Benign Termination of Runaway Electron Beams on JET, ASDEX Upgrade and TCV

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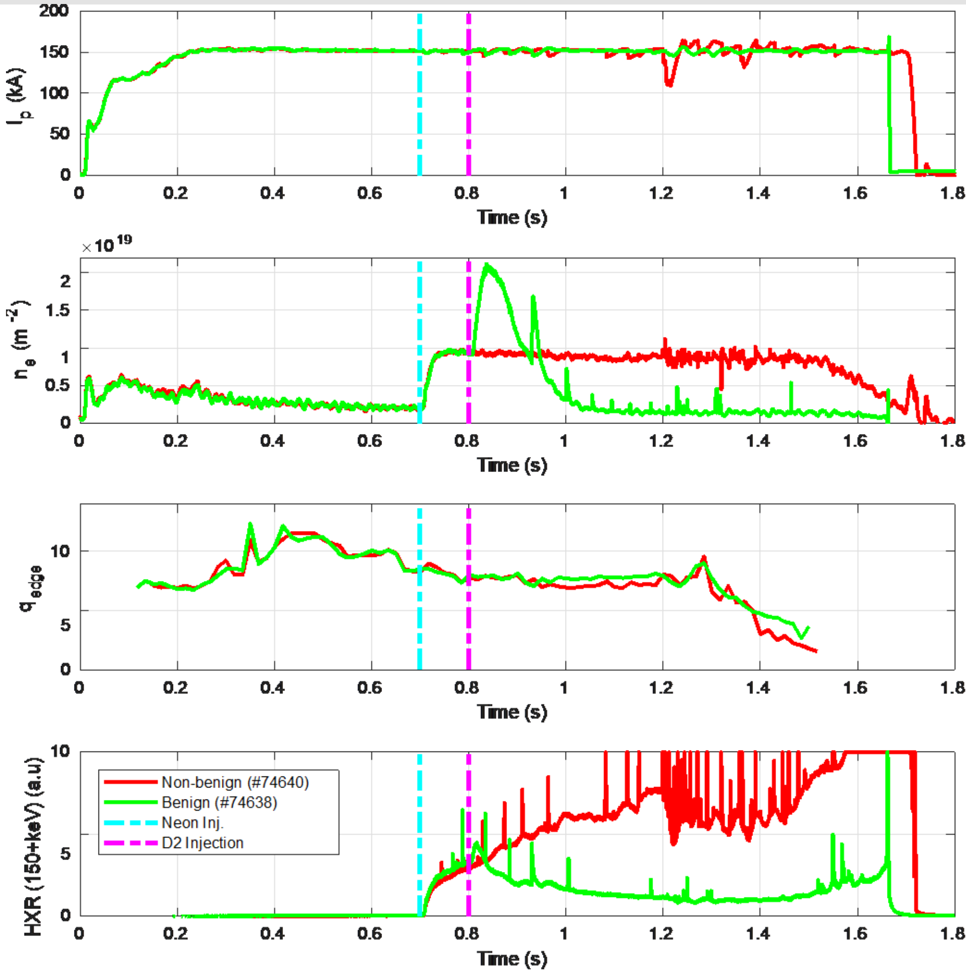
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Presentation Outline

- Benign termination scenario on TCV and AUG
- Operational domain
- Final collapse
- Heat flux inferences
  - Time allowing

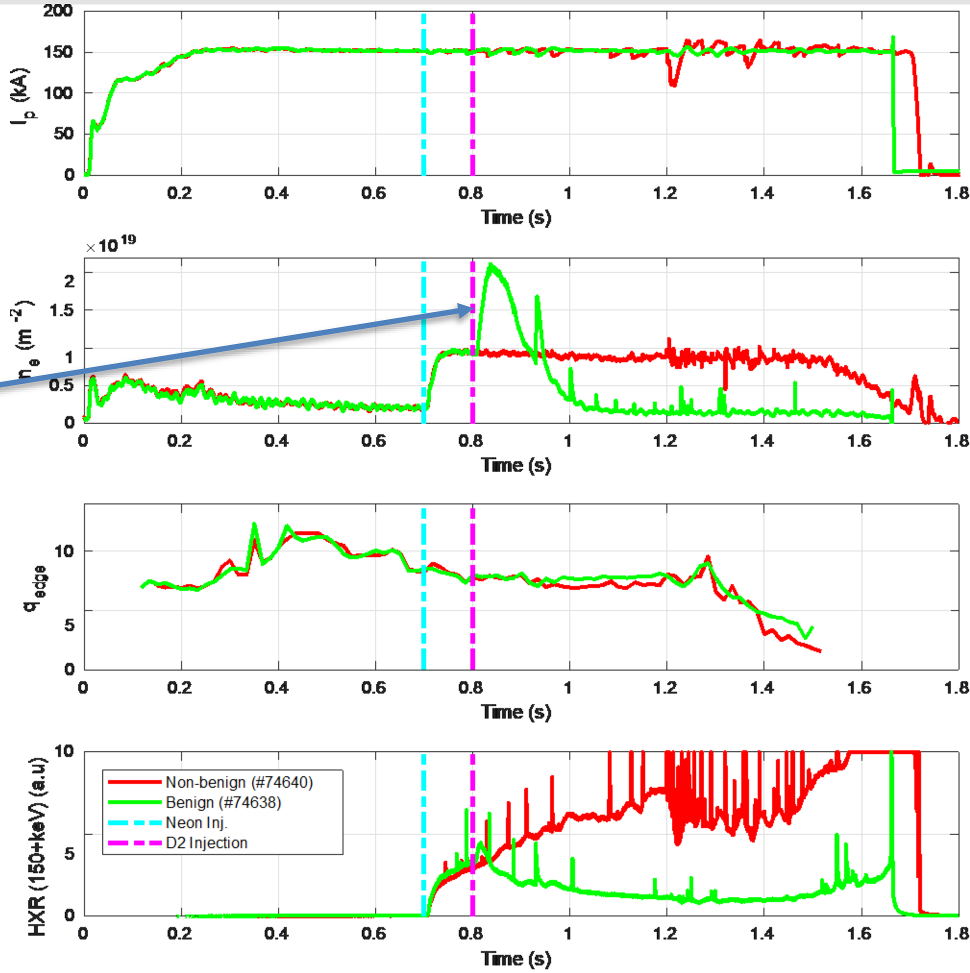
Benign Termination Scenario (TCV)

- Comparison of non-benign and benign terminations
- RE beam created with Neon injection at 0.7s
  - I_p carried by REs
  - “Companion plasma” exists
    - Low temperature (<10eV)
    - Highly resistive
    - Carries a small fraction of I_p



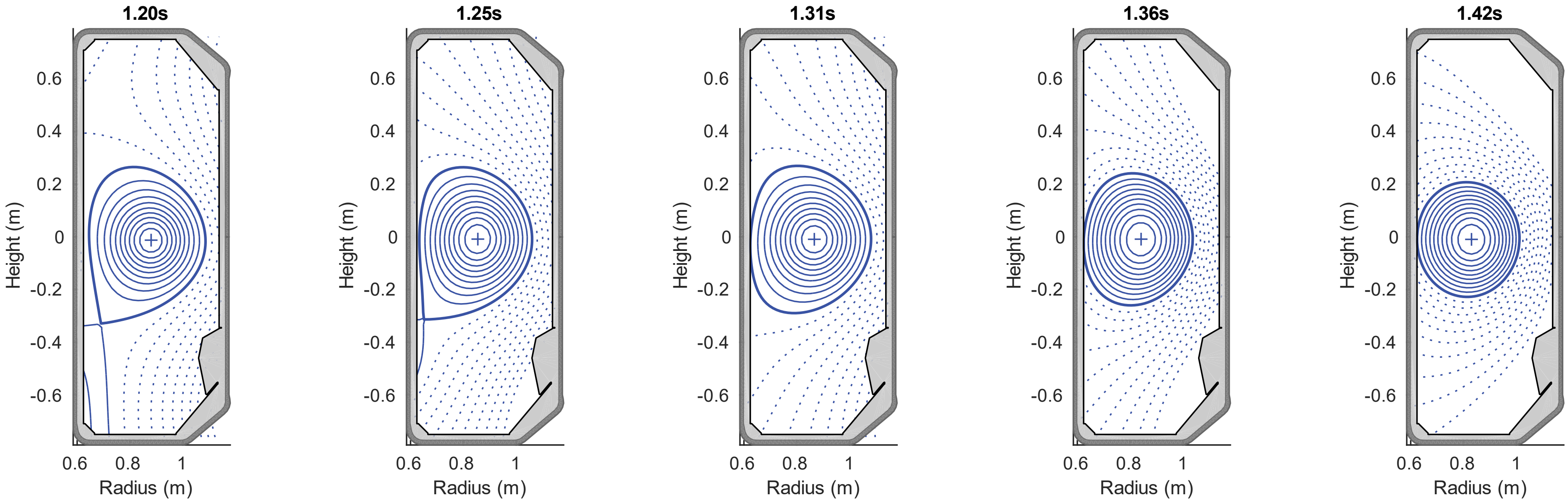
Benign Termination Scenario (TCV)

- D2 injection beings at 0.8s
  - Neutral pressure increases slowly through fueling valves
  - Density rise until companion plasma cools and recombines
    - Energy loss through radiation and neutrals conducting to wall
    - I_p entirely carried by REs
  - Reduced V_{loop} and **E**
    - Enables long duration beams
    - Facilitates access to low q_{edge}



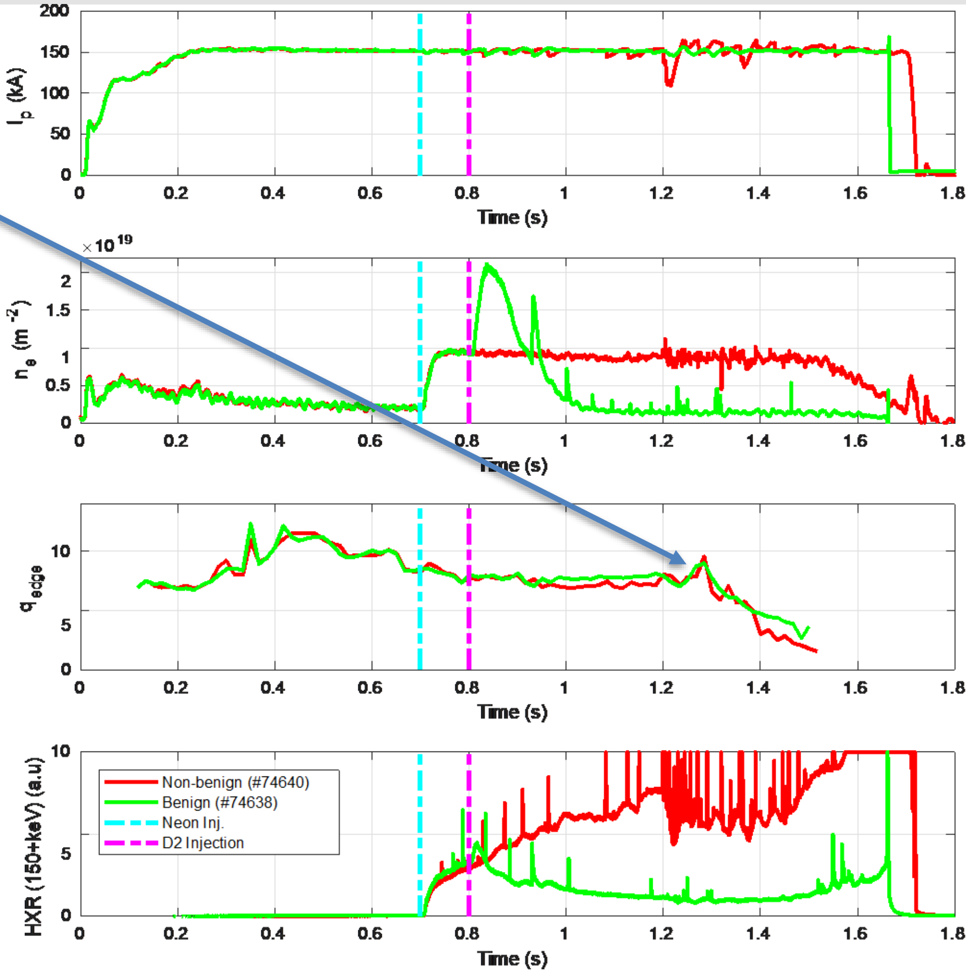
Benign Termination (TCV)

- Approach low q_{edge} to produce MHD instability
  - Compression on center column
  - Effectively reducing minor radius



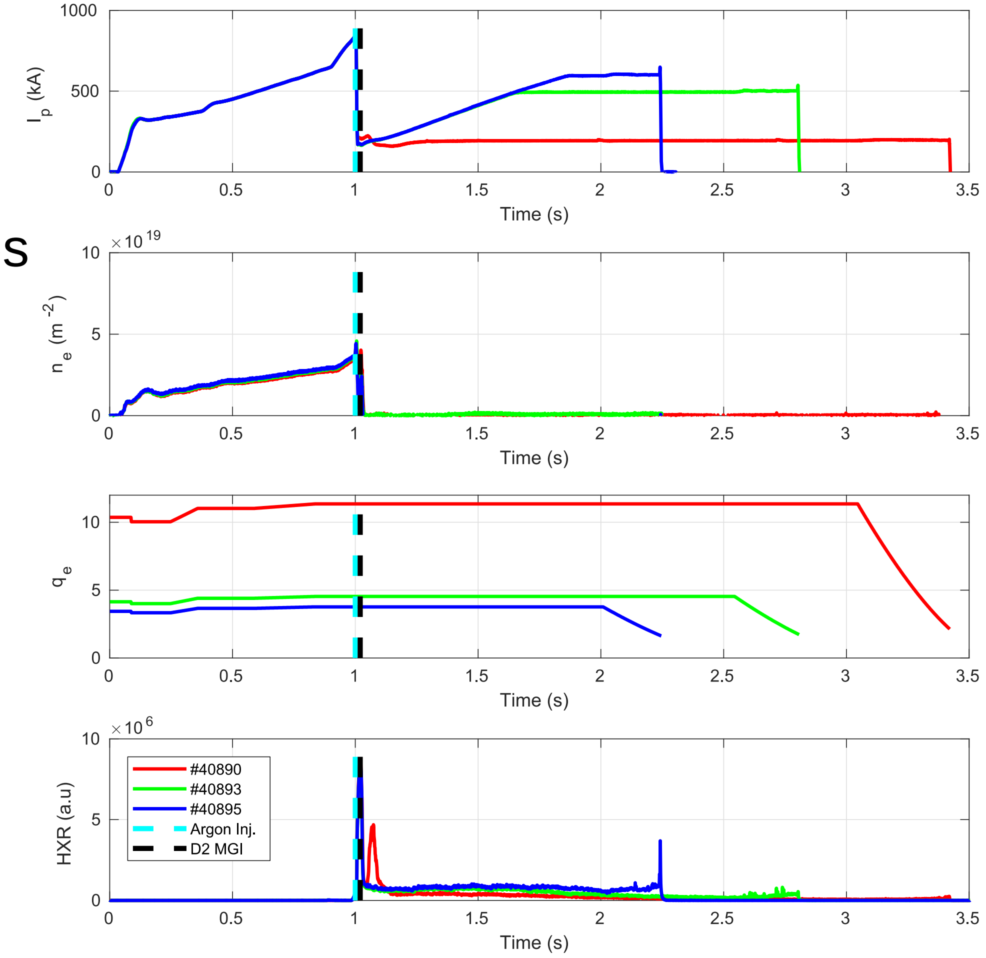
Benign Termination (TCV)

- Approach low q_{edge} to produce MHD instability
  - Compression on center column
- Fast growing MHD instability expels REs over large area
  - High mode growth rate likely due to high Alfvenic velocity
    - Low n_e companion plasma
  - I_p spike and fast CQ
    - Transition to resistive plasma
  - No HXR emission during CQ
    - No regeneration/loss of REs



