Status of the MAST Upgrade project and future plans

IT Chapman

on behalf of the MAST Upgrade Team

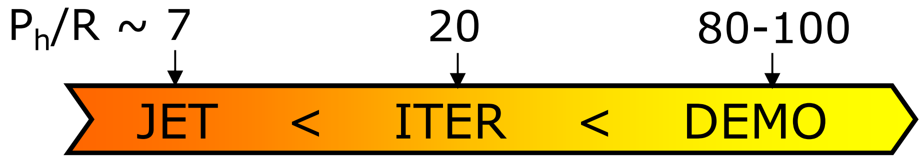
PPPL

26 January 2016

CCFE is the fusion research arm of the **United Kingdom Atomic Energy Authority.**
This work was funded by the RCUK Energy Programme [grant number EP/I501045] .

Science issues to tackle with MAST Upgrade

Main issues for fusion tokamaks

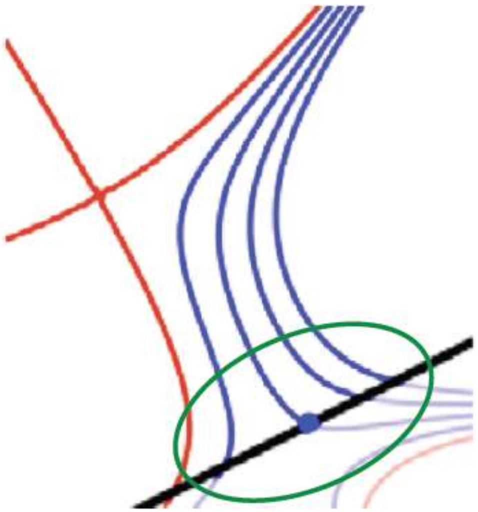


- Divertor Challenge
  - High heat flux needs to be mitigated ⇒ radiation, novel divertor concepts

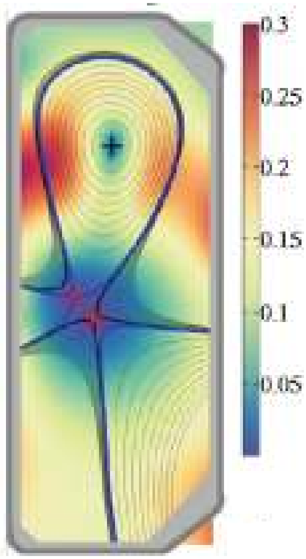
Plasma exhaust in DEMO

- To have viable heat flux on divertor plates must either:
  - Radiate many 100's MW inside separatrix
    - But is this compatible with good core plasma performance?
  - Use alternative divertor to increase divertor radiated power by ~15x
    - Limited by radiating volume, impurity density which controls power loss
    - Does it make sense from engineering perspective?

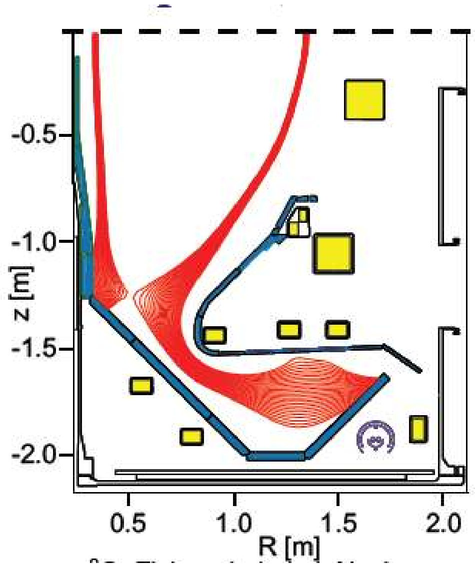
X-divertor



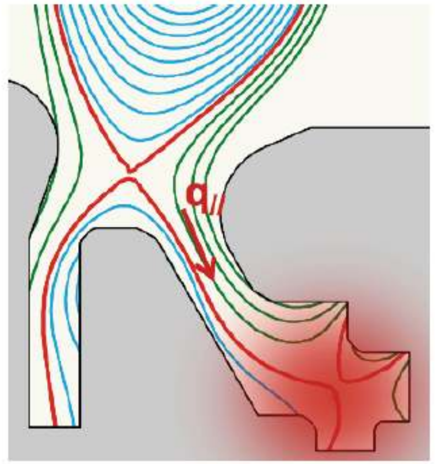
Snowflake



Super-X

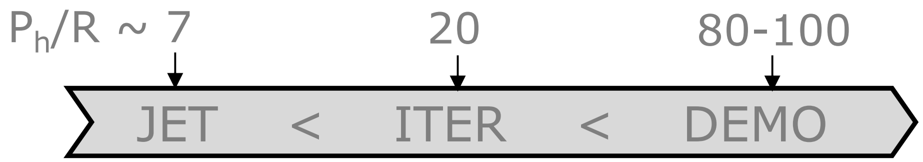


X-point Target



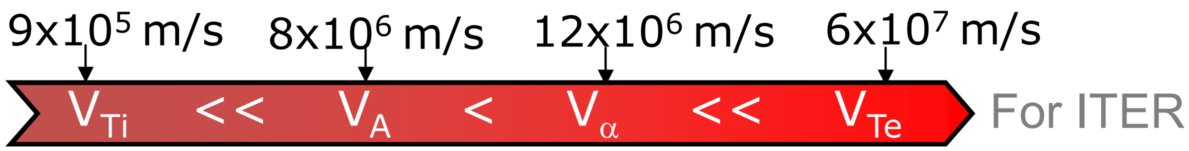
Main issues for fusion tokamaks

- Divertor Challenge



  - High heat flux needs to be mitigated ⇒ radiation, novel divertor concepts

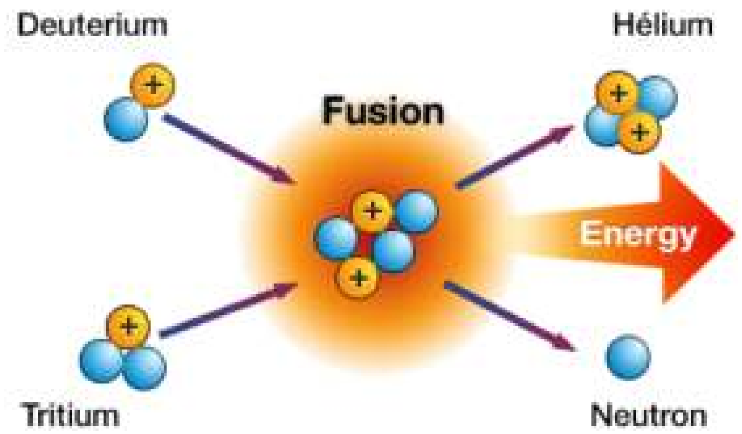
- Fast-ion physics

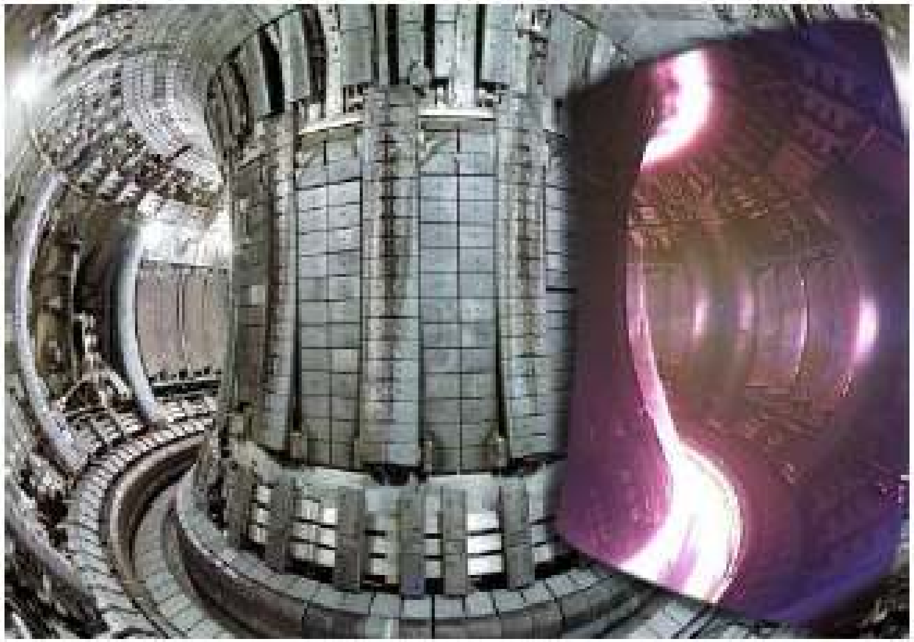


  - Fast particle driven instabilities may change confinement, current drive, fast-ion redistribution

