CCFE CULHAM CENTRE FOR FUSION ENERGY

Status of the MAST Upgrade

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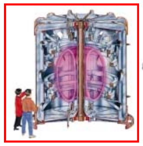
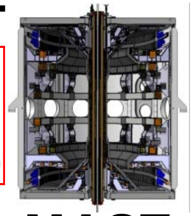
Research Councils UK Energy For a Low Carbon Future

The ST on the path to fusion

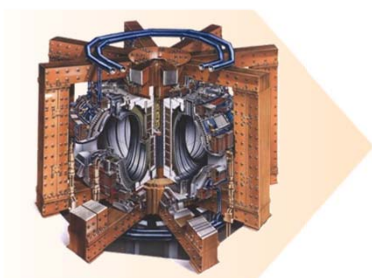
MAST





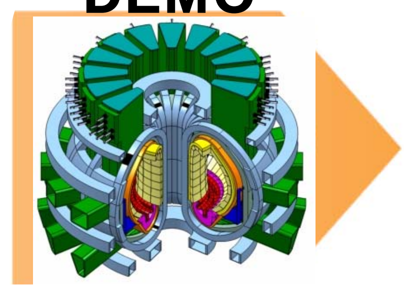
MAST Upgrade

JET



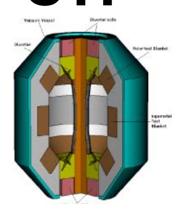
ITER

DEMO



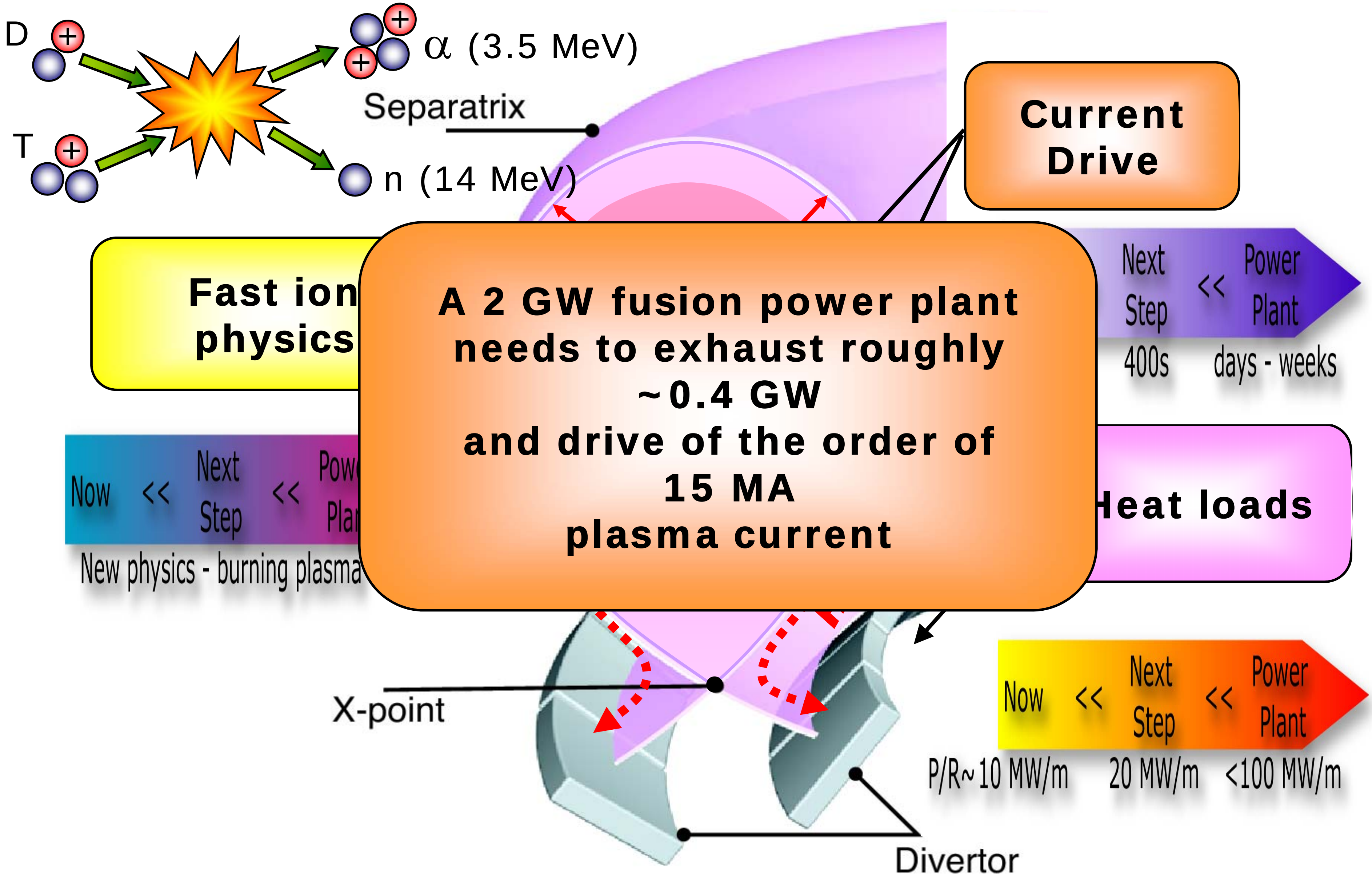
Power Plant

CTF

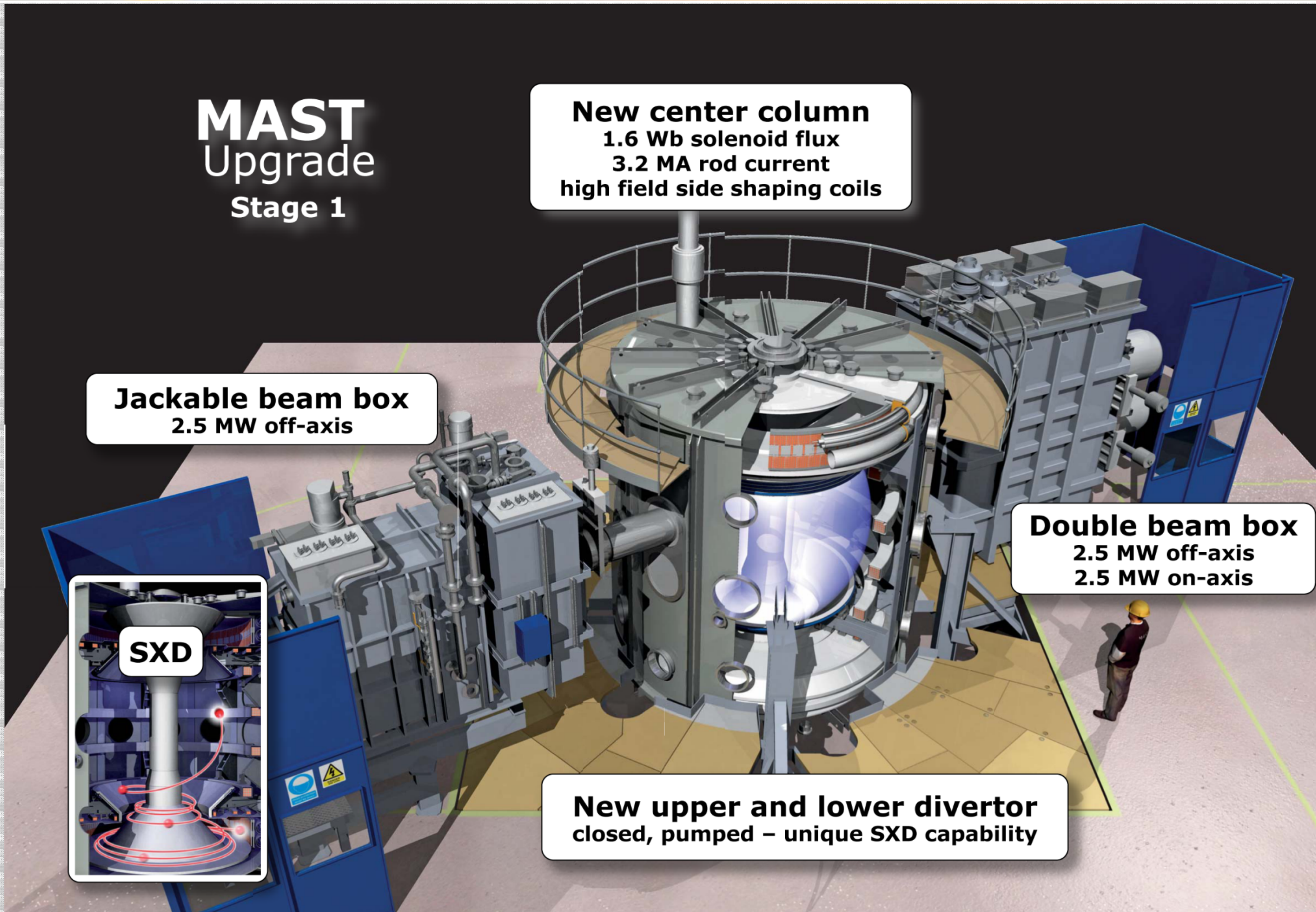


A spherical tokamak (ST) could provide a cost effective Component Test Facility (ST-CTF)

Main issues for fusion tokamaks



Three major upgrades for MAST, but ...

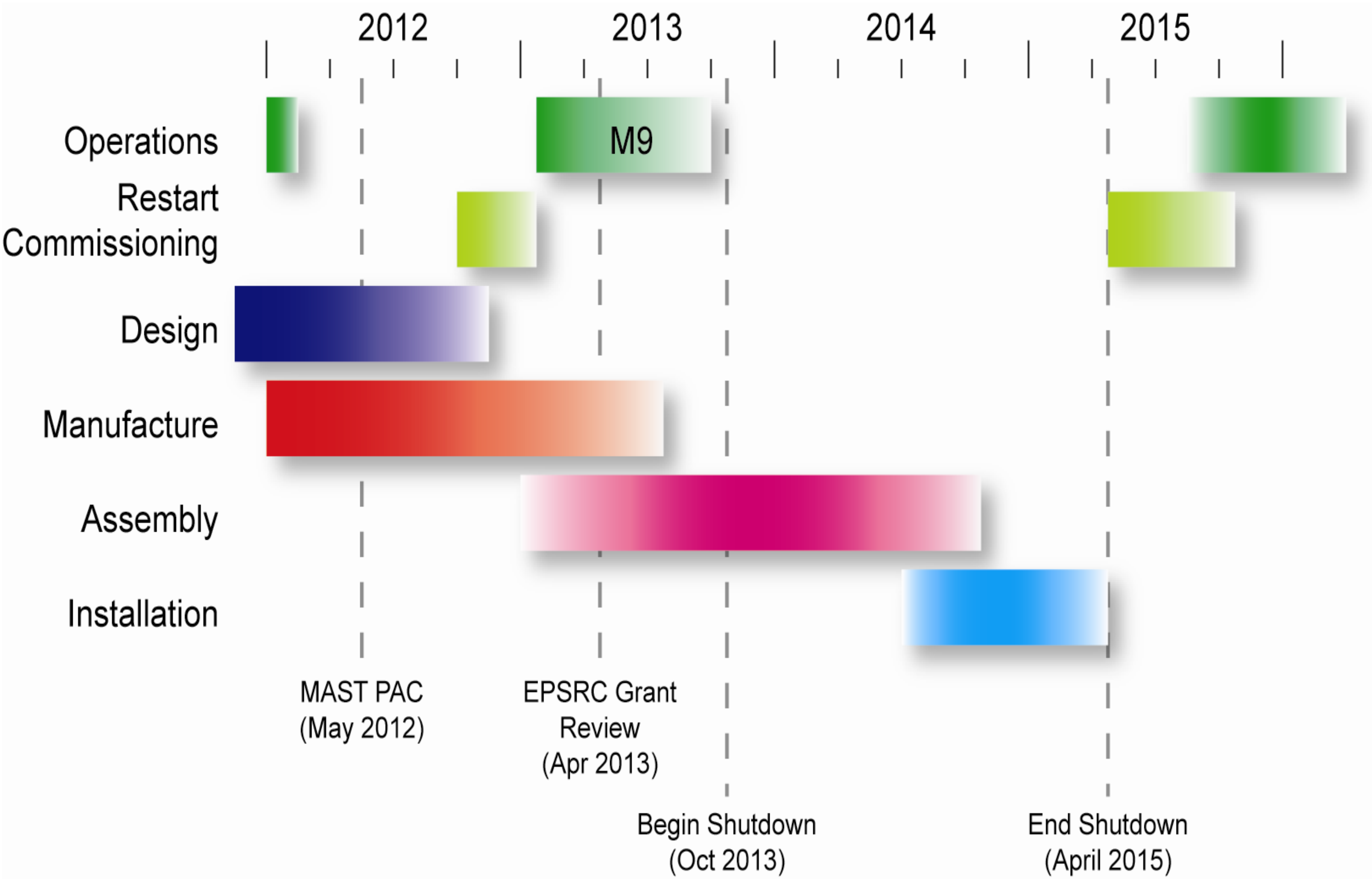


Define core scope

Major uncertainties

- 8 new 4 quadrant divertor power supplies.
  - Low level of ripple required for Super-X.
  - Contract now placed within estimated budget.
- New toroidal field power supply.
  - Contract now placed within estimated budget.
- 14 new in vessel coils.
  - Contract now placed within estimated budget.
- 3 Cyanate ester airside coils.
  - New solenoid – long conductor!
- Currently assessing which parts of Stage 1 can be re-introduced.
  - Cryo-plant and/or Double Beam box.

MAST-U simplified Time line



From the plasma core…

Enabling current drive physics

Through the plasma edge…

Enabling divertor physics

To what lies beyond the plasma

The engineering!

This talk takes you…

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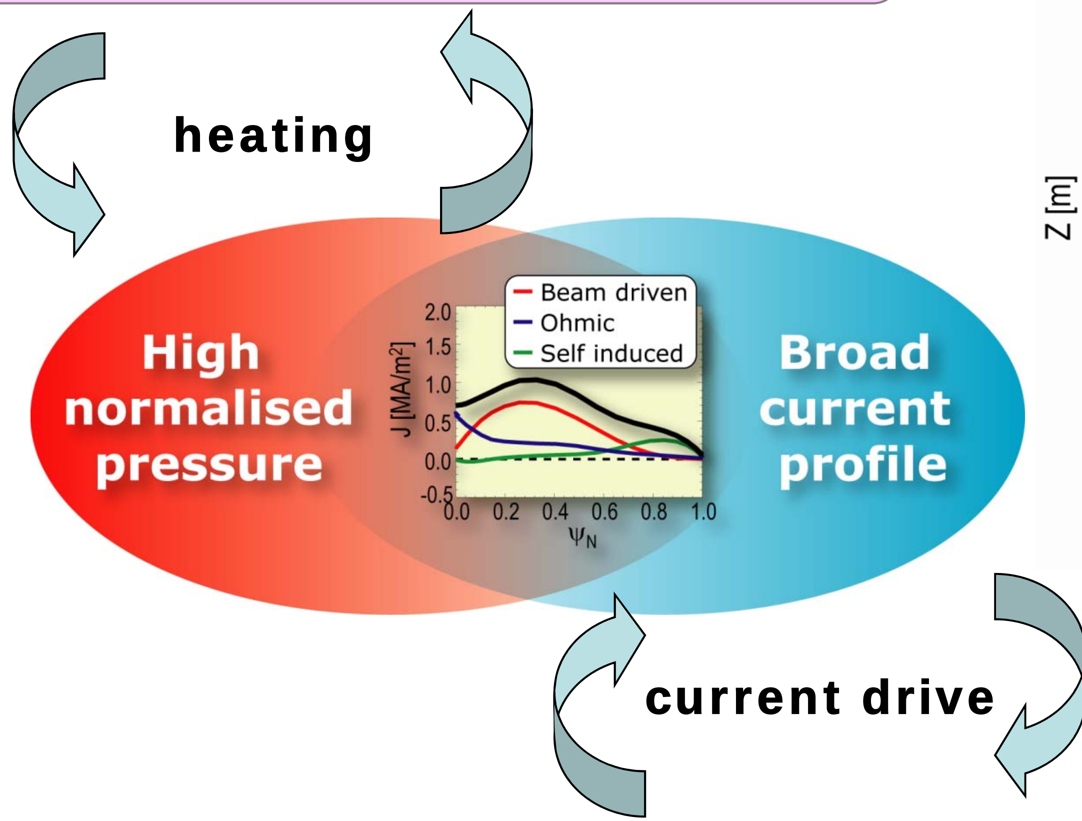
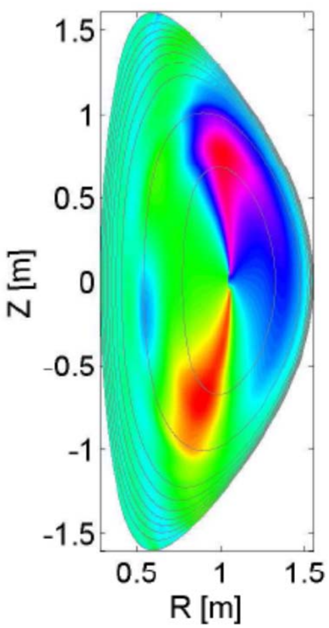
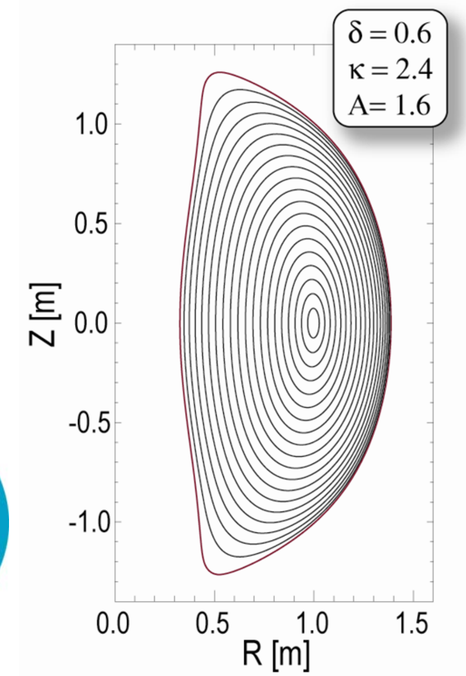
Broad current profiles are beneficial

