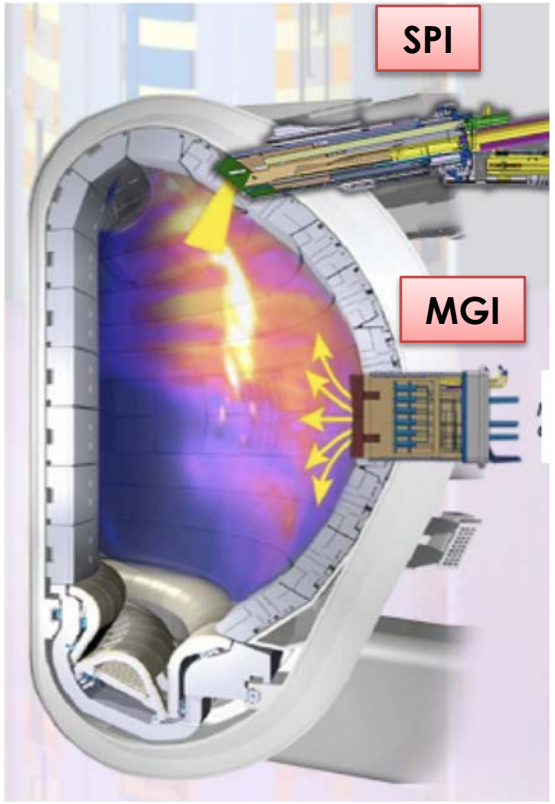
GA CTTS Project: Status and Plan and Related SCREAM and Other Research Activities

L.L. Lao[1] for the GA CTTS and SCREAM Teams and Collaborators*

CTTS APS Meeting
Fort Lauderdale, Florida

October 20, 2019



***GA CTTS and SCREAM Teams plus Collaborators:**

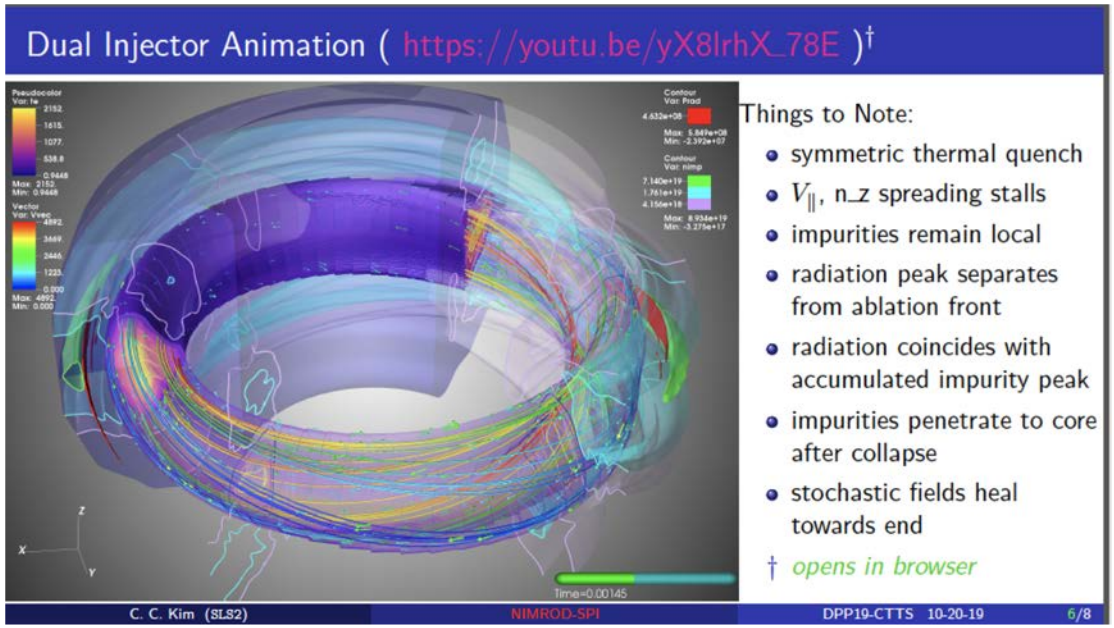
R.W. Harvey[2], V.A. Izzo[3], C.C. Kim[4], Y.Q. Liu[1], B.C. Lyons[1], J.T. McClenaghan[1], P.B. Parks[1], C. Paz-Soldan[1], Y.V. Petrov[2]

L. Baylor[5], N. Bosviel[6], D.P. Brennan[7], N.W. Eidietis[1], N.M. Ferraro[8], J. Herfindal[5], E. Hollmann[9], I. Lvovskiy[10], S.C. Jardin[8], M. Lehnen[11], A. Loarte[11], R. Samulyak[6], D. Shiraki[5]

[1]General Atomics
[2]CompX
[3]Fiat Lux
[4]SLS2 Consulting
[5]Oak Ridge National Laboratory
[6]Stony Brook University
[7]Princeton University
[8]Princeton Plasma Physics Laboratory
[9]UCSD
[10]ORAU
[11]ITER Organization

Outline

- CTTS progress since the last APS meeting
- Related SCREAM and other research activities
  - Effects of MHD instabilities and RMP on runaway electrons
  - Equilibrium reconstructions of DIII-D plasmas during disruption: VDE, SPI, and ShPI
  - Recent NIMROD Shell pellet studies



Significant Progress Made toward CTTS Disruption Mitigation Goals Since the Last APS Meeting

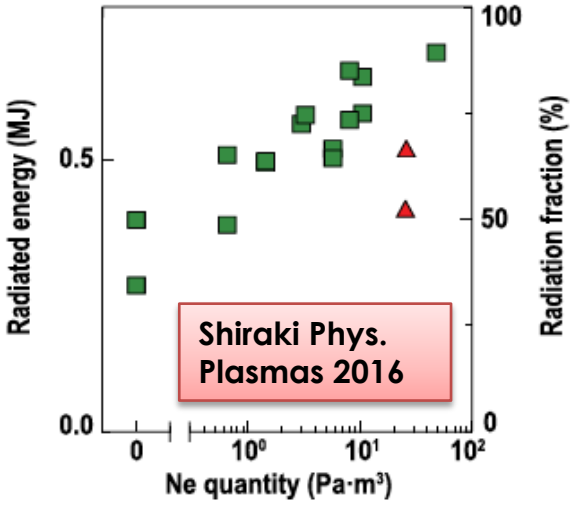
- Improved numerical treatments and began NIMROD multiple-injector SPI simulations that demonstrate the benefits of multiple injectors
  - Significantly reducing the *n*=1 dominance displayed in single injectors, and resulting in a more benign thermal quench
- Improved and began M3D-C1 modeling of pellet injection in DIII-D for validation with the experiment and verification with NIMROD.
- Developed a set of iteration algorithms to test multi-scale integration of local Lagrangian Particle code LP with global NIMROD and M3D-C1
  - Hold a summer code camp in San Diego
  - First-step data transfer between LP and NIMROD and M3D-C1 accomplished
- Continued development of a kinetic pellet plasma cooling model for use with NIMROD and M3D-C1
  - New analytical pellet ablation model with toroidal magnetic dependence based on Frontier simulations.

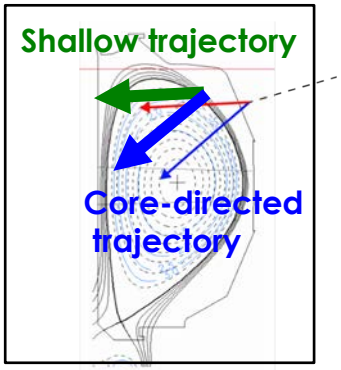
CTTS Disruption Mitigation Modeling

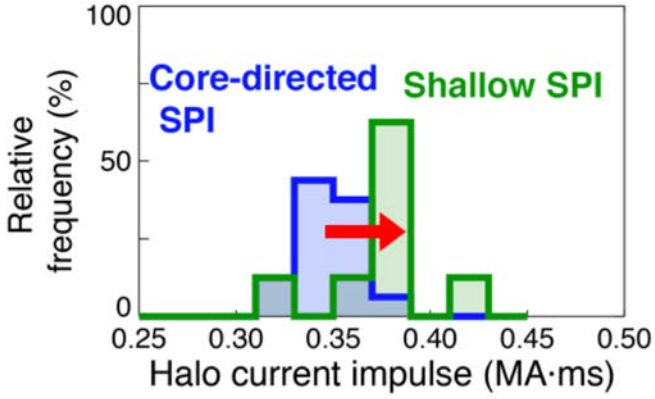
DIII-D SPI Experiments Modeling Needs (2017 CTTS Kickoff)

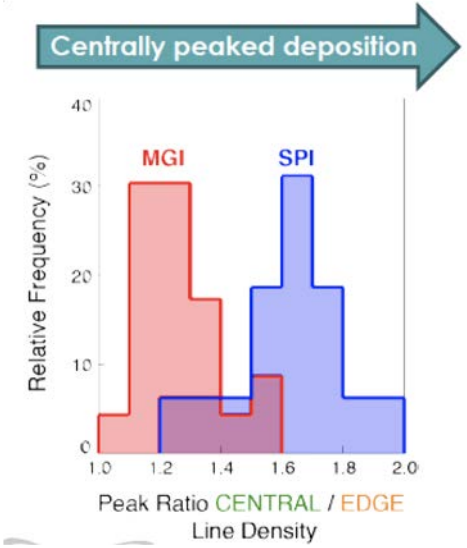
Eidietis 2017 CTTS Kickoff

- **Variation in SPI radiated energy with Ne quantity**
  - **Ne/D_2 mixture, total pellet size constant**
- **Variation in SPI assimilation with injection angle**
  - **Relative strength of ballistic versus MHD mixing**
- **Interpretation of dual SPI experiments**
  - **Multiple pellets appear to not sum directly**