Fast particle physics

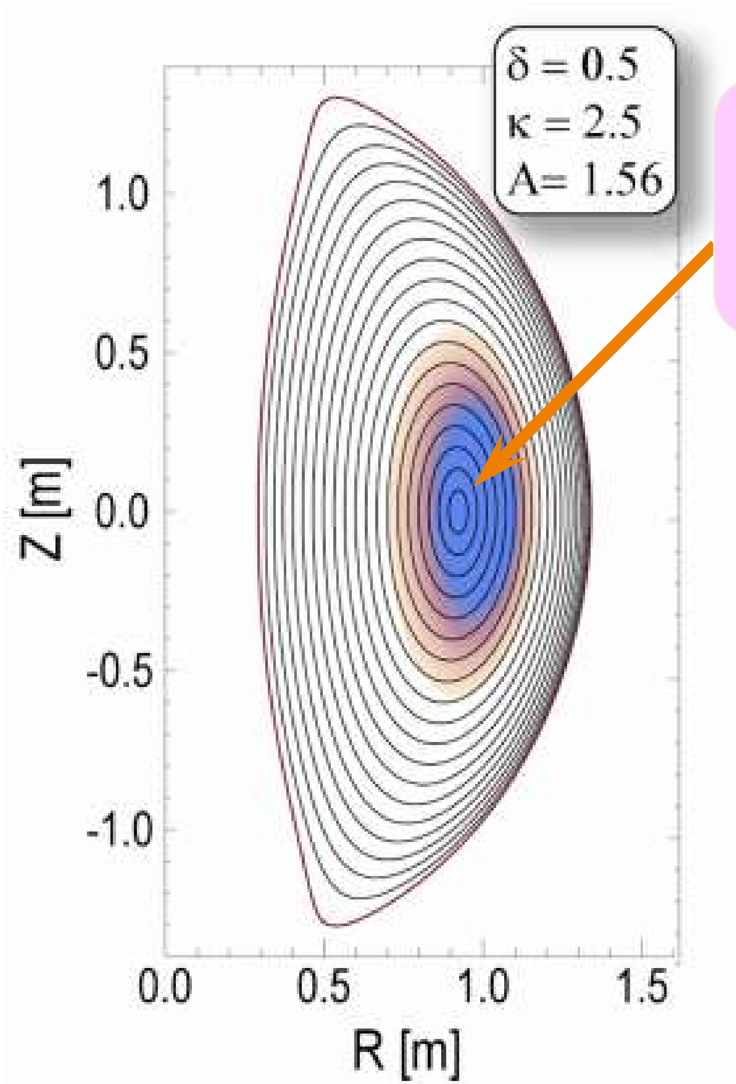
- Perhaps the biggest change in ITER will be a dominant source of fusion-born alpha particles





- Why do we care?
  - Loss of bulk heating
    - Unacceptable for efficient power plant
    - Possible ignition problems
  - Damage to first wall
    - Can only tolerate a few % losses

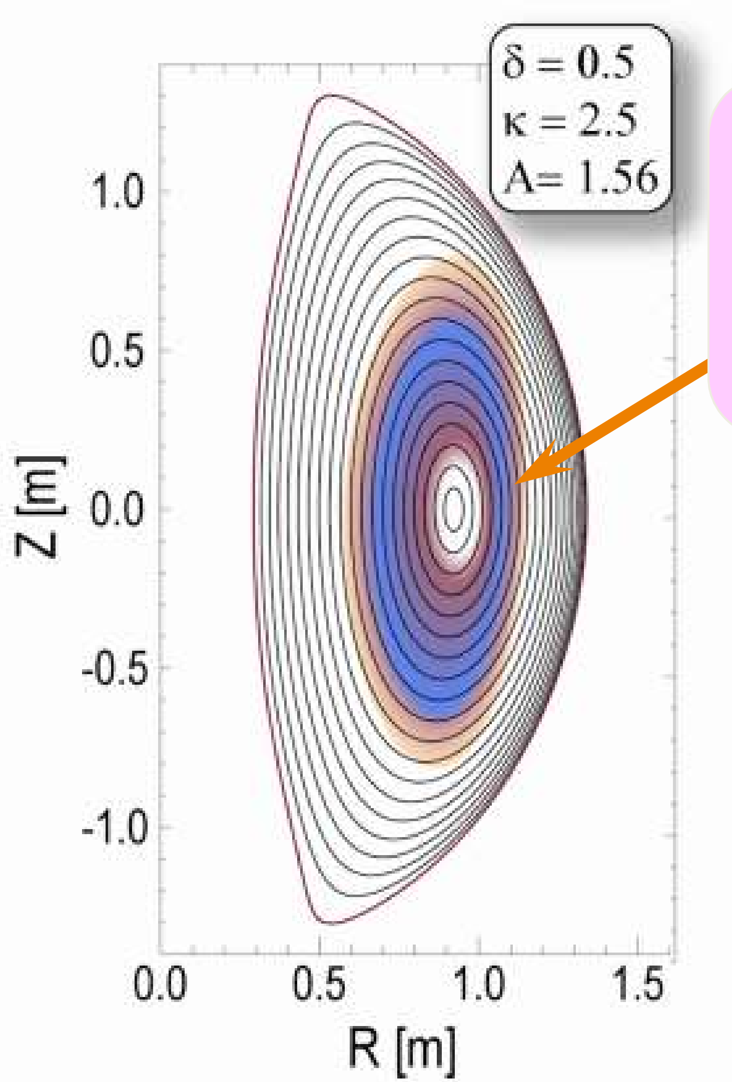
Tailoring the fast ion distribution



Provide enhanced profile control

- Core heating and current drive with on-axis NBI

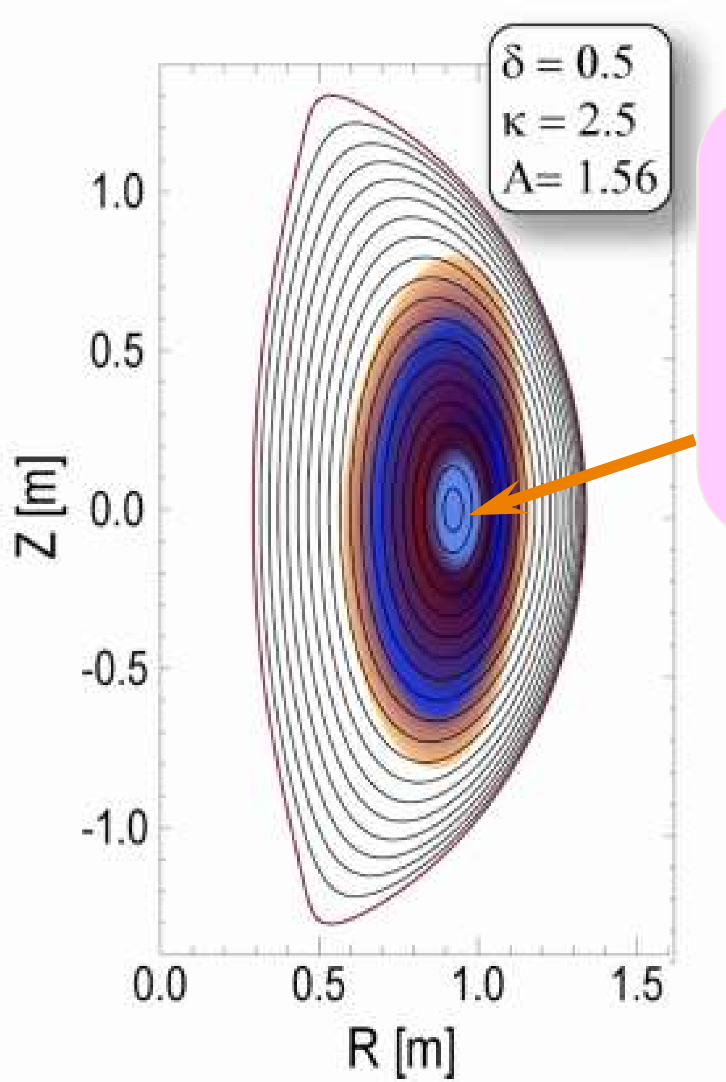
Tailoring the fast ion distribution



Provide enhanced profile control

- Core heating and current drive with on-axis NBI
- Hollow deposition with off-axis NBI

Tailoring the fast ion distribution



Provide enhanced profile control

- Core heating and current drive with on-axis NBI
- Hollow deposition with off-axis NBI
- Broad profiles with both systems

Main issues for fusion tokamaks

$P_h/R \sim 7$ — 20 — 80-100

JET < ITER < DEMO

- Divertor Challenge
  - High heat flux needs to be mitigated $\Rightarrow$ radiation, novel divertor concepts

$9\text{x}10^5$ m/s — $8\text{x}10^6$ m/s — $12\text{x}10^6$ m/s — $6\text{x}10^7$ m/s

$V_{Ti} << V_A < V_\alpha << V_{Te}$ For ITER

- Fast-ion physics
  - Fast particle driven instabilities may change confinement, current drive, fast-ion redistribution