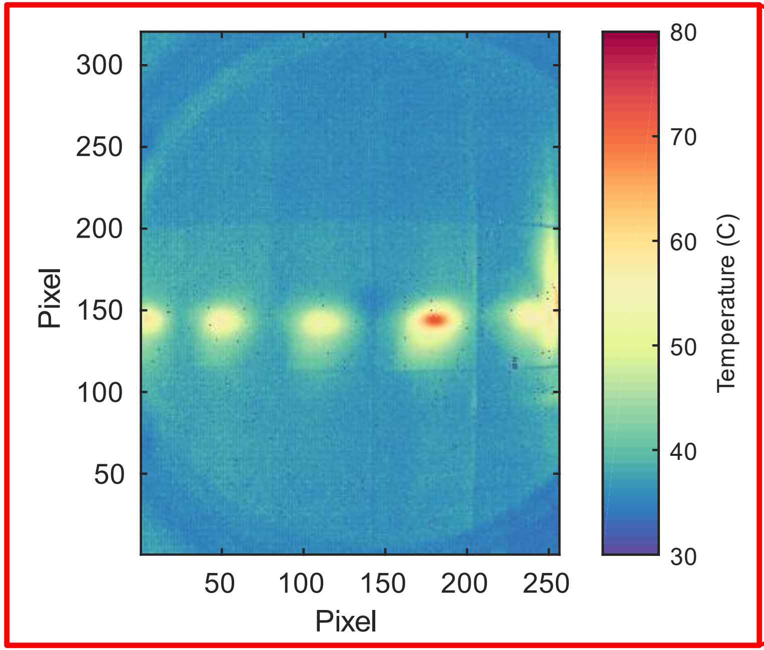
Benign Termination (AUG)

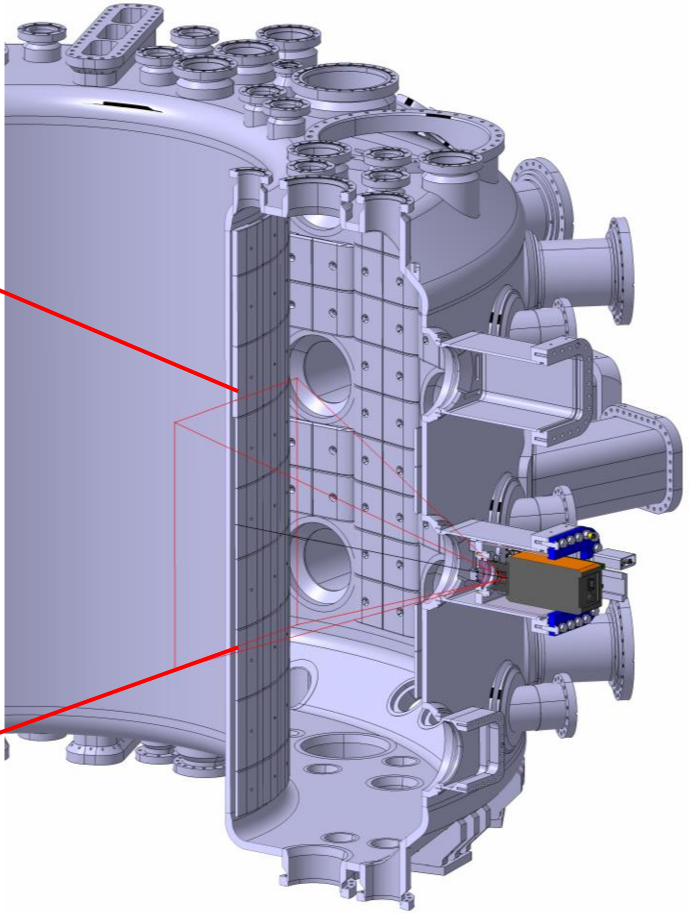
- Argon injection at 1.0s
- D2 MGI at 1.02s
    - Companion plasma recombines almost immediately
        - I_p entirely carried by REs
    - Neutral pressure maintained with fueling valves
- Compression on center column to achieve low q_{edge}
- Benign termination achieved at 200, 500 and 600kA



Benign Termination – Heat Flux

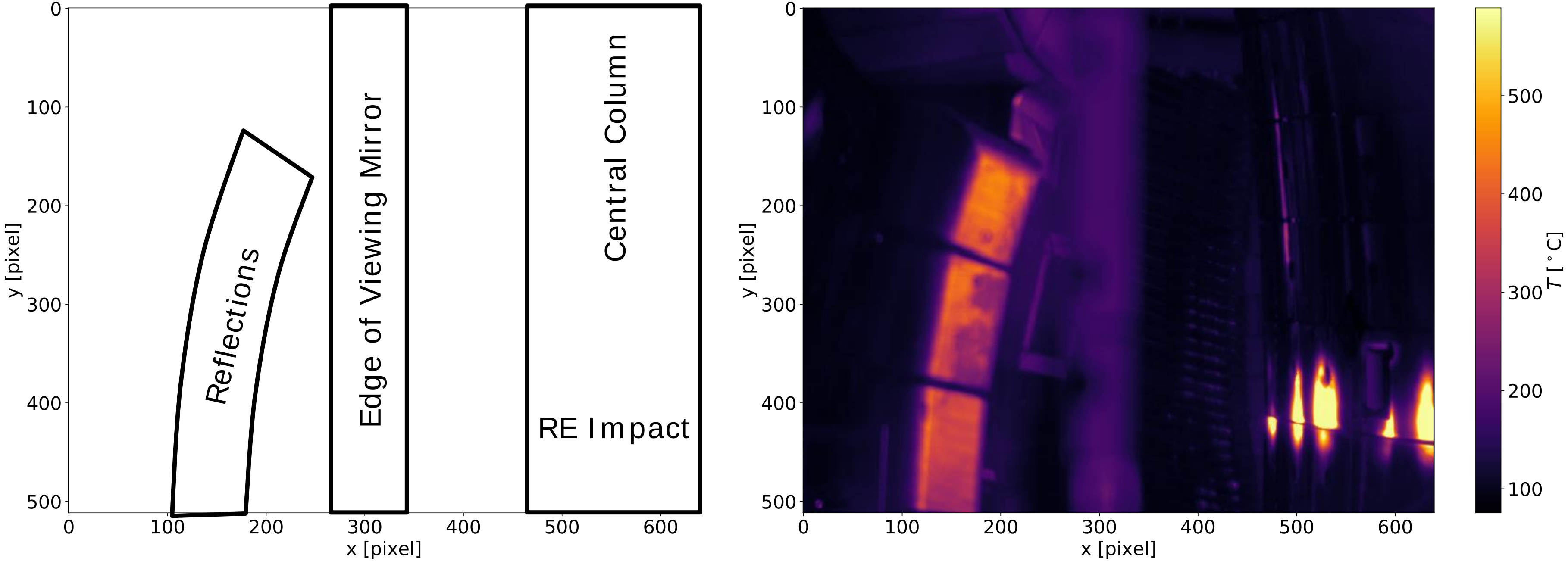
- TCV infrared camera views central column perpendicularly





Benign Termination – Heat Flux

- AUG IR camera views tangentially
  - RE impact observed on central column
    - Reflections within port on right of image

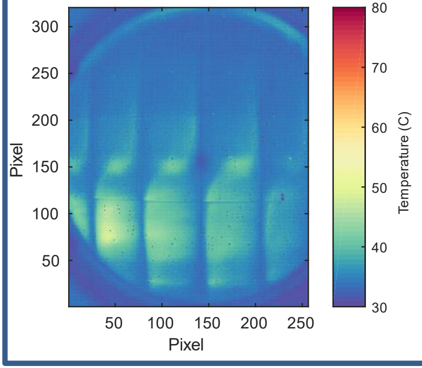


Benign Termination – Heat Flux

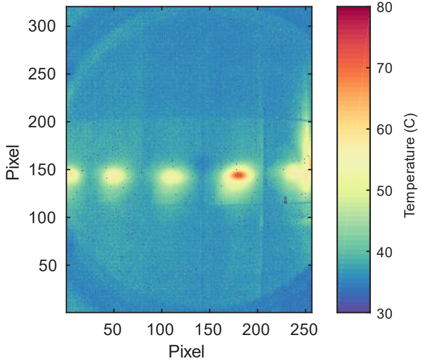
- Heat flux significantly reduced through benign termination
  - Increase in wetted area
  - Lower peak temperatures measured
    - Temperature scale varied on AUG images

TCV

Benign Termination
74638

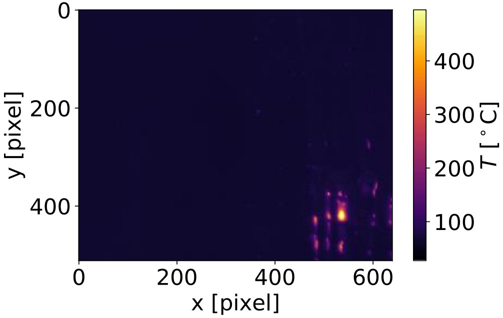


Non-Benign
74640

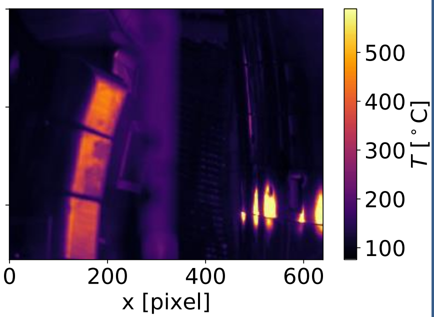


AUG

Benign Termination
40890



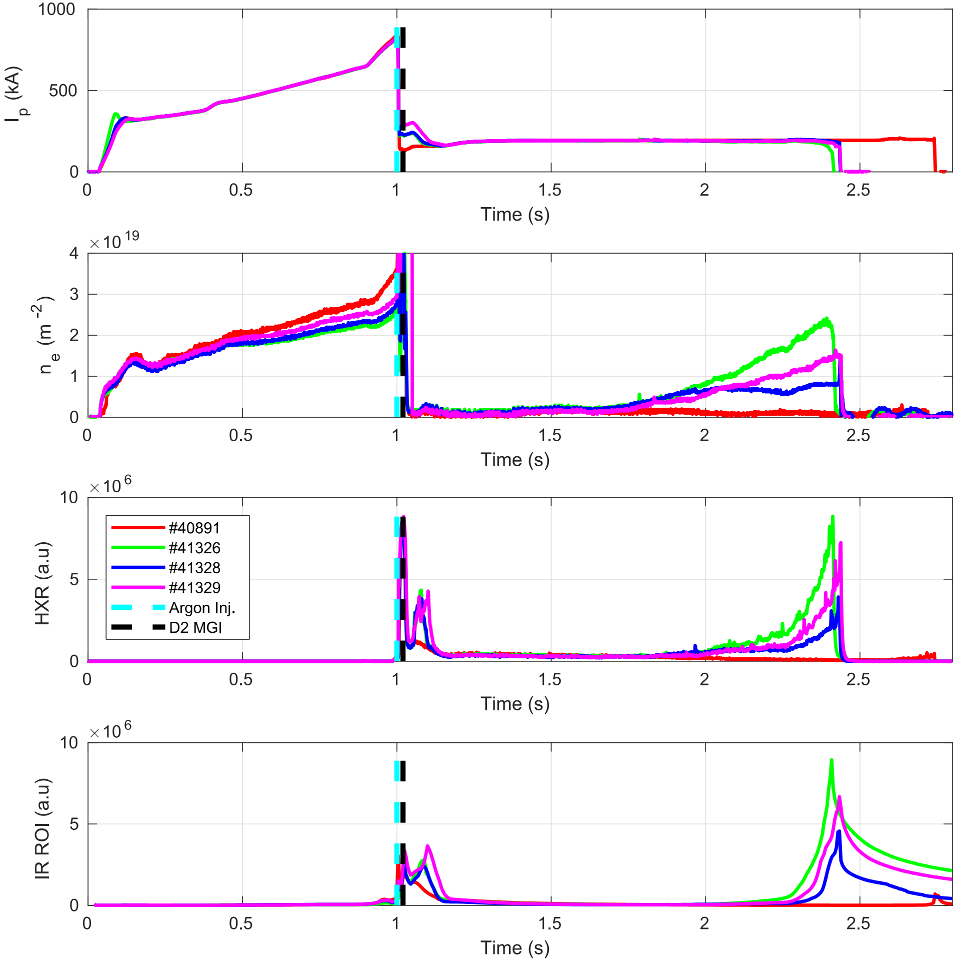
Non-Benign
41326



Operational Domain

Operational Domain

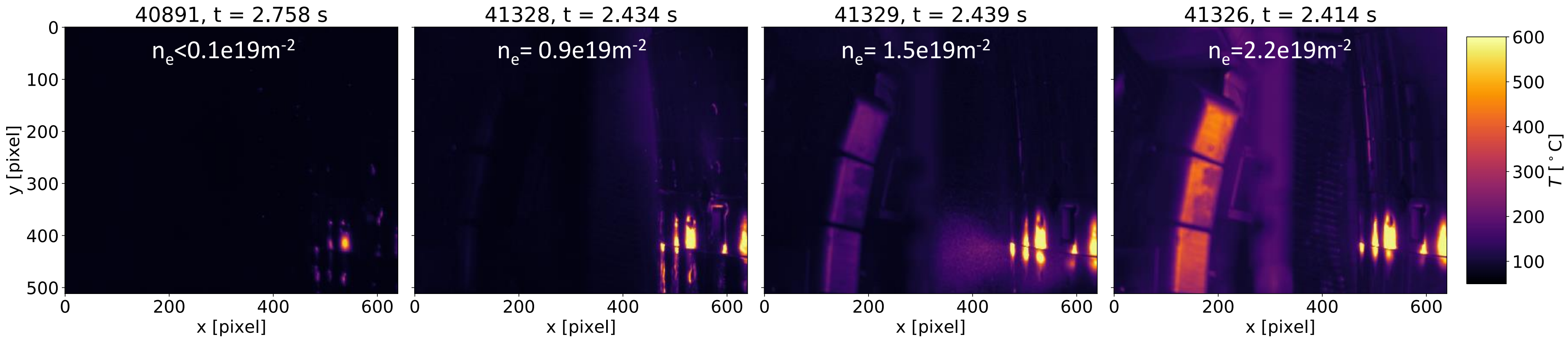
- Explored by varying parameters at collapse
  - Gas species and quantity
    - Impurity and H2/D2 for recombination
    - Injection methods
  - Path to low q_{edge}
- Plasma compression at different densities on AUG
  - Achieved with different D2 injection rates



Operational Domain

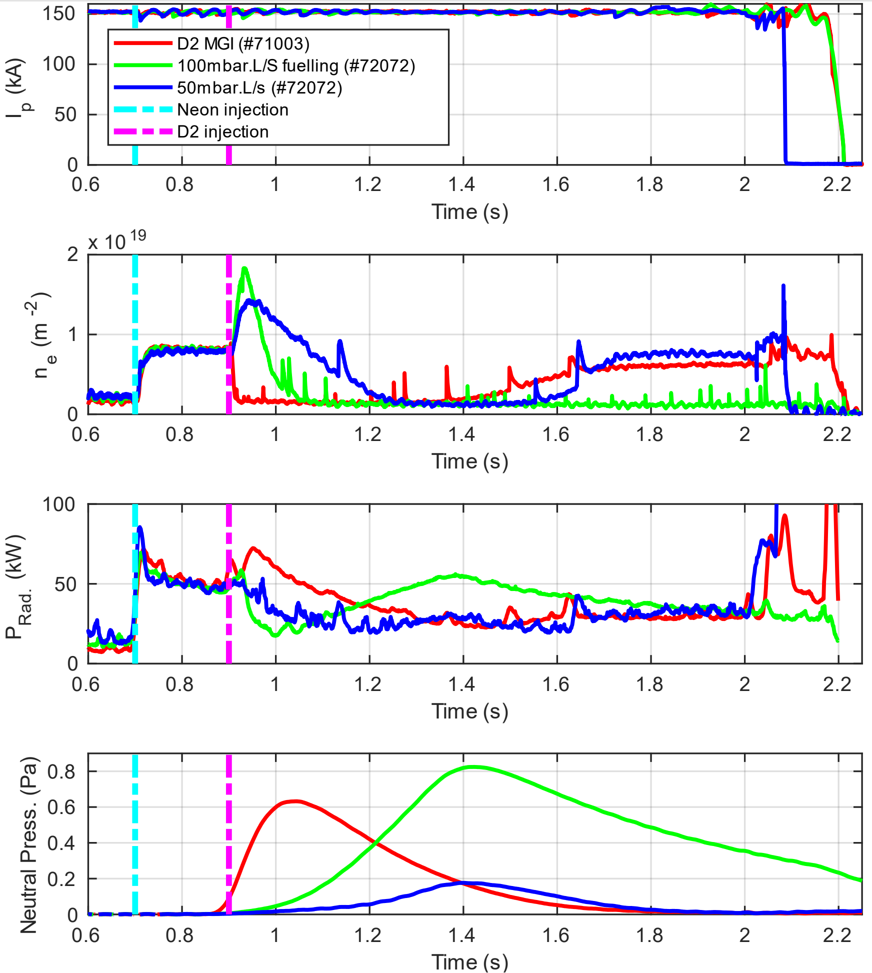
- <u>Benign termination boundary linked to n_e</u>
  - Controlled by neutral pressure
  - Impacts T_e, **E** and RE energy
  - AUG data for 200kA presented

