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

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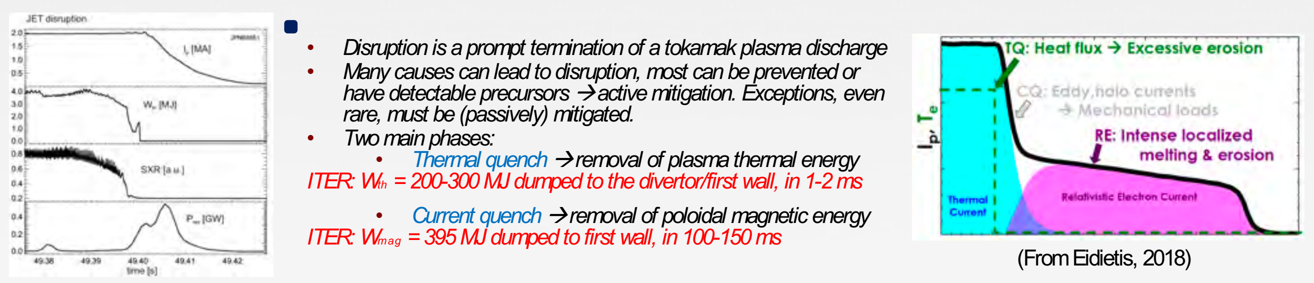
Abstract / Motivation

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



(From Eidietis, 2018)

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)

Meet the challenge of disruption-induced runaway electrons

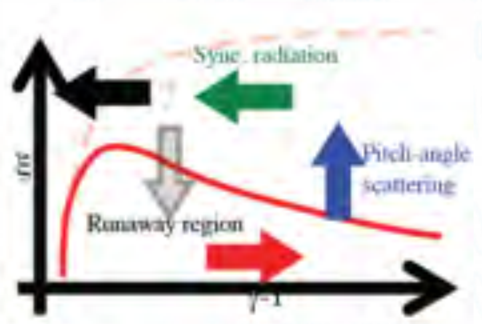
Strategy: avoid the runaway if possible, otherwise mitigate the damage on plasma-facing components by controlling (limiting) the runaway energy

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

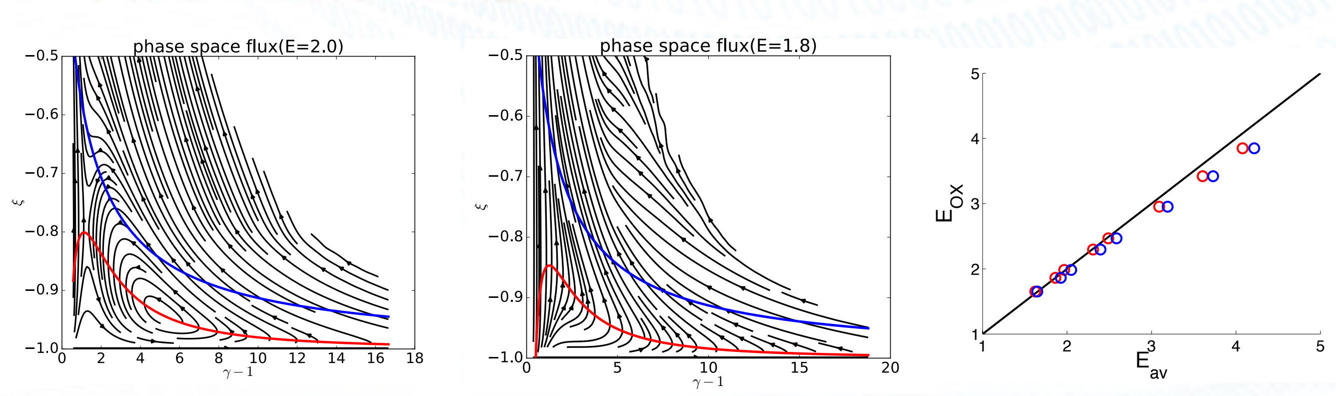
➢ Runaway Avoidance (Suppression):

Ideal but impractical: stay below the Connor-Hastie threshold electric field → no runaways

