CONFERENCE PRE-PRINT

INVESTIGATION OF THE MAGNETIC FLUX PUMPING EFFECT IN MAST UPGRADE

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Abstract

The paper presents experimental measurements of the magnetic flux pumping mechanism in MAST Upgrade. A long, stationary $q_{\min} \approx 1$ period is observed when constraining the equilibrium reconstruction code EFIT++ with both magnetic and motional Stark effect diagnostic data, which is not predicted by neoclassical current diffusion models. The flux pumping state has been ubiquitous in MAST-U plasmas heated with both on and off-axis neutral beam injection (NBI) systems, typically co-inciding with a persistent m = 2, n = 1 tearing mode. Using the ideal MHD model MISHKA, the equilibria where a stationary q profile is observed are predicted to be ideally unstable to a 1/1 mode. Analysis of the achieved β_p of several sawtoothing, on-axis only NBI heated MAST-U plasmas, and on and off-axis NBI heated plasmas with 2/1 mode activity was performed, identifying that when high $\beta_p > 0.5$ is combined with high q_{95} and low central magnetic shear the flux pumping regime is accessed. Experimentally, flux pumping phases are accessed on MAST-U by combining off and on-axis NBI heating with a zero magnetic shear q profile, with the most prevalent MHD instability being the 2/1 tearing mode. As the 2/1 activity limits β_N, scenario development was performed with the aim of achieving a flux pumping scenario whilst avoiding 2/1 mode destabilisation. Through optimisation of the timing of on and off-axis heating relative to the target q profile shape, a scenario was developed with a short period of 1/1 activity prior to 2/1 mode onset, at which point a de-transition from flux pumping to a 'sawtooth-like' event was observed. This development work highlights the importance of optimising the β_N trajectory using auxiliary heating for access to flux pumping whilst avoiding the performance limiting 2/1 tearing modes.

1. INTRODUCTION

Development of a high performance plasma scenario that can achieve steady state operation at high plasma β is of great importance to the success of future power plants. To achieve this, it is critical to control the q-profile to avoid driving magneto-hydrodynamic (MHD) instabilities unstable, which can degrade confinement and lead to disruptions. Performance limiting MHD instabilities to avoid include the neo-classical tearing mode (NTMs), which are driven unstable on low order rational $q = m/n$ surfaces, where m is the poloidal mode number and n is the toroidal mode number. $m/n = 1/1$ MHD modes such as the sawtooth instability induce periodic crashes in the core electron density and temperature, and can drive significant fast particle losses[12]. Several tokamaks have observed anomalous current profile broadening due to a phenomenon known as the "poloidal magnetic flux pumping" effect[5, 6, 7]. The central q profile remains fixed, with q_0 = 1 and sawteeth are avoided. This regime is of interest to larger scale devices to avoid sawtooth triggered NTMs as well as maximising the efficiency of on-axis electron cyclotron current drive (ECCD)[7].

Recent developments in the theoretical description of magnetic flux pumping consider the MHD dynamo effect whereby helical flow perturbations associated with an ideal pressure driven n/m= 1/1 mode produces a net toroidal electric field, driving current away from the plasma center [15]. It was shown in ASDEX-U[7] plasmas that the q profile evolution as described by neoclassical current diffusion does not agree with the measured q profile evolution, specifically when 1/1 mode activity is present, which is also observed on EAST[16]. JT-60U experiments highlighted that coupling of low frequency 2/1 tearing modes and 1/1 helical core mode occurs alongside a stationary q profile and suppression of sawteeth[5, 4] in low β plasmas.

Interaction between an edge localised mode (ELM) and a m/n = 3/2 NTM has also been previously proposed as an explanation for broadening of the current density profile [1] however more recent results indicate flux pumping also occurs in ELM free negative triangularity DIII-D plasmas via a helical core mode [6]. In the MAST tokamak, auxiliary heating consisted of two on-axis neutral beam injection (NBI) systems, and plasmas were typically performance limited by sawteeth or sawtooth triggered neoclassical tearing modes (NTMs). 1/1 mode activity such as the saturated ideal mode was observed without subsequent magnetic reconnection [9] [8], however enhanced fast particle losses and rotation breaking typically lead to plasma termination. MAST-U now has the capability for off-axis neutral beam heating for current profile shaping and longer pulse operation. MAST-U is equipped with two NBI with a combined injected power $P_{\rm NBI} < 5$MW; one on-axis and one off-axis NBI, in order to access higher β regimes through sawtooth avoidance via off-axis heating [9]. Off-axis NBI also allows q profile tailoring to fast particle instabilities [13]. Therefore, this new NBI capability, and longer pulse duration, facilitates investigation of higher β plasmas, where the flux pumping effect is theoretically predicted to occur[15].