Benign Termination → Increasing Density → Non-Benign



Neutral Pressure & Energy Balance

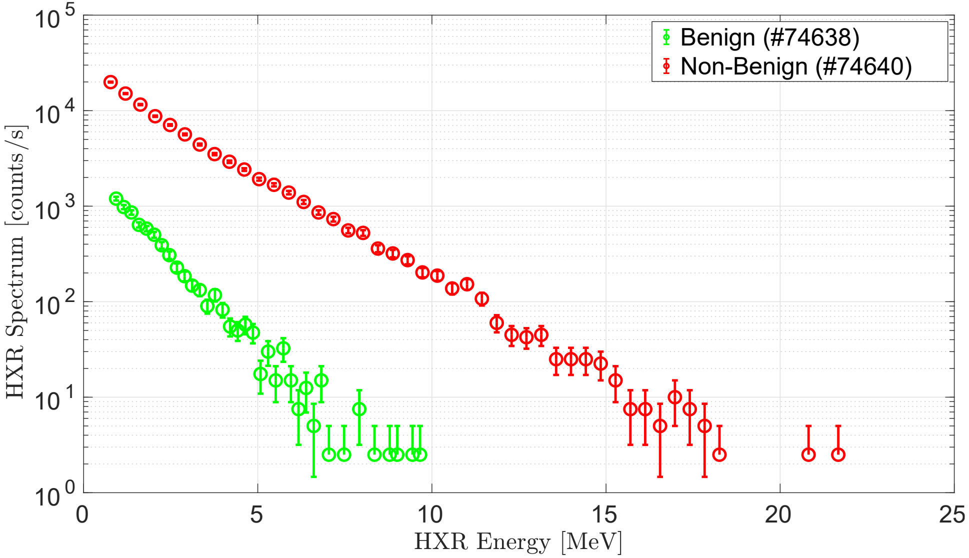
- Radiated power drops until recombination
  - Increasing neutral pressure further leads to an increase in P_{rad} due to collisions with REs
  - Agnostic to injection method
- Energy loss mechanism is conduction of energy through neutrals to the wall



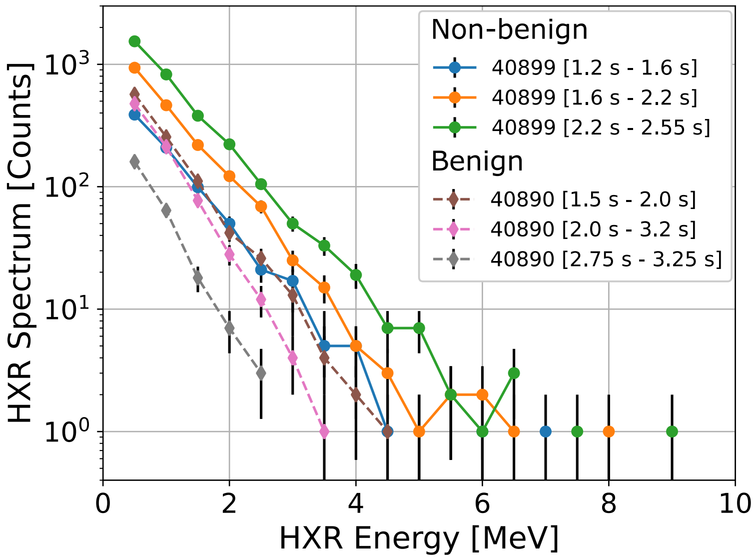
Neutral Pressure & RE Energy

- RE energy reduced in benign termination cases
  - Recombined companion plasma and low **E**
  - Measurements at detector are only an indication of RE energy

TCV

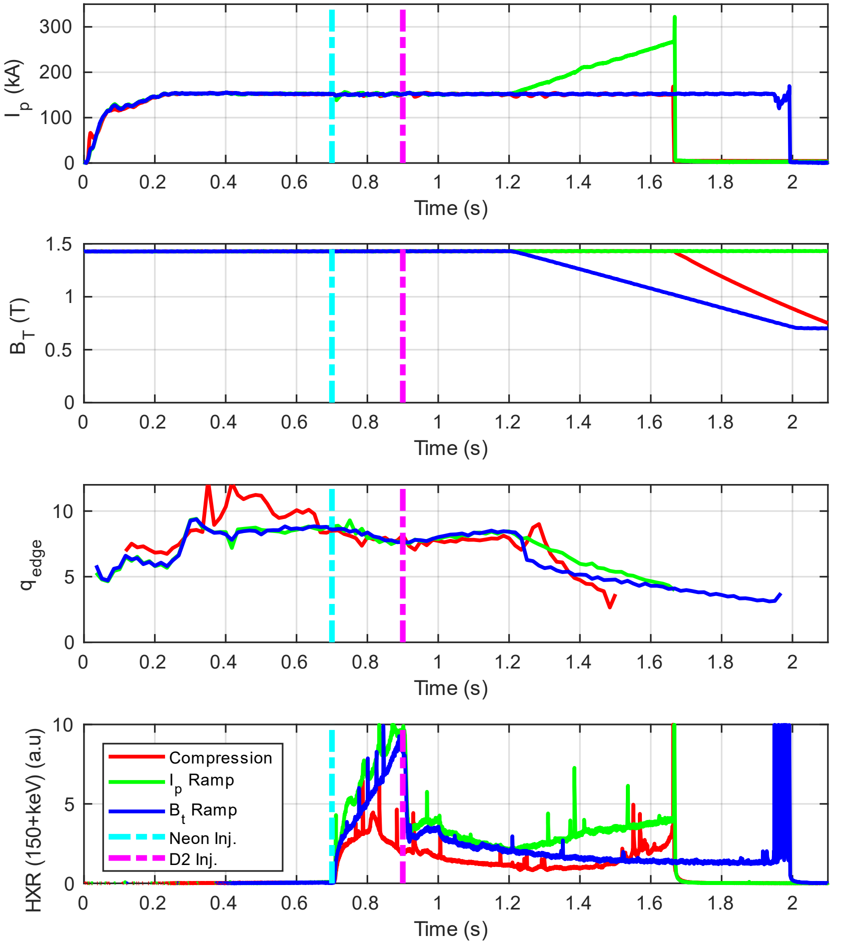


AUG



Path to Low q_{edge} (TCV)

- Three paths to low q_{edge}
- Compression on center column for reference
  - Slower compression rates may lead to instability at higher q_{edge}
- Low q_{edge} with I_p ramp up
  - Bursts at q_{edge} of ~3
  - Large HXR burst at termination
- Low q_{edge} with B_t ramp down
  - Partial collapses before final collapse
- All three methods produced benign termination
- Important for ITER -> VDE



Operational Domain: So far…

- Wetted area scales with plasma density (AUG and TCV)
  - Controlled by neutral pressure
  - Leads to low **E** and reduced RE energy
- Recombination occurs as neutrals conduct energy to walls
  - Injection method does not alter this result
- Plasma compression, I_p and B_t ramps to low q_{edge} lead to benign termination

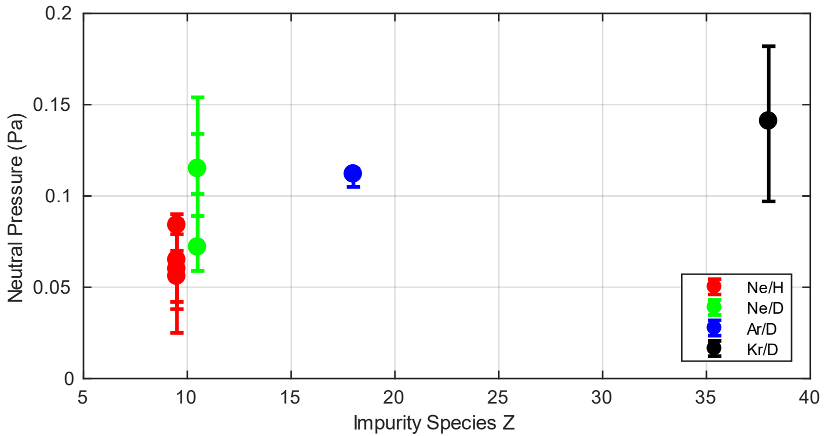
Up Next

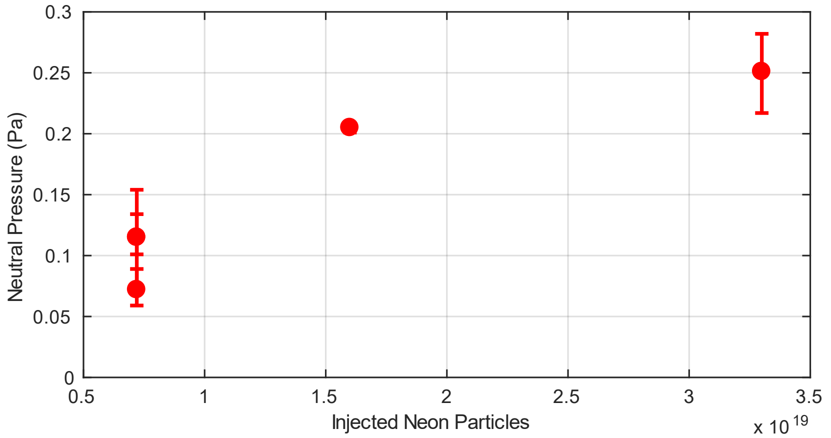
- Recombination requirements for gas species and quantities
  - Explored on TCV with Ne, Ar and Kr
    - Ar predominantly used on current devices, ITER will use Ne
  - Does the requirement change for H vs D?
    - D predominantly used on current devices, ITER will use H
- Upper threshold in neutral pressure

Recombination Requirements

Sensitivity to Gas Species (TCV)

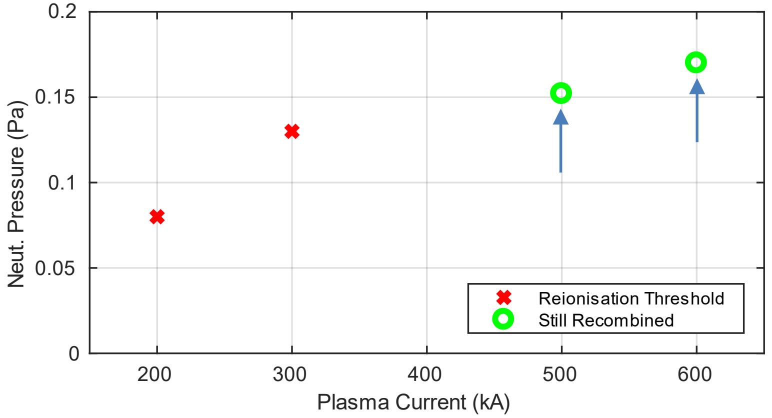
- Constant injection quantity for all impurity species
  - Required pressure for recombination increases with Z
  - H may be slightly more efficient than D for energy conduction
  - Error bars estimated from rate of change of neutral pressure
- Higher neutral pressure required for more neon
  - Non-linear dependance
- Power balance model required
  - Later in presentation

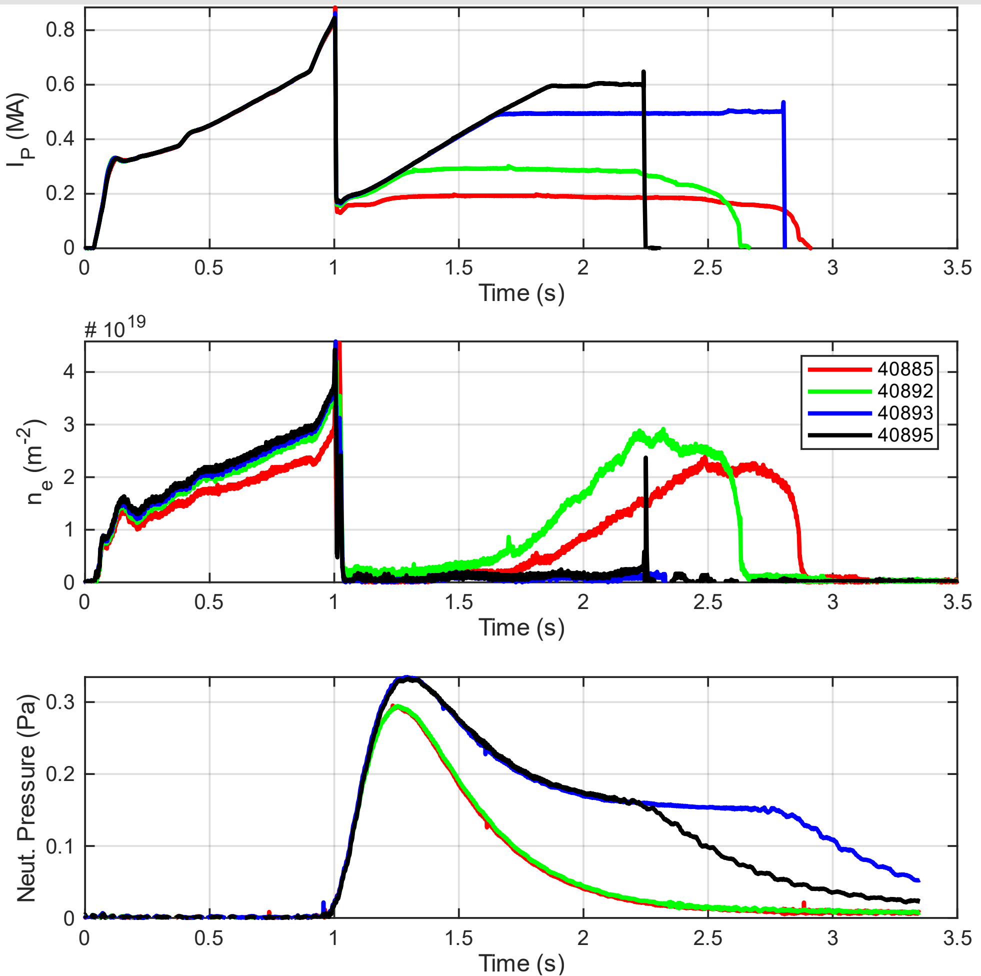




Sensitivity to Plasma Current (AUG)