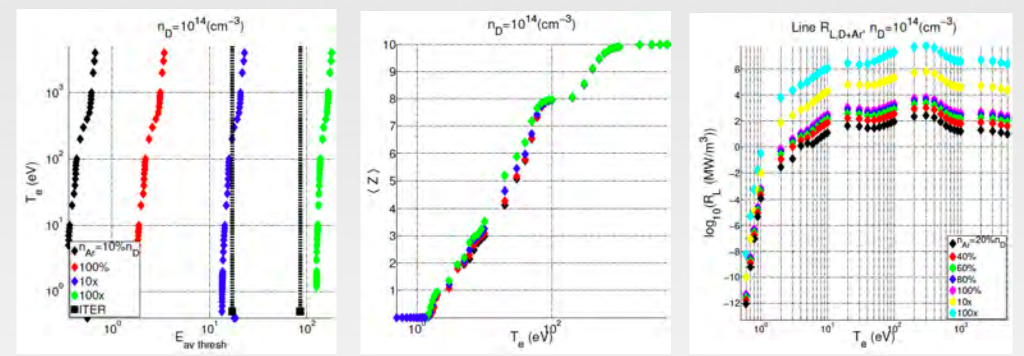
Realistic target: stay below the runaway avalanche threshold electric field → limit the runaway density (current fraction)



Momentum space topological (runaway vortex [1,2]) transition sets avalanche threshold E_{av} [3]

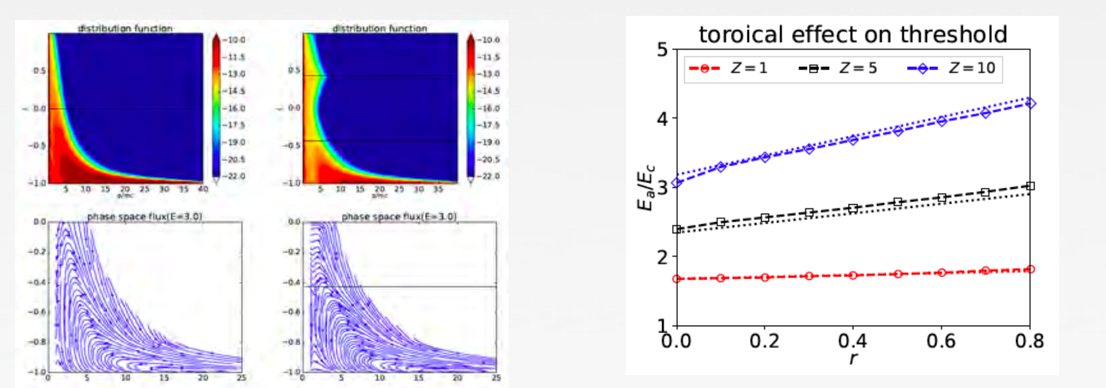


- Partial screening of high-Z impurity atoms → large pitch angle scattering rate for runaways → much higher E_{AV}
- On ITER $E<E_{av}$ still requires extremely high impurity density [4]



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

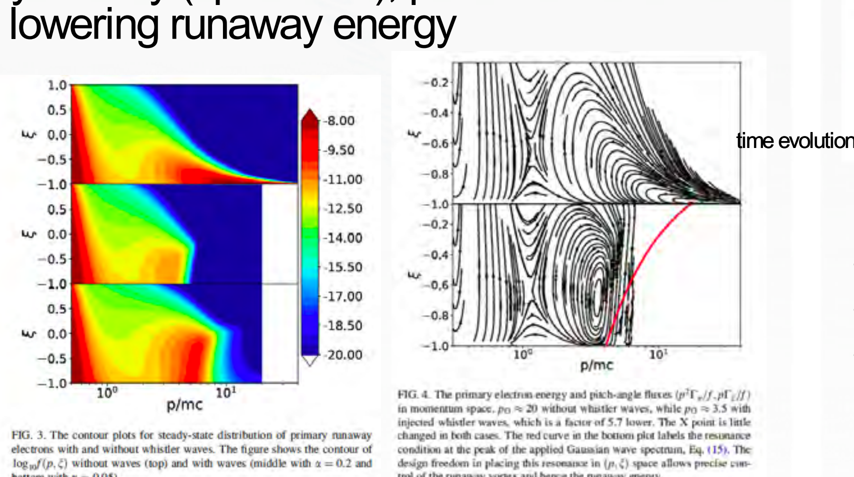
- Torodicity reshapes runaway vortex→larger E_{av}, only with high-Z impurity [5]



➢ Runaway energy control

Basis: runaway current ~ runaway density (speed is c); power flux ~ runaway energy → mitigation by lowering runaway energy