The paper presents analysis of MAST-U plasmas in which the flux pumping effect has been measured. In Section 2, experimental measurements of the q profile clamping and theoretical transport predictions are presented, in a standard MAST-U scenario performance limited by 2/1 tearing modes. In section 3, the impact of the off-axis NBI heating is presented whereby indications of the injected power level and required βN levels are discussed. In Section 4, analysis of multiple MAST-U pulses indicates the operational space, β_p, q_{95} and magnetic shear, in which flux pumping is observed on MAST-U. Finally in Section 5, progress and development of a MAST-U plasma scenario, whereby the 2/1 destabilisation is delayed, is discussed. This highlights the importance of the β_N trajectory for MHD stability and access to the flux pumping regime.

2. FIRST EXPERIMENTAL OBSERVATIONS OF MAGNETIC FLUX PUMPING ON MAST-U

2.1. Flux pumping with 2/1 tearing modes

The plasma scenario where flux pumping is observed in MAST-U is shown in Fig.1, an I_p = 750kA plasma with 7 MA/s ramp rate, and early NBI injection with total NBI power $\mathrm{P_{NBI}}$ = 3.2MW. An H mode transition occurs at t = 150ms, and a long ELM-free period between t = 400 - 750ms. Toroidal mode number analysis of the Omaha coil magnetic spectrogram in Fig.1 indicate an m = 2, n = 1 (2/1) mode is destabilized around t = 200ms as $q_{\rm min}$ 2, followed by a (3/2) mode which couples with the 4/2 harmonic of a persistent 2/1 mode. It is in this phase where $q_{\rm min} \approx 1$ until the programmed plasma rampdown, as inferred from an equilibrium reconstruction constrained with motional Stark effect (MSE) diagnostic measurements [10]. There is a long ELM free period during the flux pumping phase, demonstrating that it is feasible to access the flux pumping regime outside of the ELM-NTM coupling description [14]. Fig.2 shows the evolution of the main impurity ion rotation frequency as measured by the Charge exchange diagnostic (CXRS) before and during the flux pumping period. The plasma rotation slows significantly in the core from 20kHz to 6kHz within the $q = 1$ surface and rotation between rational q surfaces is significantly reduced, with a slight peaking of the rotation around the $q = 2$ surface, likely due to the presence of the rotating $2/1$ mode. Unfortunately standard electron cyclotron emission diagnostics are unfeasible in spherical tokamaks due to the relatively high plasma density compared to the magnetic field strength, however distortions to the central flux surfaces due to a 1/1 helical core deformation is visible using the poloidal fan of soft x-ray (SXR) diagnostic measurements, as seen in Fig.1. Central SXR channels measure an odd amplitude structure as $q_{\rm min} \approx$1.

Fig.3 shows the evolution of q_0 for pulse 47020 inferred by an equilibrium reconstruction constrained by magnetic and motional Stark effect measurements. Using the equilibrium at t=300ms as the starting condition, the current profile was then evolved using the Sauter resistivity model using the TRANSP transport code [11]. A scan in plasma effective charge, $Z_{\rm eff}$, was performed to attempt to match the q_0 evolution and the arrival of $q_0 = 1$. This was to both understand the impact of impurity concentration on the current diffusion rate and to understand if the discrepancy between the measured q evolution and the predicted could be resolved with modifications to $Z_{\rm eff}$. Using $Z_{\rm eff}$ = 3 provided the best match to the $q_0 = 1$ arrival time measured by MSE, however this leads to an overestimate in the rate of current diffusion in the phase between t=300ms and t=400ms. During this time as shown in Fig.**??**, the plasma remains ELM-free, and without a mechanism to drive out impurities (such as an ELM) it is likely $Z_{\rm eff}$ is increasing in the ELM free phase. A scan of $Z_{\rm eff}$ shows that q_0 continues to evolve steadily beyond $q_0 < 1$, which is contrary to the experimentally constrained q_0 inferred via MSE constrained equilibrium reconstruction. This is in direct agreement with experimental and modelling results from ASDEX-U[7] indicating that flux pumping is indeed present, and that an additional anomalous current diffusion mechanism is required to accurately reflect the measured current profile evolution.

