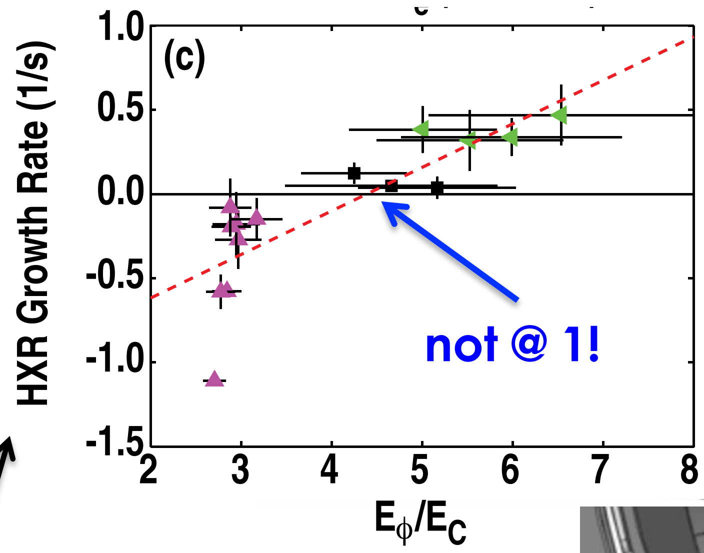
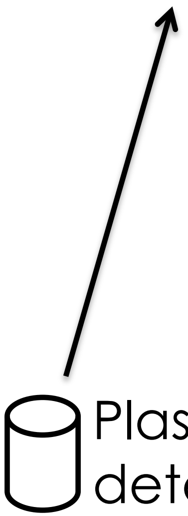
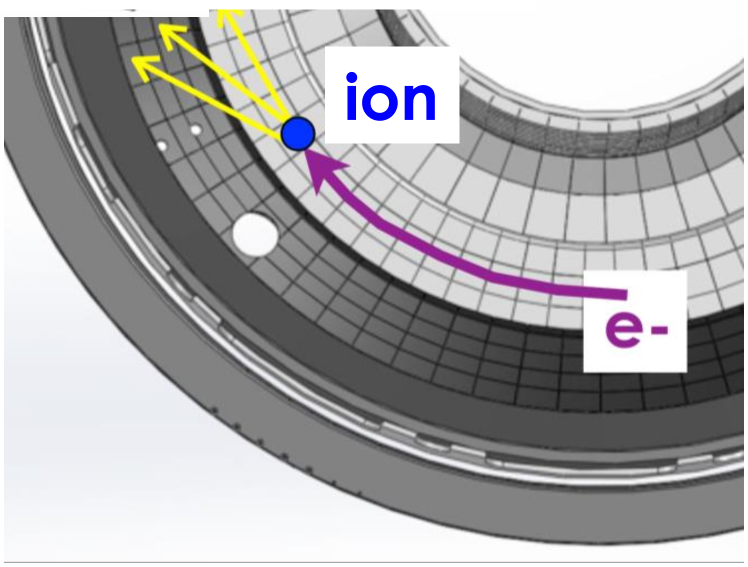
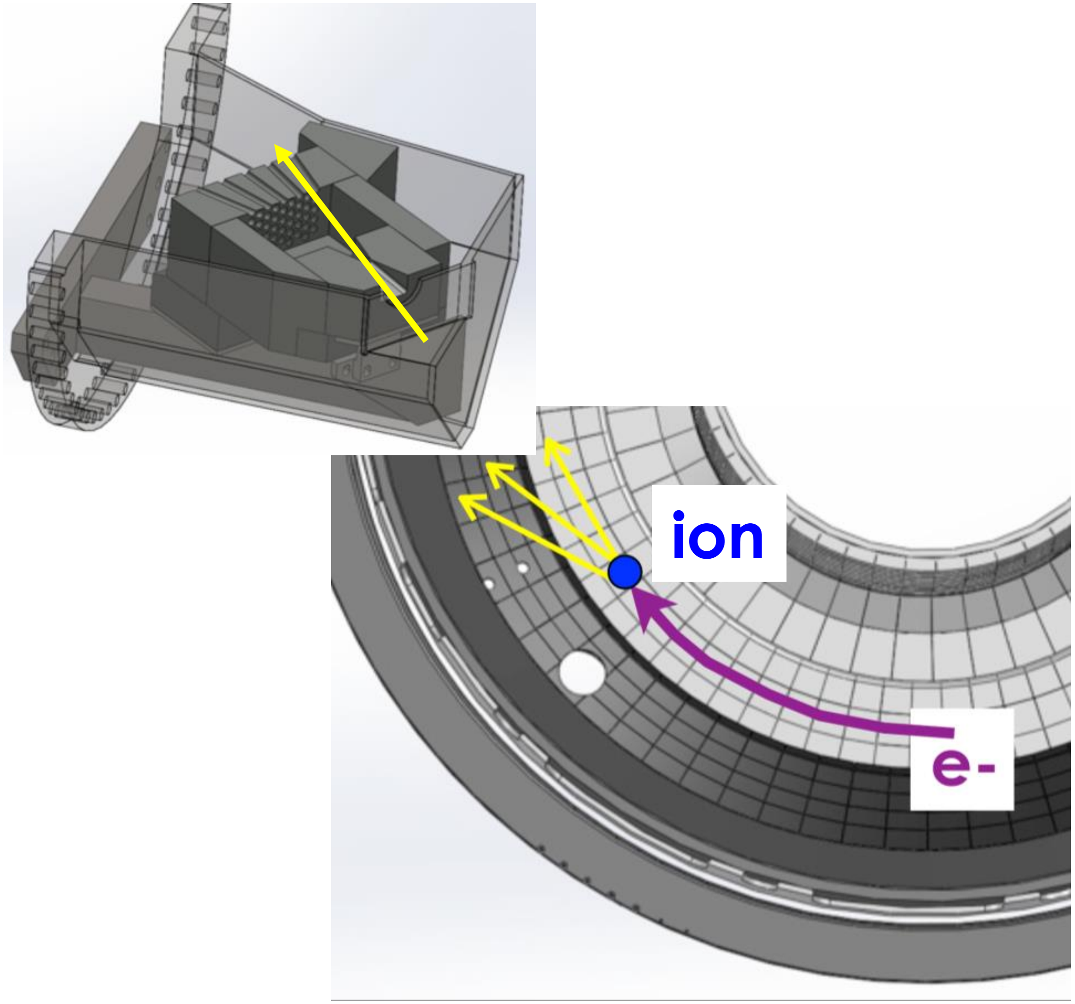


Paz-Soldan et al, PoP 2014
also in Granetz et al, PoP 2014
and Granetz invited IAEA, APS





New Gamma Ray Imager (GRI) deployed to measure spatial and energy-resolved f(E)



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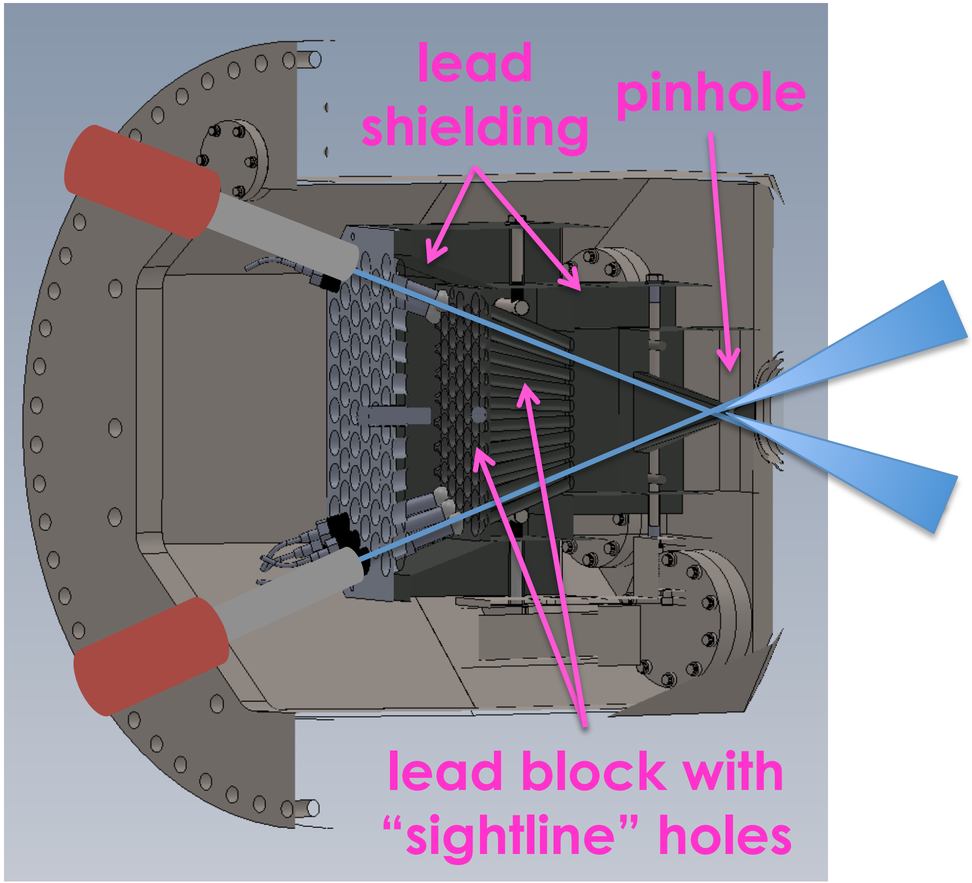
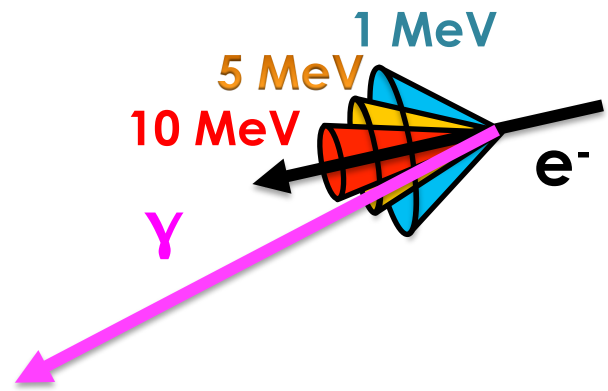
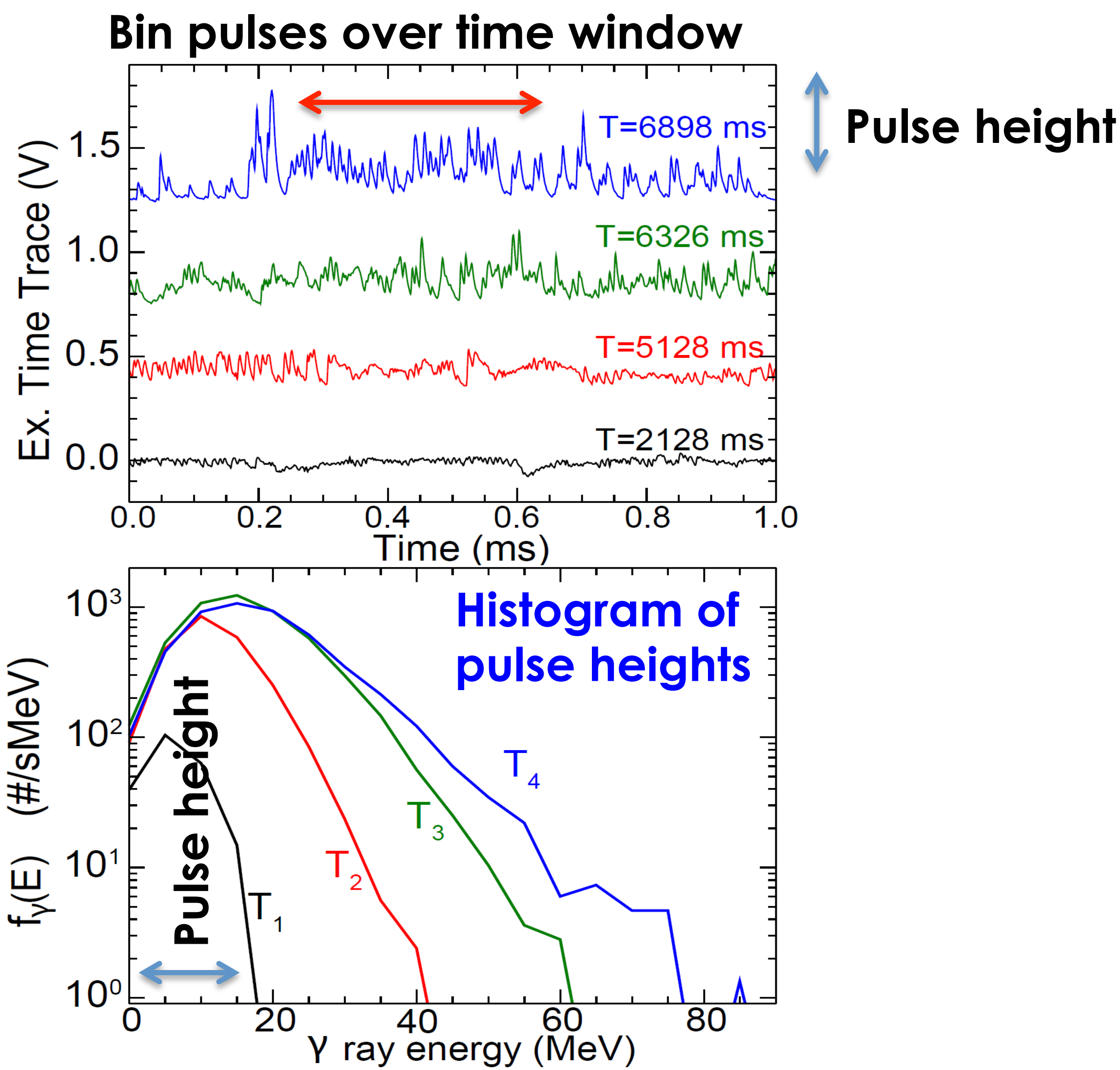




