Prospects for Machine Learning and Pulse Shaping on the Scorpius Accelerator

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E.R. Scott[1], B. Morris[2], Z.C. Shaw[1], M.E. Weller[1], T.J. Burris-Mog[1], B. Dunham[1], and P. Wiewior[1]

[1]Nevada National Security Site, North Las Vegas, NV 89030; [2]University of Nevada–Las Vegas, Las Vegas, NV 89154

Abstract

The Advanced Sources and Detectors (ASD) project aims to build Scorpius, a multi-pulse linear induction accelerator capable of delivering a 1.4 kA electron beam at energies up to 24 MeV. One of the primary advancements of Scorpius is the use of solid state pulsed power (SSPP) to provide flexibility in pulse shaping by independently triggering 45 individual stages stacked in each of 984 line replaceable units (LRU), with 168 LRUs dedicated to the injector. By leveraging circuit modeling of each LRU stage, a machine learning model of the SSPP will be developed to allow for optimization of the pulse shape, including pulse flattening and reflection mitigation. Particle-in-cell simulations of Scorpius have, for example, demonstrated that reducing reflections during multi-pulse operation mitigates beam spill by preventing the production of off-energy electrons between pulses, thereby abating stimulated ion desorption from the wall and beam charge neutralization [1]. This machine learning model will be validated and tuned with experimental data collected from the Scorpius injector and Integrated Test Stand.

Scorpius Accelerator

- Radiography provides important data from subcritical experiments since the end of underground testing.
- An important current question for stockpile stewardship is the behavior of plutonium under extreme conditions.
- The Scorpius accelerator is a linear induction accelerator (LIA) currently under development as a joint effort between multiple US laboratories to provide an intense light source for flash radiography.