2.2. Ideal MHD simulations

Fig.4 shows the simulated radial fluid displacement, $\xi \cdot \nabla\psi$, of the $n = 1$, $m = 1$ and $n = 1$,$m = 2$ and higher order m modes at the time at which $2/1$ activity is present in the magnetic spectrogram, and q_0 is fixed to $q_0 \approx 1$. Fig.4 also shows the measured $n = 1$ mode amplitude calculated from a magnetic Omaha coil, in comparison to the predicted growth rates of the

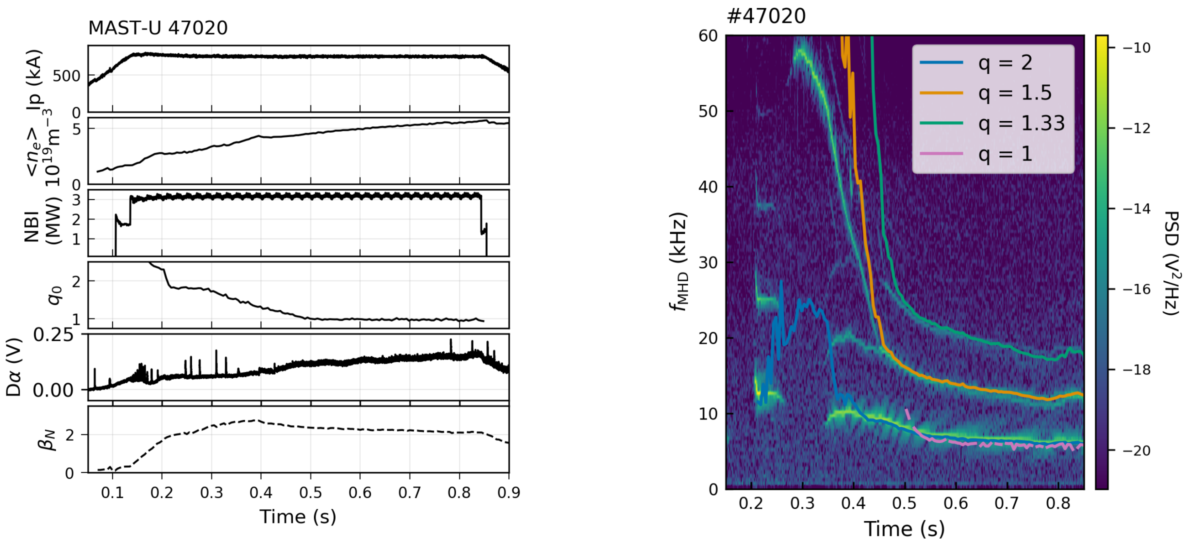

FIG. 1. ***Left:*** *Summary of plasma parameters from MAST-U plasma 47020.* ***Top to bottom****: Plasma current evolution, line averaged electron density, combined on and off axis neutral beam injected power, q at the magnetic axis* q_0*, Deuterium Balmer-*α *line emission as measured by a filtered photomulitiplier tube, evolution of the normalised plasma* β*. From t = 0.5s, there is a stationary* q_0 *1 until the plasma rampdown is initiated, co-inciding with an ELM free period.* ***Right:*** *Magnetic spectrogram as measured by a magnetic OMAHA coil for plasma 47020. Rational q surface rotation frequency is overlaid to identify the q surface location of the MHD instabilities.*

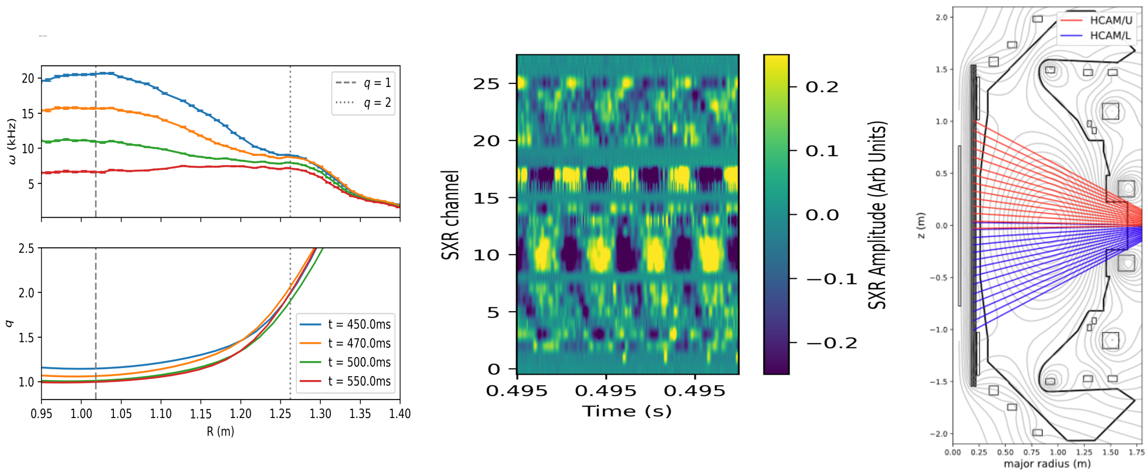

FIG. 2. ***Top Left:*** *Impurity ion rotation frequency measured by the Charge Exchange recombination spectroscopy diagnostic.****Bottom Left:*** *q profile evolution just before and during stationary phase. Rotational coupling between the* $q = 1$ *(grey dashed line) and* $q = 2$ *(grey dotted line) surfaces is observed at the onset of flux pumping.*
Right: *Mean subtracted amplitude of soft X-ray (SXR) diagnostic measurements. SXR channels 9-16 form a chord bisecting central flux surfaces in the poloidal plane. An odd amplitude oscillation is observed as* $q_0 \approx$ *1 indicates* $n = 1$ *core localized mode activity is present.*