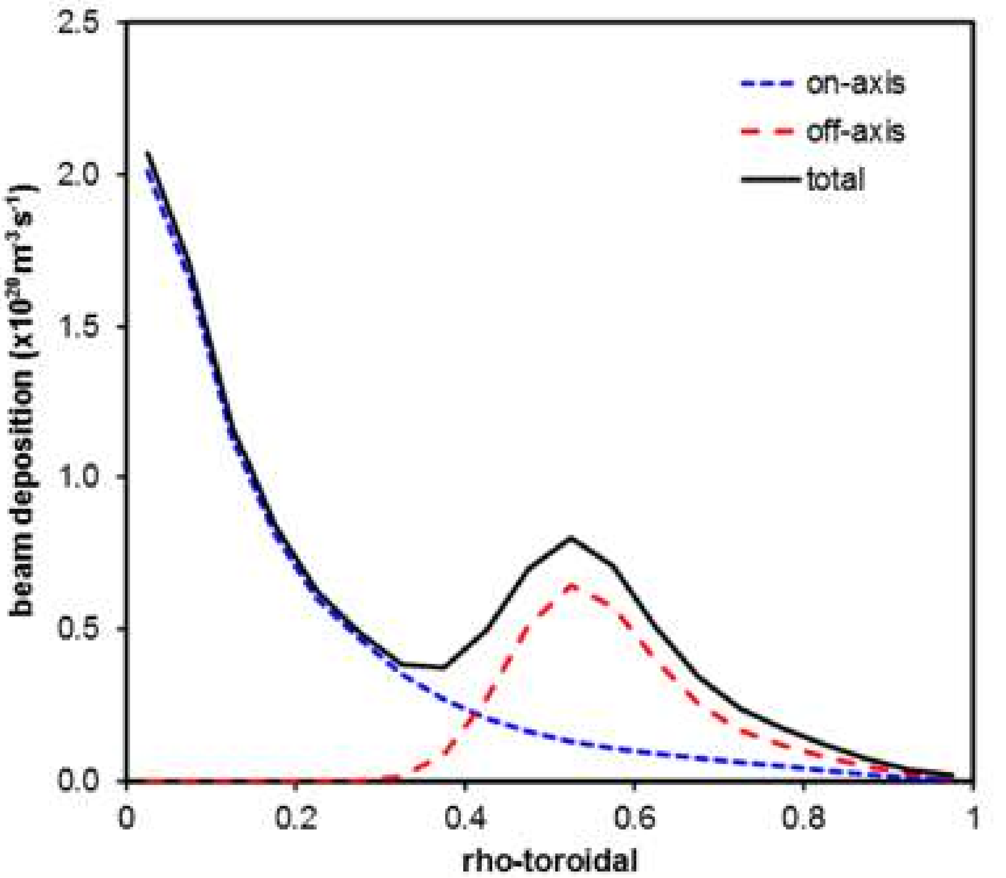
t_{pulse}< 60s — 400s (~¾ h) — d's – wk's

JET < ITER < DEMO

- **Long pulse (steady state)**
  - Need means to sustain the plasma current $\Rightarrow$ current drive schemes (NBI, RF), optimise bootstrap fraction

Current drive studies

- Off-axis NBI will provide ability to study current drive physics



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Main issues for fusion tokamaks

- Divertor Challenge

  $P_h/R \sim 7$ 20   80-100

  JET < ITER < DEMO

  – High heat flux needs to be mitigated ⇒ radiation, novel divertor concepts

- Fast-ion physics

  9×10^5 m/s 8×10^6 m/s 12×10^6 m/s 6×10^7 m/s

  $V_{Ti} << V_A < V_\alpha << V_{Te}$ For ITER

  – Fast particle driven instabilities may change confinement, current drive, fast-ion redistribution

- Long pulse (steady state)

  $t_{pulse} < 60$s   400s (~¾ h)   d's – wk's

  JET < ITER < DEMO

  – Need means to sustain the plasma current ⇒ current drive schemes (NBI, RF), optimise bootstrap fraction

- Neutron load

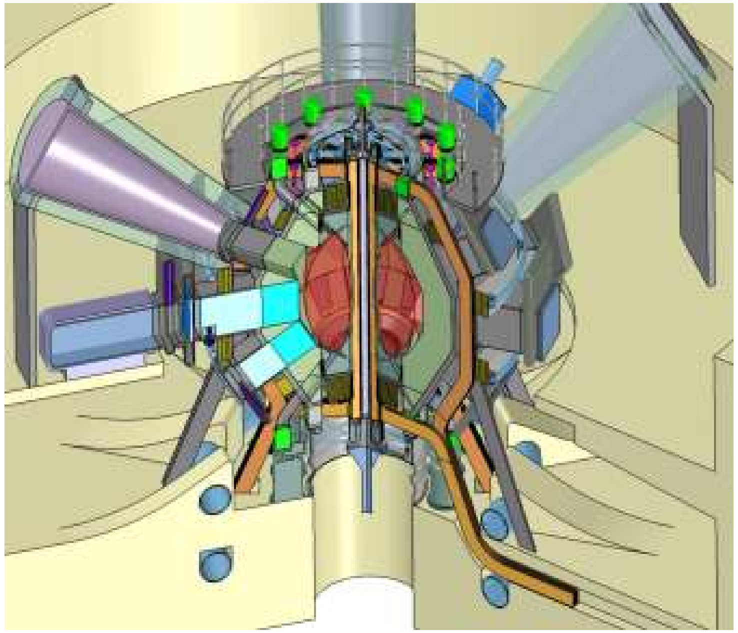
  $\Gamma_n < 0.1$ MW/m^2 0.5 MW/m^2 2.2 MW/m^2

  JET < ITER < DEMO

  – Structural integrity needs to be maintained ⇒ materials testing, components testing

Components Test Facility (CTF)

- A CTF is for prototyping components (~1m^3) in a fusion reactor environment (neutrons, heat loads, magnetic fields, cyclic stresses)
  - Smaller/cheaper [O(€1Bn) construction cost]/lower risk than a DEMO/reactor scale device
- Significant plasma physics challenges to address with MAST-U (with enhancements):
  - Starting-up the plasma (no solenoid)
  - Heat exhaust (many times present limits)
  - Particle exhaust
  - Energy confinement



MAST Upgrade

Increased TF
Improved confinement

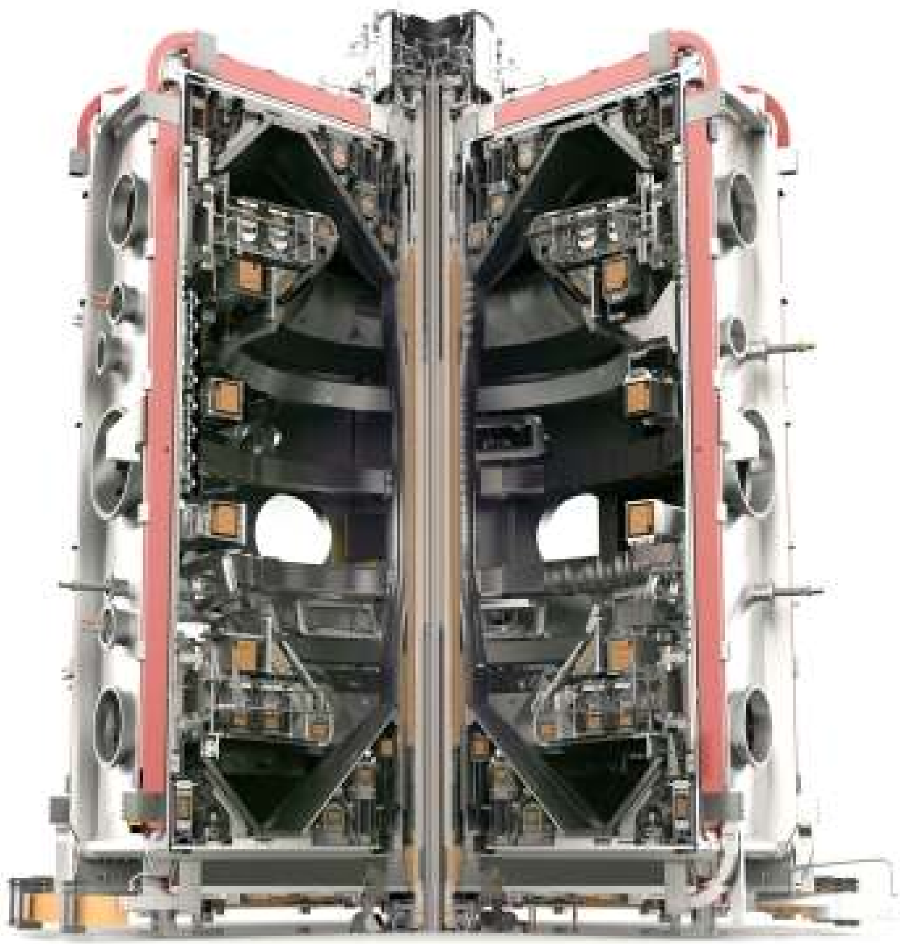
New Solenoid
Greater I_p, pulse duration

