Simulations and Validation of Disruption Mitigation

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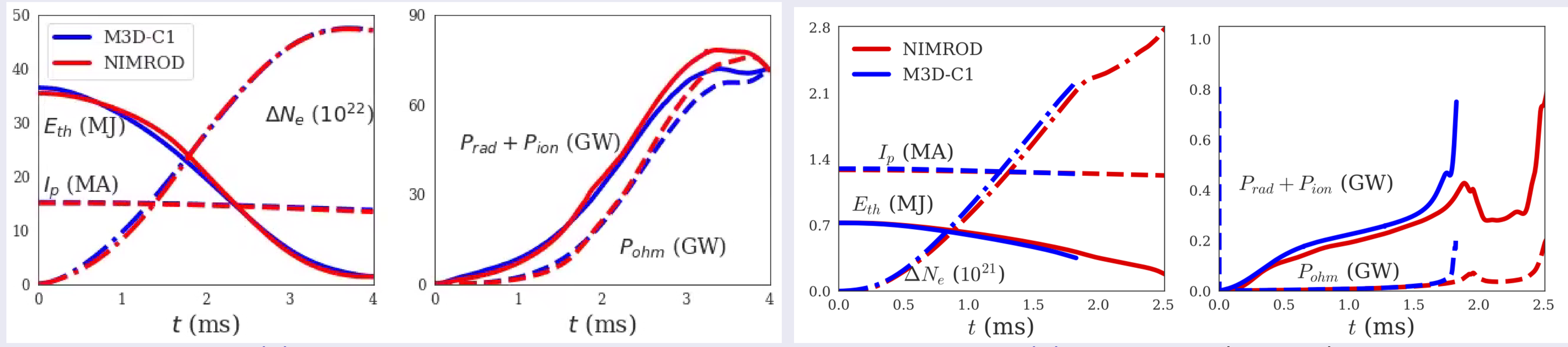
Verification Benchmark Comparisons with M3D-C1 Are Invaluable

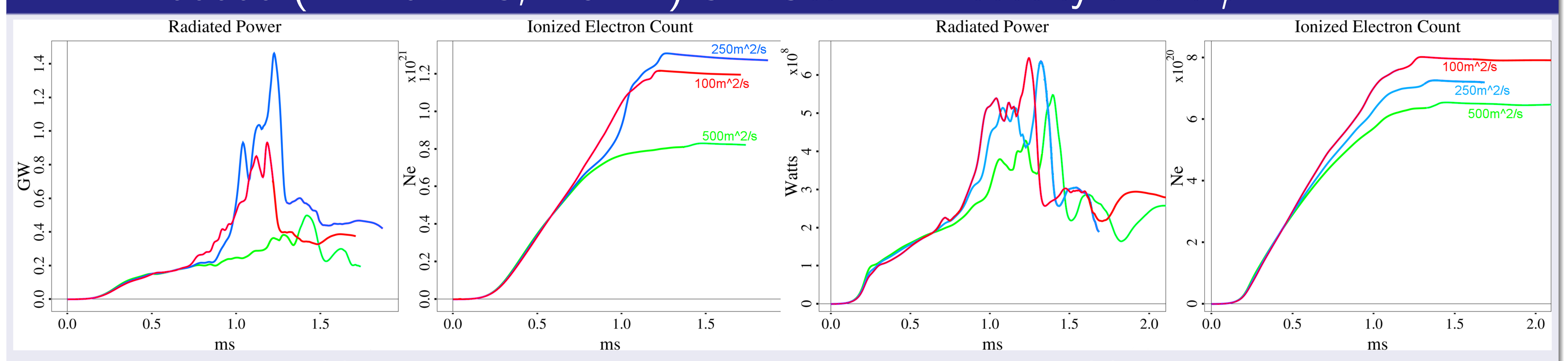


(a) 2D ITER L-mode (b) 3D DIII-D (160606)