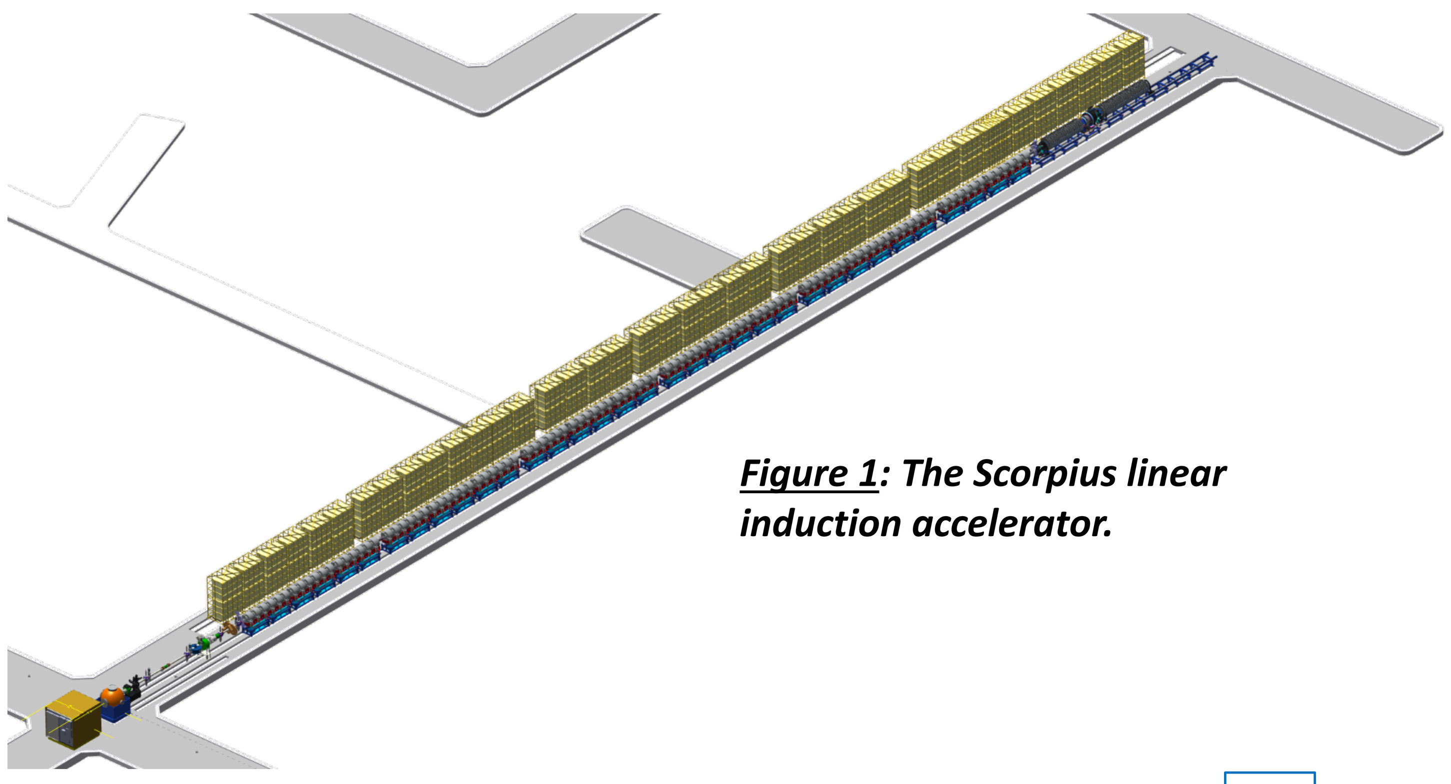

***Figure 1**: The Scorpius linear induction accelerator.*

- Scorpius will be capable of generating a relativistic 1.4 kA electron beam up to 24 MeV with a nominal beam energy of 22.1 MeV.
- In a first for LIAs, Scorpius will utilize solid-state pulsed power (SSPP) for increased flexibility in pulse shaping.

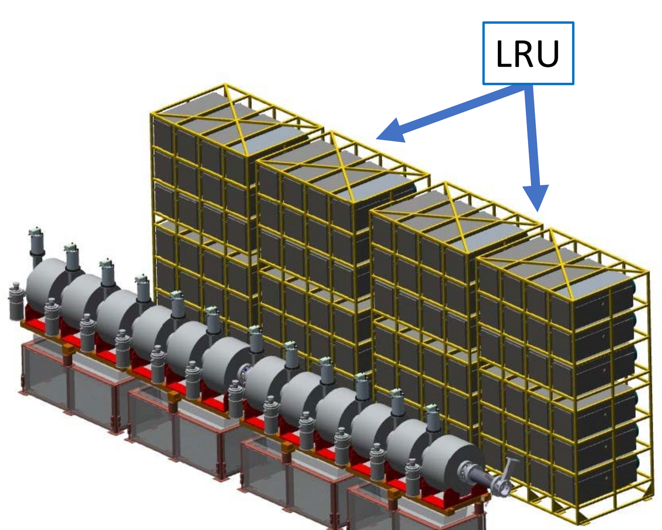

***Figure 2**: Solid-state pulsed power line replaceable units (LRUs).*

Solid-State Pulsed Power

- Conventional pulsed power systems have been replaced with solid-state pulsed power systems for Scorpius.
- Unlike conventional pulsed power systems designed to generate a particular pulse shape, a pulse generated by SSPP consists of the sum of many lower-amplitude pulses.
- Each of the 984 LRUs consists of a 45 stage Linear Transformer Driver (LTD) capable of pulse shaping via individually triggered stages.
- Individual triggering of these stages compounded by the number of LRUs allows for arbitrary pulse shaping of the injector waveform as well as the numerous accelerator gaps.
- To fully exploit this capability, automated tuning will be required to optimize the pulse shape of nearly 45,000 individual units.

