EX/10-6Ra

Disruption Mitigation using Noble Gas Jet Injection in DIII-D

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Nov. 2004
20th IAEA FEC 2004

EX/10-6Rc

Disruption Mitigation on Tore Supra

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CEA / Cadarache

TORE SUPRA

Nov. 2004
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Japan Atomic Energy Research Institute

Disruption Mitigation Experiments in the JT-60U Tokamak

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Overview of disruption mitigation

- Goal: minimize damage to walls of ITER during disruptions
  - A. Thermal quench
    - - Conducted heat loads
  - B. Current quench
    - - Induced and vessel halo currents
    - - Runaway electrons
- Two steps to disruption mitigation
  - A. Detection/triggering
  - B. Radiative shutdown scheme
    - - Killer pellet (ASDEX,JT-60U,DIII-D,T-10,etc.)
    - - Gas jet (DIII-D,Tore Supra,JT-60U,etc.)

focus of this presentation

Main results

- Massive gas jet shutdown works well in present tokamaks.

  - Low conducted heat loads, low halo currents, and low runaway electron signature seen in DIII-D.

  - Large reduction in runaway signature over normal disruptions observed in Tore Supra.

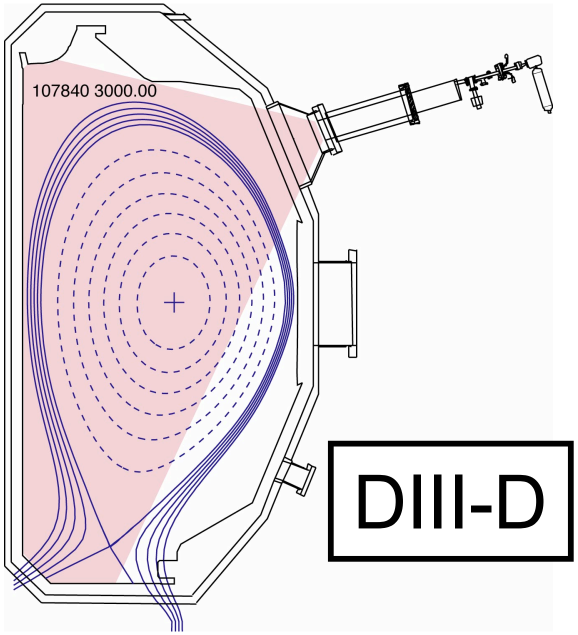
  - Reduced runaway signature using mixed-species jets observed in JT-60U.

- Predicting performance of gas jet in ITER is still work in progress.

  - Getting impurity neutrals into center of ITER challenging.

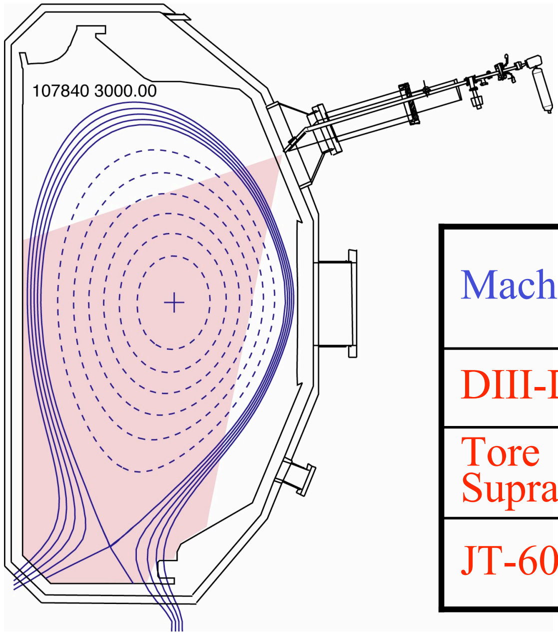
  - However, mitigation can be good even without neutrals penetrating to center.

Variety of gas jets tested



Open jet (2000-2003)

- Fast (~1 ms) rise time.
- Aimed at plasma top.
- First demonstration of good mitigation characteristics.



Directed jet (2004)

- Slower (~ 3 ms) rise time.
- Aimed at plasma center.
- Jet modified to better study neutral penetration.

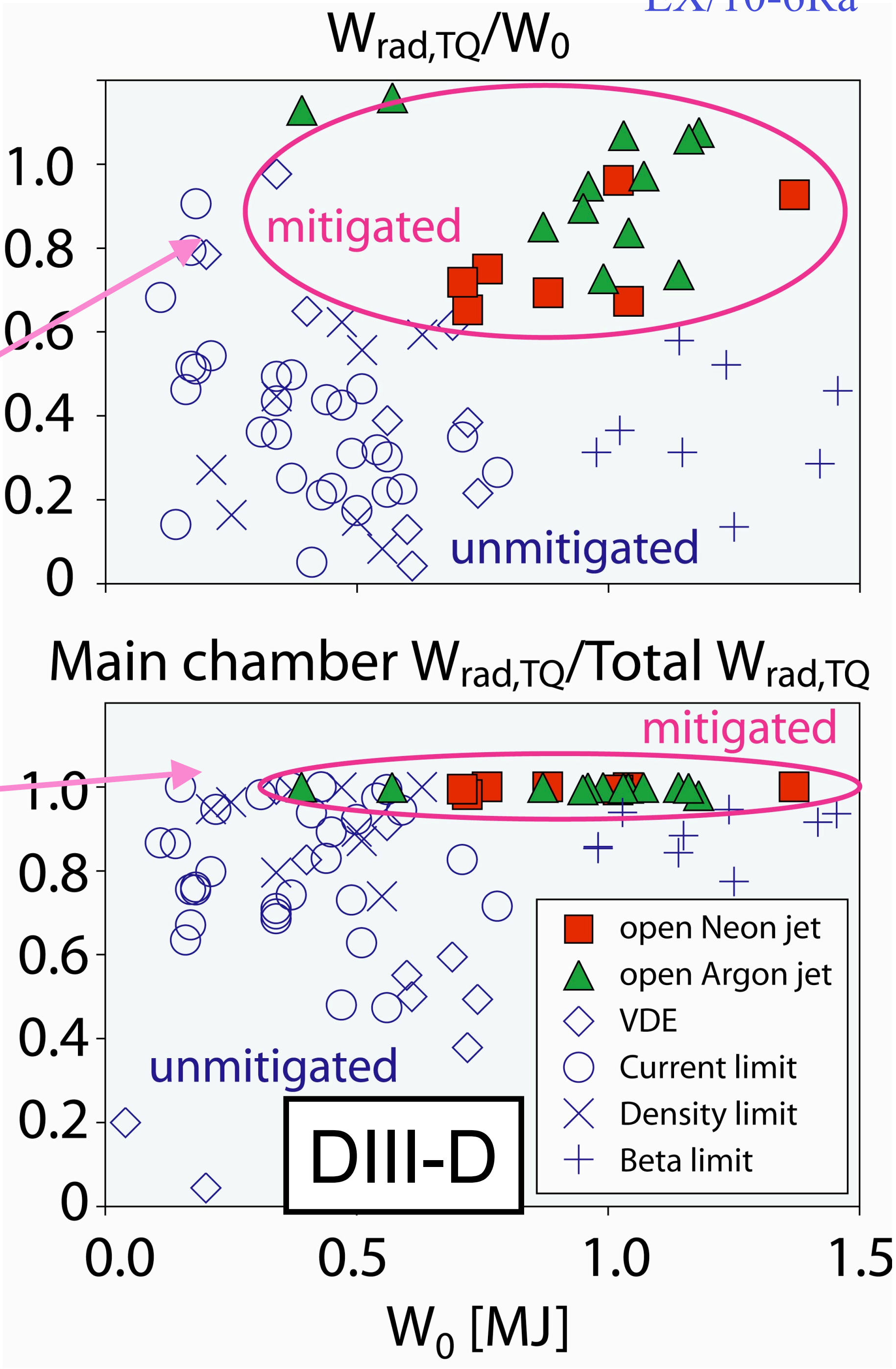
Wide range in gas jet experiments worldwide

Machine	Gas	$\frac{N_e}{V_{plasma}}$ [/m^3]	$\frac{N_{0,inj}}{V_{plasma}}$[/m^3]
DIII-D	Ne,Ar	3e19	2e21
Tore Supra	He	3e19	3e21
JT-60U	Ar,Kr, Xe,H_2	1e19	6e19

Conducted heat loads reduced

90% of thermal energy radiated away with gas jet → low heat conduction to walls.

100% main chamber radiation → low divertor heat loads.



