Parameter Scan of Viscosity and Toroidal Deposition - NIMROD SPI Simulations [1]

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NIMROD's Impurity Modified Single Fluid Resistive MHD Equations

- $$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \mathbf{V}) = \boxed{S_\alpha} + \nabla \cdot D \nabla n_\alpha$$
  - α = ions(i) and impurities(Z) (*including neutral ions and impurities*)
  - S_α source and sink due to ionization and recombination
  - electron(e) density from quasi-neutrality
- $$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p$$
  - $\rho = m_i n_i + m_e n_e + \boxed{\sum_Z m_Z n_Z}$ $\quad p = n_t T \quad n_t = n_i + n_e + \boxed{\sum_Z n_Z}$
- $$\frac{n_t}{\Gamma - 1} \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = -p \nabla \cdot \mathbf{V} - \nabla \cdot \mathbf{q} + \boxed{Q}$$
  - single temperature, $T = T_i = T_e = T_z$, assumes instant thermalization
  - heat flux $\mathbf{q}$ parameterized by constant $\chi_{||}$ and $\chi_\perp$
  - Q includes Ohmic heating and loss due to ionization, recombination and radiation
- $$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \qquad \mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J}$$
  - temperature dependent Spitzer resistivity $\eta(T)$ with high T cutoff

Particle Based SPI Model Provides Discrete Moving Source of Neutrals

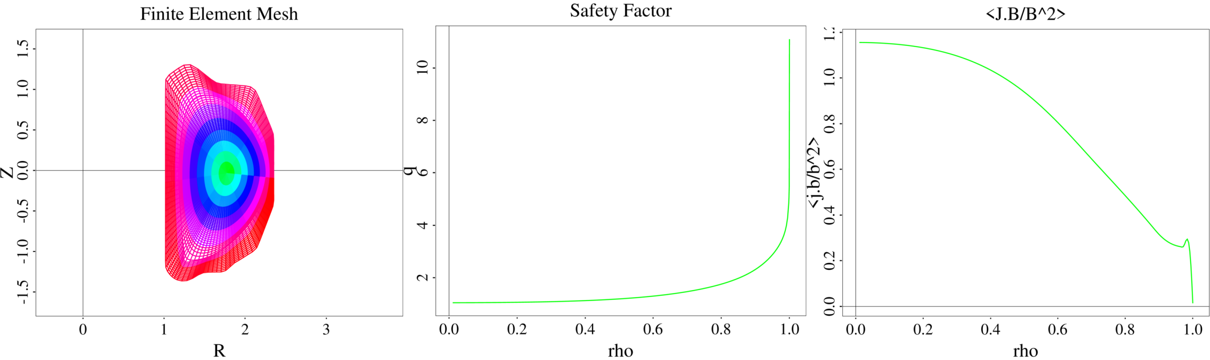
1. **does not** resolve SPI fragment, assumes point particle of radius r_f with velocity $\vec{v}_f$
   - **fragment time-of-flight: $\tau^{tof} = L_{axis}/|\vec{v}_f|$ is key time scale**
2. **does** resolve ablated cloud
   - Gaussian circle in poloidal plane and vonMises toroidal direction ϕ
     - $S(\phi|\mu,\kappa) = \frac{e^{\kappa\cos(\phi-\mu)}}{2\pi I_0(\kappa)}$, centered at μ, $\kappa = 1/(2\pi \times d\phi)^2 \sim 1/\sigma^2$
   - ablated cloud computed from mass ablation function $G(n_e, T_e, r_f, X)$ *(P.Parks)*
3. after deposition, KPRAD[2] based ionization/radiation subroutines takes over
   - same as NIMROD Massive Gas Injection[3]
4. particle based SPI model is flexible and easy to modify
   - easy to apply forces to fragments and add additional injectors

Flexible particle based source model applicable to many applications:

e.g. shell pellet, pellet fueling, ELM pacing, molecular beam, Li droplets

[2] D. G. Whyte, *GA Report* **A22639** 1997
[3] V. A. Izzo, *NF* **46** 2006

DIII-D 160606@02990ms[4], TE=0.7MJ, 1.28MA, q_{min}=1.05, q_0=1.11



- 72x96 poly_degree=3, n=[0,21]
- NERSC Cori - 704procs 96hrs ∼100K cpu-hrs
- single upper injector, 2.0mm pure neon pellet, Shatter Parameter=10
- 10.0cm pencil beam of 200 fragments in 50 bunches, 200.0m/s
- vanguard fragment starts at lcfs

