PLASMA INSTABILITY STUDIES OF THE SUSI 18 GHz SOURCE

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Abstract

Instabilities in magnetized plasmas, such as the cyclotron instabilities identified at JYFL [1], can cause fast variations of the extracted Electron Cyclotron Resonance Ion Source (ECRIS) beam current. In order to understand the effect of the radial component and longitudinal gradient of the magnetic field on plasma stability a series of measurements has taken place using the Superconducting Source for Ions (SuSI) at the National Superconducting Cyclotron Laboratory (NSCL). We present here the results from investigations into the instability characteristics of the beam current from SuSI at 18 GHz by varying longitudinal and radial magnetic field profiles, injected microwave power, and bias disk voltage. Our investigation shows multiple regions of beam current variation within the magnetic field vs. power parameter space with multiple distinct modes of variance.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) and the National Superconducting Cyclotron Laboratory (NSCL) require intense, high charge state beams for normal facility operations. As a result, any limitation of the transmitted beam current can diminish the total operational capacity of the facilities. The limitation of the extracted beam current from ion sources operated at high magnetic field strengths is one such diminishing factor. Investigations into the limitations of Electron Cyclotron Resonance Ion Source (ECRIS) performance at the high-performance limit for high charge state extraction have made great strides in the last several years. In particular the studies out of Jyväskylä [1,2] and Nizhny Novgorod [3,4] have revealed that kinetic plasma microinstabilites, in the form of cyclotron instabilities, are a driving factor of these limitations.

These instabilities occur in local regions of the ECR plasma where the magnetic field induced temperature anisotropy heavily favors the transverse component of the hot ($T > 10$ keV) electron population, $T_\perp >> T_\parallel$ [1]. Those electrons can escape into the magnetic loss cone by depositing the energy stored in their gyro-motion into the background plasma in the form of microwave radiation [3,5]. The plasma, in response to suddenly losing part of its electron population, ejects part of its ion population until quasi-neutrality can be regained. At this point the heating process returns to its desired role of creating more ions until the degree of anisotropy requires the instability to be triggered. These events create the beam current oscillations that are observed in the extracted beam.

As reported in [2], a threshold has been measured for these instabilities to occur relative to the magnetic minimum and injected microwave power within the plasma chamber. This threshold measurement does not include two key features of the magnetic field structure: the radial field and the field's gradient at the resonance surface. An electromagnet hexapole coil is required in order to probe the former and the latter must be probed by an ECR with more than two longitudinal coils. Insight to the latter issue has been given by Benitez with her measurement of the spectral temperature in VENUS [6]. It was found that the spectral temperature of the plasma is independent of the axial gradient at resonance, while having a strong dependence on the minimum of the field structure. However, this measurement is incapable of distinguishing the degree of anisotropy of the electron population in the system. This limitation is due to its reliance upon a bremsstrahlung spectrum that carries no information on the anisotropy; leaving open an avenue for exploration into the field structures influence upon the ECR plasma characteristics.

We report here measurements into the effect of the hexapole and magnetic field structure upon the state of stability of the ECR plasma. Sweeping the injected microwave power across multiple magnetic field distributions revealed stability characteristics dependent on the field distribution rather than only the minimum value. Two potentially new instabilities were found and are named here as "fast" and "slow", for their repetition frequencies with respect to the previously mentioned cyclotron instabilities. An increasing hexapole was found to decrease the probability of finding a stable operating point in three of four experimental cases. X-ray measurements were also made in order to confirm that the hot electron population is the population predominately affected by the instabilities.

