MHD and Disruptions Group

Sam Bakes, Oliver Bardsley, Daniele Brunetti, Alex Cunningham, Alexandre Fil, Lars Henden, Agnieszka Hudoba, Mengdi Kong, Mark Lafferty, Samuli Saarelma, Elisee Trier, Guoliang Xia

UK Atomic Energy Authority

What are the MHD and disruptions?

MHD or magnetohydrodynamics is a fluid description of plasma. It is used to study plasma equilibrium and stability as well as evolution of instabilities in the plasma.

Ideal MHD: Plasma is considered to be perfectly conducting (=instabilities are fast)

Resistive MHD: Plasma is considered to have resistivity (=instabilities are slow)

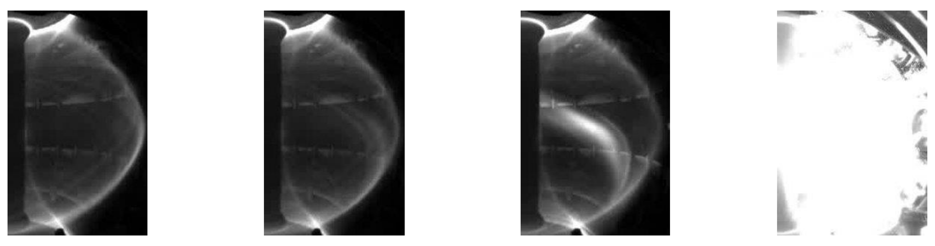
Equilibrium : Force balance plasma pressure vs. electromagnetic force used to solve the magnetic configuration of the plasma

Stability: Determination if any perturbation from the equilibrium will grow exponentially or return to stability $\xi(\boldsymbol{x},t) = \xi(\boldsymbol{x})e^{\gamma t}$

Instability: A perturbation from the equilibrium that initially grows exponentially and then either saturates or leads to a disruption.

Disruption: A complete loss of plasma confinement leading to high heat loads on plasma facing components and large electromagnetic forces on the structure. Sometimes leads to a development of a runaway electron beam.

MAST disruption:



STEP equilibrium

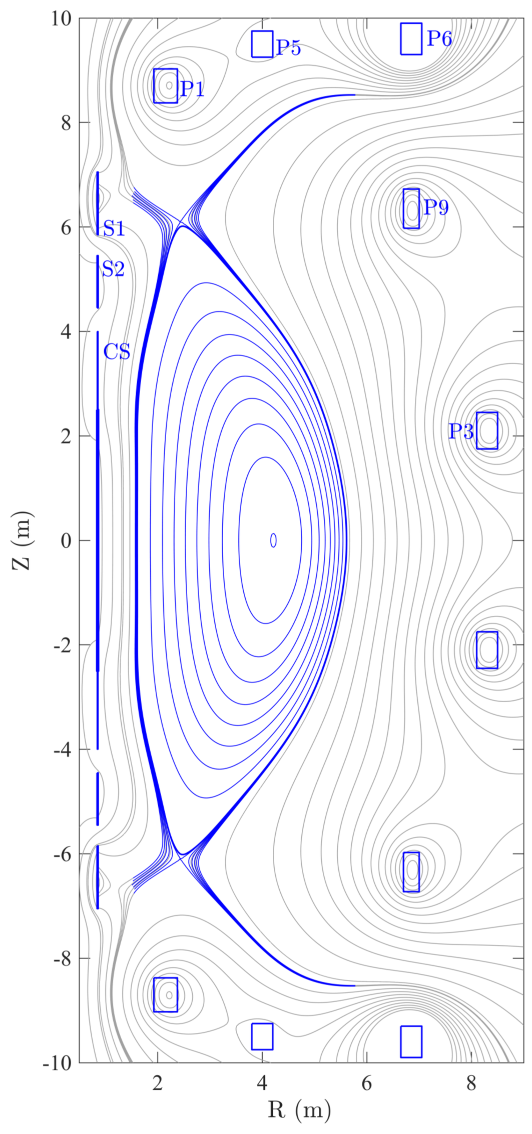
Force balance in a tokamak can be solved from the Grad-Shafranov equation:

$$\Delta^*\psi = -4\pi\mu_0 R^2 p'(\psi) - \mu_0^2 F(\psi)F'(\psi)$$

ψ = Poloidal magnetic flux

p = Pressure

F = Poloidal current flux function



Optimisation process

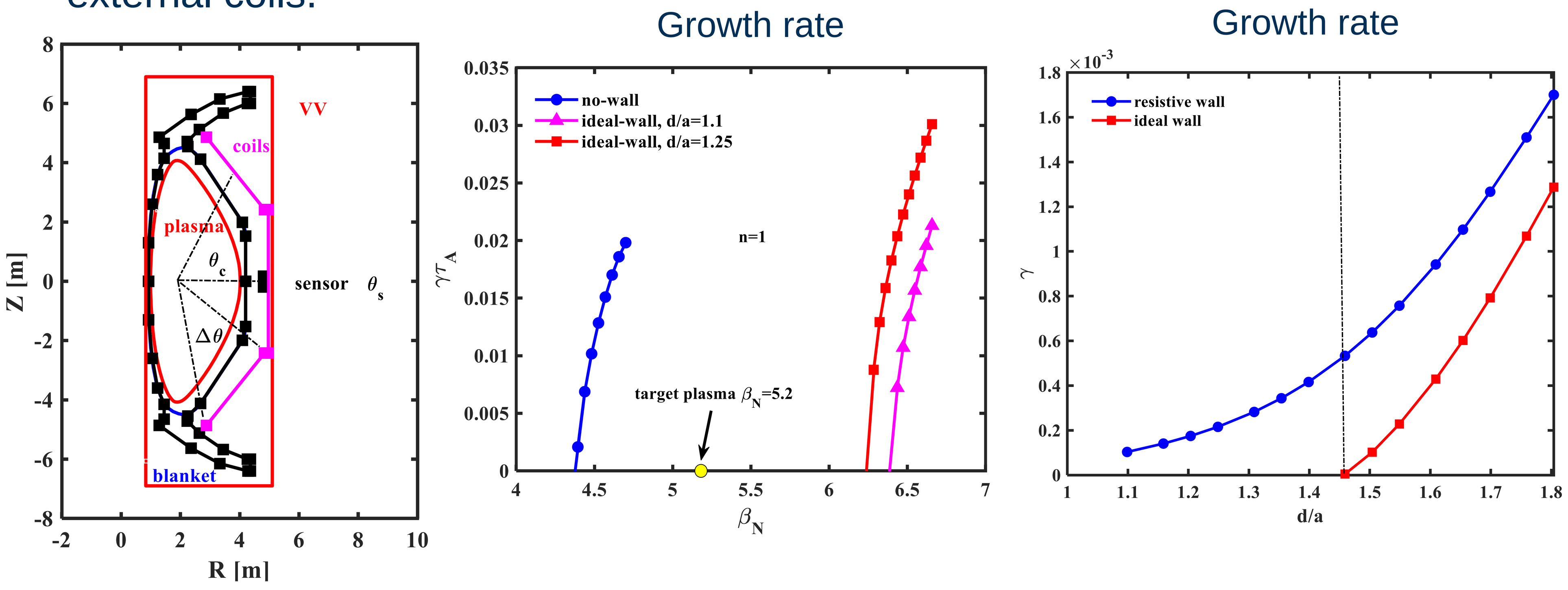
1. Integrate the core and edge plasma scenario (robust equilibrium + viable exhaust + feasible PF coilset)
2. Optimise the global magnetic configuration with advanced exhaust solutions
   a. Outer leg extended to Super-X divertor (SXD)
   b. Alternative inner solutions (standard, inner-XD, hybrid)
3. Analyse local magnetic topology of the scrape-off layer to assess divertor performance
4. Highlight advantages and disadvantages of alternative solutions in terms of:
   - Exhaust performance (simultaneous optimisation of outer SXD and inner XD)
   - Effects on the core plasma scenario (acceptable deviations from the baseline, shaping requirements, vertical stability)
   - Implications for the engineering design (spatial integration, technology requirements, plasma-facing components)