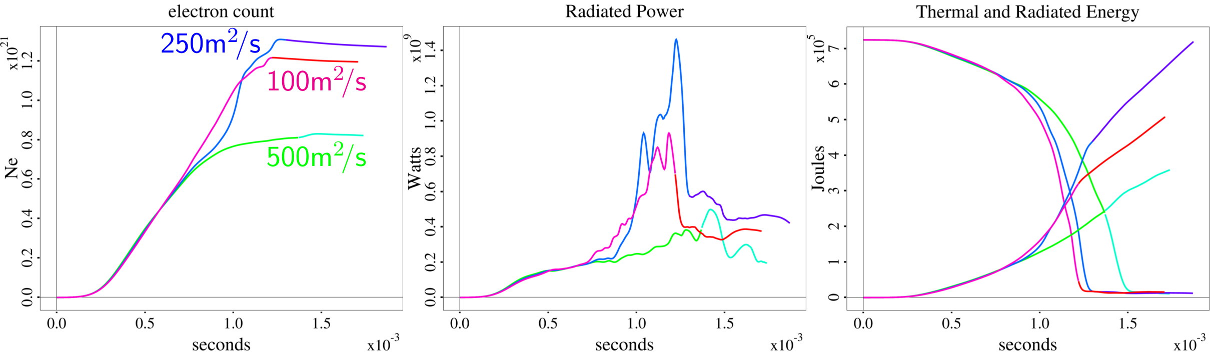
[4]Shiraki PoP 2016

NIMROD SPI Parameter Scan - Viscosity and Toroidal Deposition

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

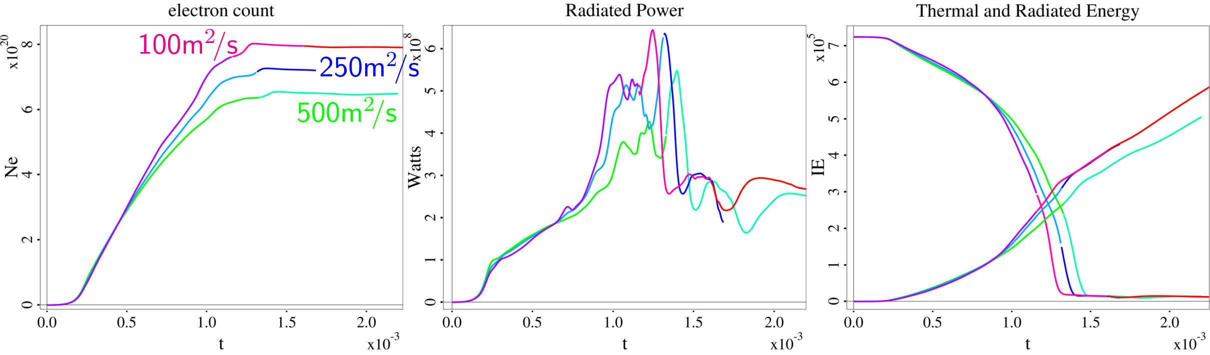
- Thermal Quench time (τ_{TQ}) $\equiv$ N_e^{max} (total e^- count)
  - peak in radiated power preceeds τ_{TQ} by $\sim$50μs
  - current spike few 100'sμs after τ_{TQ}
- decreasing viscosity accelerated dynamics
  - stronger linear response - (2,1),(3,2) - (induced by ablation?)
  - earlier nonlinear saturation but not necessarily larger amplitude
- more concentrated toroidal deposition ($d\phi$) delays dynamics
  - deeper penetration but lower assimilation

Toroidal Deposition = 0.10, Scan in Viscosity [100,250,500]m^2/s



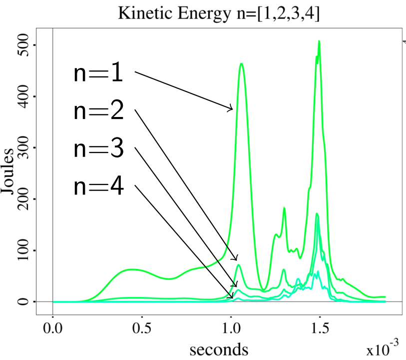
- early evolution t=[0.0,0.7]ms similar
- viscosity impact on dynamics evident in time traces
- *also impacts current quench and runaway dynamics*

