MAST: Results and Upgrade Activities

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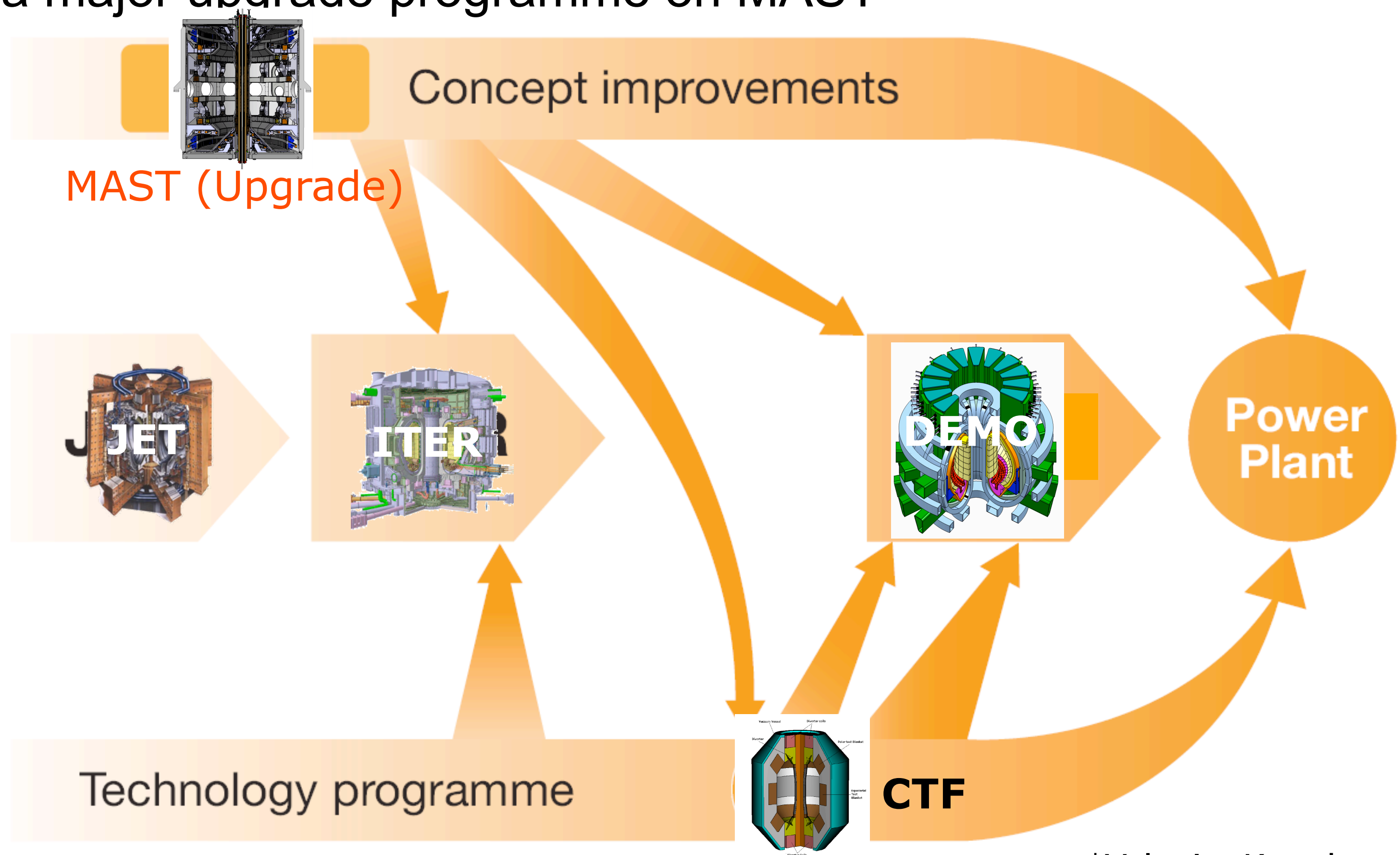
MAST position in fusion development

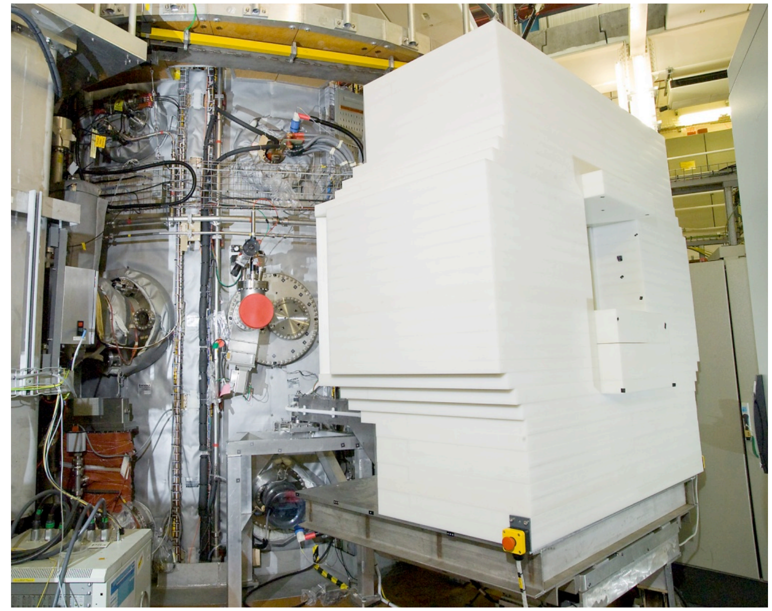
- MAST: wide range of tokamak physics for ST, ITER, DEMO (e.g. A<3)
- Need physics basis for CTF/FNSF especially steady state and exhaust
- DEMO may need innovative divertor – only MAST can test super-X*?
- ➔ a major upgrade programme on MAST



*Valanju, Kotschenreuther et al

Topics

- MAST physics studies
- Technical developments
- MAST Upgrade
- Summary



MAST: ~same size as NSTX, I_p~1MA, a~50cm

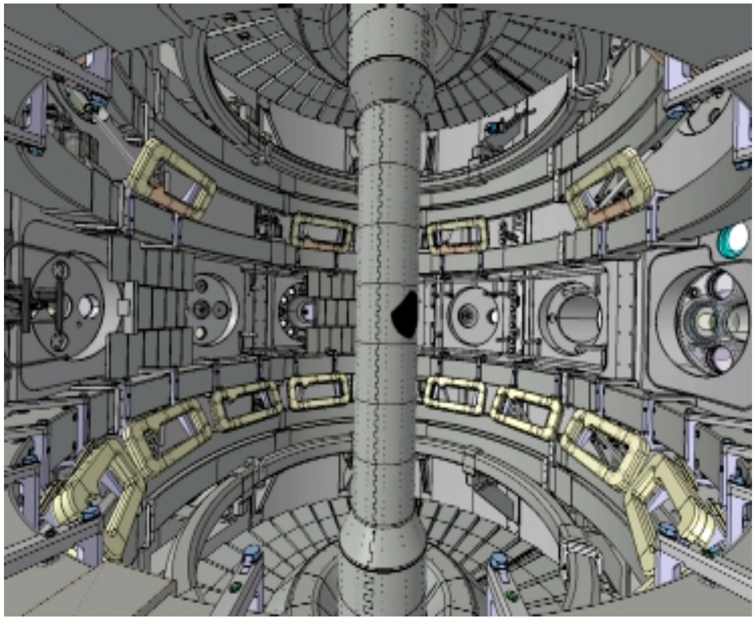
- Physics very selective here – see IAEA overview*
- Written paper has many more things

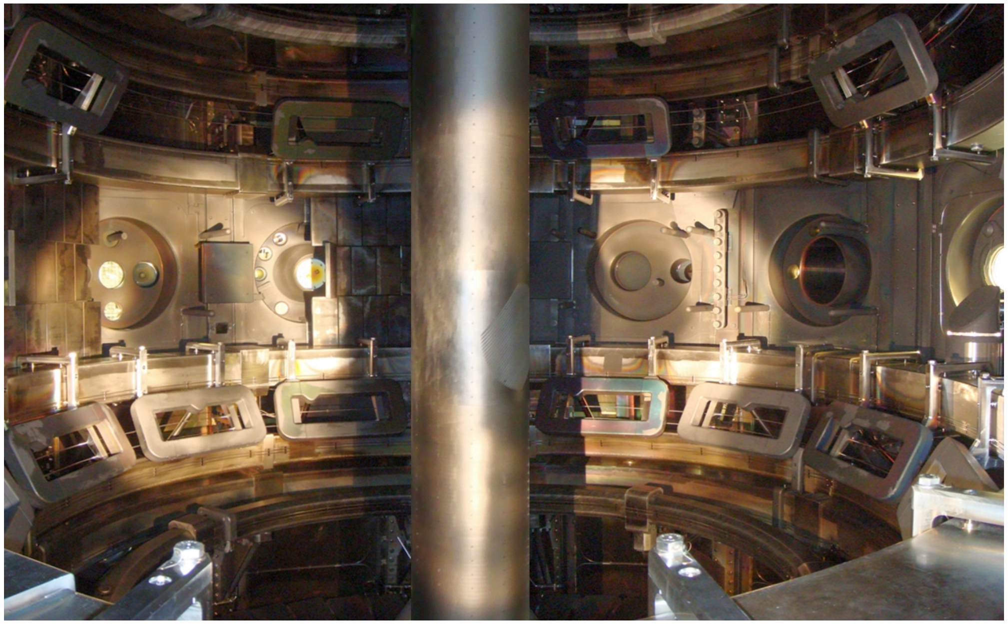
* B Lloyd, subm Nucl Fusion

ELM mitigation coils

- 18 internal ELM coils – allows n=6 (unique at present)
- Many permutations: n=3, n=4, n=6, even & odd parity
- Unusual potential to adjust angle of perturbation during pulse

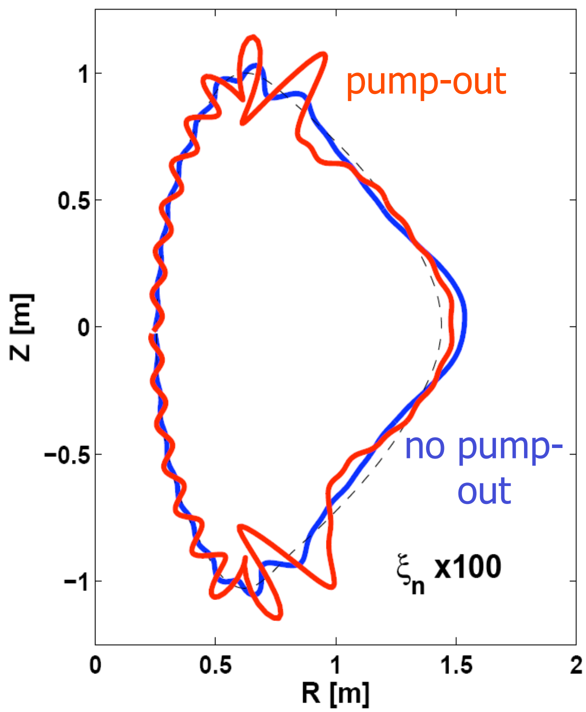
Coils: water cut aluminium, plasma-sprayed, in boron nitride case

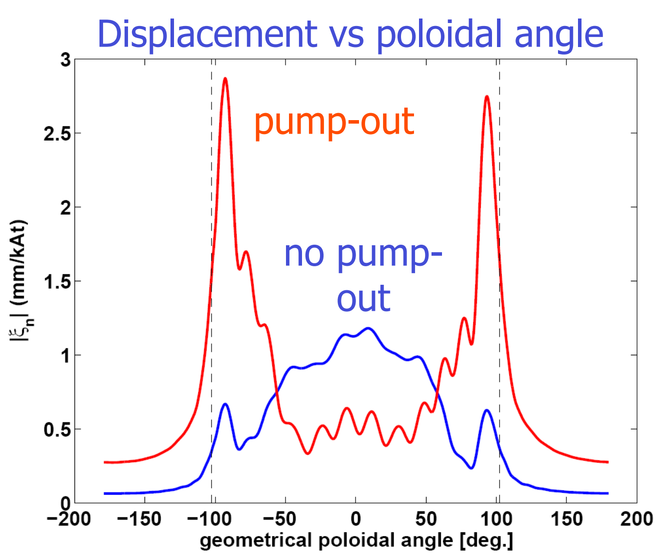




How to design ELM mitigation field?