$n = 1, 2, 3$ mode numbers. There is marginal increase of the n =1 amplitude prior to the MISHKA simulation, correlating with the onset of the 2/1 tearing mode, but due to the frequency locking of the q = 2 and q = 1 surfaces it is not possible to isolate the 1/1 mode amplitude from the magnetic spectrogram. However the onset of positive growth rate calculated by MISHKA correspond to $m = n$ modes, and the non-zero growth rate correlates with the arrival of the q = 1 surface in Fig.4. This would suggest that the equilibrium with q profile and $\hat{s}$=0 features as shown in Fig.8 is ideally unstable to the $n = 1$ mode.

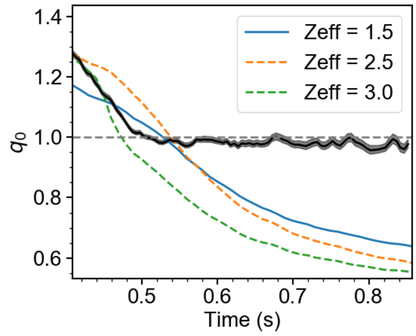

FIG. 3. *Comparison of the evolution of the safety factor at the magnetic axis q_0 inferred using an MSE constrained EFIT reconstruction (green solid line), and TRANSP modelling code predicted using neoclassical current diffusion model NCLASS from $t = 300$ms. The solid blue line shows the evolution using a flat effective charge Z_{eff}=1.5 and solid orange line with constant $Z_{\mathrm{eff}} = 3$. Increasing Z_{eff} improves agreement with the MSE EFIT reconstruction in the phase where the current is diffusing on axis, however in both instances the q profile continues to evolve during the flux pumping phase. Uncertainty in the MSE measured q profile is shown in light gray.*

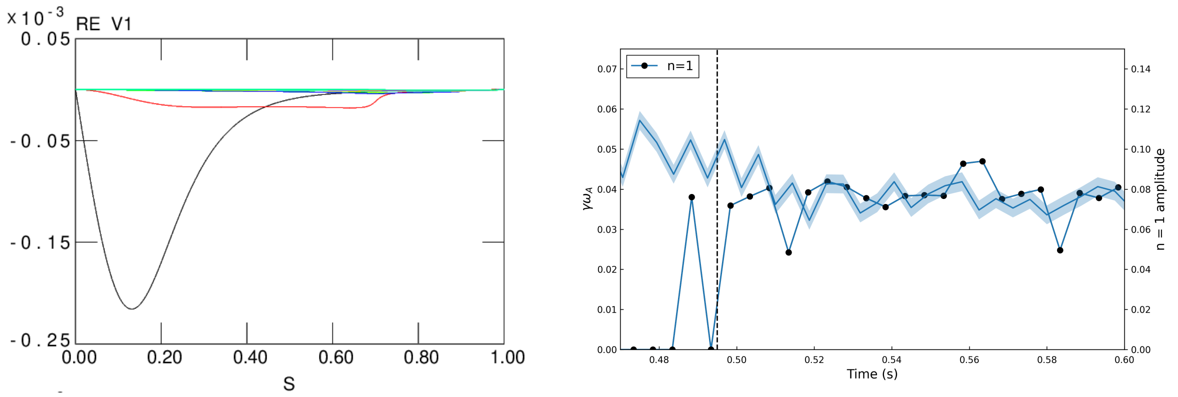

FIG. 4. *Simulated radial fluid displacement, $\xi \cdot \nabla\psi$, vs $s = \sqrt{\psi_n}$, of the $n = 1, m = 1$ (red) and $n = 1, m = 2$ (black) and higher order m (green, teal) as predicted by MISHKA in the ideal wall limit for MAST-U plasma 47020 at t = 500ms. Predicted growth rate γ/ω_A normalised to the Alfven frequency, of low n mode numbers for MAST-U plasma 47020. The n = 1 mode growth rate predicted by MISHKA (black circles) indicates the plasma is ideally MHD unstable to n = 1 from t = 485ms, which correlates with the $q = 1$ arrival time (black dashed line). The $n = 1$ mode amplitude measured by an external magnetic probe is shown in blue.*