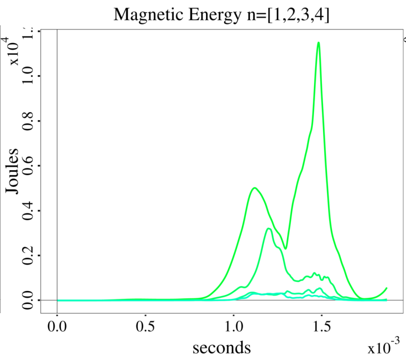
Toroidal Deposition = 0.05, Scan in Viscosity [100,250,500]m^2/s

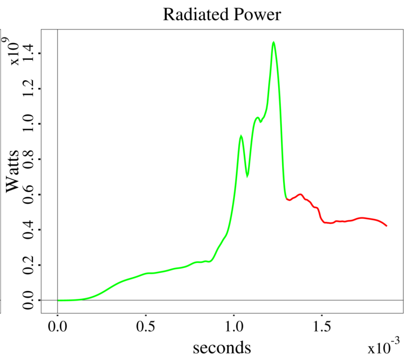


- dϕ=0.05 shows more consistent behavior
- close to toroidal resolution limit
- *requires higher mode number convergence test*
- analysis continues

Viscosity=$250\text{m}^2/\text{s}$, $d\phi = 0.10$, τ_{TQ}=1.268ms

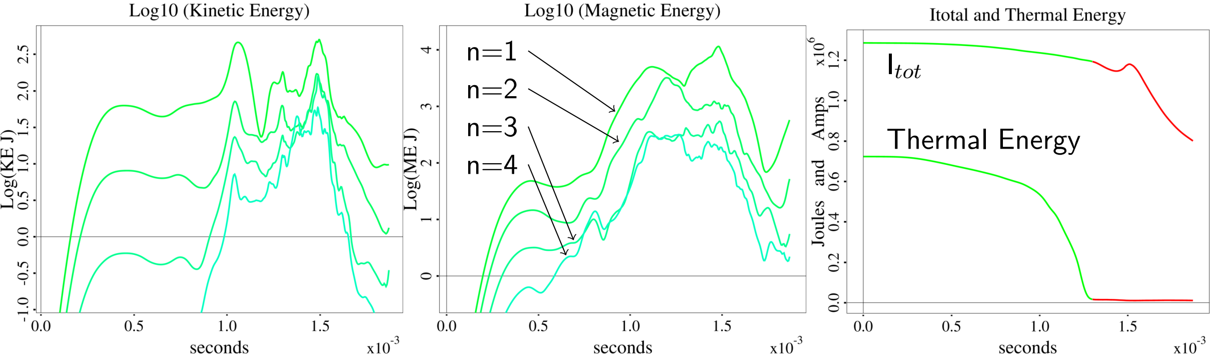






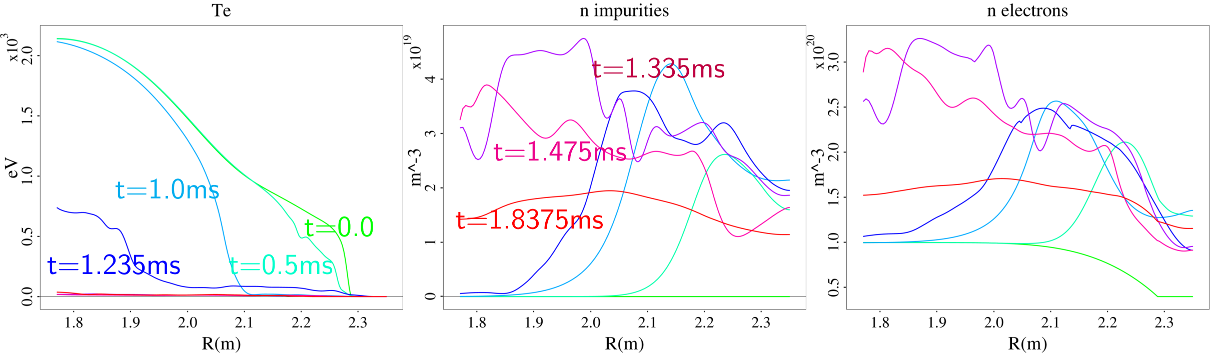
- kinetic energy small - few 100's J (TE=0.7MJ, ME=40.02MJ)
  - early n=1 (t$\simeq [0.0, 0.7]$ms) dominated by fragment
- n=1 linear phase t$\simeq [0.7, 1.1]$ms - (2,1)
  - radiation peak does not coincide with mode peaks
  - radiation peak close to n=2 peak - (3,2)
- peak at t=1.5ms associated with current spike, signals start of current quench

