Disruption mitigation with high-pressure noble gas injection

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Burning plasma experiments must develop a thorough strategy to deal with disruptions

- **Plasma operations**
  - Obtain needed performance away from known stability limits.

- **Disruption avoidance**
  - Control of plasma pressure / current profiles (e.g. NTM suppression)

- **Disruption detection**
  - Reliably determine onset of triggering instability in real-time.

- **Disruption mitigation**
  - Provide a rapid and safe emergency shutdown technique in order to alleviate damage to costly internal components.

DIII-D Experimental Results

High-pressure gas injection of noble gases simultaneously satisfies the three requirements for mitigating the damage caused by disruptions

1. **Surface thermal loading:** Focused heat loss ablates/melts divertor material
   Solution: Deliver large quantities of impurity into core plasma to dissipate ~100% plasma energy by relatively benign, isotropic radiation.

2. **Poloidal halo currents:** Large mechanical JxB stresses on vessel
   Solution: Rapid thermal quench, uniform resistive plasma and a plasma that remains centered in vessel during current quench substantially reduce vessel halo currents.

3. **Runaway electrons:** Relativistic MeV electrons (~I_p) from avalanche amplification during current quench in large-scale tokamaks (e.g. ITER)
   Solution: Runaway electrons can be suppressed by the large density of bound electrons in neutral gas in plasma volume.

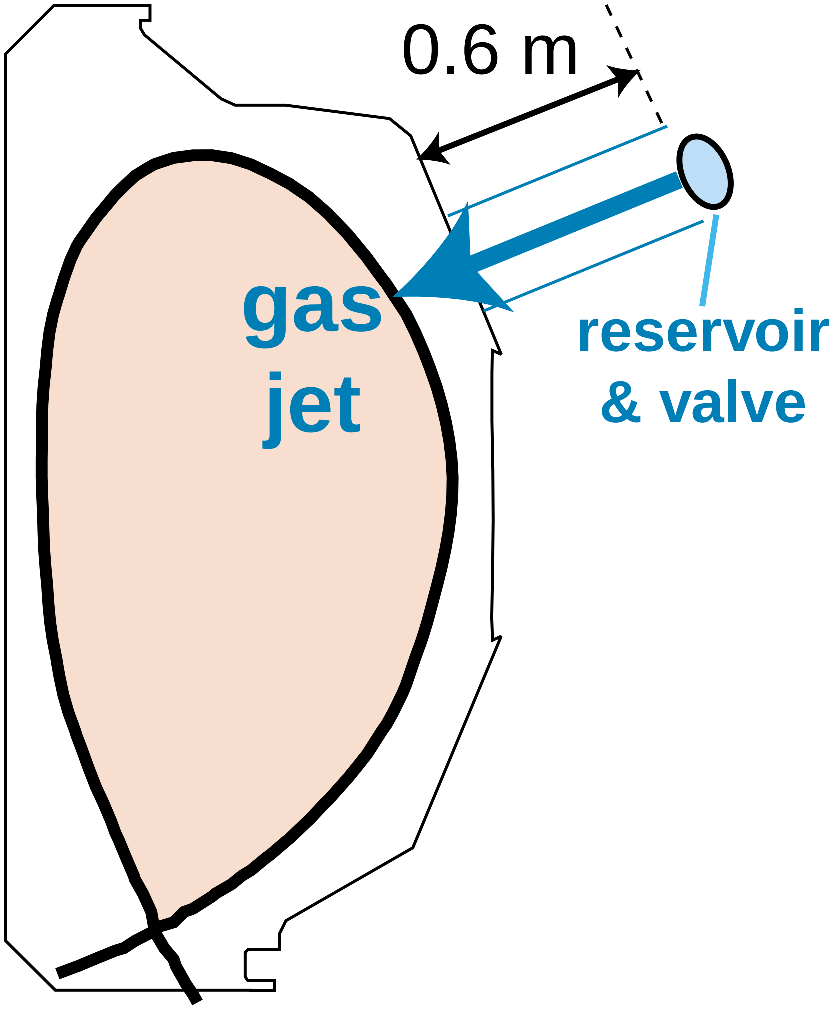
High-pressure gas injection on DIII-D delivers large impurity density to the plasma volume

Gas jet parameters

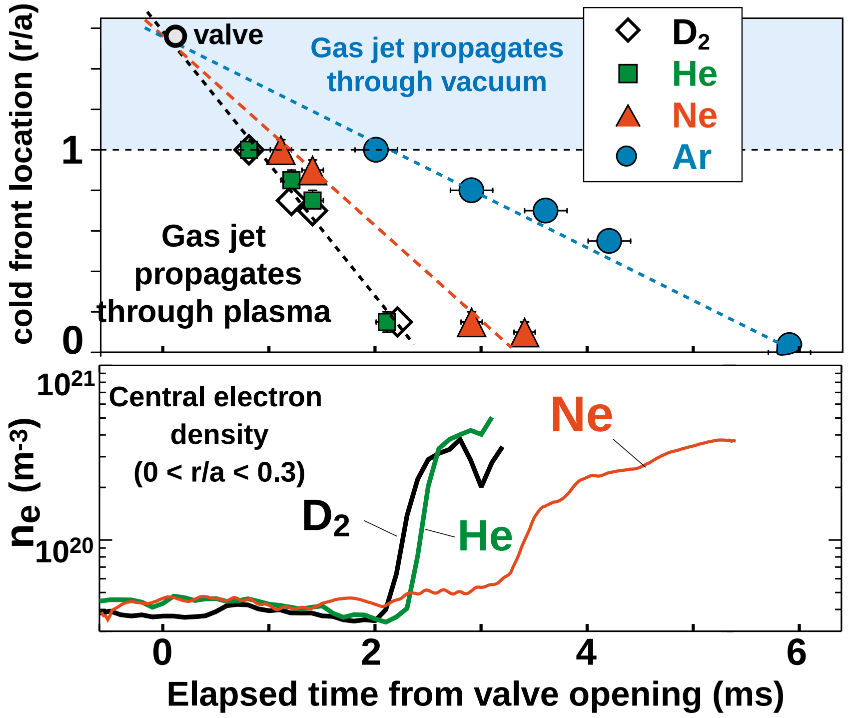
- 70 atmosphere reservoir
- ~ 1 ms response fast-valve
- $N_{inject} \sim 3\text{x}10^{22} \sim 30\ N_{e,target}$
- jet port/nozzle diameter ~0.15 m
- Gases: D_2, Helium, Neon, Argon