Advanced MHD stability ⇒ Higher pressure

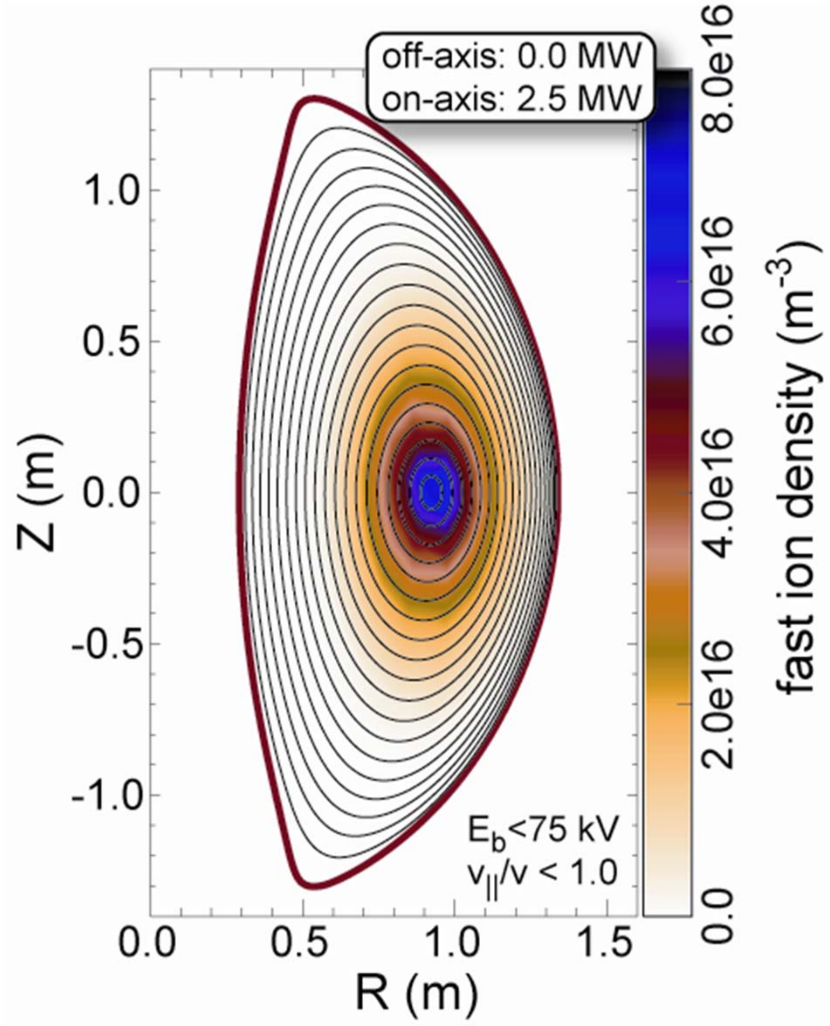






Advanced shaping ⇒ Broader current profile, improved edge stability

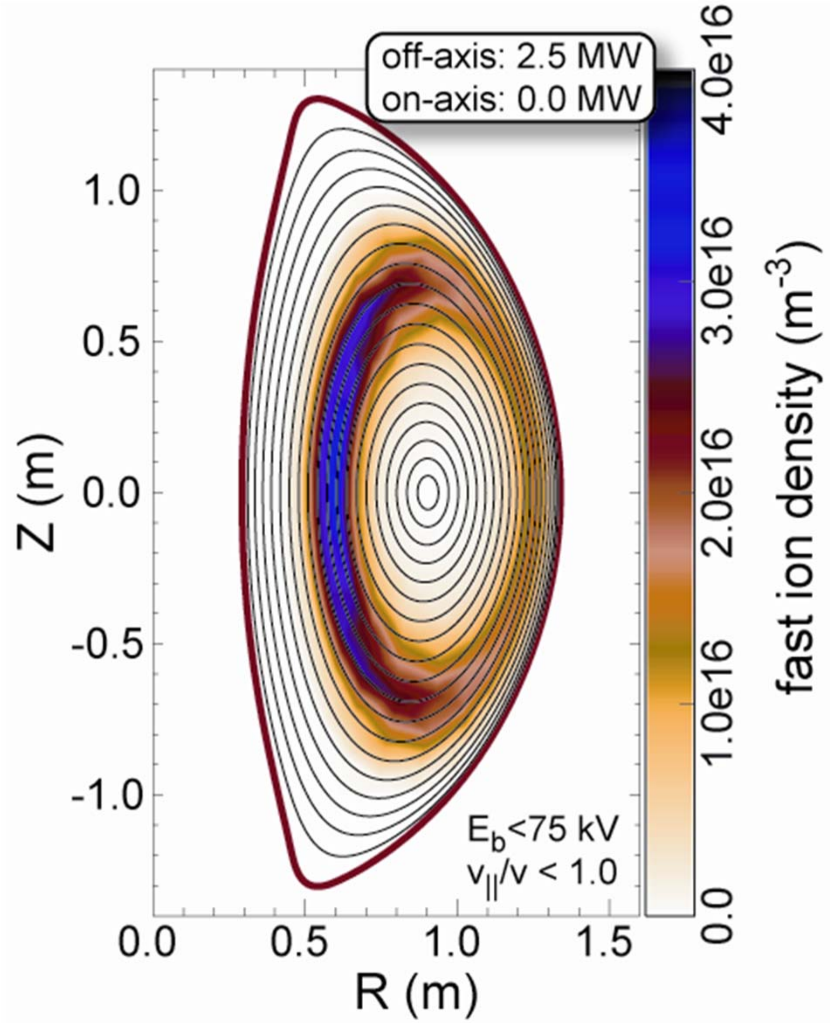
Flexibility on fast ion density profiles



Advanced profile control

- On-axis ⇒ peaked.

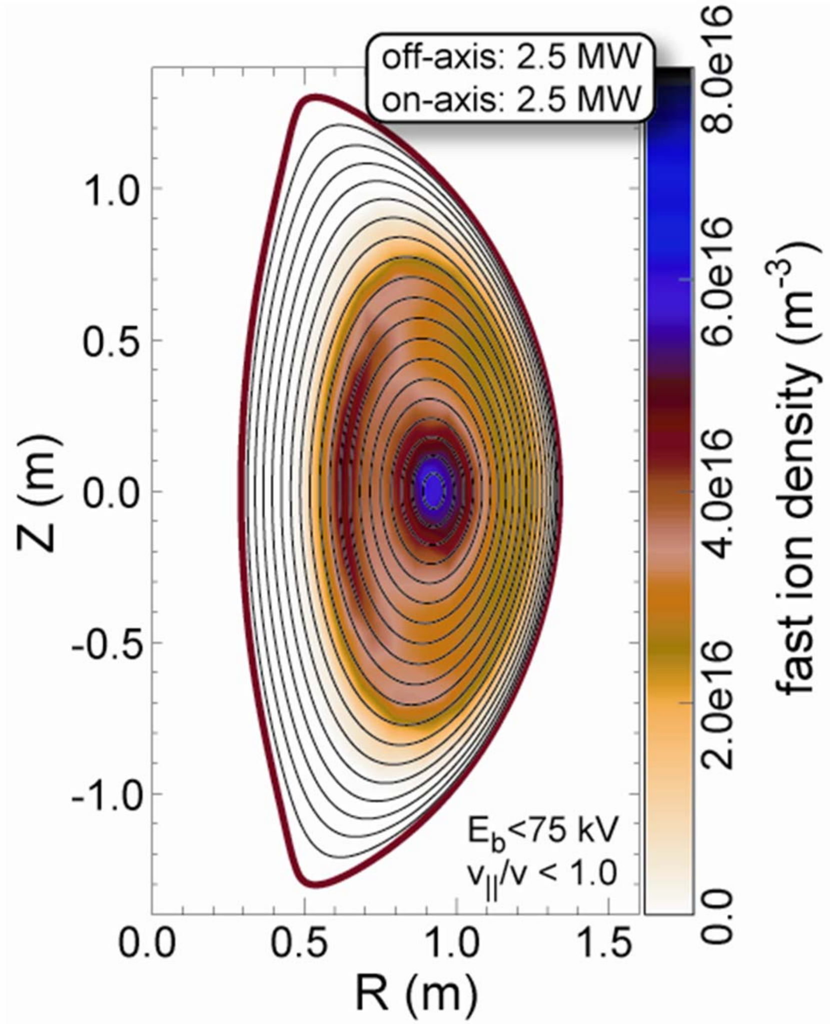
Flexibility on fast ion density profiles



Advanced profile control

- On-axis $\Rightarrow$ peaked.
- Off-axis $\Rightarrow$ hollow.

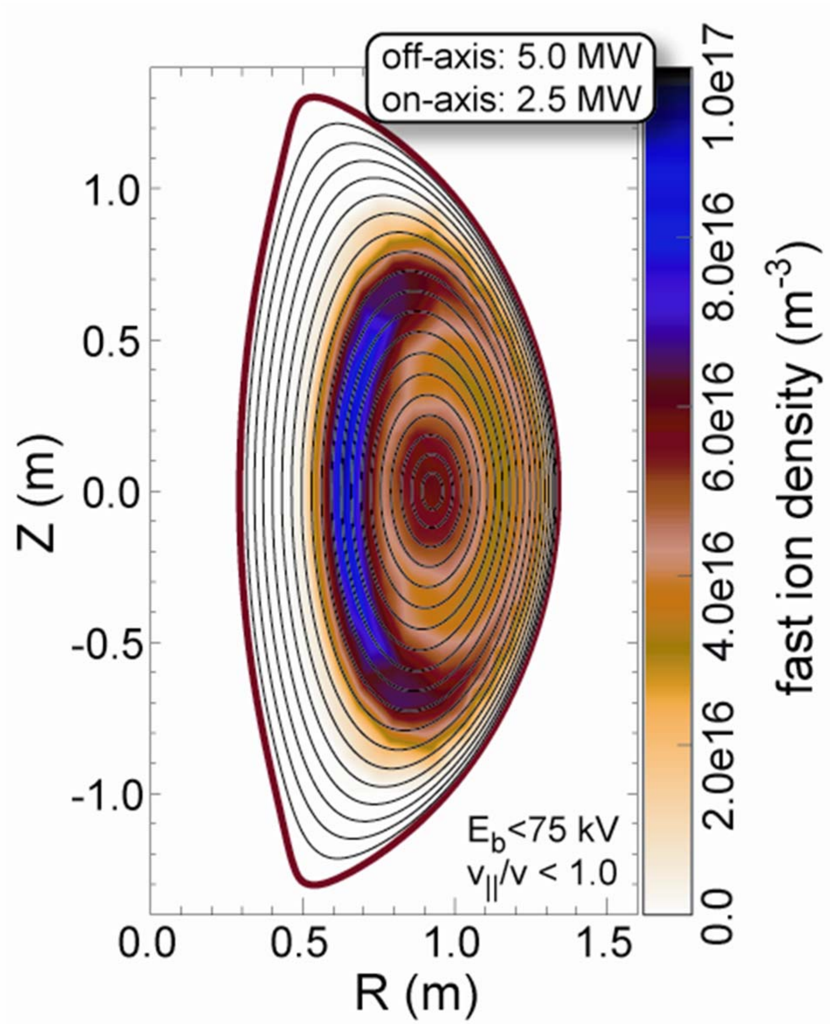
Flexibility on fast ion density profiles



Advanced profile control

- On-axis ⇒ peaked.
- Off-axis ⇒ hollow.
- On- and off-axis ⇒ broad.

Flexibility on fast ion density profiles



Advanced profile control

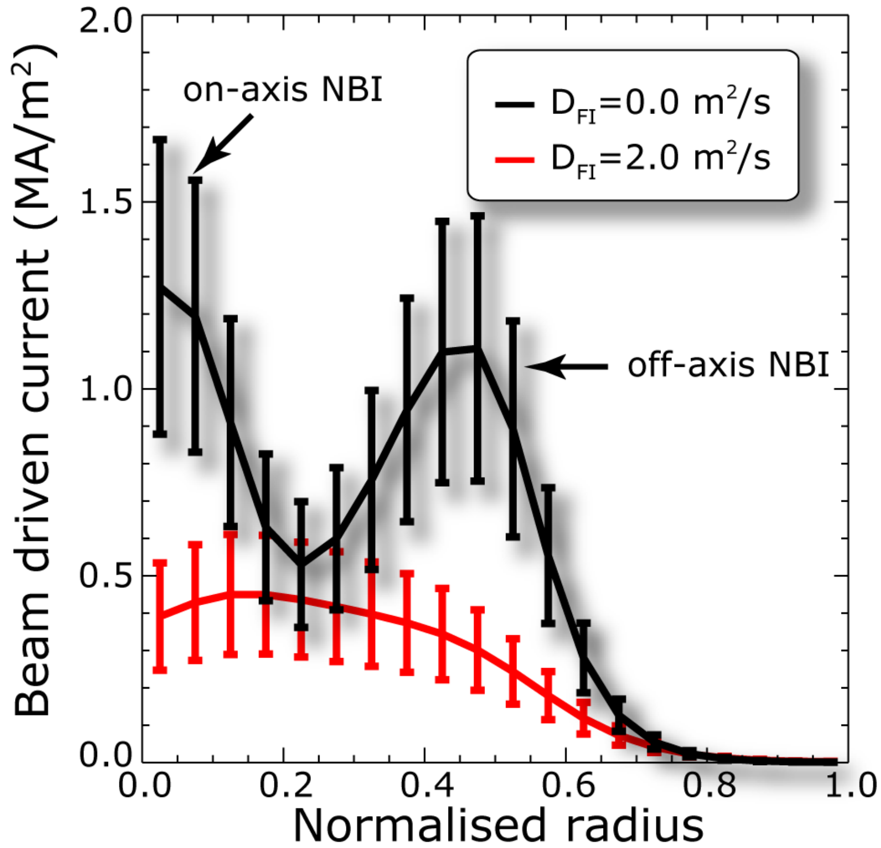
- On-axis ⇒ peaked.
- Off-axis ⇒ hollow.
- On- and off-axis ⇒ broad.