Resistive wall mode stability in STEP

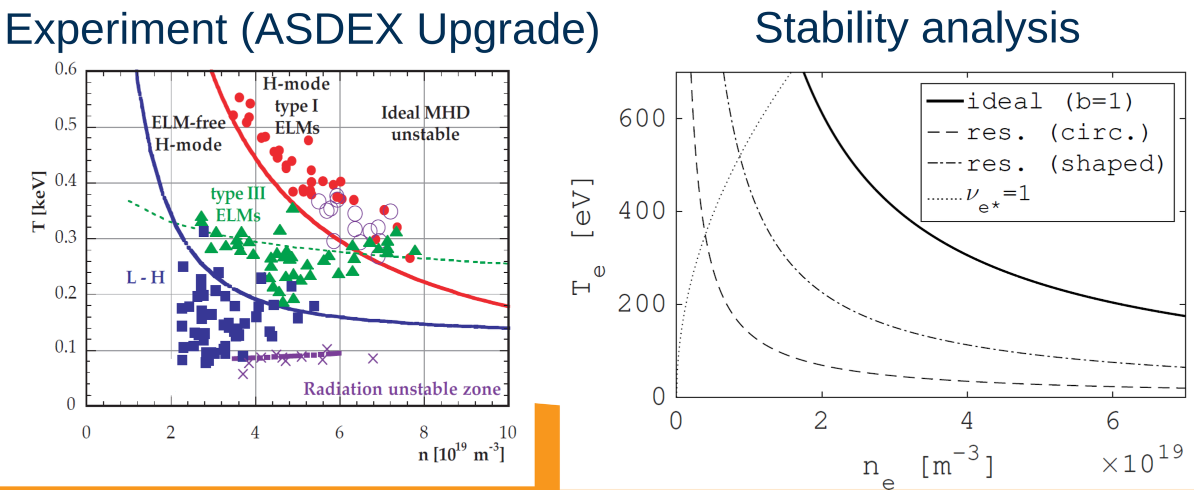
External kink modes: Instabilities that start to grow in the plasma when there is no wall and a critical value of β_N (normalized beta) is exceeded.

Ideal wall limit: The stability limit in β_N when plasma is surrounded by ideally conducting wall

Resistive wall modes: Instabilities that grow in the plasma below the ideal wall limit due to the resistivity of the wall. Can be stabilised with plasma flow or external coils.



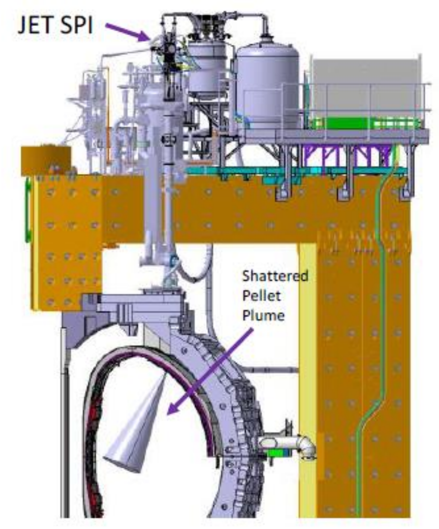
ELMs: Periodic instabilities at the plasma edge.



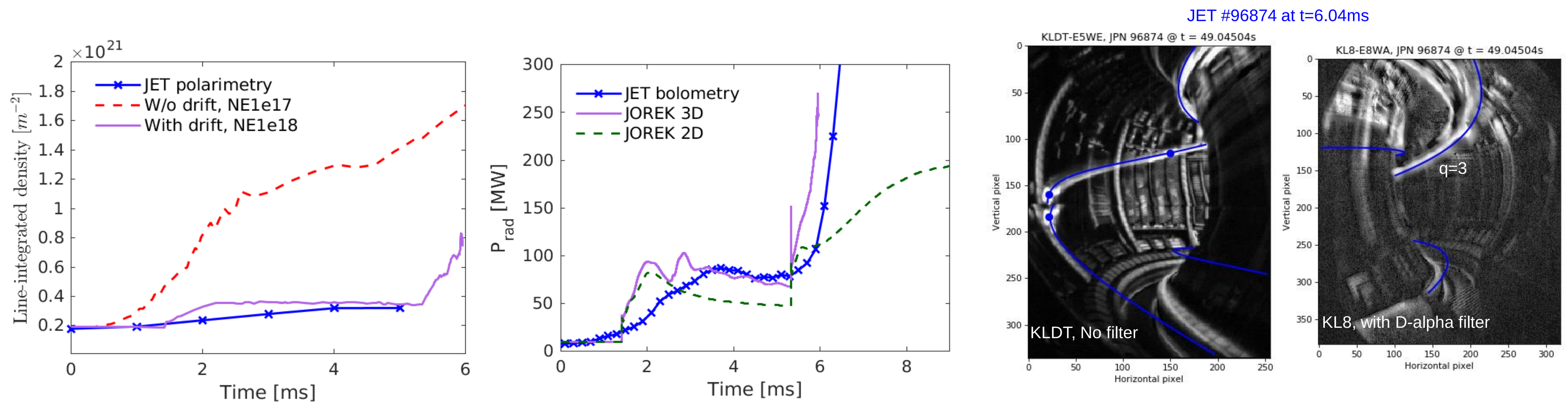
Stability analysis results:
Type I ELMs are ideal instabilities
Type III ELMs are resistive instabilities

