Impurity Assimilation During Massive Gas Injection for Disruption Mitigation in DIII-D

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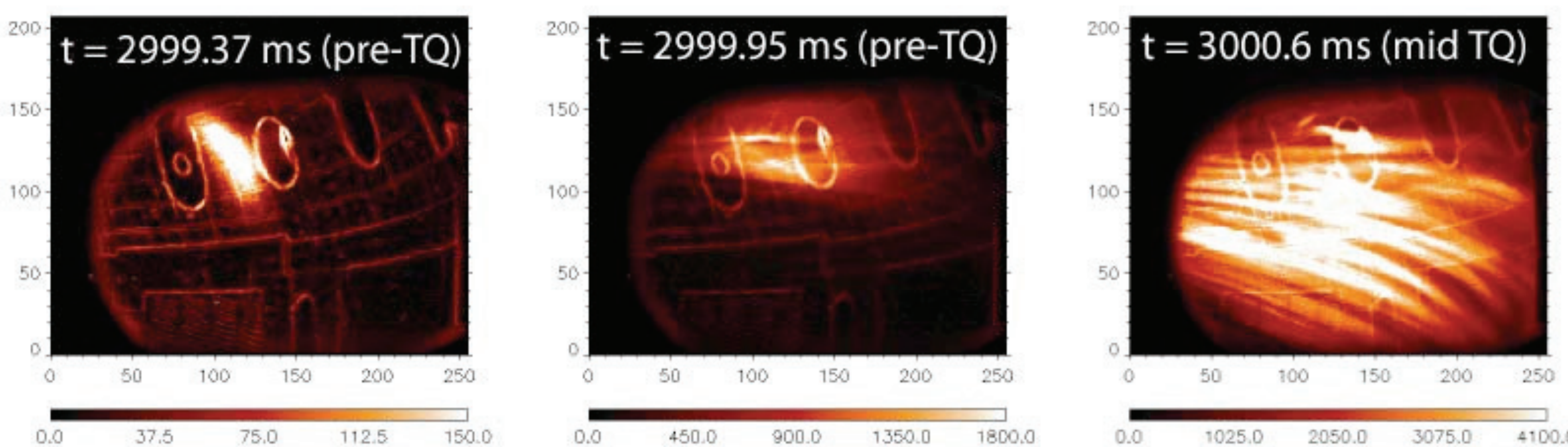
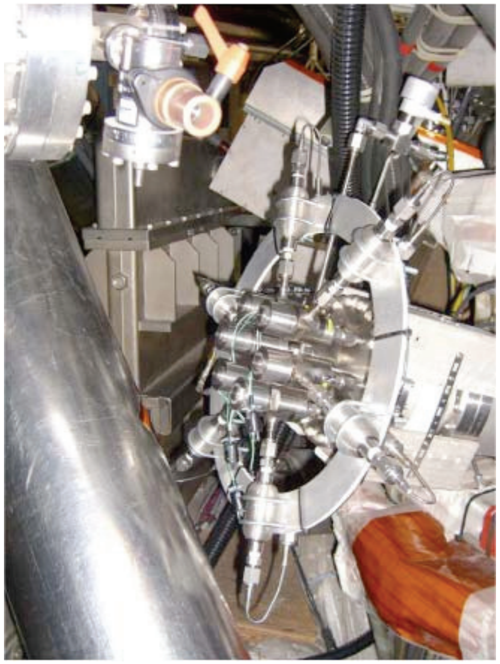


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

APS DPP, Dallas. G03.00012, Tuesday Nov 18, 2008

Motivation

- Future large tokamaks will need a safe fast shutdown scheme to use as a last resort in the event of an unavoidable disruption
- Massive gas injection (MGI) is presently the anticipated fast shutdown method for ITER
  - straightforward to implement.
  - works well in present devices (reliable, fast, low vessel forces, low heat loads)