APPARATUS AND PROCEDURE

All measurements were taken using SuSI at the NSCL. The four superconducting solenoid coils and superconducting hexapole create its longitudinal and radial magnetic fields respectively [7]. The four solenoids coils allow us to create different magnetic field distributions with the same B_{min} but with different magnetic mirror ratios at injection and extraction; isolating the effect of the magnetic field distribution from its local minimum. Four sets of fields were used to explore the stability characteristics of the ECR plasma. Each set was designed to have a magnetic mirror ratio that was either larger or smaller than the standard operating field scaling laws [8], for both the injection and extraction sides of the

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Table 1: Multiple Experimental Ranges Of the Confining Feld Were Used. Each Range's Injection And Extraction Mirror Ratio Were Set To Be Higher Or Lower Than the Standard Operating Feld. Calculations Were Performed Using Poisson.

	Standard	Range 1	Range 2	Range 3	Range 4
B_{min}/B_{ecr}	0.71	0.70	0.70	0.70	0.70
B_{inj}/B_{ecr}	3.96	4.08	3.70	3.42	4.10
B_{ext}/B_{ecr}	1.94	2.02	1.77	1.94	1.60

ECR plasma chamber. Table 1 shows an example calculation comparing the characteristics of each of the fields, with a B_{min}/B_{ecr} = 0.7, to that of the standard operational field, B_{min}/B_{ecr} = 0.71. Each of the longitudinal field ranges were measured with each of the radial field settings used, $B_{r,wall}$ = 1.1 T, 1.2 T, and 1.322 T, with SuSI's standard operational field setting being $B_{r,wall}$ = 1.22. During the measurement the microwave power was swept from 50 W to 550 W in 100 W steps for each magnetic field setting. The extracted beam current, reflected microwave power, and bias disk current were measured during this time to determine if the plasma was unstable. Any operating point that showed periodic beam current oscillations and bursts of microwave radiation were classified as unstable. This created a map of the source's stability characteristics for each field and power setting.

The source was held at a fixed bias of 20 kV during these measurements each of the measurements described above. A 90° dipole was used for charge selection followed by a solenoid focusing lattice to guide the selected charge state current into a Faraday cup. Reflected/emitted microwaves from the plasma chamber were measured with an HP 8473C Low Barrier Schottky Diode connected to a bi-directional waveguide coupler along the path of the injection waveguide. Measuring fluctuations in the bias disk current required connecting an analog-to-fiber converter in parallel with the bias disk power supply. A fiber-to-analog receiver converted the optical signal to a measurable electrical signal. All three electrical signal were measured and recorded in coincidence using a Tektronix MDO3054 oscilloscope. Bremsstrahlung measurements were taken on axis using a High Purity Germanium Detector (HPGe).

An Argon plasma heated with a Klystron driven at 18 GHz was used for all measurements. During the field mapping process the neutral gas pressure was held at 130 nTorr at the injection side of the plasma. The bias disk was held at a constant -17 V as it was found that higher voltages created noise in the measured current that made it difficult to disentangle an unstable operating point from one with a lot of electrical noise.

RESULTS

The measurement revealed an unexpected result: three different kinds of beam current oscillations. Along with the previously reported cyclotron instabilities we also found what have been named "fast" and "slow" instabilities; with the names being a reference to their repetition frequency, f_{rep}, relative to the cyclotron instabilities ($f_{\text{rep,slow}} < f_{\text{rep,cyclotron}} < f_{\text{rep,fast}}$). Figure 1 shows an example each of these instabilities for the 2+ and 8+ charge states of Argon.

