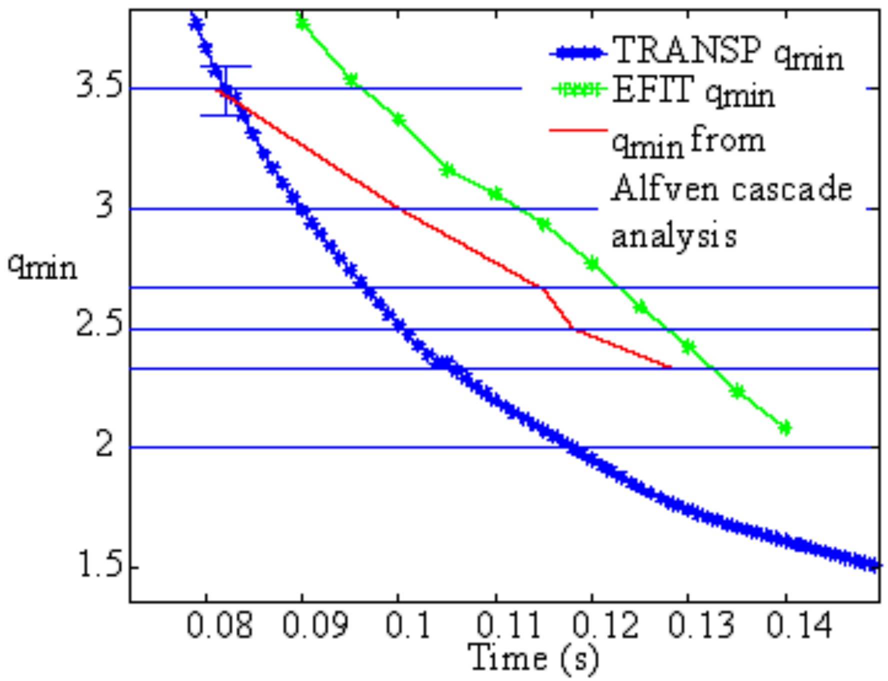
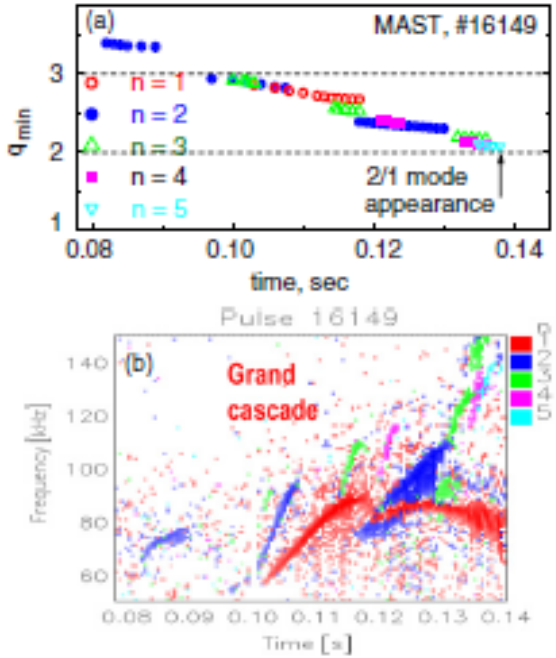
MAST
Ip diffusion

Ip diffusion

- During the M6 campaign, an experiment was executed looking at the effect of different Ip ramp-rates and density on the resultant q-profile.
- In the TRANSP analysis, it was found that toroidal current diffused faster than predicted by the TRANSP Poloidal Field Diffusion Equation (PFDE) assuming neoclassical resistivity, even though surface voltage check appeared OK.
- It was suggested that the issue was to do with NBI fast ion population.

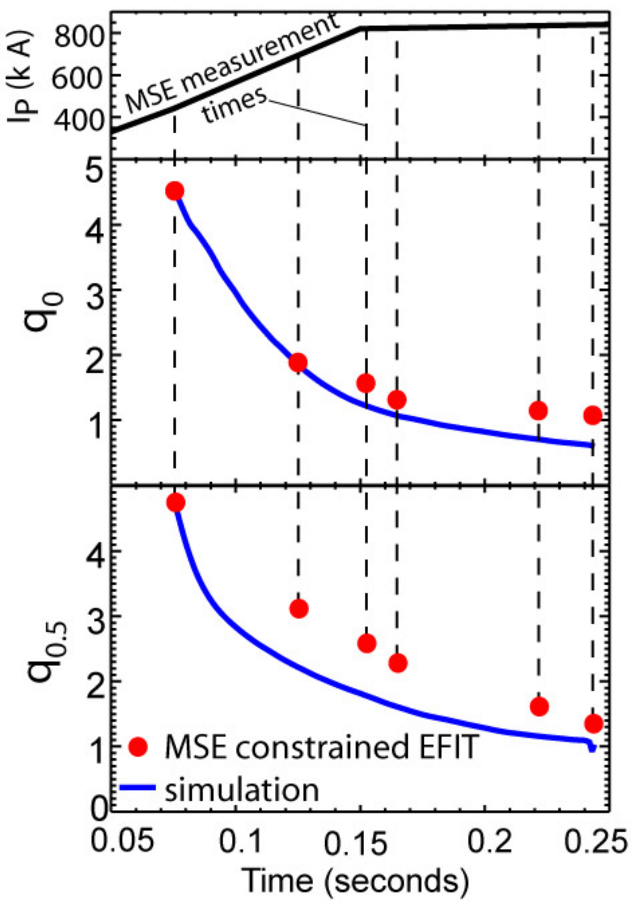


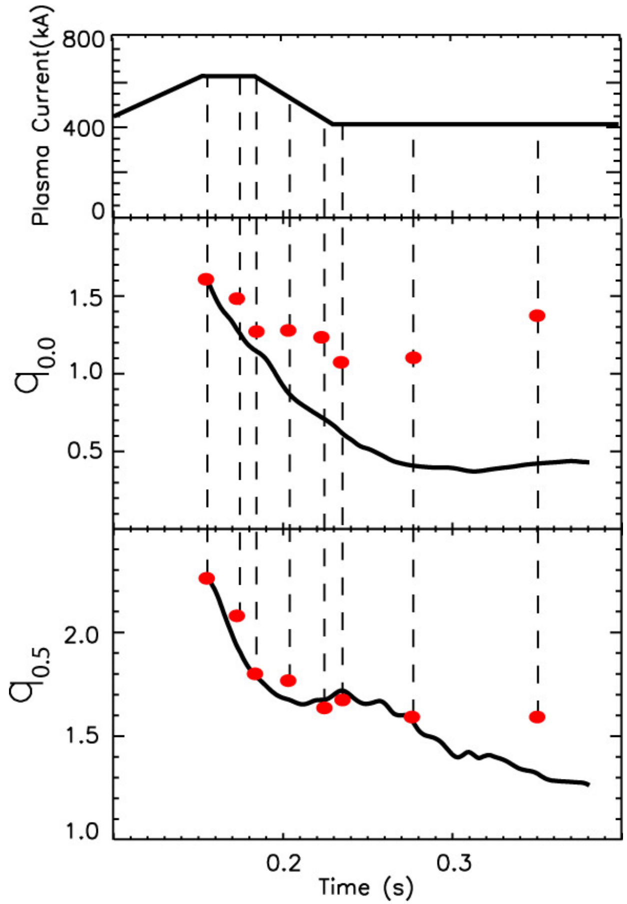
D. Keeling, EPS 2008



M. Gryaznevich *et al*, NF 2008

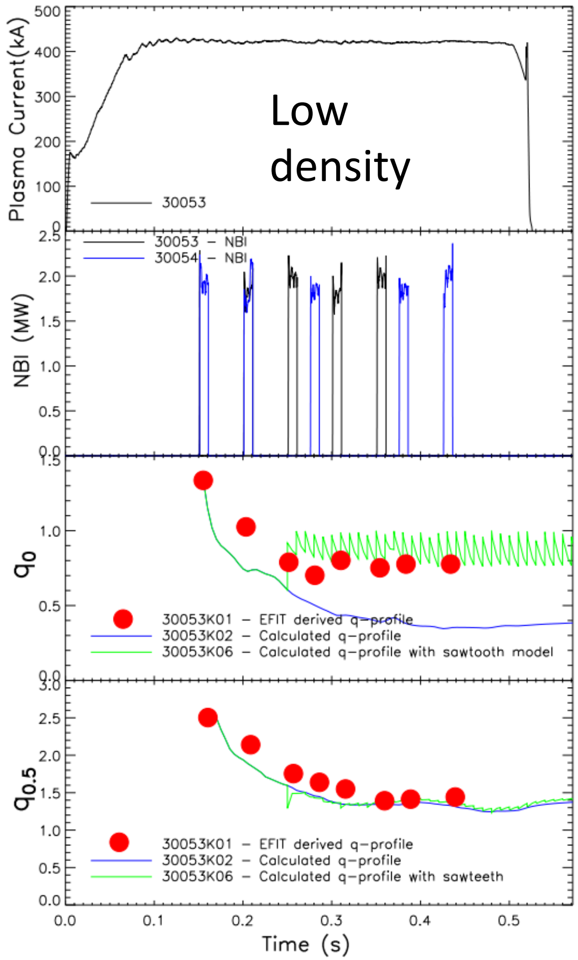
Ip diffusion – ramp-up/ramp-down

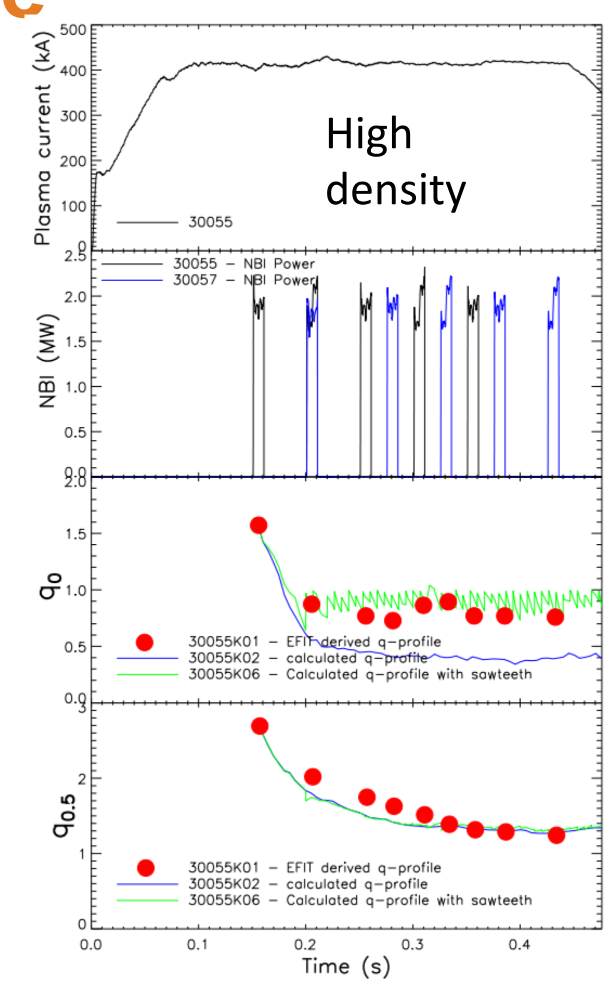




- Measurements in Ohmic plasmas Ip ramp-up and Ip-ramp-down show modelled current diffusion faster than seen in experiment (Keeling, EPS 2011)…

Stationary state





- Modelling of stationary state appears to satisfactorily reproduce the correct current profile
- Still not understood what processes are involved in the anomalous modelling during Ip ramps.

