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Quasi-interchange Modes and Sawteeth

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ABSTRACT

- Fast sawtooth-type crashes in tokamaks and other fusion plasmas that follow different types of MHD instability appear to be interchange instabilities driven by the large normal (poloidal) magnetic curvature created by the background instability
- Common features: rapid onset, fast and accelerating growth rate, nearly ideal nature, strong poloidal localization of similar widths (flow ``nozzle''), final radial expulsion of plasma beyond the original rational q surface; seen in experiments and simulations

BACKGROUND

- Fast sawtooth crashes that flatten the central pressure and current in fusion plasmas have many common features, despite differences in the initial MHD instability: resistive $q_s=1$ internal kink (IK) modes and $q_s>1$ double tearing modes (DTM), nearly ideal $q_s=1$ quasi-interchange (QI) modes
- Previous work has usually considered the crash to be a nonlinear extension of the initial instability, but ignores major differences
  - Different driving factors: The original instability can continue to grow as the fast crash begins; it is terminated by the flattening of the final crash
  - Fast crash is nearly independent of resistivity regardless of the type of the initial instability
- New work on the $q_s=1$ QI sawtooth helps clarify the difference.
  - QI is nearly ideal, but its plasma configuration just before the crash has similarities to the resistive double tearing mode (DTM) configuration

RESULTS

INITIAL INSTABILITIES HAVE THEIR OWN QUIRKS

- q=1 internal kink sawtooth: hot core must become small to have a narrow poloidal curvature at q=1; fast crash starts late. Seen in experimental 2D ECE Imaging (e.g., TEXTOR, H. Park, PRL) and MHD simulations (Fig. 1).

