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# A radiometer to diagnose parametric instabilities during linear excitation of electron Bernstein waves in the Mega Amp Spherical Tokamak (MAST) Upgrade

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Highly overdense magnetically confined fusion plasmas, such as the Mega Amp Spherical Tokamak (MAST) Upgrade, cannot easily be heated using conventional electron cyclotron resonance heating because high density cutoffs block microwave access to the plasma core. Instead, electromagnetic waves can be coupled to electron Bernstein waves (EBWs) through the O-X-B mode coupling scheme, and the EBWs can then be absorbed at higher densities. The excitation of EBWs occurs near the upper hybrid (UH) layer where nonlinear wave interactions, called parametric decay instabilities (PDIs), are known to occur at reduced power thresholds. We present a design for a radiometer to detect PDIs during O-X-B in MAST Upgrade. The radiometer will aid in determining at what power levels PDIs become important as well as to infer various parameters about both electrons and ions near the UH layer. We estimate a gyrotron power density threshold for PDI and expected frequency shifts to be produced in them. The design allows for shifts from several decays involving lower hybrid (LH) waves to be observed.

## I. INTRODUCTION

High power microwaves are popular for heating and current drive in magnetically confined fusion plasmas due to efficient gyrotron sources, modest space requirements on the reactor walls and good accessibility in the plasma. However, the gyrotron beams can be cut off from the confined plasma core if its density exceeds a critical level and becomes overdense. This is a challenge in particular for spherical tokamaks such as the Mega Amp Spherical Tokamak (MAST) Upgrade. A mode coupling scheme known as O-X-B may remedy this as it allows the electromagnetic gyrotron waves to couple to electrostatic waves known as electron Bernstein waves[1] (EBWs). The EBWs may propagate without a high density cutoff and have performed well in low power heating and current drive experiments[2]. For MAST Upgrade, new high power gyrotrons have been acquired specifically to utilize EBWs at unprecedented power levels. However, the excitation of EBWs is also associated with parametric decay instabilities (PDIs). The PDIs are able to divert power from a gyrotron wave into waves shifted in frequency. The impact of PDIs scales nonlinearly with the gyrotron power and EBW operation could turn out to be significantly inhibited in MAST Upgrade. Still, the low power O-X-B experiments indicate that EBWs can drive current better than conventional microwave based current drive schemes. For this reason, EBWs are under consideration as the main method of heating and current drive for the UK national prototype fusion power plant STEP. Thus a detailed experimental investigation of potential limitations of this heating due to PDIs is essential prior to the final design

Waves generated in PDIs may undergo an inverse O-X-B conversion and be observed outside the plasma. This was reported in ref. 3 from ASDEX Upgrade where strong microwave bursts were observed outside the plasma on the low field side, and similar observations were reported about in W7-AS[1] during PDIs inside the plasma. A detailed study of PDIs in MAST Upgrade can be build around using a radiometer to observe the escaping waves, which are characteristic of the plasma. In order to build a radiometer for such a study, the frequencies of the escaping waves must be known. The frequencies can be determined by solving selection rules in the PDI interaction region near the UH layer.

In this work, we analyze the possibility of PDI in MAST Upgrade and propose a radiometer design capable of observing signature radiation of PDIs. The specifics of the radiometer and notch filter are backed by a theoretical analysis to allow for an appropriate range and resolution of frequencies to be observed whilst attenuating the gyrotron signals. The design includes a plan on how to integrate the diagnostic into the MAST Upgrade.

## II. THEORY

### A. The O-X-B mode coupling scheme

A magnetized fusion plasma can support a plethora of both electromagnetic and electrostatic waves. For heating and current drive purposes, two electromagnetic

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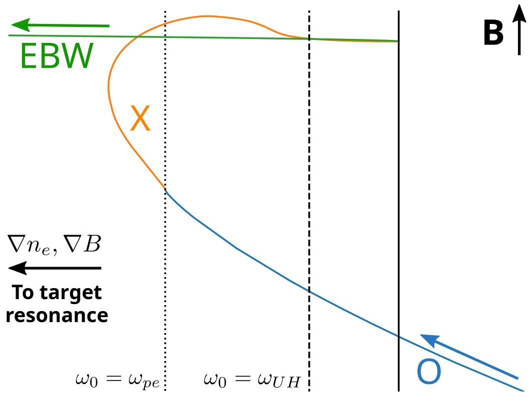

