TRANSP use for MAST data analysis and MAST-U scenario specification

D. Keeling

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Research Councils UK Energy For a Low Carbon Future

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Contents

- TRANSP simulations for turbulence analysis
- Current diffusion studies
- Fast ion redistribution by fishbone modes
- Studies related to MAST-U scenarios and future NB system layout
- Conclusion

TRANSP for gyro-kinetic simulation input

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TRANSP analysis for Gyro-kinetic simulation with TRINITY

Goal:

- Can ETG turbulence explain electron thermal transport in MAST?
- Provide input data for global, gyro-kinetic simulations using TRINITY
- TRINITY transport solver: multiple GS2 simulations of ETG transport
- TRANSP output file provides required input profiles, e.g. $T_{i,e}$, $n_{i,e}$, $Q_{i,e}$, etc
- Aim to compare two cases: with/without anomalous, ion-scale ITG transport, i.e. comparing L-mode (periphery) and H-mode plasmas
- Ion-scale turbulence measurements available on MAST with imaging BES to confirm level of ion-scale turbulence

Preparation:

- TRANSP input files generated using MC^3 (MAST Chain Control Code)
- MC^3 uses MSE constrained EFIT++ (run from MC^3) to map kinetic profiles
- Full suite of world-class, high-resolution diagnostics on MAST (TS, CXRS, Bremstrahlung imaging for Z_{eff}, linear D_α camera, etc)

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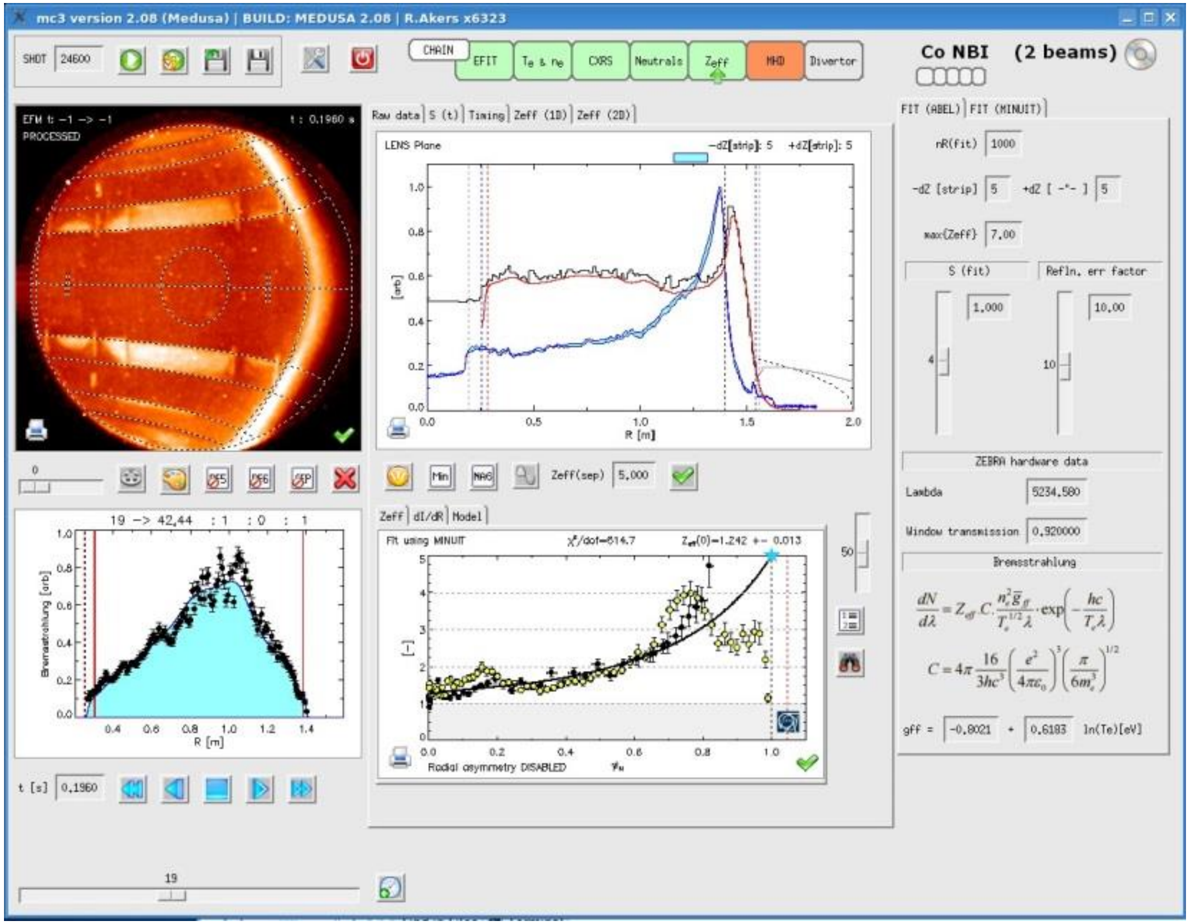
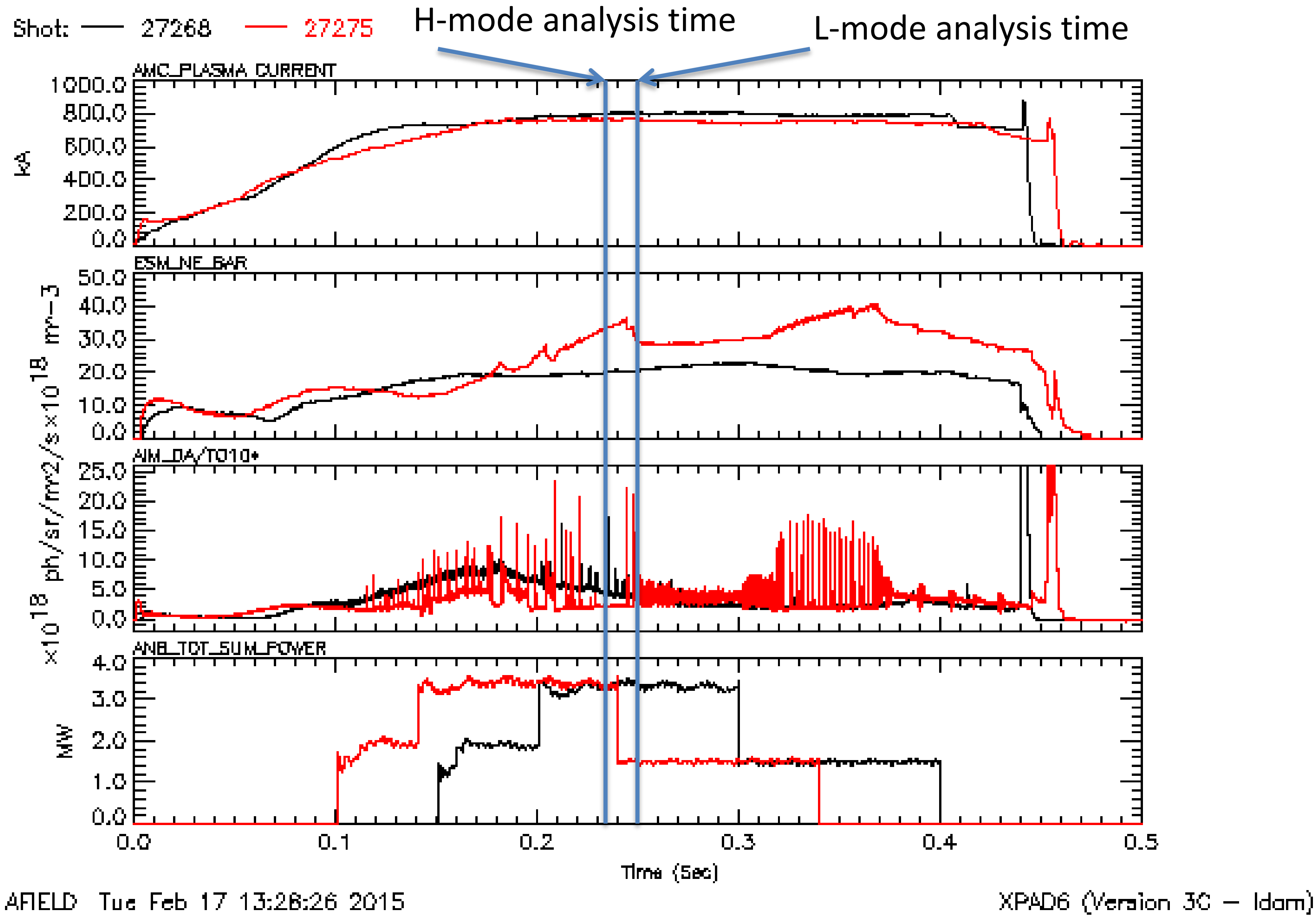
MAST Chain-Control Centre (MC^3)



- Integrated analysis chain prepares TRANSP input data
- Re-runs EFIT++, including pressure and MSE constraints
- Profile fitting of TS…
- …CXRS, etc, including rotational asymmetry
- Z_{eff} from analysis of visible bremsstrahlung imaging (ZEBRA)
- Neutral source from analysis of D_{α} emission profile (LINCAM)

Target L & H-mode discharges



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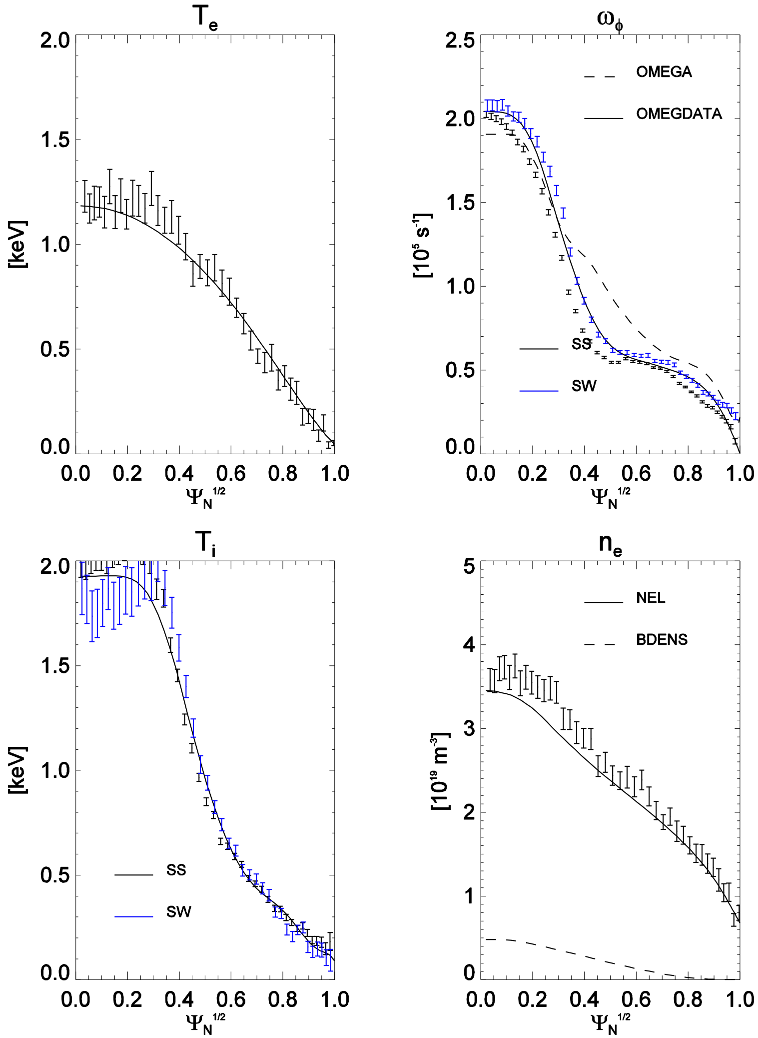
Kinetic Profiles

