Measurements and modeling of pre-thermal quench non-thermal electron formation during pellet injection shutdowns in DIII-D

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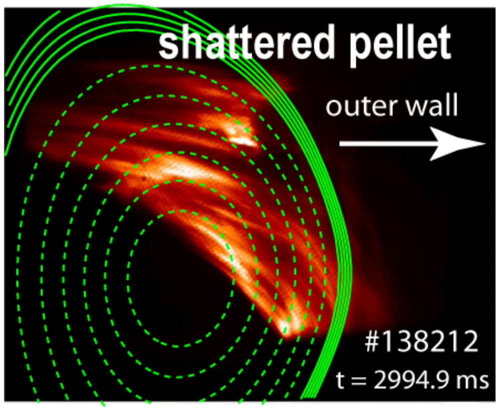
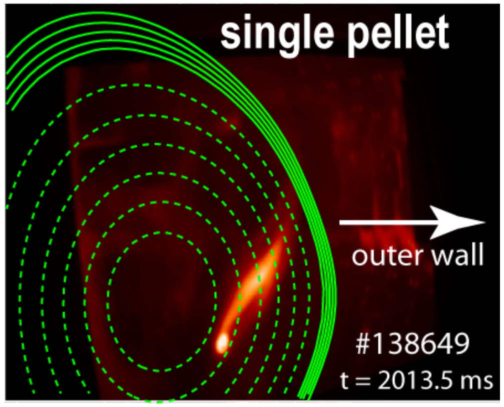
Motivation

- Massive material injection seems like best option for last-resort disruption mitigation in ITER and other large tokamaks.
- Want to design a delivery method and material composition that best minimizes chances of wall damage from heat loads, REs, and vessel forces.
- Dominant path for RE formation in ITER is typically expected to be hot tail seed formation during impurity injection, followed by avalanche amplification.

  - Need to develop experimental methods to measure early non-thermal electrons and use these to improve numerical predictions of final RE plateau current.





Outline

DIAGNOSTICS

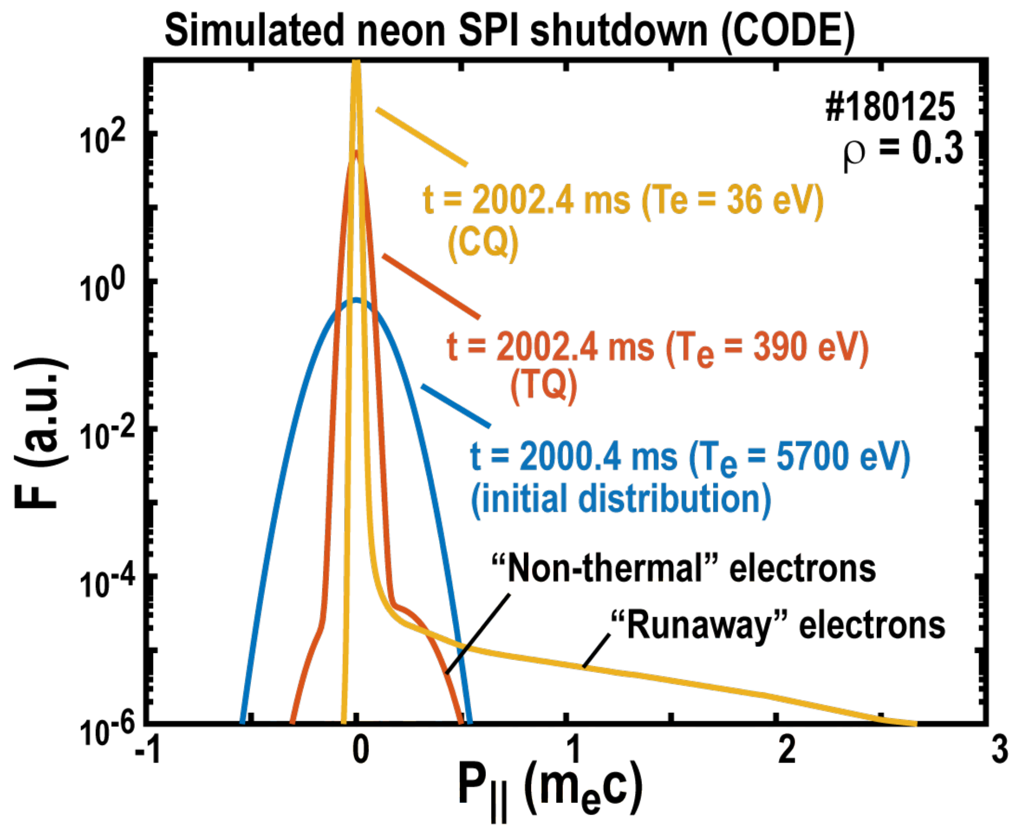
- Pre-TQ non-thermals can potentially be seen in a variety of diagnostics:
  - electron cyclotron emission (ECE)
  - soft and mid x-ray emission (SXR, MXR)
  - extreme ultra-violet lines (EUV)
  - Thomson scattering (TS)

MAIN SCIENTIFIC FINDINGS

- Non-thermals appear to form ahead of injected pellet
  - rapid impurity transport?
  - rapid electron transport?
- Non-thermals could carry significant current
  - could affect TQ and CQ MHD?
- Non-thermals do not automatically form relativistic runaway electrons
  - large loss to wall?
- Non-thermals can dominate pellet ablation

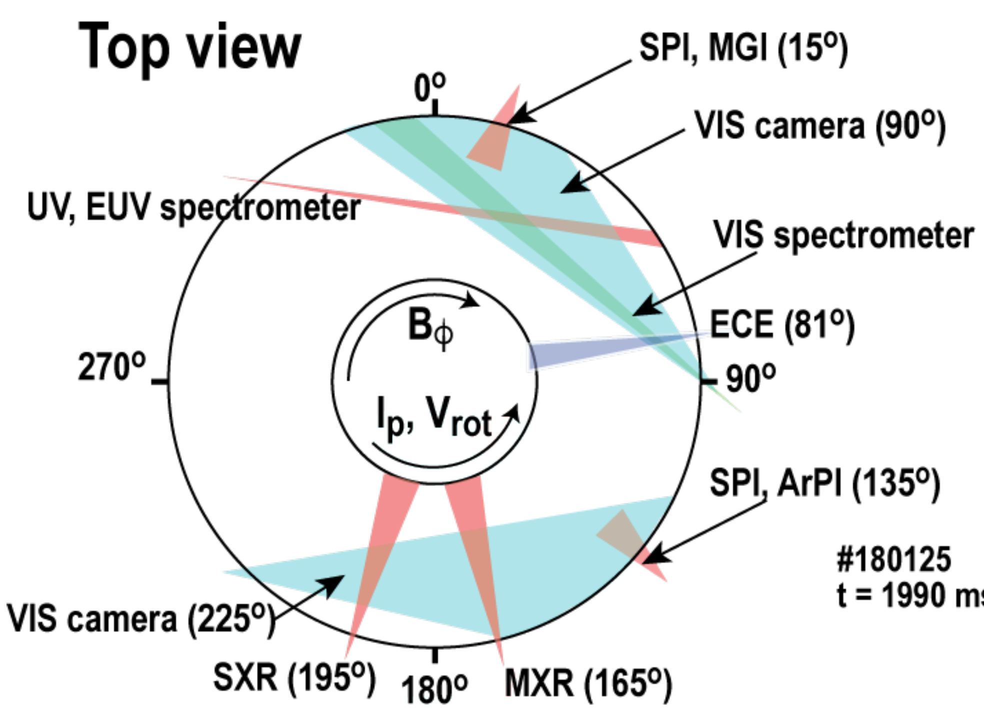
Definition of “non-thermal” electrons used here