3. COMPARISON OF ON AND OFF-AXIS NBI HEATING

To understand the effect of the NBI heating on accessing the flux pumping regime, Fig.5 shows two additional MAST-U pulses. In the first case failed application of the on-axis beam provided an off axis heated plasma, and a second pulse in which the off-axis heating beam switches off around the $q_0 = 1$ arrival time. In the latter case, the rotation frequency of the 2/1 mode decreases correlating with a reduction in β_N, however q_0 remains fixed to $q_0 \approx 1$ indicating that the flux pumping state is maintained even as β_N drops to levels consistent with sawtoothing cases in Fig.7. Fig.6 shows the $n = 1$ mode amplitude decreases slowly as β_N reduces, due to the reduced NBI power. However the mode amplitude is similar to the full power case, suggesting that if the mode amplitude is sufficient, the flux pumping state could be maintained. Finally an off-axis NBI powered case is shown in Fig.5, to investigate whether a 2/1 with sufficiently large mode amplitude for flux pumping occurs at any level of off-axis power injection. Although detailed q profile reconstruction is not possible in off-axis heated pulses, as the MSE diagnostic views emission from the on-axis NBI, the magnetic spectrogram in Fig.5 suggests that an $n = 1$ mode of similar frequency is destabilised similar to the 2/1 mode in other pulses. Using the soft X-ray poloidal array as shown in Fig.6, clear sawteeth and inversion of the SXR emission crahses are measured indicating that $q_0 < 1$. The $n = 1$ mode amplitude is also significantly smaller than the other two presented cases, suggesting this is below the mode amplitude threshold to transition from sawteeth to flux pumping at this injected power level. Further studies look to perform a detailed power scan around this threshold power level, including short on-axis NBI 'blips' to measure the q profile using MSE.

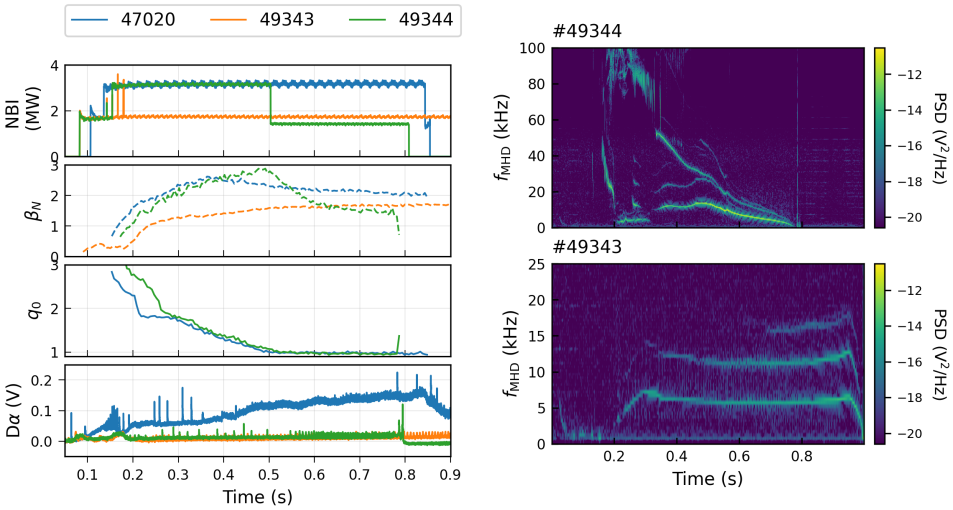

FIG. 5. ***Left:*** *Total injected NBI power, plasma normalized β, q_0 evolution inferred from MSE constrained EFIT. This data is unavailable for the off-axis only heated case (orange lines) and tangential D_α intensity demonstrating all pulses during the analysed time window are in H mode.* ***Right:*** *MHD spectrograms for NBI power ramp down pulse 49344 (top) and off-axis only heated pulse 49343 (bottom). Small sawteeth are visible co-existing with 2/1 mode in this case.*

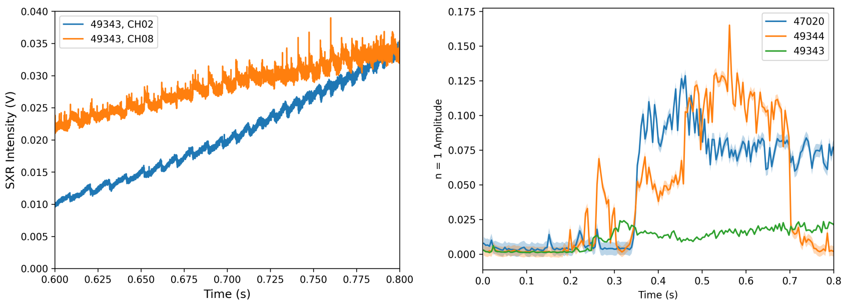

FIG. 6. ***Left:*** *Two chords from the poloidal soft X-ray detector arrays where sawteeth are measured for the lower power off-axis only heated case.* ***Right:*** *Estimate of the $n = 1$ mode amplitude for all three injected power levels. Note that in the case of early off-axis NBI power reduction, flux pumping still continues until 2/1 mode locks which leads to plasma termination.*

