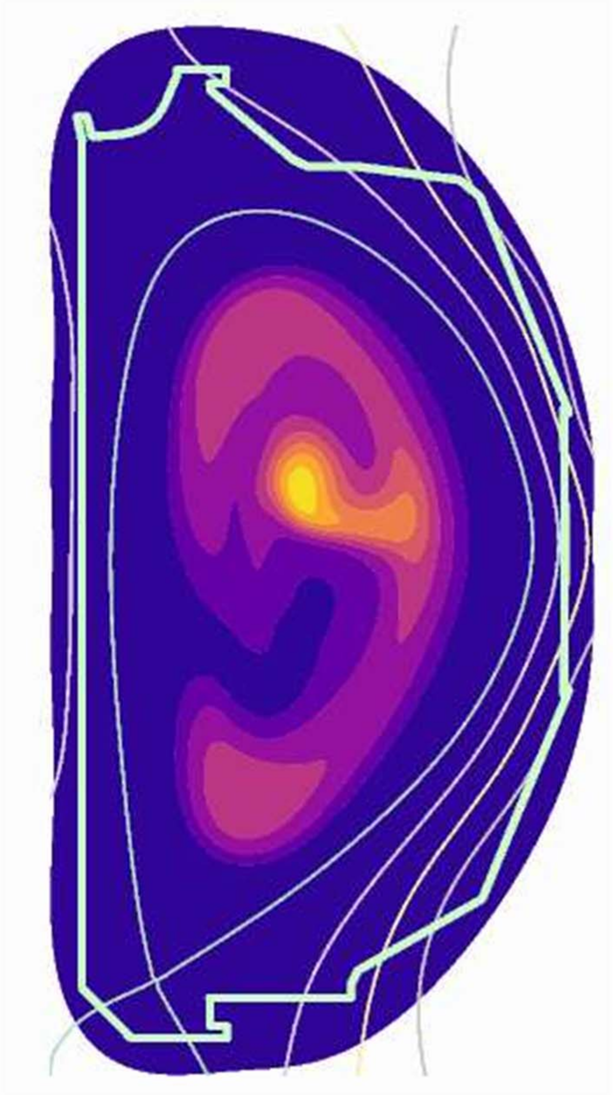
Shell-pellet injection modeling and runaway electron pitch-angle scattering effects

V.A. Izzo *(University of California San Diego)*
P.B. Parks *(General Atomics)*
E. Hirvijoki *(Princeton Plasma Physics Laboratory)*

2017 PPPL Workshop: Theory and Simulation of Disruptions
18 July 2017
Princeton, NJ



Outline

- Description of shell-pellet injection concept and previous work
- NIMROD modeling: evolution of thermal quench and current quench, species dependence
- Recent upgrades to NIMROD runaway electron orbit integration model
- Runaway electron results including pitch angle scattering effects
- Summary

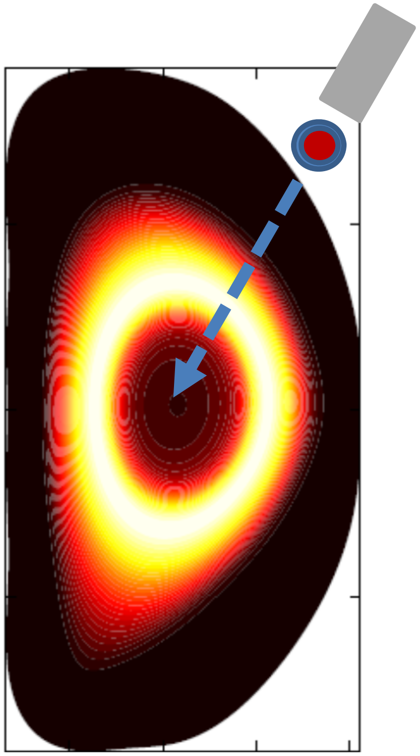
Outline

- Description of shell-pellet injection concept and previous work
- NIMROD modeling: evolution of thermal quench and current quench, species dependence
- Recent upgrades to NIMROD runaway electron orbit integration model
- Runaway electron results including pitch angle scattering effects
- Summary

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UC San Diego

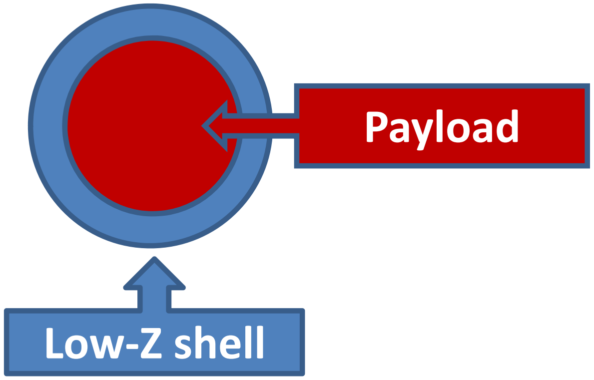
"Shell Pellet" concept* seeks to deliver radiating payload directly to center of plasma



Shell pellet concept:

Hard, low-Z shell ablates as it passes through the edge plasma then breaks open in the plasma center, producing "inside-out" thermal quench (TQ)

In this talk I will alternately refer to it as **EPPI** (Encapsulated Payload Pellet Injection)

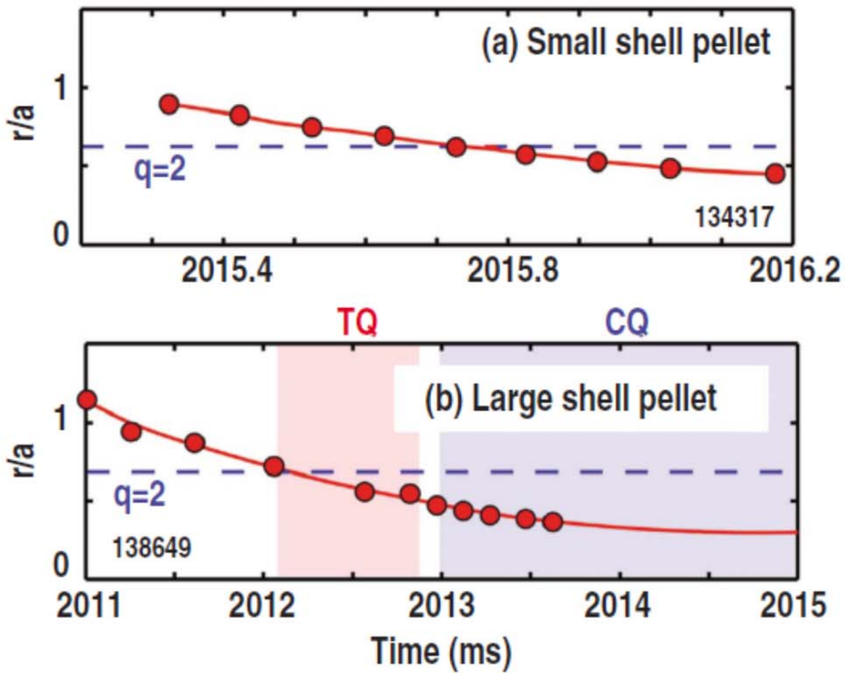


Dispersive payload may consist of dust or compressed gas with impurity species dependent on desired TQ characteristics