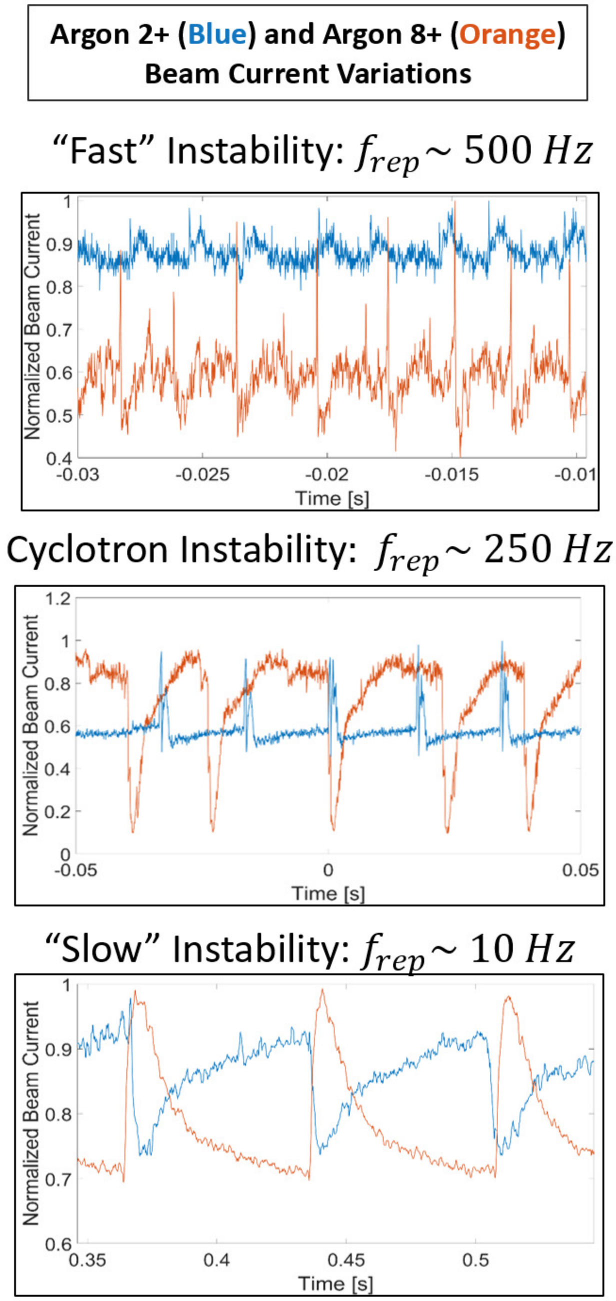


Figure 1: Plots of the manifestations of the instabilities in the extracted beam current.

The "fast" instabilities tend to have spike in beam current lasting about 5μs followed by a sudden drop in the beam current leading to a slower recovery period lasting ~100μs. The cyclotron instabilities demonstrated the characteristics expected from the previous studies, [1,2]. The instability begins with a fast drop in the current lasting ~10μs followed by a recovery period on the order of milliseconds to tens of milliseconds. The final instability, the "slow" instability, has the opposite current features of the other two instabilities. For the 8+ charge state we see that there is a first a drop in the beam current on the order of 10μs followed by a slow rise and recovery period lasting on the order of 20 ms. As a result, the "slow" instability increases the average beam current extracted from the ion source for a short time. Further investigation shows that each of these instabilities can manifest in each of the extracted charge states. It is easy to see that both the "fast" and cyclotron type instabilities gain current on average for low charge states and lose current on average for high charge states, acting consistently with the features described in [1]. The "slow" instabilities act in the opposite manner; with low charge states losing current on average and high charge states gaining current.

Plots of the microwave signals in coincidence with the oscillating beam current for each of the instabilities are given in Fig. 2. Both the "fast" and cyclotron instabilities are characterized by a sudden burst of microwave energy that lasts on the order hundreds of microseconds for the "fast" instabilities and ~5μs for the cyclotron instabilities. The slow instabilities on the other hand only have a sudden increase in the detected microwave power, emitted from the source chamber, that continues to increase slowly and appearing to follow the extracted beam current.

Stability Map

To fully understand how the confining field and the injected microwave power can affect the plasma stability we have created a series of color maps (Fig. 3) displaying whether or not the plasma is unstable and in what way. The first column and the last row (both in green) represent the injected microwave power and B_{min}/B_{ecr}, creating a coordinate grid for each of the field settings used. The maps display the manifestations of the instability, as “fast”, cyclotron, or “slow”; displayed as blue, yellow, and red, respectively, in each of the grid coordinates. Each of the maps then represents a single radial field setting, given above each map.