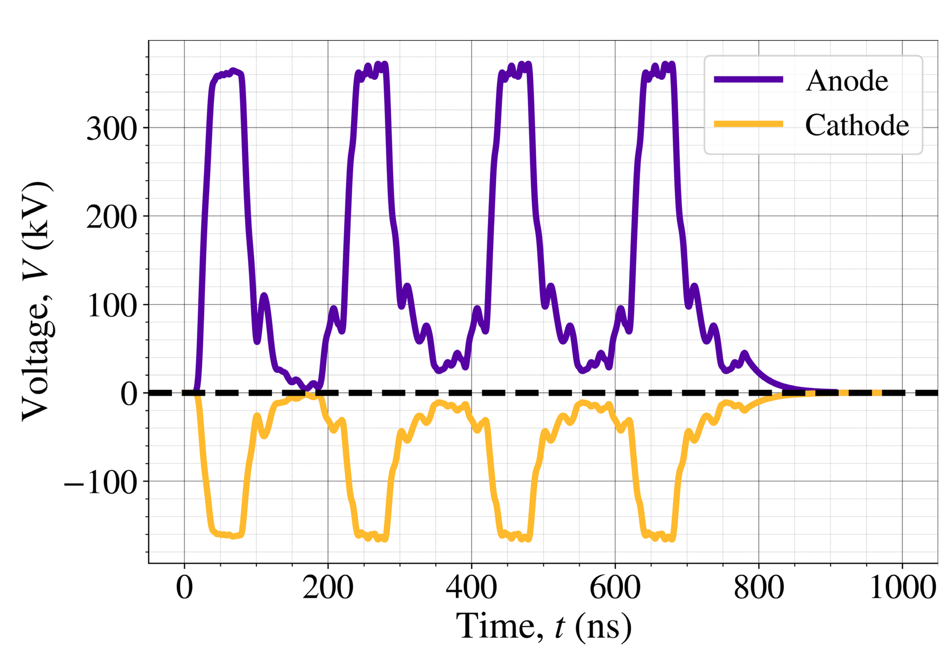

***Figure 3**: Push-pull anode and cathode voltages in the injector*

Circuit Modeling

- Existing circuit models of Scorpius SSPP have been used to simulate the expected pulse shape for the A-K gap and accelerating gaps.
- These models have been used to hand-tune the pulse shape to meet high-level beam parameter requirements for Scorpius.
- Circuit models of the SSPP continue to be refined to better match experimental data and accurately model secondary effects, e.g. reflections.
- Accurate circuit models are currently being developed for training initial machine learning models of the SSPP system

Applications: Pulse Flattening

- Variations in amplitude during the flat-top of the current pulse lead to slight differences in electron energy after acceleration.
- Because beam transport given a magnetic tune is energy-dependent, the combination of different electron energies results in different spot sizes at the target, thus blurring the radiograph.
- Accurate circuit modeling and machine learning may determine SSPP combinations that better produce a flat-top current pulse and thereby reduce these off-energy electrons.