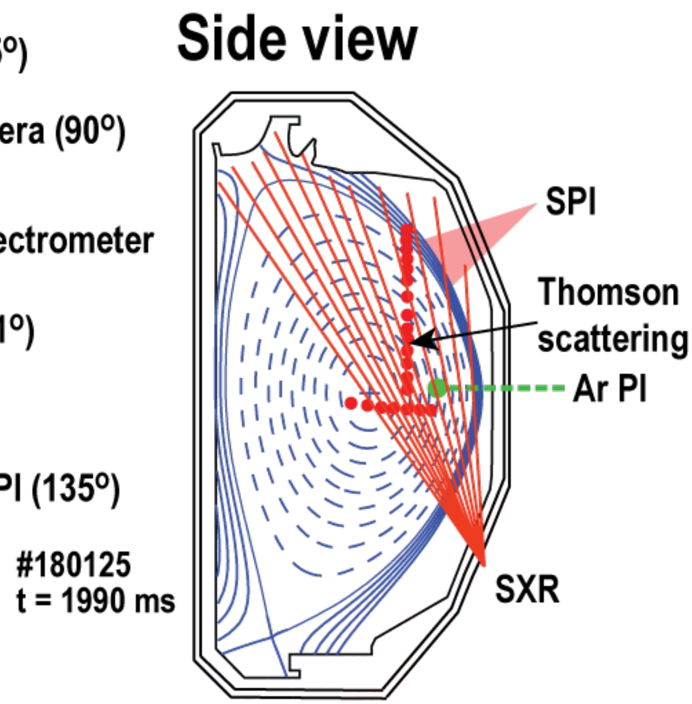
- This talk will focus on “non-thermal” electrons (hot electrons ~ 10 keV that are abandoned by hot tail mechanism during pre-TQ and TQ).
  - Not significantly accelerated yet.
- Will call MeV electrons that are accelerated to relativistic energies during CQ “runaway” electrons.



Hardware overview

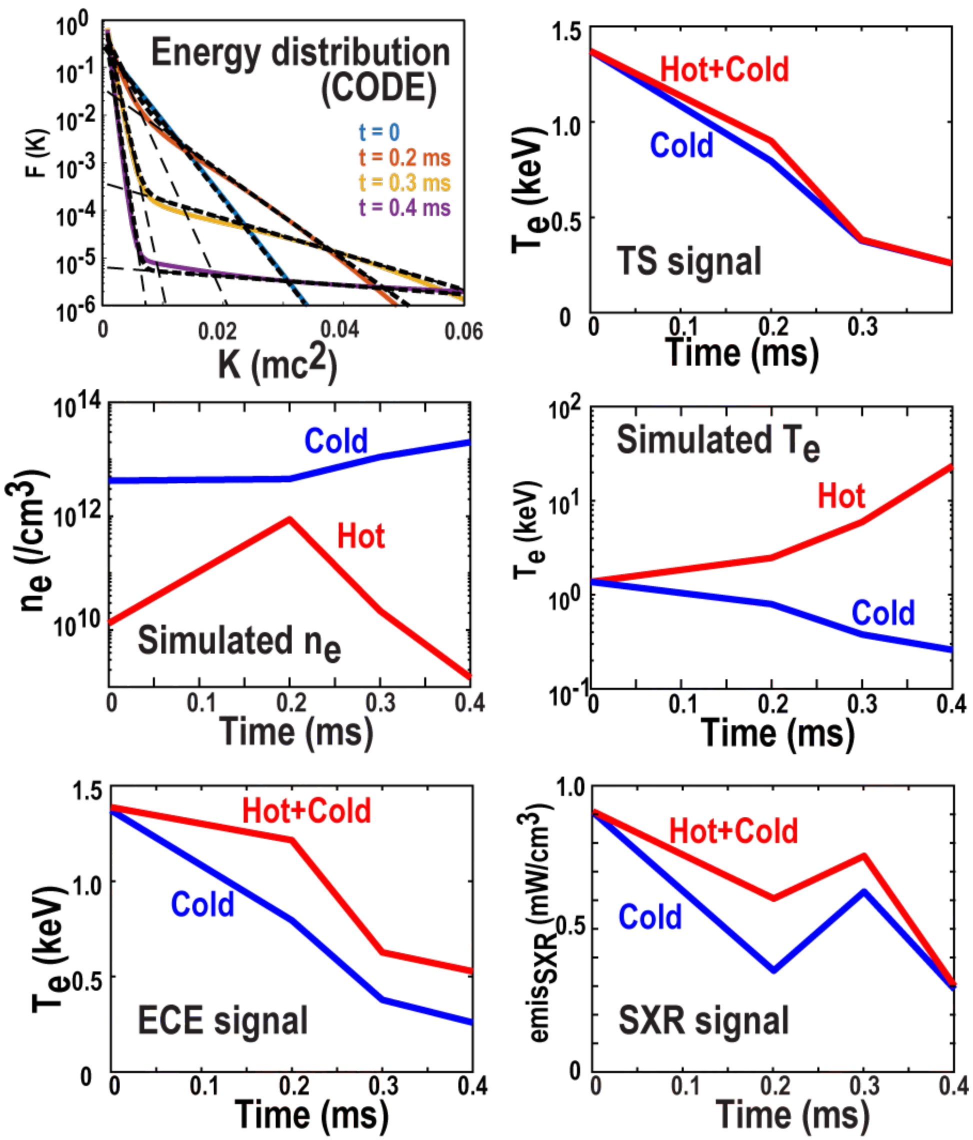
- This talk focuses on "healthy" H and L-mode target plasmas shut down by single Ar pellets, Ne or (Ne/D_2) shattered pellets, or Ne gas injection in DIII-D tokamak.
- Target plasmas include IWL, USN, and LSN
- Main diagnostics used here are ECE, SXR, MXR, TS, and EUV.





ECE can be used during pre-TQ of Ar pellet shutdowns

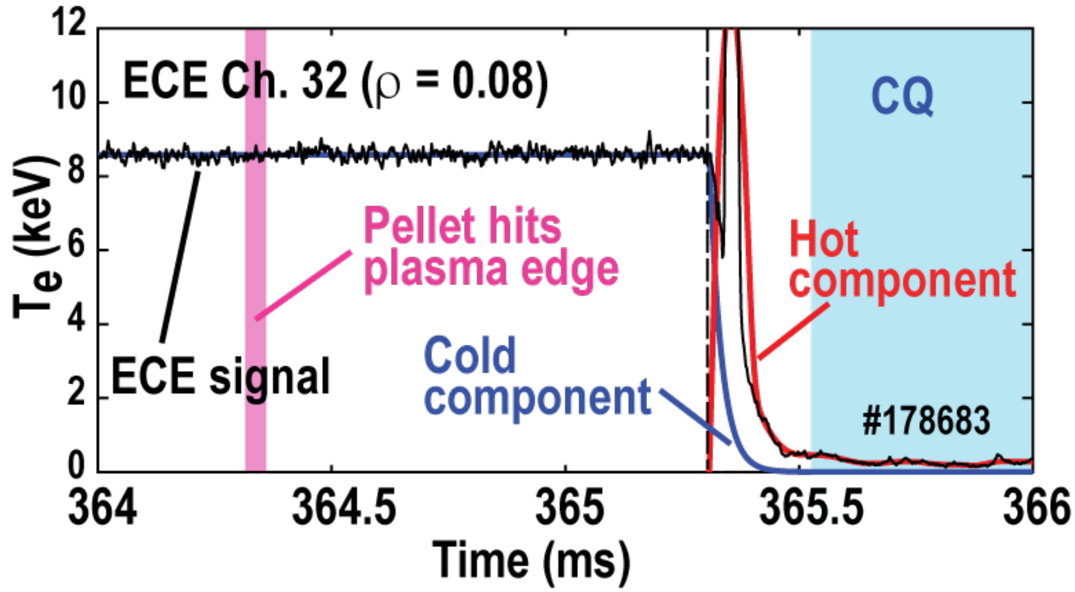
- ECE expected to have large perturbation due to non-thermal electrons.
- ECE can be used during early times of ArPI shutdowns:
  - Density perturbation is low ECE (not cutoff yet).
  - Harmonic overlap in ECE low (T_e < 20 keV).
- Assume early-time electron distribution can be approximated as 2-temperatures (for purposes of modeling ECE emission).

