Tokamak Disruption Simulation (TDS) *for Mitigation Design*

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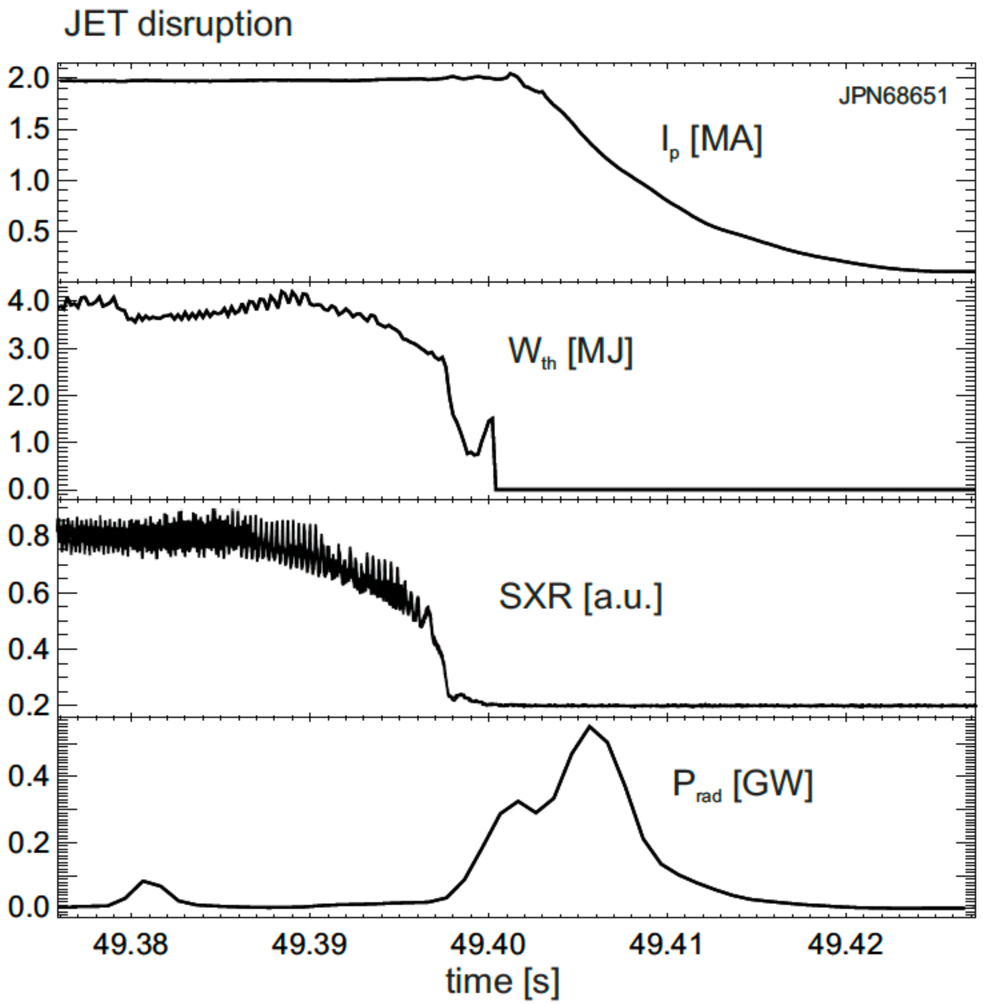
Outline

- *A primer for tokamak disruption and its mitigation*
- *Brief introduction of the Tokamak Disruption Simulation (TDS) SciDAC team and research roadmap*
  - *Programmatic and physics objectives*
  - *Physics components*
  - *ASCR components*
- *Recent advances in*
  - *Runaway avoidance and mitigation*
  - *Plasma energy and particle exhaust during thermal quench*
  - *Core plasma cooling*

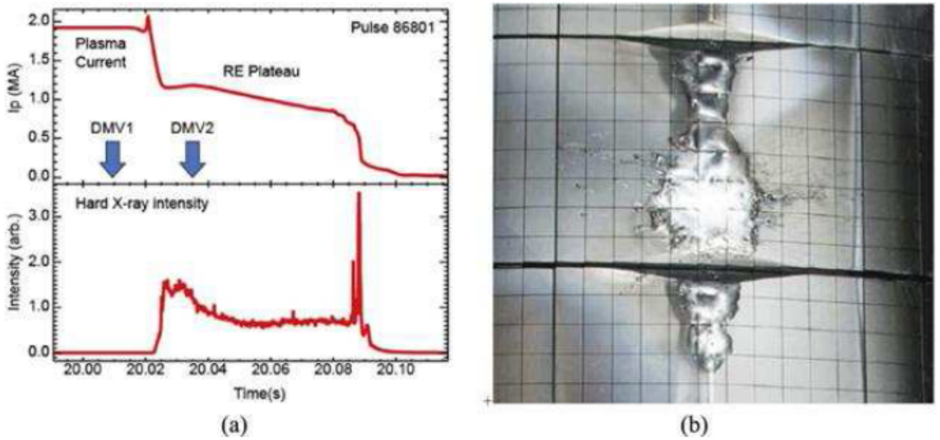
What is a tokamak disruption?



- *Disruption is a prompt termination of a plasma discharge in a tokamak.*
- *Many causes can lead to disruption, most can be prevented or have detectable precursors → active mitigation. Exceptions, even rare, must be mitigated.*
- *Two main phases:*
  - *Thermal quench → removal of plasma thermal energy*
    - *ITER: W_{th} = 200-300 MJ dumped to the divertor/first wall, in 1-2 ms*
  - *Current quench → removal of poloidal magnetic energy*
    - *ITER: W_{mag} = 395 MJ dumped to first wall, in 100-150 ms*

Thermal quench mitigation – ITER perspective

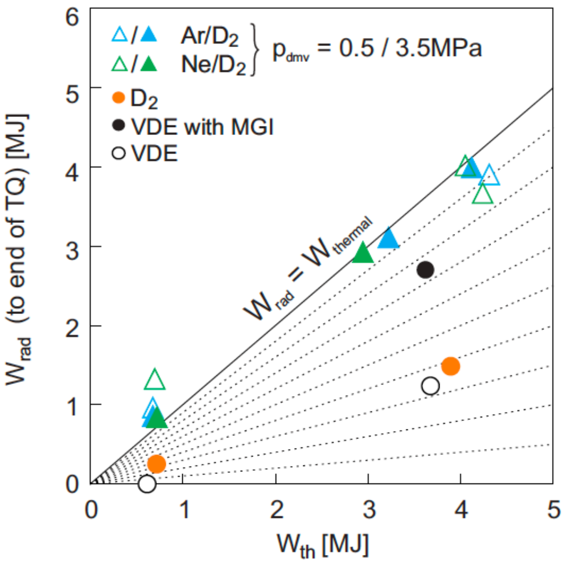
- *The thermal load challenges are extreme:*
  - *loss of W_{th}=200-300 MJ in ~1 ms → 400 MW/m² (on average) to GW/m² (divertor)*
    - *Broad range of a few to 100% arrived at divertor surface*
  - *Heat load of 120-380 MJ m^{-2} $s^{-0.5}$ on divertor, 570 MJ m^{-2} $s^{-0.5}$ on main chamber in hot VDE*
    - *material melting: Be ~ 20 MJ m^{-2} $s^{-0.5}$; Tungsten ~ 60 MJ m^{-2} $s^{-0.5}$ (Sugihara, 2007)*



(a) Be melting by RE in JET (G. Matthews 2016 Phys. Scr.)

- *Base ITER design scenario:*
  - *MGI injects 10^{23-24} atoms of He, Ar, Ne (species mix currently undefined) in less than 10 ms.*

JET: fraction of radiated thermal energy



- *Current development path:*
  - *Active mitigation by (high-Z) impurity injection to form radiative mantle to spread the heat load as uniform as possible → requirements*
    - *reliable precursor detection*
    - *fast delivery of impurities inside the separatrix.*
      - *Massive Gas Injection (MGI) → Shattered Pellet Injection → Shell Pellet Injection*

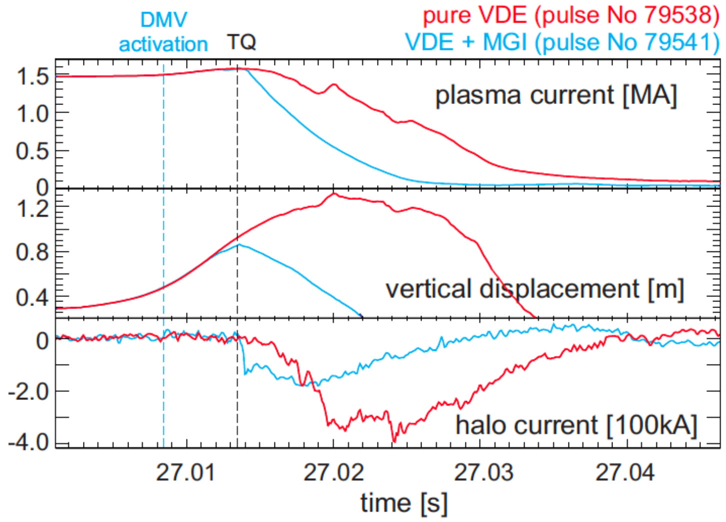
E D

Current quench mitigation – ITER perspective

- ***Electromagnetic force loading must be limited:***
  - ***Plasma current ramp-down shall not be too fast (> ~36 ms)***
    - ***To avoid excess eddy current that damages blanket module***
  - ***Plasma current ramp-down shall not be too slow (< ~150 ms)***
    - ***Experimental scaling of excess halo current with slow current quench that can damage the vessel → needs MHD & kinetic physics***