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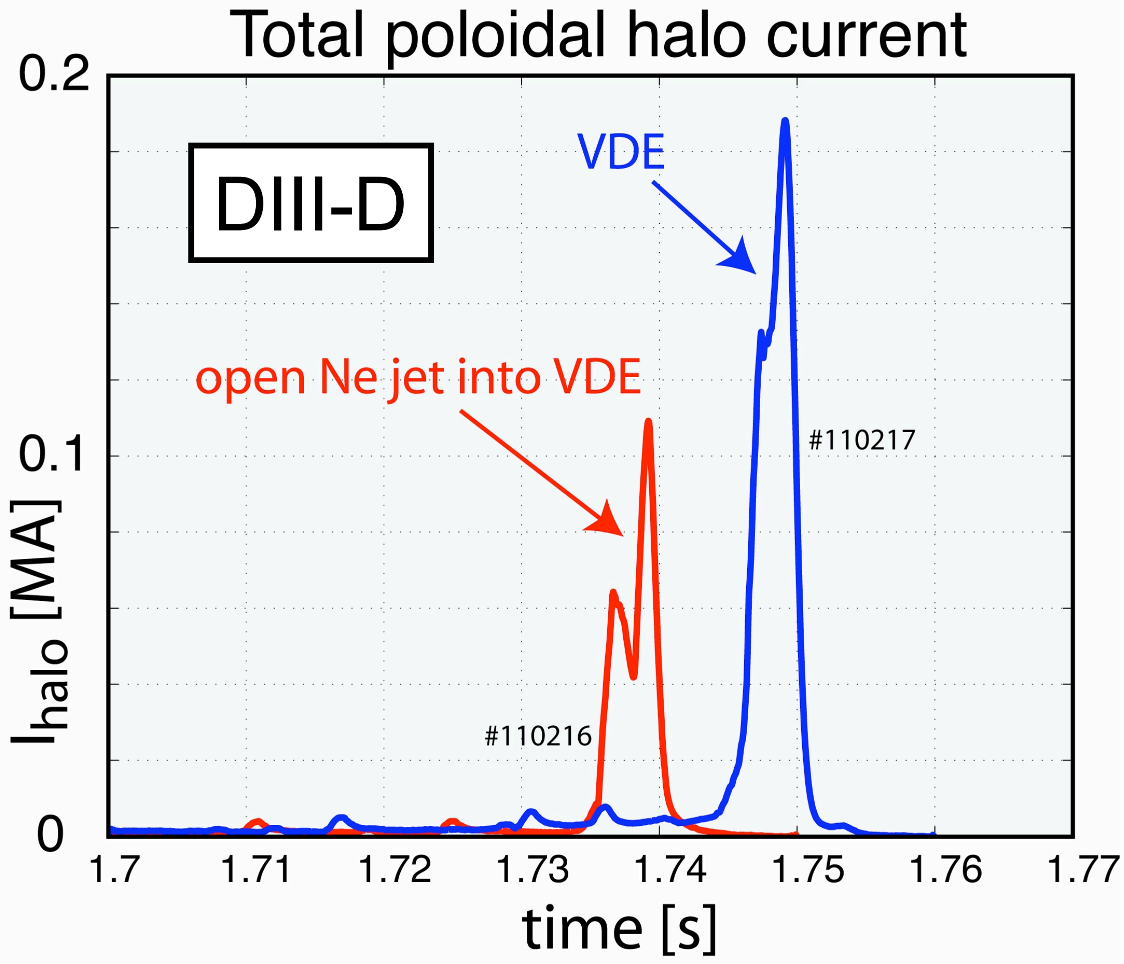
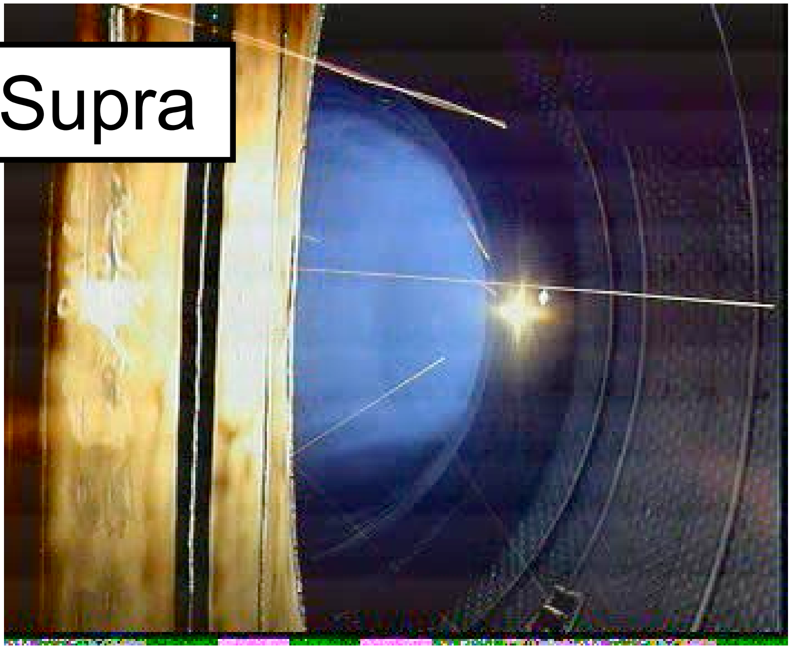
4× reduction in halo current forces on vessel

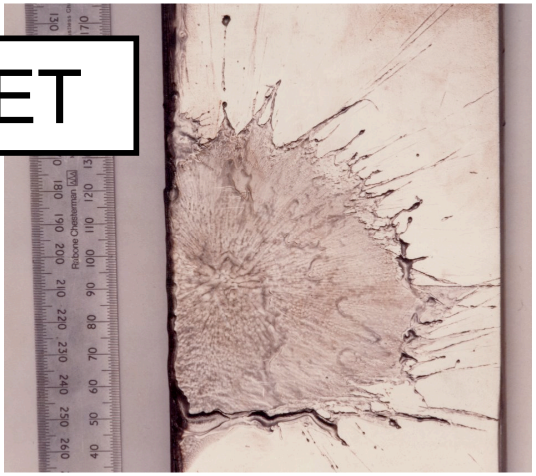
- 2× reduction in halo currents when jet sent into vertically unstable plasma.
- Complete disappearance of toroidal peaking in halo currents.



Runaway electrons can cause localized wall damage



Visible light photograph of runaway beam striking wall.



Wall damage caused by runaways. Serious concern for ITER.

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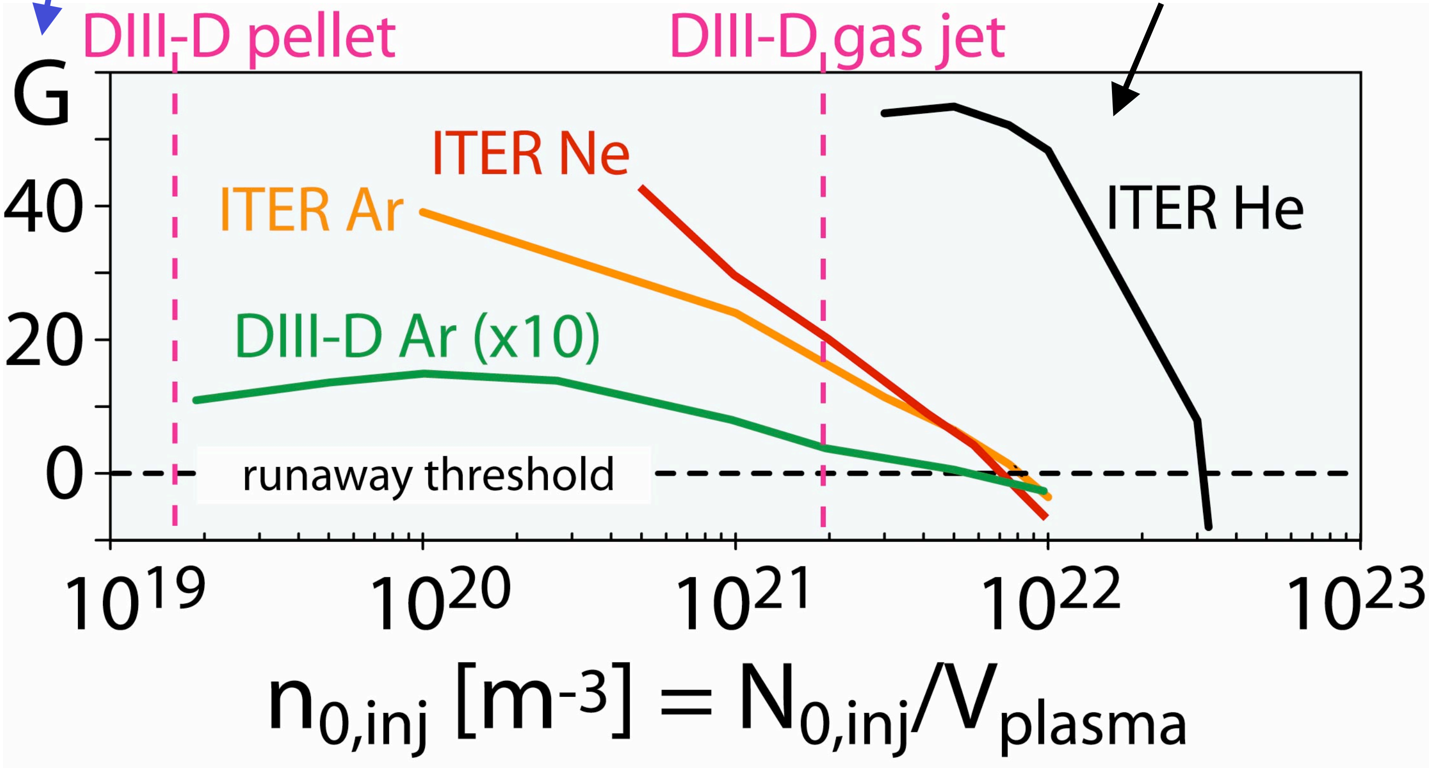
Runaway avalanche suppressed with sufficient impurity injection