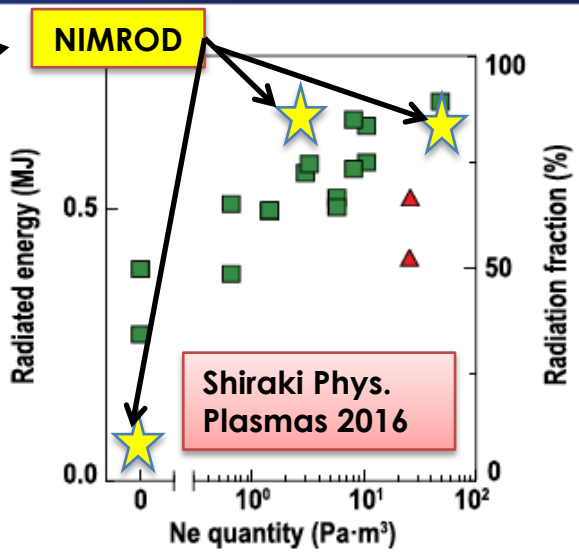
CTTS Disruption Mitigation Modeling

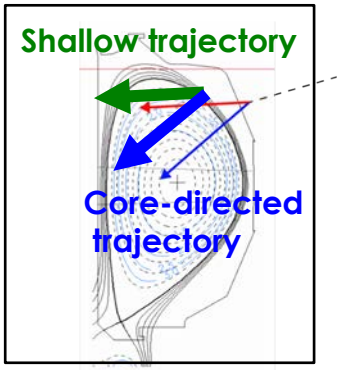
DIII-D SPI Experiments Modeling Needs (2017 CTTS Kickoff)

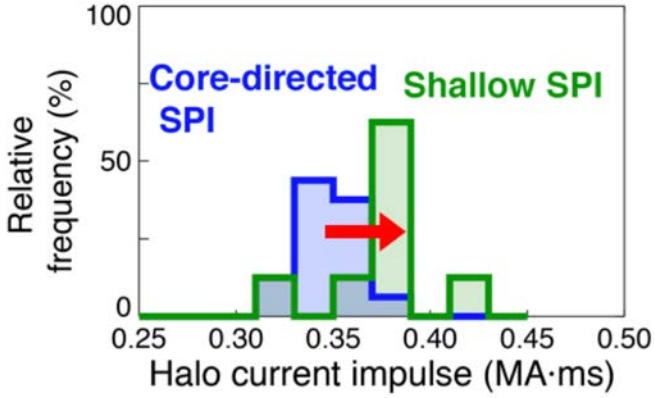
Eidietis 2017 CTTS Kickoff

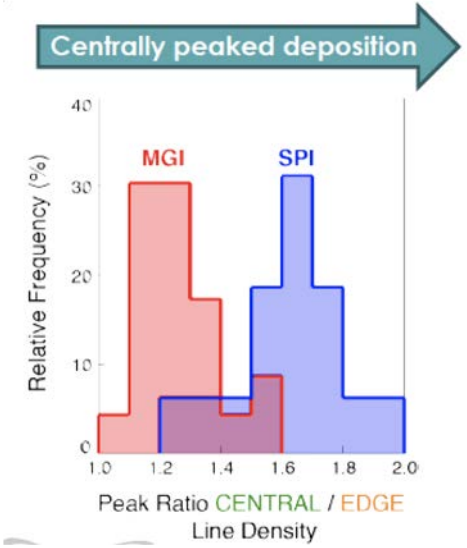
Kim 2018 APS Invited
Phys Plasmas 2019

- **Variation in SPI radiated energy with Ne quantity**
  - **Ne/D_2 mixture, total pellet size constant**
- **Variation in SPI assimilation with injection angle**
  - **Relative strength of ballistic versus MHD mixing**
- **Interpretation of dual SPI experiments**
  - **Multiple pellets appear to not sum directly**









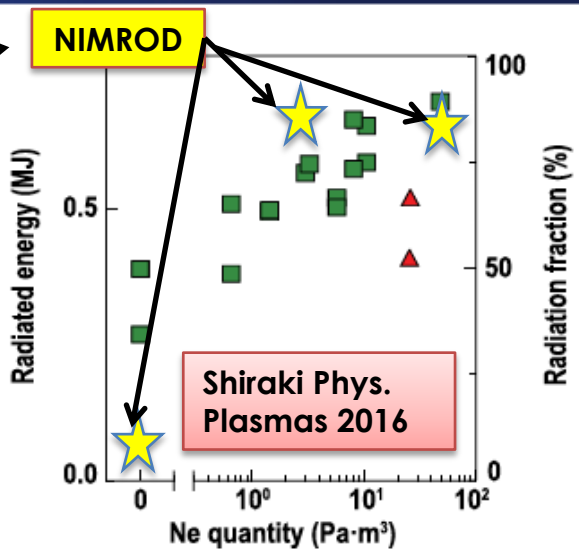
CTTS Disruption Mitigation Modeling

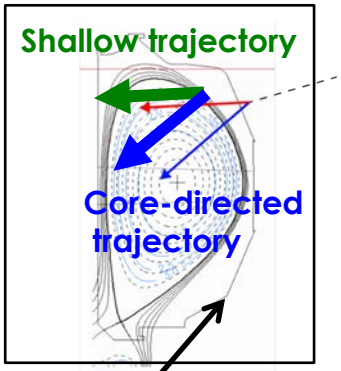
DIII-D SPI Experiments Modeling Needs (2017 CTTS Kickoff)

Eidietis 2017 CTTS Kickoff

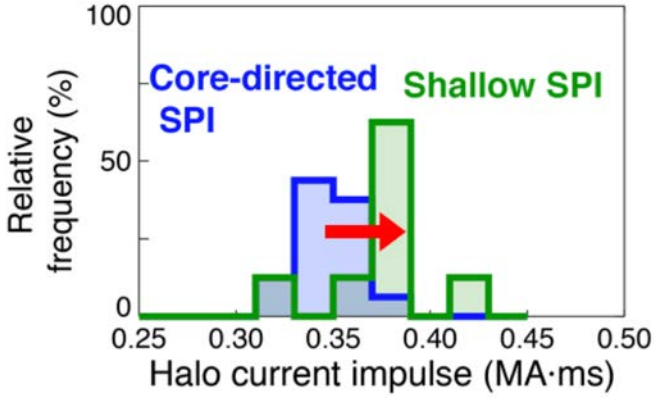
Kim 2018 APS Invited Phys Plasmas 2019

- **Variation in SPI radiated energy with Ne quantity**
  - **Ne/D_2 mixture, total pellet size constant**
- **Variation in SPI assimilation with injection angle**
  - **Relative strength of ballistic versus MHD mixing**
- **Interpretation of dual SPI experiments**
  - **Multiple pellets appear to not sum directly**



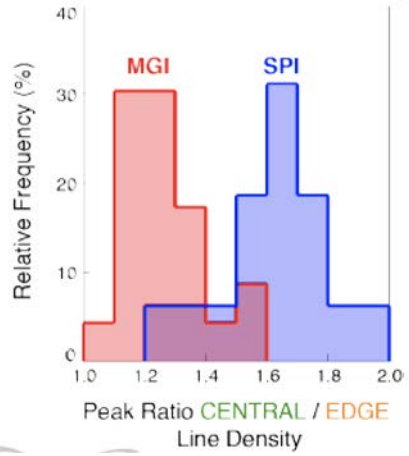


NIMROD Multiple SPI Simulations



Herfindal APS DIII-D Oral Tuesday Afternoon

Centrally peaked deposition



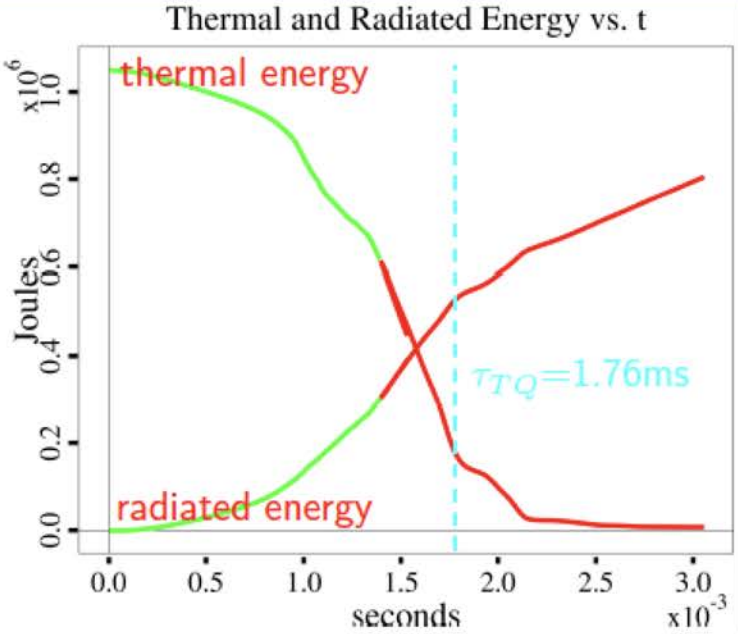
NIMROD Numerical Treatments Has Been Significantly improved To Allow More Robust and Accurate SPI Simulations: Multi-Injectors

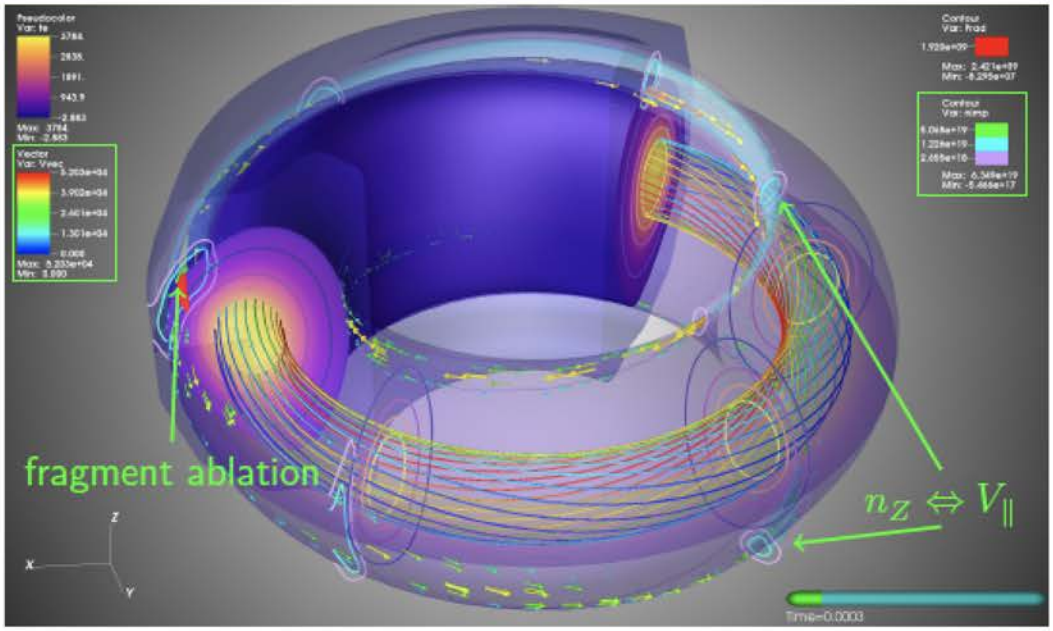
Improved Numeric Parameters - Less Reliant on Dissipation