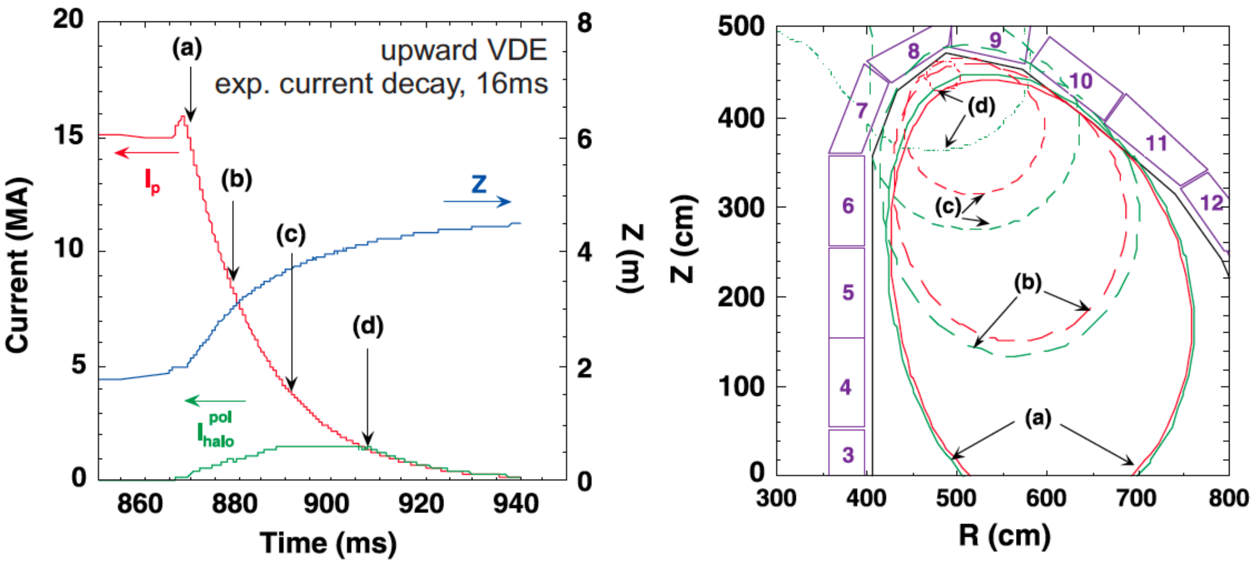
- ***Base ITER design scenario:***
  - ***MGI injects $10^{25\text{-}26}$ atoms of He, Ar, Ne (species mix currently undefined) in less than 10 ms.***

JET: MGI into VDE



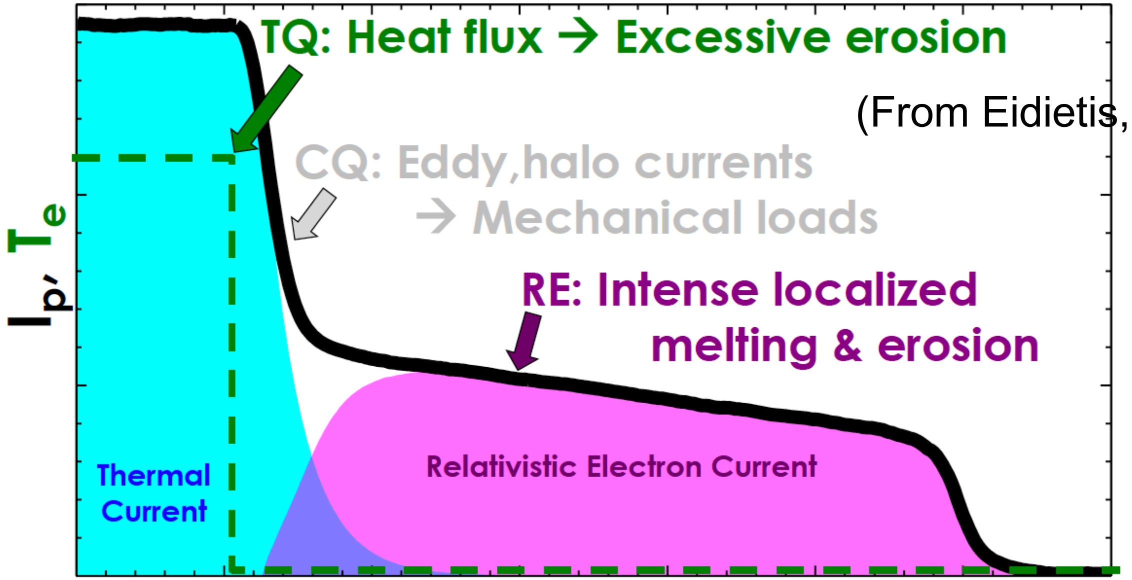
(Lehnen, 2015)

DINA simulation for ITER, M. Sugihara, NF 2007



Runaway electrons remains the biggest uncertainty

- *Most of the poloidal magnetic flux (or current) will decay over a period of ~100 ms.*
  - *A large fraction of this energy (395 MJ) can be channeled through runaway electrons.*
    - *Up to 10 MA and 15-150 MJ*
- *Potential for significant PFC damage*
  - *Localized power deposition (tied to dynamical evolution of 3D fields)*
  - *Deep penetration depth by high energy electrons*
- *Scaling relations:*
  - *Runaway current scales with runaway density (speed is c)*
    - *Only needs a minute density to account for 10 MA current*
  - *Runaway power flux scales with runaway energy (relativistic factor)*



(From Eidietis, 2018)

- *Current strategy for ITER relies on impurity injection*
  - *Suppress runaway growth if possible*
  - *Expedite runaway current dissipation*

- *Uncertainties due to physics gaps:*
  - *Current drive under strong E field*
  - *High-Z impurity radiative cooling*
  - *Plasma transport in 3D fields*

Tokamak Disruption Simulation (TDS) SciDAC Center

- *TDS Objective:*
  - *Develop the predictive science underlying disruption mitigation design via state-of-the-art simulations, in tandem with theoretical advances and experimental validation*
- *Who we are:*
  - *Nine-institution collaboration led by LANL (Lead PI: Xianzhu Tang)*
  - *LANL: Luis Chacon, Zehua Guo, Chris McDevitt, Todd Elder, Nathan Garland, Josh Burby, …*
  - *SNL: John Shadid, Tim Widley, Edward Philips, postdoc*
  - *PPPL: Weixing Wang, Ed Startsev, Stephane Ethier, Min-Gu Yoo*
  - *LLNL: Xueqiao Xu, Ilon Joseph, Ben Zhu, students*
  - *ANL: Barry Smith*
  - *Columbia: Allen Boozer*
  - *Virginia Tech: Bhuvana Srinivasan, postdoc + student*
  - *Maryland: Howard Elman, student*
  - *UT-Austin: Tan Bui-Thanh, student*
- *Assembled expertise:*
  - *Physics: Extended MHD, core transport, edge/boundary physics, runaway electron physics, atomic physics & radiation, plasma-material interaction, plasma-neutral gas dynamics*
  - *Math/Computing: scalable solvers, high-order discretization, uncertainty quantification, etc*

TDS research roadmap – disruption mitigation strategy

Runaway avoidance

Complete avoidance means no runaways

$E < E_C$ (Connor-Hastie)

Deemed impractical to date (extremely high n_e at all T_e → D injection)

Limit runaway current fraction via avalanche avoidance

$E_c < E < E_{AV}$

Avalanche threshold theory

Discharge trajectory design

Plasma transport cooling

Radiative cooling

Impurity transport & assimilation

Cooling history

Impurity content

Runaway energy control

Actuators

3D B fields

Impurity injection

Wave injection

Material damage ∝ runaway current × runaway energy

Energy control ← phase-space engineering of runaway vortex

Reshape the runaway vortex by removing the high-energy part

Actuator accessibility & efficiency

TDS research roadmap -- physics objectives

Runaway avoidance

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Limit runaway current fraction via avalanche avoidance

Consistency with core transport for cooling & impurity assimilation

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Reshape the runaway vortex by removing the high-energy part

Discharge trajectory design

Consistency with a boundary plasma solution for power exhaust

Actuator accessibility & efficiency

TDS research roadmap – physics models & integration

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Consistency with core transport for cooling & impurity assimilation

Material damage ∝ runaway current × runaway energy

$E < E_C$ (Connor-Hastie)

(1) Runaway electron dynamics: relativistic Fokker-Planck-Boltzmann model (LAPS)
(2) Magnetic reconnection: extended MHD & multi-fluid model (PIXIE3D & Drekar)
(3) Core plasma transport in 3D fields: gyrokinetic model (GTS)
(4) Edge plasma transport: gyrofluid model (BOUT++)
(5) Impurity transport and injection: plasma-neutral multifluid & fluid/kinetic hybrid (Drekar)
(6) Radiative cooling: collisional-radiative model (FLYCHK)
(7) Boundary plasma and PMI: kinetic plasma/neutral model (VPIC)

