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Current Quench Avoidance using Lower Hybrid Current Drive in the Alcator C-Mod Tokamak

M.L. Reinke[1], S.D. Scott[2], R. Granetz[3], J.W. Hughes[3], S.G Baek[3], K. Montes[3], C. Rea[3], S. Shiraiwa[3], S.J. Wukitch[3], and the Alcator C-Mod Team

[1]Oak Ridge National Laboratory, Oak Ridge, TN

[2]Princeton Plasma Physics Laboratory, Princeton, NJ

[3]MIT Plasma Science and Fusion Center, Cambridge, MA

Outline

- canonical example of high-Z impurity-induced disruption in a tokamak
- discussion of a LHCD C-Mod plasma where thermal quench occurs, $T_e \sim 0$ moves all the way into the core while I_p, n_e unchanged
- possible physical mechanisms
- implications and future work

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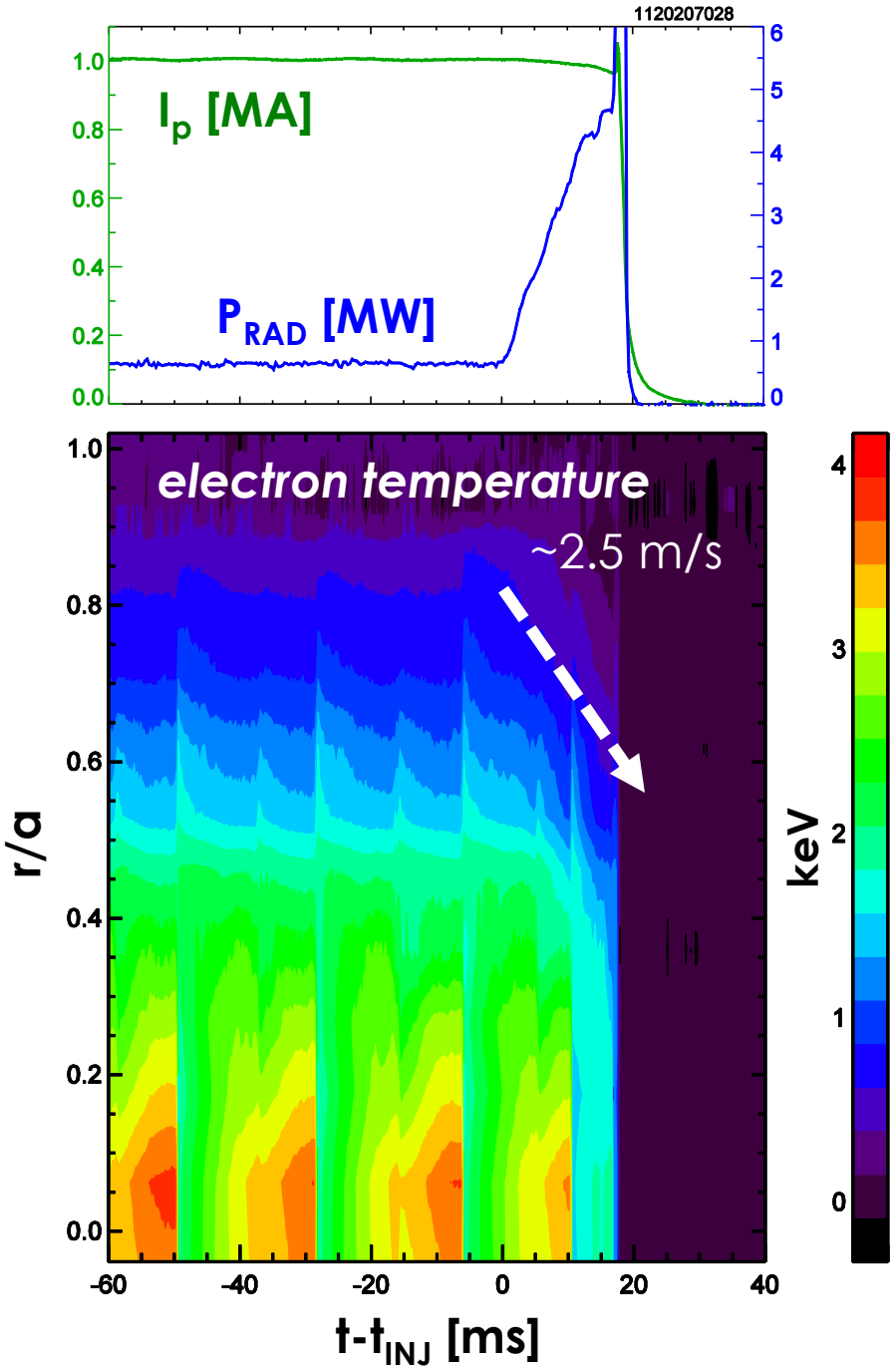
Tokamaks Need Improvements in Disruption Avoidance and Mitigation for 'Bricks' from High-Z Wall

- unplanned, unforeseen high-Z influx (dust, flake) leads to increased P_{RAD}
- cooling wave quickly moves into core, large 2/1 mode destabilized when low-T_e reaches q=2 surface (right)



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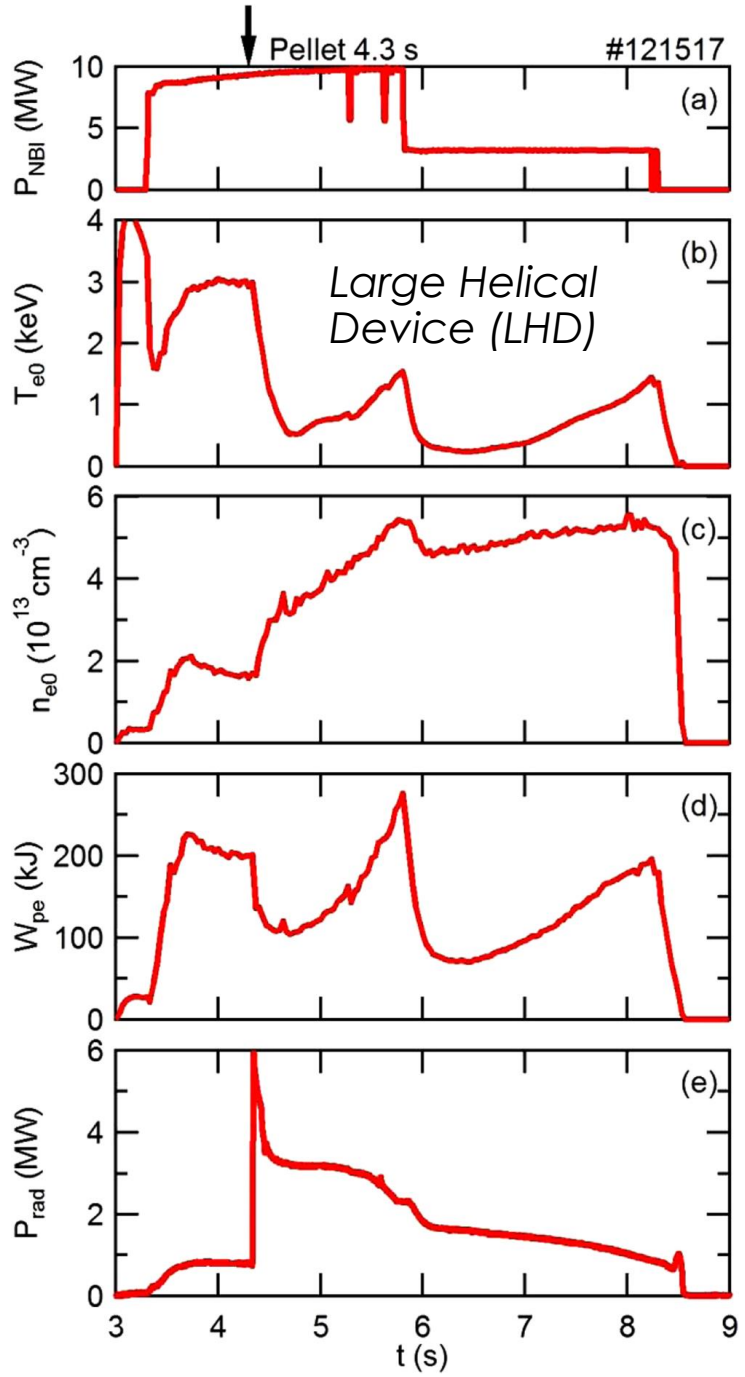
- cooling wave quickly moves into core, large 2/1 mode destabilized when low-T_e reaches q=2 surface (right)
- 'bricks' have much more benign impact on helical devices
  - LHD shows substantial 'thermal quench' without impact to macrostability
  - worst-case is full T_e collapse, ending discharge without 'current quench'



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A long time ago in a tokamak that is no longer running…

1101201020	mlreinke	BOLO	Dec 1 2010 01:44:31:960PM		

Core AXUV emissivities are about 3 MW/m^3, core SXR and Ar brightnesses goto (below) zero. Suggestive that core TS Te profile are qualitatively right for some of the time between 1.15 and 1.5. This got REALLY cold and looks more like a sustained plasma after a thermal quench. Perhaps because of the strong LHCD?