- higher resolution: `poly_degree`=3 n=[0,21] (`mx`,`my`)=[72x96 - 128x128]
  - more local deposition for ablated neutral impurities: r_d=5.0cm $\Delta\phi$=0.05($\times 2\pi$)
- modest density diffusion (`nd_diff`=5 m^2/s , nz_diff=10 m^2/s)
  - separate diffusion coefficients for background ions and impurities
- more reasonable viscosity (`iso_visc`~100 m^2/s , `par_visc`~1000 m^2/s)
- Spitzer resistivity (`elecd`=$[0.1, 1.0 \times 10^5]$, S~ $[10 - 10^7]$)
- fixed thermal conduction parameters: $\chi_{\parallel} = 1 - 5 \times 10^9$ m^2/s $\quad \chi_{\perp} = 0.2 - 0.5$ m^2/s
  - temperature dependent χ may be important for current quench
- reduced perpendicular thermal conduction ($\chi_{\perp}$) improves robustness of simulations
  - initially plagued by large amplitude tearing modes ⇒ lots of 3D-ness, unstable computation
  - maintaining higher T (low `elecd`) keeps modes small ⇒ less 3D-ness, more stable
- T_floor=0.5-2 eV, turn off radiation/impurity at T_off=T_floor+few eV's=1-5eV
  - **current quench sensitive to T_off!!!**
- increase thermal diffusion for T<T_floor, prevent T<0
- more robust SPI simulations ⇒ better success continuing into current quench
  - *progress handicapped by slow NERSC turnaround*

NIMROD DIII-D Single-Injector SPI Simulation: Early Phase

Single Injector Monolithic Neon Fragment #137611.01950 @t=0.3ms

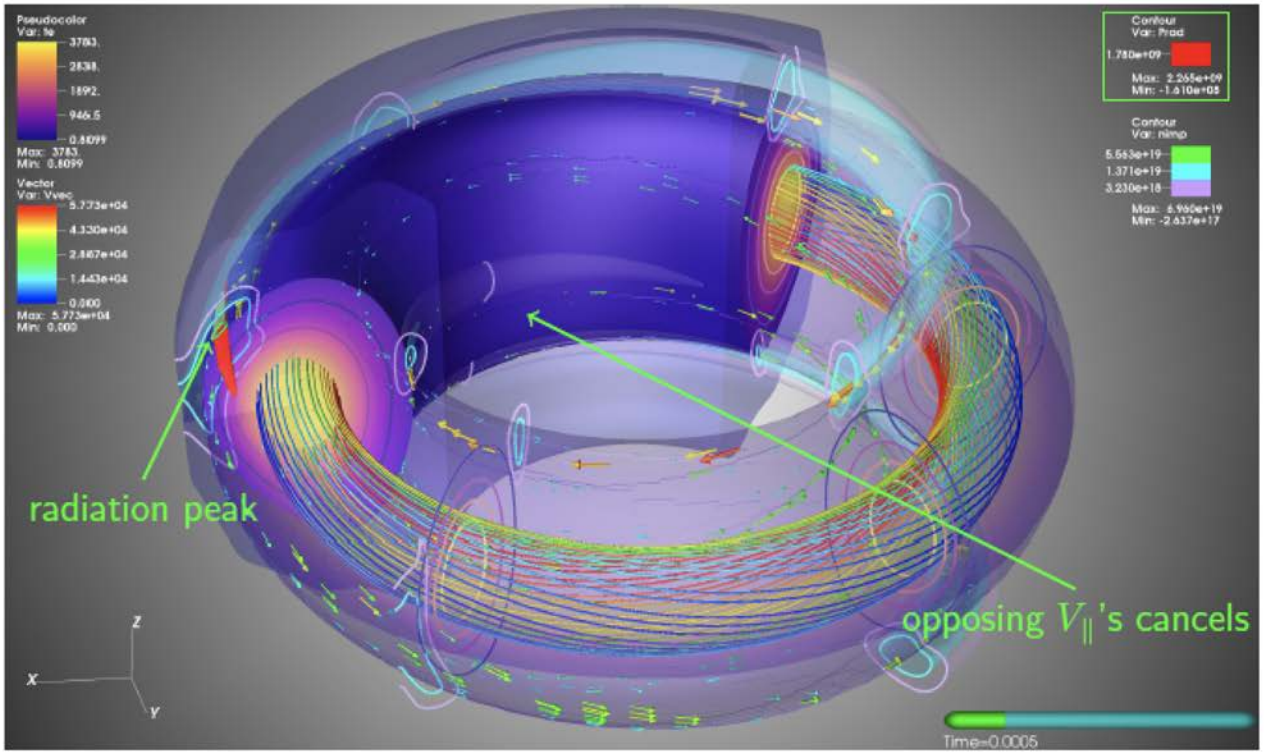




- visualization shows dominant $V_{\parallel}$(MAX$\sim 5\times10^4$m/s) mechanism of impurity spreading
  - bright early radiation ($\simeq$2GW/m^2) coincident with ablation front (peak $n_z^{tot} \simeq 5\times10^{19}$)
- thermal quench τ_{TQ}=1.76ms (@max n_e), radiation fraction$\simeq$60%
  - unclear if this is typical for single injector monolithic fragment or particular to equilibrium

NIMROD DIII-D Single-Injector SPI Simulation: Intermediate Phase

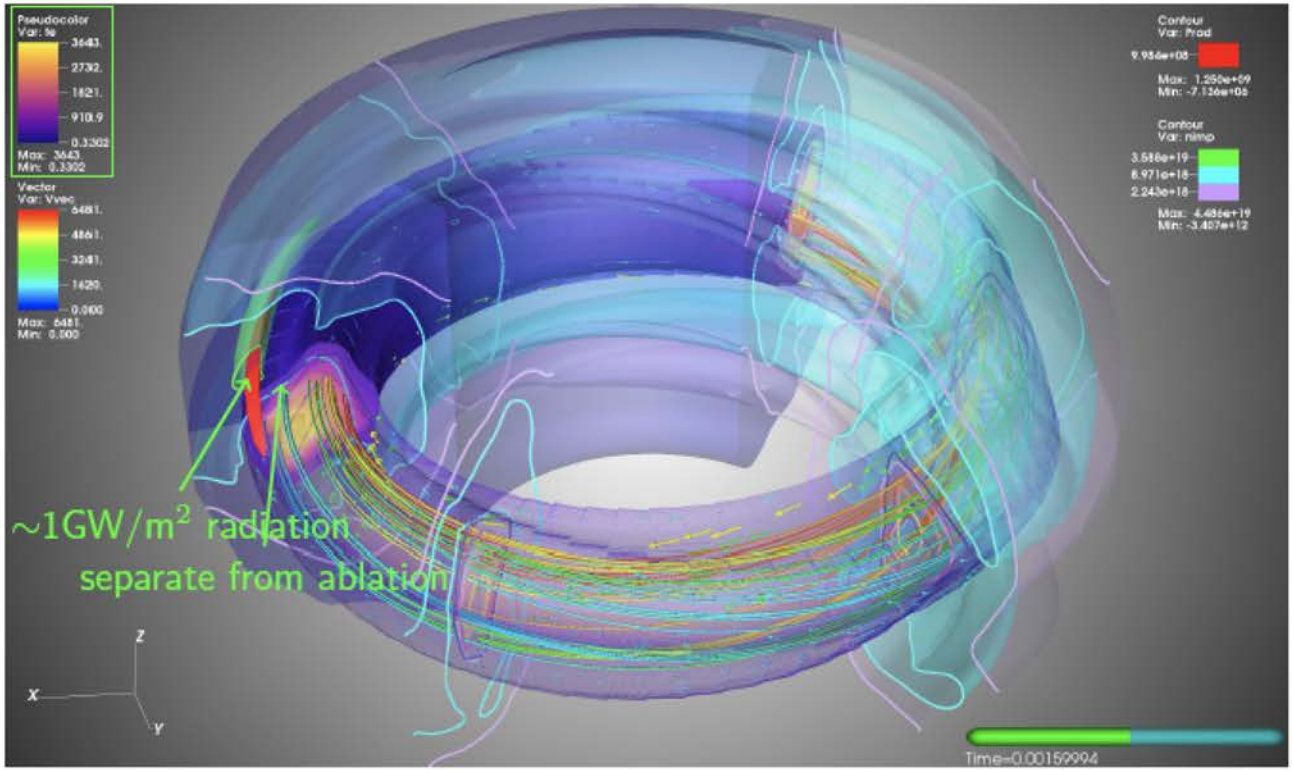
Single Injector Monolithic Neon Fragment #137611.01950 @t=0.5ms



- radiation is coincident with ablation front
- n_z ϕ-spreading stalls
  - plume meets tail
  - opposing $V_\parallel$'s cancel
- n_z remains localized
- *clumps of impurity contours at each toroidal slice*

