Magnetic Reconnections Studies on MAST

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Objectives of Reconnection Studies

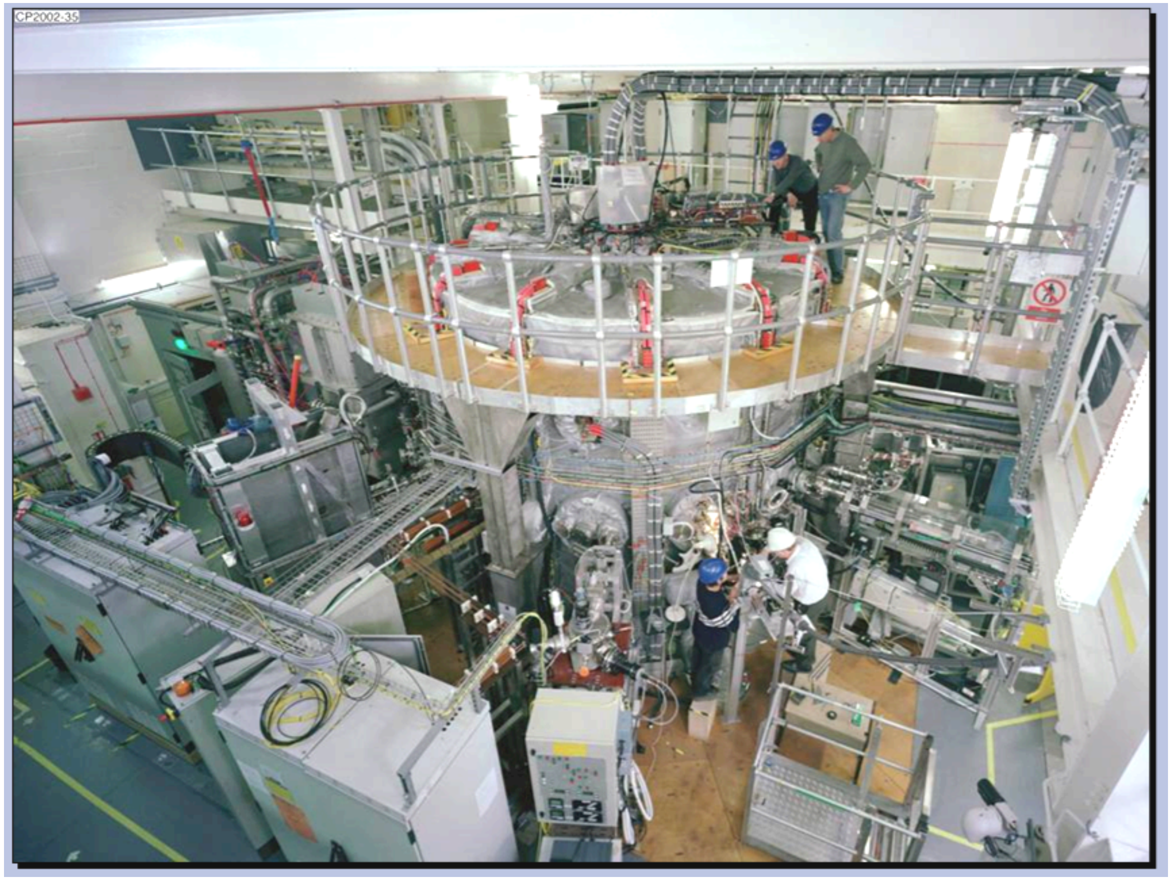
• Changes in topology of magnetic field lines ("magnetic reconnection") thought to play important role in redistribution of energy & particles in many astrophysical, space & laboratory plasmas

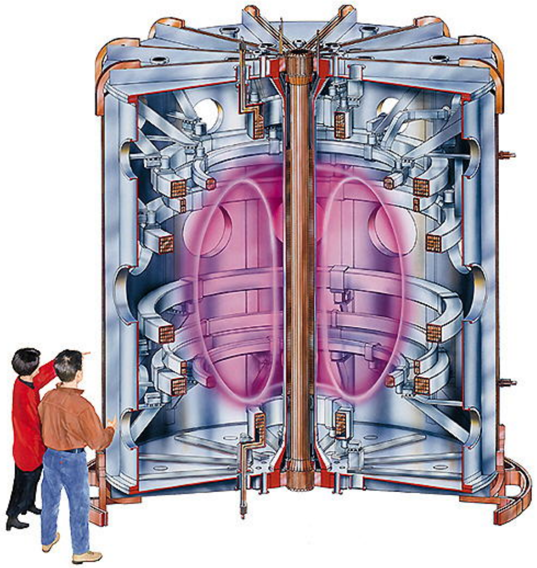
Three key elements of our studies:

- Provide reliable breakdown and current formation on MAST using merging-compression formation method
- Investigate magnetic reconnections in high temperature low collisional plasmas with extended MAST diagnostics facilities
- Validate reconnection theories providing experimental data for benchmarking

- Magnetic Reconnection studies in laboratory plasma may help understanding solar corona reconnections (and possibly predict consequences ?)