GRI counts discrete pulses from bremsstrahlung radiation (HXR), and bins in time to yield distributions



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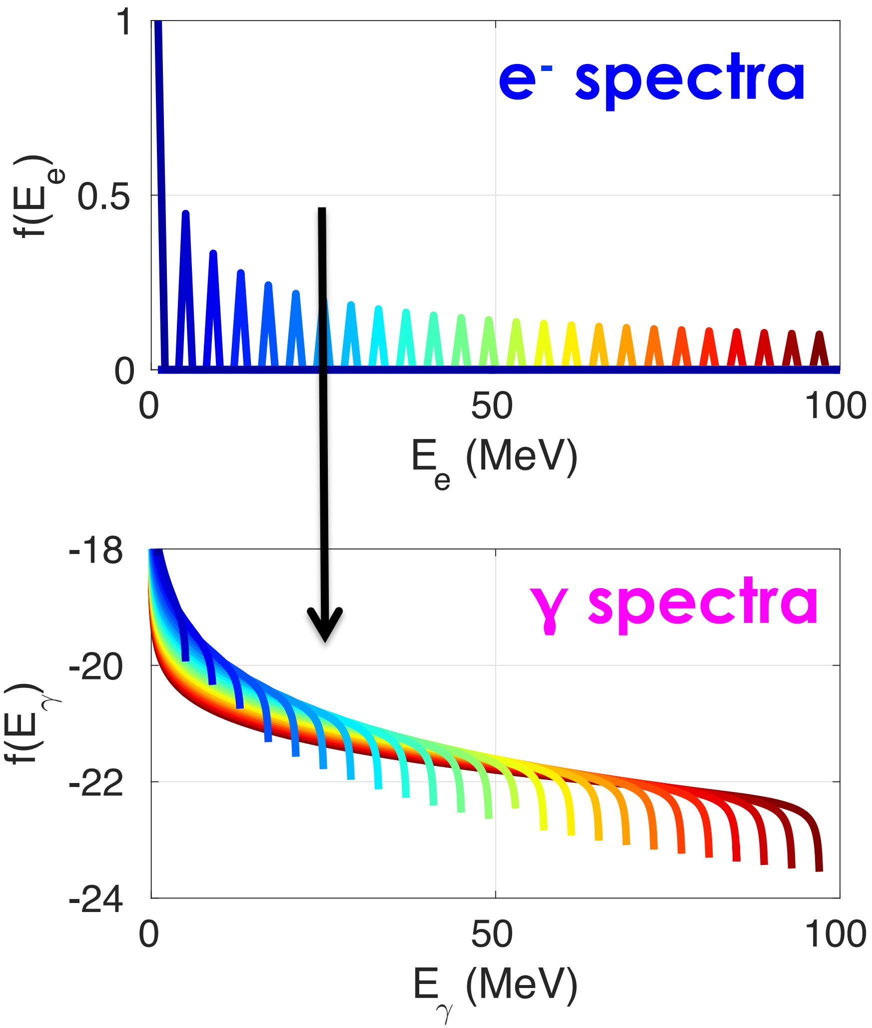
A mono-energetic electron produces a spray of HXRs

- **Use a synthetic diagnostic that takes into account detector sightline and equilibrium fields**
- **Causality exists in energy domain:**
  - gamma must be equal or lower energy than electron



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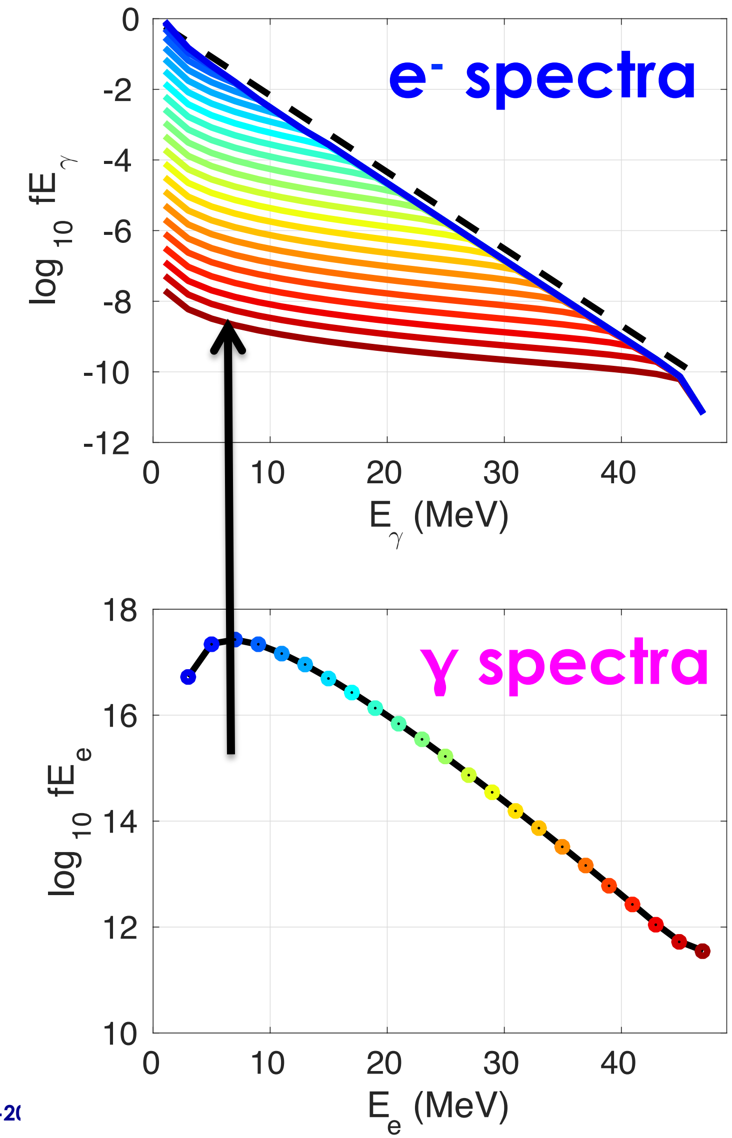
A mono-energetic electron produces a spray of HXRs … inversion possible working from high energy down

- **Use a synthetic diagnostic that takes into account detector sightline and equilibrium fields**
- **Causality exists in energy domain:**
  - gamma must be equal or lower energy than electron
- **Onion peel method from high energy down can be used to go from gamma to electron spectrum**
  - Must assume zero pitch angle
  - … and spatial homogeneity



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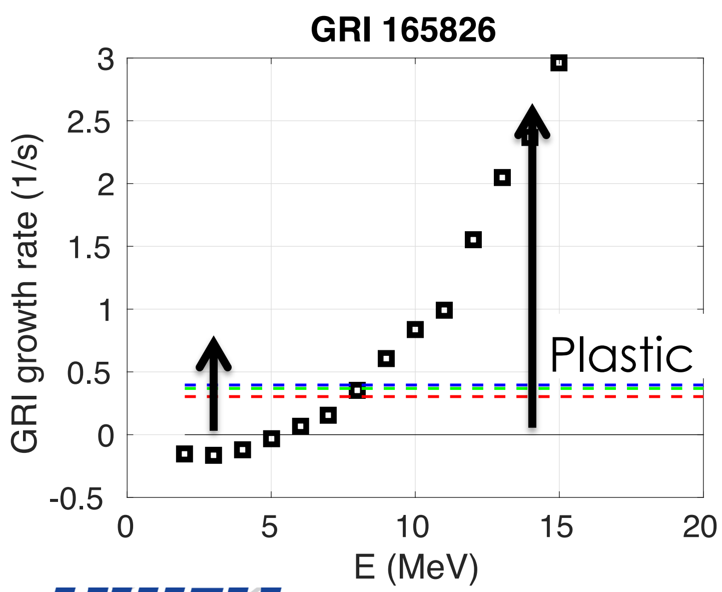
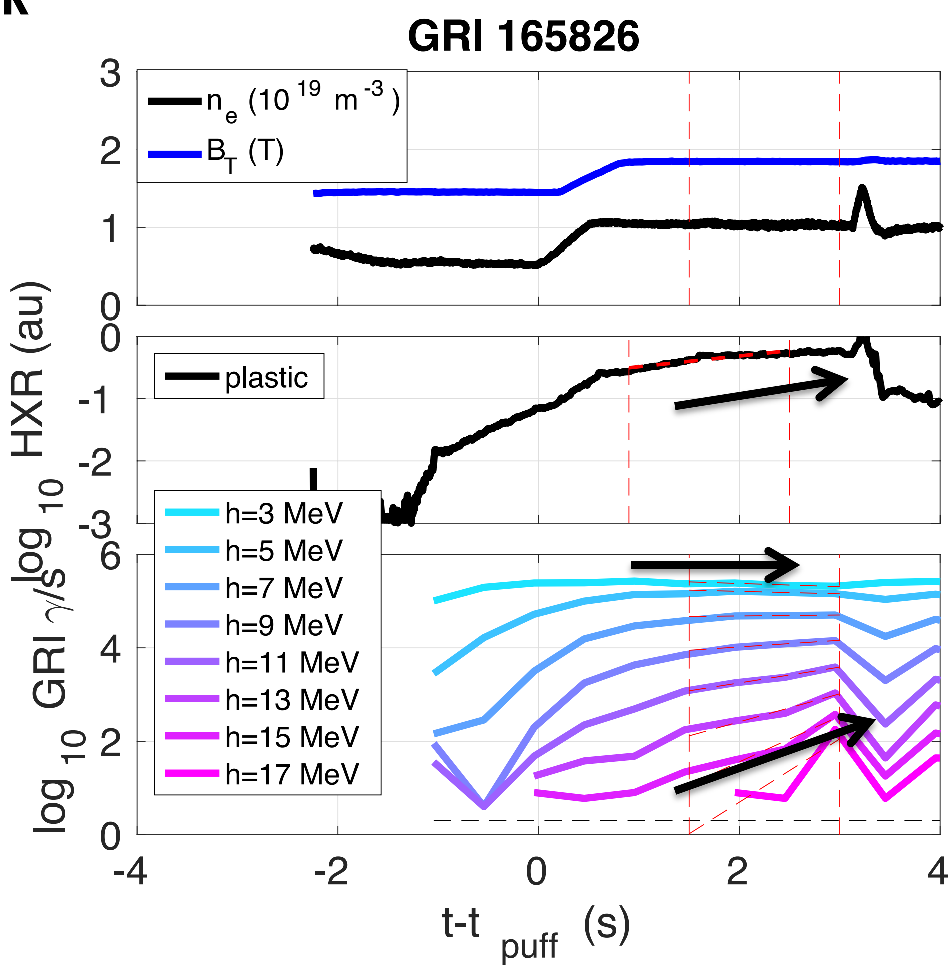
GRI demonstrates energy-dependent growth rate in the HXR spectrum

- **Growth rate of individual HXR energy ranges increases with energy**
  - High energy HXR grows faster than low energy HXR and plastic
- **Indicates phase space re-arrangements present**





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GRI demonstrates energy-dependent growth rate in the HXR spectrum … modeling qualitatively agrees