- Impact depend on configuration and plasma effects, not just field level
- Look at density pump-out:
  - often seen with ELM mitigation
  - hard to compensate with fuelling
- New observations: pump out when distortion largest close to X-points
- Design mitigation configurations that don't cause fuelling problems?





Pump-out: experiment

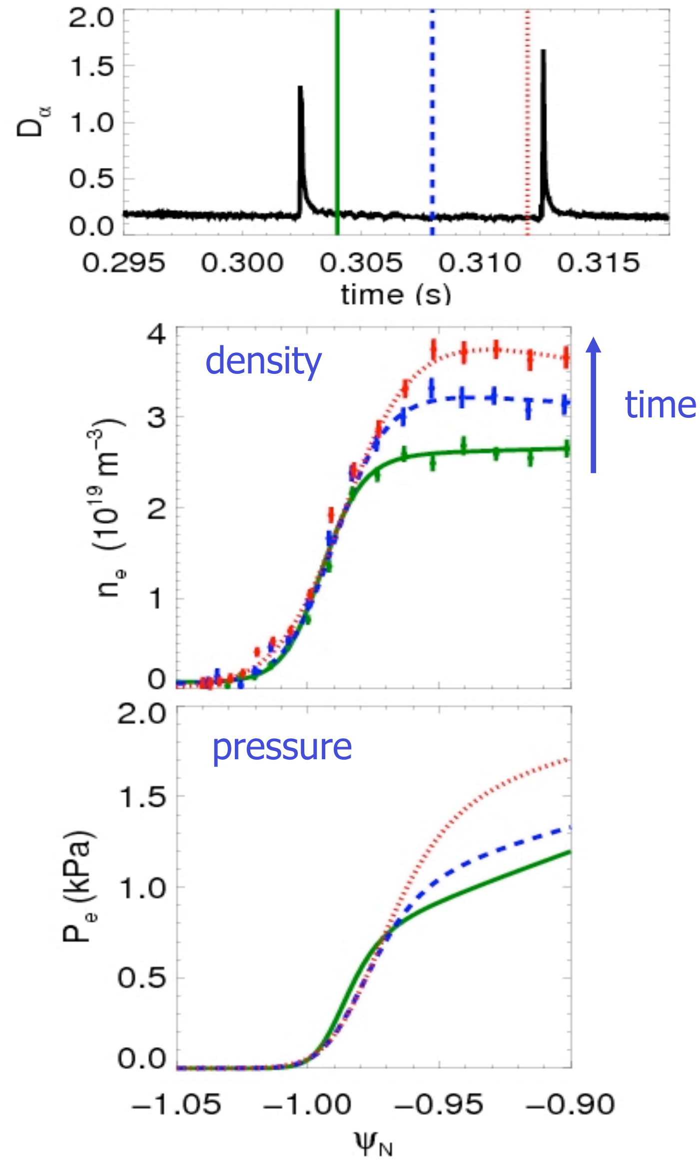
Curves: model.

Chirikov parameter similar.

Modelling MAST with MARS-F MHD code

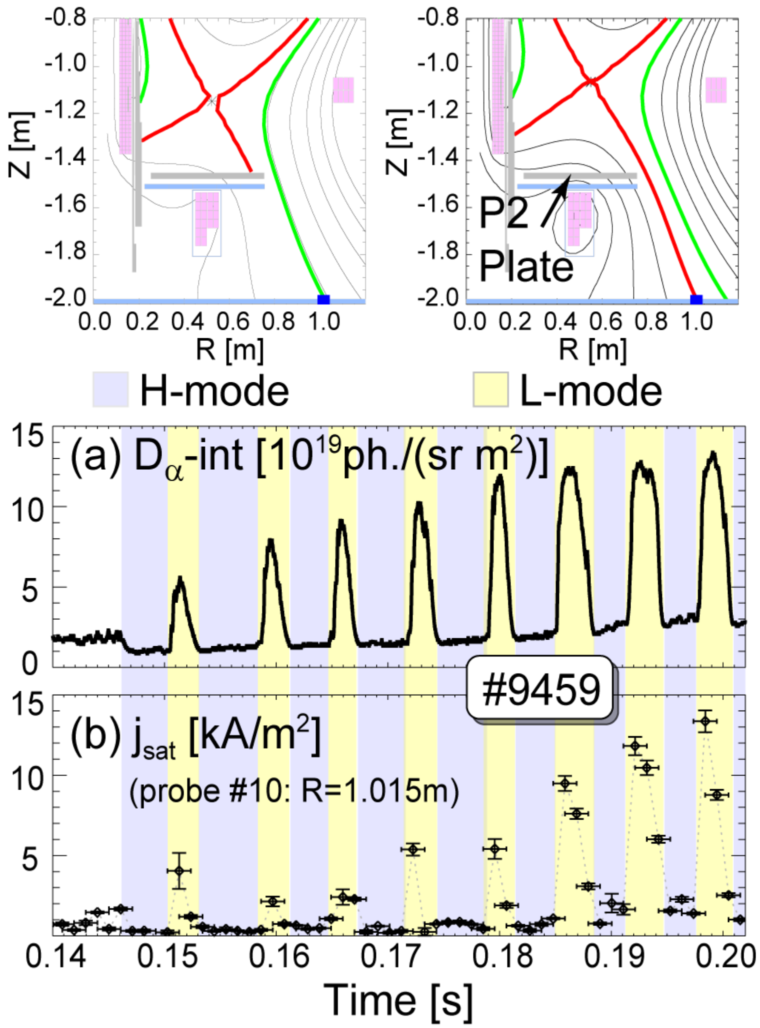
Why do ELMs crash?

- Does EPED* type model fit ST?
- Can resolve pressure gradient
  - ~constant during ELM cycle
  - n ≤ 25 seen in MAST
- Model
  - kinetic ballooning controls gradient (tested with GS2 microstability code)
  - pedestal widens, peeling stability boundary moves down
  - n~25 peeling mode unstable at end
- Still need to understand:
  - why type-III ELM physics (resistive MHD?) is absent for type-I ELMs
  - pedestal formation, L-H transition



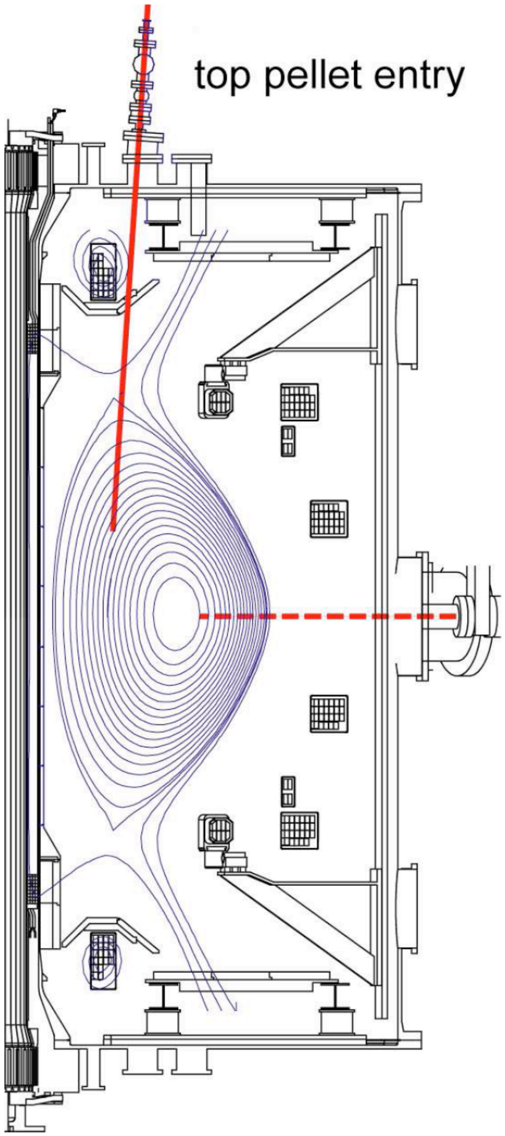
* P Snyder, H Wilson et al

H-mode access and divertor design

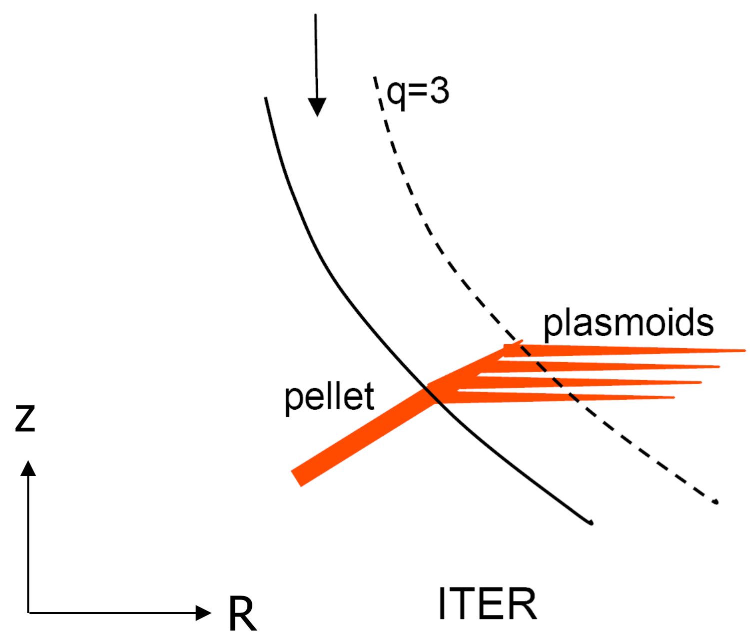


- MAST (and other) data shows H-mode sensitive to divertor structure
- MAST upgrade divertor should clarify
  - Continuous variation of connection length possible

Pellet fuelling: what sets depth?



- Deep fuelling on ITER etc may rely on localised plasmoids that can propagate inwards
- First data on plasmoids in MAST from high resolution bremsstrahlung imaging.