Mega Amp Spherical Tokamak MAST





R, m	0.85
a, m	0.65
k	2.4 (3)
I_p, MA	1.4 (2)
B_t, T	0.5
P_{aux}, MW	3 NBI (5) + 1 EC (1.5)
τ_{pulse}, s	0.75 (5)

Red – design values

Achieved core parameters:

T_i, T_e up to ~ 3keV; n_e ~ 10^{19}-$10^{20}m^{-3}$, β ~ 15% ;

Reconnection Studies on MAST

Reconnection studies during last 12 years in collaboration with University of Tokyo and NIFS, Japan:

- Internal Reconnection Events (IRE)

- Magnetic reconnection during merging-compression formation

• First collaboration on IRE studies on START and MAST, T Hayashi, NIFS

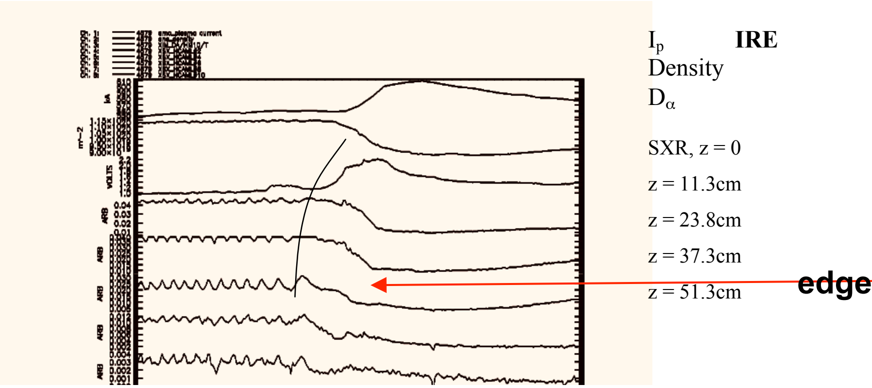
- modelling of START IRE, PhD of Naoki Mizuguchi
"Simulation Study on Relaxation Phenomena in Spherical Tokamak"
March 31, 2000

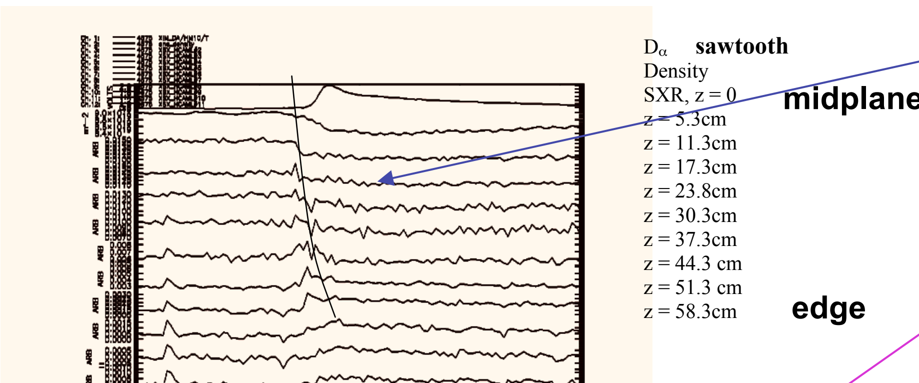
• Followed by collaboration with the University of Tokyo

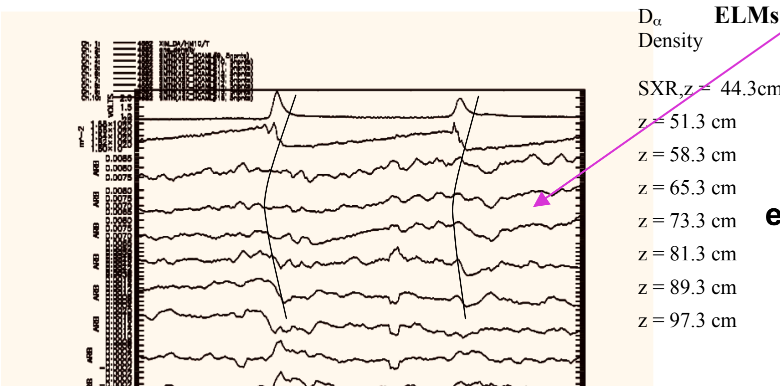
- studies of MAST IREs, PhD of Hiroshi Tojo, 2008
- merging-compression studies, PhD of R Imazava, 2010
- several visitors: Takuma Yamada, Hiroshi Tanabe (current PhD student)
– on reconnections studies

Close contacts with a number of theory groups at Theory Division of CCFE, Oxford University, Manchester University, St Andrews University etc.

Reconnections in tokamaks: IRE, sawtooth, ELM and "forced"







Spontaneous Reconnections:

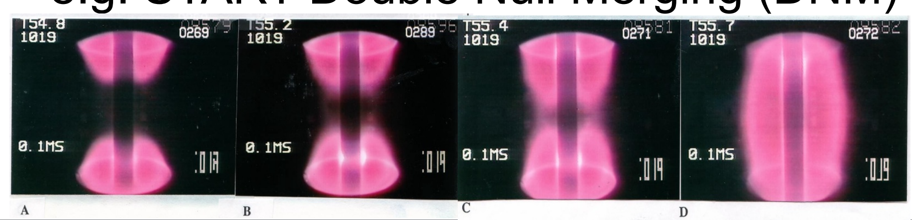
MAST, chord SXR signals

IRE: global reconnection, starts at periphery, penetrates to the core

- **Sawtooth:** core reconnection, starts at the core (q~1), penetrates to the edge
- **ELM:** edge reconnection, starts near the edge, penetrates in both directions

… and "forced" reconnections: merging of two plasma rings during formation

e.g. START Double Null Merging (DNM)



IRE: 3D resistive MHD simulations:

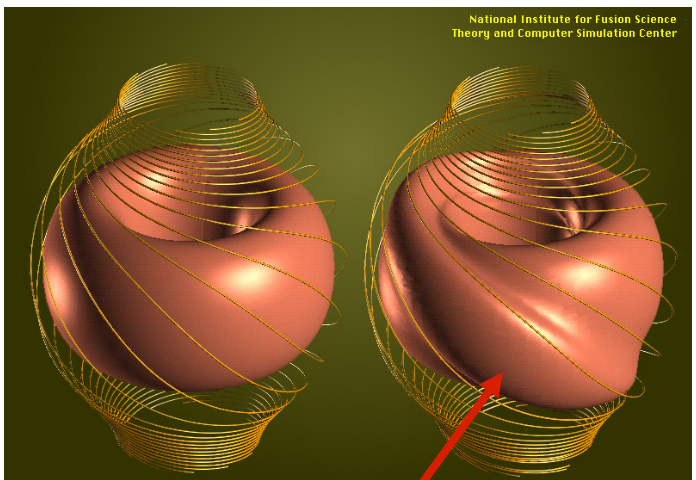
*N. Mizuguchi, T. Hayashi et al., Phys. Plasmas, **7**, 940 (2000)*

