Experiments in DIII-D Toward Achieving Rapid Shutdown with Runaway Electron Suppression

by

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with

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Disruptions result in rapid loss of plasma thermal and magnetic energy

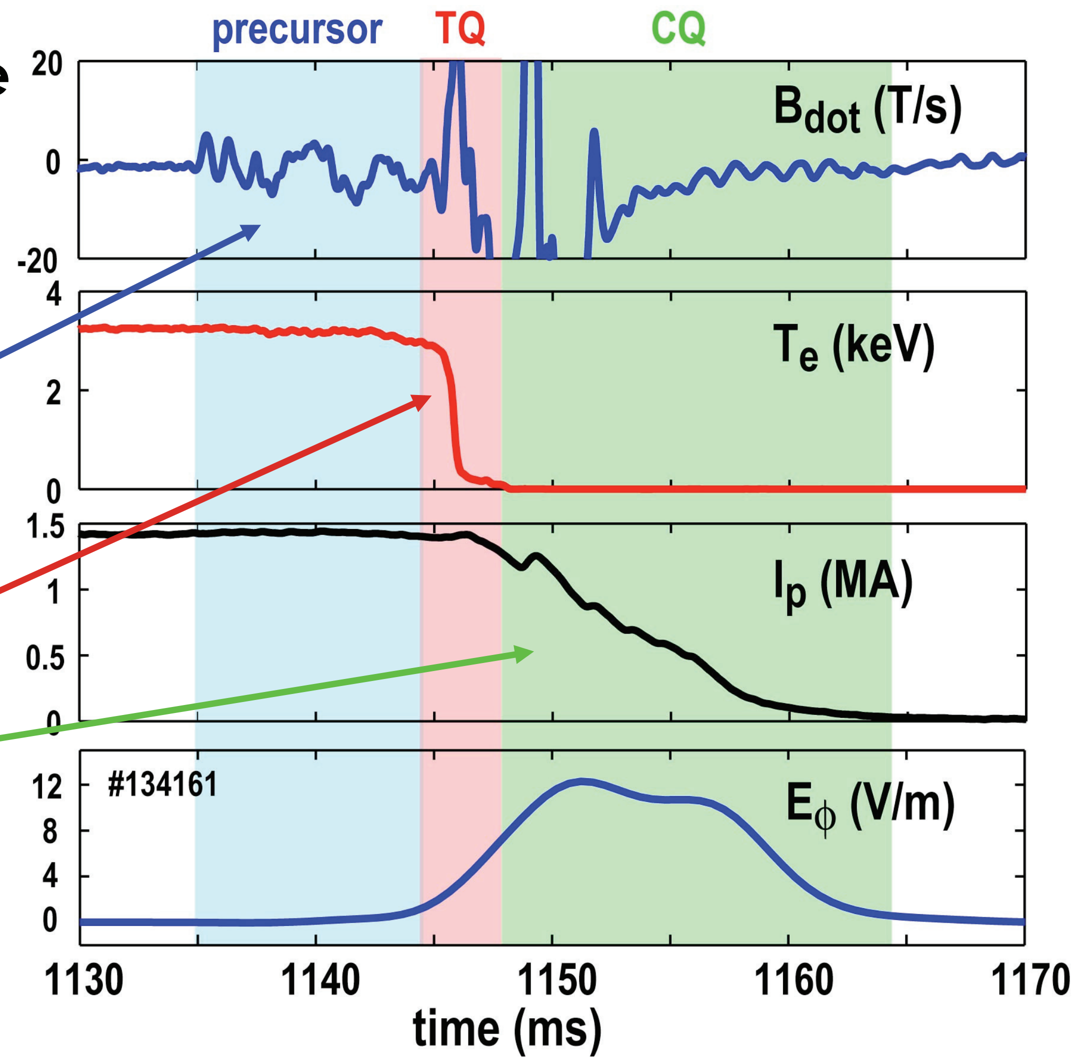
- **Disruption is a global MHD instability which terminates the tokamak discharge**
  - Caused by crossing stability boundary or by control/ power system failure
  - Three main phases:

    Precursor

    thermal quench (TQ)

    current quench (CQ)
  - Large toroidal electric field during CQ can create runaway electrons

Disruption time sequence



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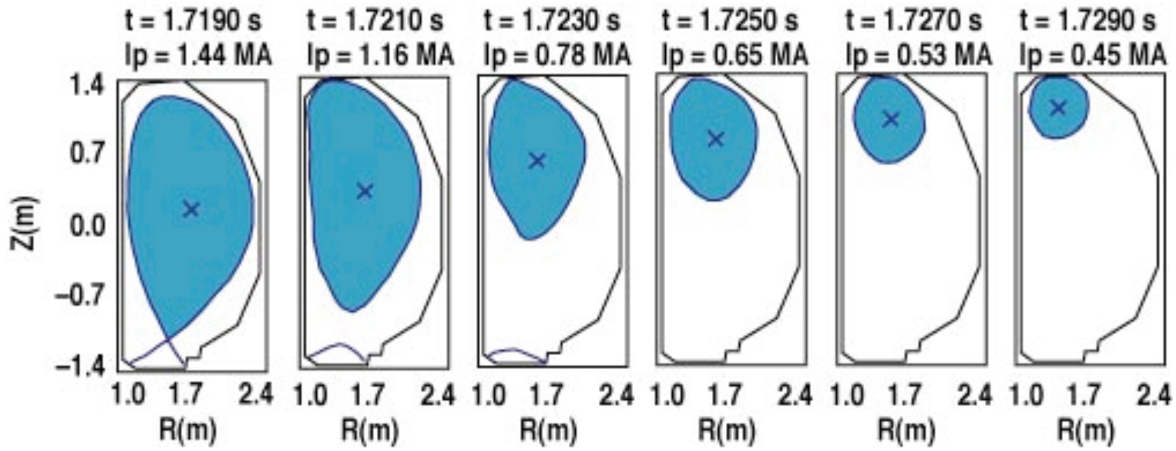
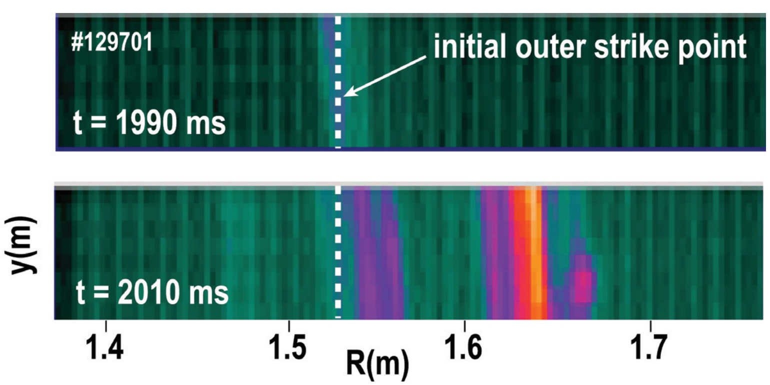
Rapid loss of plasma thermal and magnetic energy during disruption can damage walls

- Divertor heat loads (TQ)
- Vessel forces (CQ)
- Runaway electrons (CQ)

Reconstruction of current channel during disruption

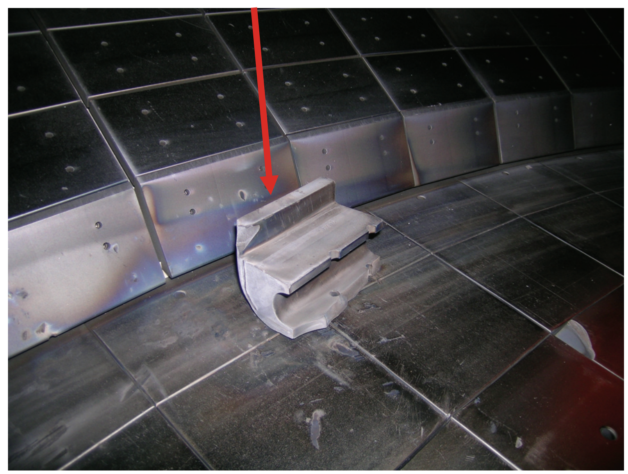


Thermography of DIII-D outer strike point during disruption



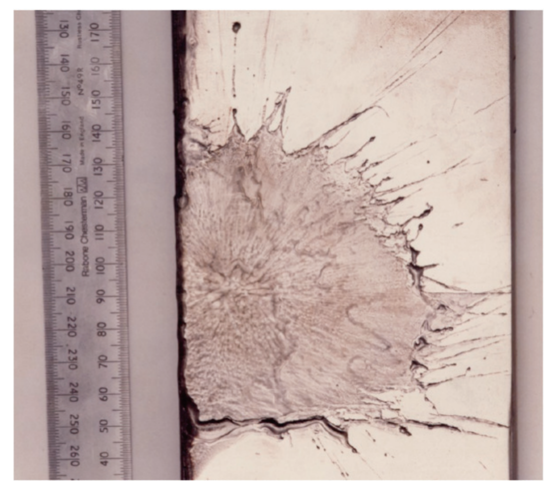
(courtesy of C. Lasnier)

Tile broken by disruption forces in DIII-D



(courtesy of A. Kellman)

Tile damage due to RE beam on JET



(courtesy of G. Martin)

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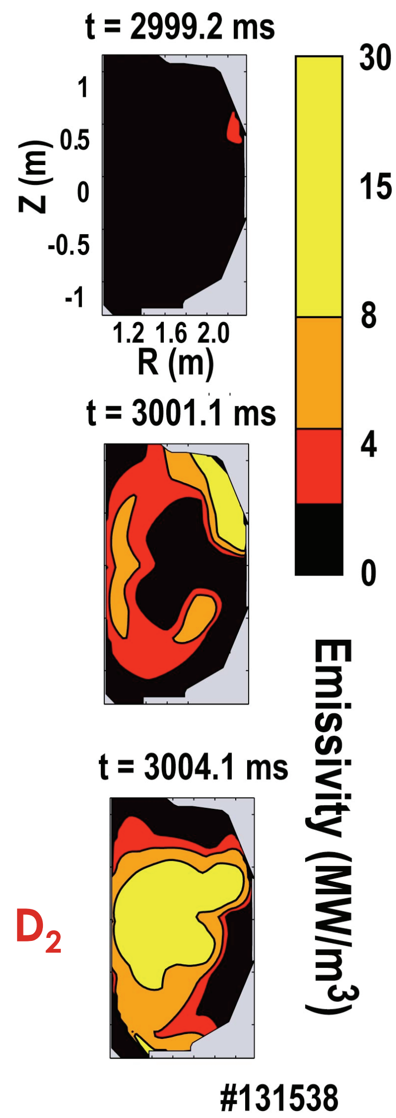
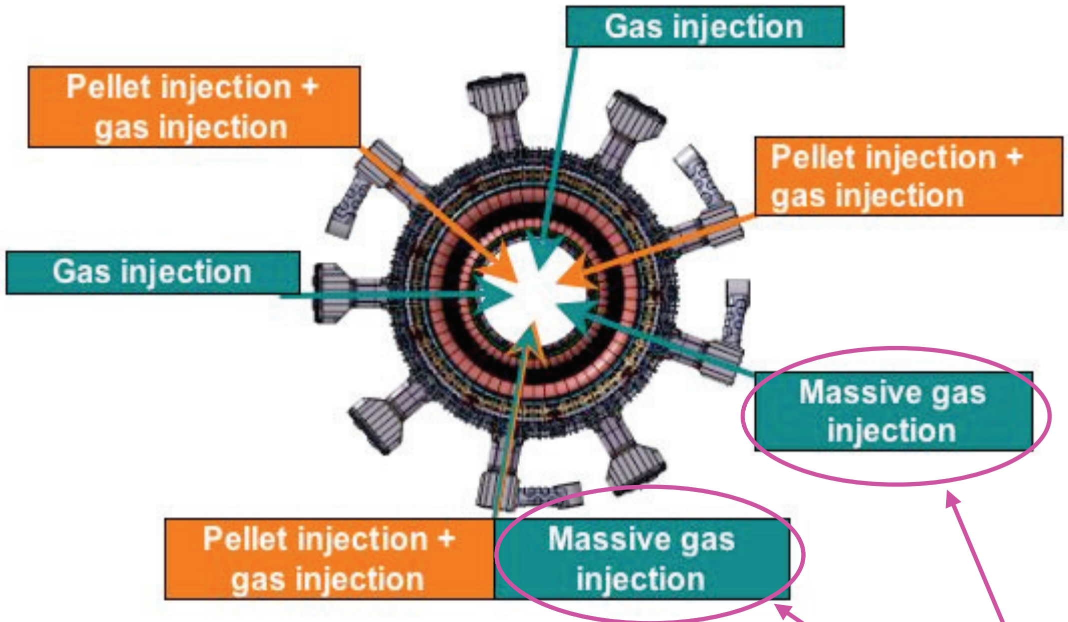
Shutdown by impurity injection reduces wall damage compared with unmitigated disruptions.