NIMROD DIII-D Single-Injector SPI Simulation: Later Phase

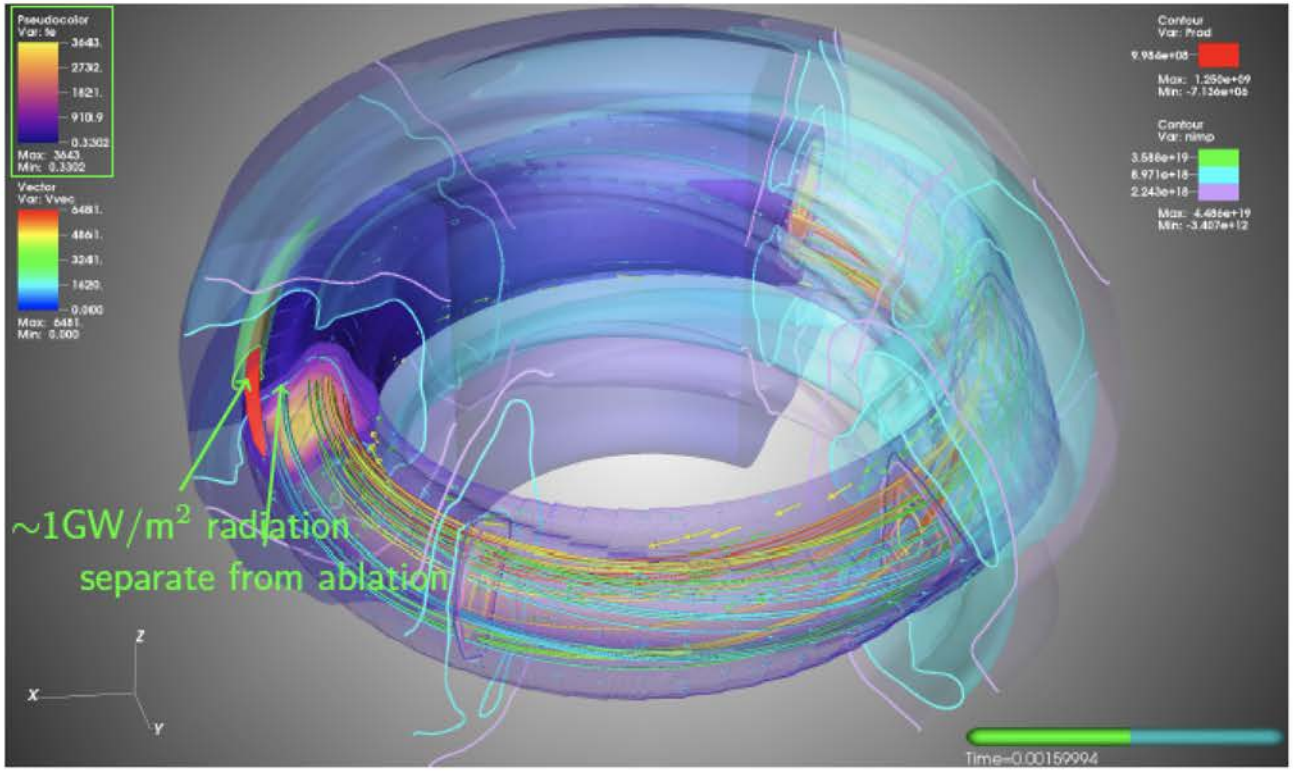
Single Injector Monolithic Neon Fragment #137611.01950 @t=1.60ms



- radiation peak separate from ablation front
- core temperature beginning to drop
- n_z retains localization near injector
  - poloidal spreading
  - reduced $V_{\|}$
- distorted field lines indicate flux surface motion→stochastization

NIMROD DIII-D Single-Injector SPI Simulation: Final Phase

Single Injector Monolithic Neon Fragment #137611.01950 @t=1.60ms

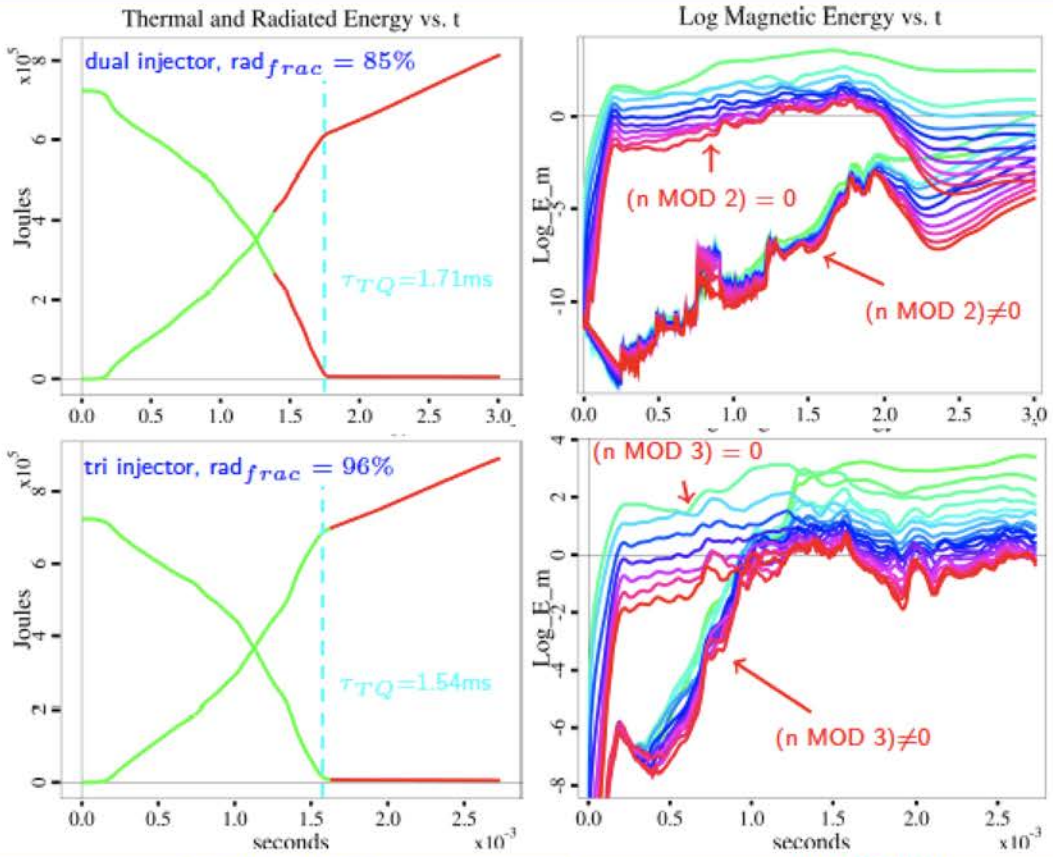


- radiation peak separate from ablation front
- core temperature beginning to drop
- n_z retains localization near injector
  - poloidal spreading
  - reduced $V_{\|}$
- distorted field lines indicate flux surface motion→stochastization

C. C. Kim (SLS2) NIMROD-SPI DPP19-CTTS 10-20-19 4/8

NIMROD DIII-D Dual-Injector SPI Simulation

Simultaneous Symmetric Multi- Midplane Injectors - shot#160606.02990

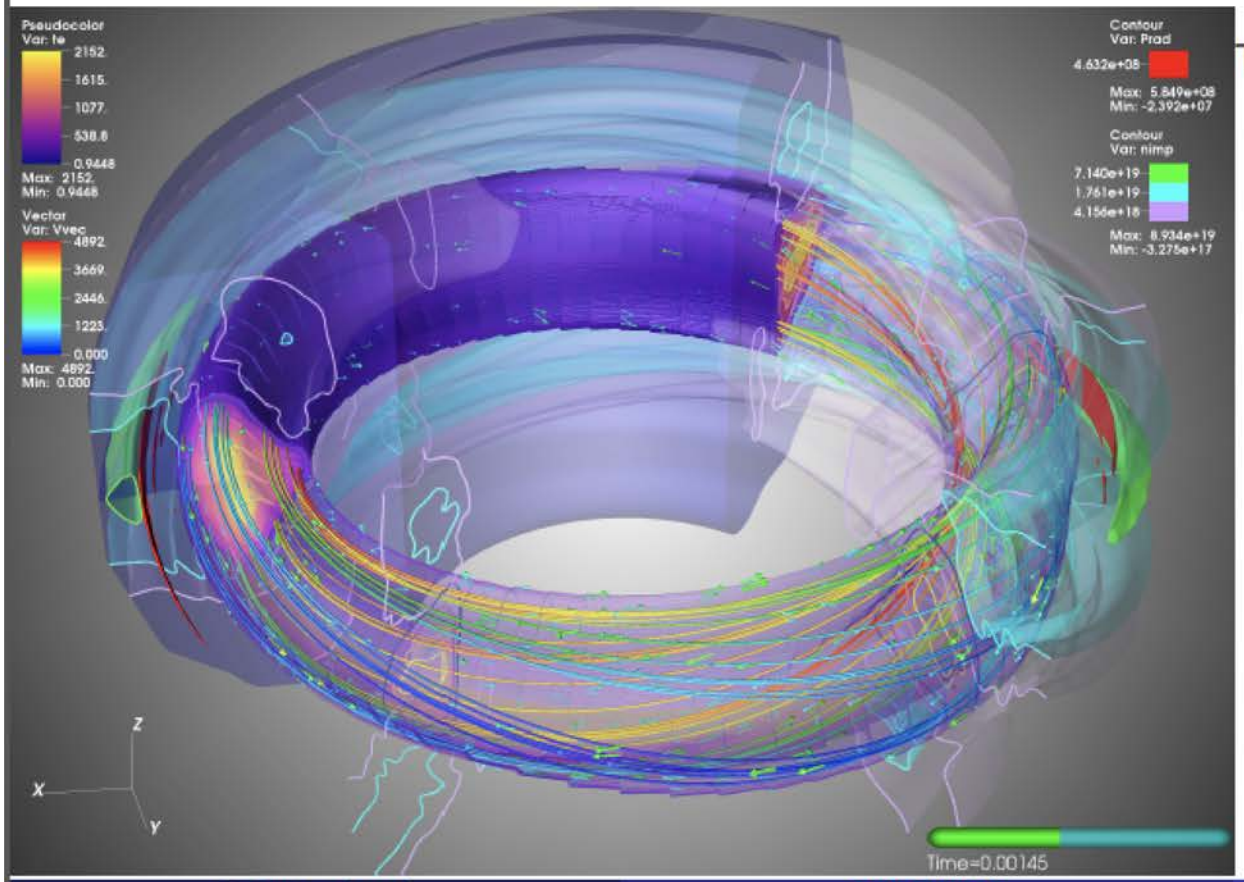


- dual (180' separation) and tri-(120' separation) injectors produce quiescent thermal quench: rad$_{frac}$=(85%,96%)
- symmetric injection precludes n=1 (single injector)
- nice numeric experiment; verification of implementation symmetry of deposition, radiation and ionization
- simultaneous timing may be difficult to realize
- sensitivity to time delay between injectors is being studied