- To avoid runaway amplification in ITER, gas jet should deposit impurity densities > $10^{22}/m^3$ (~0.4 mbar)

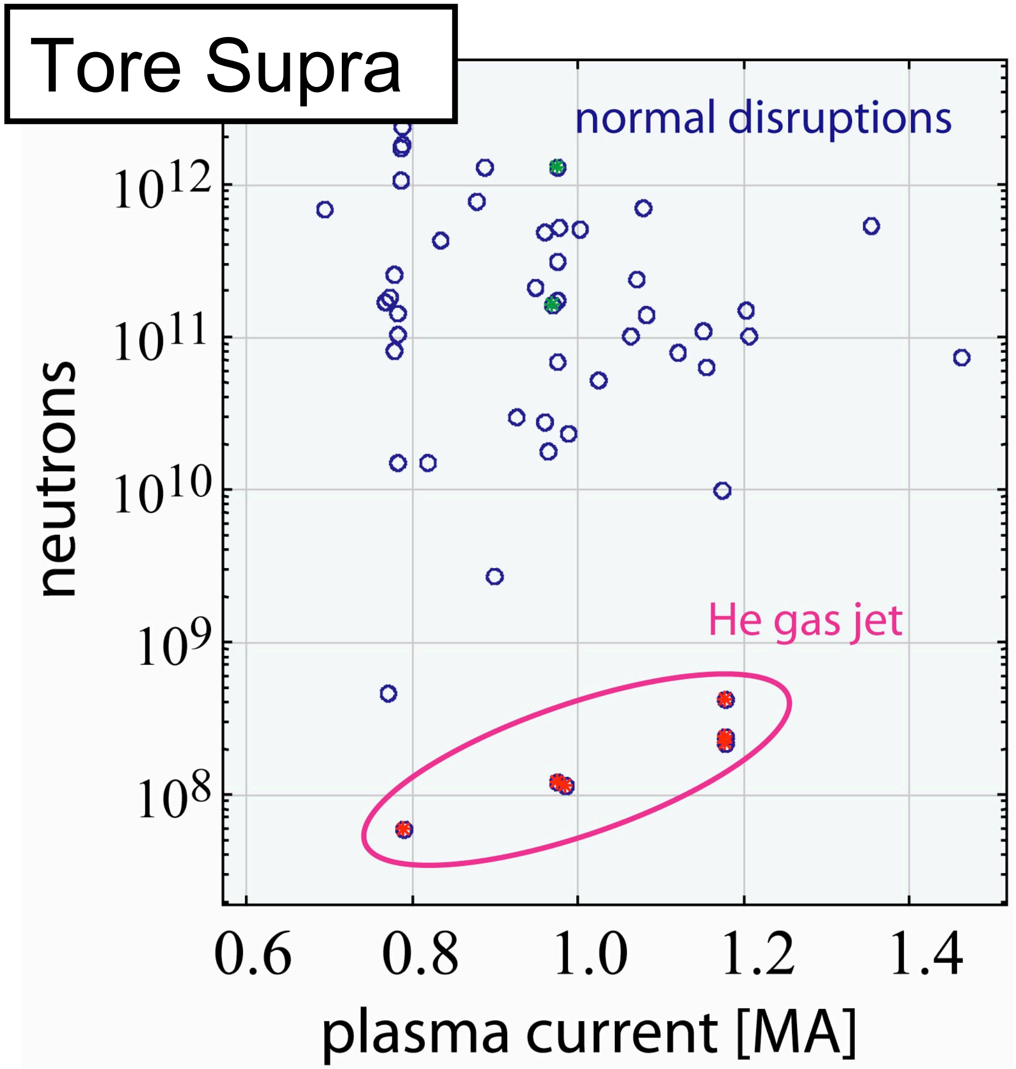
RE gain ~ exp(G)

KPRAD (0D) simulations



He jet terminates discharge with low runaway generation

- Runaways produced during normal disruptions in Tore-Supra.
- Photo-neutrons give indication of MeV runaway electrons striking wall.
- Helium gas jet terminated plasmas have much lower runaway signature than normal disruptions.



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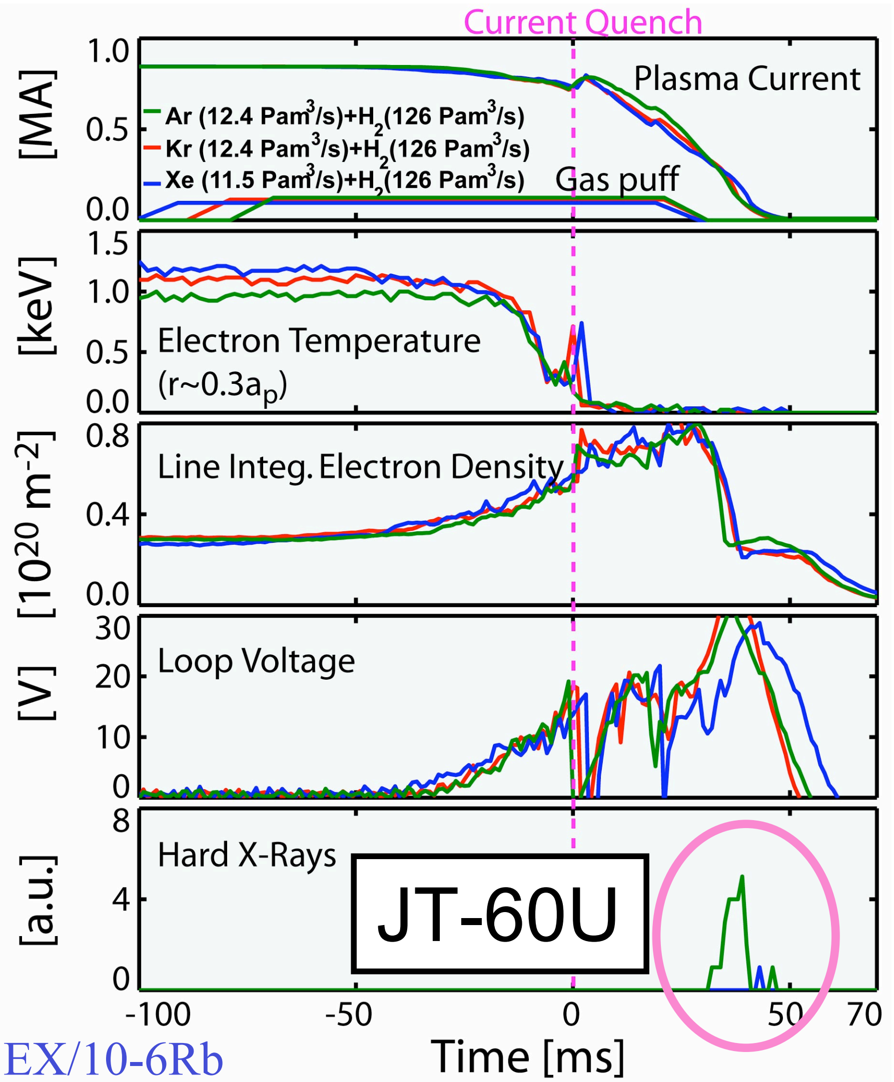
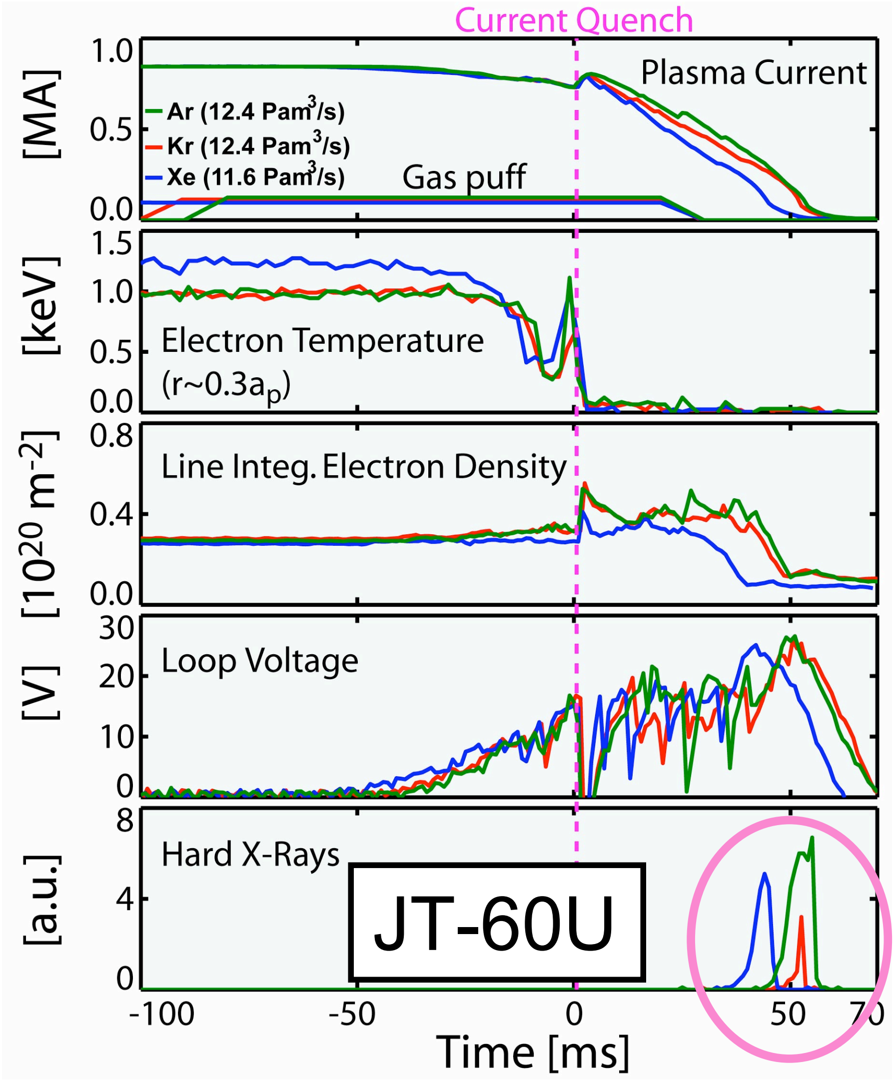
Kr + H_2 gas jet terminates discharge with no runaways striking wall