4. IMPACT OF β_N AND MAGNETIC SHEAR ACCESS TO FLUX PUMPING

4.1. β threshold analysis

Analysis across a small database of MAST-U pulses was performed to attempt to quantify a β_N threshold for the onset of magnetic flux pumping associated with 2/1 tearing mode activity on MAST-U. The MAST-U pulses comprised of a set of I_p=750kA, conventional divertor configuration, connected double null plasmas with either; on-axis NBI heated pulses, with an average injected power level of $P_{\mathrm{NBI}} = 1.5$MW, or off and on axis heated plasmas $P_{\mathrm{NBI}} \approx 3.2$MW. Fig.7 shows the distribution of achieved β_N in the single beam heated, sawtoothing plasmas, compared with the flux pumping two beam heated cases. Aside from the case discussed in section 3, all pulses with *on-axis* at low injected power levels lead to sawtoothing periods. In some instances sawteeth triggered 3/2 or 2/1 tearing modes during these pulses, however temporal analysis was constrained to sawtoothing periods visible in SXR channels and magnetic spectrograms, and are compared with pulses where $q_0 \approx 1$ without sawteeth, in which all of those cases both *on and off-axis* NBI is applied and a 2/1 tearing mode was present. Fig.7 indicates a β_N threshold of around $\beta_N > 2$ where flux pumping is most likely to occur, which is marginally lower than the reported threshold β_N in conventional aspect ratio machines[7]. However there is clear overlap in the achieved β_N of both flux pumping and sawtoothing pulses at β_N = 1.75 - 2.3, which could be due to the detrimental impact of the 2/1 mode on plasma confinement in the flux pumping plasmas, but also indicates that achieving β_N>2 is not enough alone to trigger flux pumping. The same pulses were analysed in terms of β_p and q_{95} where a more clear trend emerges in Fig.7. This indicates that sawtoothing cases occur mostly at low β_p and low q_{95}, however again there is overlap in β_p performance of sawtoothing

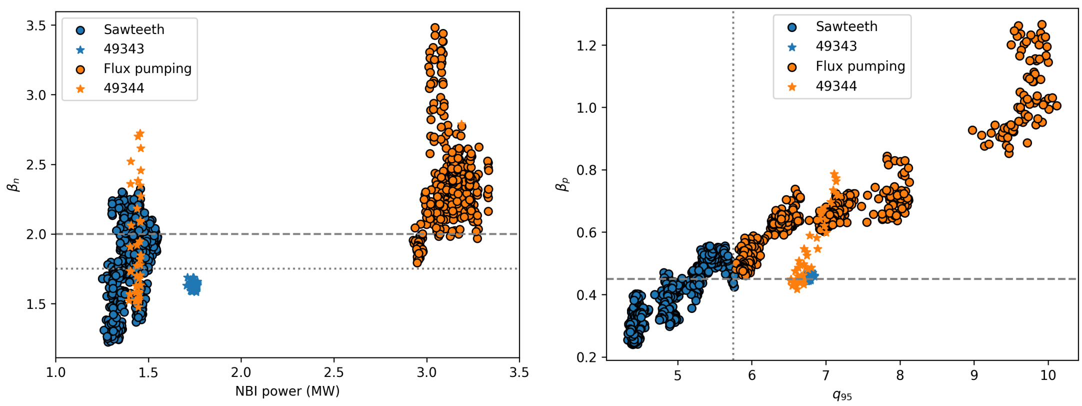

FIG. 7. *MAST-U double null, conventional divertor configuration, I_p = 750kA pulses with on-axis NBI heating (blue circles) compared with on and off-axis heated pulses (orange circles). All cases of on axis NBI heated pulses lead to a sawtoothing phase, whereas additional off-axis NBI power facilitates access to flux pumping regimes. Flux pumping phases within the off-axis power scan pulses (green, stars) correlate with β_N >2.*

and flux pumping cases. Targeting $q_{95} > 6$ seems to be a good indicator of accessing flux pumping. On the other hand, this data effectively highlights the parameter regime in which the 2/1 mode is destabilised for MAST-U. Previous database studies of MAST plasmas demonstrated a 2/1 saturated island width of around 6cm would be present at $q_{95} \approx 6$ with $\beta_p \approx 0.6$ [17]. Future work will look at performing a scan in q_{95} to further specify the operational regime for flux pumping in MAST-U.