Viscosity=250m^2/s, $d\phi = 0.10$, τ_{TQ}=1.268ms



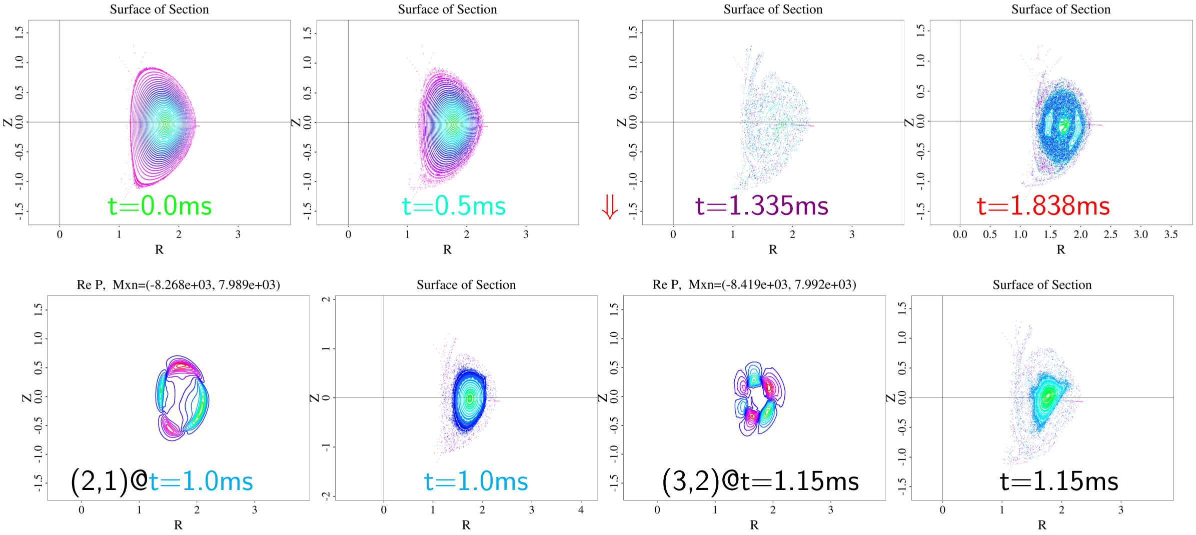
- early activity (t$\simeq$ $[0.0, 0.7]$ms) broad spectrum - resolving deposition of fragments
- kinetic energy small - few 100's J (TE=0.7MJ, ME=40.02MJ)
- (2,1) linear phase t$\simeq$ $[0.7, 1.1]$ms, (3,2) linear phase t$\simeq$ $[1.0, 1.2]$ms
  - radiation peak t=1.22ms
- current spike at t=1.5ms associated with mode energy MAX, start of current quench
  - $\sim$250μs gap between end TQ and start of CQ

Viscosity=250m^2/s, dϕ = 0.10, τ_{TQ}=1.268ms

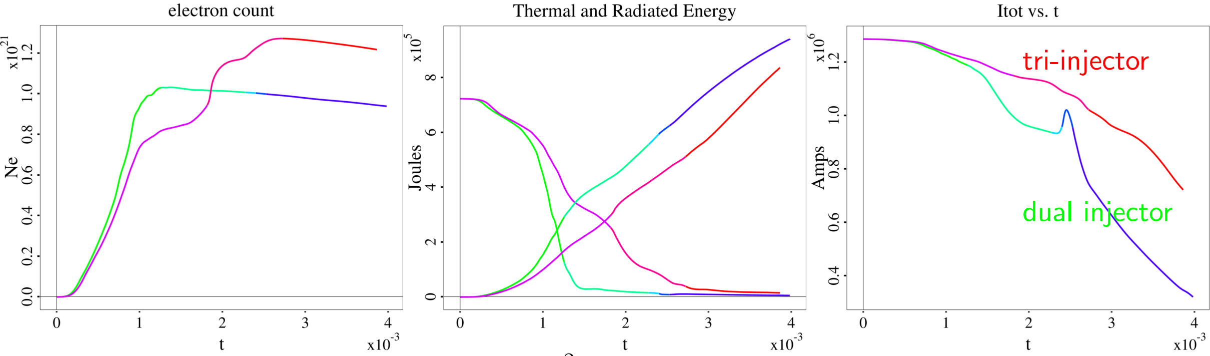


- outboard midplane profile at t=[0.0,0.5,1.0,1.235,1.335,1.475,1.8375]ms
- core temperature maintained throughout early phase of quench (t=[0.0,0.5,1.0])
- impurities mix into core after rapid thermal collapse of core (t=[1.335,1.475,1.8375]ms)
- core temperature increases at t=1.8375ms ∼40eV (lowest 10-20eV @ t=[1.335,1.475]ms)