Kr+H_2 Xe+H_2 Ar+H_2

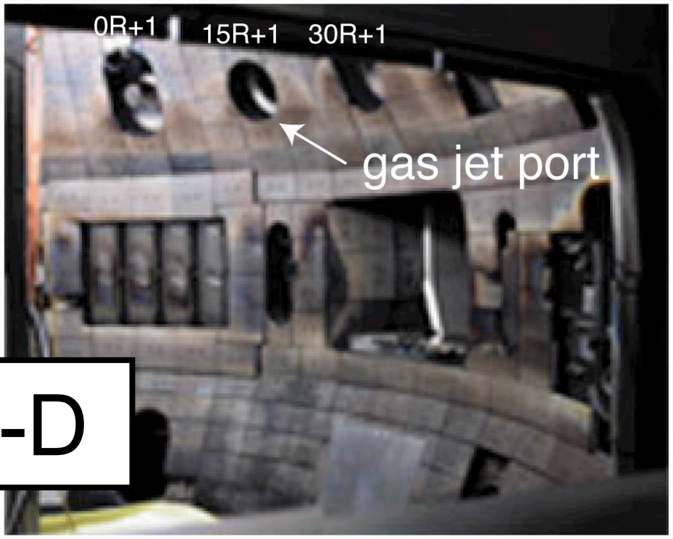


Kr Xe Ar



Neutrals ionize at plasma edge

Camera view of vessel



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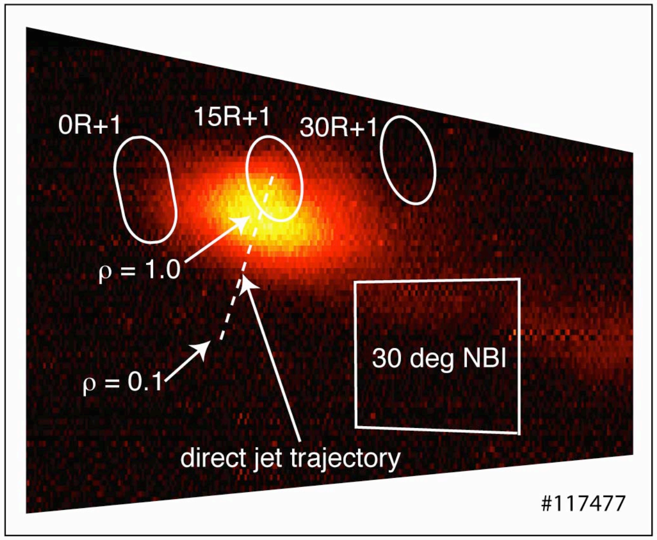
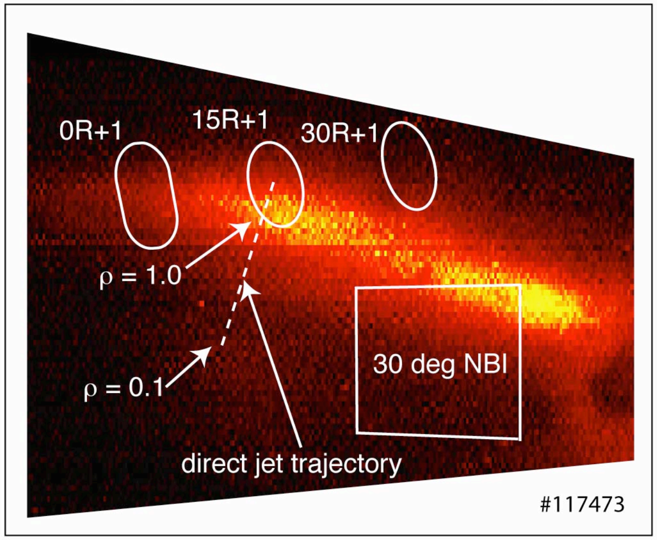
At start of core thermal collapse, jet neutrals (Ar) and ions (Ar^+) at edge of plasma.

Ar^+ ions seen to stream along edge field lines.

Neutral argon image



Argon ion (Ar-II) image



(directed Ar jet)

