

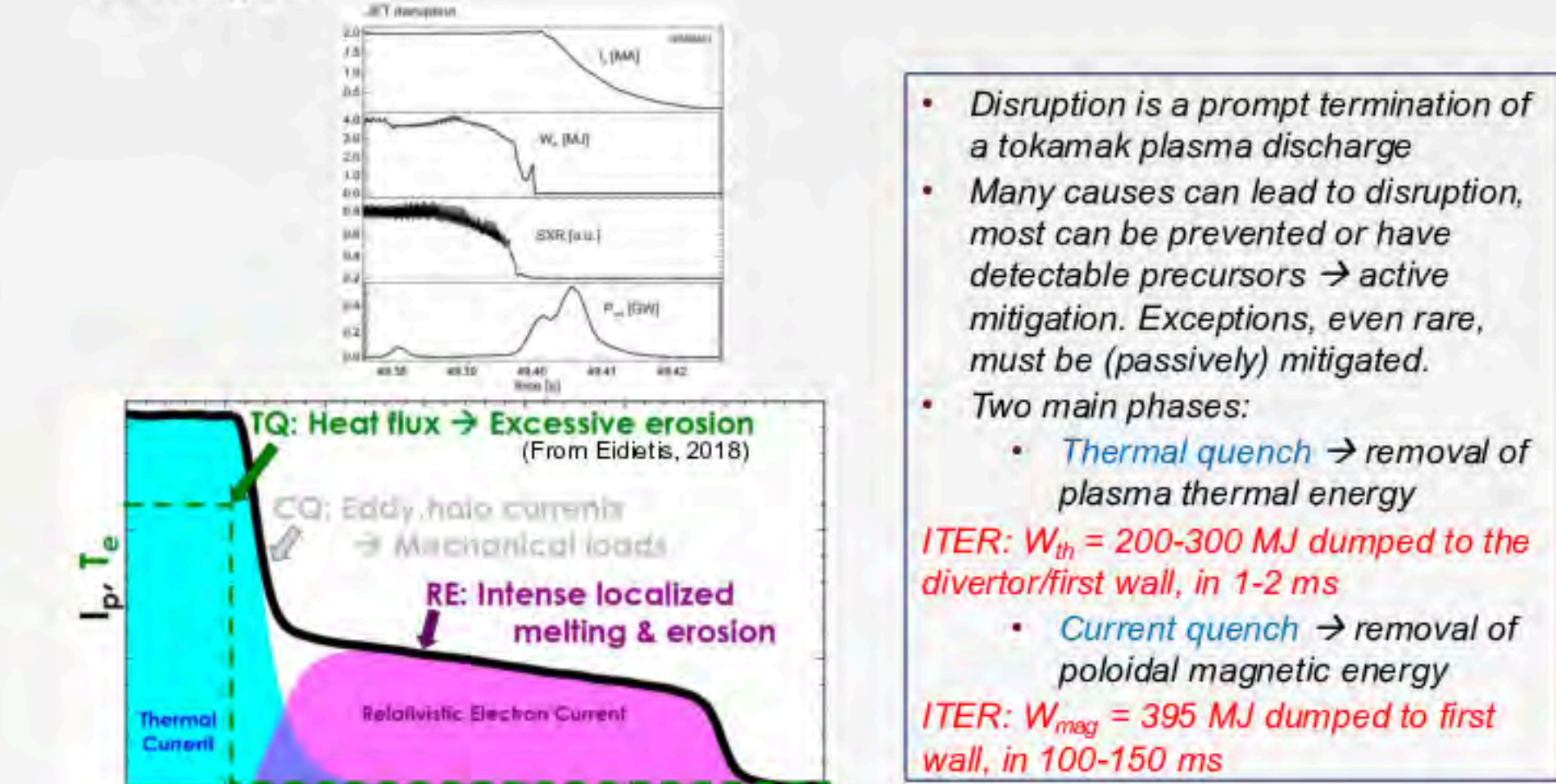
Tokamak Disruption Simulation (TDS) Center: Charting a Path for Disruption Mitigation using Large-Scale Predictive Simulations

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Abstract / Motivation

Tokamak disruption, if not completely avoided, must be effectively mitigated in a fusion reactor like ITER to prevent:

- (1) Rapid erosion of wall surface through melting, vaporization, and sublimation due to the orders of magnitude increase in the power exhaust in the thermal quench phase;
- (2) Breaking and shifting of vacuum vessel and blanket modules due to the extreme electromagnetic loading by eddy and halo currents in the current quench phase
- (3) Deep damage of surface and substrate in the plasma facing components by runaway electrons that can induce costly secondary damages