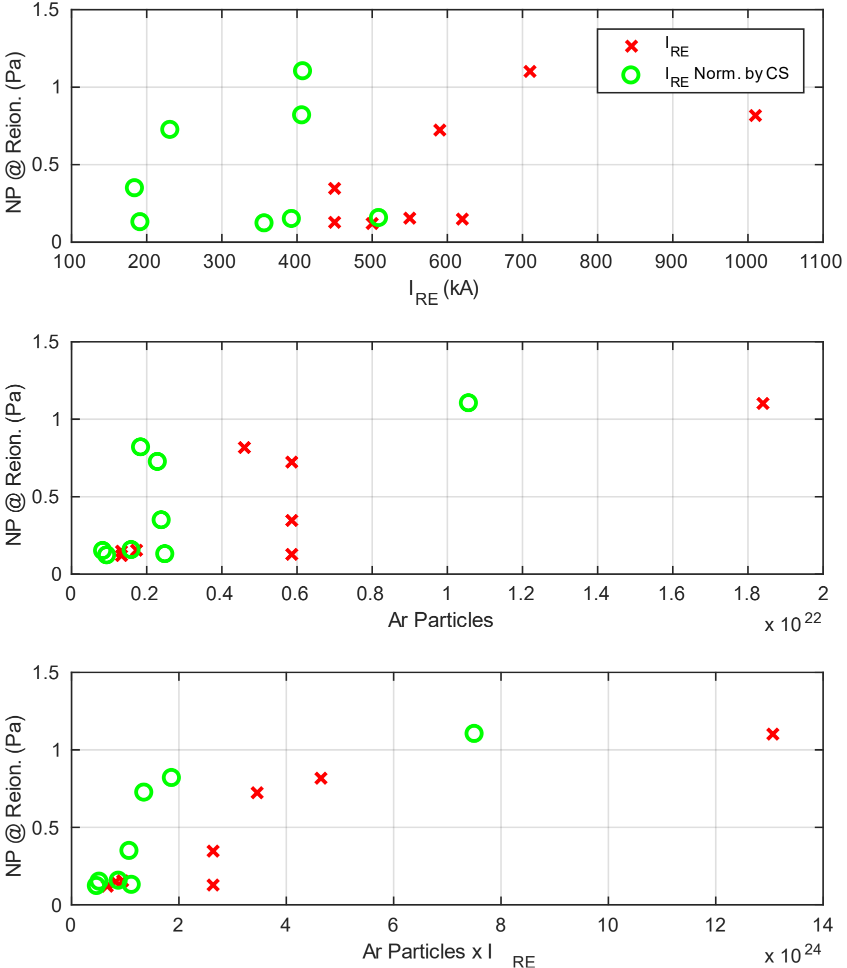
- Required pressure for recombination increases with plasma current
- Non-linear dependence
  - Further experiments and power balance model required





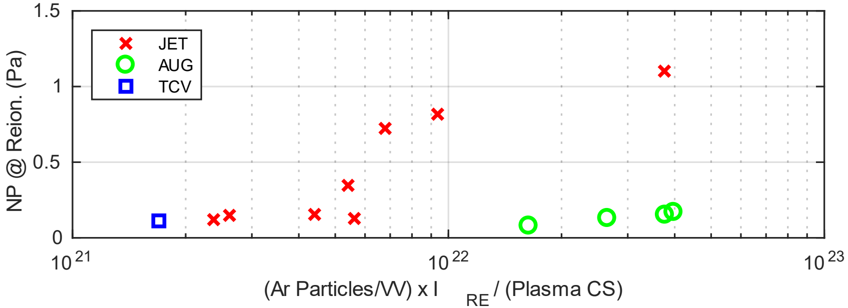
JET Recombination Requirements

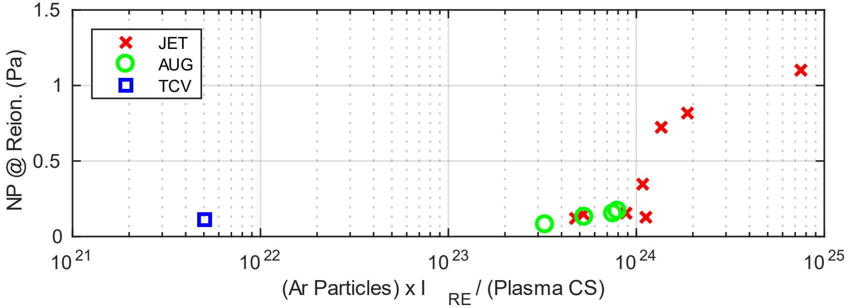
- Plasma current, cross-section and injected quantity varied
  - All D2 data shown
  - Re-ionisation with H2 not yet observed
  - <u>NP estimated from injected particles minus pumping</u>
- Required neutral pressure is influenced by plasma current and injected quantity
  - Stronger dependance on injected quantity
  - Difficult to assess if plasma cross-section (CS) has impact

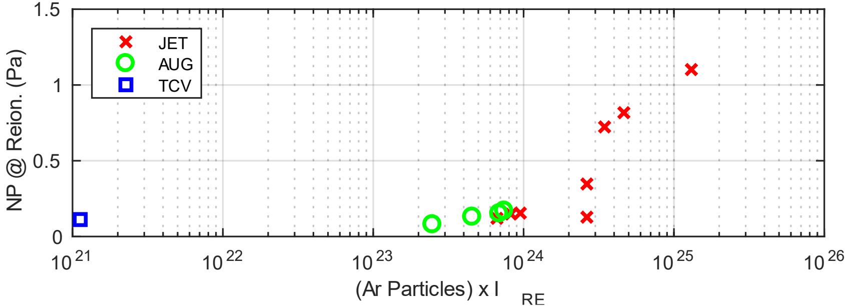


Cross Machine Comparison

- First order approximation:
  - Impurity is spread over vacuum vessel (VV)
  - REs confined in plasma CS
- Scaling does not follow
  - Potentially due to neutral density gradient
    - Due to heat from plasma
    - Fewer neutrals in RE path
- Clearest scaling if VV ignored
- Step in JET data to be explored







Recombination Requirements

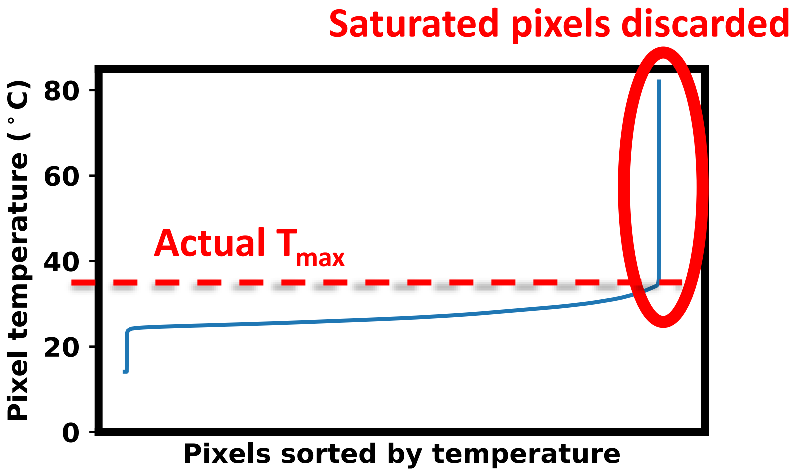
- Summary:
- Required neutral pressure for recombination increases with Z-number of species, injected quantity and Ip
- No clear metric to link machine yet
  - Power balance model being developed

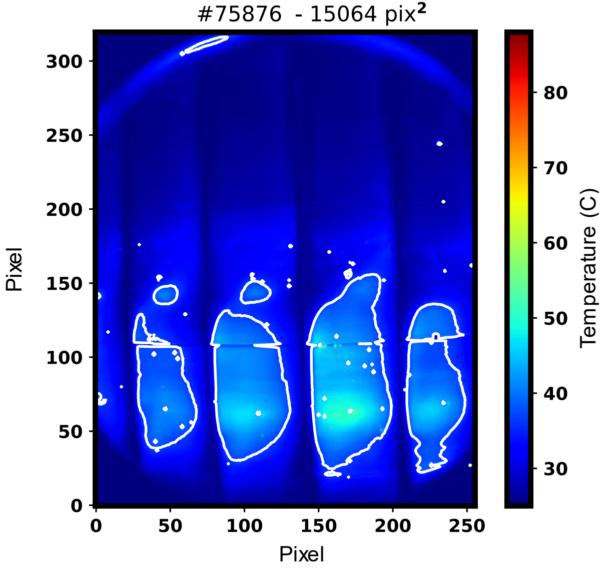
Upper Limit for Neutral Pressure

Only Observed on TCV (and DIII-D not shown)

Wetted Area Calculation

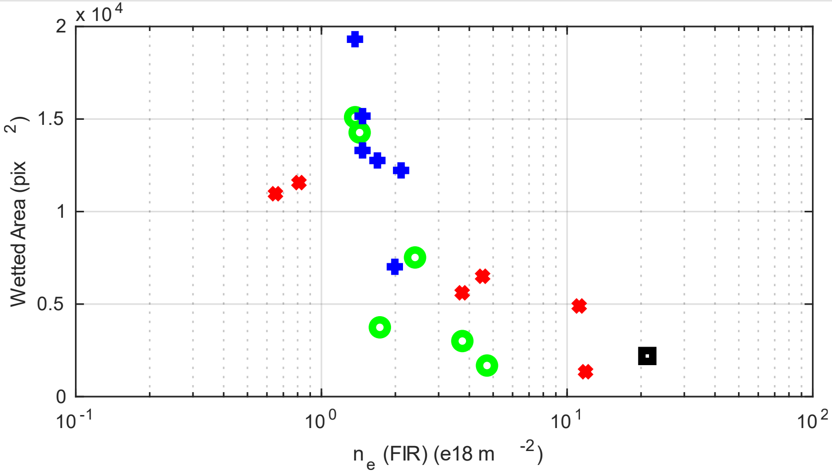
- Threshold temperature: $T_{th} = T_{max} – 0.7(T_{max} – T_{avg})$
- Count pixels with $T > T_{th}$
- Hard x-rays pollute image by saturating pixel
  - Use statistics to find max temperature (T_{max})

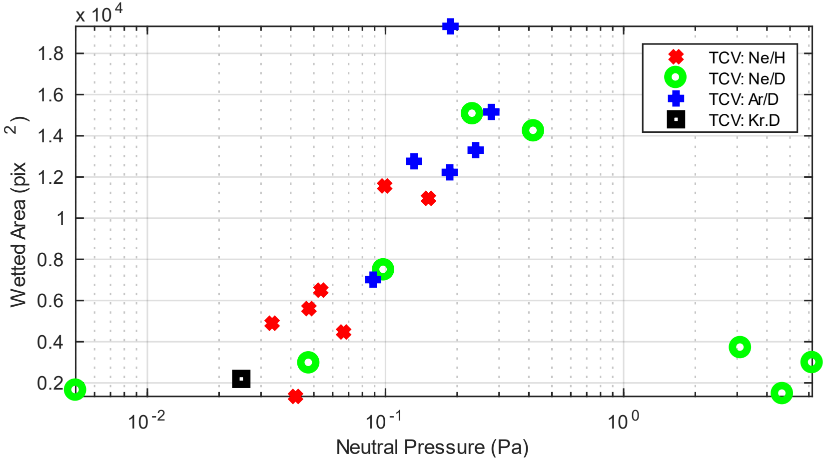




Sensitivity to Gas Species (TCV)

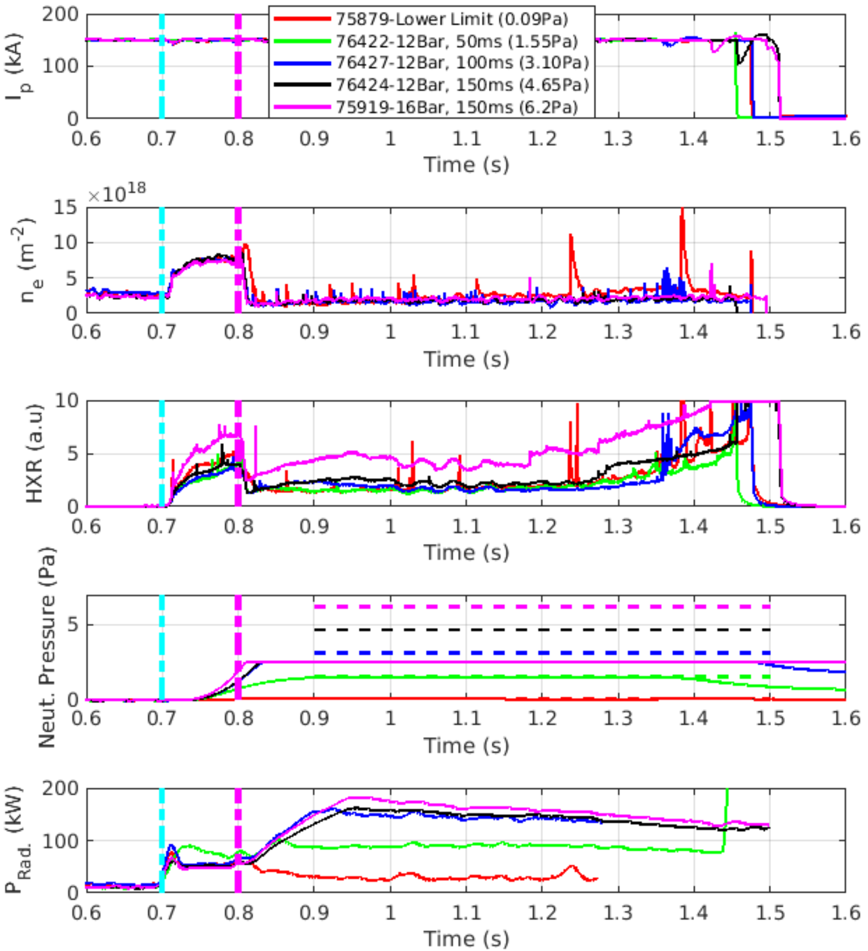
- Scenario boundary explored Ne/H, Ne/D, Ar/D and Kr/D
  - Done at 150kA
- Wetted area scales with electron density and neutral pressure
  - Wetted area used a proxy for heat flux
- Wetted area begins to decrease at high neutral pressure on TCV
  - Explored with Ne/D
  - Upper limit not observed on AUG
  - Seen on DIII-D (Paz-Soldan 2021)





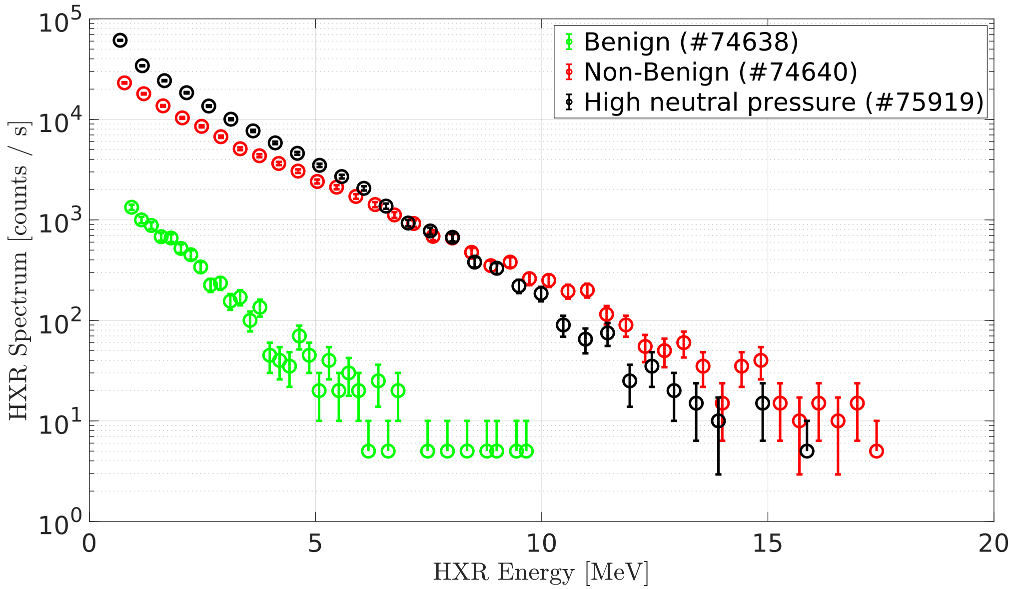
Neutral Pressure Upper Limit (TCV)

- No increase in density apparent in time trace
- HXR emission increases at higher neutral pressures
  - RE collisions/losses at high neutral pressure
  - Higher V_{loop} was required to maintain I_p