- Cause rapid shutdown by massive impurity injection into main chamber (gas injection, pellet injection)
  - Reduced divertor heat loads by radiating thermal energy into main chamber
  - Reduced halo currents by making plasma more resistive and shutting down before plasma drifts into wall
  - Improved runaway electron avoidance by collisional drag on runaways?

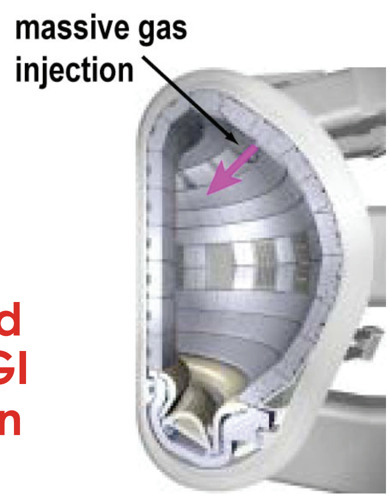


Fast bolometry of massive D_2 gas injection into DIII-D

Rapid shutdown to be used as last resort in ITER



(ITER top view courtesy of S. Maruyama)



Planned ITER MGI location

1) Avoid disruptions by avoiding stability boundaries and control system failures

2) If disruption should occur, attempt "soft landing" (current rampdown, turn off heating, etc)

3) As last resort, use pre-emptive rapid shutdown

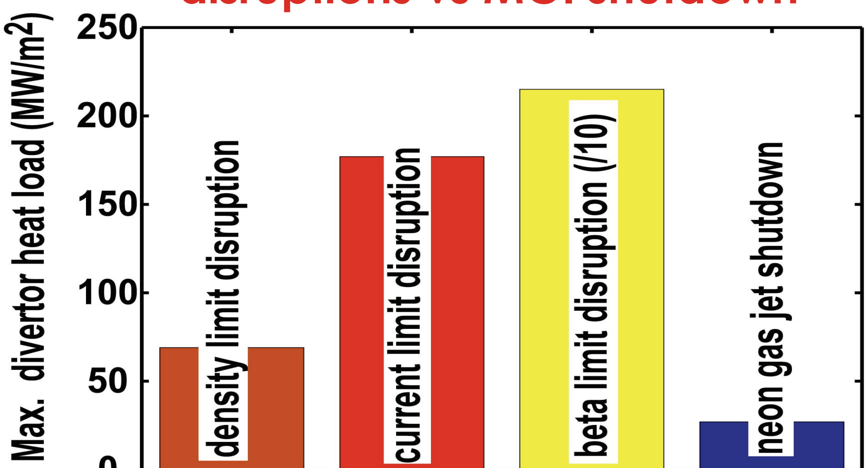
– Presently envision using massive gas injection (MGI) in ITER: 2 ports allocated

– Alternate rapid shutdown methods being considered

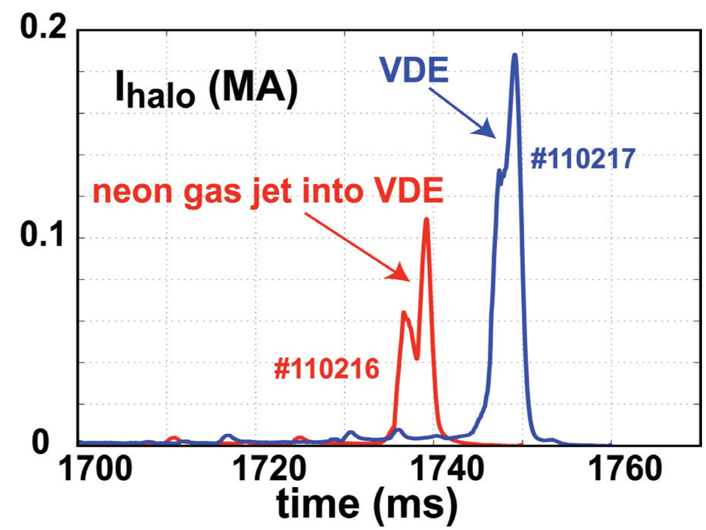
Massive gas injection works well in present tokamaks

- Massive gas injection (MGI) has been successfully implemented on many tokamaks (DIII-D, C-MOD, JET, ASDEX-U, etc.)
- MGI gives reliable heat load and halo current reduction compared with disruptions
- MGI heat load and vessel force reduction is expected work in ITER also. RE characteristics still uncertain

DIII-D divertor heat loads from disruptions vs MGI shutdown



DIII-D vessel currents reduced by MGI shutdown



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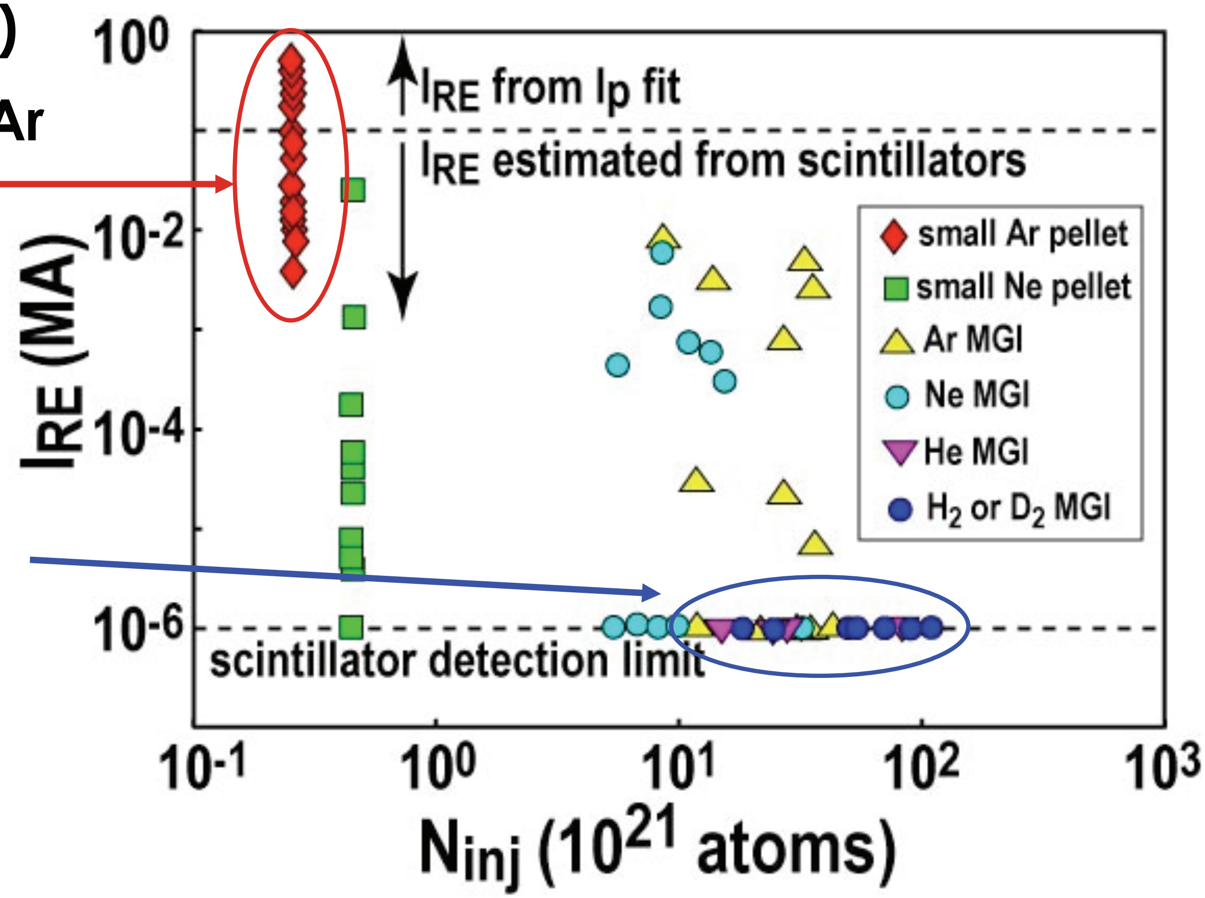
Rapid shutdown gives wide range of runaway electron levels in DIII-D

- Very small RE current in normal disruptions (I_{RE} < 1 A)
- Significant RE currents with Ar pellet shutdown
- Very small (I_{RE} < 1 A) RE current with low-Z (He, D_2, or H_2) MGI
- In ITER, larger RE avalanche gain (>10^{10} in ITER vs ~50 in DIII-D), so even a 1 A seed could be dangerous!

RE current estimated in CQ



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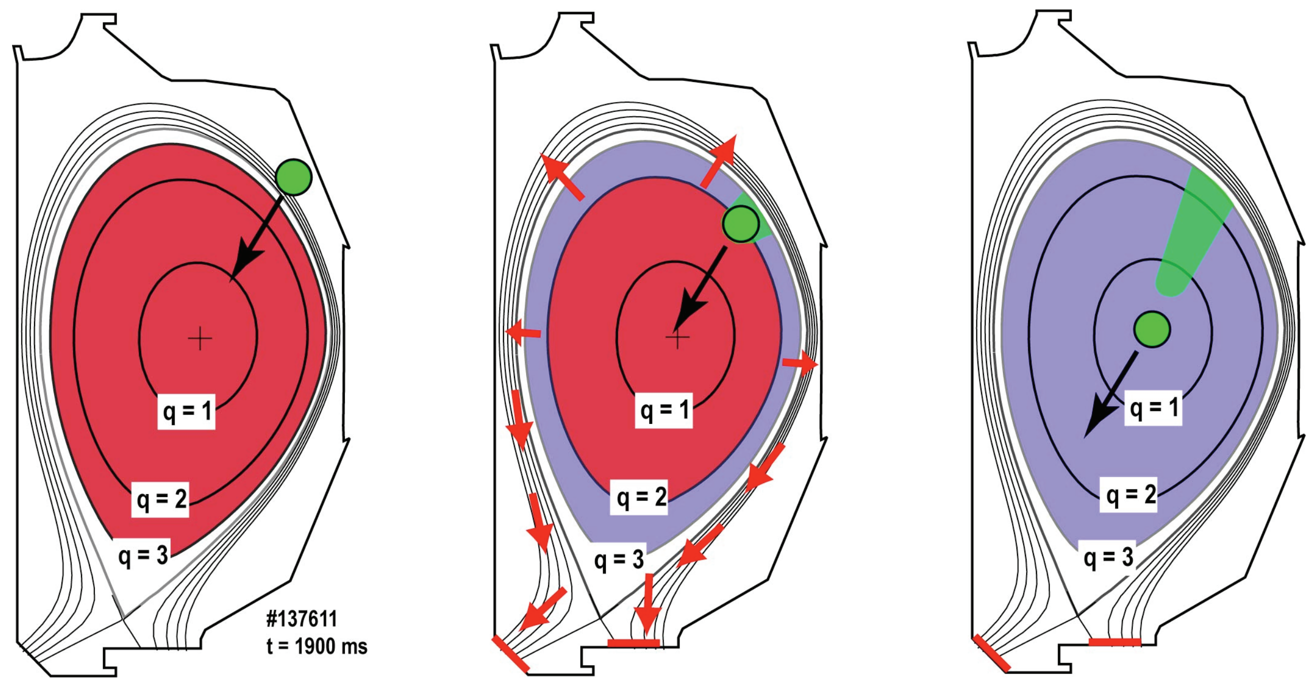
Sufficiently massive particle delivery could achieve complete runaway electron suppression

- Complete suppression of RE formation predicted to occur at total electron density $n_{tot} \sim n_{crit} \sim 4\times10^{16}/cm^3$ in plasma current channel [Rosenbluth,1997]
- DIII-D investigating three different massive particle delivery methods (massive gas injection, large shattered pellets, shell pellets)
- Uniform deposition of large densities challenging due to short (< 1 ms) TQ

Large solid pellet is not considered, because …

Incomplete impurity deposition due to TQ onset:



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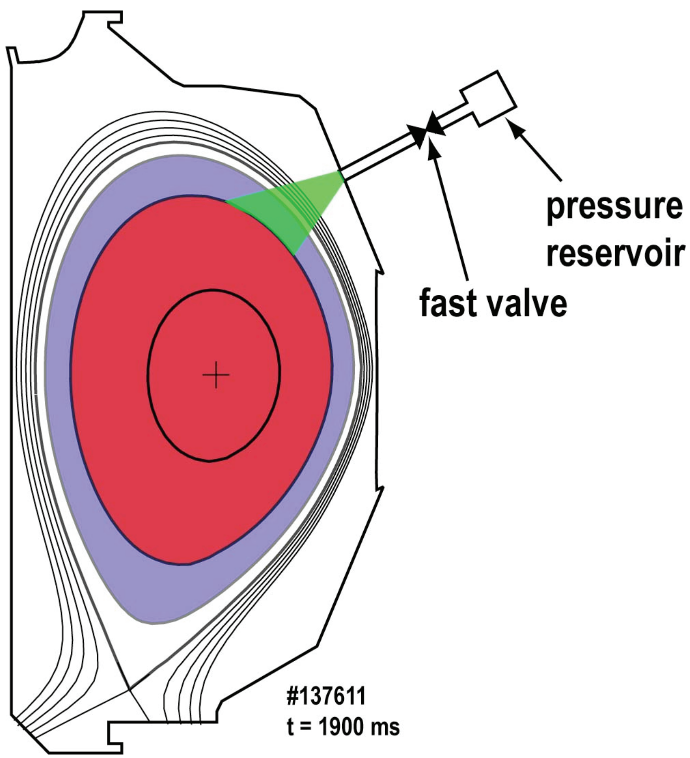
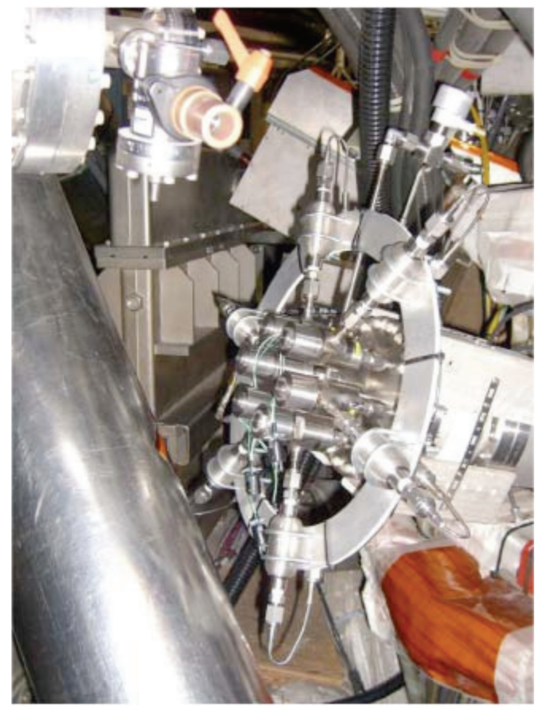
Massive gas injection

- Fire short (~2 ms) pulse of high pressure gas into plasma
- To optimize delivery before TQ onset, want fast pressure rise
- Best results obtained by simultaneously firing multiple small valves

MGI system overview



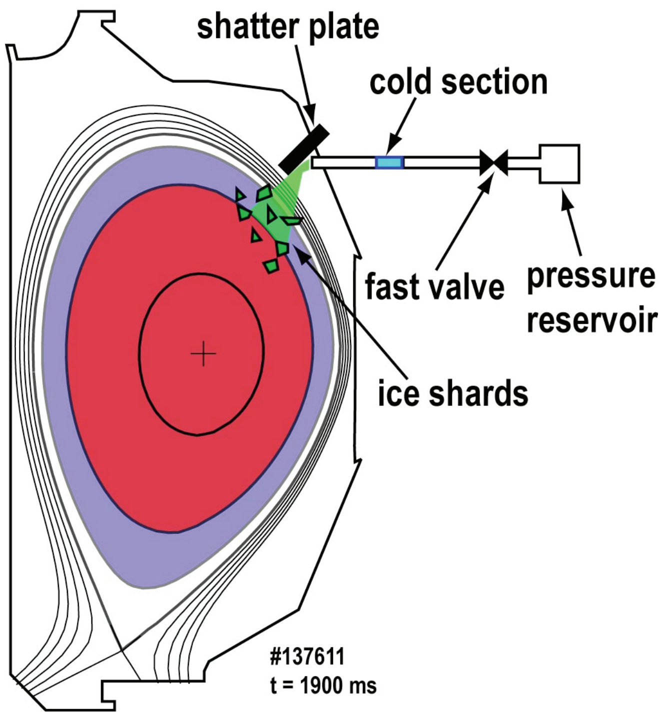
6-valve MGI flange



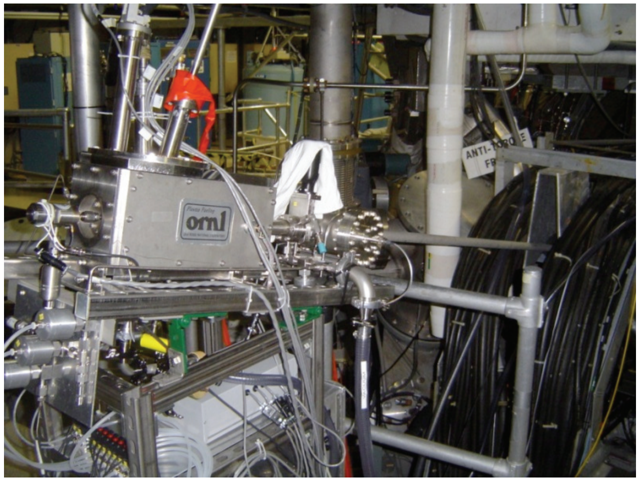
Large shattered pellets

- Intermediate between gas injection (no penetration into plasma) and single large pellet (goes all way through plasma)
- Fire large frozen pellet into shatter plate to break into ice shards [Jernigan, JP8.00090]

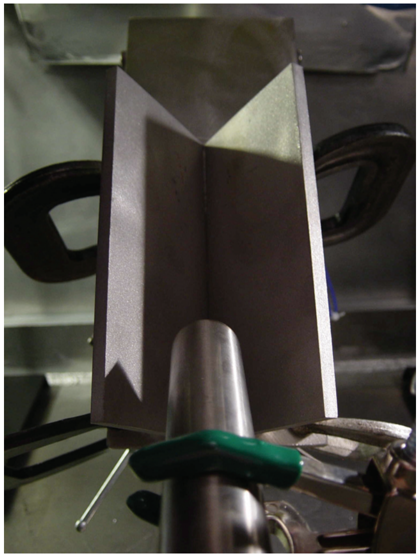
Shattered pellet system overview



Large frozen pellet injector

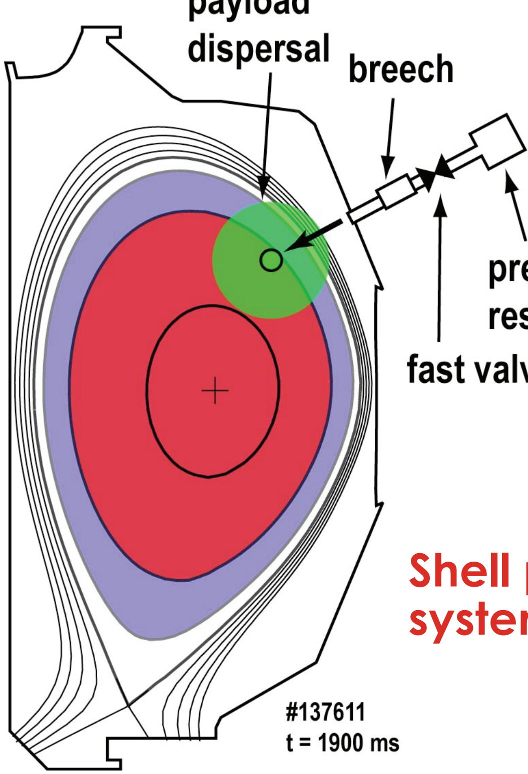


V-groove shatter plate



Shell pellets

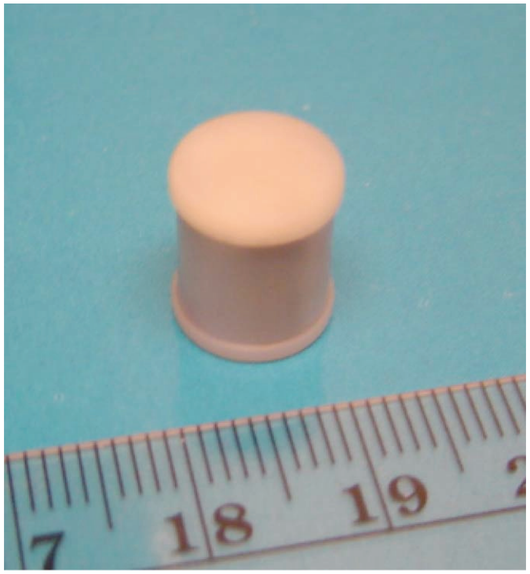
- **Shell pellet concept is to surround dispersive payload with thin low-Z shell which burns off in plasma edge**
- **Have tried small shell pellets (D = 2 mm polystyrene filled with boron powder or 10 atm Ar gas) and large shell pellets (D = 1 cm polystyrene filled with boron powder)**



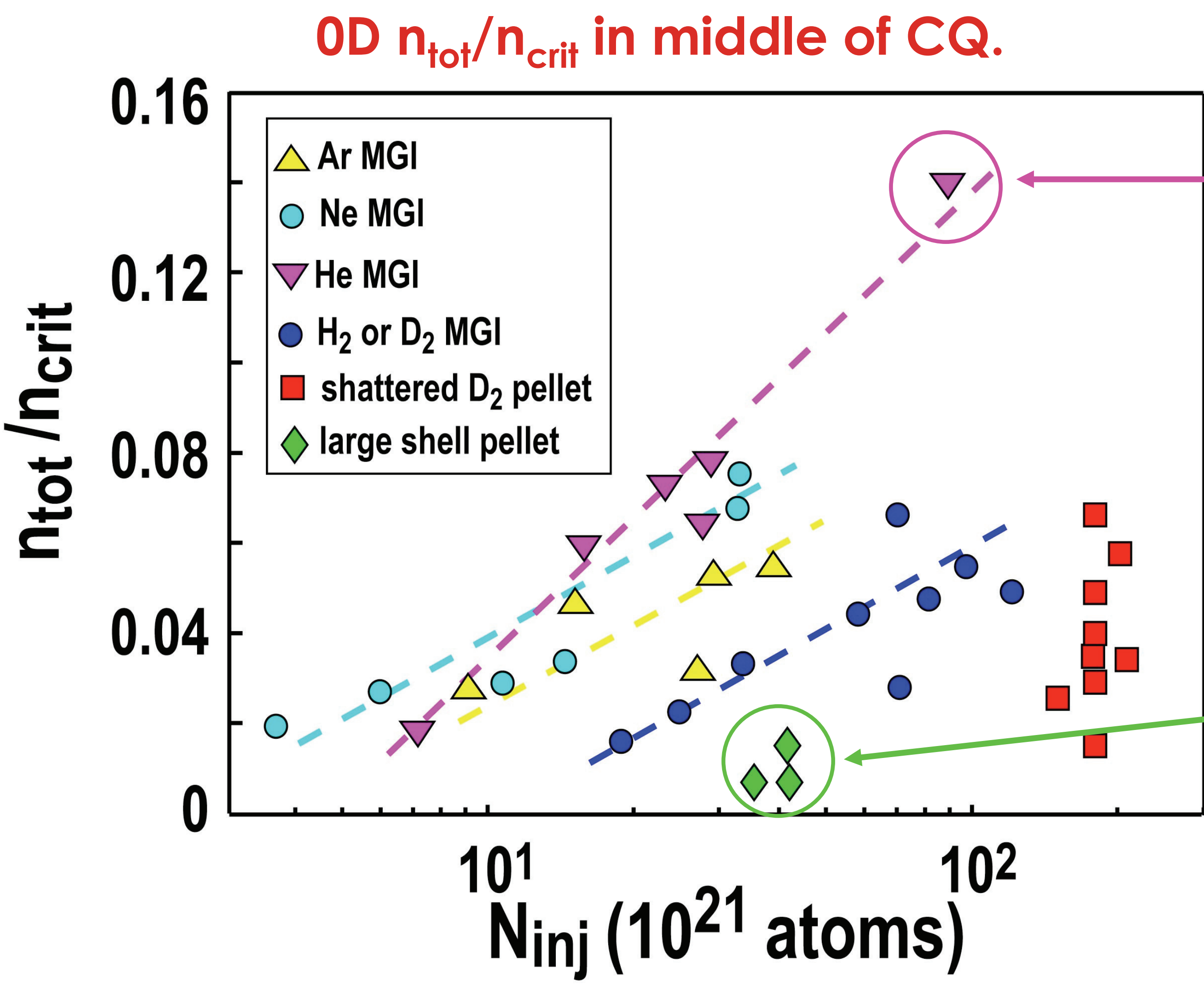
Shell pellet system overview

Small shell pellets

Large shell pellet



Massive impurity injection methods typically give ~ 5-10% of desired mass deposition



- Highest 0D mid-CQ n_{tot}/n_{crit} ~ 14% achieved using 5 valve He MGI
- Highest local n_e achieved with shattered D_2 pellet in TQ
- Large shell pellet payload not released (deposition from shell only)