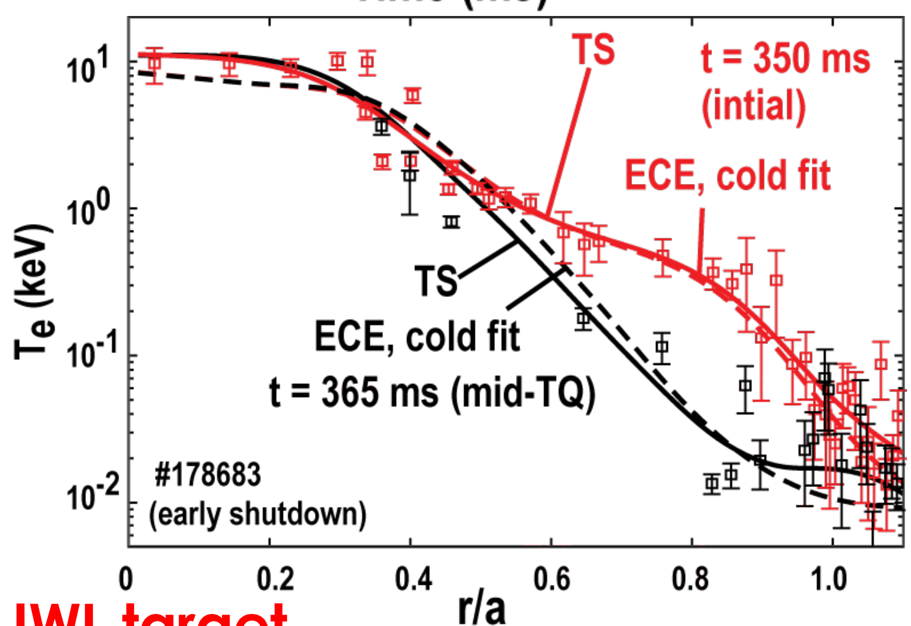


Problem #1: separating out cold and hot components: TS too slow for Ar pellet shutdowns

- During ArPI shutdowns, TQ is fast: T_e collapse timescale at each radius is too fast to be captured by TS (at 0.3 ms/pulse).

- Assume cold plasma temperature at each radius collapses exponentially to 5 eV at CQ onset.
    - Consistent with available TS profiles.



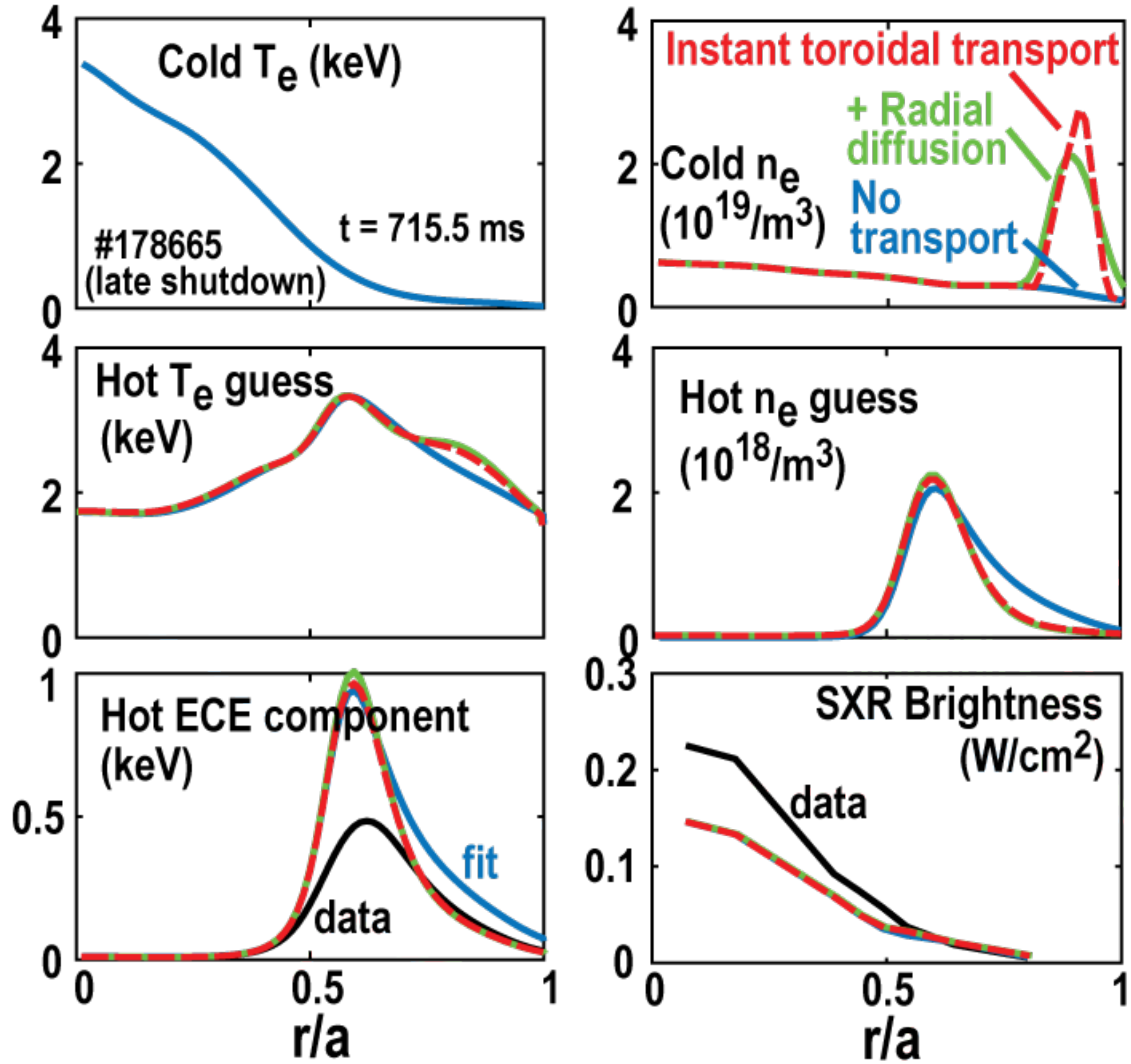


ArPI IWL target

Problem #2: hot component not uniquely determined by ECE hot component alone

- Hot ECE component does not uniquely determine non-thermal T.
  - Non-thermals optically gray, so ECE brightness depends on both hot T_e and hot n_e.
  - Add SXR brightness to help constrain solution.
- Deposition of Ar known from camera data, but subsequent Ar ion transport not well known; explore various limits for error analysis:
  - Instant toroidal transport filling flux surface
  - No toroidal transport
  - 5 m^2/s radial transport
- Overall, can fit ECE, SXR profiles within about 2x.