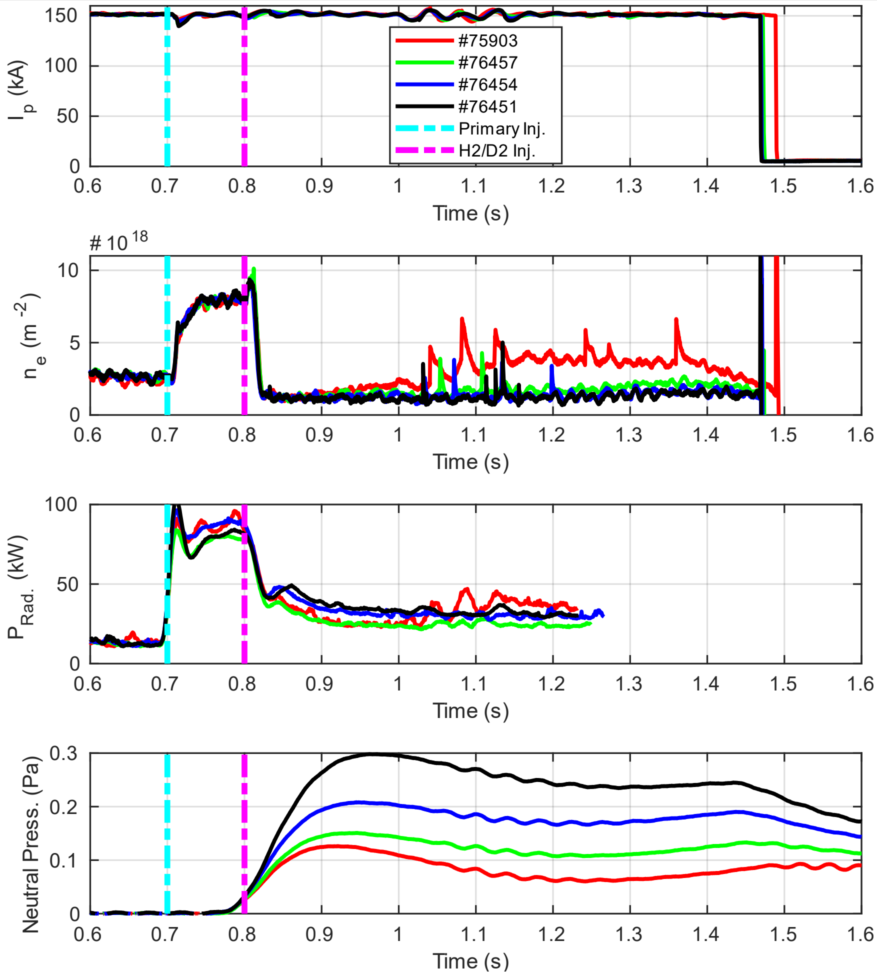
Neutral Pressure Upper Limit (TCV)

- Higher V_{loop} leads to increased E field
- Increases the energy of the RE
  - RE energy may play a role in the benign termination process



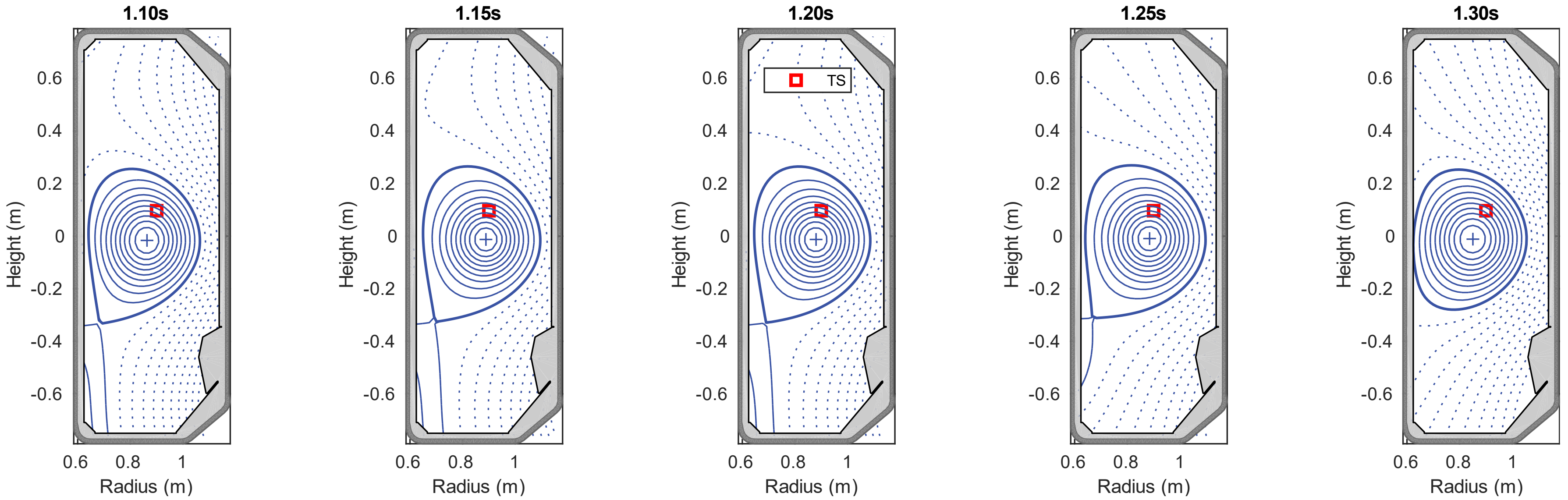
Stable Region After Low-Z Injection

- Neutral pressure maintained through fueling valves
  - Allows steady state conditions
  - Example of Ar/D compressions
- Values averaged over 200ms
  - Between 1.1-1.3s
- Allows investigation into ionization and recombination rates



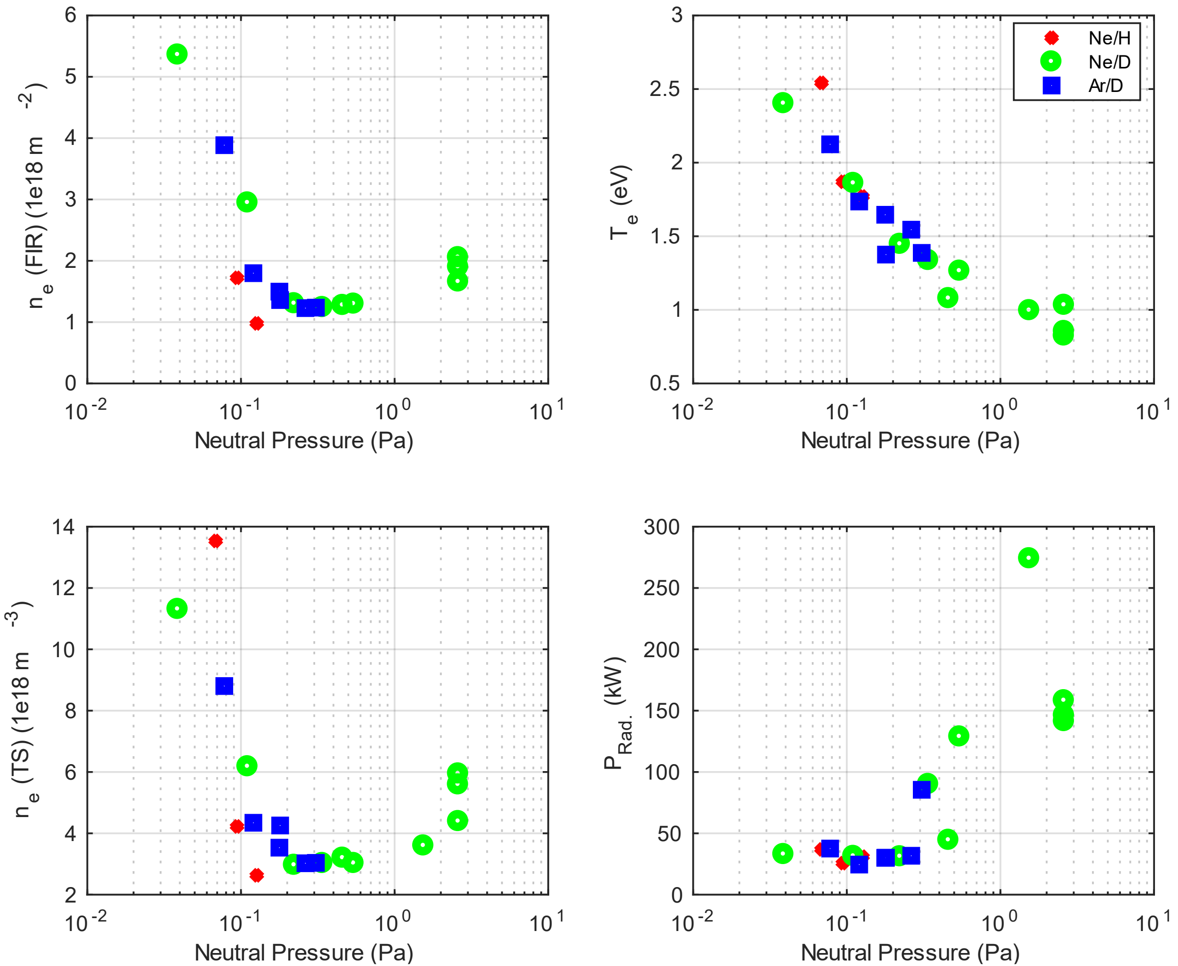
Thomson Scattering Measurements

- Low temperature TS chord near the core
  - Capable of sub eV measurements*
  - Wavelengths: 1025, 1048.5, 1058.4 and 1061.5nm
  - Spectral width: 40, 19, 6.4 and 1.9nm



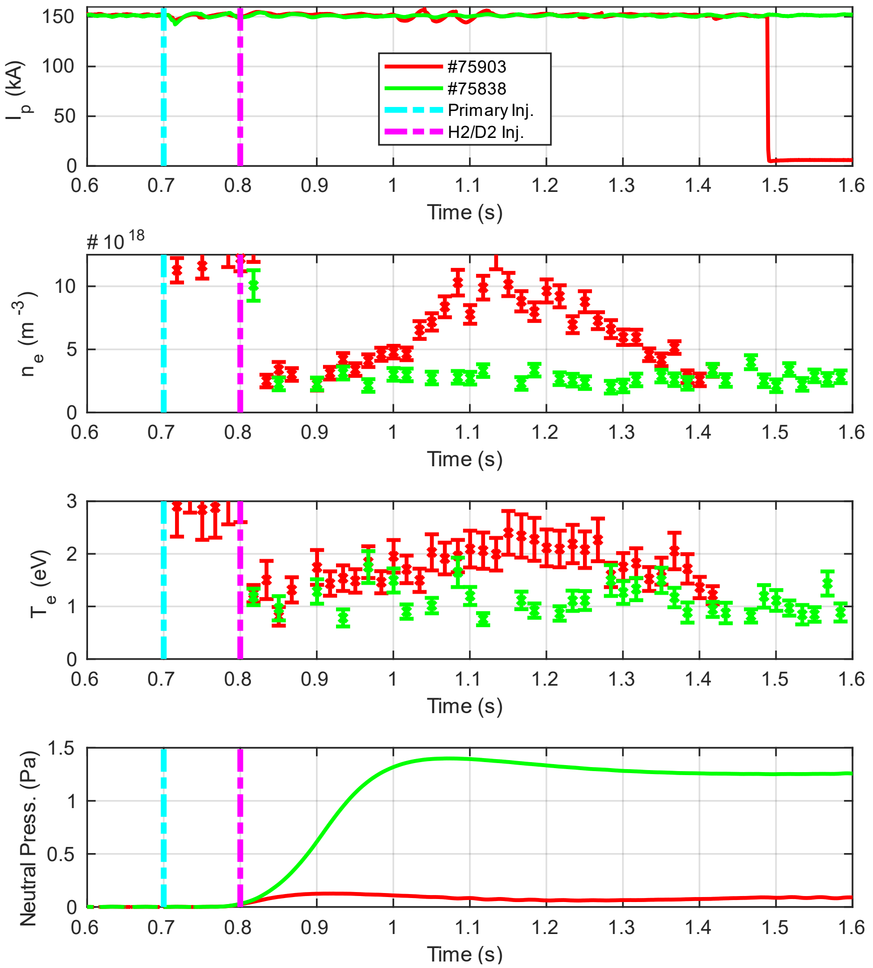
Stable Region After Low-Z Injection

- Temporal averaging shows n_e increase at high NP
  - <u>On both FIR and Thomson diagnostics</u>
- T_e continues to decrease at high NP
- Increased radiated power measured
  - Higher collisionality between REs and neutrals
  - Suspected cause of increased n_e



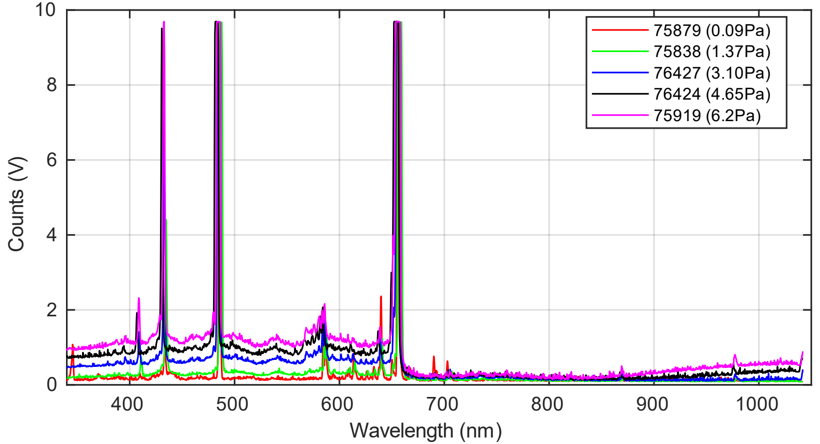
Time Evolution of Thomson

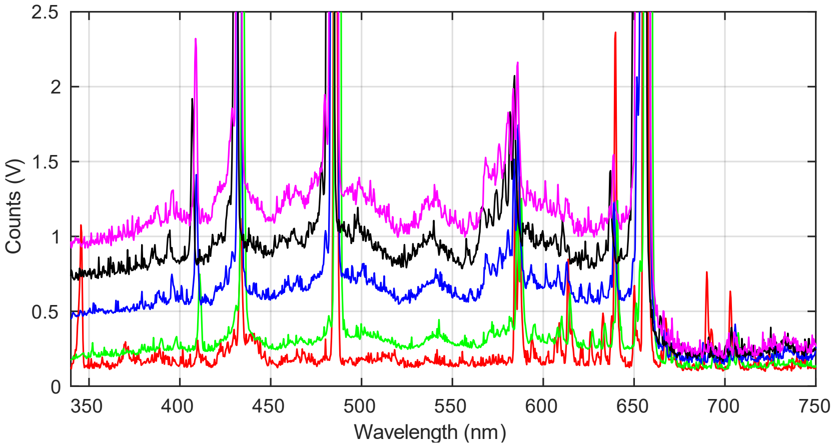
- Clear increase in density during re-ionisation at low NP
  - Low n_e at high NP
- Temperature reduced at high NP for duration of stable time range
  - Reliable measurement
  - Low uncertainty in T_e from automated analysis



Spectroscopy Inferences

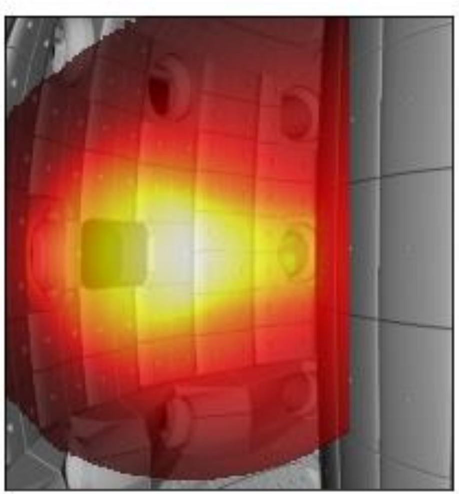
- Increase in continuum (?) spectra at high neutral pressure
  - No increase between 656-900nm
  - Not yet understood (recombination?)
- Molecular emission significant ~5eV
  - Molecular bands expected at ~600nm
  - Below 5eV even at low neutral pressure
- Electron-ion recombination important at T_e ~< 1 eV
  - Seen by increase in high-n Balmer lines intensity