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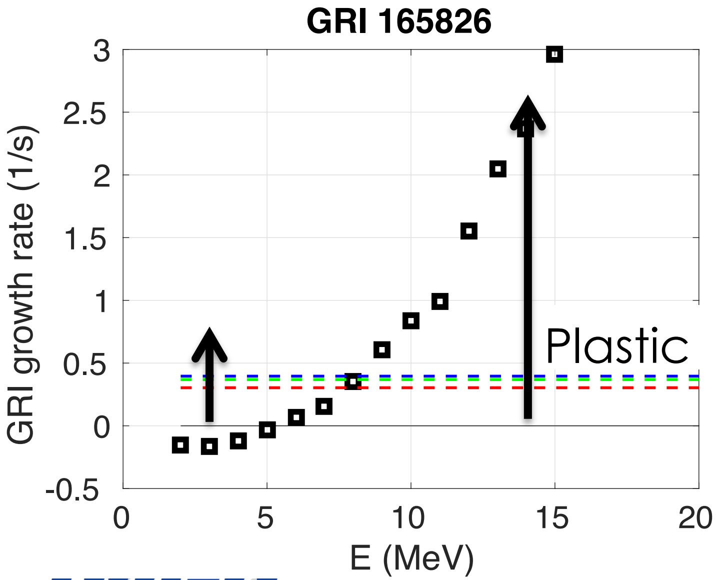
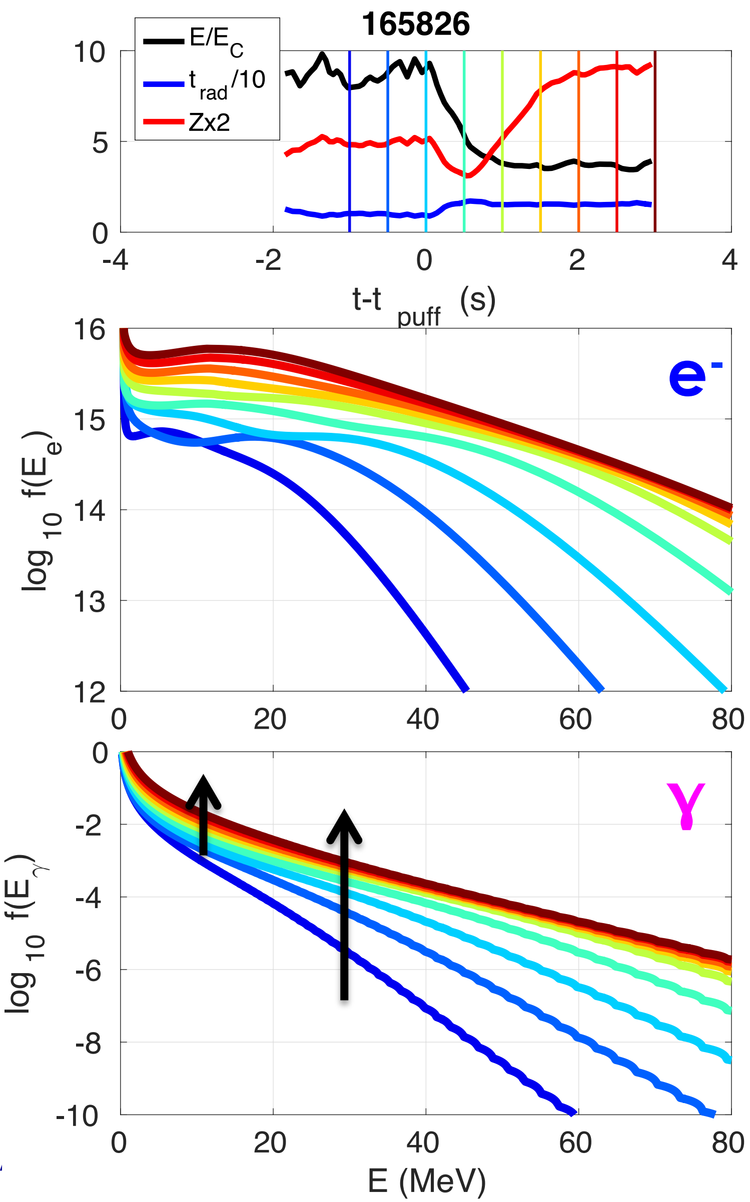
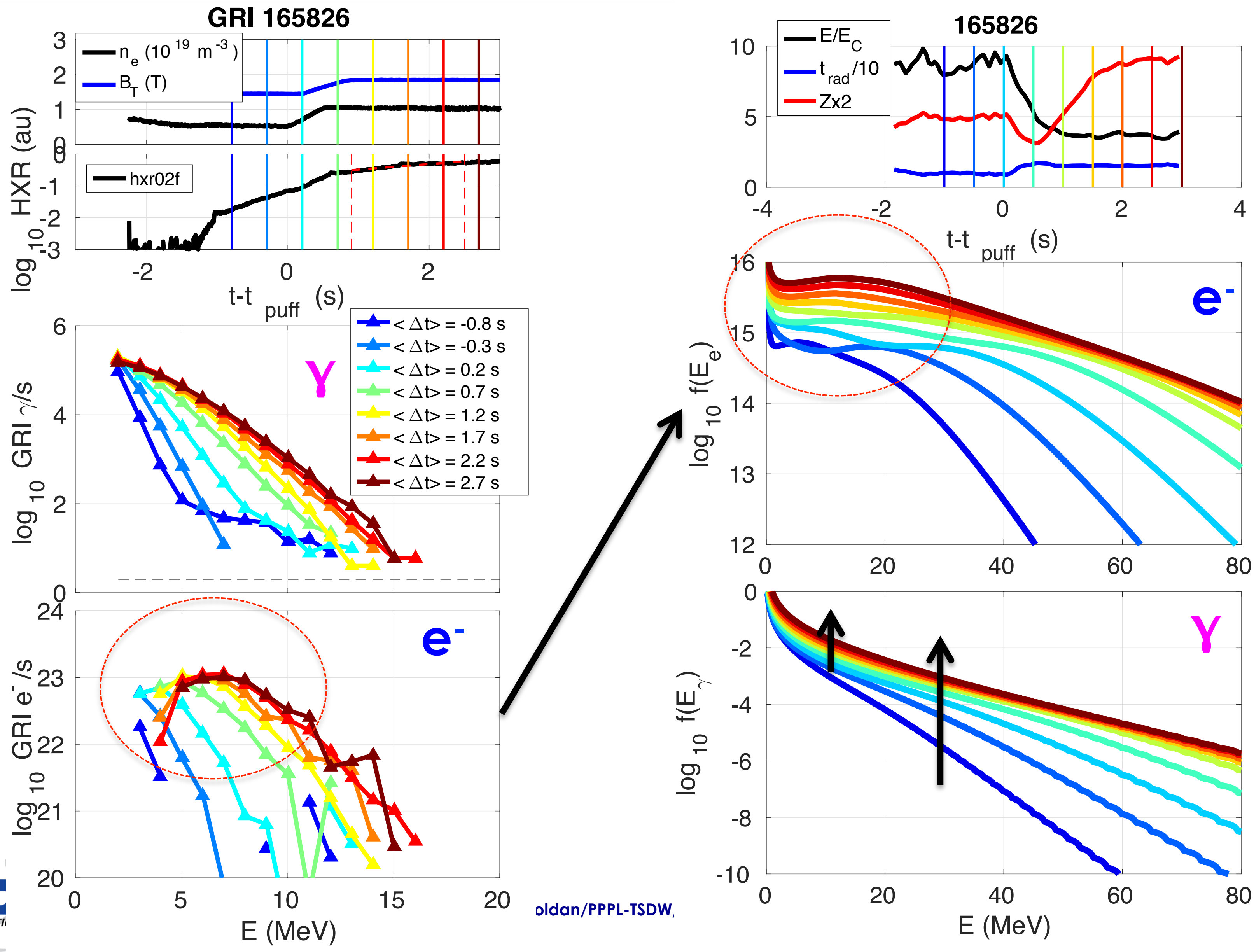


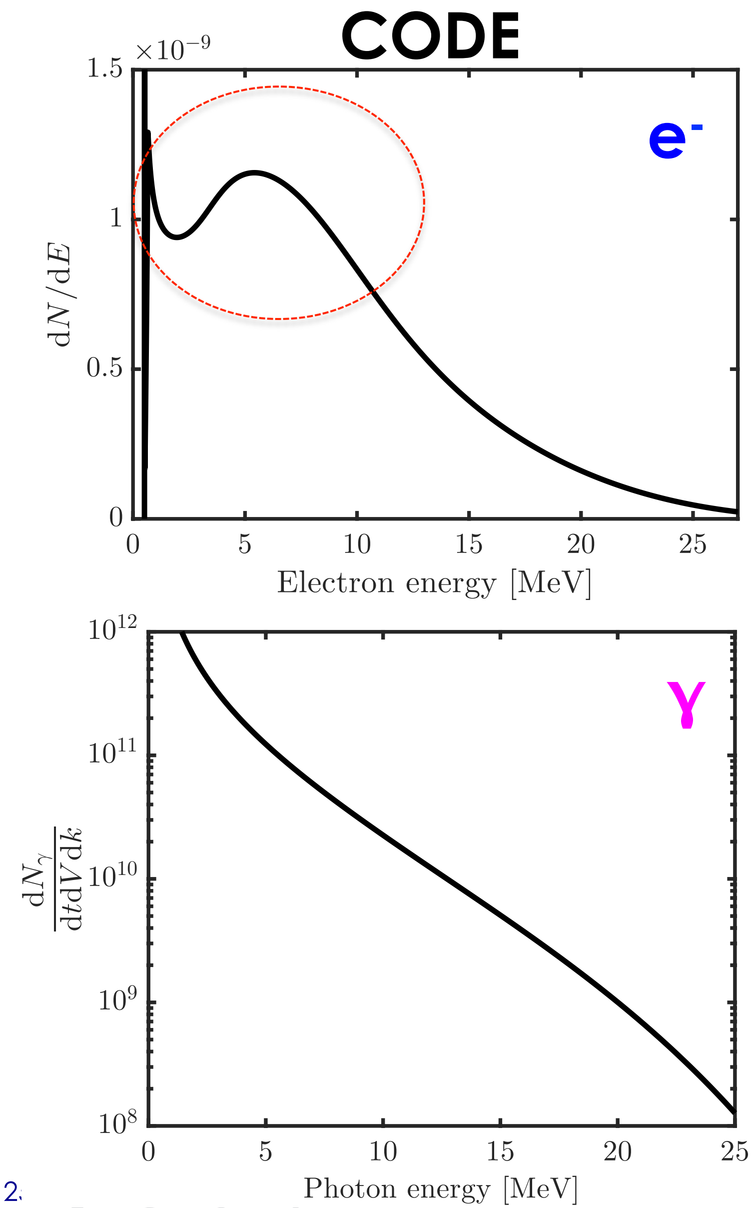


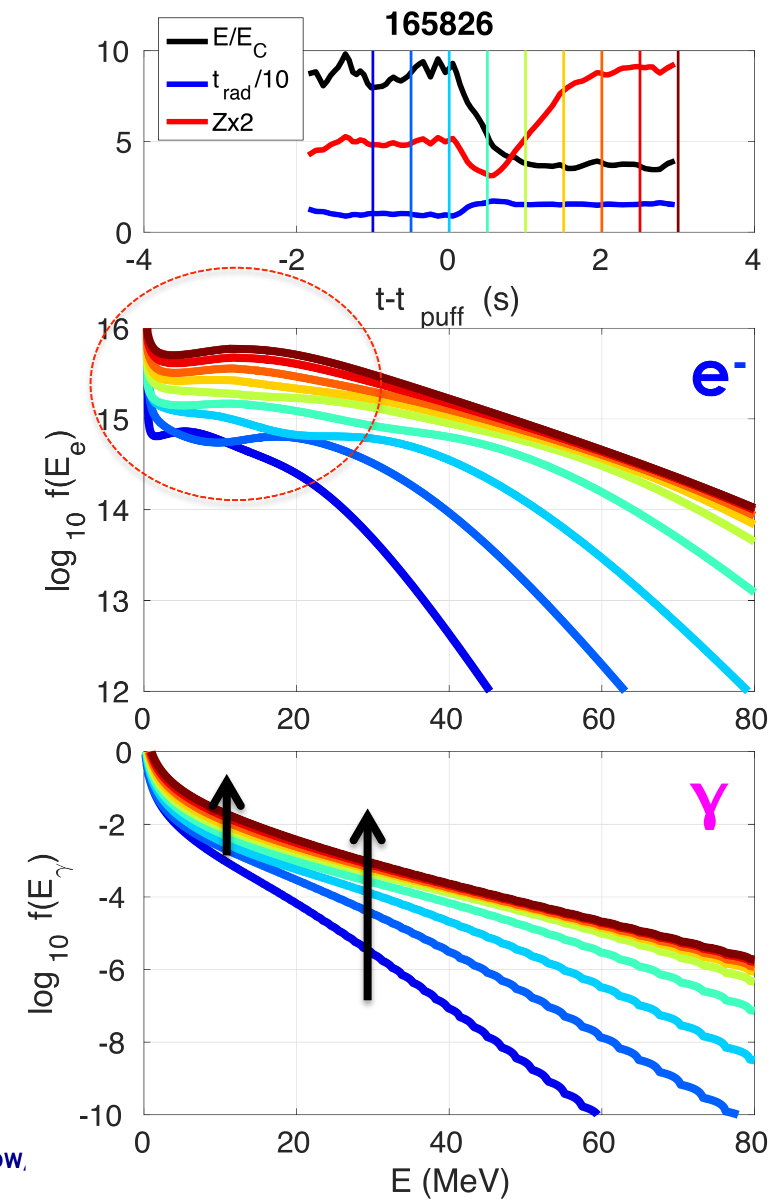
First-look inversions of experimental HXR spectra are promising, bump-like feature in appears in both



oldan/PPPL-TSDW,

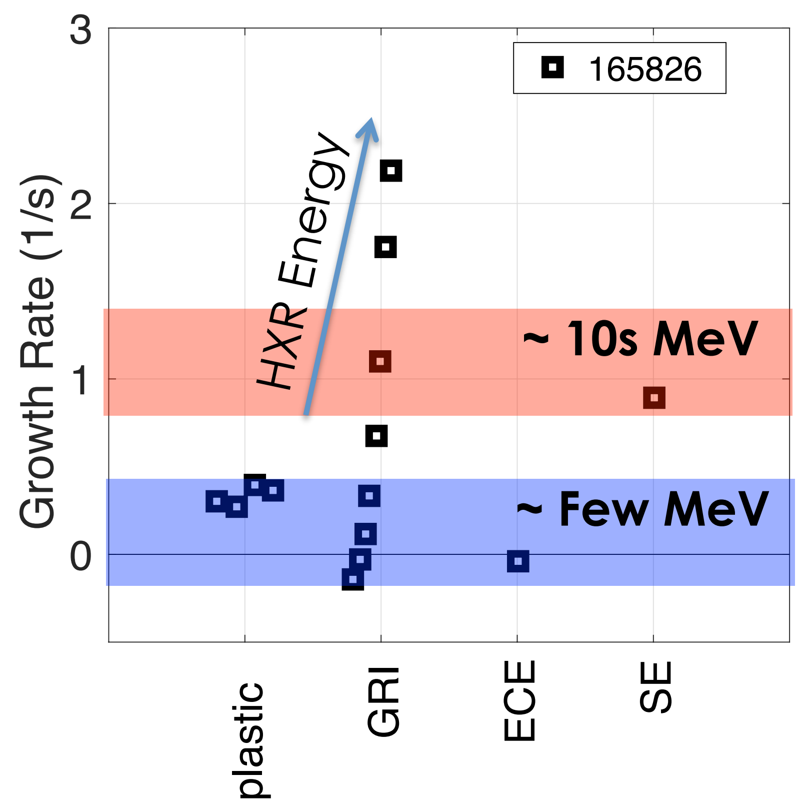
Both Aleynikov analytic model and CODE computation find (small) bump formation for 165826





Growth rates across diagnostics are not the same … further evidence of f(E) re-arrangements

