Disruption and Runaway Electron Mitigation with Massive Gas Injection in DIII-D

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GENERAL ATOMICS

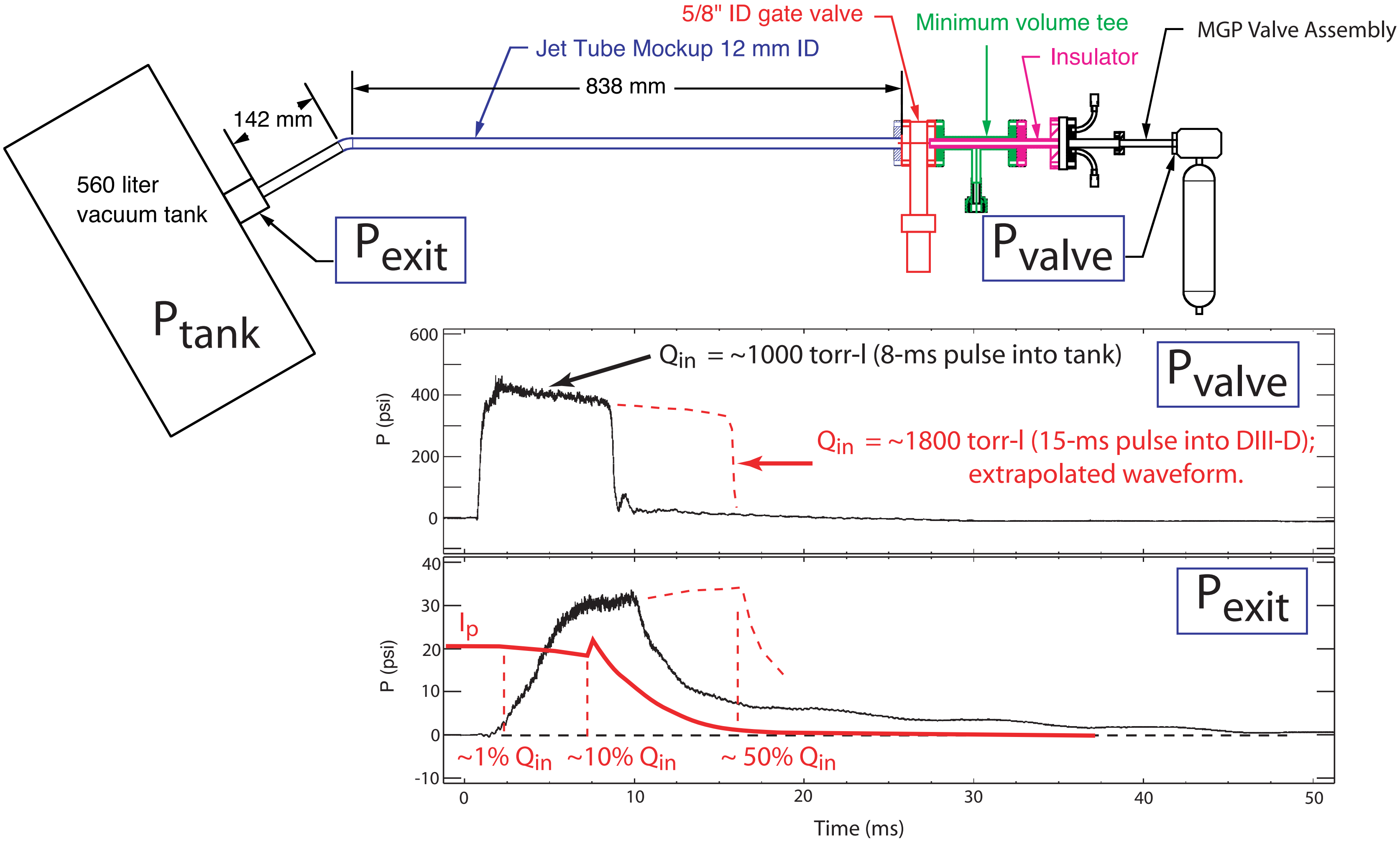
Motivation for Massive Gas Injection (MGI) Experiments