1101201020	granetz	PHYSICS_OPERATOR	Dec 1 2010 01:41:57:140PM

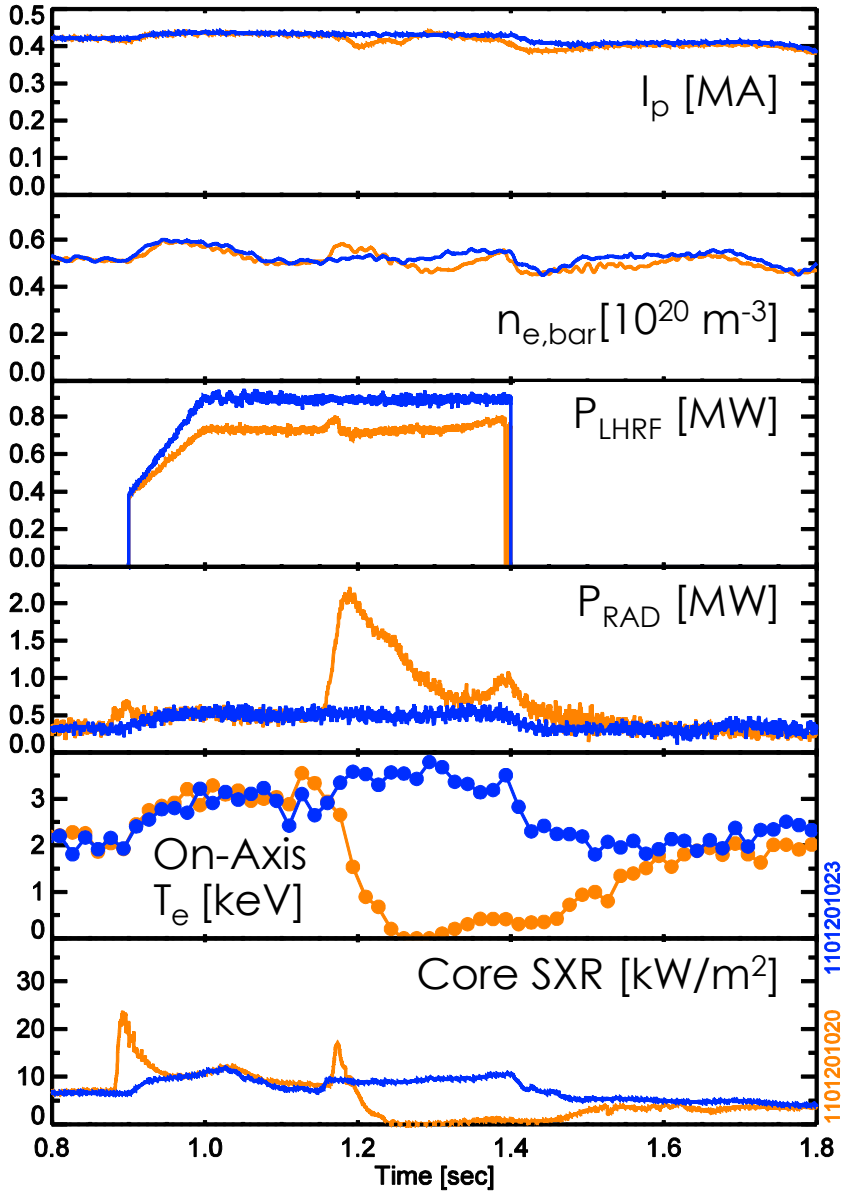
Shot 20 -- Plasma, full length. Shot lasts until t=2.1 s. 0.4 MA, 5.4 T, 0.3e20 m-2, USN, cryopump.
P_LH=0.7 MW. DNB fired 6 pulses. ECE and TS showed bizarre central electron temperatures.
Neuts_hards saturated after t=1.2 s through the end of the discharge.

Next shot: move RCUR in by 2 mm; turn on ICRF at t=1.65 s

- e-mail chain (9/13/2013) "wierd behavior on shot 1101201020" (Steve Scott presentation to C-Mod Science Meeting)
- e-mail chain (1/26/2015) "Non-Inductive Disruption Mitigation" discussion on new experiments based on 1101201020 (no actions)
- e-mail chain (2/22/2017) "LHCD and impurity injection" discussion of 1101201020 w/ KORC team indicated interest (no actions)

C-Mod Has Observed Separation of the Thermal Quench from Current Quench during LHCD

- C-Mod low-I_p, L-mode plasmas can be sustained fully non-inductively w/ LHCD
- **unplanned tungsten influx raises P_{RAD} causes plasma to thermal quench,**
  - core T_e and SXR emission collapse to 'zero'
  - plasma recovers over 300-400 ms
- n_e and I_p unaffected (~10% variation) compared to **low P_{RAD} reference**



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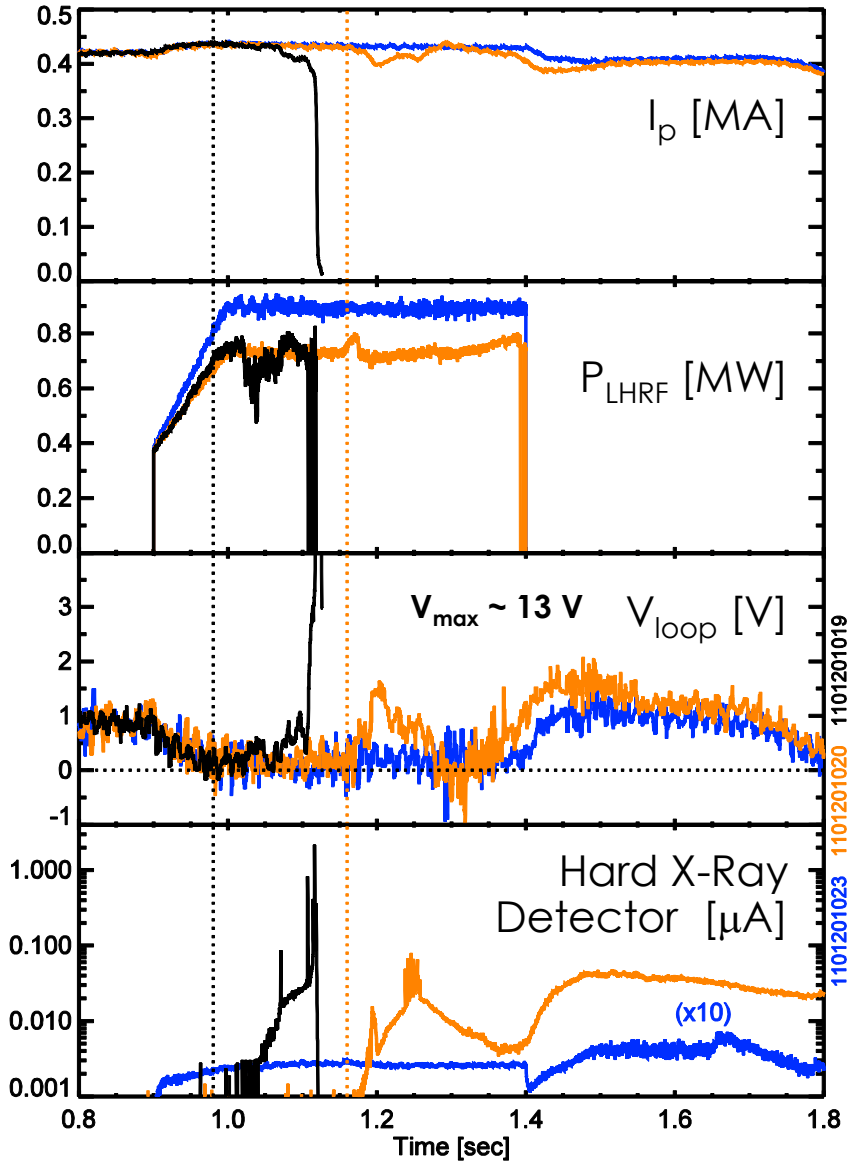
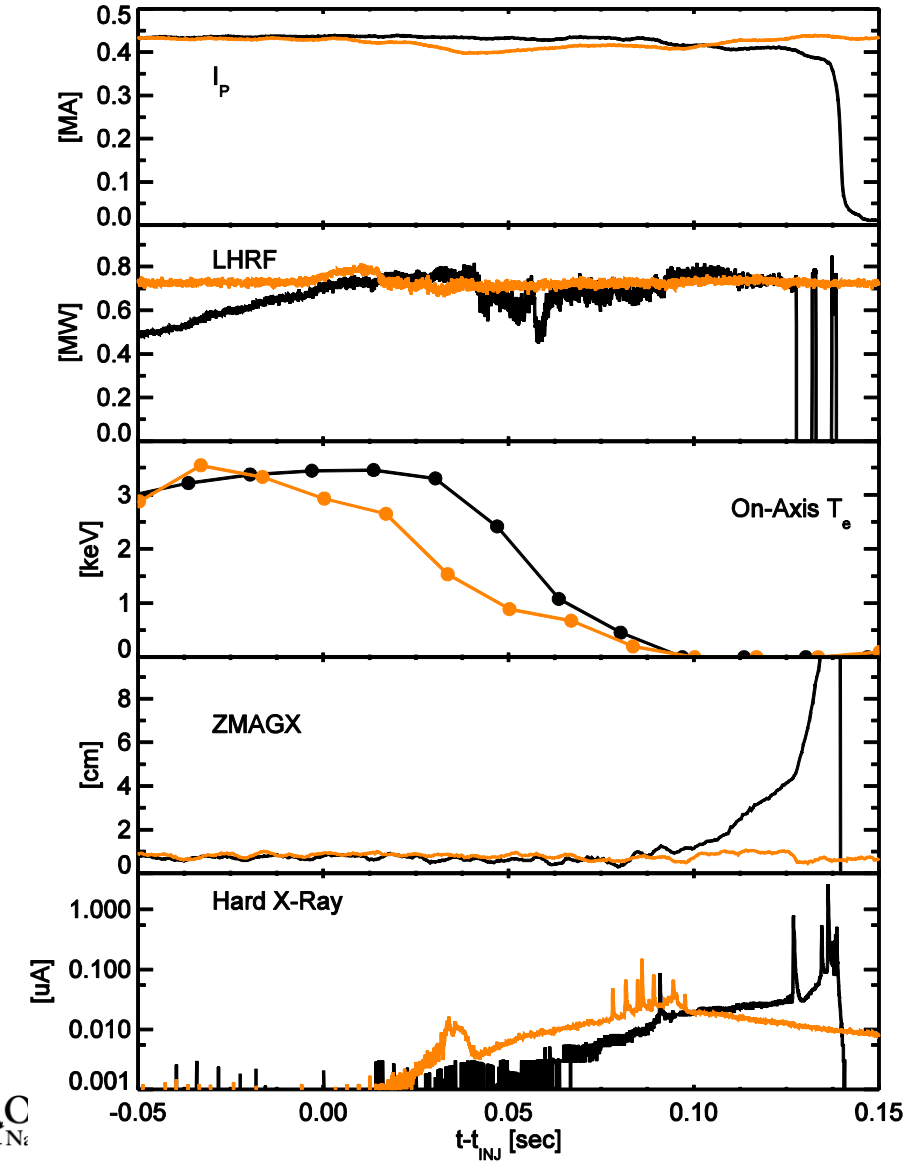
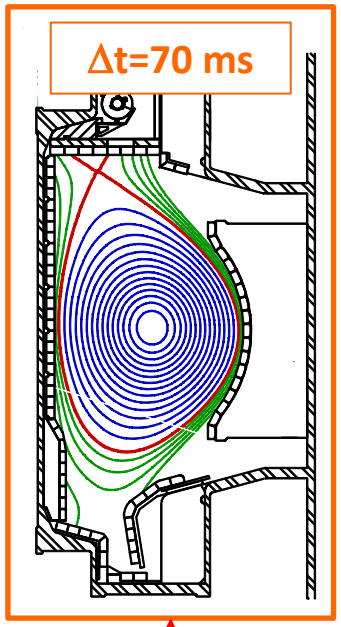
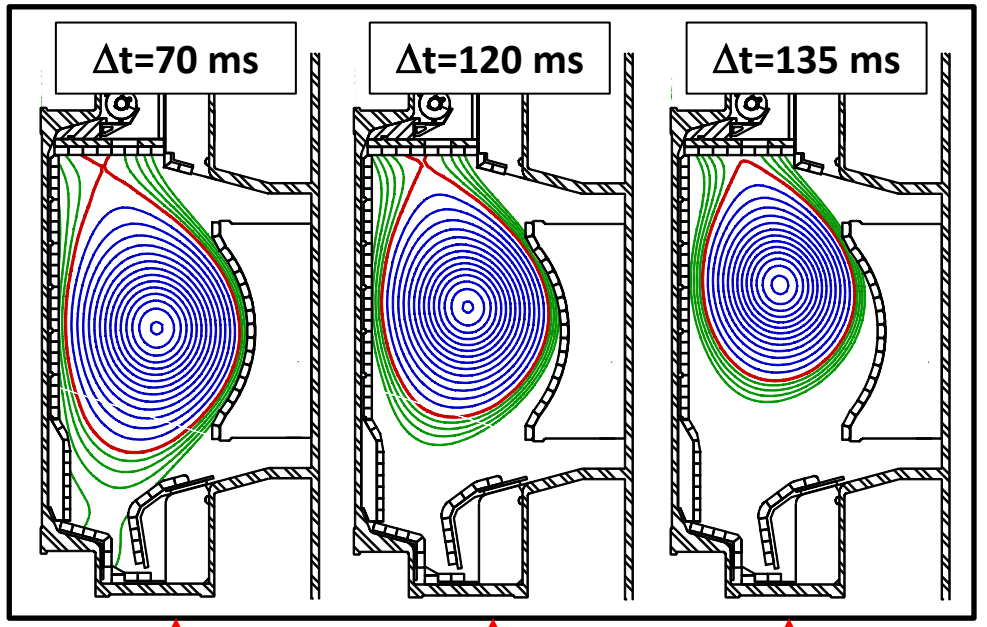
- **similar plasma** shows T_e collapse but lacks vertical stability control, current quench follows loss of fast e^-, P_{LHRF}