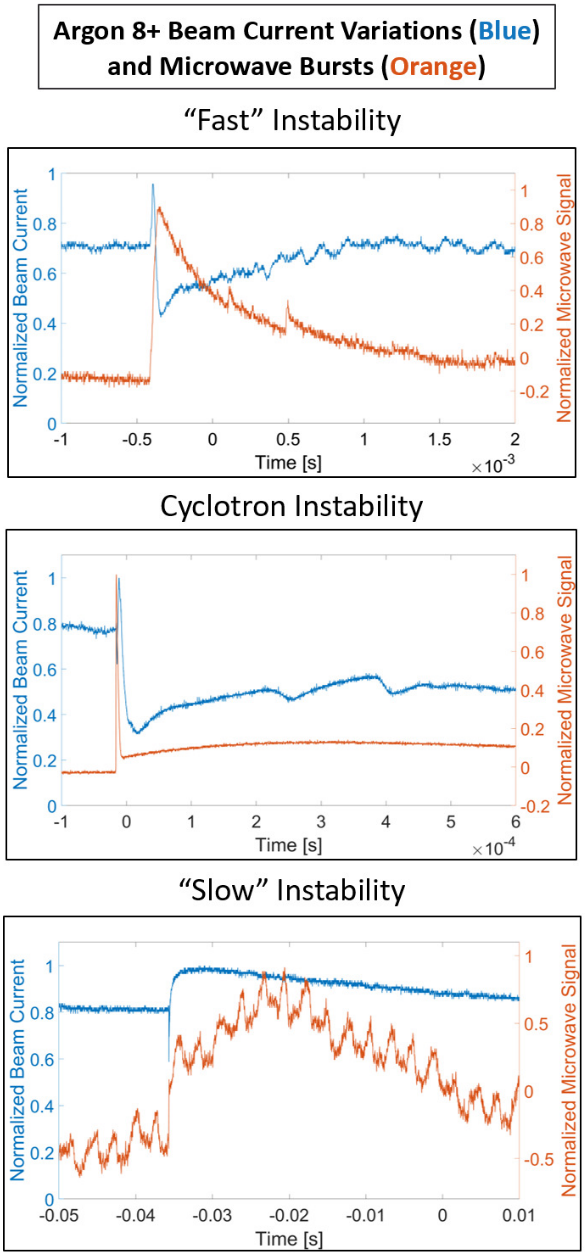
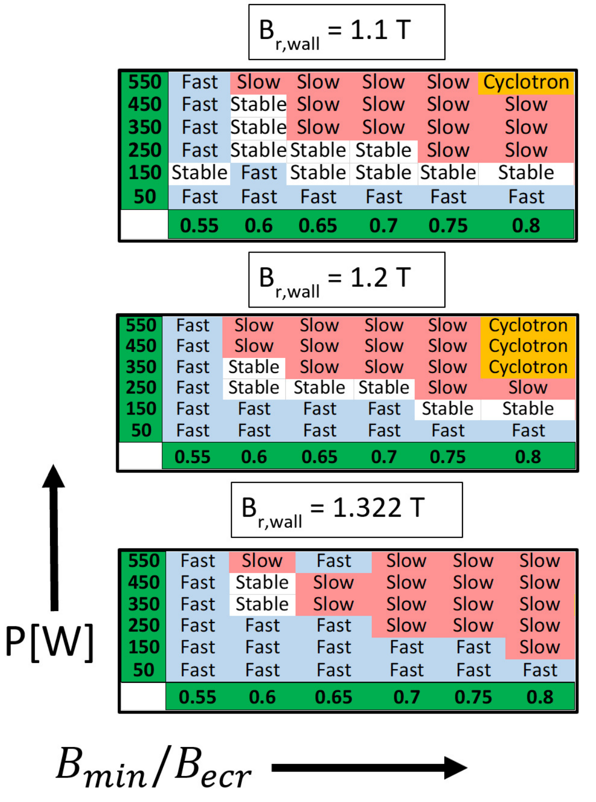


Figure 2: Measurements of each of the instability manifestations for the 8+ charge state in coincidence with their corresponding reflected microwave signal.