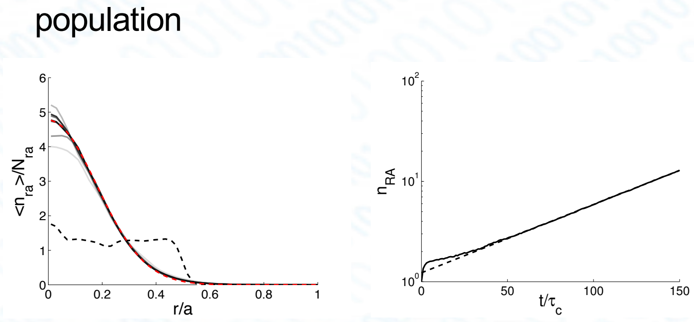
- Impurities can lower runaway energy at fixed electric field -- Location of runaway vortex depends on impurity content
- Prompt loss via 3D magnetic fields can limit the runaway energy gain through confinement degradation.
- For an otherwise fixed plasma discharge condition, resonant wave-particle scattering via externally injected whistler wave, can reshape the runaway vortex by removing high energy part. [6]

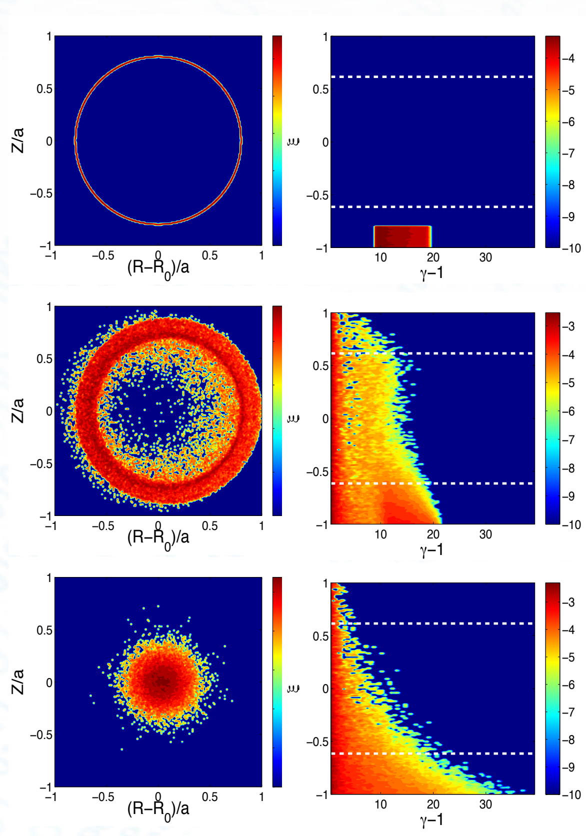


➢ Runaway transport

Key findings: in a strongly mitigated disruption, spatial transport is strong (diffusion + ware pinch) → avalanche spatial eigenmode [7]

- 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





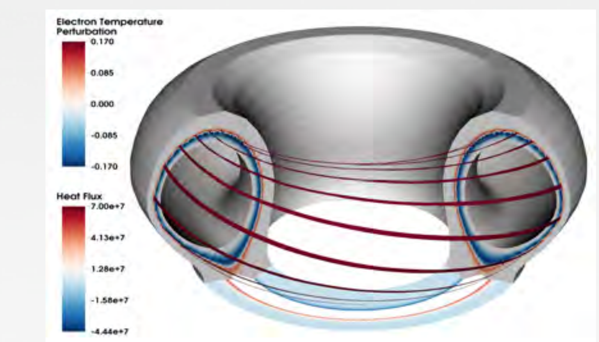
Runaway electron simulations are performed by LAPS-RFP code: relativistic Boltzmann-Fokker-Planck for both small- and large-angle collisions, radiation damping, quasilinear diffusion for wave-particle interaction, bounce-average; has both continuum and particle methods