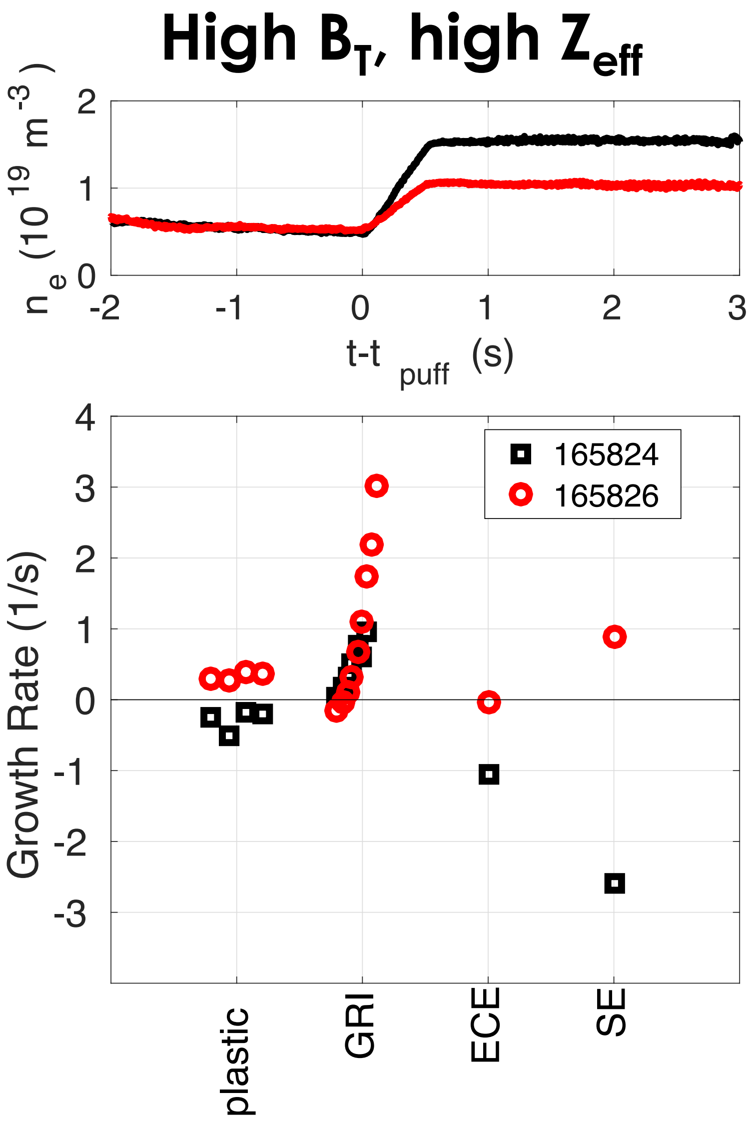
- **Note low energy GRI looks more like plastic, electron cyclotron emission (ECE)**
- **High energy GRI looks more like synchrotron (SE)**
- **This is expected based on sensitivity of ECE, SE**



All diagnostics confirm faster decay rate when density is increased

- **All boats are sunk by increasing density**

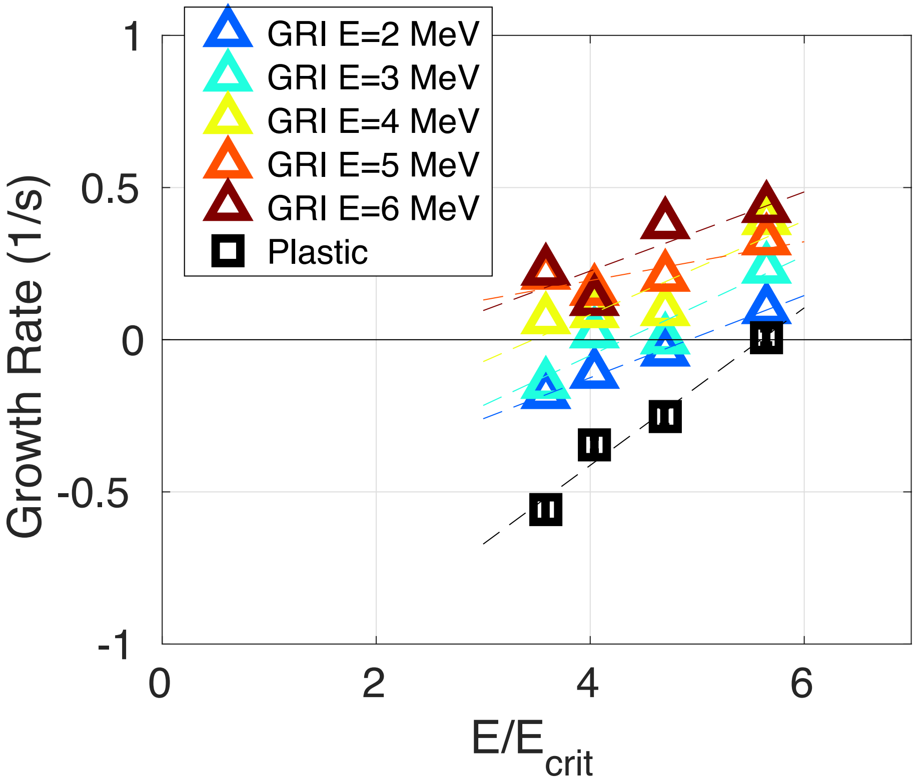
- **But, high energy GRI still grows!**



Paz-Soldan/PPPL-TSDW/…

GRI energy resolved measurements demonstrate anomalously high E/E_{crit} limited to low energy HXRs

- **2014 plastic HXR growth-decay transition reproduced in 2016 E/E_{crit} scans**
- **Higher energy HXR pulses still grow, extrapolate to lower E/E_{crit}**
- **Demonstrates energy redistribution effects are taking place**
  - Simultaneous decay @ low E and growth @ high E



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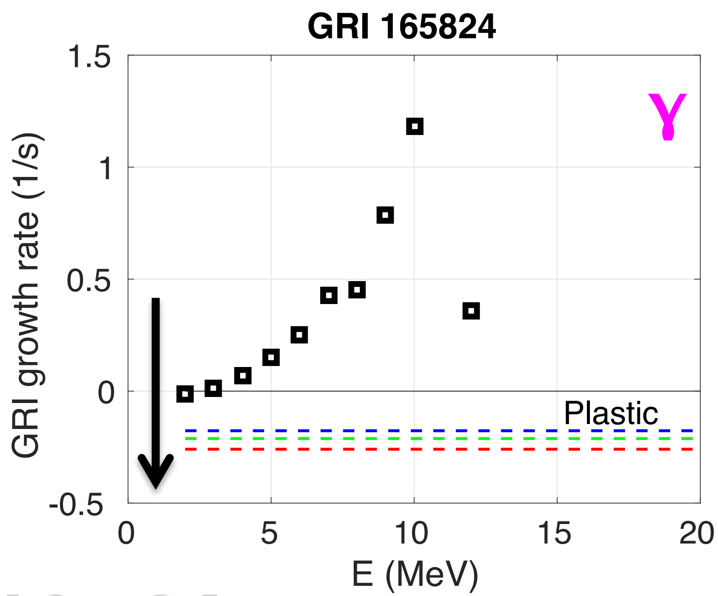
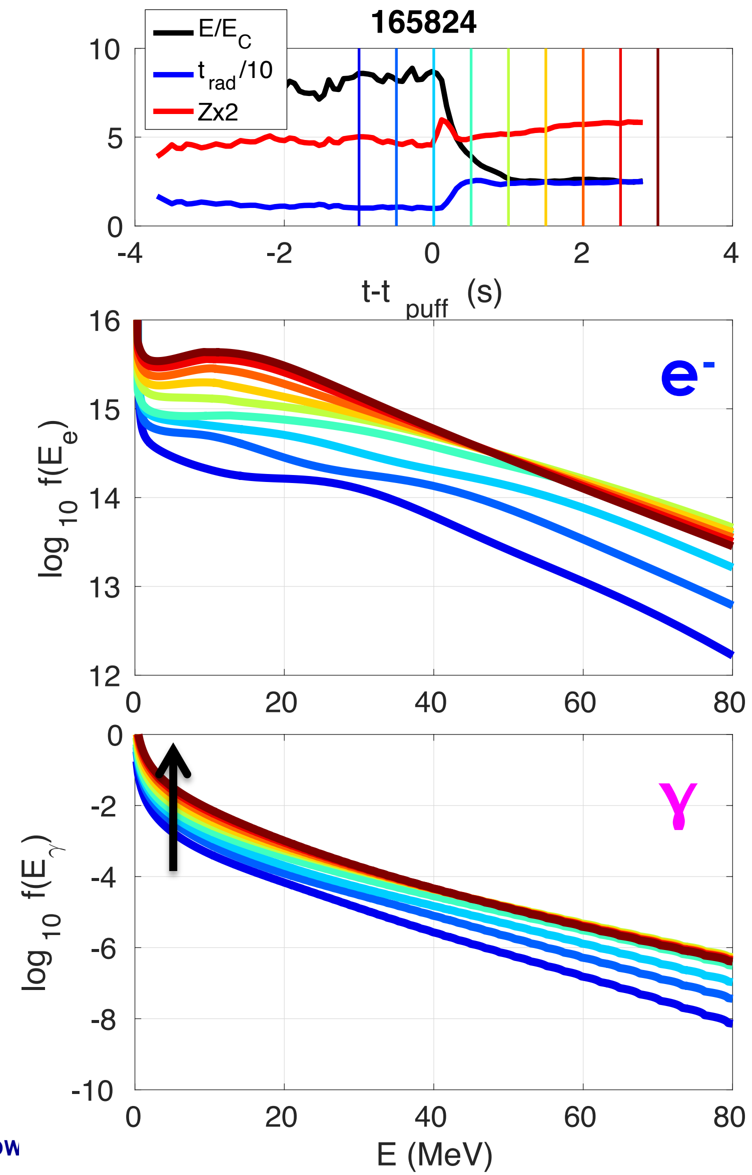
Reduction of low energy (and plastic) is still anomalous as compared to modeling

- **Decaying plastic HXR and low energy GRI not consistent with distribution function modeling**
  - "Anomalous loss" still present

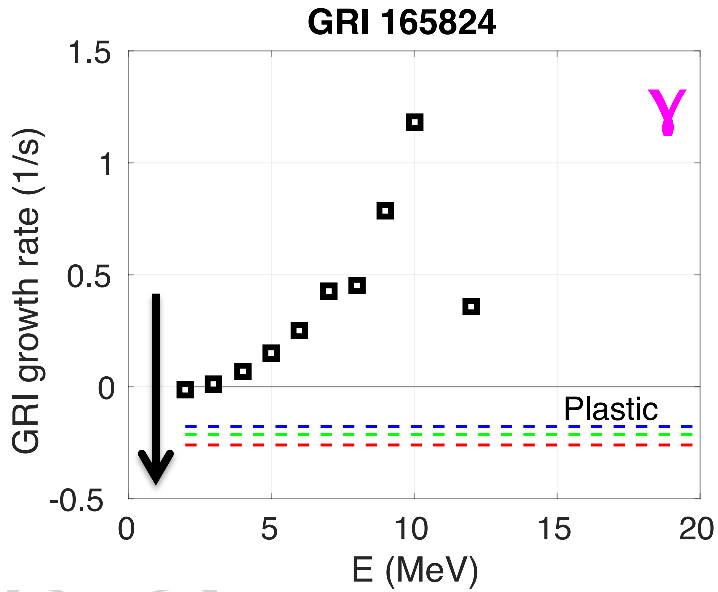


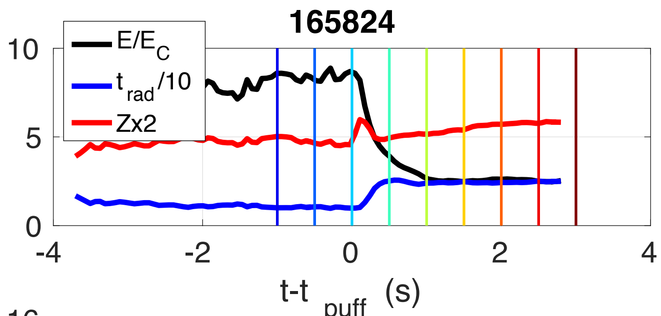


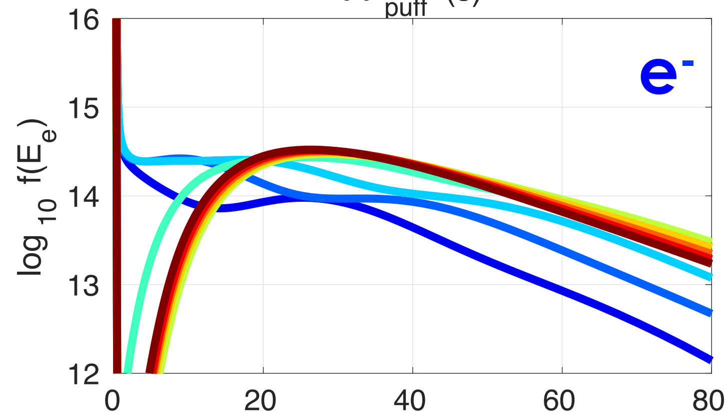
Paz-Soldan/PPPL-TSDW

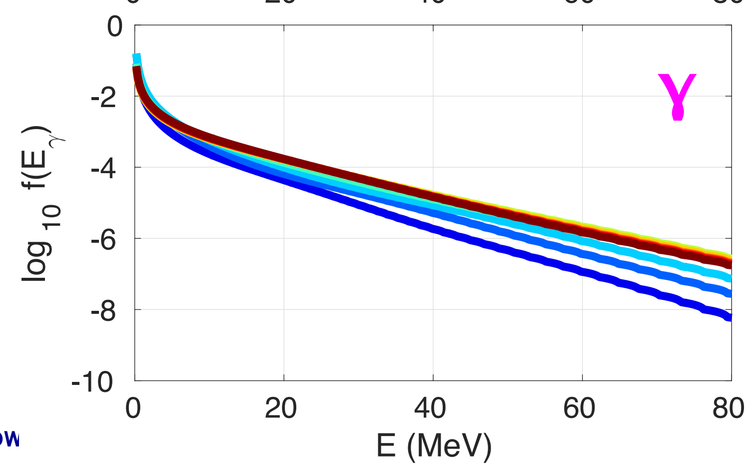
Reduction of low energy (and plastic) is still anomalous as compared to modeling