Shattered pellet injection for disruption mitigation

- **Shattered pellet injection (SPI)**
  - Chosen method for the ITER disruption mitigation system (DMS) to minimize thermal loads, mechanical forces and effects of runaway electrons (REs) in case of disruptions
  - Cryogenic pellets launched & shattered before injected into the plasma
- **Pure deuterium (D2) SPI**
  - Expected to increase electron density strongly and reduce plasma energy before thermal quench (TQ), contributing to **RE avoidance**
  - However, **drifts of ablation plasmoids towards tokamak low field side (LFS) & existence of background impurities** could limit the effectiveness of LFS D2 SPI strategy
- **Modelled using 3D non-linear MHD code JOREK**

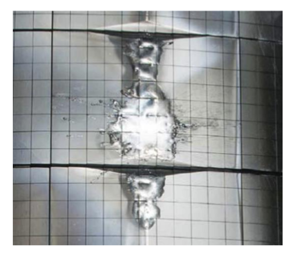


- JOREK modelling has reached a reasonable agreement with the measured density & radiated power (purple traces)
- Drifts of the ablation plasmoids have found to cause an about 70% reduction of the central line-integrated density in the considered D_2 SPI discharge (bottom left plot)
- Background neon (left from mixed-neon SPI experiments) has shown to dominate the radiation during SPI
- 3D effects have proven crucial for the strong radiative cooling and TQ onset at t~6ms (bottom middle), as supported by the helical emission structures observed by JET fast cameras (bottom right)
- Limited core fueling due to drifts and strong radiative cooling & MHD with background impurities could limit the effectiveness of LFS D_2 SPI in RE avoidance and are worth considering in the ITER DMS design



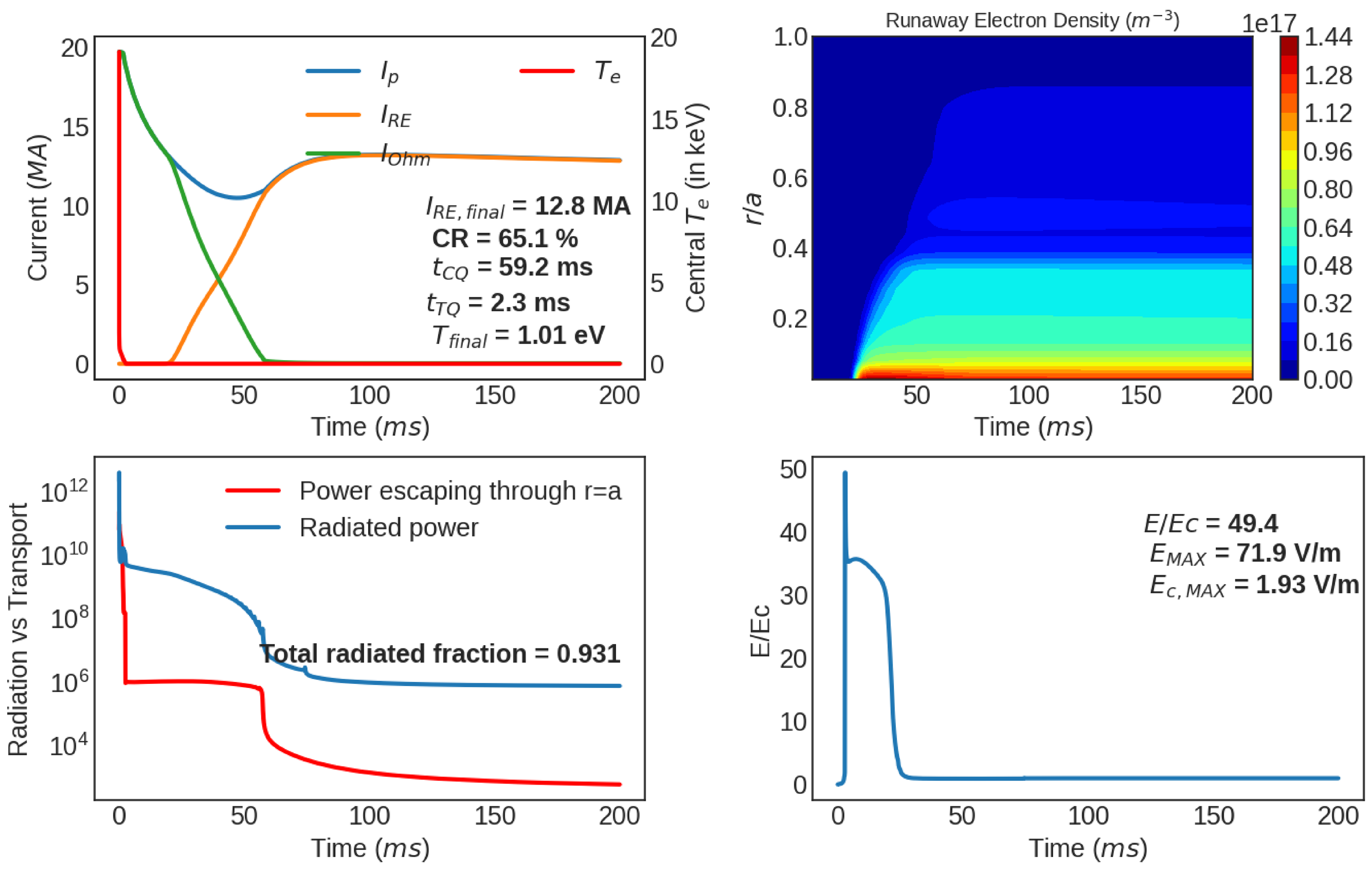
Runaway electrons generation and avoidance/mitigation