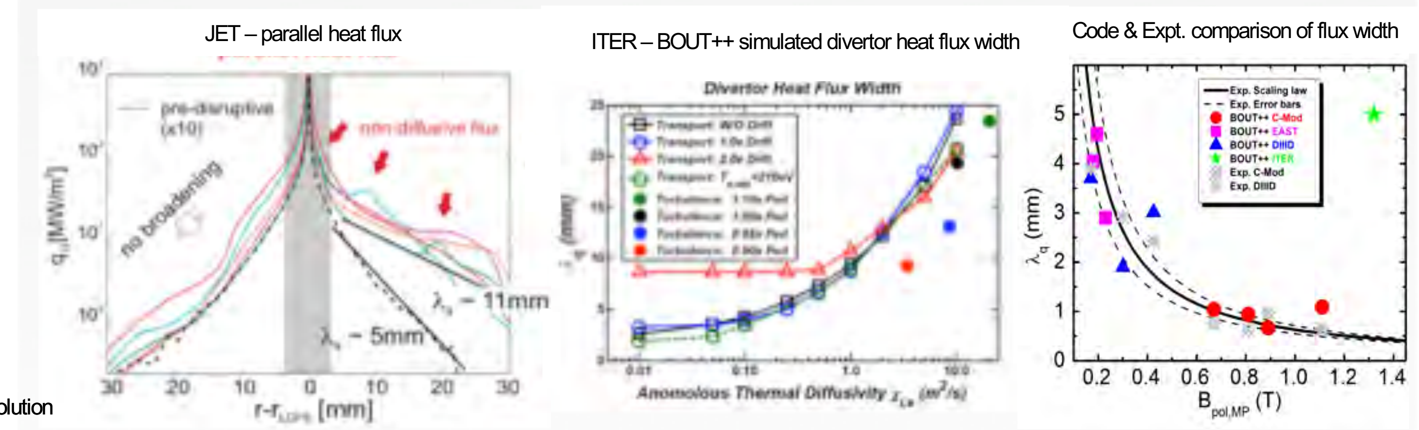
Meet the challenge of disruption-induced particle & energy exhaust

➢ 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
  - Significant scrape-of-layer broadening, in the range of 5-20,
  - Significant toroidal and poloidal inner/outer asymmetry

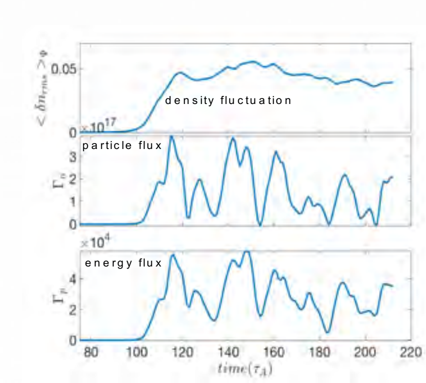
- The core temperature collapses in τ_{TQ}~1 ms, the peak thermal load arriving at the divertor is spread over a longer time period τ_d. On JET, for density limited disruptions, τ_d/τ_{TQ} is observed to be 3-8.
- Ideally, favorable mitigation would result in the largest λ_{TQ} and the longest τ_d that are possible



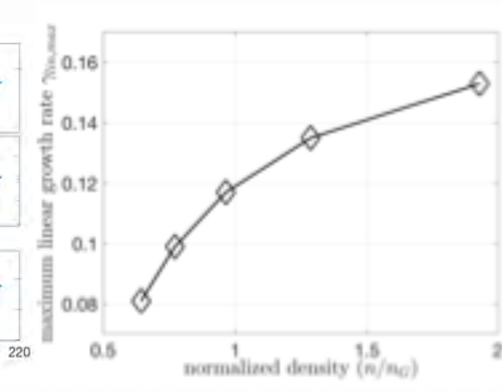


➢ Uncover the physical processes for density limited disruptions

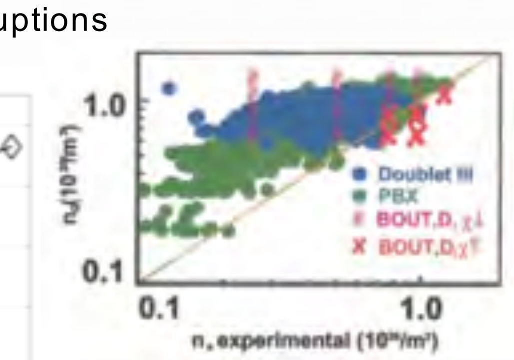
- Six-field fluid simulation of DIII-D shot #110222
- Proceed to Greenwald limit by ramping up density
- At high edge density, perpendicular turbulent transport dominates parallel classical transport, leading to substantially reduced contact with divertor plates, and the region of high transport then extends inside the last closed flux surface
- Impurity radiation leads to an X-point MARFE, edge cooling, current profile shrinkage , and finally density-limit related disruptions