Poincare Plots - Viscosity=250m^2/s, dϕ = 0.10, τ_{TQ}=1.268ms

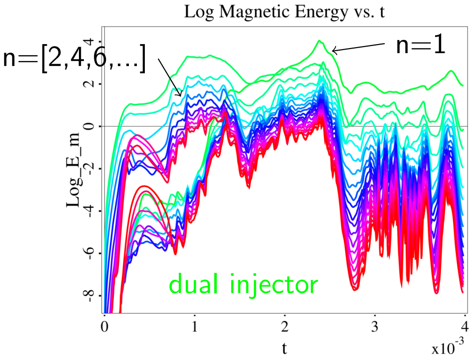


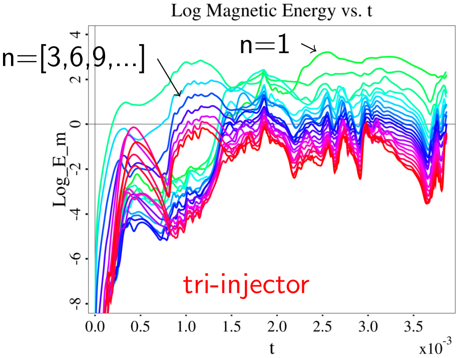
Simultaneous Symmetric Multi-Injector SPI



- r_{frag}=0.2mm , $d\phi$=0.05, visc=100m/s^2
- dual(180' separation, 200 fragments) and tri(120' separation, 150 fragments)
- τ_{TQ}^{dual}=1.374ms τ_{TQ}^{tri}=2.723ms, radiation fraction 46% and 70%
- tri-injector much more benign - magnetic mode energy order of magnitude smaller
  - current spike absent
  - numeric curiosity - probably physically unrealizable

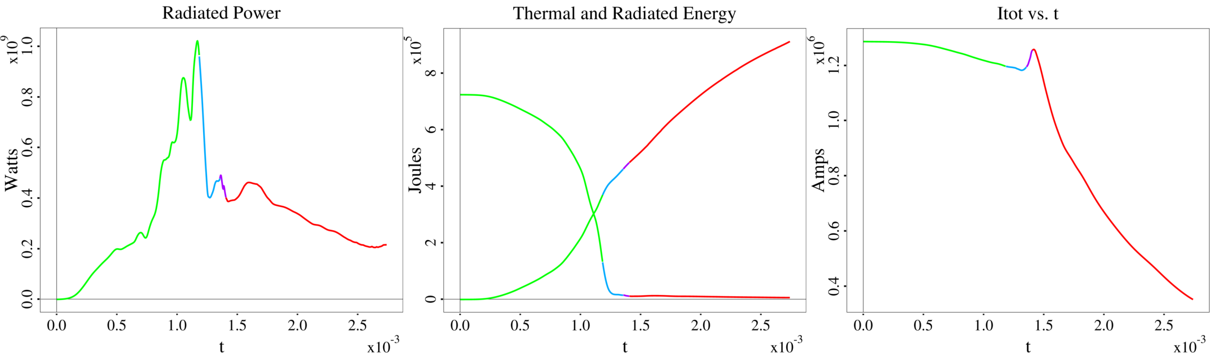
Simultaneous Symmetric Multi-Injector SPI