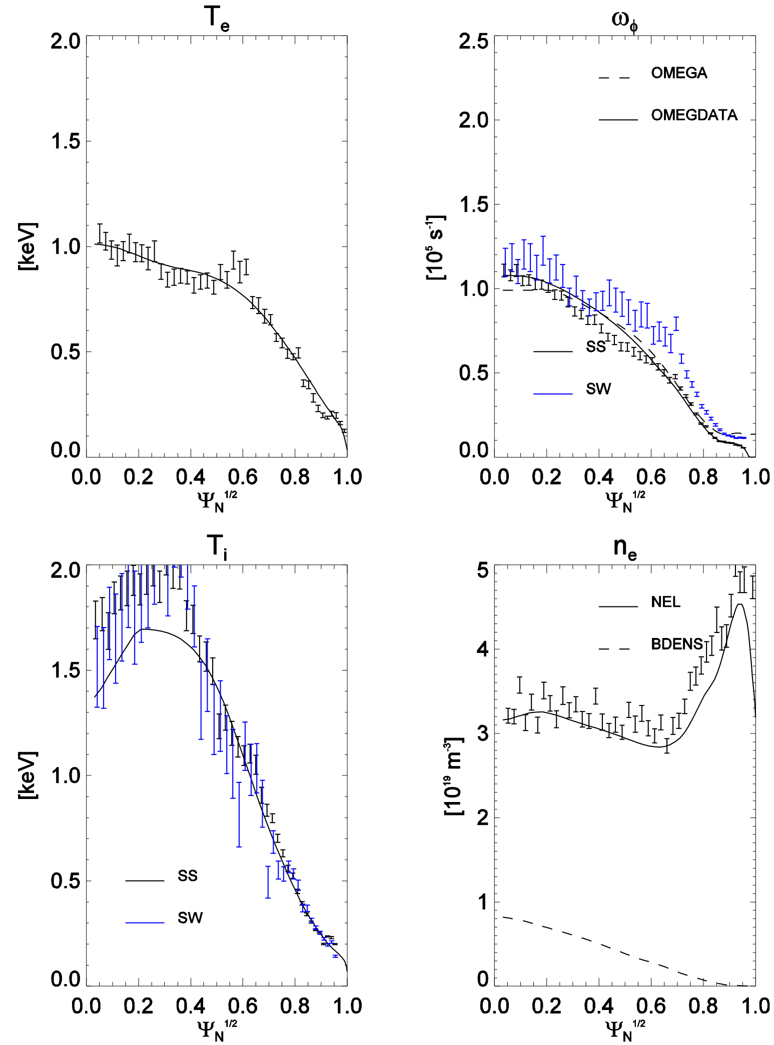
L-mode

MAST TRANSP Data: Shot #27268, Run F13, 0.250 s

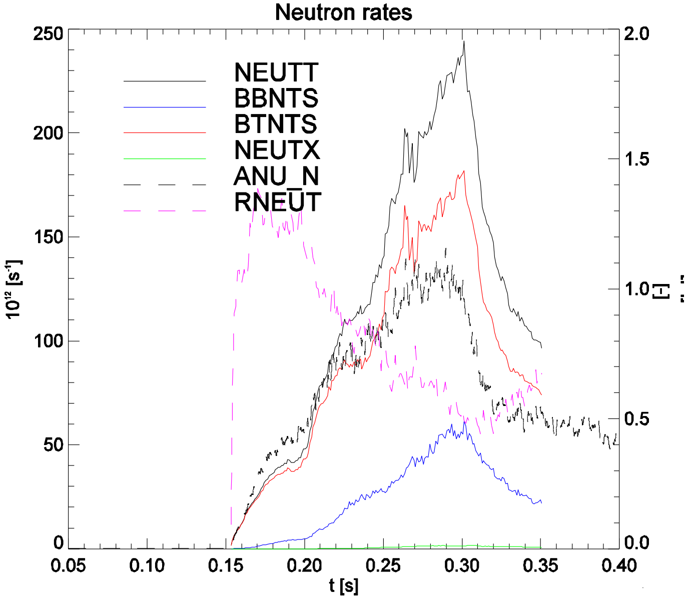


H-mode

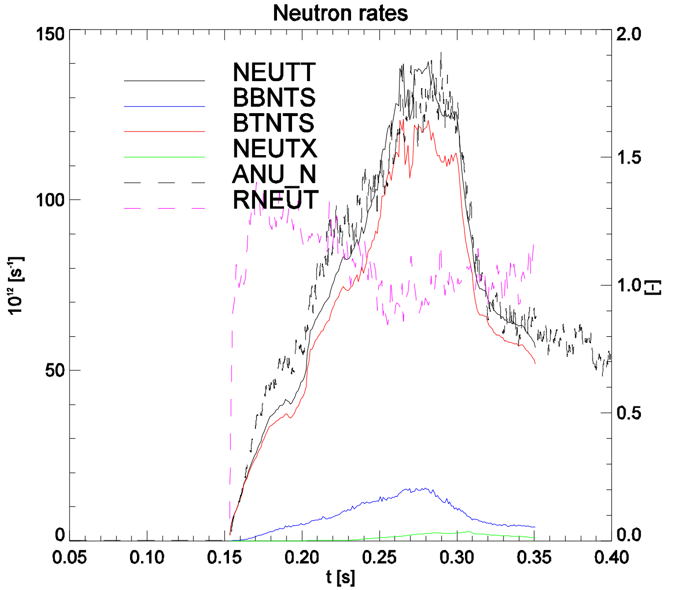
MAST TRANSP Data: Shot #27275, Run F06, 0.235 s



Data consistency – FI losses



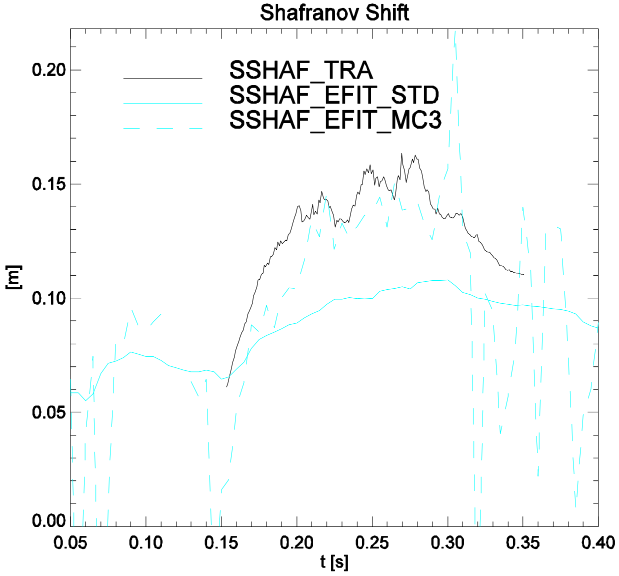
#27268: F01, classical F.I. dynamics



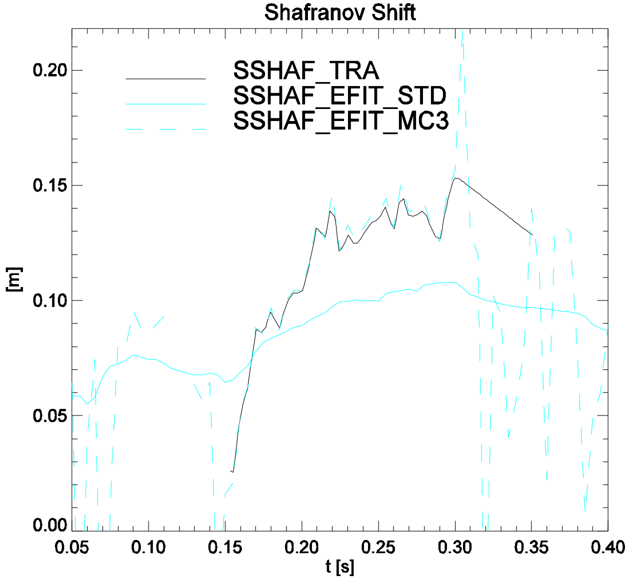
#27268: F02, including anomalous FI diffusion (~2m²/s)

- Fast-ion MHD fishbone modes drive significant anomalous fast ion-losses
- Modelled by invoking D_{FI} ~ few m^2/s
- 'Diagnostics' for FI pressure are:
  - Total neutron rate, R_N
  - Plasma pressure, W_{MHD}
  - Shafranov shift, R_{Sh}

Data consistency – FI losses



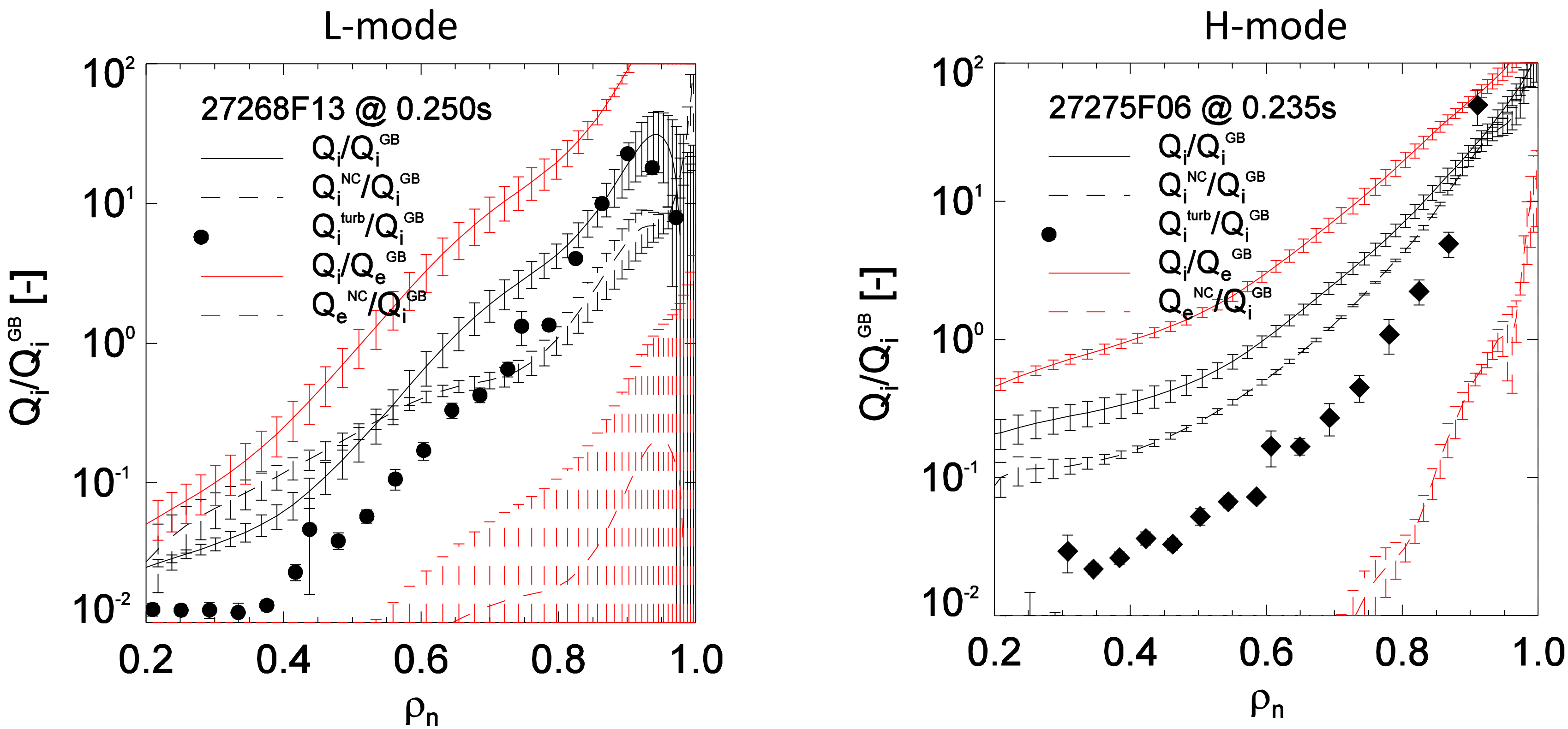
#27268: F02, including anomalous FI diffusion (~$2 m^2/s$)



#27268: F13, using pressure/MSE constrained EFIT eqm.

- Use MSE constrained EFIT++ equilibria so R_{Sh} is determined
- EFIT++ consistently underestimates W_{MHD}
- Best match achieved to R_N with:
  1 beam: D_{FI} ~ 1 m^2/s; 2 beam: 2 m^2/s
- D_{FI} strongly affects beam heating hence derived power fluxes $Q_{i,e}$
- Runs use 10k M.C. particles in NUBEAM

Comparison with turbulent heat flux



- Turbulent ion heat flux can be estimated from BES data:

$$\tilde{Q}_{i,BES}/Q_{i,GB} \sim k_y \rho_i \left(\frac{T_e}{T_i}\frac{\delta n_e}{n_e}\right)^2 \left(\frac{R}{\rho_i}\right)^2$$

See: Field *et al* PPCF **56** (2014) 025012

- In L-mode, $Q_i/Q_{i,NC} > 1$ in plasma periphery, where $\tilde{Q}_{i,BES} \leq Q_{i,PB}$
- In H-mode, $Q_{i,PB}$ is within a factor 2-3 of $Q_{i,NC}$ across the whole profile

Current diffusion studies

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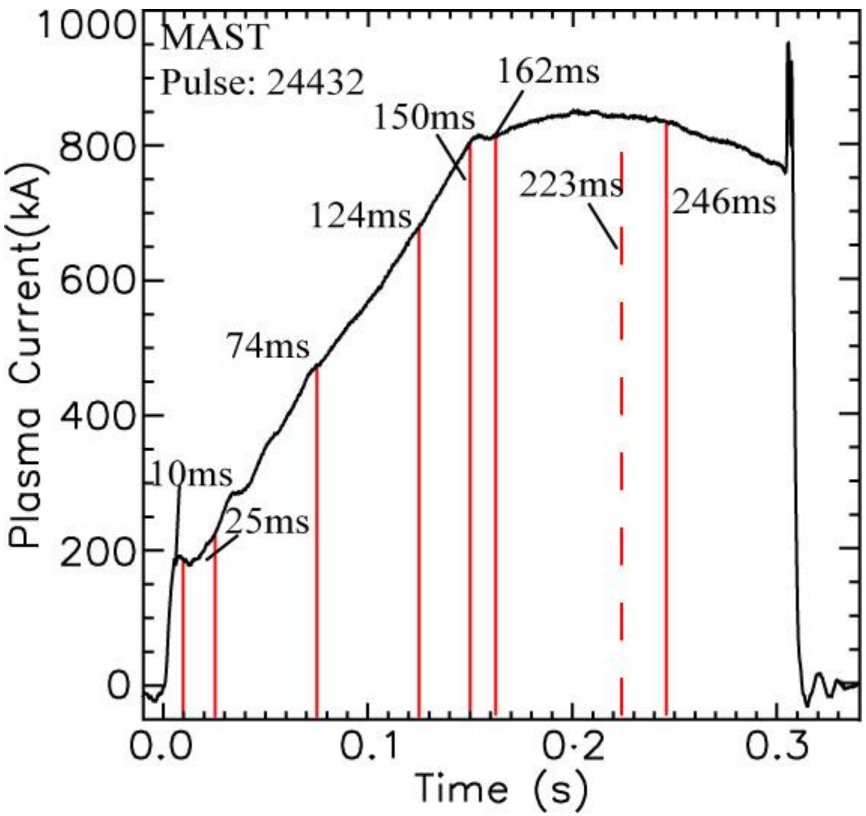
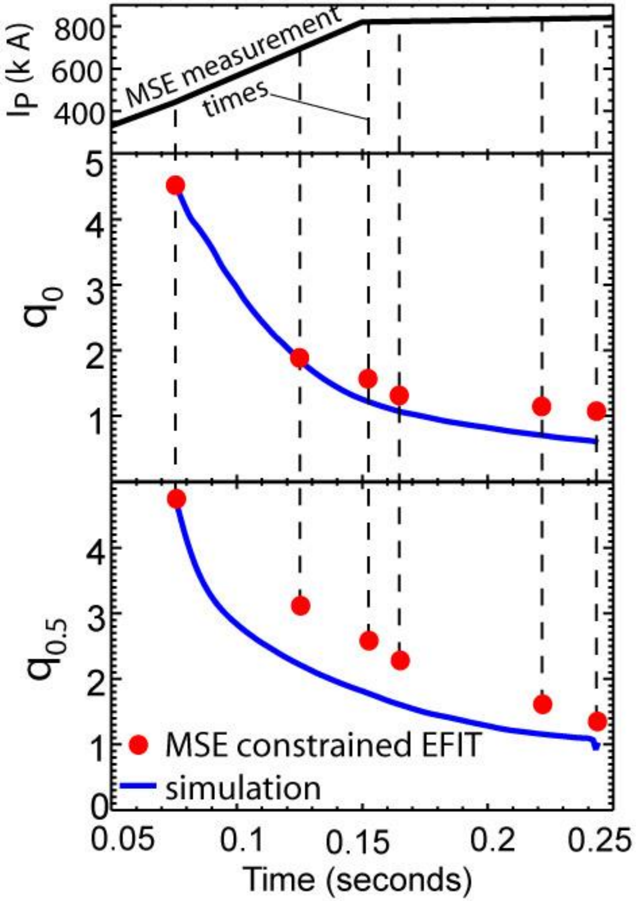
Test of current diffusion modelling in current ramp-up