4.2. Magnetic shear analysis

Helical core modes associated with the driving the MHD dynamo, are more easily destabilized with low or weakly reversed magnetic shear in the presence of strong pressure gradients, and so a similar assessment is performed focusing on the magnetic shear $\hat{s} = \frac{r}{q}\frac{dq}{dr}$ in sawtoothing and flux pumping MAST-U plasmas. In MAST-U pulse 48821 the toroidal field was increased B_t = 0.72T and only on-axis beam heating, to encourage weakly negative magnetic shear and a delayed $q = 1$ arrival time. Fig.8 shows the MHD activity present correlated with q_0 and β_N trajectory. There is clear 1/1 activity proceeding a phase of chirping modes, which on MAST was a signature of the onset of the so-called 'long lived mode'[9], without a 2/1 mode present. There is a brief window where $q_{\min} \approx 1$ and core $\hat{s}$ = 0, during 1/1 mode activity, which could be the indicator for a short flux pumping phase. Evidently this plasma achieves a similar target $\beta_N \approx 2$ as $q_0 \approx 1$, however the MSE inferred q_0 continues to evolve as weakly negative magnetic shear re-appears and a sawtooth crash occurs at t = 480ms, after which mode locking leads to plasma termination. Fig.8 shows the evolution of the magnetic shear, where $\hat{s} < 0$ up to t = 430ms and $q_0 \approx 1$ and beyond t = 480ms when $q_0 < 1$. A brief period of zero shear co-incides with 1/1 activity and $q_0 \approx$1, however it is not sustained, indicating that small changes to the shear can lead to the loss of the flux pumping drive, even at relevant β_N values. Comparing the magnetic shear in Fig.8, flux pumping is maintained with zero central and positive off-axis magnetic shear, compared to the negative shear in the non-flux pumping case.

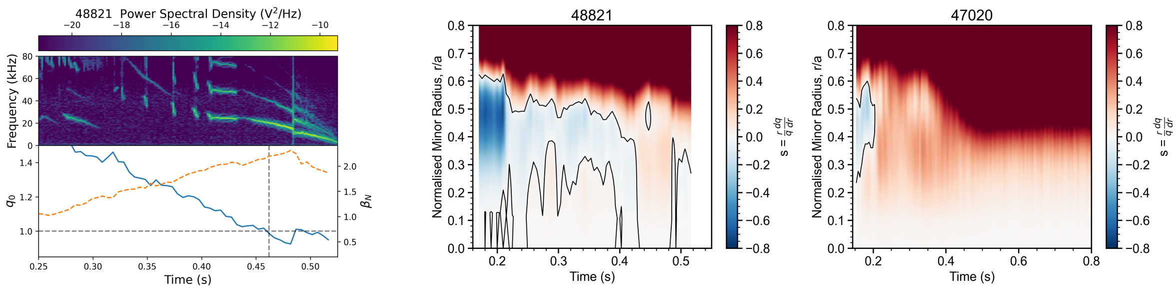

FIG. 8. ***Upper Left:*** *Magnetic spectrogram for MAST-U pulse 48821, where a short phase of chirped modes is observed before the onset of 1/1 activity, leading to a sawtooth prior to 500ms.* ***Lower:*** *q_0 evolution (blue, solid line) and β_N trajectory (orange, dashed line) during the 1/1 activity.* ***Middle:*** *Magnetic shear $\hat{s}$ for the unsustained flux pumping case, with 1/1 activity at $\beta_N \approx 2$.* ***Right:*** *Magnetic shear for the sustained flux pumping case 47020, with 2/1 tearing mode activity at similar β_N to 48821.*

5. FLUX PUMPING SCENARIO DEVELOPMENT

In most of the MAST-U standard scenarios are typically performance limited by the onset of 2/1 tearing modes, which persist throughout the plasma current flat top phase. Scenario optimisation was undertaken to develop a plasma scenario in which the 1/1 MHD instability was dominant, to allow cross machine validation of flux pumping regimes with machines such as ASDEX-U[7]. Performing a slow plasma current ramp rate of 3 MA/s lead to reconnection free ramp ups which had a significant impact on the q profile evolution in previous MAST-U scenarios[3]. Additionally improved control of the plasma β trajectory lead to a phase of 1/1 mode activity and chirping modes. This was achieved through extending the limiter phase until plasma current flat top is achieved and increasing the gas injection rate during the plasma flat top. The LH transition time was controlled by injection of the on-axis NBI. Fig.9 shows the variation in MHD instabilities when optimizing the off-axis NBI injection relative to the on-axis NBI. Injecting the off-axis NBI during the chirped modes lead the appearance 1/1 mode, however once $\beta_N >$ 2.3 a 2/1 mode was destabilised and q_0 drops below 1 and a 'sawtooth-like' event was observed. However, when off-axis NBI is applied after sawteeth were established, a 3/2 mode is triggered at $\beta_N > 2$, however the *average* β_N in the flat top phase is significantly improved over flux pumping cases with the 2/1 mode, although small amplitude sawteeth still co-exist with the 3/2 mode, similar to the hybrid scenario with 'mild MHD activity' in JET and DIII-D[2]. Further work then looks to optimize the level of off-axis NBI power to fully stabilize the sawteeth.