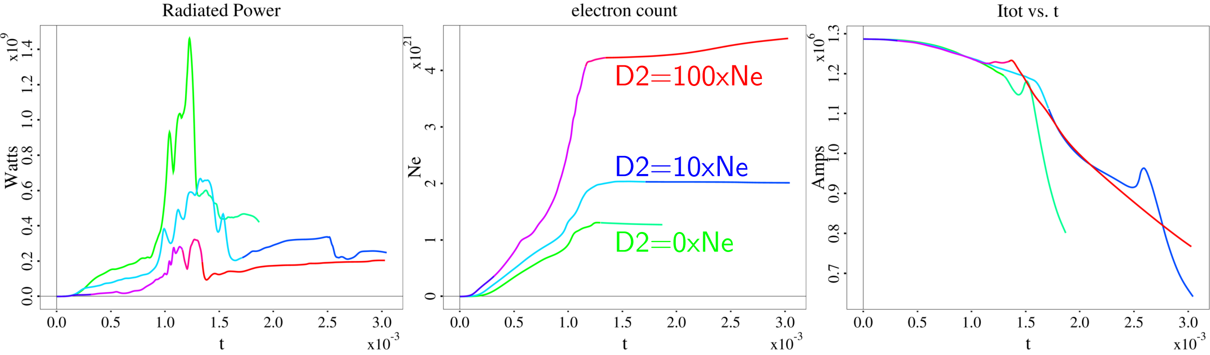
- energy spectrum shows symmetric mode separation early on
- nonlinear mixing as fragment penetrates core / core collapse (t≃1.2ms)
  - narrower deposition increases nonlinear mixing (recall APS19/CTTS presentation)
- n=1 emerges as dominant mode despite initial symmetry
  - tri-injector peak order of magnitude smaller than dual injector
- *toroidal resolution marginal - spikey structure in high-n, late in dual*

120' Dual Injector SPI



- r_{frag}=0.2mm , dϕ=0.10, visc=250m/s^2, 400 fragments
- τ_{TQ}=1.218ms, radiation fraction 58%, t^{spike}=1.418ms
- any finite delay reverts to single injector
  - thermal quench simulations require initial plasma rotation?
- *each color represents 48hr on 704 Cori/Haswell ~140K cpuhrs*
  - *resolving quench to current spike is computationally most expensive*

D2 Scan

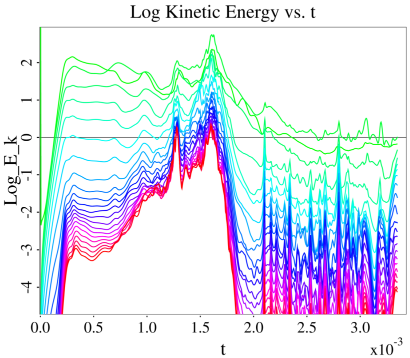


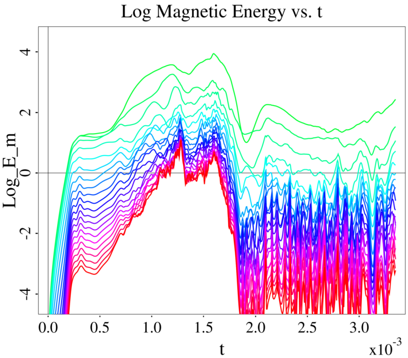
- $d\phi$=0.10, visc=250m/s^2, D2=[0x,10x,100x]Ne
- τ_{TQ}=[1.27,1.57,1.35]ms, radiation fraction [58,50,14]%, t^{spike}=[1.51,2.61,1.38]ms
  - current spike significantly delayed for D2=10xNe
  - D2=100xNe has a 'softened/gentler' current spike
  - analysis continues

Summary and Conclusions

- lower viscosity → shorter thermal quench time due to stronger linear response
  - faster growth rates and earlier saturation
  - saturation amplitude may vary outside of trend
    - peak radiated power and radiation fraction also vary
  - also has impacts current quench and runaway dynamics
- dϕ=0.05 looks "converged" but close to toroidal reolution limit
  - computation more challenging and costly
  - use dϕ=0.10 as standard
- more energetic plasmas are more even more challenging
  - 137611@01950ms : TE=1.05MJ, ME=62.2MJ, I=1.46MA
  - DIII-D SuperH : TE=2.23MJ, ME=62.2MJ, I=1.56MA
  - JET, KSTAR, ITER
- *relativistic drift kinetic equations implemented for hybrid kinetic-MHD model in NIMROD*
  - *continuing development and benchmark against MARS results*
  - *coordinating with M3D for a benchmark*
  - *working with CQL3D to couple codes and benchmark*

Viscosity=$100m^2/s$, $d\phi = 0.05$, τ_{TQ}=1.316ms





- late high-n spikes are typical
  - probable culprit in numeric terminations
  - worse for higher energy density equilibria
- *toroidal resolution marginal*