- Specific experiment carried out in campaign M7 making use of newly commissioned MSE system.
- Series of MSE "snapshots" taken of an ohmic plasma current ramp using many repeated shots:



D. Keeling, EPS 2011



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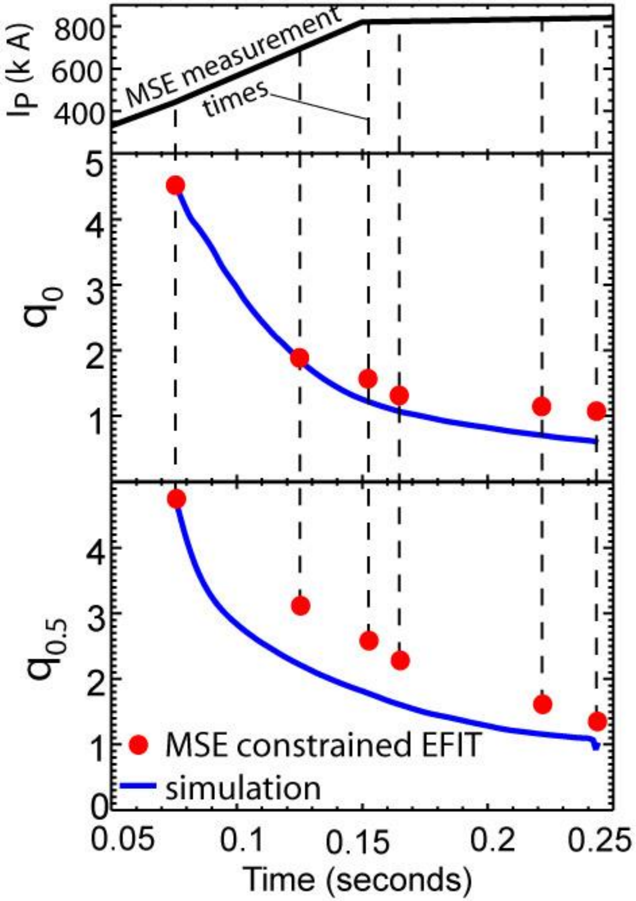
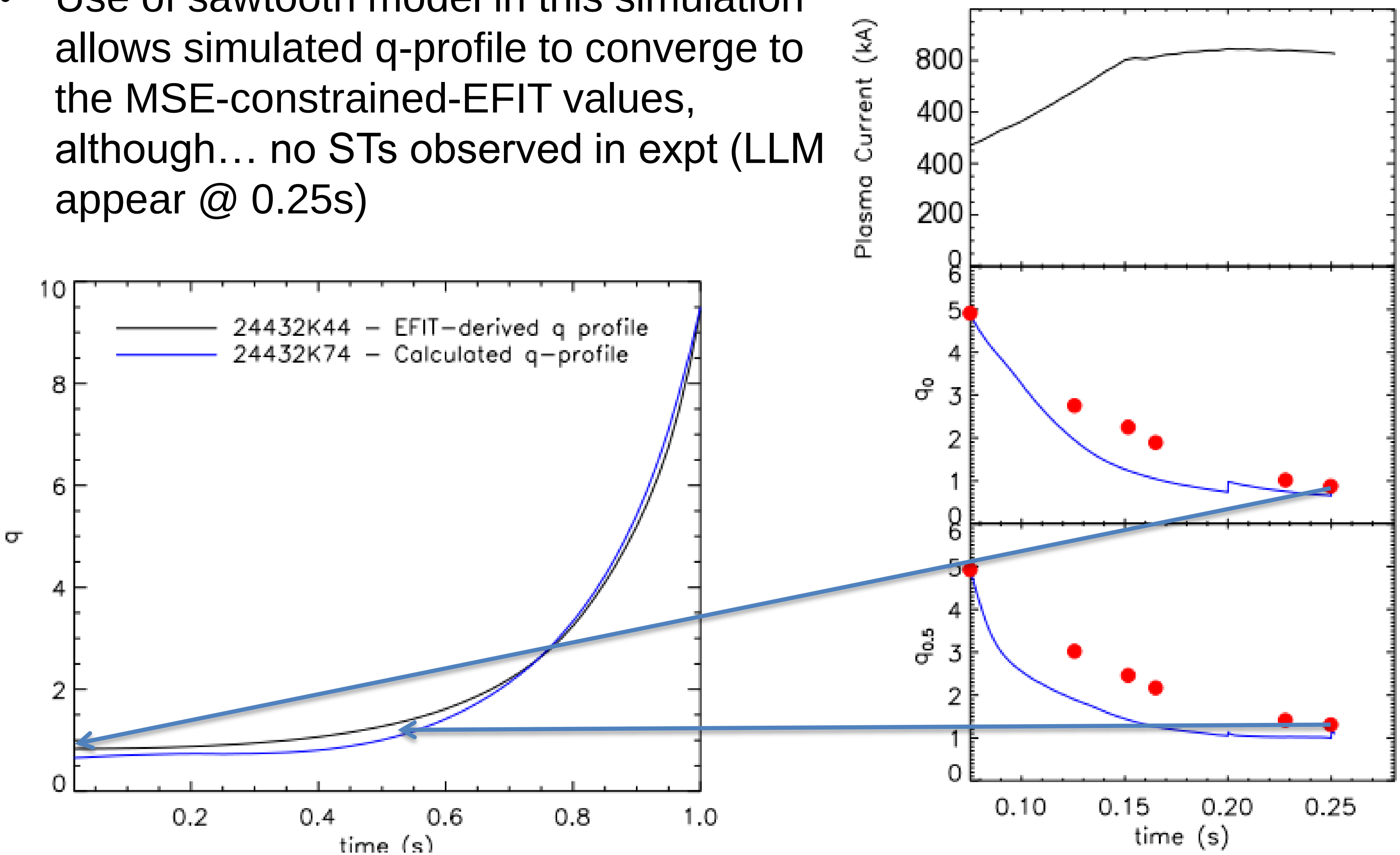


- q_0 initially modelled quite well but starts to diverge after t=0.162ms as q_0 passes below 1.
- $q_{0.5}$ diverges rapidly at start of simulation due to rapid inward current diffusion but starts to converge again later on as current diffuses deeper into core.

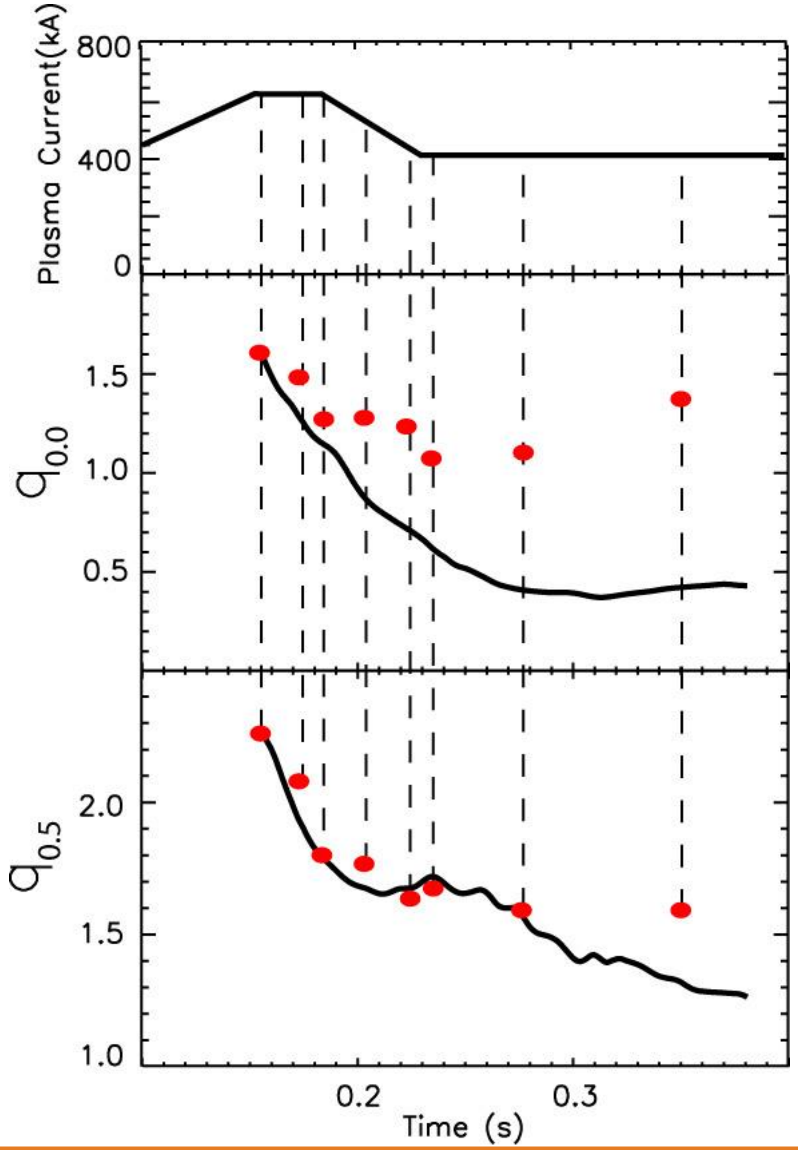
Test of current diffusion modelling in current ramp-up

- Use of sawtooth model in this simulation allows simulated q-profile to converge to the MSE-constrained-EFIT values, although… no STs observed in expt (LLM appear @ 0.25s)



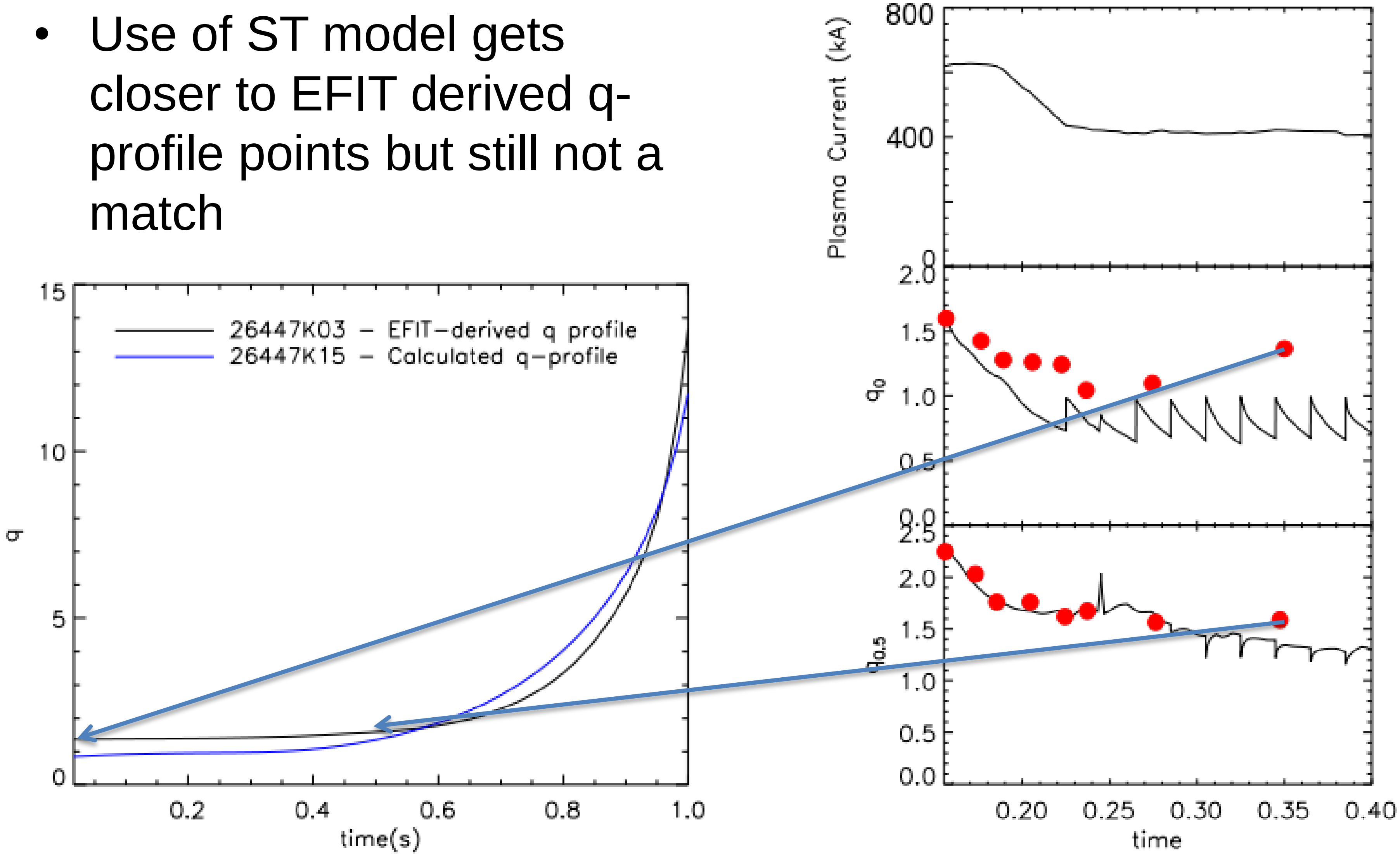
Test of current diffusion modelling in current ramp-down

- Same technique used to investigate Ip ramp-down during campaign M8.
- This time, current at psiN~0.5 modelled well initially and getting worse after ramp
- q_0 diverges rapidly from start value dropping below 1 soon after start of simulation and remains below 1 (no sawtooth model used)
- LLM appear at 0.235s, STs from 0.27s (~150Hz)



Test of current diffusion modelling in current ramp-down

- Use of ST model gets closer to EFIT derived q-profile points but still not a match