19 New PF Coils
Improved shaping

Super-X Divertor
Improved power handling

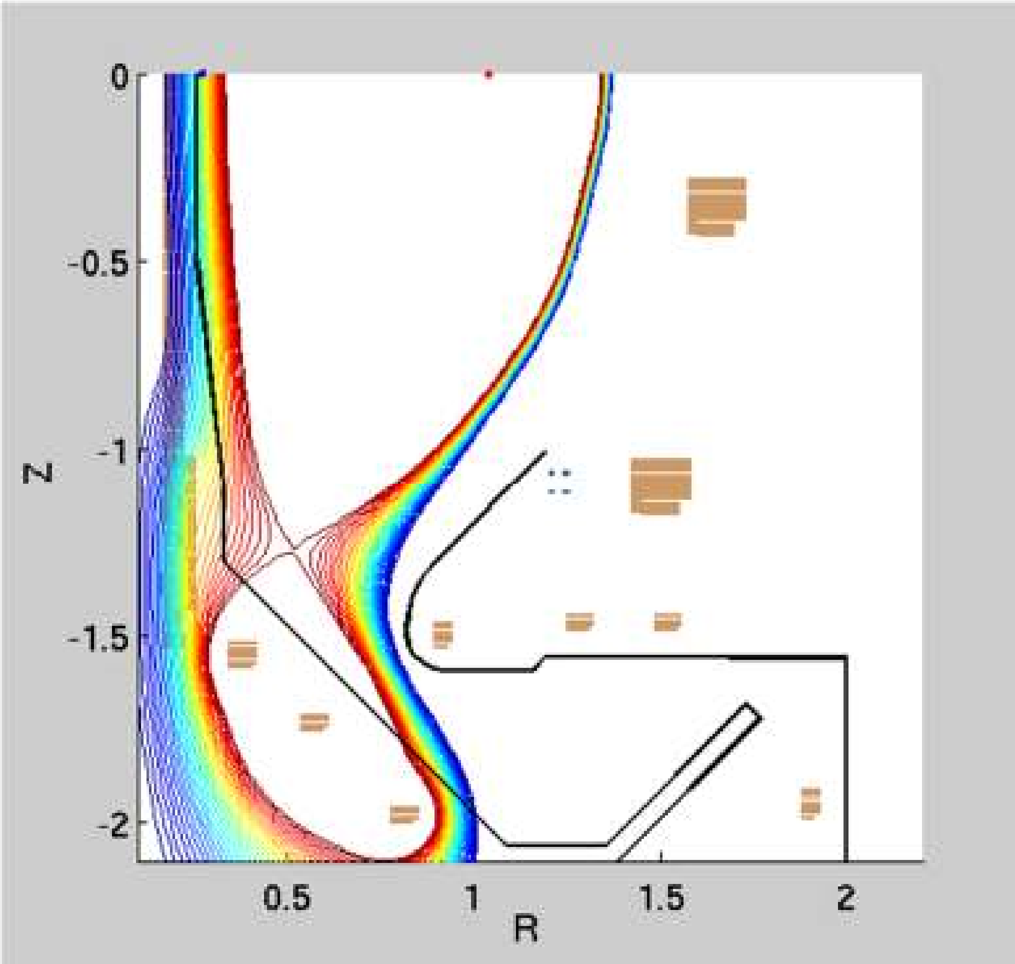
Off-Axis NBI
Improved profile control

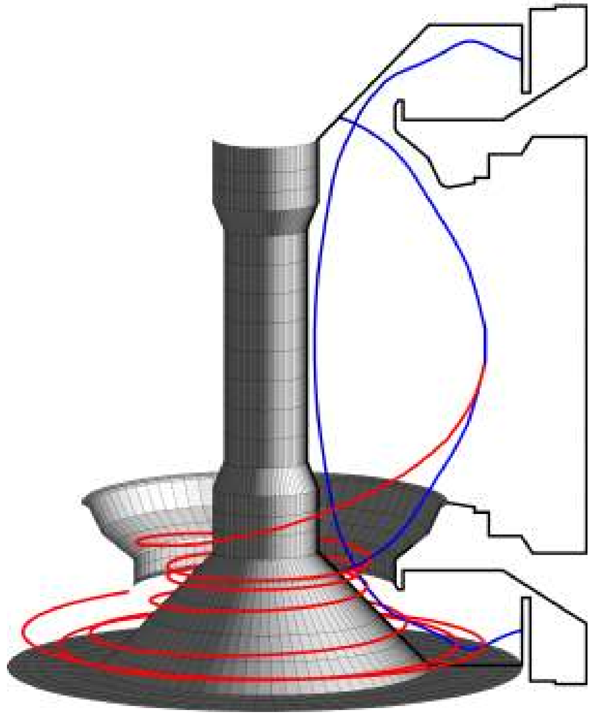
MAST-Upgrade after initial construction ("core scope")



Divertor configurations in MAST Upgrade

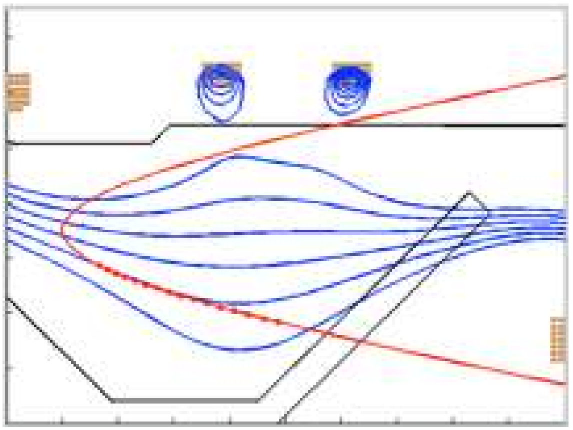
- Flexible poloidal field coil set allows for a wide variety of magnetic geometries in MAST Upgrade



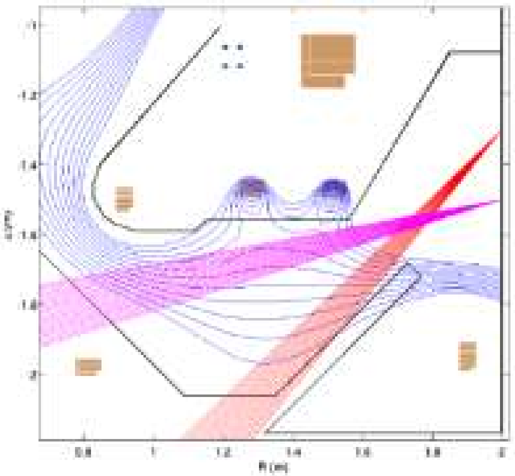


S Lisgo, EPS, 2009
G Fishpool, J Nucl Mat 2012

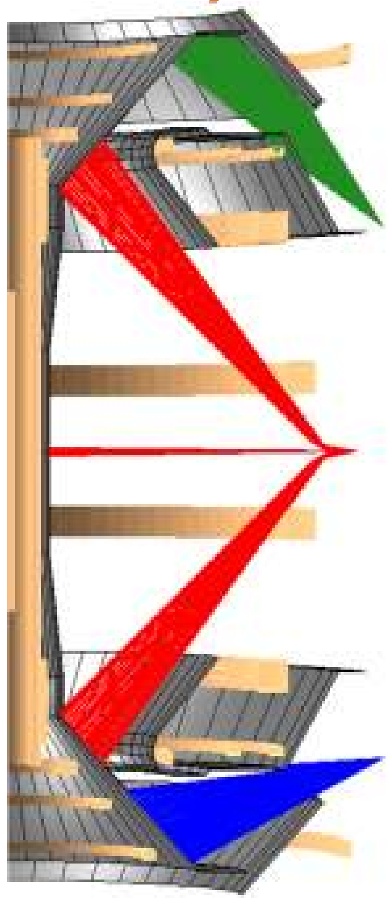
Divertor diagnostics (main systems)



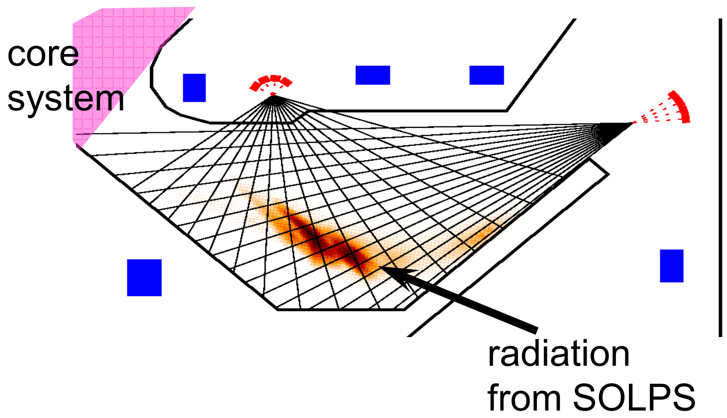
Divertor Thomson scattering



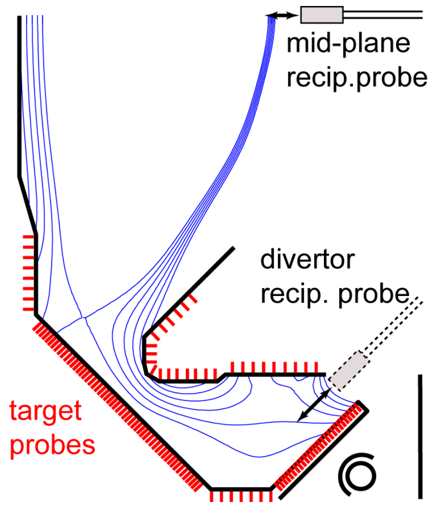
Spectroscopy



Infra red views of PFCs



Bolometer arrays for divertor



Langmuir probes

Others, especially
- Coherence imaging (flows)
- Divertor science facility

Scientific Goals of MAST-U (Core Scope)

- Improving the understanding of exhaust physics
  - Closure and connection length
  - Flux expansion at the divertor targets
  - Volumetric losses and detachment
- Fast ion physics and current drive
  - Tailoring super-Alfvenic fast ion distribution
  - High elongation plasmas with reduced fast ion redistribution
- Other high-priority ITER, DEMO and CTF needs
  - RMP ELM control
  - Pedestal & core turbulence at low collisionality

New diagnostics for 2017

- Divertor Thomson scattering system (MST2)
- Fast ion loss detector (CIEMAT)
- Adaptable reciprocating probe head (MST2)
- Doppler backscattering (SWIP)

- Plus bids for other systems:
  – Improvements to coherence imaging (Durham)
  – MANTIS – array of high speed cameras (York)
  – X-pt imaging bolometer (Mexico)