- **Disruptions can damage in-vessel structures and PFC surfaces in large tokamaks**
  - Localized thermal energy loads to divertor and FW PFCs
  - Eddy-current forces and torques on vacuum vessel and in-vessel components (d*I*/dt, halo currents)
  - Impact of runaway electrons **(Coulomb avalanche!)**
- **MGI is promising approach for disruption mitigation (rapid shutdown in event of unavoidable disruption)**
  - Easy to install and implement; fast response; reliable
  - Works well for divertor and HC mitigation in present tokamaks (AUG, C-Mod, DIII-D, JT60-U, TEXTOR, ….)
  - Effectiveness in larger/higher-energy future tokamaks and for RE mitigation still under study **($n_e \rightarrow n_{crit}$?)**

2004–2005 DIII-D Experiments Have Elucidated MGI Shutdown Sequence and Mechanisms

- **Gas delivery pulse shape important**
  - Leading edge of gas effects shutdown
- **Neutrals stop at plasma edge**
  - Shown for wide range of DIII-D target plasmas
  - Data suggests role of magnetic ($B^2/2\mu_o$) pressure
- **MHD effects "mixing" of core W_{th} and edge-delivered impurities**
  - Initiated by destabilization of m=2; accelerated by destabilization of m=1; result = ~100% radiation of W_{th}
- **Lack of runaway electrons (RE) not due to collisional suppression**
  - Too few impurities (electrons) added to suppress RE avalanche
  - Assimilation fraction for injected gas/electrons less than unity

ORNL Tests Show ~10 ms Exit Pressure Rise Time (Ar)

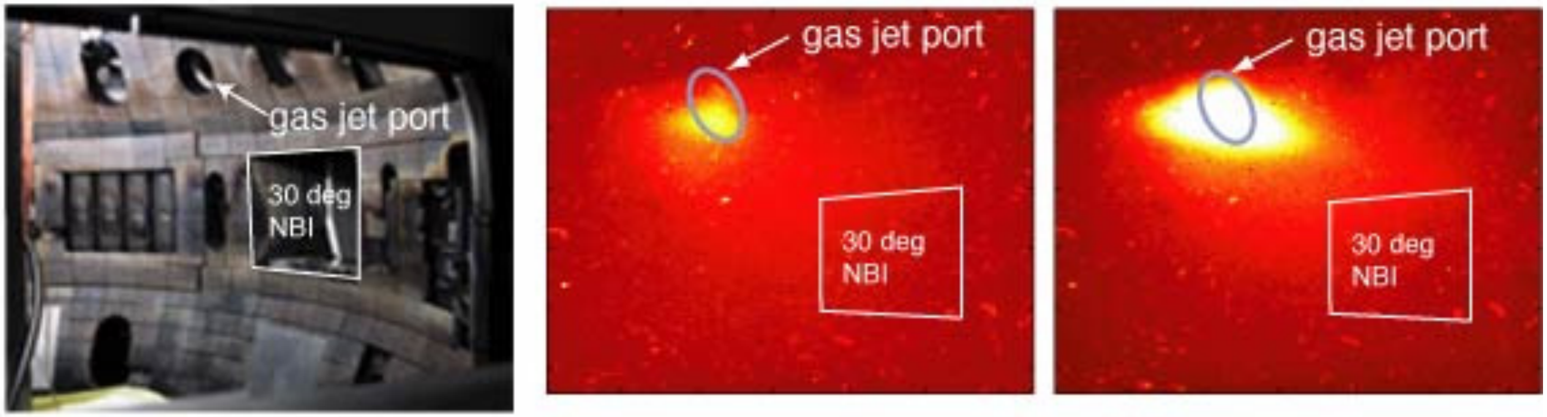


Gas valve pressure

Tube exit pressure

Fast Camera Imaging: Jet Does Not Penetrate More Than a Few Centimeters

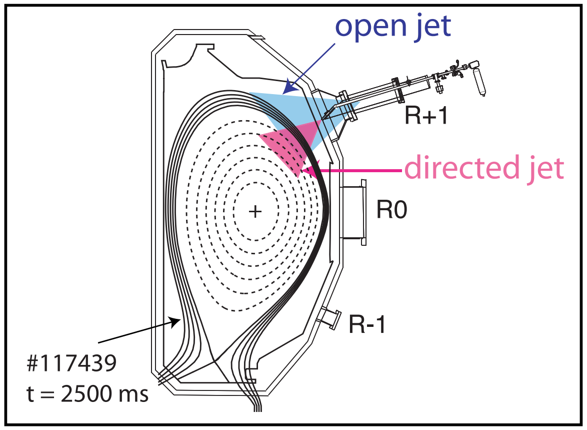
- Ar_I images show surface-localized ionization + along-*B* streaming