- **Decaying plastic HXR and low energy GRI not consistent with distribution function modeling**
  - "Anomalous loss" still present
- **Artificially turning off avalanche term improves agreement (??)**
  - Likely proxy for losses









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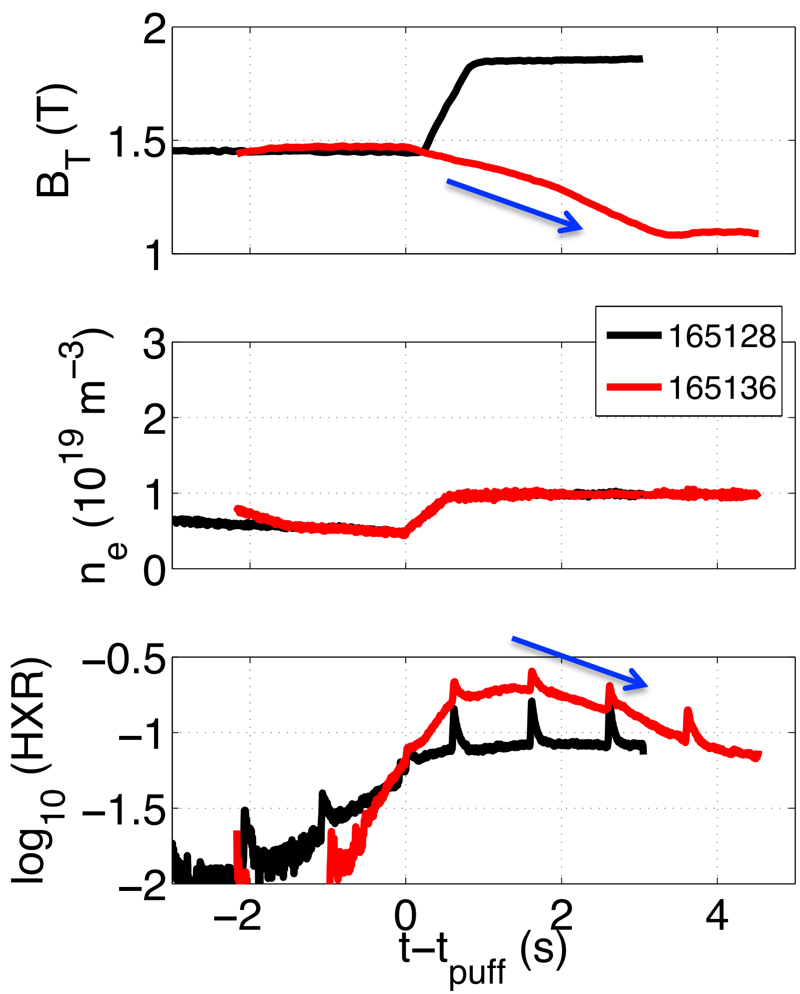
BT effect on plastic HXR was clear – lower BT made faster HXR decay (thus loss of low energy REs)

- **Vary BT at constant density**
  - Same low density front end
- **Low BT causes faster decay of plastic HXR**



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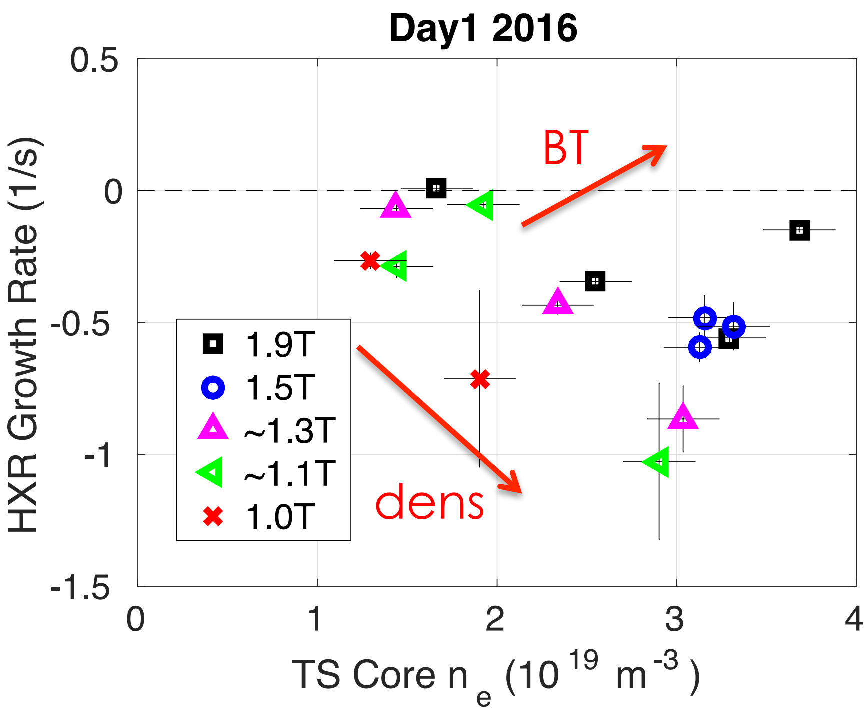
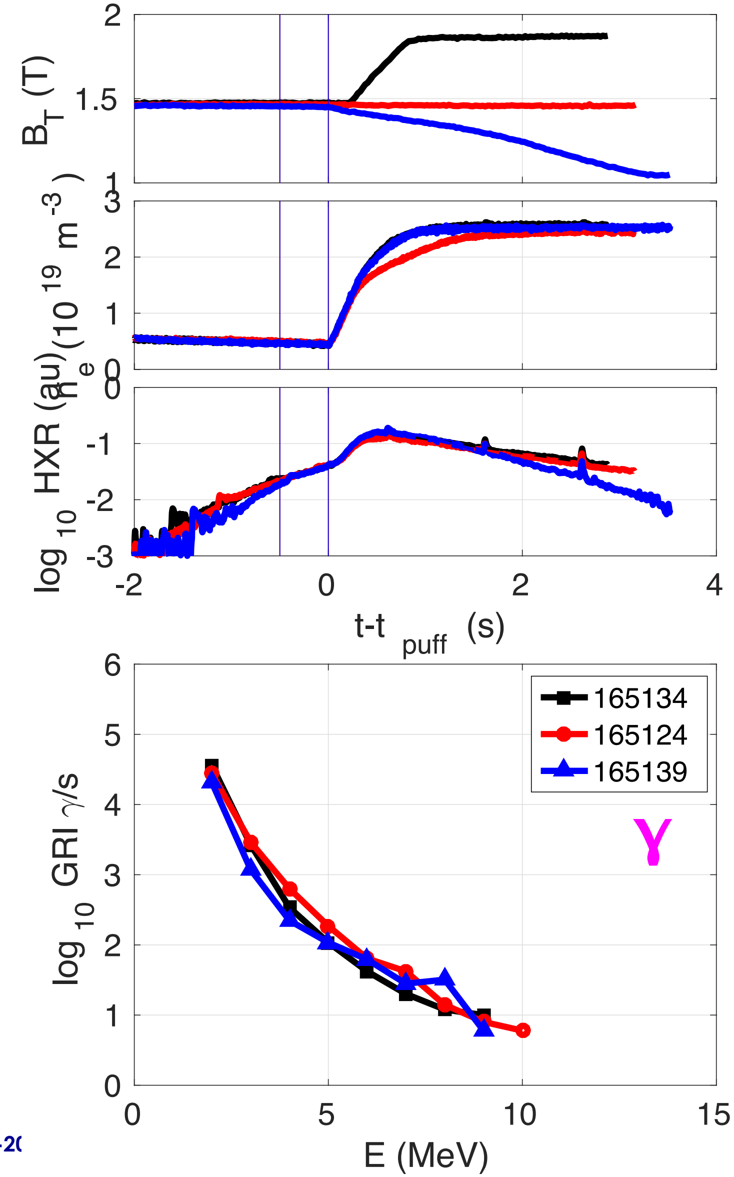
- **Low BT causes faster decay of plastic HXR**

- **Confirmed by analysis across entire dataset**



GRI spectrum hardness varies based on BT level: Synchrotron energy limit likely observed

- **Consider 3 shots with very similar pre-puff seed populations**
  - Different post-puff trajectories



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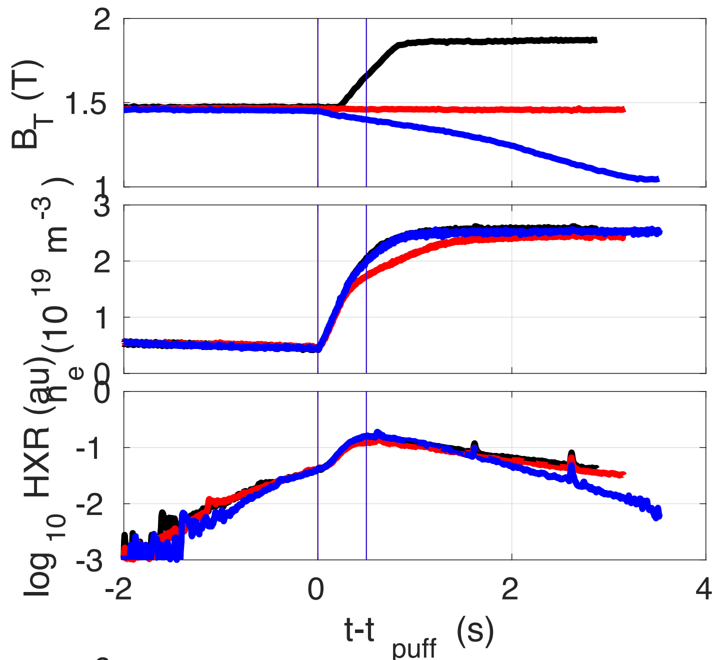
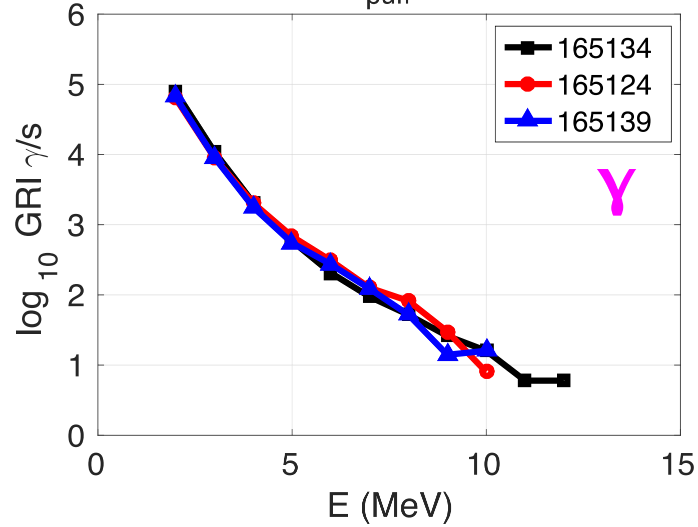
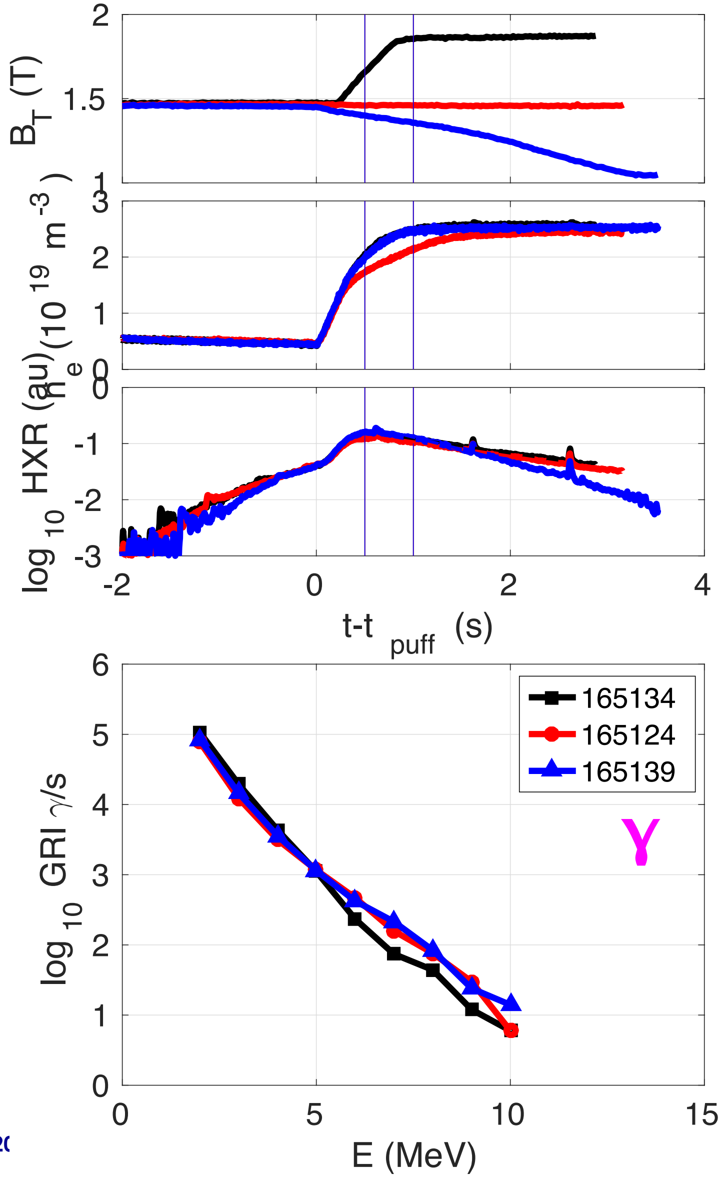




GRI spectrum hardness varies based on BT level: Synchrotron energy limit likely observed

- **Consider 3 shots with very similar pre-puff seed populations**
  - Different post-puff trajectories