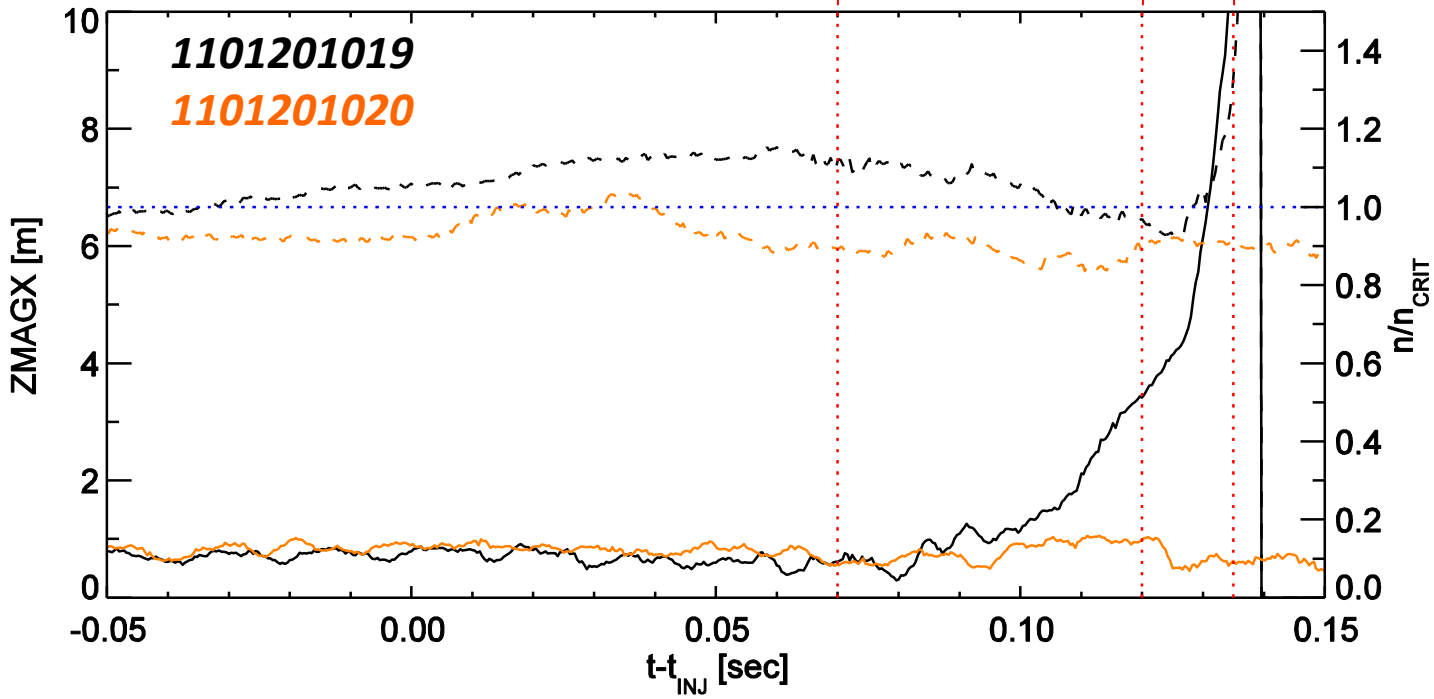


Vertical Stability Needs to Be Maintained



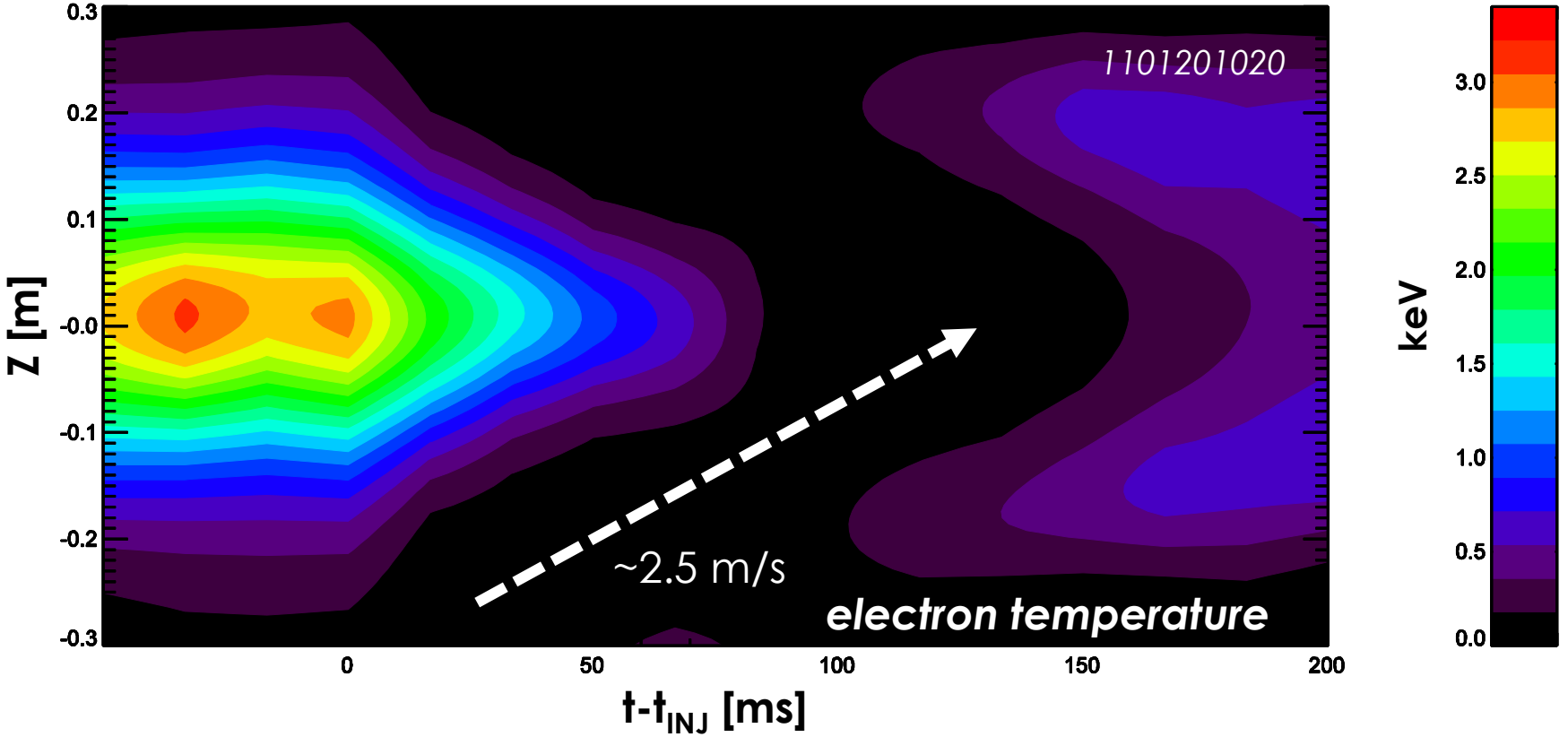






Thermal Wave Reaches All the Way to the Core and Slow Reheat Begins Off-Axis

- LH stabilizes sawteeth, $q_{min} > 1$
  - helps n_z, P_{RAD} peak on-axis
- thermal wave moves to axis without large scale MHD
  - no dI_p/dt avoids V_{loop} spike, < x2 of OH level
- as impurities leave the plasma, P_{RAD} drops and T_e recovers off-axis