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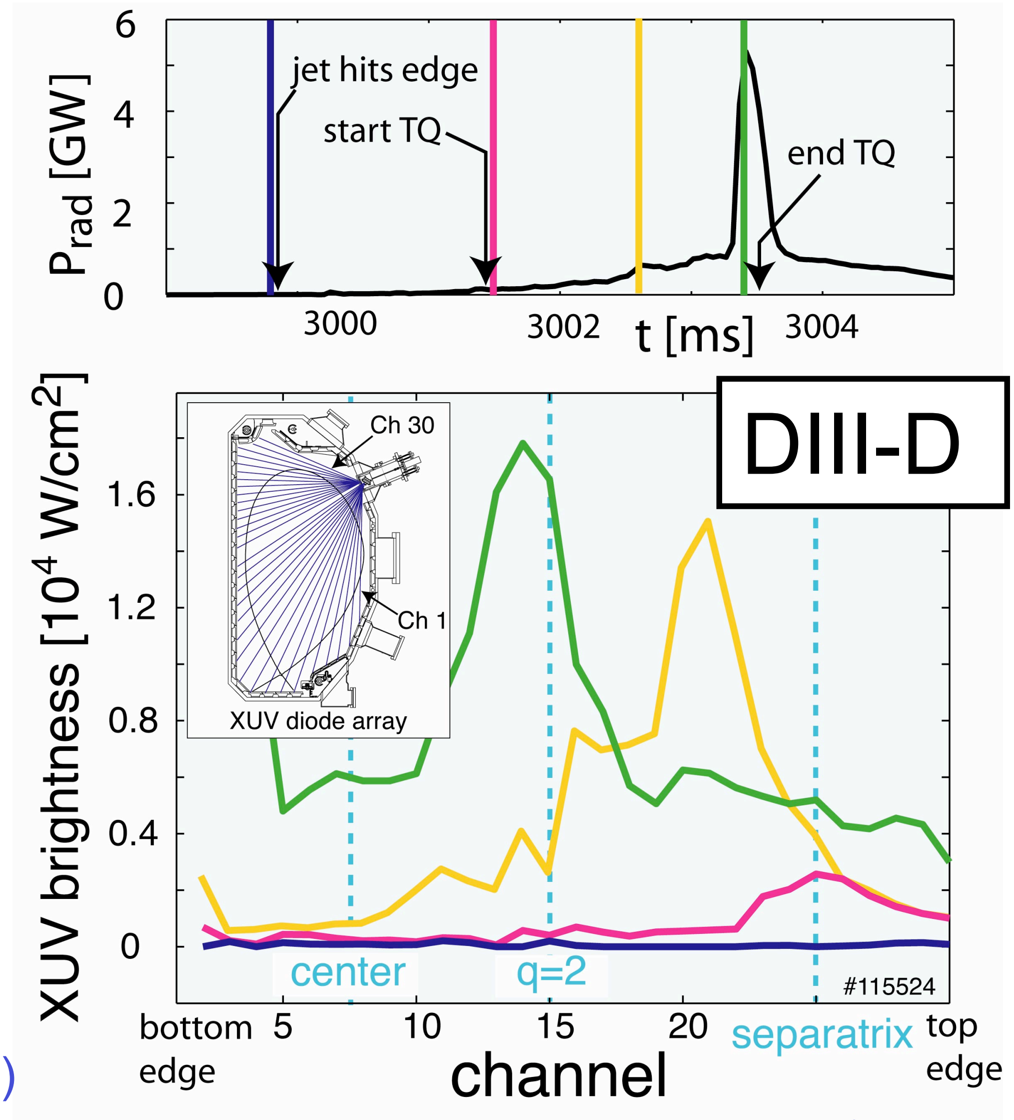
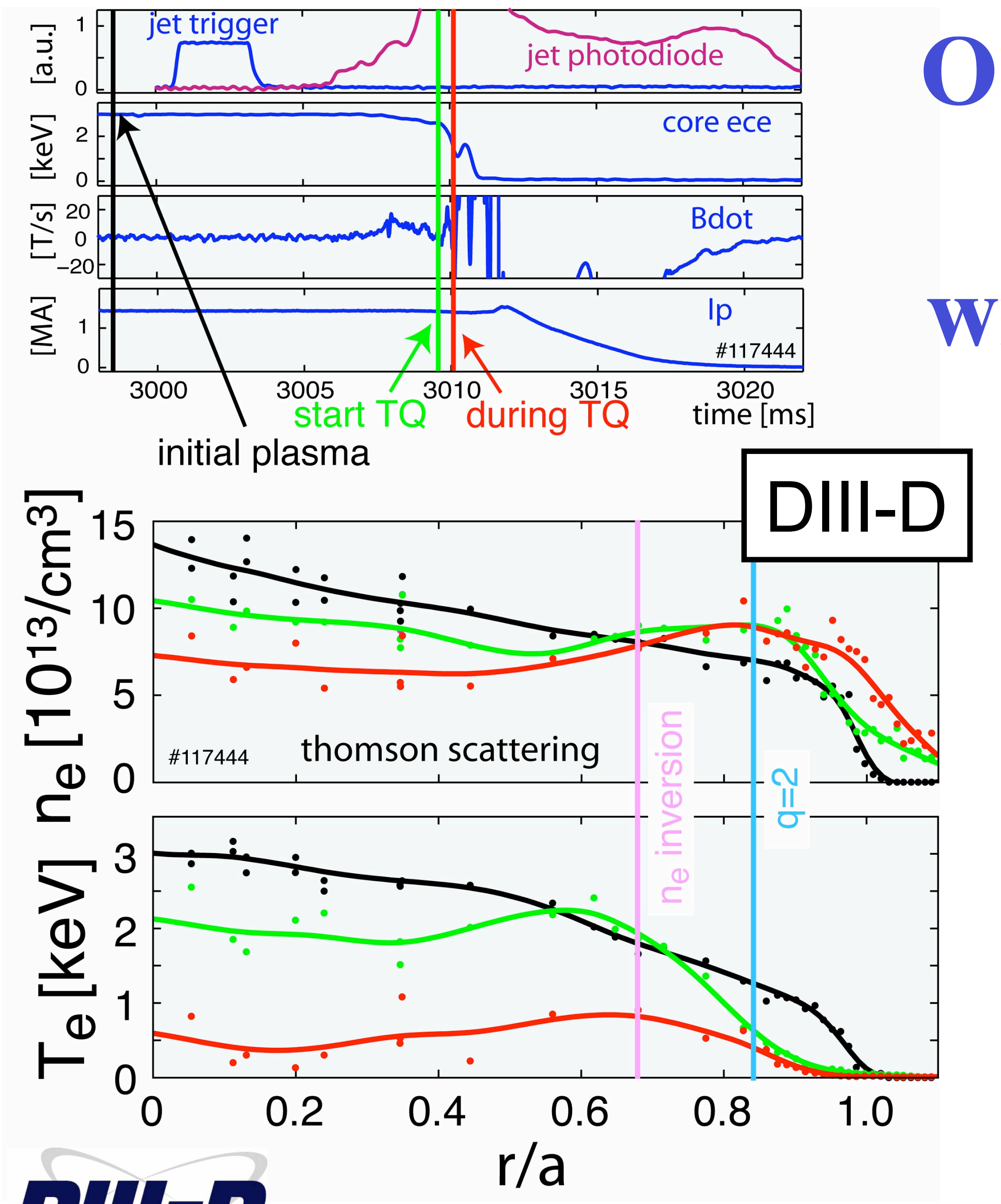
Impurity ions move rapidly toward center of plasma

- At start of thermal quench, impurity ions at edge of plasma.
- Fast inward transport of impurity ions during thermal quench, ending in large radiation spike.



(open Ne jet)

Onset of central T_e collapse occurs without impurities



(directed Ne jet)

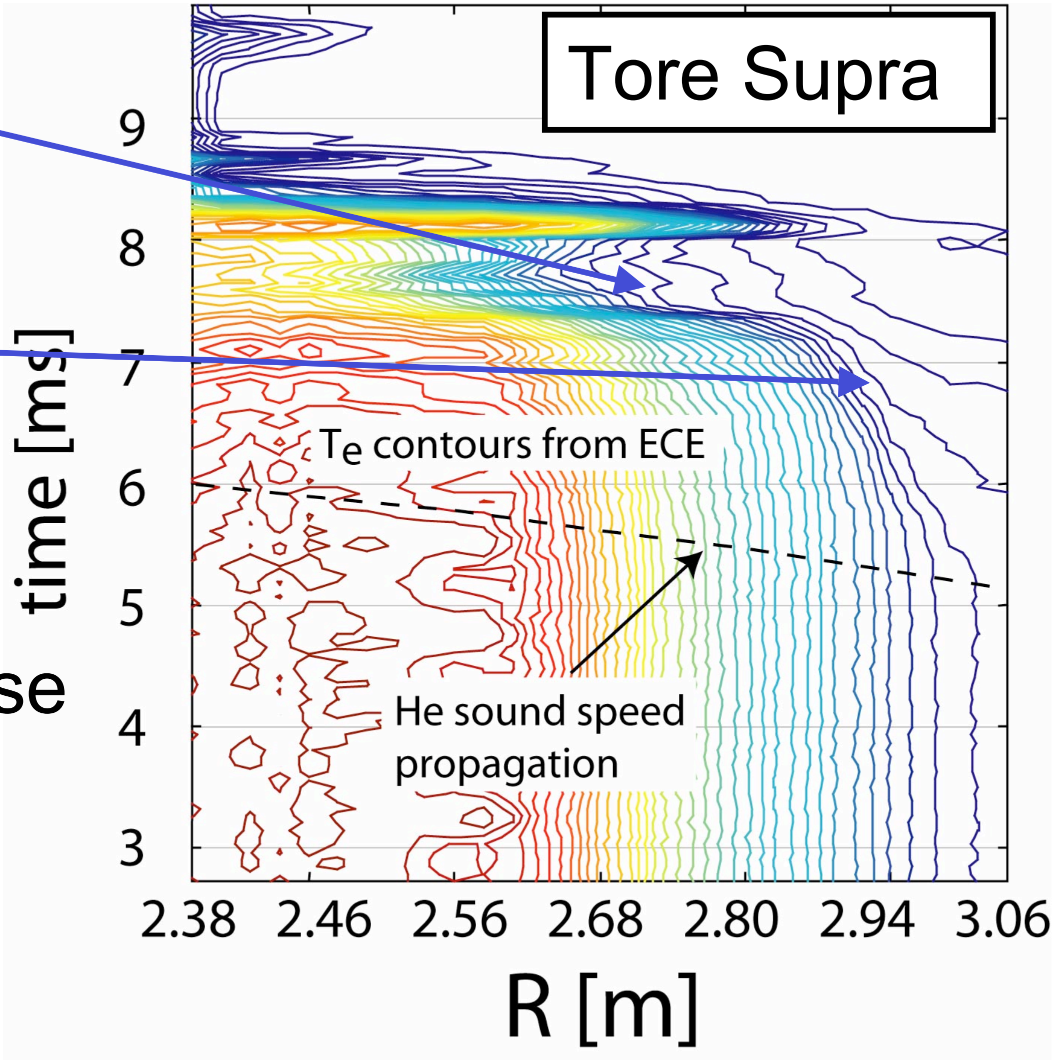
- n_e inversion suggests impurities at r/a > 0.7 during TQ.
- Increasing MHD when cold front at q=2.
- Increasing MHD coincides with core T_e collapse; could cause fast heat transport.

