Summary of dispersive shell pellet injection experiments on DIII-D

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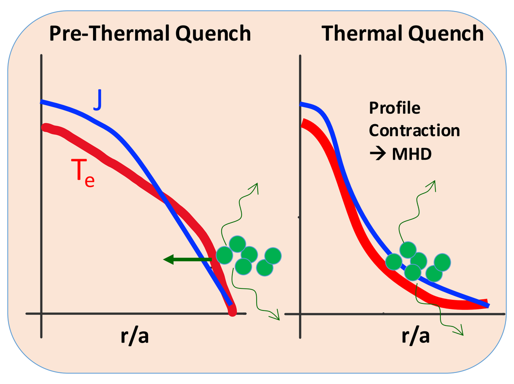
ABSTRACT

Dispersive shell pellet (DSP) injection is currently being developed as an alternative disruption mitigation technique to massive gas injection and shattered pellet injection. The main advantage of DSP injection is the core deposition of the payload which is expected to result in higher assimilation fractions and an inside-out thermal quench (TQ). DSPs have been successfully launched into DIII-D Super H-Mode plasmas, resulting in the rapid shutdown of the plasma current. Core payload deposition was most readily achieved using high density carbon (HDC) shells with 3.6 mm outer diameter and 40 μm wall thickness. Both low-Z (boron dust) and high-Z (tungsten grains) payloads have been investigated. Initial experiments have shown that the pellet penetration increased with pellet velocity, however the assimilation fraction remained approximately constant (0.5 – 0.9). The assimilation fraction decreased when using larger shells with larger payloads, but this may be due to added perturbation from the increased shell mass and surface area. Both small and large HDC shells have been found to be too perturbative to produce a true inside-out TQ. To remedy this, materials with lower atomic numbers than carbon have been proposed as an alternative coating/shell material. The development of 50 – 100 μm thick lithium coatings for future DSP experiments on DIII-D is underway.

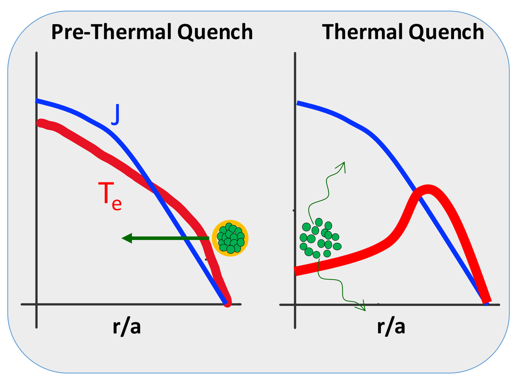
BACKGROUND & MOTIVATION

- **Successful disruption mitigation requires:**
  - High radiation fraction
  - Regulation of CQ duration
  - Runaway electron avoidance/mitigation
- **Issues with outside-in mitigation:**
  - Poor assimilation fraction due to immediate ablation of radiator
  - High-Z radiators needed to obtain large radiation fraction, increased chance of REs
- **DSPs seek to achieve core impurity deposition using a non-perturbative shell**
  - High assimilation fraction due to payload deposition location
  - Enables use of low-Z payloads

Conventional Mitigation (SPI) "Outside-in"



Ideal Core Impurity Deposition "Inside-out"

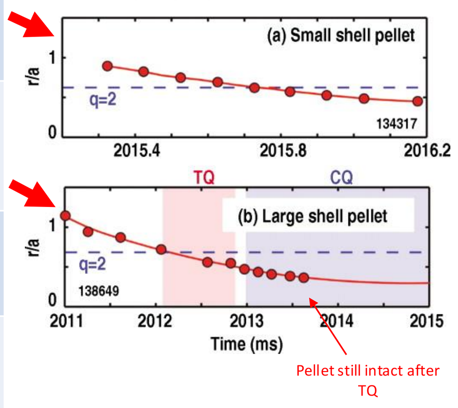


INITIAL DSP EXPERIMENTS ON DIII-D

Several shell/payload materials were developed to achieve core deposition of the payload