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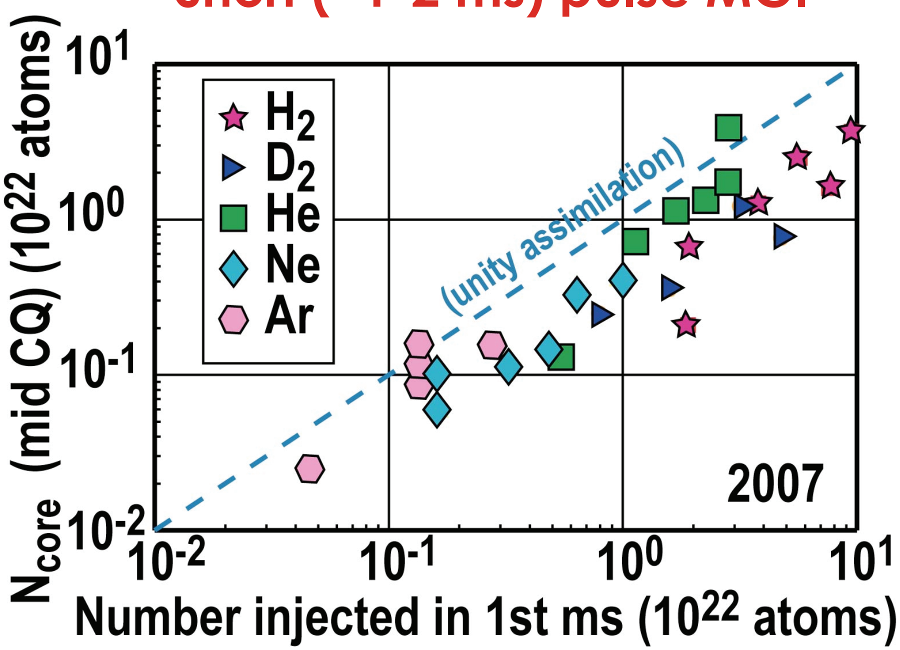
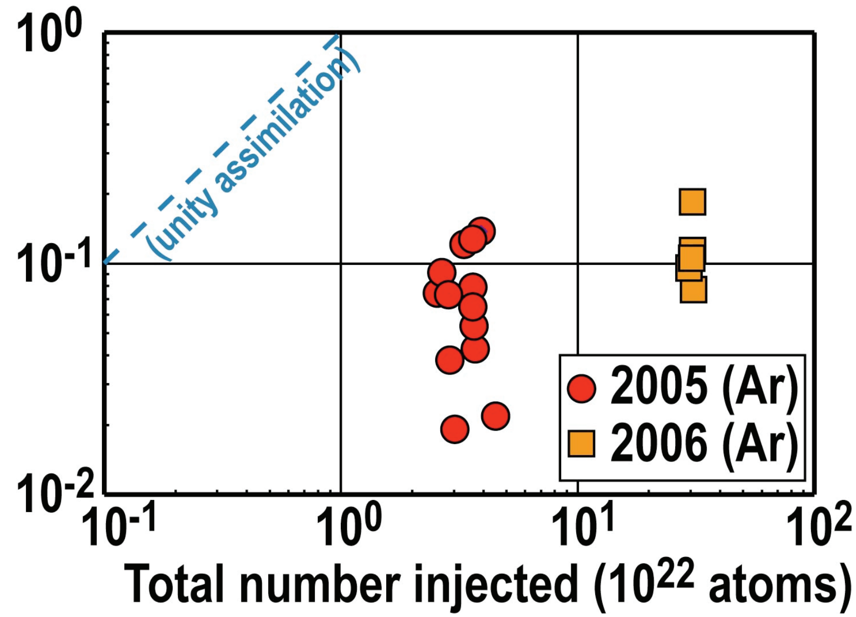
Impurity delivery of massive gas injection limited by finite gas flow rise time

- TQ MHD destabilizes when MGI-induced edge cold front propagates in radially to q ~ 2 (takes ~ 1 ms)
- During TQ, efficient mixing (20% or more) of edge impurities into core
- Later-arriving (during CQ) gas not well-assimilated

Short (~1-2 ms) pulse MGI



Long (~10-15 ms) pulse MGI



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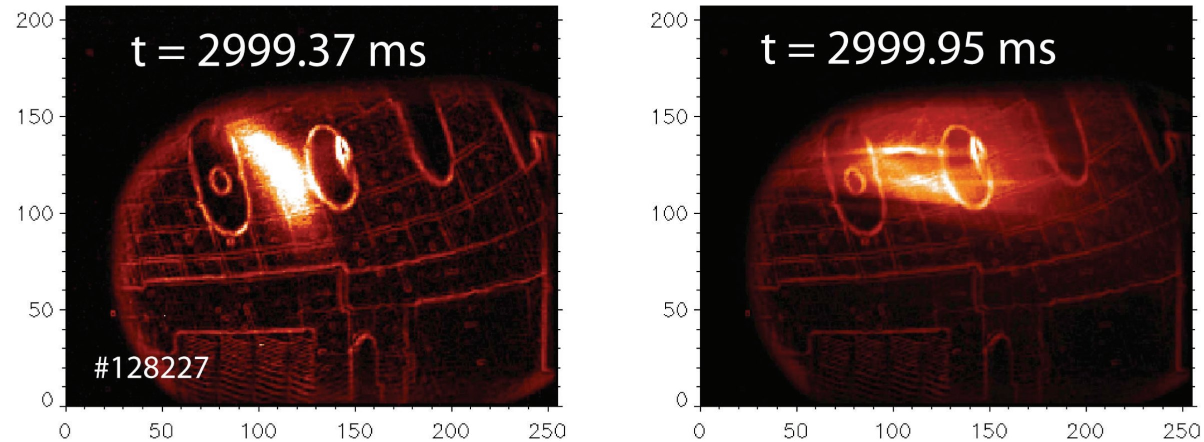
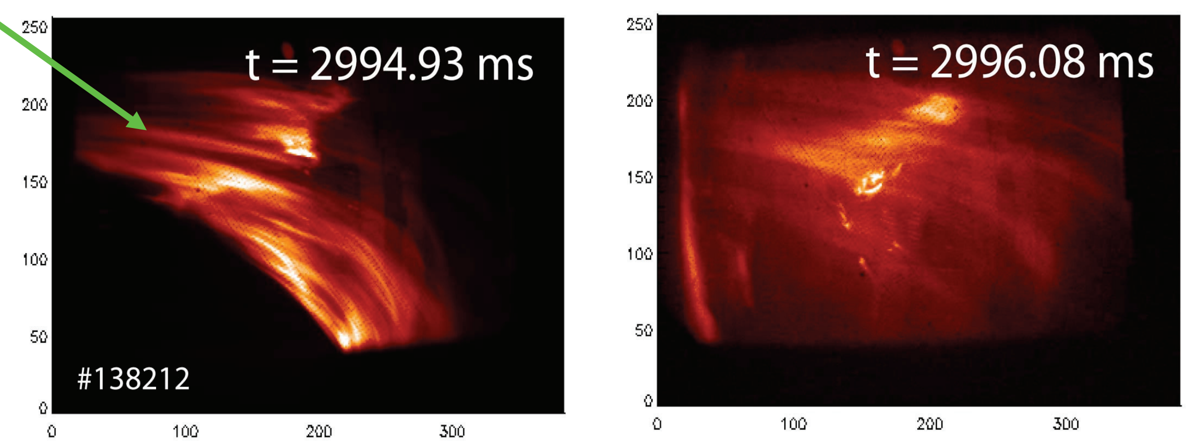
Large shattered D_2 pellets give faster, more direct impurity deposition than gas injection

- Fast camera images show D_2 ice shards depositing particles rapidly and less localized to port than MGI

Fast camera images of He MGI shutdown

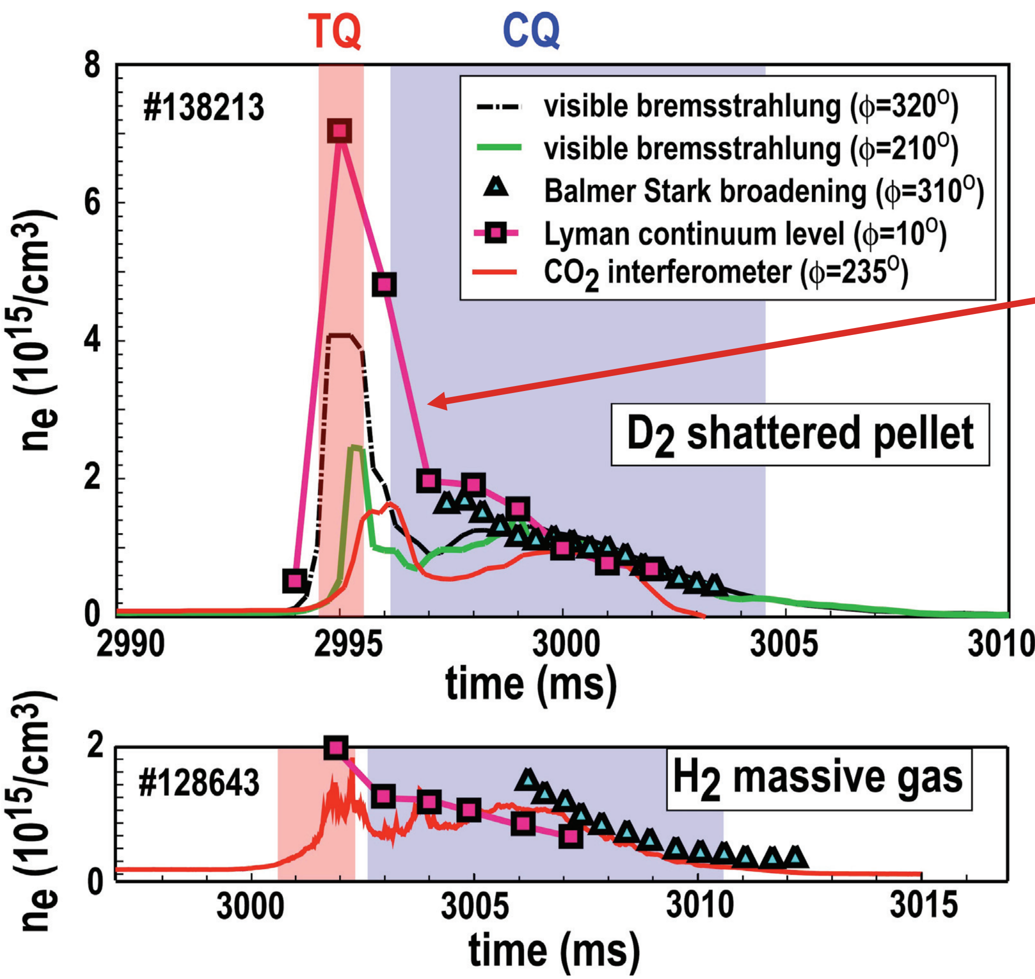


Images of shattered D_2 pellet shutdown



Large shattered D_2 pellets achieve very high local density during TQ

Electron density at different toroidal locations vs time



- Electron density measured with different diagnostics at different toroidal locations
- Extremely large $n_e \sim 7\times10^{15}/cm^3$ observed transiently at injection port
- During CQ, density becomes lower and more isotropic toroidally [Commaux, UOP. 00004]
- Mid-CQ density similar to MGI
- Ideally, would like to have high density throughout CQ