1. Plasma deformation

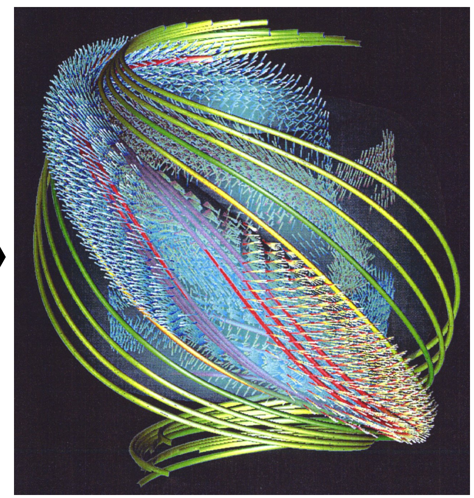
• IRE is a magnetic reconnection between inside and outside magnetic flux

2. During IRE plasma energy is lost along magnetic field lines through fast parallel transport

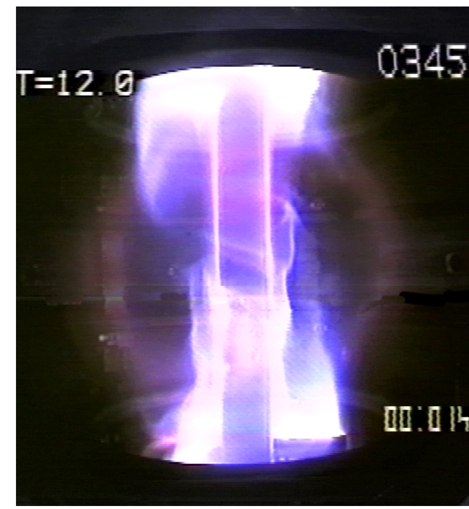
Plasma deformation



Energy flow

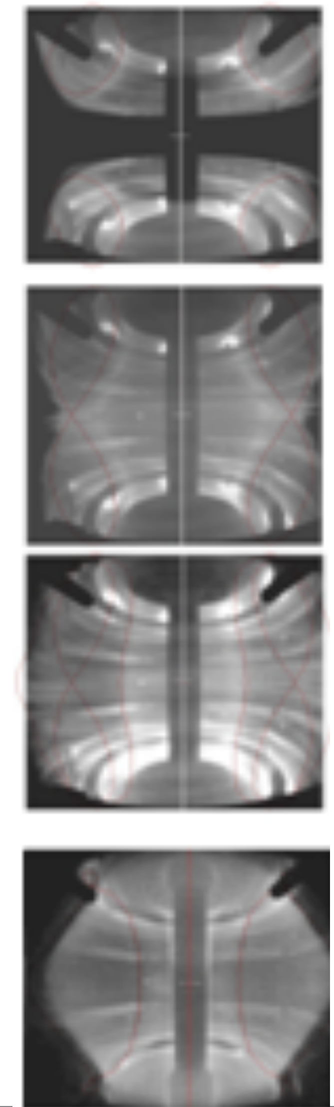


CCD picture, START



• Helical deformation, followed by reconnection, is caused by **linear and non-linear** growth and coupling of **pressure-driven modes**

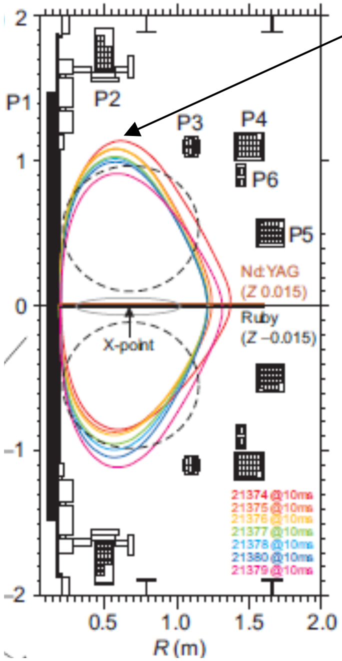
MR during merging-compression



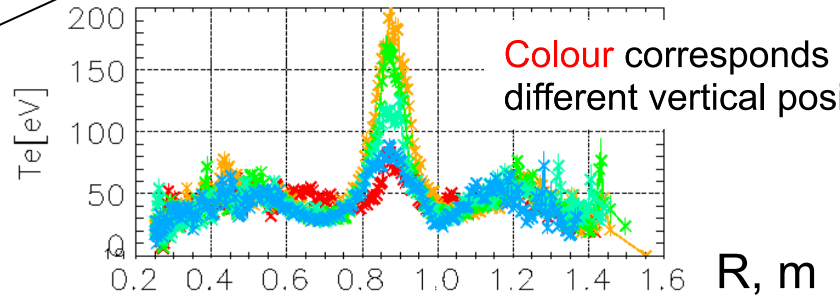
How 2D Te profile was measured:

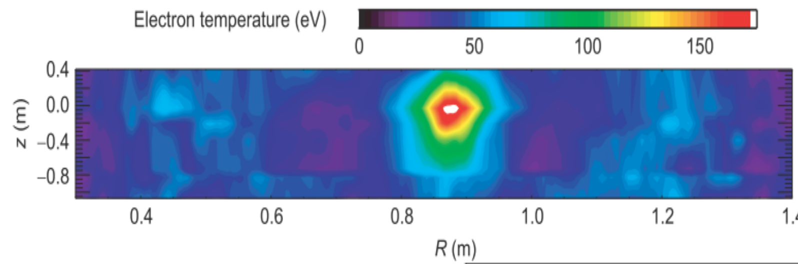
TS (Ruby and NiYg) measure horizontal (radial) profile

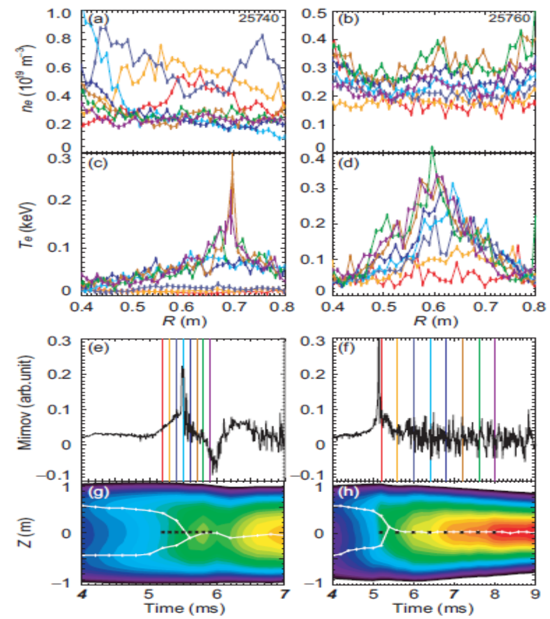
- plasma was shifted up/down to get vertical profile

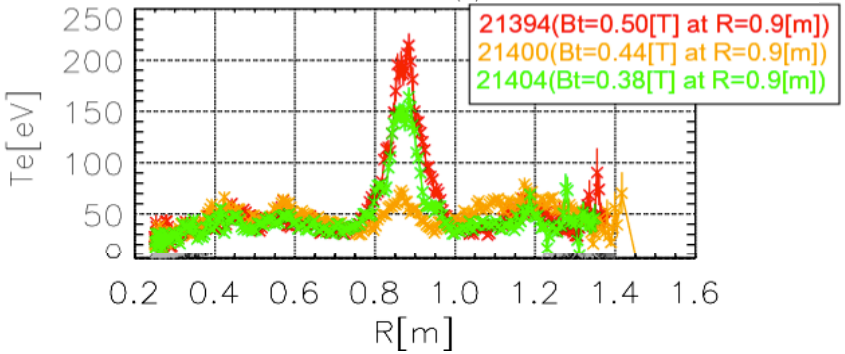


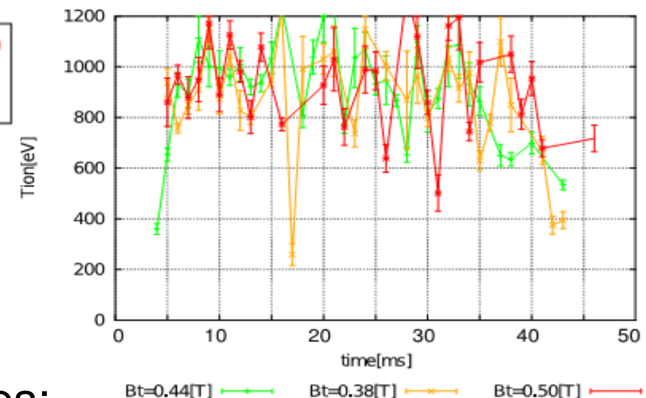
EFIT reconstructio
after reconnection











Toroidal field scan to benchmark reconnection theories:

Electron heating depends on B_t ! (but not ion heating ?)

Estimates of length & time scales

- Both electrons & ions strongly heated during merging compression in MAST, & at similar rates
- Some estimates of length & time scales (*Ken McClements*):

  Alfvén timescale $\tau_A \sim 2\pi/\omega_A \sim$ few μs

  2D T_e profiles $\Rightarrow$ current sheet thickness ~ 10 cm

  Identifying this as reconnection length scale δ_r, assuming Spitzer resistivity & setting T_e equal to 10^5 K ($\Rightarrow \eta = \eta_0 T_e^{-3/2} \sim 5\times10^{-5}$ ohm m)

  $\Rightarrow$ resistive timescale $\tau_r \sim 250\mu$s >> τ_A

  ion skin depth $\delta_i = c/\omega_{pi} \sim 14$ cm, electron skin depth $c/\omega_{pe} \sim 2$ mm,

  ion Larmor radius ~ 1 mm, electron Larmor radius ~ 0.01 mm

- electron inertia & finite Larmor radius effects negligible, but Hall term cannot be neglected in induction equation since $\delta_i \sim \delta_r$:

  $\Rightarrow$ two-fluid (or possibly kinetic) analysis of reconnection process is necessary

Estimates of length & time scales

- Based on rate at which plasma rings approach each other, assuming Spitzer resistivity with T_e~10 eV, magnetic Reynolds number is of order

$$R_m = \frac{\mu_0 LU}{\eta} \sim 10$$

- (NB R_m << Lundquist number since inflow velocity << Alfvén speed)
  - highly dissipative plasma
  - Post-reconnection el-ion collisional energy equilibration time $\tau_E \sim 10^2$ ms >> τ_r, & longer than actual equilibration time (~20ms)
- If T_e~T_i~10 eV electron collision time $\tau_e \sim 0.1\mu$s;

  ion collision time $\tau_i \sim 6\mu$s
- Simulations also potentially relevant to solar corona
  - plasma beta is similar & high Lundquist number $S \approx 10^5$ implies that resistive scale length could be comparable to or less than ion skin depth