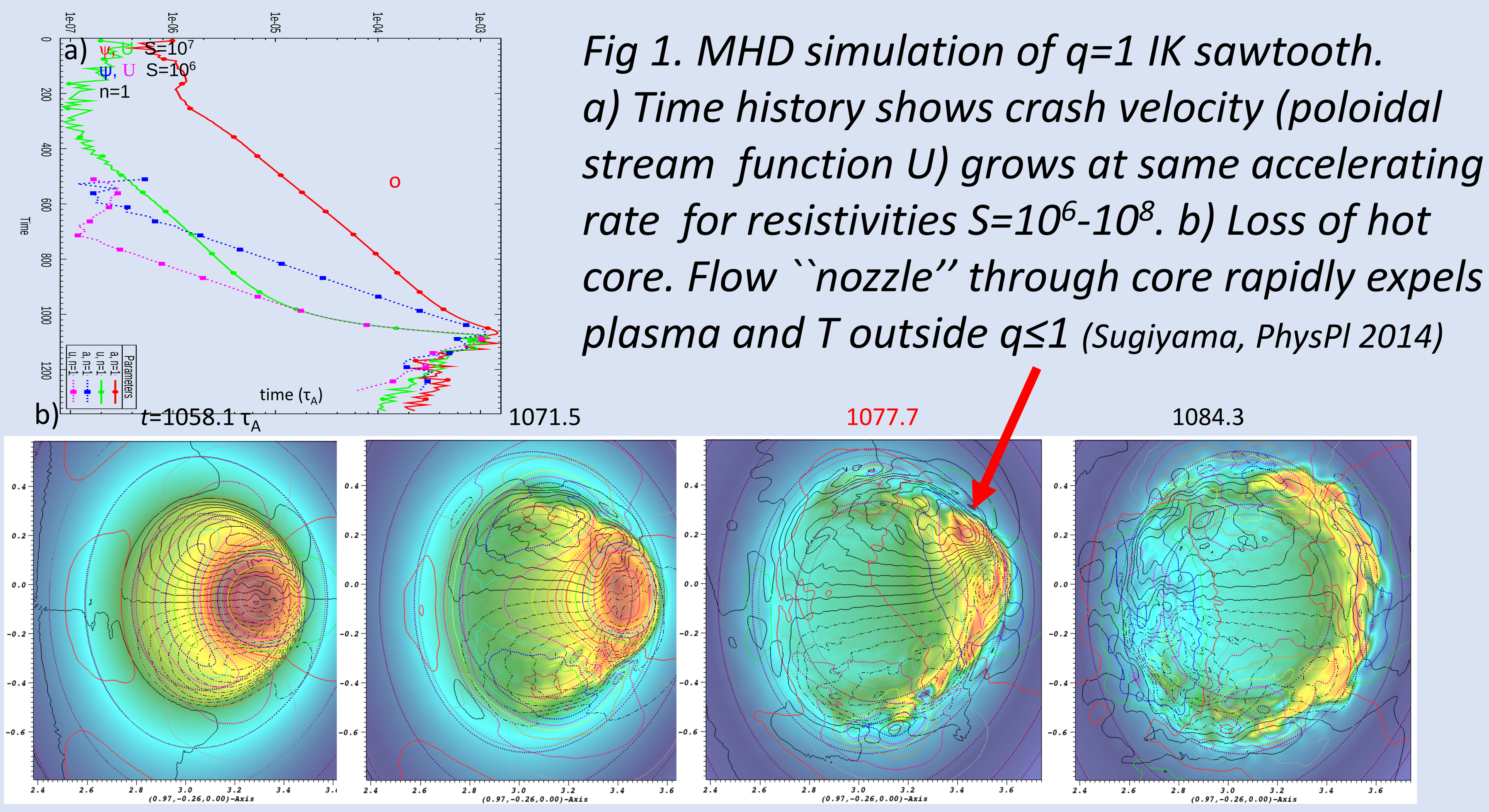


Fig 1. MHD simulation of q=1 IK sawtooth. a) Time history shows crash velocity (poloidal stream function U) grows at same accelerating rate for resistivities $S=10^6$-10^8. b) Loss of hot core. Flow ``nozzle'' through core rapidly expels plasma and T outside q≤1 (Sugiyama, PhysPl 2014)

- DTM: two $q_s=m/n$ surfaces around $q_{min}<q_s$. Magnetic islands start at each surface, with X- and O- points anti-aligned. Outer islands grow large, squeeze inner islands into narrowing ``spokes'' on a wheel. Spokes extend radially out to outer q_s surface (c); interchange triggered there (Fig. 2)