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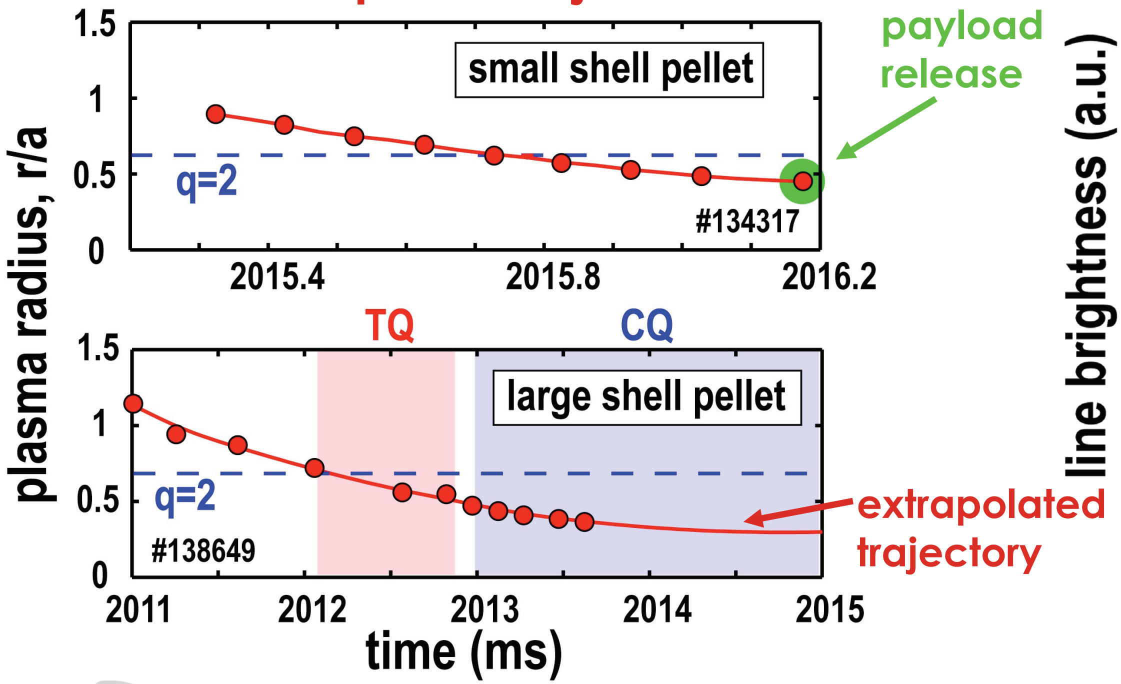
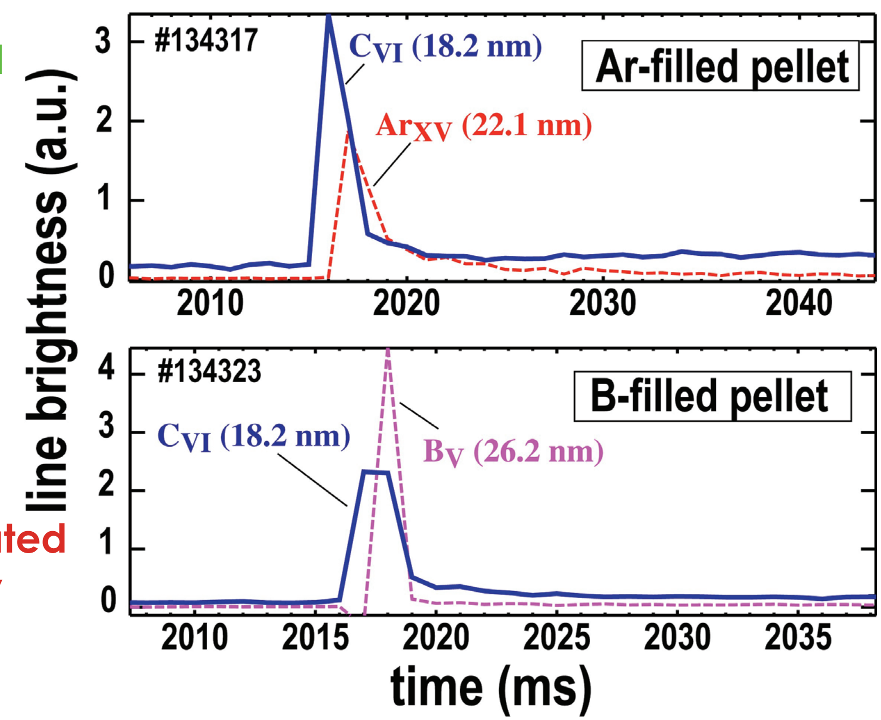
Need to design large shell pellet which will release payload during thermal quench

- Small (D = 2 mm, t = 0.4 mm) shell pellets successfully demonstrated burn-through and payload deposition in plasma core
- Large (D = 1 cm, t = 0.4 mm) polystyrene shells passed through plasma - shell made too thick!
- Initiated thermal quench at q = 2 surface

Shell pellet trajectories



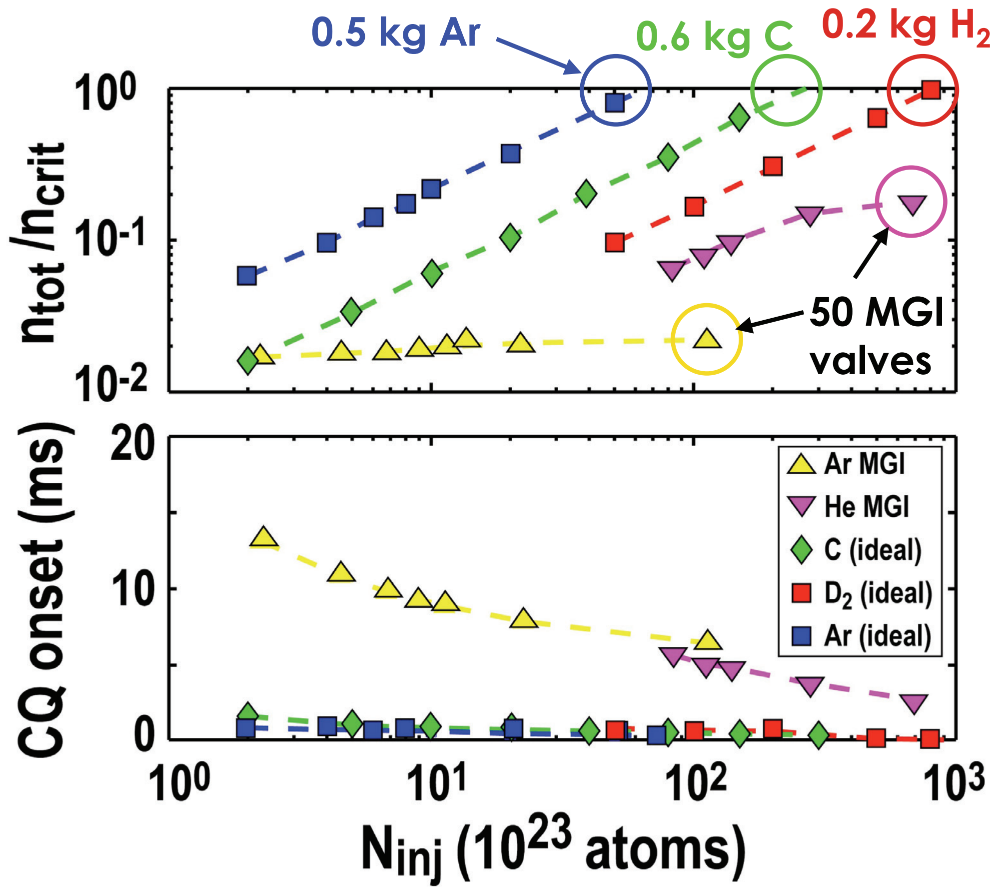
Small shell pellet payload release



Ideal deposition of impurities expected to achieve collisional runaway suppression in ITER

- 0D simulations ignoring radial loss of heat or particles
- For MGI, assume *L* = 5 m, *D* = 2 cm delivery tube, 10 ms pulse, and 20% TQ mixing efficiency
- For 'ideal' deposition assume all impurities deposit in 1 ms pulse with 100% efficiency
- Ideal deposition achieves $n_{tot}/n_{crit} > 1$ for sufficiently massive deposition
- MGI doesn't achieve $n_{tot}/n_{crit} > 1$ even for 50 valves

0D simulations of massive impurity deposition in ITER



Disruption runaway electron studies

- **Achieving n_{tot}/n_{crit} > 1 throughout the ITER volume may be challenging**
- **Important RE questions:**

–Is $n_{tot}/n_{crit} > 1$ really necessary for RE suppression?

–How large will RE seeds be in ITER during rapid shutdown?

–Can RE confinement be influenced with external magnetic fields ?

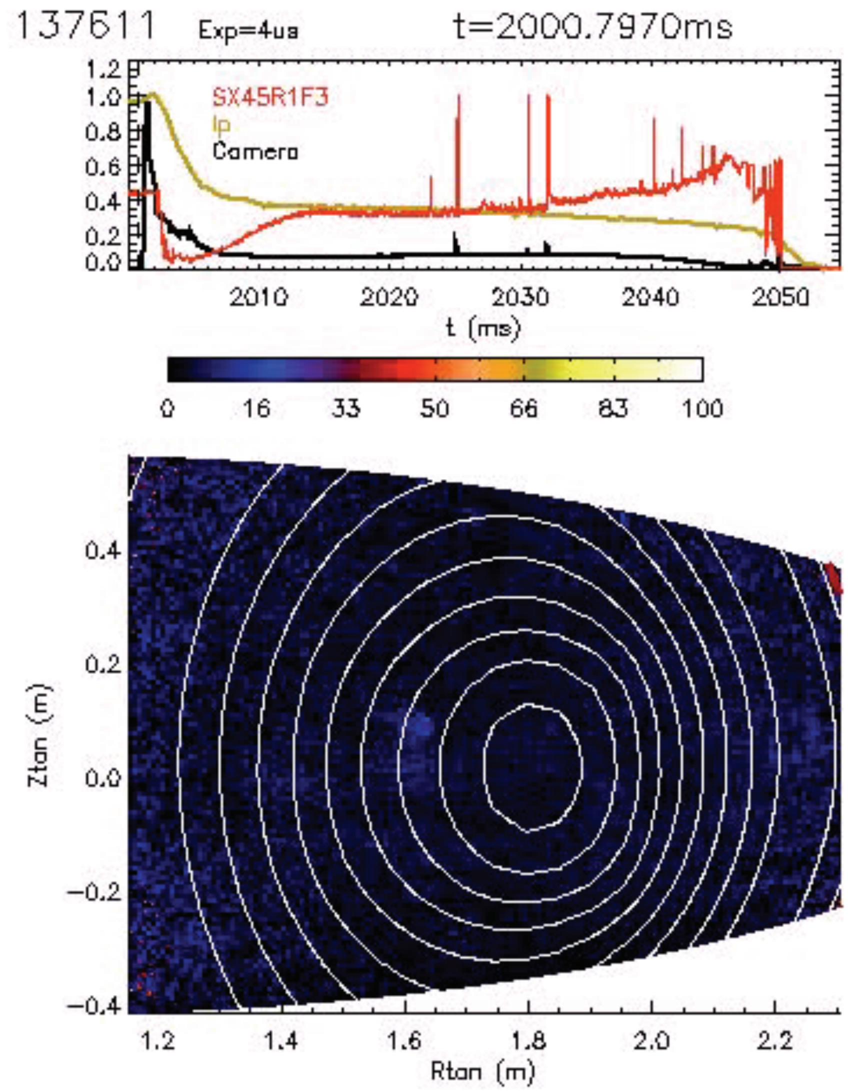
- **Pursuing RE studies with dedicated experiments and new diagnostics**
  - RE synchrotron imaging
  - RE gamma scintillator array

Gamma scintillator

Runaway electron beams observed via visible synchrotron emission

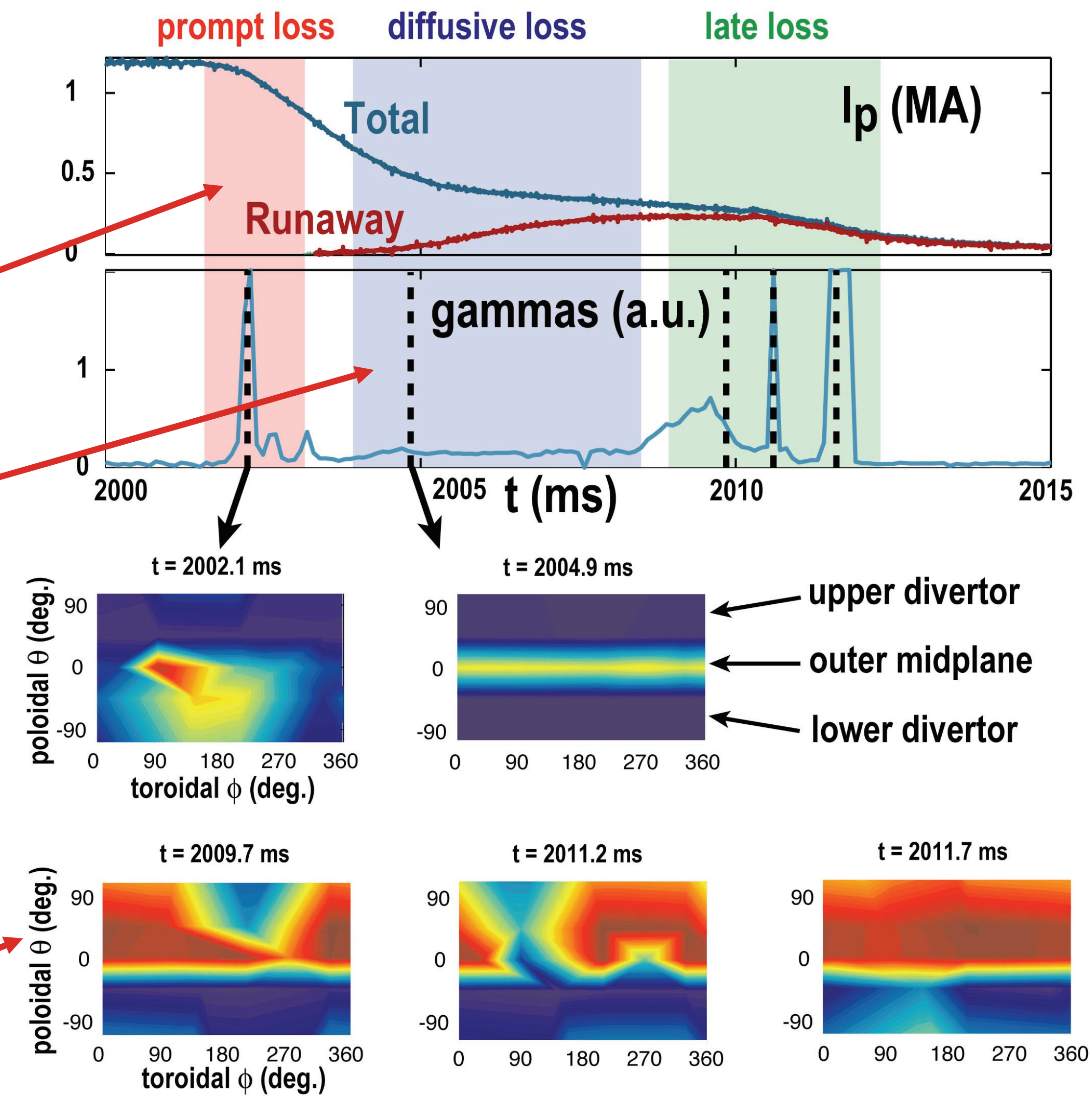
- Strong ($I_{RE} \sim I_p$) RE beams can be created by Ar pellet injection and imaged with visible camera [Yu, JP8.00096]
- RE beam consistently seen to drift into upper divertor
- RE location well-described by JFIT flux contours (white lines)