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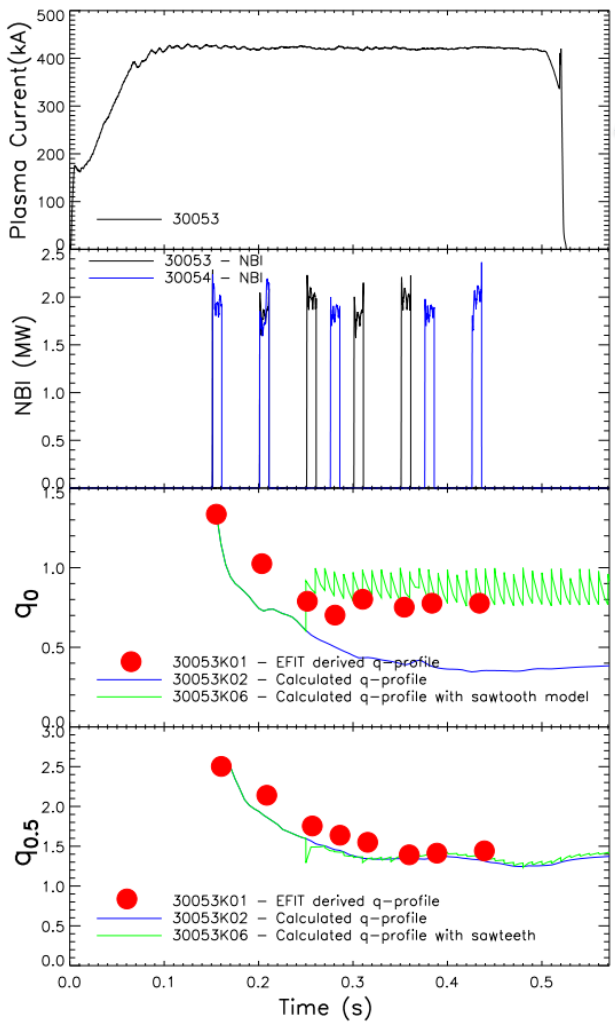
Implications for MAST-U baseline scenarios

- MAST-U baseline scenario performance has been based on a series of interpretive TRANSP simulations with the following features:
  - n_e/T_e profile shapes based on NSTX-like H-mode.
  - $n_{e,0}$ chosen to match particular Greenwald fraction, $T_{e,0}$ chosen to produce $H_{98}(y,2)$~1
  - NBI geometry chosen to give most control over q-profile through particular NB current-drive profiles.
  - Plasma boundary from FIESTA equilibrium using MAST-U PF coil set.
  - Full TF (0.785T)
  - Simulations run to 5s simulation time to allow full relaxation of current profile.
- The big question: given the uncertainty in modelling q-profile *evolution* in MAST, is this technique sufficient to give us confidence that the MAST-U baseline scenarios represent a reasonable prediction of likely MAST-U performance?

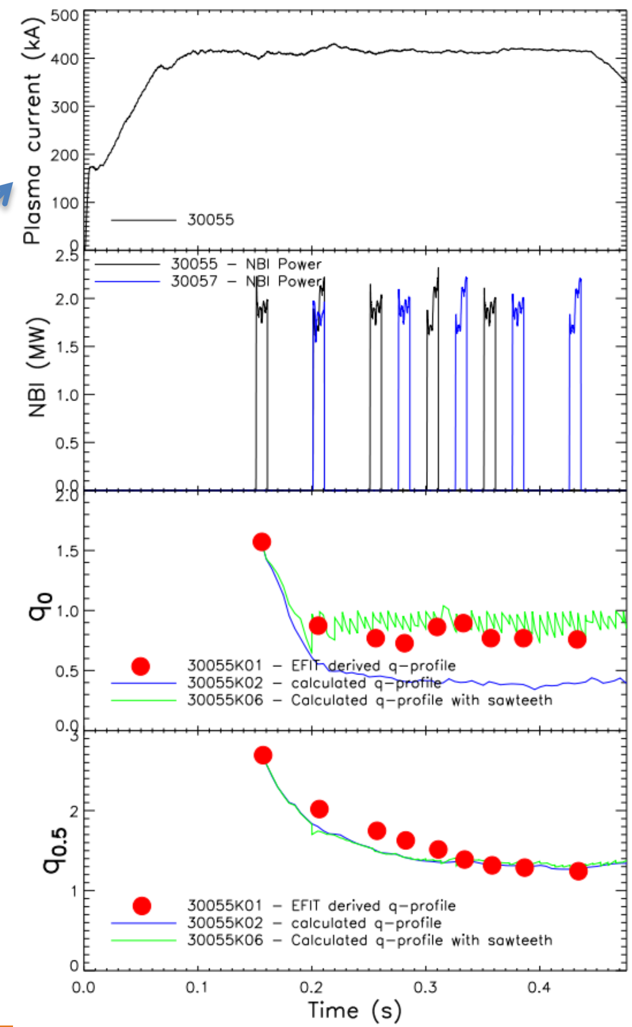
TRANSP modelling of stationary state

- Experiments carried out to measure q-profile in stationary state. TRANSP modelling carried out using Sauter neoclassical resistivity, with and without sawtooth reconnection model



Low density

High density



In both cases, q-profile match is achieved after ~200ms of simulation time using neoclassical resistivity and the sawtooth model

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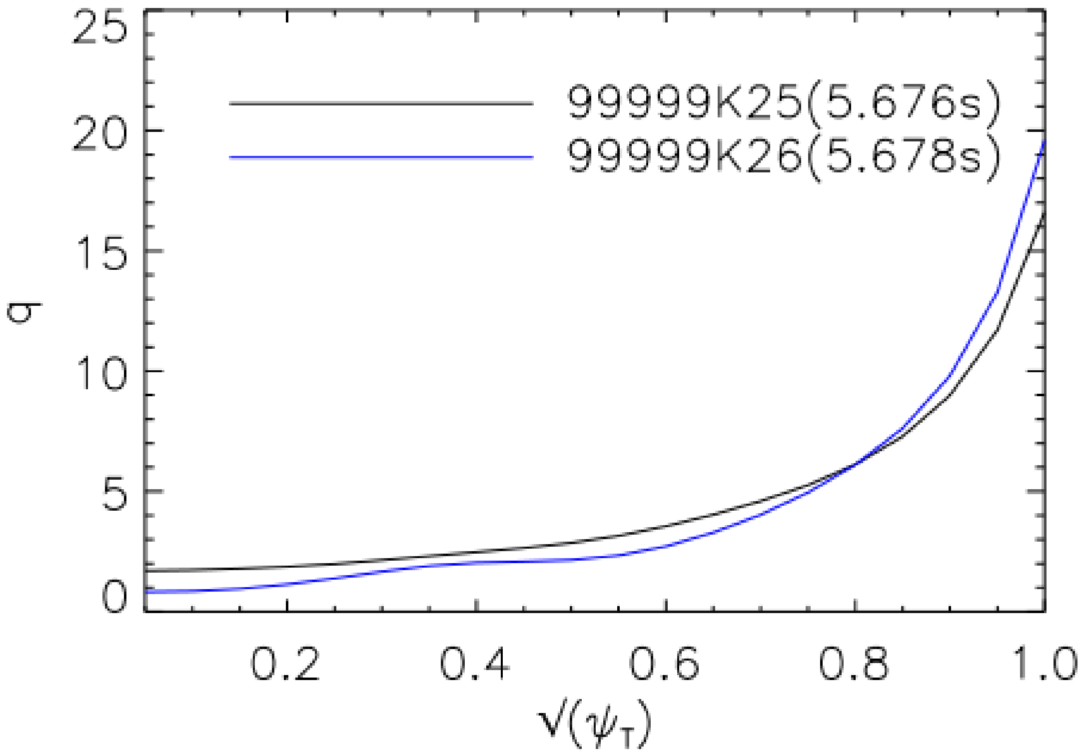
Baseline scenarios – q-profiles

- 2 baseline scenarios are of particular note: Scenario A1 (n_{GW}/n ~0.58) and scenario A2 (n_{GW}/n ~0.23).
- q-profiles in the core-scope versions of these runs indicate that (in the absence of Anomalous Fast-Ion Diffusion, i.e. redistribution by MHD), q=1 surface should be avoidable or of minimal extent:



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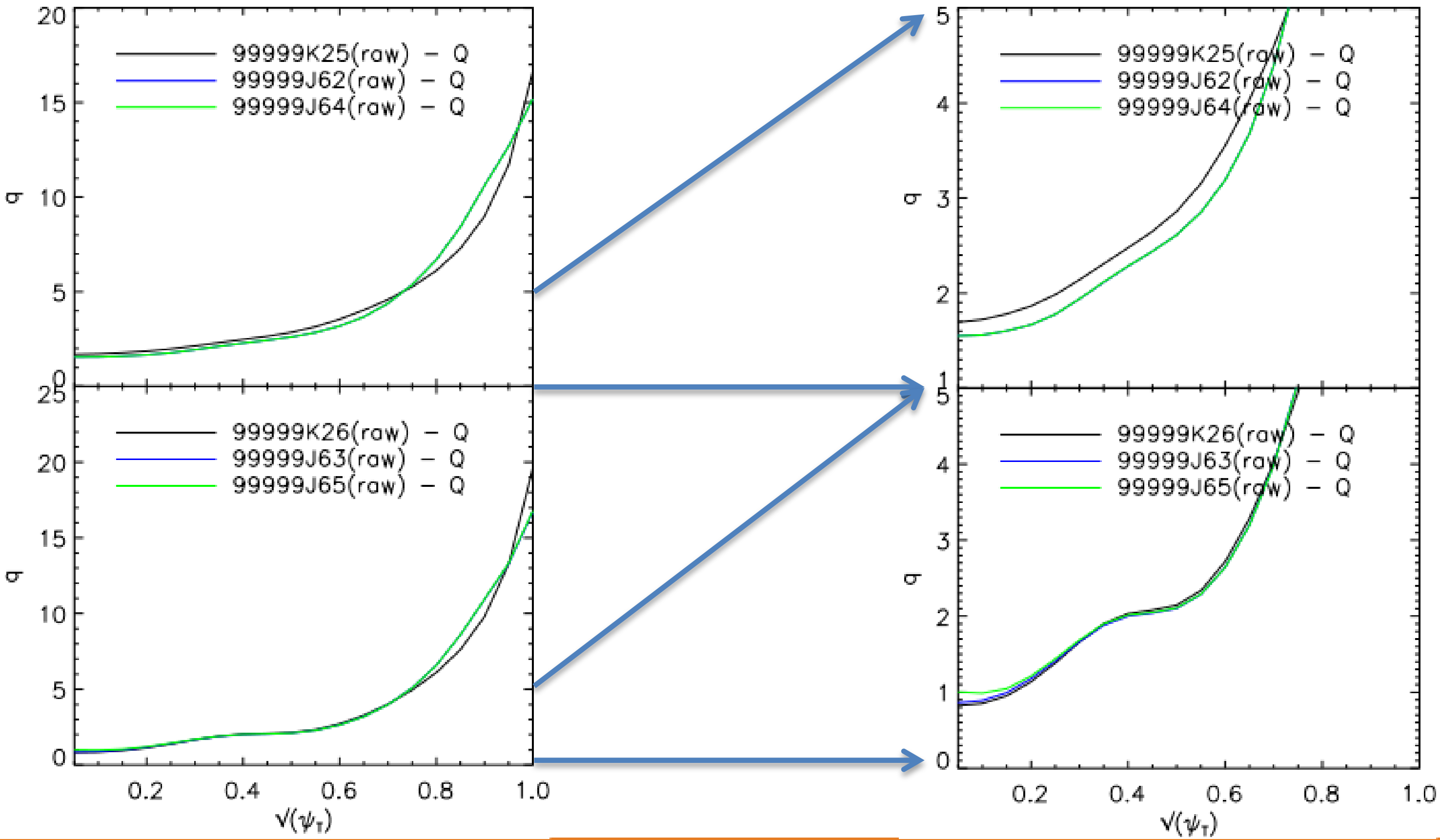
Baseline scenarios with/without sawtooth model

- Successful stationary state interpretive MAST simulations required use of sawtooth model.
- Simulations re-run with MAST H-mode kinetic profiles (shot 22788/315ms) – blue lines, small effect in Hi n_e scenario
- … and again with Kadomtsev sawtooth model – green lines, small effect in Lo n_e scenario

Hi n_e

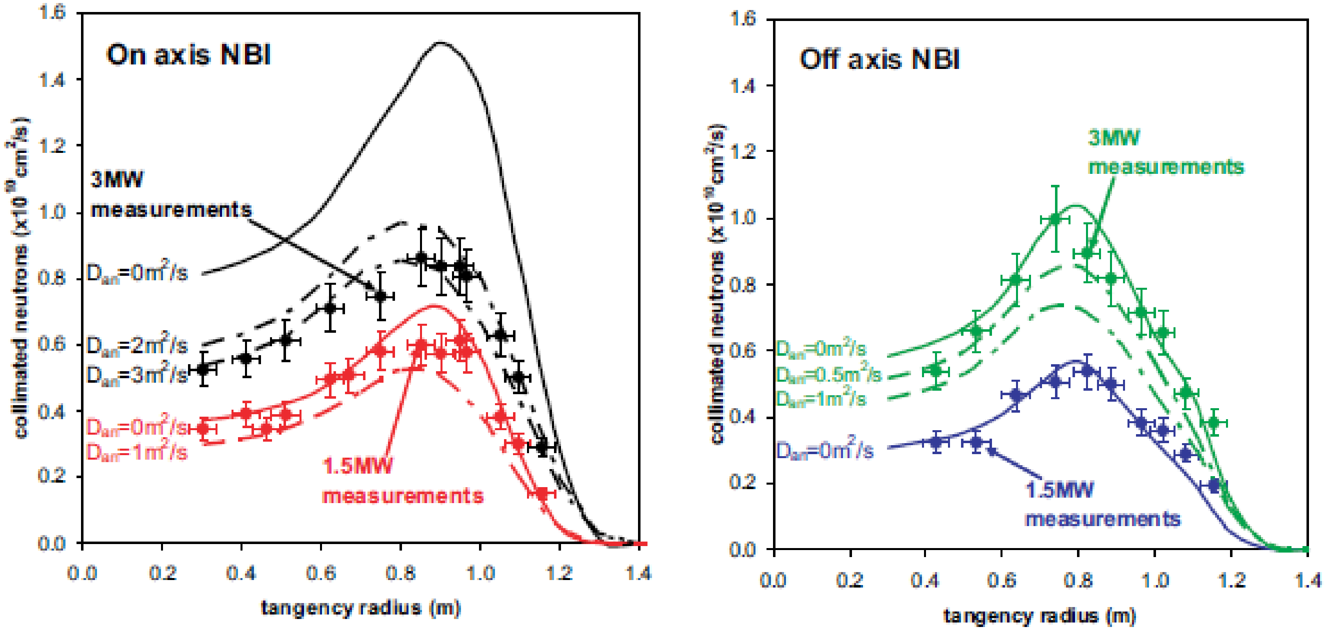
Lo n_e



FI redistribution by fishbones

Background - Experiment

- Low power or off-axis NBI found to mitigate the FI redistribution/expulsion



*Turnyanskiy *et al* (2013)

- Graphs* show:
  - At low power, neutron emission prediction matches measurements -> no FI redistribution.
  - At high power on axis injection, neutron emission prediction much higher than measurements -> FI redistribution.
  - At high power off-axis, neutron emission prediction close to measurements -> FI redistribution mitigated.