Shell Material	Shell Parameters	Payload Material	Result
Polystyrene	OD ~ 2 mm t ~ 0.4 mm	Ar Gas (~ 0.015) Boron Dust	Payload deposited at $\rho \sim 0.5$, too small for shutdown
Polystyrene	OD ~ 1 cm t ~ 0.4 mm	Boron Dust	Shell too thick, rapid shutdown, but no payload release
High Density Carbon (HDC)	OD ~ 3.6 mm t ~ 0.04 mm	Boron Dust (~ 20 mg)	Payload release and rapid shutdown
High Density Carbon (HDC)	OD ~ 3.6 mm t ~ 0.04 mm	Tungsten Grains and Boron Dust (~ 20 mg)	Payload release and rapid shutdown

Pellet trajectories of polystyrene shells



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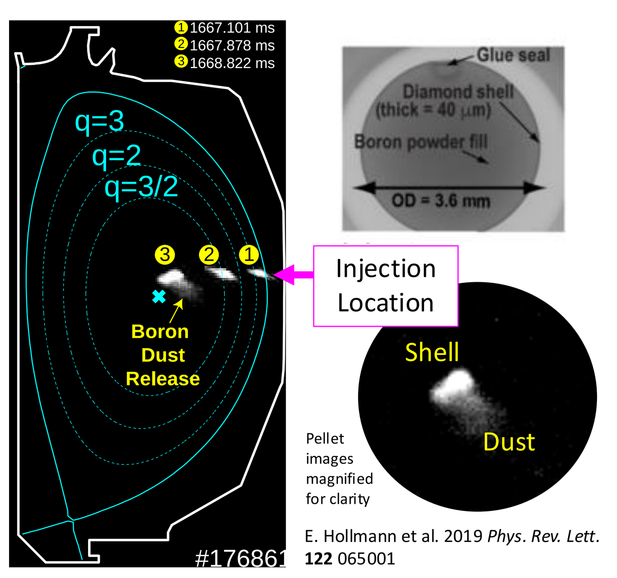
Rapid shutdown successfully achieved using 3.6 mm OD HDC shells with ~ 20 mg of boron dust



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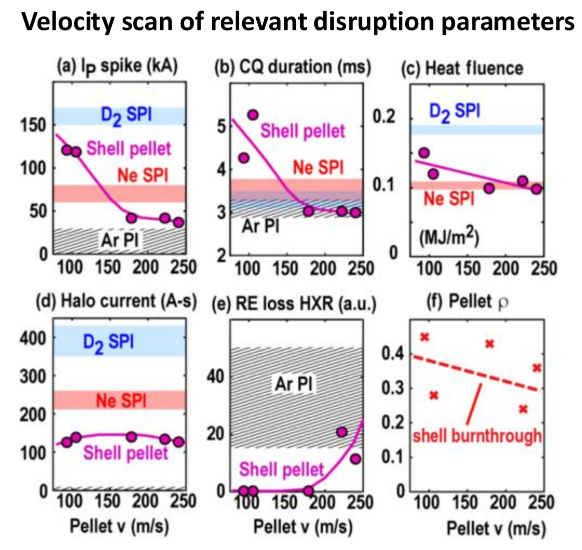
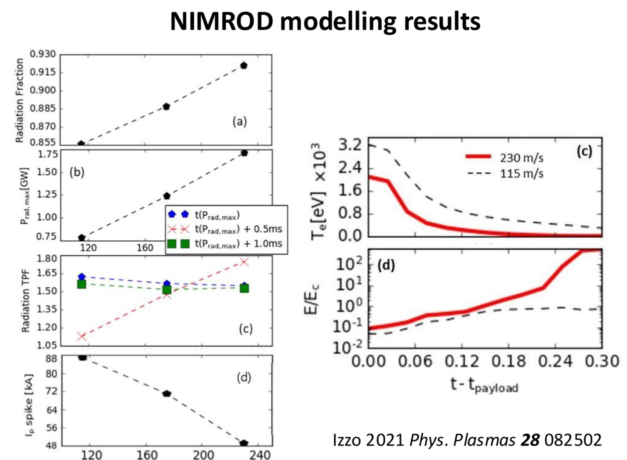
- **Shell pellets launched at different velocities to evaluate impact of payload deposition location**
- **Faster pellets penetrated deeper into the plasma, leading to:**
  - Lower I_p spike magnitudes (less MHD mixing)
  - Shorter CQ durations
  - Lower heat fluences
  - Production of RE seeds (possibly due to better preservation of edge flux surfaces)
- **NIMROD modelling consistent with experimental trends**