Thermal collapse shows two time scales

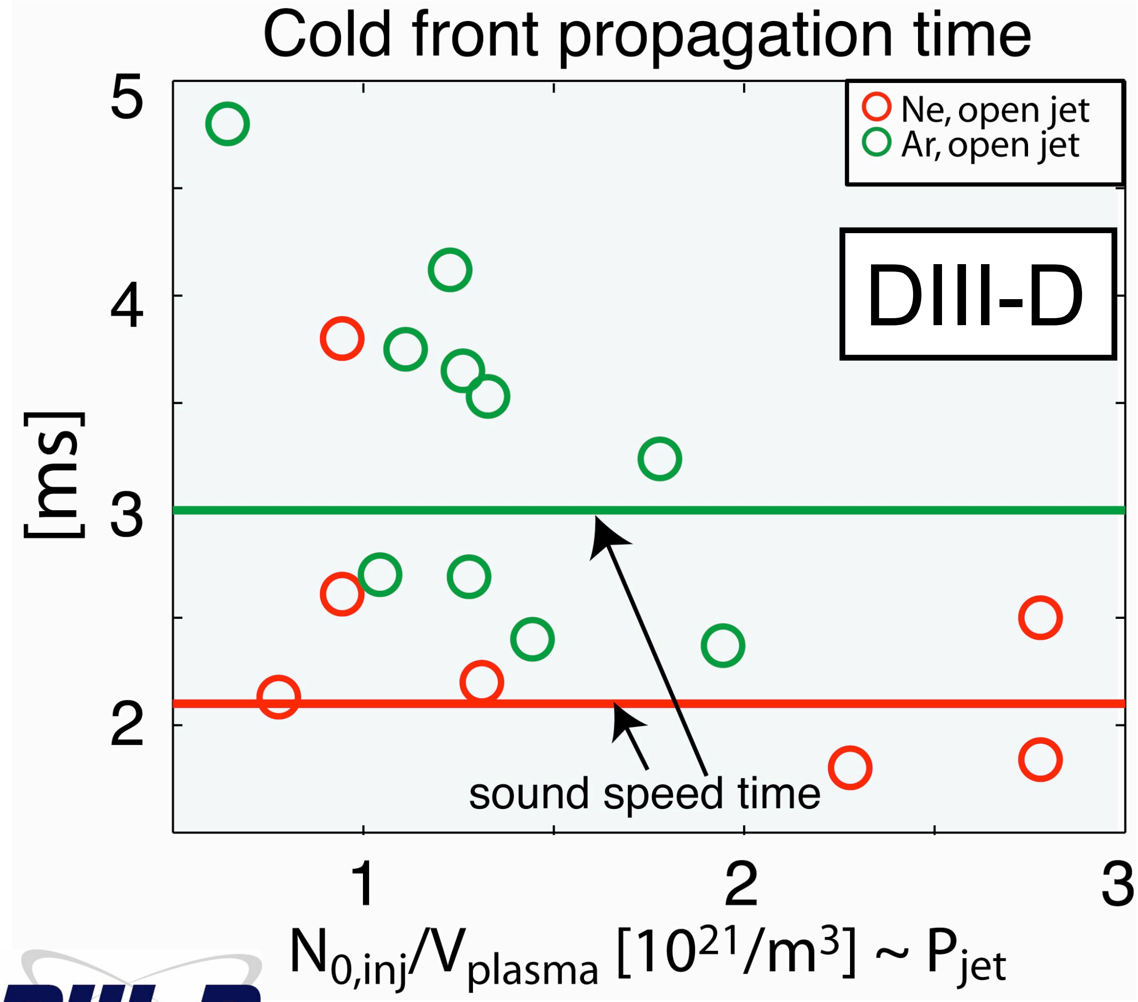
Final core T_e collapse very rapid.

Initial cold front propagation slower than He sound speed.

- DIII-D thermal collapse qualitatively similar.



Increasing gas jet pressure increases impurity propagation rate



- Higher jet pressures give faster cold front propagation.
- Argon slower than Neon, suggests mass dependence in impurity transport.
- Propagation rates up to ~ neutral sound speed obtained.

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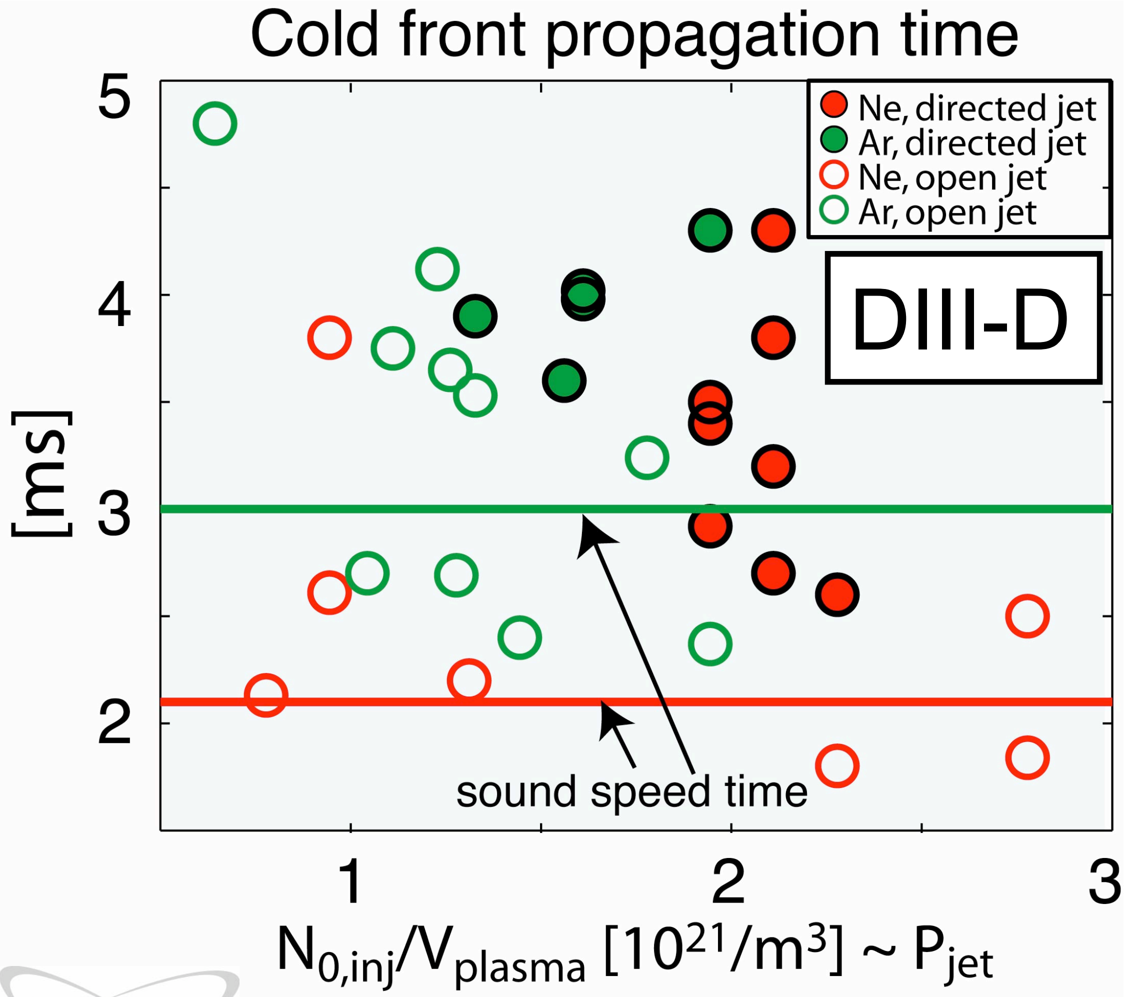
Modifying gas jet geometry affects impurity propagation rate

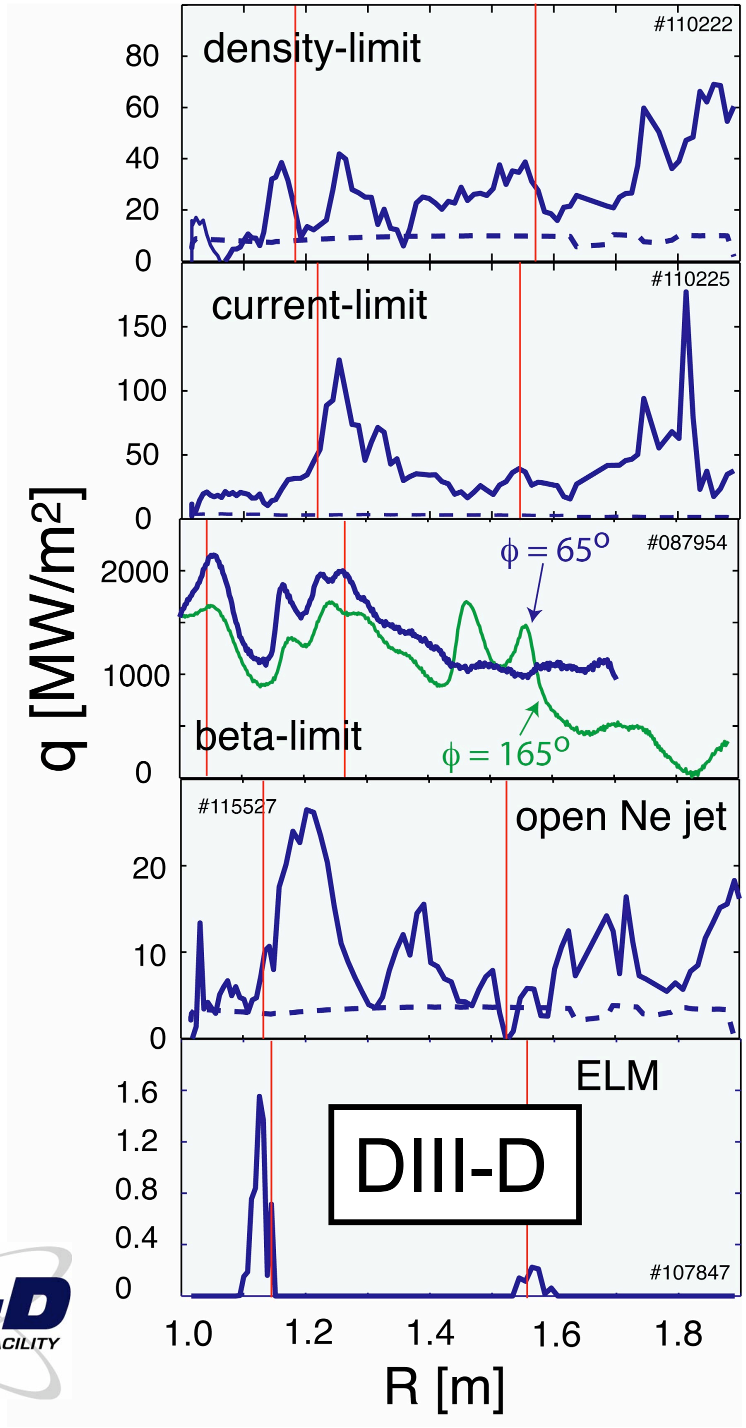


- Directed jet has slower cold front propagation rate than open jet.