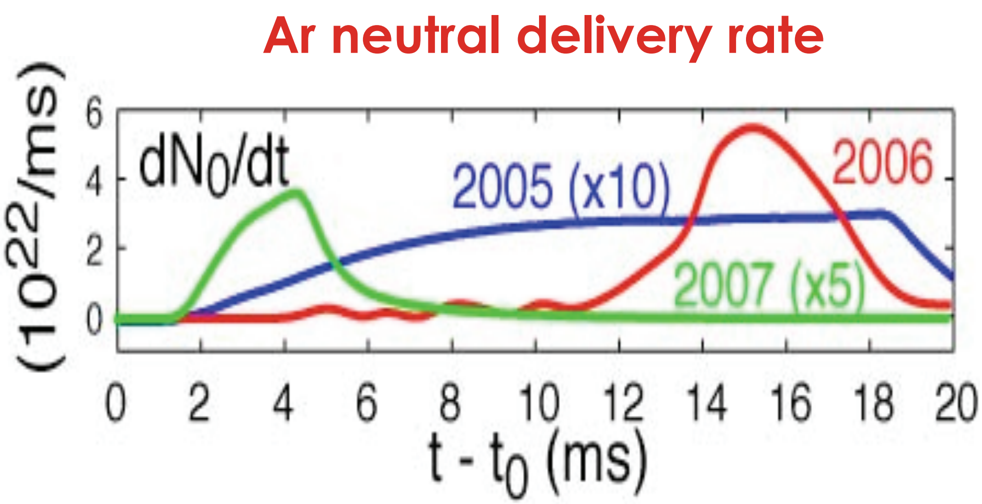


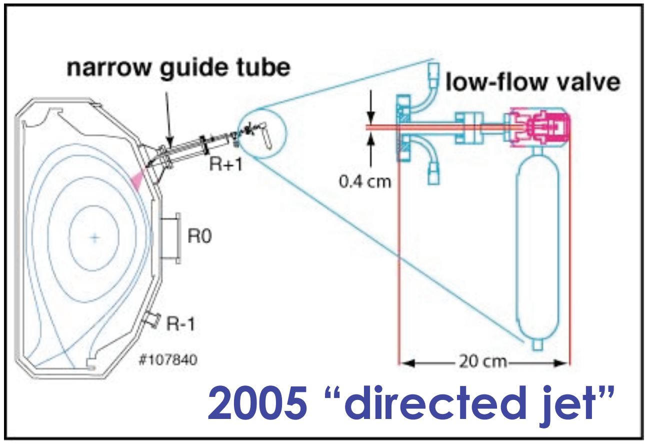
2007 "Medusa" DIII-D MGI system

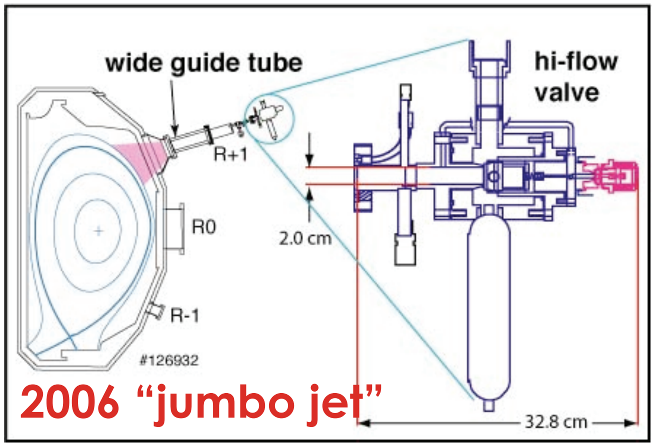
- Understanding assimilation of impurities into plasma during MGI shutdown is crucial for predicting how well MGI will work in ITER.

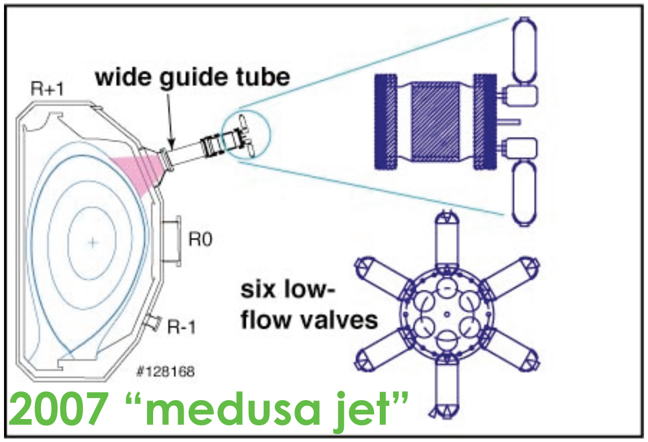
2005-2007 MGI hardware

- **2005 MGI delivered ~1,000 torr-l (~3x10^{22} particles) in ~15 ms long pulse**
- **2006 MGI delivered ~10,000 torr-l in ~10 ms long pulse.**
- **2007 MGI delivered ~1,000 torr-l in ~2 ms long pulse.**