MAST-U physics studies

- About 1 MA of non-inductive current drive ⇒ long pulse length.
  - Needs all 3 beams!
- High fast-ion pressure (60% of total pressure)

Plasma may spread fast ions out

- Fast ions have only few collisions.
  - Should be localised to sources.
- Experiments suggest source profile broadens.
  - Instabilities? – yes, localised?
  - Turbulence? – yes, how?
- Modelled as "anomalous" diffusion $D_{FI}(r,E,...)$
  - Crude, ad hoc.
  - Wrong for instabilities.



- Need Integrated modelling
  - Current profile affects stability/turbulence.
  - stability/turbulence changes current drive.

Neutron Camera – measuring sources

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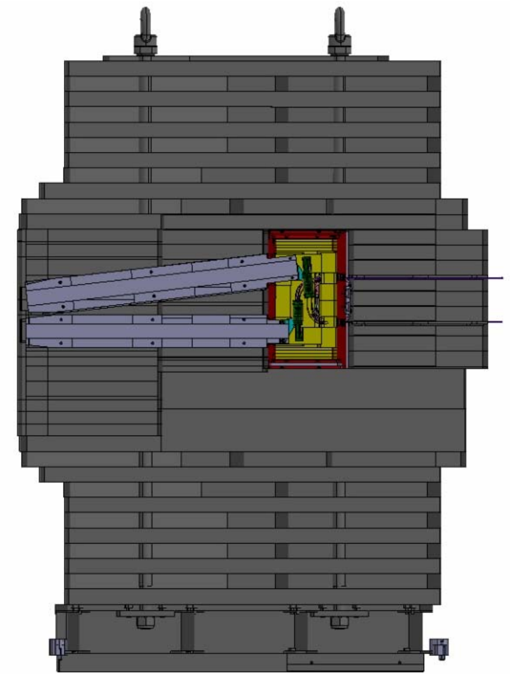
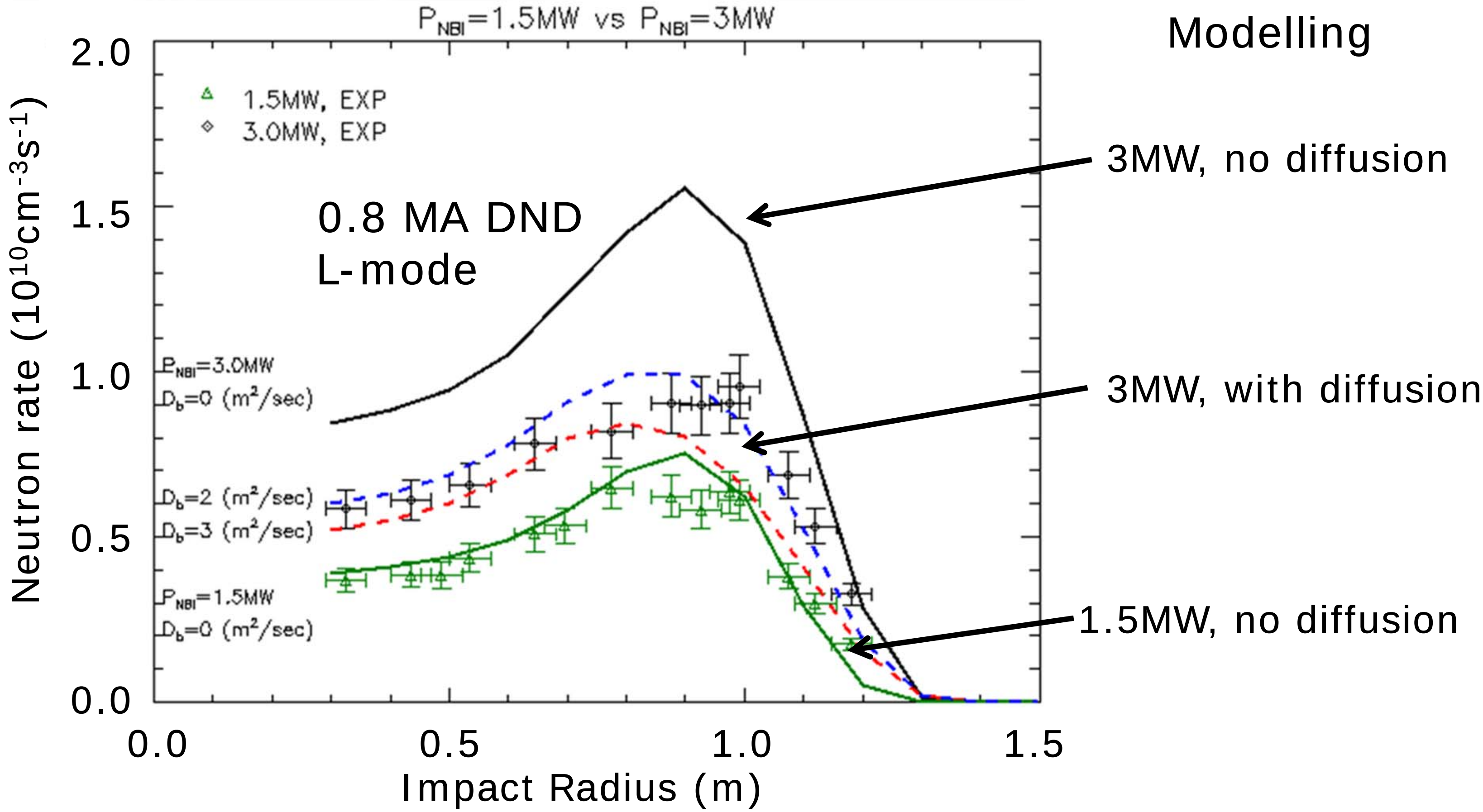


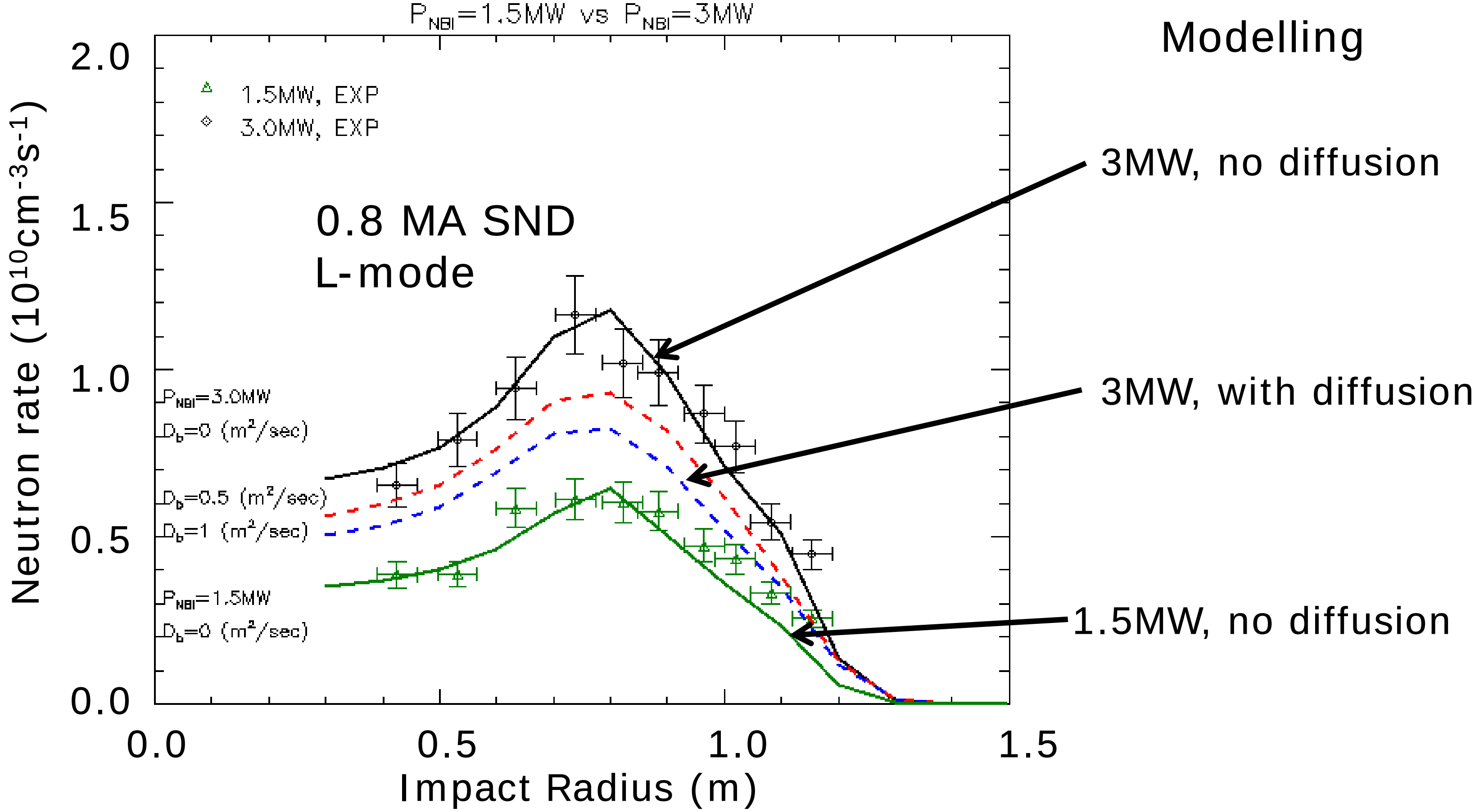
- 4 channel neutron camera in collaboration with Uppsala University (Sweden).
- Can be scanned from shot to shot.

Neutron Camera – measuring sources



- High fast ion redistribution in DN MAST discharges with 2 beams (I_p=0.8 MW)
- With one beam no redistribution is needed.
- Off axis heating may be more beneficial.

MAST-U: $q_{min} > 1.3 \Rightarrow$ less redistribution.

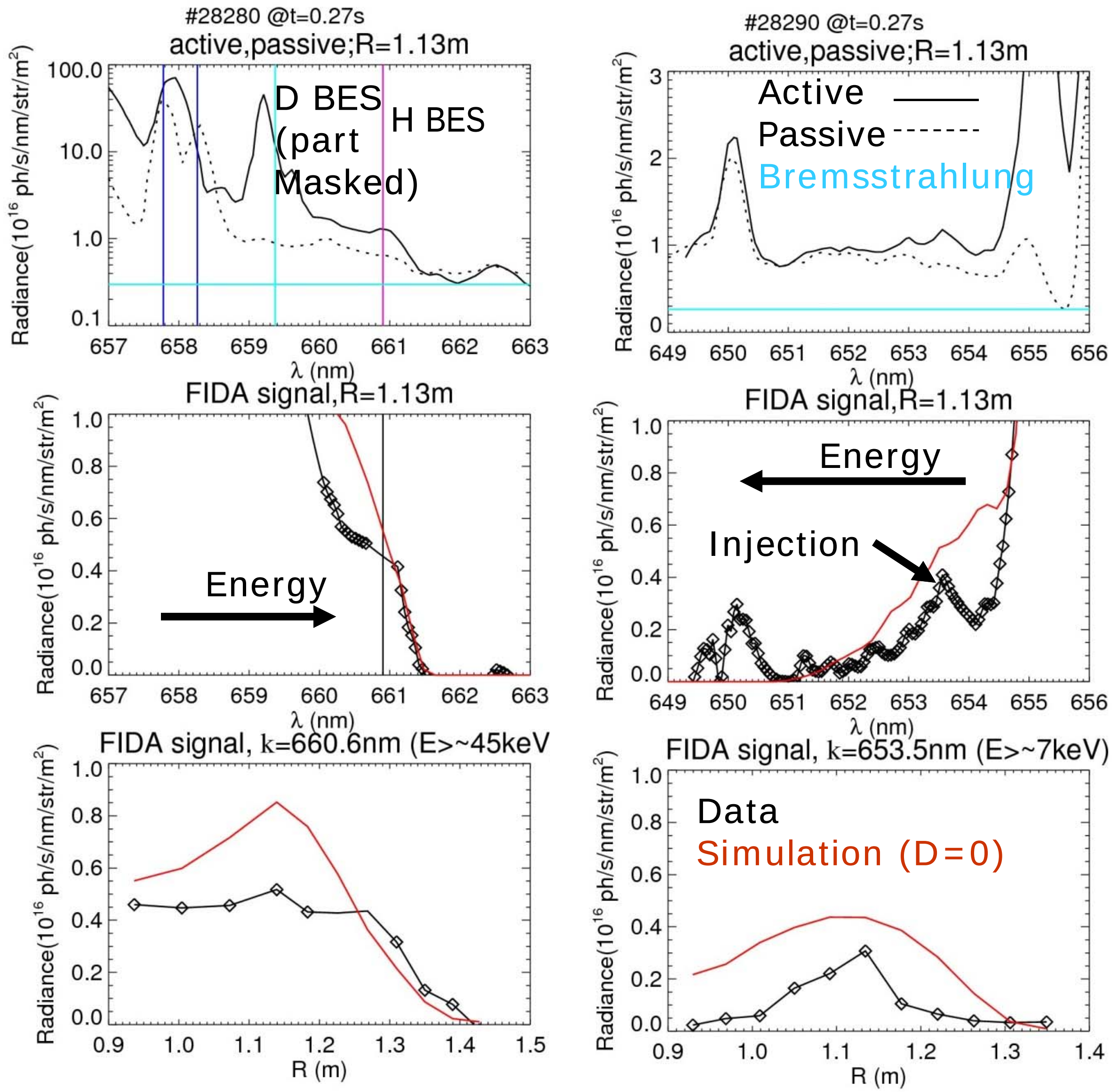


- Higher $q_{min} > 1.3$ helps to avoid detrimental MHD.
- Neutron rate doubles with double the beam power.

Horizontal and Vertical FIDA

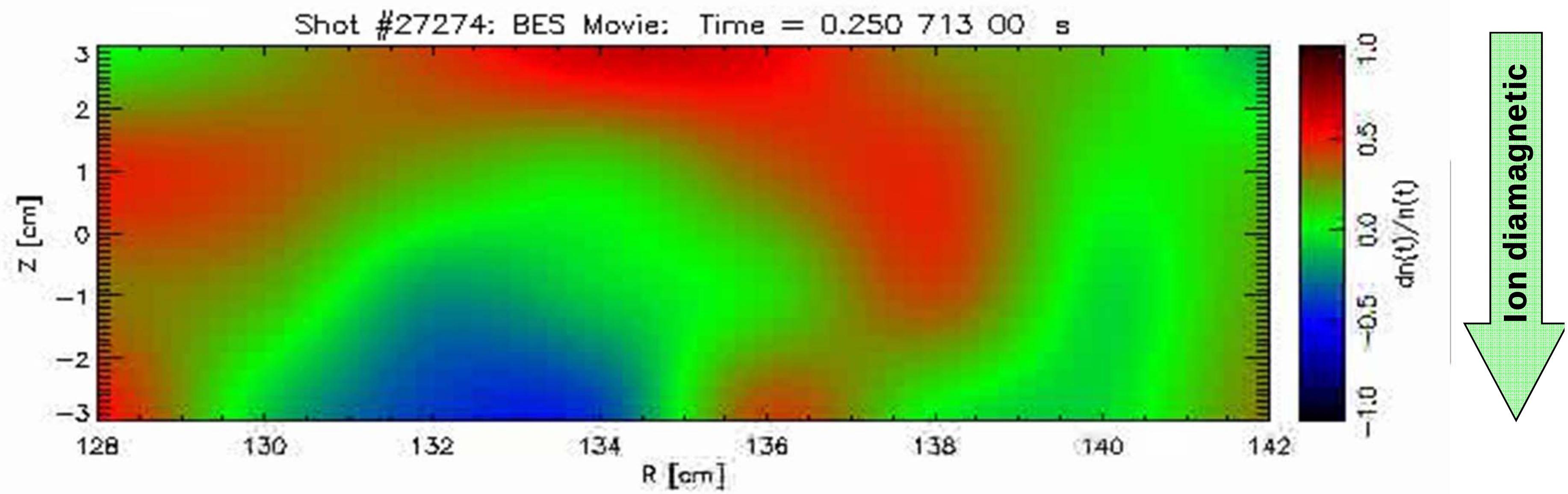
- Fast ion transport with TRANSP/FIDASIM modelling.
- Example: 1 beam SND (D_{FI}=0, classical).
- Horizontal: below classical in core and above in edge.
- Vertical: Signal is much lower indicates loss of trapped particles.