MAST Upgrade project status

Progress against milestones

Serial No.	MILESTONE	Stretch Target	Status	Latest plan
	1.3. LOAD ASSEMBLY			
B3.M52	Lower Divertor Cassette installed in MAST-U Vacuum Vessel	30-Jun-15	Complete	24/09/2015
B3.M58	Strengthened legs for MAST vessel installed	30-Sep-15	Complete	30-Sep-15
B3.M60	Lower End plate assembly available for installation	31-Oct-15		18/01/2016
B3.M61	MAST-U Vacuum Vessel installed in MAST Blockhouse	30-Nov-15		10/02/2016
	1.4. HEATING AND FUELLING			
B3.M62	Neutral Beam mechanical pre-assemblies completed	30-Nov-15	Complete	27-Nov-15
	1.6. POWER SUPPLIES			
B3.M53	Local Commissioning of the TFPS Completed	30-Jun-15	Complete	02-Jul-15
B3.M65	Local Commissioning of the DFPS Completed	31-Dec-15		29-Jan-16
B3.M66	MAST Power Supply Area, ready for RFPS Commissioning	29-Feb-16		04-Mar-16
	1.7. BUILDINGS AND INFRASTRUCTURE			
B3.M56	Services complete for TARDIS room	31-Aug-15	Complete	02-Sep-15
B3.M57	Blockhouse pit area and services complete	31-Aug-15	Complete	28-Aug-15
B3.M63	Fibre Backbone Network installed	30-Nov-15		24-Dec-15
B3.M67	Blockhouse area and services complete	29-Feb-16		12-Feb-16
	1.8. MACHINE CONTROL, PROTECTION AND DATA ACQUISITION			
B3.M54	PASS for the PS Area, ready for DFPS Off-coil Commissioning	30-Jun-15	Complete	17-Jul-15
B3.M55	Local tests completed for the TF hardwired protection	31-Jul-15	Complete	11-Aug-15
B3.M59	Local tests of the P1 coil hardwired protection completed	30-Sep-15	Complete	22-Oct-15
B3.M68	Core Datac hardware installed	29-Feb-16		03-Mar-16
B3.M69	Plasma Control System hardware installed	29-Feb-16		08-Mar-16
	NON-MAST-U FUNDED REFURBISHMENTS			
B3.M64	New Control room available for Handover	30-Jun-15	Complete	29-Jun-15