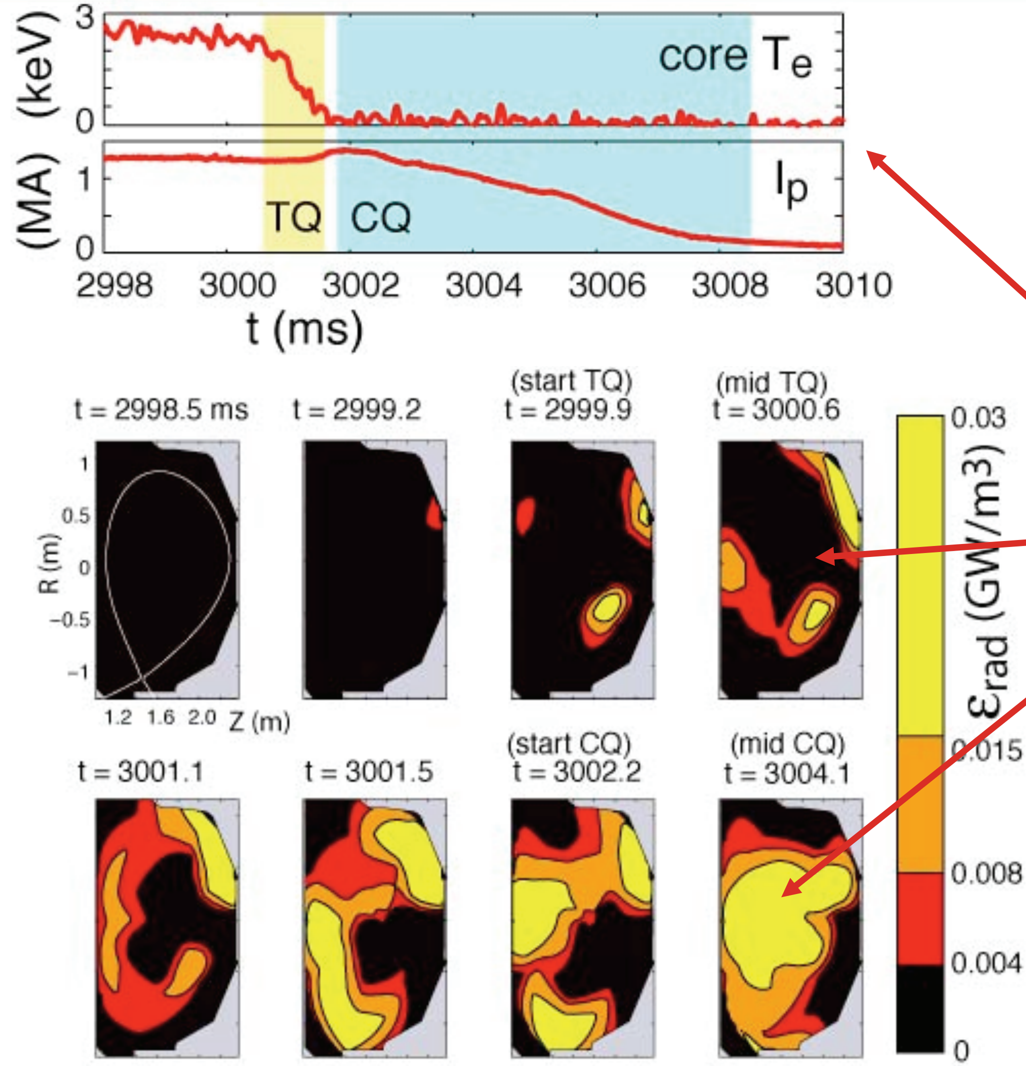








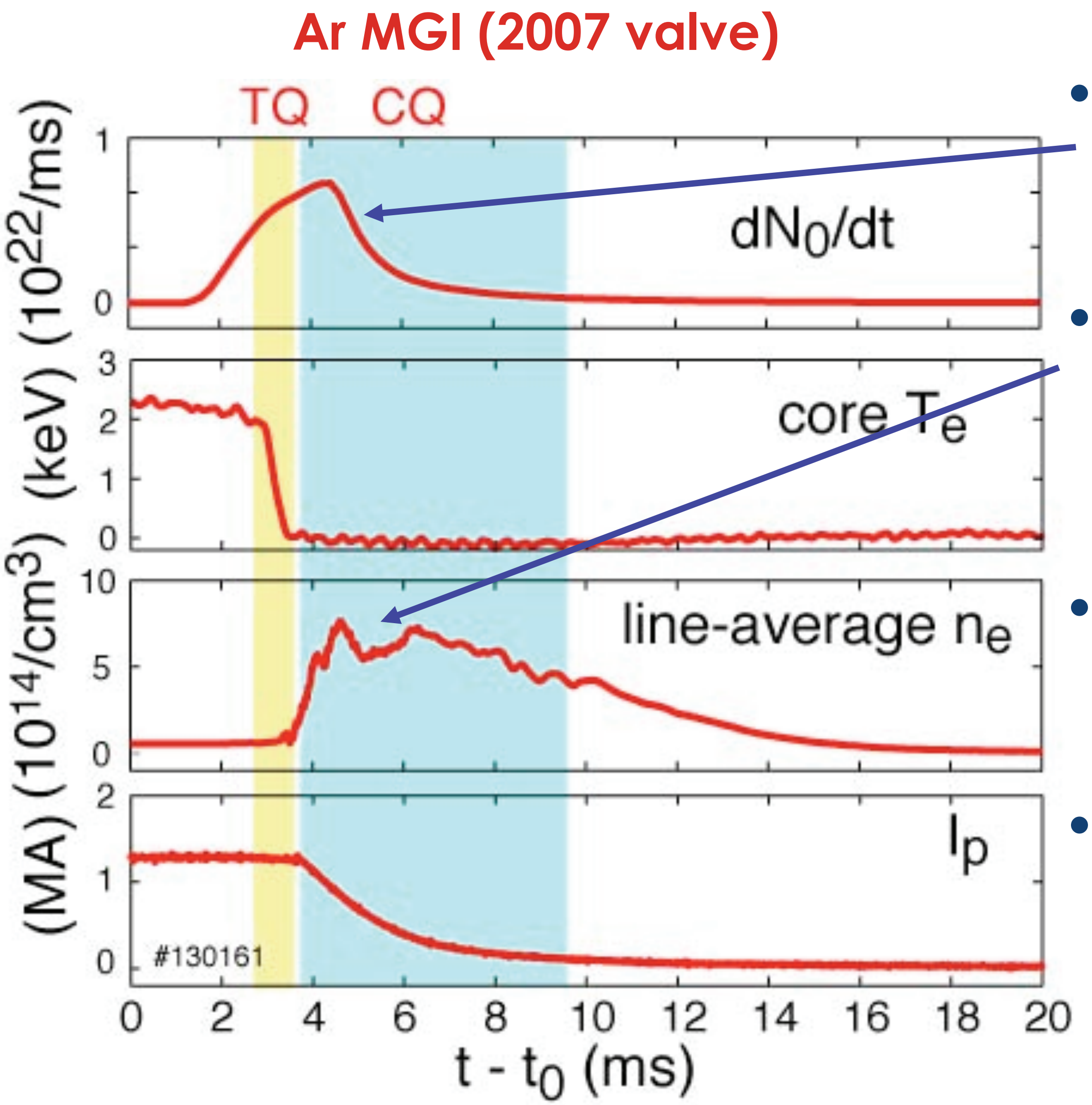
Assimilation mostly completed by end of TQ



Total radiated emissivity, D_2 MGI #131538

- MGI shutdown has fast thermal collapse (TQ), followed by slower current quench (CQ).
- During TQ phase, rapid impurity mixing takes place.
- By middle of CQ, injected impurities appear to be fairly well-mixed through plasma.