Time evolution at separatrix



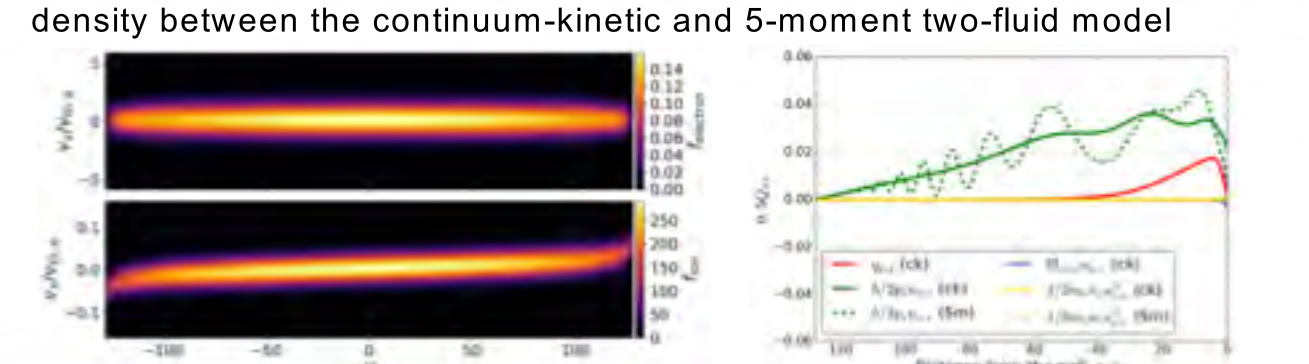
Maximum growth rate vs density



A contour plot of transport coefficient at separatrix versus plasma current n∝Ip/πa[2] and line averaged density. The large transport boundary (at the separatrix D > 10m^2/s) shown by the x's is consistent with experimental operational density limit

➢ Uncover the kinetic physics of boundary plasma and PSI

- Self-consistent modeling of sheath/presheath taking into account the interactions between plasma/neutral/radiation
- Distribution function of electrons and ions using a continuum-kinetic code to study sheaths, and comparing the different terms of the particle energy flux density between the continuum-kinetic and 5-moment two-fluid model



Meet the challenge of disruption-induced core temperature collapse

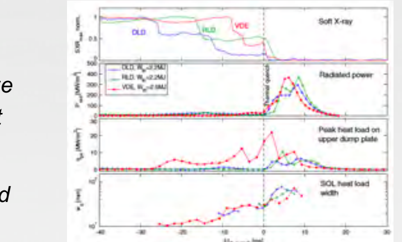
Plasma cooling history → Ohmic-to-runaway current conversion

- *Key core and core/edge coupling transport issues*

  How 3D magnetic fields set the time duration of core thermal collapse due to enhanced plasma transport

  thermal quench onset & duration

  How does impurity produced by PMI get transported into the core plasma?