FIG. 1. Illustration of the O-X-B mode coupling scheme using ray tracing and MAST Upgrade parameters. An injected O-mode wave (blue) can couple to X-mode (orange) at the plasma frequency (dotted line), which in turn couples to an EBW at the UH layer (solid line), past the UH frequency (dashed line) in an overdense plasma. The UH layer is also associated with nonlinear losses.

modes known as O- and X-mode are typically injected from vacuum and low magnetic field into the plasma to be absorbed at the electron cyclotron resonance. Both O- and X-mode waves have reflection points in the plasma which may prevent them from reaching electron cyclotron harmonics in highly dense plasmas. The electrostatic EBWs, on the other hand, can propagate without high density cutoffs but propagate as electron density perturbations and can therefore not simply be excited in vacuum and injected into the plasma as is done with O- and X-mode. However, Preinhaelter and Kopecký[4] proposed a mode coupling scheme known as O-X-B which would connect injected O-mode to an EBW through an intermediate X-mode. If an O-mode wave reaches its cutoff with an optimal wavenumber along the magnetic field, then it can convert fully into an X-mode wave which can in turn convert into an EBW at the upper hybrid (UH) layer. The scheme is illustrated in figure 1. The O-X-B scheme has been the subject of a number of low power EBW heating and current drive experiments[1,2,5] and recently the excited EBW was measured directly using a probe[6] in the LATE device. The O-X-B scheme has the potential to provide a method for microwave based heating and current drive in overdense plasmas which is often the case in spherical tokamaks.

### B. Parametric decay instabilities (PDIs)

Whilst the O-X-B scheme is a linear conversion scheme relying on different modes coalescing in certain regions of the plasma, the injected waves may also interact nonlinearly with other waves. The three-wave interactions are some of the simplest nonlinear effects that can occur. Above an amplitude threshold for the injected pump wave, it may decay into two daughter waves if they satisfy the simple selection rules

$$\omega_0 = \omega_1 + \omega_2, \quad \mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2, \tag{1}$$

where $\omega_0$ and $\mathbf{k}_0$ are the angular frequency and wave vector of the pump wave, and subscripts 1 and 2 refer to that of the daughter waves. Above the pump wave threshold, this process is known as a parametric decay instability (PDI)[7–9]. The daughter waves are characteristic waves of the plasma and the selection rules might only be satisfied locally, in which case the daughter waves are also characteristic of the region in which they PDI occurred. For O-X-B, the region around the UH layer is well known for PDIs as indicated in figure 1, and the observation of daughter waves has sometimes been taken as an indication of successful excitation of EBWs[1]. The typical PDIs to occur near the UH layer involve interactions between an X-mode pump wave, a slightly downshifted EBW and an ion wave of corresponding frequency, e.g. a lower hybrid (LH) wave or an ion Bernstein wave (IBW). After the excitation of ion waves, they may recombine with the pump wave to produce similarly upshifted EBWs. Depending on how strongly the waves interact, this can result in cascades of PDIs excite multiple daughter wave frequencies shifted by integers of characteristic ion frequencies around the pump frequency. For MAST Upgrade parameters, the LH frequency is ∼ 200 MHz so cascades of PDIs would produce peaks shifted by ∼ 200 MHz in the observed frequency spectrum. An example of this is shown in figure 2 which is the result of particle-in-cell[10] simulations of a 37 GHz gyrotron wave converting into an EBW at the UH layer in MAST Upgrade, see Ref. 11 for more details. The threshold gyrotron beam power density threshold for this process is estimated to be on the order $\sim 0.1 - 1.0\mathrm{MW/m}^2$ using Ref. 12. Similarly, interactions with IBWs would produce shifts of ∼ 4 MHz. The trajectories of the daughter waves are highly dependent on the plasma and may in worst case cause great heating and current drive losses. The EBW daughter waves may escape the plasma through an inverse O-X-B, allowing it to be measured outside the plasma by a radiometer. The escaping waves may provide indications of local plasma parameters at the UH layer, of a power threshold and on how the PDIs affect O-X-B operation above the threshold.

## III. RADIOMETER SPECIFICATIONS

A schematic of the radiometer design for PDI detection at MAST Upgrade is presented in the box diagram in figure 3. The design comprised of a horn, a radio frequency (RF) line, a mixer-low frequency amplifier (LFA) and a fast acquisition module. In the following, we present arguments for the modules and their specifications.