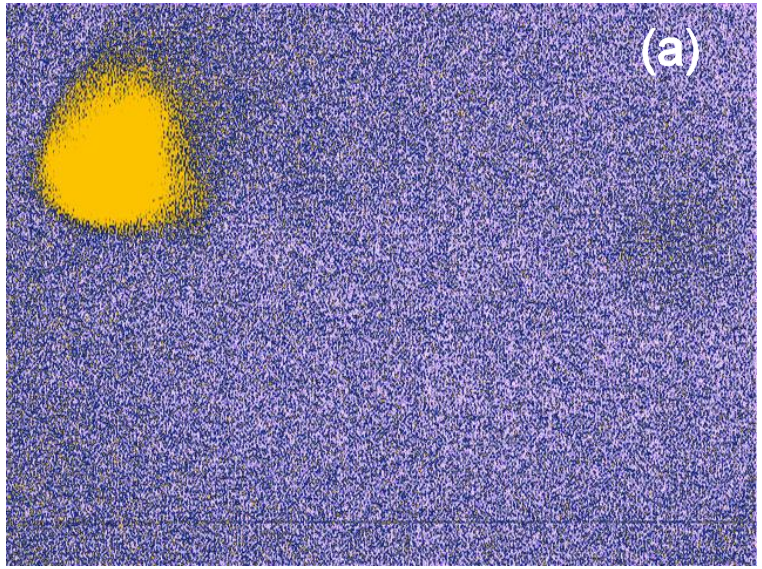


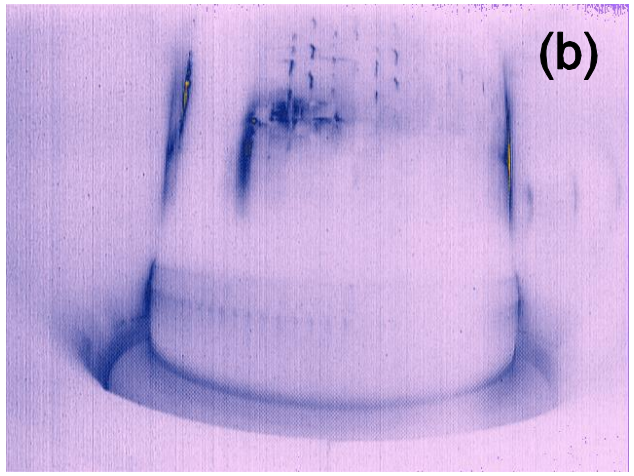
Hypothesis: non-thermal electrons sustained by LH wave-interactions maintain current profile independent of impact to thermal electrons

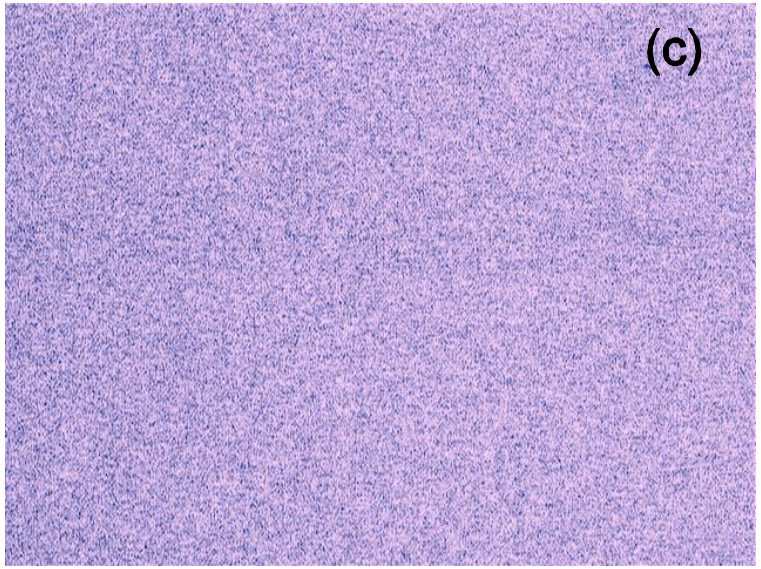
Fast, But Not Relativistic Electrons Observed During LH Shot