C. C. Kim (SLS2) NIMROD-SPI DPP19-CTTS 10-20-19 5/8

NIMROD DIII-D Dual-Injector SPI Simulation: Animation

Dual Injector Animation (https://youtu.be/yX8lrhX_78E)†



Things to Note:

- symmetric thermal quench
- $V_{\|}$, n_z spreading stalls
- impurities remain local
- radiation peak separates from ablation front
- radiation coincides with accumulated impurity peak
- impurities penetrate to core after collapse
- stochastic fields heal towards end

† *opens in browser*

C. C. Kim (SLS2) NIMROD-SPI DPP19-CTTS 10-20-19 6/8

NIMROD SPI Simulations: Discussions

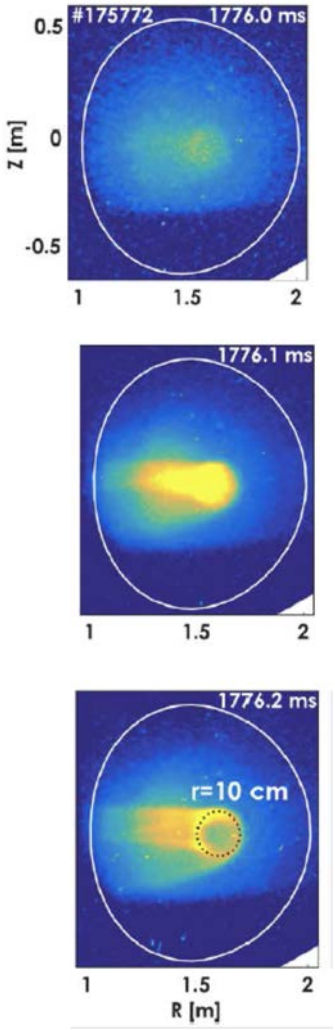
Preliminary Observations and Continuing Studies

- multiple SPI scenarios demonstrate $V_{\|}$ dominant mechanism to impurity spreading
  - impurities remain field aligned and localized near injector
  - spreading stalls when plume encounters counter flow from other end
  - deeper mixing into magnetic axis requires core collapse and associated MHD
- late radiation spikes occur in remnant impurity plumes away from fragment and hot core
  - escaping heat reionizes impurities that intersect open/stochastic field lines
  - toroidal peaking of radiation due to local maxima of impurities
  - ?MGI after SPI for more volumetric fill $\Rightarrow$ more symmetric radiation?
- multi-injector SPI simulations demonstrate benefit of simultaneous injection
  - simultaneous symmetric dual and tri- injectors show reduced mode activity
  - maybe difficult to realize necessary accuracy of timing
- ongoing study of different SPI scenarios
  - time delayed multi-injector scenarios
  - JET and KSTAR
  - extend simulations through current quench (+PiC RE's) and connect to *SCREAM*

Related GA SCREAM Research Activities

- **Implemented a new drift RE orbit modeling tool into MARS-F and successfully tested against Argon-initiated DIII-D post-disruption RE experiments.**
  - **Full loss of RE current when 3D perturbed field reaches ~ 1kG level consistent with experiment.**
- **Started integration of NIMROD with the CQL3D 3D Fokker-Planck code to investigate effects of MHD turbulence on RE dynamics**
  - **Demonstrated initial file-based coupling and presented results at 2018 IAEA FEC**
- **Started development and implementation of PiC-based RE model in NIMROD**
  - **Based on the NIMNROD hybrid kinetic MHD model used for energetic ion simulation**

DIII-D Post-Disruption RE Beam Relaxation Lvovskiy APS ITER Oral Wed Afternoon



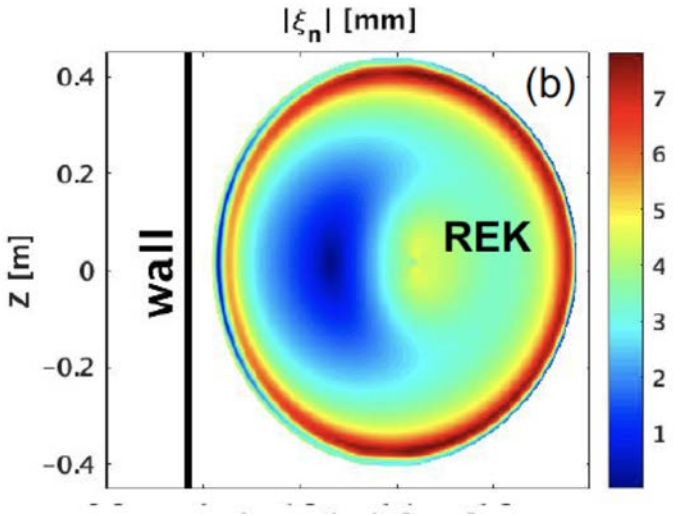
A New RE Drift-Orbit Modeling Tool Has Been Implemented into MARS-F and Tested against DIII-D RE Experiments

- **MARS-F guiding-center orbit equations**

$$\frac{ds}{dt} = \mathbf{v}\cdot\nabla s,$$
$$\frac{d\chi}{dt} = \mathbf{v}\cdot\nabla \chi,$$
$$\frac{d\phi}{dt} = \mathbf{v}\cdot\nabla \phi,$$
$$\tau_c \frac{dp}{dt} = \mu E - \left(1+\frac{1}{p^2}\right) - \frac{\lambda p \gamma b}{\tau} - F_B,$$
$$\tau_c \frac{d\lambda}{dt} = -\frac{2\mu\lambda E}{p} + \frac{2\mu^2\gamma}{bp^3}(1+Z) - \frac{2\lambda\mu^2}{\tau\gamma},$$

Synchrotron Radiation

Computed MARS-F Resistive Kink Mode for a DIII-D RE Experimental Equilibrium

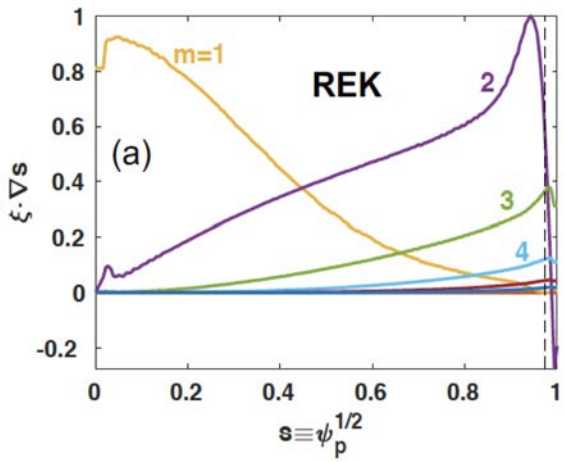


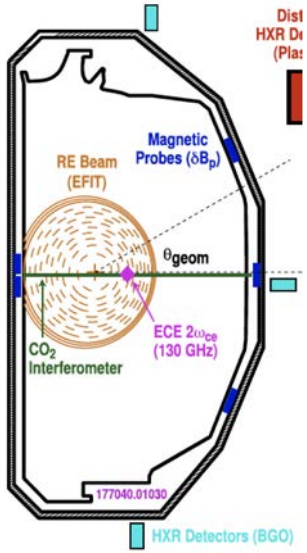
- **Modeling results consistent with DIII-D Argon-initiated post disruption RE experiments**
  - **Full loss of RE beam when the resistive kink mode amplitude reaches ~ 1kG**
  - **Mode becomes internal at higher q**

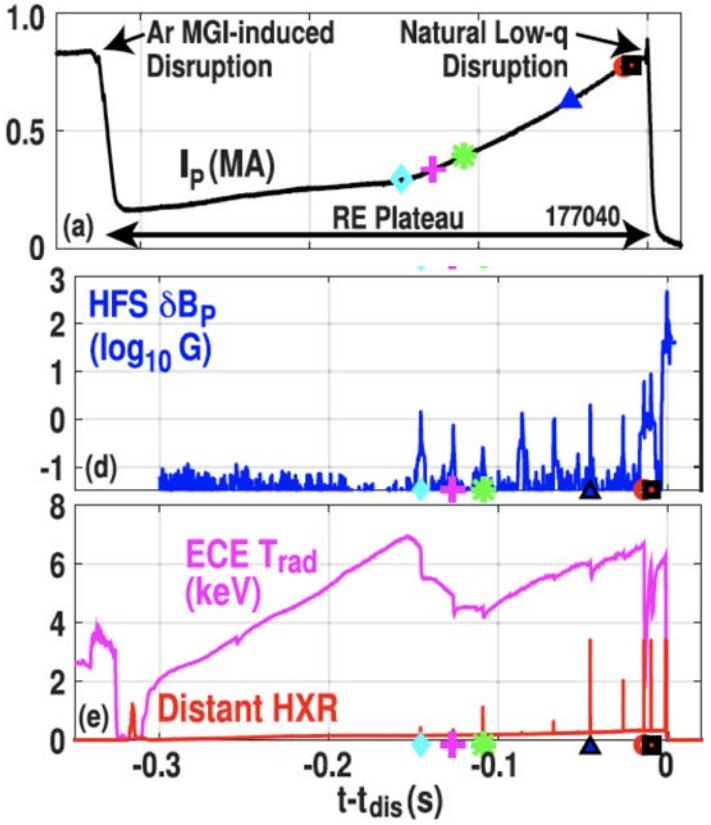
Y.Q. Liu, Nuclear Fusion 2019
APS Invited Wed Morning