HORIZONTAL (PASSING) **VERTICAL (TRAPPED)**



Low-k turbulence

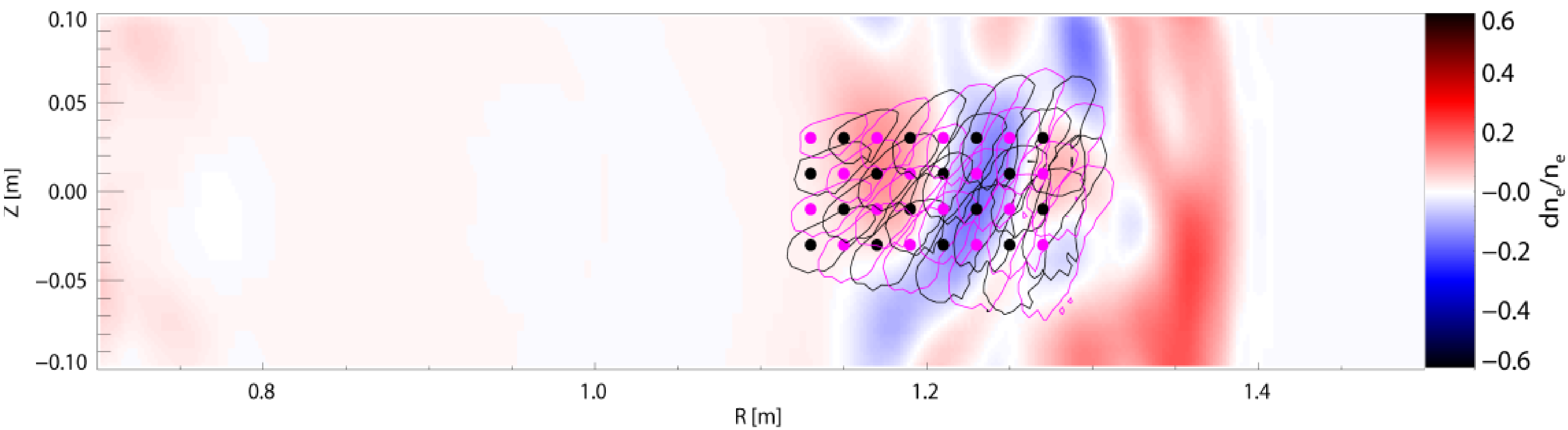
- Ion-scale density turbulence measured with 2D BES
- Allows study of interaction of flow-shear and anomalous, ion-scale turbulent transport
- Signal-to-noise sufficient to measure core turbulence



Low-k turbulence

- Ion-scale density turbulence measured with 2D BES
- Allows study of interaction of flow-shear and anomalous, ion-scale turbulent transport
- Signal-to-noise sufficient to measure core turbulence
- Synthetic diagnostic to compare with GK modelling.

ORB5 density fluctuations, dn_e/n_e, orb5_22807_0.25_01



This talk takes you…

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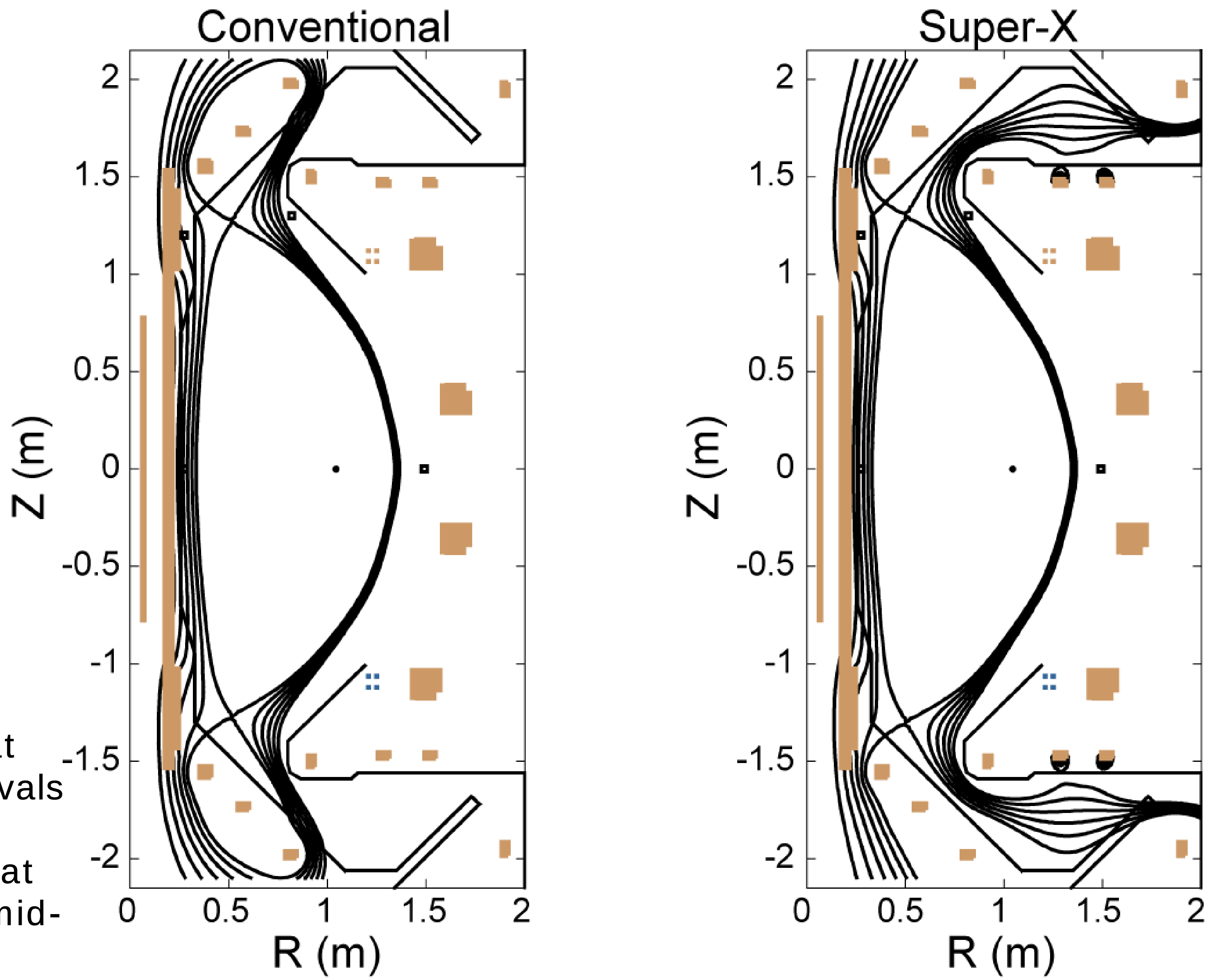
Enabling current drive physics

Through the plasma edge…
Enabling divertor physics

To what lies beyond the plasma
What is upgraded?

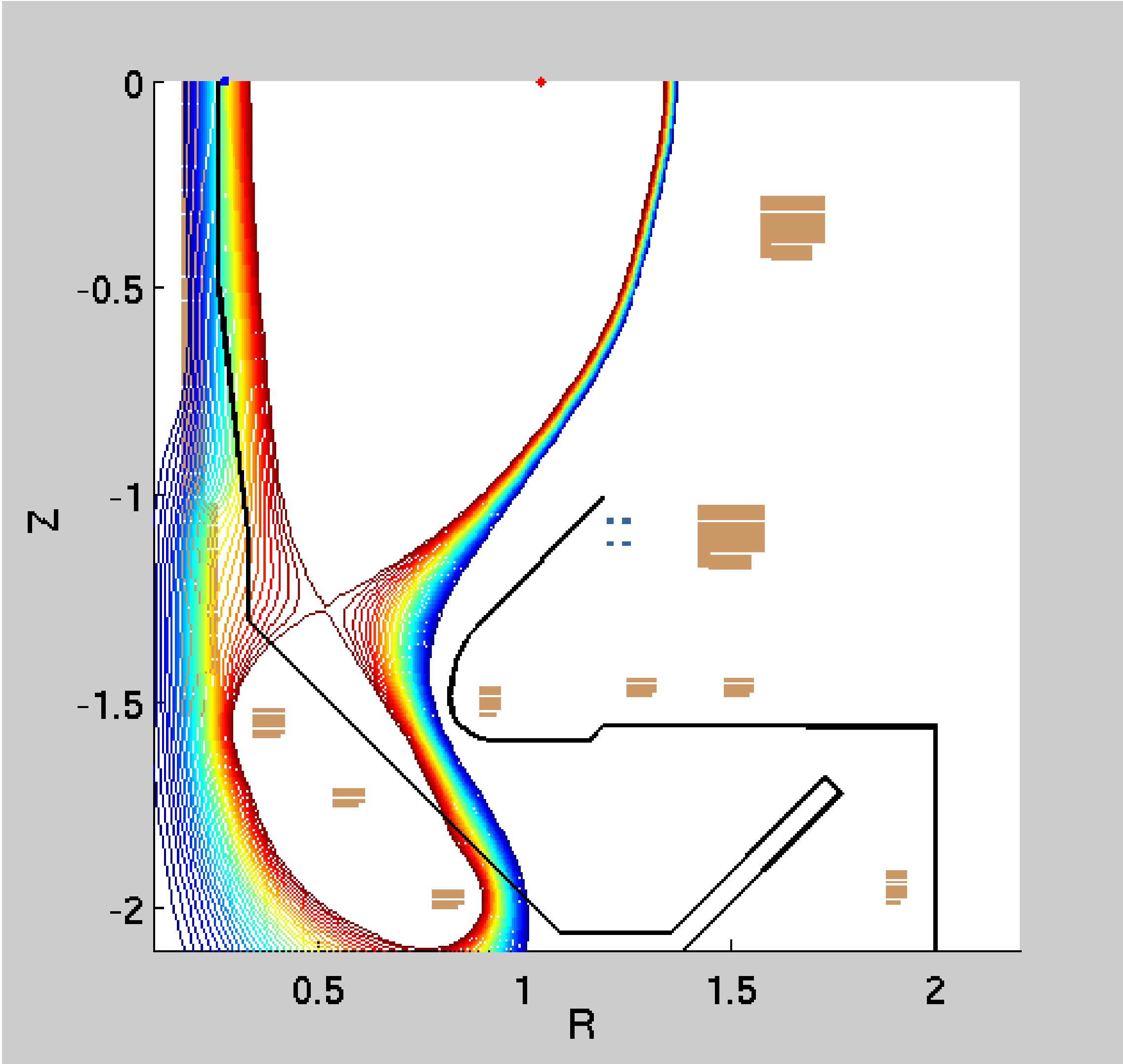
Conventional *versus* Super-X



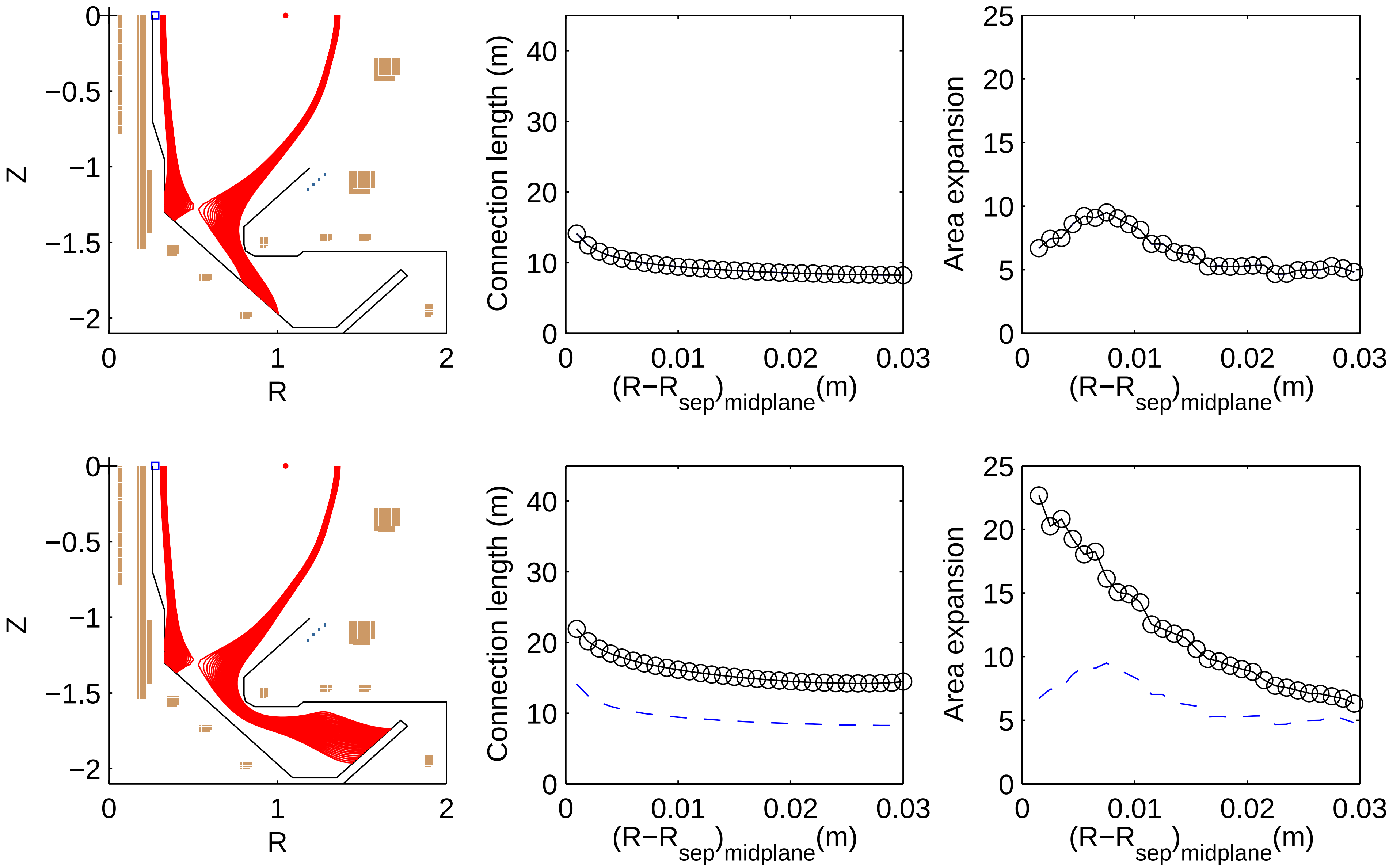
Contours at 5mm intervals from separatrix at outboard mid-plane

Flexible divertor geometry

- Unique divertor concept ⇔ Super-X
- Large plasma volume in the divertor.
  - Neutral-plasma interactions.
  - Impurity radiation.
- Can the target heat load be reduced?
- Can the geometry be controlled?