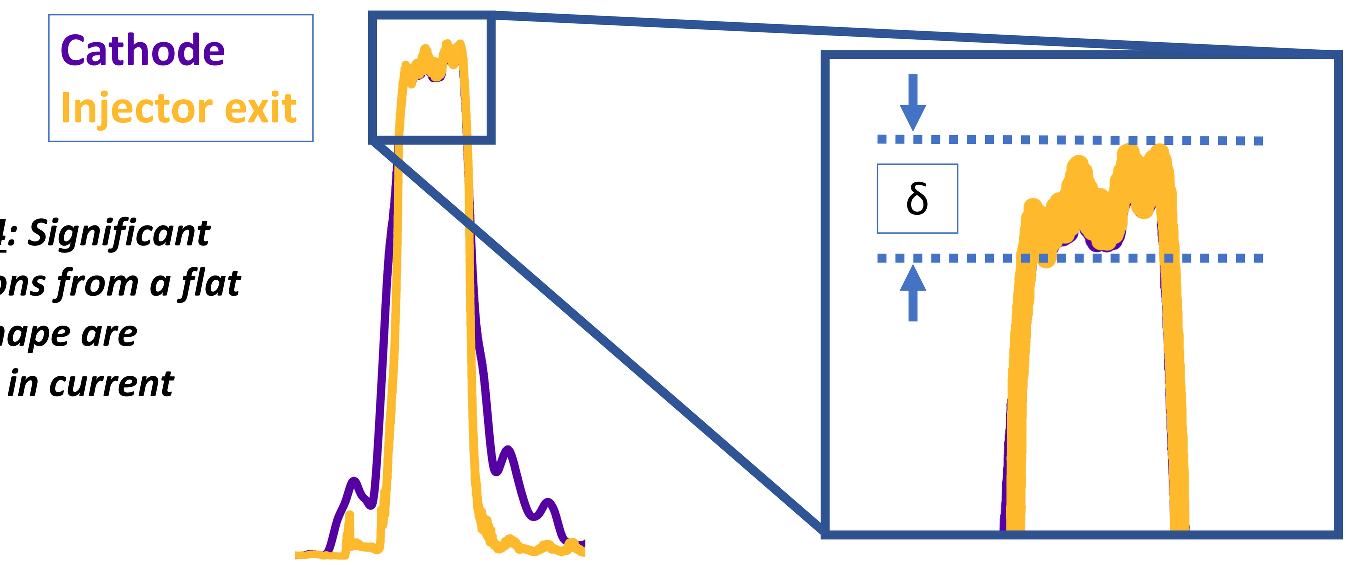

***Figure 4**: Significant deviations from a flat pulse shape are present in current models.*

Applications: Inter-Pulse Voltage

- With Scorpius being designed as a multi-pulse LIA, the inter-pulse region is also of interest when tuning to an ideal pulse shape for a particular pulse train.
- Reflections within the SSPP system cause substantial non-zero voltages in the inter-pulse region, resulting in emission of off-energy electrons at much lower energies than the magnetic tune can transport effectively.
- These highly off-energy electrons result in substantial beam spill in the injector region are capable of causing significant ion desorption [1].
- By optimizing the pulse using circuit models that include reflections, combinations of SSPP timing and amplitudes may be found that reduce the spurious voltage in the inter-pulse region, thereby reducing beam spill and ion desorption.

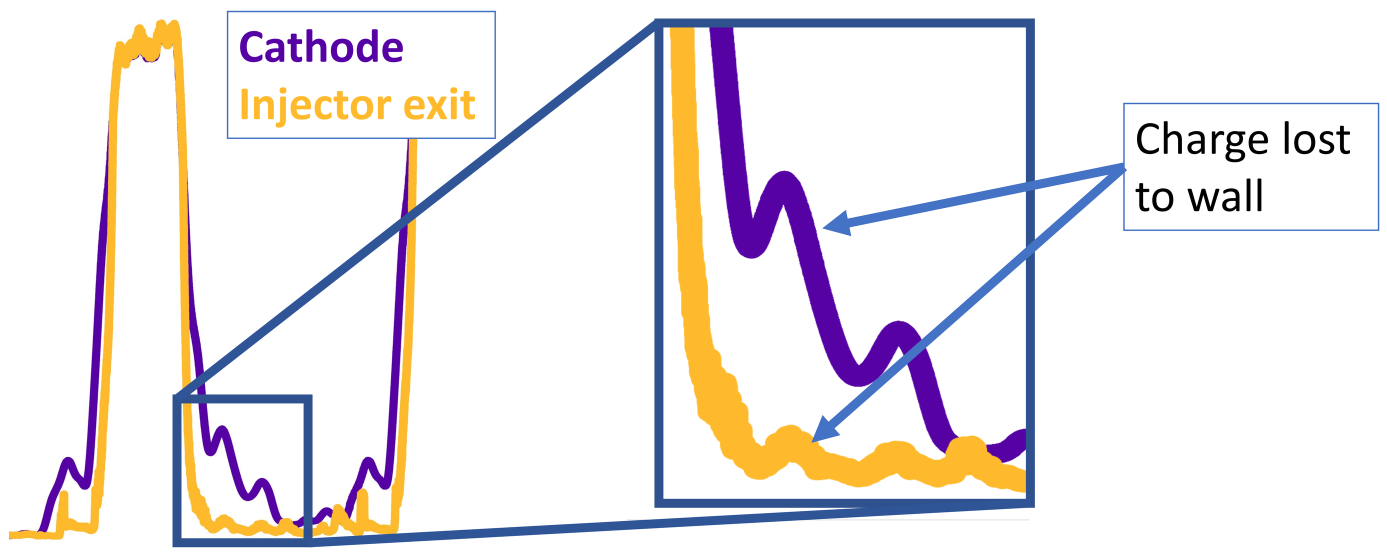

***Figure 5**: Inter-pulse reflections cause significant off-energy electron emission. The difference between cathode and injector exit beam currents represents charge lost to the wall.*

Next Steps and Future Work

- Circuit modeling of the SSPP units to match experimental data.
- Run simulations of SSPP model varying timing and state of SSPP units to develop the parameter space of interest required for an ML model.
- Analyze results of ML model when asked to match an "ideal" pulse shape.
- Begin development of a *Scorpius digital twin.*
  - Initial ML models based on vetted particle-in-cell codes
  - As experiments begin, want to continually update model with available experimental data to further refine the digital twin.

References

1. M. E. Weller, T. J. Burris-Mog, E. R. Scott, and C. A. Ekdahl, "Beam physics simulations for the Scorpius accelerator," in 2022 IEEE International Conference on Plasma Science (ICOPS), 2022.

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