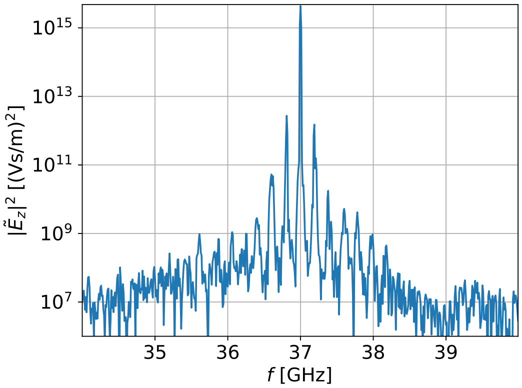

FIG. 2. Transverse electric field frequency spectrum from Particle-in-cell simulations of conversion from X-mode to EBW at the UH layer in MAST Upgrade, displaying several PDI daughter wave frequencies shifted by approximately integer multiples of the LH frequency of ∼0.2 GHz from a 37 GHz pump wave. The spectrum of the component associated with O-mode in the same frequency range is at $\sim 10^6$ (Vs/m)$^2$. More details on the simulations can be found in Ref. 11. Note the simulation was made with a higher 37 GHz pump frequency as this was previously considered for MAST Upgrade, however, it is expected that a 34.8 GHz gyrotron can produce similar spectra.

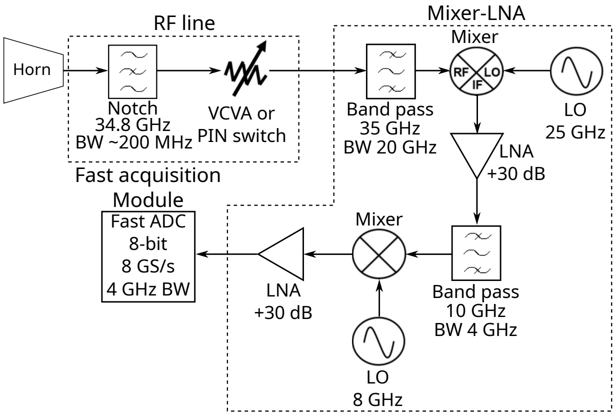

FIG. 3. Box diagram of the radiometer, comprised of the RF line, which protects the diagnostic from the gyrotron lines, the Mixer-LNA, which down mixes the signal, and finally a fast acquisition module to record bursts of high sample rate signals.

### A. Protection from the gyrotron lines in the RF line

As shown in the simulations in figure 2, PDIs can excite frequencies at shifted by characteristic ion frequencies around the gyrotron frequency, here LH frequency shifts of ∼200 MHz. The challenge is now that the gyrotron lines must be attenuated to protect the radiometer but the shifted lines generated by PDIs must still be visible. The frequency tolerances of the two new 0.9 MW gyrotrons at MAST Upgrade is ±100 MHz so a 80 dB notch filter with a bandwidth (BW) of 200 MHz should block out the gyrotron lines but leave shifts of an LH frequency available on either side. Unfortunately, the relatively weakly magnetized ions have an ion cyclotron frequency of ∼ 4 MHz, which is much lower than the frequency tolerances, and daughter waves from primary PDIs with low IBW branches can therefore not be observed safely.

In addition to the notch filter, a 40 dB voltage controlled variable attenuator (VCVA) is added. This component attenuates the entire signal when the gyrotrons start and protects the radiometer as the gyrotron lines may initially chirp from outside the notch filter while the gyrotron cavities warm up[13]. Furthermore, it may protect the radiometer from strong PDI signals.

### B. Heterodyne mixing

In the mixer-Low Noise Amplifier (LNA) block, the signal is down mixed using a local oscillator (LO) at 25 GHz. The motivation to shift the obtained signals down to a lower frequency range is that amplification and filtering typically can be performed more optimally at lower frequency, resulting in better signal to noise ratios. The principle of heterodyne mixing in the context of microwave diagnostics is explained in greater detail in Refs. 14 and 15. In heterodyne mixing, both a down- and upshifted signal are produced. A band pass filter first blocks out signals below 25 GHz and above 45 GHz which may interfere with the frequencies of interest after the mixing. After shifting the signal to an intermediate frequency (IF) range, the signal is amplified using a 30 dB LNA before going to another set of band pass filter, mixer and LNA. This time the band pass filter has a 4 GHz BW around 10 GHz and the signal is further downshifted using an 8 GHz LO. The LNA is again 30 dB and the signal then leaves the mixer-LNA block. The choice of two separate heterodyne mixing stages rather than a single is to relax the requirements of the filters before the mixers and may allow for later extensions if another frequency range is desired.