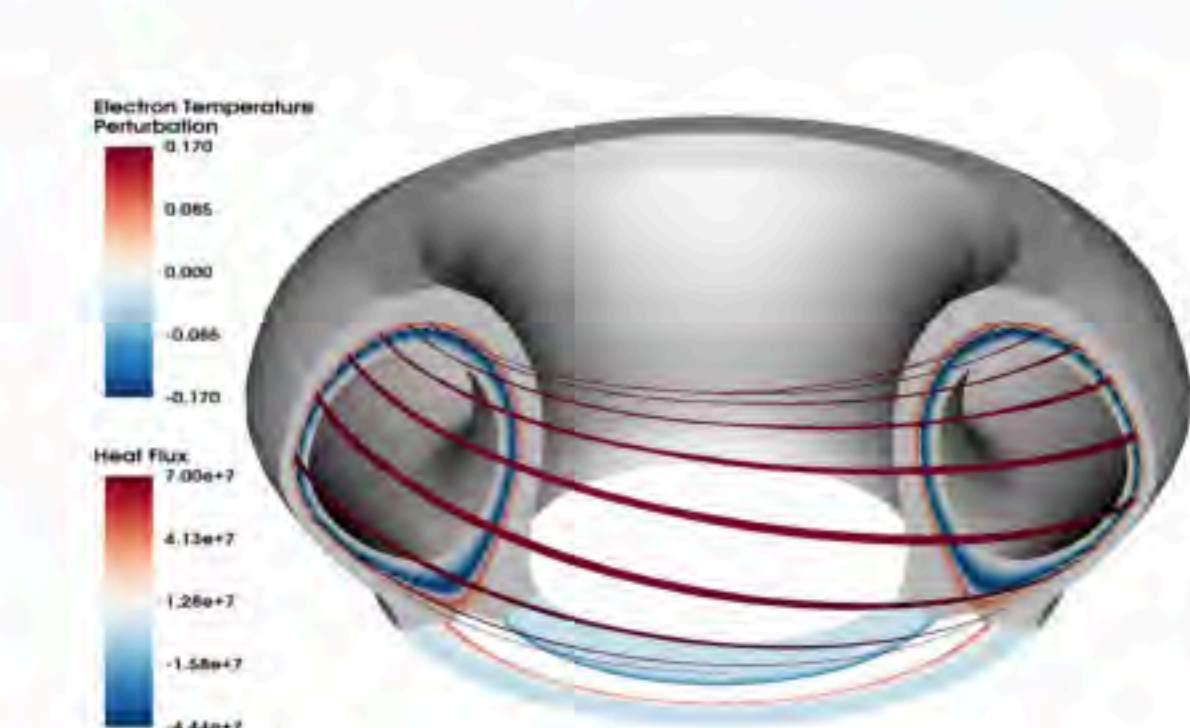


The TDS SciDAC Center applies large-scale simulations to establish the fundamental physics for charting a path for effective disruption mitigation:

- Transport (gyrokinetic and gyrofluid) calculations of particle and energy in 3D magnetic fields for (1)
- Kinetic calculations of runaway generation & transport for (3)
- Multi-fluid and fluid/kinetic calculation of plasma/neutral dynamics for (2)

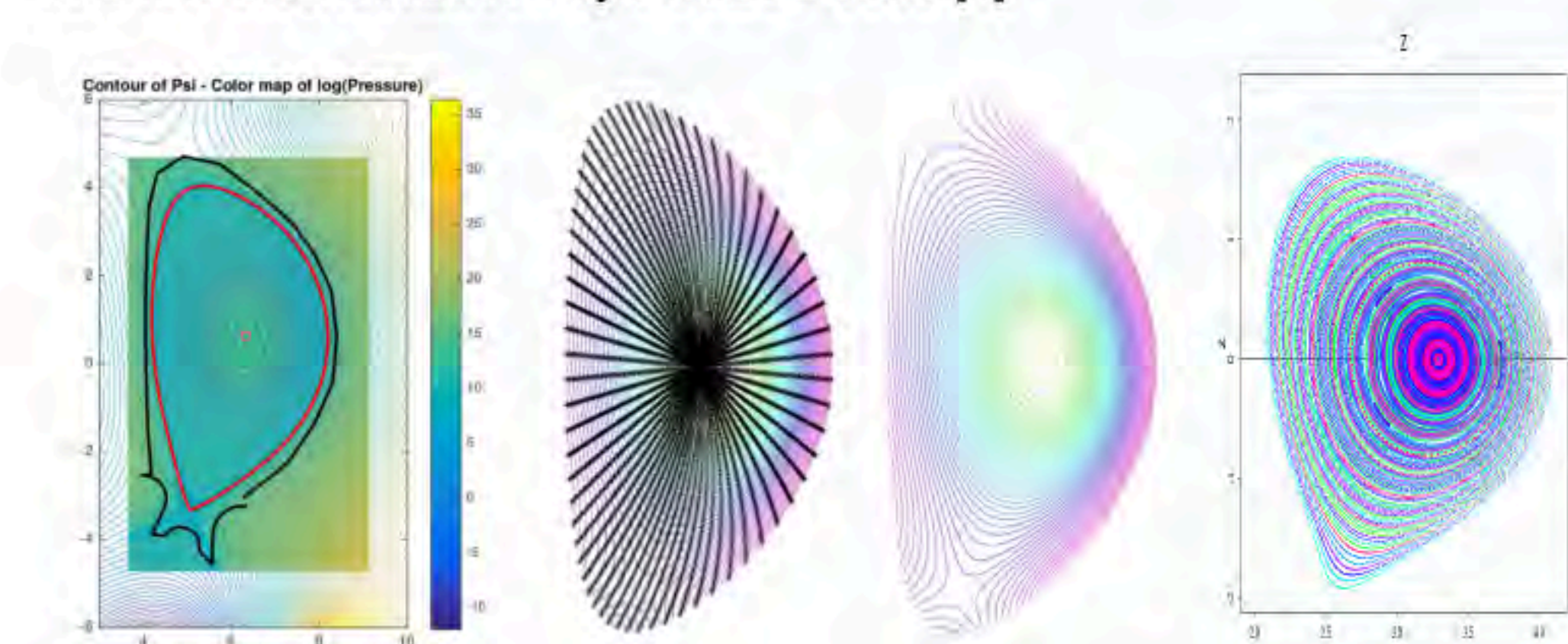
ITER base scenario: 10 MA of a 15MA discharge can turn into runaway current. Injection of massive amount of high-Z impurities to suppress and terminate the runaway current