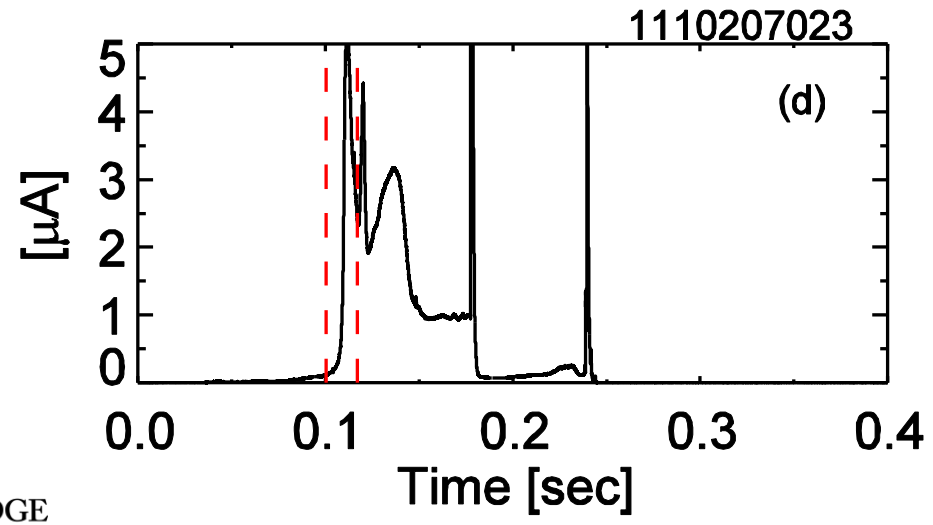
Synchrotron Emission Example

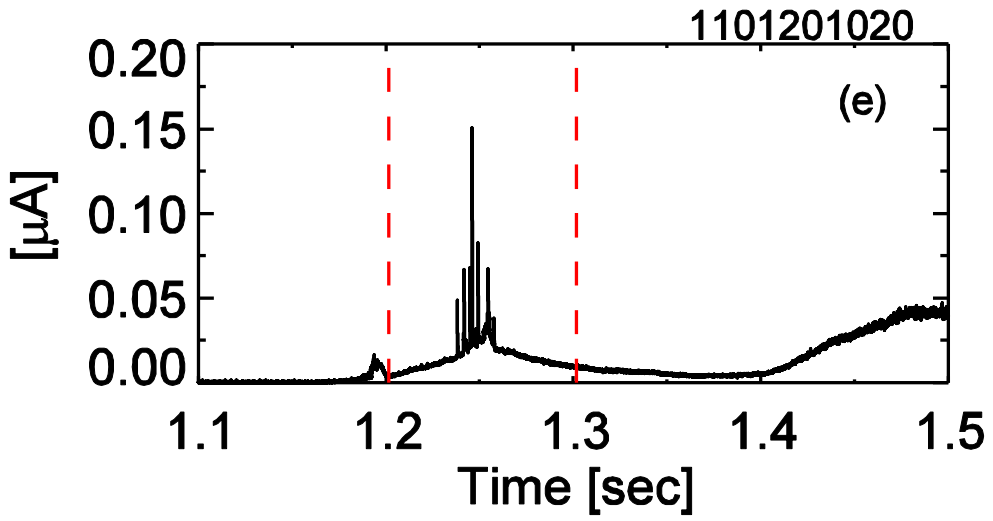
Hard X-Rays During LHCD TQ





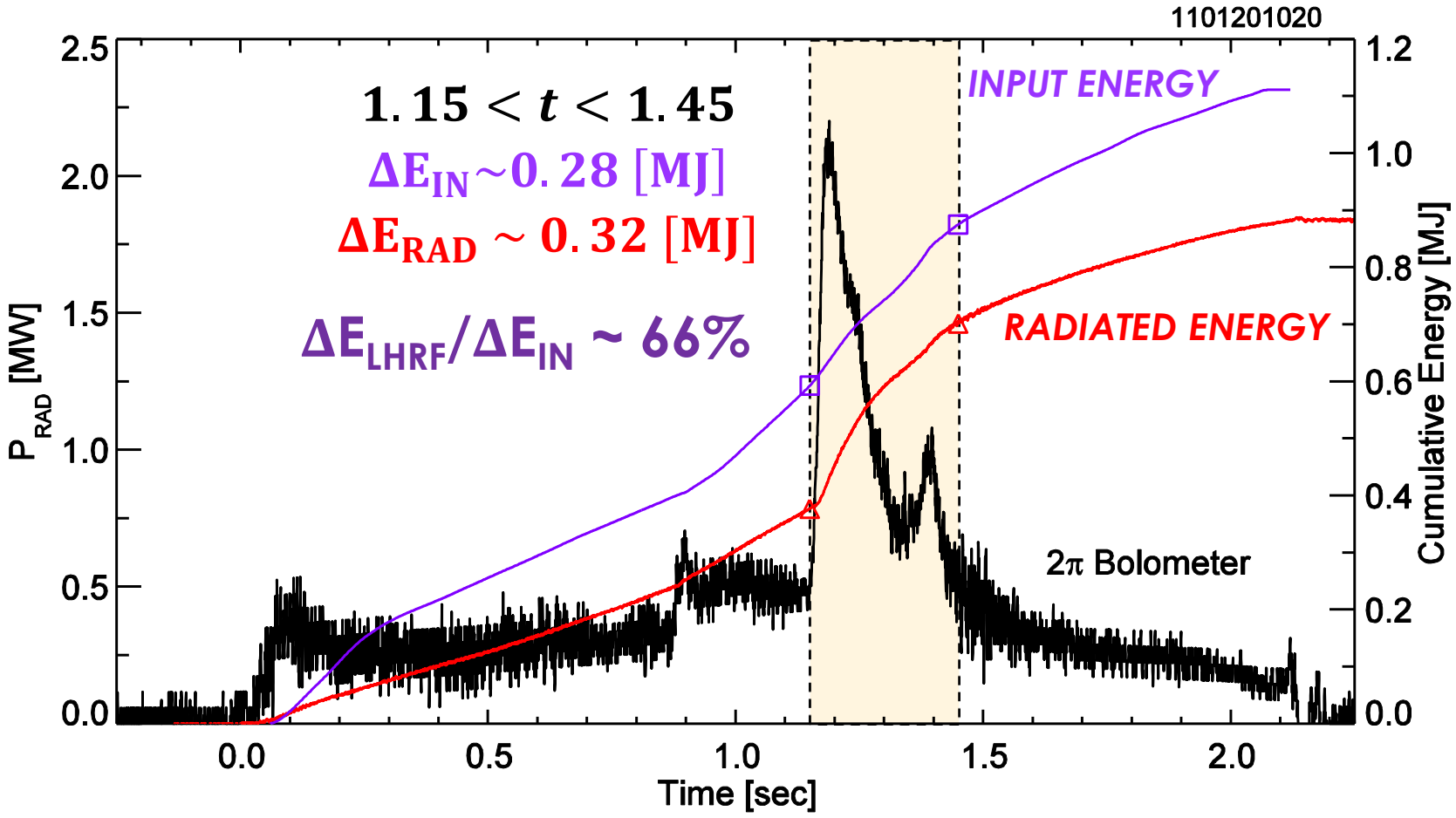






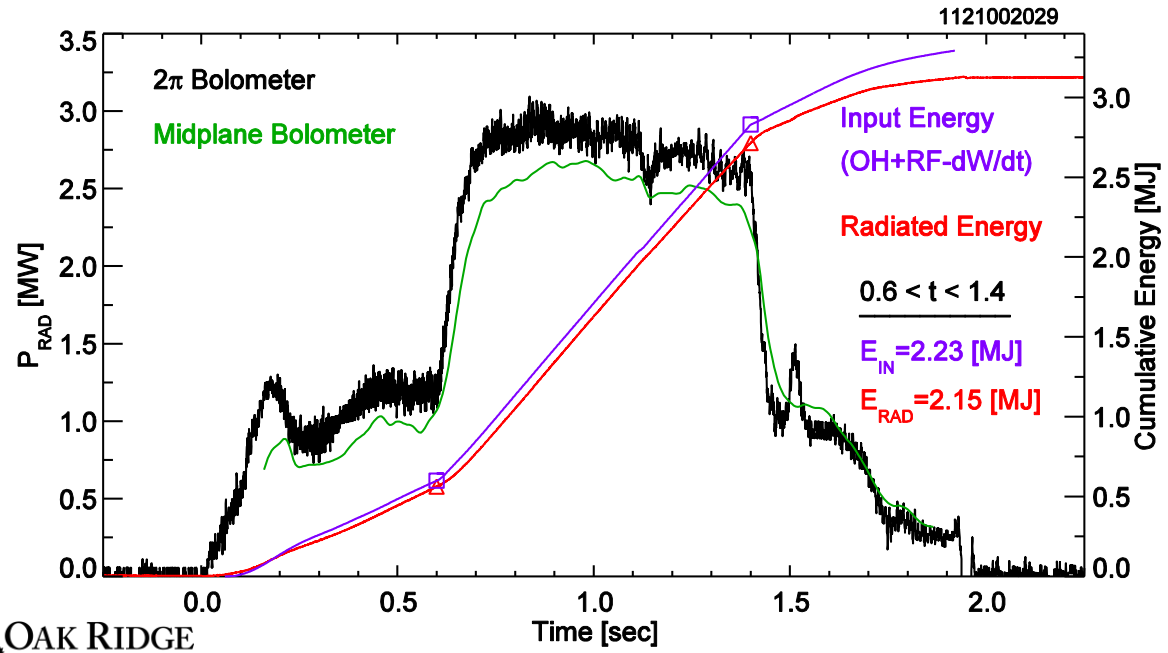
Power Balance and Timescales Indicate Lower Hybrid Power Continues to Sustain Current Density Profile

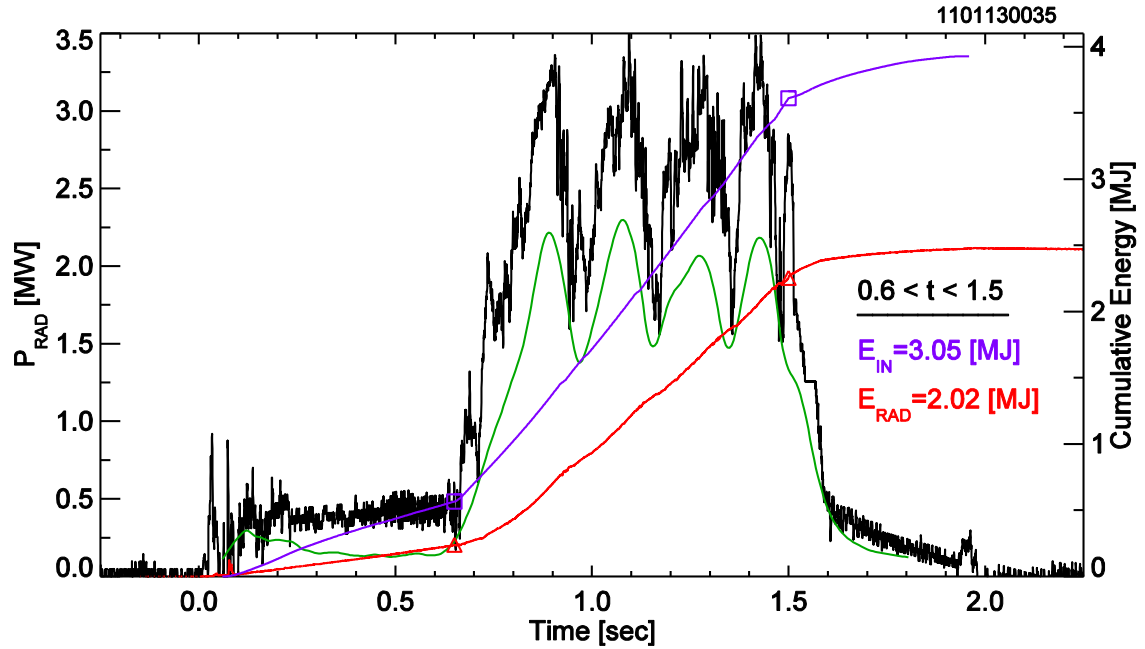
- from injection to end of LH pulse, 320 kJ radiated for 280 kJ input (E_{OH} + E_{LHRF}), meaning LH power must be deposited

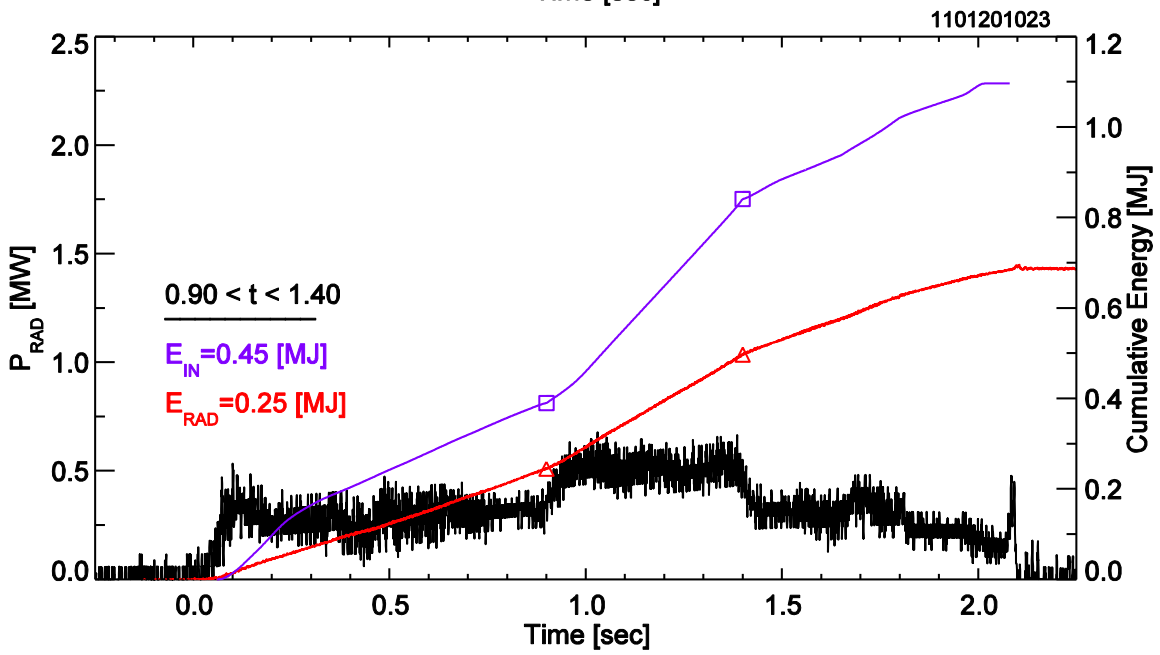


Power Balance Examples

- 2π bolometer 'calibrated' against high P_{RAD} examples
  - 1121002029, limited w/ ICRF
- gives reasonable results in L/H/L radiative collapse and non-inductive







Power Balance and Timescales Indicate Lower Hybrid Power Continues to Sustain Current Density Profile

- duration of low-T_e, implies <u>continued non-thermal e^- drive</u>

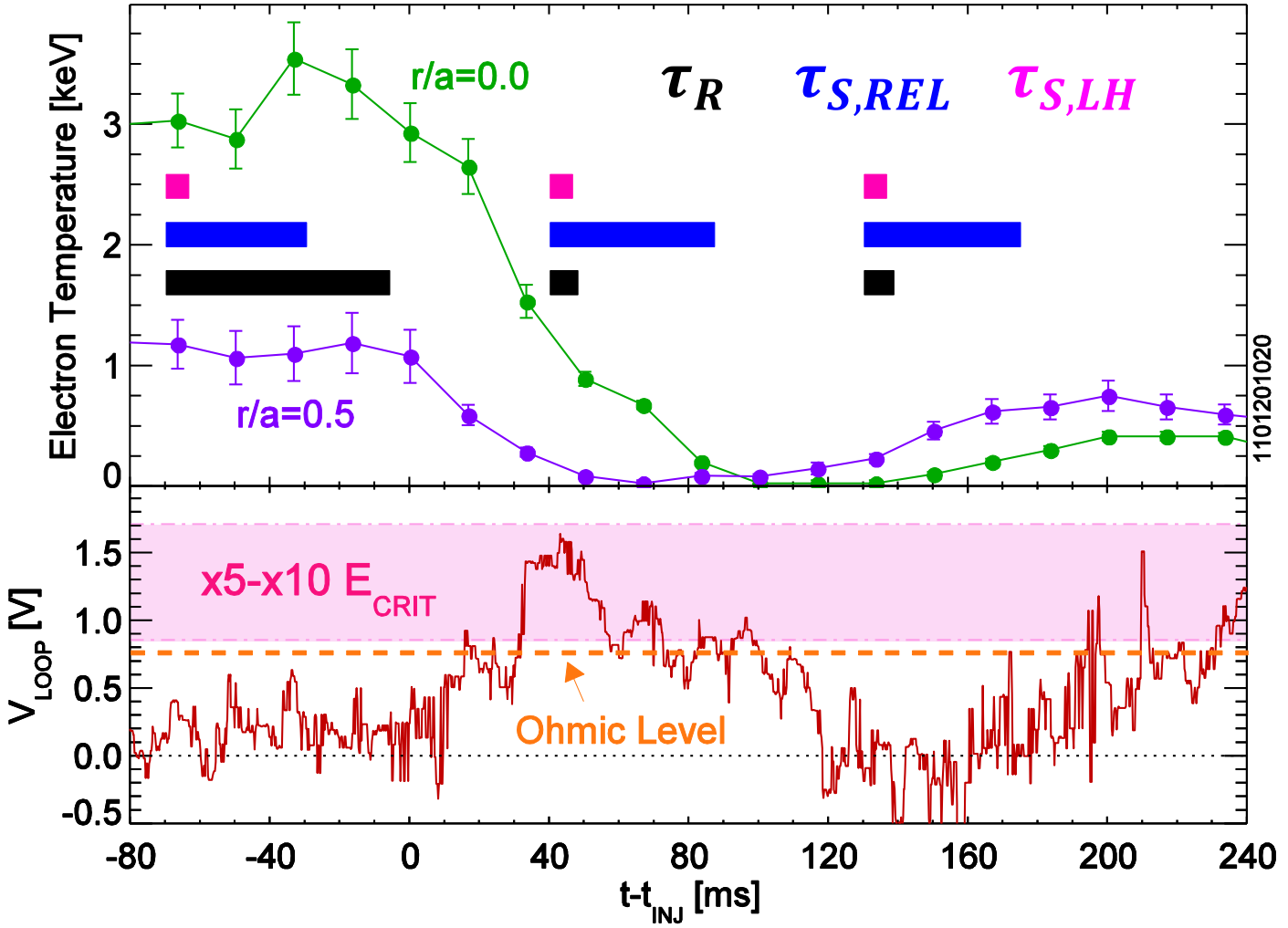
Timescales

τ_R: current relaxation time w/ measured T_e, n_e for $\langle \sigma \rangle$

$\tau_{S,REL}$: electron slowing down time assuming v_e=c

$\tau_{S,LH}$: electron slowing down time calculated from post-LHRF decay (1101201023)

V_{LOOP} transients likely contributing to fast-electon but cannot be the whole story



Future Experiments and Data Mining Activities

e.g. have we seen this before/could we do this again if we tried?