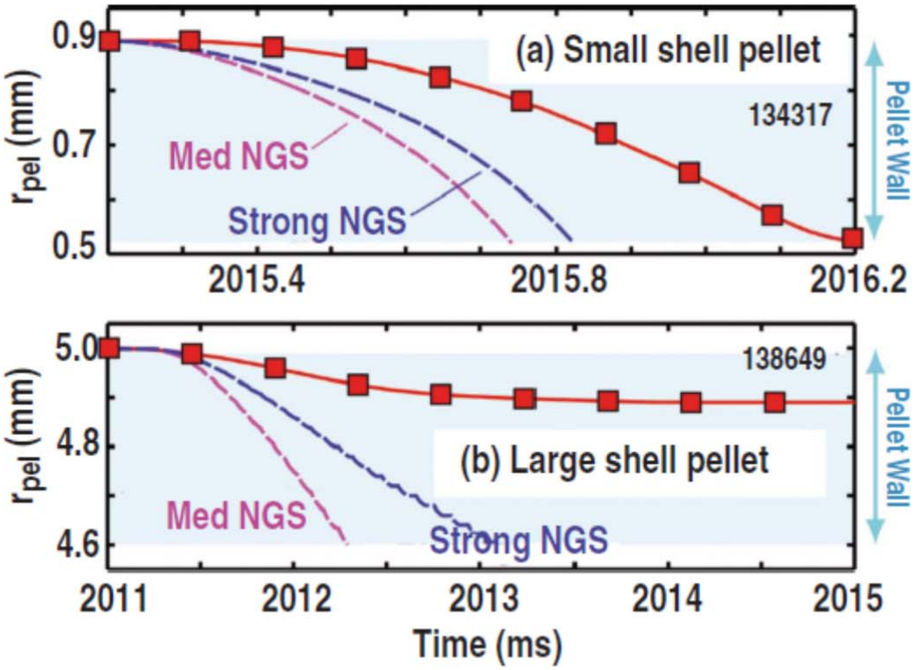
*P. B. Parks, "Dust ball pellets for disruption mitigation," Invention Disclosure DOE Case No. S-113–472 (2007).

Future DIII-D experiments will build on previous proof of principle experiments [1,2]

Small pellets demonstrated ability to deliver payload to core



Large pellets did not break open, needed thinner shell, improved ablation model



[1] E. M. Hollmann, N. Commaux, N. W. Eidietis, T. E. Evans, D. A. Humphreys, A. N. James, T. C. Jernigan, P. B. Parks, E. J. Strait, J. C. Wesley, J. H. Yu, M. E. Austin, L. R. Baylor, N. H. Brooks, V. A. Izzo, G. L. Jackson, M. A. van Zeeland, *and* W. Wu *Physics of Plasmas* **17**, 056117 (2010)

[2] N. Commaux, L.R. Baylor, S.K. Combs, N.W. Eidietis, T.E. Evans, C.R. Foust, E.M. Hollmann, D.A. Humphreys, V.A. Izzo, A.N. James, T.C. Jernigan, S.J. Meitner, P.B. Parks, J.C. Wesley and J.H. Yu, *Nucl. Fusion* **51**, 103001 (2011).

Some advantages and challenges of the shell pellet concept

Advantages:

- Outer flux surfaces are not (substantially) perturbed before radiative cooling begins in the core→ less core heat conducted to the divertor, high radiated energy fraction
- High assimilation efficiency of material in the core→ possibility of runaway electron suppression and faster post-mitigation recovery

Challenges: (experiments needed)

- Will shell be truly non-perturbative? What about pre-existing MHD
- Better model for shell ablation is needed. Can we reliably deliver the payload close to the center? What about changes in plasma parameters?

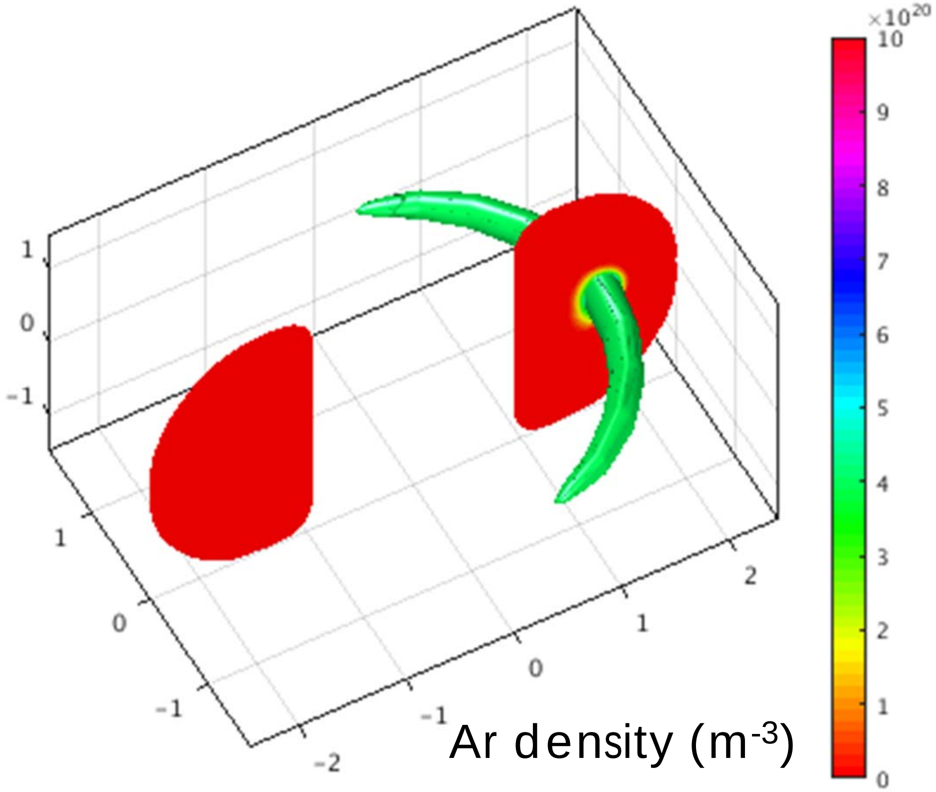
Outline

- ✓ Description of shell-pellet injection concept and previous work
- NIMROD modeling: evolution of thermal quench and current quench, species dependence
- Recent upgrades to NIMROD runaway electron orbit integration model
- Runaway electron results including pitch angle scattering effects
- Summary

High-Z case uses Ar impurities deposited directly into the core very rapidly

Ar is used as a proxy for any high-Z material (highest Z available in NIMROD)

Impurities are deposited in a localized plume with 15cm radius and 1.5 m half-width in the toroidal direction.