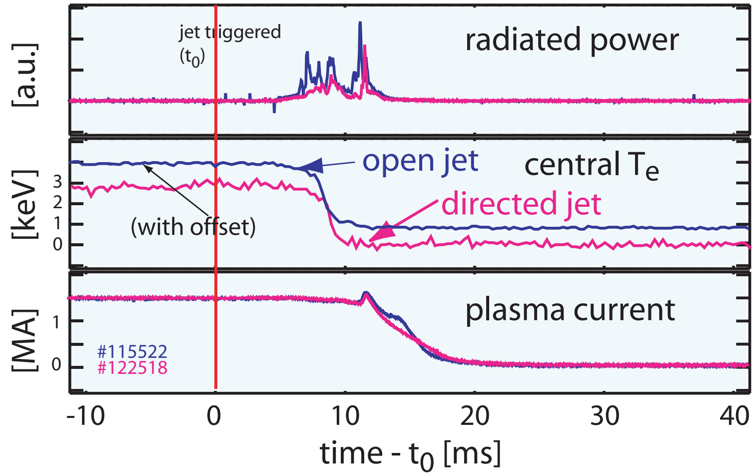


- Thomson scattering T_e profiles, radiated power profiles, and current profile contraction data all confirm optical observations of only minimal neutral penetration
- No increase in penetration for B_T = 0.5 T, $W_{th} \approx 0$, or ~5 eV CQ plasma
- No difference in penetration for directed jet vs. open jet

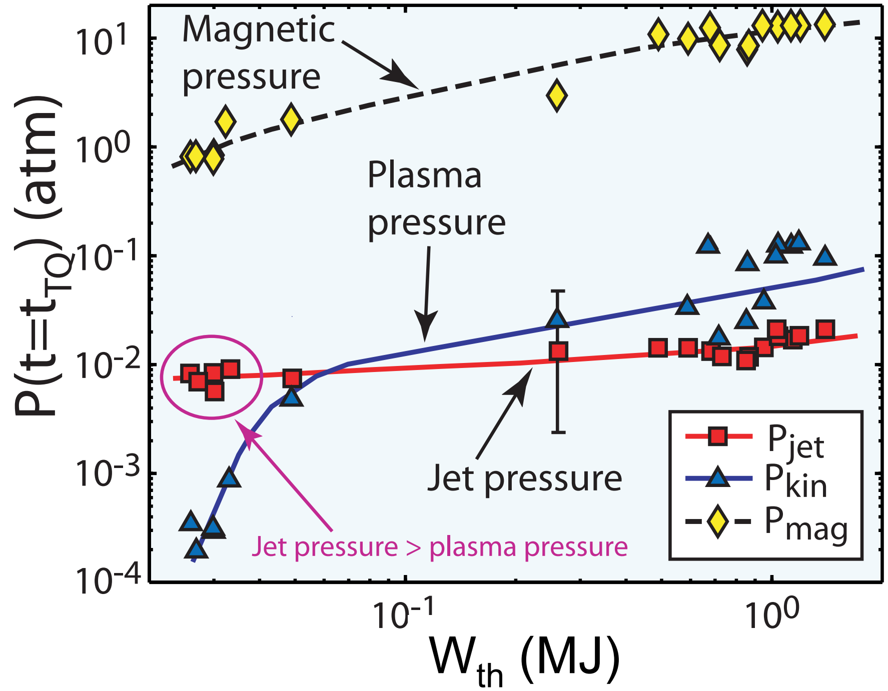
Jet and Target Plasma Variations Have Little Effect

- **Diffuse vs. focused jet doesn't change shutdown effect**





- **Varied target plasma W_{th}, B_T, q_{95}: jet always stops at plasma edge**
- **Jet stops at edge, even for jet pressure >> local plasma pressure: implies magnetic pressure contributes to (dominates) neutral stopping**



