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MICROCONTROLLERS AS GATE AND DELAY GENERATORS FOR TIME RESOLVED MEASUREMENTS

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Abstract

The diffusion of electrons from ECRIS plasmas results in the emission of a continuous energy distribution of photons from the plasma chamber. Measurements ECRIS bremsstrahlung that are both time and energy resolved of the are often difficult to perform due to the 10's – 100's ms timescale that the plasma evolves over. However, the advancement of low-cost microcontrollers over the last decade makes timing and gating photon spectrometers easier. We present a proof of principle measurement which uses an Arduino microcontroller as a gate-and-delay generator for time resolved ECRIS bremsstrahlung measurements. An example plot of the time resolved spectrum, triggered by beam current variation induced by kinetic instabilities is shown.

INTRODUCTION

Accelerator facilities like the National Superconducting Cyclotron Laboratory (NSCL) and the Facility for Rare Isotope Beams (FRIB) require high intensity, high charge state ion beams for facility operations. These facilities rely on electron cyclotron resonance (ECR) ion sources (ECRISs) to produce stable ion beams for their operations. The microwave heated plasmas within these devices can produce beams of highly charged ions. Those ions must undergo multiple ionizing collisions before escaping from the plasma chamber, making the ion confinement time and the electron-ion collision frequency two of the most important characteristic time scales within ECR ion source plasmas [1].

However, the ECR ion source plasma is also prone to microinstabilities that decrease the confinement time of ions. The combined microwave heating and loss-cone confinement creates populations of hot electrons ($E_{kin} > 10\,\text{keV}$) with large temperature anisotropies, $T_{\perp} >> T_{\parallel}$. The anisotropic electrons can excite and amplify electromagnetic plasma modes within the plasma chamber and, in doing so, drive themselves into the loss cone [2, 3]. By driving the hot electrons into the loss-cone, the instabilities limit the confinement time of highly charged ions and cause quasi-periodic losses of extracted beam current [4, 5].

Performing time-resolved measurements can provide insight into the dynamics of the electron and ion populations during unstable operation. To that end, we require non-invasive diagnostic whose acquisition systems can be triggered by the instabilities, rather than an external trigger [6–8]. Doing these kinds of measurements can be difficult, particularly if the measurement must take place over milliseconds. However, we can use Ardunio micro-controllers (AMC) as programmable gate and delay generators to take time-resolved measurements of the ion source bremsstrahlung during unstable operating.

This paper presents a proof-of-principle measurement of this technique using the facilities at the NSCL and seeks to demonstrate its feasibility as a low-cost method of performing time-resolved measurements. In particular, we will show the results of a test measurement where an AMC is used as a gate and delay generator of Bremsstarhlung measurements of the ECRIS plasma chamber, during unstable operation.

APPARATUS

This measurement was performed with the Superconducting Source for Ions (SuSI) at the NSCL[9] (Fig. 1). The ion source's confining magnetic field is created with four superconducting solenoids and a superconducting hexapole coil. The four axial solenoid coils provide longitudinal confinement while allowing for control over the injection and extraction maxima and the field minimum. The system's design allows each of the longitudinal field extrema to be varied independently. The extraction, einzel lens, and puller voltages were fixed at 20 kV, −18 kV, and −0.3 kV, respectively. Oxygen ions were extracted from the plasma chamber with a fixed neutral gas pressure of 131 nTorr, as measured by an ion gauge on the injection side of the plasma chamber. A 90° dipole was used for charge selection and guided the ions into a solenoid focusing lattice to guide the selected

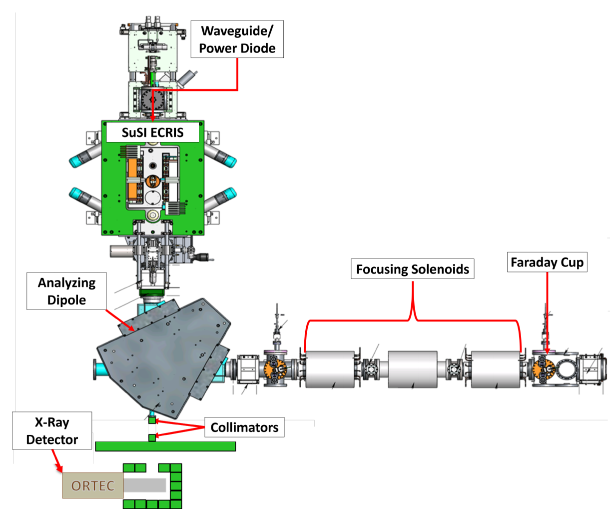

Figure 1: A schematic of the source-beamline configuration used for this test.

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charge state current into a Faraday cup. An Ortec High Purity Germanium (HPGe) detector was placed in line with the longitudinal axis of the ion source's plasma chamber. Two lead bricks and a cylindrical piece of tungsten collimated the flux of bremsstrahlung radiation emitted from the source.