Visible/near-IR fast camera movie



Runaways lost to wall in 3 phases

- Runaways give gamma flashes (ε > 0.5 MeV) upon hitting wall
- Strong prompt loss flash of REs lost into lower divertor at start of CQ
- Weaker loss of REs into main chamber wall during CQ
- Strong late loss flashes when RE beam drifts into wall at end of CQ
- Toroidal structure seen in late loss [James, JP8.00095]



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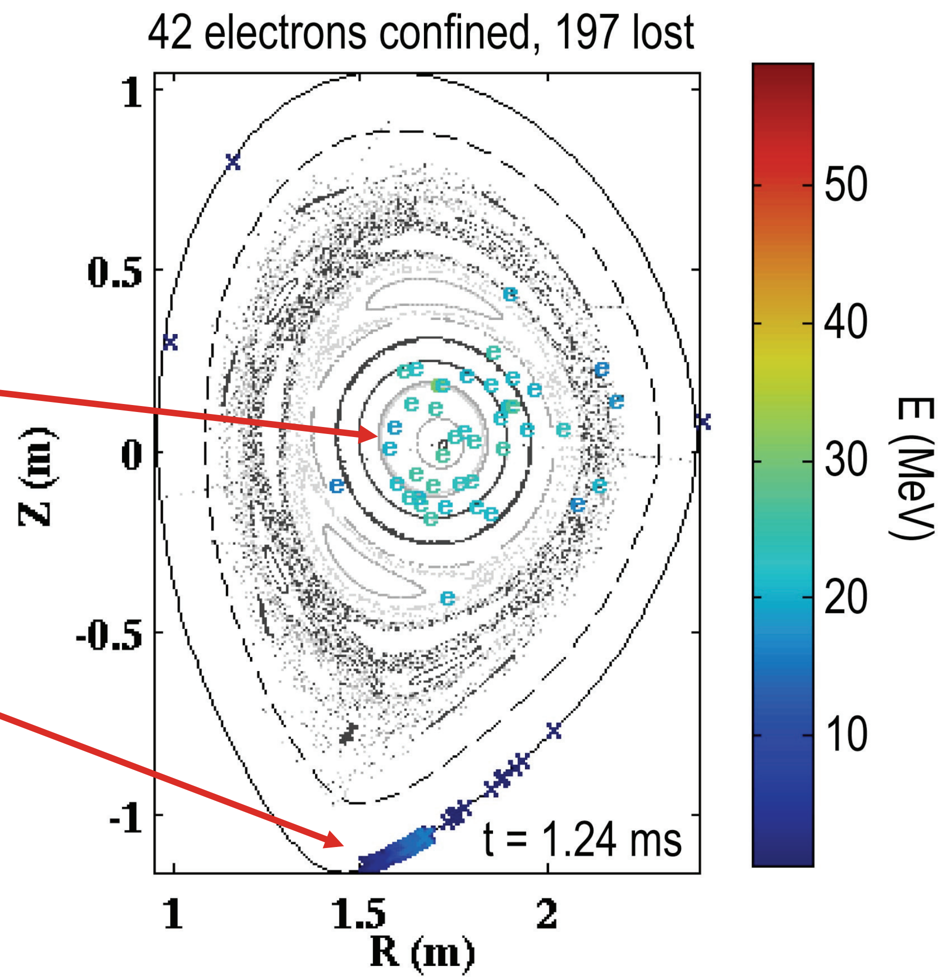
Presence of prompt runaway loss consistent with NIMROD simulations

- RE transport in DIII-D fast shutdowns simulated with NIMROD 3D MHD code
- A beam of REs can remain on good flux surfaces in core [Izzo, CO4.00010]
- After TQ, many REs are lost along destroyed flux surfaces to lower divertor

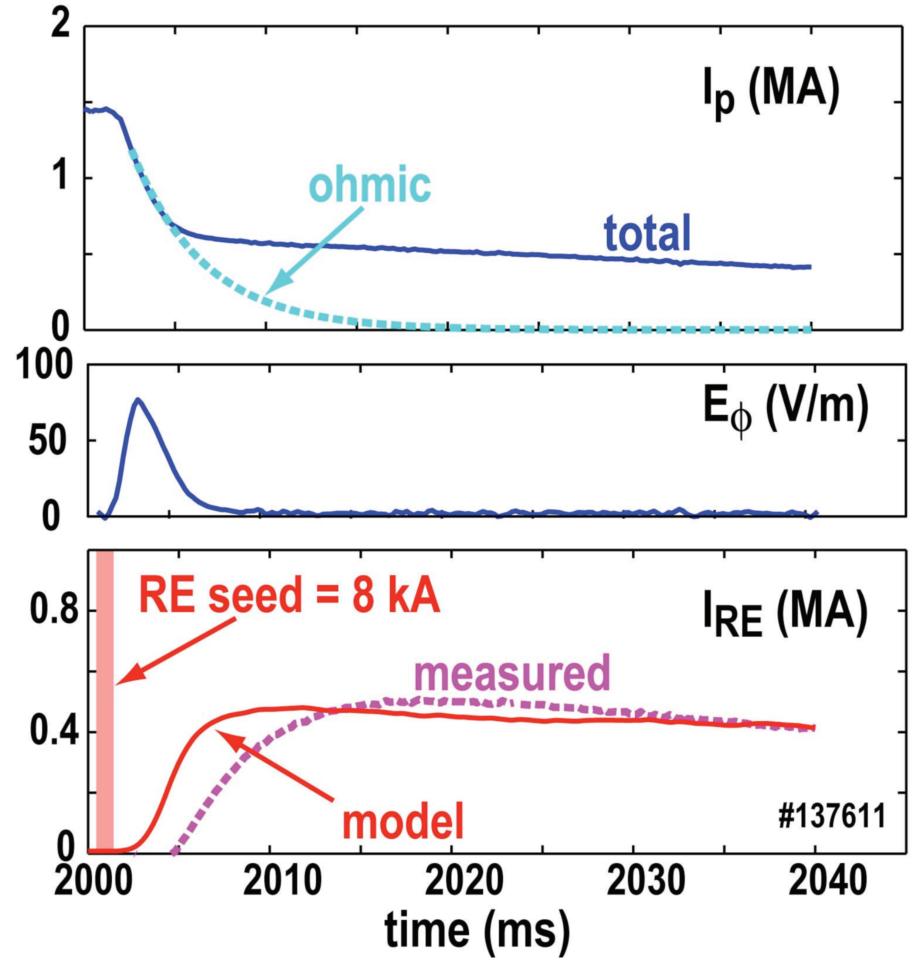
NIMROD simulation of ideal (0D deposition) Ar rapid shutdown in DIII-D



Estimated avalanche growth time ~ 2 ms consistent with 0D model

- In large RE current shots, can estimate RE current from shape of I_p vs time
- 0D estimate of avalanche growth time ~ 2 ms consistent with data
- Only free parameter is size of seed term; RE seed appears to be ~ 8 kA in this shot, giving ~ 50x gain from avalanching

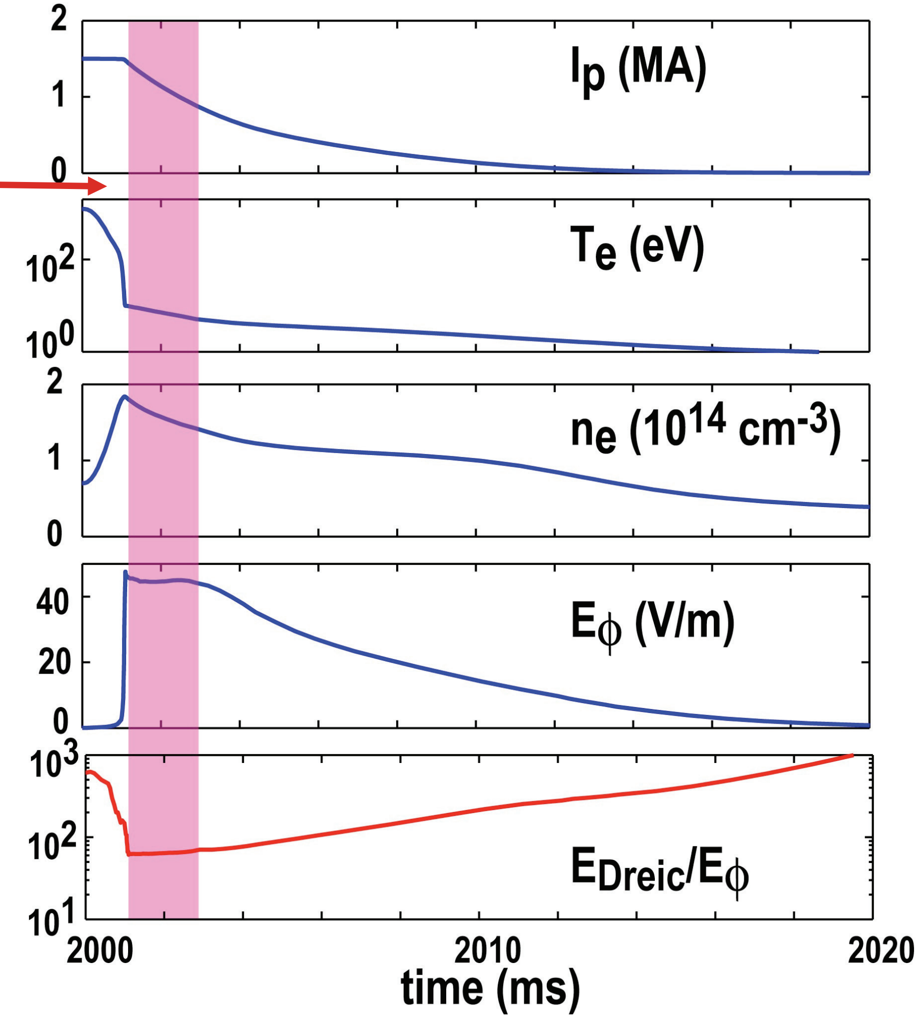
Estimate of RE avalanche gain from I_p fit vs 0D model



Negligible runaway seed term predicted during CQ from 0D model

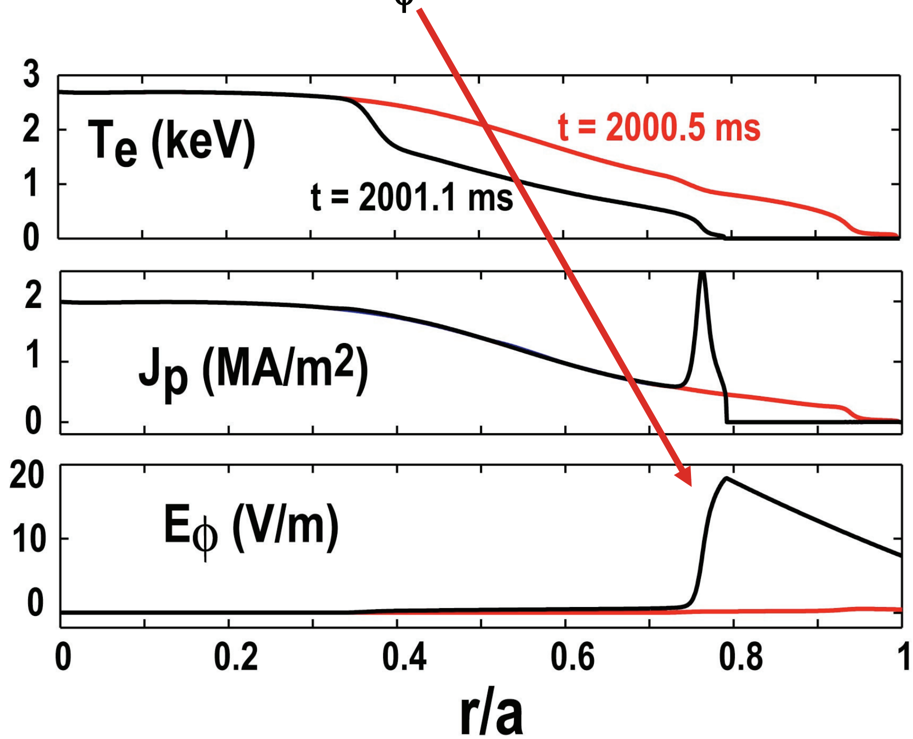
- **Standard Dreicer model for RE seed: $\gamma_{RE} \sim \exp(-E_{Dreic}/E_\phi)$**
- **0D Dreicer seed would appear during CQ**
- **Minimum predicted value of $E_{Dreic}/E_\phi \sim 10^2$, too large for measurable Dreicer seed!**
- **Possible explanations for measured RE seed**
  - Local effect (1D or 2D)?
  - Time-dependent effect (hot-tail seed)?
  - Magnetic reconnection?