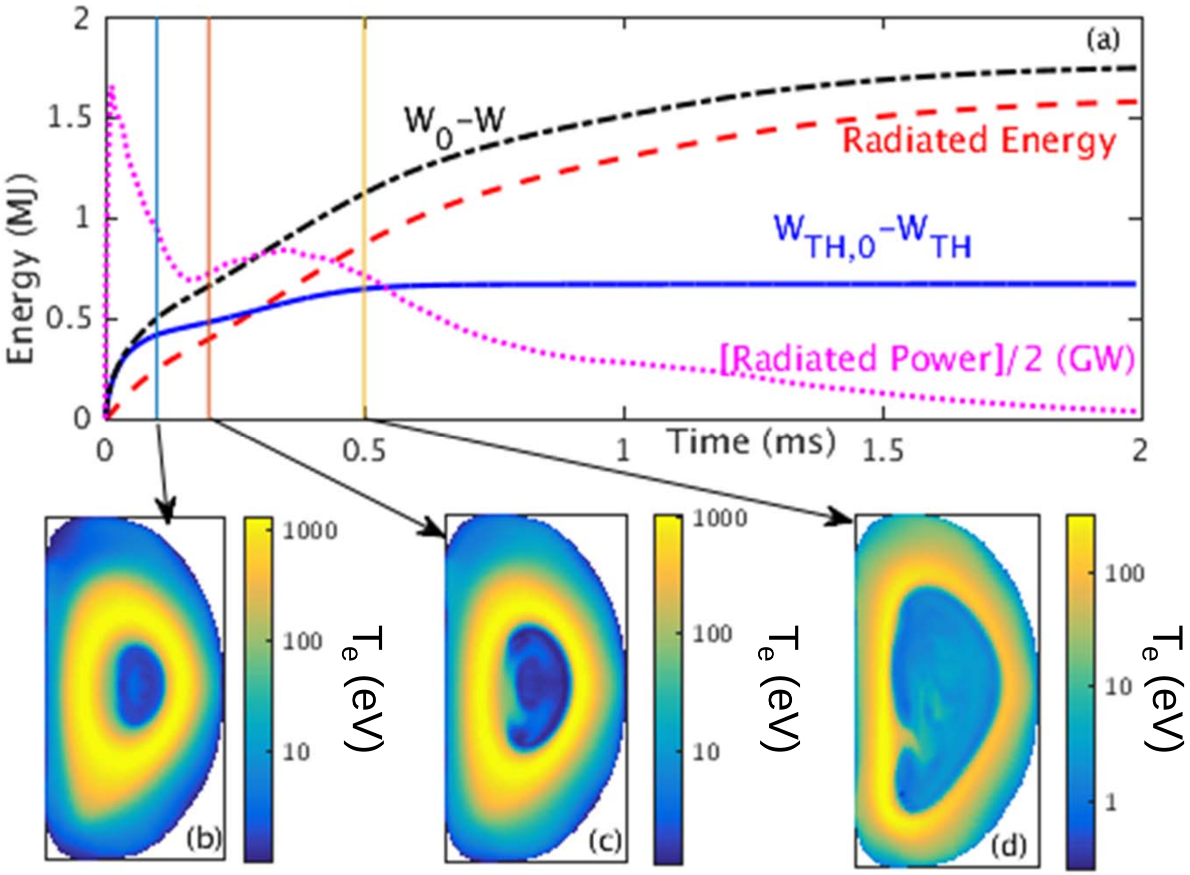


Ar density (m^{-3})

Neutral Ar is deposited during a short 0.1 ms time window

Total of 20 Torr-l Ar is deposited; smaller than total quantities for MGI, but assimilated quantity is similar due to 100% core assimilation by design for EPPI

Plasma cools from the inside out, with most of the thermal energy radiated in first 0.1 ms



TQ is complete within 0.5 ms

Radiated energy fraction

$$= \frac{W_{rad}}{W_0 - W}$$

ultimately exceeds 90%

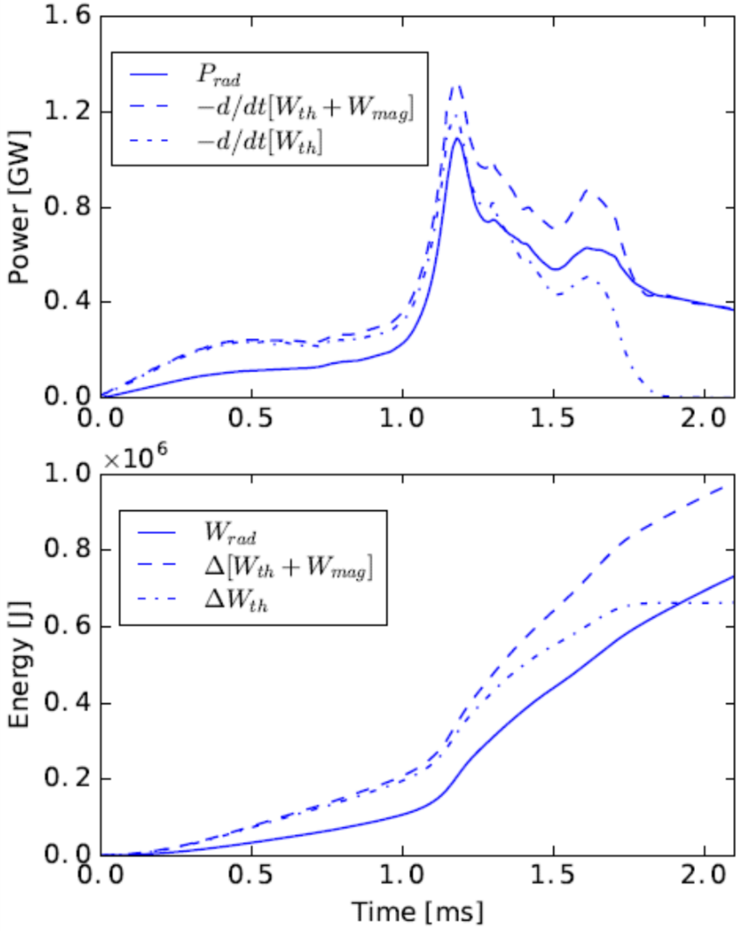
V. A. Izzo , P. B. Parks, Physics of Plasmas **24**, 060705 (2017)

In comparison, MGI produces slower TQ and lower radiated energy fraction

MGI simulation has 1ms pre-TQ as plasma cools edge

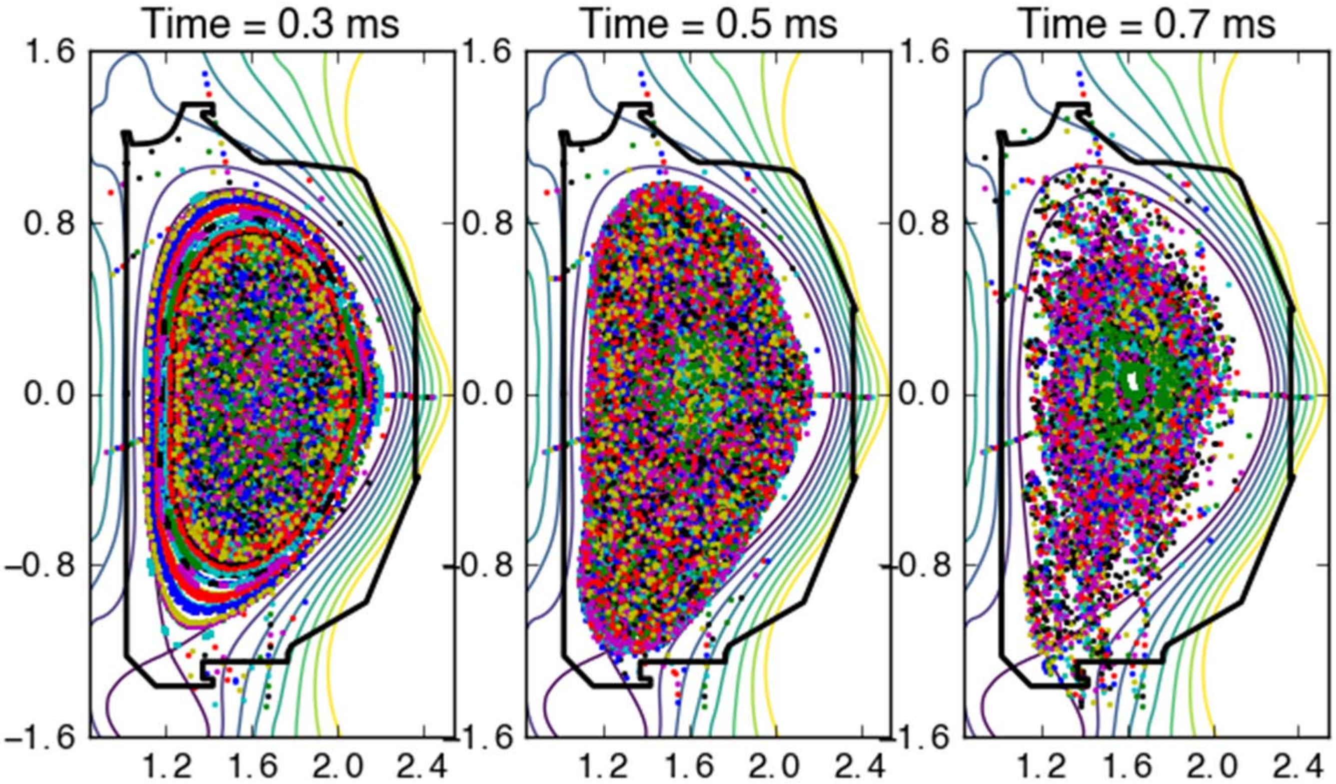
TQ begins when MHD is triggered and breaks up flux surfaces