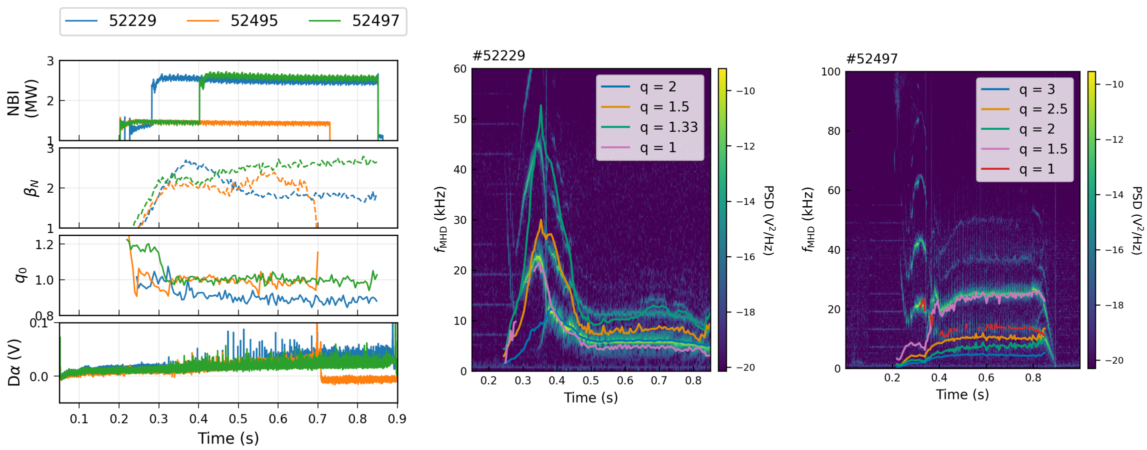

FIG. 9. ***Left:*** *Summary of plasma parameters for three MAST-U plasmas where the off axis NBI timing is varied between pulses.* ***Middle:*** *Magnetic spectrogram of an Omaha magnetic probe for pulse 52229. Chirping modes precede the onset of n = 1 activity at 300ms, before a 2/1 mode is seeded and interaction between the two modes leads to $q_0 < 1$. Rotation frequency at the rational q surfaces is also shown.* ***Right:*** *MHD spectrogram for pulse 52497 with delayed off-axis NBI heating.*

6. SUMMARY

MAST-U plasmas exhibiting 2/1 tearing mode MHD activity demonstrate stationary q profiles, indicative of the magnetic flux pumping effect. The q profile evolution has been measured using the motional Stark effect diagnostic, which demonstrated a clamping of the q profile around $q_0 \approx 1$, whereas transport models predicting neoclassical current diffusion lead to continual peaking of the current density profile and this affect cannot be resolved with modifications to the plasma effective charge. Typically flux pumping has been observed in the present of persistent $2/1$ modes which are a standard feature of NBI heated plasmas on MAST-U. Ideal MHD stability code MISHKA indicates equilibrium after the $q = 1$ arrival time are ideally unstable to $m = n$ 1/1 modes. Experimental measurements of the plasma rotation showed that there is little differential rotation $q = 1$ and $q = 2$ surfaces during flux pumping phases. The impact of on and off-axis NBI injected power on the plasma MHD stability and flux pumping access was studied, which showed that low levels of either on or off axis NBI lead to sawtoothing pulses. However off axis NBI heated plasmas tend to lead to 2/1 mode activity where flux pumping is observed. It was shown that if flux pumping can be maintained provided the mode amplitude is sufficient even if there is a reduction in β_N. Finally, sufficiently high β_N and mode amplitude must be coupled with zero or weakly positive magnetic shear in order to facilitate flux pumping. Scenario optimisation was performed to avoid destabilisation of the 2/1 mode, where the importance of the β_N trajectory was demonstrated for avoidance of the 2/1. Further studies look to develop the plasma scenario absent of 2/1 mode activity to further maximise the plasma performance and identify the operational space in which stationary plasma regimes can be achieved on MAST-U.

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