Deemed impractical to date (extremely high n_e at all T_e → D injection)

Discharge trajectory design

Consistency with a boundary plasma solution for power exhaust

Actuator accessibility & efficiency

TDS research roadmap – integrated ASCR research & deployment

Runaway avoidance

Runaway energy control

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Consistency with core transport for cooling & impurity assimilation

Material damage ∝ runaway current × runaway energy

$E < E_C$ (Connor-Hastie)

(1) Scalable algorithms: physics-based preconditioning (parabolizing hyperbolic equations)
(2) Scalable solvers: multigrid or multilevel solvers, for both elliptic/parabolic field equations and hyperbolic equation
(3) High-order discretization
(4) Multi-physics and multi-scale coupling: fluid/kinetic hybrid model, asymptotic preserving, continuum-discrete coupling, implicit and IMEX
(5) Uncertainty quantification: parametric sensitivity, multi-fidelity model discrimination, stochastic inversion, reduced-order model

Deemed impractical to date (extremely high n_e at all T_e → D injection)

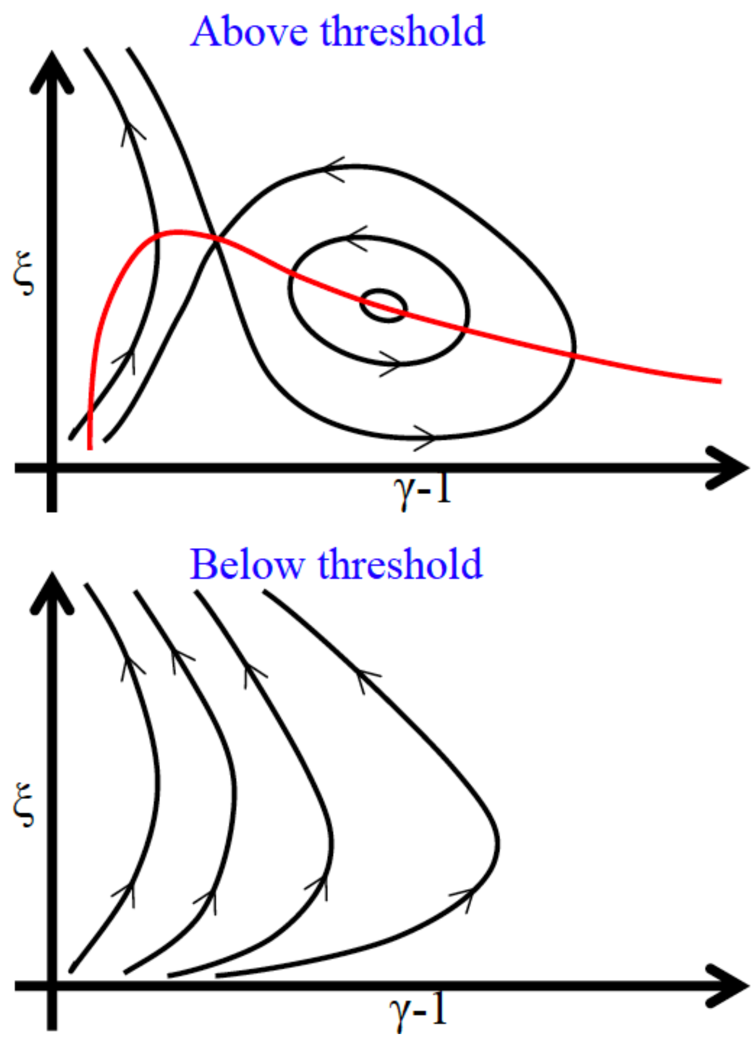
Discharge trajectory design

Consistency with a boundary plasma solution for power exhaust

Actuator accessibility & efficiency

The central concept in runaway physics → runaway vortex

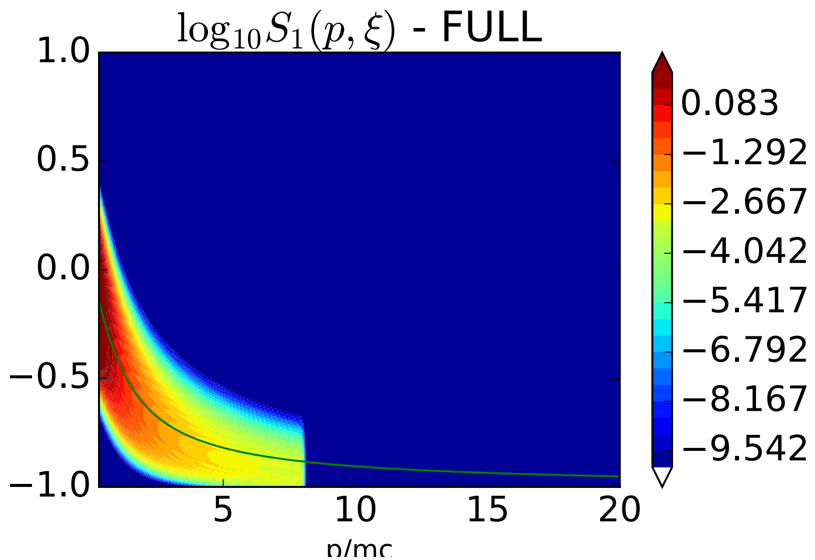
- Once radiation damping (dominated by synchrotron rad. In MeV to tens of MeV energy range) is taken into account, runaway electrons actually run around in momentum space
  - Runaway vortex → a cyclic process of electron acceleration and deceleration in (p, ξ) space
- Presence of runaway vortex provides a retainer for secondary runaways to accumulate → onset of avalanche growth → E_{av}
  - E_{av} is slightly above E_{ox} due to energy conservation in knock-on collisions.
- For $E>E_{ox}$, the runaway vortex sets the energy distribution of the runaways
  - Runaway energy control → reshape runaway vortex

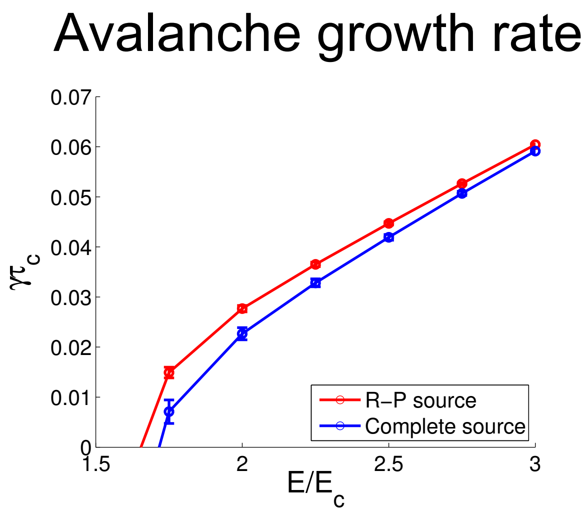


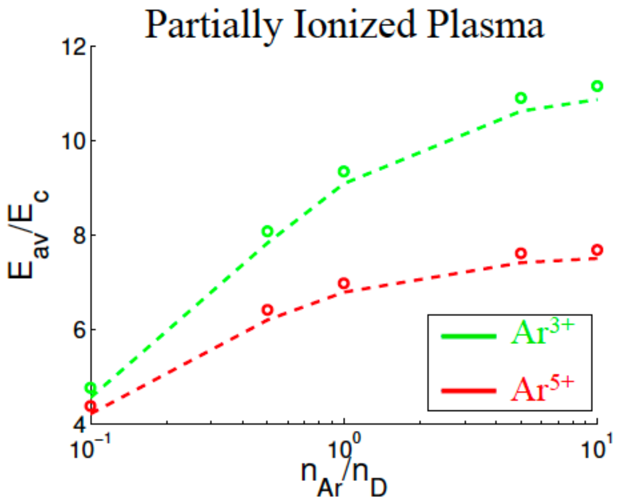
Guo, McDevitt, Tang, PPCF 2017;
McDevitt, Guo, Tang, PPCF, 2018

Must get the collisions right to predict runaways

- **For small-angle collisions with runaways, the Coulomb logarithm must retain its dependence on runaway energy.**
- **For large-angle (knock-on) collisions, Boltzmann operator is needed, along with a modified Coulomb logarithm for small-angle collisions to avoid double-counting.**
- **For runaway collisions with high-Z impurities, partial screening effect must be taken into account to understand the avalanche threshold and runaway energy distribution. (Hesslow, PRL, 2017)**