Radiated energy fraction is closer to 75%



V.A. Izzo, Phys. Plasmas **24**, 056102 (2017)

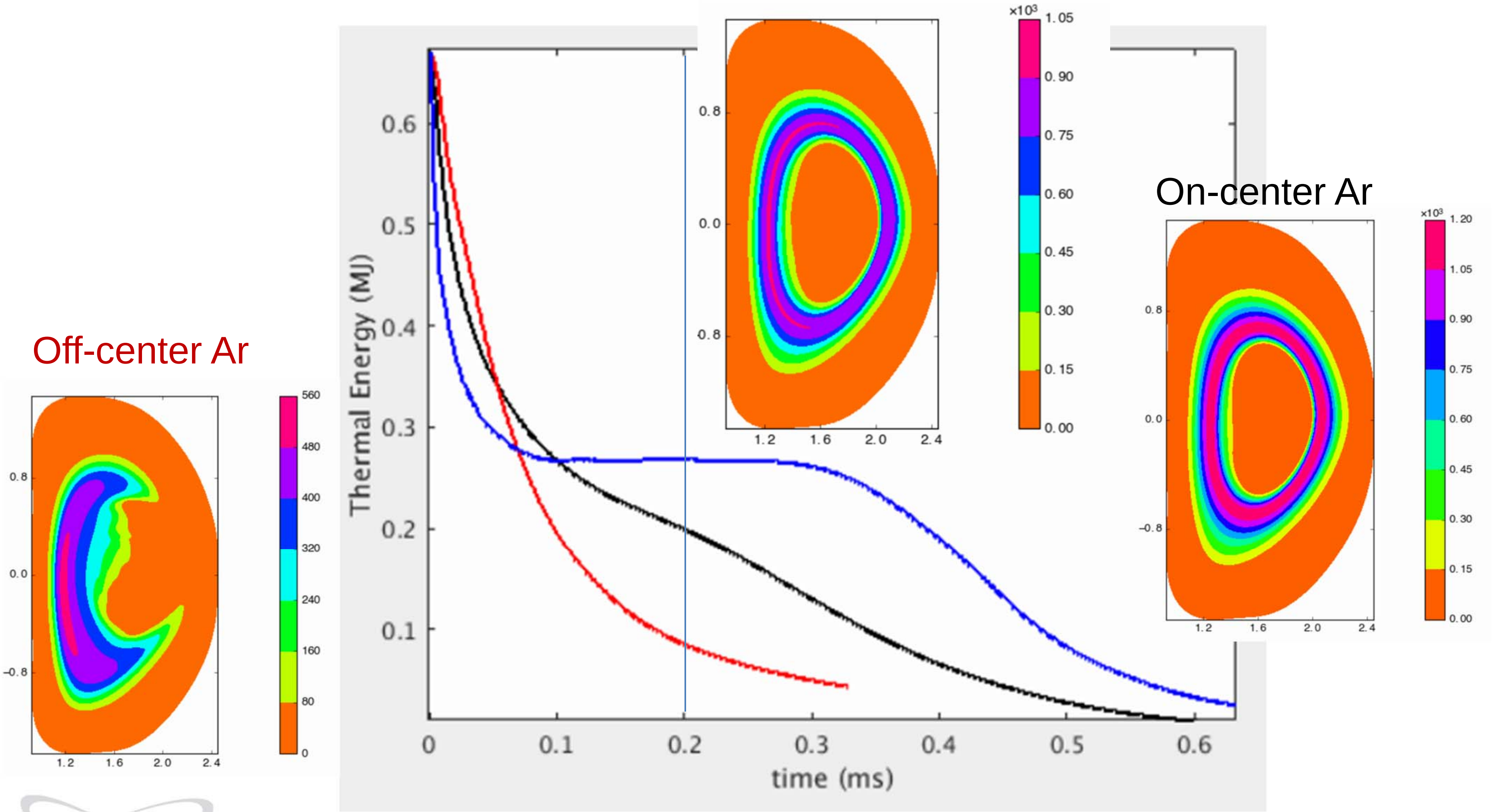
Shell pellet injection breaks up flux surfaces from the inside out



Outermost surfaces remain intact until the end of the TQ, resulting in minimal conduction of core heat to the divertor