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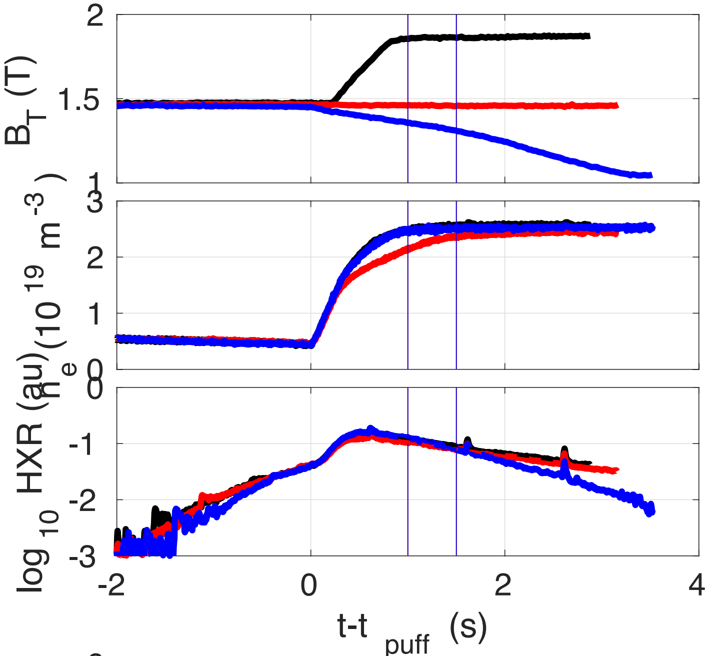

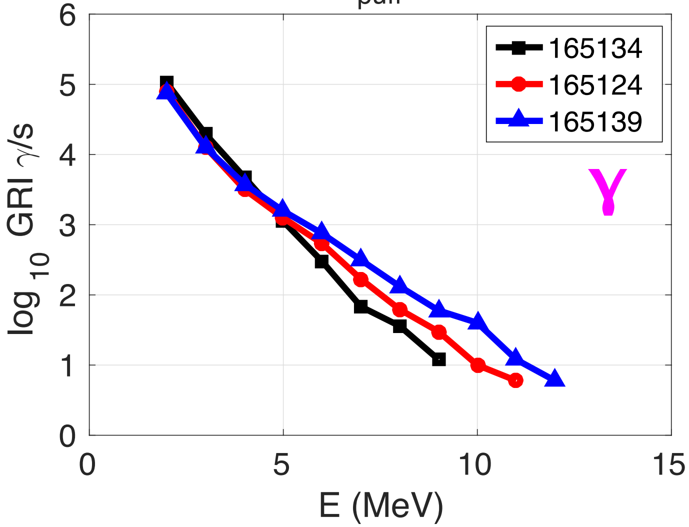

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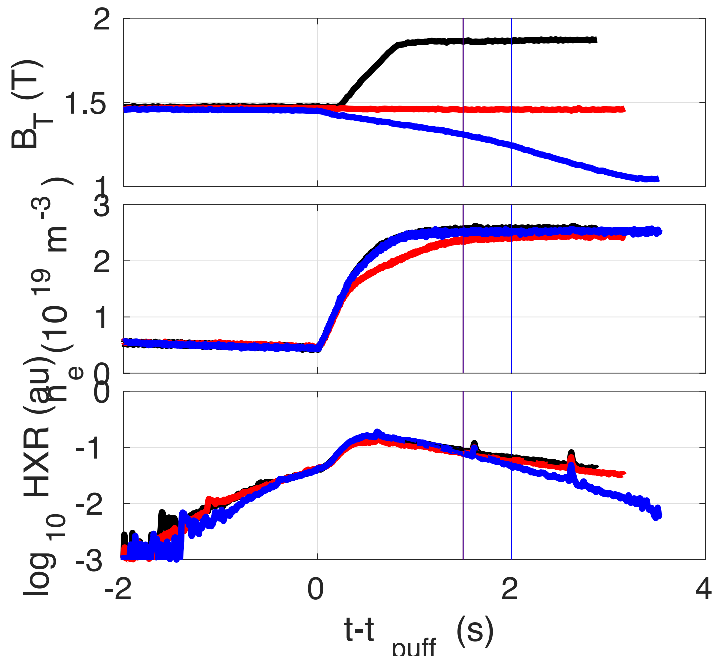

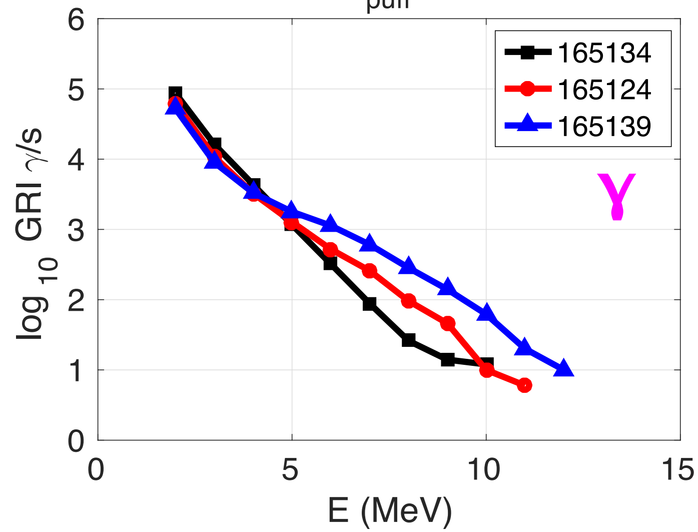

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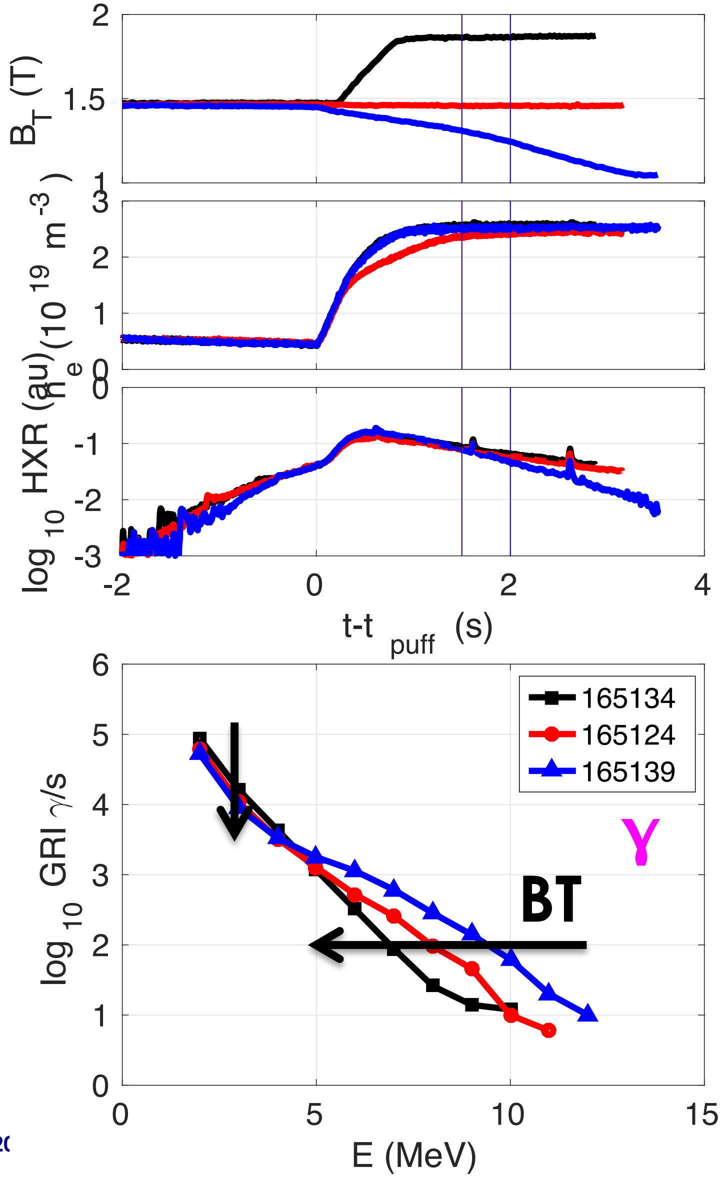
GRI spectrum hardness varies based on BT level: Synchrotron energy limit likely observed

- **Consider 3 shots with very similar pre-puff seed populations**
  - Different post-puff trajectories

- **After puff, lower BT discharges contain higher energy gammas**

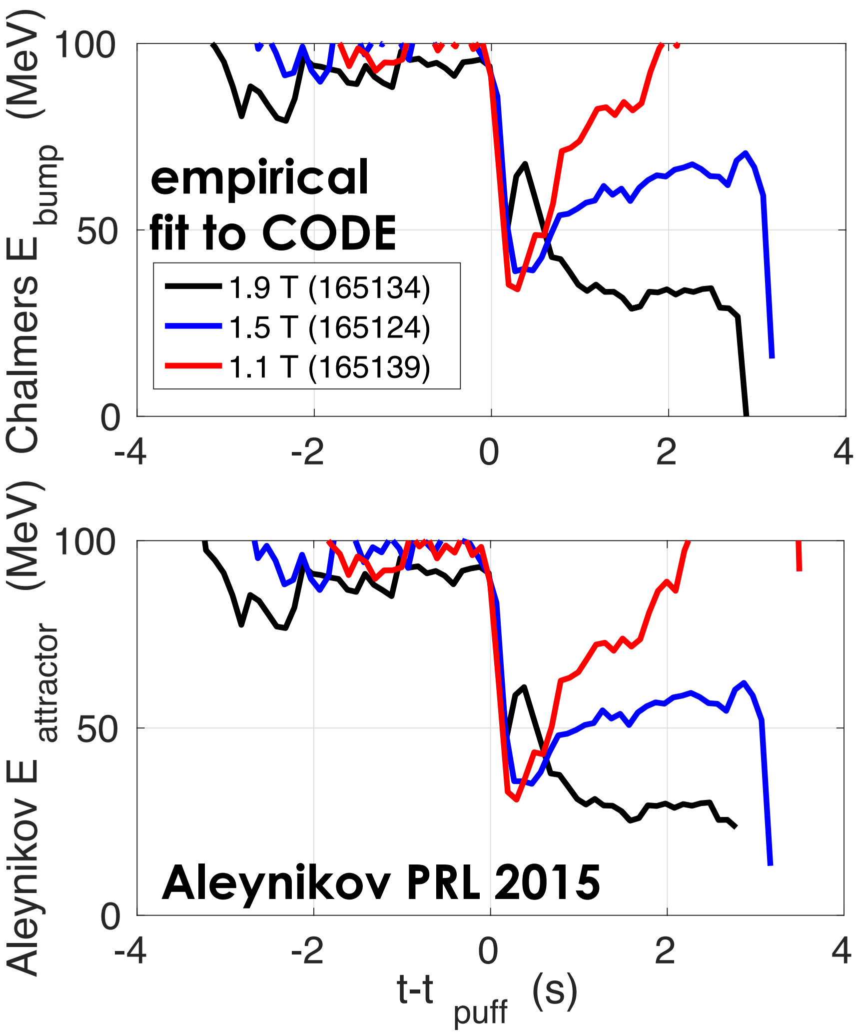
- **Opposite trend at low energy**
  - Confirms plastic HXR picture



Paz-Soldan/PPPL-TSDW/07-2(

Modeling of evolution of phase space attractor reveals higher energy attractor at low BT

- **Model evolution of discharge and track location of phase space attractor**
  - Excellent agreement between two different computations



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- **Model evolution of discharge and track location of phase space attractor**
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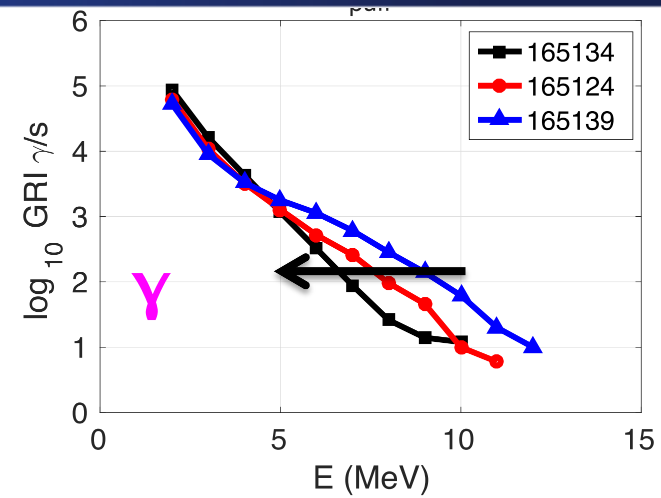
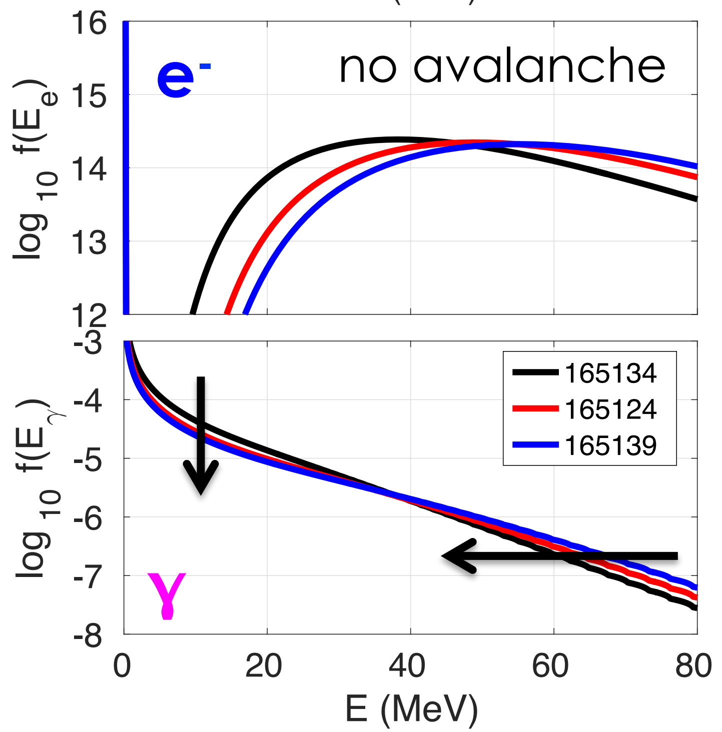
- **Comparison of electron and gamma distributions qualitatively reveal similar features**
  - … but GRI effect much stronger
  - … but avalanche turned off again