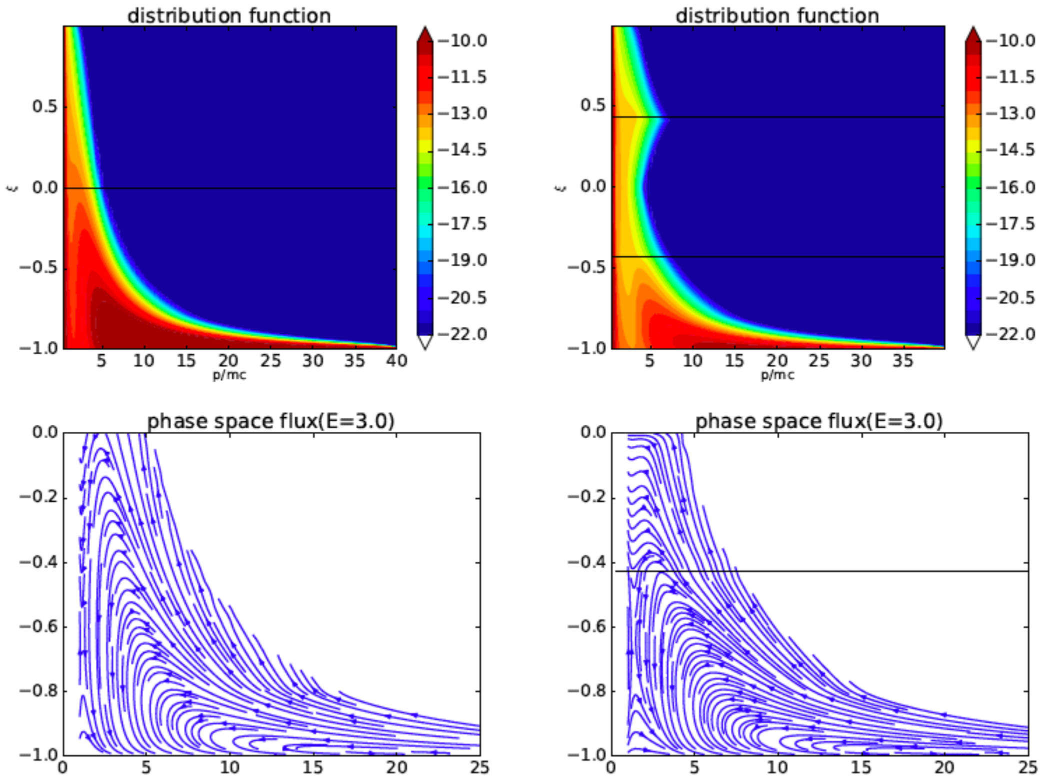


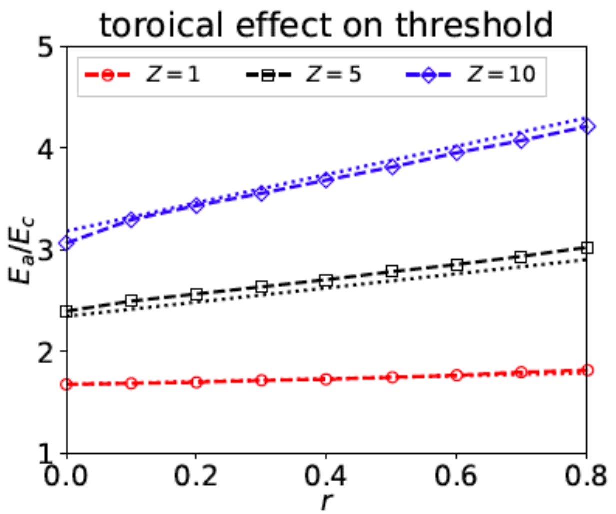
Drastic increase in Eav by high-Z impurities implies that ion charge states must be evaluated accurately by atomic physics model

McDevitt, Guo, Tang, PoP, 2018

Toroidicity + high-Z impurities → much large effect on runaways

- Avalanche threshold grows much higher at large radius due to reshaping of runaway vortex by magnetic trapping
  - But this happens only when Zeff (high Te) or partial screening effect of high-Z impurity (low Te) is present
    - Otherwise the runaway vortex is far away from trapped-passing boundary



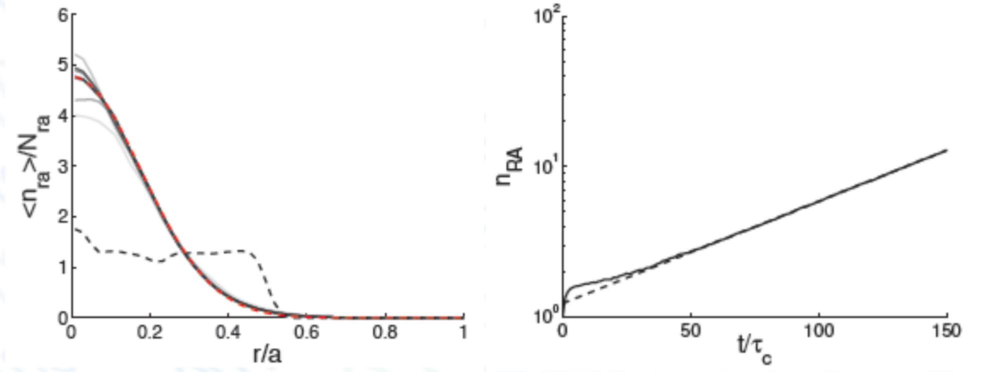


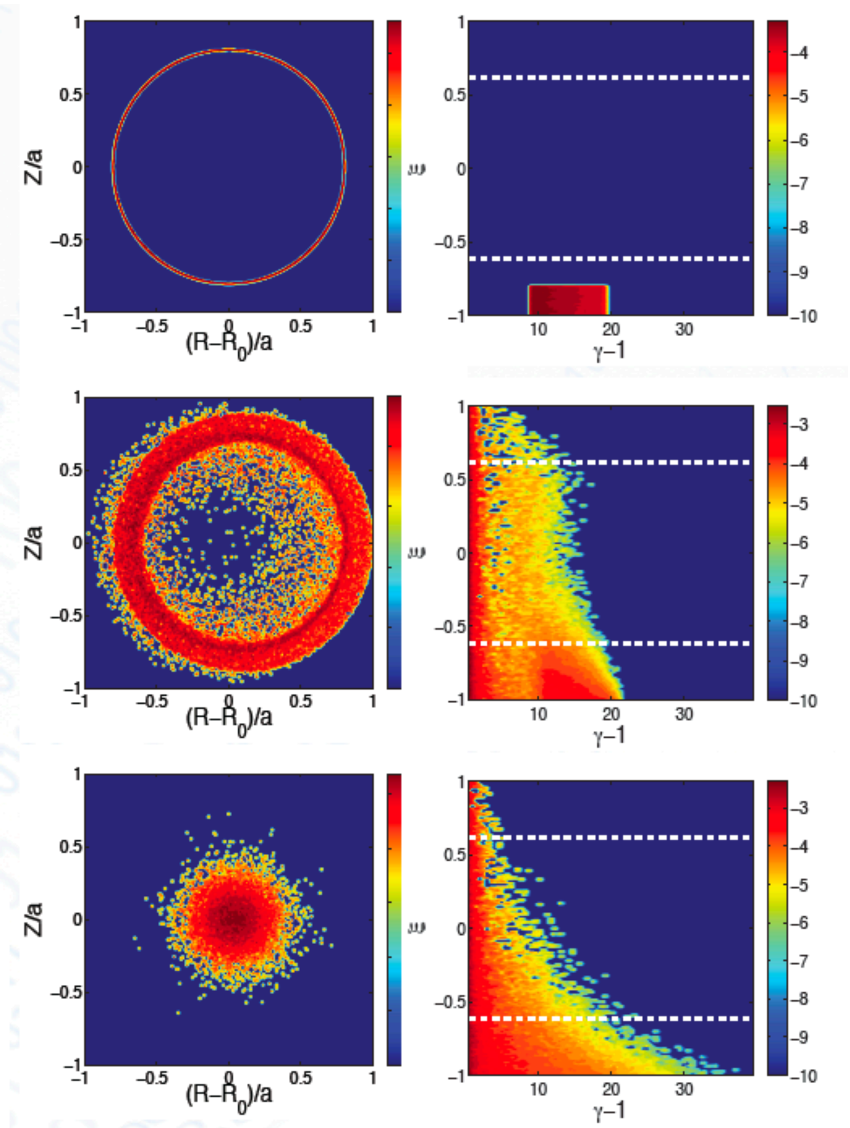
Guo, McDevitt, Tang, PoP, 2018

Toroidicity + partial-screening by high-Z impurities → radial transport

- Key findings: in a strongly mitigated disruption, spatial transport is strong (diffusion + ware pinch) → avalanche spatial eigenmode

  - Considering a ring of electrons initialized at a large radius (r/a~0.8) and aligned with B-field
  - Strong pitch-angle scattering leads to the formation of trapped energetic particle population
  - Ware pinch convects the trapped energetic electrons inward
  - Inwardly convected electrons are detrapped ➔ run away
  - Provide “seed” for avalanche instability near r/a~0
  - Resulting runaway population strongly peaked near tokamak magnetic axis
  - Final state largely independent of phase space distribution of “seed” electron population





McDevitt, Guo, Tang, PoP, 2018

Discharge trajectory design for runaway avoidance

- Using a volume averaged (0-D) model to understand "discharge trajectory design"
- Discharge trajectory in T and E_φ space
  - Temperature: T(t) from T_0 to T_{min}
  - Poloidal magnetic flux: $\Psi(t)$ from Ψ_0 to Ψ_{min} → $E_\varphi(t)$
- Discharge trajectory design goal
  - Avalanche threshold $E_{av}(T(t)) > E_\varphi(t)$
- Discharge trajectory design variables (actuators):
  - Atomic composition of the plasma as a function of T(t)
    - Fuel and impurity species density $\{n_s\}$
- Physics model constraints
  - Atomic physics of collisional radiative dynamics → charge state distribution for each species of atom, $\{n_{s,Z}(T(t))\}$, as functions of T(t) → quasineutrality: $n_e(T(t))$
  - Runaway avalanche threshold physics → $E_{av}(T(t),\{n_s(t)\})$