Load Assembly

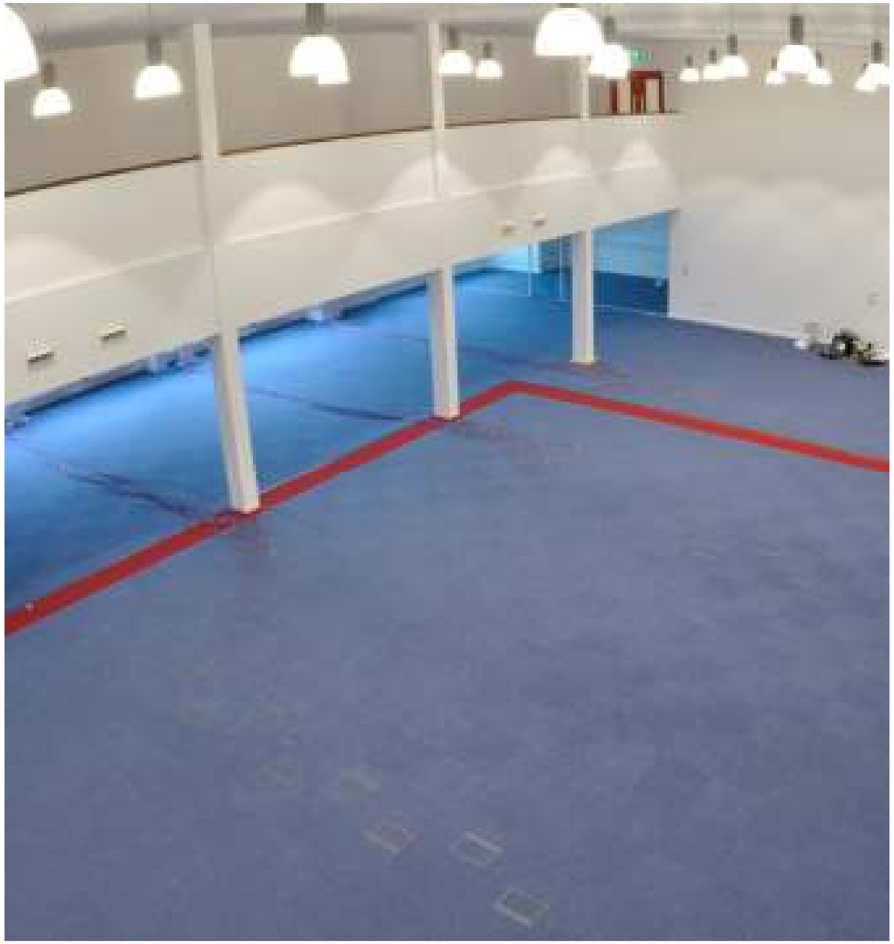
Load Assembly

Strengthened vessel supports

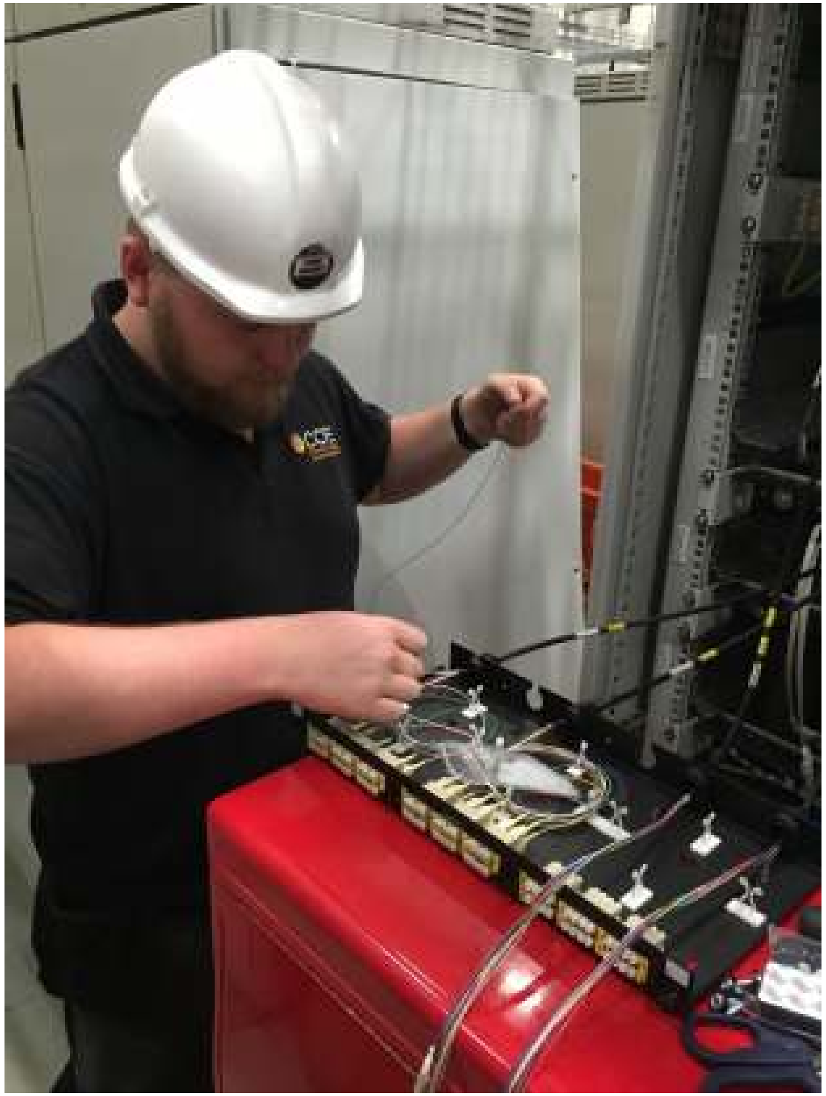
All NBI components ahead of schedule

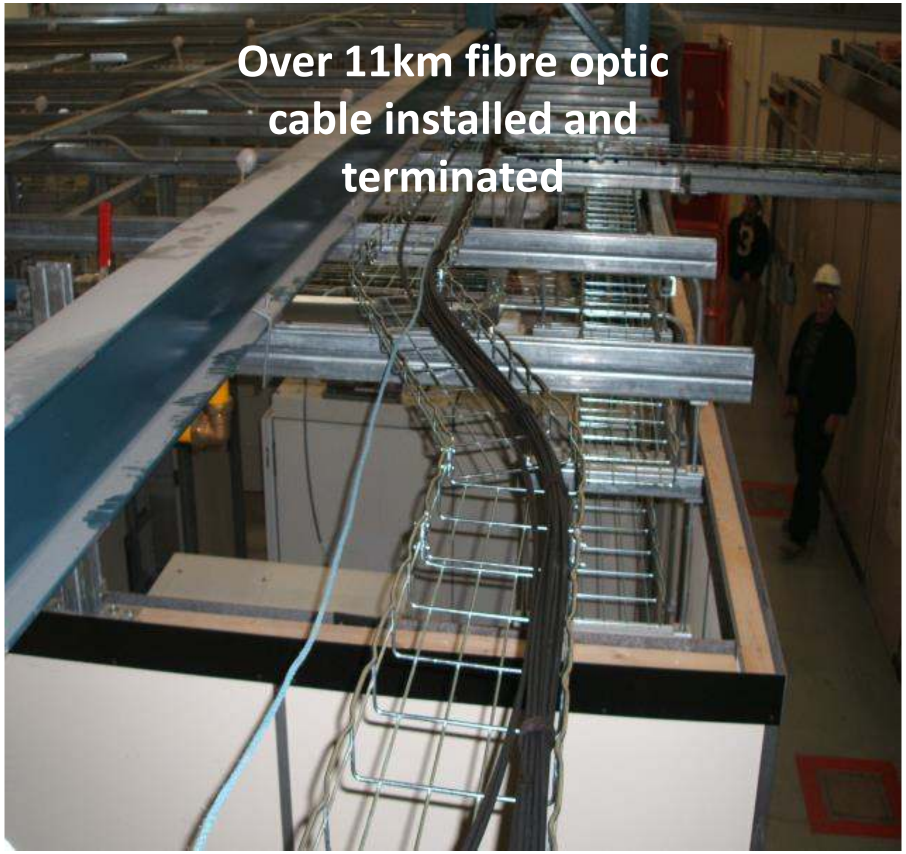
All centre column diagnostics fitted

Control room completed on time

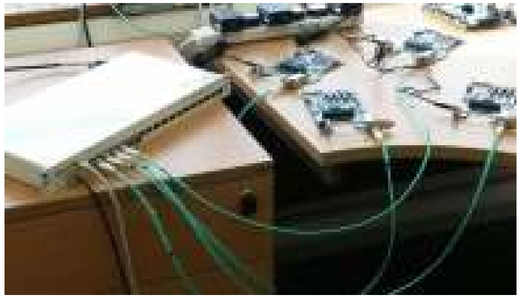


New networks on schedule



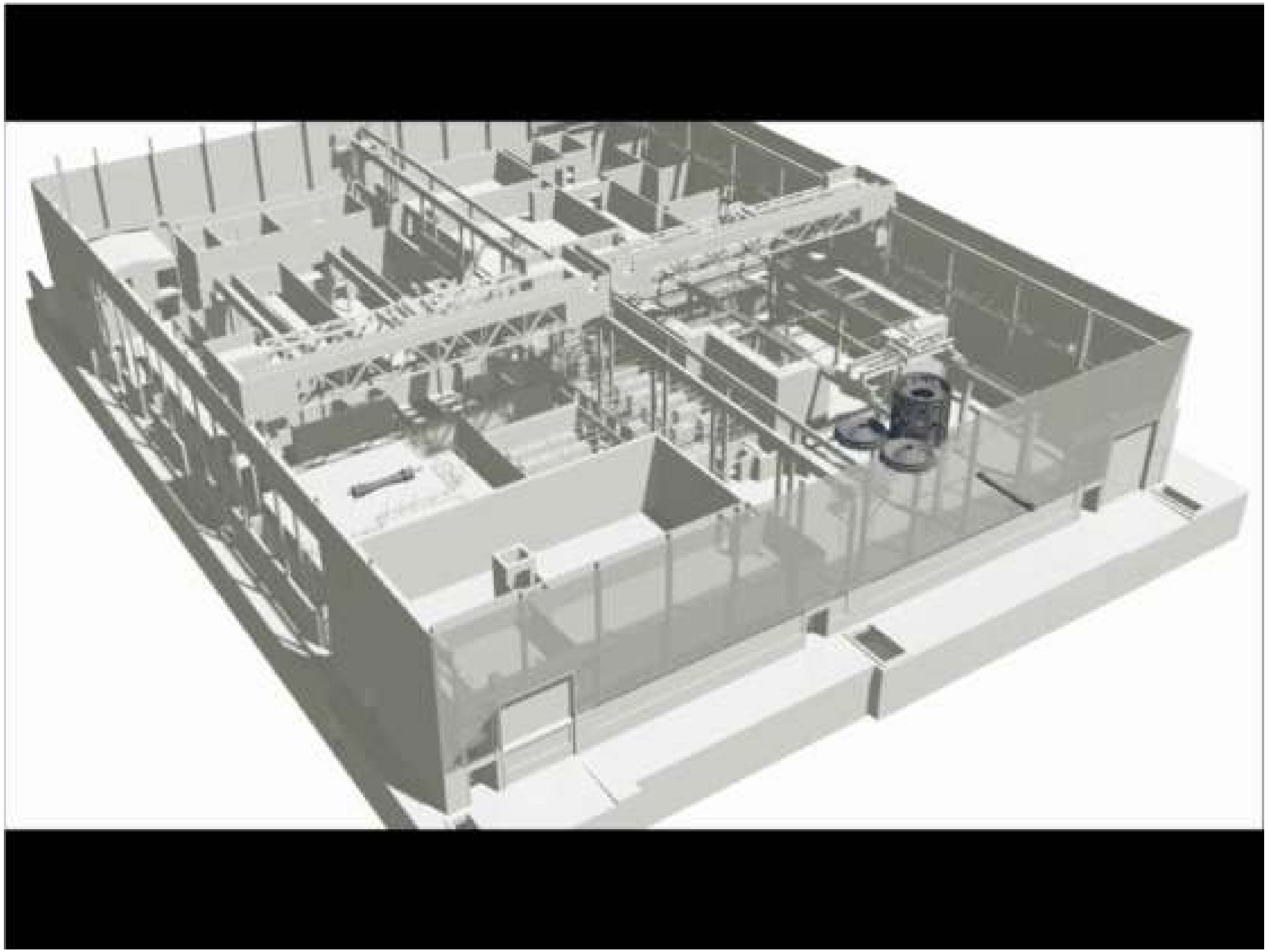


Other infrastructure needed



Other infrastructure needed

Begin putting it all back together soon



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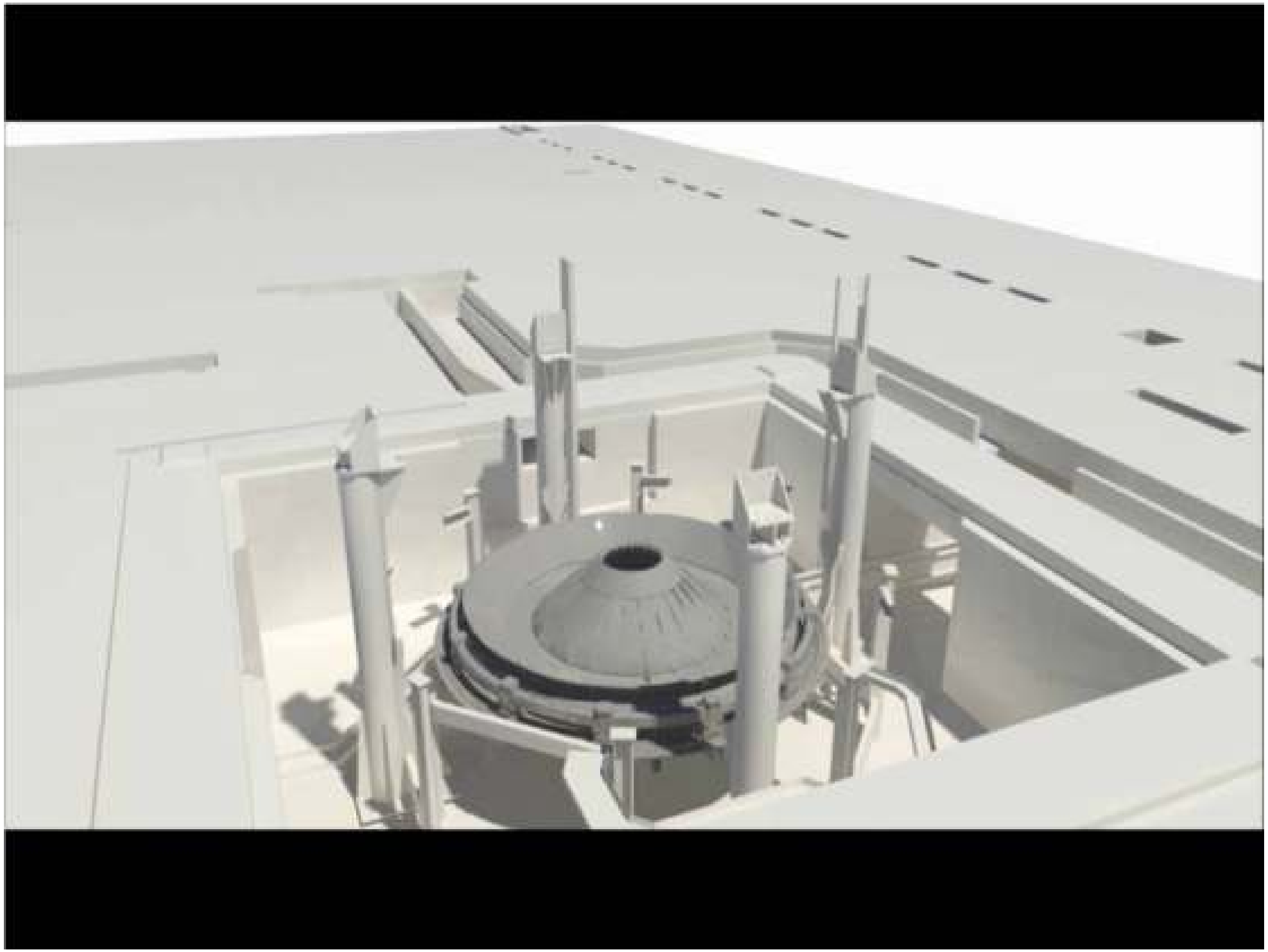