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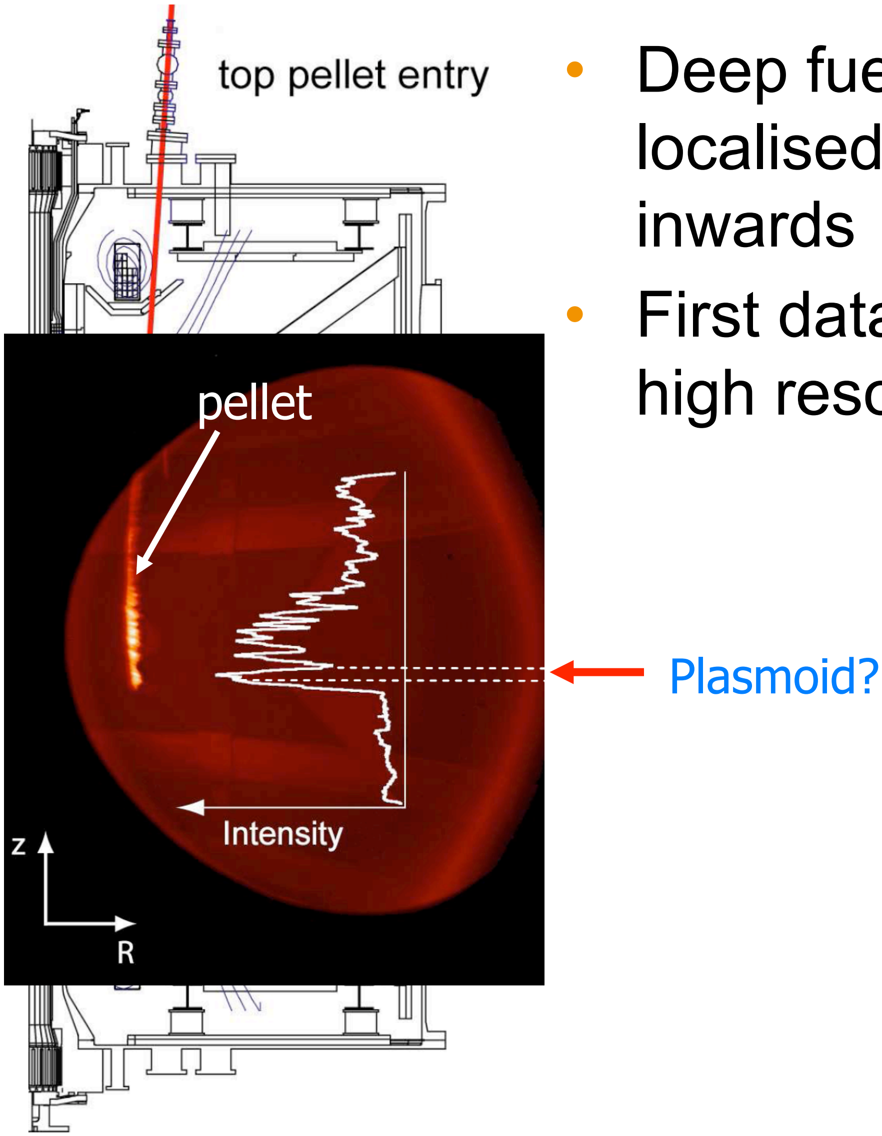

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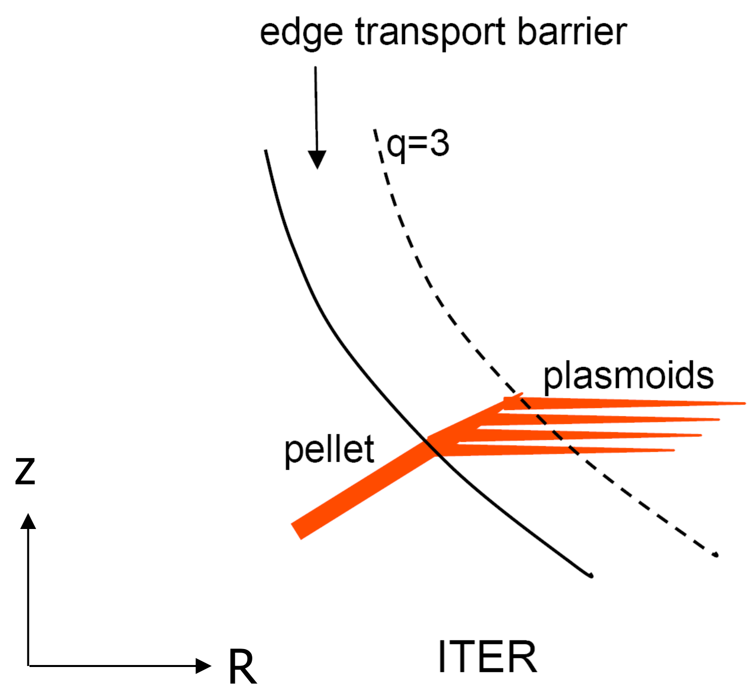
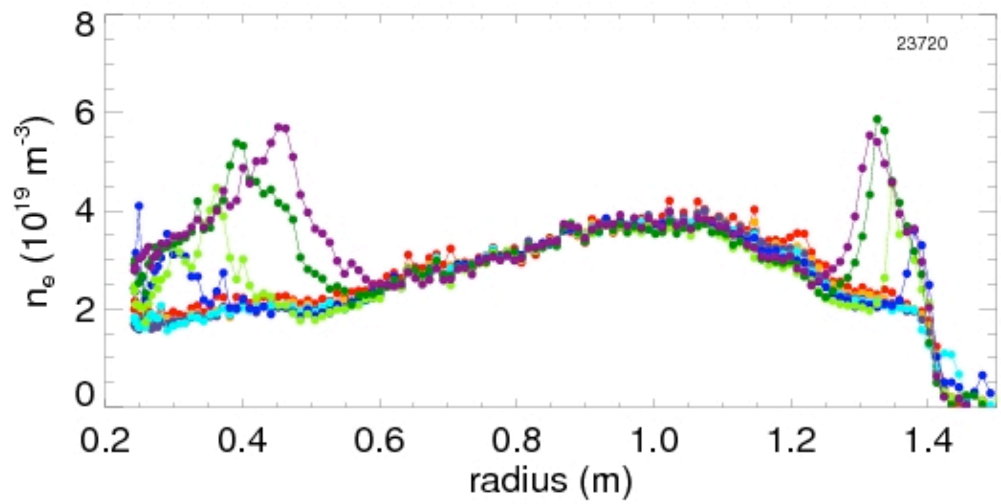


FPGAs change MAST capability

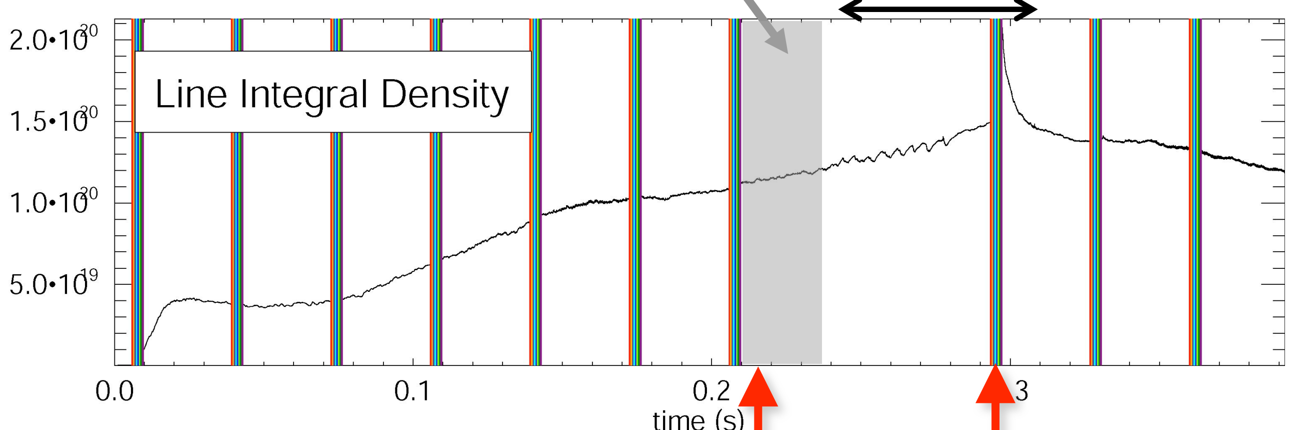
MAST Physics	MAST technical developments	MAST Upgrade

- Active triggering via FPGA used for pellet ablation and density evolution – would have taken days before, now one shot…



8 lasers charging – inactive period

Triggers allowed



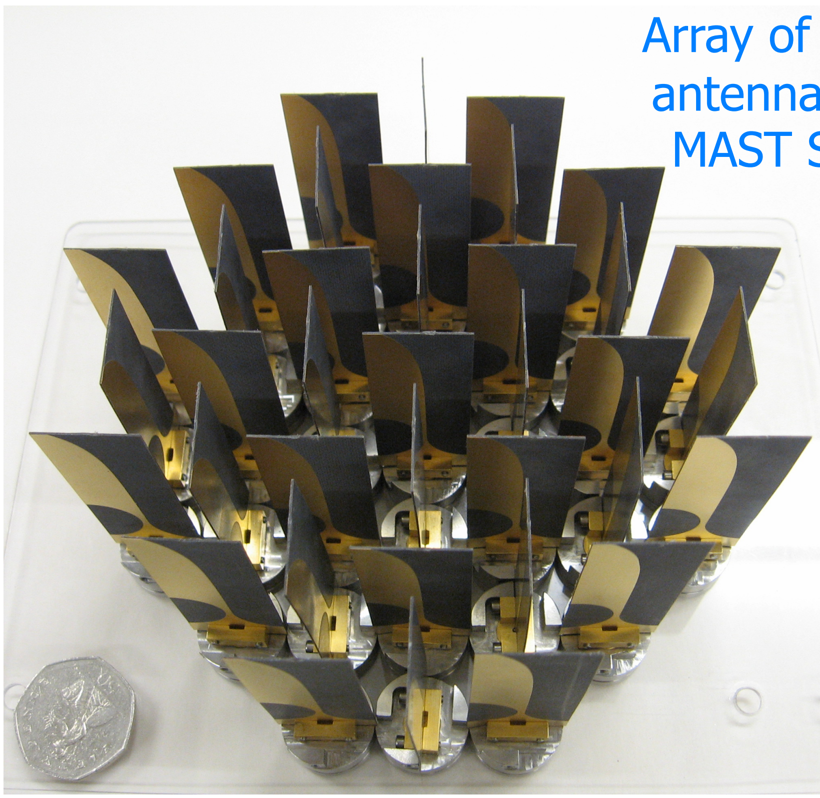
FPGA=Field Programmable Gate Array

Pellet passes sensor - Hold lasers

Pellet enters plasma – fire 8 lasers 500μs apart

EBW imaging for edge current

- ELM and bootstrap current models need high resolution edge current density data (space and time) – electron Bernstein waves a tool
- Synthetic aperture microwave imaging (SAMI) 10-35GHz radiometer* installed and first data – novel antennae
- Uses FPGA for data acquisition: 16 channels, 14 bit, 250MHz, 0.5s



Array of "flat" antennae for MAST SAMI

Cost-effective FPGA-based EBW data acquisition and signal processing

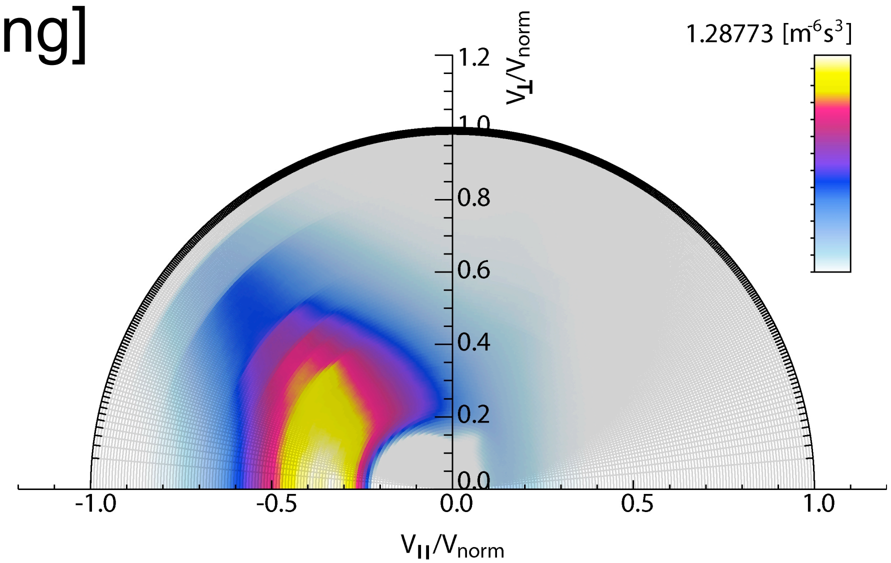
*University of York

GPUs can transform modelling

- Fast particle physics needs detailed distribution functions for
  - fusion product diagnostics (neutron cameras, proton first orbit detectors)
  - drive for instabilities (e.g. input to HAGIS code)
- GPGPU: supercomputer on desktop. Many applications.
- Fast: e.g. 2 million orbits in ~6hrs.
- [Also used for materials modelling]

4 “gamer” GTX480 Fermi cards.