- good agreement in impurity/ionization models demonstrated with stationary, axisymmetric, on-axis source[a]
- benchmarks extended to two more cases : SPI in (a) 2D ITER L-mode and (b) 3D DIII-D (160606[b])
- good agreement in test of marker particle model for SPI fragments
- comparison of thermal quench metrics : total current(I_p), thermal energy(E_{th}), ionized electron count(ΔN_e), radiated power($P_{rad}+P_{ion}$), Ohmic power(P_{ohm})
- verification comparisons have also caught bugs and inconsistencies - very useful exercise!
- high confidence in implementation SPI model

[a]B. Lyons PPCF 2019
[b]Shiraki PoP 2016

DIII-D 160606 (TE=0.7MJ, 1.3MA) SPI Scan in Viscosity and $d\phi$



(a) $d\phi$=0.10 (b) $d\phi$=0.05

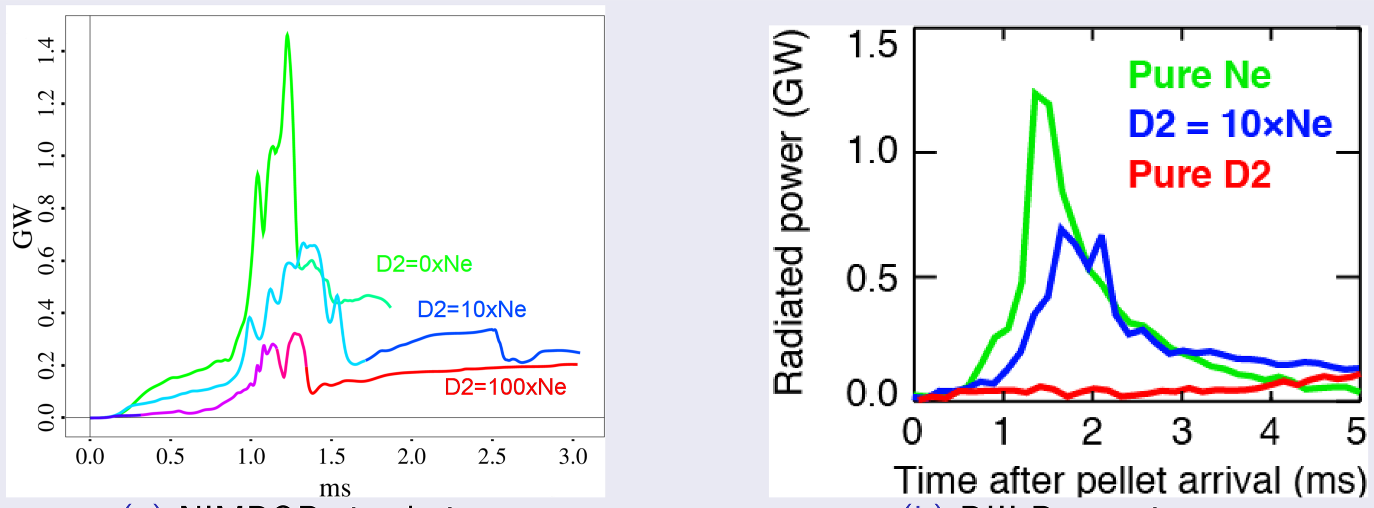
- more consistent trends for $d\phi$=0.05 - narrower deposition crosses fewer flux tubes
- decreasing viscosity accelerates dynamics - earlier t_{rad}^{peak}, τ_{TQ}, t_I^{spike}
  - larger P_{rad}^{peak} due to stronger linear response - (2,1),(3,2)
  - earlier nonlinear saturation but not necessarily larger amplitude

viscosity	$d\phi/2\pi$	t_{rad}^{peak}	τ_{TQ}	t_I^{spike}	$P_{rad}^{peak}(GW)$	E_{rad}/E_{th}	assim.
500m^2/s	0.10	1.417ms	1.478ms	1.728ms	0.50	40%	0.42
250m^2/s	0.10	1.224ms	1.268ms	1.510ms	1.46	58%	0.66
100m^2/s	0.10	1.180ms	1.227ms	1.390ms	0.93	45%	0.61
500m^2/s	0.05	1.393ms	1.451ms	1.804ms	0.55	45%	0.34
250m^2/s	0.05	1.320ms	1.379ms	1.680ms	0.64	47%	0.38
100m^2/s	0.05	1.245ms	1.316ms	1.670ms	0.64	44%	0.41

radiation peak (t_{rad}^{peak}), thermal quench time (τ_{TQ}), current spike peak (t_I^{spike}), peak radiated power (P_{rad}^{peak}), radiated energy fraction (E_{rad}/E_{th}), impurity assimilation.