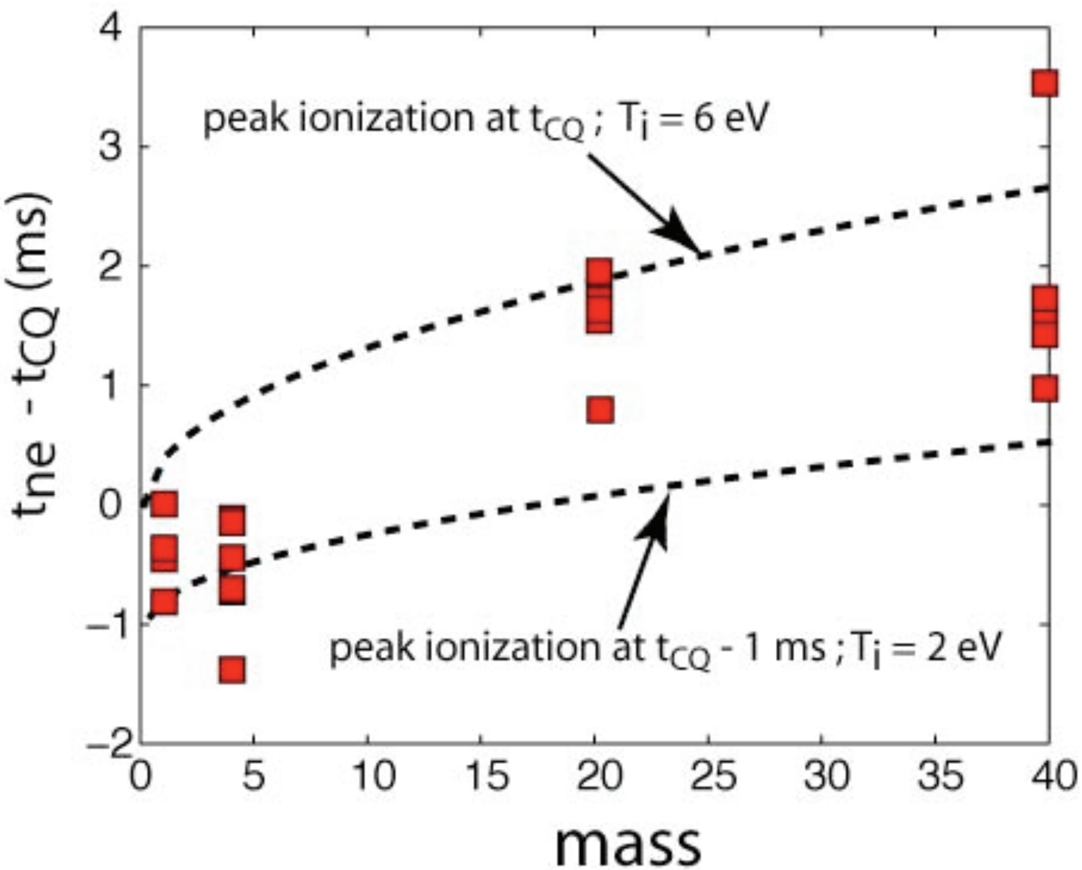
0D mixing efficiency estimate



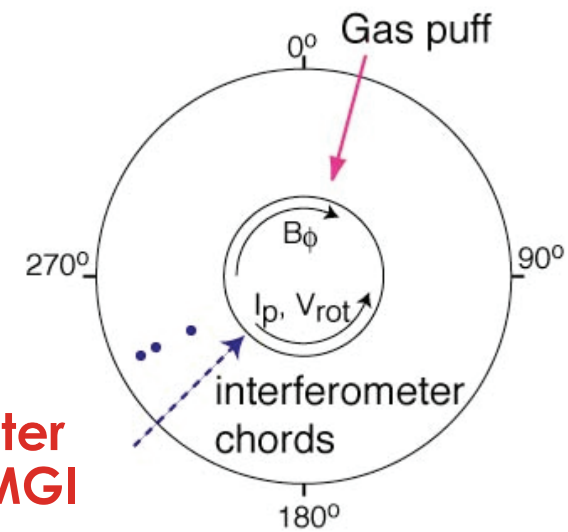
- Injected particle number known from 1D fluid modeling and from pressure gauges.
- Plasma well-mixed in CQ, so can estimate impurity number in core from n_e rise: $N_{core} = V_p \Delta n_e / \langle Z \rangle$.
- D_2 released from walls is usually small (< 20%) contribution to measured n_e rise.
- <Z> can be estimated from measured CQ T_e assuming ionization-recombination equilibrium.

Delay in density peak due to toroidal transit

Time delay of n_e peak



- **Peak in measured n_e with interferometers often occurs during CQ.**
- **Can be explained by peak ionization occurring during TQ plus 1-2 ms toroidal transit time due to T_i ~ 2-6 eV.**

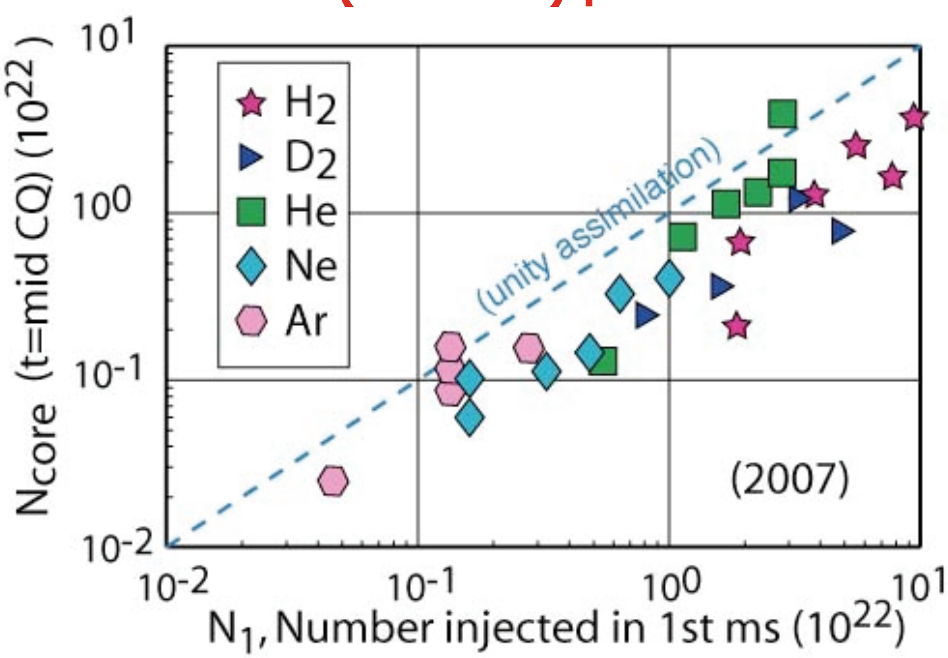


Interferometer relative to MGI

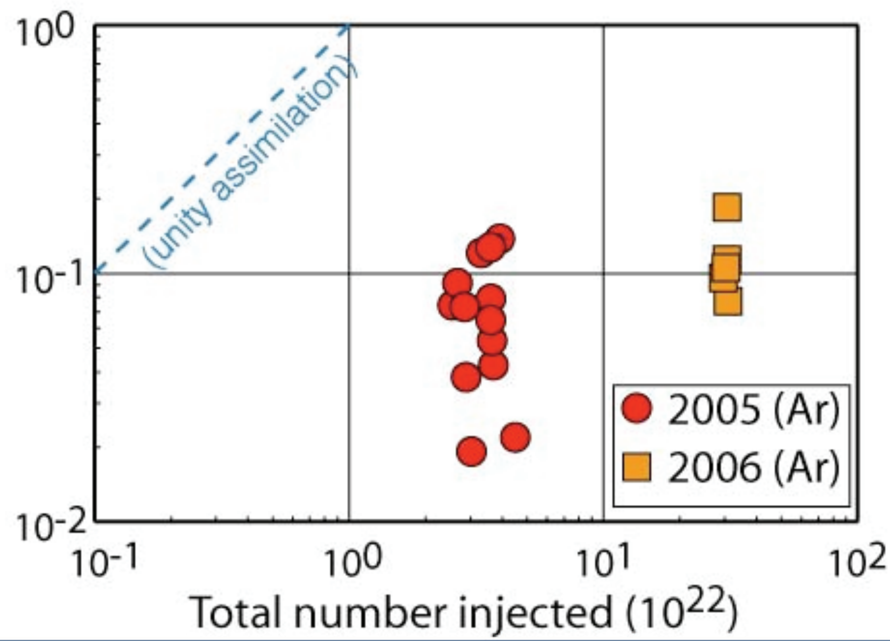
Assimilation mostly completed by end of TQ