GPGPU = General Purpose computation on Graphics Processor Unit

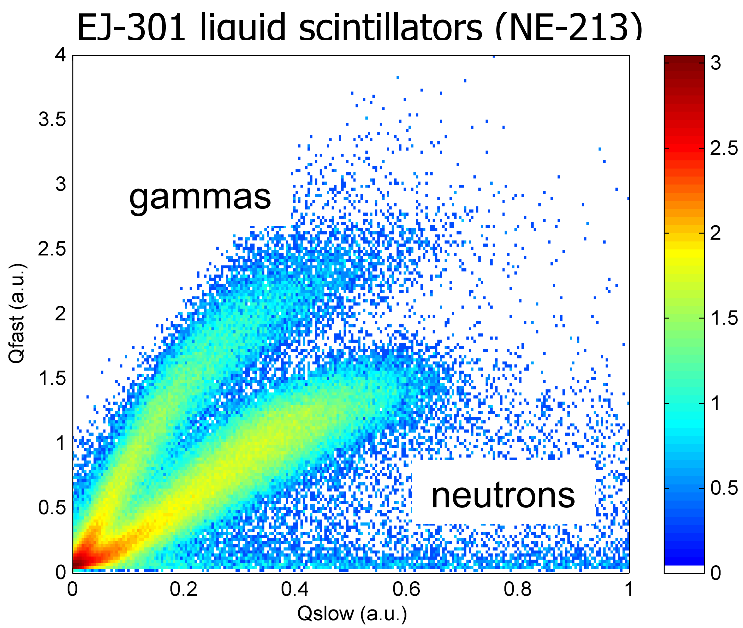


MAST steady-state fast ion distribution function. 2 beams including E_0, $E_0/2$ $E_0/3$ species (6 in all)

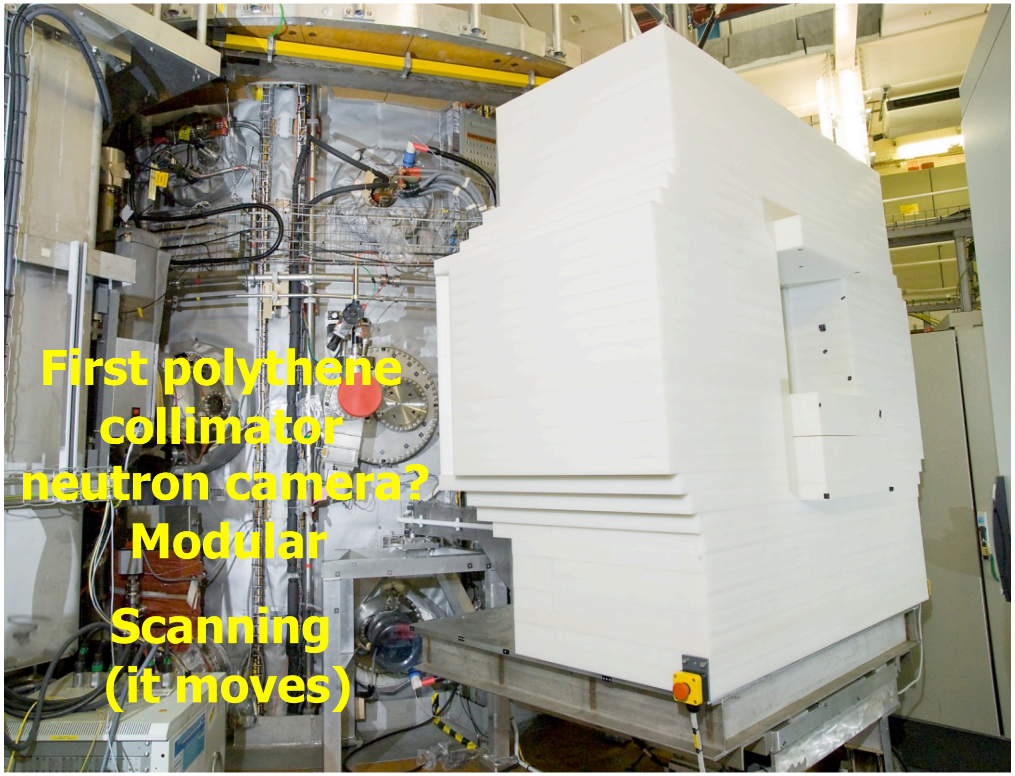
Neutron camera development

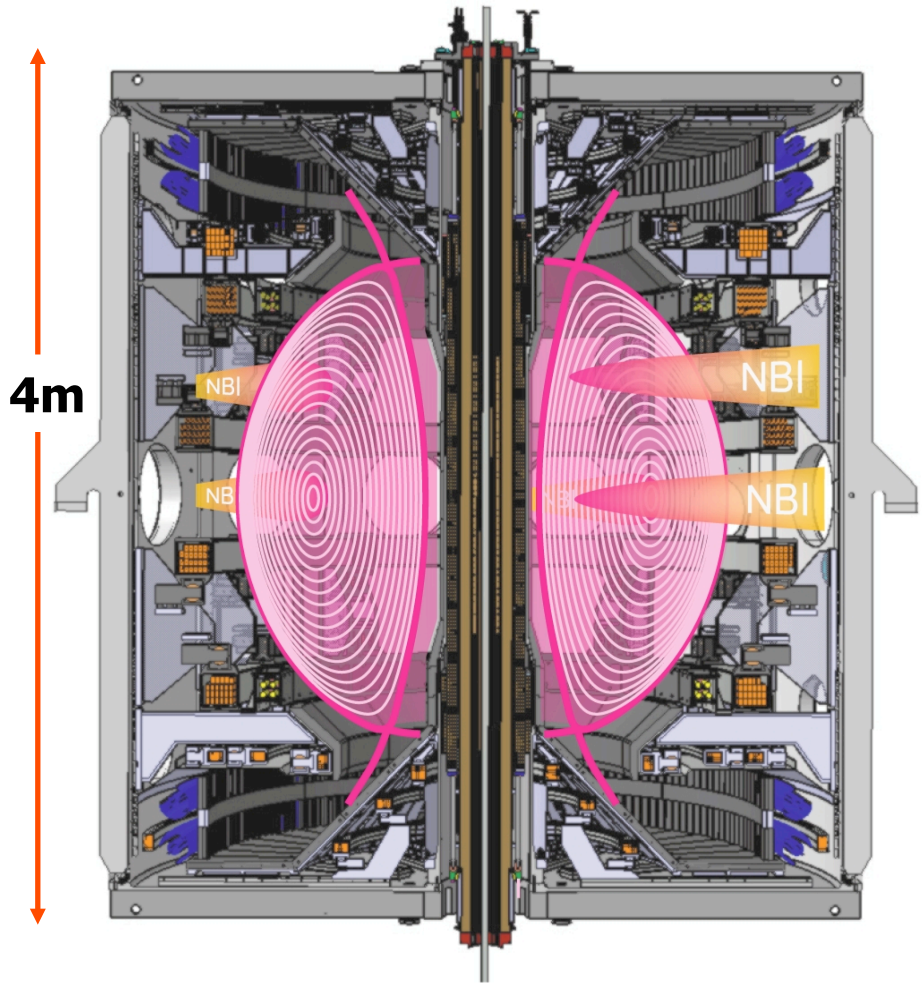
MAST Physics	MAST technical developments	MAST Upgrade

- Fast ion physics: neutron profiles needed
- Polythene-collimator prototype camera built by Uppsala* (EFDA support)
- Interlocking-plate polythene shield modelled with MCNP
- Lead to stop 2.23MeV γs.
- Photomultiplier magnetic shield: 10mm Fe + 0.5mm mu-metal ➔ <1.5G

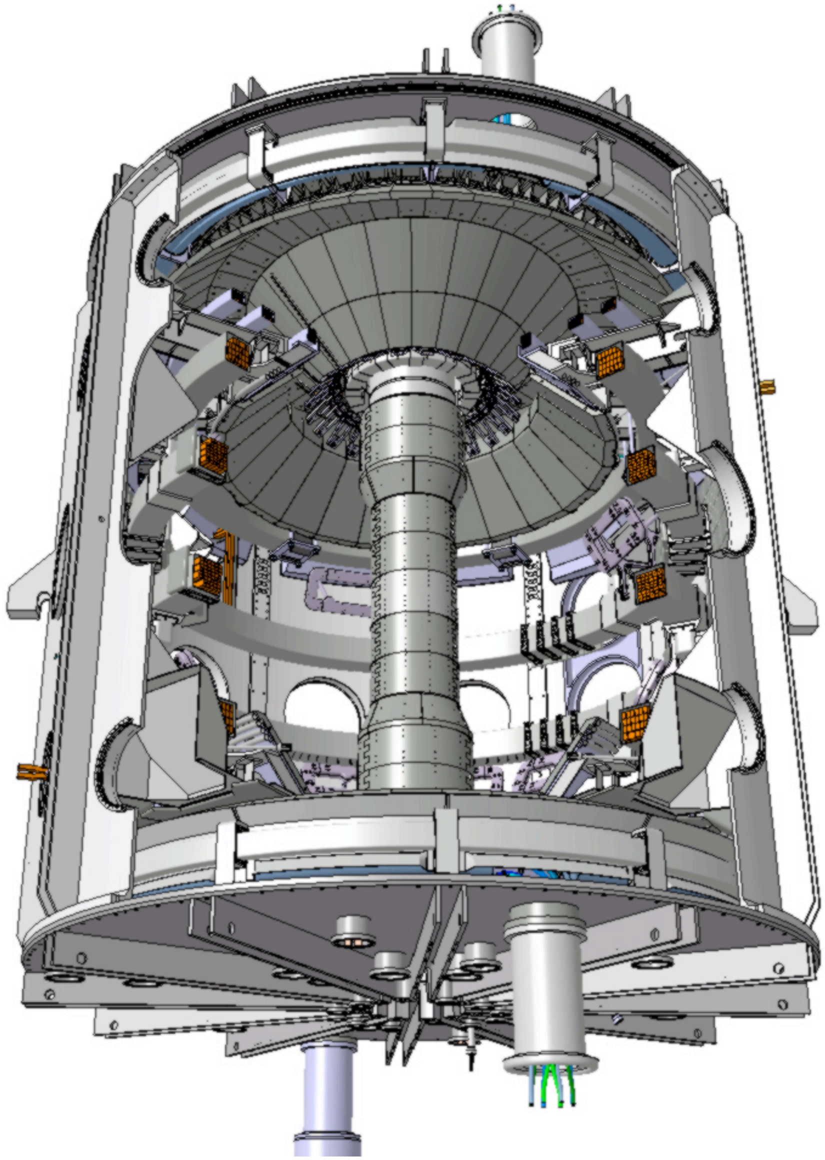


* M Cecconello et al





- For physics basis for CTF and ITER/DEMO input
- Aims (do in stages)
  - science of long-leg divertors
  - fast particle instabilities and confinement - models
  - transport at lower collisionality
  - steady state current profiles
  - ramp-up without solenoid
  - ST physics at high-β_N in sustained pulses
- Complements NSTX