For this test measurement, we used an Arduino UNO microcontroller as our gate and delay generator for the multichannel analyzer connected to our HPGe. For this test, the AMC (Fig. 2) measured the voltage drop created by the varying current across a variable resistor using the digital input port. Using the ion current as the trigger signal delayed the measurement by the ion the transit time, $\Delta T = 2.7\,\mu s$ for O^{6+} ions. The AMC measured the resulting voltage using the digital input port, which minimized the computational time necessary to trigger the TTL by bypassing the system's internal analog-to-digital converter (ADC), cutting the input-to-output time down to ~0.667 μs. For the duration of the measurement, we stored the AMC in an aluminum mesh cage to prevent sparking, with a BNC bulkhead connecting the AMC to the Faraday cup.

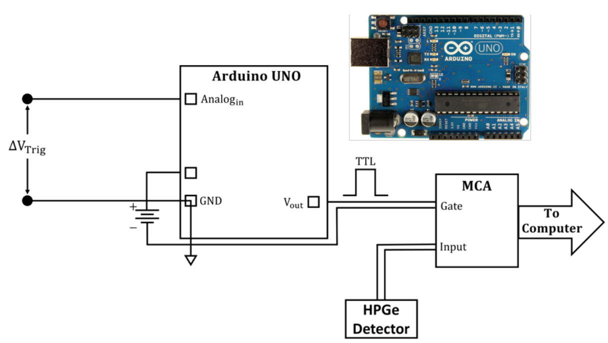

Figure 2: When the AMC measured a decrease in the measured current (voltage drop across a resistor, $V_{sig} < 500$ mV for a digital signal input), it would output a TTL signal to gate the MCA used to collect data from the HPGe detector. The MCA then sent the gated data to a computer running the ORTEC MAESTRO spectrometer program.

We performed two measurements as part of this test, with the goal of observing how the bremsstrahlung distribution would change over the duration of the instability. In the first measurement, the TTL was output immediately following the measured beam current variation, $\delta t = 0.667\,\mu s$. In the second measurement, we manually programmed an 8 ms delay into the micro-controller. The output TTL width was fixed at w = 100 μs and the instability repetition period was approximately 50 ms, for an average duty cycle of 0.2%. Figure 3 shows an example cartoon of the gate timing for both measurements and an example picture of the measured current and gate signals, as seen during the measurement.

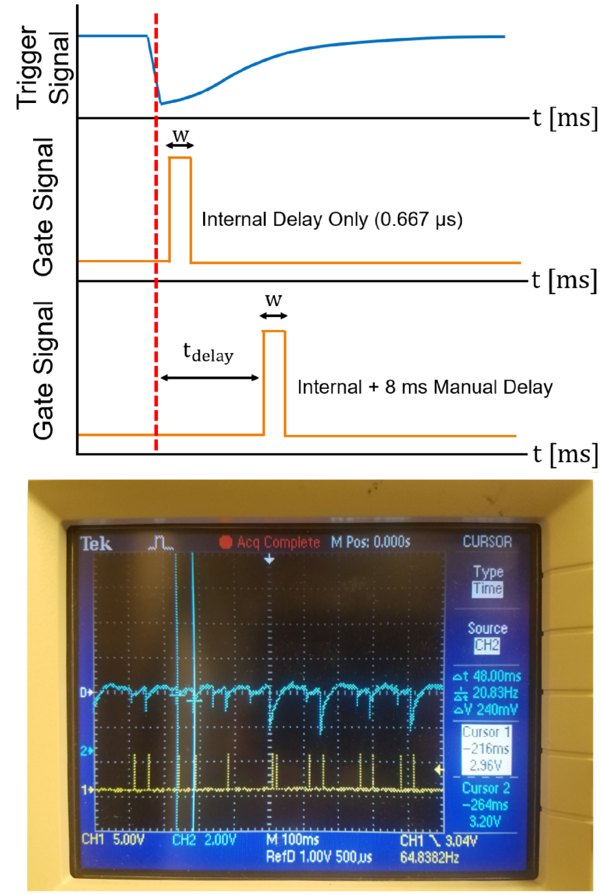

Figure 3: (Top) Two test measurements were performed: one where a TTL was output immediately after the isntability event, within 0.667 μs, and one where the TTL was delayed by 8 ms. (Bottom) Example picture of showing the TTL output along side the measured O^{6+} beam current, on an oscilloscope.

RESULTS

Figure 4 shows the results of this test. As we might expect, the total count rate is higher immediately after the instability event (no delay), indicating an increased electron diffusion rate. However, the count rate is at least an order of magnitude lower than what we would expect during time-averaged measurements (see [10, 11]). The low count rates introduce a large uncertainty in the energy-resolved portion of this measurement and make it difficult to observe any

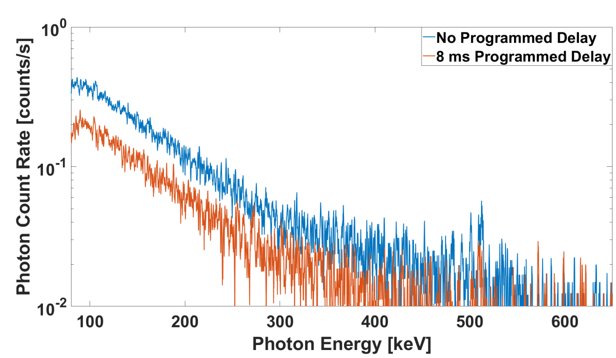

Figure 4: Comparison between the measured bremsstrahlung distributions when the gating TTL is output immediately after (blue) and 8 ms after (orange) the emission triggering of the AMC. The total measurement period for each distribution was 2000 s.