- **Short pulse MGI experiments show that final (mid CQ) assimilated particle number correlates well with particles delivered early (in first several ms).**
- **Long pulses (~10 ms) do not assimilate well.**
- **Consistent with mixing occurring dominantly during TQ phase.**

Short (~1-2 ms) pulse MGI



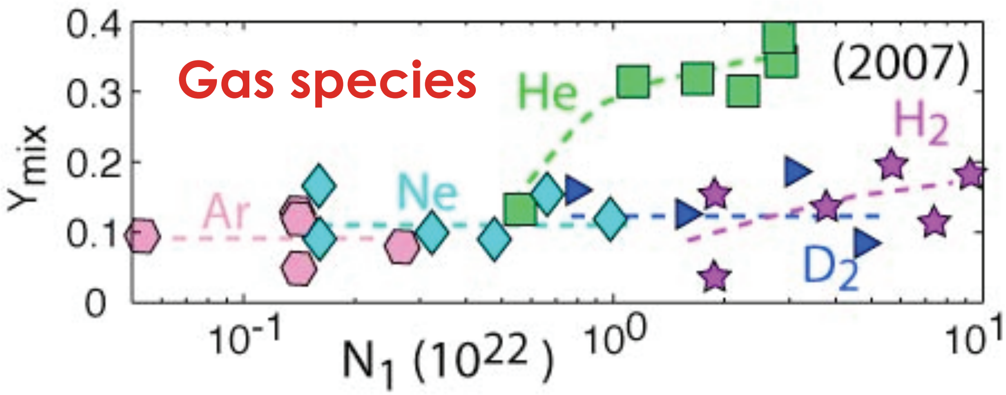
Long (~10-15 ms) pulse MGI



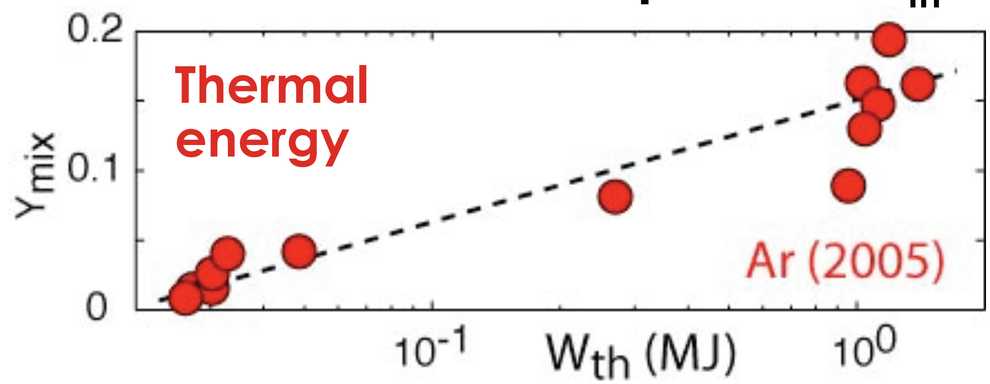
Mixing efficiency dependences

- Define 0D mixing efficiency as $Y_{mix} = N_{core}/N_{inj}$

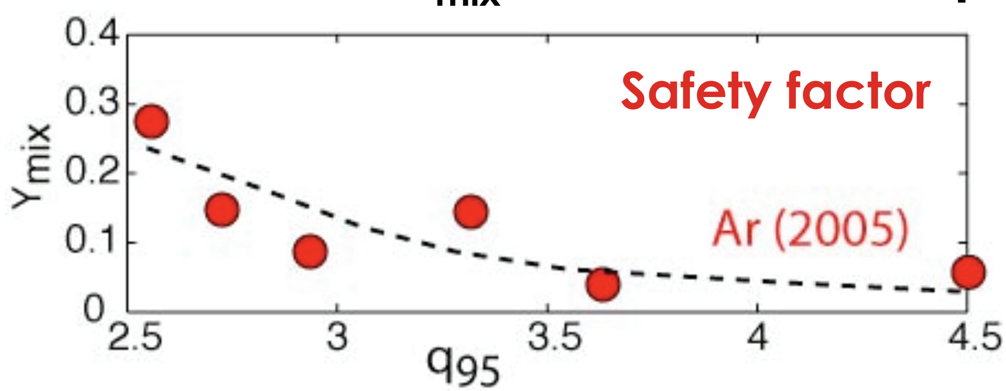
- No clear trend with species mass



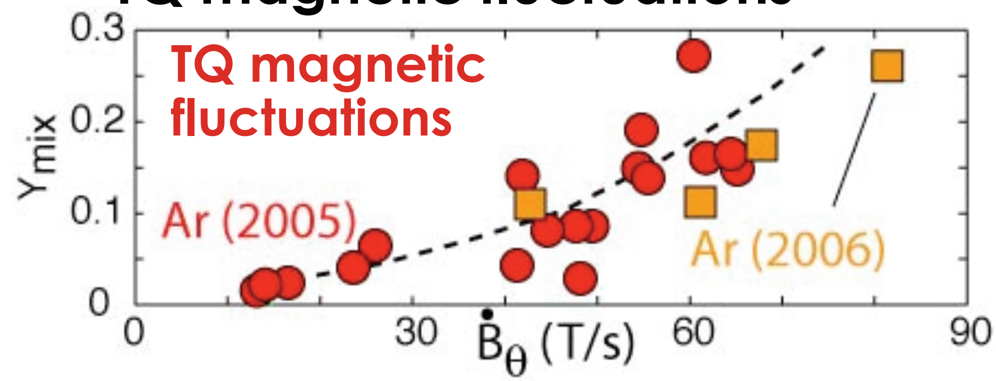
- Slow increase with plasma W_{th}.