The ECR itself divides the instability region into two sections: with lower power and field settings predominately displaying “fast” instabilities and high field and power settings predominately displaying “slow” instabilities. If there is a stable point to be found, then it would appear between these two regions. While the stability maps presented do show more complexity than the ones presented in [1] and [2] the same general trend with respect to the magnetic field and power does persist. We observe that as the magnetic minimum increases that a stable operating point is more likely to occur for lower injected power, agreeing with the results found at JYFL. We find that the hexapole does influence the stability characteristics of the ECRIS plasma, with a general trend of decreasing the probability of finding a stable operating point as the hexapole field increases. As the hexapole field increases the stable region slowly starts to disappear as the two unstable regimes converge towards one another. This trend exists for three of the four experimental ranges used in our measurements, with the exception being the fourth experimental range where the trend reverses. It is also interesting to note that the cyclotron type instabilities are not well represented across the charts, with the “fast”



$B_{r,wall}$ = 1.1 T

550	Fast	Slow	Slow	Slow	Slow	Cyclotron
450	Fast	Stable	Slow	Slow	Slow	Slow
350	Fast	Stable	Slow	Slow	Slow	Slow
250	Fast	Stable	Stable	Stable	Slow	Slow
150	Stable	Fast	Stable	Stable	Stable	Stable
50	Fast	Fast	Fast	Fast	Fast	Fast
	0.55	0.6	0.65	0.7	0.75	0.8

$B_{r,wall}$ = 1.2 T

550	Fast	Slow	Slow	Slow	Slow	Cyclotron
450	Fast	Slow	Slow	Slow	Slow	Cyclotron
350	Fast	Stable	Slow	Slow	Slow	Cyclotron
250	Fast	Stable	Stable	Stable	Slow	Slow
150	Fast	Fast	Fast	Fast	Stable	Stable
50	Fast	Fast	Fast	Fast	Fast	Fast
	0.55	0.6	0.65	0.7	0.75	0.8

$B_{r,wall}$ = 1.322 T

550	Fast	Slow	Fast	Slow	Slow	Slow
450	Fast	Stable	Slow	Slow	Slow	Slow
350	Fast	Stable	Slow	Slow	Slow	Slow
250	Fast	Fast	Fast	Slow	Slow	Slow
150	Fast	Fast	Fast	Fast	Fast	Slow
50	Fast	Fast	Fast	Fast	Fast	Fast
	0.55	0.6	0.65	0.7	0.75	0.8

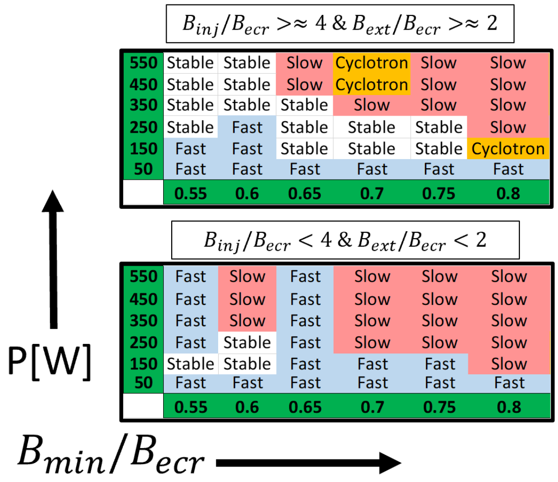
Figure 3: The instability field maps for experimental range 3 at every hexapole field used. The green row and column show B_{min}/B_{ecr} and the injected microwave power, respectively. The blue, orange, and red cells represent the "fast", cyclotron, and "slow" instabilities respectively.

and “slow” type instabilities being the most commonly observed. Once again, the exception to this rule was the fourth experimental range.