Magnetic reconnection & thermal quench

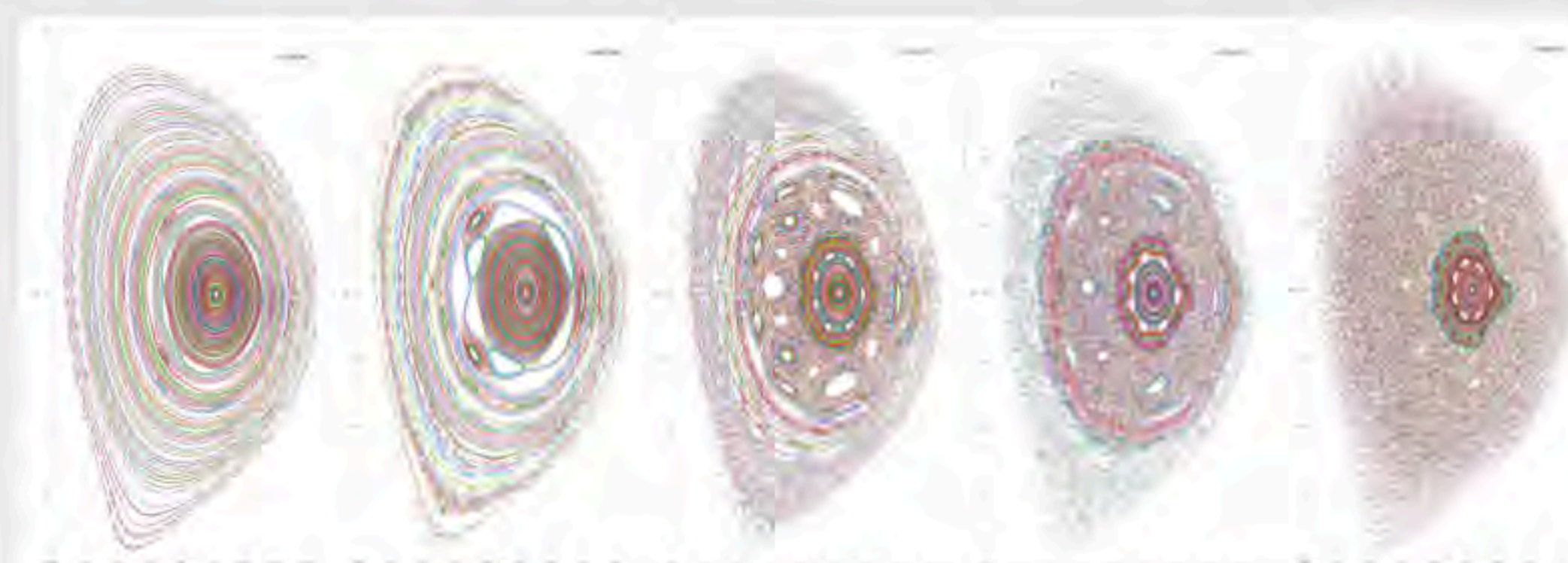


- The core temperature collapses in $\tau_{TQ} \sim 1$ ms, precipitating enhanced impurity radiation cooling (figure above)
- Flux surface breakup and global stochasticity believed to trigger the fast thermal quench due to parallel transport

- Global magnetic field line stochasticity from nonlinear evolution of MHD instabilities
- 3D nonlinear MHD simulation of tokamak magnetic reconnection and field line stochasticization by PIXIE3D code [1]



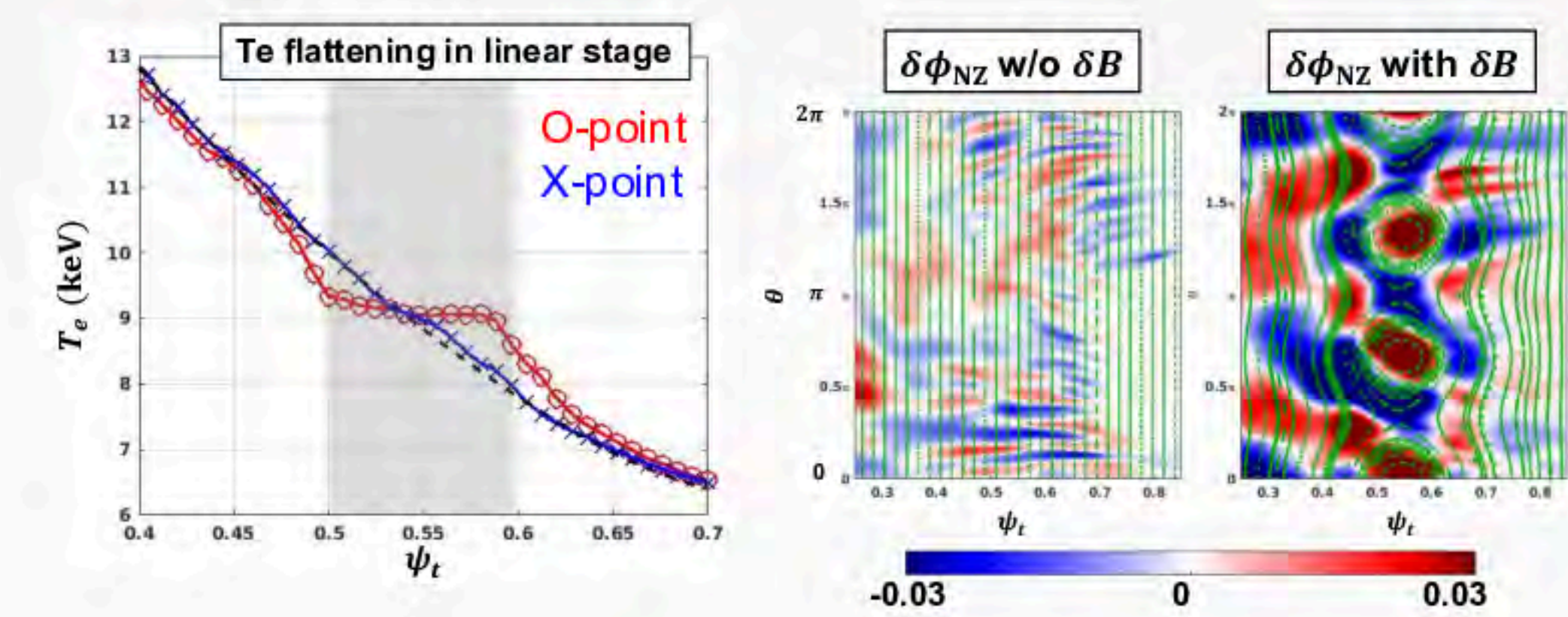
- Double-tearing in ITER profile [2]: global magnetic relaxation