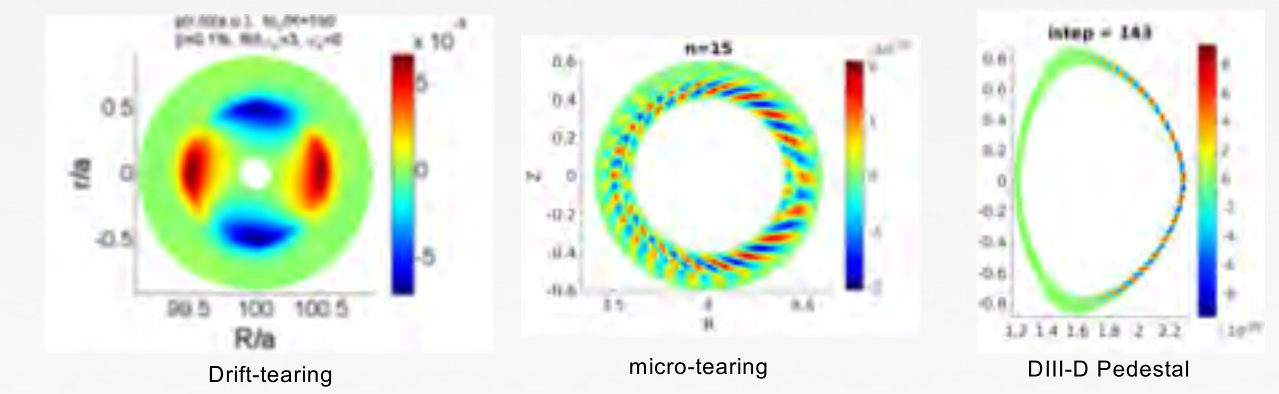


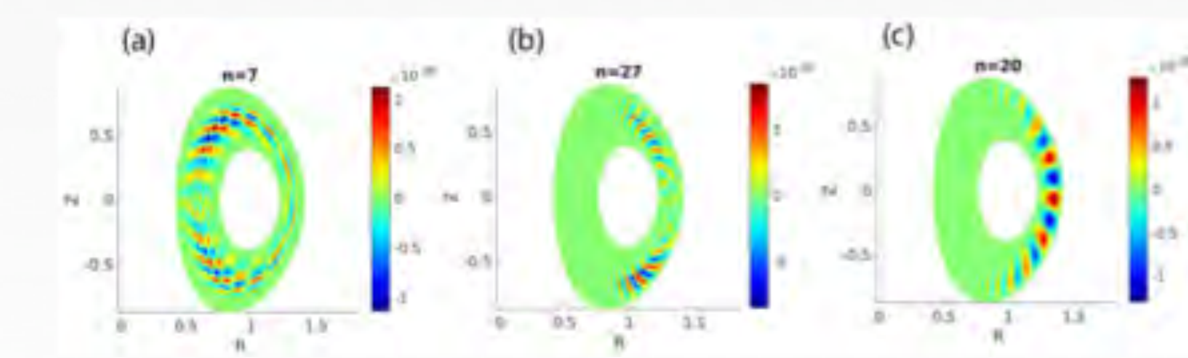
Amoux, JET, NF (2009)

➢ Towards self-consistent plasma transport & magnetic dynamics

Critical capability enhancement for electromagnetic version of GTS gyrokinetic code

Successful benchmark of a variety of modes in different tokamak geometries

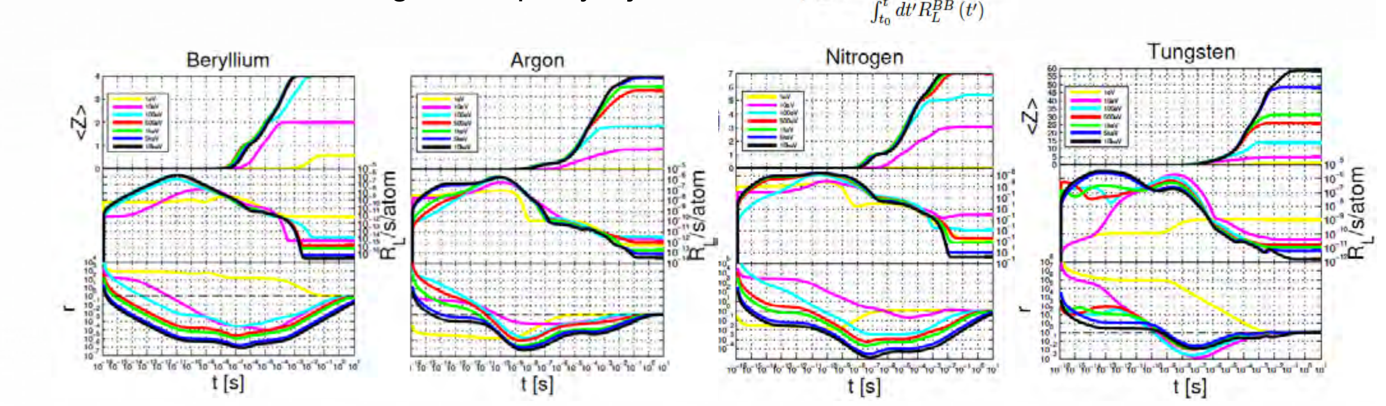




NSTX electron beta scan of (a) 0.5%, (b) 1.6%, and (c) 3.2%. With increasing electron beta, the unstable low-n micro-tearing mode (MTM) (a) which has its maximum on high-field side switches to high-n MTM (b) on he low-field side. In the highest electron beta case (c), kinetic ballooning mode is destabilized on the low-field side of NSTX.

➢ Towards improved radiative cooling with high-Z impurities

Time-dependent collisional-radiative model is essential to understand transient radiative radiative cooling with impurity injection



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