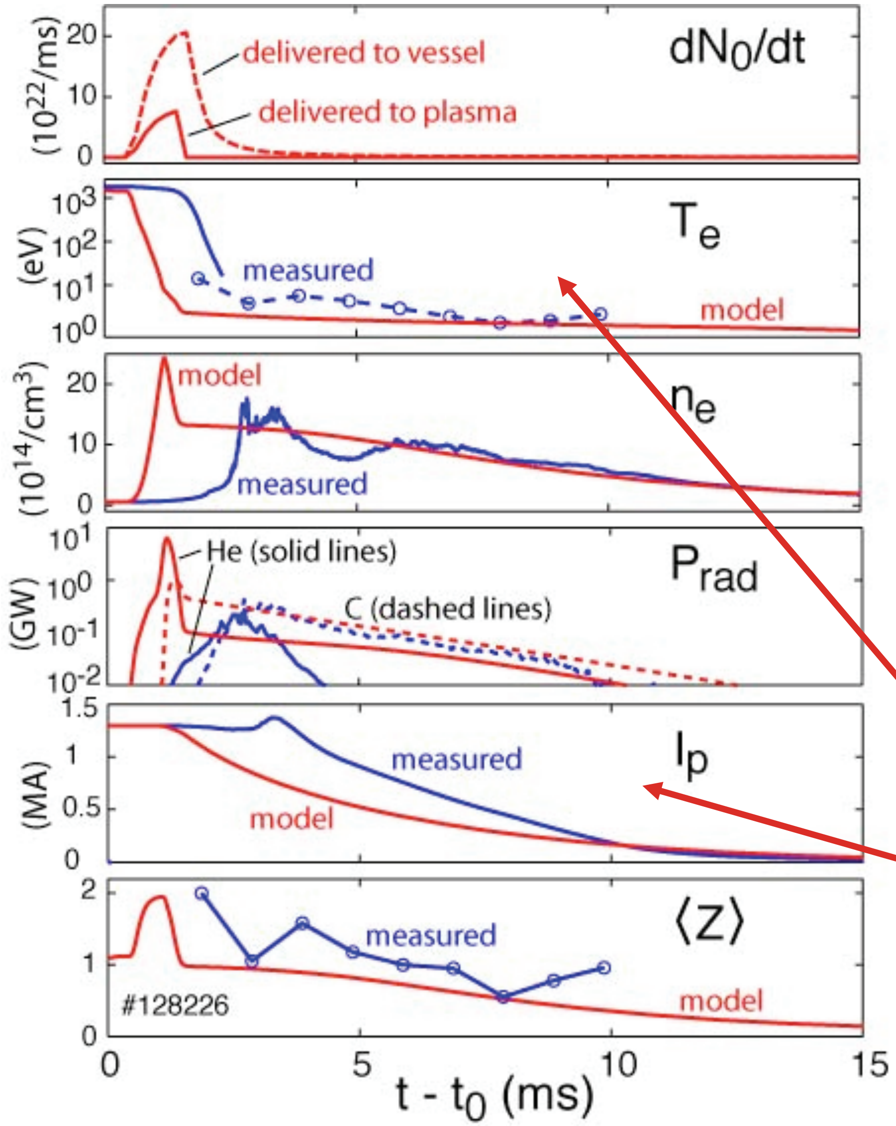
- Decrease in Y_{mix} with increased q



- Increased mixing with larger TQ magnetic fluctuations

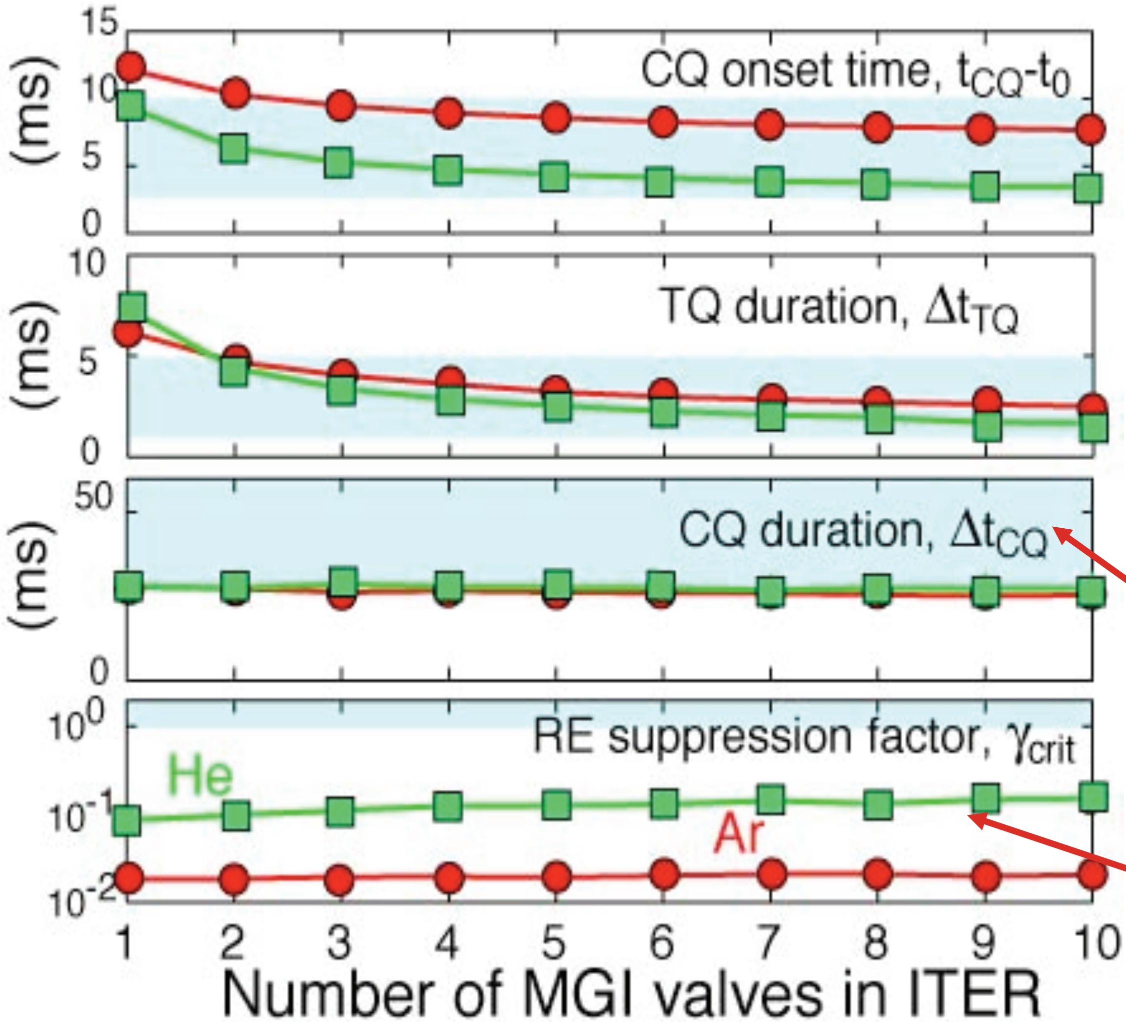


0D simulations of DIII-D MGI shutdown



- Use measured Y_{mix} and deliver particles at rate $Y_{mix}dN_0/dt$ directly to 0D core.
- Use classical plasma resistivity (no runaway electrons).
- Include symmetric hoop wall current.
- Include intrinsic initial 2% C.
- Include opacity in 1D cylindrical escape factor approximation.
- TQ onset time underestimated (need 1D model?) but TQ and CQ durations match reasonably well.