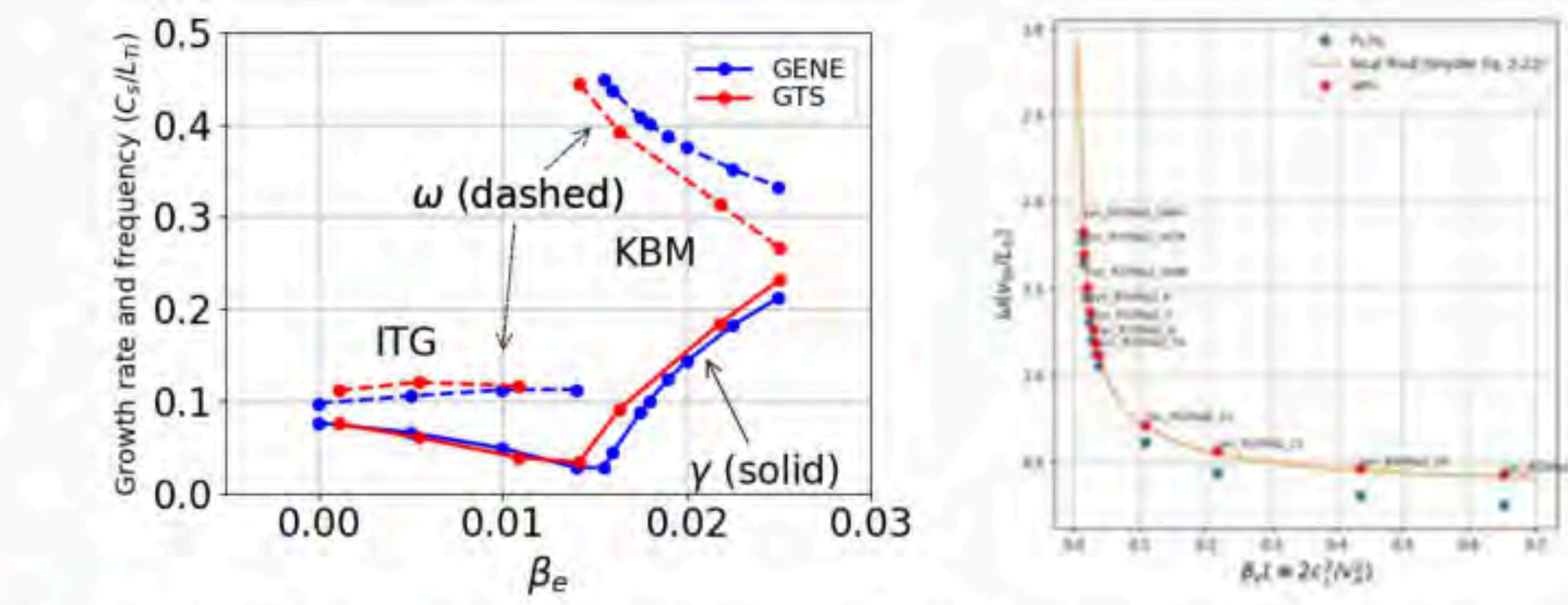
- Modification of transport by magnetic islands [3]

Global gyrokinetic simulation of 3D transport with magnetic islands

- Te flattening due to fast electron streaming along δB in linear stage
- In the nonlinear saturated stage, a strong ExB flow could arise around the magnetic island and influence the plasma transports
- A large magnetic island could mitigate or suppress the ITG turbulence around the magnetic island due to a strong shear of helical ExB flow