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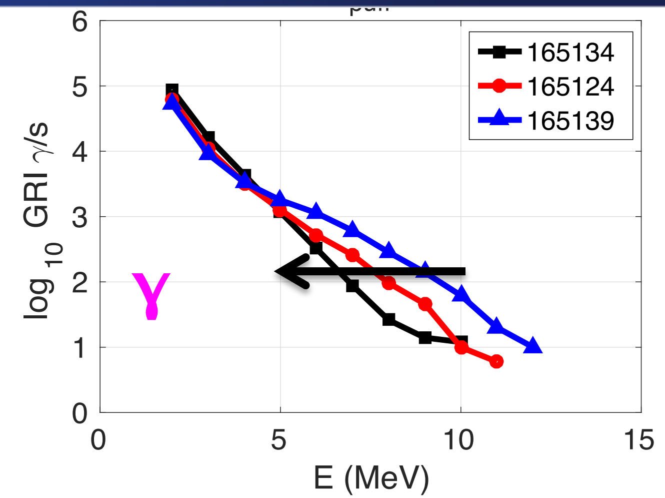
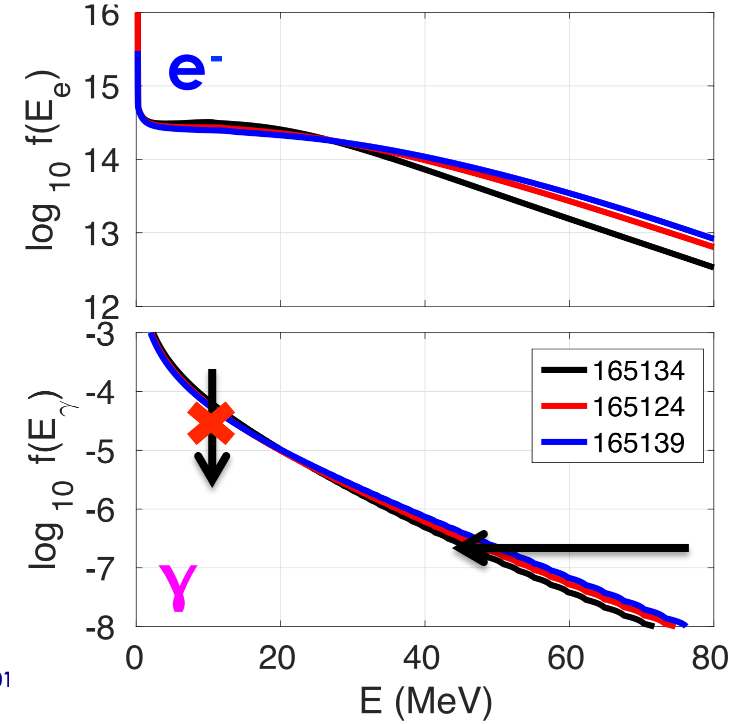
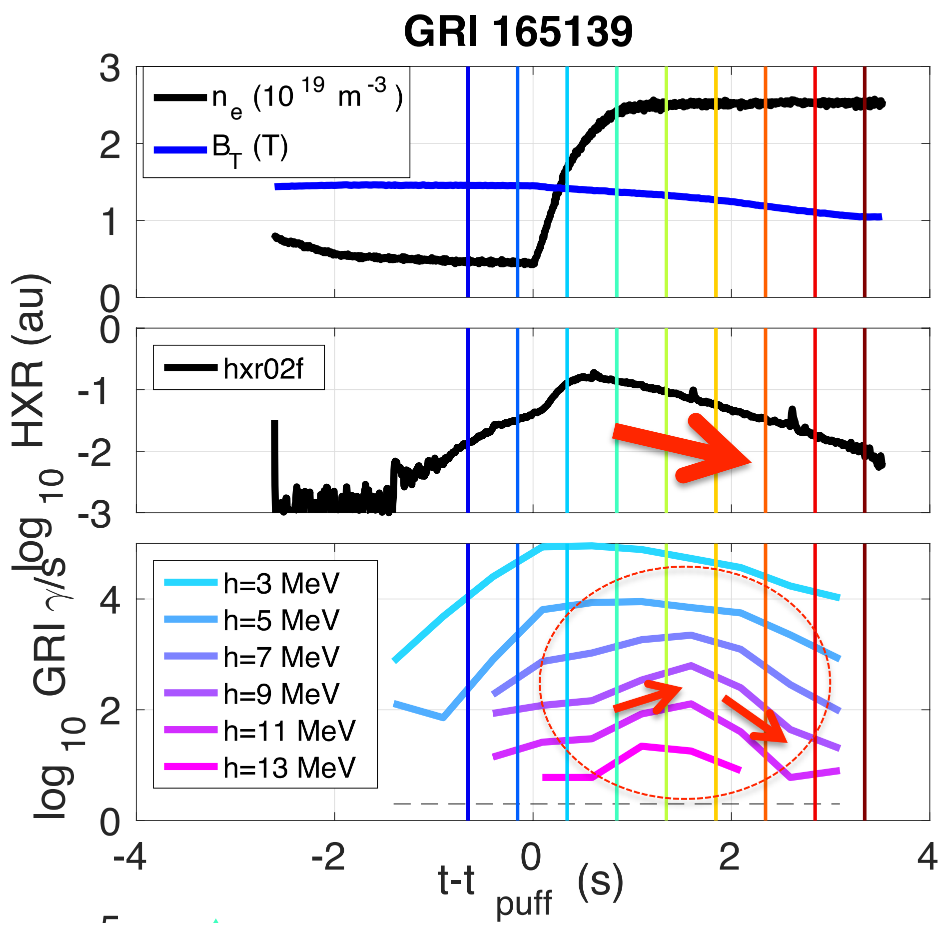
- **Turning on avalanche again causes diagreement in low energy region**





At low toroidal field limit, bulk RE deconfinement appears to be occurring

- **Early in BT rampdown, GRI high energy grows quickly**
  - Simultaneously with GRI low energy and plastic decay
- **Spectrum hardness reaches maximum, then high energy lost as well**
  - Deconfinement ?



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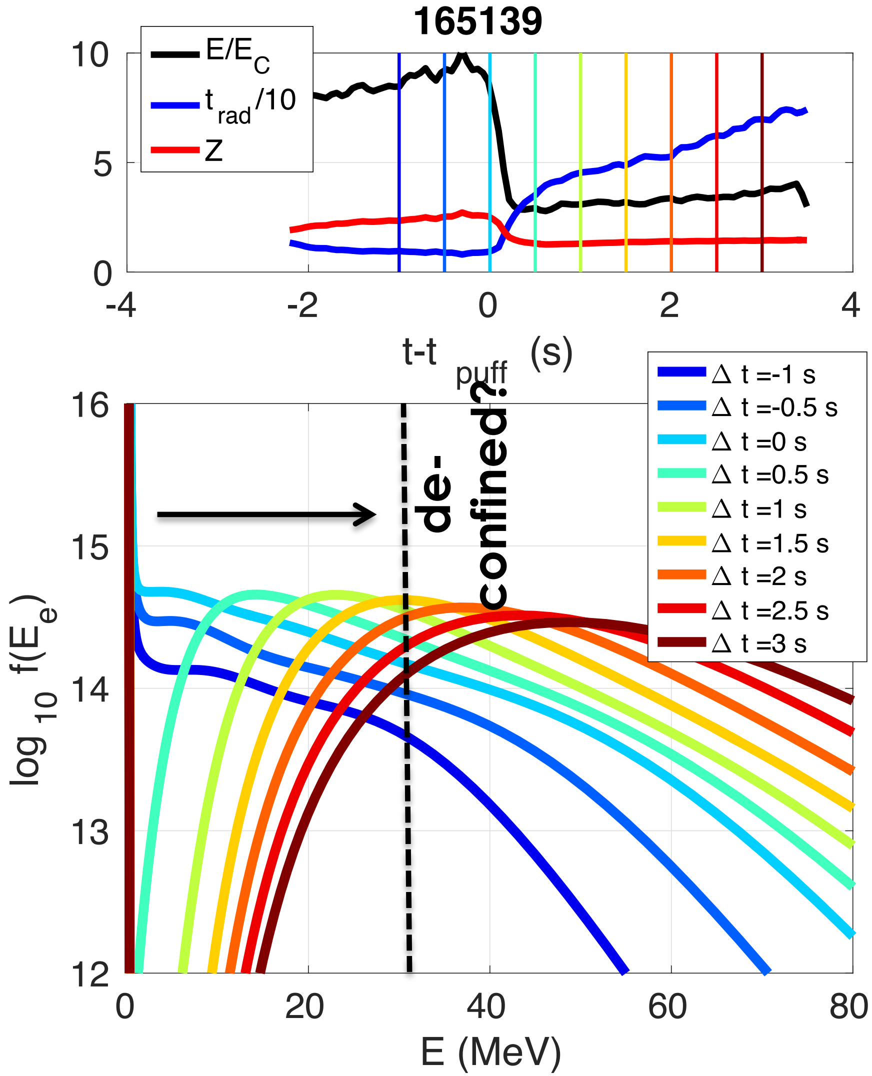
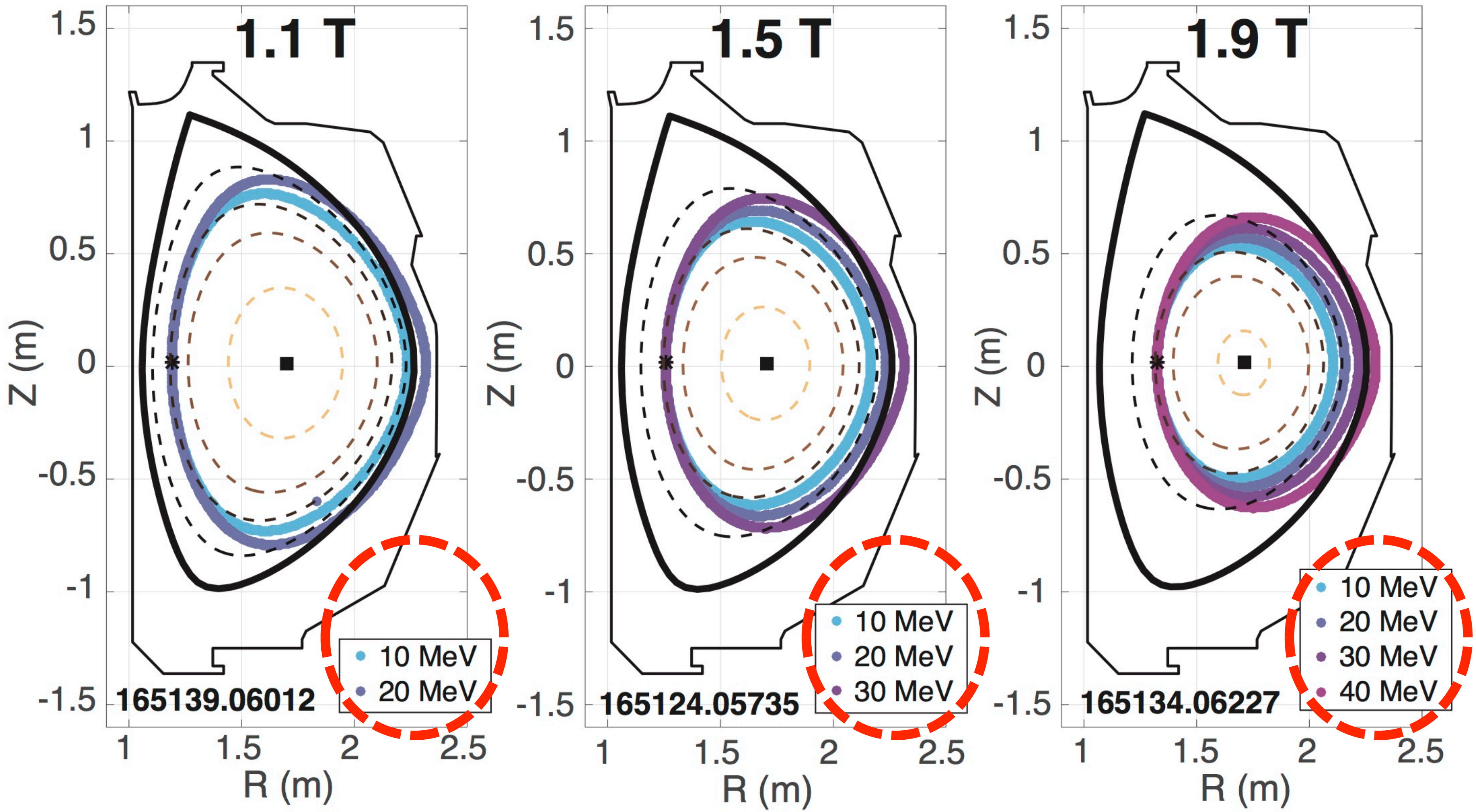
- **Recall modeling predicts phase-space attractor moves to very high energy**
  - (ignoring avalanche for illustration)



Changing BT also affects drift-orbits and RE confinement … about 10 MeV max RE energy drop per BT step



RE orbits courtesy A. Wingen, ORNL

Outline:

- Recap of Theory Progress and Important Parameters
- Recap of QRE Regime to Study RE Dissipation
- Introduction to GRI Diagnostic and f(E) Inversion
- Spectrum Effect of Electron Density (Collisions)
- Spectrum Effect of Toroidal Field (Synchrotron)
- Conclusion and Future Directions

Conclusion: Much more can be said about evolution of runaway distributions during controlled dissipation

- **Dissipated similar RE populations with variable E/E_{crit}, $t_{rad\text{-}hat}$, Z_{eff}**
  - Thanks to this group for supporting experiment. It was worth it!
- **Evidence found for phase-space attractors and bump formation in some conditions**
  - When synchrotron and pitch angle scattering are largest
  - When avalanche is weakest (in modeling)
- **Low energy HXR decay observed simultaneously with high energy HXR growth**
  - Direct evidence of f(E) re-distribution taking place
  - Plastic HXR detector only tells the low energy story
  - Anomalous E/E_{crit} observation does not extend to high energy REs
- **"Anomalous" loss still needed to explain low energy RE decay**

Conclusion: Much more can be said about evolution of runaway distributions during controlled dissipation

- **Lowering E/E_{crit} was found to cause more decay in all diagnostics (HXR, ECE, Sync)**
  - Collisional damping compresses the time-axis
- **B_T scan demonstrates effect of synchrotron on the most energetic particles**
  - Maximum energy constrained by synchrotron
  - Effect appears stronger experimentally than in modeling
- **Enhanced decay of low energy REs with low B_T appears to be simply due to flow of REs to higher energy (due to weaker synchrotron)**
- **At low enough B_T, the REs are likely lost due to deconfinement**
  - Peculiar to DIII-D, limit of experimental technique

Future Directions: much also remains to be done … … what can we say about losses, kinetic instability?