Changing the axial field distribution was also found to change the stability characteristics of the plasma. Figure 4 gives an example of the stability map for two of these field distributions for a constant hexapole field strength. It can be seen that lowering the injection and extraction field maximum away from the classical scaling laws makes the plasma more unstable. It is also important to note that the extracted current peaks at a B_{min}/B_{ecr} = 0.8 around the distribution prescribed by the scaling laws. This peak occurs at a B_{min}/B_{ecr} = 0.65 in the distribution that deviates from those laws. From this we observe that the stability characteristics of the plasma are not entirely dependent on the B_{min}/B_{ecr} value.

Bremsstrahlung Measurements Across the Stability Threshold

Measurements of the bremsstrahlung spectra were taken for both stable and unstable operating conditions. All measurements were taken using experimental range 1, $B_{inj}/B_{ecr} \geq 4$ and $B_{ext}/B_{ecr} \geq 2$. Figure 5 compares the x-ray spectra for two operating points on either side of an instability threshold. Changing the longitudinal magnetic field profile from B_{min}/B_{ecr} = 0.567 to 0.577 induced a "slow" type instability. The injected microwave power and radial field at the wall were fixed at 400 W and 1.1 T, respectively, during these measurements. It is clear from the plot that the spectra do not change from one side of the threshold to the other. This may result from the low duty cycle of the x-ray bursts from the source cavity. It is reasonable to assume that the spectra will look very similar as minor changes to the system will not greatly affect the diffusion of electrons unaffected by the instability out of the plasma. It is necessary to time resolve these measurements for comparisons around the instability threshold. Figure 6 compares the results of the bremsstrahlung spectra for three different magnetic field operating points with fixed injected microwave power and radial field strength at the wall. The first two spectra behave as described in [6] with the final spectra, B_{min}/B_{ecr} = 0.8, exhibiting a lowered energy peak over the 75 – 100 keV range but an increased count rate within the 200 – 400 keV portion of the high energy tail. Figure 7 shows four spectra



$B_{inj}/B_{ecr} >\approx 4$ & $B_{ext}/B_{ecr} >\approx 2$

550	Stable	Stable	Slow	Cyclotron	Slow	Slow
450	Stable	Stable	Slow	Cyclotron	Slow	Slow
350	Stable	Stable	Stable	Slow	Slow	Slow
250	Stable	Fast	Stable	Stable	Stable	Slow
150	Fast	Fast	Stable	Stable	Stable	Cyclotron
50	Fast	Fast	Fast	Fast	Fast	Fast
	0.55	0.6	0.65	0.7	0.75	0.8

$B_{inj}/B_{ecr} < 4$ & $B_{ext}/B_{ecr} < 2$

550	Fast	Slow	Fast	Slow	Slow	Slow
450	Fast	Slow	Fast	Slow	Slow	Slow
350	Fast	Slow	Fast	Slow	Slow	Slow
250	Fast	Stable	Fast	Slow	Slow	Slow
150	Stable	Stable	Fast	Fast	Fast	Slow
50	Fast	Fast	Fast	Fast	Fast	Fast
	0.55	0.6	0.65	0.7	0.75	0.8

Figure 4: The instability maps for experimental ranges 1 (top) and 2 (bottom). The hexapole field for both maps is 1.1 T at the plasma chamber wall.

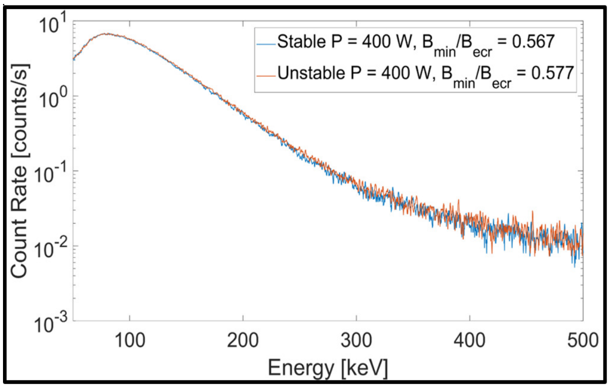


Figure 5: This figure compares the bremsstrahlung spectra on either side of the instability threshold.