V. A. Izzo , P. B. Parks, Physics of Plasmas **24**, 060705 (2017)

Species and pellet centering can effect the TQ rate


On-center Be

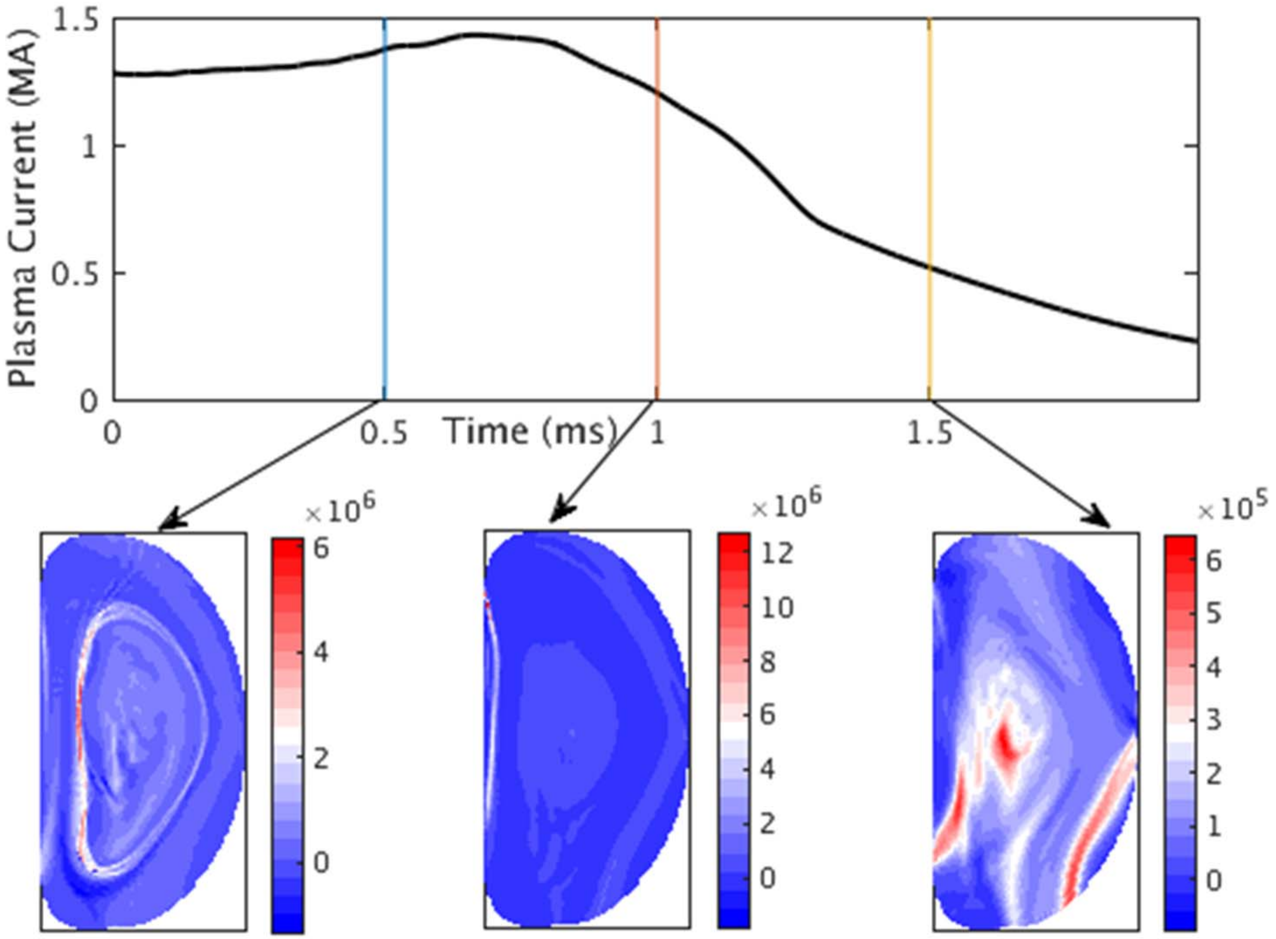
On-center Ar

Off-center Ar

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

UC San Diego

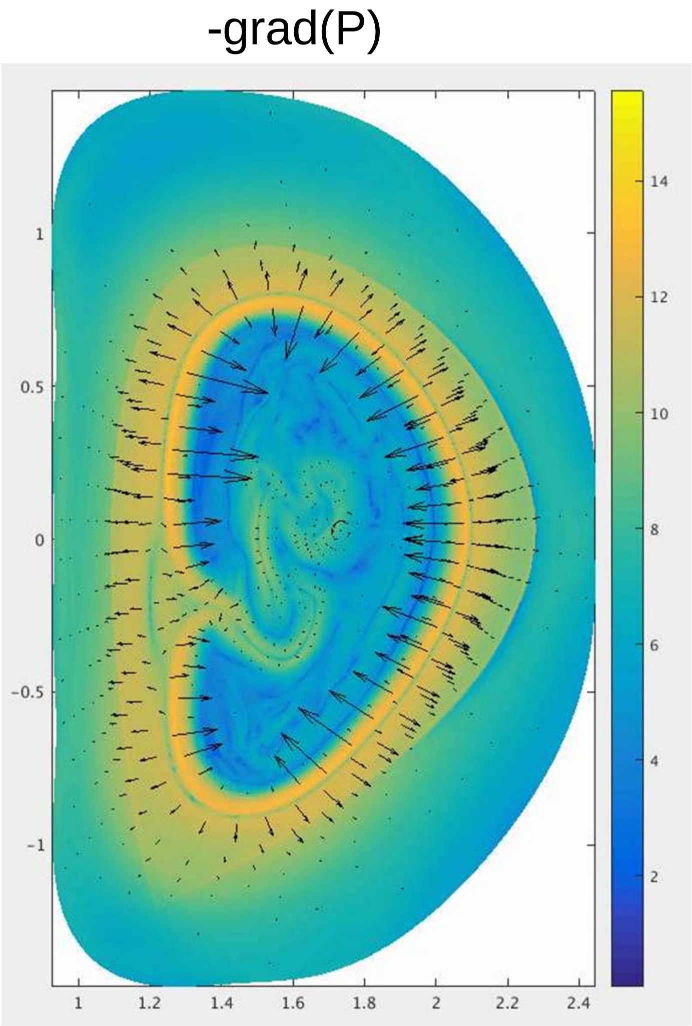
Current quench starts fast due to narrow current channel then slows as current redistributes

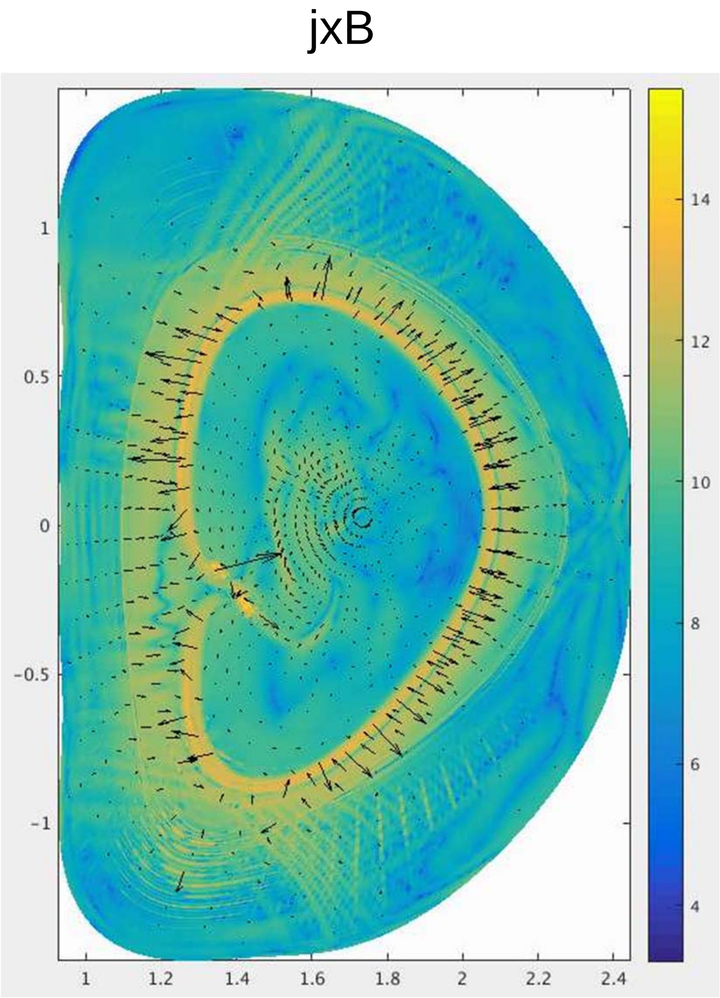


Toroidal Current Density (A/m^2)

V. A. Izzo , P. B. Parks, Physics of Plasmas **24**, 060705 (2017)

As pressure collapses from the inside out, outward jxB force keeps current ring expanding