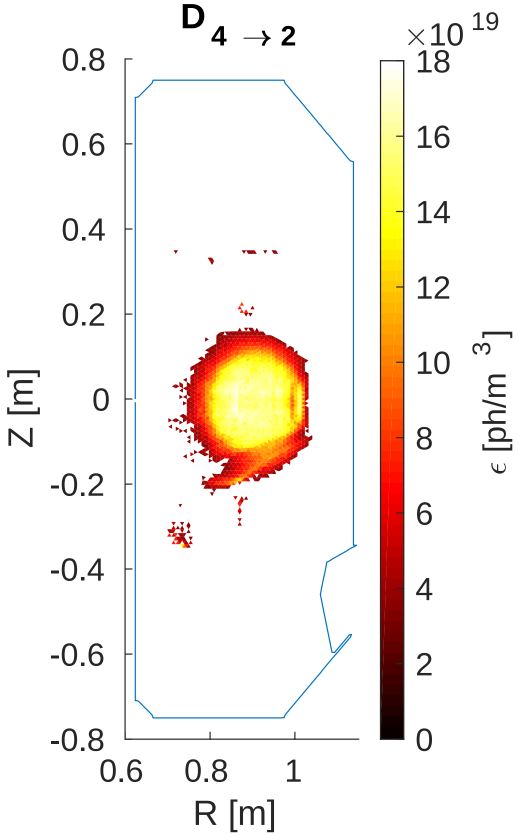
Multispectral Imaging

- MANTIS: filtered imaging
  - Deuterium Balmer emission ($D_{n\to2}$)
  - Neon-I (587, 640 nm)



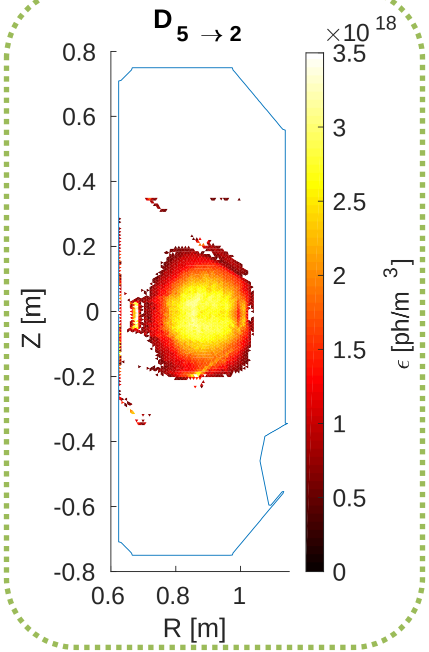
LFS HFS

tomography

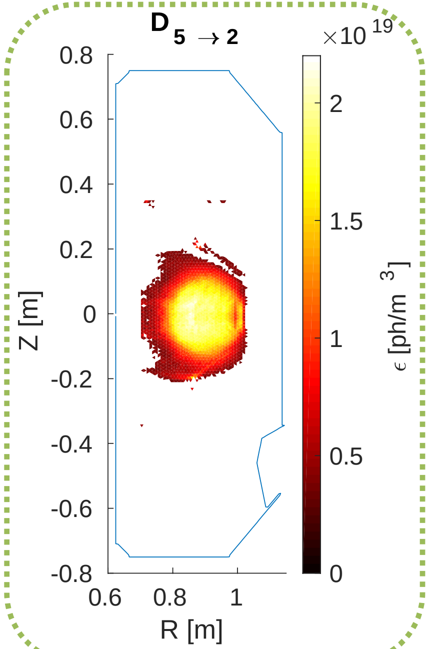


Deuterium Balmer Emission

#75876 (0.22Pa)



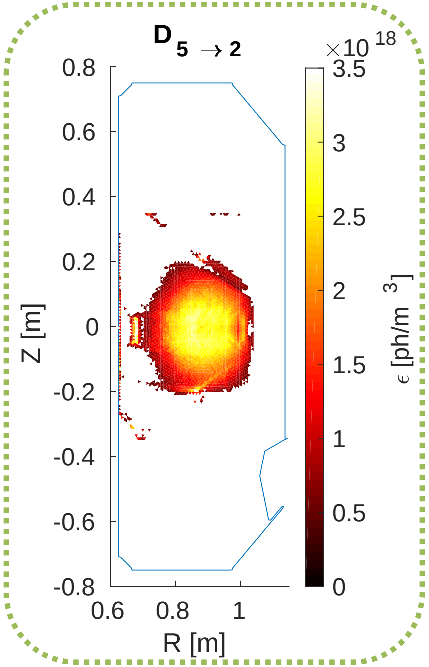
#75919 (6.2Pa)



Balmer emission higher for high pressure (~x6) in line with total radiated power

Deuterium Balmer Emission

#75876 (0.22Pa)



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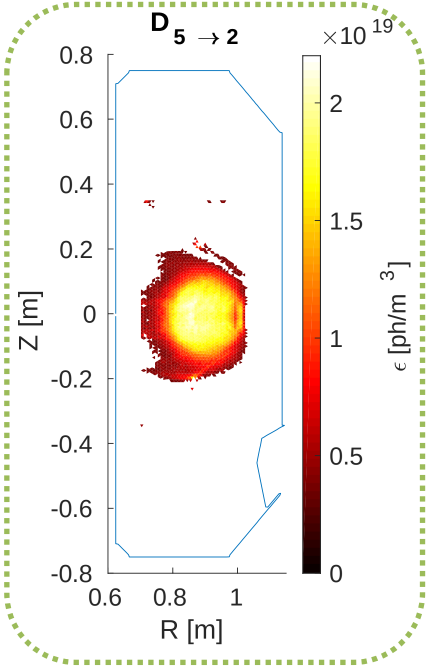

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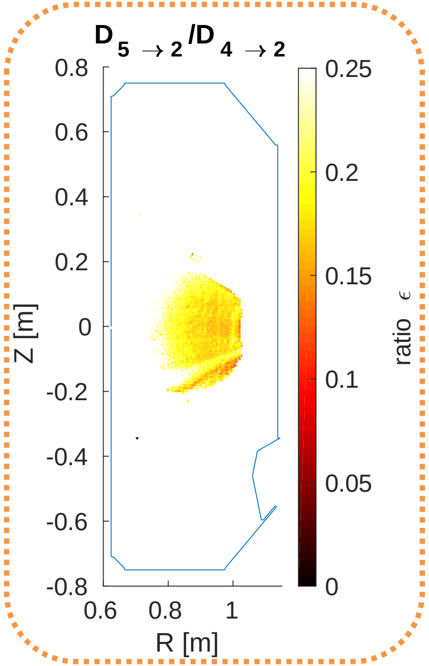

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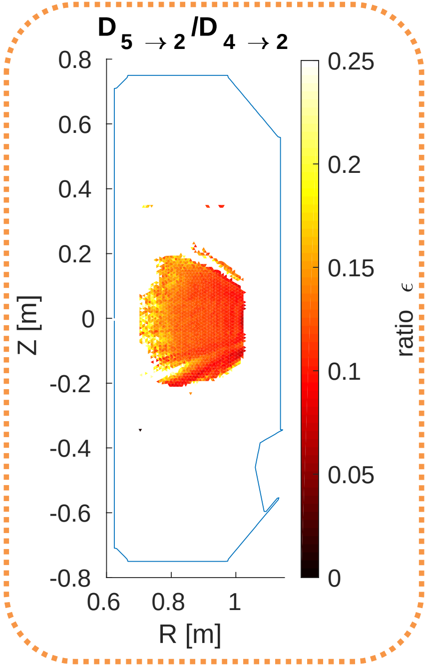
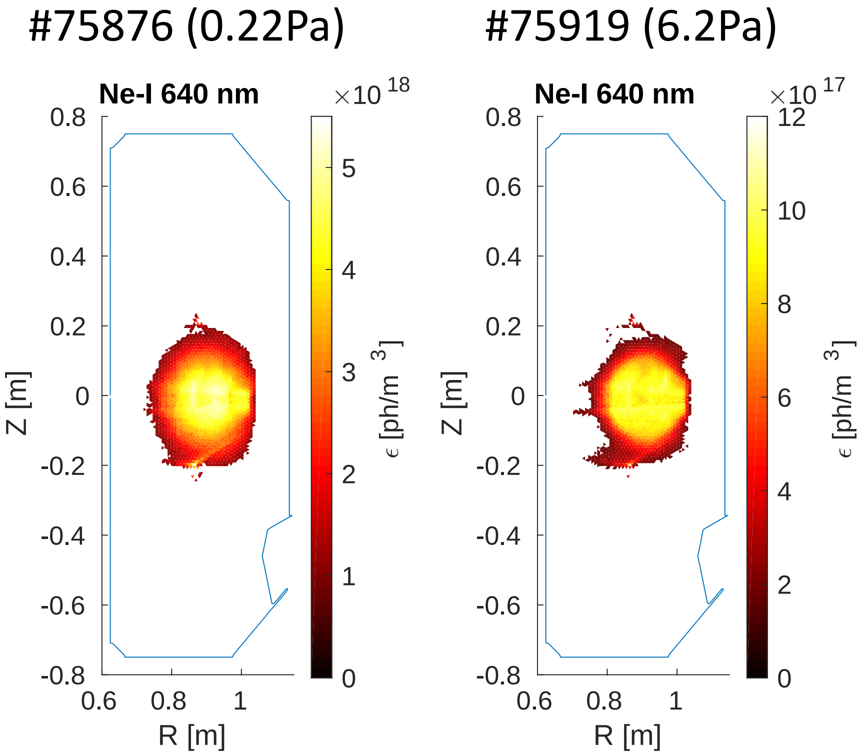


Balmer emission higher for high pressure (~x6) in line with total radiated power

High n lines relatively increased. Suggests increased recombination emission at higher pressure

Ne-I (640 nm) Emission

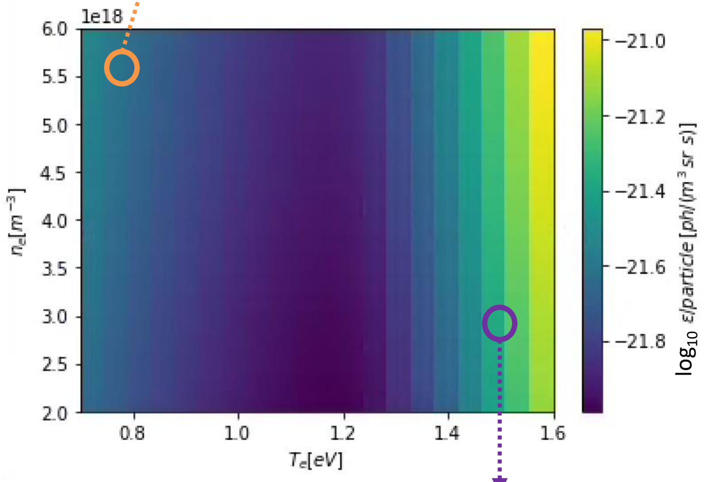
- Ne-I emission expected to peak <2 eV and decrease at lower T_e
  - Below electron-impact ionisation
- 2-5x higher Ne-I emission at lower pressure
- At higher pressure emission is lower despite higher electron density
  - Suggest lower T_e
  - Constant Ne-I content assumed



Ne-I (640 nm) Emission

- Simplified collisional radiative model for illustration
  - RE excitation ignored
  - Ionisation fraction constant
- Reduced Ne-I emission by factor of ~3.75
  - Experimentally measured ~2.5x
- Supports low T_e measurement from TS at high NP

High neutral pressure
$n_e = 3 \cdot 10^{18}$ m^{-3}
$T_e = 0.8$ eV
ϵ/particle $= 1.9 \cdot 10^{-22}$ ph/(m^3 sr s)



Low neutral pressure
$n_e = 5.6 \cdot 10^{18}$ m^{-3}
$T_e = 1.5$ eV
ϵ/particle $= 7.1 \cdot 10^{-22}$ ph/(m^3 sr s)

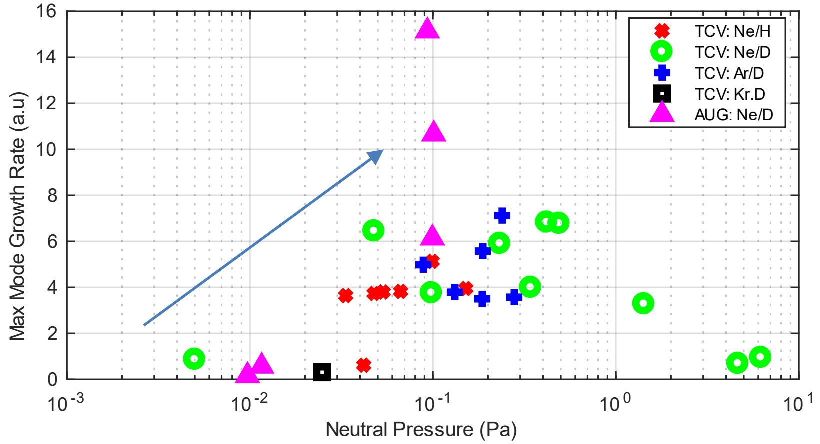
Neutral Pressure Upper Limit

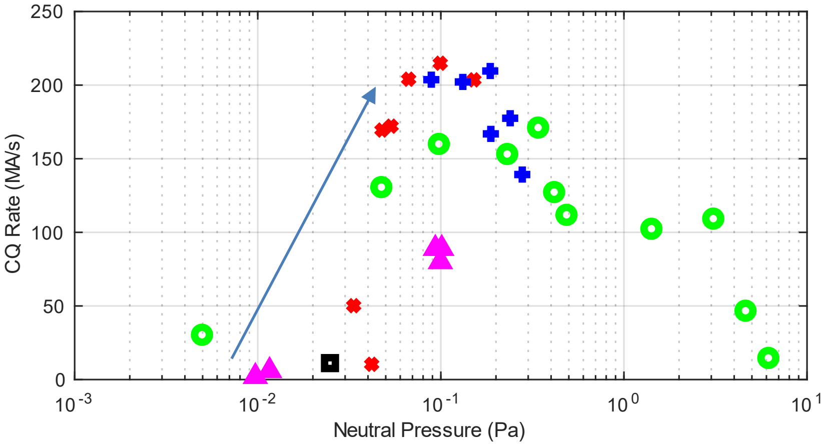
- Summary:
- Benign termination not successful at high neutral pressure
- Density increases at high neutral pressure
- Temperature continues to decrease
- Continuum or molecular spectra not yet understood
- Neon and D Balmer filtered images indicate increased recombination rates at high neutral pressure

Final Collapse

Mode Growth and CQ Rate

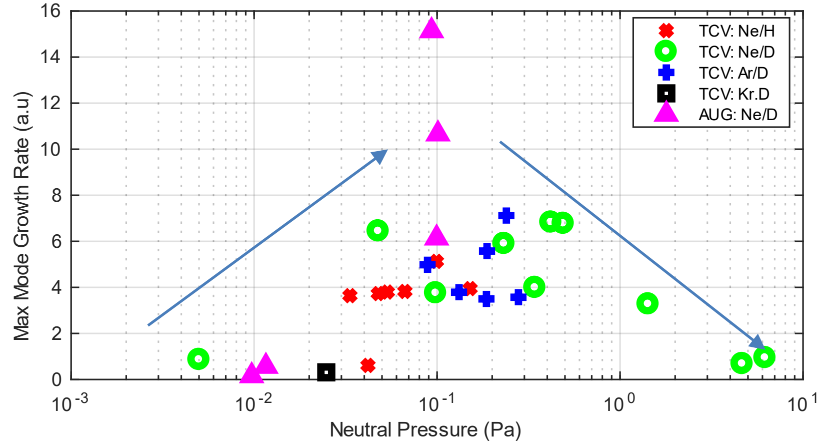
- Mode growth and CQ rates sensitive to neutral pressure
  - Large mode expels REs
    - High Alfvenic velocity at low n_e
  - I_p carried by cold resistive plasma
    - High CQ rate
- AUG data at 200kA