Background - Theory

- The growth rate of fishbone modes is related to gradients in the FI distribution function[1,2]:

Fishbone mode growth rate

$$\gamma \propto \omega \frac{\partial f_{FI}}{\partial E} - n \frac{\partial f_{FI}}{\partial P_{\varphi}}$$

Energy gradient

Gradient w.r.t. canonical angular momentum

Energy gradient-> negative -> damping term

approximate

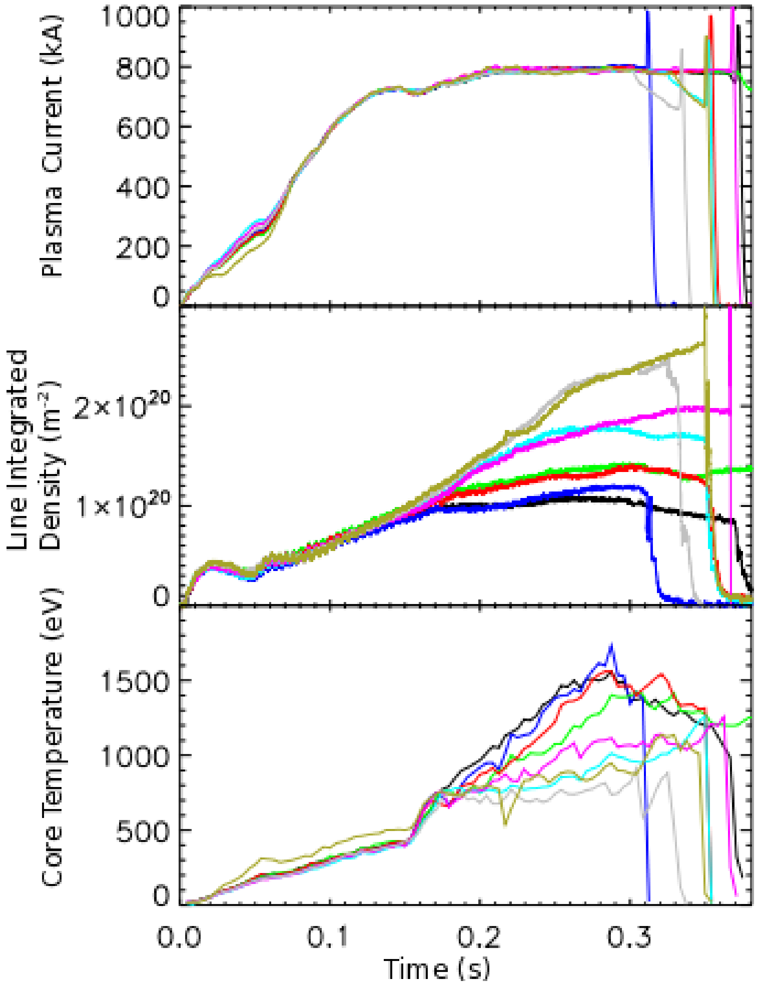
Canonical angular momentum

$$P_{\varphi} \approx \cancel{mR}v_{\varphi} + e\psi$$

Radial gradient -> negative -> driving term

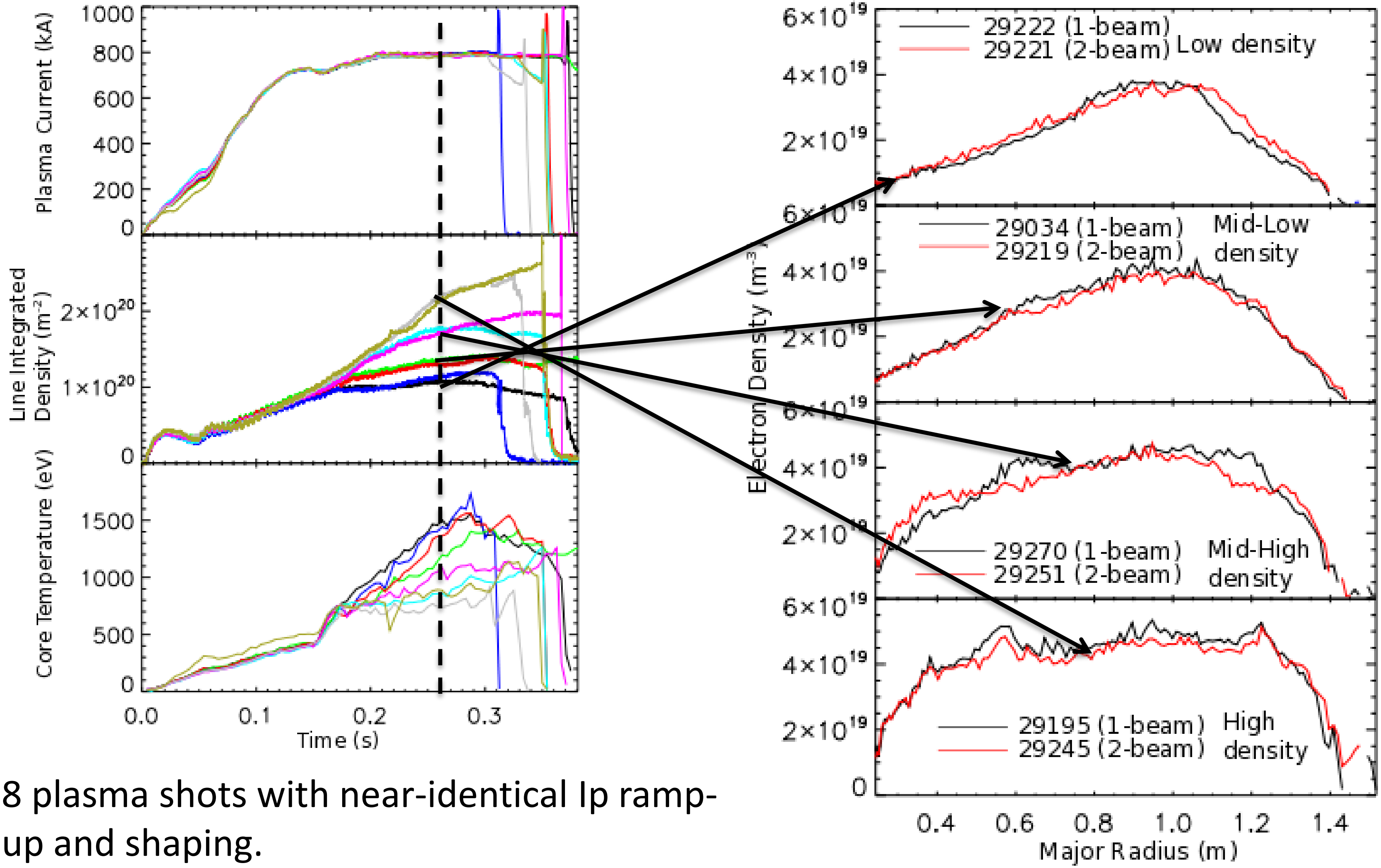
[1]Chen L. *et al* 1984 *Phys. Rev. Lett.* **52 (13)** 1122, [2]Heidbrink W.W. 2008 *Phys. Plasmas* **15** 055501

Density/Power scan



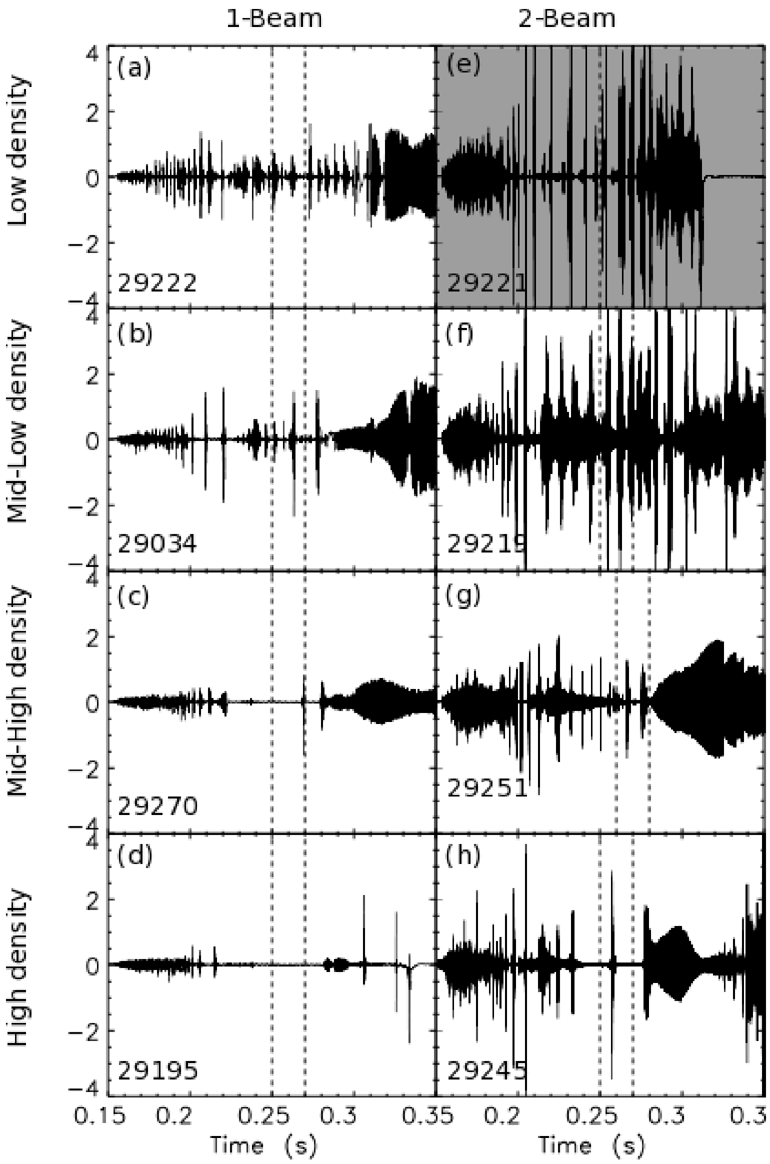
8 plasma shots with near-identical Ip ramp-up and shaping.

Density/Power scan

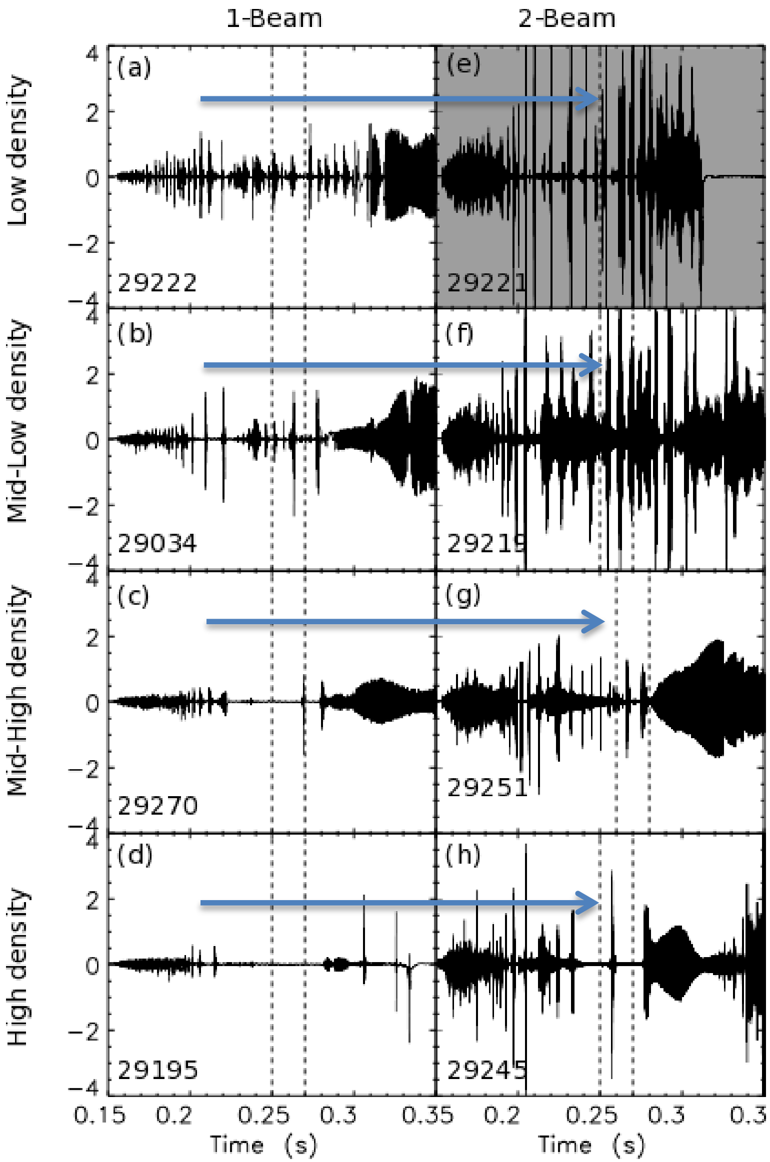


8 plasma shots with near-identical Ip ramp-up and shaping.