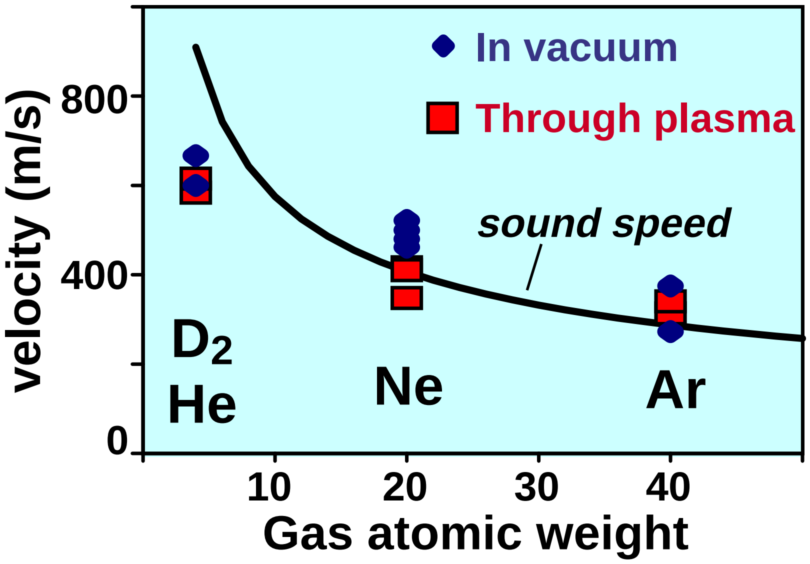
At entry to plasma:

- $n_{jet} \sim 10^{24}\ m^{-3}$: $P_{jet} \equiv \rho\ v^2 \sim 20$ kPa
- $v_{jet} \sim c_s \sim$ 300-700 m/s



All gas jet species penetrate through to central plasma at approximately sonic velocity