-grad(P)


jxB

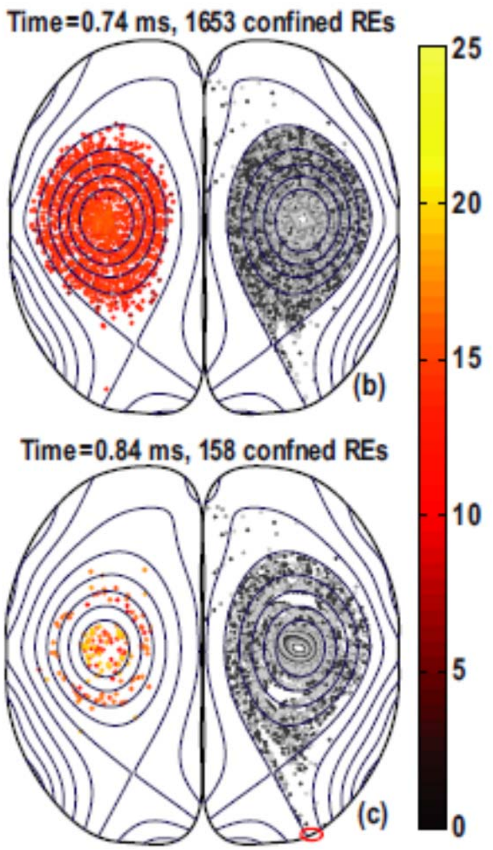
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

UC San Diego

Outline

- ✓ Description of shell-pellet injection concept and previous work
- ✓ NIMROD modeling: evolution of thermal quench and current quench, species dependence
- Recent upgrades to NIMROD runaway electron orbit integration model
- Runaway electron results including pitch angle scattering effects
- Summary

NIMROD RE orbit model designed to follow drift orbits of RE test particles during disruption simulations



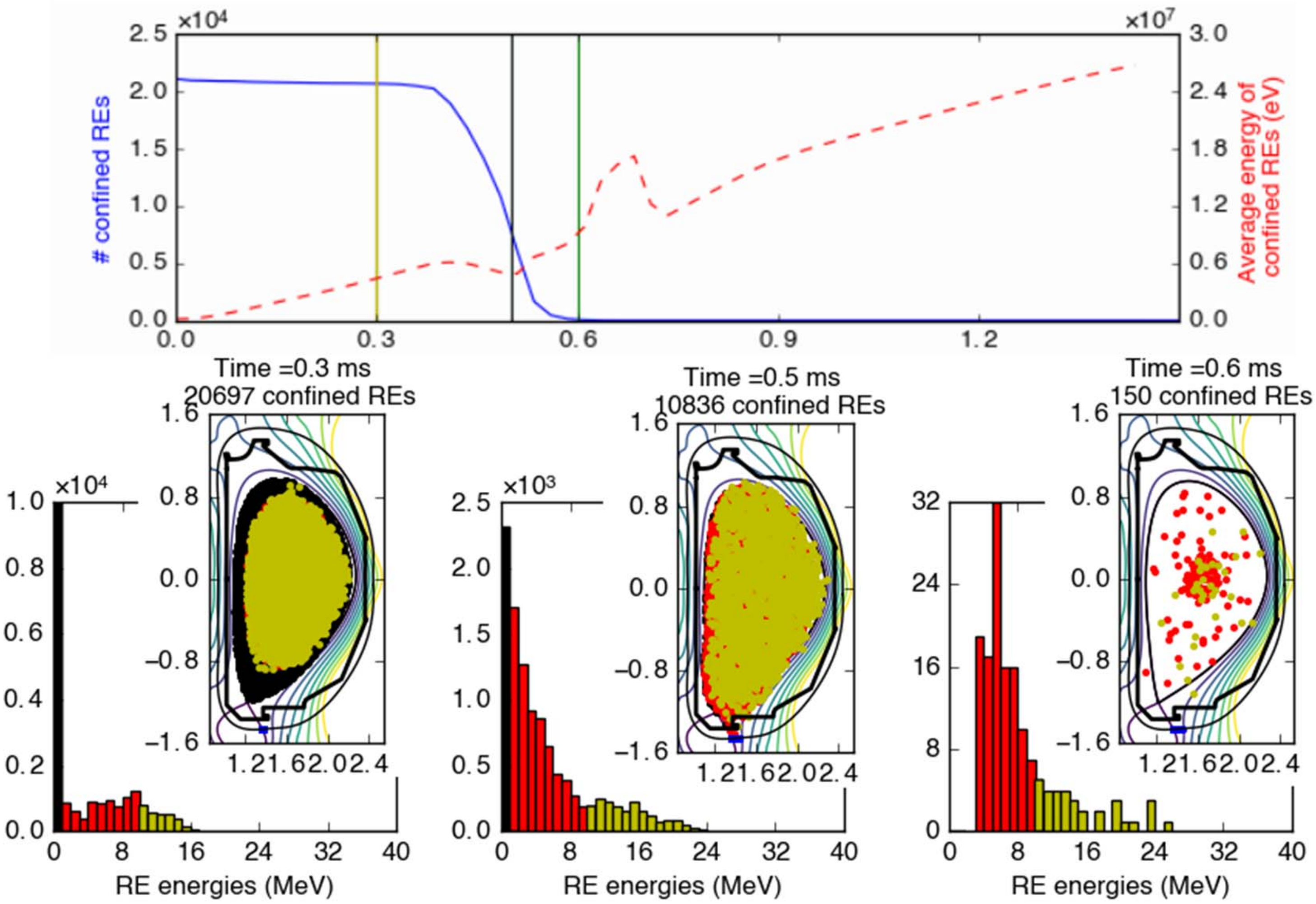
Previous model included E-field acceleration, deceleration due to (small-angle) collisions, synchrotron and bremsstrahlung radiation, but..

Assumed small pitch angle, neglected pitch angle scattering, neglected distribution function of bulk (assumed $v_{re}>>v_{th}$)

Primary aim of model was to examine losses due to field stochastization during the TQ.