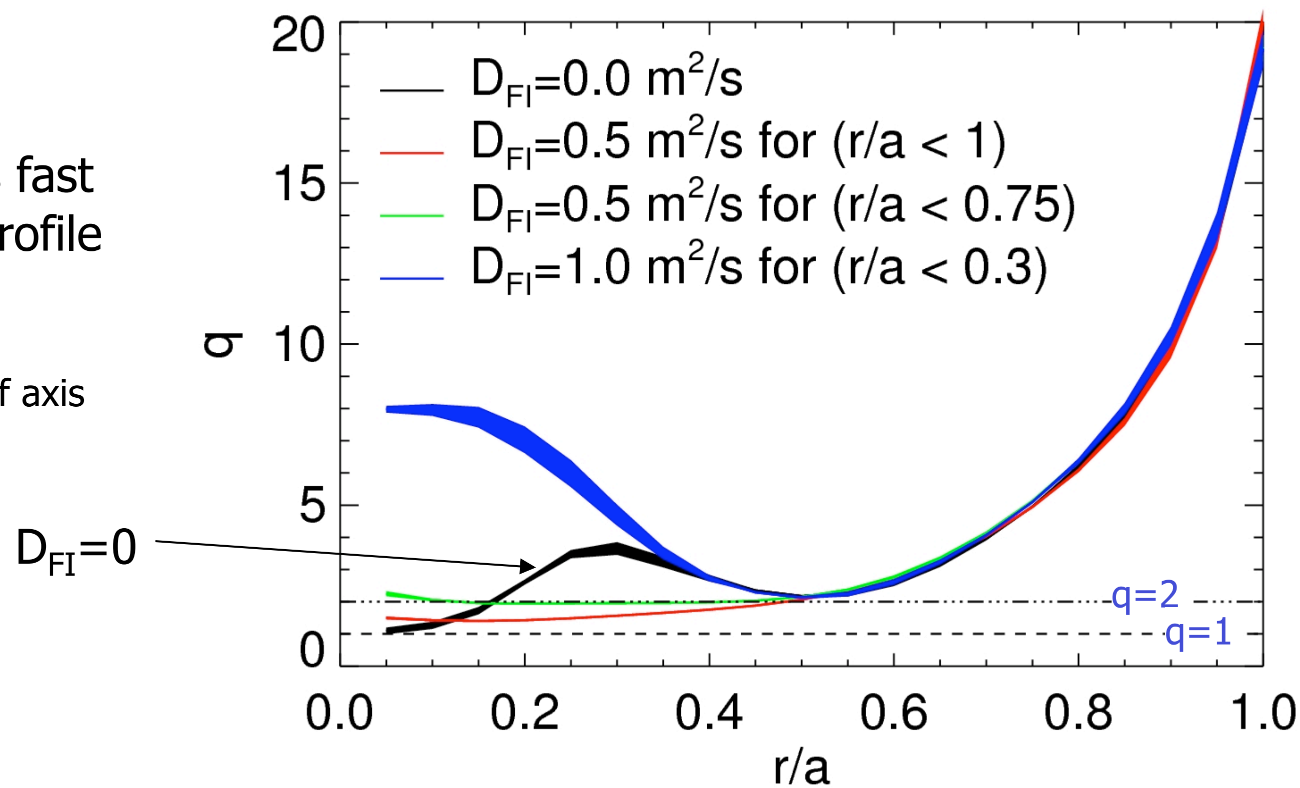
- Scope (implement in stages)
  - 17 new PF coils (14 in-vessel)
  - divertor: closed with cryopump. Conventional as well as super-X
  - increase TF (50%) & flux swing (nearly double)
  - increase NBI, with off-axis
  - long pulse (up to 5s)
  - diagnostics (divertor & fast ion)
  - (high frequency pellet injection)
  - (electron Bernstein wave heating and current drive)

MAST-U Physics design - NBCD

- Design plasma scenarios then design machine to achieve them
- Neutral beam current drive for steady state a key aspect – q_{min}>2?
- Fast ion diffusion has big effect – useful in core (keeps q(0) high), bad at edge (weakens off-axis current drive).
- Scan R,Z to find optimal beam position (PF coils constrain)

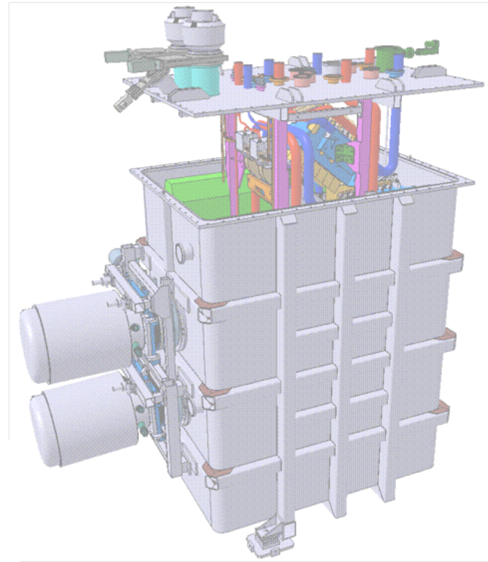
Effect of anomalous fast ion diffusion on q profile

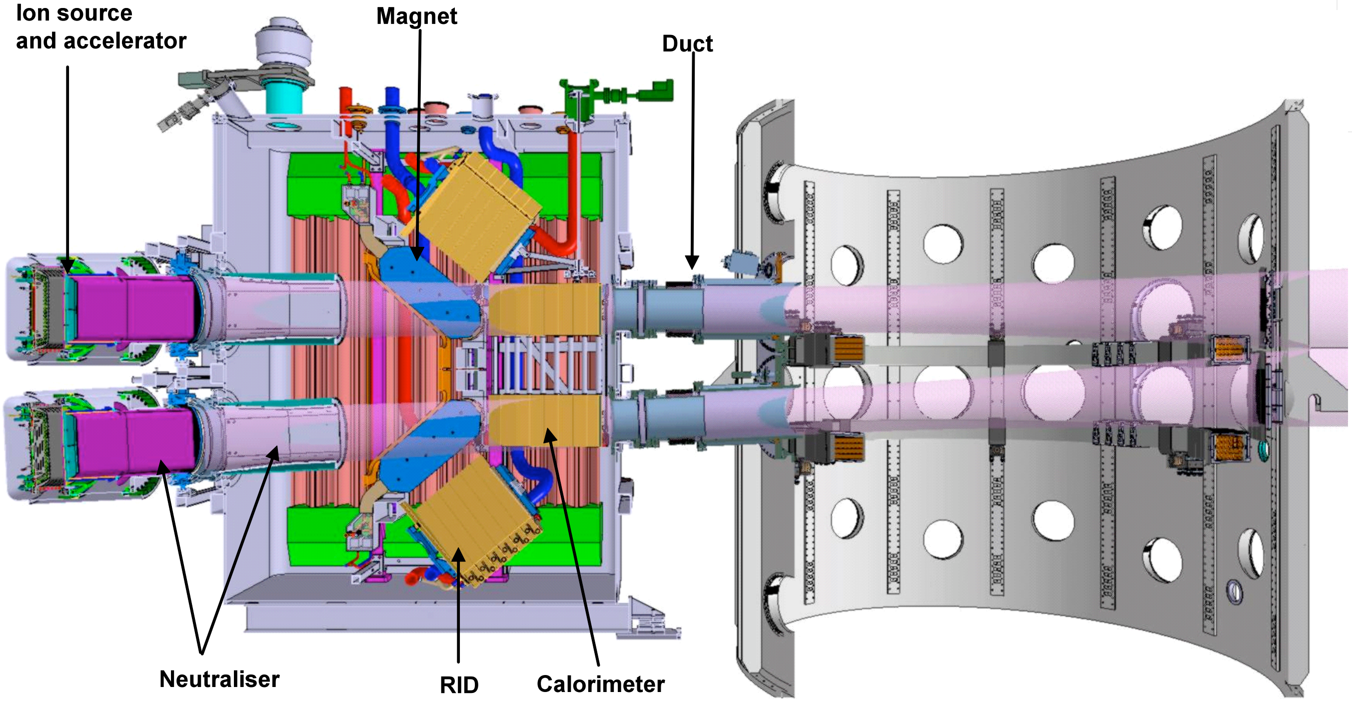
2.5MW on-axis, 5MW off axis

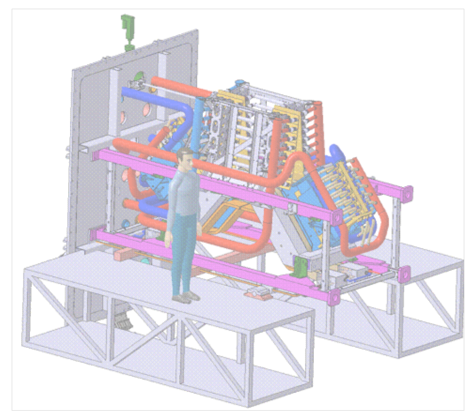


Neutral beams: double beam box

- Beam R,z from physics optimisation
- Tetrode PINIs: 75kV, 65A in D_2.
- Residual Ion Dump: 10.5 MW/m^2
- Calorimeter: 15MW/m^2, 5s / 2 mins
- ➔ HyperVapotrons, use JET fatigue data