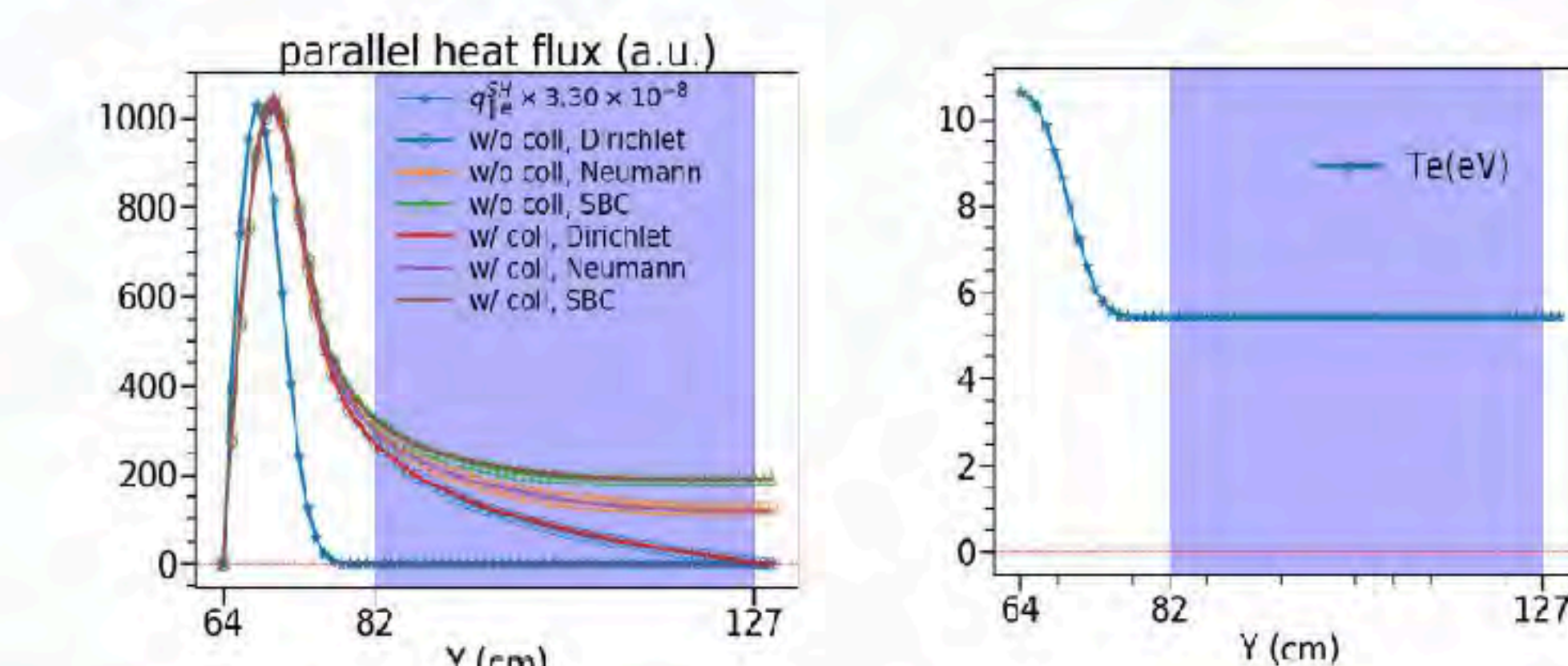


- Global Gyrokinetic simulation with electromagnetic effect
- New EM-GTS development produces Alfvén wave and ITG-KBM transition benchmark [4]



- Extension of Landau-fluid closure to weakly collision regime

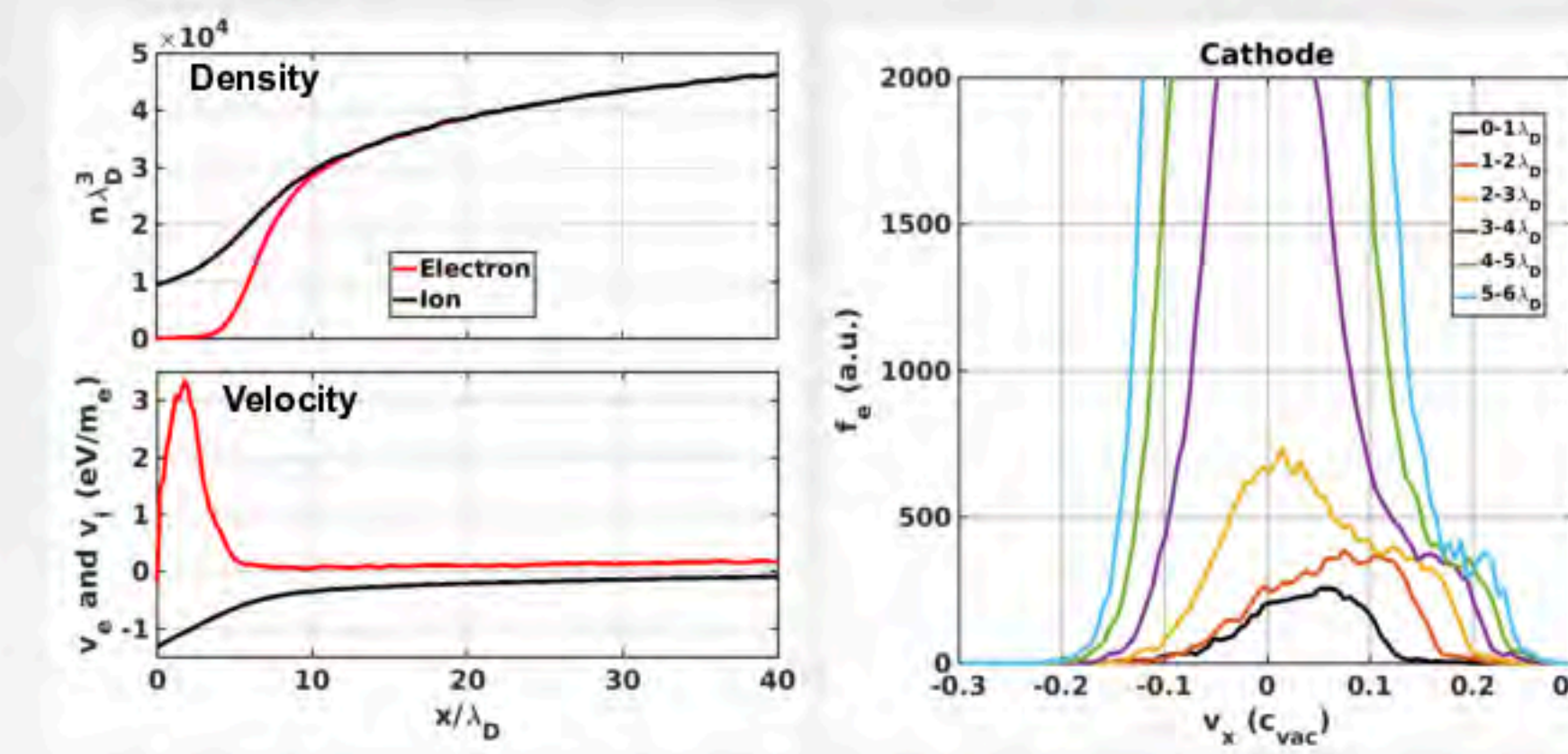
Parallel heat flux calculated from collisional ("w/ coll") and collisionless ("w/o coll") Landau-fluid (LF) closure with different boundary conditions: Dirichlet, Neumann, and Sheath boundary condition (SBC). $q_{||e}^{SH}$ is the parallel heat flux calculated from classical Spitzer-Härm expression. Te profile has a flat region to highlight nonlocal effects [5]. Improved heat flux closure feeds into BOUT++ gyrofluid simulation of edge plasma during a tokamak disruption.