MAST Upgrade future plans

EUROfusion Plasma Exhaust Call

- **Proposals for EU support for enhancements to existing facilities / new facilities to advance plasma exhaust strategy due Jan ’16**
  - Expect funding of order €50M in total
  - Opportunity to secure EUROfusion support for Stage 1&2 enhancements

MAST Upgrade with enhancements

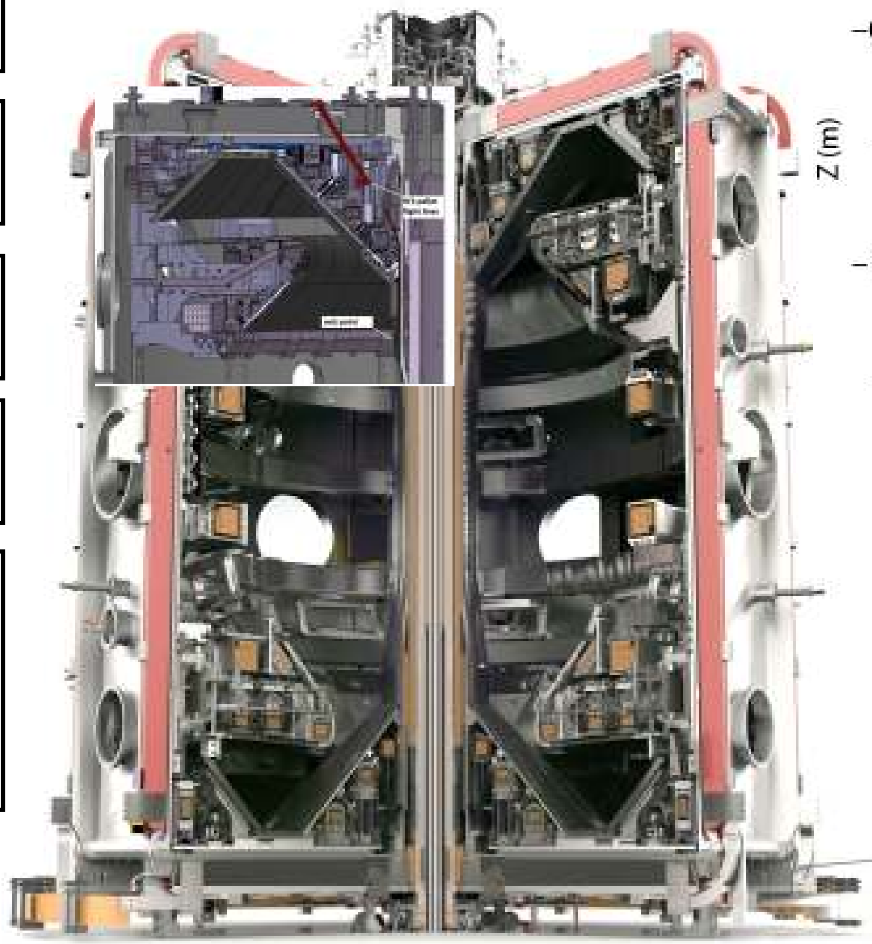
Cryoplant
Divertor particle control

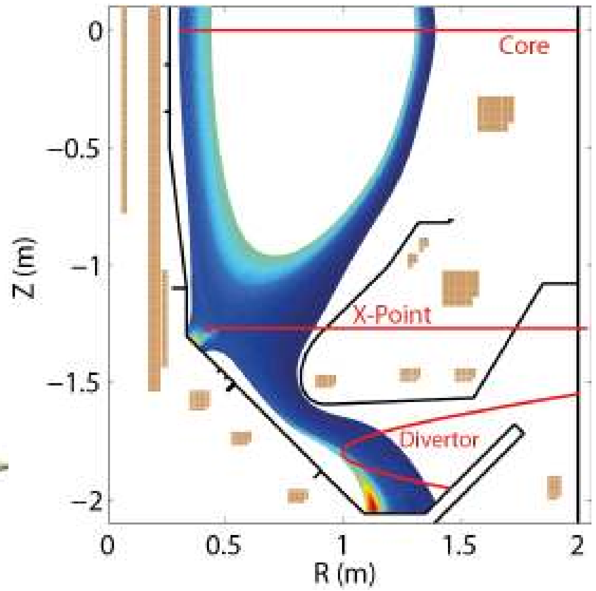
Double NBI Box
10MW auxiliary heating

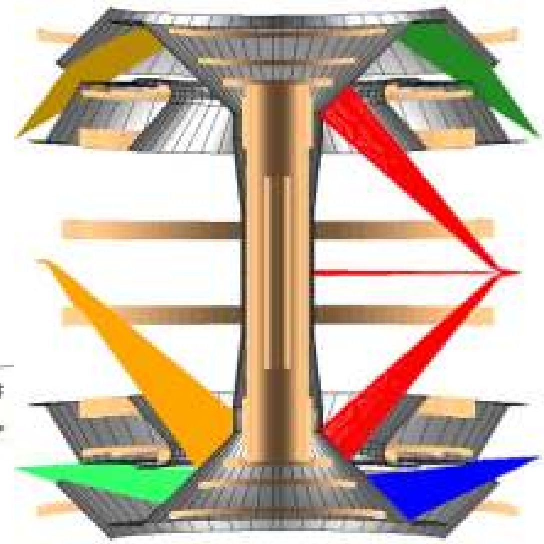
Flexible Fuelling
HFPI + 48 gas valves

Upgraded control
New RFPS and software

Extra diagnostics
X-pnt Thomson scattering
RT Langmuir probes
Multiple extra IR cameras
2x1MHz visible cameras





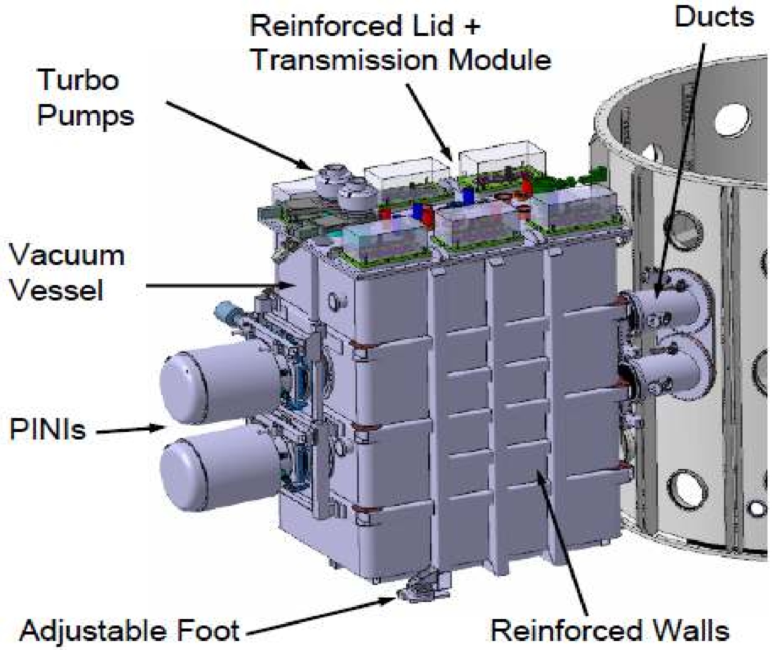


MAST-U + Enhancements

- Proposed enhancements would provide a uniquely flexible machine for exhaust physics:
  - Understanding exhaust physics in both conventional and novel divertor geometries;
  - Demonstrating specific requirements for successful adoption of novel divertors different to the needs of conventional configurations;
  - Demonstration of exhaust control schemes and credible integration with high-performance core scenarios

MAST Upgrade Enhancements: Heating

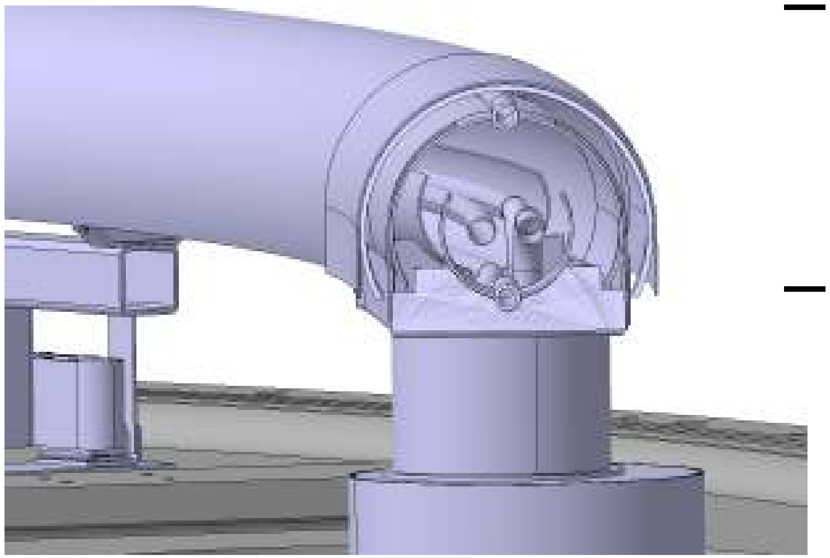
- NBI power up to 10MW
  - Increased divertor heat flux, P/R~8, wider window of detachment etc
  - Access to high β physics
  - Flexible fast ion & torque profiles