Early Results from Fluid Simulations

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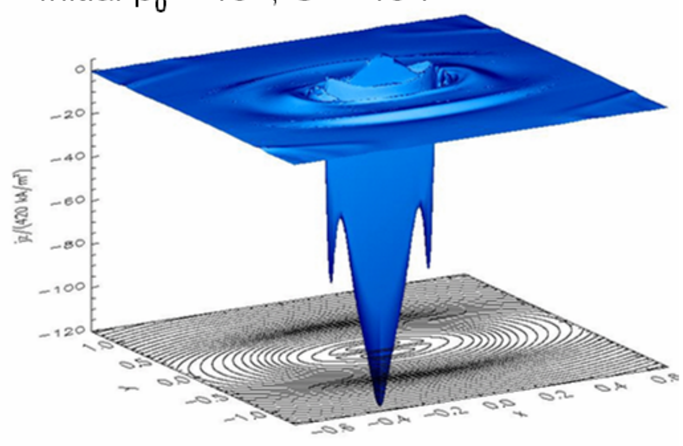
Set-up

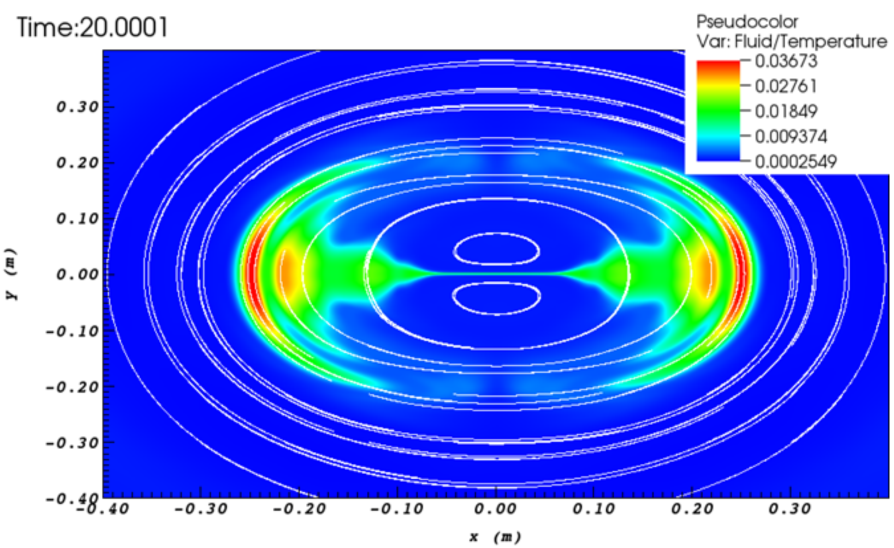
- Two plasmoids 200 kA each with width = 0.3 m.
- Initial separation = 0.8 m, starting in non-equilibrium (far from P3 coils).
- Constant toroidal field B = 0.5 T, density = 5 x 10^{18} m^{-3}, deuterium plasma.
- Initial $\beta_0 = 10^{-3}$, S = 10^5.



Current profile during the merging.

Results

- Merging time: $\approx 40\ \tau_A$ in resistive MHD (sloshing)
  $\approx 10\ \tau_A$ in Hall-MHD (δ_i = 0.14 m)
- Current sheet width ≈ 5 mm, pile-up field ≈ 0.15 T
- Temperature plots show similar hollow profile to experimental T_e measurements – significant heating contribution by viscous damping of outflows.



Temperature (colour) and B-field (white).

*See **Poster** by A. Stanier et al, **Fluid Modelling of Reconnection During Merging-Compression in MAST***

Modelling of Electron Heating During MR in MAST

Alessandro Zocco et al, CCFE, *see Alessandro Zocco and Alexander A. Schekochihin, Phys. Plasmas, 18(10) 102309, 2011*

• Electron thermal effects become very important, breaking the isothermal assumptions typically used in electron models, and driving electron-temperature-driven modes.

• Developed hybrid fluid-kinetic relies on a rigorous low-β_e expansion of the electron gyrokinetic equation - Kinetic Reduced Electron Heating Model (KREHM)

• The model contains collisions and can be used both in the collisional and collisionless reconnection regimes. The two-fluid dynamics are coupled to electron kinetics - electrons are not assumed isothermal and are described by a reduced drift-kinetic equation. The model therefore allows for irreversibility and conversion of magnetic energy into electron heat via parallel phase mixing in the velocity space.

• The model provides a new framework to understand experimental evidences of electron heating in MAST: numerical nonlinear studies (in some simplified cases) show evidences of non-isothermal effects in weakly collisional reconnection.