Current-carrying plasma scrape-off

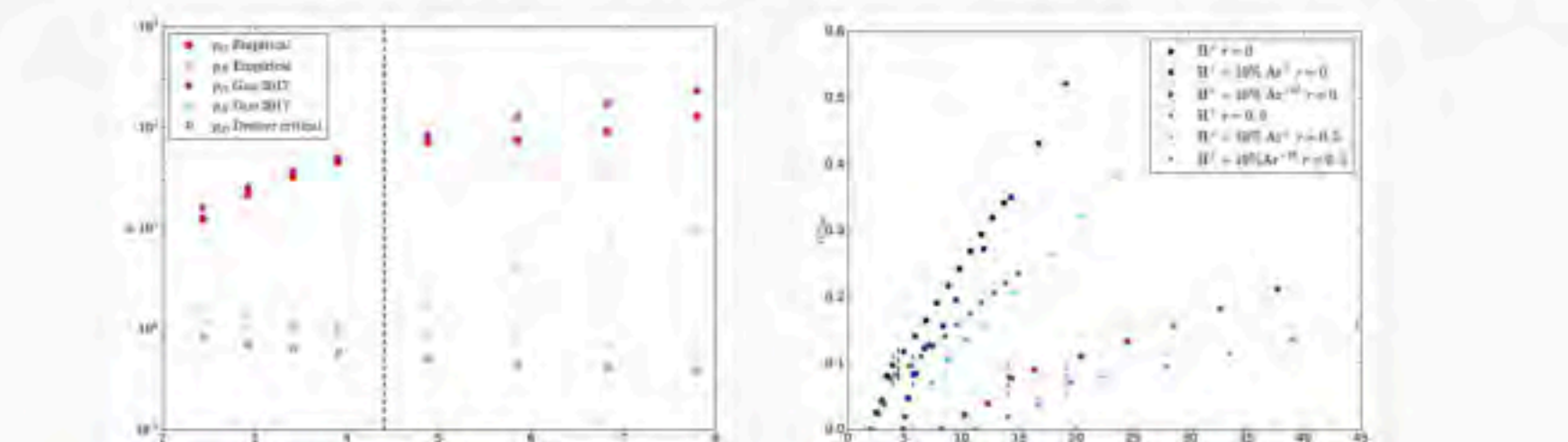
- New development in VPIC allows plasma-neutral interaction and radiative cooling [6], both crucial to understand scrape-off of disrupting plasmas by the wall

- Plasma sheath near the cathode ($x = 0$ in the figure) greatly expands when current-carrying plasma scrapes off the wall, has strongly non-Maxwellian electron distribution [7]



Runaway electron dynamics

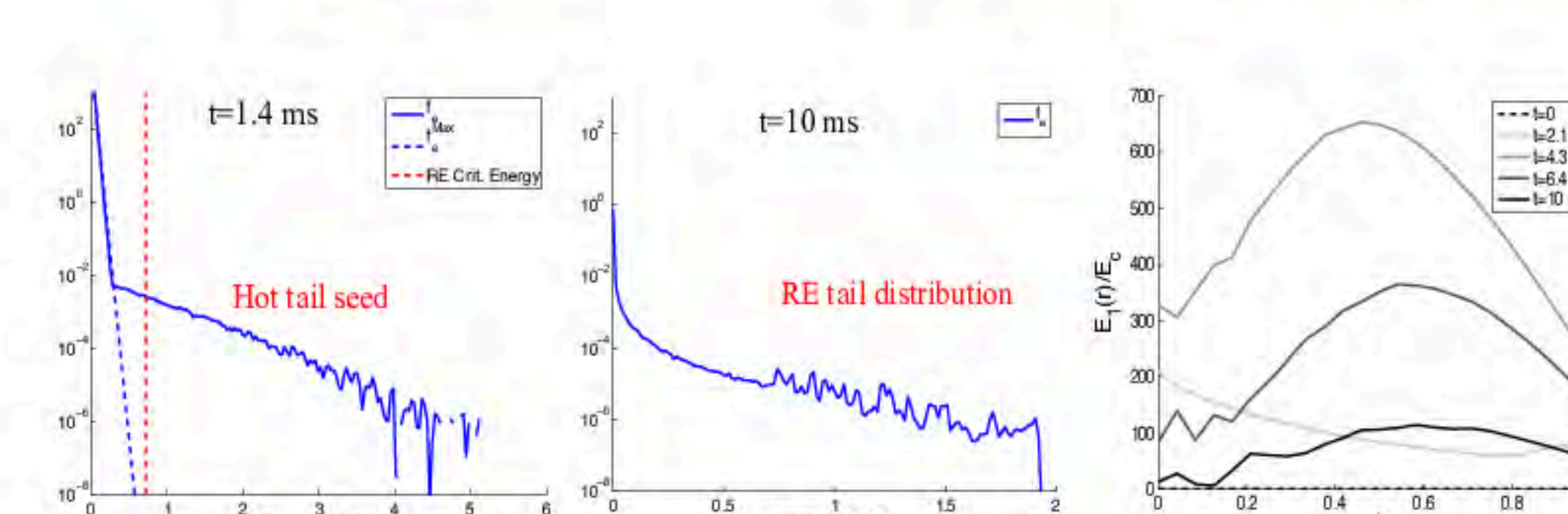
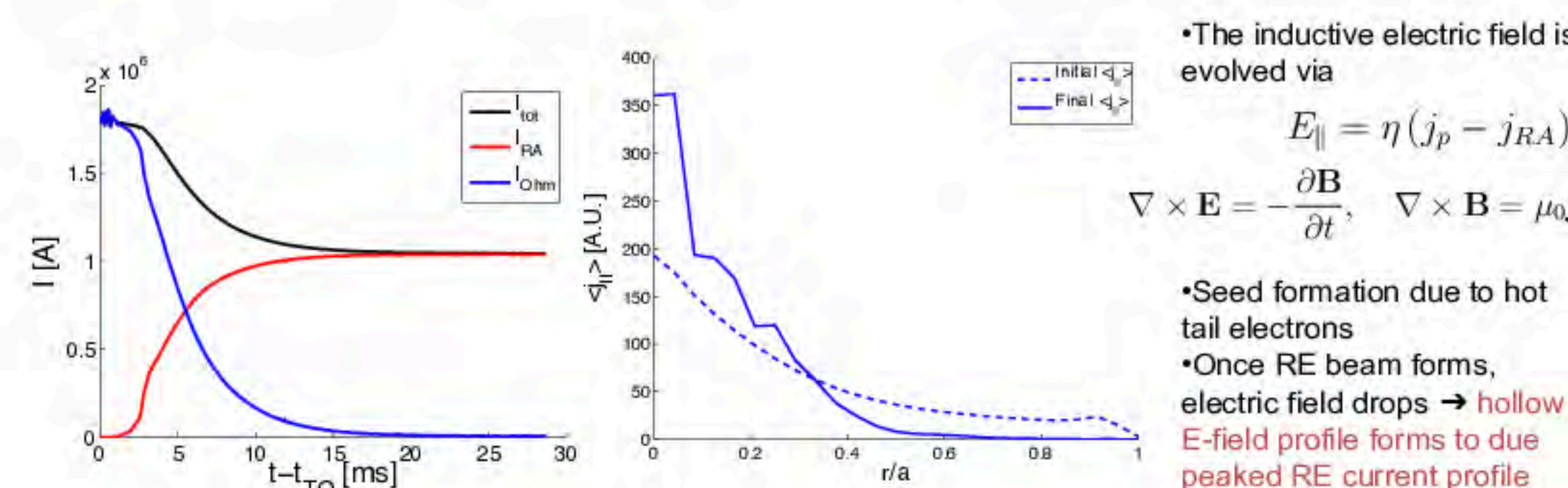
- Runaway vortex [8,9] and avalanche knee [10]
- Runaway vortex: p of X point reverses trend as E increases
- Correlates with an avalanche knee: runaway vortex regime versus Rosenbluth regime of avalanche growth rate as a function of E