MARS-F Simulations Consistent with DIII-D Post-Disruption RE Experiments

- **Full loss of RE beam when the resistive kink mode amplitude reaches ~ 1kG**

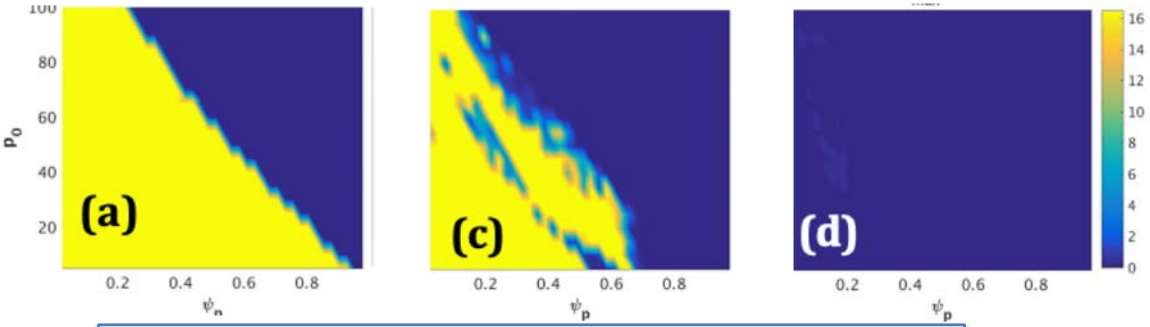






Paz-Soldan PPCF **61** (2019)
APS DIII-D Oral Tuesday Afternoon

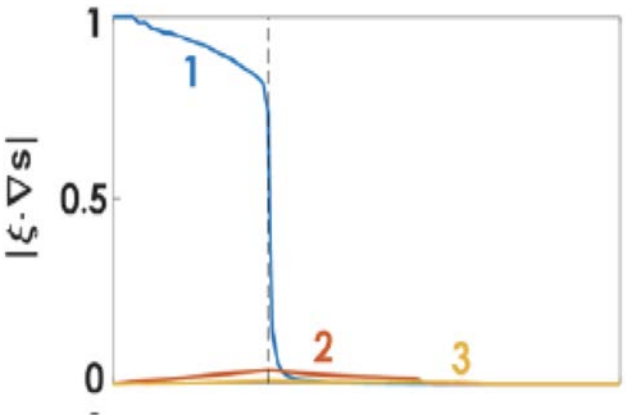
δB= 0 | δB= 200G | δB= 1kG

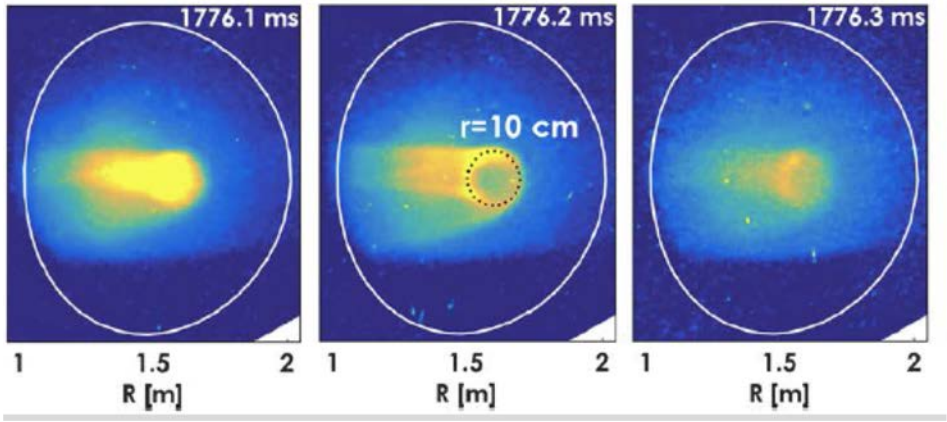


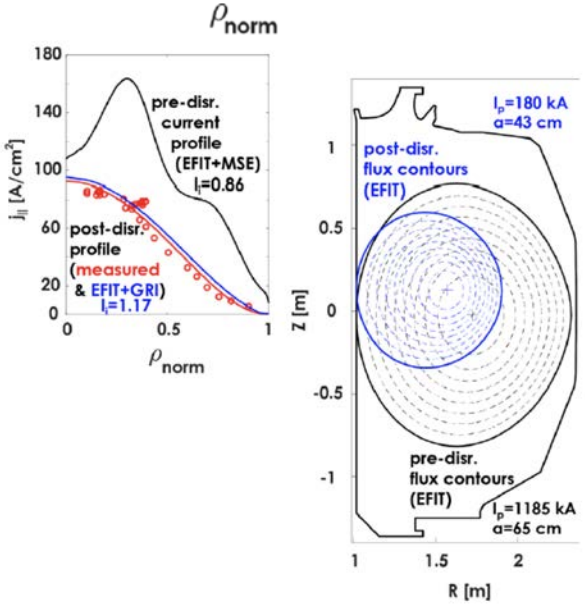
Y.Q. Liu Nuclear Fusion 2019, APS Invited Wed

MARS-F Simulations Consistent with DIII-D Post-Disruption RE Experiments

- **Resistive kink mode becomes internal at high q**







DIII-D #175768

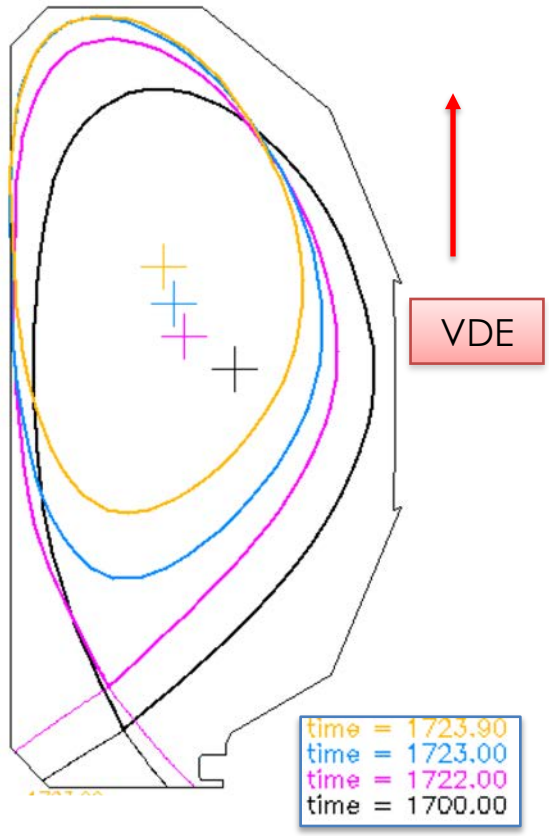
Lvovskiy APS ITER Oral Wed Afternoon

EFIT Reconstruction with GRI

Equilibrium Reconstructions of DIII-D Plasmas during Disruption: VDE, SPI, and ShPI

- **Poloidal halo attached currents play an important in the VDE dynamics**
- **During the early current quench phases, the Plasmas stay nearly axisymmetric as halo attached current starts to flow poloidally**
- **As the current further decays, plasma continues to shrink and could become vertically unstable and start drifting**
- **3D effects becomes increasingly more important during the thermal or the subsequent current quench phase**

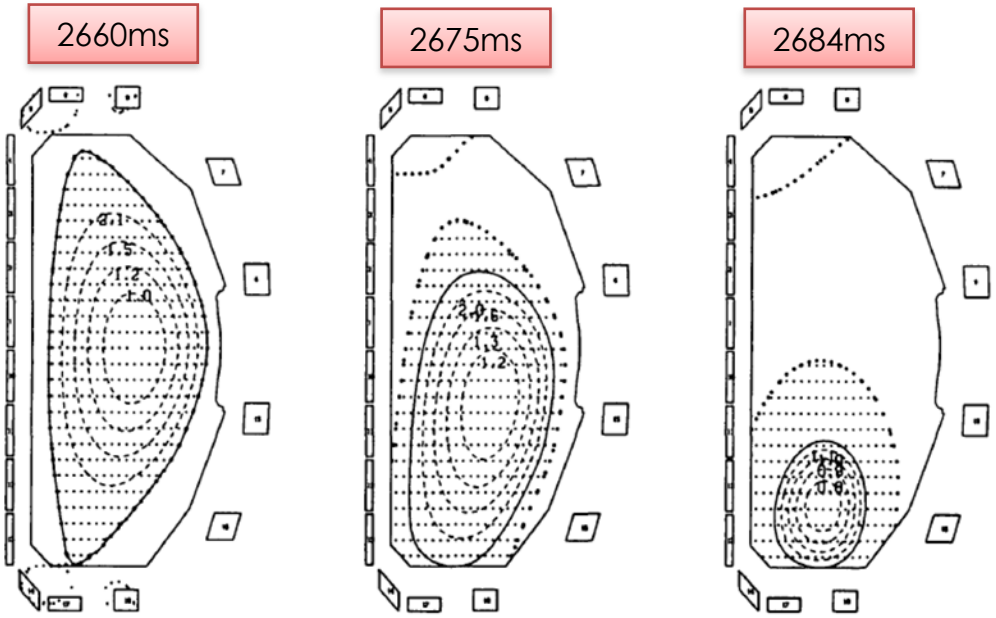
DIII-D 88806 Neon Pellet Mitigated VDE Discharge