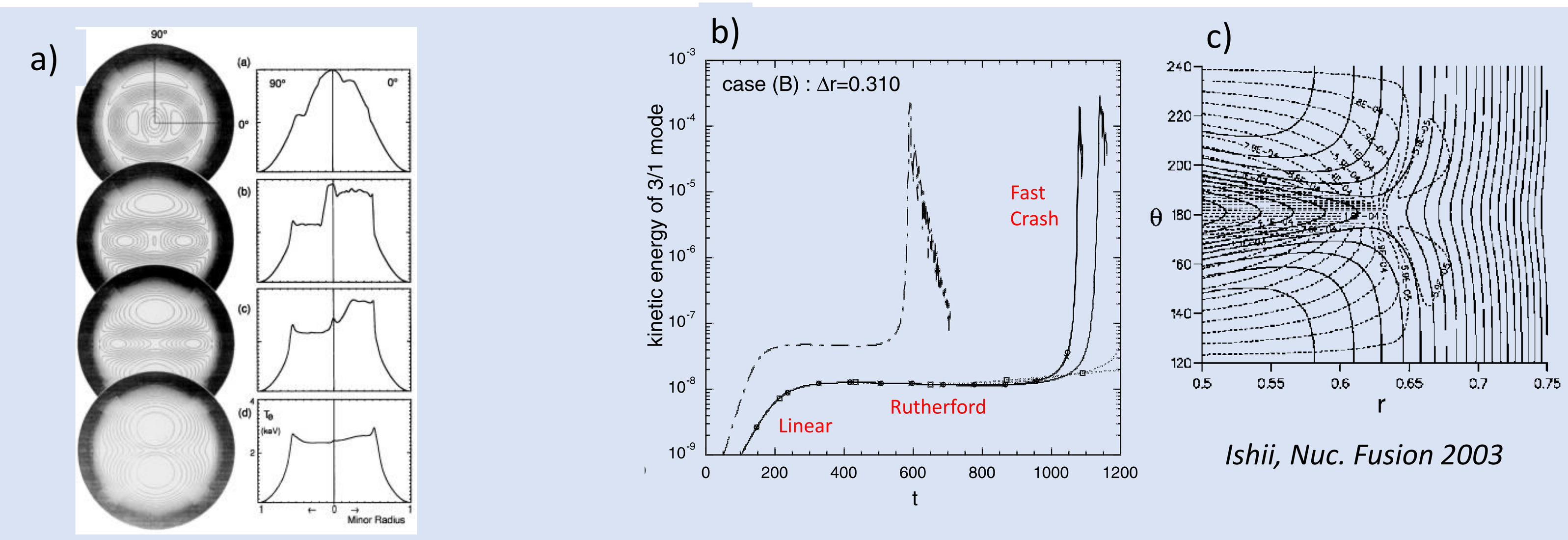


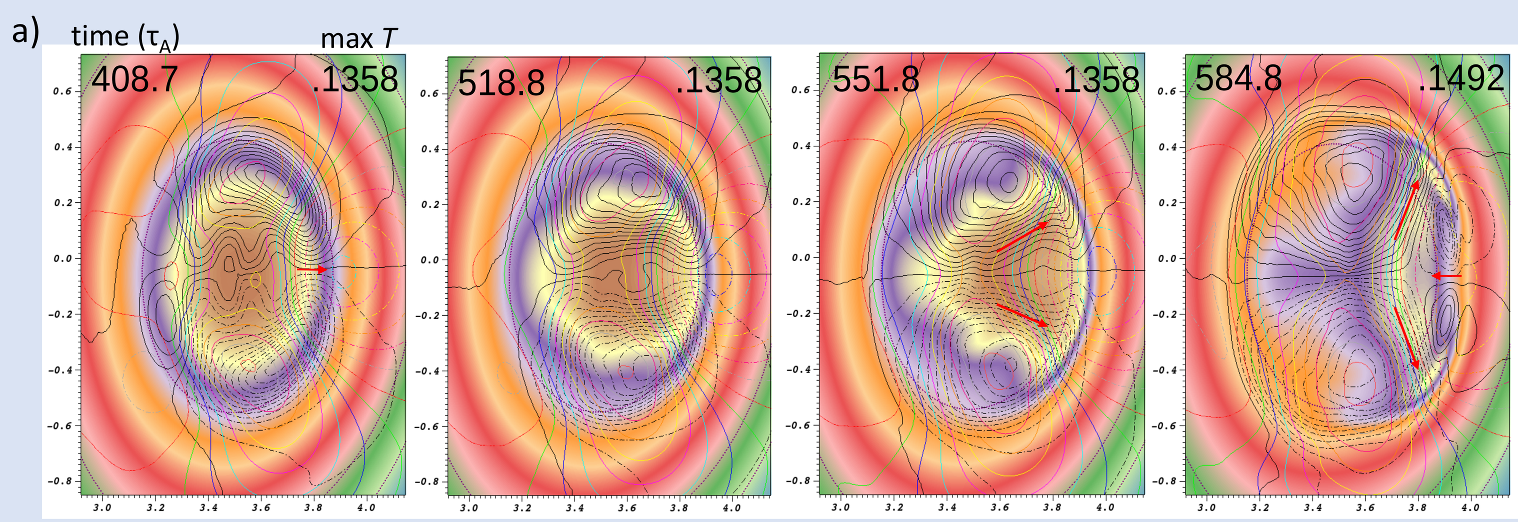
Fig 2. a) q=2 DTM, TFTR simulation (Chang, PRL 1996). b,c) q=3 DTM simulation, showing b) growth phases. c) Inner island narrows to fast crash.