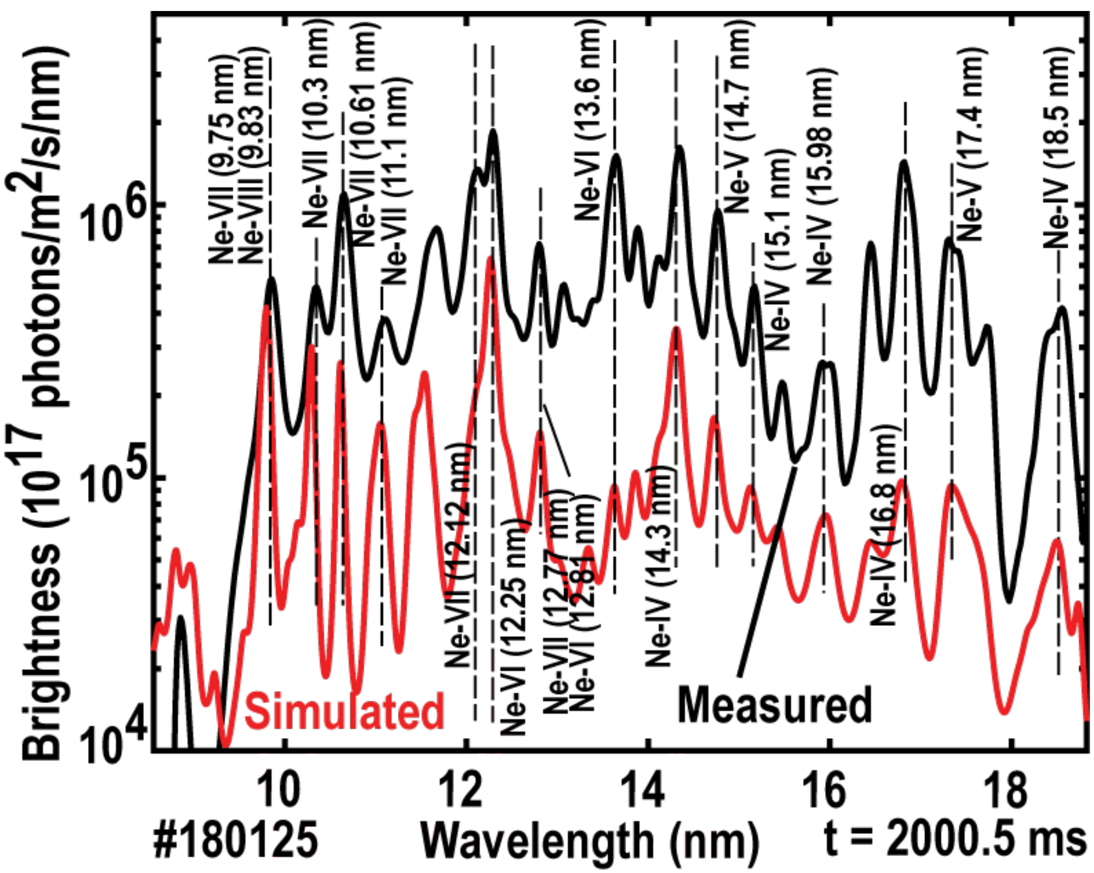
ArPI IWL target



EUV data can be used in case of neon SPI shutdowns

- For Ne/D_2 SPI shutdowns, more material and faster toroidal transport: ECE tends to cut off !
- Brightness of EUV neon ion lines strongly affected by presence of non-thermals.
- Model with PrismSPECT collisional-radiative code in two-temperature approximation.
- Investigate two approaches to analyzing spectrum:
  - EUV brightness (just integrate over wavelength)
  - Line ratio technique (ratio of lines with strongest T_e dependence to lines with weakest T_e dependence)

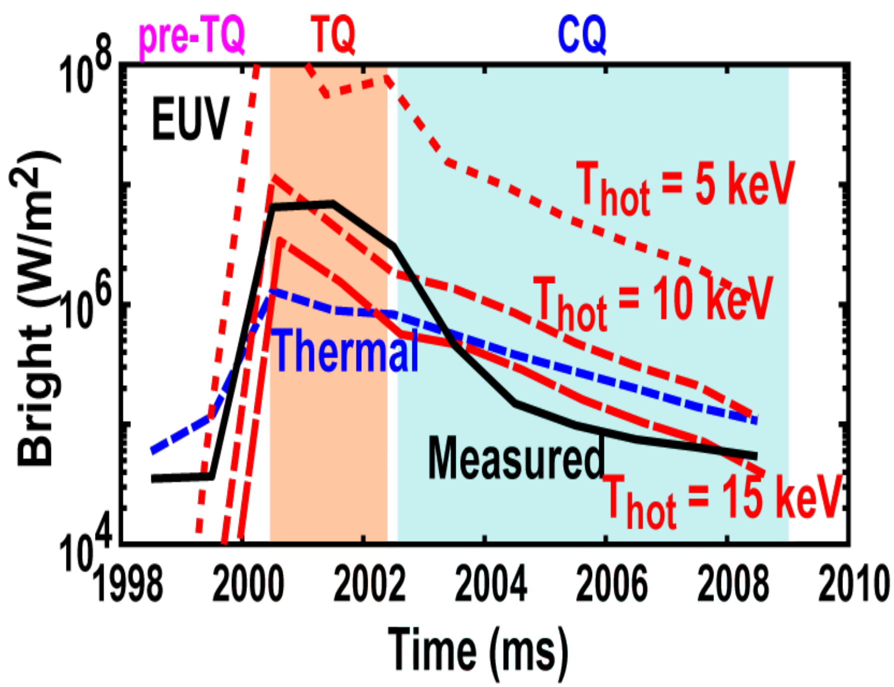
Ne/D_2 SPI USN target



EUV brightness suggests 10 keV non-thermal temperature during Ne/D_2 or pure Ne SPI TQ

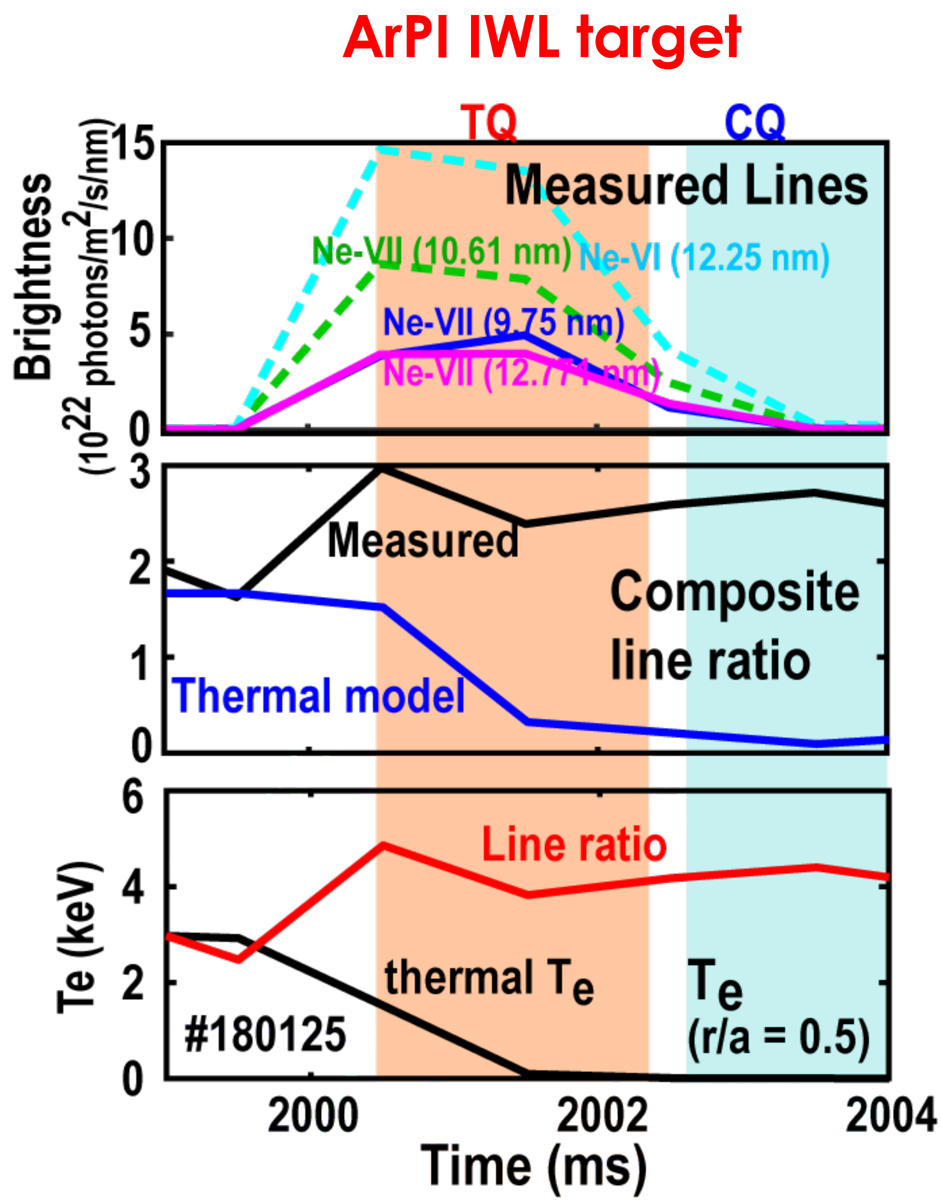
- Pre-TQ EUV brightness below thermal prediction.
  - Impurity ions not at other side of machine yet.
- TQ to mid-TQ EUV brightness above thermal prediction.
  - Interpret as due to non-thermals
- After mid-CQ, vertical drift of plasma
  - Not valid after mid CQ
- As with ArPI analysis, use SXR brightness profiles to help constrain non-thermal radial density profile.
- Assume toroidally symmetric impurities (only really valid in TQ and CQ).
- Just assume single non-thermal T across all radii.
- Can match to TQ EUV brightness assuming non-thermals with T ~ 10 keV