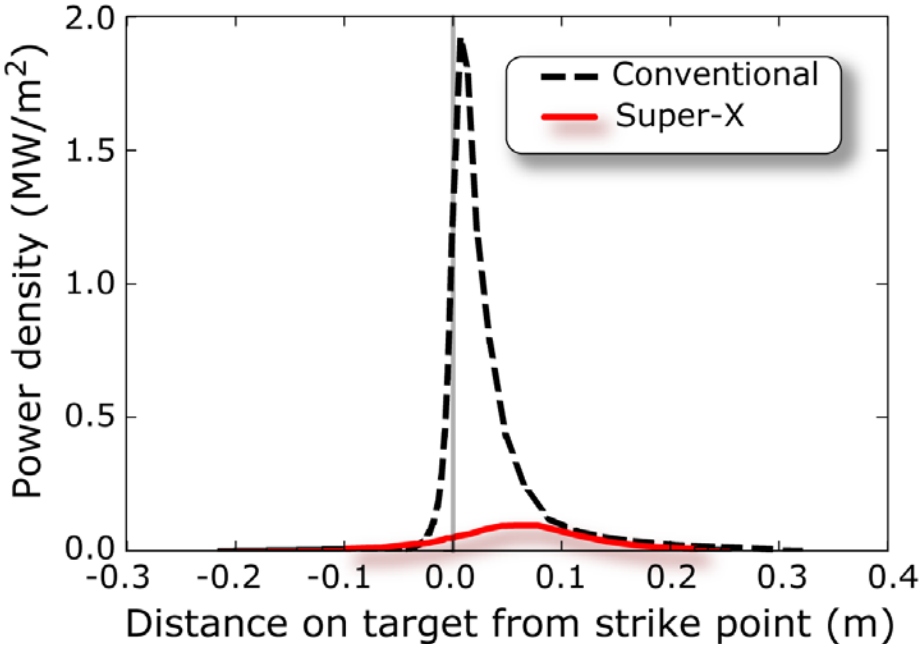


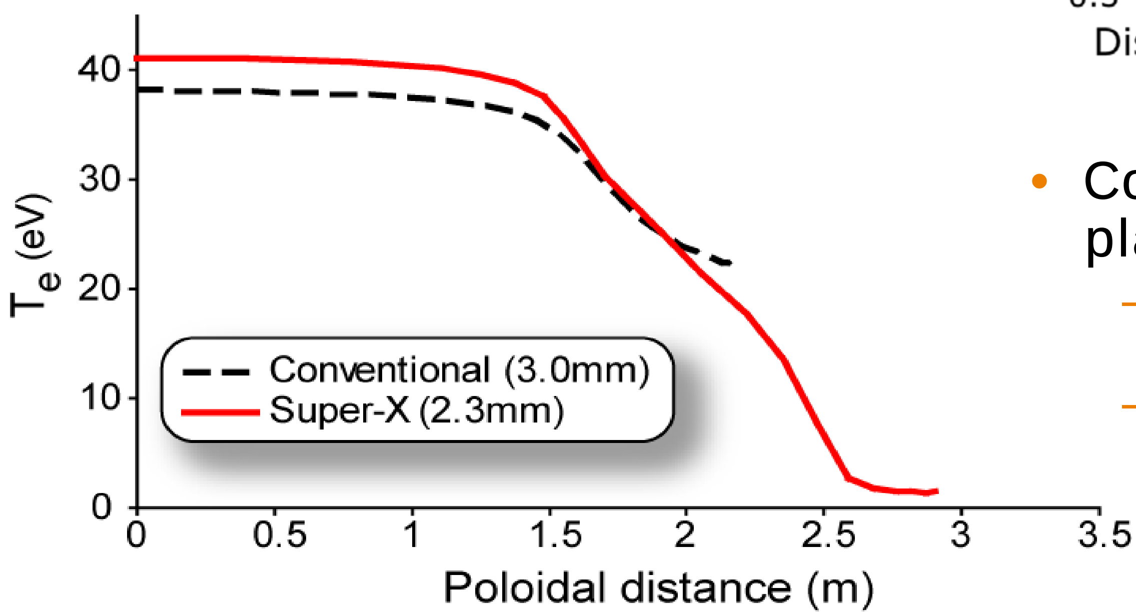
Geometric Advantage of Super-X



Plasma Physics Advantage

- Low collisionality (hot SOL)
  - ⇒ T const. along the field line
- High collisionality
  - ⇒ T drops towards the target.
- Increased connection length
  - ⇒ increased collisionality.
  - ⇒ increased temperature drop along field line

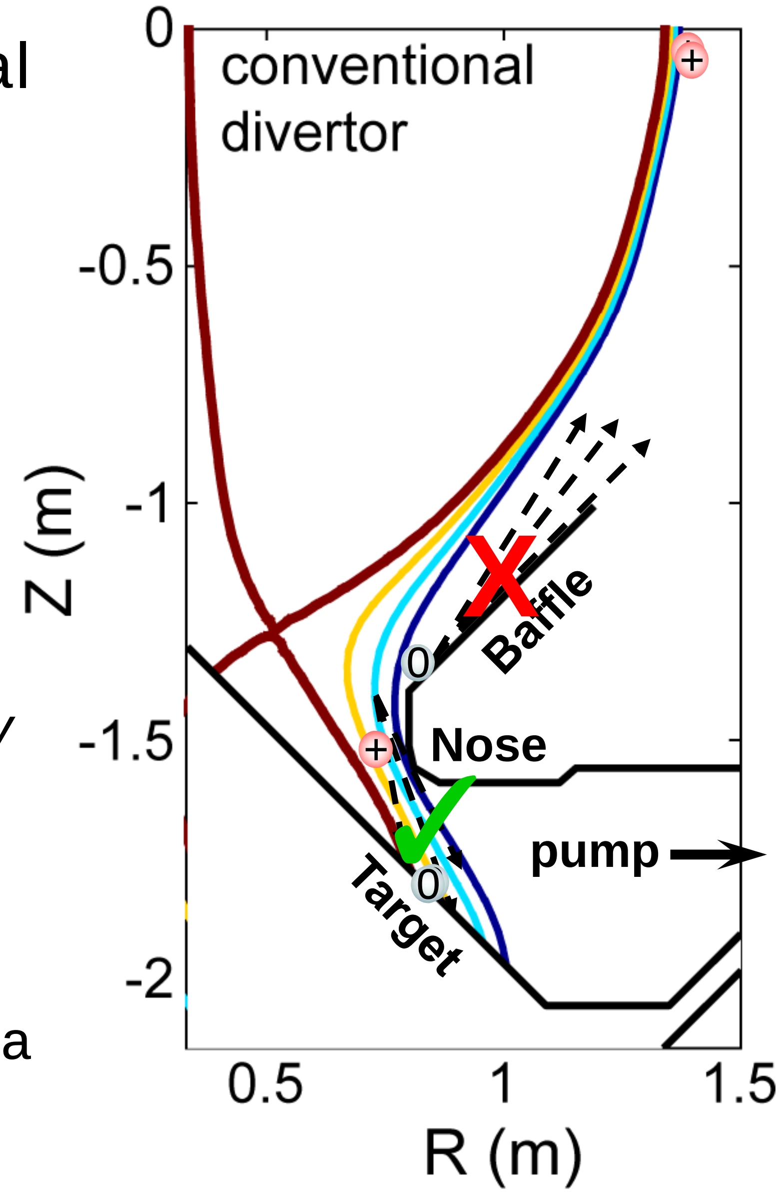




- Confirmed by 2D fluid edge plasma simulations:
  - Here, low power (1.8MW) into SOL, but …
  - high power simulations show same trend.

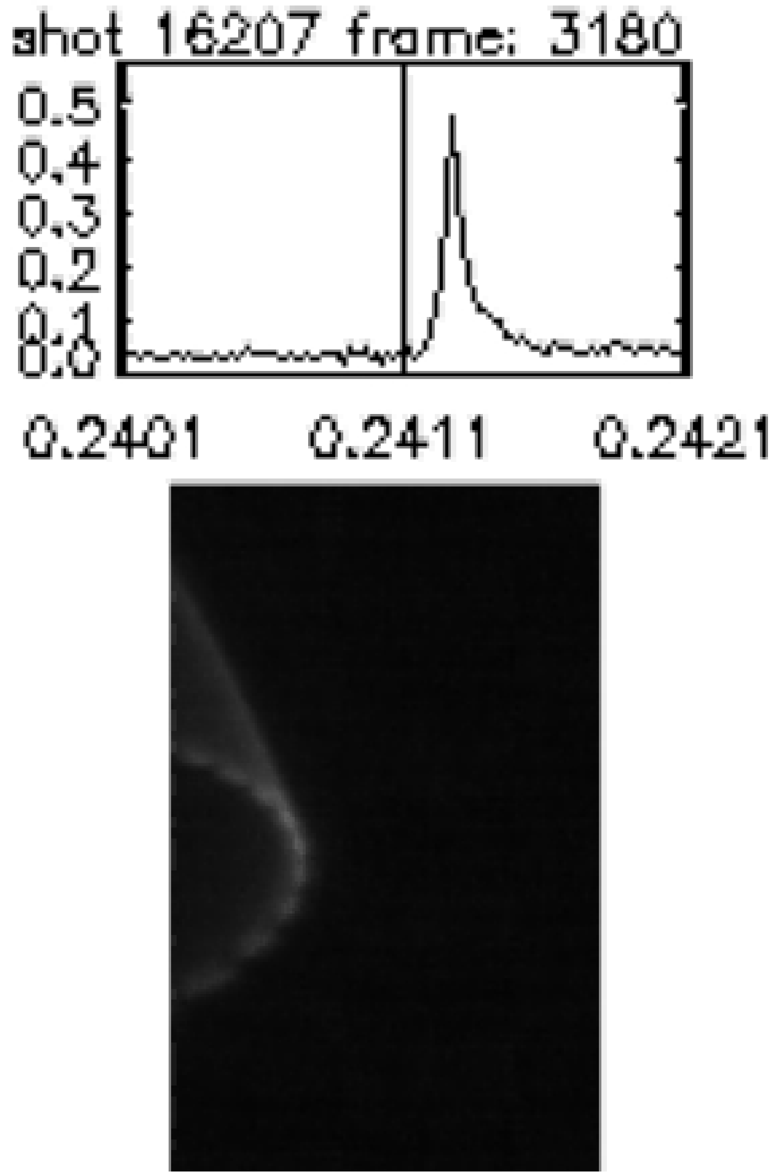
The Particle Control Compromise

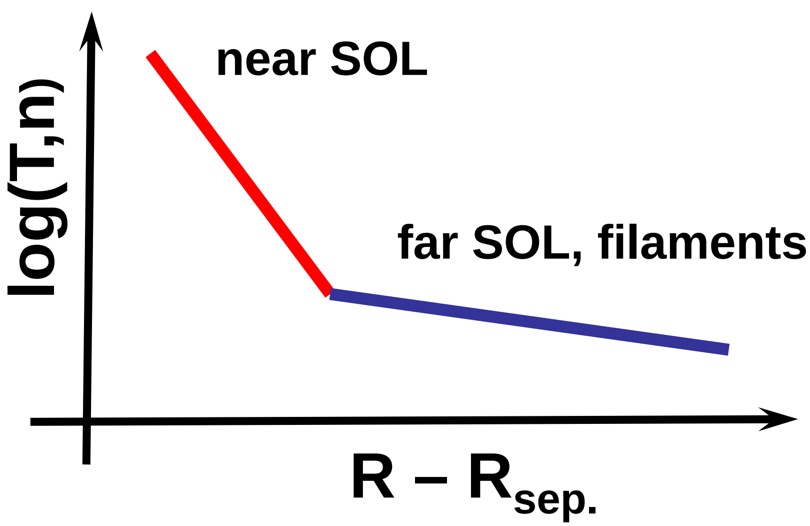
- Density control is fundamental to MAST-U.
- Seek high neutral density in the divertor ⇔ efficient pumping
  - ⇒ Require sufficient plasma in throat
    - *to prevent divertor neutrals leaving*
    - *for low main-chamber density*
- Seek minimal recycling from the main-chamber baffle surface
  - ⇒ require sufficiently diffuse plasma at edge of throat



ELM filaments will still hit the baffle

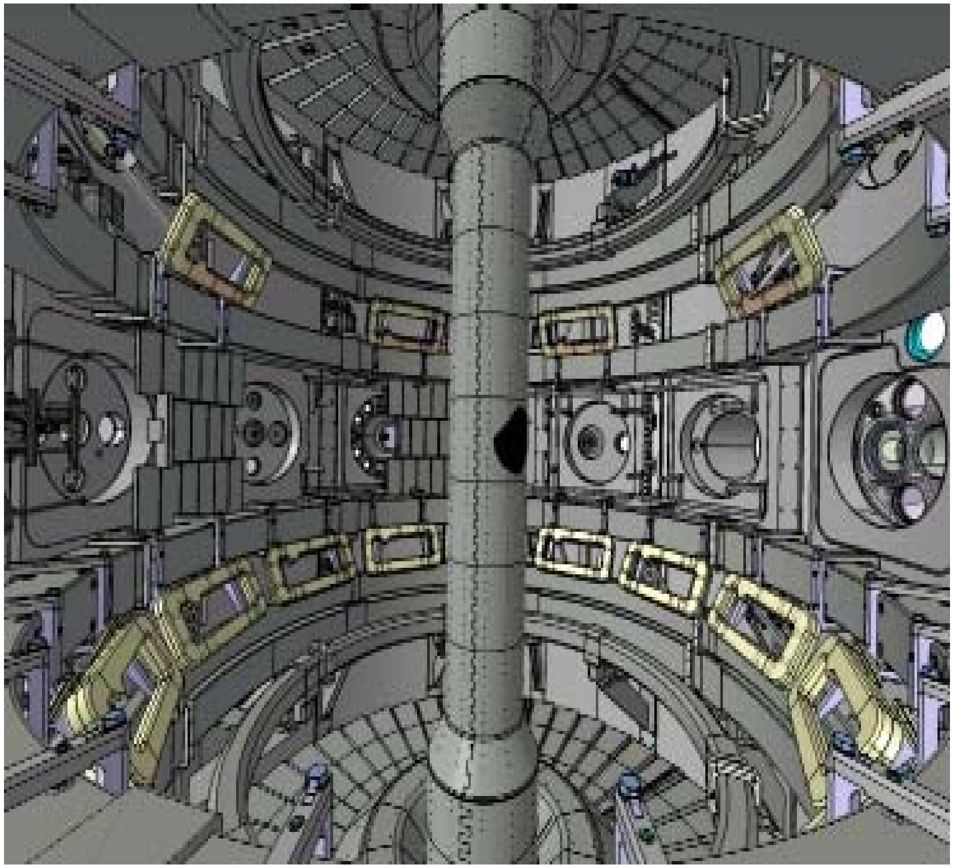
- Perpendicular SOL transport is not diffusive.
- Mean field approximation is not sufficient.
- Need a further understanding of the ELM and ELM avoidance.