Collisional-radiative model from FLYCHK

- **Input -- Te, atomic density of all species {n_s}**
- **Output – charge state distribution of all ion species {$n_{s,Z}$}, and n_e by quasineutrality**
- **Balance between collisional excitation (incl. ionization) & de-excitation & recombination processes.**

Solves populations equations for ground-state and excited states of each charge-state for elements from hydrogen to gold

$$\frac{dn_i}{dt} = n_i \sum_{j \neq i}^{N_L} R_{ij} + \sum_{j \neq i}^{N_L} n_j R_{ji}, \quad 1 \leq i \leq N_L \longrightarrow \mathbf{R}\vec{n} = \dot{\vec{n}}$$

For upward transitions,

$$R_{ij} = n_e(C_{ij} + \gamma_{ij}) + \sigma_{ij} + I_{ij}$$

For downward transitions,

$$R_{ji} = A_{ji} + n_e(D_{ji} + \alpha_{ji}^{RR} + \kappa_{ji}) + n_e^2 \delta_{ji}$$

N_L(number of atomic levels per charge-state) determined by screened hydrogenic model, ranges from 25-31 levels per charge-state

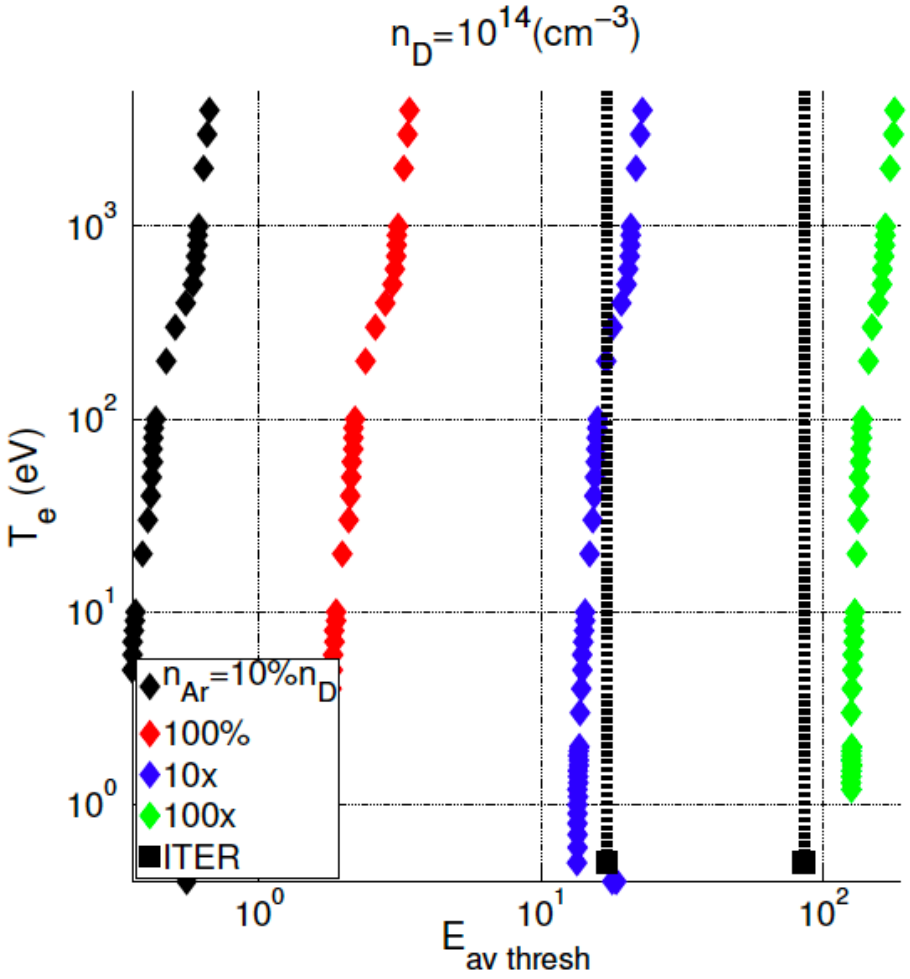
$$I_n = \frac{Q_n^2 e^2}{n^2 2a_0}\left(1 + \left[\frac{\alpha Q_n}{n}\right]^2 \left[\frac{2n}{n+1} - \frac{3}{4}\right]\right)$$

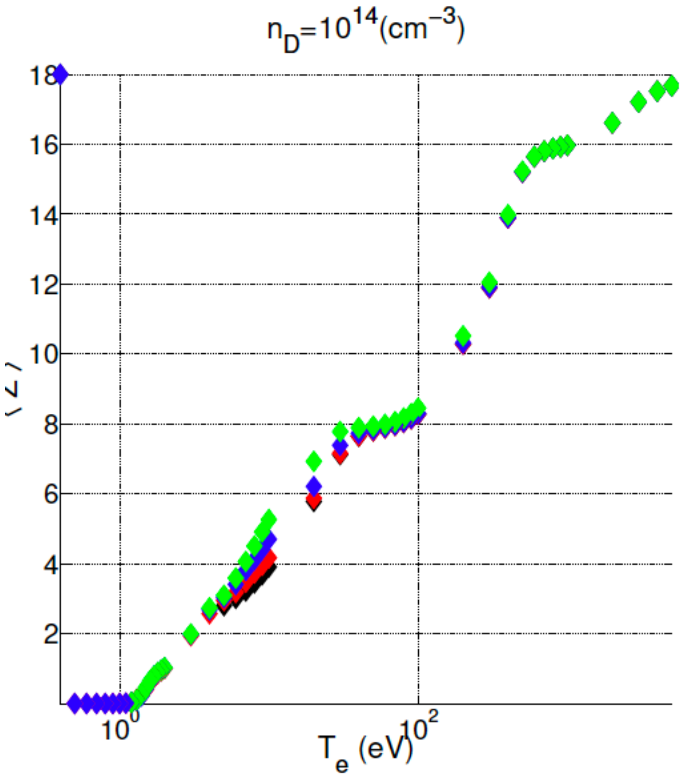
$$Q_n = Z_n - \sum_{m<n} \sigma(m,n) P_m - 0.5\sigma(n,n)(P_n - 1)$$

C_{ij} : collisional excitation
γ_{ij} : collisional ionization
σ_{ij} : autoionization
I_{ij} : non-thermal electron collisions

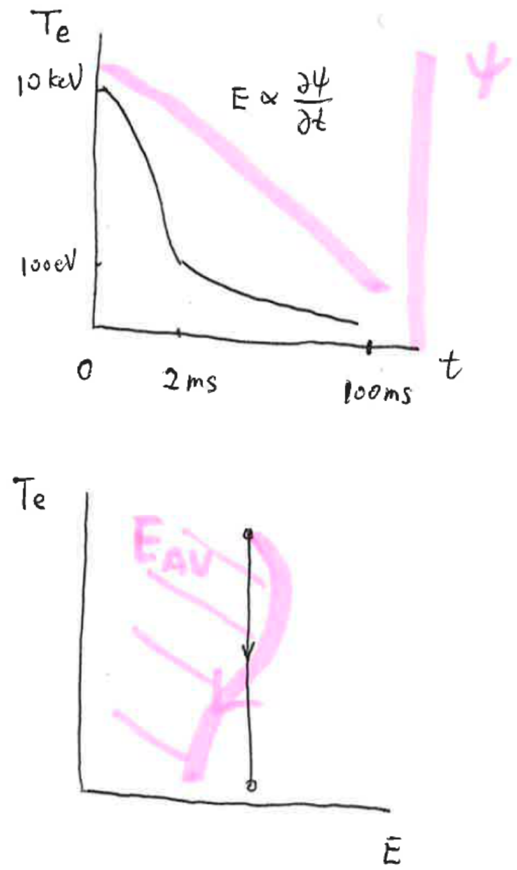
A_{ji} : spontaneous emission
D_{ji} : collisional de-excitation
α_{ji}^{RR} : radiative recombination
κ_{ji} : electron capture
δ_{ji} : collisional recombination