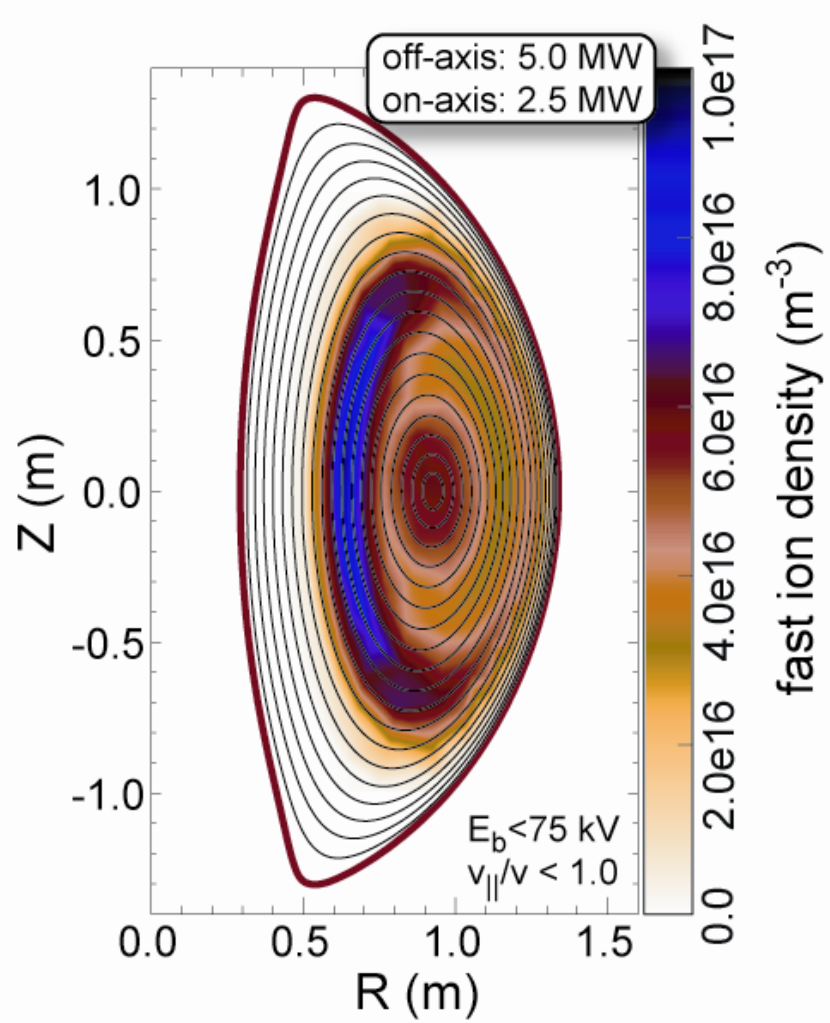






Maintenance

Flexibility on fast ion density profiles



Advanced profile control

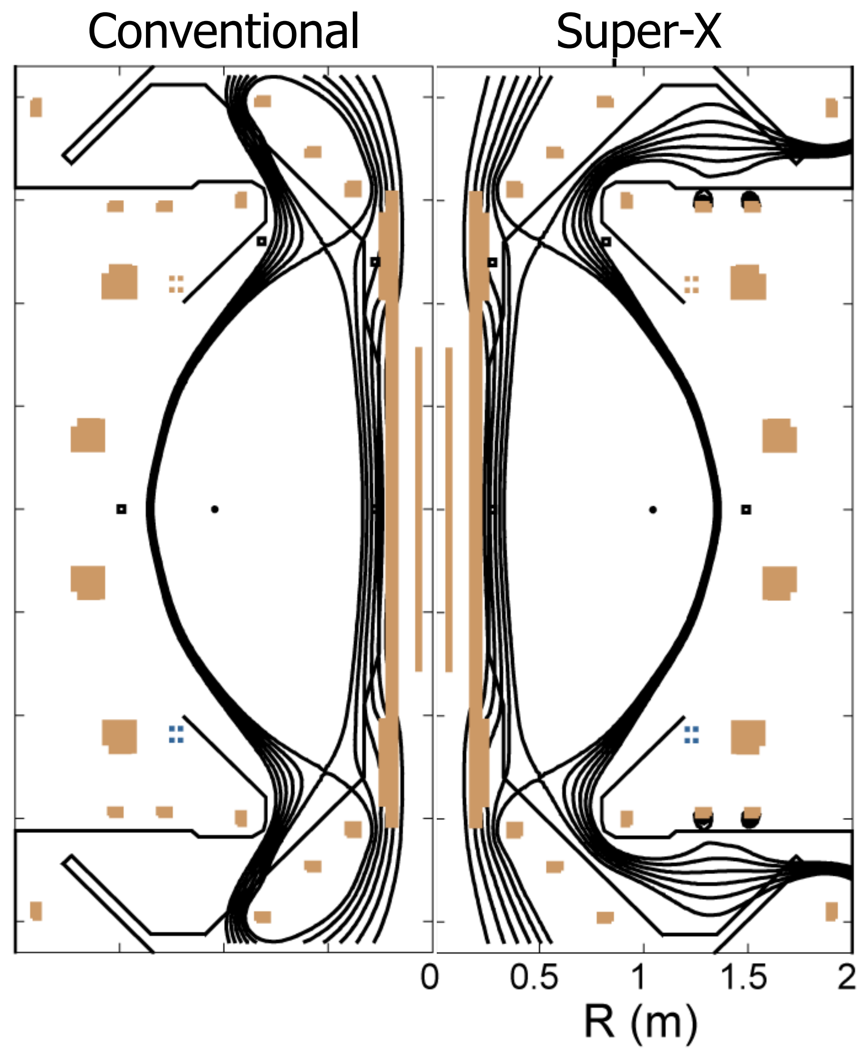
- On-axis ⇒ peaked.
- Off-axis ⇒ hollow.
- On- and off-axis ⇒ broad.
- Different drive for fast ion instabilities
- Test effect of instabilities on core and off-axis ions

Future options:

- Counter current beam ⇒ rotation control.
- More beams ⇒ more torque, more heating.

MAST super-X divertor

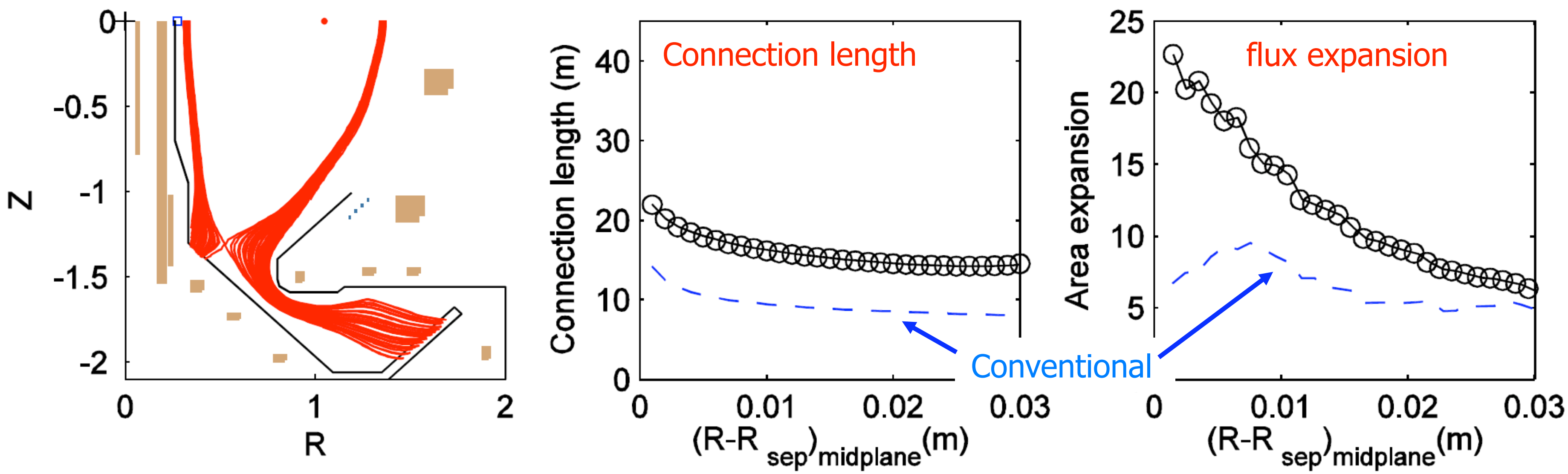
- MAST may be the only place to test super-X*
- Aim:
  - explore physics of long-leg (e.g. compare to “snow-flake”)
  - help clarify options for DEMO and CTF/FNSF
- Not test of specific DEMO, CTF configuration
- Have shown Super-X in CTF with shielded coils



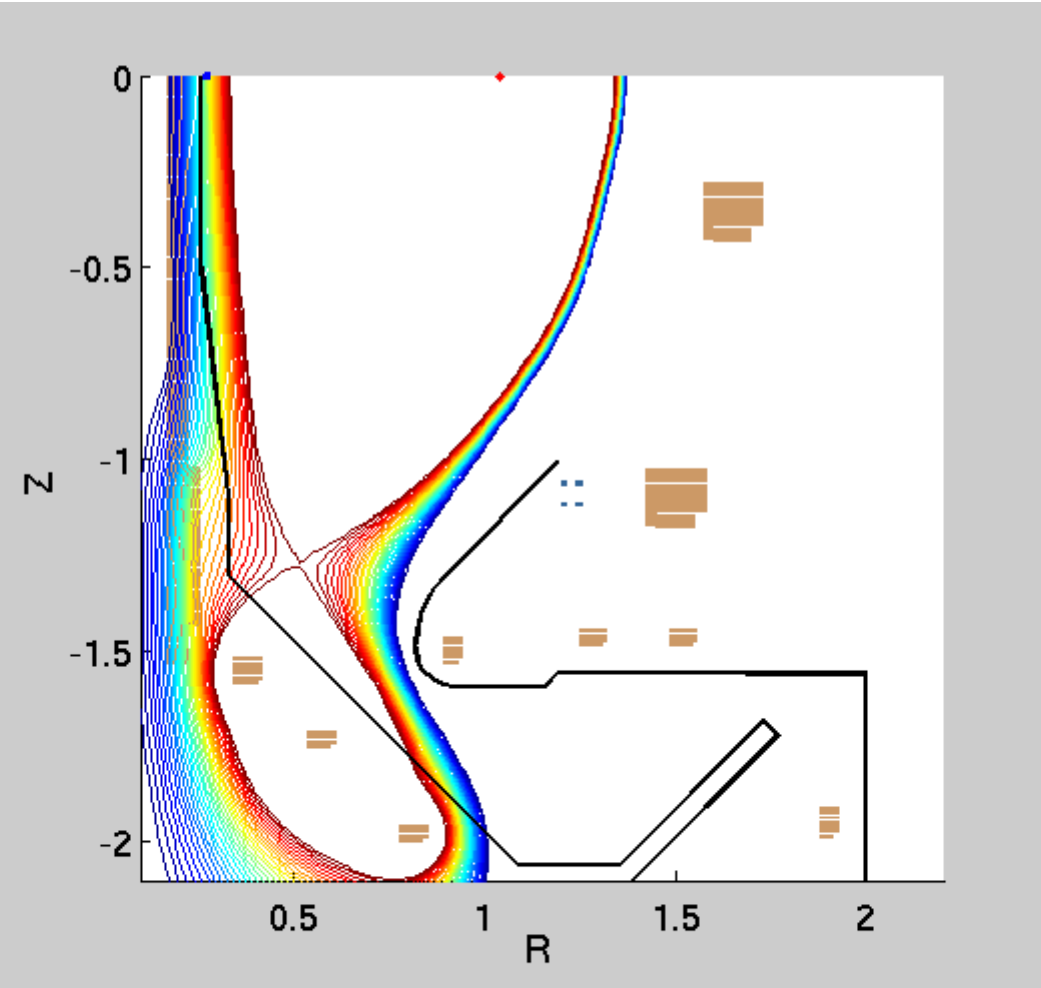
*Valanju, Kotschenreuther et al

MAST super-X divertor

- Super-X combines
  - long connection length,
  - flux expansion and
  - large volume to radiate power
- to get cold, low-power-density plasma at target
- Low poloidal field region to increase connection length in limited space