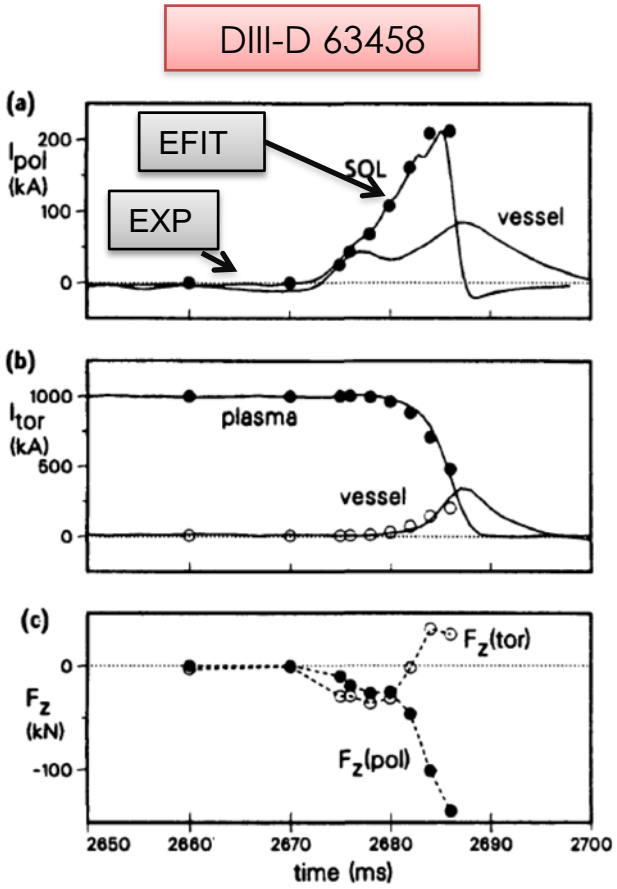


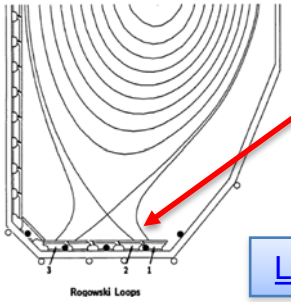
Lao APS DIII-D Poster Monday Morning

EFIT Reconstruction Results Based on the Force-Free Halo Current Model Are Consistent with DIII-D VDE Experiments

- VDE induced by increasing elongation to ~ 2.3 toward the vertical stability limit
- Similar attached currents observed in other discharges disrupted for other reasons
- Reconstructions difficult without attached halo SOL current





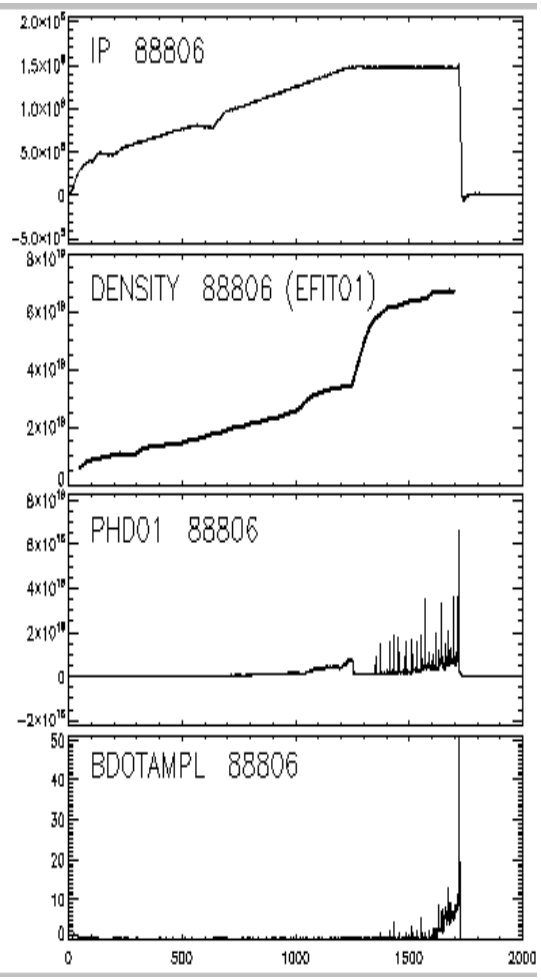


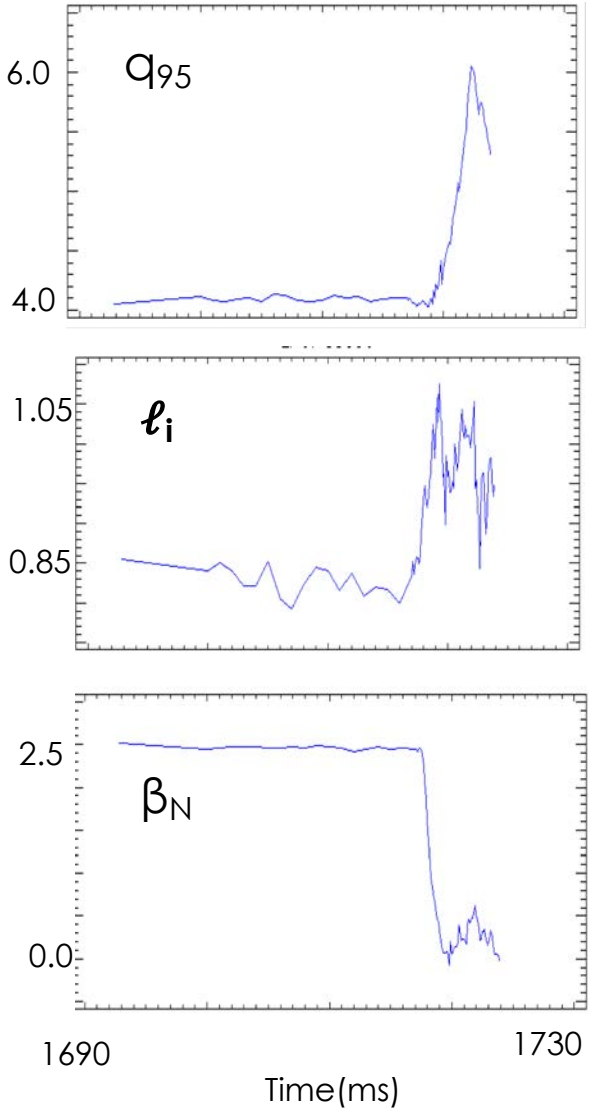
Rogowski Loops

Strait, Lao, Luxon, and Reis Nuclear Fusion 1991

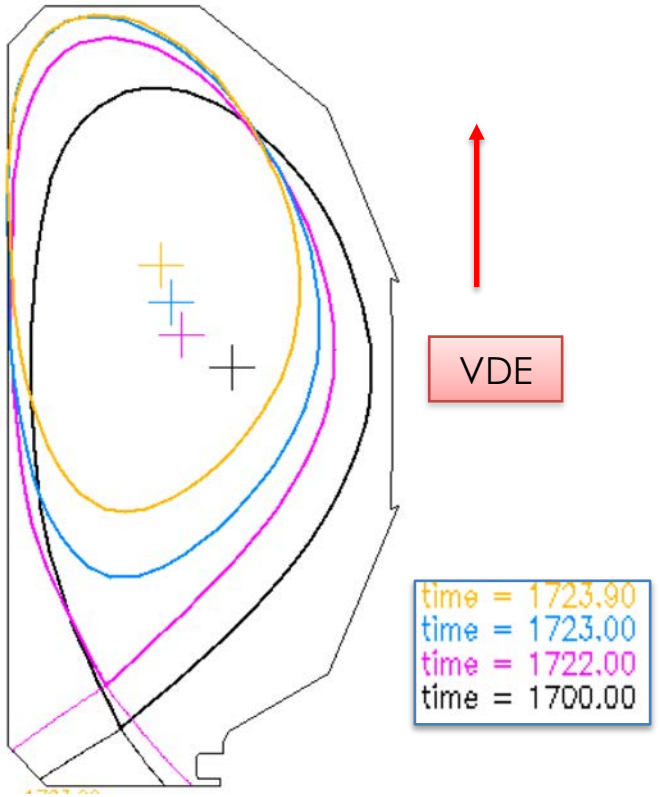
Lao and Jensen Nuclear Fusion 1991

Previous DIII-D Equilibrium Reconstructions Show a Nearly Axisymmetric VDE Sequence with increasingly Important 3D Effects



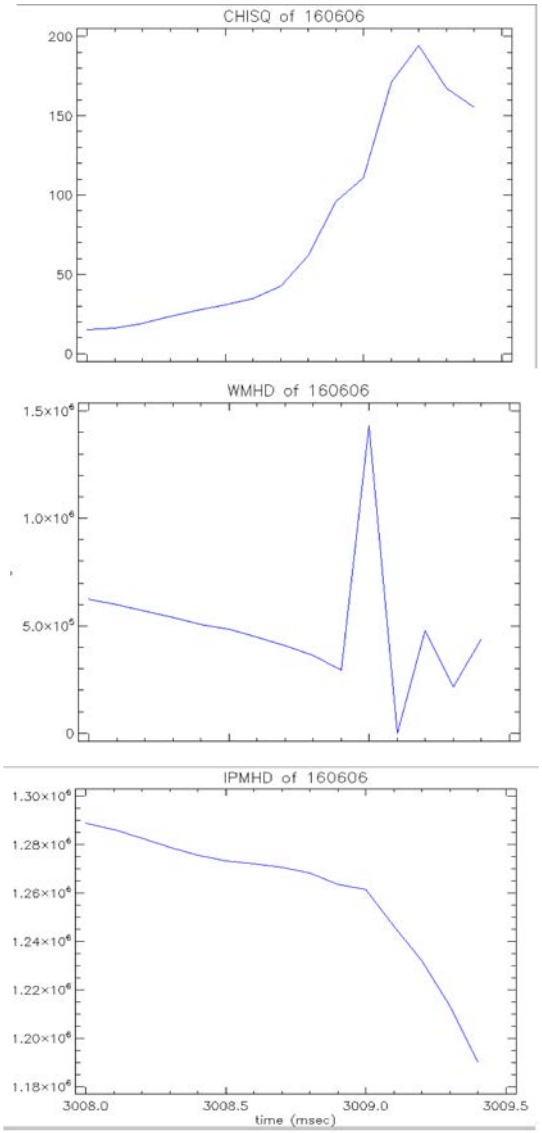


DIII-D 88806 Neon Pellet Mitigated VDE Discharge 1700-1724ms



P. Taylor Phys. Plasmas 1999

3D Effects Becomes Increasingly More Important during Early Thermal Quench in SPI Discharge