Staying below E_{av} in ITER requires a lot of Ar



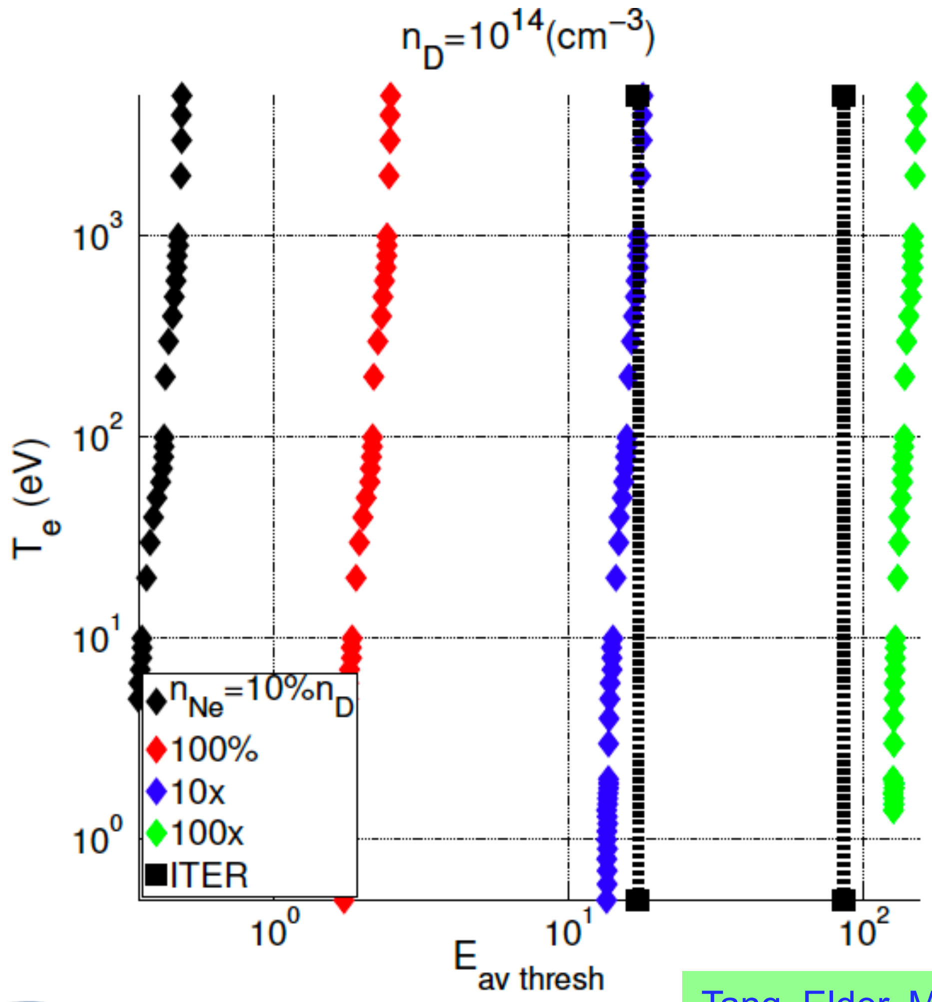


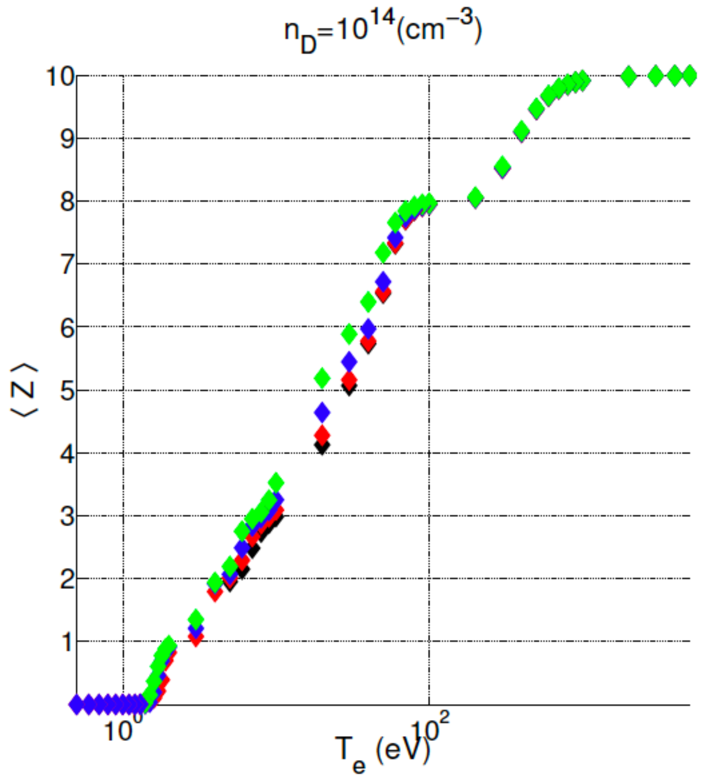
ITER target discharge trajectory



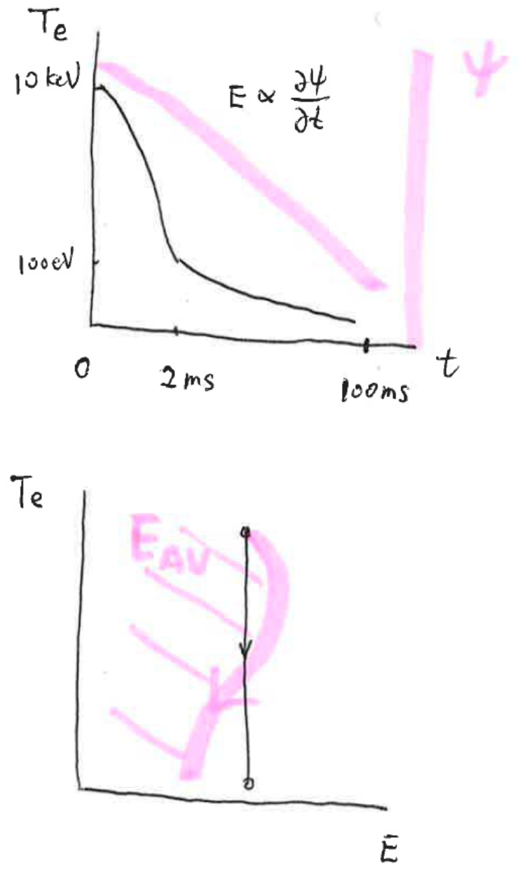
Tang, Elder, McDevitt, Guo, TTF (2018)

Staying below E_{av} in ITER requires a lot of Ne as well



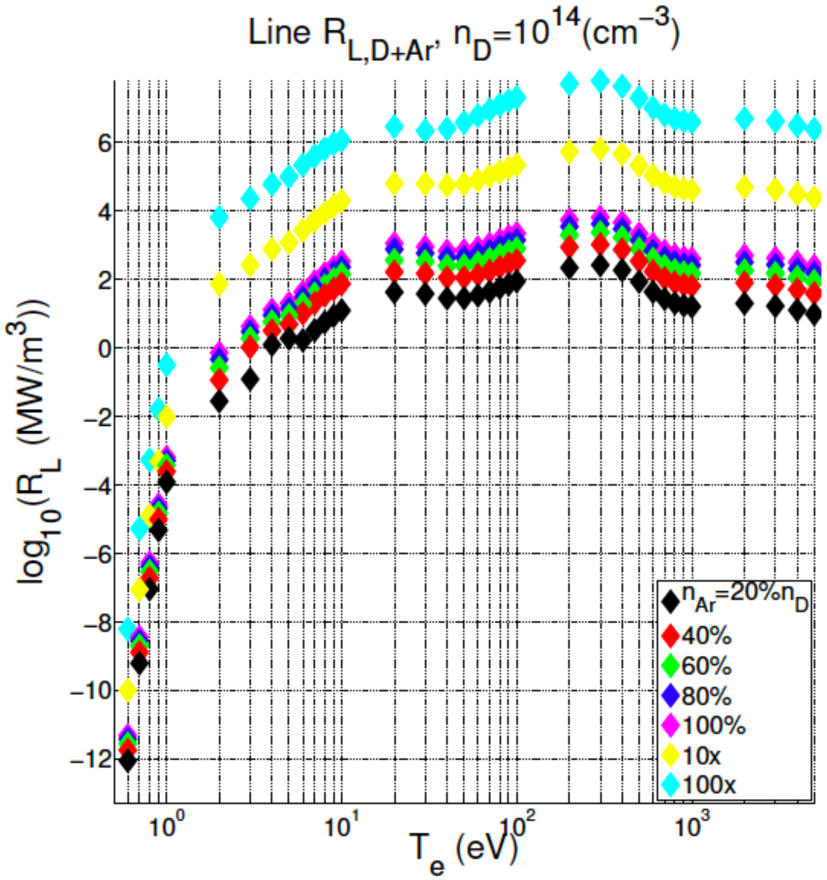


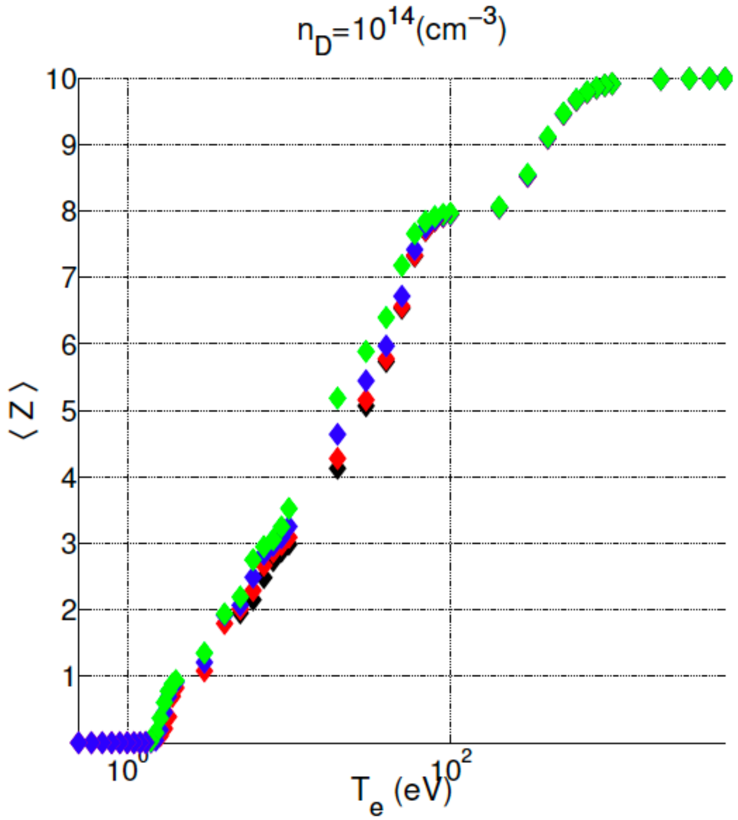
ITER target discharge trajectory



Tang, Elder, McDevitt, Guo, TTF (2018)