  - Widens H-mode operating space in B_t, I_p and n_e
    - More robust access for type-I ELMy H-mode
  - Higher probability to allow operation at $q_{min} > 1.3$ enabling longer pulses
    - Broader heating profile, increased off-axis current drive

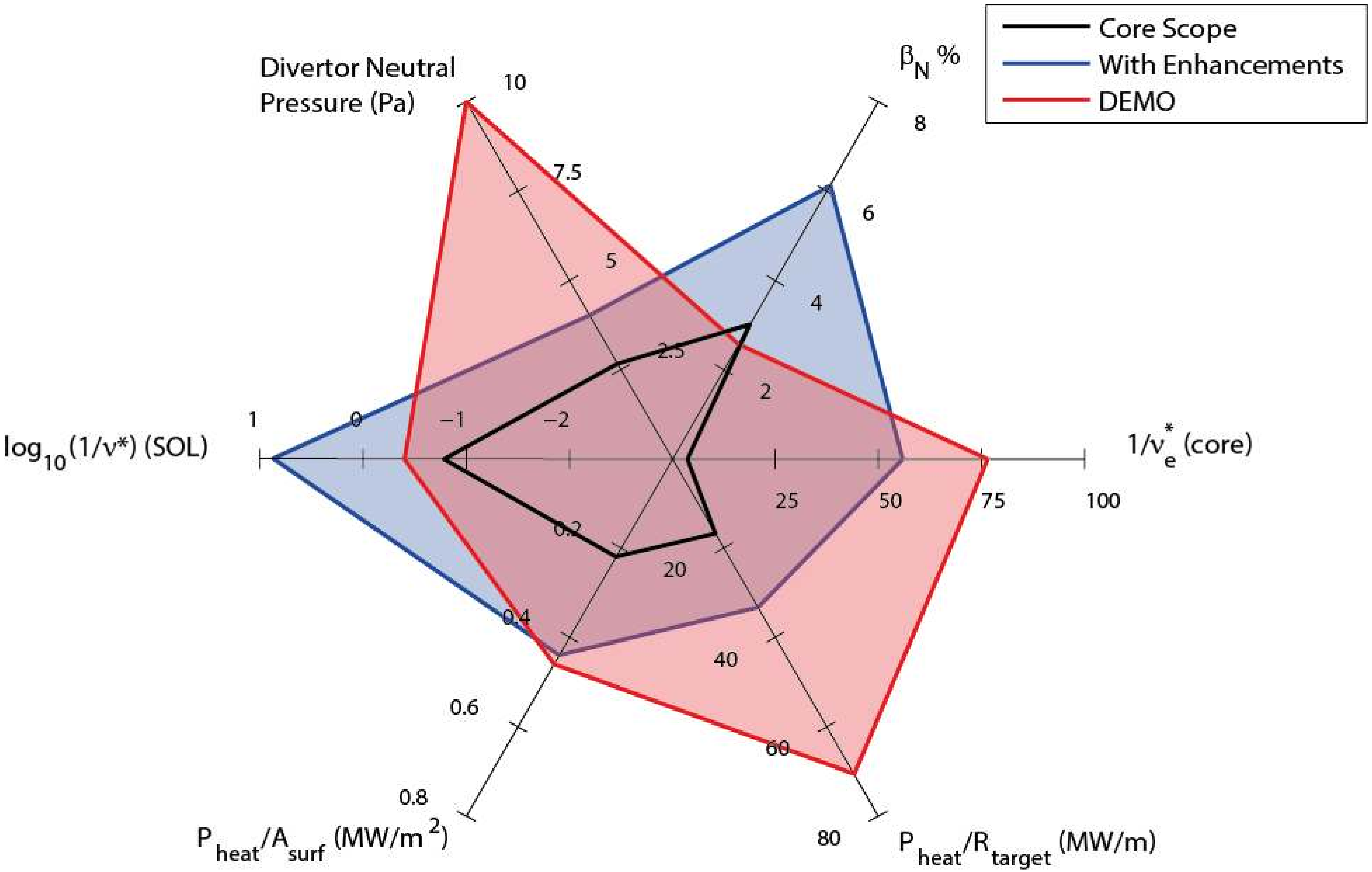
MAST Upgrade Enhancements: Cryoplant

- Provision of cryoplant for installed cryopumps
  - Access to stationary divertor conditions
  - Access to lower density and lower collisionality
    - Increased fast particle fraction
    - Hotter plasma (pedestal) $\Rightarrow$ broader T_e profile



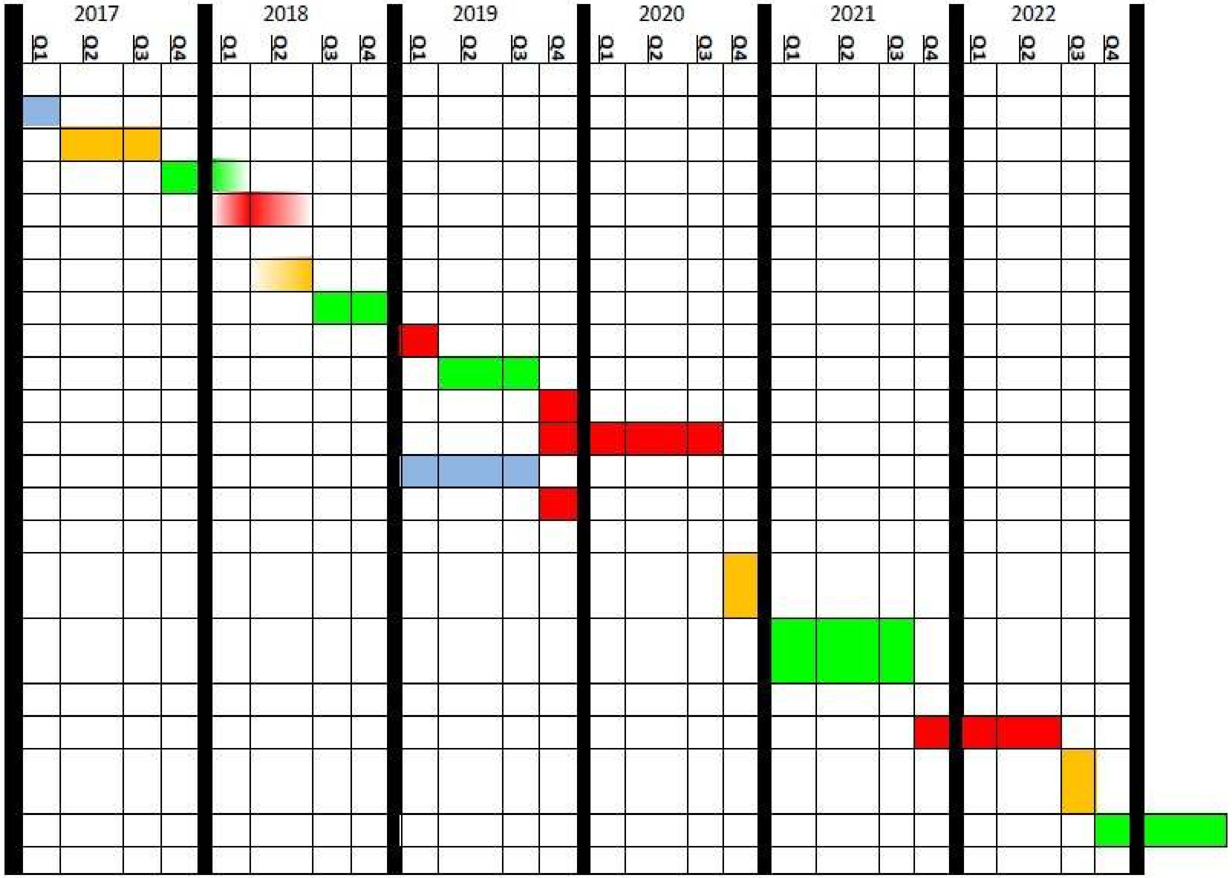
  - May enable better access to type-I ELMy H-mode
    - Cleaner due to impurity gas pumping
  - May enable access to longer pulses due to more efficient off-axis current drive

Much wider operational space



Timeline

<u>Operations activities</u>



Integrated commisioning of power supplies into coils
Plasma restart and scenario development
1st physics campaign
Shutdown (TF sliding joint, NBI getter + other maintanence)

Plasma restart and scenario development (for 2nd campaign)
2nd physics campaign
Engineering break (limited activity)
3rd physics campaign
Shutdown (Installation of Galden cooling, chilled air etc)
Installation of 3rd NBI (if funding avaialble)
Installation and local commissioning of cryoplant
Local connection of cryoplant to machine

Plasma restart and scenario development (for 3rd campaign) - commisioningof cryoplant and/or 3rd beam
4th physics campaign (longer pulse length + 3rd beam and/or cryoplant (funding permitting)

Shutdown (Installation of 4th beam - funding permitting)
Plasma restart and scenario development (for 4th campaign) - commisioning of 4th beam
5th physics campaign (Stage 2 complete (funding permitting)

Off load commissioning
Plasma restart
Physics campaign
Shutdown

Summary

- MAST Upgrade is an exciting new facility focussed on exhaust & advancing ST physics

- MAST Upgrade Research Plan found here:

http://www.ccfe.ac.uk/assets/documents/other/MAST-U_RP_v3.pdf

- Assembly complete by end of 2016
- Commissioning and new start (not restart!) for much of 2017 with first campaign from September 2017

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