- decreasing viscosity accelerates dynamics - earlier t_{rad}^{peak}, τ_{TQ}, t_I^{spike}
- narrower toroidal deposition ($d\phi$) delays dynamics - later t_{rad}^{peak}, τ_{TQ}, t_I^{spike}
  - implies deeper penetration but shows lower assimilation
- peak in radiated power, t_{rad}^{peak}, precedes τ_{TQ} by $\sim$50μs, current spike, t_I^{spike}, few 100'sμs after τ_{TQ}

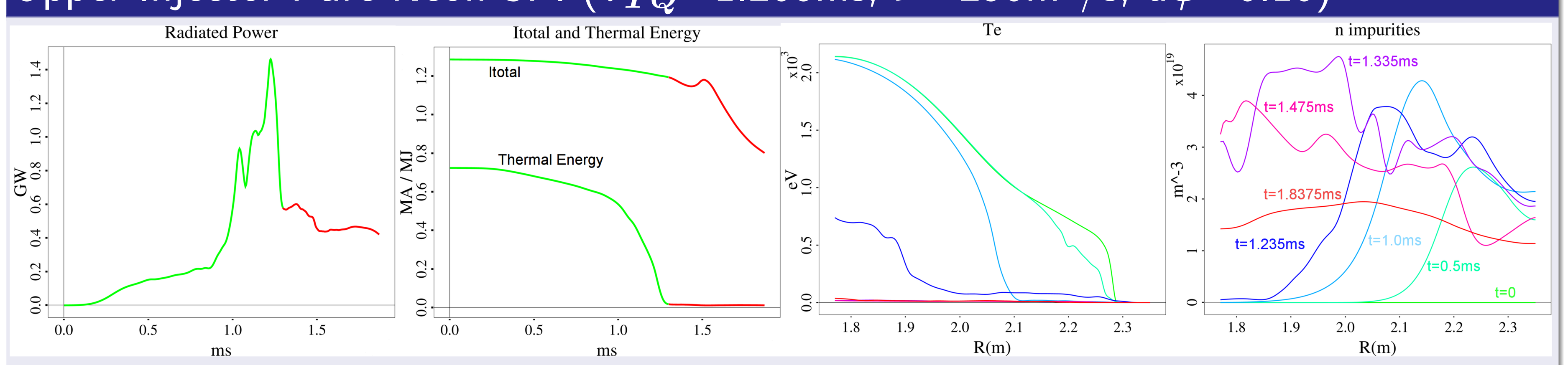
Good D2 Fraction Validation



(a) NIMROD simulation (b) DIII-D experiment

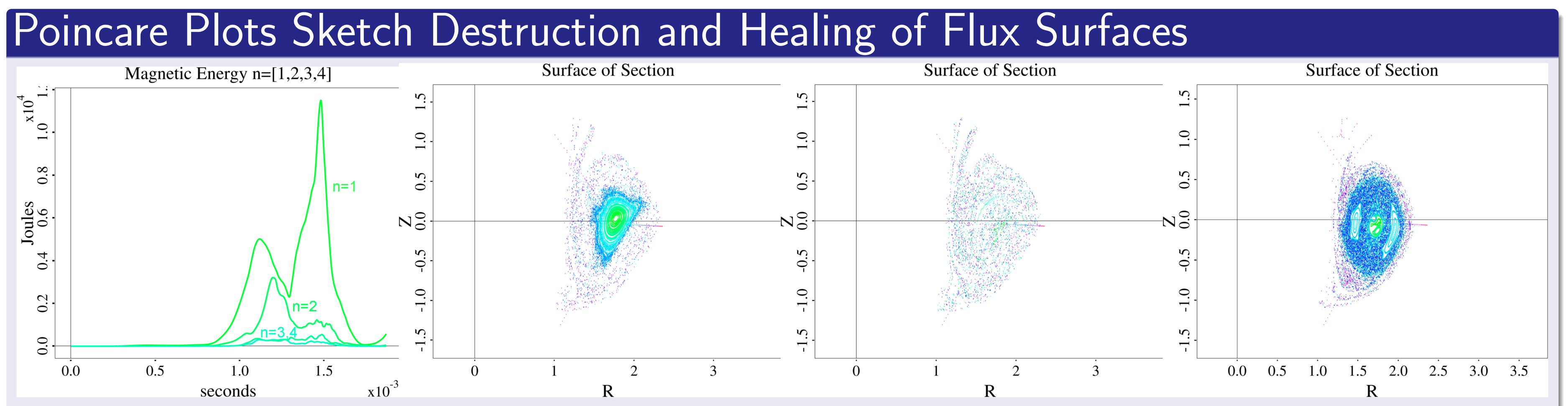
- single upper injector, v=200m/s, $d\phi$=0.10, visc=250m/s^2, D2=[0x,10x,100x]Ne
  - τ_{TQ}=[1.27,1.57,1.35]ms, radiation fraction [58,50,14]%
- good agreement with DIII-D experiment (Shiraki PoP 2016)

Upper Injector Pure Neon SPI (τ_{TQ}=1.268ms, ν=250m^2/s, $d\phi$=0.10)