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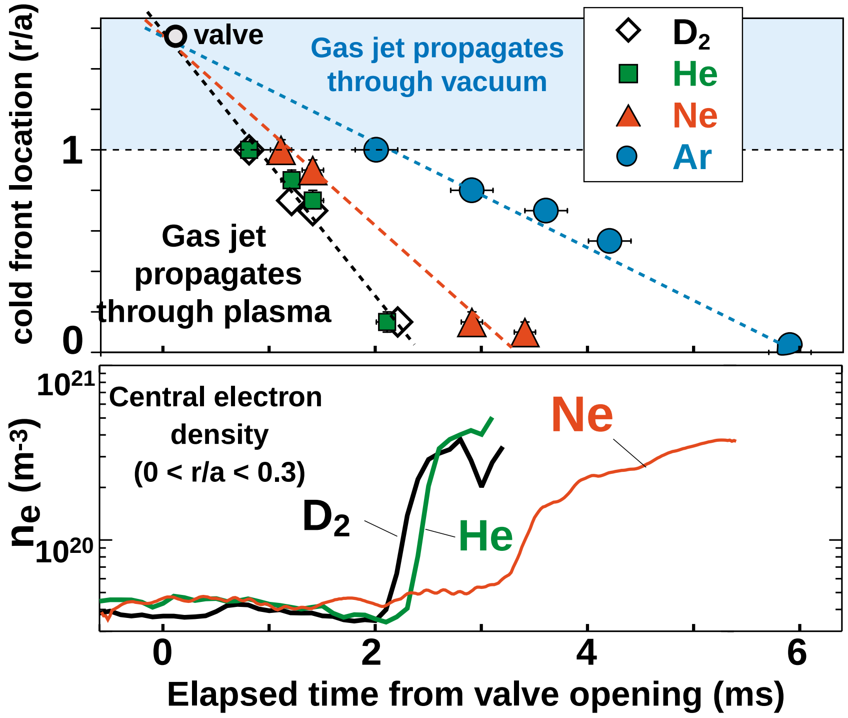
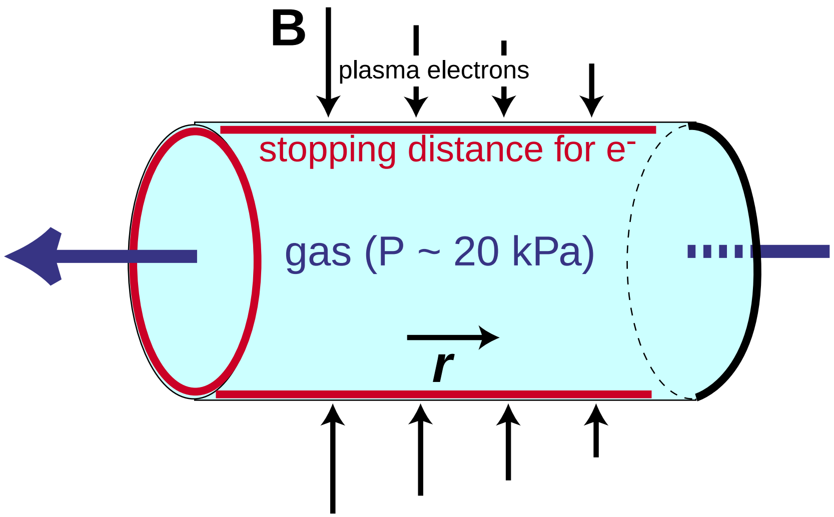
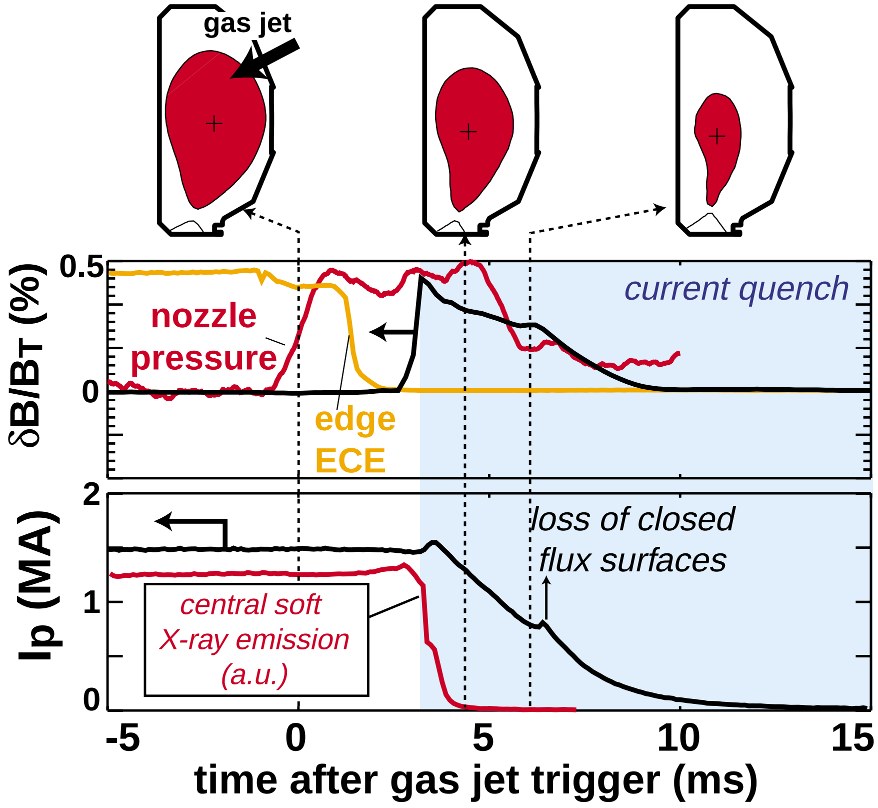
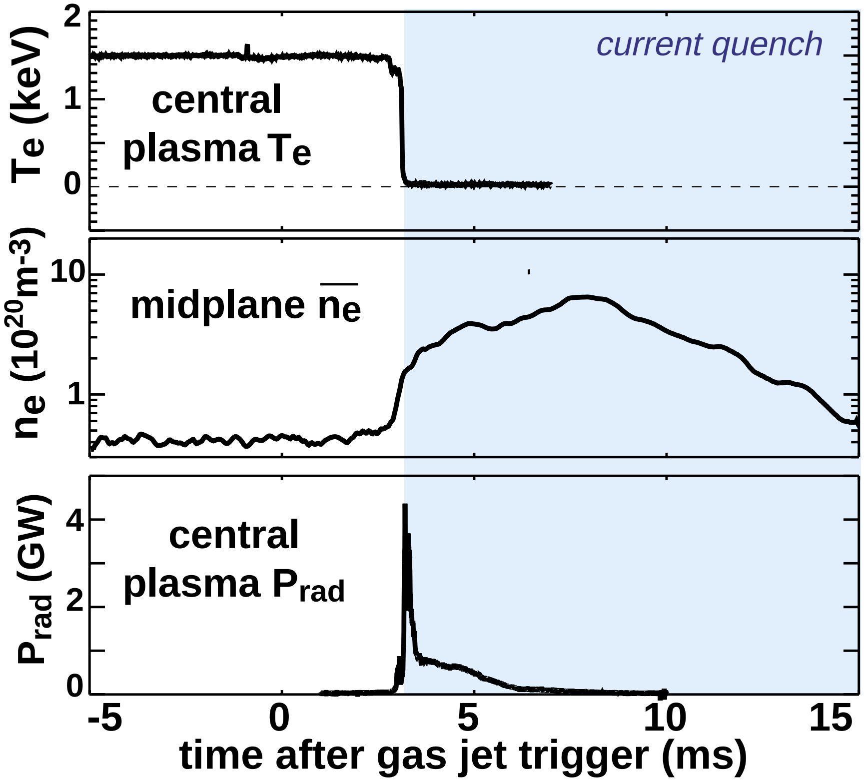


- Empirical observations suggest neutral gas penetration:
  - *Hydrodynamics*: $P_{jet} \sim P_{recoil} > P_{e,plasma}$
  - *Electron dynamics*: stopping distance of keV electrons << jet diameter.
  - No dependence on radiative properties of gas species.
- Gas jet dynamics / penetration currently not well diagnosed or understood.



An example pre-emptive neon gas jet impurity injection into a stable plasma demonstrates a rapid, radiative plasma termination with no runaway electrons.