0D model of Ar pellet rapid shutdown

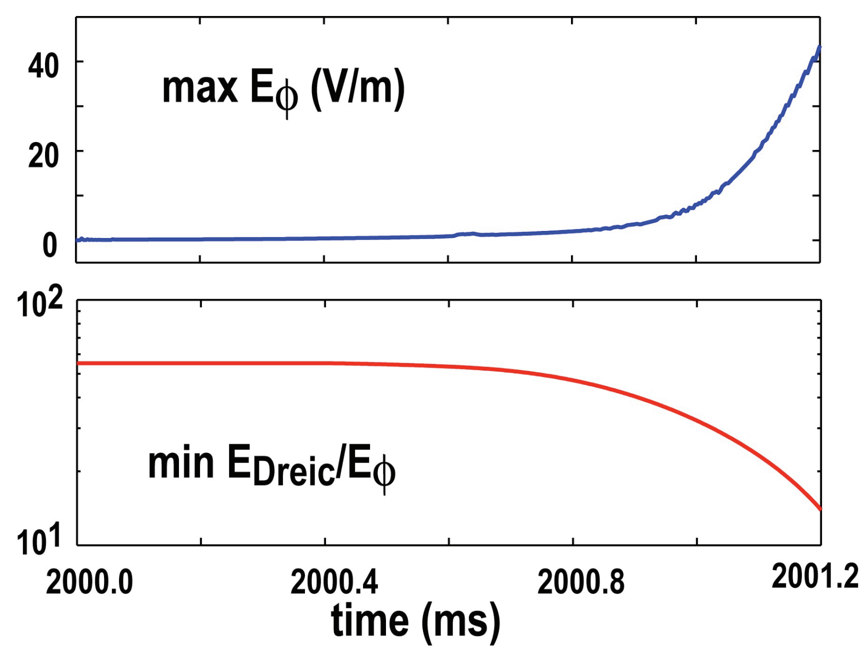


Negligible runaway seed term predicted during pre-TQ phase from 1D model

- **Before TQ MHD, can use 1D current diffusion model to estimate E_ϕ**
- **Model predicts peak with enhanced E_ϕ at cold front**



- **1D TQ Dreicer seed larger than 0D CQ model, but still negligibly small**



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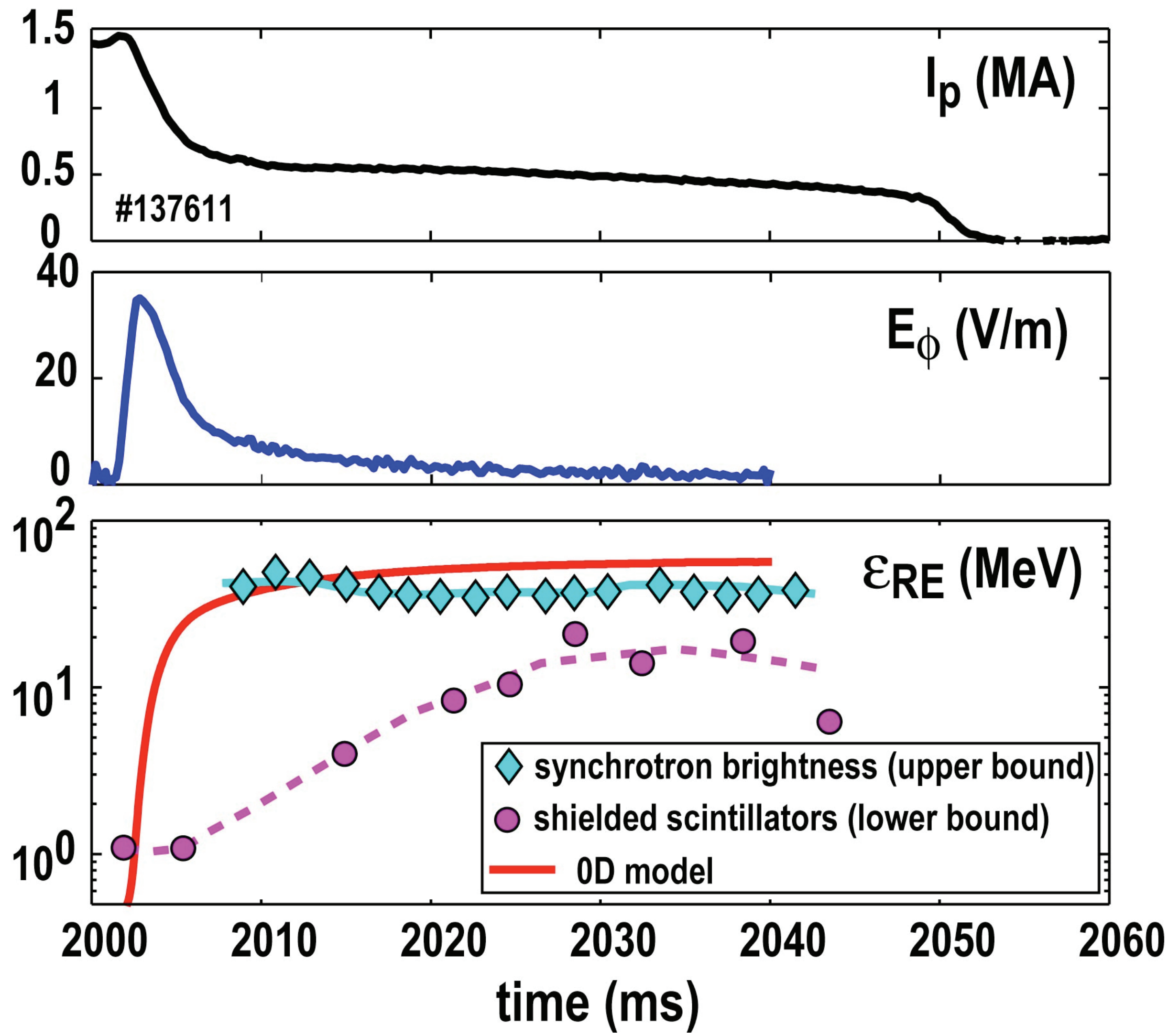
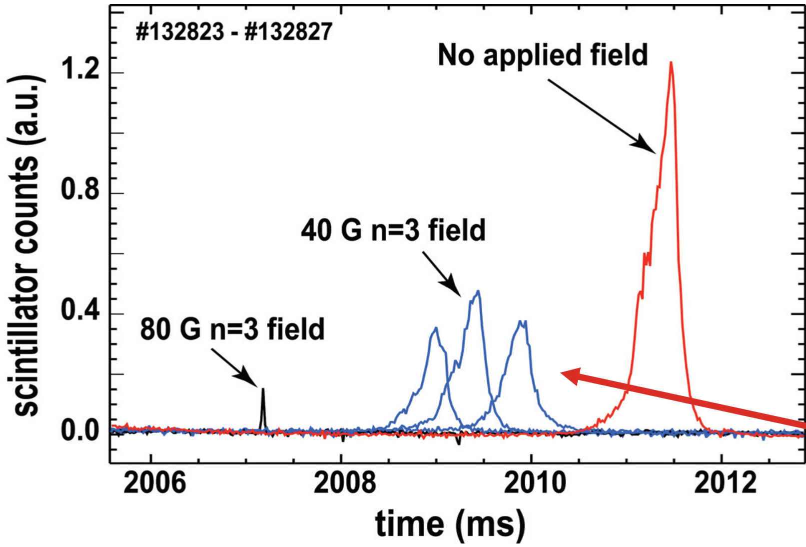
Measured peak runaway energy roughly consistent with 0D model

- Estimates of RE energy can be made from synchrotron brightness and shielded scintillator array
- Data gives peak RE energy around 30-40 MeV, slightly lower than 50-60 MeV from 0D model

Measured and 0D model of RE energy

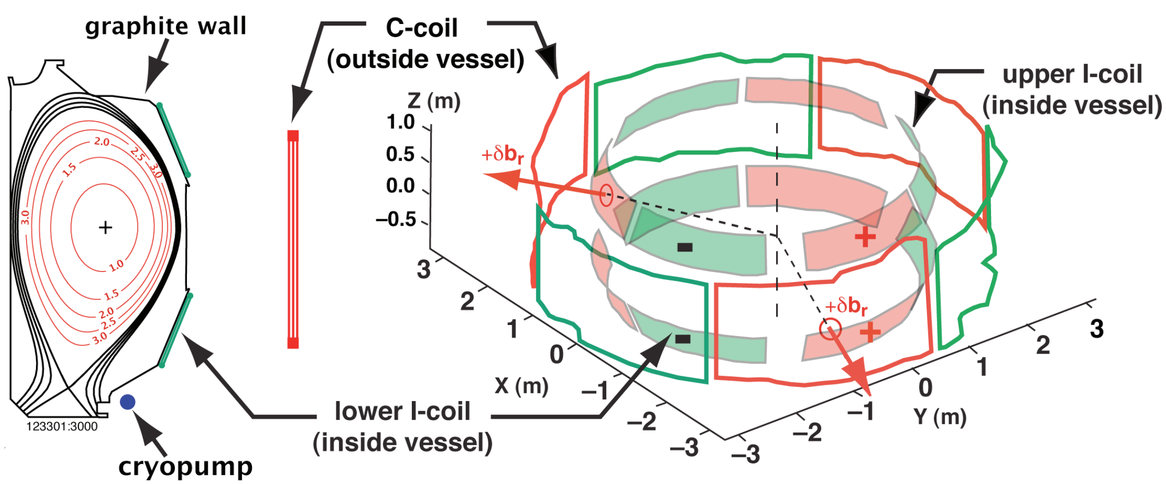


Deconfinement of weak runaway beams seen with applied *n* = 3 perturbation



1 valve Ne MGI + *n* = 3 RMP

- **Possible supplement to MGI is applied magnetic perturbation to deconfine REs**
- **Observing deconfinement challenging because of high variability in RE seed term**
- **Appear to see enhanced deconfinement with *n* = 3 field applied to weak RE beams [Humphreys, JP8.00091]**
- **Trend is not clear in case of *n* = 1 perturbation or with strong RE beams**



n=3 I-coil and C-coil configuration
(with even parity I-coil)