MAST
Neutron emission studies

I. Klimek and M. Cecconello

First Benchmark of DRESS with TRANSP/NUBEAM

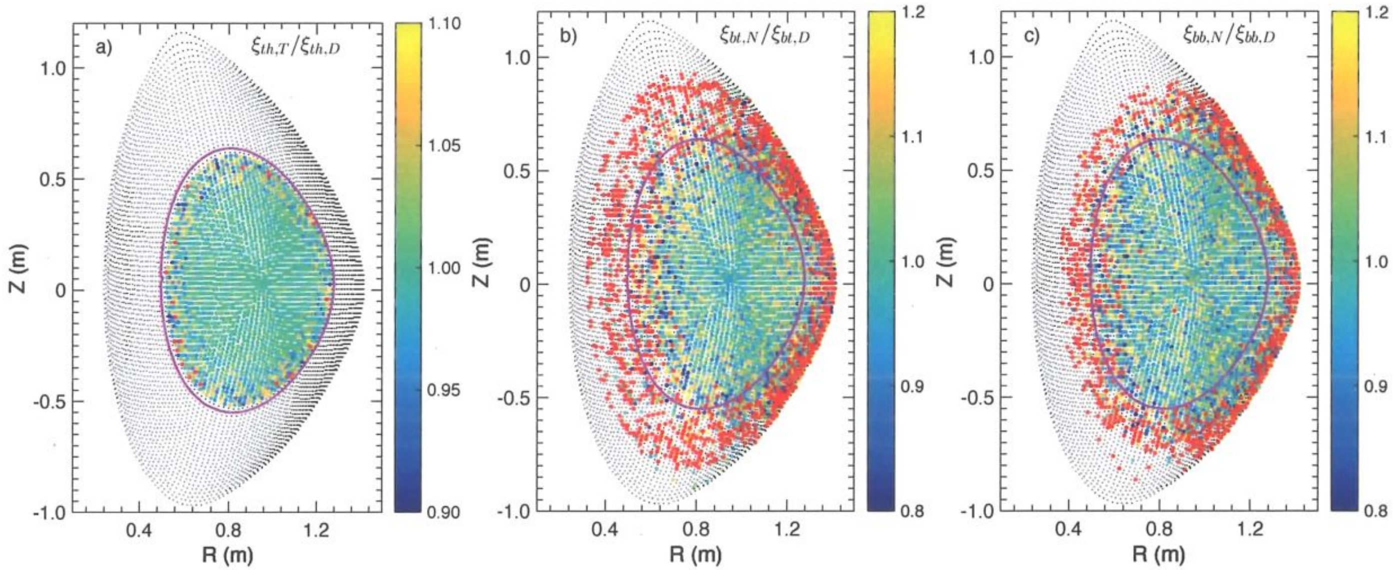


Figure 5: Pulse 29909: ratio of TRANSP/NUBEAM to DRESS calculated a) thermonuclear, b) beam-thermal and c) beam-beam emissivities at $t = 0.216$ s. The flux surface restricting the plasma region from which 99% of all neutrons are emitted is shown in magenta. The ratios exceeding 1.2 are plotted in red while spatial points for which the evaluated ratio is zero or below 0.8 are plotted in black.

- TRANSP/NUBEAM used to generate FI distribution function for use with DRESS code
- DRESS computes neutron production rate using differential fusion reaction x-section.
- Images show ratio of neutron emission calculated by TRANSP and DRESS.
- Total neutron emission only changed by ~0.5% since largest relative differences in local neutron emissivity (>20%) occur in plasma regions accounting for small proportion of total neutron emission (<<1%).

Klimek *et al*, sub. *Nuclear Fusion*

First Benchmark of DRESS with TRANSP/NUBEAM

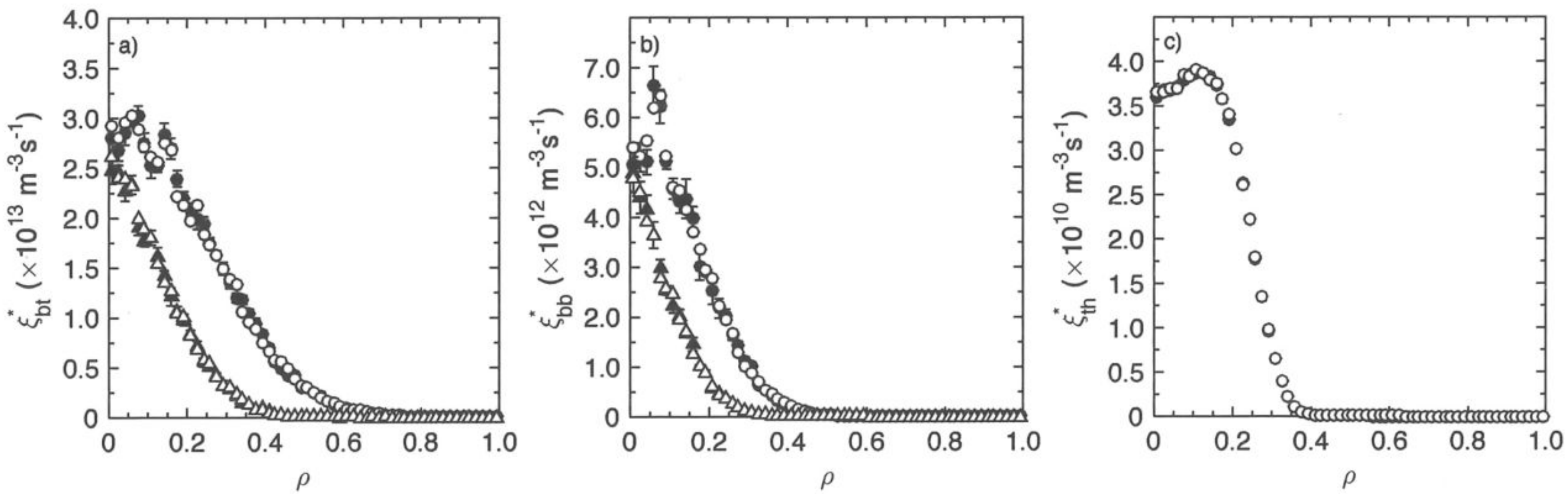


Figure 7: Pulse 29909: a) beam-thermal, b) beam-beam and c) thermonuclear neutron emissivities along the plasma mid-plane predicted by TRANSP/NUBEAM (full circles and triangles) and DRESS (open circles and triangles) at $t = 0.216$ s. The circles and triangles represent the neutron emissivities calculated along the mid-plane for points going from the plasma center to outboard and inboard side, respectively.

- Mid-plane inboard/outboard neutron emission profiles calculated by TRANSP/ NUBEAM and DRESS agree very well!

Klimek *et al*, sub. *Nuclear Fusion*

Modelling FI loss using specific cuts in E and v||/v

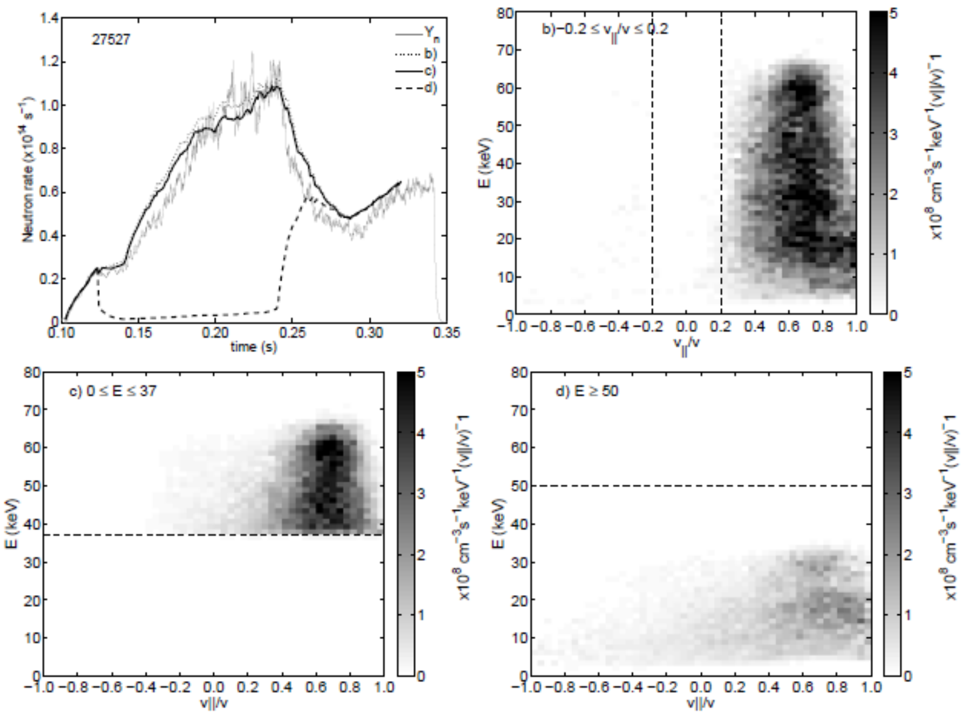
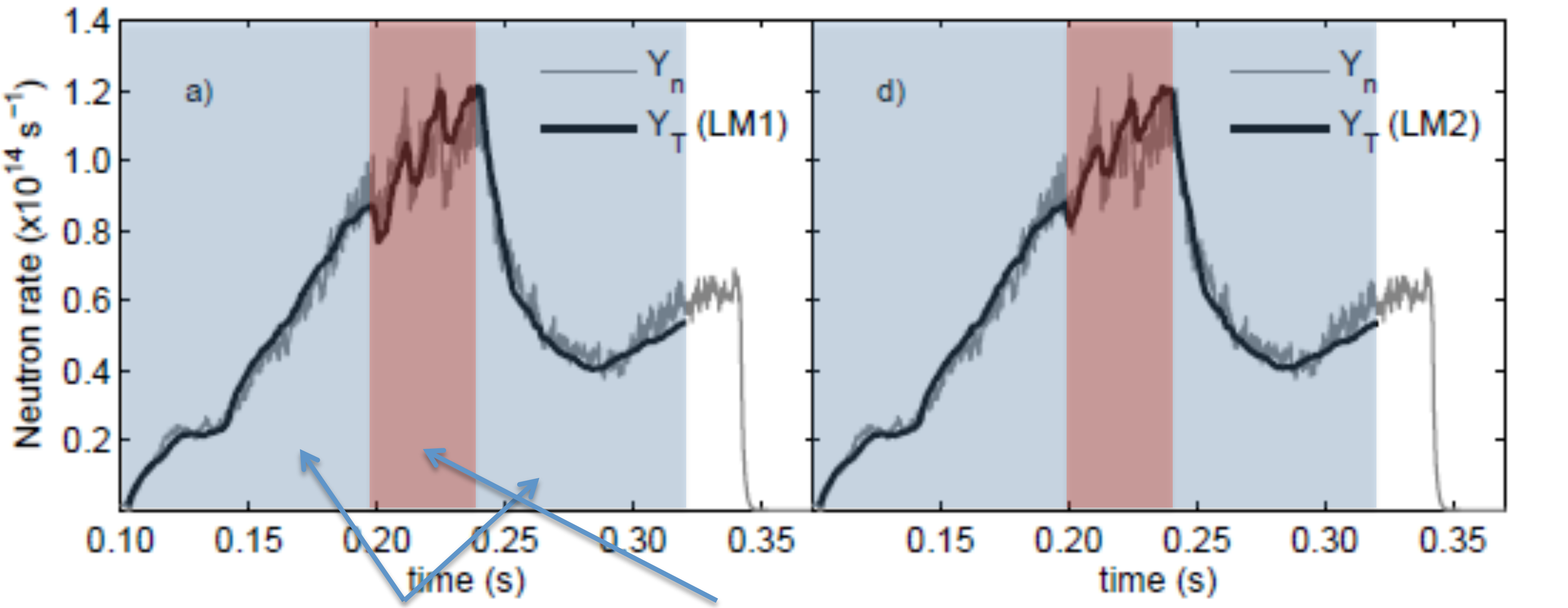