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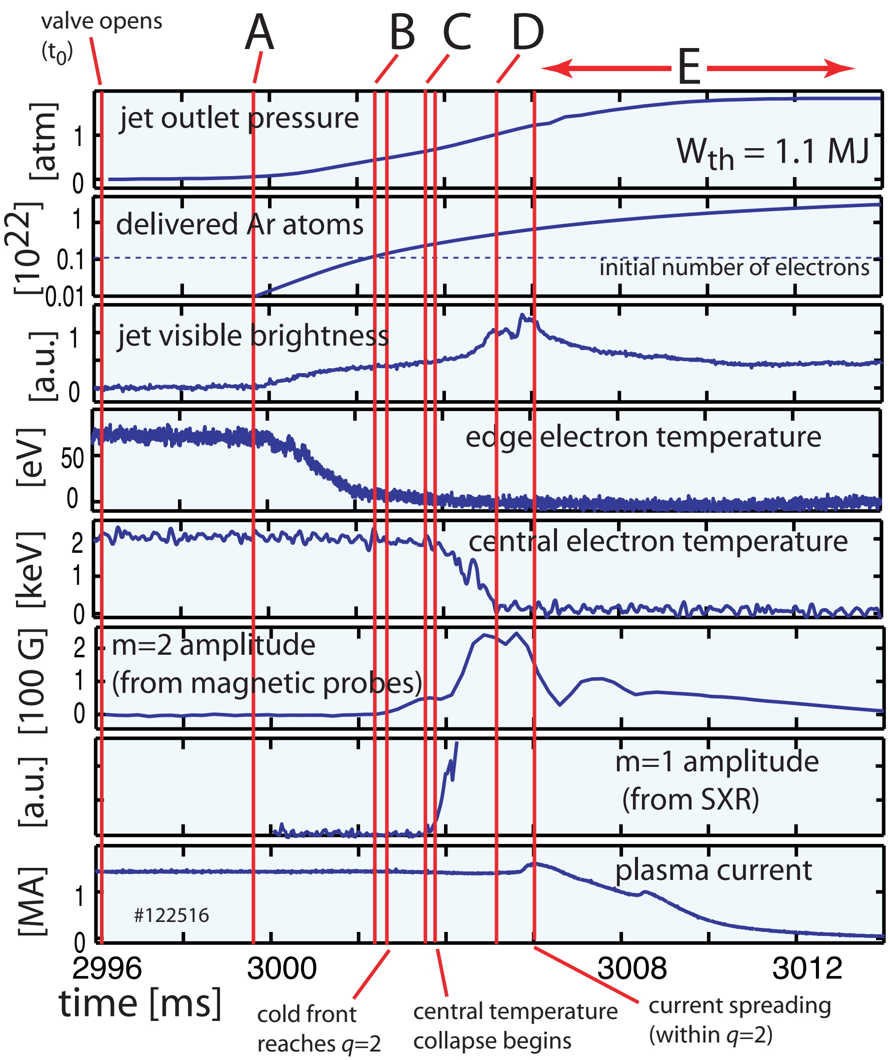
Gas Surface Fueling + MHD Mixing Cause a Radiative Dissipation of W_{th} that is Followed by a Fast CQ



A) **Gas reaches plasma edge**. Ar radiation cooling produces edge $j(r)$ reduction and high edge dj/dr

B) ***m*=2 destabilized**; Ar ions mixed inward, $j(r)$ contraction continues

C) ***m*=1 destabilized**; central W_{th} begins to be transported to cold radiating edge region (**radiating "shell"**)

D) **Core W_{th} radiation is complete** ~5 ms after "first gas"; rapid internal ($q \leq 2$) current spreading follows (I_p spike)

E) **"Fast" ~5-ms CQ**, consistent with low T_e (~5 eV), hence **low I_{halo}** and **low halo current TPF** (toroidal peaking factor)