Velocity scan of relevant disruption parameters

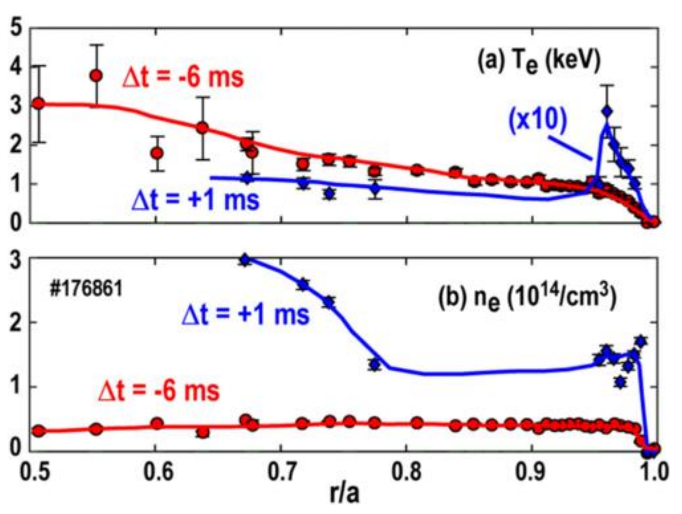


NIMROD modelling results



Izzo 2021 *Phys. Plasmas* **28** 082502

T_e and n_e profiles before and after DSP arrival (t = 0 ms)



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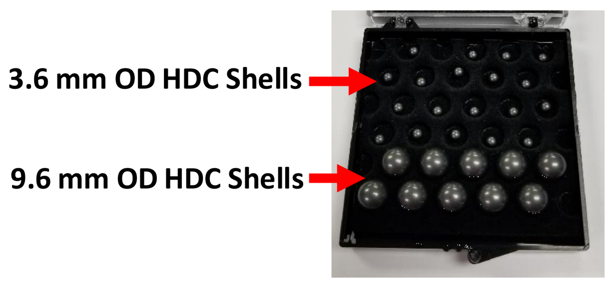
- Hollow T_e profile observed, but before payload deposition (red – before pellet arrival, blue – after pellet arrival but before payload dispersal)

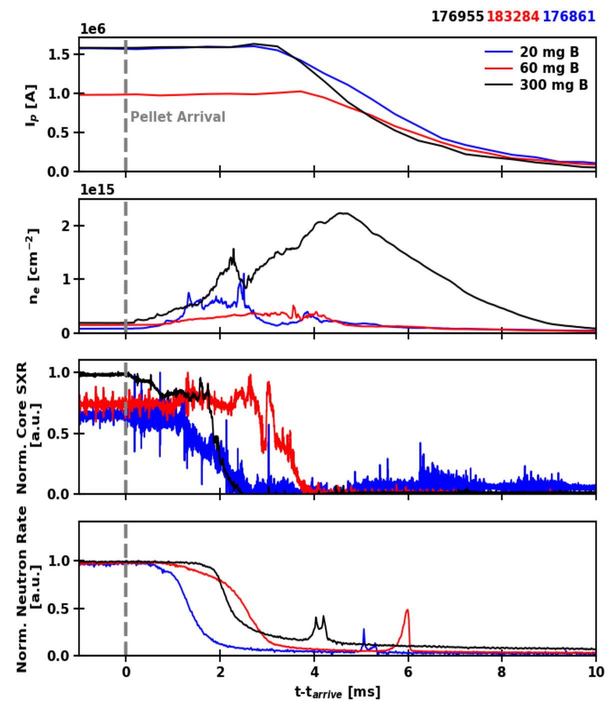
- HDC shell likely too perturbative, reduces assimilation efficiency
- Faster pellet velocity or less perturbative coating needed for true inside-out thermal quench