Figure 11: Plasma discharge 27527: a) Y_{n} and Y_{T} modelled using LM1 when the cuts presented in panels b), c) and d) were applied to $f_{\mathrm{i}}(R, Z, E, v_{||}/v)$. Panels b), c) and d) show $f(R = 0.98\ \mathrm{m}, Z = -0.01\ \mathrm{m}, E, v_{||}/v)$ averaged over time interval $0.19 \le t \le 0.20$ s when the following regions were selected for fast ion removal: b) $v_{||}/v \in [-0.2, 0.2]$ regardless of their energy, c) $E \in [0, 37]$ keV regardless of their pitch angle and d) $E \in [50, 75]$ keV regardless of their pitch angle.

- Drop in measured neutron emission rate due to LLM and modelled using various ‘cuts’ in FI distribution to simulate prompt FI losses.

Klimek *et al*, *Nuclear Fusion* **55** (2015) 023003

Modelling FI loss using specific cuts in E and v||/v



Ad-hoc anomalous FI diffusion term only used in these periods (D=1.5m^{2}s^{-1})

Fishbone loss model used in this period:
LM1= all ions E<55keV and -0.5<v||/v<0.5.
LM2= trapped ions only E<55keV and -0.5<v||/v<0.5 with D=0.5m^{2}s^{-1}

Klimek *et al*, *Nuclear Fusion* **55** (2015) 023003

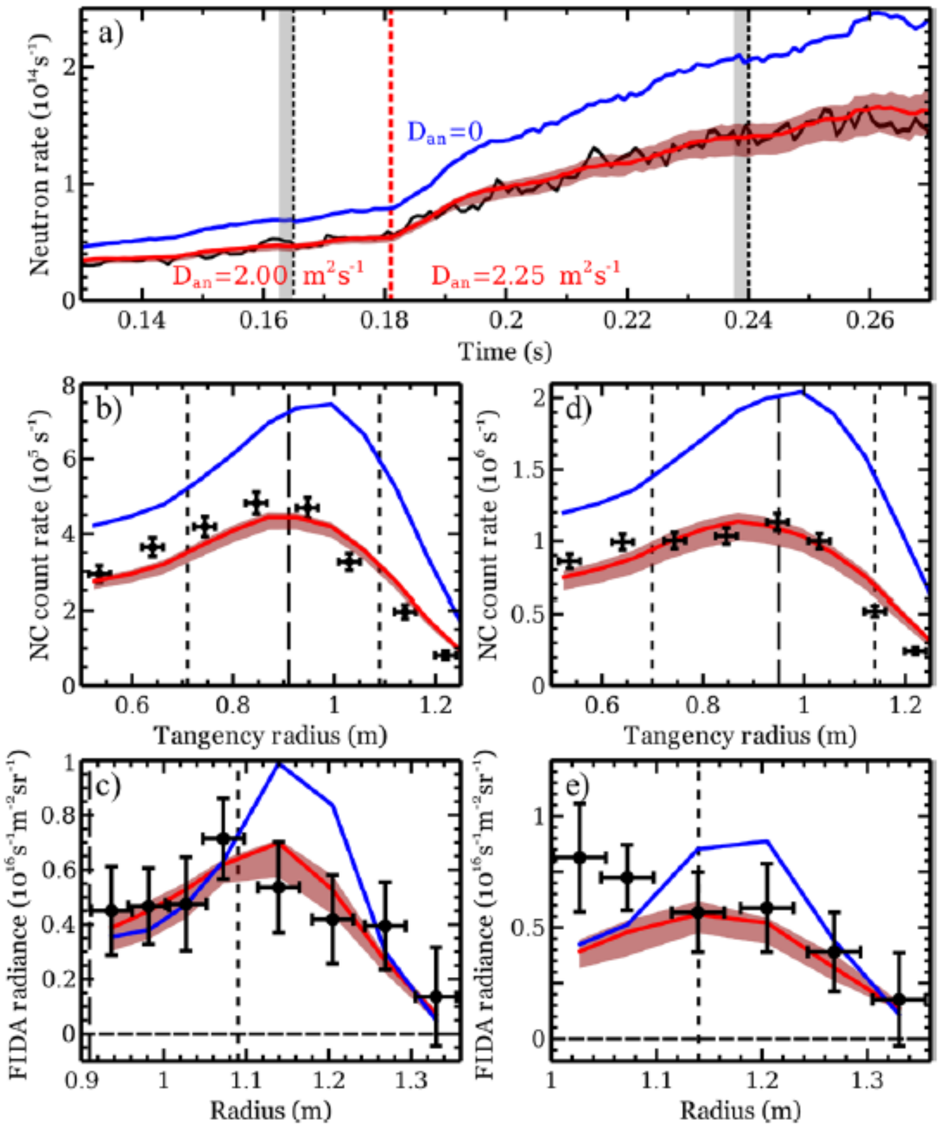
FI losses due to MHD

- Neutron emission rate reproduced accurately using combination of anomalous FI diffusion and selected FI losses
- Ongoing work: Comparison of available sawtooth models Kadomtsev/Porcelli:
    - Use sawtooth models to generate 2-D non-flux averaged neutron emission before/after sawteeth
    - Compare with experimental NC profiles
    - Research to be presented at EPS later this year.

MAST
FIDA studies

O. Jones

FIDA

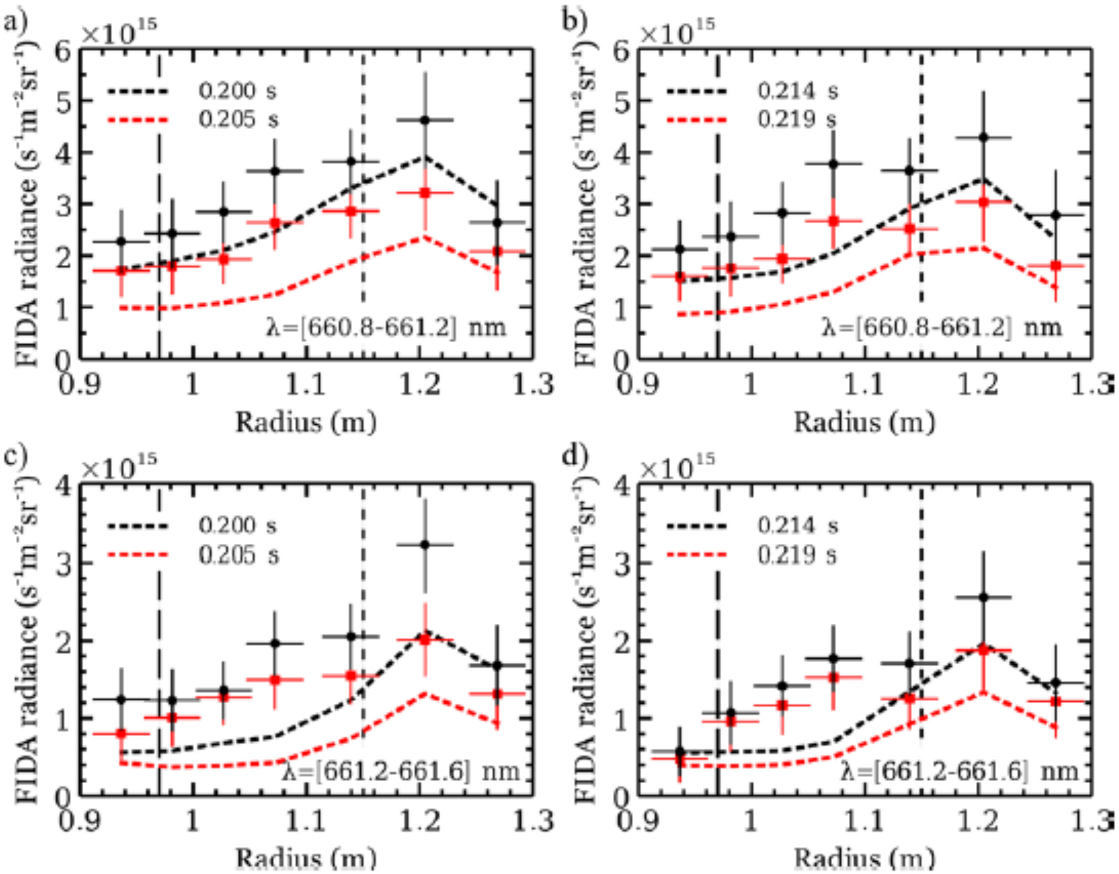


- TRANSP used to model shot in presence of TAE and fishbones
- Match to observed neutron emission rates achieved again using anomalous FI diffusion term

- NUBEAM FI distribution used with FIDAsim to simulate expected FIDA signal and compared with expt. data

O. Jones *et al, PPCF* **57** (2015) 125009

FIDA signal change due to fishbones



- TRANSP fishbone loss model used with 2 loss schemes A (top panels a and b) and B (bottom panels c and d)
- Scheme A tuned to best reproduce observed FIDA signal changes
- Scheme B tuned to best reproduce observed global and local neutron rate

A= all ions 50keV<E<75keV and 0.69<v||/v<0.93 (co-passing)
B= all ions 60keV<E<70keV and 0.0<v||/v<0.7 (trapped and co-passing)

- A overestimates magnitude of FIDA change, B underestimates in core but matches at edge
- Conclude a spatially varying model necessary preferably based on first principles resonant transport (e.g. HALO code in development)

MAST Upgrade scenario specification

MAST-U – Scenario specification

- The stated MAST-U "Top-level goals" include:
  - Development of a confinement scaling and ST relevant transport model for plasmas with **strong off-axis current drive**, high plasma rotation and ***qmin* >1**
  - Establishment of a **strongly driven plasma scenario** with **sustained operation at low *li*, high κ** and H-mode confinement with mitigated (or no) ELMs
  - Sustained operation of plasmas with high-Z plasma facing components and tolerable core impurity accumulation (employing core electron heating if required)
  - Demonstration of a integrated, non-solenoidal start-up scheme allowing development of mega-amp current from breakdown
  - **Sustained operation of a divertor concept in plasma conditions (esp. target heat flux) relevant to power-plant scale devices**

(i.e. Super-X)

Plasma scenarios – optimisation of NBI

Each of "The Magnificent 7" demonstrates a different aspect of CTF/ITER/DEMO physics.