- Self-consistent runaway dynamics (axisymmetric plasma)

- A 3D-2V relativistic drift kinetic solver has been developed to accurately account for runaway formation and evolution during a tokamak disruption [11]

- Self-consistent evolution of flux-surface averaged inductive electric field
- Transport and finite orbit width effects [12]
- Provides an efficient means of evaluating magnitude and spatial profile of runaway current

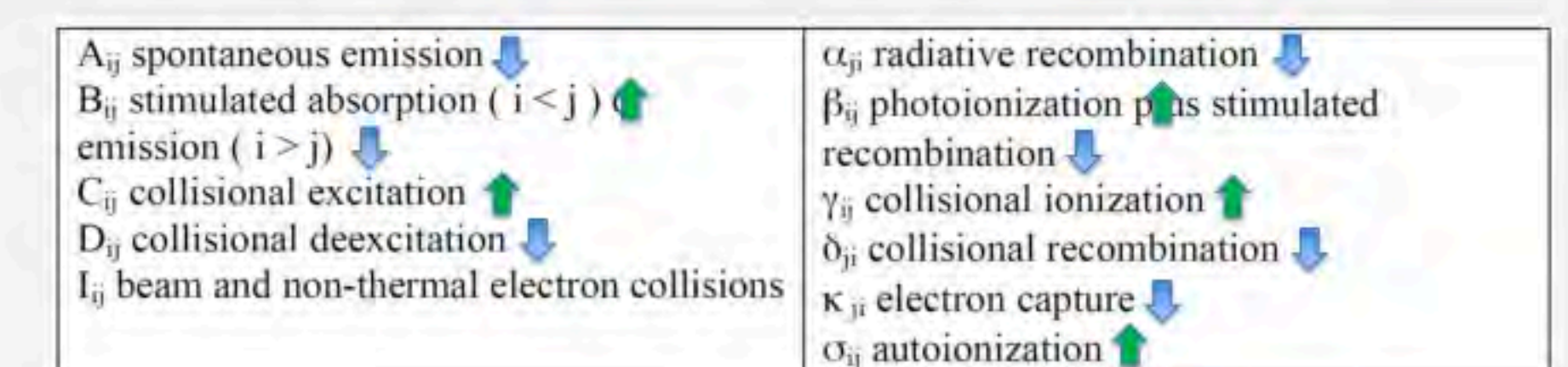


Runaway modification of charge state distribution and radiation power loss rate

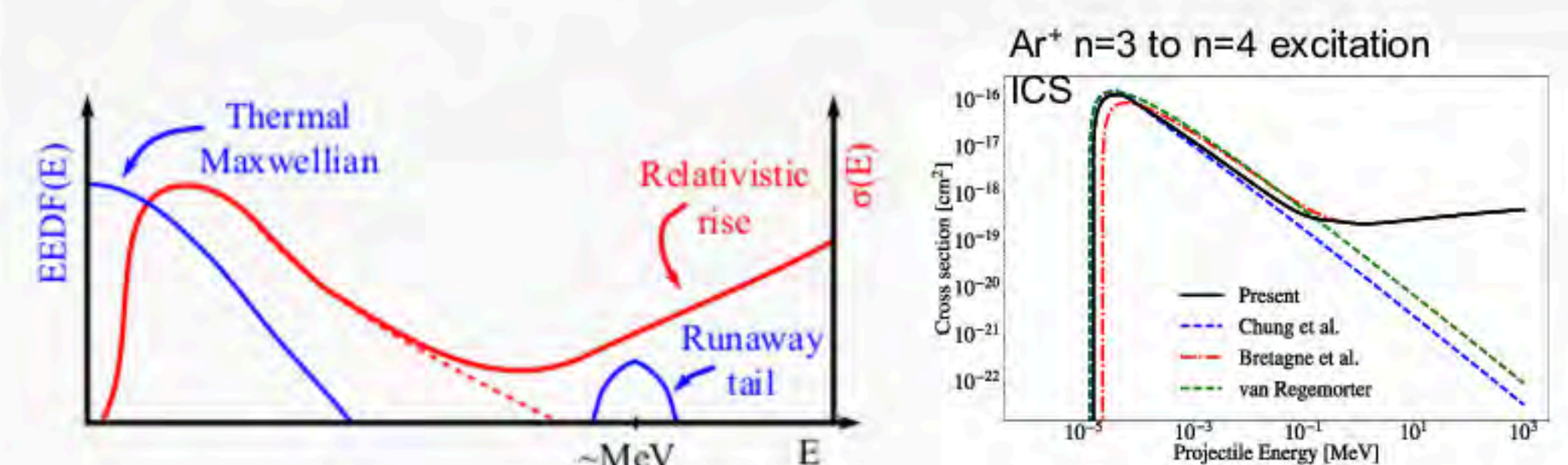
- Ion charge state distribution and radiation power loss rate are described by collisional-radiative model