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major differences between the two distributions. For example, the spectral temperature, T_s ($\ln I_\gamma = -\hbar\omega/T_s$), between the two distributions are consistent with $T_{s,0ms}$ = 93 keV ± 27 keV and $T_{s,8ms}$ = 94 keV ± 11 keV. Time-averaged measurements with the same 'live-time' typically have an order of magnitude lower uncertainty in their spectral temperatures ($\delta T_s \sim$ 1–2 keV). Furthermore, Fig. 5 shows that there is little difference between the normalized distributions of each measurement. A higher count rate may demonstrate a larger difference between the two distributions. However, this result may indicate that the instability affects electrons across a broad energy domain, an observation made in some time-resolved measurements of electrons escaping from confinement from an ECR ion source during unstable operation [6].

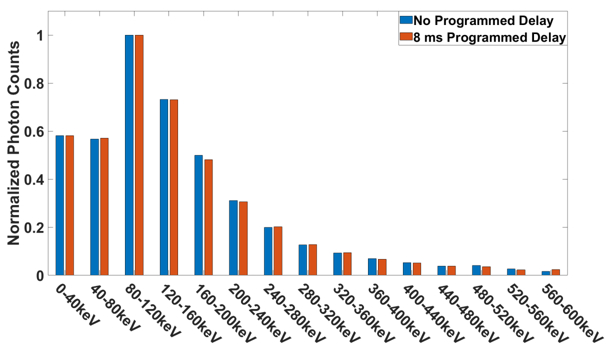

Figure 5: The re-binned and normalized (by largest value) bremsstrahlung distributions show that there is very little difference between the shapes of the two distributions, suggesting that the instability forces electrons of a broad range of energies into the loss cone during, or immediately after, the instability.

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REFERENCES

[1] R. Geller, "Electron cyclotron resonance sources: Historical review and future prospects (invited)," *Review of Scientific Instruments*, vol. 69, no. 3, pp. 1302–1310, 1998. doi:10.1063/1.1148797.

[2] I. Izotov *et al.*, "Microwave emission related to cyclotron instabilities in a minimum-B electron cyclotron resonance ion source plasma," *Plasma Sources Science and Technology*, vol. 24, no. 4, p. 045 017, Jul. 2015. doi:10.1088/0963-0252/24/4/045017.

[3] A. G. Shalashov, E. D. Gospodchikov, and I. Izotov, "Electron-cyclotron heating and kinetic instabilities of a mirror-confined plasma: the quasilinear theory revised," *Plasma Physics and Controlled Fusion*, 2020. doi:10.1088/1361-6587/ab7f98.

[4] R. Geller, *Electron Cyclotron Resonance Ion Sources and ECR Plasmas*. Routledge, Dec. 2018. doi:10.1201/9780203758663.

[5] O. Tarvainen *et al.*, "Limitation of the ECRIS performance by kinetic plasma instabilities (invited)," *Review of Scientific Instruments*, vol. 87, no. 2, 2016. doi:10.1063/1.4931716.

[6] I. Izotov *et al.*, "Measurements of the energy distribution of electrons lost from the minimum B-field—The effect of instabilities and two-frequency heating," *Review of Scientific Instruments*, vol. 91, no. 1, p. 013 502, Jan. 2020. doi:10.1063/1.5128322.

[7] O. Tarvainen *et al.*, "The biased disc of an electron cyclotron resonance ion source as a probe of instability-induced electron and ion losses," *Review of Scientific Instruments*, vol. 90, no. 12, Dec. 2019. doi:10.1063/1.5126935.

[8] R. Kronholm *et al.*, "Spectroscopic study of ion temperature in minimum-B ECRIS plasma," *Plasma Sources Science and Technology*, vol. 28, no. 7, Jul. 2019. doi:10.1088/1361-6595/ab27a1.

[9] P. A. Zavodszky *et al.*, "Design of SuSI - Superconducting source for ions at NSCL/MSU - I. The magnet system," *AIP Conference Proceedings*, vol. 749, pp. 131–134, 2005. doi:10.1063/1.1893382.

[10] B. Isherwood, E. Pozdeyev, G. Machicoane, J. Stetson, and D. Neben, "Plasma Instability Studies of the SUSI 18 GHz Source," in *Proc. 23th International Workshop on ECR Ion Sources (ECRIS'18)*, Catania, Italy, 2018, pp. 157–161. doi:10.18429/JACoW-ECRIS2018-WEA3.

[11] B. Isherwood and G. Machicoane, "Measurement of the energy distribution of electrons escaping confinement from an electron cyclotron resonance ion source," *Review of Scientific Instruments*, vol. 91, no. 2, p. 025 104, Feb. 2020. doi:10.1063/1.5129656.