A 4-beam system (10MW) was specified that would allow achievement of all aims!

SCENE equilibrium

FIESTA equilibrium guided by SCENE

TRANSP run from FIESTA eqm.

Common parameters:

- Ip=1.2MA
- κ=2.5
- A=1.6
- li(3)=0.5

(except where stated otherwise)

TRANSP Scenario A	TRANSP Scenario B	TRANSP Scenario C	TRANSP Scenario D	TRANSP Scenario E	TRANSP Scenario F	TRANSP Scenario G

- A1,A2 : baseline, CTF-like q profile, 2 density variants
- B : high fast particle content - confinement, f_{NI}=0.9, β_N=6,
- C1, C2 : long pulse, f_{NI}>1, β_N=6.7, reduced TF, 2 I_p variants
- D : high β_T, I_p=2MA, q0~1, test fast particle β limit
- E : 'touch-base', high l_i, low β
- F : high [illegible]=0.6, β limit and confinement scaling
- G : high thermal β_T (β_N up to 7), I_p=2MA, n_g=1, β limit testing

"Core-scope"

- Since full 3/4-beam scenario simulations produced, scope of project reduced – 2 beams in on/off-axis locations, no cryo-pumping.

Extract from Hendrik Meyer ISTW2013 talk:

"Core Scope still delivers all main aspects:

Longer pulses

Flexible heating and fast-ion distribution

on axis $P_{NBI} < 2.5$ MW

off-axis $P_{NBI} < 2.5$ MW

New Divertor (Super-X, Snowflake, Conventional and in between)

but will be limited at accessing low density and low collisionality."

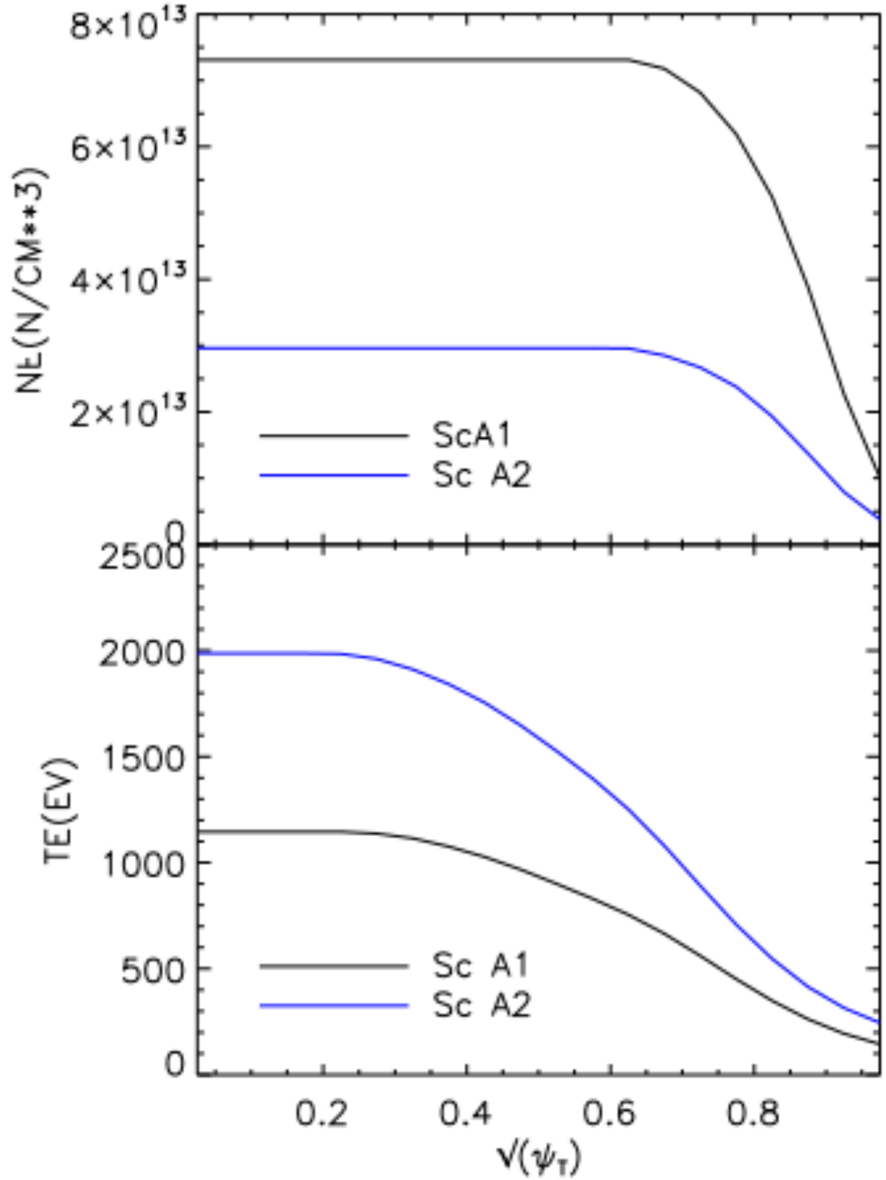
Core Scope Capability (PAC 8 – Sept 2013)

Key features of Core Scope operation:

- I_p up-to 2 MA, I_{rod} up-to 3.2 MA (B_t = 0.9 T at R=0.7m) possible after integrated commissioning (not for first campaign)
- Closed divertor and wall pumping should allow exploration of lower density regimes at least transiently (wall pumping + divertor filling ~ 1s)
- Most MAST Diagnostics will be available during first physics campaign.
  - Final sequencing still to be decided.
  - Early emphasis on divertor diagnostics (IR, DIVCAM)
- High elongation < 2.5 at $l_i(2) < 1$ should be possible with new RFPS and P6 coils and passive structures.
  - Performance assessed with typical large ELM response from MAST scaled by factor of two in size and duration.

Plasma scenarios

Scenario / Parameter	A1 (K25)	A2 (K26)
I_P	0.999 MA	0.999 MA
B_0	0.785 T	0.785 T
H_{98}	1.02	0.983
t_0	48.9 ms	35.9 ms
P_{abs}	4.24 MW	3.70 MW
P_{inj}	5.00 MW	5.00 MW
V_{surf}	0.231 V	0.030 V
$l_i(1)$	0.692	0.931
q_0/ q_{min}/ q_{95}	1.64/ 1.64/ 10.1	0.801/0.801/ 9.44
d_{95}	0.354	0.294
k_{95}	2.48	2.48
b_t	7.31%	9.31%
b_p	1.50	2.28
$b_N^{thermal}$	2.51	1.60
f_{bs}	0.28	0.16
f_{NBCD}	0.14	0.66



CCFE CULHAM CENTRE FOR FUSION ENERGY

Plasma scenarios

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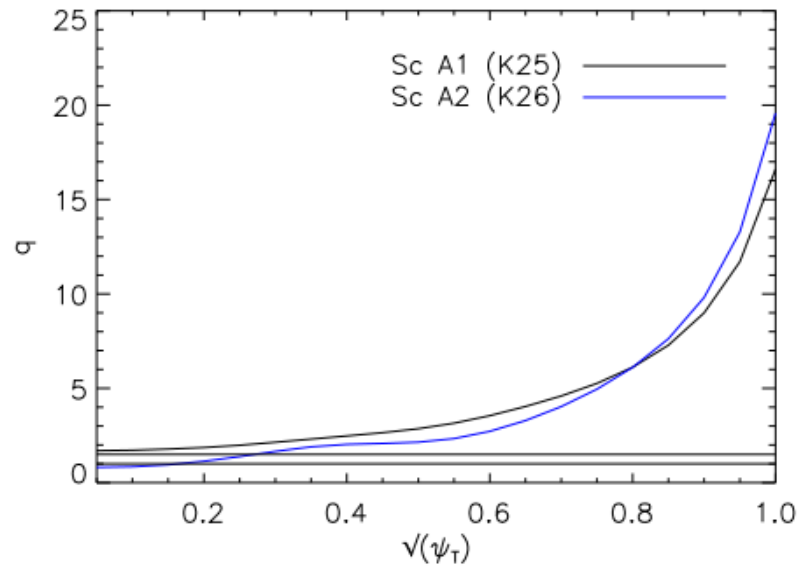

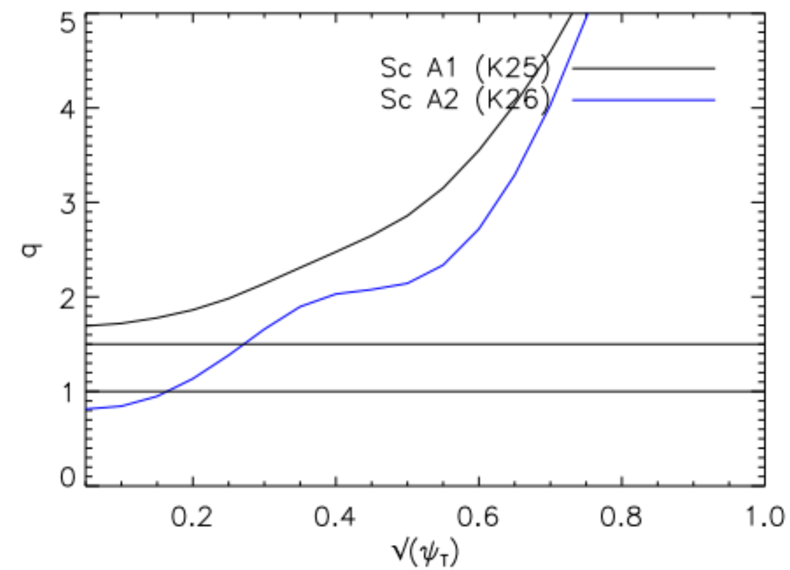

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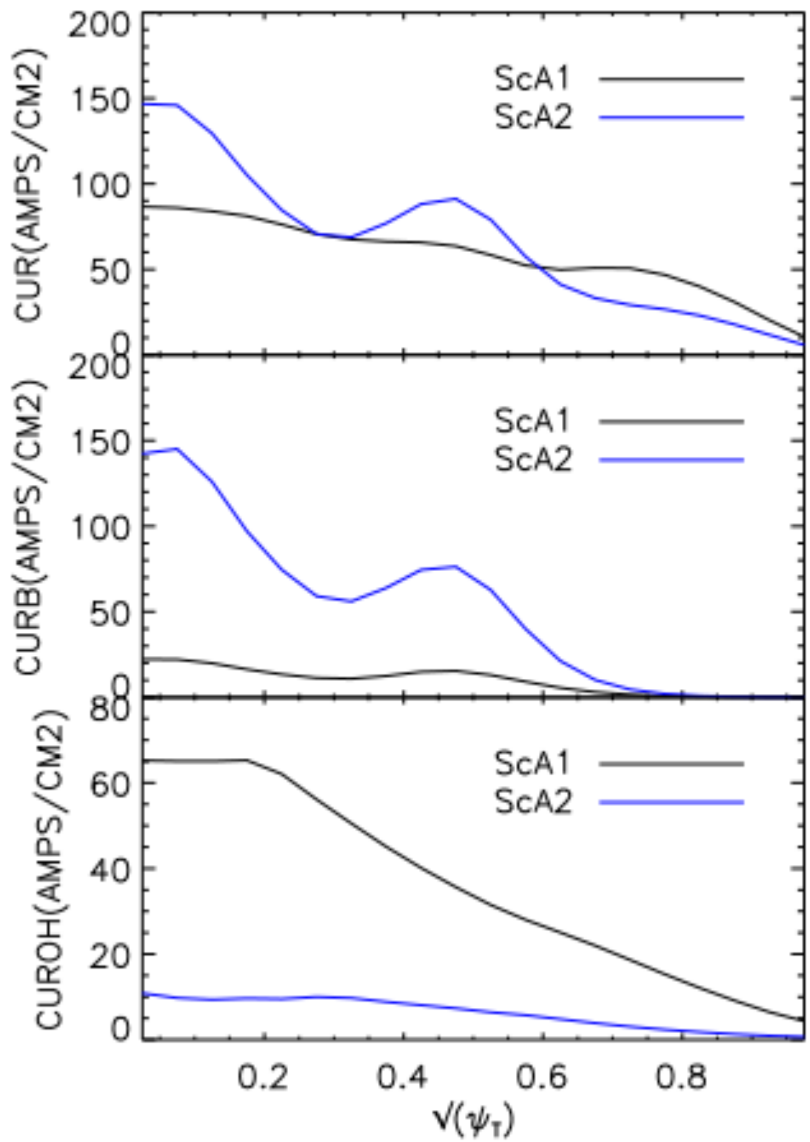