V A Izzo *et al* Plasma Phys. Control. Fusion **54** (2012) 095002

In Ar EPPI case, rapid losses are seen at end of TQ

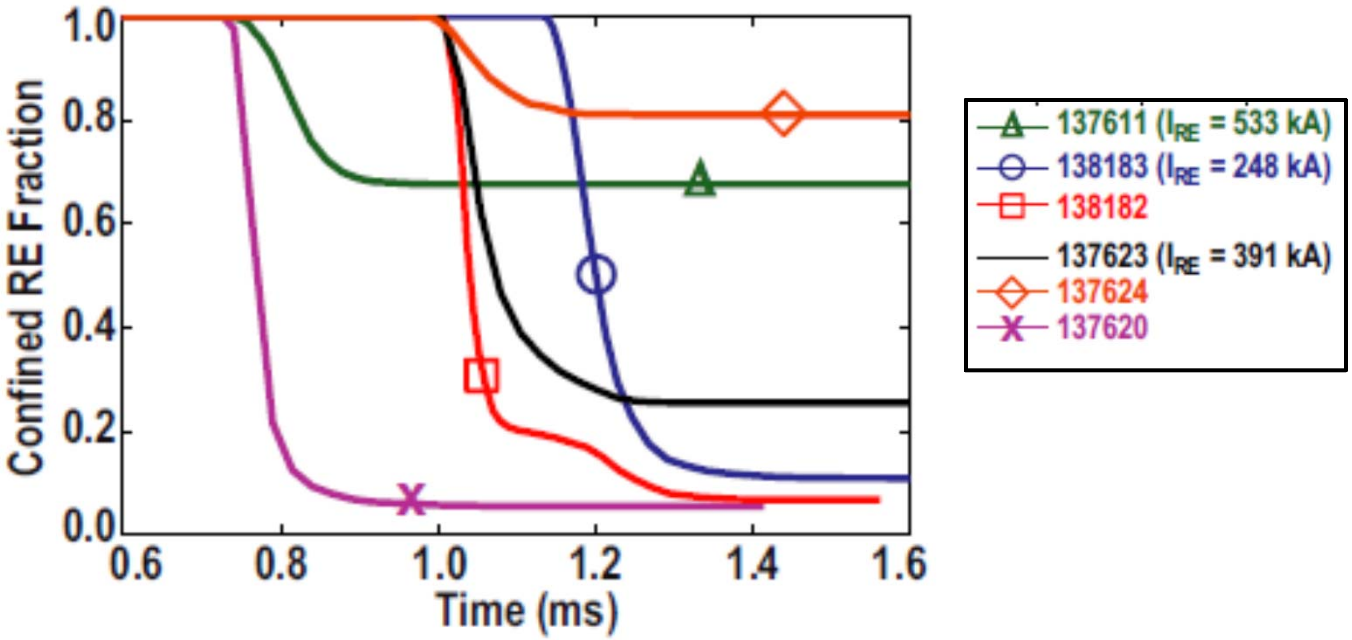


V. A. Izzo , P. B. Parks, Physics of Plasmas **24**, 060705 (2017)

MGI simulations of DIII-D retain from 5%-80% of seed REs

Variation over a range of DIII-D diverted equilibria due to differences in MHD

Compare to 0.01% in Ar EPPI simulation



V A Izzo *et al* Plasma Phys. Control. Fusion **54** (2012) 095002

New model couples NIMROD with AMCC code*

- AMCC code from Eero Hirvijoki (PPPL) working within SCREAM collaboration

- Mote Carlo code to calculate effects of small and large angle collisions with an arbitrary number of species, with the bulk plasma distribution function accounted for

- After following drift orbit for one NIMROD time step (~1 microsecond), AMCC is called once to update the parallel and perpendicular momentum using average values of densities and temperatures over the integrated orbit.

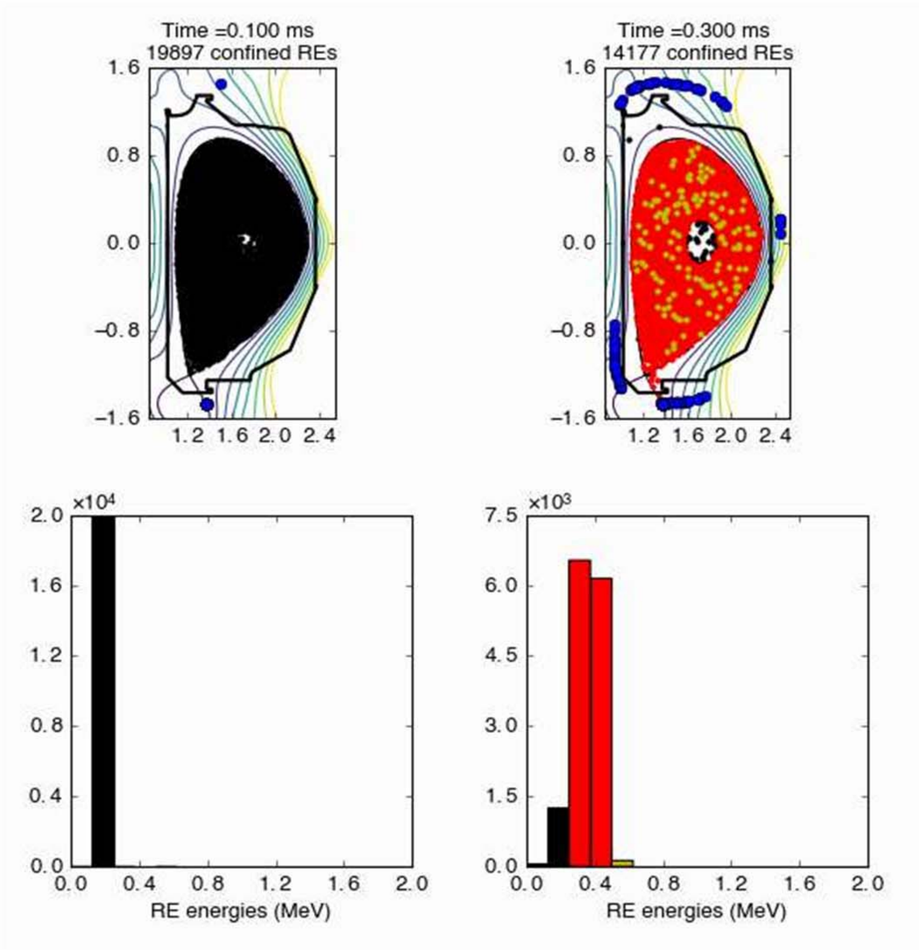
*“Adaptive time-stepping Monte Carlo integration of Coulomb collisions”
Konsta Särkimäki, Eero Hirvijoki, Juuso Terävä, https://arxiv.org/abs/1701.05043

Outline

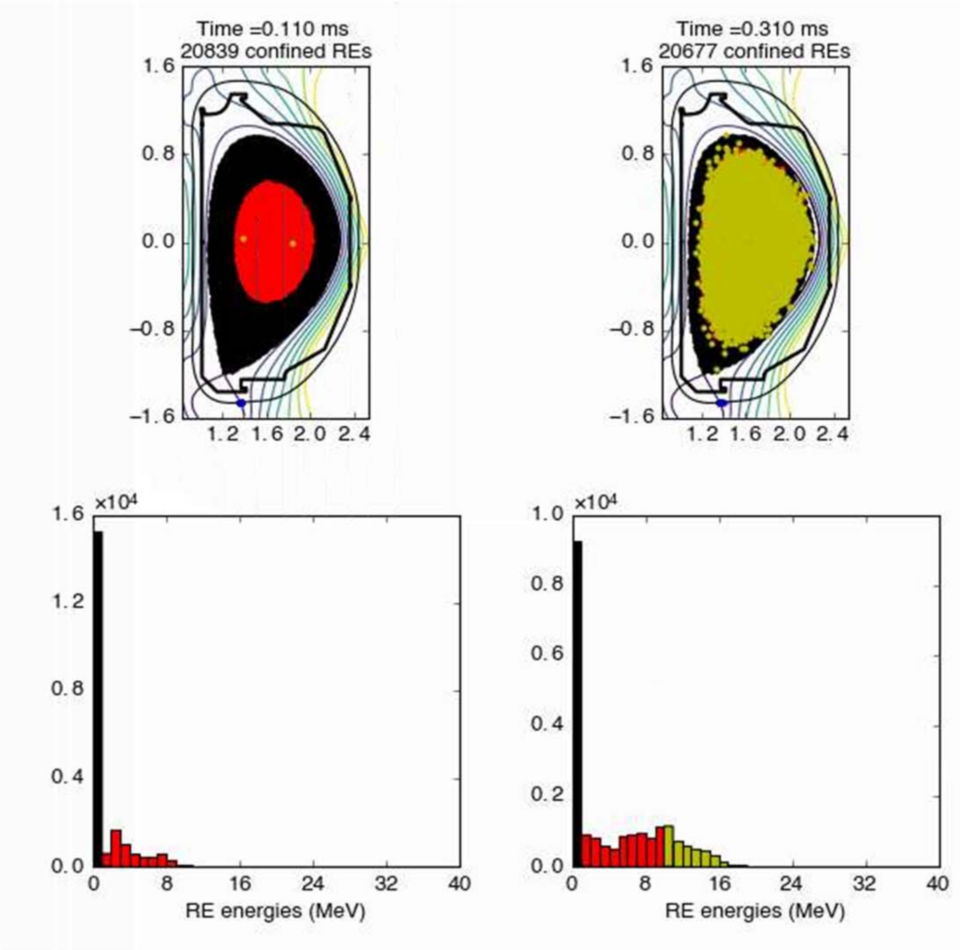
- ✓ Description of shell-pellet injection concept and previous work
- ✓ NIMROD modeling: evolution of thermal quench and current quench, species dependence
- ✓ Recent upgrades to NIMROD runaway electron orbit integration model
- Runaway electron results including pitch angle scattering effects
- Summary