MHD activity

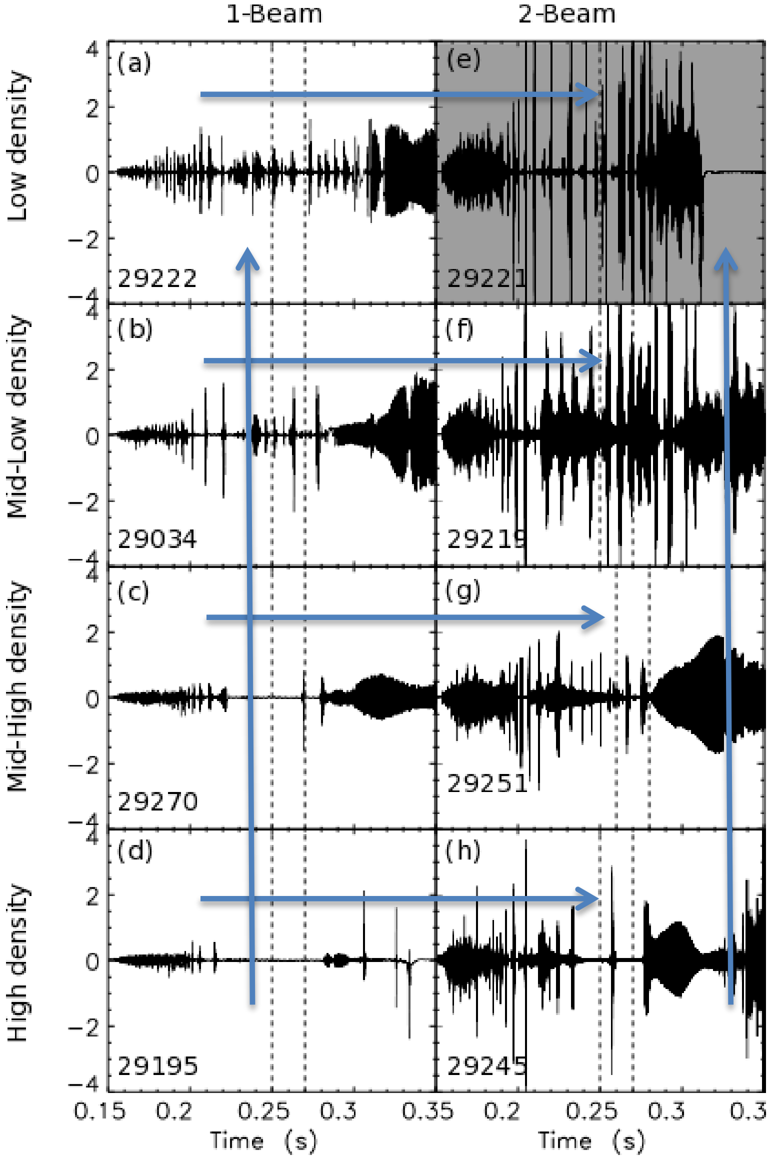


MHD activity



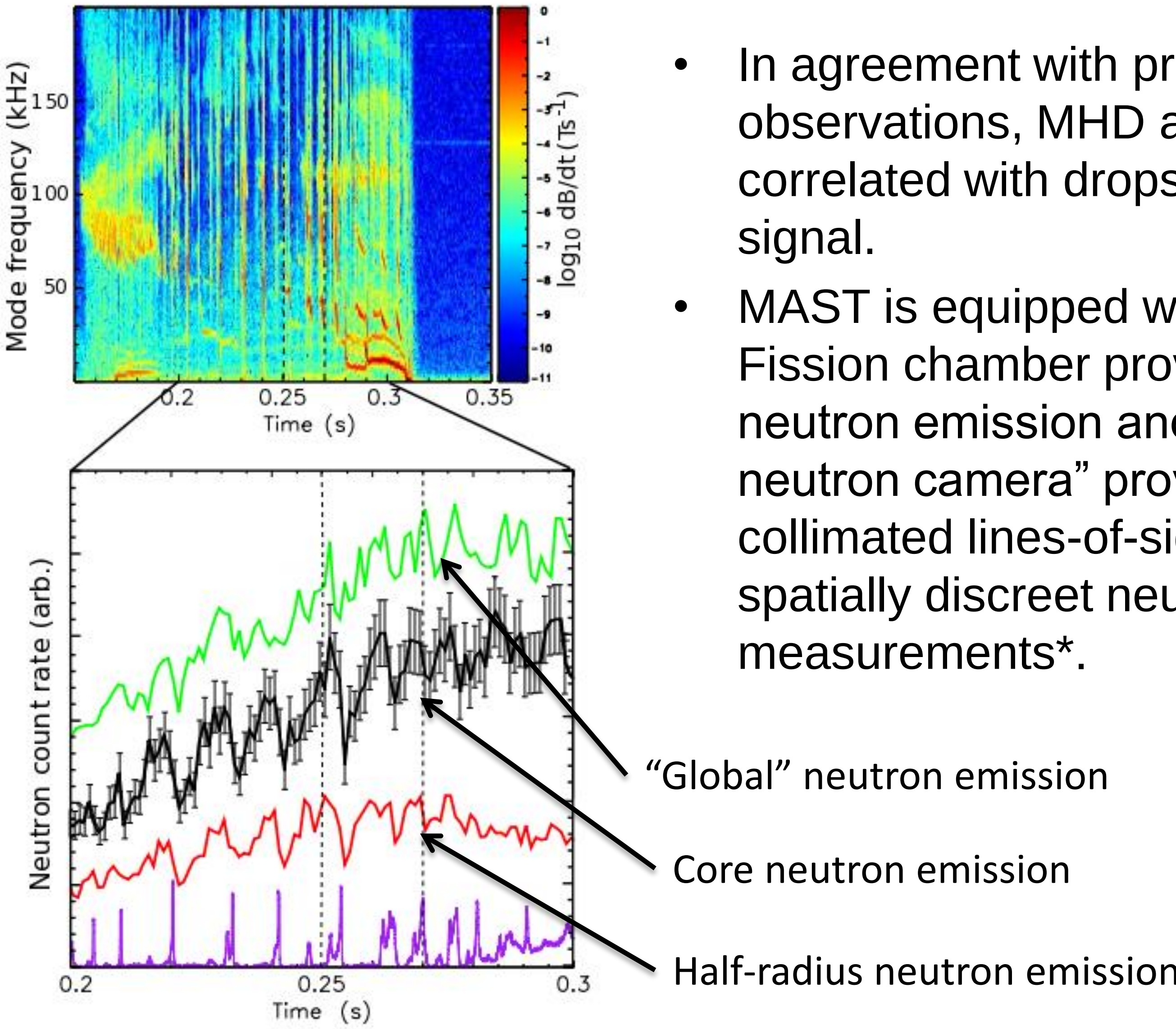
- Higher power shots have larger amplitude and/or more frequent MHD activity.

MHD activity



- Higher power shots have larger amplitude and/or more frequent MHD activity.
- Lower density shots have larger amplitude and/or more frequent MHD activity

MHD activity and neutrons

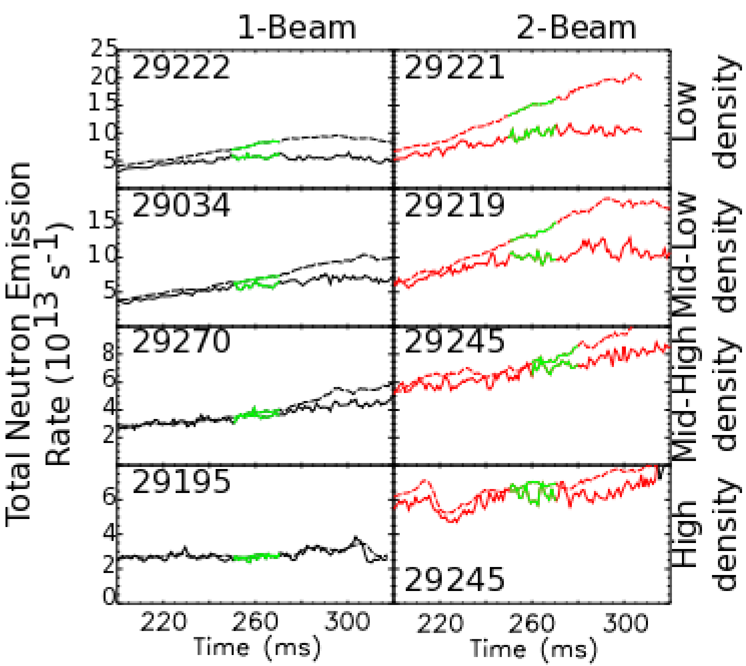


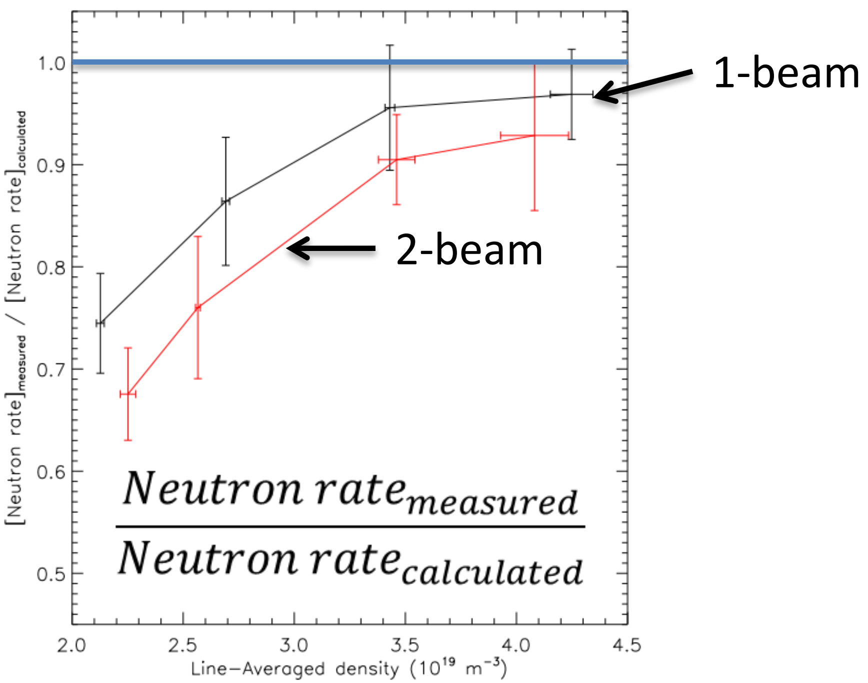
- In agreement with previous observations, MHD activity is correlated with drops in the neutron signal.
- MAST is equipped with both a Fission chamber providing global neutron emission and a "scanning neutron camera" providing highly collimated lines-of-sight and thus spatially discreet neutron emission measurements*.

*for more details see next presentation by Marco Cecconello

Global neutron emission – comparison with modelling

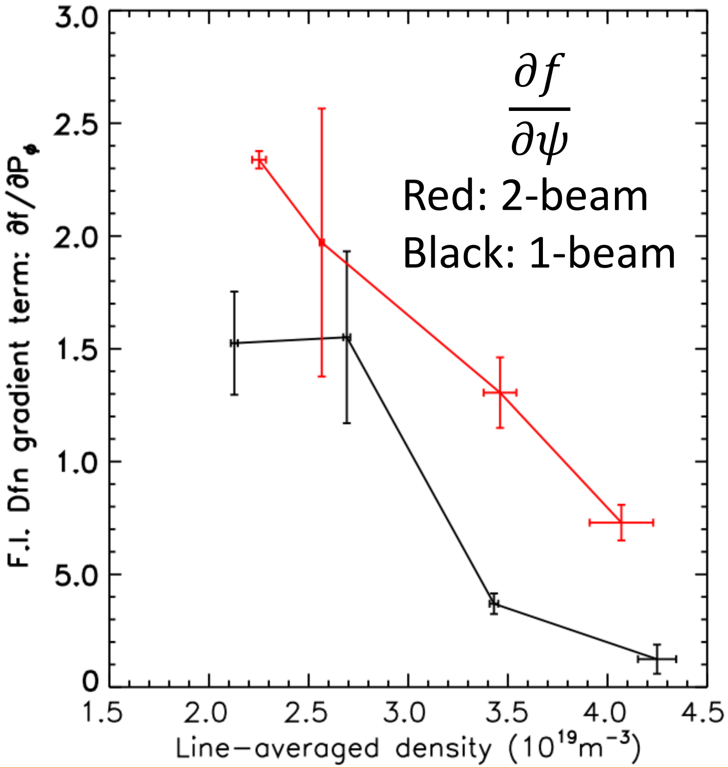
- The 8 shots in the scan were analysed using the TRANSP code: interpretive transport code with Monte Carlo NBI module NUBEAM.
- Given basic magnetics and kinetics data to describe the plasma and details of the NBI injection, TRANSP predicts the neutron emission which can be compared with experimental measurements.

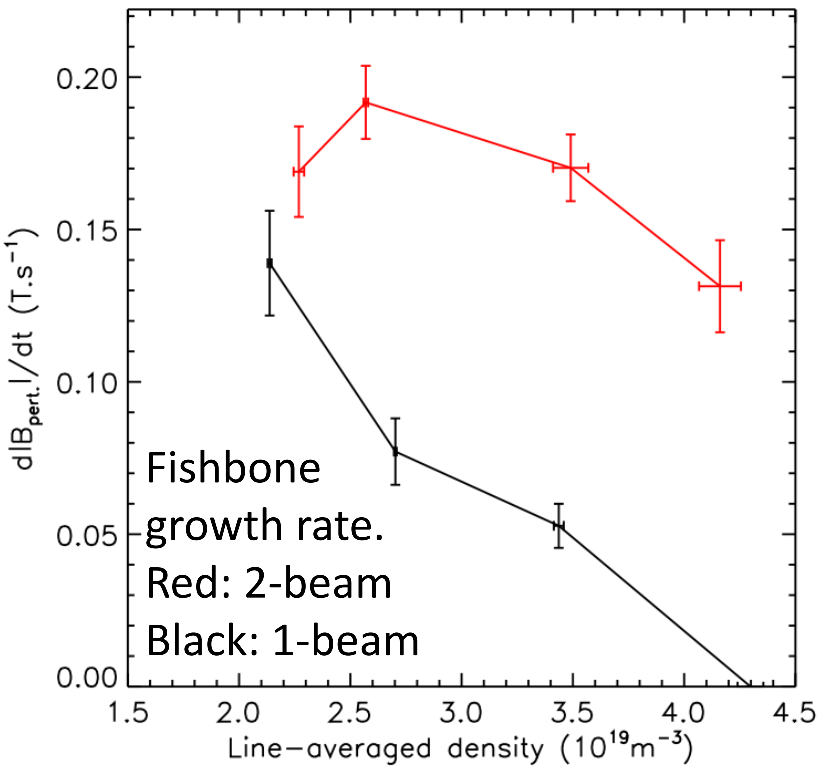




Examination of FI distribution Function

- Radial gradient of FI Dfn (outboard mid-plane) assessed from TRANSP output.
- The FI Dfn. Is typically noisy due to finite Monte Carlo particles -> some smoothing used and time-average of FI Dfn taken at 250, 260 and 270ms.
- Used processed Mirnov coil signal (estimate of $|B_{pert.}|$ due to MHD) to assess growth rate of fishbone modes.