Plasma scenarios

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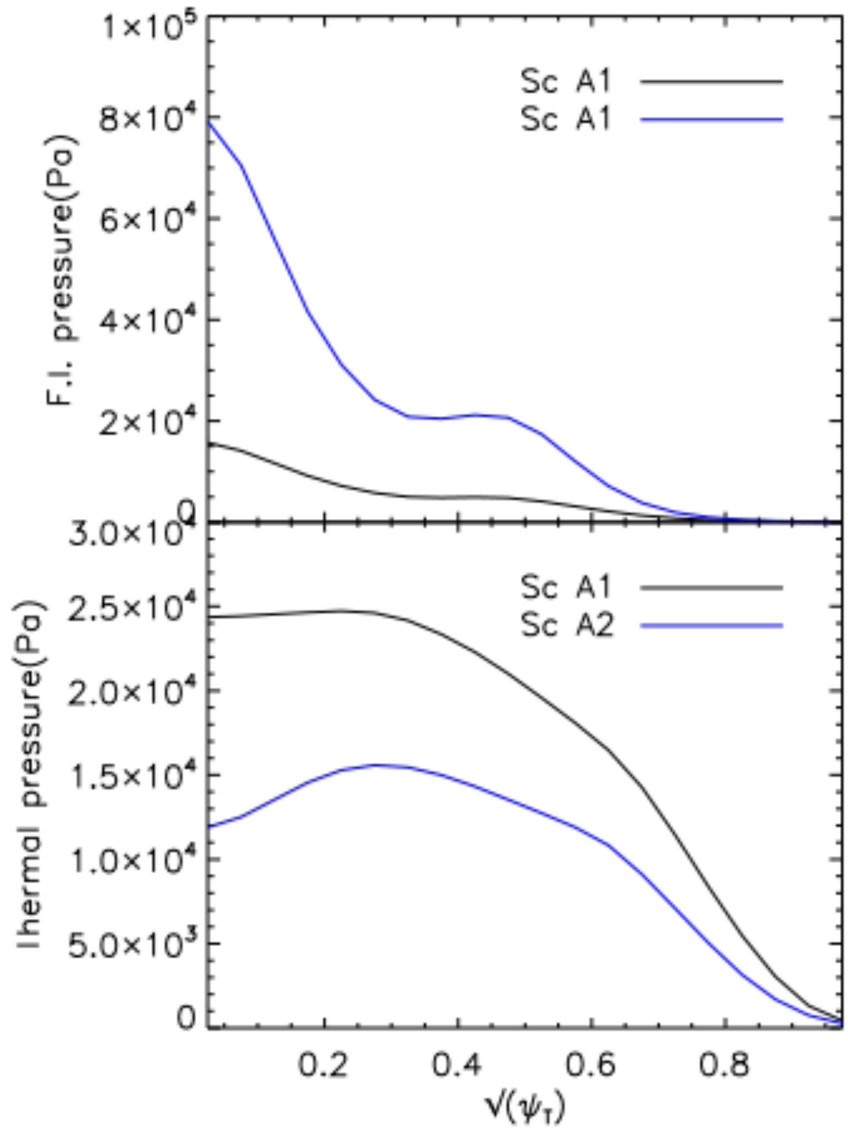
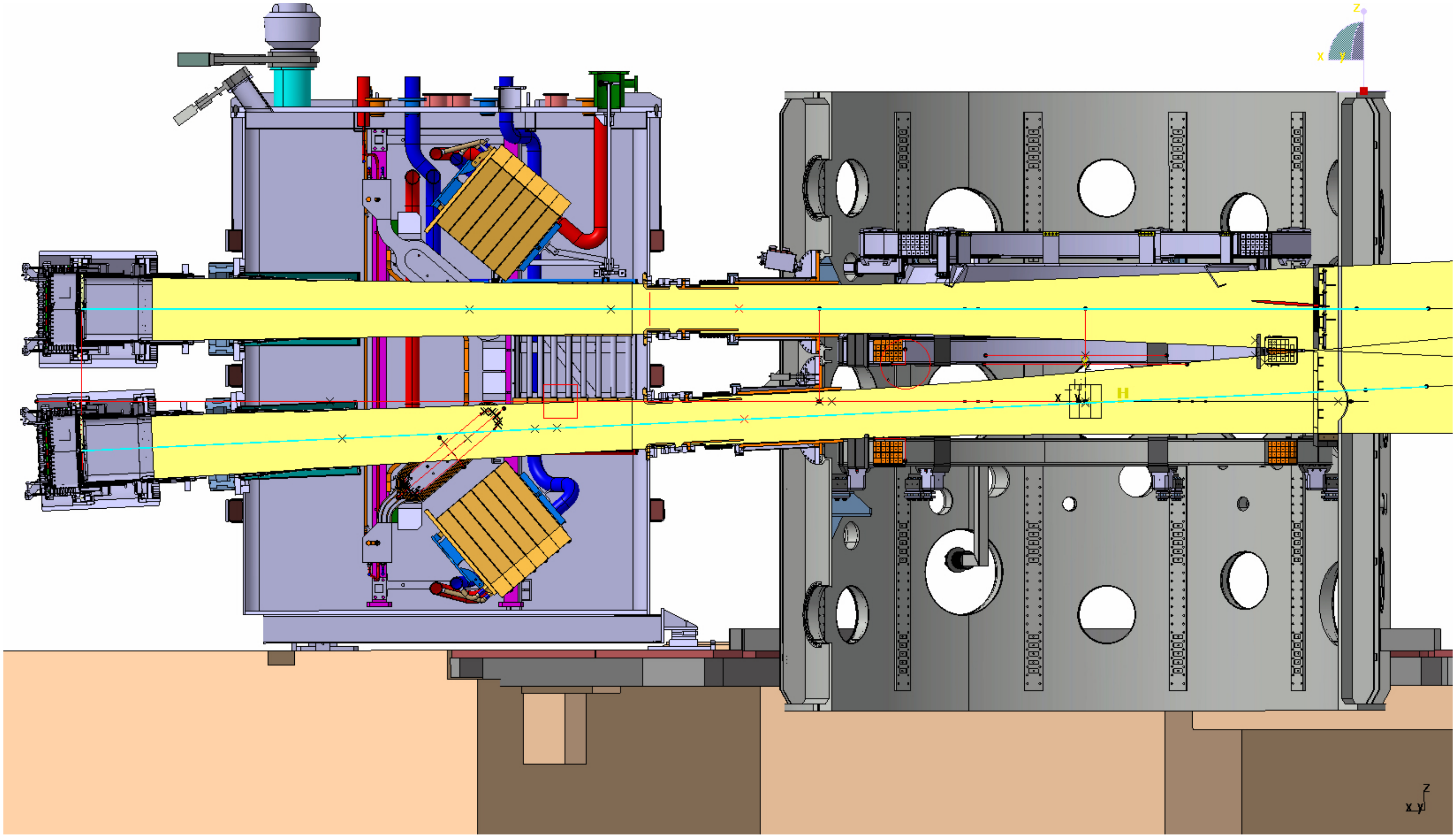