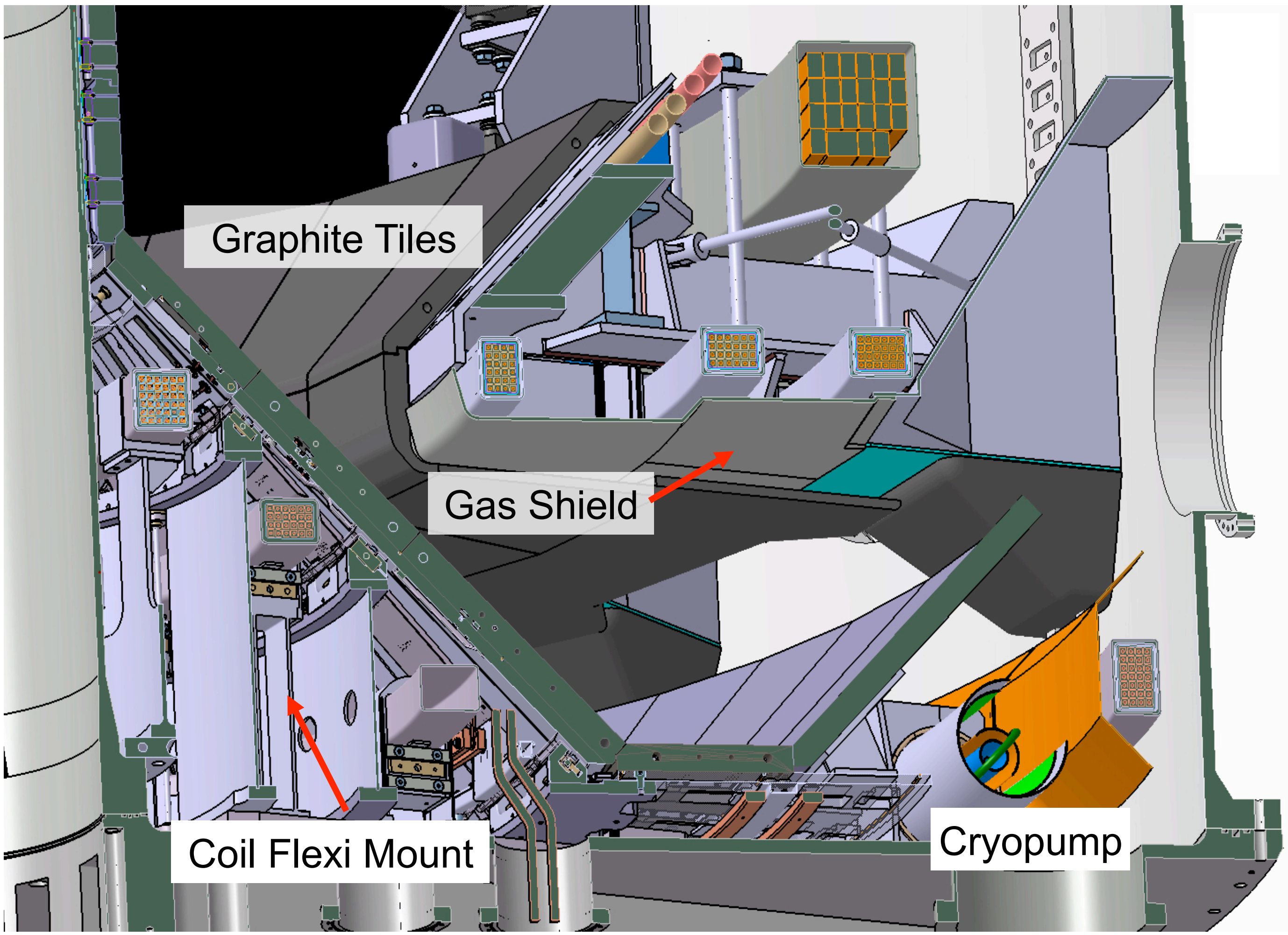


MAST super-X divertor



- PF design tests
  - can have any configuration between conventional and super-X
  - can compensate the stray solenoid flux during swing
  - estimated control accuracy of currents (~1% or better)

Super-X mechanical design



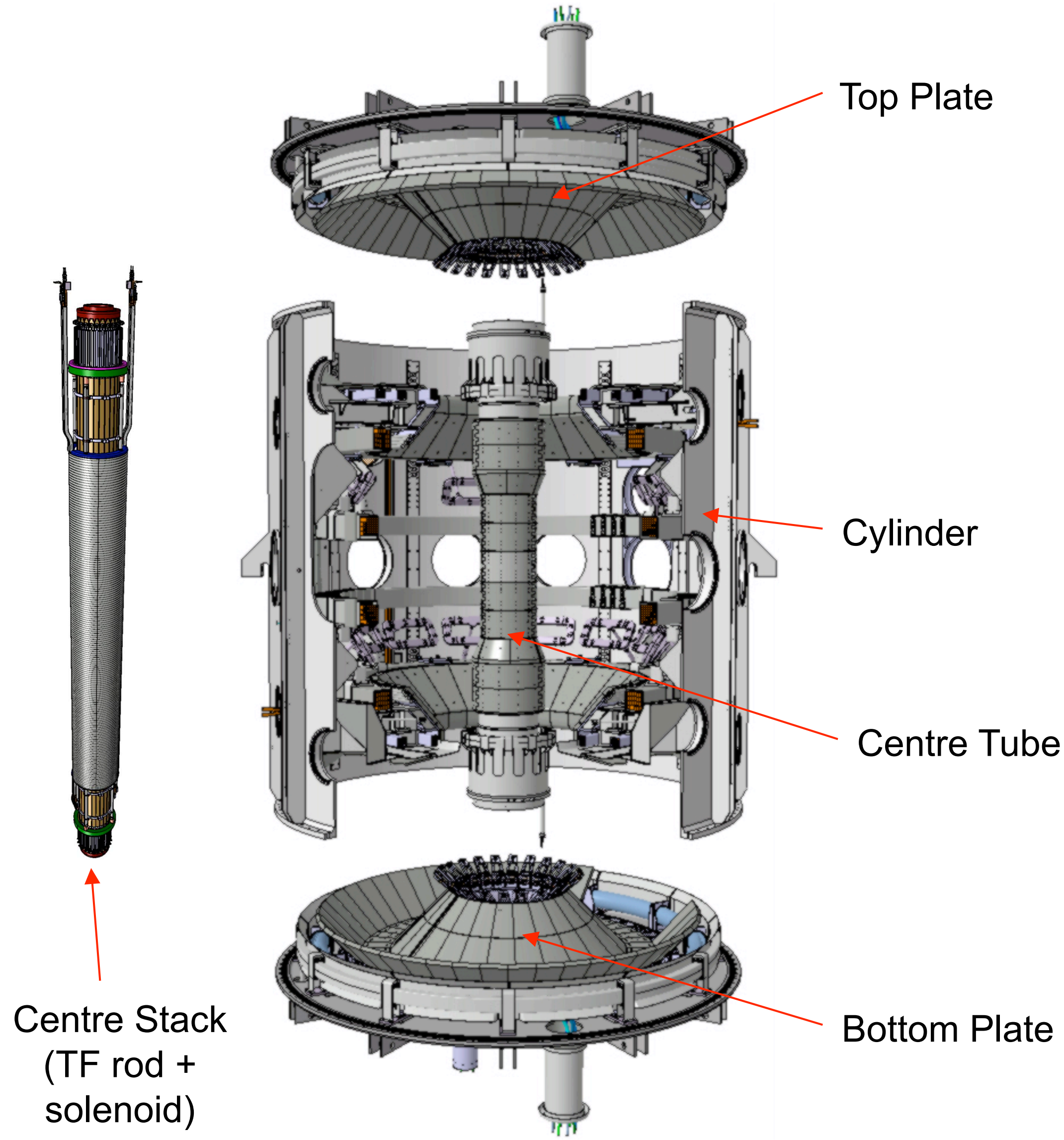
Graphite tiles (can run hot)

Gas shield

- high divertor pressure
- low main chamber pressure

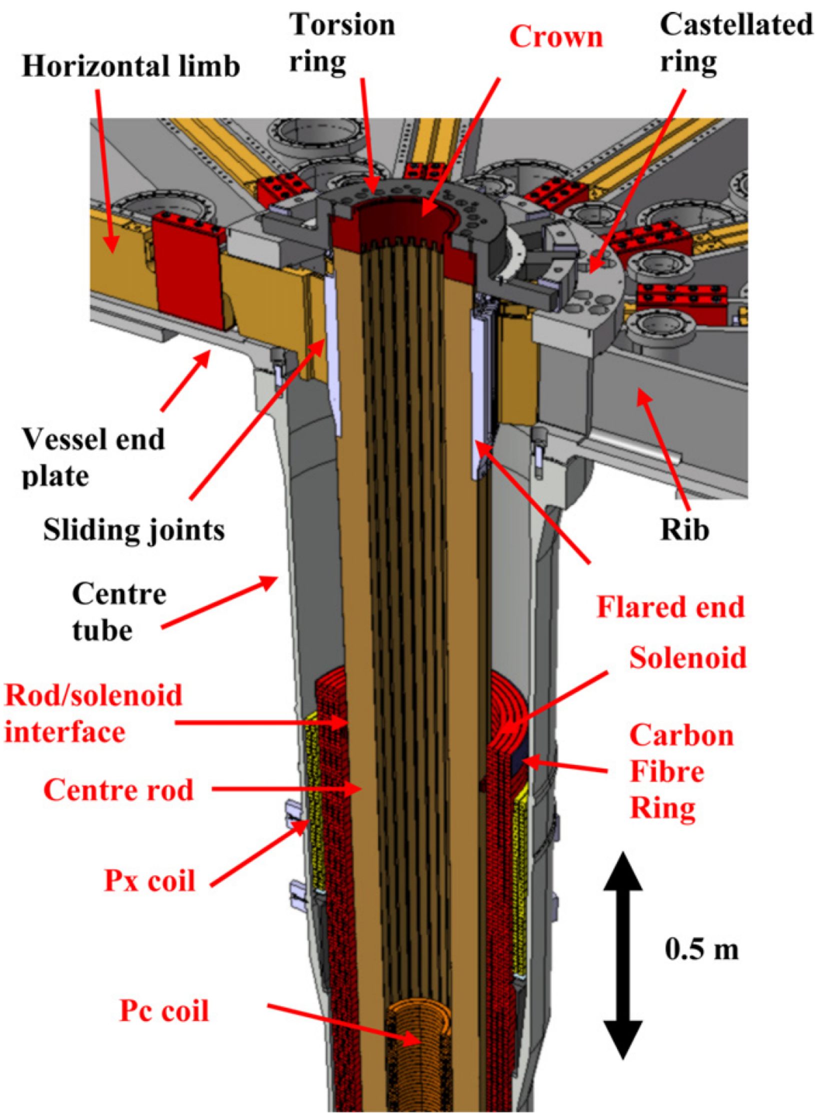
Load assembly

MAST Physics	MAST technical developments	MAST Upgrade

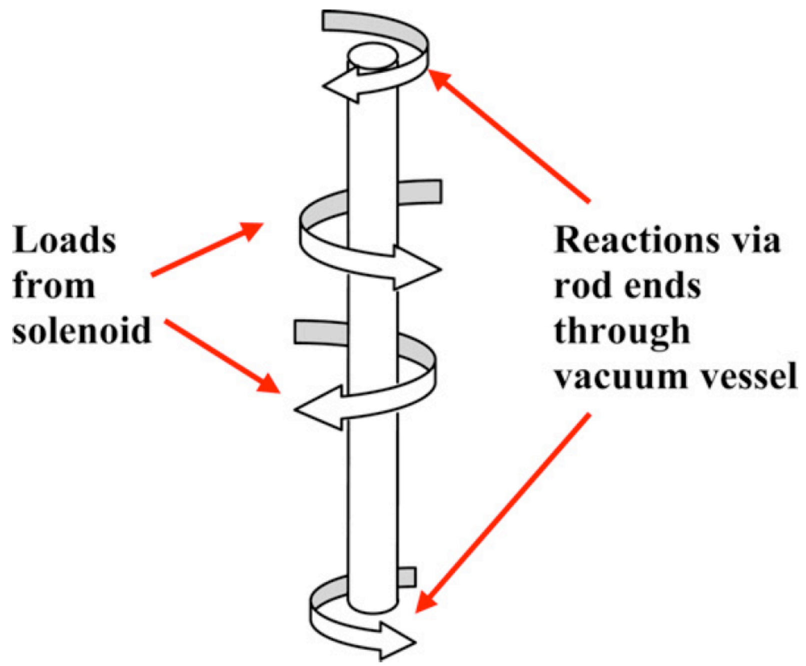


- Modular design option for parallel assembly (keep shutdown short)
- Main engineering issues:
  - Centre rod+solenoid thermal + e.m. stresses
  - TF sliding joints – thermal + e.m. stresses
  - Super-X divertor assembly and maintenance
  - magnetic alignment of coils