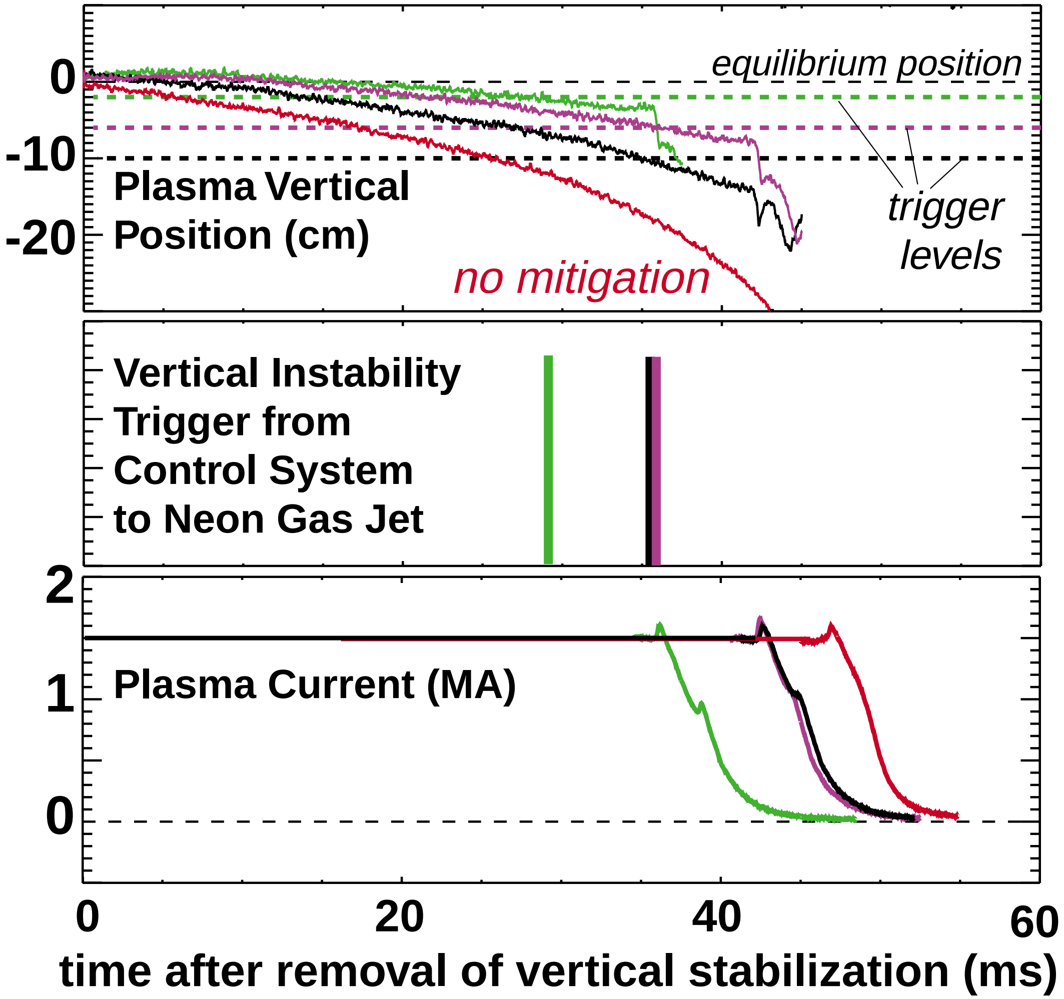
- Plasma remains well-centered in the vessel

- Injection is very benign to tokamak
  - ✓ No pump system damage
  - ✓ Injected gas absent in breakdown of subsequent discharge.

DIII-D has demonstrated real-time disruption detection, which is used to trigger gas jet injection for disruption mitigation.

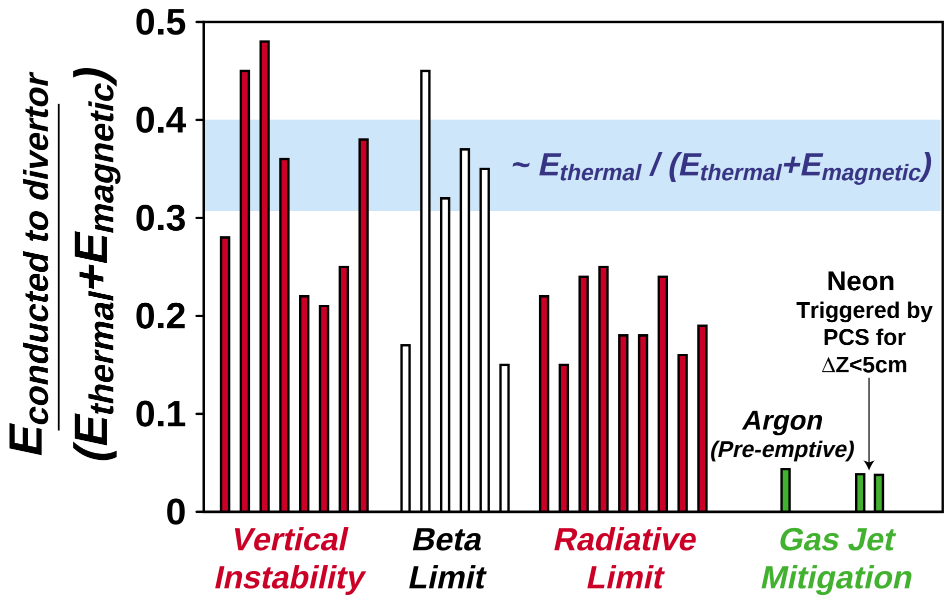
- VDE detection algorithm tracks vertical stability in real-time.
- Triggered neon gas jet reproducibly terminates plasma in ~ 5 ms, before plasma vertically displaces into vessel wall.
- Other disruption detection algorithms developed & tested.
  - Radiative/density limit
  - Growing tearing modes leading to disruption.

VDE detection and gas jet mitigation

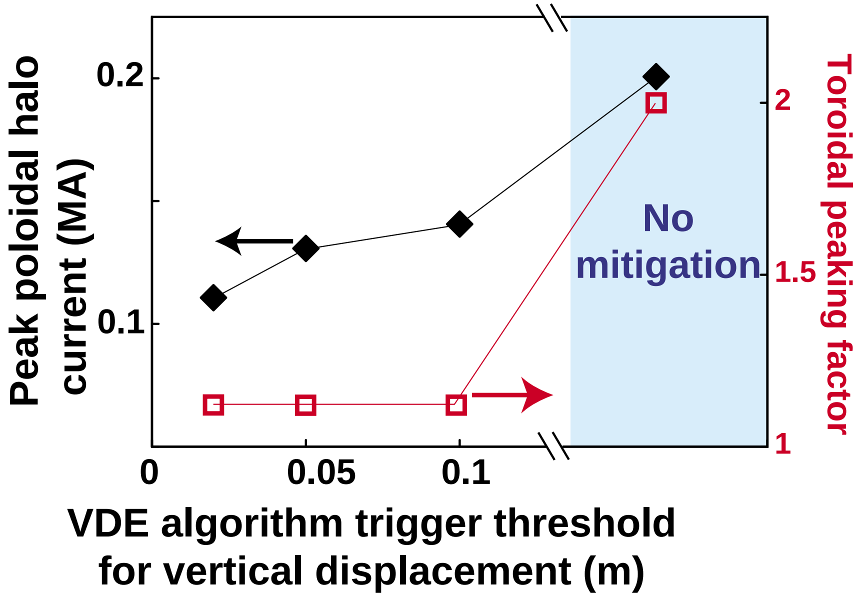


Radiative dissipation of plasma energy by impurities provides optimal mitigation of thermal loading and vessel forces

Divertor thermal loading reduced to level similar to type-I ELM



Divertor JxB forces caused by VDE reduced:
Rapid, centered current quench



Physical models of disruption mitigation have been developed and validated

- Ionization / energy balance of plasma in presence of large density of injected impurity: **KPRAD**.
  - Full charge-state dependent atomic data (non-coronal).
  - Self-consistent time evolution of Z_{eff}, $<Z>$, T_e, T_i, P_{rad}, P_{ohmic} .
  - Injected impurity species, n_{imp} and $j_{//}$ imposed from experiment.
  - Performed on individual flux surfaces or volume averaged.