RESULTS Cont'd

NORMAL CURVATURE INTERCHANGE DIFFERS FROM EQUILIBRIUM MODE

- Free energy $\int d^3x\, \boldsymbol{\xi} \cdot \mathbf{G}(\boldsymbol{\xi})$ of fast growing perturbation triggered on top of a slowly changing non-axisymmetric background created by the initial instability. Background flows kept, but mostly small.
- Same interchange term $(\boldsymbol{\xi} \cdot \nabla p)(\boldsymbol{\xi} \cdot \boldsymbol{\kappa})$, where $\boldsymbol{\kappa}$ is magnetic curvature. Equilibrium has large geodesic curvature (lies in the flux surface), forcing mode to have large geodesic displacement $\boldsymbol{\xi}_g$ and small radial $\boldsymbol{\xi}_r$. A large normal (i.e., poloidal) curvature allows large $\boldsymbol{\xi}_r$ and strong interchange.
- Typical fast crash normal curvature corresponds to poloidal harmonic m~6, compared to geodesic m≲1, a large increase in free energy.
- RMHD conundrum: Interchange term comes from compressible term $(\boldsymbol{\xi} \cdot \nabla p)(\nabla \cdot \boldsymbol{\xi})$, which is zero in RMHD. Possible to derive from **J**×**B** directly, as $(\boldsymbol{\xi} \cdot \mathbf{J}\times\mathbf{B})(\boldsymbol{\xi} \cdot \boldsymbol{\kappa})$. Consistent with analytic RMHD DTM solution (Dewar, et al 1993).

- q=1 low magnetic shear QI sawtooth in DIII-D. Initially, both n=1 and 2 harmonics. Driven by cross-field interchange flows; no resonant reconnection. 1/1 mode splits to two channels at symmetrical poloidal angles; core narrows to a 'bent angle' with bend near the magnetic axis and legs that resemble DTM spokes. (Fig 3.)



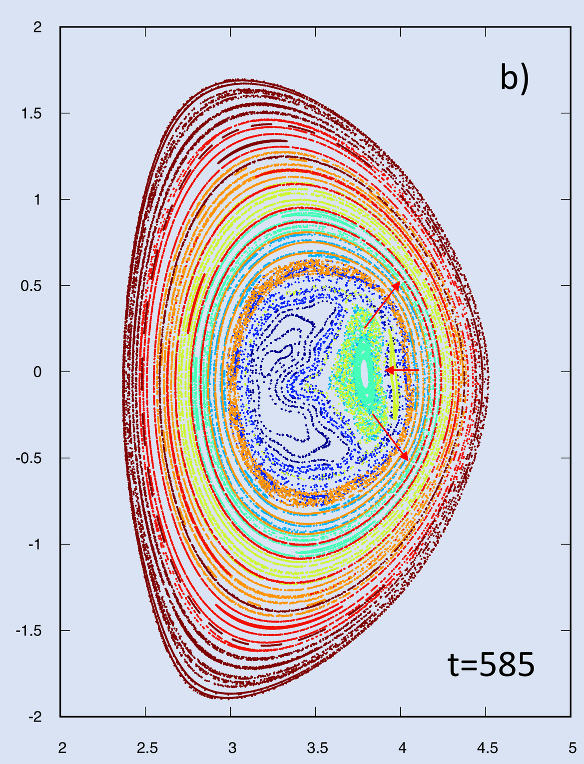


Fig 3. q=1 QI sawtooth, M3D MHD simulation of DIII-D plasma. a) Temperature in core (color) and QI mode outflow (red arrows, follows velocity stream function, black contours). Outflow splits; fast crash flows through two channels to roughly 1/4 to 1/3 the distance between q=1 and q=3/2 ($t=584.8\tau_A$). b) Magnetic puncture plot approximately follows flow channels .

CONCLUSION

- Unifying theory of fast sawtooth crashes in tokamaks and other plasmas
  - Fast sawtooth crashes may be interchange modes driven by a large, localized normal (poloidal) magnetic curvature produced by an initial MHD instability that grows to large amplitude.
  - Typical MHD instabilities (1/1 modes, DTMs) can easily create such conditions
- An interchange trigger and nature can explain many of the properties of fast crashes that are seen in experiments and simulations.
- In fusion burning plasmas, higher pressure gradients may increase instability.

ACKNOWLEDGEMENTS / REFERENCES

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