- outboard midplane profiles of T_e and n_Z at t=[0.0,0.5,1.0,1.235,1.335,1.475,1.8375]ms
- core temperature maintained throughout early phase (t=[0.0,0.5,1.0])
- peak radiation associated with core collapse (t=[1.235 -])
- impurities mix into core after rapid thermal collapse of core (t=[1.335,1.475,1.8375]ms)
- current spike (t_I^{spike}=1.510ms) occurs after thermal quench

Poincare Plots Sketch Destruction and Healing of Flux Surfaces



(a) toroidal mode energy (b) t=1.15ms (c) t=1.335ms (d) t=1.838ms

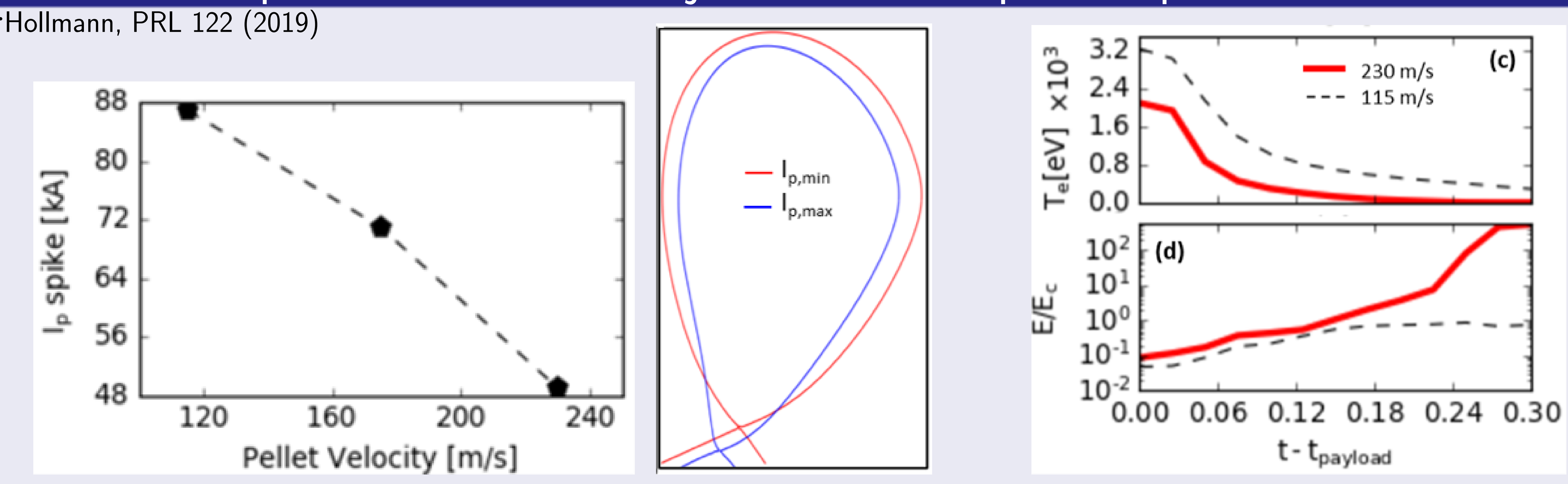
(a) toroidal energies dominated by n=1,2 correspond to radiation peak and current spike
(b) t=1.15ms corresponds to first n=1 peak, retains core flux surfaces
(c) post thermal quench (t=1.335) stochastic fields
(d) late after thermal quench flux surfaces heal - core and (2,1) islands