ASSIMILATION SCALING WITH LARGER SHELLS/PAYLOADS

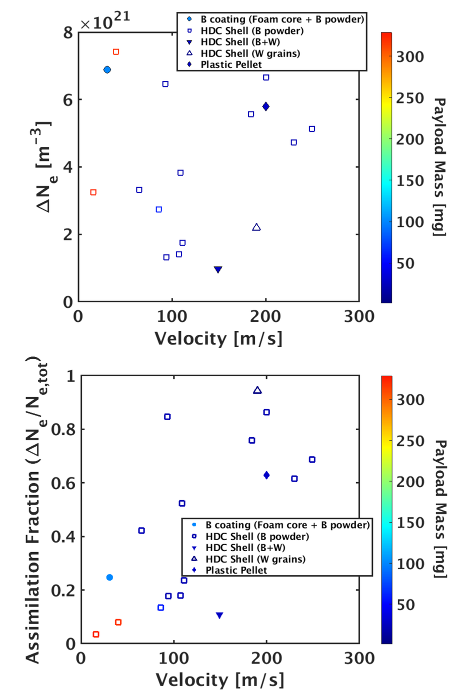
Shell Material	Shell Parameters	Payload Material
High Density Carbon	OD ~ 9.6 mm t ~ 0.1 mm	Boron Dust (~ 300 mg)
Boron Coating	OD ~ 9.6 mm t ~ 0.01 mm	Foam core (C-H Aerogel) and Boron Dust (25 – 100 mg)
High Density Carbon	OD ~ 5 mm t ~ 0.04 mm	Boron Dust (~ 60 mg)



Comparison of 3.6 mm, 5 mm, and 9.6 mm OD HDC shells (B dust payload)

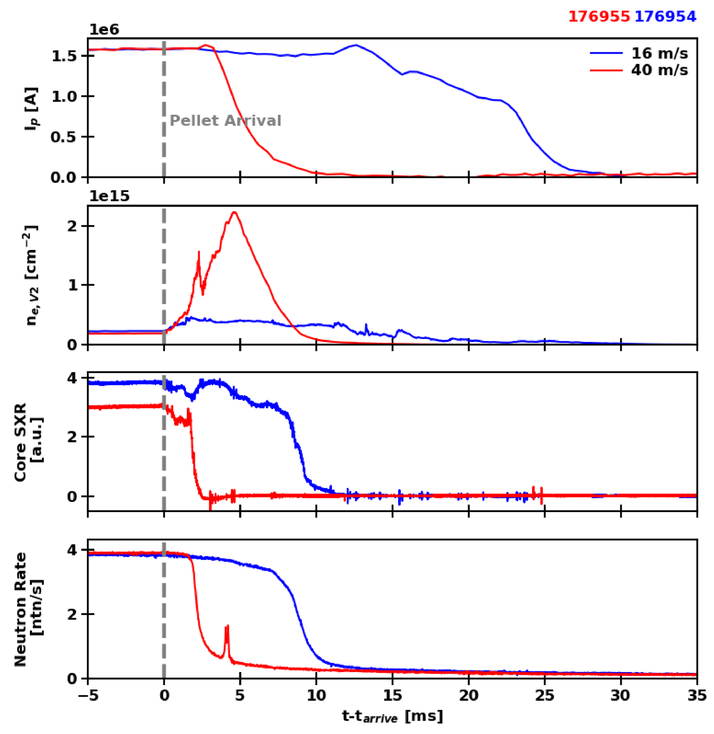


Large pellets (5 – 9.6 mm OD) had very low assimilation fractions



- **Larger shells with more massive payloads were developed to test assimilation limits**
- **9.6 mm OD shells led to larger increase in ΔN_e but with very low assimilation fractions**
  - Likely due to low velocity and increased perturbation from larger shell mass/surface area
- **Faster 9.6 mm OD pellet had much more rapid shutdown due to higher velocity**
  - Better deposition location resulted in much quicker and larger assimilation
  - Faster assimilation led to earlier TQ onset