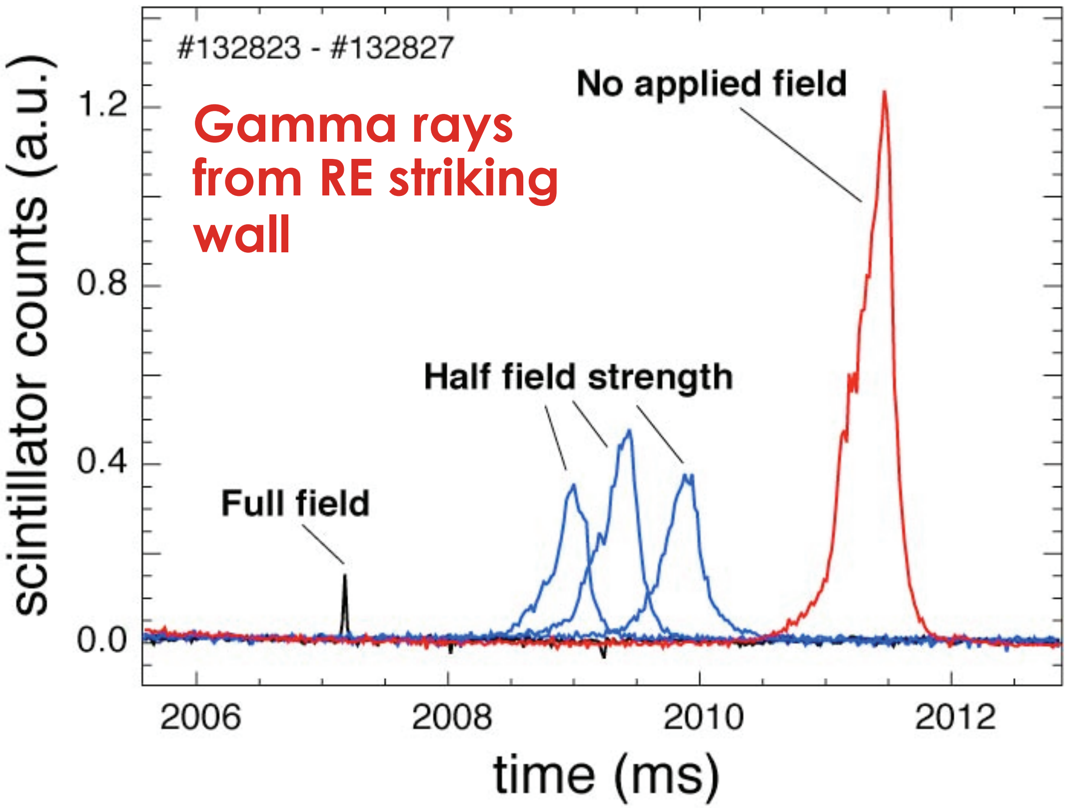
0D simulations of ITER MGI shutdown



- Use standard ITER target plasma. Assume 2% intrinsic Be.
- Assume (optimistic) Y_{mix} = 0.5 for He and 0.25 for Ar.
- Assume L=5 m delivery tube, D=2 cm valve, and 50 atm reservoir.
- CQ onset time, TQ duration, CQ duration all within desired range (blue bands).
- Insufficient material delivered even with 10 valves for collisional suppression of runaways.

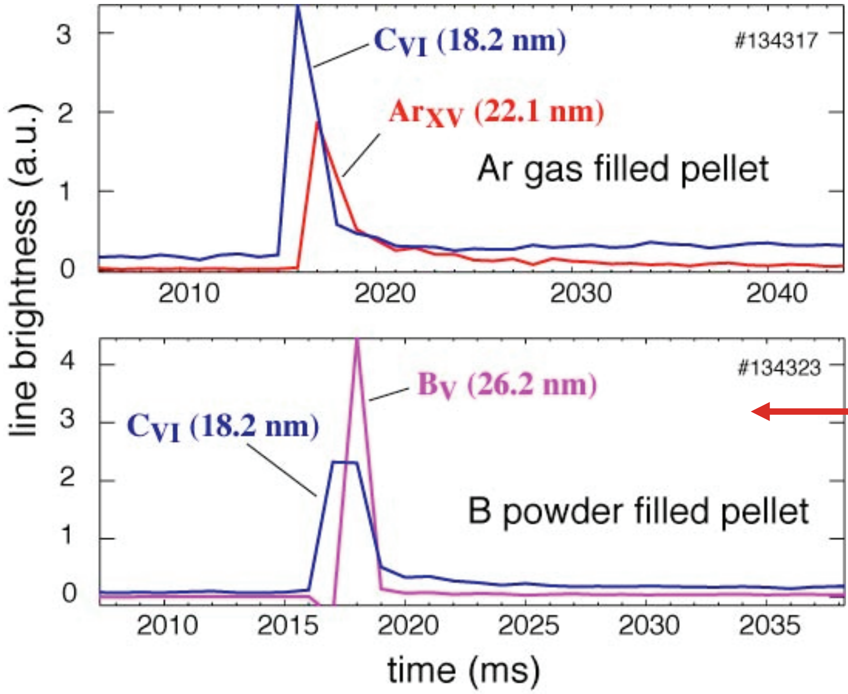
Applied magnetic perturbations to reduce RE