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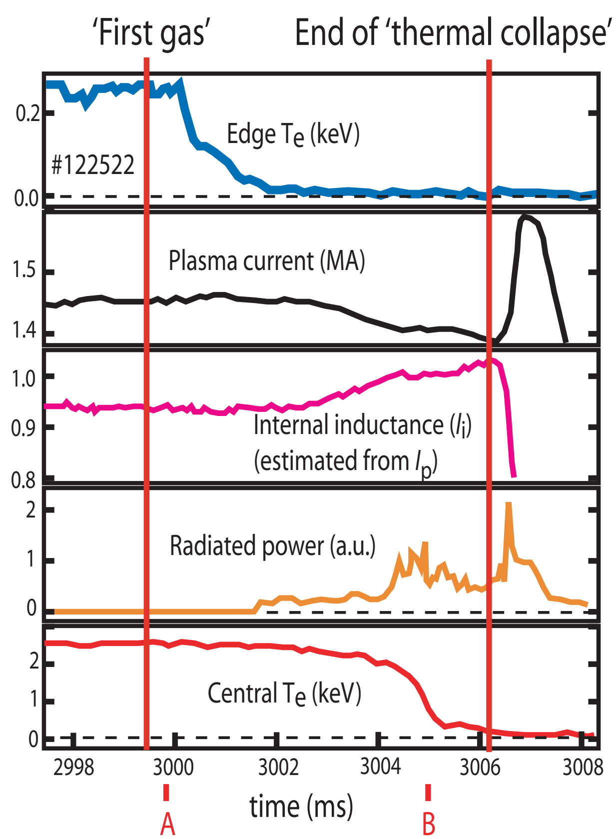
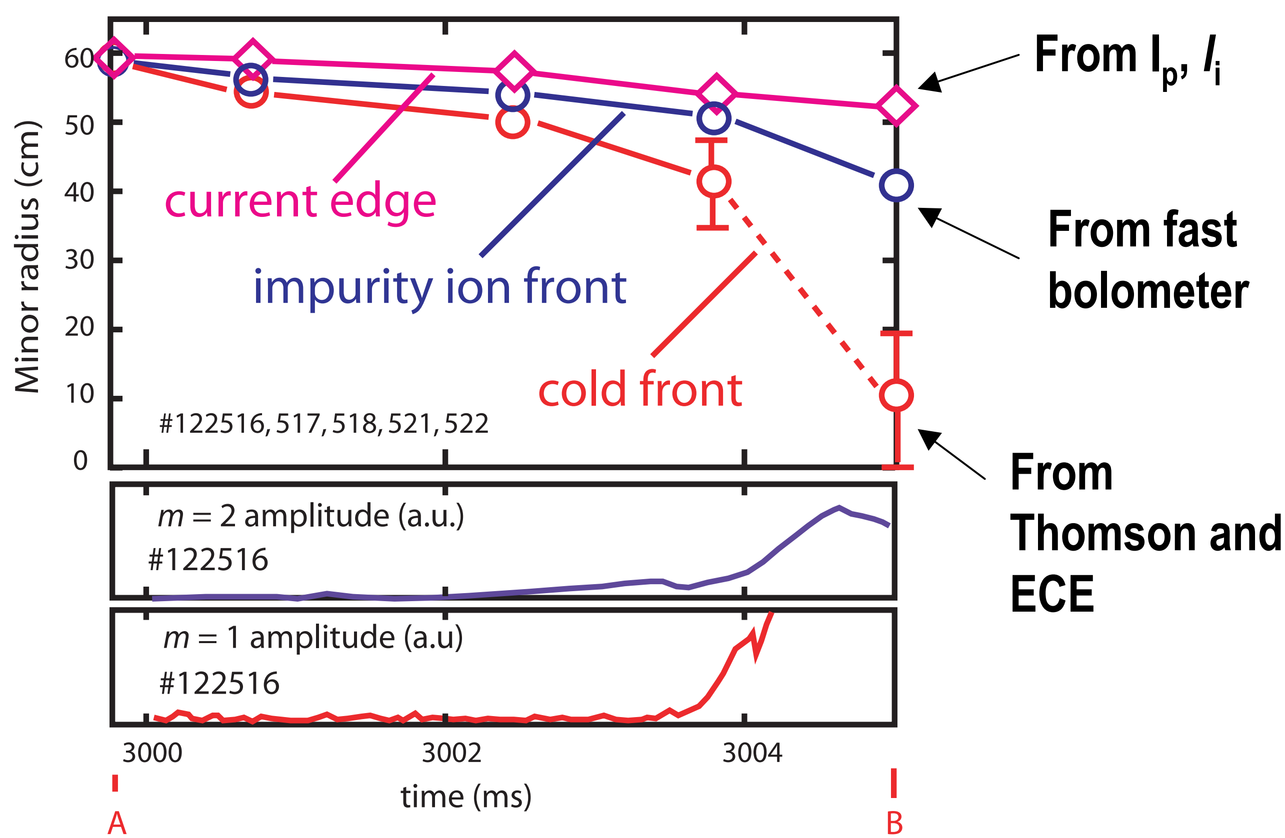
Profile data: radial propagation of the T_e 'cold front' precedes the inward propagation of argon ions