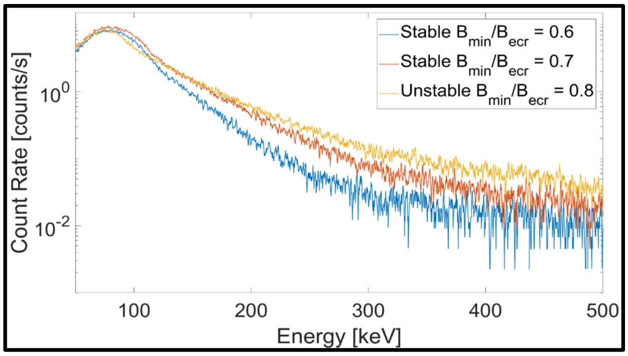


Figure 6: Bremsstrahlung spectra for a constant injected microwave power of 250 W and hexapole field strength at the wall of 1.1 T.

demonstrating the effect of keeping a constant B_{min}/B_{ecr} ratio while varying the injected power and radial field at the wall. The stable operating point with 250 W injected microwave power and a 1.1 T magnetic field at the wall acts as a good point for comparison. We can see that increasing the radial field at the wall by 0.1 T, changing the plasma into the “fast” instability regime, will give a similar effect on the spectra as simply increasing the microwave power by 200 W. Increasing both the injected microwaved power and the radial field at the wall makes the plasma undergo a “slow” type instability and causes a drastic change in the measured spectra. Rather than observing an increase in the count rate equal to the sum of the increase presented by the changing the radial and injected power individually, we find that the 75 keV peak has a lower count rate with a bulging of the 110 - 300 keV portion of the high energy tail.

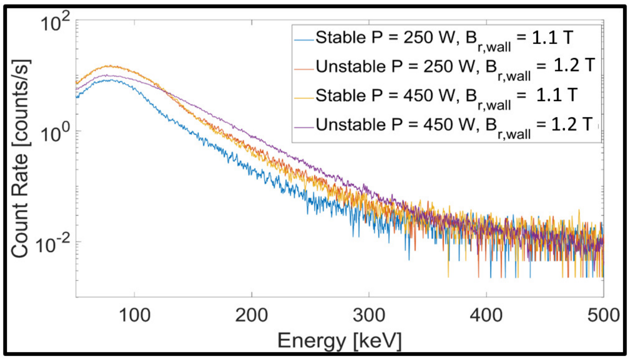


Figure 7: Bremsstrahlung spectra for a constant B_{min}/B_{ecr} = 0.8.

CONCLUSIONS

Our recent measurements have provided us insight into how the magnetic field distribution of the ECR ion source confining field affects the stability characteristics of the plasma. We found that the variations of the extracted beam currents, induced by plasma instabilities, can manifest in three different ways named here as "fast", cyclotron, or "slow". Parametric stability maps were accumulated that found that an increasing hexapole field strength made the plasma less stable. It was also found that changing the field distribution away from the scaling laws also makes the plasma more unstable. Bremsstrahlung measurements far from the stability threshold show that higher energy electrons are more likely to escape into the loss cone while the plasma is unstable. Future measurements of the energy spectra around the threshold need to be time resolved in order to determine the shift in the energy content of the distribution of lost electrons.

Future work will include determining the nature of each of the two new instability manifestations. From this we hope to conclude whether or not the different manifestations are caused by different mechanisms. Efforts into creating a time resolved measurement system for the bremsstrahlung spectra are also being planned.

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