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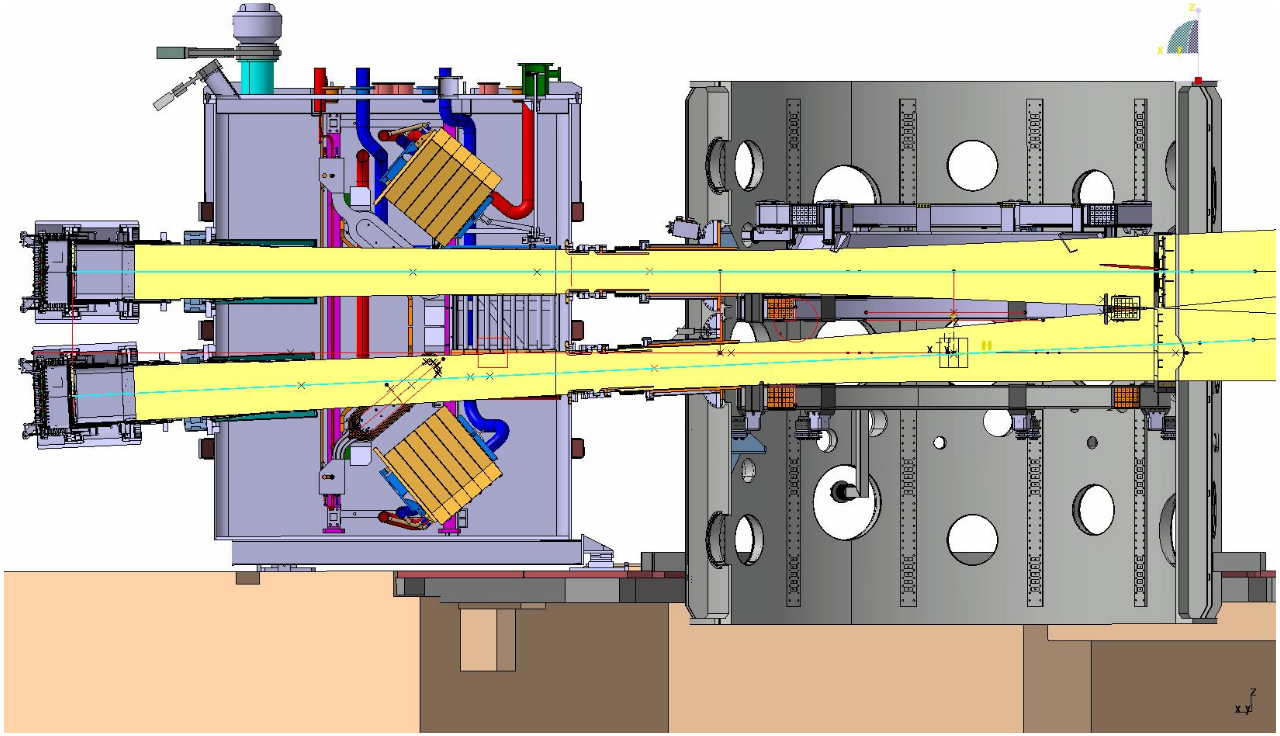
Studies investigating future MAST-U NBI system

The MAST-U Double Beam Box

- The Double-beam-box, to be added to MAST-U in the next stage of the upgrade, provides capability for an extra on-axis beam and an extra off-axis beam, together with the existing on-axis beam.
- It was proposed that if the on-axis beam is angled upwards to an intermediate on/off axis position, the beam system would be capable of producing a radial fast-ion pressure profile with reduced radial gradient.

Current geometry 2.7 deg lower beam tilt



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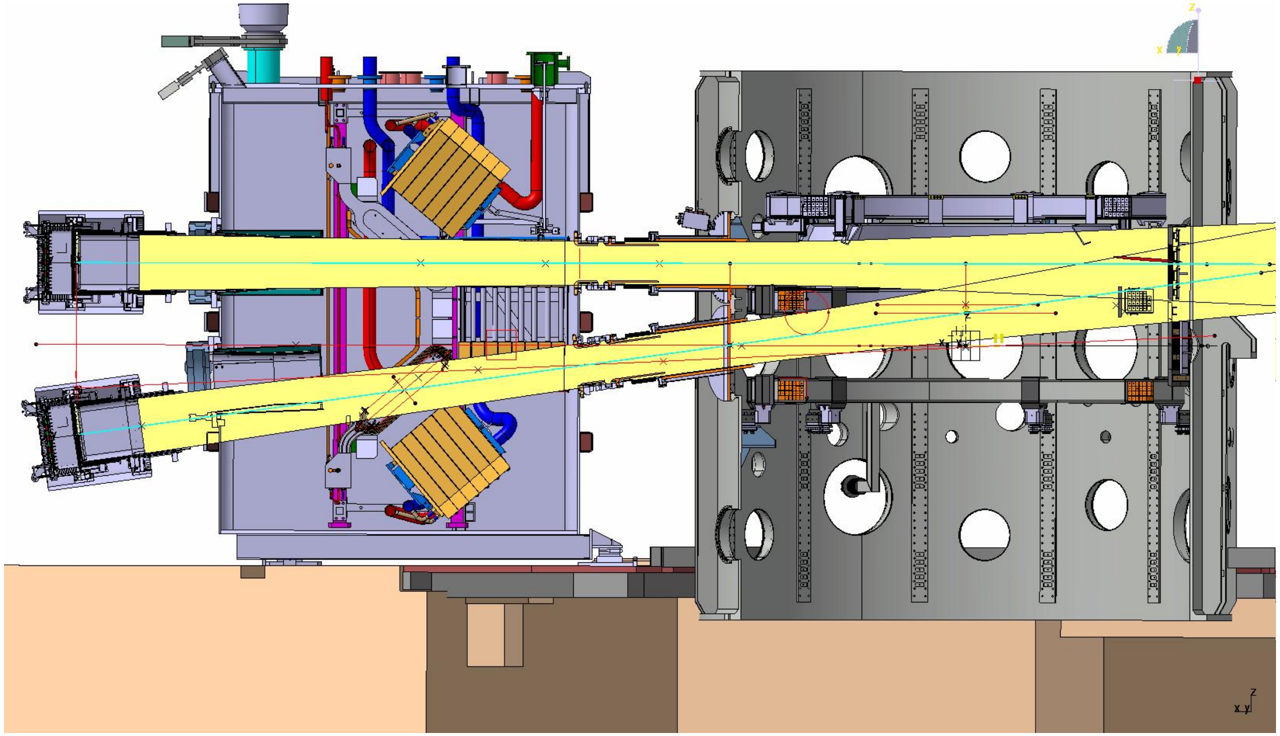
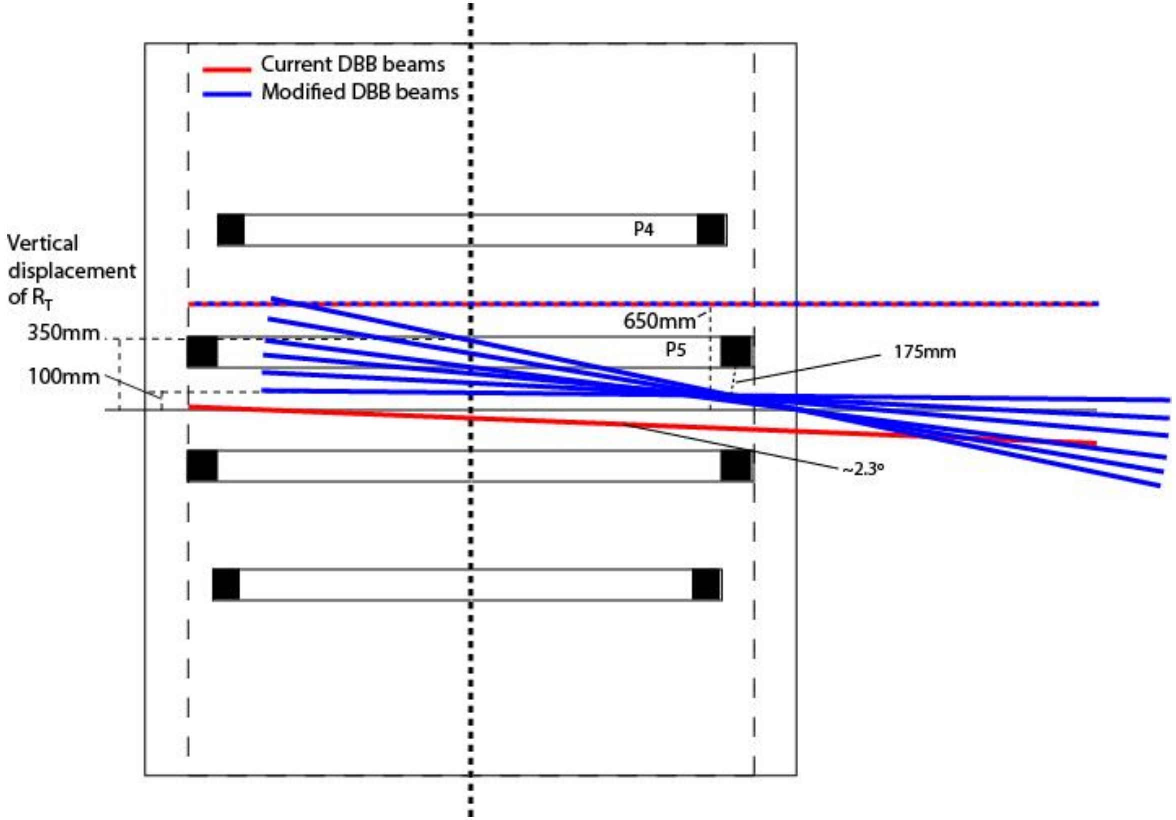
New position
7.8º tilt



Details of simulations

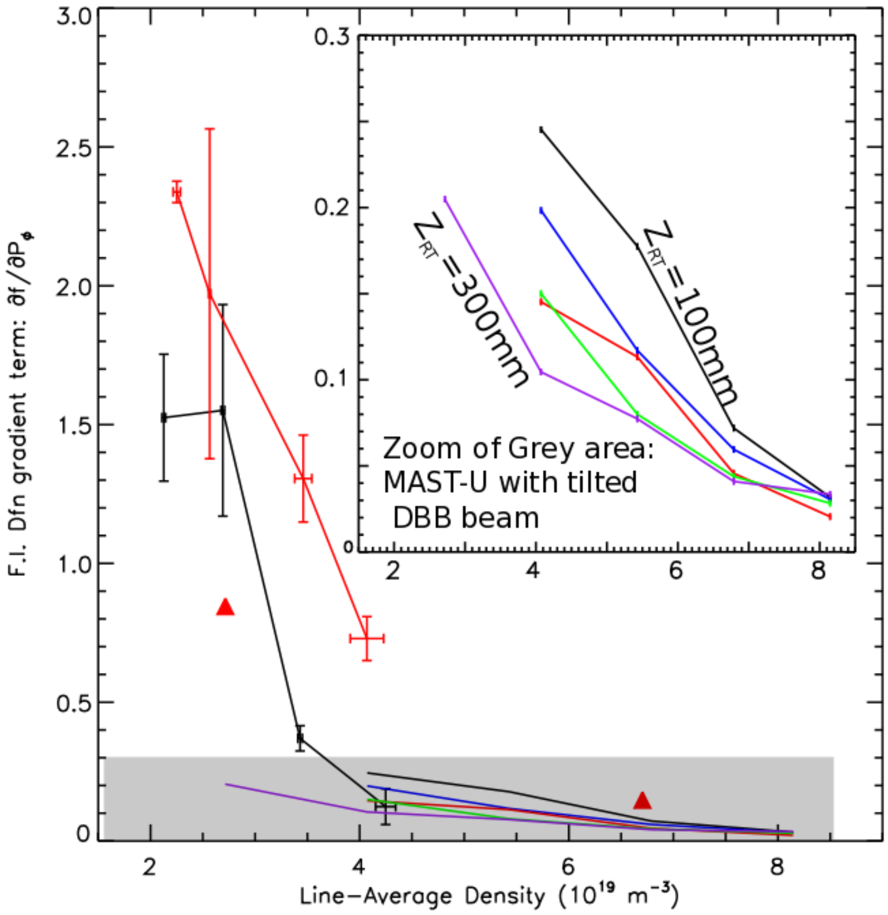
- Standard TRANSP simulations have been carried out as part of the physics basis for MAST-U.
- These were used to assess the effect of the proposed re-orientation of the on-axis DBB beam.



- A range of beam angles and plasma density were tested
- In all cases, bulk plasma temperature was adjusted to maintain $HH_{IPB(y,2)}$~1

Graph showing effect of mitigation

- Radial gradients of the FI Dfn were assessed as before and compared with experiments.



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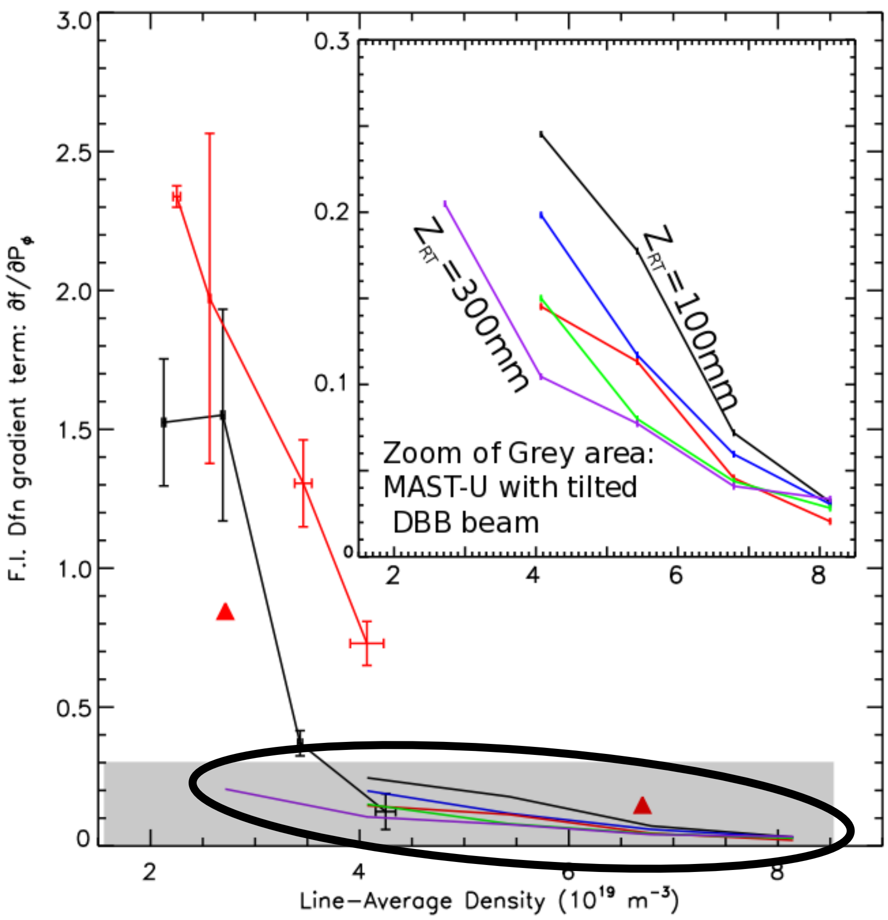
Graph showing effect of mitigation

- Radial gradients of the FI Dfn were assessed as before and compared with experiments.