- Account for populations of states (ion level, excited state) undergoing collisional-radiative transitions [13]

$$\frac{dn_i}{dt} = -n_i \sum_{j \neq i} W_{ij} + \sum_{j \neq i} n_j W_{ji} \quad 1 \leq i \leq N_L$$

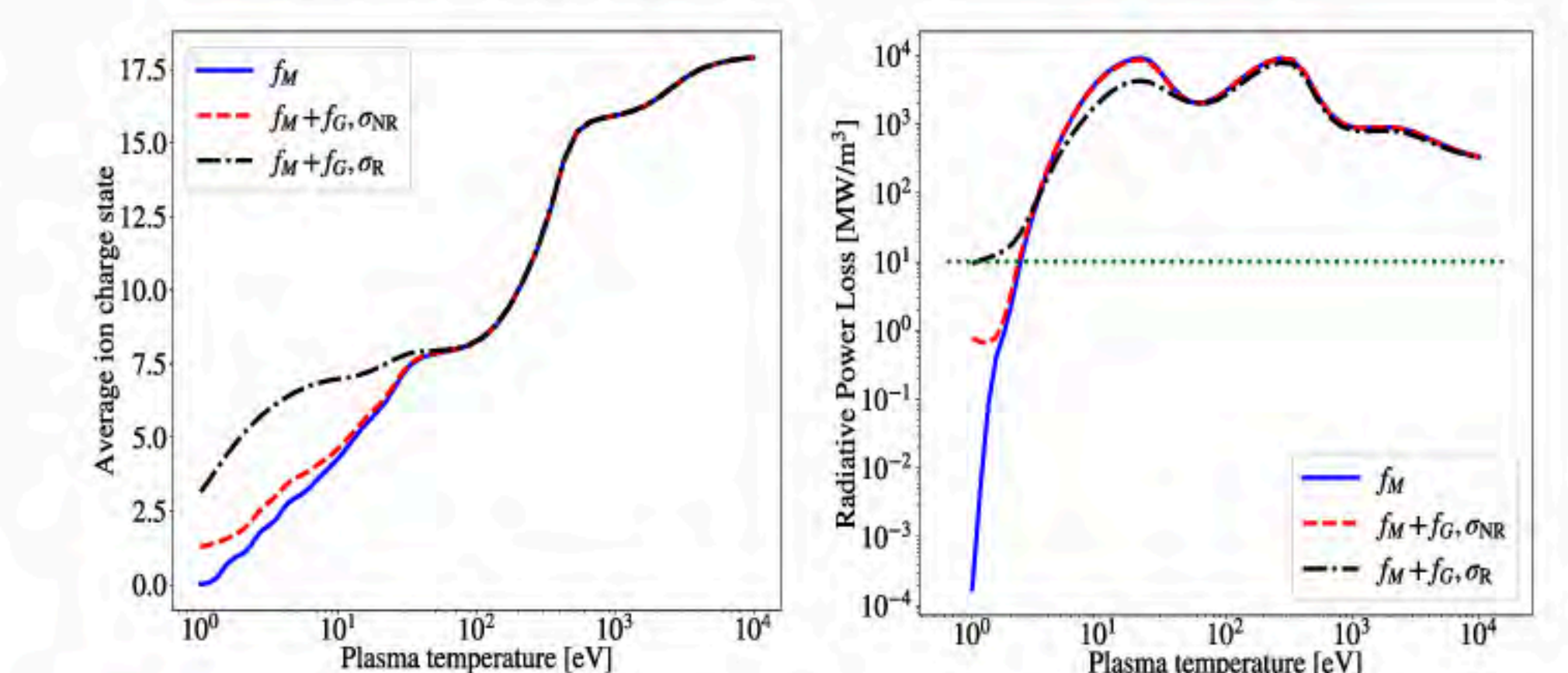


- QED effect boosts ionization and excitation cross section at relativistic energy



- With a cold background plasma, runaways can dominate the charge state distribution and radiative power loss rate

- $n_{Ar} = 10^{14} \text{ cm}^{-3}$; Runaway fraction (10^{-3} - 10^{-4}) carrying an ITER-like current (~ 10 MA) [14]



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