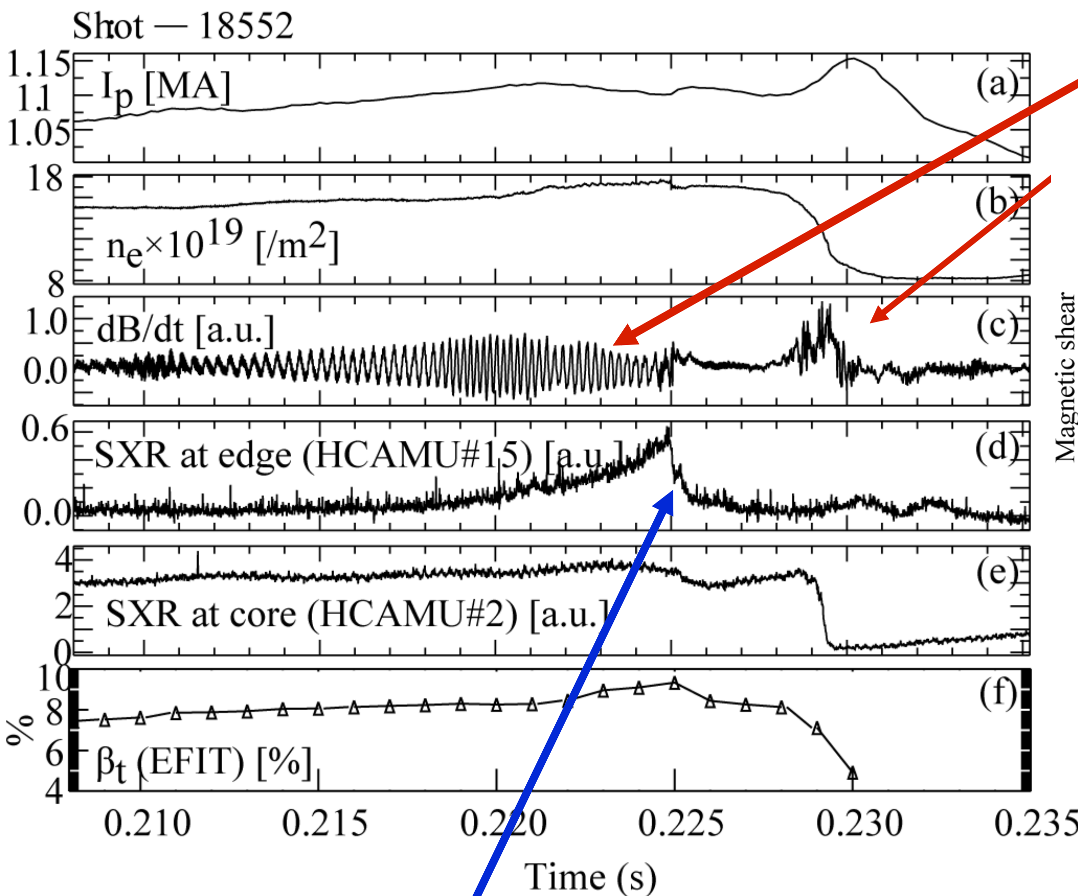
Summary

- Merging-compression method of start-up in MAST provides opportunity to study reconnection in high temperature plasma with strong guide field, under conditions approximating those of solar corona
- Reconnection associated with rapid heating of ions & electrons;
- High frequency instabilities & filamentary structures observed during & following reconnection, suggesting presence of fast ions & turbulence
- Detailed theoretical model of reconnection during merging-compression in MAST yet to be worked out and any such model would need to include two-fluid (& possibly kinetic) effects
- Focus of solar flare acceleration studies generally on electrons, since these can be detected whereas sub-MeV ions cannot (at least not easily); but MAST reconnection results suggest that reconnection leads more naturally to acceleration of ions than of electrons
- Detailed studies of ion and electron heating, utilising unique diagnostic capability of MAST, are on-going in collaboration with the University of Tokyo and other groups