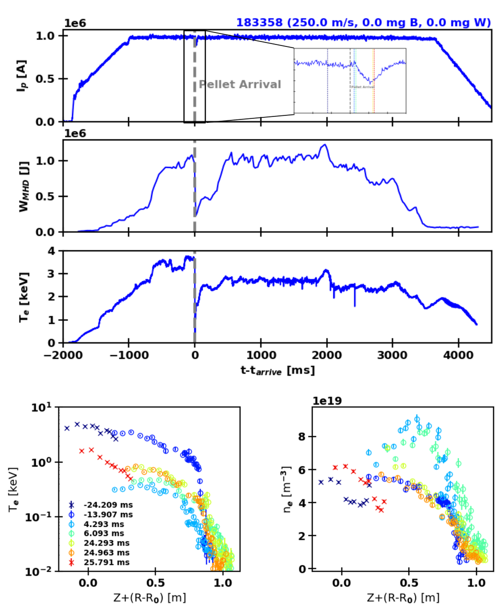
Comparison of large DSP shells with different velocities

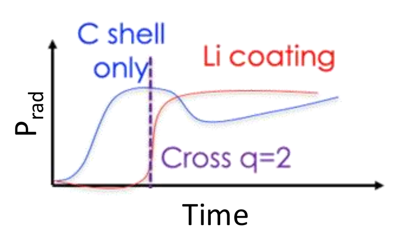


LITHIUM COATINGS TO REDUCE EDGE PERTURBATIONS

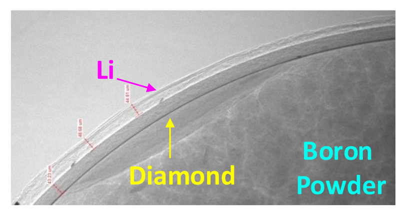
- **HDC shells shown to be too perturbative for DIII-D plasmas**
- **Lithium coating proposed as alternative shell material**
- **Simulations suggest ~ 100 μm of Li needed for core payload deposition**

Impact of empty 3.6 mm OD HDC shell

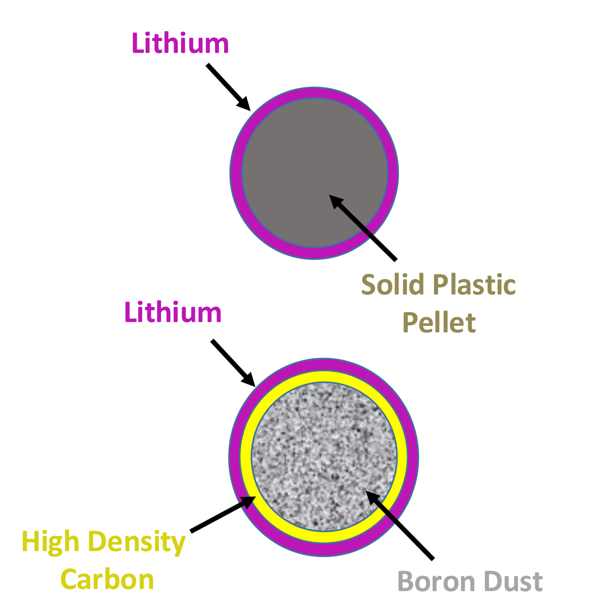




Li-coated HDC Shell



Proposed pellets/shells for the next DSP experiments



- HDC shells prone to breakage due to the thin shell thickness, new launcher required to achieve higher velocities
- Plastic pellets will be prioritized as the payload for initial Li coating experiments
  - Li-coated plastic pellets successfully fired with gas-gun launcher used in previous experiments
- Sabot launcher in development for "gentle" fast launch of Li-coated HDC shells
  - Compact vs. sparse payload comparison
  - Further investigate RE generation at high velocities

CONCLUSIONS

- **A variety of dispersive shell pellets have been successfully launched into DIII-D plasmas, resulting in rapid shutdowns**
- **High assimilation fractions have been observed for 3.6 mm OD HDC shells**
  - Large shells (5 – 9.6 mm OD) were able to assimilate more electrons, but at very low assimilation fractions
- **Heat fluence and I_p spike magnitude were shown to decrease with pellet velocity (penetration)**
  - NIMROD modelling confirms experimental trends
  - RE seeds observed at highest velocities (possibly due to less edge perturbation)
- **HDC shells found to be too perturbative to observe inside-out TQ**
  - Li coatings being explored as an alternative
- **Li-coated plastic pellets will be tested in the Spring 2025 run campaign**

ACKNOWLEDGEMENTS

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