### C. The fast acquisition module

The final module is where the signal is recorded. The signal is sent to a fast digital-to-analog converter (ADC) capable of recording 8 GS/s of 8-bit data with a 4 GHz bandwidth and 2 GB memory. This frequency range will allow for several LH frequency shifts to be observed around the gyrotron lines as well as possibly larger shifts from higher order nonlinearities such as four-wave mixing. The fast acquisition module is to be connected to the last LNA through a short BNC cable to lower losses at this stage. The memory would allow for ∼300 ms measurements to be made. However, the samples are continuously read out from memory and is stored externally,

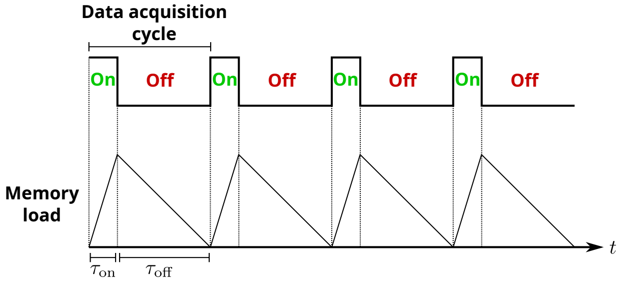

FIG. 4. Illustration of the data acquisition cycle of the fast acquisition module. The module records data to its memory while at the same time unloading it to external storage at a slower rate. It records for an on time of $\tau_{\text{on}}$, then stops for an off time of $\tau_{\text{off}}$ until the memory is unloaded completely.

albeit at a slower rate than they are being written to the memory. This may extend the length of a signal that can be recorded to more than a second. There are two data acquisition strategies. One is to measure in pulses throughout a discharge. Since the duration of a discharge may exceed the memory capacity, data is recorded for an on time of $\tau_{\text{on}}$ and stopped before the memory limit is exceeded. Then the data is unloaded for an off time of $\tau_{\text{off}}$. Afterwards, the data acquisition starts over, see figure 4. We define the duty cycle as $d = \tau_{\text{on}}/(\tau_{\text{on}} + \tau_{\text{off}})$ which we expect will typically be around 10% but can be varied. The alternative acquisition strategy is to record transient events continuously without exceeding the memory capacity. In this case, the duty cycle is $d = 100\%$.

### D. Exploiting gyrotron launchers for the receiver

The receiver can be integrated into the transmission line of one of the midplane gyrotron launchers. This will allow the diagnostic to utilize the directional capabilities of the launcher to map the spatial distribution of PDI daughter wave radiation. Integration into the transmission line means that one gyrotron must be off for the diagnostic to be used. The benefit, however, is that no modifications have to be made to the vacuum vessel and that the receiver can be located outside the tokamak hall.

There are different ways in which the PDI daughter waves may reach the radiometer. One way is for the frequency shifted EBW daughter wave to be generated in a way such that it performs an inverse O-X-B conversion, resulting in O-mode radiation which may reach the radiometer either directly or indirectly by bouncing between the walls and plasma cutoffs multiple times first, see figure 5. This possibility is investigated using ray tracing. First, a gyrotron O-X-B trajectory is traced. Next, the selection rules are evaluated along the first ray, using a hot dispersion relation for the frequency shifted EBW daughter wave and assuming unmagnetized ions for the LH daughter waves[3]. If the selection rules are satisfied and the resulting EBW daughter waves are able to perform inverse O-X-B, their trajectory out of the plasma is recorded. In order to satisfy the selection rules, escaping waves do not return directly back to the gyrotron, instead they emerge further along the direction of the magnetic field lines. The other midplane launcher, found further down the field lines, can therefore be aimed at interaction region, see figure 6. A switch is integrated into the transmission line of one of the gyrotrons which allows the launcher to be used for the radiometer, see figure 7. The switch, when engaged, leads the received signal from the launcher to a corrugated horn[16] optimized for the gyrotron frequencies which then goes to the radiometer. The switch and radiometer are to be placed outside the blockhouse and the high voltage area surrounding the gyrotrons to allow for easy access.