Back-up slides

IRE with m/n=2/1 precursor and low-n mode coupling

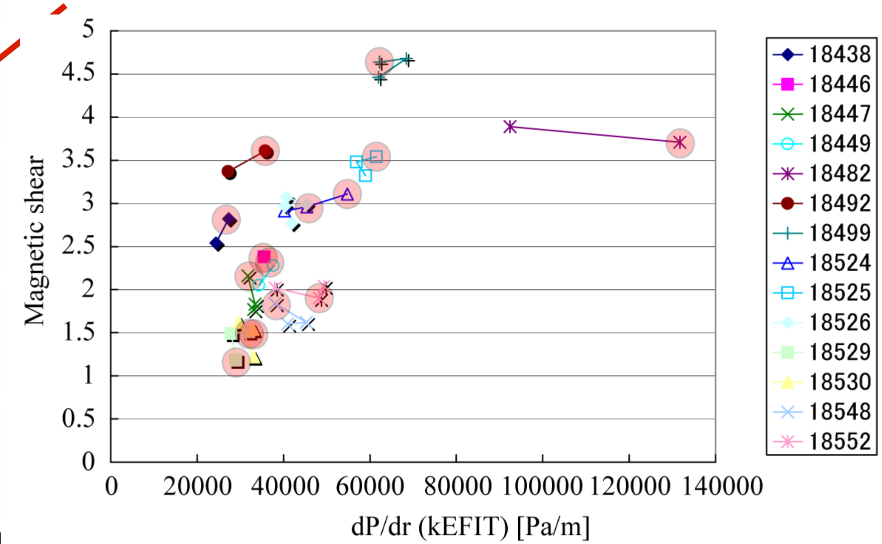
H. Tojo et al., submitted to PPCF



2/1 precursor

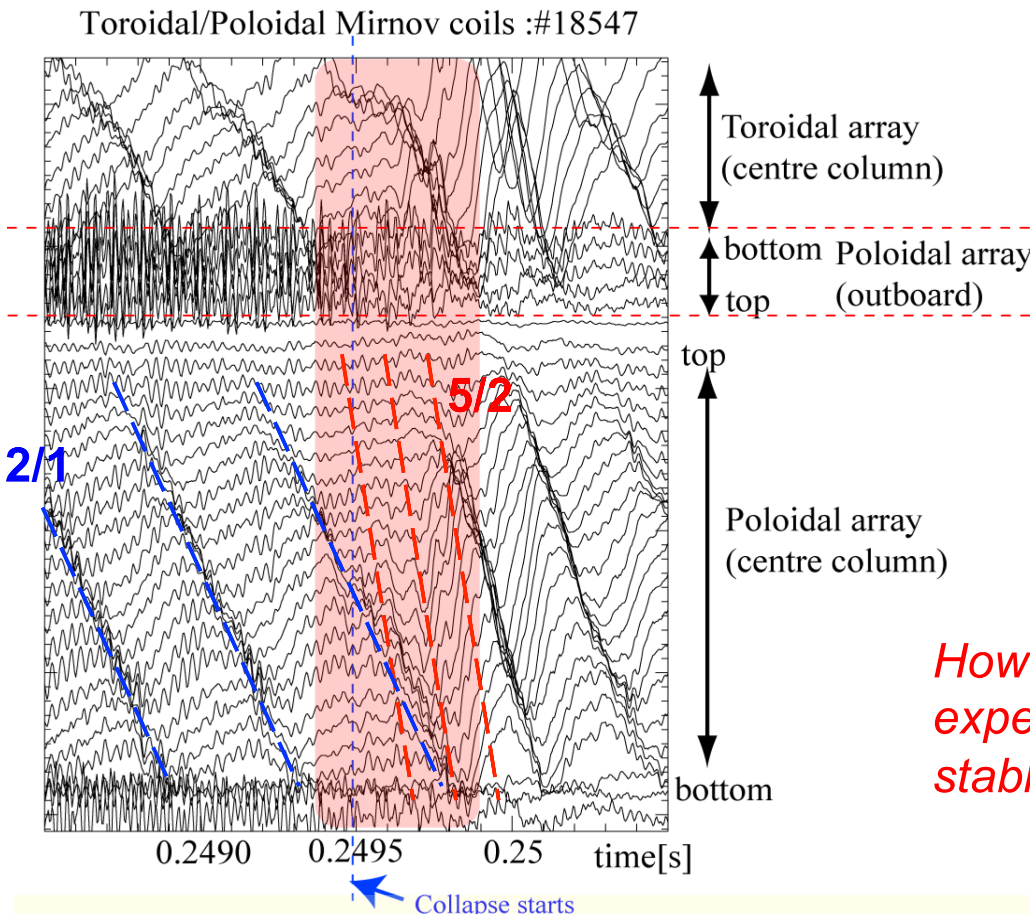
high-*n* modes

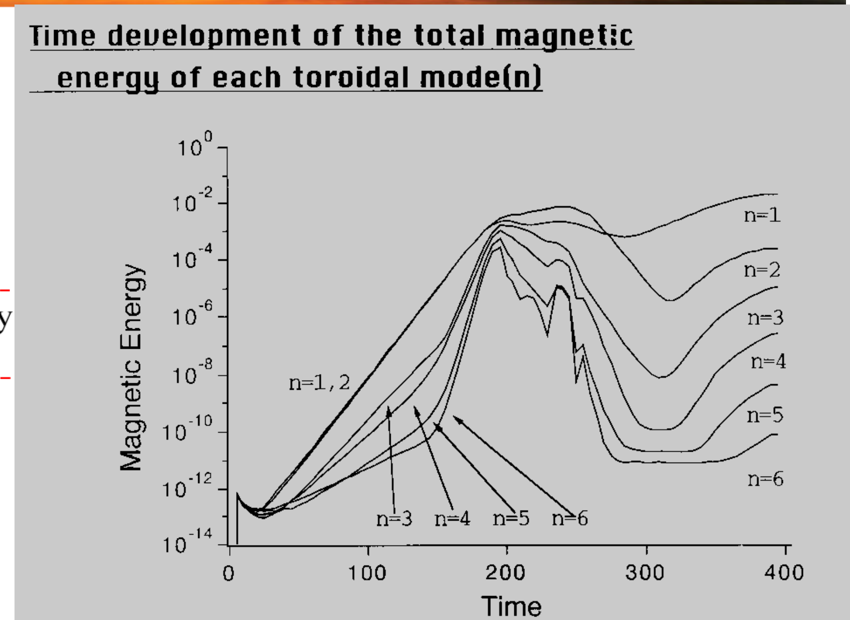
Start of IRE



Trace of magnetic shear (S) and pressure gradient at q=2 rational surface before (0~21ms) IRE. The red shaded circles indicate just before the IRE.

Experimental observations:





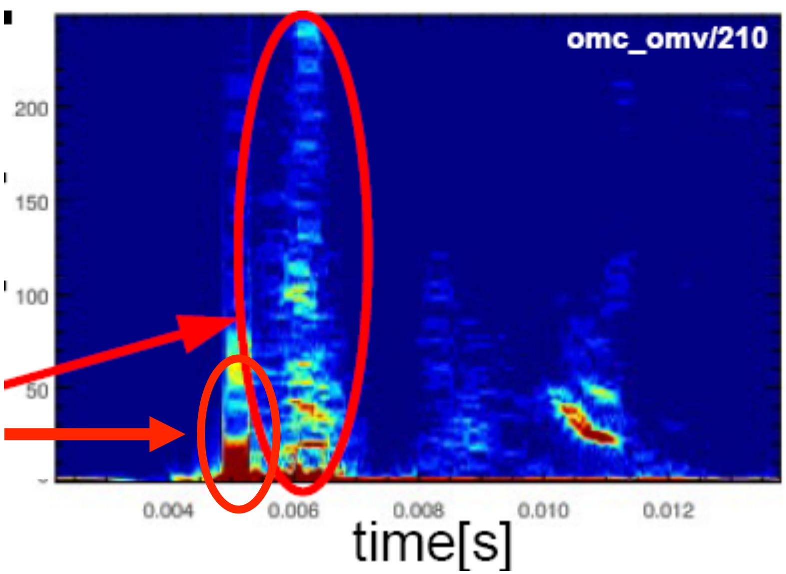
However, after "excessive" pressure is expelled, some modes can become stable ("disruption resilience")