1 valve Ne MGI + n=3 RMP

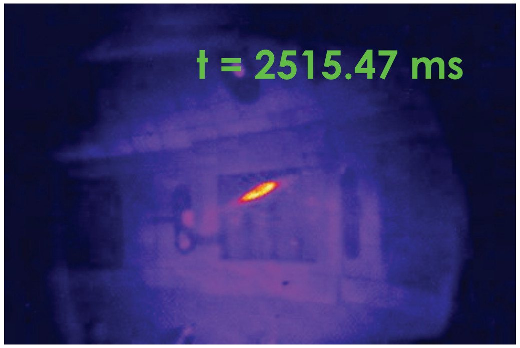


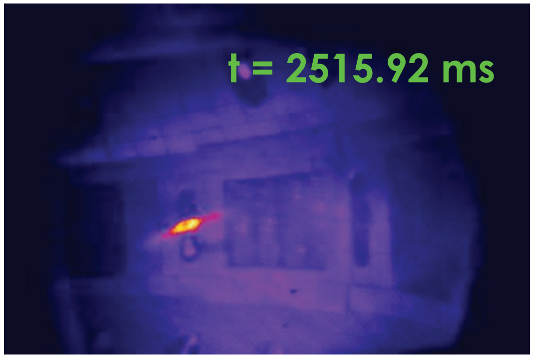
- **Possible supplement to MGI is applied magnetic perturbation (RMP) to deconfine runaways (RE).**
- **Promising initial results in 2008 showed reduced RE-wall strikes in gamma scintillator with n=3 RMP.**
- **n=1 RMP results not as clear.**

Shell pellets show impurity delivery to core



- Shell pellets are possible alternate to MGI.
- Shell pellet experiments performed in 2008 used hollow polystyrene (C_8H_8) pellets to deliver payload directly to plasma core.
- Delivery of 10 atm Ar gas or boron powder seen with core UV spectrometer.





Shot #134325 (polystyrene cylinder pellet filled with boron powder, imaged in C-II

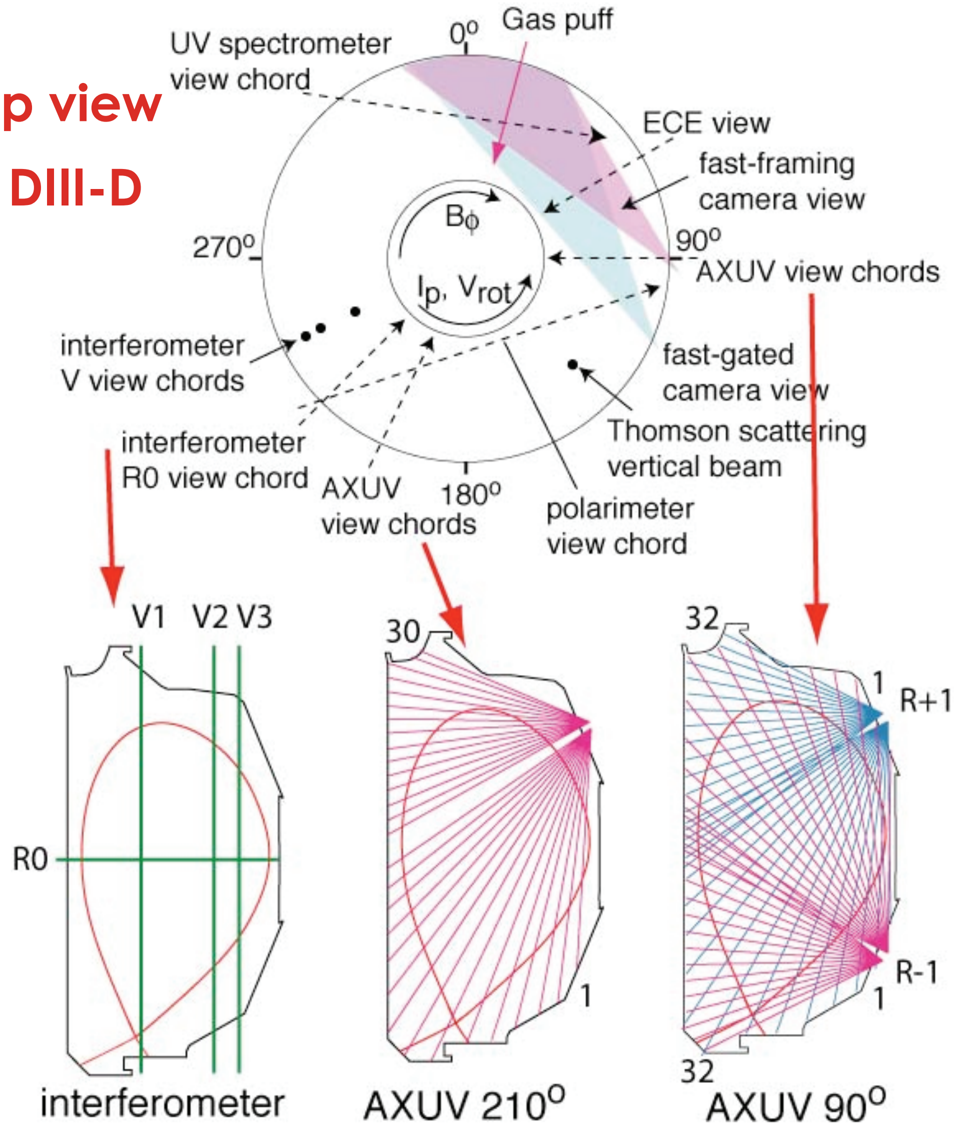
Conclusions

- Range of MGI fast shutdown experiments completed on DIII-D
  - different gas valves, target plasmas, gas species
- Impurity mixing dominantly during TQ phase
  - TQ mixing efficiency ~5%-20%.
  - Possibly due to low-order MHD reconnection?
- Estimates made for MGI in ITER based on 0D model
  - TQ and CQ durations good.
  - Collisional RE suppression not achieved.
- Future work will investigate supplements/alternates to MGI
  - External magnetic perturbations
  - Shell pellets, jumbo cryogenic pellets.

Shell pellets

Diagnostic overview

Top view of DIII-D



- MGI jet at 15° viewed by visible cameras around 90°
- UV survey spectrometer measures impurity concentration
- Interferometer measures electron density
- AXUV photodiode arrays used for fast radiated power measurements