MAST Upgrade Stage 1 Double Beam Box design

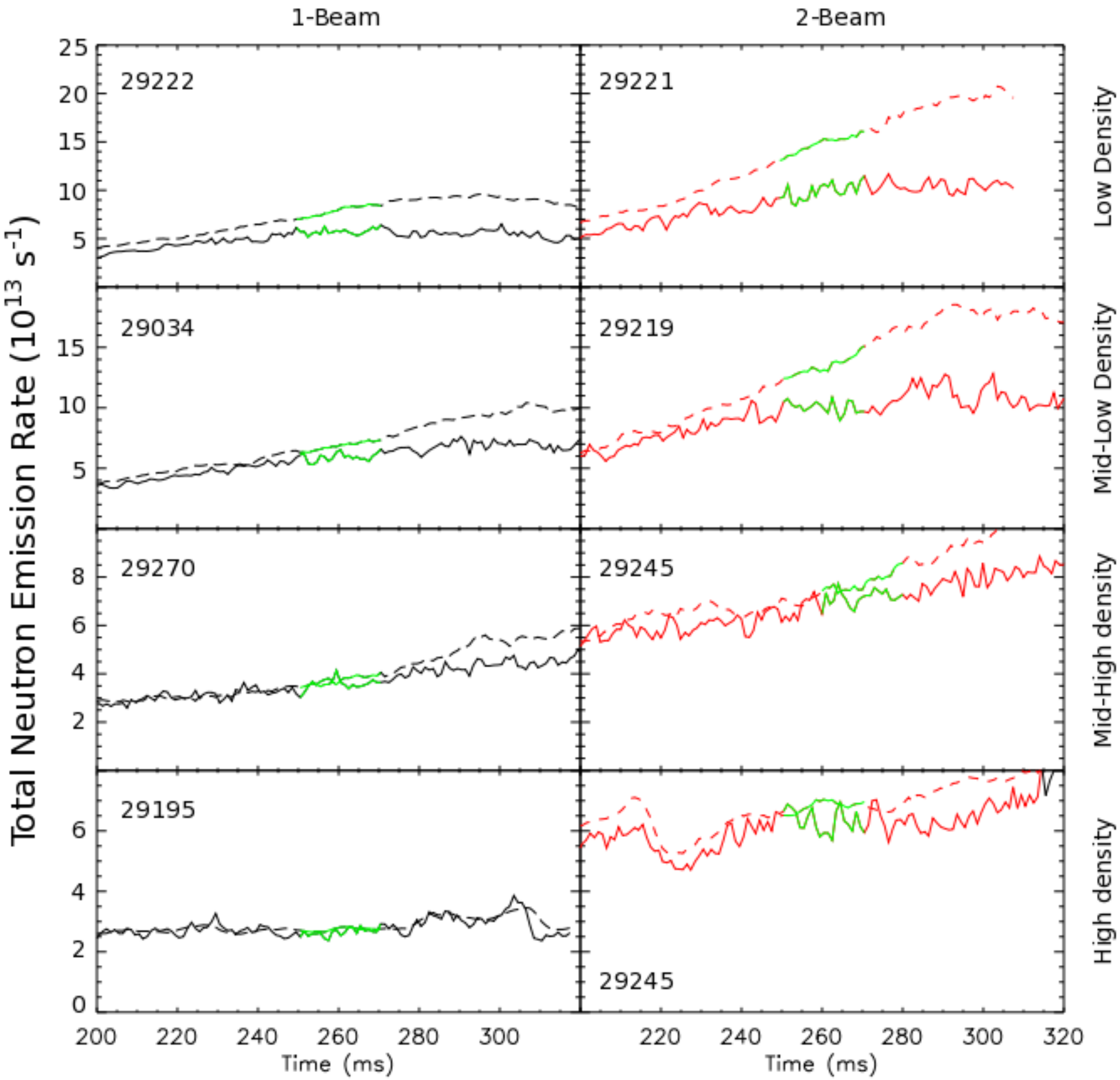
Double Beam-box – original design



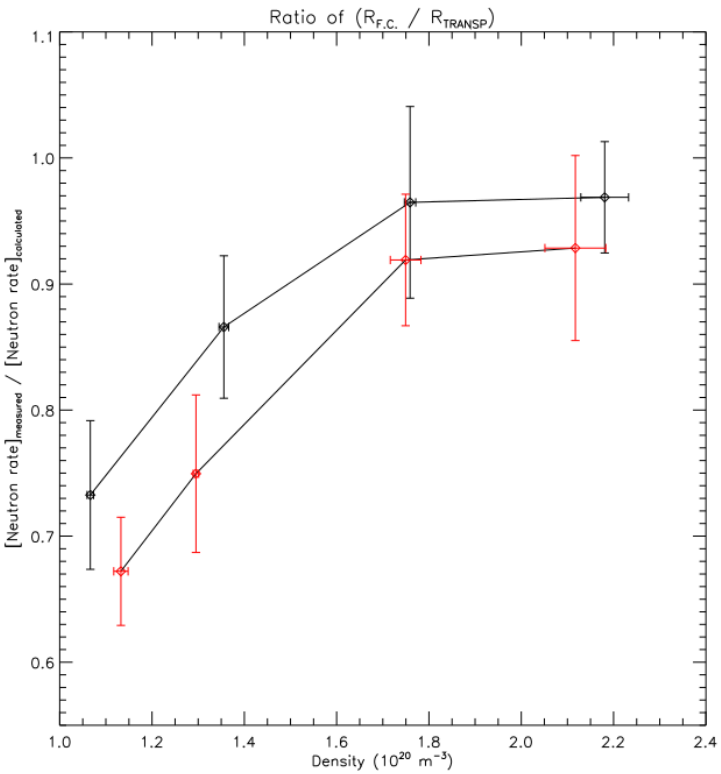
- Current geometry: 2.7 deg lower beam tilt
- Angle dictated by physical size of source body

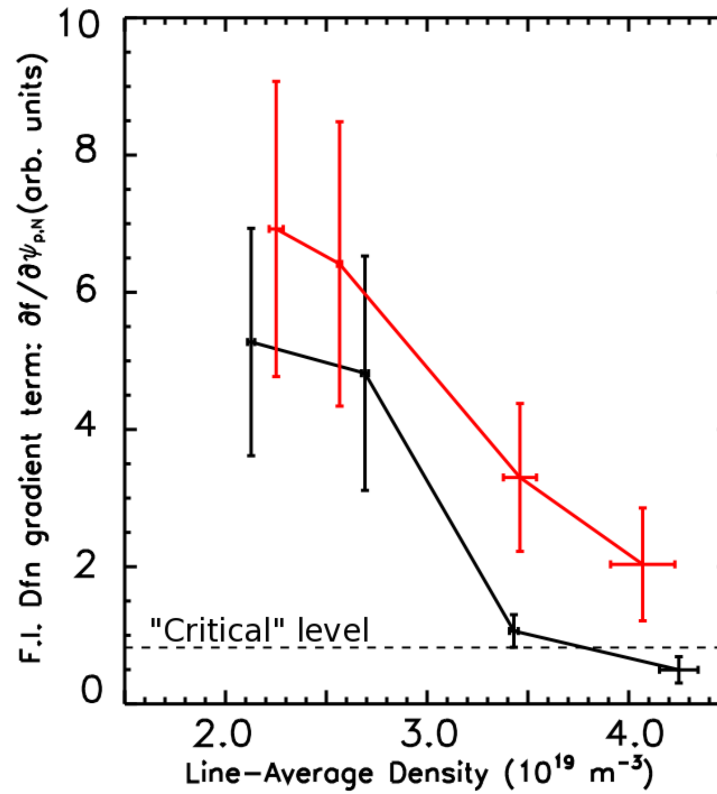
Re-cap: MAST – FI redistribution by fishbones

- A scan in beam power (1/2 PINIs) and density (4 density levels) was executed.
- Neutron emission rate simulated with TRANSP



MAST experimental results from TRANSP

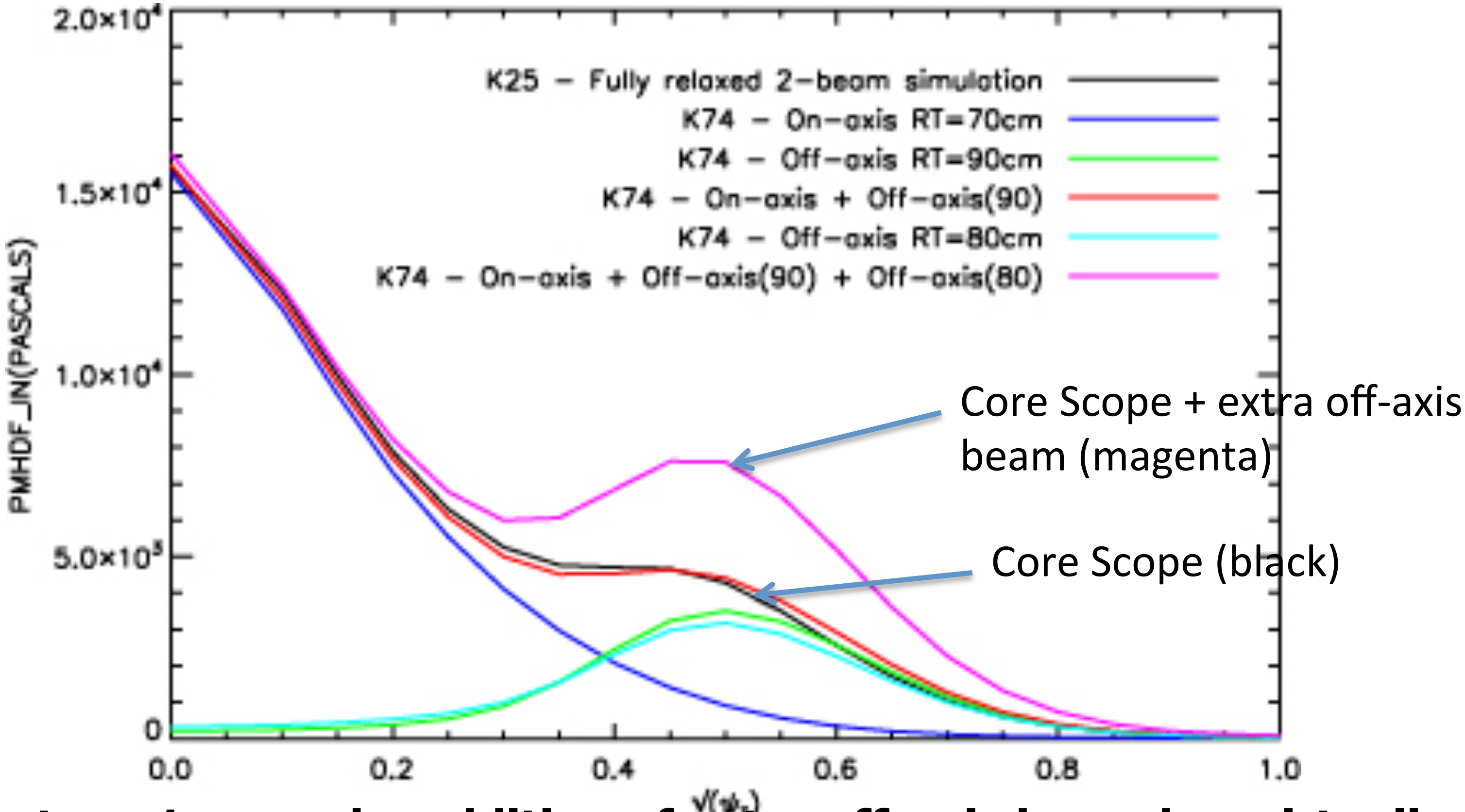




- Experimentally, reduction in observed neutron rate cf. calculated (left) is evidence of detrimental instabilities
- Magnitude of effect well-correlated with FI pressure gradient (right), as expected from theory (see WW Heidbrink, PoP **15** (2008) 055501)

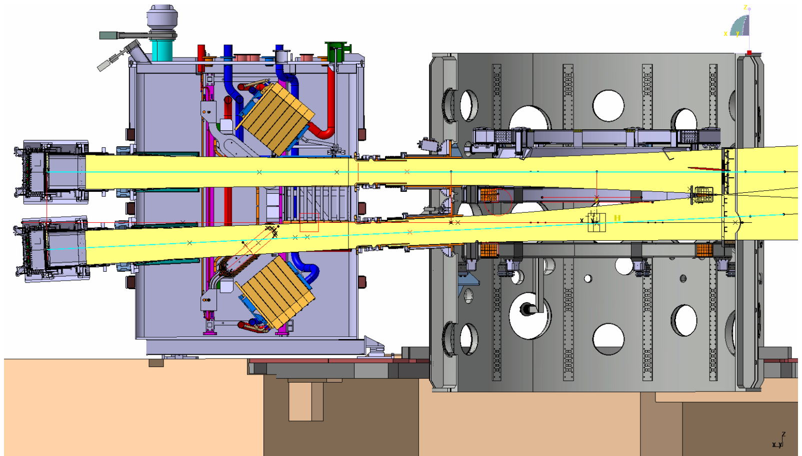
Keeling et al, *Nucl. Fusion* **55** (2015) 013021