Current Quench And Runaway Electrons Pose Bigger Challenge

- SPI thermal quench simulations well in hand
- current quench and runaway electron simulations are more challenging
- current quench and runaway electrons involve two extremes
  - cold dirty plasma and relativistic electrons
- several hybrid approaches - combining kinetic and fluid models - underway
  - MARS-F
  - M3D-C1 + fluid RE, M3D-C1 + KORC
  - NIMROD RE tracers, NIMROD hybrid kinetic RE
  - NIMROD+CQL3D
- *additional work exists outside cohort of collaborators*

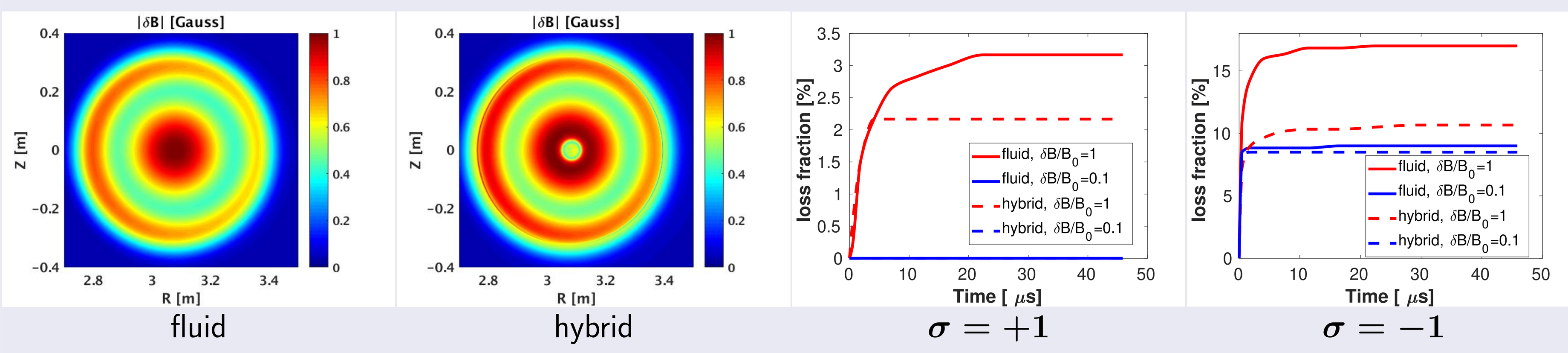
NIMROD Dispersive Shell Pellet Injection Sims Explain Experimental[†] Trends

†Hollmann, PRL 122 (2019)



- reproduces larger I_p spike for slower pellets
- slower pellet $\rightarrow$ less dissipated flux at o-point $\rightarrow$ more reconnected flux at x-point at I_p spike
- RE seeds only for fastest pellet
- $\mathbf{E}/\mathbf{E}_{crit} > 1$ only for fastest pellet required for hot-tail generation