Radial propagation estimates



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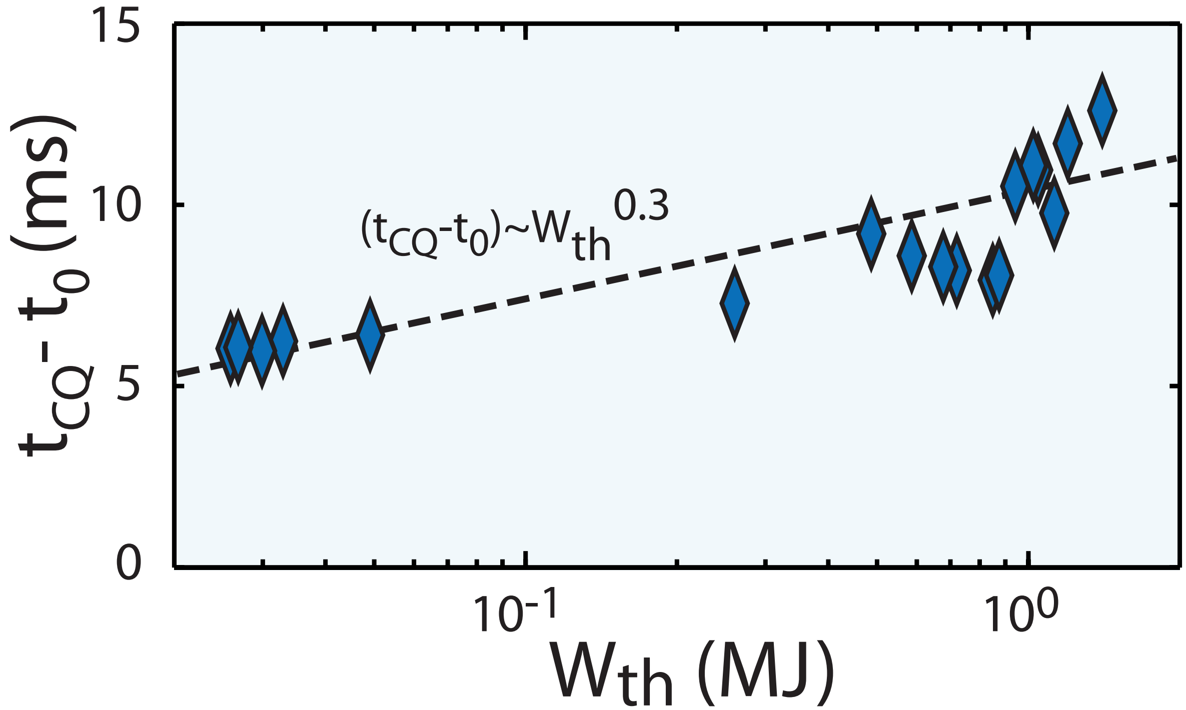
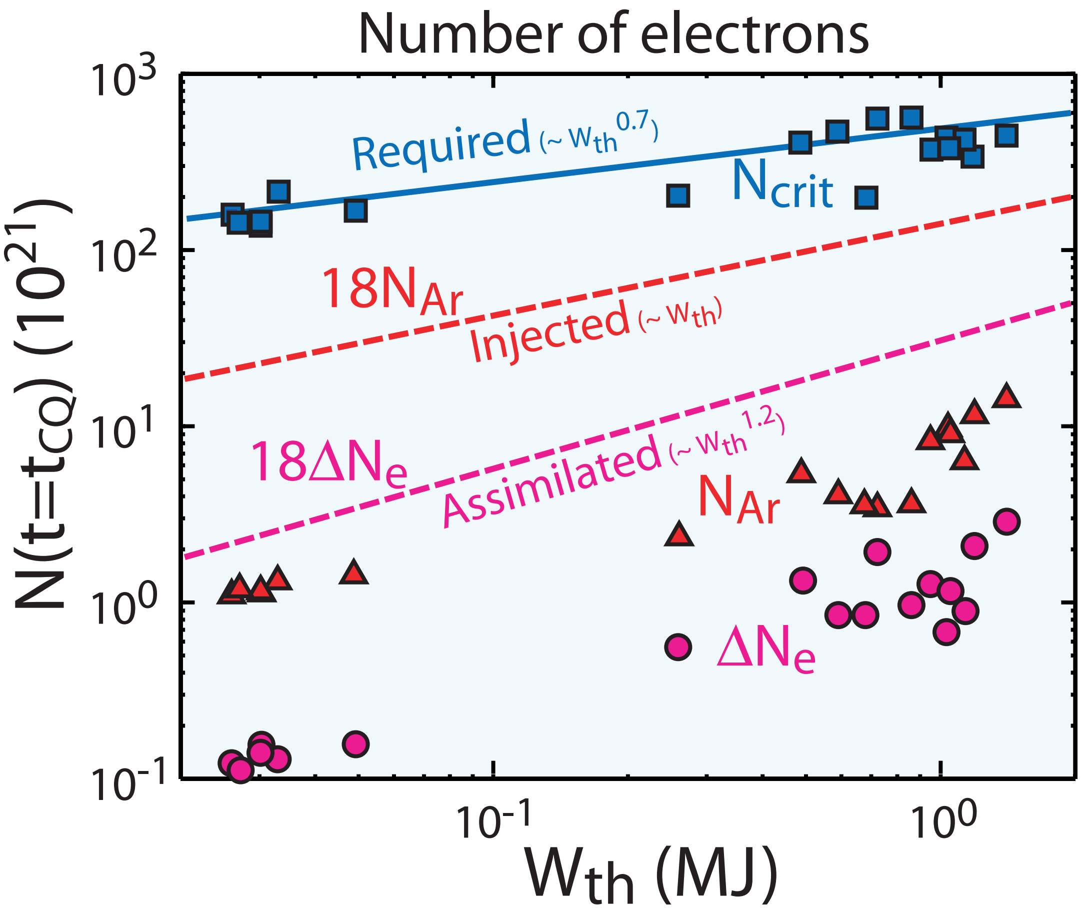
Thermal Quench Duration (Time to CQ Onset) Increases With Increasing Thermal Energy (W_{th})