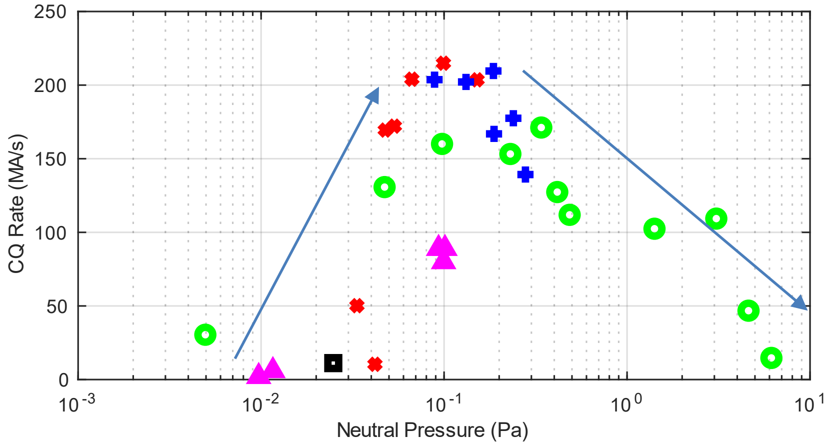




Mode Growth and CQ Rate

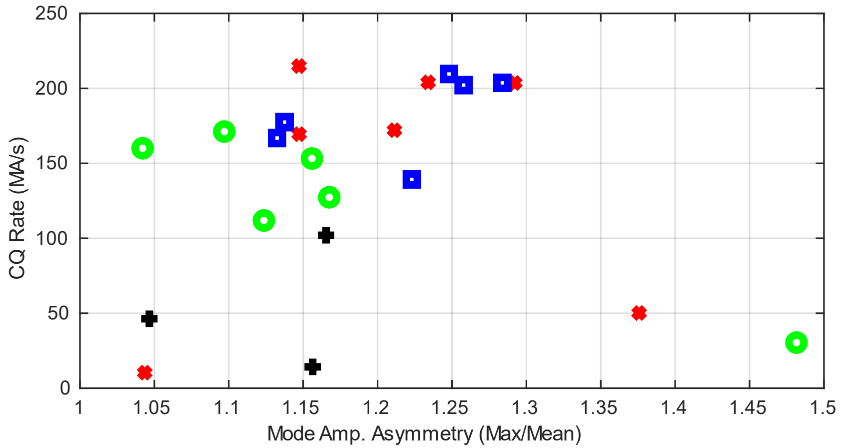
- Rollover observed at higher neutral pressure on TCV
  - Stable region analysis suggests this may be linked to increased density
- Further experiments planned
  - Stable periods for enhanced density measurements
  - Upper limit threshold in Ar

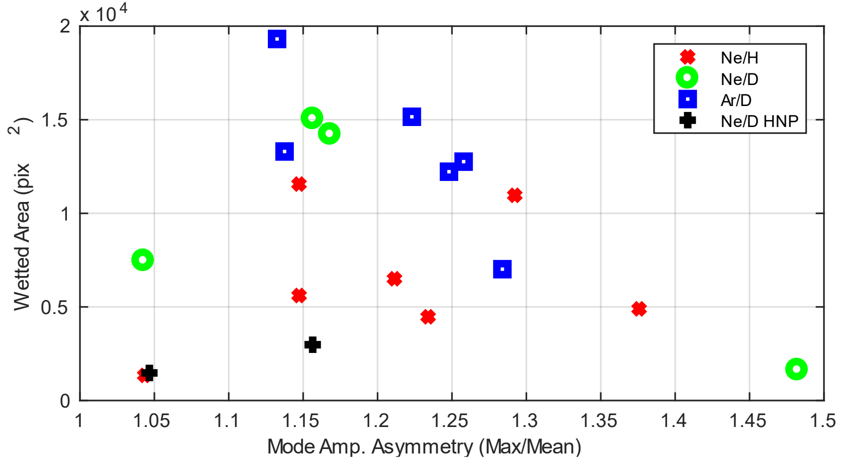




Mode Asymmetries

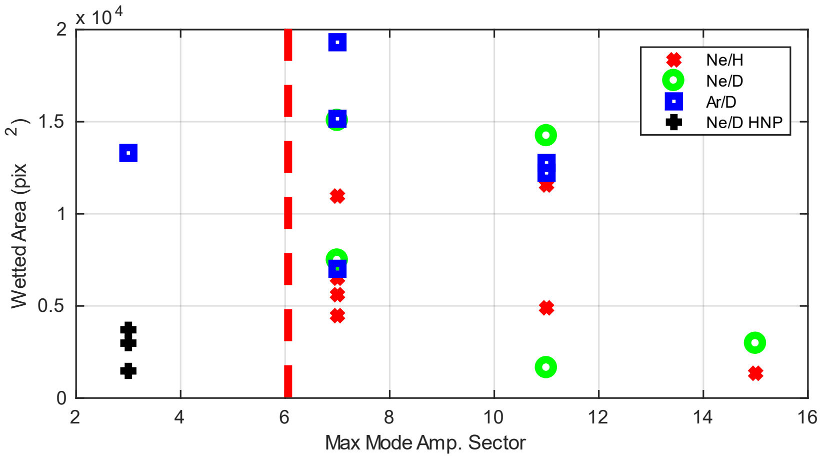
- TCV has a full magnetics suite in four sectors
  - Equally spaced toroidally
- Mode asymmetry higher at large CQ rate
  - Higher asymmetry for benign terminations
- No correlation with wetted area
  - Due to fixed location of IR measurement

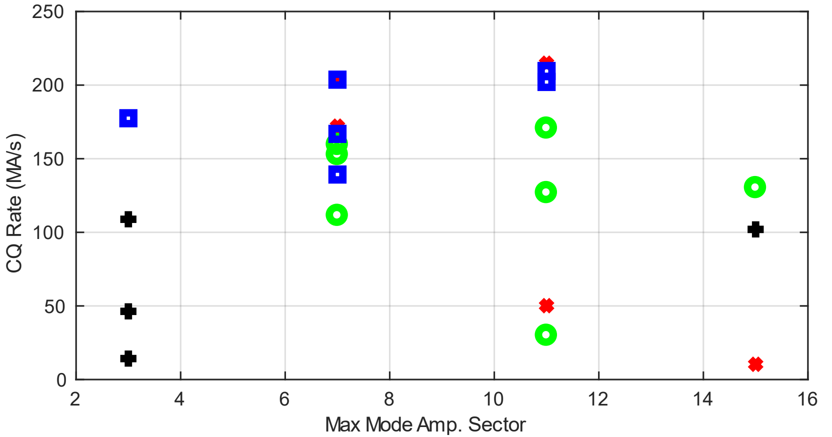




Mode Asymmetries

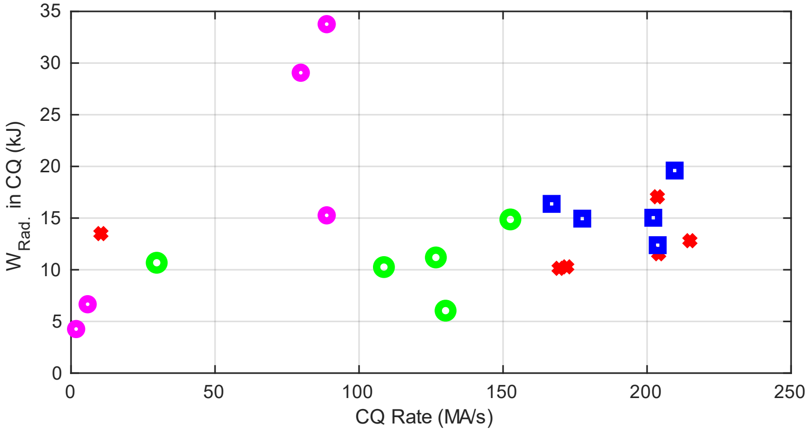
- IR camera used to measure wetted area is in sector 6
- Max mode amp sector weakly correlates with wetted area
  - Suggests heat flux footprint is not completely toroidally asymmetric
  - Experiments planned to study this
- CQ rate and sector with max mode amp do not correlate
  - Benign termination can be achieved with max mode in any sector

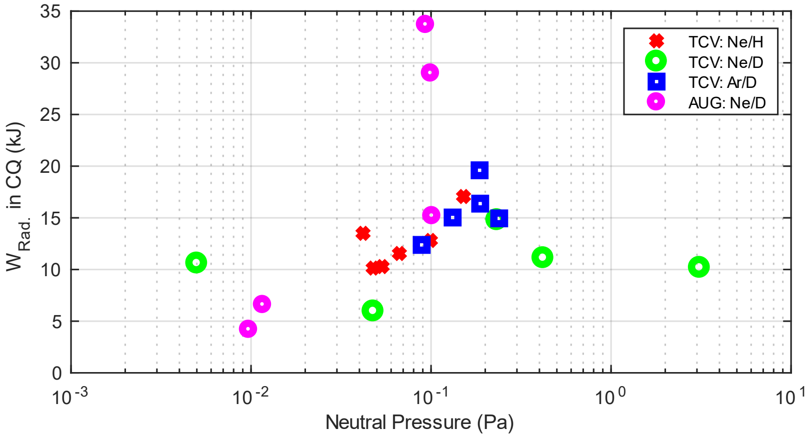




Conversion of W_{Mag} to W_{Rad}

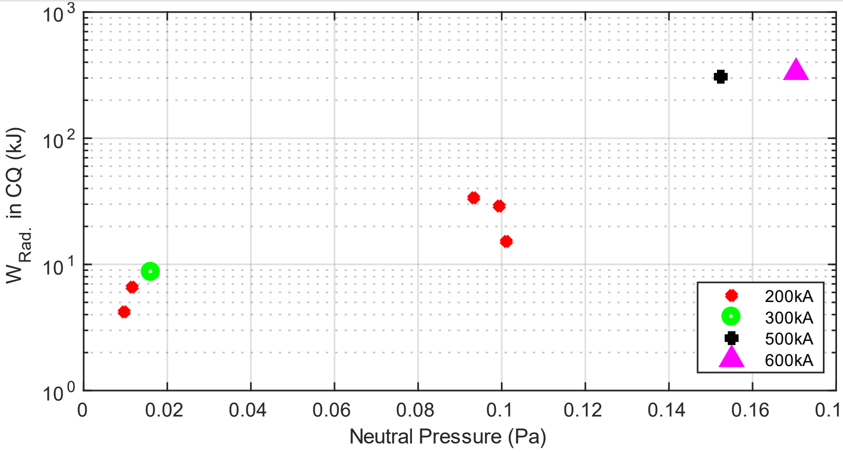
- Higher conversion of magnetic energy to radiated energy at high CQ rate
  - Faster energy loss
- Increased conversion of magnetic energy to radiation with increasing neutral pressure
  - Rollover at high neutral pressure
  - Limitations to bolometers at high neutral pressure

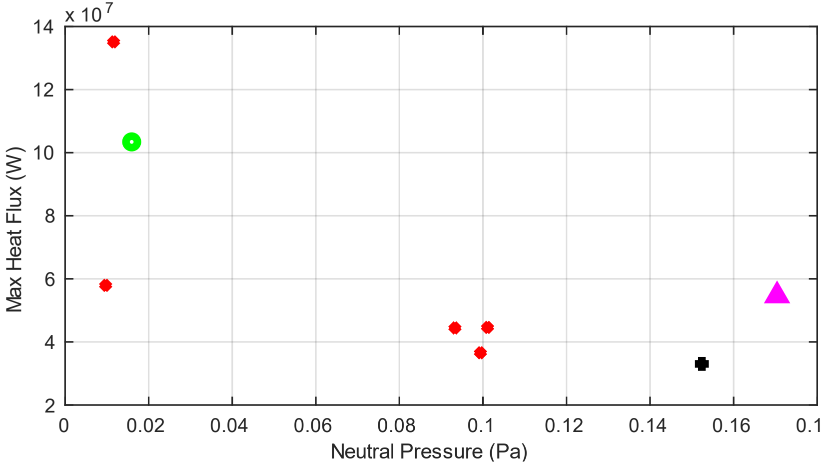




Conversion of W_{Mag} to W_{Rad}

- Increased radiated energy at higher current
  - Higher magnetic energy (I_p^2)
- Maximum heat flux significantly reduced
  - Low heat flux maintained from 200kA to 600kA
  - Inferences using THEODOR
    - Extrapolation over saturation
  - <u>Preliminary results</u>





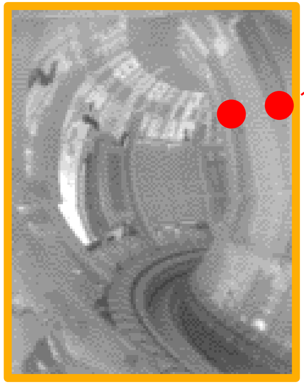
Final Collapse

- Summary:
- Mode growth rate linked to increasing wetted area
  - Roll over seen at high neutral pressure
- Conversion of magnetic energy to radiated energy evident in benign termination
  - Heat flux remains low at high plasma current on AUG
- Max mode amplitude sector varies on TCV
  - Need to further investigate toroidal heat flux variance

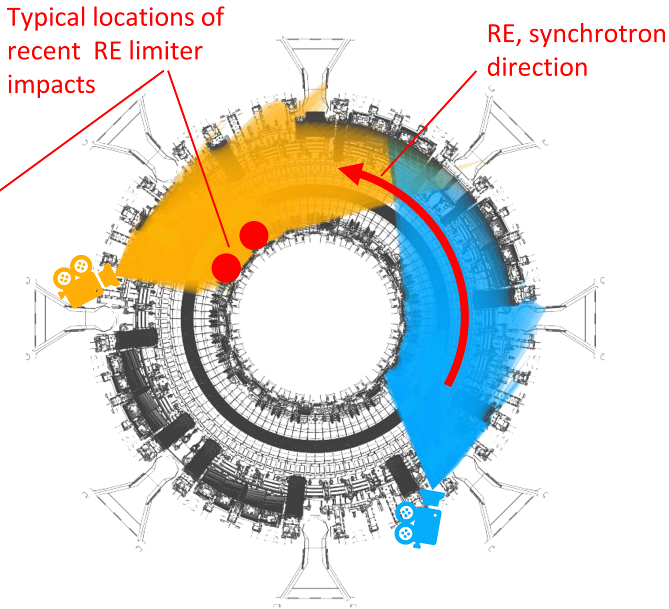
Heat Flux Inferences

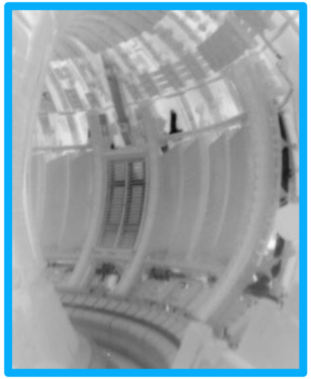
Wide angle IR Cameras on JET

- Wide angle medium-wave IR cameras on JET looking in both toroidal directions:



KLDT-E5WC
~1kHz frame rate



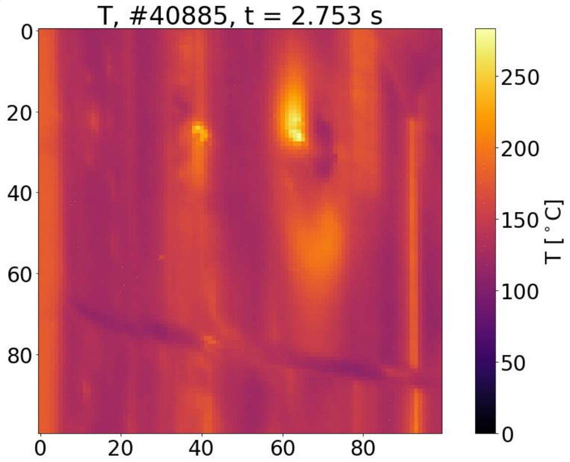


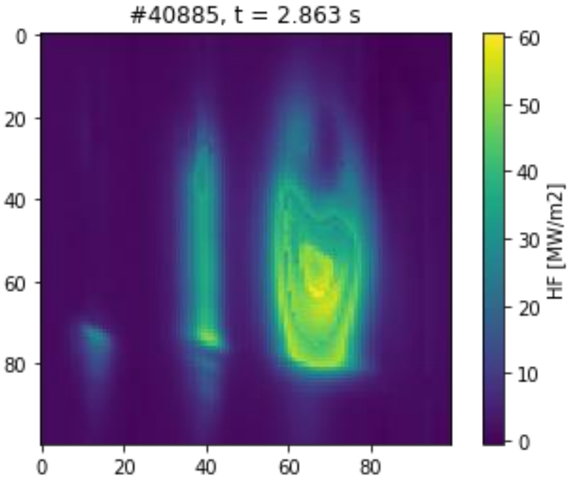
KL7-E8WB
~100Hz frame rate

- Most recent non-benign terminations impact the walls in the KLDT-E5WC (left) view which also has higher time resolution (1kHz) – analysis concentrated on this data