Hybrid MHD-RE Model in MARS-F Used to Study Interaction with Internal Kink



fluid hybrid $\sigma = +1$ $\sigma = -1$

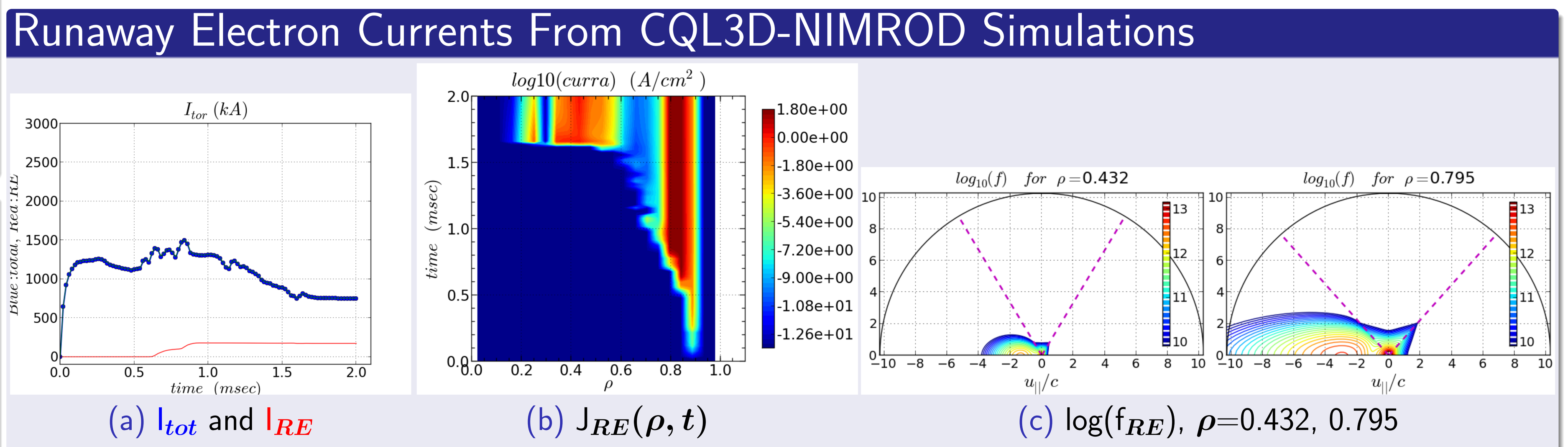
- RE fluid found to destabilize n=1 ideal internal kink and modify eigenmode structure
- kink does not produce significant RE loss unless perturbation field comparable to equilibrium
- RE hybrid model produces less RE loss than RE fluid model

Loose Forward Coupling with NIMROD and CQL3D (Y. Petrov)

- CQL3D - relativistic collisional/quasilinear bounce-averaged Fokker-Planck equation
  - solves for distributions of electrons and ions
  - flux surface averaged fields, toroidal geometry
  - options for RF/neutral beam/particle sources, applied E-field, and radial diffusion
- early coupled sims demonstrated sensitivity to the details of the thermal quench[a]
- forward coupling feeds NIMROD flux surface averaged fields into CQL3D
  - loose forward coupling: NIMROD is run once independently
  - output fields from NIMROD $\rightarrow$ input fields for CQL3D
- initial calculations do not consider RE loss
- tighter feedback in time coupling planned for future work
  - file based, python driven

[a]R. W. Harvey, NF 2019

Runaway Electron Currents From CQL3D-NIMROD Simulations



(a) I_{tot} and I_{RE} (b) $J_{RE}(\rho, t)$ (c) log(f_{RE}), ρ=0.432, 0.795

(a) $\sim$170kA of runaway electron current produced from initial I_{tot0}=1.3MA
(b) majority of runaway current produced at $\rho \simeq 0.8$
(c) runaway electrons accelerated to MeV's

- electron loss not taken into account - recall Poincare plots
- loose coupling does not feed back RE's into NIMROD
  - future work

Summary and Future Work

- verification benchmark comparisons with M3D-C1 are invaluable
- NIMROD simulations reproduce and explain many experimental trends
  - D2 impurity scan, dominant role of n=1, DSP RE trends
- parameter scans reveal numeric sensitivity landscape
- SPI thermal quench simulations are well in hand
- more challenging current quench and runaway electron simulations under way
- continue more detailed validation comparisons with experiment
- extend simulations to ITER predictions