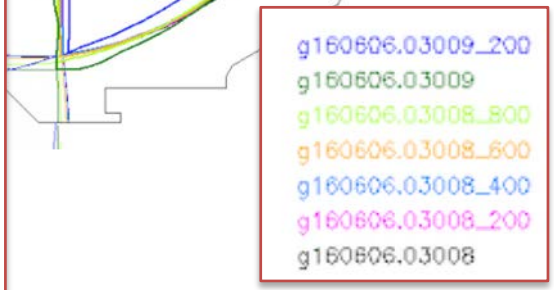


DIII-D 160606 SPI
3008.0-3009.2 ms

Time(ms) = 3008.0
χ^2 = 15.1
W = 625kJ
I_P = 1.29MA

Time(ms) = 3008.8
χ^2 = 61.7
β_N = 365kJ
I_P = 1.27MA

Early Thermal Quench μ=0



Magnetic Fitting Parameter

Measured Signals, physics constraints

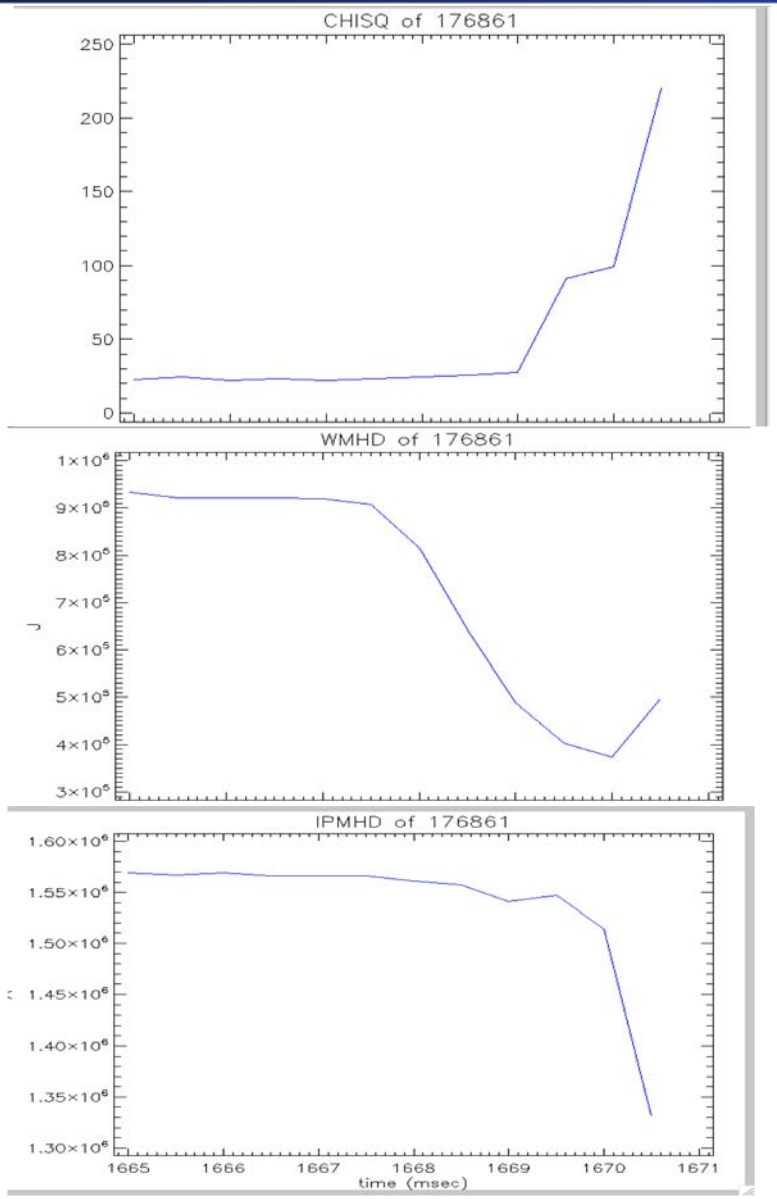
Computed Signals, Physics Constraints

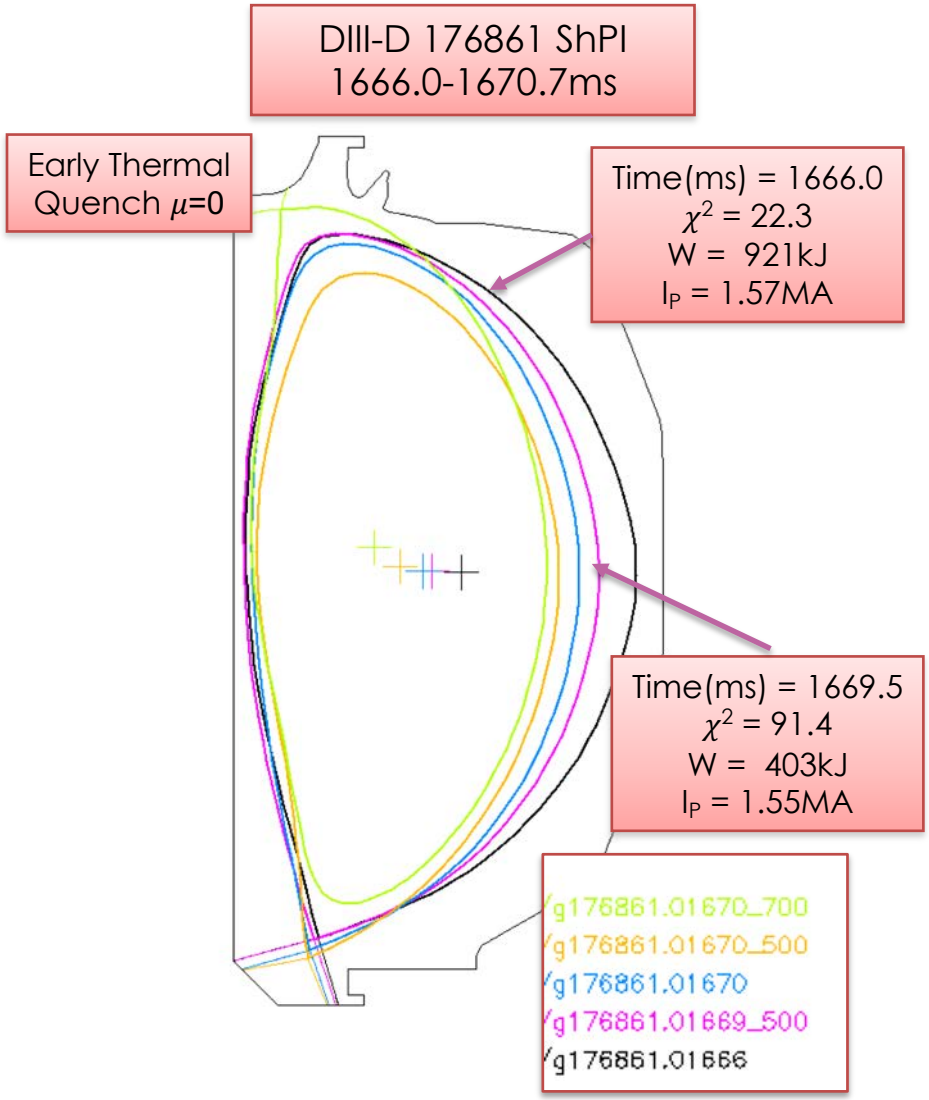
$$\chi^2 = \sum_i \left(\frac{M_i - C_i}{\sigma_i} \right)^2$$

Measurement/constraint Uncertainty

Shiraki Phys. Plasmas 2016

Shell-Pellet Mitigated Discharge Remains More Resilient during Thermal Disruption

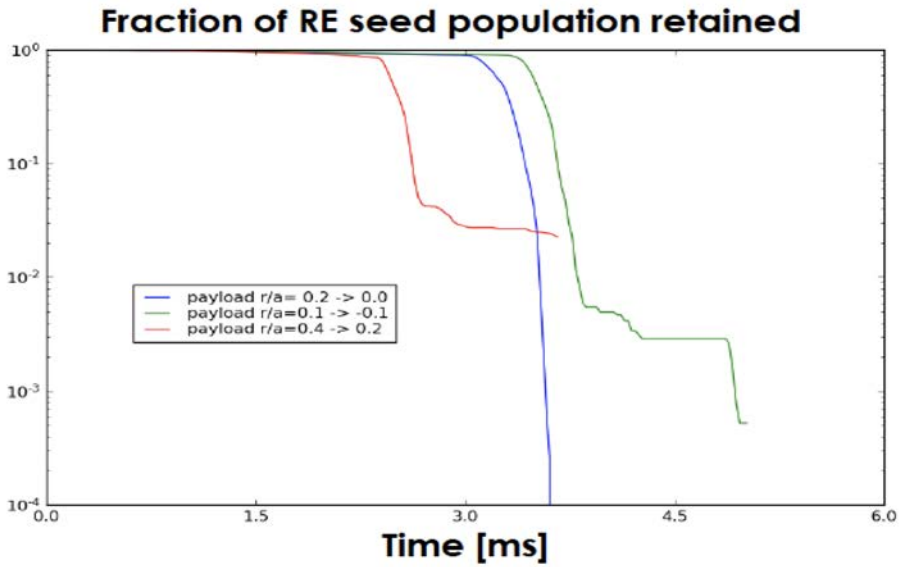




Hollmann Physical Review Letters 2019

Recent NIMROD Shell-Pellet Studies

- Simple shell pellet model in NIMROD finds ideal-like (non-perturbative) shell interaction near (just below) experimental quantities
- In simulations, significant pre-TQ Te drop is not associated with significant pre-payload loss of thermal energy
- Very small I_p spikes are seen in some cases, but further work needed to produce ~100kA spike observed
- Fast loss of runaway electrons at the end of the TQ, with variation dependent on payload delivery location



Izzo DIII-D Science 2019

GA 2019-2020 CTTS Plan and SCREAM and Other Related Research Activities

- Further develop NIMROD and M3D-C1 SPI simulation capability, validation against DIII-D experiments, and bench-markings
  - DIII-D Multi-injector SPI simulations and validation plus optimization
- Test and improve multi-scale SPI integration of local LP with global NIMROD and M3D-C1
- NIMROD and M3D-C1 JET and KSTAR SPI simulations and collaborations
- Continue development and implementation of PiC-based RE model in NIMROD
- Explore coupling algorithms to integrate NIMROD and CQL3D and test against DIII-D post-disruption RE experiments
- Upgrade NIMROD shell-pellet source model with more realistic shell ablation rates and to incorporate capability for multiple impurity species and test against DIII-D experiments
- Equilibrium reconstructions of of DIII-D plasmas during disruption: VDE, SPI, and ShPI