With Ar a dramatic difference is seen in early time energy evolution (NB: different color scale)

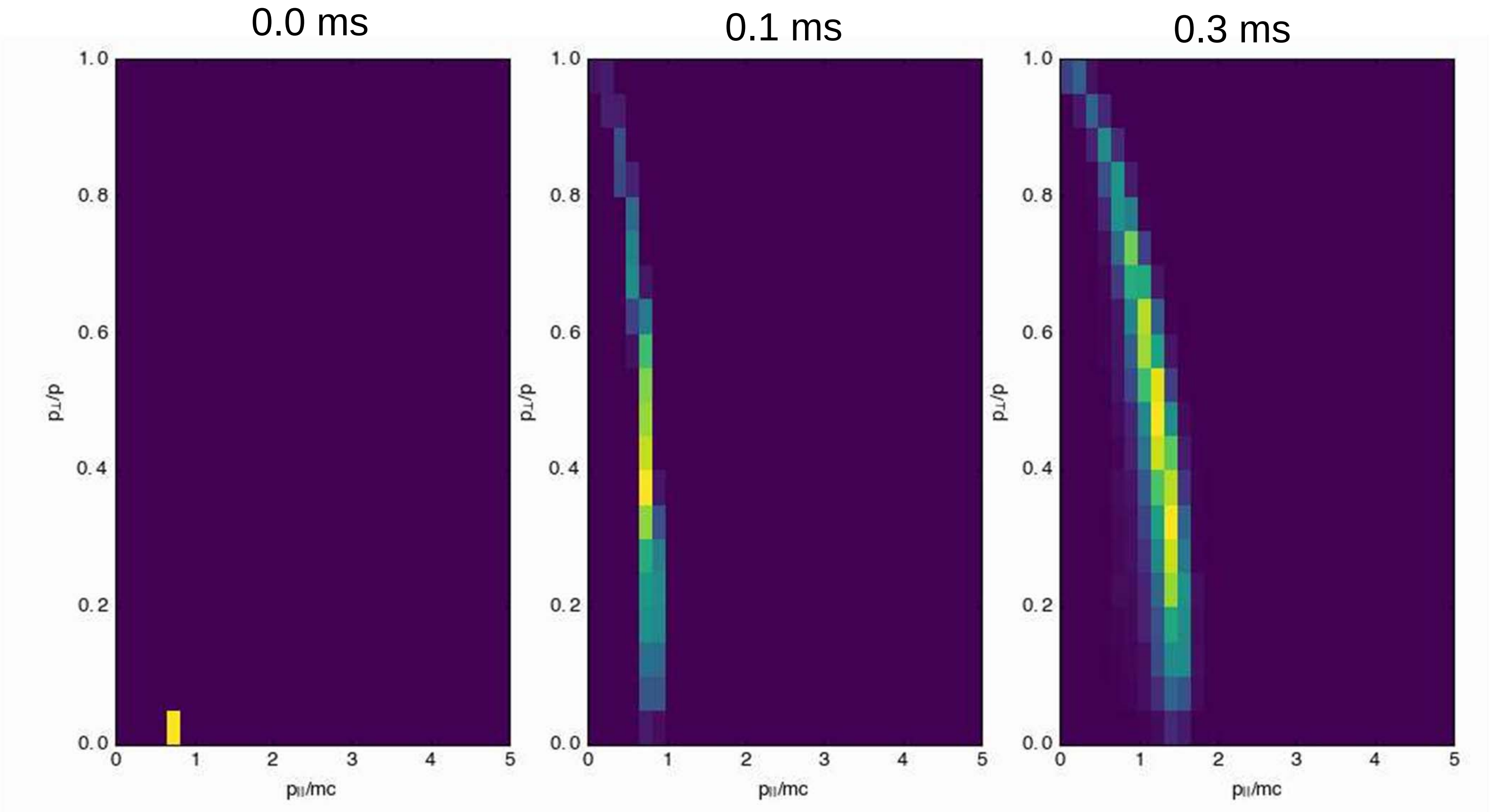
w/ pitch angle scattering



original model



Most test electrons have scattered to pitch angle between 0.2 - 0.5



Outline

- ✓ Description of shell-pellet injection concept and previous work
- ✓ NIMROD modeling: evolution of thermal quench and current quench, species dependence
- ✓ Recent upgrades to NIMROD runaway electron orbit integration model
- ✓ Runaway electron results including pitch angle scattering effects
- Summary

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

UC San Diego

Summary

- Shell pellets concept designed to deliver radiating impurities to the core without strongly perturbing edge flux surfaces
- Proof of principle shell pellet experiments have already been performed on DIII-D
- NIMROD simulation demonstrate many of the potentially promising features of shell pellet injection, including inside-out break up of flux surfaces leading to high radiated energy fraction and fast loss of seed REs at the end of the TQ
- NIMROD has recently been coupled with AMCC Monte Carlo code for better treatment of RE collisions.
- Inclusion of pitch angle scattering effect with Ar EPPI results in significantly lower energies and faster losses of RE seeds after a short time

References

Shell pellet concept:

P. B. Parks, "Dust ball pellets for disruption mitigation," Invention Disclosure DOE Case No. S-113–472 (2007).

Shell pellet experiments:

E. M. Hollmann, N. Commaux, N. W. Eidietis, T. E. Evans, D. A. Humphreys, A. N. James, T. C. Jernigan, P. B. Parks, E. J. Strait, J. C. Wesley, J. H. Yu, M. E. Austin, L. R. Baylor, N. H. Brooks, V. A. Izzo, G. L. Jackson, M. A. van Zeeland, and W. Wu Physics of Plasmas **17**, 056117 (2010)

N. Commaux, L.R. Baylor, S.K. Combs, N.W. Eidietis, T.E. Evans, C.R. Foust, E.M. Hollmann, D.A. Humphreys, V.A. Izzo, A.N. James, T.C. Jernigan, S.J. Meitner, P.B. Parks, J.C. Wesley and J.H. Yu, Nucl. Fusion **51,** 103001 (2011).

EPPI (shell pellet) modeling:

V.A Izzo, P.B. Parks, Physics of Plasmas **24,** 060705 (2017)

AMCC Code:

"Adaptive time-stepping Monte Carlo integration of Coulomb collisions" Konsta Särkimäki, Eero Hirvijoki, Juuso Terävä, https://arxiv.org/abs/1701.05043

RE modeling with NIMROD:

V.A. Izzo, et al, Plasma Phys. and Control. Fusion **54** (2012) 095002

MGI modeling with NIMROD:

V.A. Izzo, Phys. Plasmas **24**, 056102 (2017)

Two-stage process with central-fueling:

P.B. Parks and W. Wu, Nucl. Fusion 51 (2011) 073014

P.B. Parks and W. Wu, Nucl Fusion 54 (2014) 023002