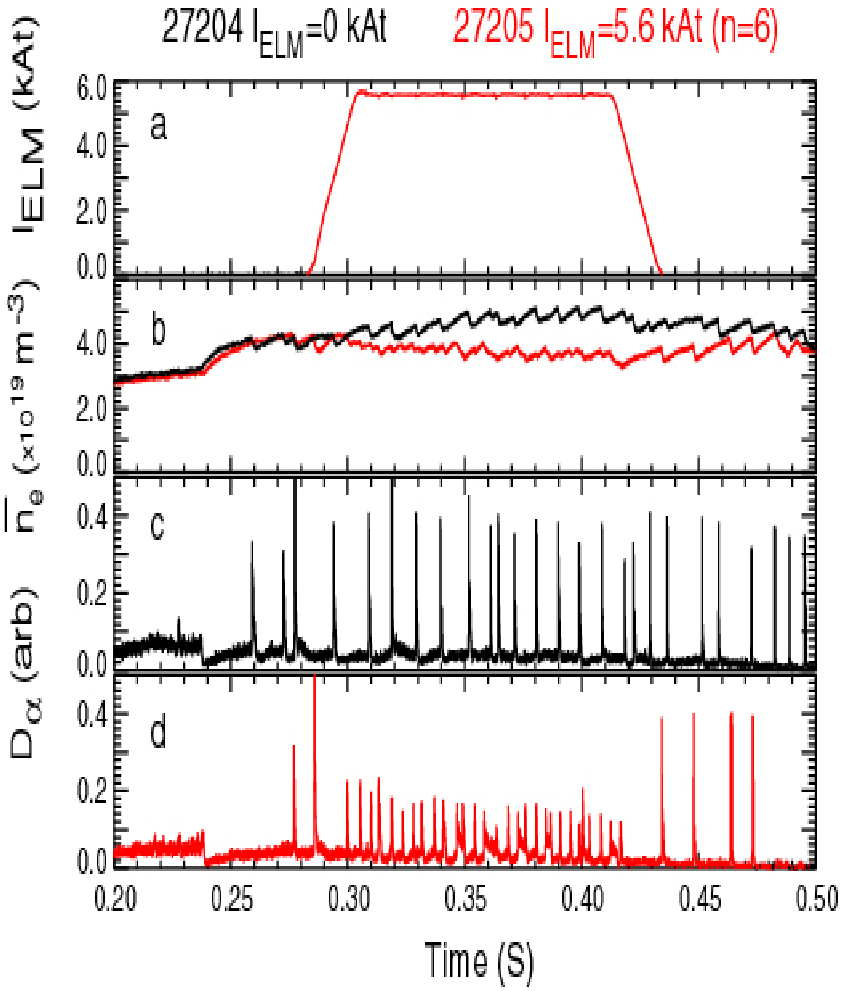


ELMs can be mitigated using 3D B fields

18 in vessel coils for ELM mitigation

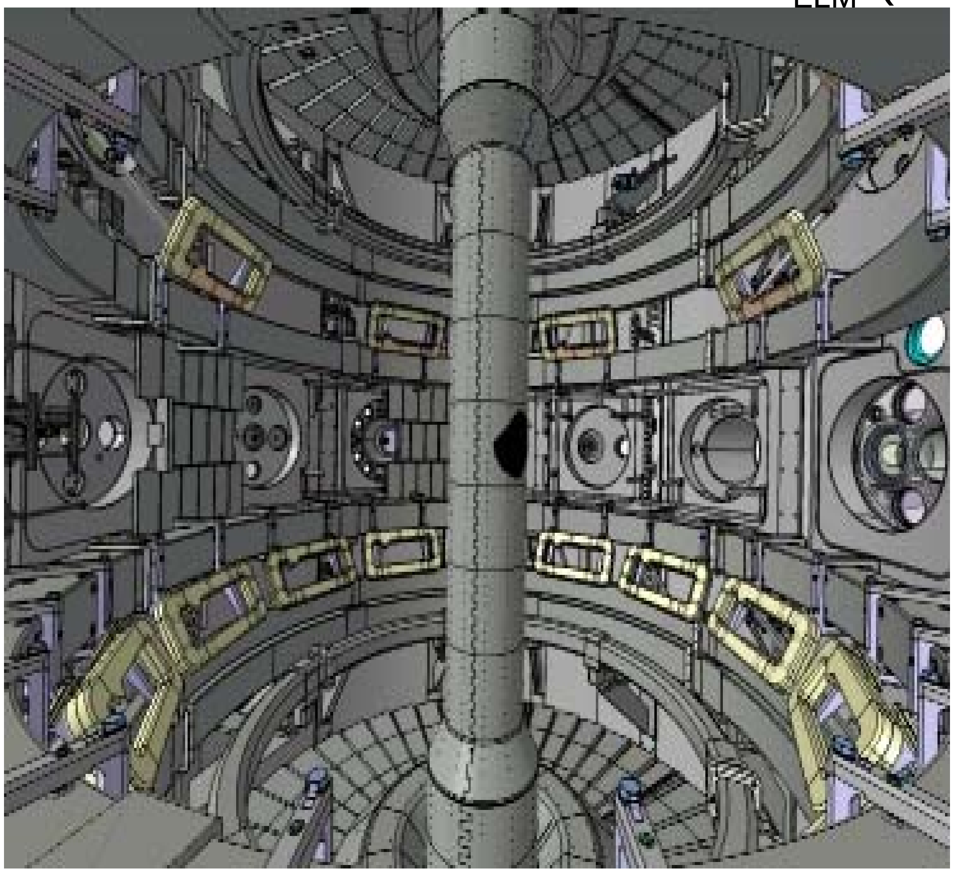


Application of resonant magnetic perturbations in n=6



Observation of lobes near the X-point

18 in vessel coils for ELM mitigation

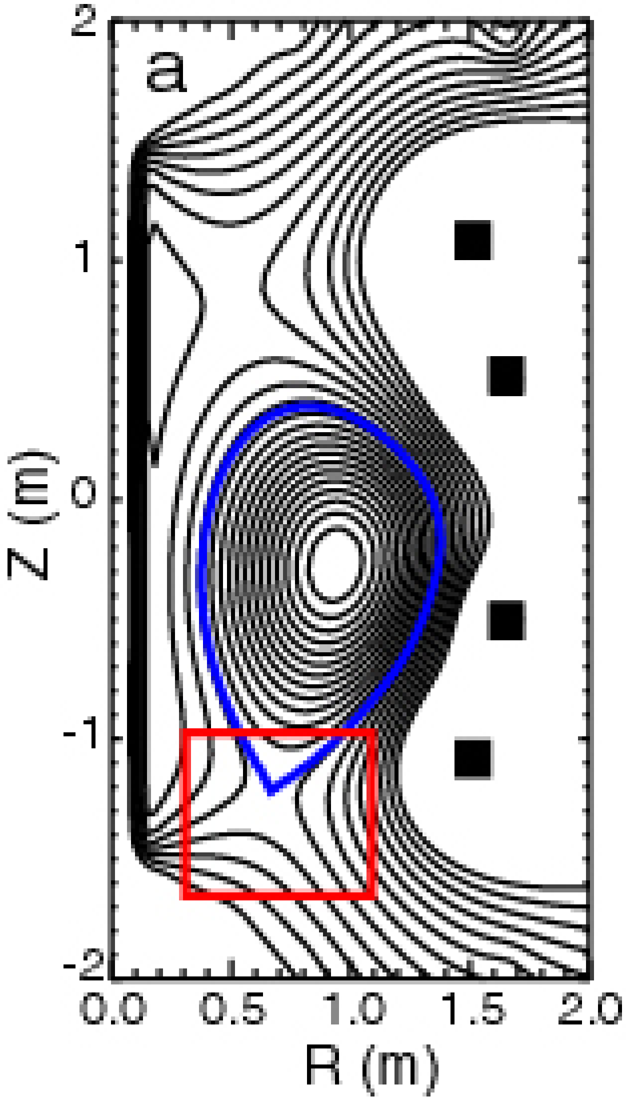


Application of resonant magnetic perturbations in n=6

I_{ELM} (kA)

Lobe structures are observed when $I_{ELM} > I_{THR}$

Observation of lobes near the X-point



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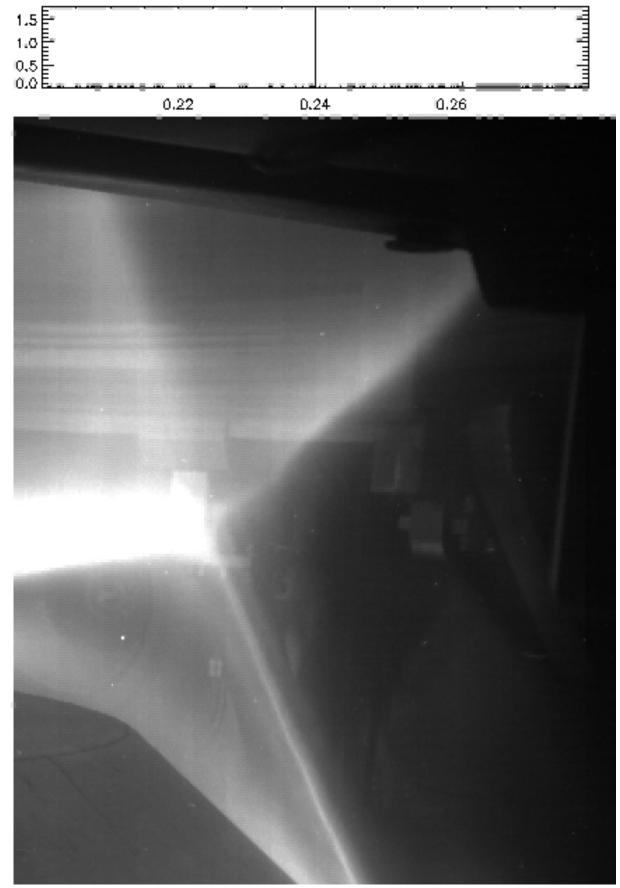
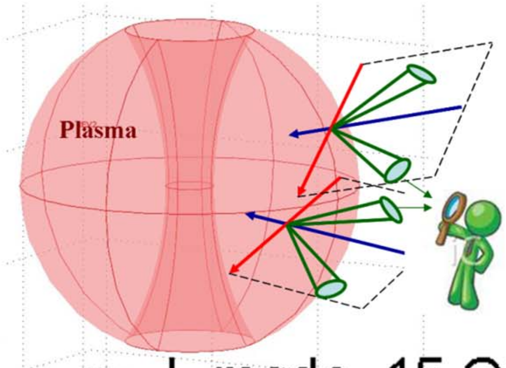
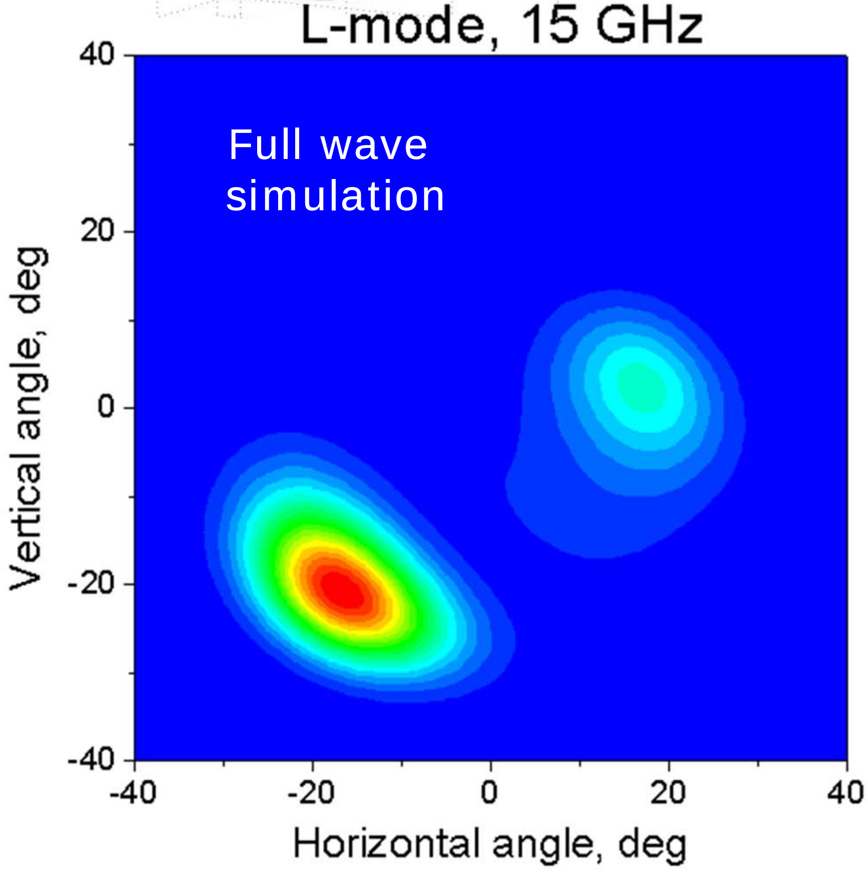


Lobe structures are observed when $I_{ELM} > I_{THR}$

EBW imaging – j(r) during the ELM

- Electron Bernstein Wave mode conversion mechanism contains information on ∇n_e and B.
  - Need to measure EBW emission window.
- The new Synthetic Aperture Microwave Imaging (SAMI) diagnostic uses a novel technique for producing images of thermal emission in the range 10 - 40 GHz.





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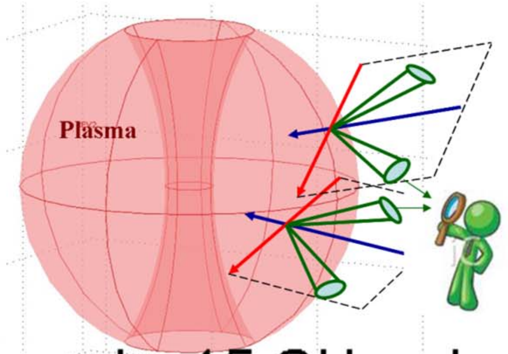
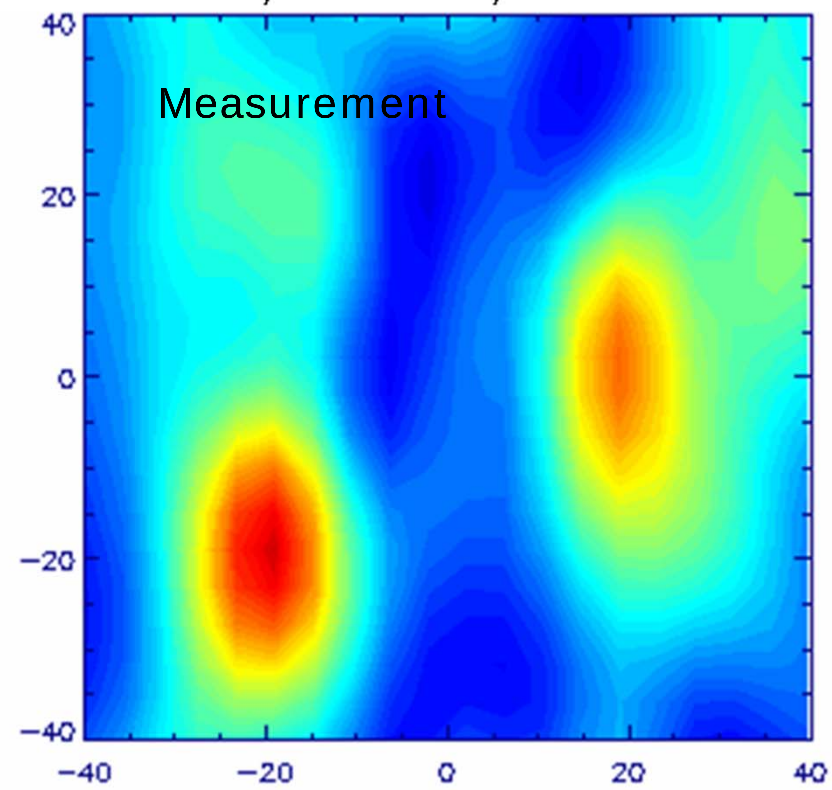
- Electron Bernstein Wave mode conversion mechanism contains information ∇n_e and B.
  - Need to measure EBW emission window.
- The new Synthetic Aperture Microwave Imaging (SAMI) diagnostic uses a novel technique for producing images of thermal emission in the range 10 - 40 GHz.
- First SAMI images from EBW emission obtained.
  - Technique works, but some differences between experiment and simulation.
- First steps to calculate j(r).