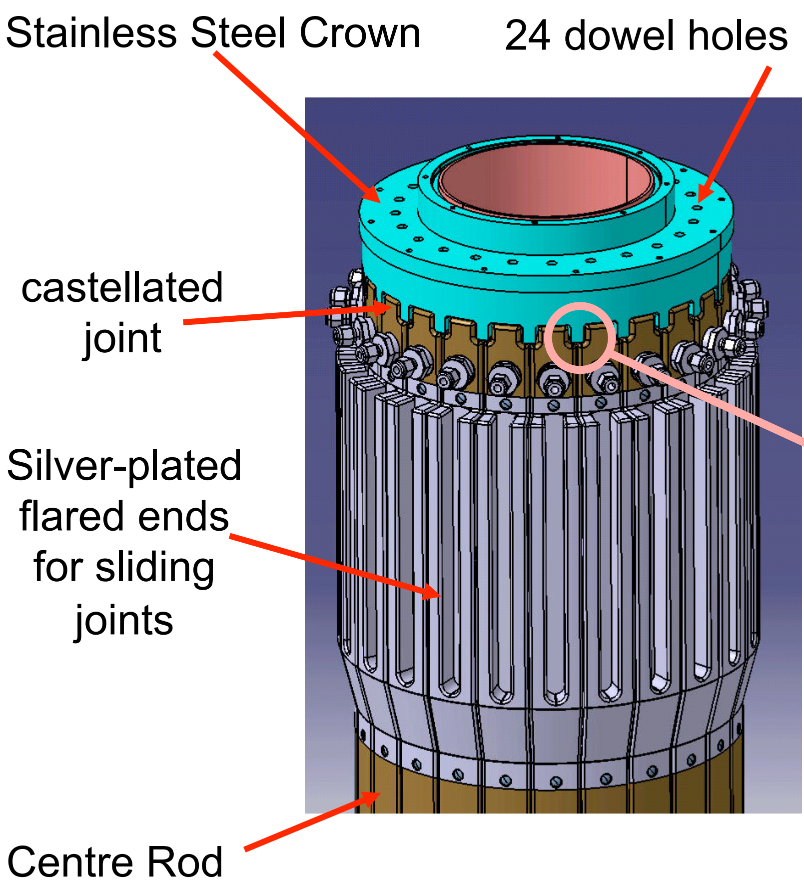
MAST Upgrade centre rod



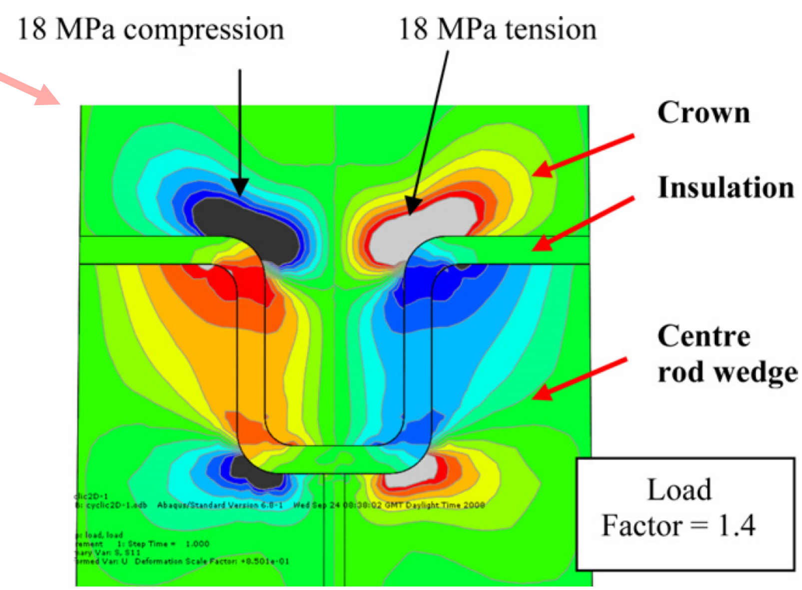
- As usual in STs, centre rod is the biggest engineering challenge
- Upgrade aims to increase TF I^2t by factor 5, if possible



MAST Upgrade TF rod

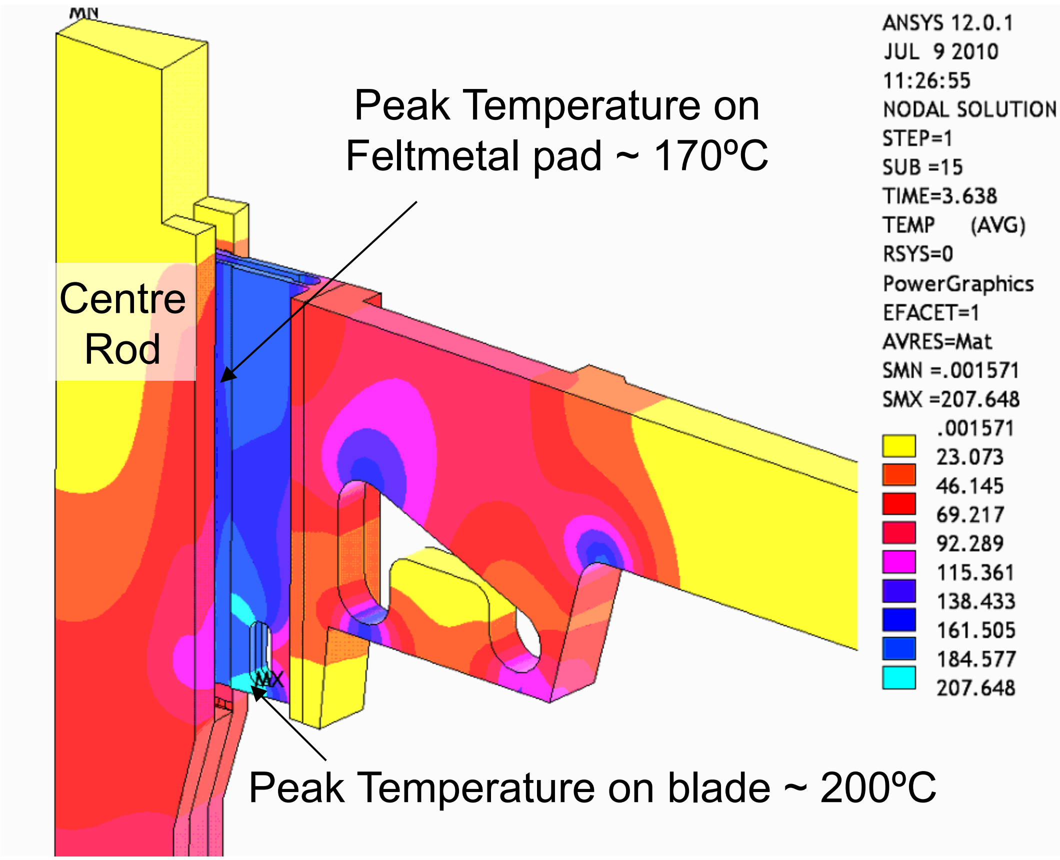


- 24 Galden-cooled copper wedges
- "Crown" transfers torque to vessel
- Issues:
  - torsional stiffness of the rod`
  - insulator between crown and wedges
- Challenging (and interesting…) design



MAST Upgrade sliding joints

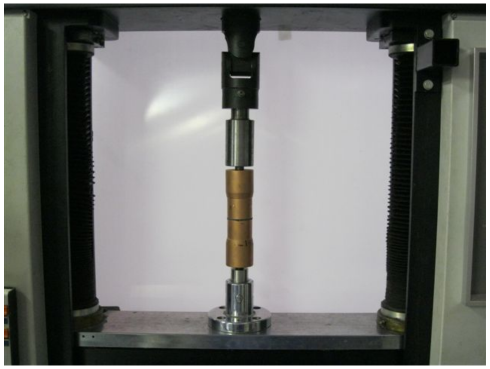
Sliding Joints

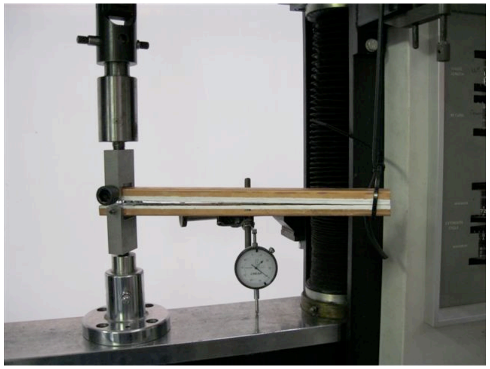


3D transient thermal analysis (due to current density). Some further optimisation required.

- Sliding joints carry TF current (up to 130kA each)
- 200mm long (cf 150mm now)
- Improved Feltmetal™
- Improved joint pressure control (thicker “tongue”, more flexible link to horizontal limbs)
- Cut-outs control current path in wedges (torque distribution) and joint (I^2t)
- Testing prototypes on MAST to check heating model
- In use for >2 months – fine so far!

Cyanate Ester resins





- Higher TF I, I^2t need better insulator (stronger at higher temperature)
- Cyanate Ester resins have attractive properties
- Tests of resin/primer underway – tensile and shear stress
- Properties seem OK

- Trial coil with CE resin
- Tested to 95°C (10kA pulses)

Summary

- Physics (ITER, DEMO, CTF, basic understanding)
  - ELM mitigation with adaptable coils (n=6). Clues on density pumpout.
  - Pedestal: stability, H-mode access with long leg divertor
  - Pellet plasmoids (deeper fuelling?)
- Technical advances
  - Neutron camera – first with modular polythene construction?
  - Novel EBW antenna array for edge current measurements
  - Enthusiastic use of new computer hardware: FPGAs and GPUs
- MAST Upgrade in advanced stage of design
  - Aim at ITER, DEMO, CTF/FNSF issues
  - Super-X divertor – adaptable configuration
  - Flexible higher performance longer pulse device
  - Engineering aspects: sliding joints, centre rod insulator (cyanate ester?)