DBB – FI pressure gradients

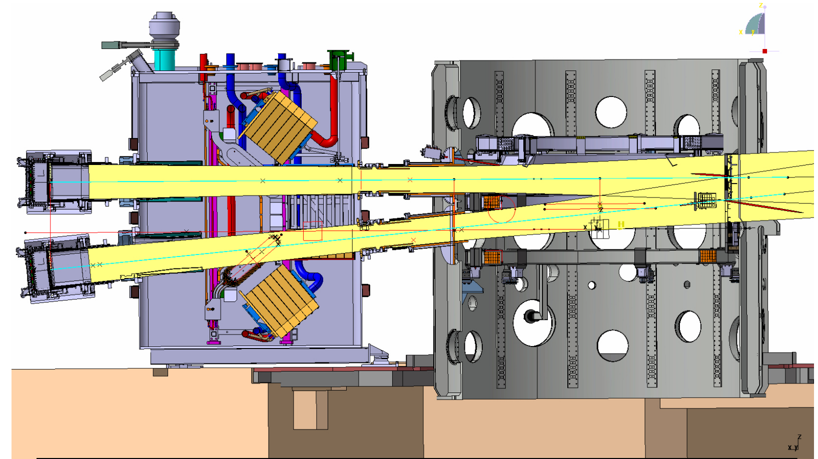


- **In stage 1 upgrade, addition of extra off-axis beam has virtually no impact on maximum FI pressure gradient**
- **Radial FI pressure gradient is energy source for FI driven instabilities (Alfven eigenmodes, fishbones…)**
- **Addition of further on-axis source will lead to larger gradient → larger instabilities**

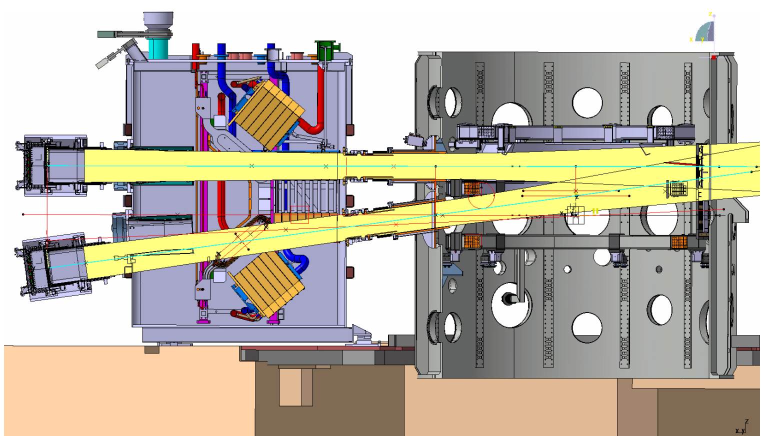
Initial engineering assessments



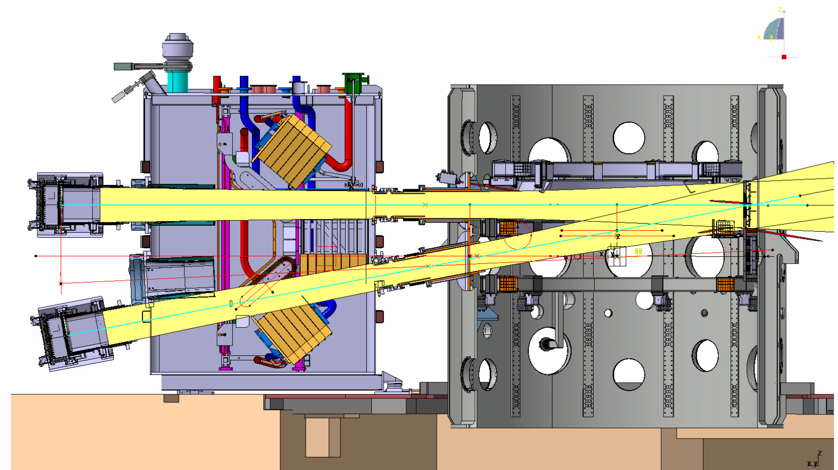
2.7° lower beam tilt



5.5° Option

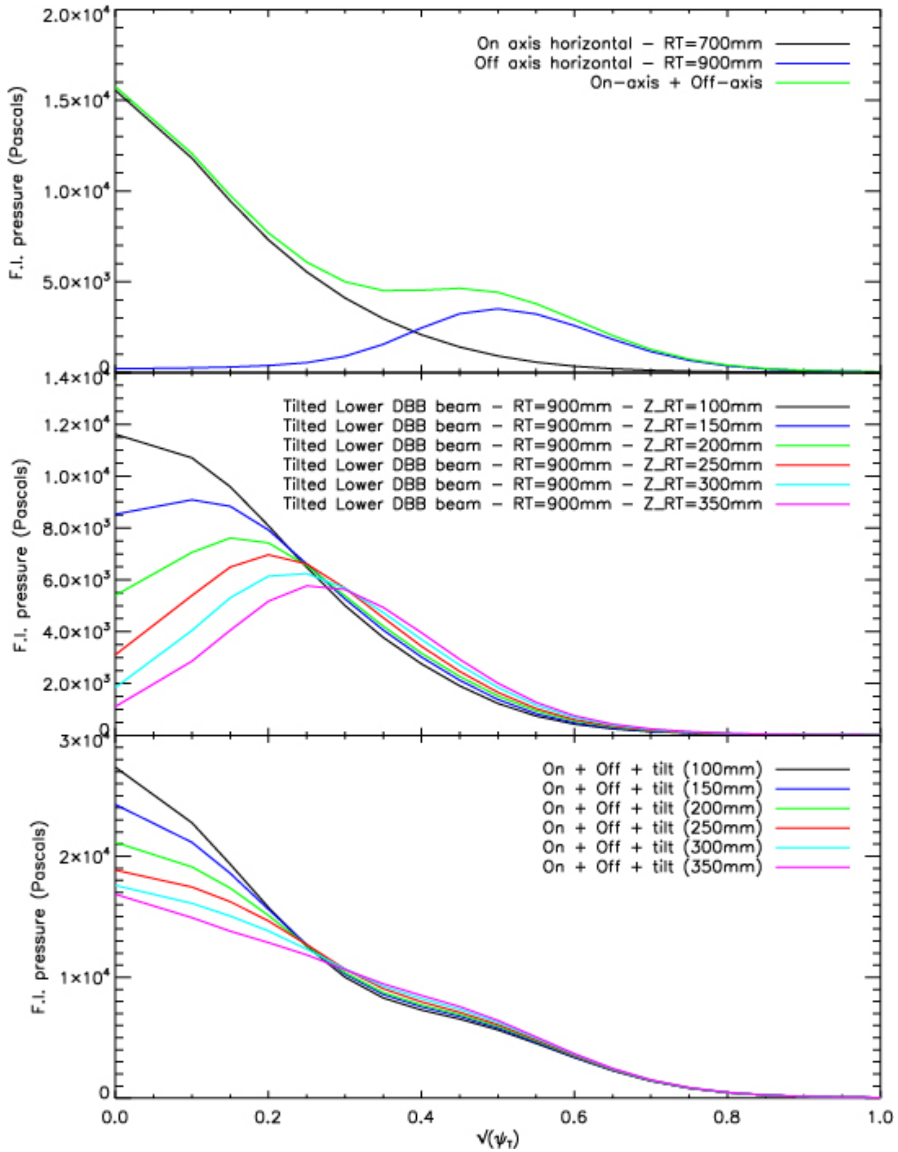


7.8° Option



Maximum,10.8° Option

Intermediate position scan

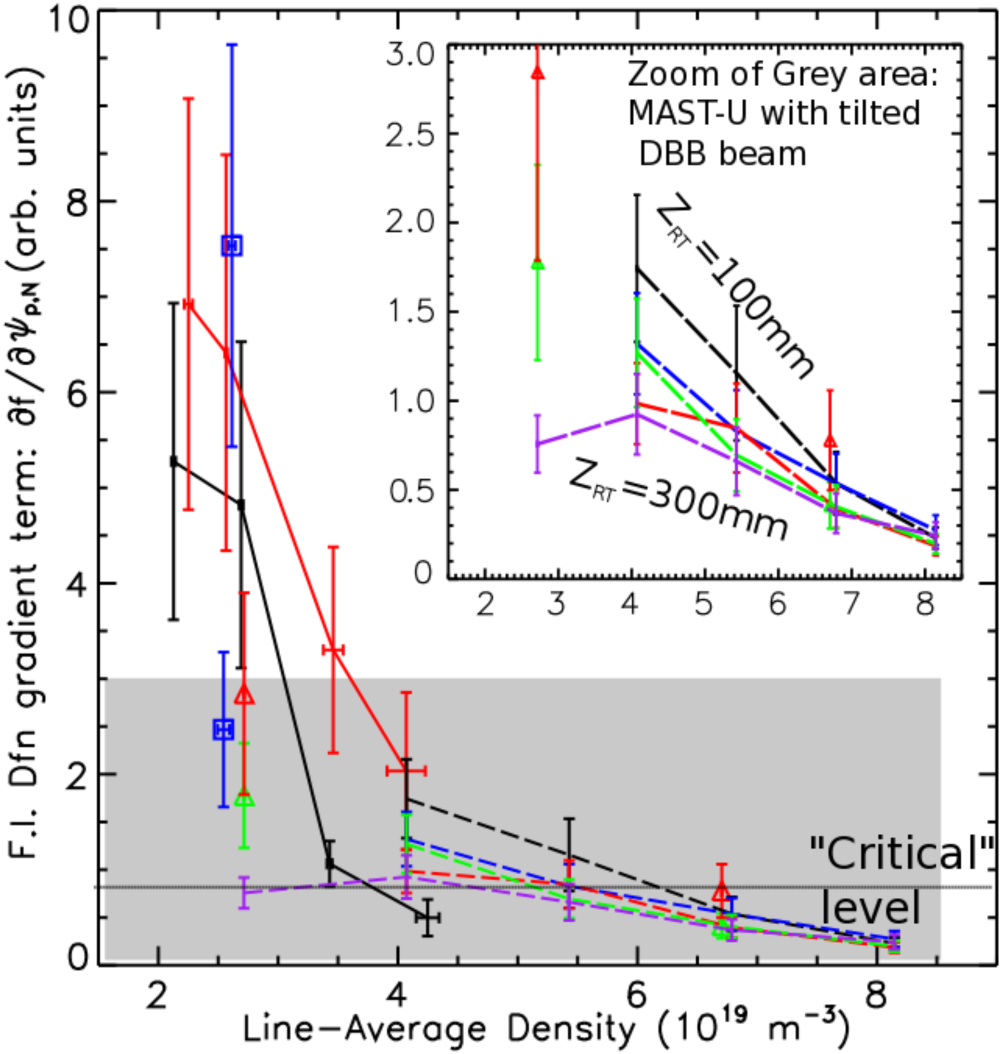


Starting with this…..

… and adding these….

… results in these FI pressure profiles.