L-mode, 15 GHz, shot #27022



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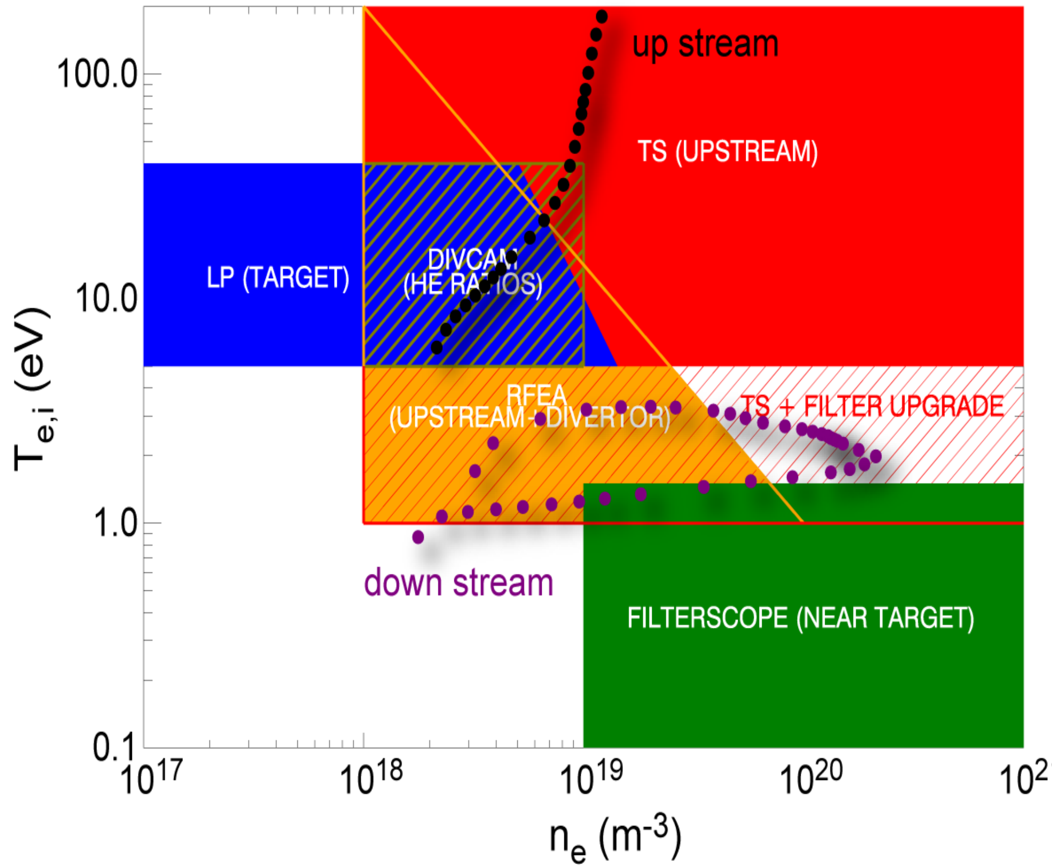
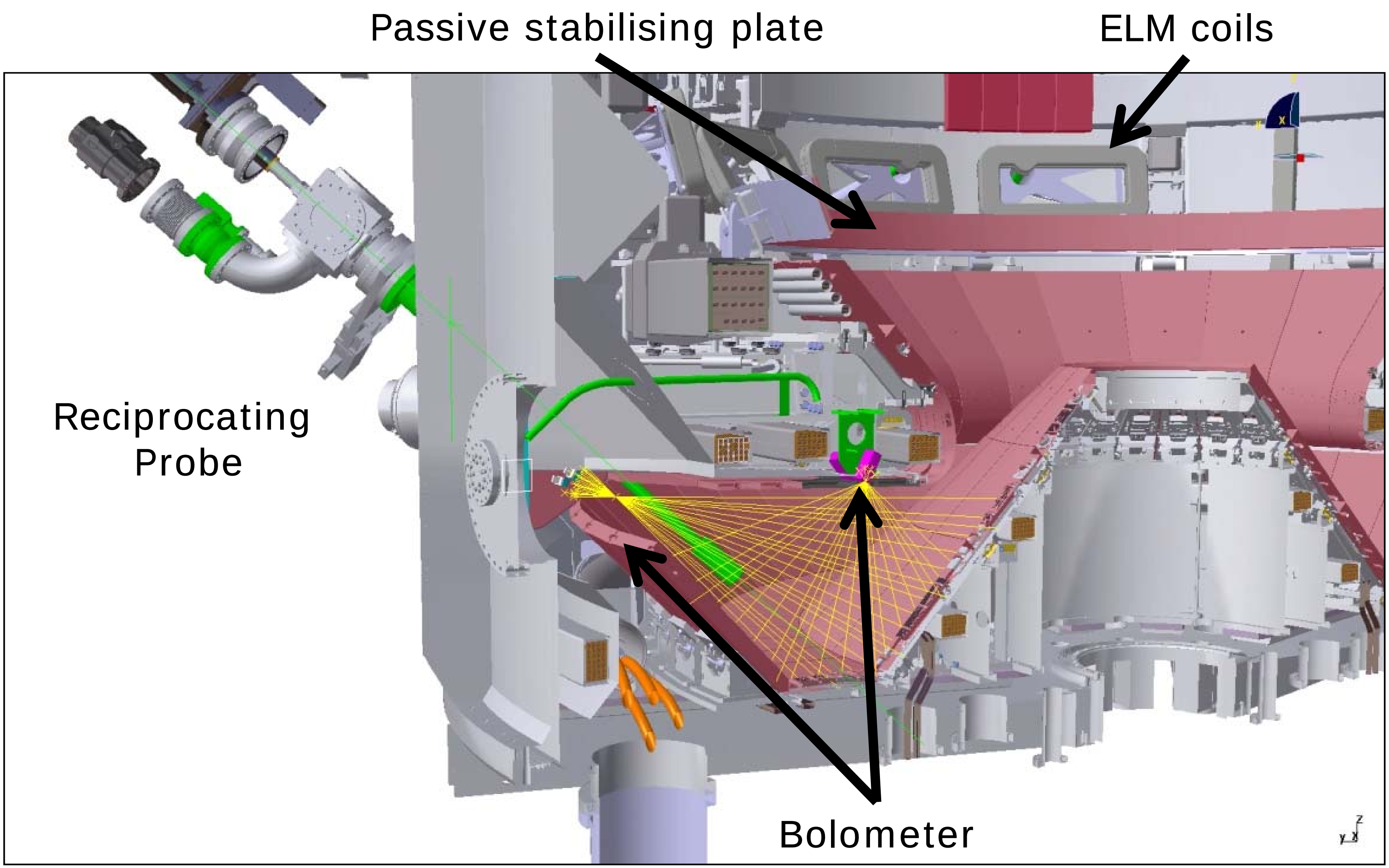
Divertor diagnostic challenge

- Large range in n_e and T_e in the SOL.
- Low temperature plasma.
  - ⇒ Neutrals, impurities
  - ⇒ Line radiation, atomic data.



- The SOL is turbulent: $\delta n/n \sim O(1)$
- Many different diagnostics needed

Divertor diagnostic challenge



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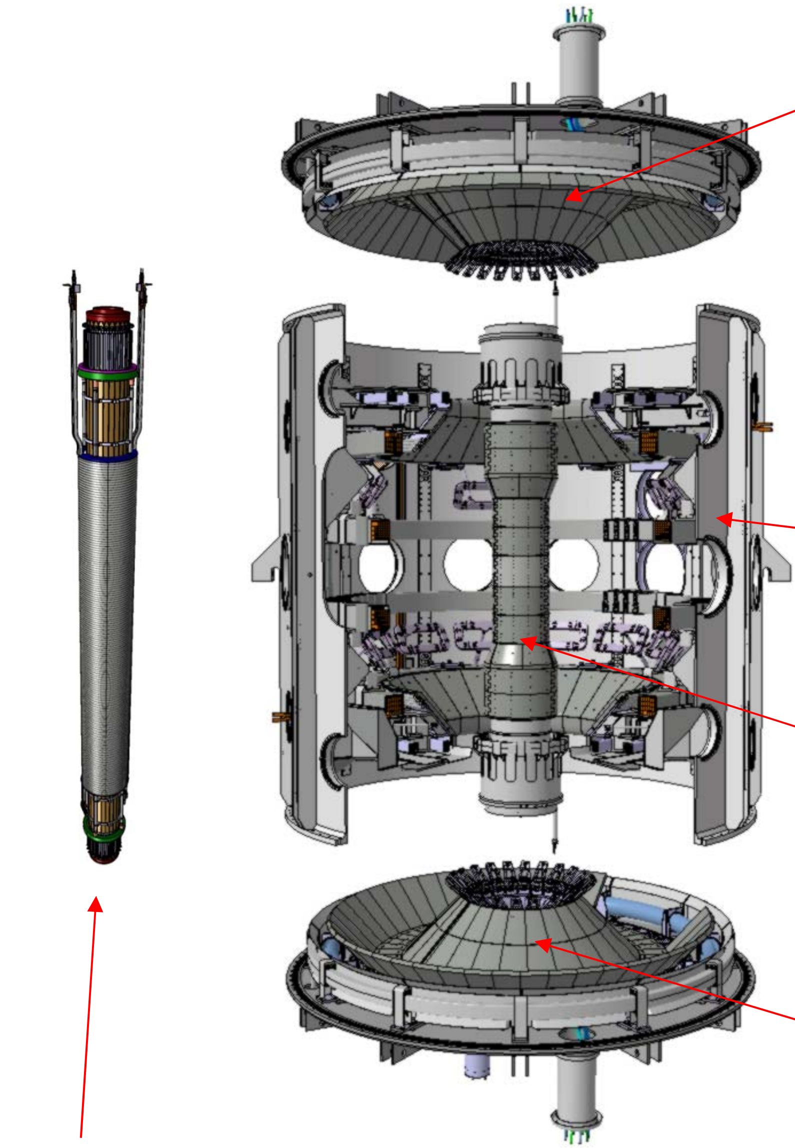
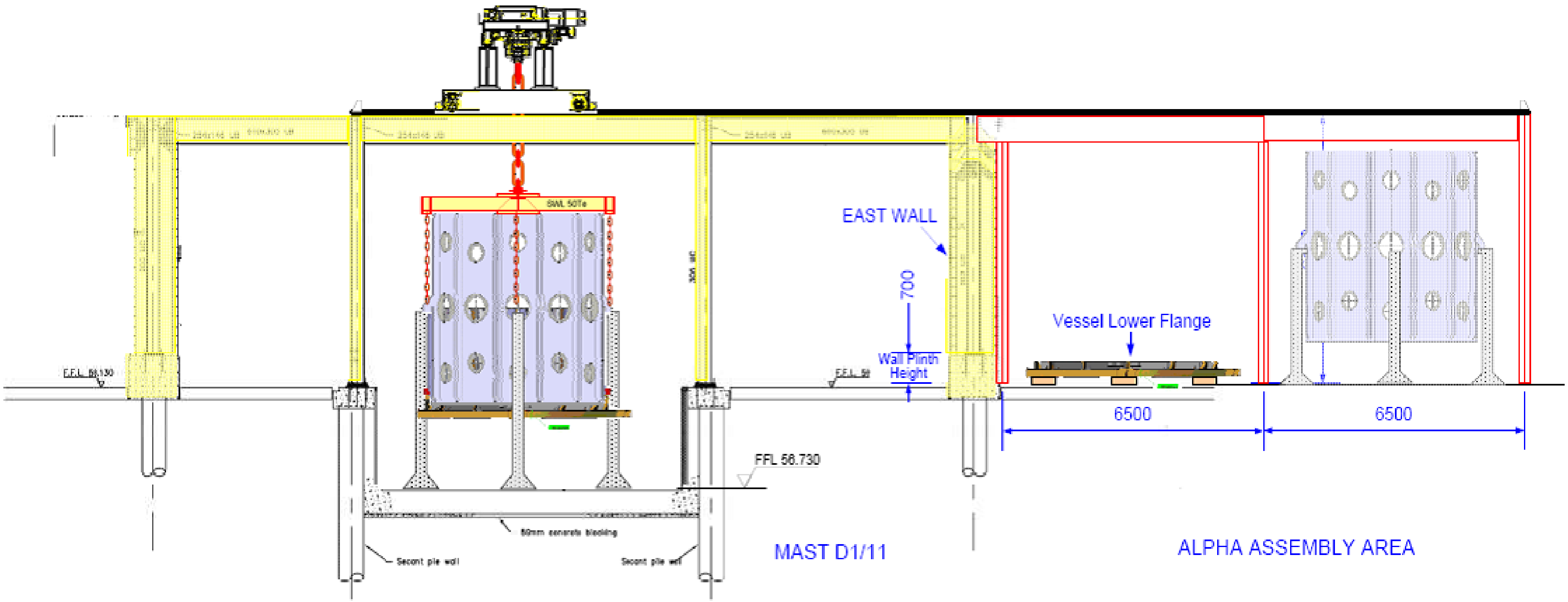
Modular assembly



- Optimise engineering break.
- Progress work in parallel.
- Better alignment.

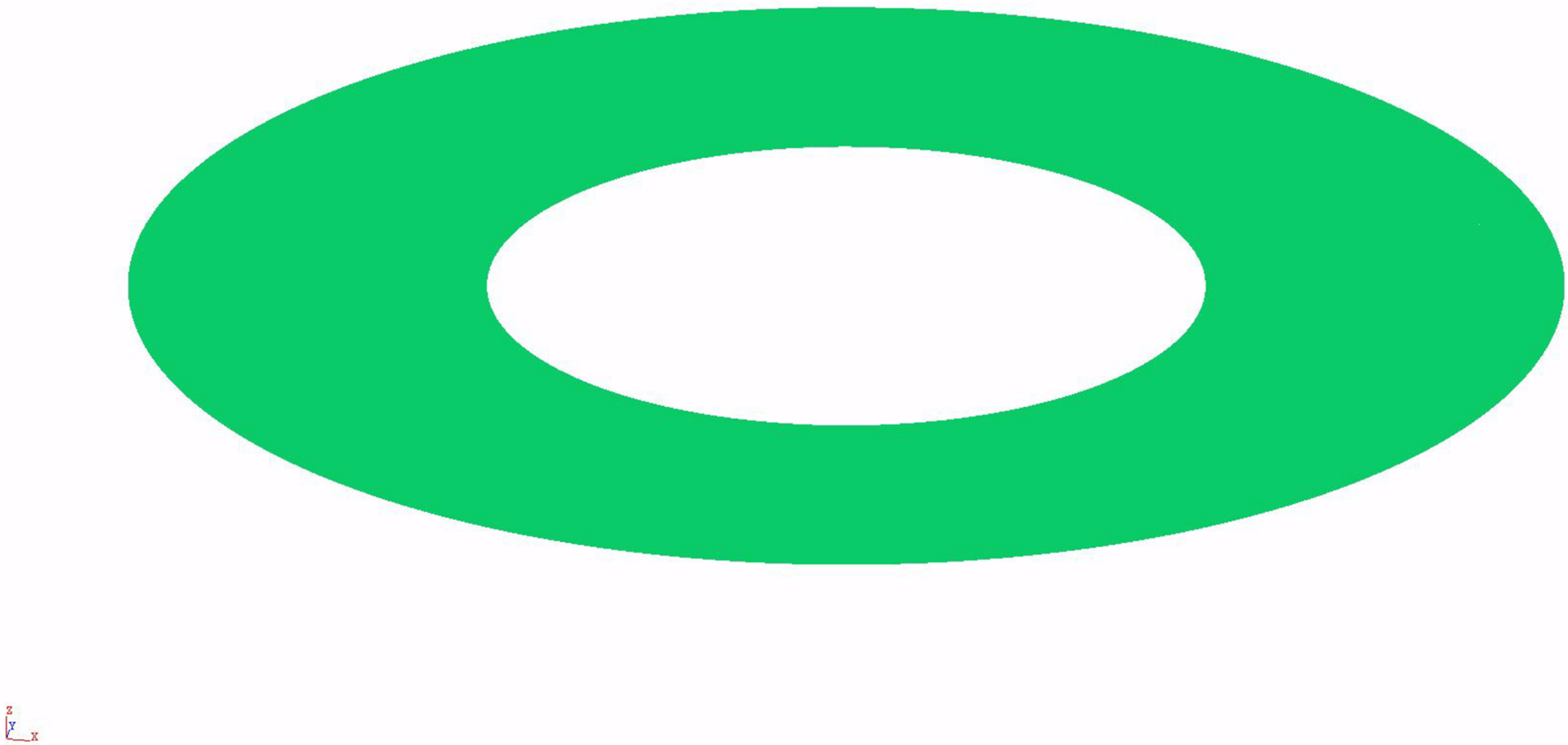
New crane enables fast assembly



- Move MAST out of the block house (test cell).
- Parallel assembly outside the machine area.

Coil cans - Explosion forming

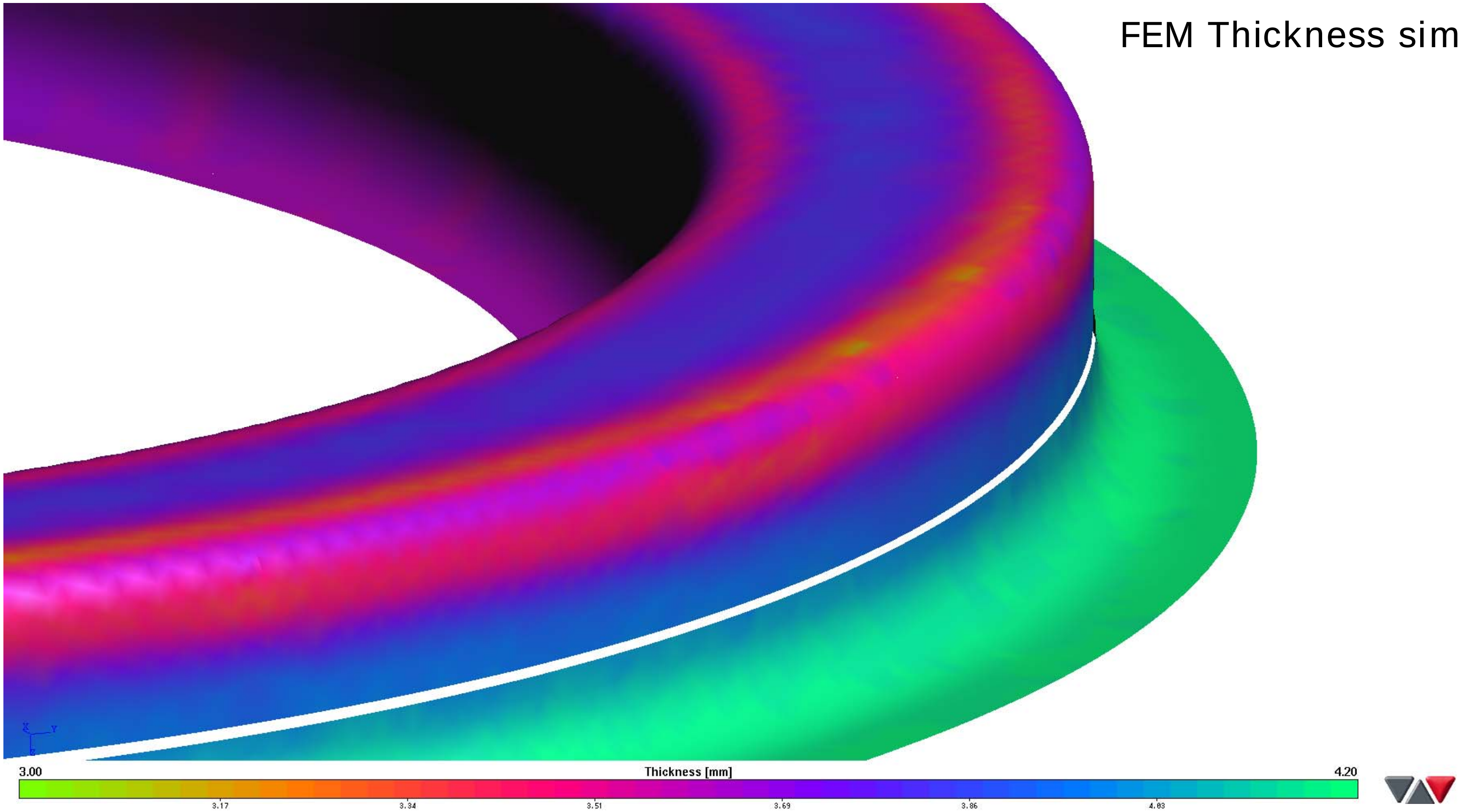
FEM Strain simulation



- D1 can (4mm SS 316L) most complicated.
- Assessment of prototype is positive.