EUV brightness for Ne/D_2 SPI USN shutdown

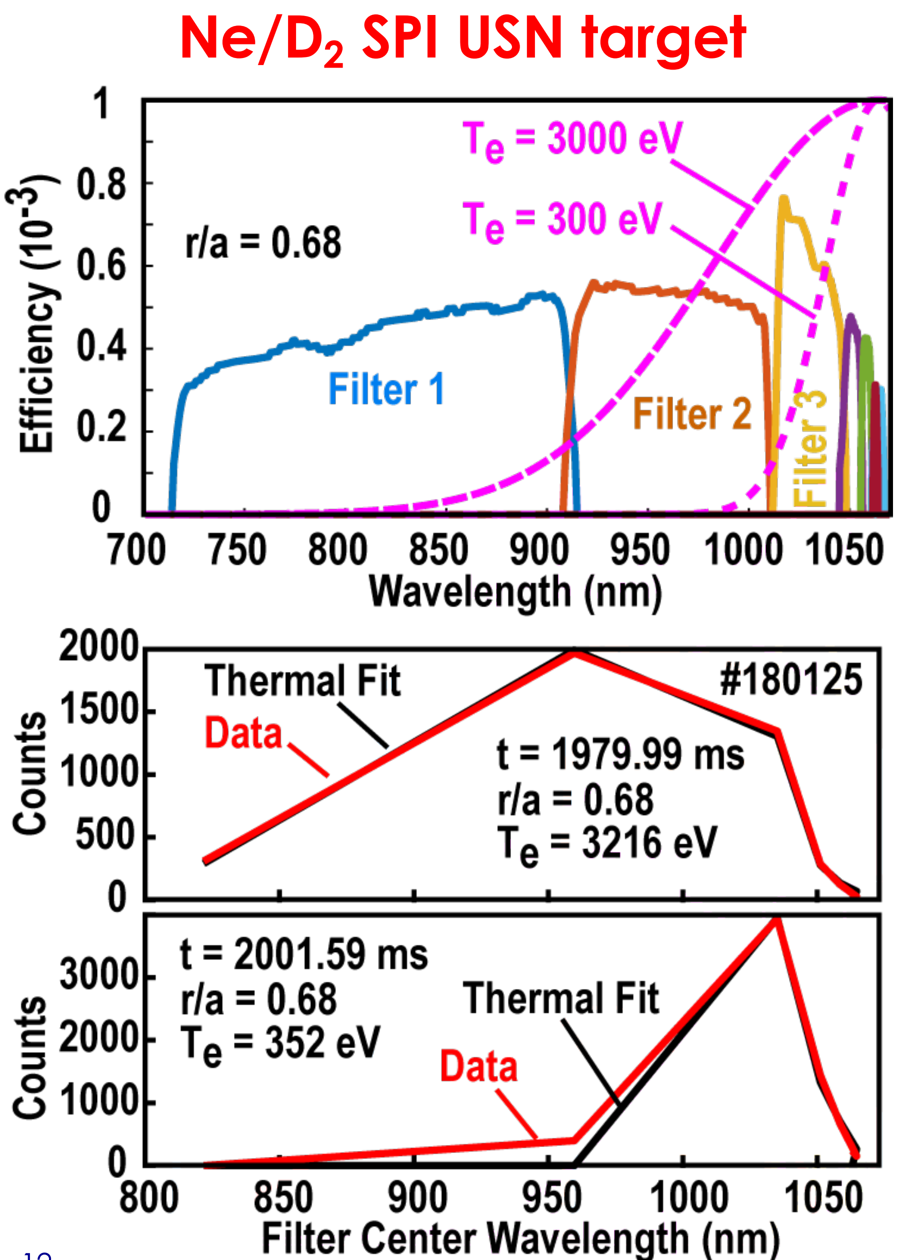


Neon line ratio technique gives TQ non-thermal T_e ~ 5 keV

- Line ratios frequently used as plasma diagnostics.
  - Advantage: not sensitive to absolute calibration
  - Disadvantage: heavily dependent on accurate atomic physics modeling.
- Requires finding lines which are more strongly dependent on T_e and others which are more weakly dependent on T_e.
- Make "composite" line ratio of two strong measured lines divided by two different strong measured lines.
- Predicted non-thermal T_e during TQ ~ 5 keV, so about 2x lower than EUV brightness method.



Extracting early-time non-thermal profile directly from TS data (1/2)



- For T_e < 10 keV, non-thermal density profile can in principle be extracted directly from TS.
  - Look for small excess in counts about thermal cold T_e fit.