- existing data archives that could be examined for examples like this C-Mod plasma (easy search on 0D data: P_{RAD}, I_p, n_e, T_e)
  - metal machines (FTU, EAST, WEST) [Alcator C?]
  - carbon (JET, Tore-Supra, JT-60U) [PLT, ASDEX?]
- new experiments can answer simple questions
  - What fraction of I_p needs to carried by LH to avoid the CQ?
  - For what range of high-Z impurity fractions can the CQ be avoided?
  - Can LHRF reliably be turned on at the start of the thermal collapse?
- does LHCD interfere with disruption mitigation techniques?
  - would need to install SPI on a LHRF tokamak (or vice-versa)

Future Theory and Modeling Activities

e.g. can we numerically show why the C-Mod shot survived?

- do we need new theory + models or just to link existing methods together?
  - full-wave (TORIC) and ray-tracing (GENRAY, C3PO) codes for LHRF
  - 3D MHD codes that include high-Z radiation (NIMROD, M3D-C[1])
  - kinetic simulation of runaway electrons (KORC) and lots of focused brainpower through the SCREAM project
- what data are needed? what observations should we also be looking for? (benefit from theory-guided examination of data)
- contribution to modeling activity drives ownership
  - PRL, invited talk is likely for whomever can numerically explain this
  - empirical observations (present data) will be submitted to NF soon

Possibilities for Future Work and Implications

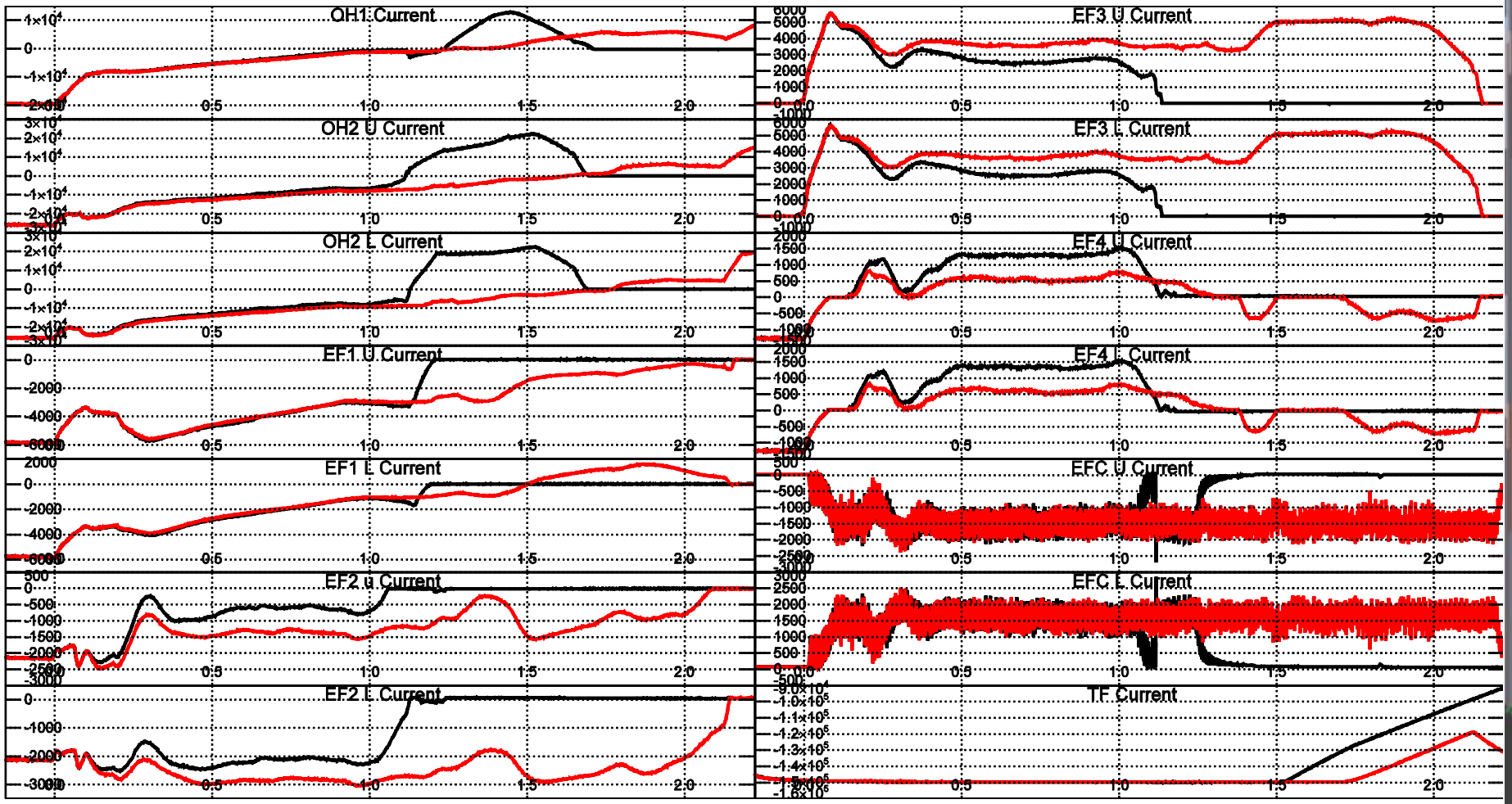
Takeaway: Alcator C-Mod observed a plasma exhibiting features of a full thermal quench without a current quench when the plasma current is sustained non-inductively through the use of LHCD

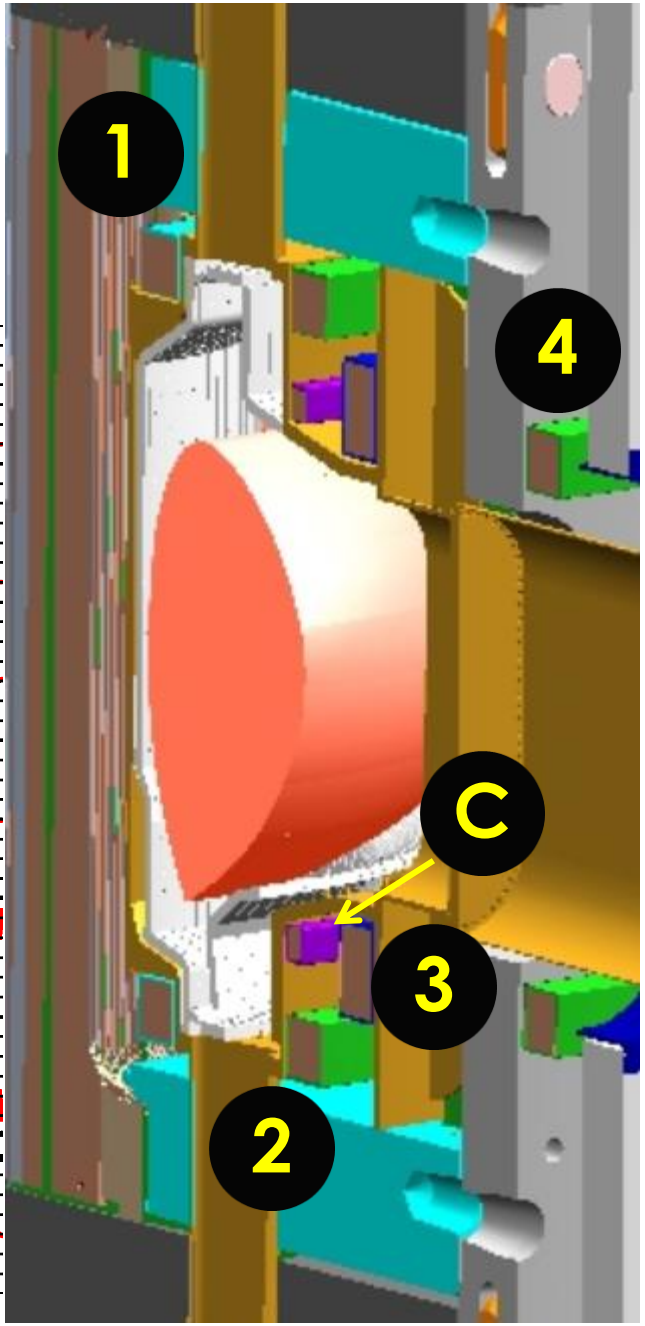
- can the C-Mod evolution be reproduced numerically?
- has this been seen before but not reported? (JET, TS, FTU, EAST)
- can we reproduce this deliberately with new experiments?
  - EAST & WEST: LHRF, non-inductive operations w/ high-Z walls
  - DIII-D: future installation of LHRF, multiple means of controlled high-Z injection and a suite of fast-electron diagnostics
- **LHCD could offer a pathway to disruption avoidance for instances of unexpected impurity influx and radiative collapse**
  - if our hypothesis is correct, this is a unique property of LHCD relative to other techniques (bootstrap, ECCD, NBCD) tied to thermal electrons

EXTRA SLIDES

Changes to Equilibrium for 019 and 020

- between **019** and **020**, max EF4 current was reduced, control increased EF2 and EF3