Assessing the FI pressure gradient



- **Adding tilted beam to Core-scope beams results in dashed lines**
- **At density 4e19, more than a factor of 2 reduction in FI pressure gradient cf. 2×on-axis MAST beams**
- **At lowest density simulated, large reduction cf. Core-Scope-with-reduced-on-axis-power (green triangle).**

Other considerations

- Along with expected mitigation of FI driven MHD this system allows for flexibility in experiment design
- Intermediate geometry beam allows for tailoring of non-inductive current drive profile and heating profile
- Intermediate beam has lower shine-through fraction than off-axis beam→ more absorbed power, lower risk to in-vessel components.
- Allows access to wider range of experimental parameter space than beams with identical geometry.
- Recently (last few weeks) had funding for stage 1 agreed (EUROfusion + EPSRC, not dependent on Brexit outcome) including DBB and cryoplant

MAST Upgrade Stage 1 Assessment of TEXTOR Beamline

TEXTOR Beams

- A PINI and beamline is available from TEXTOR, possibly to use for later stages of MAST-U
- It is desirable to know:
  - What effect this would have on the plasma in terms of increase of heating power, FI pressure, beam-driven current etc and
  - How this compares to the addition of a PINI mounted in the Double-Beam box
- To give a first indication, comparisons are shown using Scenarios A1 and A2 of
  1. Core Scope scenarios
  2. CS with additional inclined-on-axis PINI
  3. CS with additional off-axis PINI
  4. CS with additional on-axis TEXTOR beam
  5. CS with additional off-axis TEXTOR beam

TEXTOR beamline – Sc A1

Parameter \ Scenario	K25	J73	J85	J86
I_P	0.999 MA	0.999 MA	0.999 MA	0.999MA
B_0	0.785 T	0.785T	0.785T	0.785T
H_{98}	1.02	0.901	1.00	0.990
t_0	48.9 ms	27.3ms	39.6 ms	40.4ms
P_{abs}	4.24 MW	8.30MW	5.63 MW	5.39MW
P_{inj}	5.00 MW	10.0MW	6.63 MW	6.63MW
V_{surf}	0.231 V	0.121V	0.181 V	0.185V
$l_i(1)$	0.692	0.683	0.675	0.660
q_0/ q_{min}/ q_{95}	1.64/ 1.64/ 10.1	2.33/2.14/ 10.6	1.46/1.46/ 10.2	1.85/1.85/ 10.3
d_{95}	0.354	0.366	0.361	0.364
k_{95}	2.48	2.48	2.48	2.48
b_t	7.31%	9.34%	8.22%	7.92%
b_p	1.50	1.89	1.66	1.60
$b_N^{thermal}$	2.51	2.74	2.70	2.64
f_{bs}	0.28	0.3	0.31	0.30
f_{NBCD}	0.14	0.33	0.18	0.18

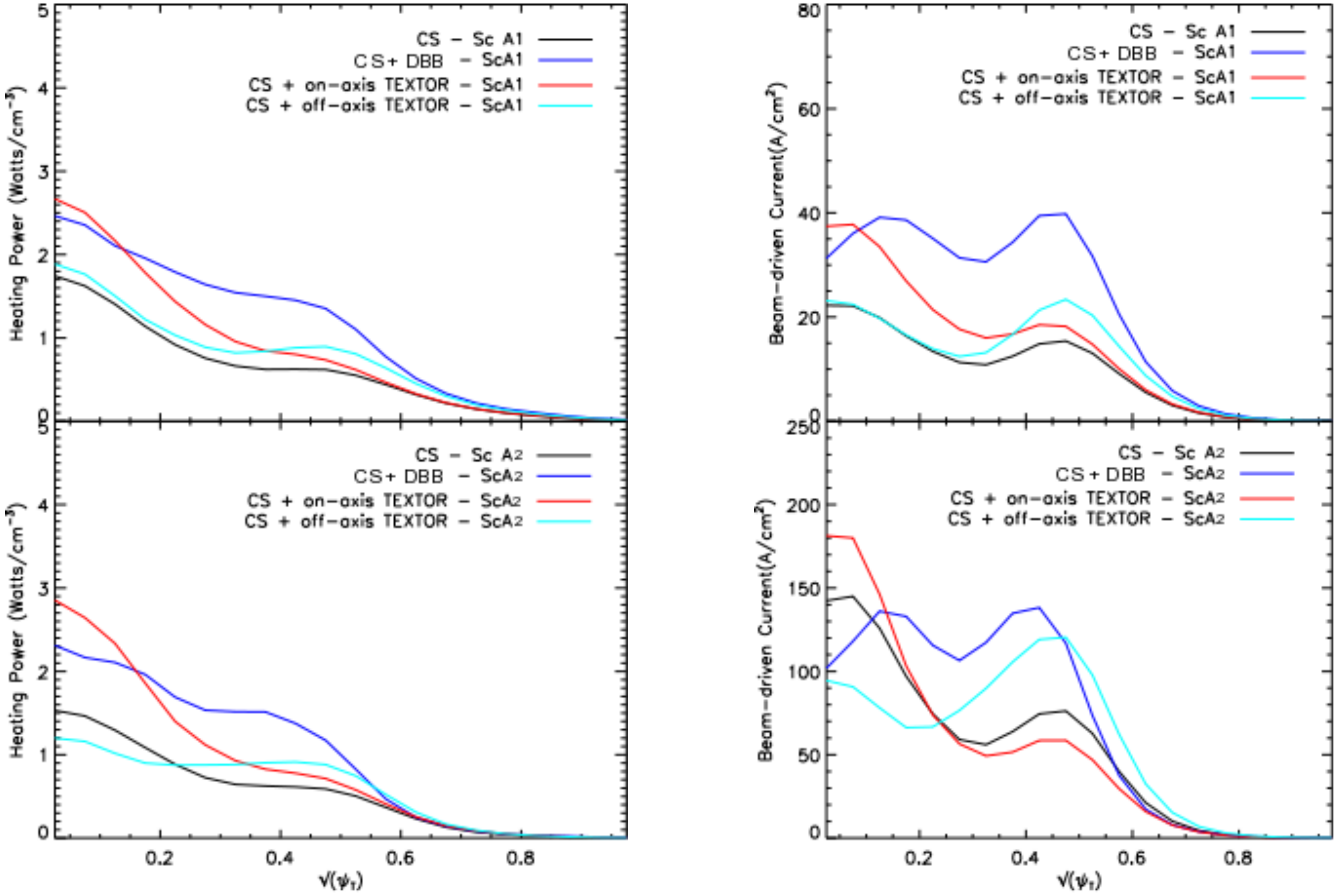
K25 – Core scope
J73 – CS + DBB (1×off, 1×on inclined)
J85 – CS + TEXTOR on-axis
J86 – CS + TEXTOR off-axis

TEXTOR beamline – Sc A2

Scenario / Parameter	K26	J74	J87	J88
I_P	0.999 MA	0.999MA	0.999MA	0.999MA
B_0	0.785 T	0.785T	0.785T	0.785T
H_{98}	0.983	1.19	1.02	0.997
t_0	35.9 ms	30.4	32.5ms	30.9ms
P_{abs}	3.70 MW	7.47MW	5.36MW	4.69MW
P_{inj}	5.00 MW	10.0MW	6.63MW	6.63MW
V_{surf}	0.030 V	-0.088V	0.032 V	-0.035V
$l_i(1)$	0.931	0.781	0.900	0.804
q_0/ q_{min}/ q_{95}	0.801/0.801/ 9.44	3.84/1.98/11.9	0.548/0.548/9.46	1.71/1.71/11.1
d_{95}	0.294	0.384	0.313	0.346
k_{95}	2.48	2.48	2.48	2.48
b_t	9.31%	15.6%	10.3%	11.3%
b_p	2.28	3.24	2.31	2.51
$b_N^{thermal}$	1.60	2.75	2.10	1.75
f_{bs}	0.16	0.28	0.23	0.18
f_{NBCD}	0.66	1.1	0.60	0.91

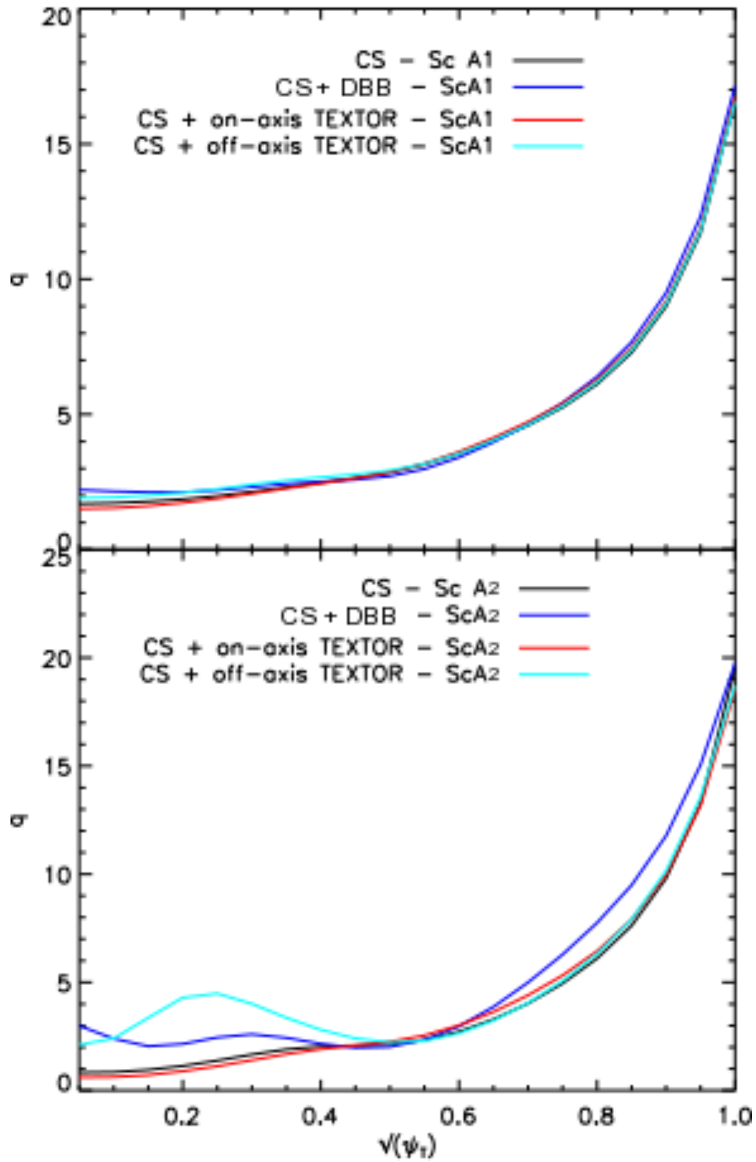
K26 – Core scope
J74 – CS + DBB (1×off, 1×on inclined)
J87 – CS + TEXTOR on-axis
J88 – CS + TEXTOR off-axis

TEXTOR beamline – deposition and NBCD



CCFE
CULHAM CENTRE FOR FUSION ENERGY

TEXTOR beamline – q-profile



So… what's next?

MAST-U needs near-term

- In the near term (12-18 months) there are no specific development needs, MAST team need to concentrate on ensuring TRANSP production runs can be executed
  - Need to resurrect MAST-Chain-Control-Centre (MC^3, data preparation tool) to be compatible with MAST-U data.
  - Train more MC^3/MAST-U TRANSP user
- One possible easy win is to make the fishbone 'kick' operator (as used by Mario Podesta) easily available (if it already is then some instructions for use would be welcome)

MAST-U needs medium-term

- Medium Term (18-24/30 months) - Specific development requirements likely to come out of first experience operating MAST-U
- Possibly inclusion of more synthetic diagnostics (e.g. FILD)
- Install MAST-U into OMFIT (needs local manpower but assistance would be welcomed)
- Use measured global neutron emission as constraint in TRANSP/NUBEAM (e.g. to adjust AFID/fishbone model)
  - Still thinking about this, need to complete a cross-calibration exercise FC/NC/FILD