Conclusions

- Massive gas jet shutdown works in present devices.
  - Low conducted power to wall.
  - Low halo currents.
  - Low runaway electrons.
- Improving understanding of impurity dynamics in present devices.
  - Present work suggests penetration of neutrals to core not necessary for good mitigation.
  - Variation of thermal collapse rate with jet pressure and shape suggests jet can be tailored to give desired TQ time.
- Extrapolation to ITER work in progress.
  - Need more experiments, better diagnostics, and cross-machine comparisons.
  - Need integrated modeling (impurity dynamics + MHD).

Low divertor heat loads



- Gas jet gives divertor heat loads lower than all types of disruptions.
- Beta-limit disruption gives highest conducted heat loads.

(heat fluxes averaged over thermal quench)

Thermal quench MHD low-order

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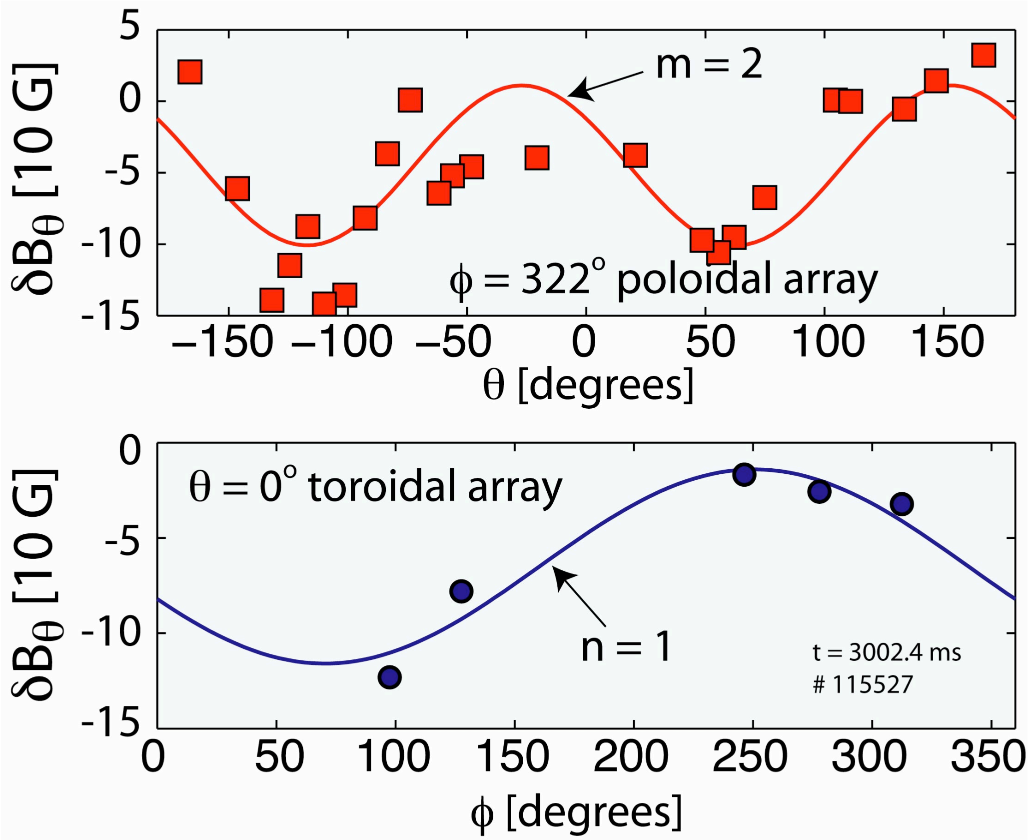

- Wall magnetic signals usually low order: well-fit by n=1, m = 1, 2.
- Rise time of MHD fast (< 1 ms), suggesting plasma near ideal limit.
- Mixing of impurities/heat in/out of core during fast MHD.

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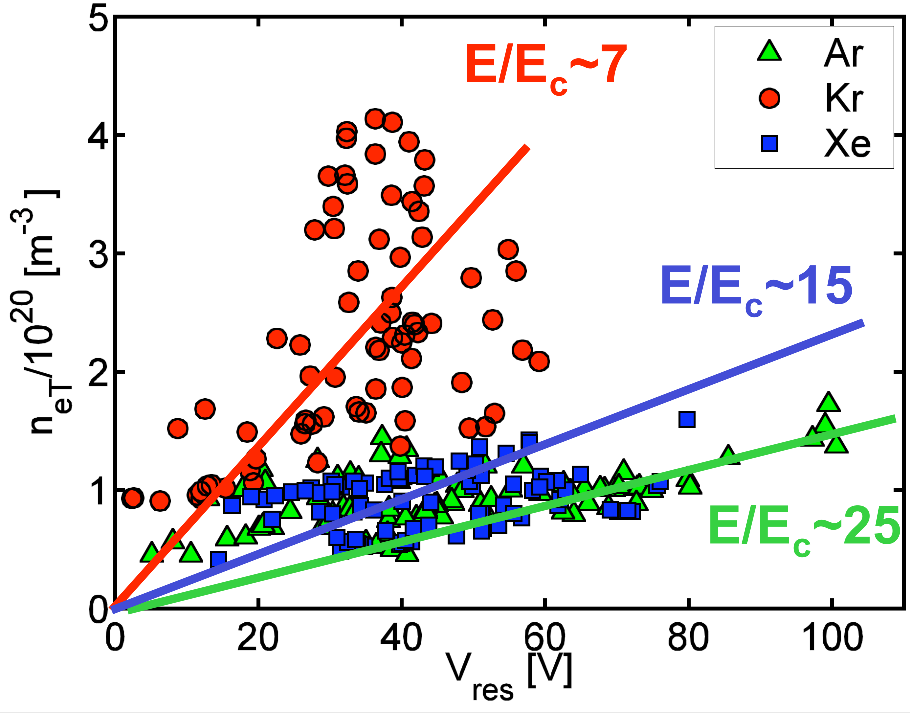
(open Ne jet)

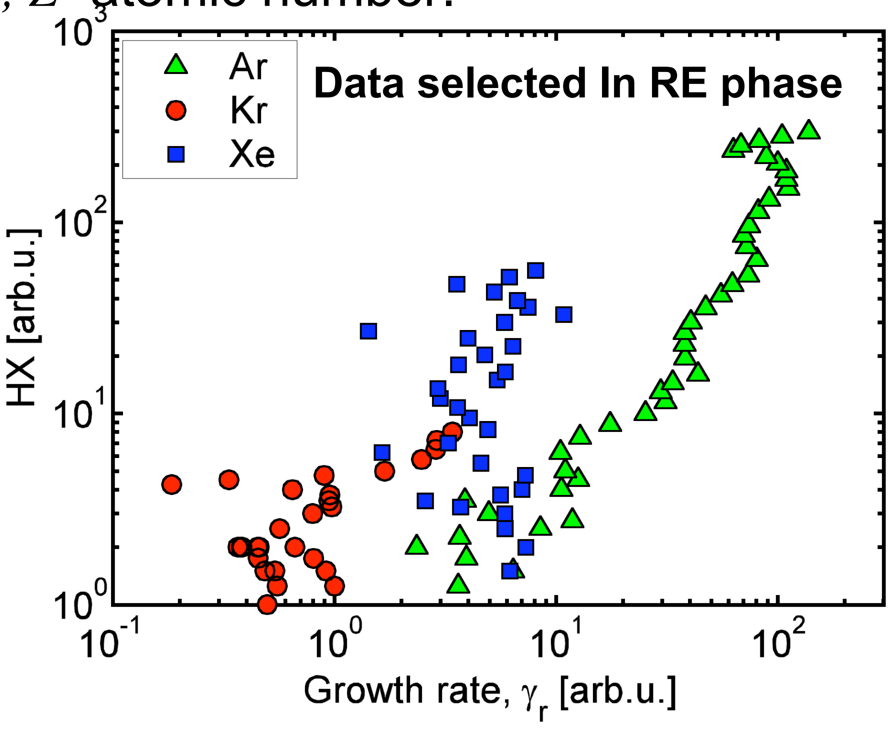
HXR emission proportional to runaway growth rate in JT-60U

Runaway electron avalanche growth rates and the HX-ray emissions are lower with Krypton and they are higher with argon.