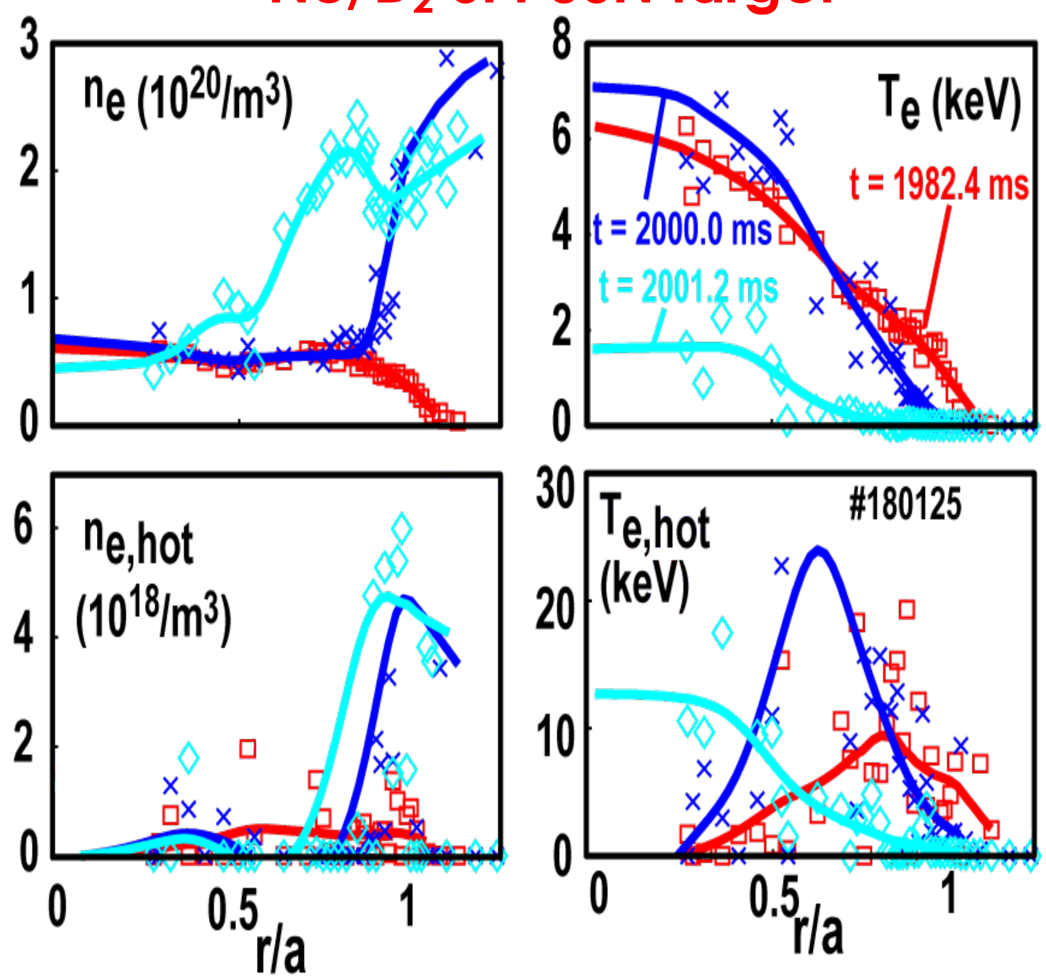
- Challenging to do because of small counts, fast time scales, and large background signal levels.

Extracting early-time non-thermal profile directly from TS data (2/2)

- Promising preliminary results obtained for ArPI, Ne SPI, and Ne MGI shutdowns.

- Scatter in data quite large, but numbers for non-thermal n_e, T_e appear roughly consistent with other techniques.

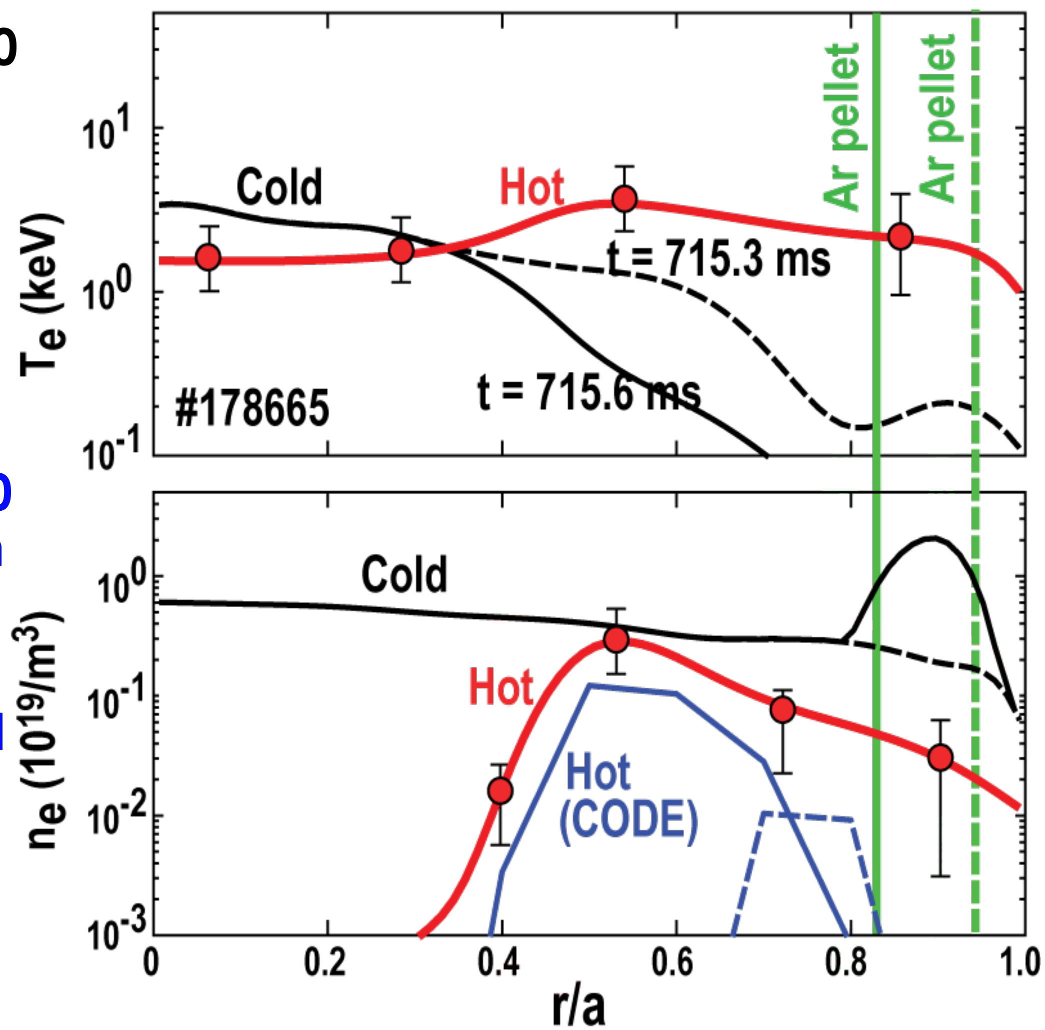
Ne/D_2 SPI USN target



Some non-thermals appear to be exist ahead of injected pellets

- Observed most clearly for slow(250 m/s) single ArPI experiments.
  - Non-thermal profiles reconstructed with ECE method.
- Not sure if this is due to fast Ar ion transport or fast electron transport?
  - Required impurity diffusion coefficients extremely high ~ 100 m^2/s > Bohm suggesting electron transport?
  - But, CODE can capture non-thermal profile without any radial electron transport, suggesting Ar ion transport?