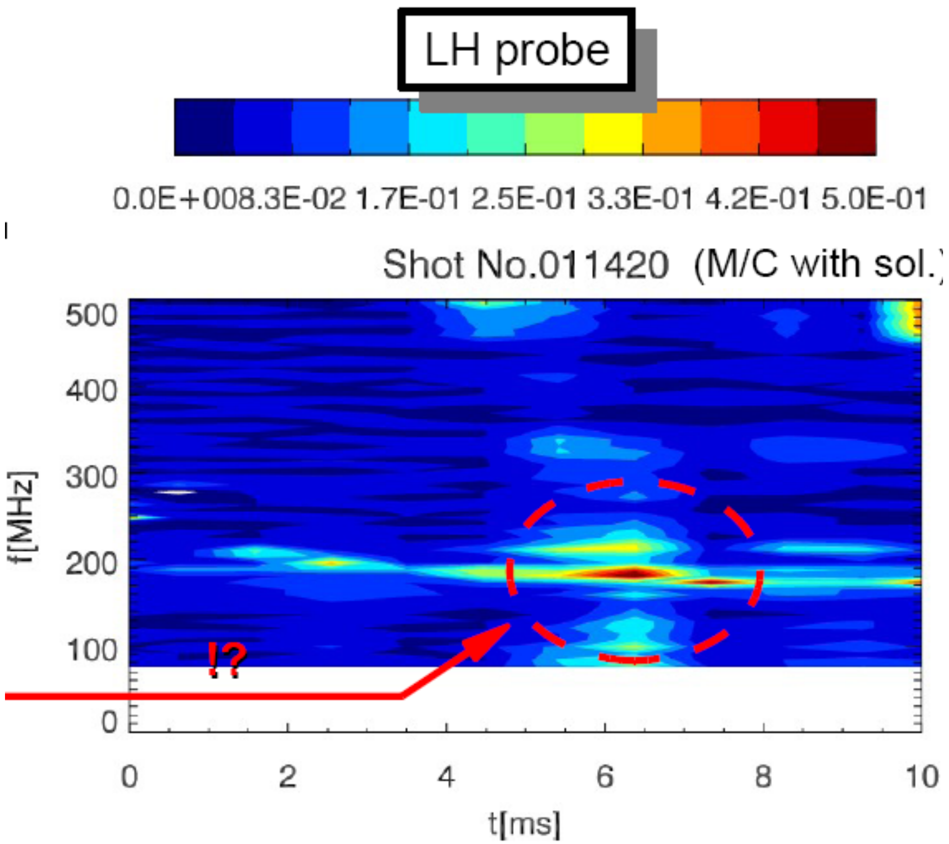
T Hayashi et al, NIFS

- Appearance of a faster n = 2 mode followed by **non-linear toroidal coupling** of two modes (phase alignment)
- Violation of a local stability threshold due to coupling (phase alignment) may also cause ballooning modes

High-frequency MHD after reconnection

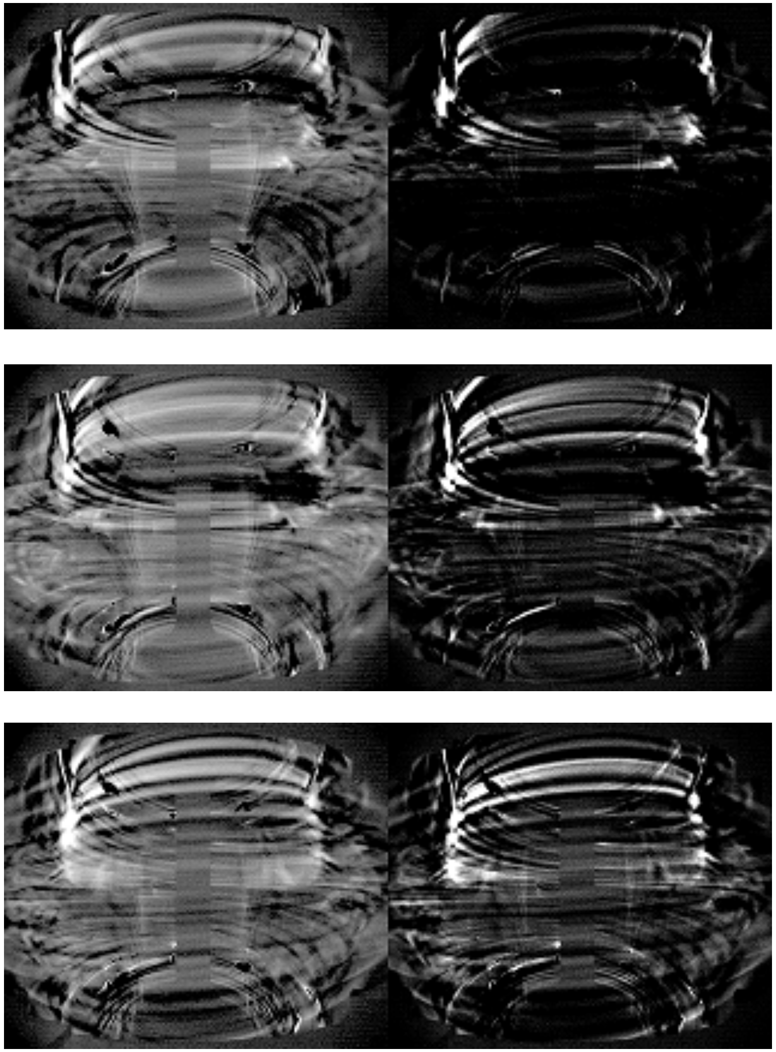
- Low frequency MHD is always present during and after reconnection
- Chirping modes – evidence for fast ions





- Instabilities in Low Hybrid frequency range have also been observed during reconnection – one of possible causes of anomalous heating

Filament ejection in MAST



- Filamentary structures can be seen during merging compression in background- subtracted optical images
- These are observed following spike in line-integrated density, implying radial ejection of plasma following reconnection

- **Goals of reconnection studies:**

  - reconnection during m/c: astrophysics, diagnostics, theory
  - IRE studies: scenario development
  - sawteeth: next step?
  - ELMs: next step?