- **Can we utilize ad-hoc RE loss terms in modeling to better match experiment? What does that actually teach us?**

- **Other diagnostics can be deployed in model-experiment comparison: Electron cyclotron and Synchrotron emission**
  - Spectral data available for both!
  - Chalmers group has excellent synchrotron synthetic diagnostics
  - PPPL group developing ECE synthetic diagnostics

- **Looking ahead: Can we create conditions to maximize observation of kinetic instability in controlled RE beam?**

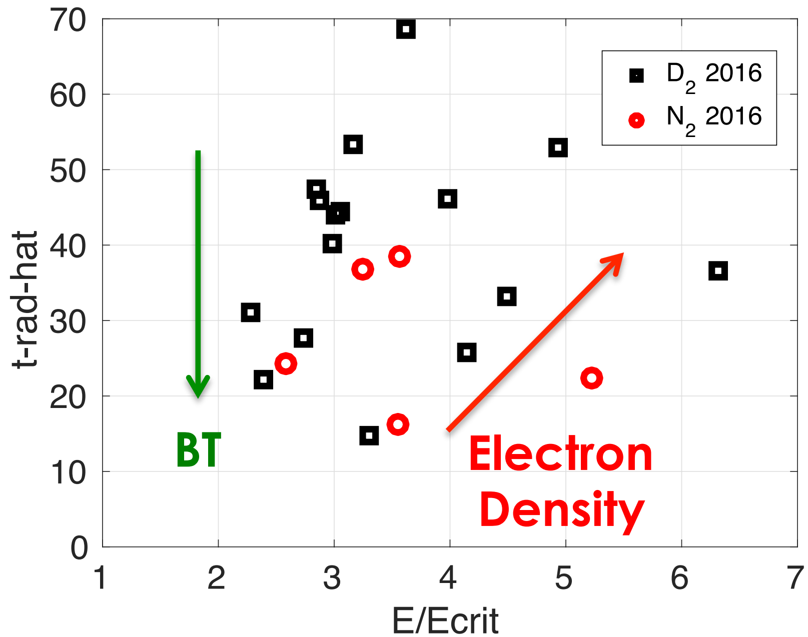
- **GRI hardware improvements are planned:**
  - 1) Detector and grounding to improve signal/noise ratio
  - 2) More shielding for intense HXR fluxes found in post-disruption RE

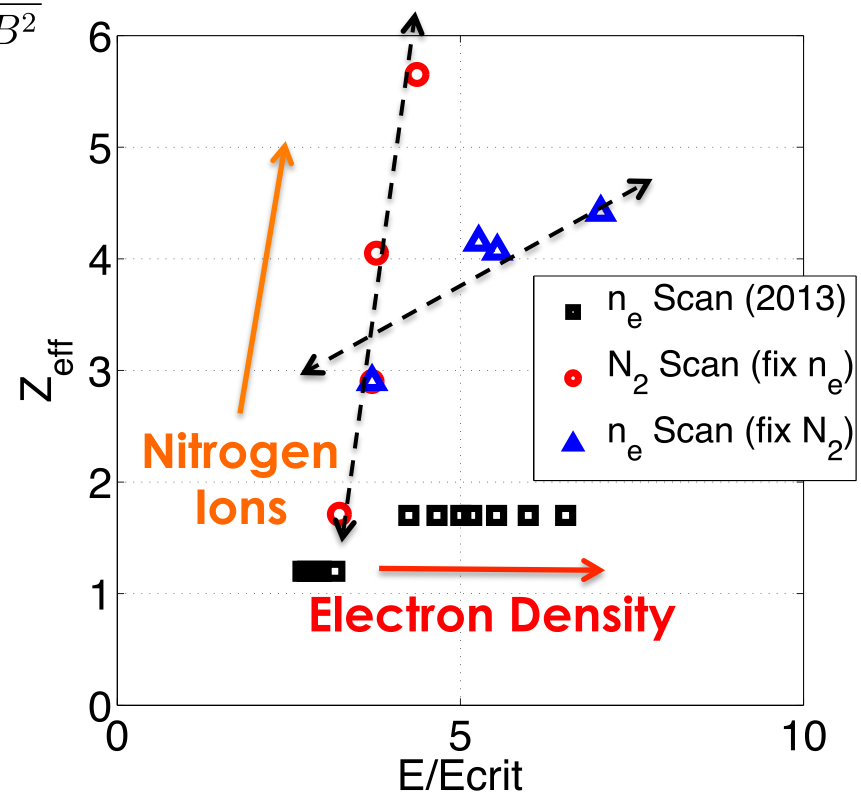
BONUS SLIDES

QRE can traverse E/E_{crit}, t-rad-hat, Z_{eff} orthogonally → density, B_T, nitrogen are decoupling actuators

$$\frac{E}{E_C} = 2\left(\frac{\varepsilon_0^2 m_e c^2}{e^3 \ln\Lambda}\right)\frac{V_{\mathrm{loop}}}{n_e R} \approx 10\cdot\frac{V_{\mathrm{loop}}[V]}{n_e[10^{19}]}$$

$$\hat{\tau}_{\mathrm{rad}} = \frac{3}{2}\left(\frac{m_e \ln\Lambda}{\epsilon_0}\right)\frac{n_{\mathrm{eff}}}{B^2} = 278\cdot\frac{n_{\mathrm{eff}}[10^{20}]}{(B[T])^2}$$





- Changing BT vs. density explores E/E_{crit} and t-rad-hat space
- Ratio and quantity of D_2 to N_2 scans Z_{eff} – E/E_{crit} space
- Full ionization is key

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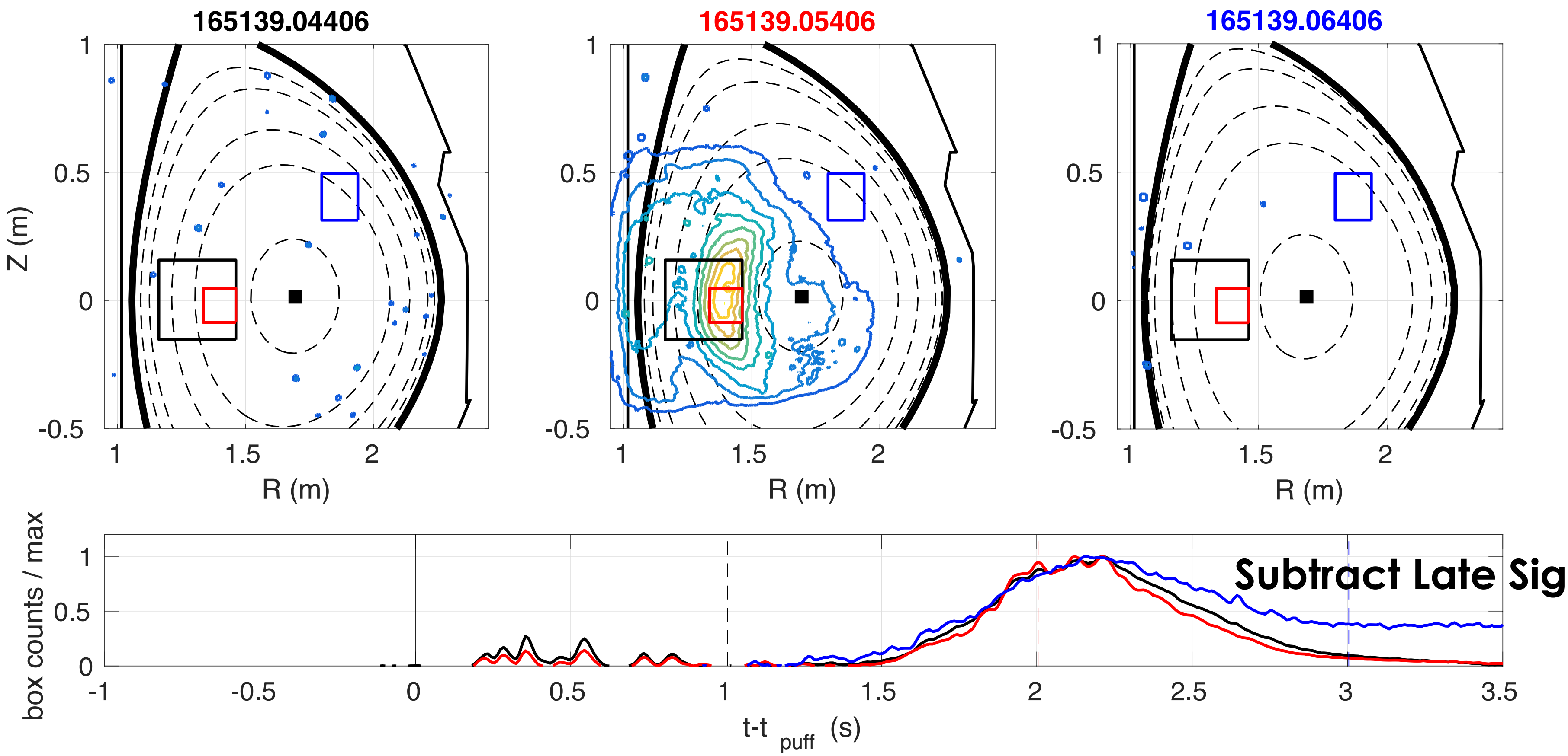
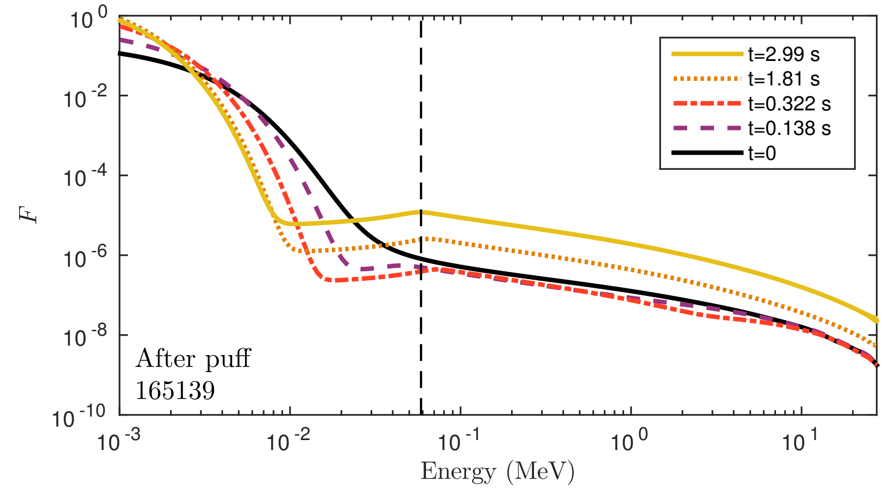
Synchrotron camera confirms emergence of late "bump"

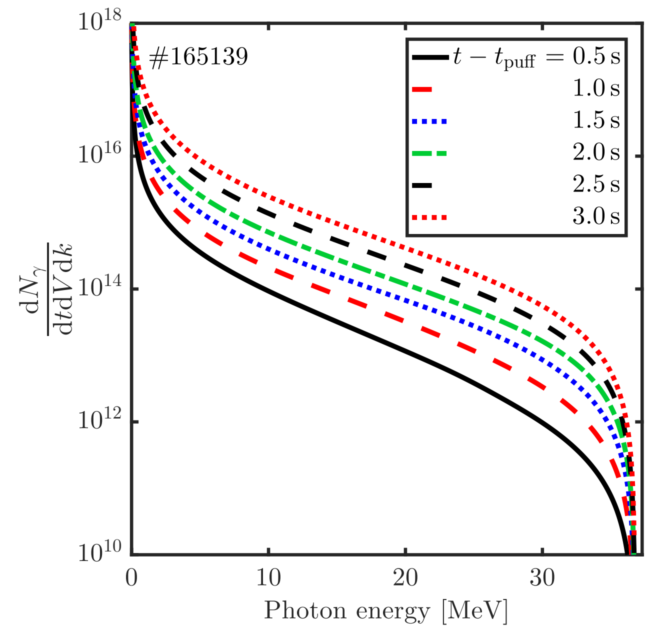


- Baseline is likely dominated by visible Brems
- Single-slice late baseline subtraction works for full flat-top
- Movie shows emission convecting to center post

CODE simulations are presently swamped by avalanche, obscuring phase-space dynamics

- **Dominance of avalanche yields self-similar evolution of f(E)**
  - No phase-space changes
- **Inferred HXR spectrum also increases self-similarly**
- **Future work will mock up radial diffusion and artificially suppress avalanche to see if experiment can be better matched**





Even with self-similar f(E) evolutions, rise and fall of synchrotron during BT rampdown captured

- **Suggests this effect need not invoke phase-space effects**