$\frac{\partial f}{\partial \psi}$ from MAST – U tilted beam scan

Graph showing effect of mitigation

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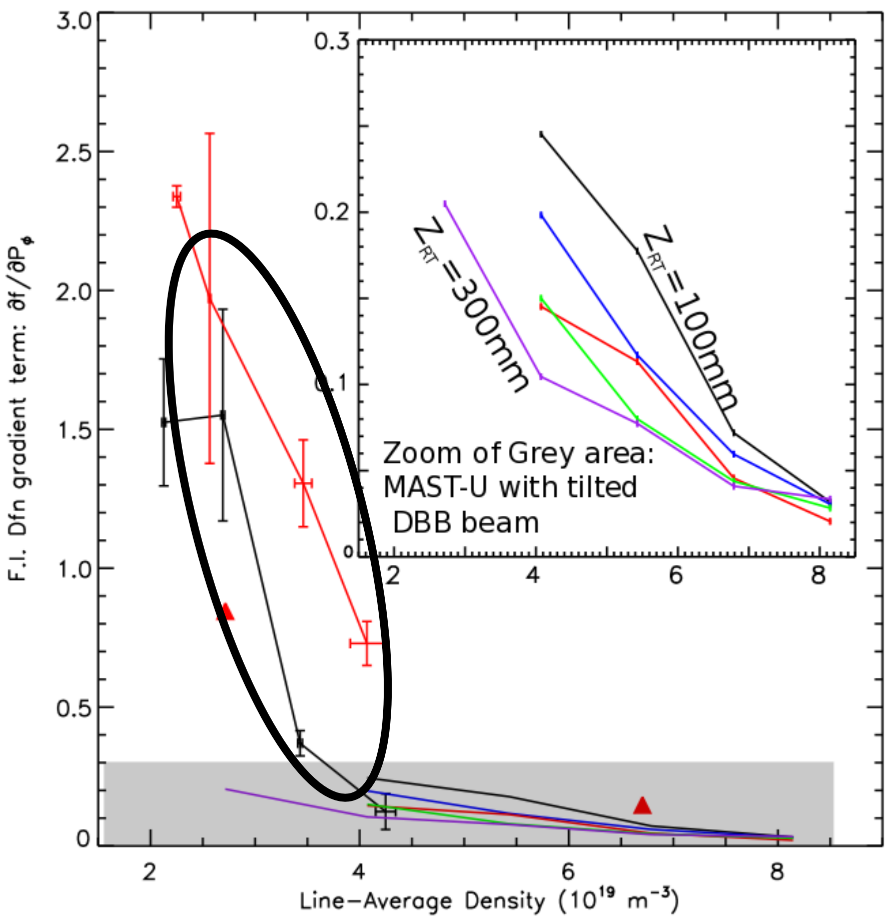
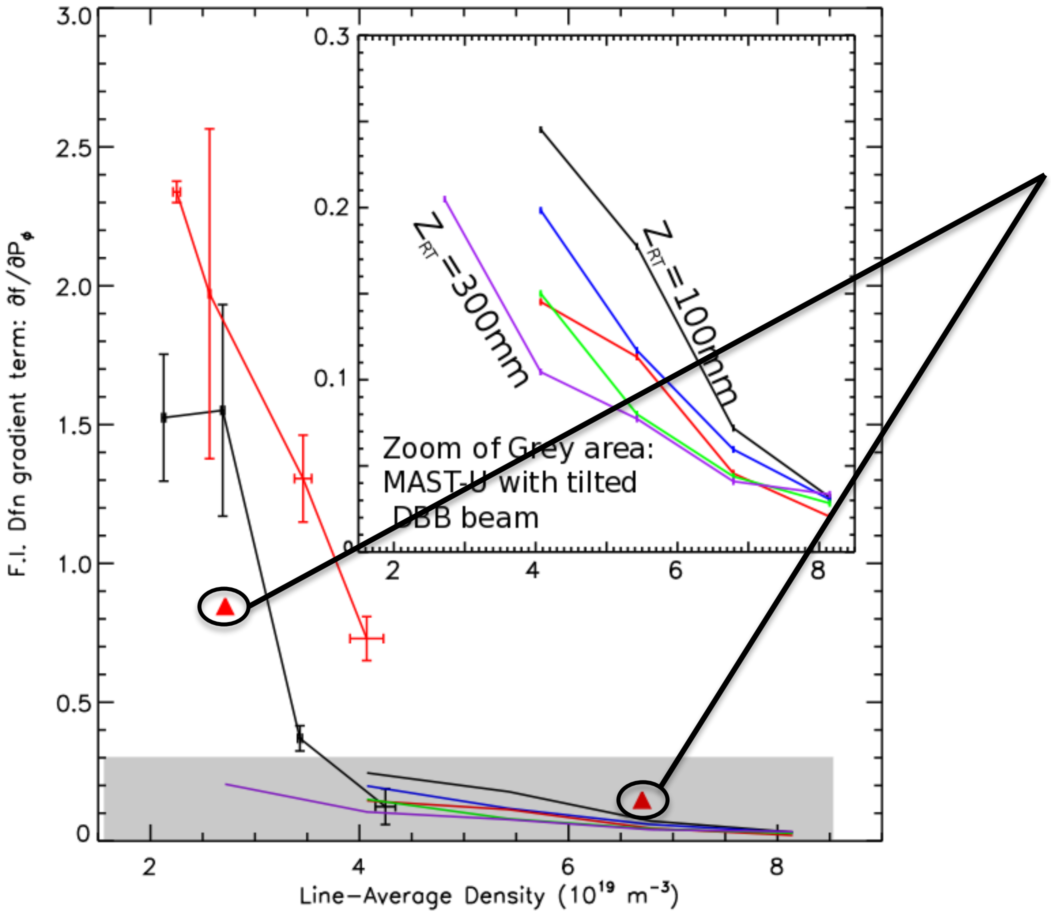


$\frac{\partial f}{\partial \psi}$ from MAST power/density scan

Graph showing effect of mitigation

- Radial gradients of the FI Dfn were assessed as before and compared with experiments.



High/Low density versions of 3-beam MAST-U with “standard” DBB beams (i.e. 2 × off-axis + 1 × on-axis beams)

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Graph showing effect of mitigation

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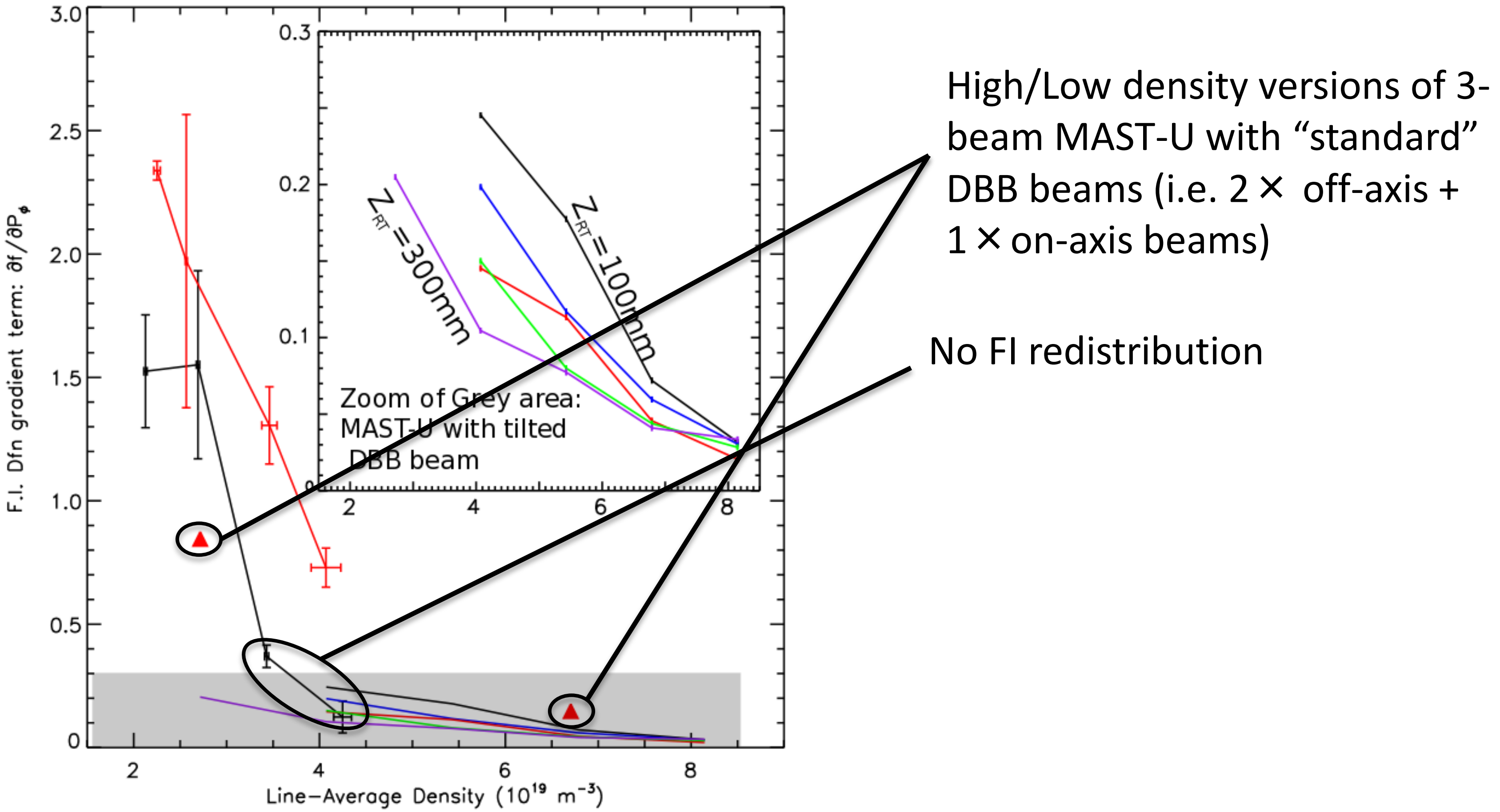

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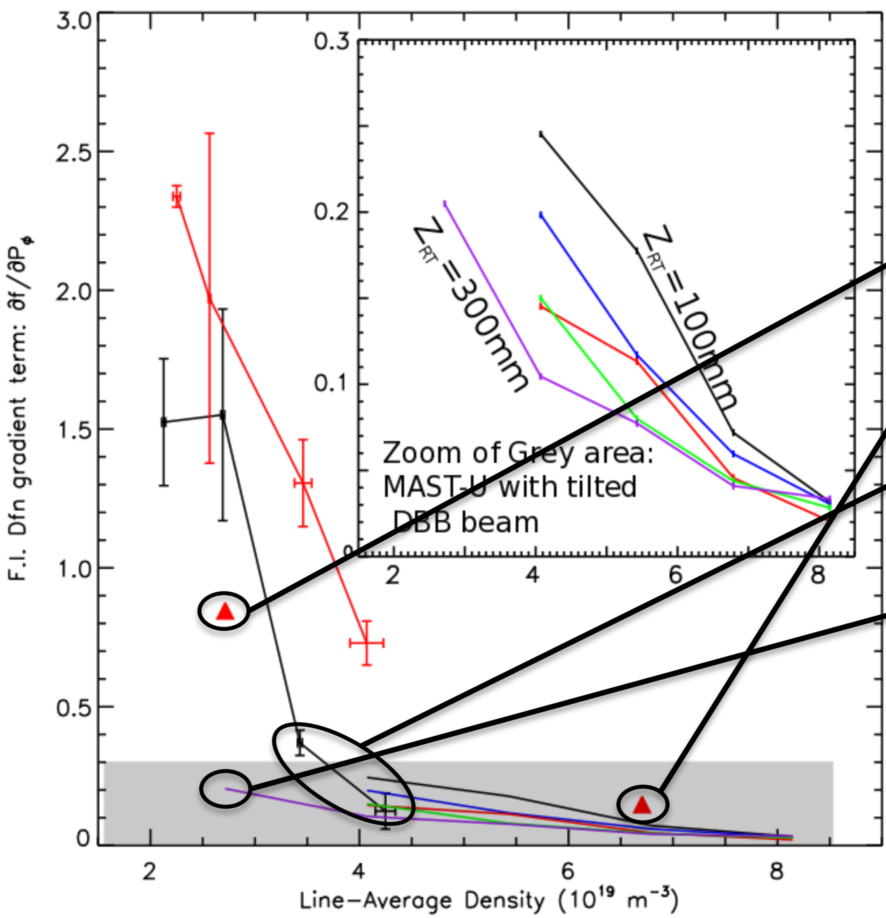

High/Low density versions of 3-beam MAST-U with "standard" DBB beams (i.e. 2 × off-axis + 1 × on-axis beams)

No FI redistribution

Mitigated FI redistribution at low density with tilted DBB beam

Conclusion

- TRANSP has been, and remains, one of the principal tools used in analysis of MAST experiments
  – Detailed physics, especially NUBEAM module
  – Synthetic diagnostic output
- TRANSP has also been used to assess likely performance of MAST-U scenarios, particularly in relation to NBI heating and CD.

Wishlist

- A synthetic FIDA diagnostic (i.e. inbuilt FIDAsim), although I.P. might be an issue, or a reduced output consisting of beam/halo emission.
- Could the beam-stopping and excitation cross-sections used in TRANSP be made more easily available in publicly accessible repositry? This would help when comparing/benchmarking TRANSP results with other codes (e.g. FIDAsim).
- A simpler mapping between different radial co-ordinates $(R-R_0)/a$, X, XI and particularly poloidal flux (tools exist for post-processing but easier if included in output).