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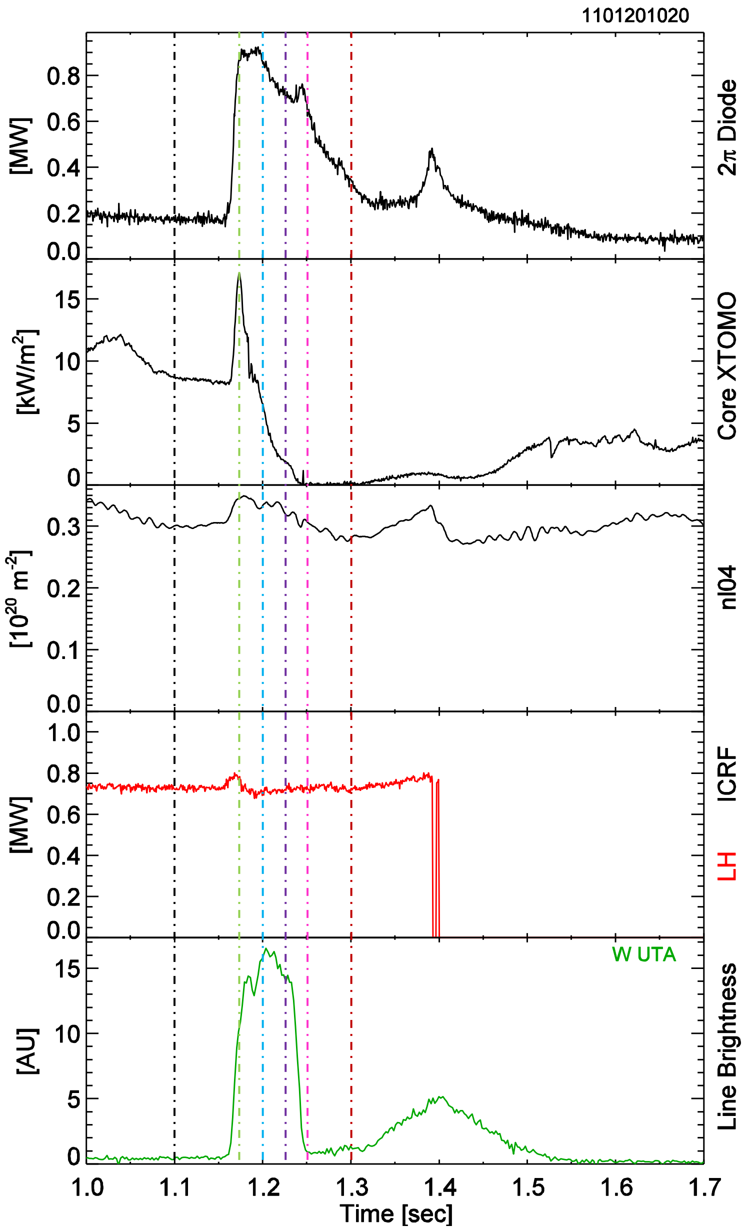
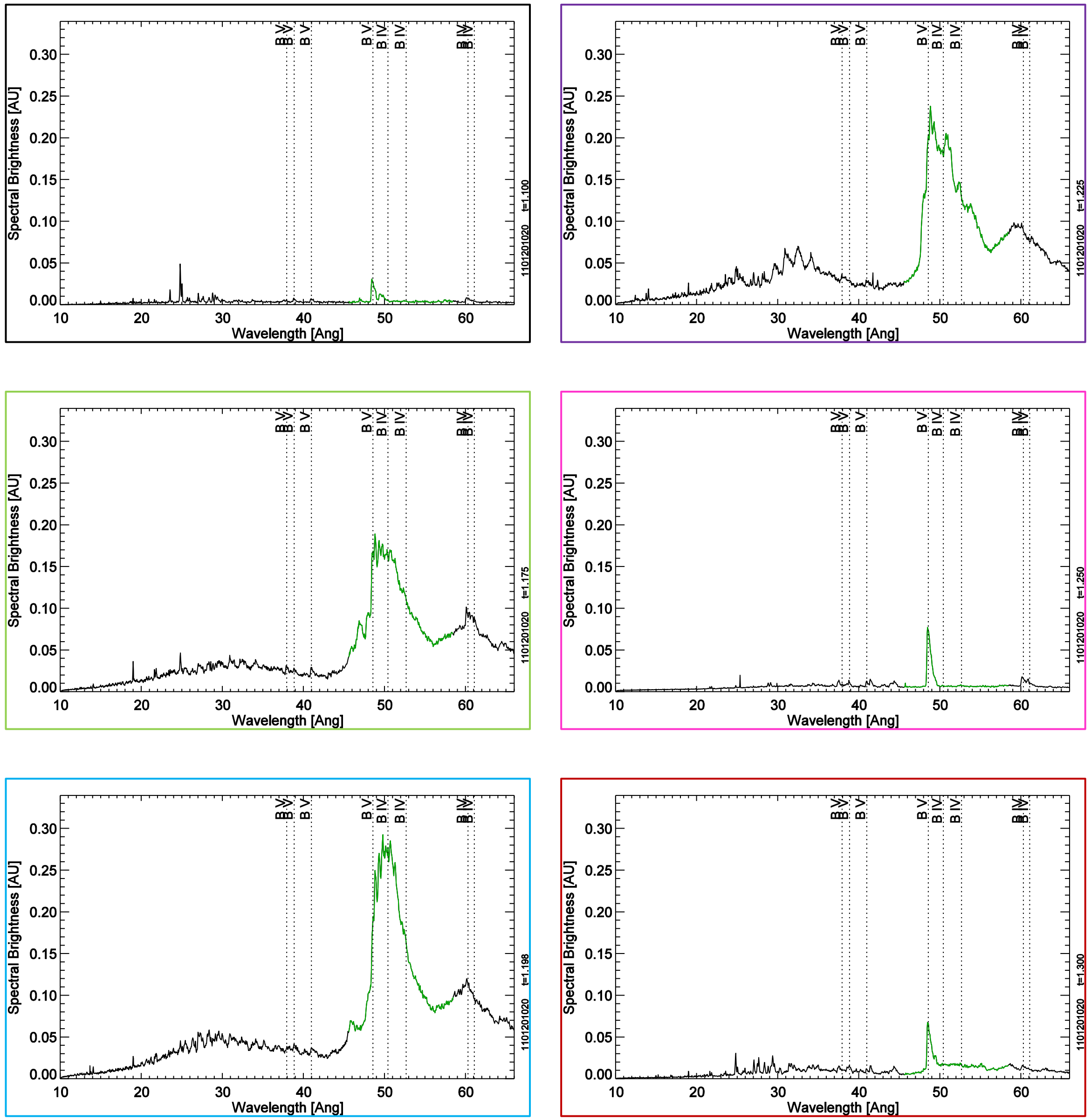
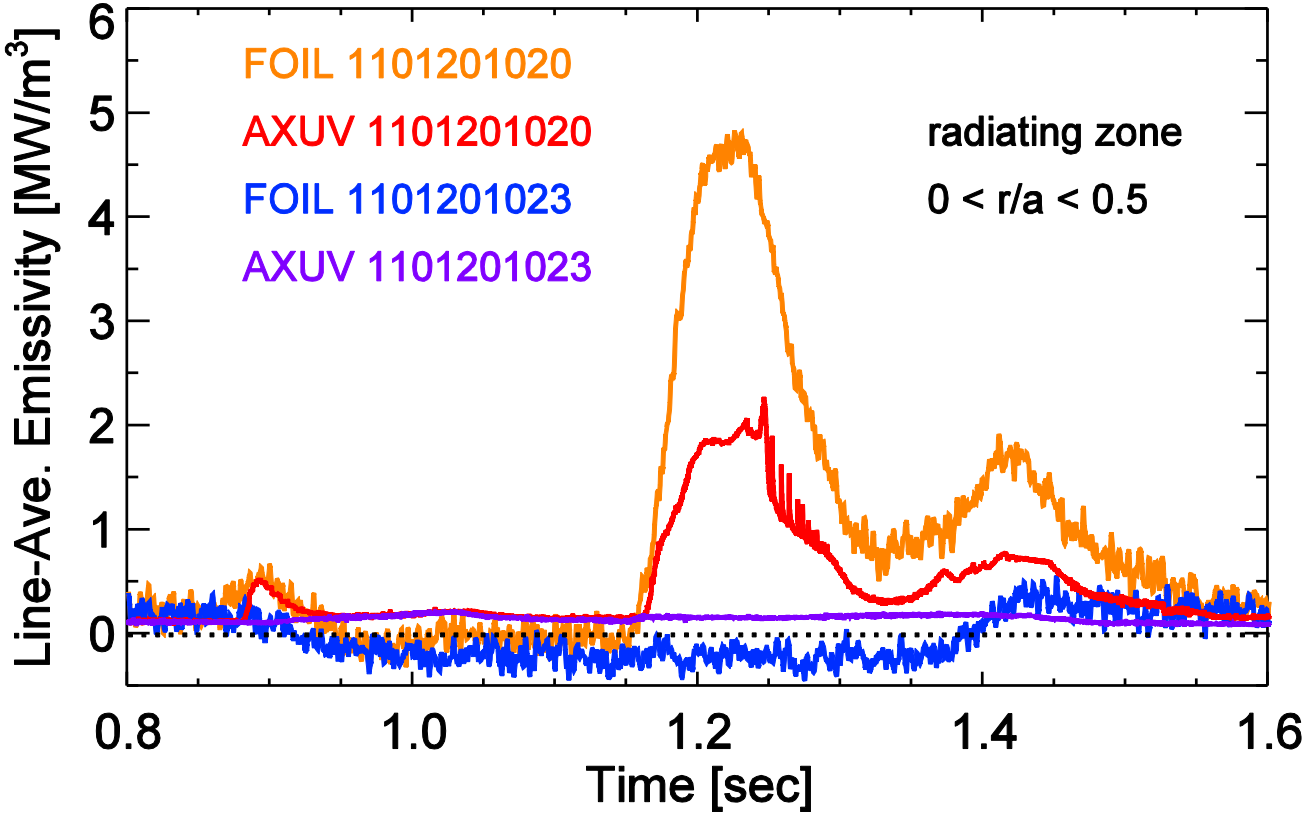
VUV Spectroscopy Shows Tungsten and Low T_e