Coil cans - Explosion forming

FEM Thickness simulation

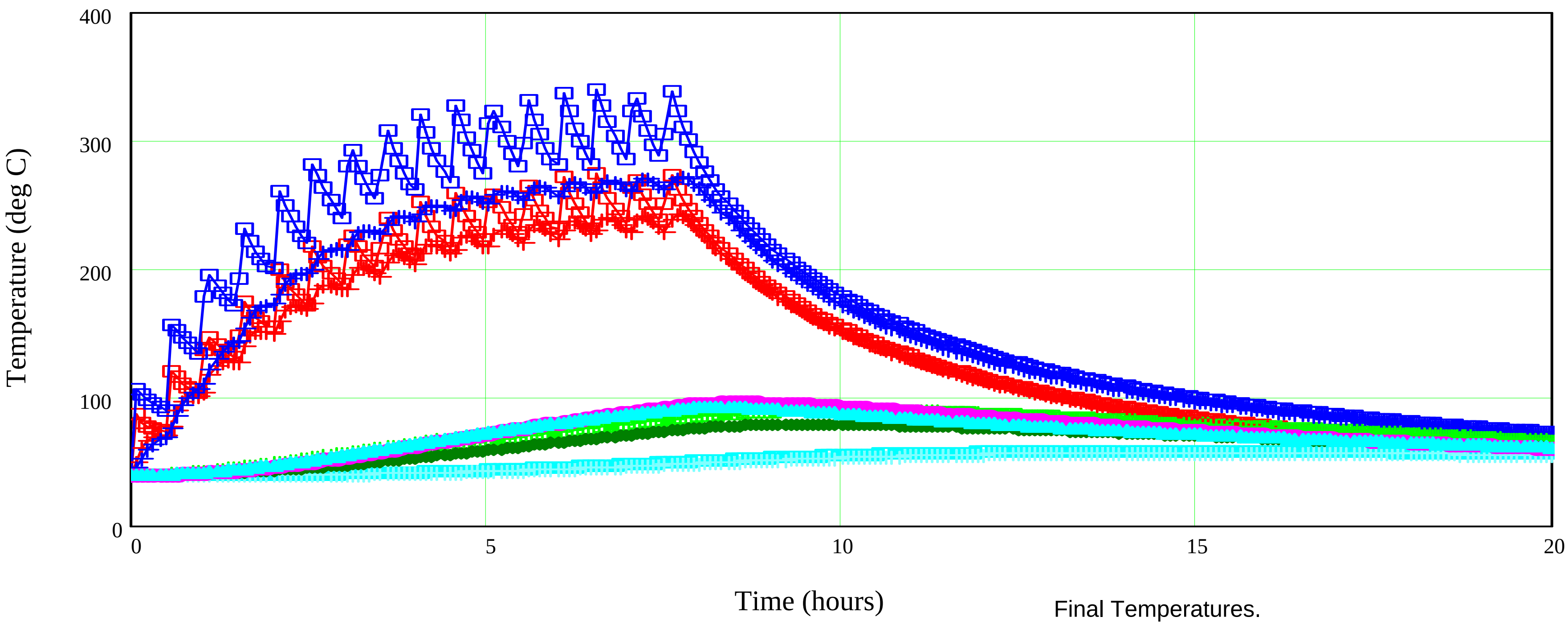


3.00 mm 4.20 mm

- D1 can (4mm SS 316L) most complicated.
- Assessment of prototype is positive.

Divertor temperature during operations

MAST-U Divertor Cooling



- DT1 Tiles
- DT2 Tiles
- DT3 Tiles
- DT4 Tiles
- B1 Back-Plate
- B2 Black-Plate
- B3 Back-Plate
- B4 Back-Plate
- Strike Plate
- Nose
- Baffle

Heating Fractions

$\lambda_{DT1} = 0.2$

$\lambda_{DT2} = 0.8$

$\lambda_{DT3} = 0.0$

$\lambda_{S} = 0.0$

$\lambda_{B} = 0.0$

Final Temperatures.

$T1t_{n_{int}} = 61.3$ C DT1

$T2t_{n_{int}} = 73.4$ C DT2

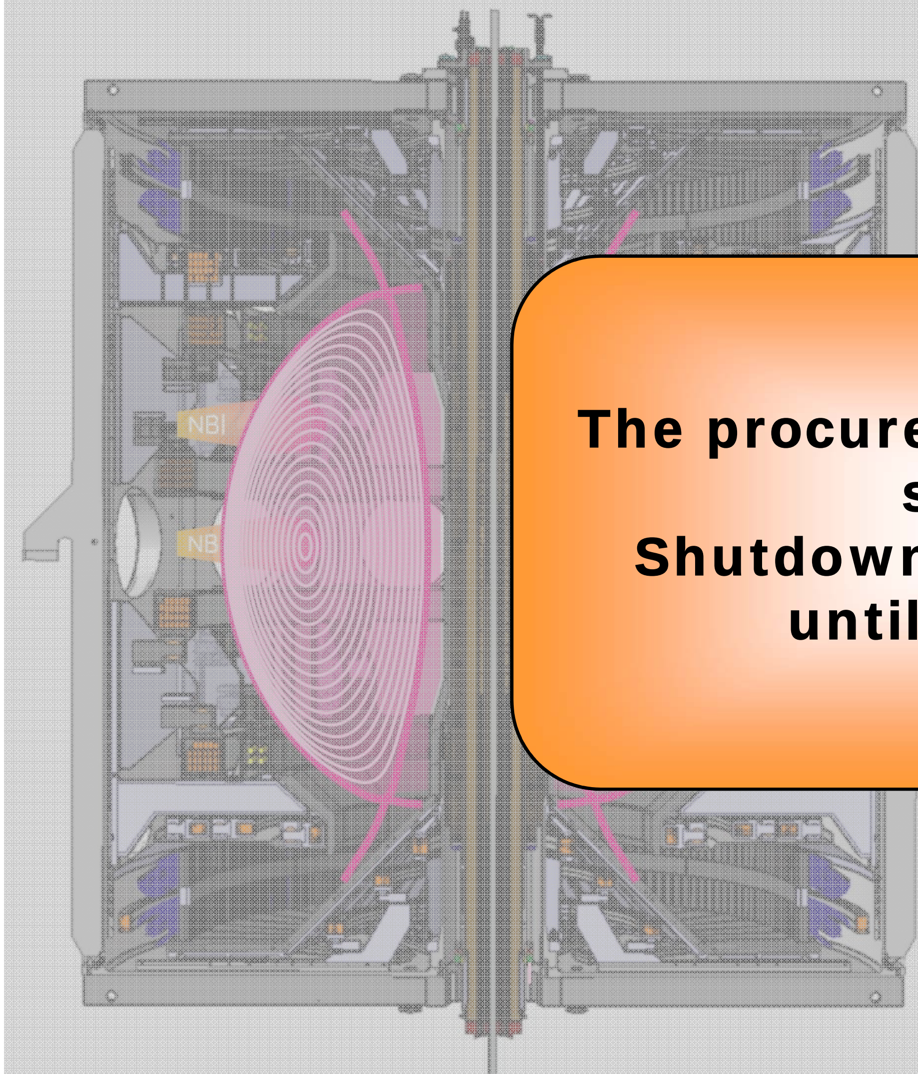
$T3t_{n_{int}} = 67.9$ C DT3

$T4t_{n_{int}} = 56.4$ C DT4

$\lambda_{bo} = 0.0$

$\lambda_{op} = 1.0$

MAST-U – a major step for fusion



Super-X divertor
⇒ Finding solutions for the exhaust problem

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ng plasmas

The procurement process has started!
Shutdown from Oct. 2013 until April 2015

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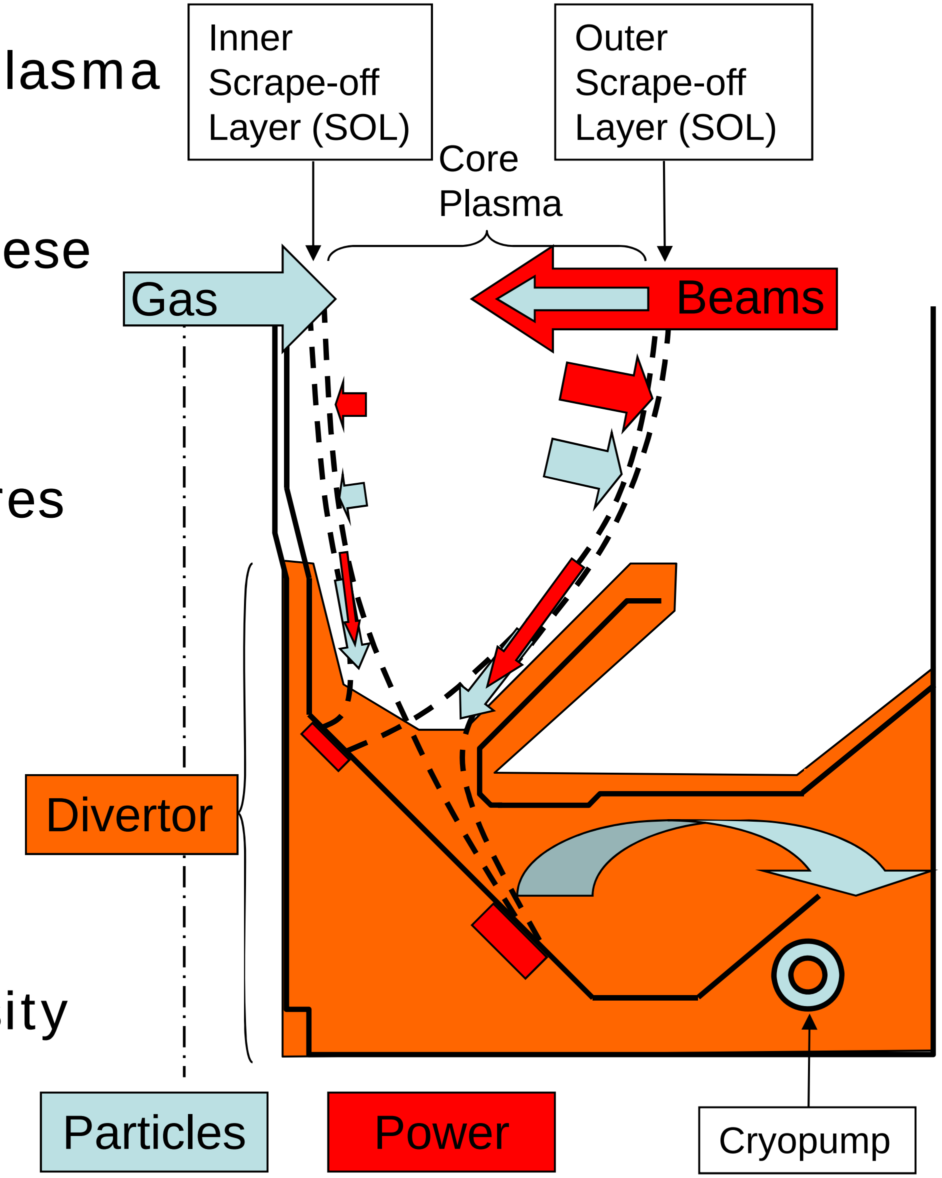
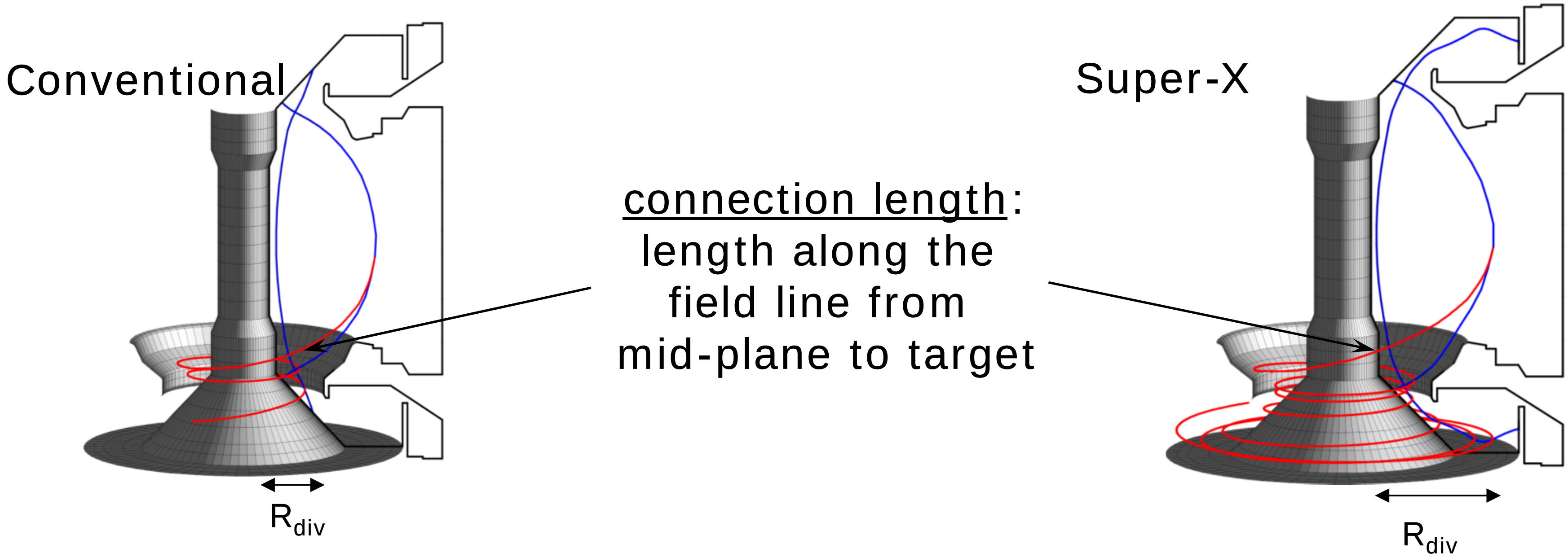
Advanced current profiles
⇒ Advanced stability for better confinement

A Divertor (Simplistically…)

- Put heat + particles into core plasma
- Transport processes remove these
- Divertor handles "exhaust":
  - Controls surface temperatures
  - Controls impurities
  - Removes particles
- Benefits:
  - Improved performance
  - Cleaner experiments
  - Control of core plasma density



Super-X Concept



- *Basic concept:* Increase radius of strike point (R_{div}).
  - Larger R_{div} $\Rightarrow$ larger wetted area.
  - Lower toroidal field $\Rightarrow$ lower parallel heat flux.
- Increased connection length using low poloidal field in divertor chamber.
  - Increased volume for plasma interactions.

Super-X concept:
Valanju et al. Phys. Plasmas 16, 056110 (2009)