Balance E • J against radiative cooling → plasma must be very cold





300 MJ magnetic energy dissipated over 100 ms → average 3 GW power exhaust → if radiated away from a plasma volume of 300 m^3, radiative cooling power is about 10 MW/m^3

- **Power balance implies rapid cooling to Te < 2eV**
  - **Energetic electrons can contribute significantly to ionization**
  - **Thermal plasma too cold to carry large current**

Tang, Elder, McDevitt, Guo, TTF (2018)

Enhanced radiative cooling conflicts with runaway avoidance

- Interestingly, JET-ILW experiments → reduced radiative cooling → long quench time → runaway is rare compared with JET-CFC experiments
  - Plasma transport in 3D fields becomes the deciding physics in discharge trajectory.
  - Likely inconsistent with the current time scale requirement on ITER (too slow)
- The current approach for ITER mitigation, with high-Z impurity injection, is the most robust way to generate runaways on even small tokamaks of very modest plasma current.

JET Data, Lehnen et al, NF (2013)

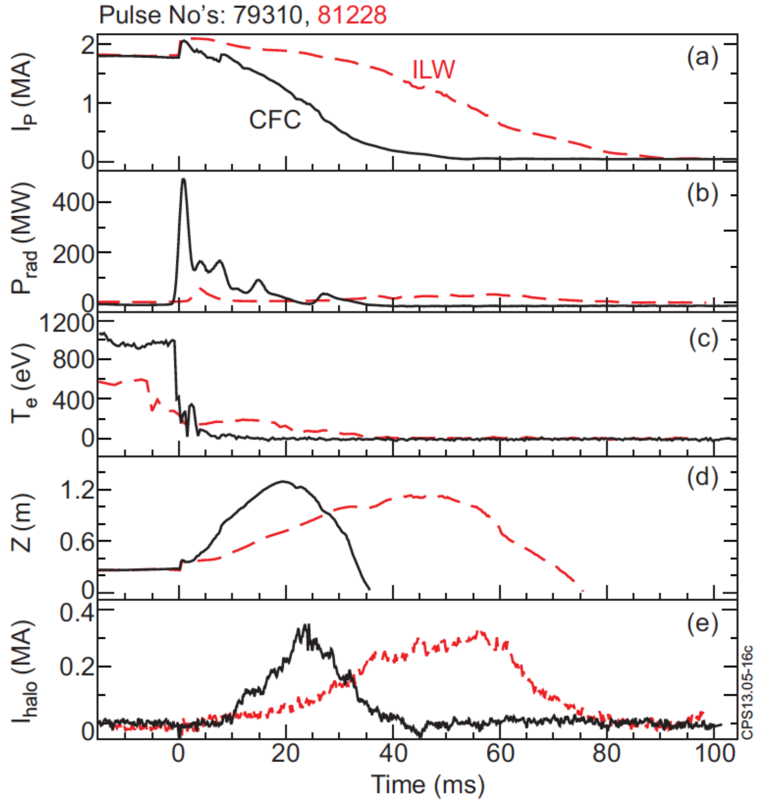


Figure 1. Comparison of two high triangularity ($\langle\delta\rangle \approx 0.42$) disruptions with CFC and ILW, which reflect the typical changes with introduction of a metallic wall: (*a*) plasma current, (*b*) total radiated power, (*c*) central electron temperature, (*d*) vertical plasma position, (*e*) poloidal halo current.

Runaway mitigation by runaway energy control

- Impurities can lower runaway energy at fixed electric field
  - Location of runaway vortex depends on impurity content
- Prompt loss via 3D magnetic fields can limit the runaway energy gain through confinement degradation.
- For an otherwise fixed plasma discharge condition, resonant wave-particle scattering via externally injected whistler wave, can manipulate the runaway vortex by cutting off the high energy part.

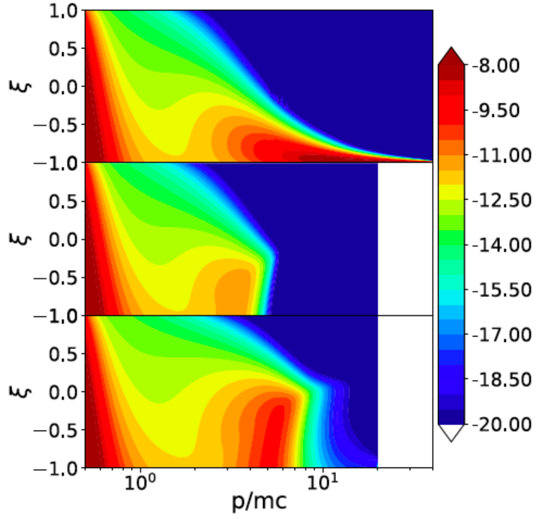


FIG. 3. The contour plots for steady-state distribution of primary runaway electrons with and without whistler waves. The figure shows the contour of $\log_{10} f(p,\xi)$ without waves (top) and with waves (middle with $\alpha = 0.2$ and bottom with $\alpha = 0.05$).

The physics works even better in a torus

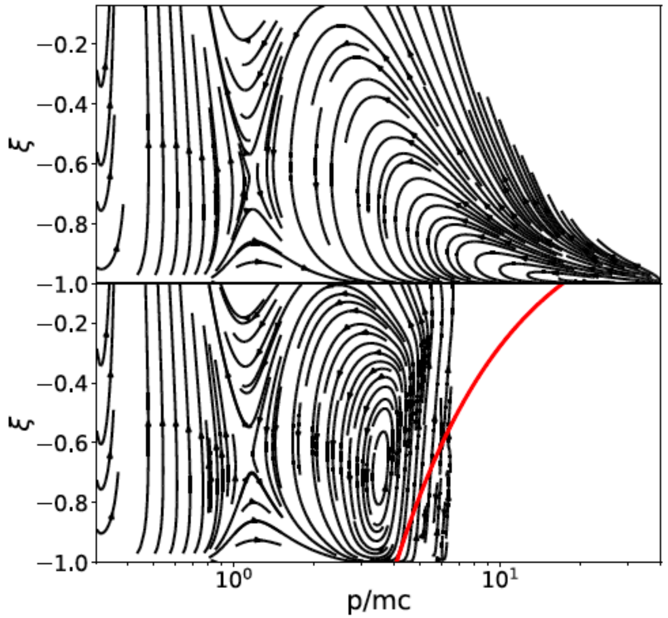
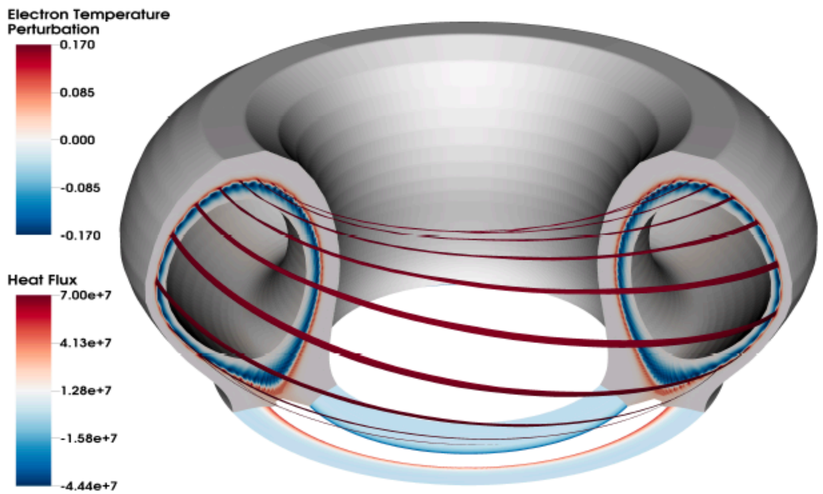


FIG. 4. The primary electron energy and pitch-angle fluxes $(p^2\Gamma_p/f, p\Gamma_\xi/f)$ in momentum space. $p_O \approx 20$ without whistler waves, while $p_O \approx 3.5$ with injected whistler waves, which is a factor of 5.7 lower. The X point is little changed in both cases. The red curve in the bottom plot labels the resonance condition at the peak of the applied Gaussian wave spectrum, Eq. (15). The design freedom in placing this resonance in (p, ξ) space allows precise control of the runaway vortex and hence the runaway energy.