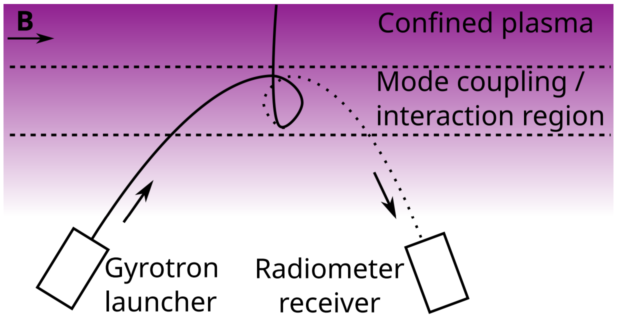

FIG. 5. Illustration of a gyrotron beam performing O-X-B (solid line) and producing a PDI daughter wave (dotted line) which escapes through inverse O-X-B to a receiver found further down the magnetic field lines.

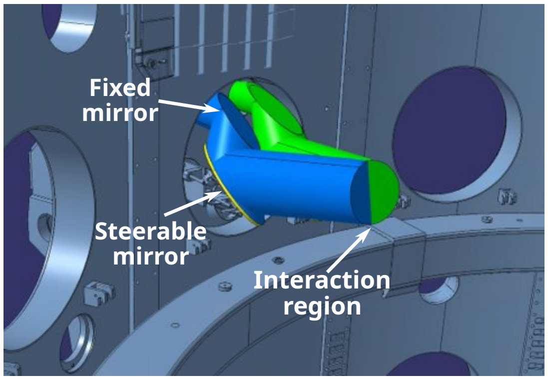

FIG. 6. CATIA illustration of the in-vessel midplane launchers. One can be used as a gyrotron launcher (green) while the other can be operated as a receiver for the radiometer (blue), aiming its viewing cone at the PDI interaction region.

Another possibility for daughter waves to be observed outside the plasma is for the EBWs to tunnel out through the evanescent region between the UH layer and the R-cutoff. Waves that tunnel a shorter distance will be more likely to be observed outside the plasma and would typically be waves propagating perpendicular to the flux surfaces. The steeper the gradients are, the more of the waves will tunnel out and this contribution to the signatures outside the plasma would therefore be more promi-

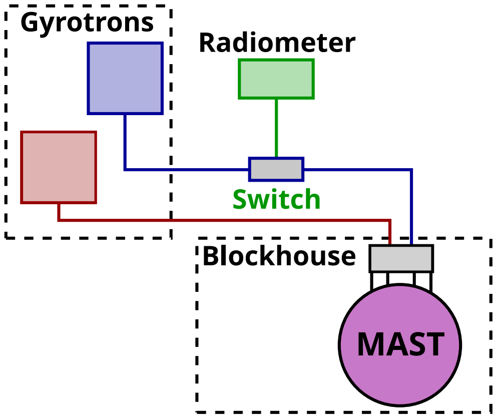

FIG. 7. An overview of how the radiometer is integrated into the transmission line of one of the gyrotron. A switch is placed inside the transmission line which when engaged leads waves coming from the vessel to the radiometer.

nent in H-mode than in L-mode. The tunneling waves are likely not going to propagate directly to either of the midplane launchers, however, they may bounce around outside the plasma and eventually reach the launcher as transmission back into the plasma after each reflection at the walls will be incomplete.

## IV. CONCLUSION

As MAST Upgrade prepares for O-X-B heating and current drive with new 0.9 GW gyrotrons, there is an interest in investigating the impact of nonlinear wave interactions on the mode coupling scheme, in particular PDIs near the UH layer. The PDIs can generate daughter waves at frequencies shifted by $\sim$ 200 MHz from the 28/34.8 GHz gyrotron lines, some of which may be observed outside the plasma. Integrating a microwave receiver into the transmission line of one of the two midplane gyrotron launchers will allow for observations of escaping PDI daughter waves to be made. The steering capabilities furthermore enables spatial mapping of the PDI signatures. A design for the radiometer was presented, which includes a notch filter and a VCVA to protect the radiometer from the chirping gyrotron lines. The radiometer will be capable of recording 8-bit data with a 4 GHz bandwidth continuously for upwards a second or alternatively operate with a $\sim 10\%$ on-off duty cycle. The diagnostic will be essential for investigating the viability of high power O-X-B in MAST Upgrade, which may have a profound impact on the design of STEP.

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