Summary

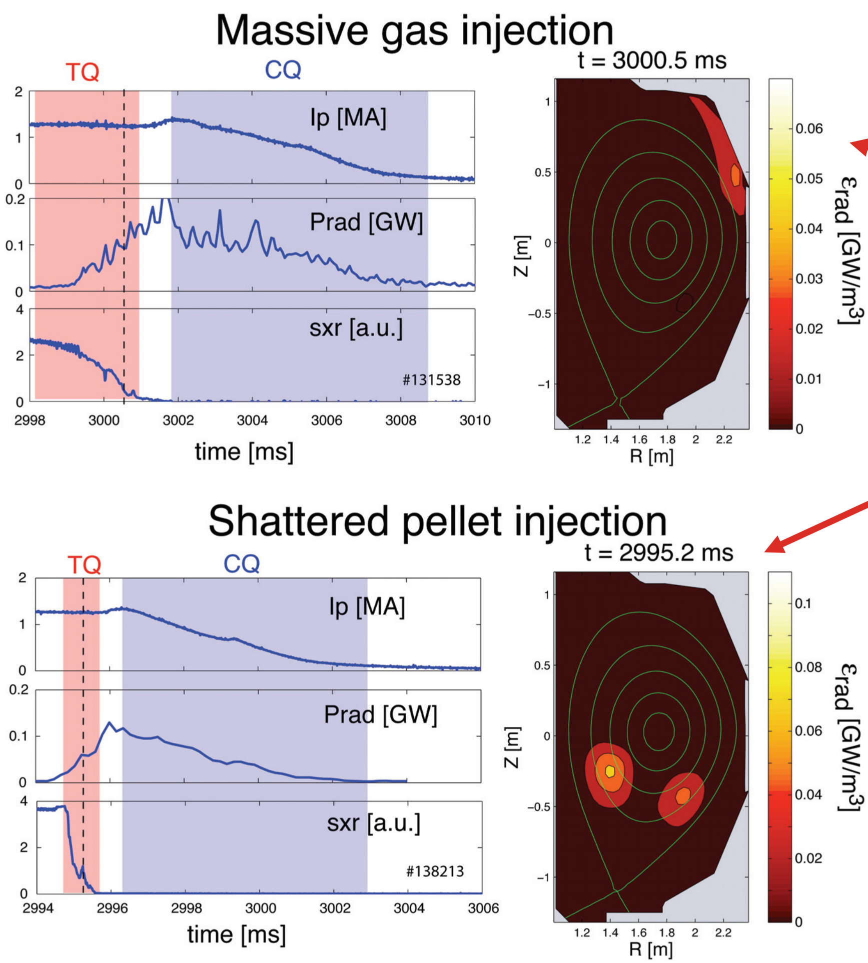
- DIII-D has developed unique new rapid shutdown capabilities to study feasibility of achieving collisional RE suppression
  - Multi-valve massive gas injection
  - Shattered massive cyrogenic pellet injection
  - Large shell pellet injection
- Presently, have achieved n_{tot}/n_{crit} ~ 14% with multi-valve He MGI
- DIII-D has developed new diagnostics for RE studies
  - Visible synchrotron imaging
  - Gamma scintillator array
- RE amplification and acceleration matched with 0D models
- Disruption RE seed term in DIII-D experiments not understood yet
- Applied magnetic perturbations for deconfining RE seeds show promising preliminary results

Future plans

- Improved understanding of RE formation, amplification, and loss, including effect of magnetic perturbations
- Continue massive impurity deposition experiments (massive gas injection, shattered pellets, shell pellets)
- Attempt to control RE beam with feedback control
- Fire pellets through REs for RE beam diagnosis and mitigation
- Improved modeling and predictive capability

Thermal quench impurity deposition in core by shattered D_2 pellet

Fast bolometry of D_2 shutdowns



- Fast bolometry shows that impurities are mostly still localized to injection region at TQ onset for MGI.
- For shattered pellet, TQ impurity deposition appears to be throughout plasma.
- TQ duration appears to be significantly (~2x) faster for shattered pellet shutdown than D_2 MGI, consistent with more direct impurity deposition.

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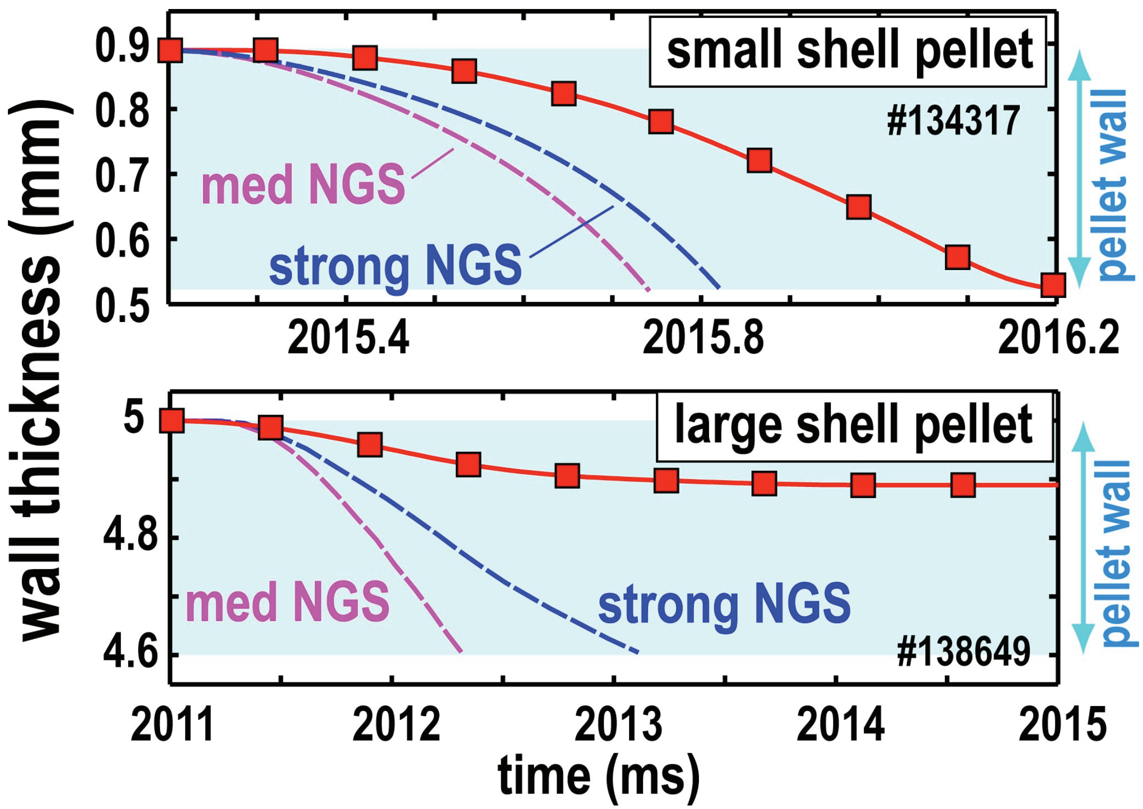
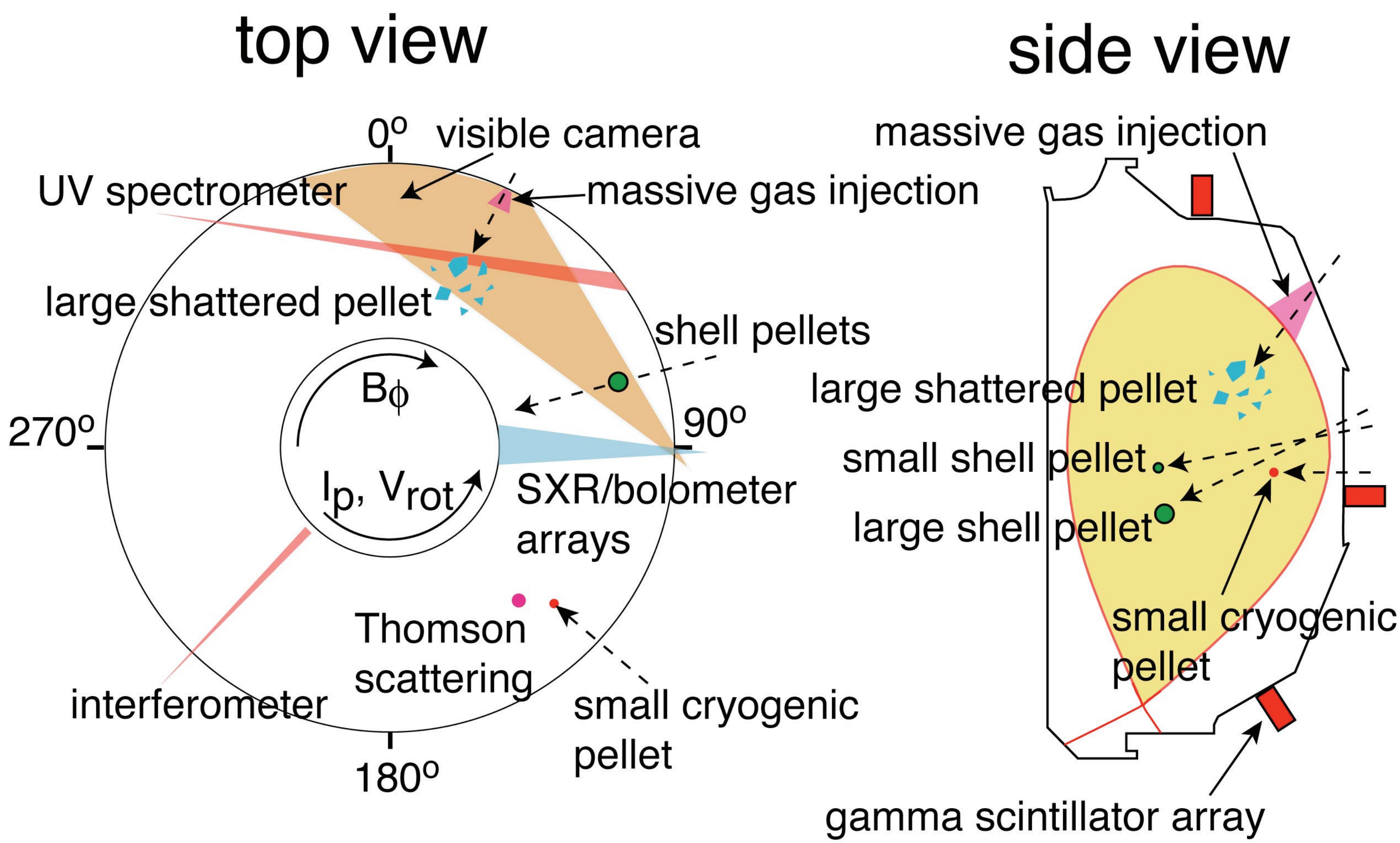
Shell ablation rate fairly well-predicted for small pellets

- Strong shielding [Parks,1998] and medium shielding [Sergeev, 2006] ablation models work reasonably well for small polystyrene shell; worse for large polystyrene shell.



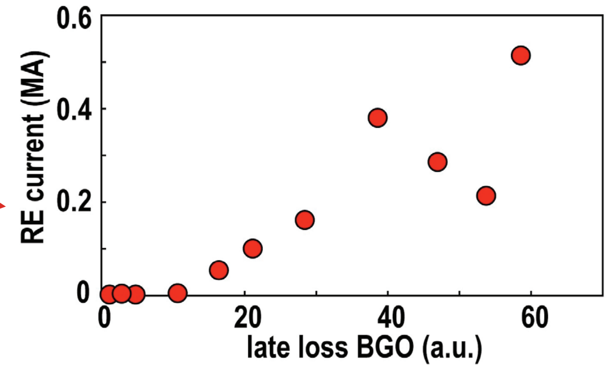
Measured vs predicted polystyrene shell burn-through

Diagnostic layout

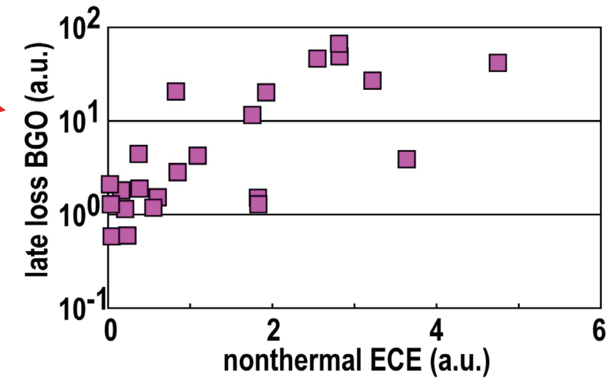


Large scatter in runaways created appears to be due to seed term variation

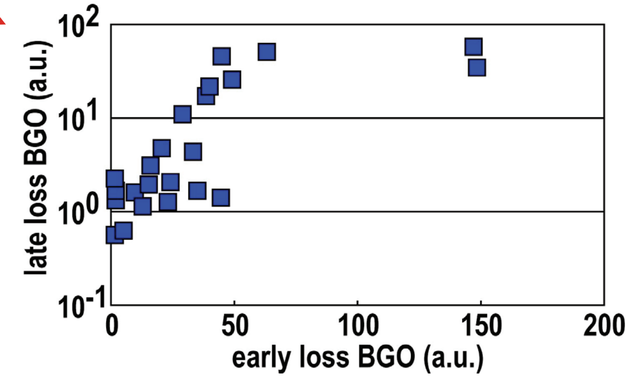
- Late-loss gamma scintillator flash good qualitative measure of RE current.



- Non-thermal ECE best measure of early confined RE population - late RE current scatter ~ 10x relative to early population.



- Early loss RE also ~ 10x scatter relative to late RE population.



- Suggests that early RE loss fraction and CQ RE amplification are not varying by 3 orders of magnitude shot-shot.

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