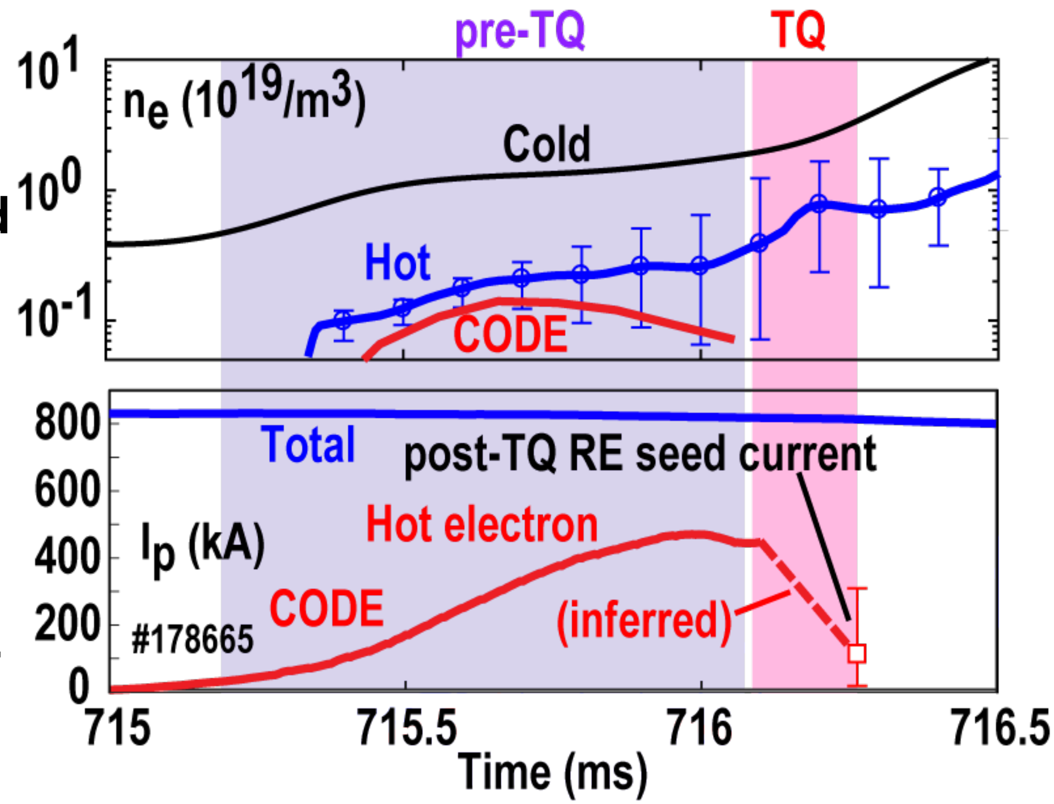
ArPI IWL target



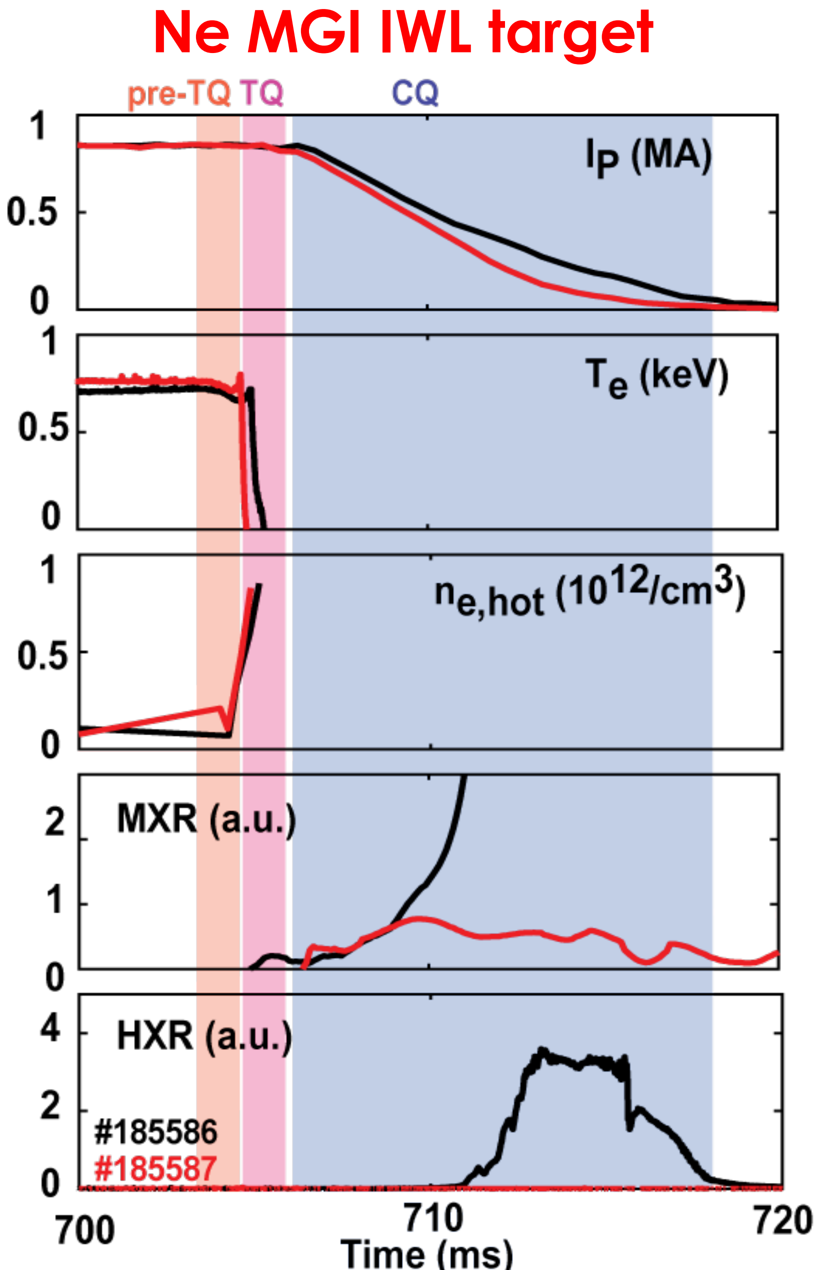
Pre-TQ non-thermals may carry significant plasma current

- Do not have diagnostic to measure pre-TQ non-thermal current.
- Non-thermal current inferred from interpretive Fokker-Planck modeling.
- Comparison between simulation and reconstructed density 2x, gives some confidence in modeling.
- Non-thermal current predicted to be up to 50% of total current during pre-TQ.
  - Significant effect on TQ MHD?
- Inferred post-TQ non-thermal current (from RE plateau + avalanche) can be lower than pre-TQ level.
  - Suggests TQ may cause net loss of non-thermal electrons?

ArPI IWL target



Pre-TQ non-thermal electrons do not automatically generate runaway electrons

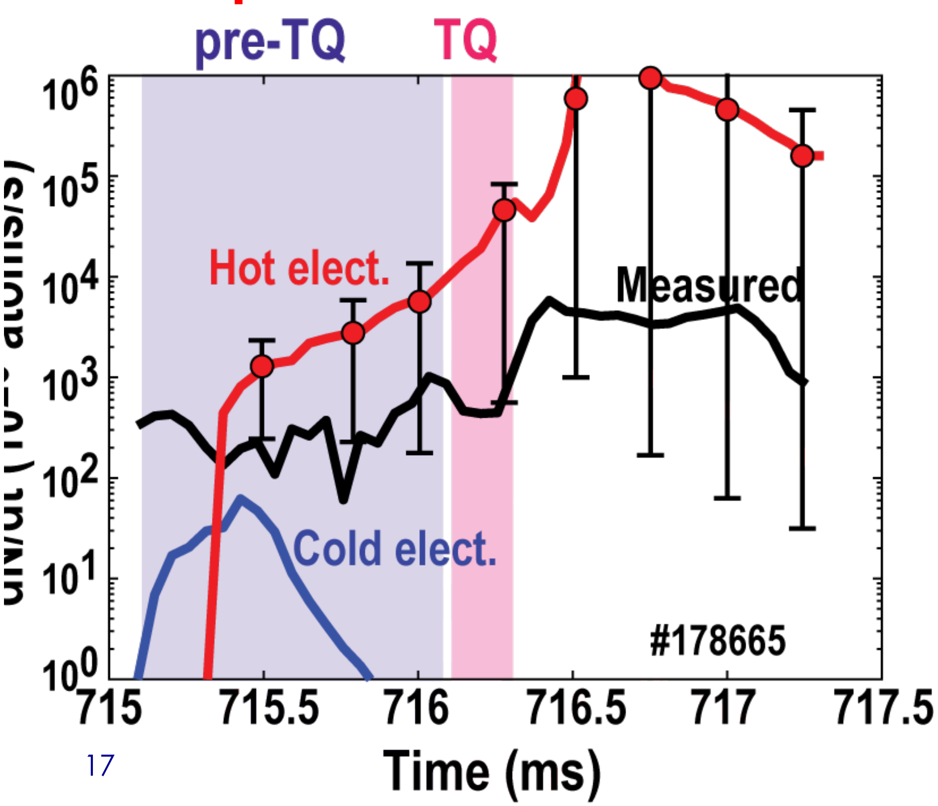


- **Preliminary analysis suggests that large scatter in RE current levels seen at end of CQ is not necessarily due to scatter in pre-TQ non-thermal level.**
  - **- Shot pairs with very similar pre-TQ non-thermal levels can have drastically different post-CQ RE levels.**
  - **- Suggests that TQ and CQ loss to wall (TQ MHD, Ip spike MHD, CQ current scrape off) can differ dramatically shot-shot.**