- **Higher thermal energy plasmas take longer to shut down**
- **Delivered argon gas rises rapidly with time ($\propto t^2$), so more argon ions and electrons are delivered as shutdown time increases**

Observed in-plasma N_e Also Increases With W_{th}, But Gas and Electron Assimilation Fractions are <1 Unity



- **Higher W_{th} plasmas** take longer to shut down, show more assimilation of Ar ions and electrons (free + bound)
- **But…** higher I_p(= higher W_{th}) plasmas have higher E_{tor}; need higher n_e for collisional suppression. For 2004-2005: **$N_{e,\ total} \approx 18\Delta N_e$ always << N_{crit}**
- Possibly favorable scaling (assimilated N_e increasing faster than N_{crit}) suggested; **need more R&D**

Summary and Implications for ITER

- **Neutral jets have finite rise time**
  - Jet tube exit flow rise time limits initial rate of gas delivery
  - For directed jet (Ar, 15 ms pulse) only 10% of Ar delivered by CQ onset
- **Neutrals do not penetrate beyond the plasma edge**
  - Neutral stopping at edge, even at very low W_{th} and even during CQ
  - Suggests dominant role of $B^2/2\mu_o$ magnetic pressure
- **MHD "mixing" effects gas/impurity assimilation and radiation of W_{th}**
  - Mixing of heat and impurity ions occurs during "slow" TQ (3-9 ms)
  - Mixing initiated by destabilization of (2/1) mode, accelerated/completed by destabilization of (1/1) mode. Core $W_{th} \rightarrow$ larger-r radiating "shell"
- **Lack of RE in directed-jet experiments not due to collisional suppression**
  - Total electron densities 10-50x too low for avalanche suppression
  - Observed low levels of RE would probably avalanche in a larger tokamak