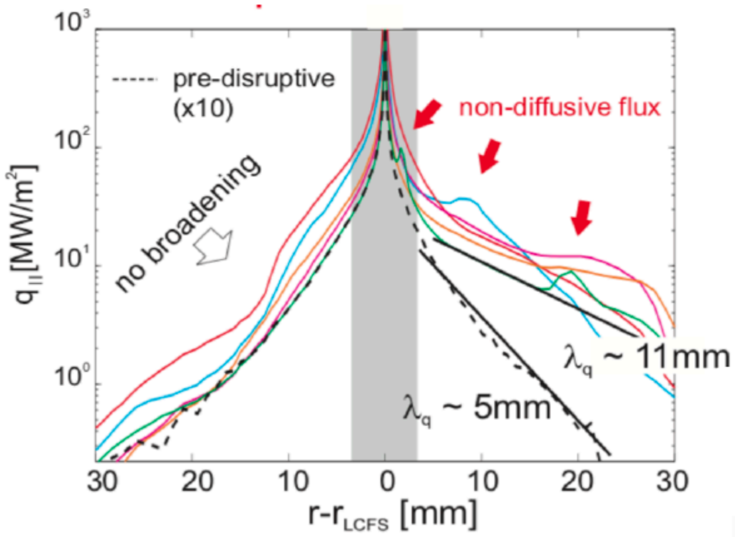
Guo, McDevitt, Tang, PoP, 2018

Progress update: power exhaust during thermal quench

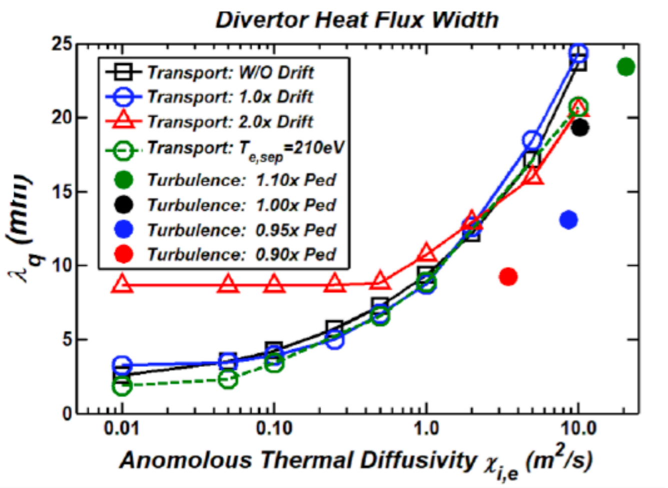
- ➢ Uncover the physics governing distribution of high heat flux to PFCs during thermal quench of disruption
- Radial structure of divertor heat loads can be quite different from normal plasma
  - o Significant scrape-of-layer broadening, in the range of 5-20,
  - o Significant toroidal and poloidal inner/outer asymmetry



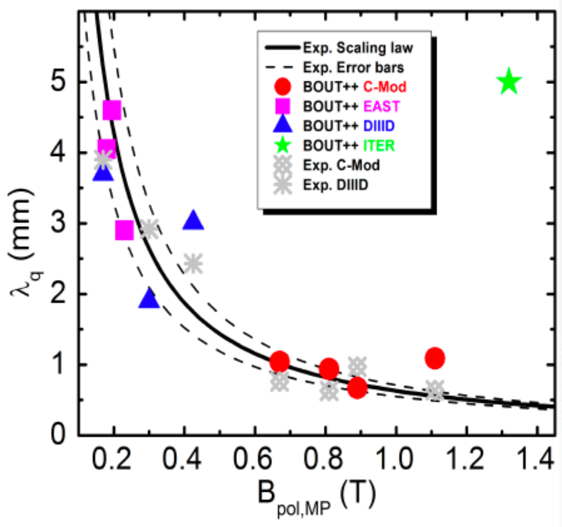
JET – parallel heat flux



ITER – BOUT++ simulated divertor heat flux width

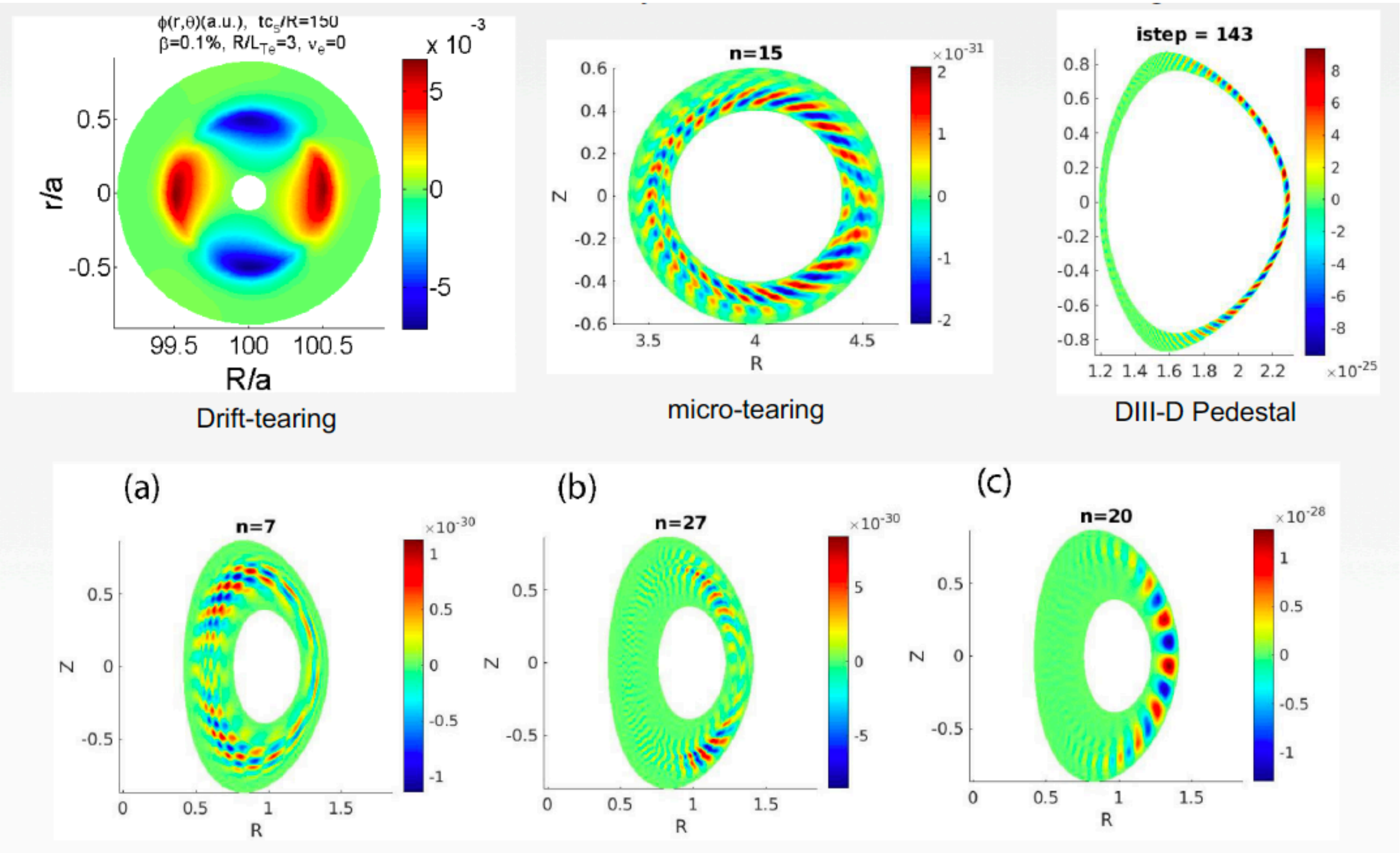


Code & Expt. comparison of flux width



Progress update: plasma transport contribution to core thermal collapse

- Towards self-consistent plasma transport & magnetic dynamics (3D fields)
  Critical capability enhancement for electromagnetic version of GTS gyrokinetic code
  Successful benchmark of a variety of modes in different tokamak geometries



(a) β_e=0.5%, micro-tearing (high field side)

(b) β_e=1.6%, micro-tearing (low field side)

(c) β_e=3.2%, kinetic-ballooning

Summary

- *Transport issues dominate the physics of disruption mitigation*
  - *Transport of plasma particle and energy in 3D magnetic field*
    - *Key to thermal quench mitigation*
  - *Formation and transport of runaways*
    - *Key to current quench mitigation*
- *Runaway (avalanche) avoidance & mitigation (via runaway energy control) drive the discharge trajectory design/optimization ←→ accessibility & efficiency of actuators*
  - *Constrains the operational regime for thermal quench-induced power exhaust mitigation*
- *In addition to those highlighted here, progress is being made in a number of physics areas and in applying UQ to critical fusion physics problem (see two TDS posters)*
- *Reaching TDS' physics objectives crucially depend on*
  - *Deployment of scalable solvers for plasma models under ASCR base program (e.g. extended MHD and multifluid codes – PIXIE3D and Drekar) and SciDAC program (e.g. new multigrid-based nonlinear relativistic Fokker-Planck solver)*
  - *Adoption of scalable algorithms & solvers in critical TDS physics codes (e.g. BOUT++ and GTS)*
  - *Development of new multiscale and multiphysics coupling schemes for TDS physics integration towards high-fidelity whole device disruption simulation codes*