IR Thermography to Heat Flux

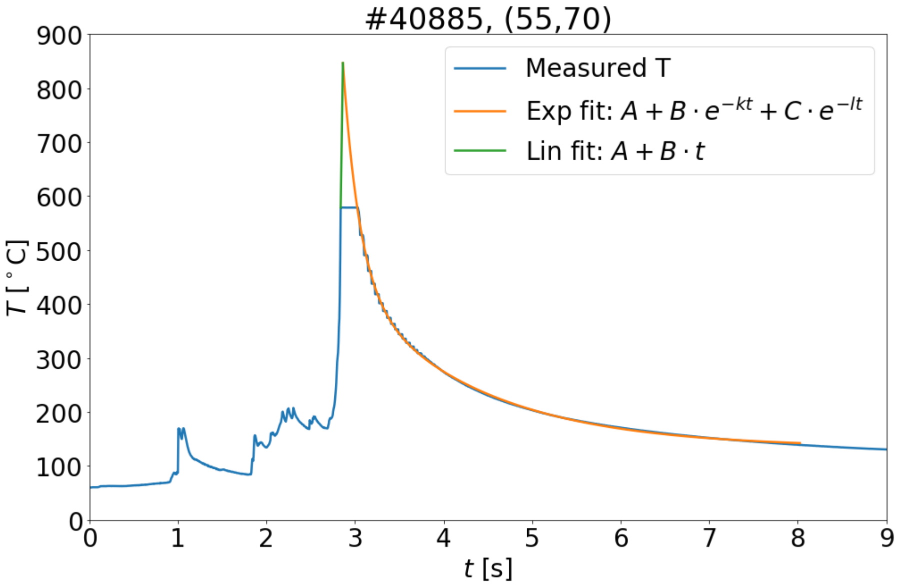
- THEODOR used to compute heat flux using evolution of temperature
  - Heat flux computed in 1D in poloidal plane
  - 2D image created via composition of 1D profiles
    - Diffusion across tiles negligible
- Uncertainties due to
  - Emissivity of tiles and plasma emission
  - Heat transmission from surface
  - Vessel temperature





Challenges Specific to REs

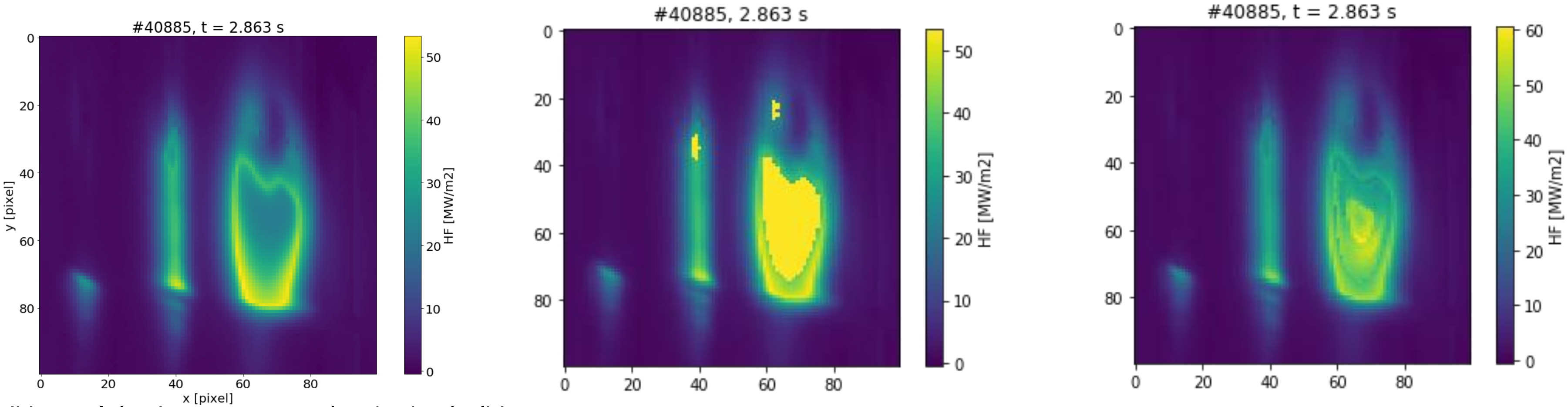
- Saturation due to high temperatures
- Two methods explored:
  - Saturated pixels replaced with maximum HF from current frame
  - Interpolation of temperature for each saturated pixel
    - Exponential fit from cooling
    - Linear fit from heating



Challenges Specific to REs

- Saturation due to high temperatures
- Two methods explored:
  - Saturated pixels replaced with maximum HF from current frame
  - Interpolation of temperature for each saturated pixel

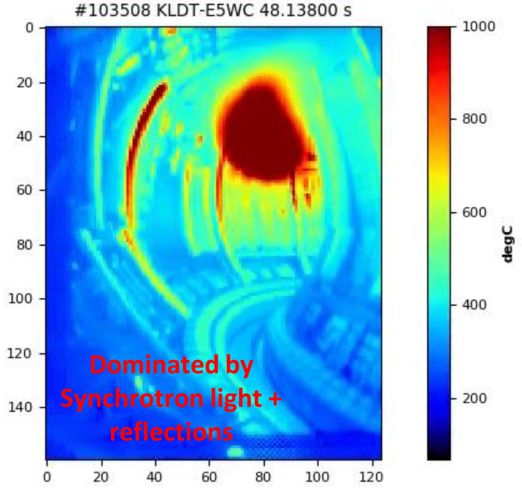
Saturated pixels | Max. heat flux | Interpolation



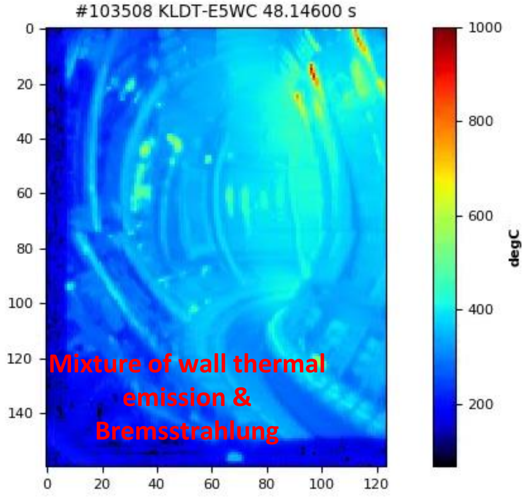
Challenges Specific to REs

- Blinding through synchrotron emission from REs
- No solution possible during RE beam
- Can use only frames after RE expulsion

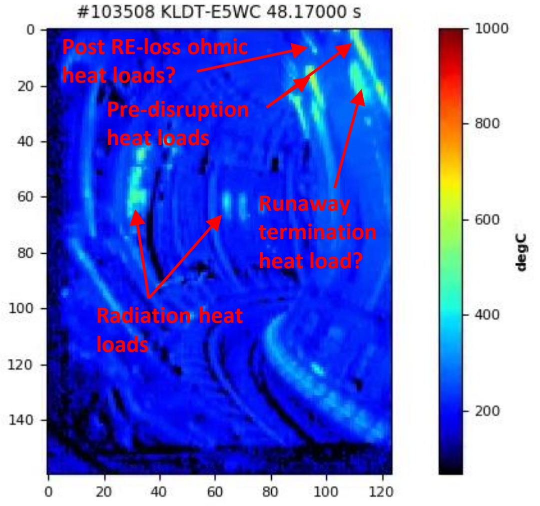
During RE beam



During benign termination



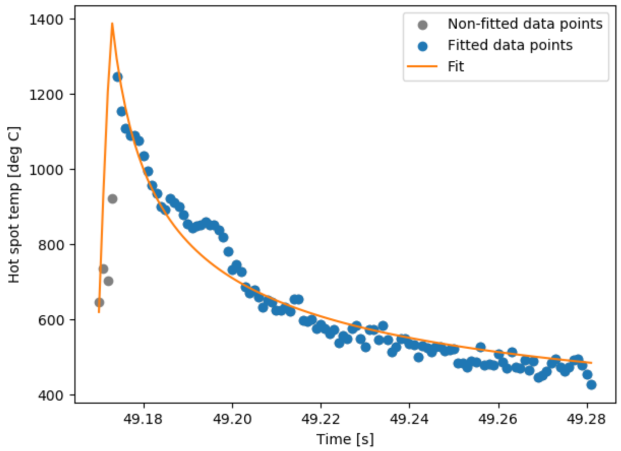
After benign termination



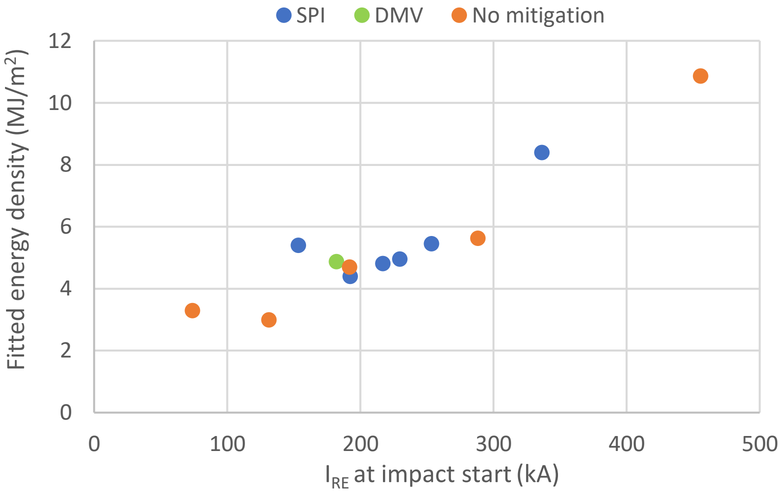
Challenges Specific to REs

- Blinding through synchrotron emission from REs
  - For non-benign cases with visible hot-spots, fit cool-down curve of the hot-spot against a model of heat deposition and 1D heat conduction into the tile to estimate the energy density

Example hot-spot cooldown fit from JPN 94554

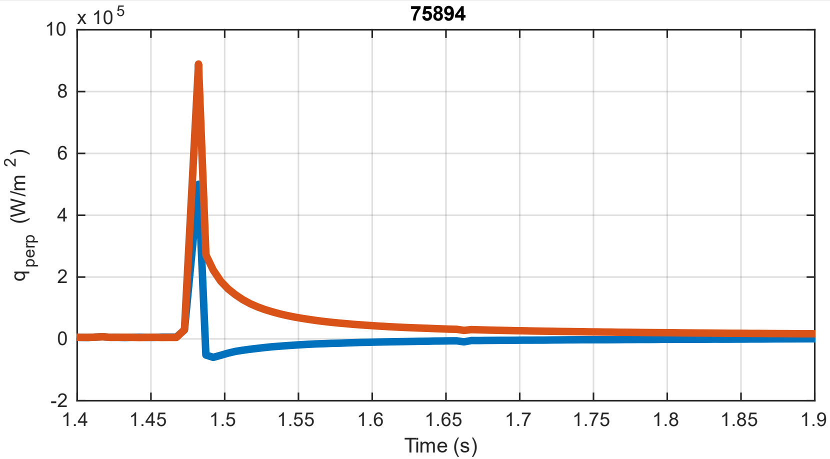


Estimated wall energy density for non-benign termination cases



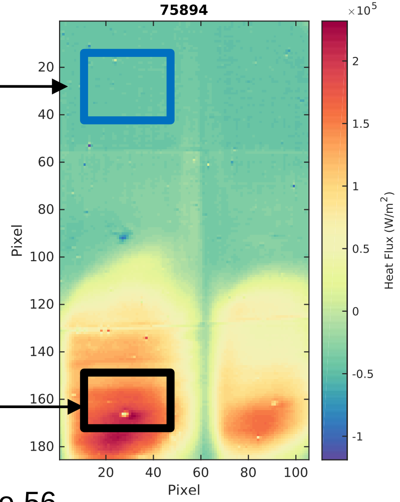
Challenges Specific to REs

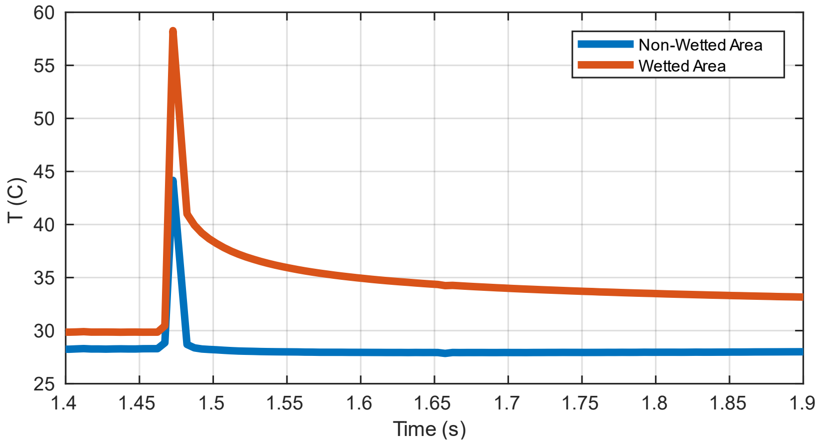
- Variation in heat transfer rate
  - Due to deep deposition of energy
  - Appears as post disruption heating
- Negative values in non-wetted area due to radiation flash



Non-wetted area

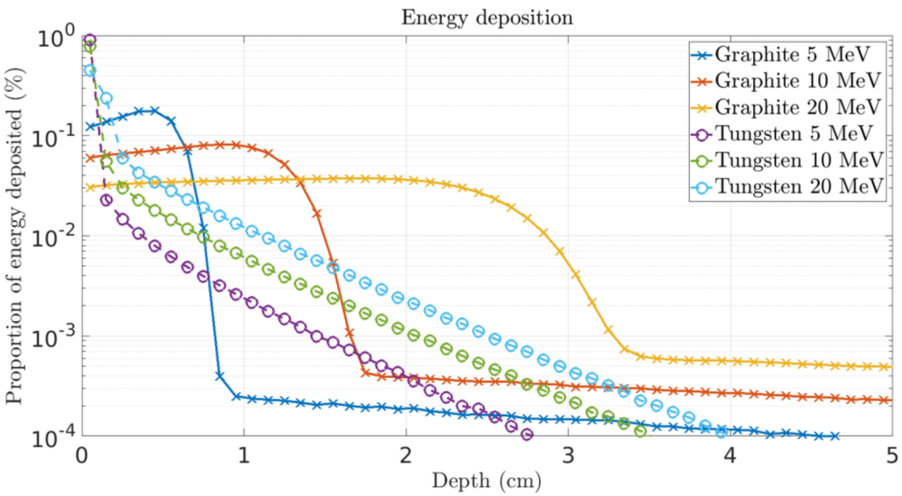
Wetted area

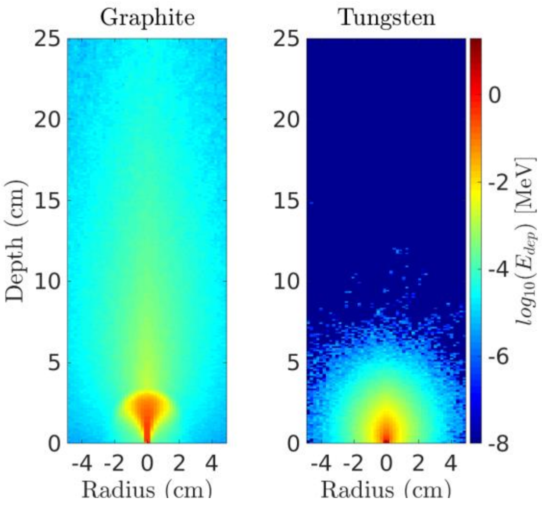




RE Energy Deposition Depth

- Geant4 simulations used to simulate energy deposition in first wall of tungsten or carbon and generation of HXRs
- Point source of mono-energetic electrons impacting a semi-infinite slab (20MeV example)





Conclusions

Conclusions

- Benign termination operational domain explored
  - Requirements for recombination are a non-linear function of species, quantity and plasma current
    - Power balance model being developed -> need for extrapolation to ITER
    - Agnostic to H/D injection method and path to low q_{edge}
    - Density increases at high neutral pressure, could be limiting factor
      - T_e continues to decrease (TS and spectroscopy)
- Wetted area scales with neutral pressure
  - High mode growth and CQ rates in benign terminations
    - Conversion of magnetic energy to radiated power
    - Rollover at high neutral pressure
- Challenges of heat flux inferences with REs are being overcome
- Analysis and modelling underway to extrapolate to ITER

Thank you!