In the Kr case E_{res}/E_c is low which leads to low growth rate: $\bar{Z} \sim Z$ $\gamma_r \propto \frac{1}{(\bar{Z}+1)} \frac{E_{res}}{E_c}\left(\frac{E_{res}}{E_c}-1\right)$

E_c [V/m]=0.12n_{eT} [m^{-3}]/10^{20}, and $E_{res}=V_{res}/2\pi R$. Low V_{res} and high n_{eT} cause a low γ in krypton case. Note: $n_{T}=n_{H}+n_zZ$, Z=atomic number.





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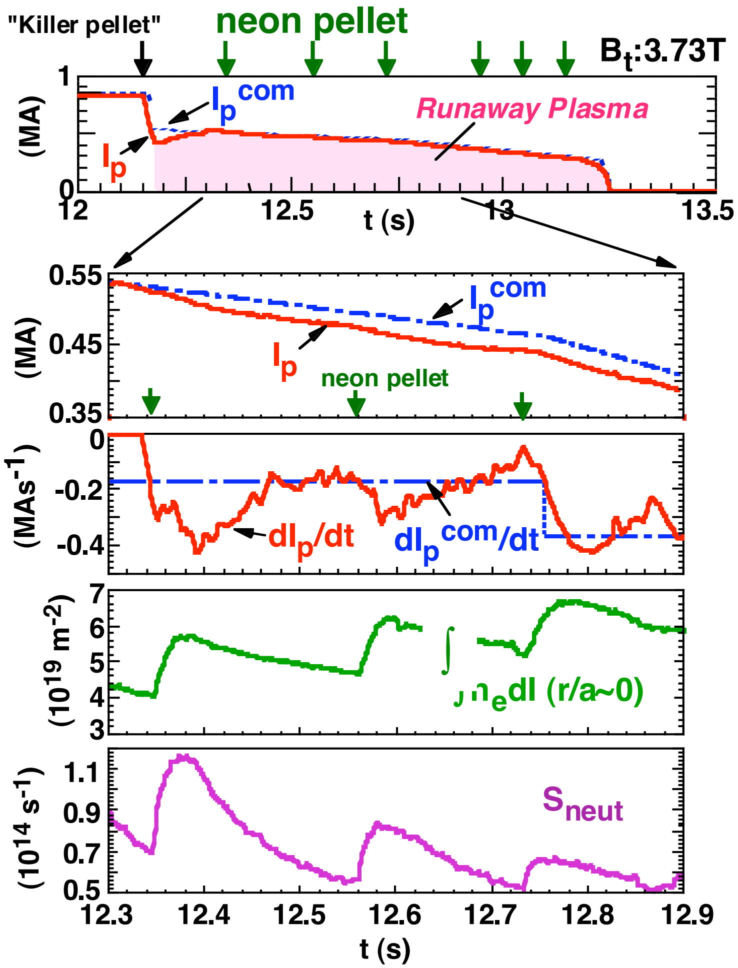
Enhanced loss of runaways by impurity pellet injection in JT-60U

Neon ice pellets (2.1mmx2.1mm, ~700 m/s, 5 Hz, LFS) are injected into a post-disruption runaway plasma

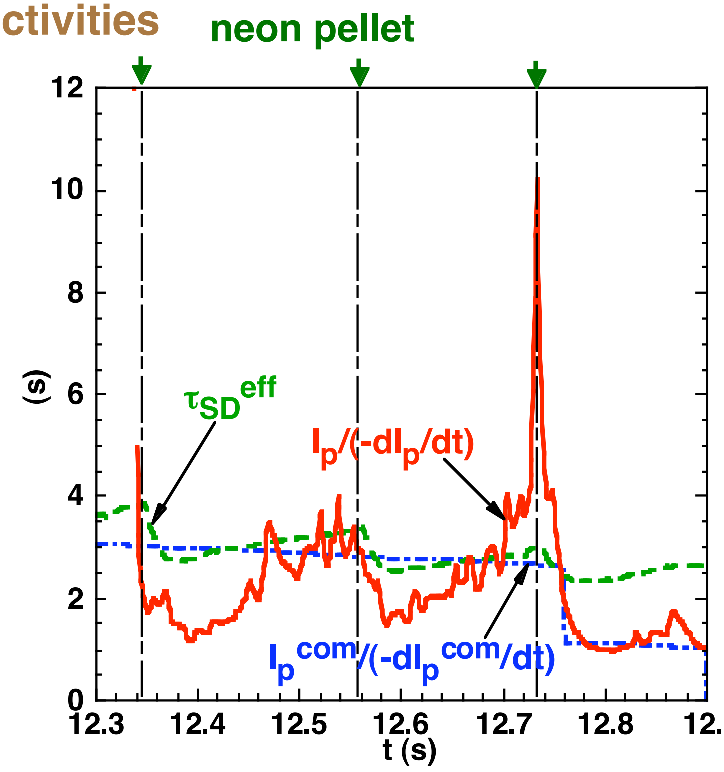


Bulk electron density increased --> pellet deposited

Photo-neutron increased --> loss of runaways to wall

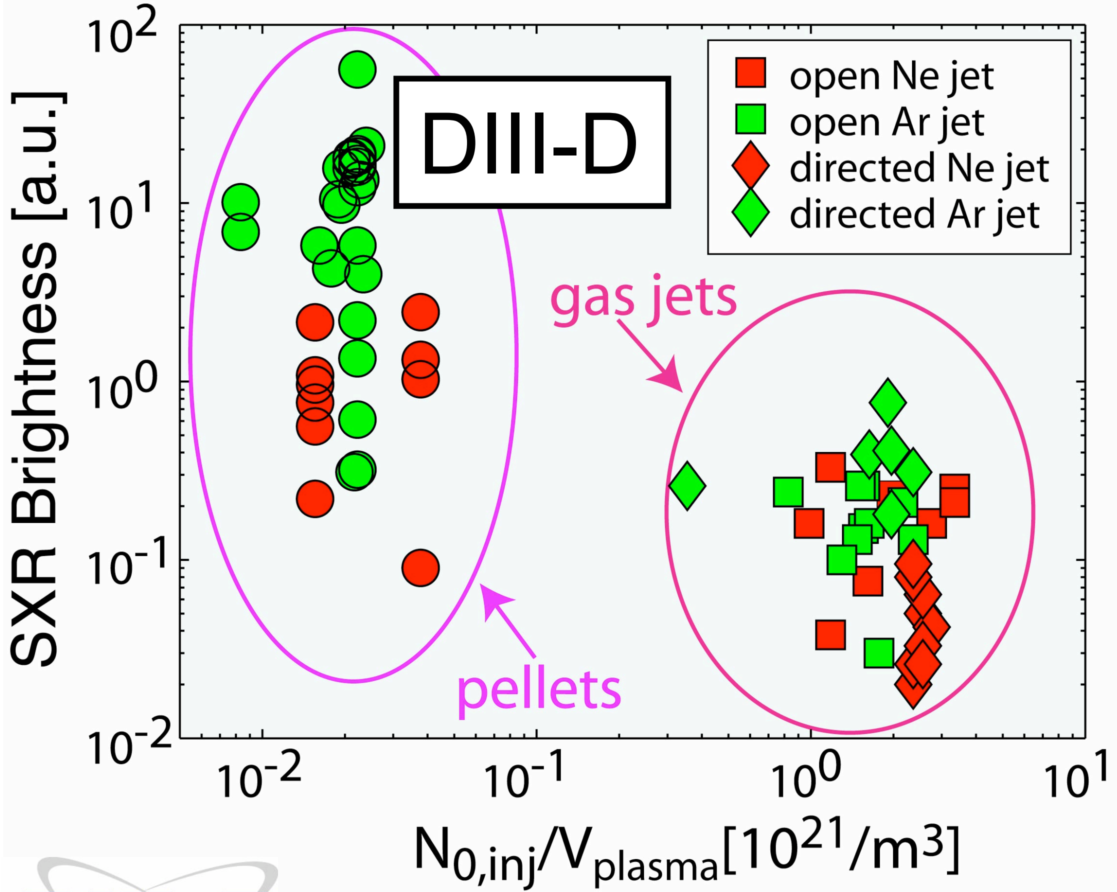
Current decay time shortened:from ~3 s to ~1.5 s

No large MHD activities



Runaways reduced with gas jet over pellet injection

Current quench x-ray signals from runaways



- Less runaways are created with gas jet than with pellets, consistent with more impurities.
- Argon causes more runaways than neon, consistent with T_e lower for Argon.
- Scatter from MHD and/or variation in strike location of runaways ?

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