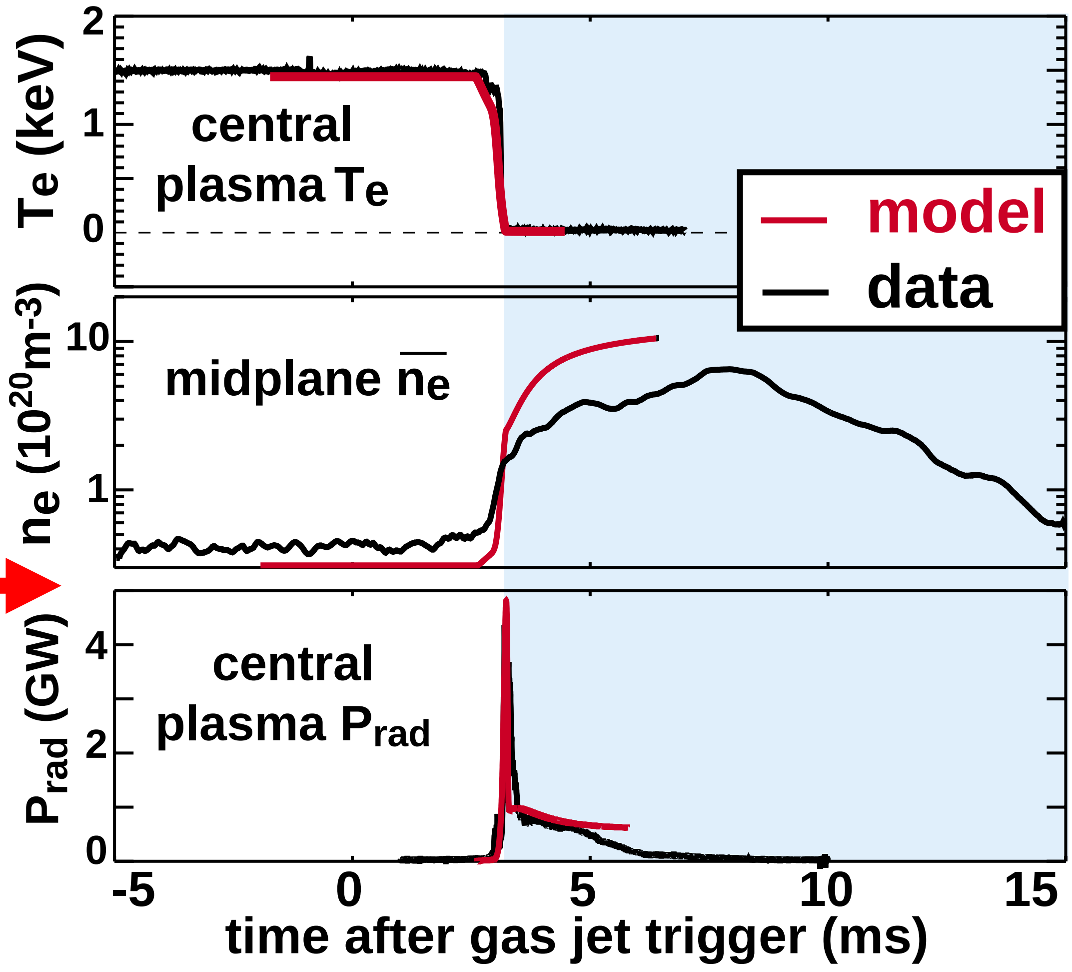
- Poloidal halo currents
  - Analytic circuit equation for core/halo/wall coupling (GA halo).

- Runaway electrons
  - Parallel electric field from KPRAD and Ohm’s law: $E=\eta j$
  - Rosenbluth, et al. formulation for RE avalanche amplification.

Ionization/energy balance model (KPRAD) matches key features of gas jet mitigation experiments:

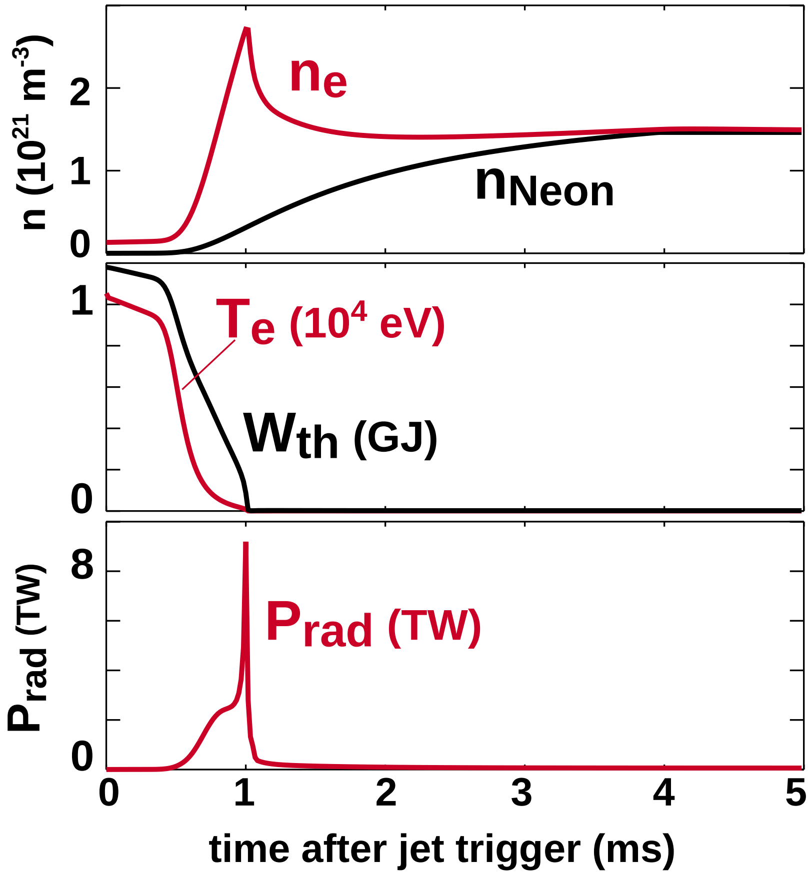
Initial burnthrough → P_{rad} → T_e collapse → n_e clamped