- Fast quench of the plasma current during a disruption can generate a high energy electron beam.
- Beam hitting the wall before dispersing can cause damage



~ 0.8 MA RE beam impact in JET (2015)

- STEP simulations of runaway electrons using the code DREAM:

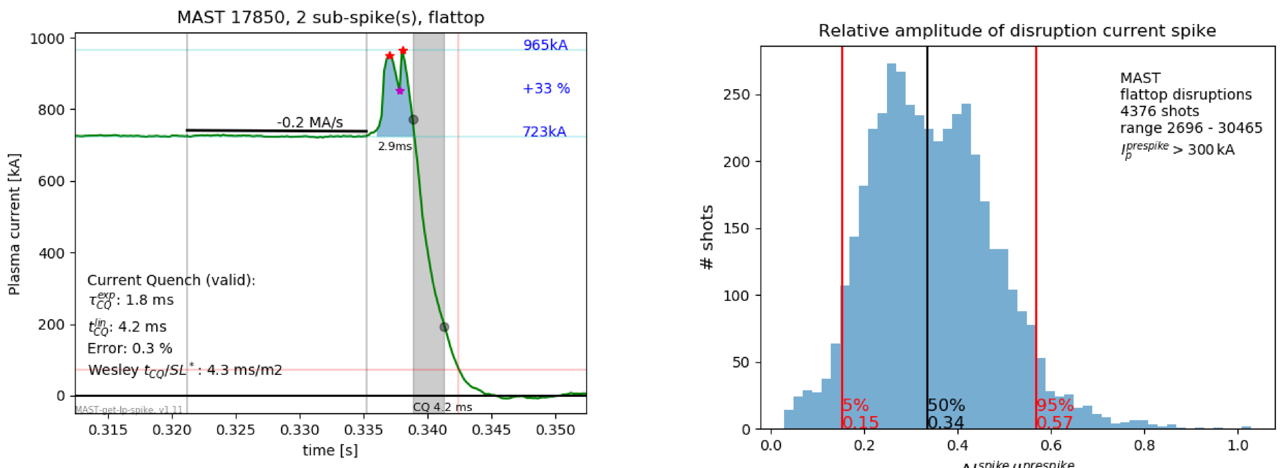


Runaway electron generation during mitigated disruption with Neon and D_2 impurity injections in STEP (n_{Ne} = 5x10^{19} m^{-3}, n_{D2} = 10^{21} m^{-3})

- Simulated injections of Argon/Neon/D_2 to mitigate disruptions (radiation, CQ control).
- Insufficient in STEP for runaways, still large RE beam carrying > 10 MA

MAST current spike

- In a disruption before current quench the plasma current in MAST increases due to change in internal induction.
- This may potentially make the disruptions even more dangerous
- Statistical analysis of current spike in MAST disruptions



Future directions:

- Spherical harmonics used in the equilibrium reconstruction
- Non-linear MHD disruption modelling
- Design of ELM mitigation coils for STEP

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