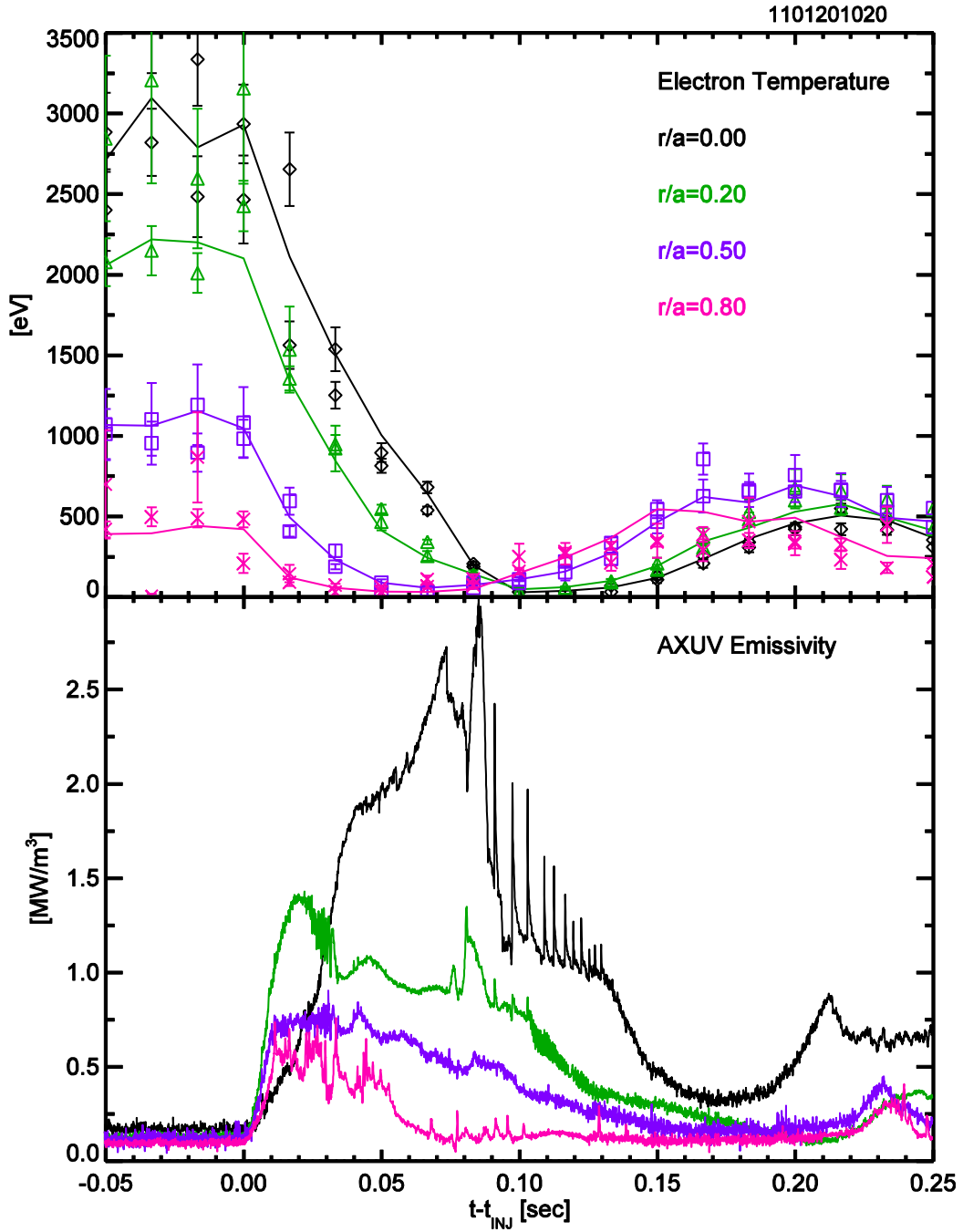




too cold for W UTA emission, see B IV/V

Just More Data Dumps





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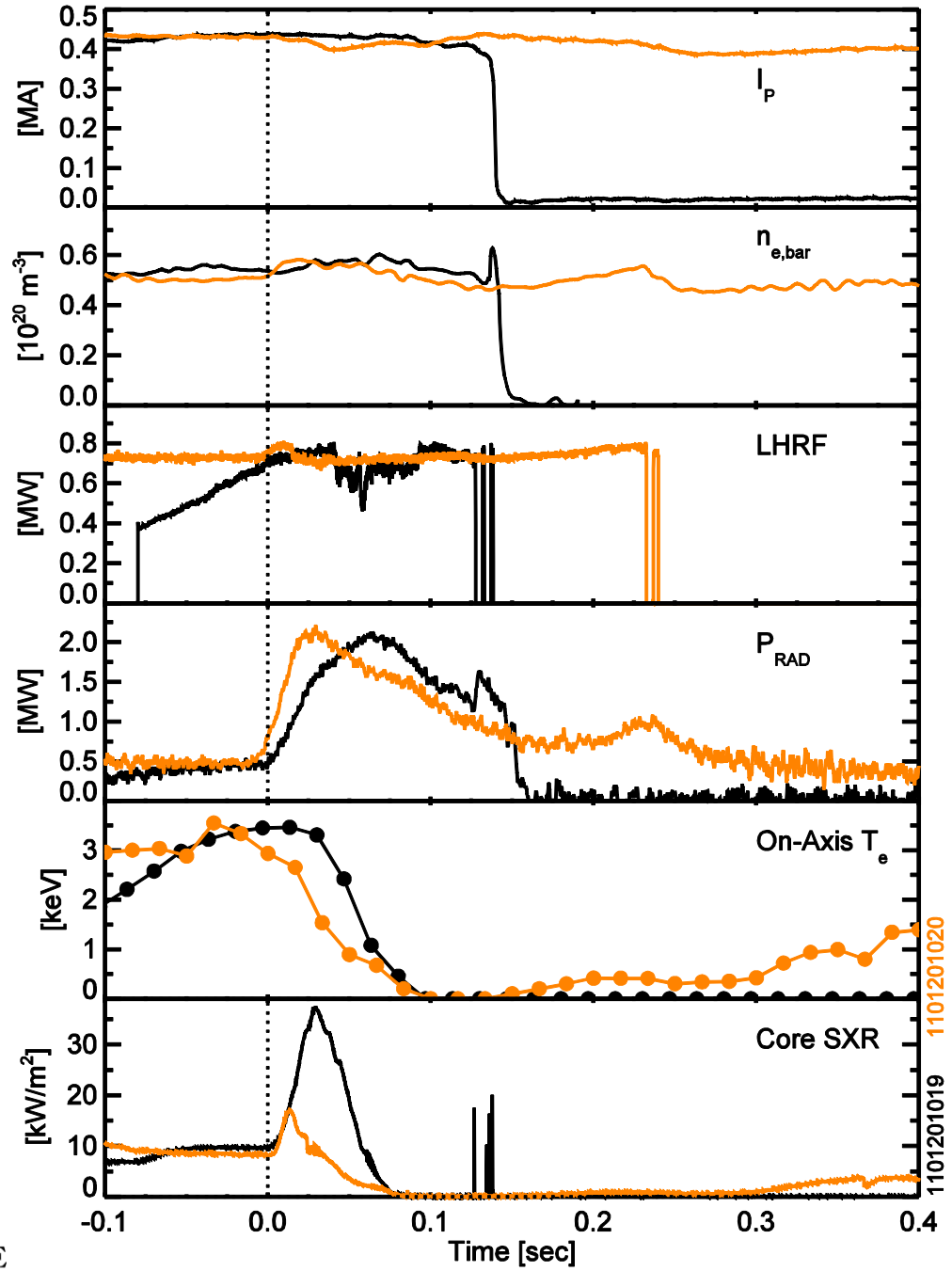

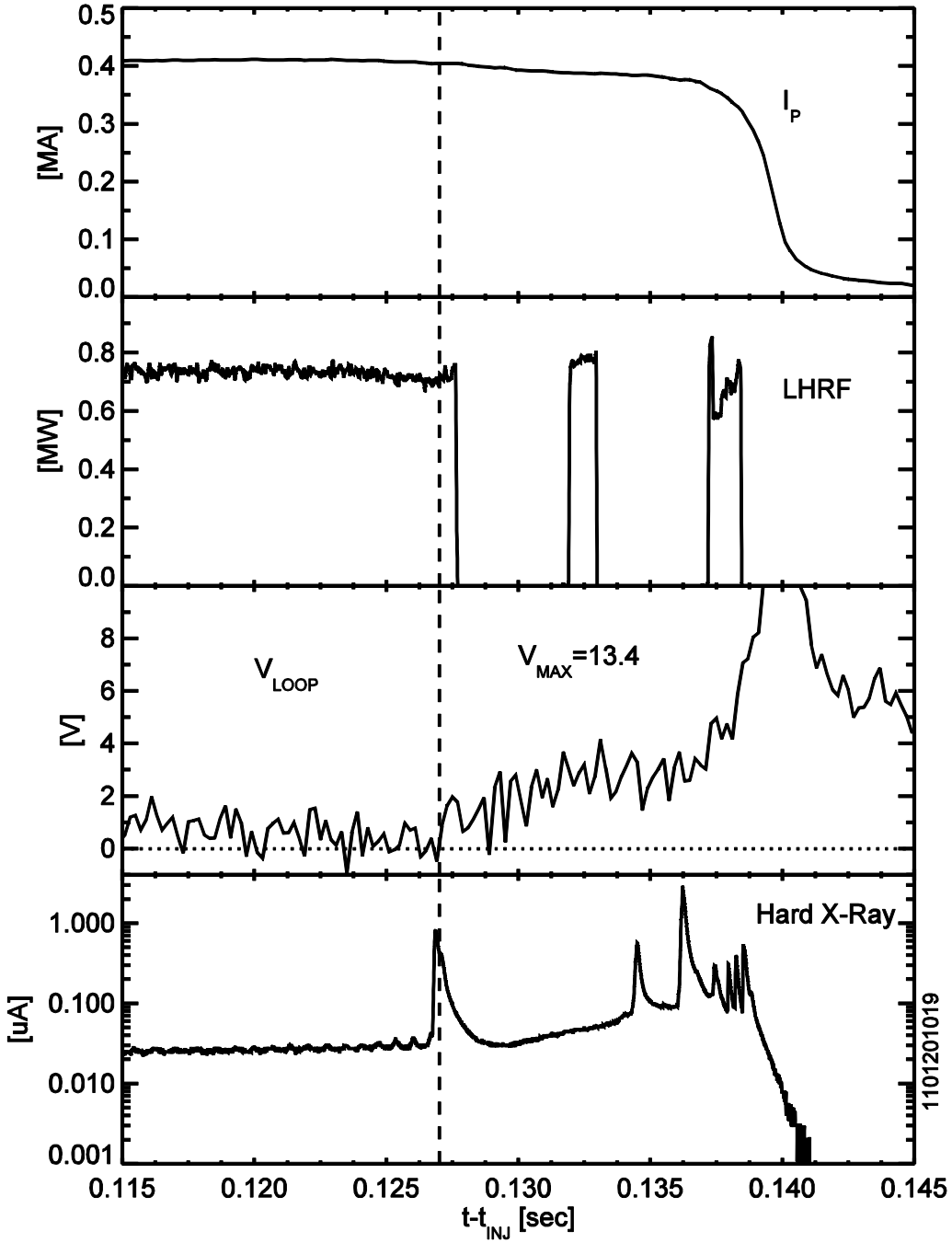

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