Model result:
Neon gas jet into DIII-D

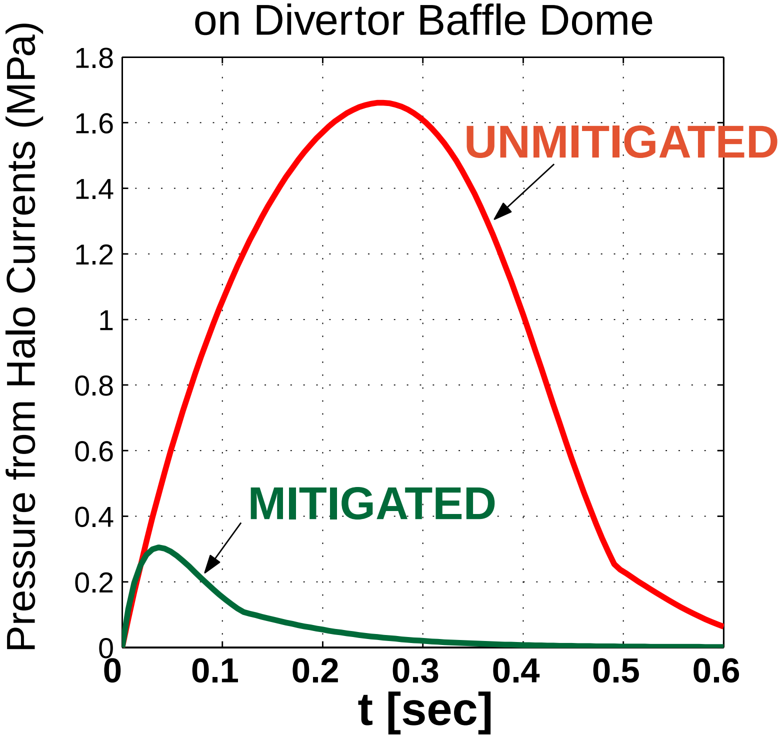


KPRAD and halo current modeling show effective mitigation using gas jets in a burning plasma device.

Neon gas jet into example burning plasma device: ITER-EDA (R~8m)



ITER FEAT Simulation:
Disruption Stress
on Divertor Baffle Dome



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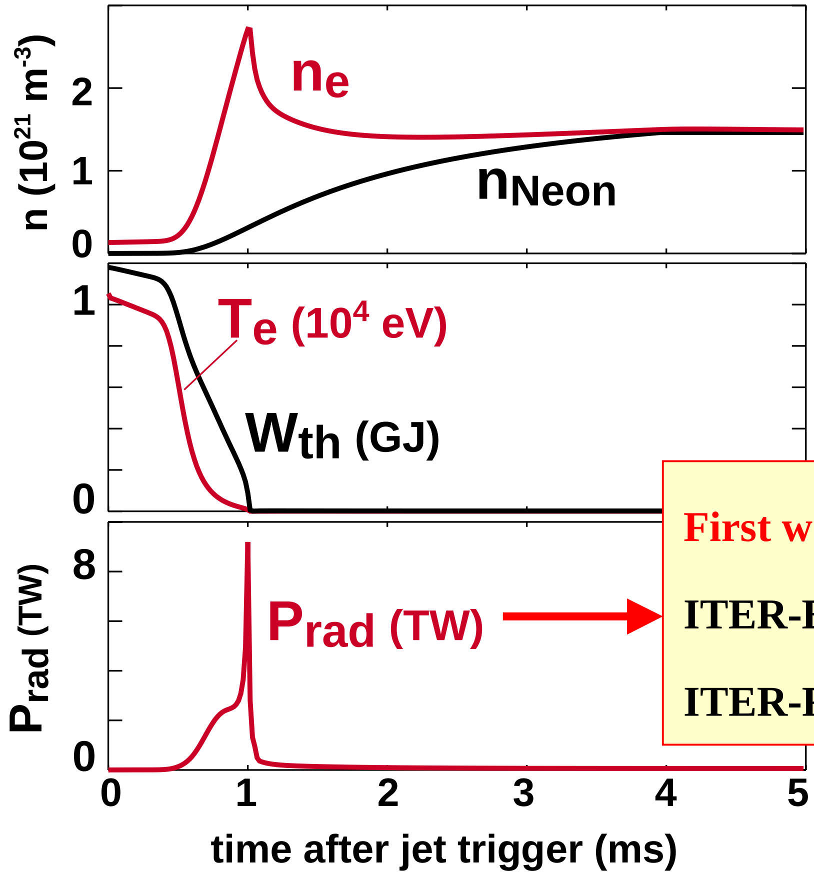


First wall heating:

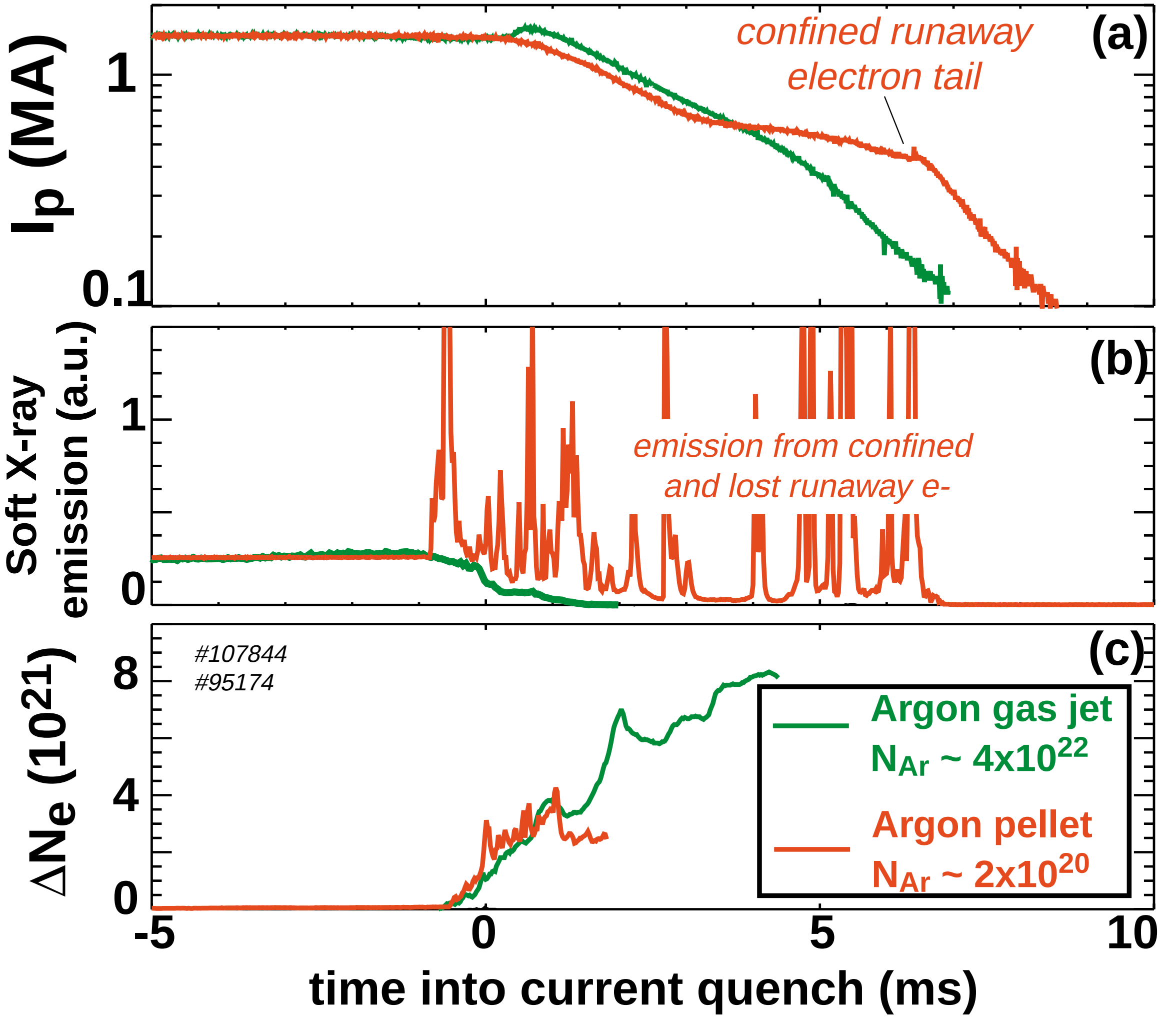
ITER-EDA → 33 MJ m^{-2}s$^{-1/2}$

ITER-FEAT → 21 MJ m^{-2}s$^{-1/2}$

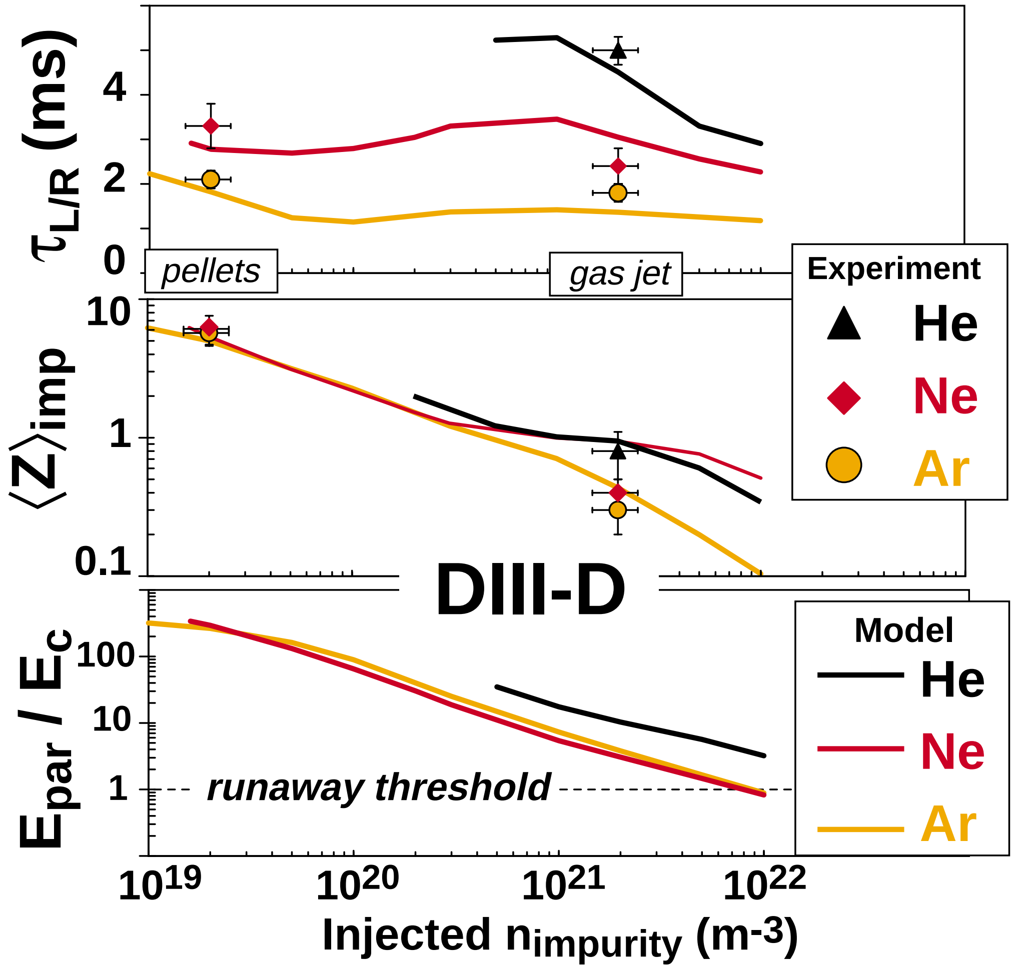
Melt/ablate limits:

Beryllium	~ 25 MJ m^{-2}s$^{-1/2}$
Tungsten	~ 45 MJ m^{-2}s$^{-1/2}$
Carbon	~ 40 MJ m^{-2}s$^{-1/2}$

Runaway electrons are controlled on DIII-D due to high total density of injected impurities



KPRAD model describes key features for runaways: E_{par} and <Z> for gas jet and impurity pellets

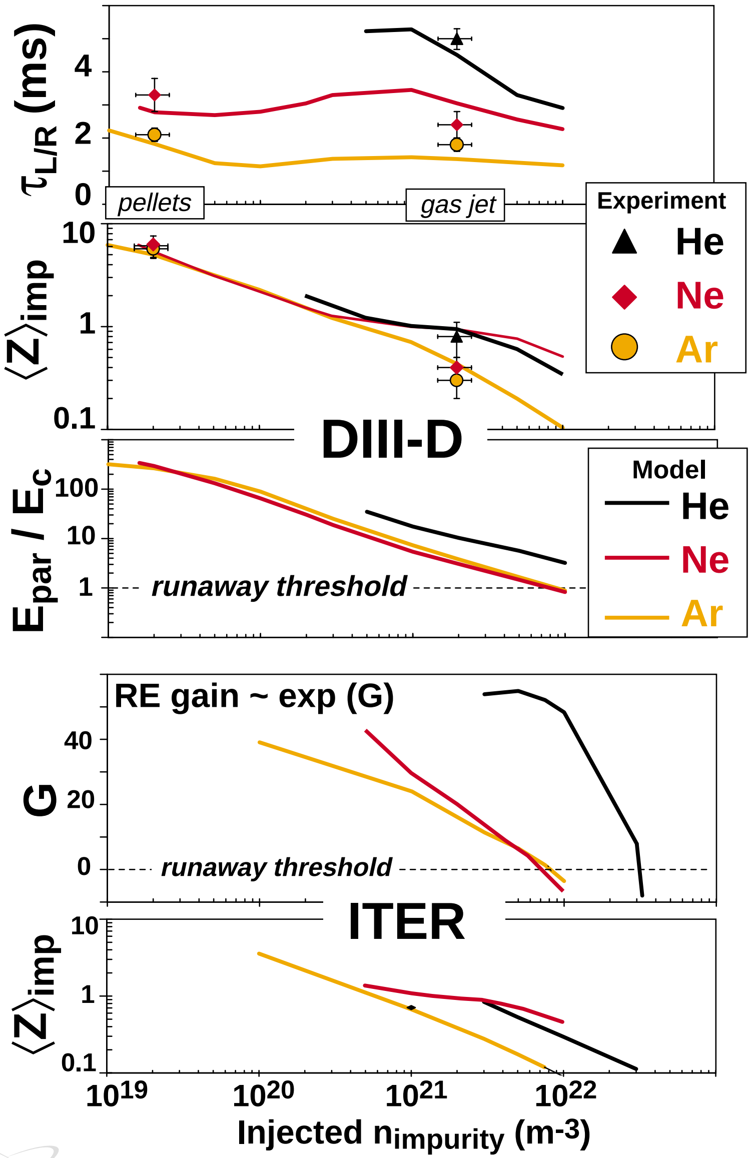


- ✓ Constant $E_{par} \propto 1 / \tau_{L/R}$ only sensitive to injected species.
- ✓ Average impurity charge state falls below unity.
- ✓ Dreicer evaporation criterion is broken at high n_{imp} suppressing runaways:

  $E_{par} > E_c$ $(= 10^{-21} n_{e,total})$ [V/m]

  e^- acceleration > frictional drag.

KPRAD model predicts runaway suppression in ITER as $n_{impurity}$ increases, $E_{parallel}$ ~ constant, Z_{imp} decreases



- Runaway amplification growth rate:

  $I_{RE} \propto \exp(G)$

  $G \propto (E_{par}/E_c - 1)\ \tau_{L/R}$

- Reasonable scaling to ITER
  - ✓ **< 2 liter reservoir at 100 atmospheres needed for ITER size device.**
  - ✓ **Conservative calculation since runaway transport losses are ignored.**
  - ✓ **Relatively simple technology.**

Issues regarding application of gas jet to burning plasmas

- Optimizing mitigation scenarios by choices of impurity
  - Neon and argon: high radiation rates & optimal RE suppression
  - Helium: low radiation rate, RE suppression at higher n_{imp}, slower current quench.
- Development of reliable triggers for gas jet.
  - Physics-based parallel disruption algorithms now being test on DIII-D
- Gas jet development
  - Ram pressure > several atmosphere needed to penetrate burning plasma
  - Create and benchmark detailed model for jet penetration.
  - Experiments on larger, higher T_e (JET) and high B (C-Mod) tokamaks.

A simple and robust method of mitigating the damaging effects of disruptions has been developed

- High pressure jet penetrates to center of core plasma.
- Centrally deposited radiating impurity provides optimal thermal and halo current mitigation.
- A sufficient quantity of injected gas suppresses runaway electrons by collision damping on neutrals.
- Physical models of mitigation have been developed and validated on DIII-D, giving confidence in our extrapolation of this technique to burning plasma experiments.