Non-thermals can dominate Ar pellet ablation during pre-TQ, TQ, and CQ

Ar pellet Ar-I image

Ar pellet ablation rate

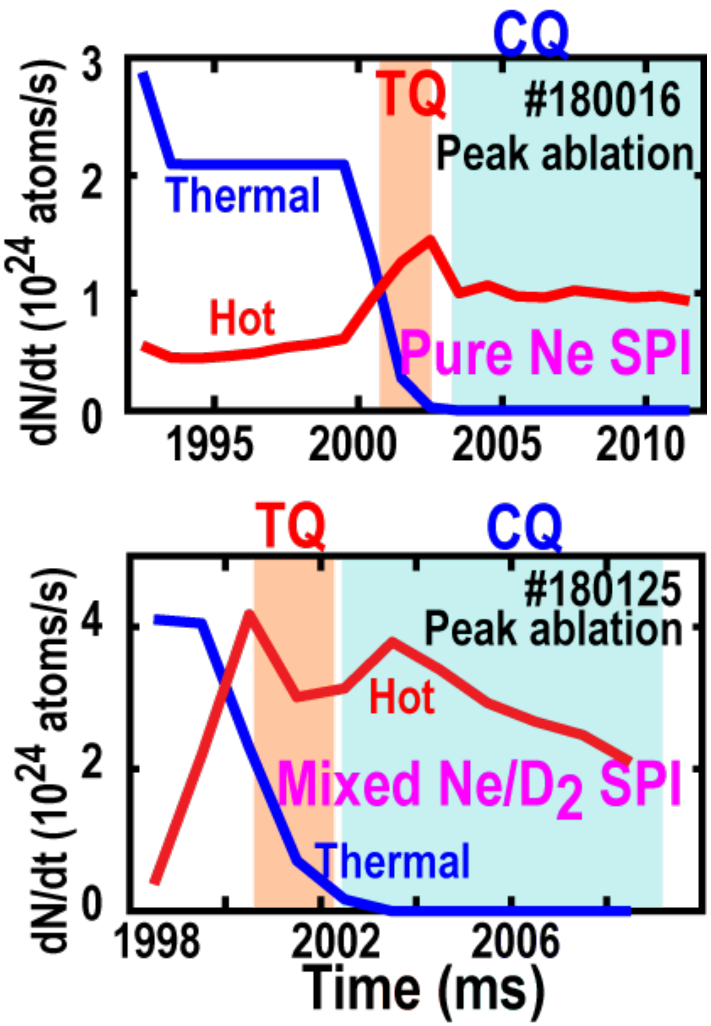


- Pellet ablation rate can be estimated from absolutely-calibrated light emission from pellet ablation plume.
- Reconstructed non-thermal n_e, T_e profiles can then be used to estimate non-thermal ablation rate.
  - Just treat thermal and non-thermal ablation separately (present models do not allow for non-Maxwellian background plasma).
- Despite huge error bars, measured ablation rate clearly more consistent with non-thermal electrons than cold electrons.

Non-thermals possibly also affect SPI shard ablation, especially during TQ and CQ

- Reconstructed non-thermal n_e, T_e profiles can be used to estimate non-thermal ablation rate.

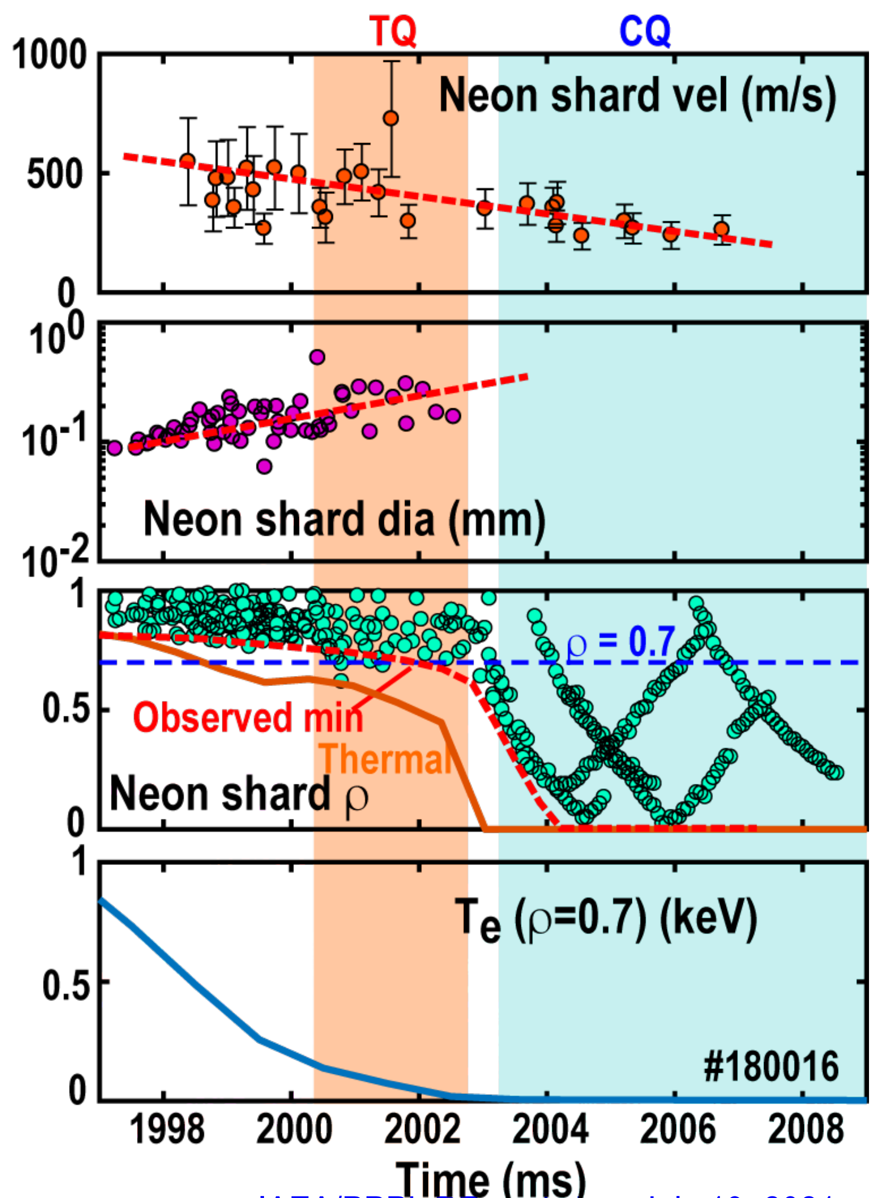
- Expect non-thermal ablation to become significant during pre-TQ and dominate during TQ.



Penetration depth of SPI shards appears to show effect of enhanced ablation due to non-thermals

- Hard to make nice single ablation rate curve because of many small shards
- Camera images can be used to track shard velocities.
- Shard sizes can be inferred from absolutely-calibrated light curves for resolvable shards.
  - Small fast shards arrive first, then larger slow shards
- Burn-through radius for shards not consistent with thermal ablation; shards stopped closer to edge of plasma.
  - Indicates non-thermals are ablating shards.

Ne SPI USN target



Summary

- Pre-TQ non-thermals can potentially be seen in a variety of diagnostics.
  - work ongoing to improve measurements and analysis.
- Non-thermals appear to form ahead of injected pellet
  - rapid impurity transport?
  - rapid electron transport?
- Non-thermals could carry significant current
  - effect on TQ and CQ MHD?
- Non-thermals do not automatically form relativistic runaway electrons
  - large loss to wall?
- Non-thermals can dominate pellet ablation
  - injected pellets will stop closer to edge than expected!