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INITIAL EXPERIMENTAL ANALYSIS INTO THE ERHIC POLARIZED ELECTRON BEAM TRANSPORT SYSTEM

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Abstract

Stangenes Industries is working closely with Brookhaven National Lab in the United States to develop the eRHIC future ion collider. The collider requires a polarized electron source with high average current, short bunch length and small emittance. An array of photocathodes with their beams funnelled into a common trajectory is utilized to achieve the required beam current and charge lifetime. Stangenes Industries is tasked with delivering the prototype injector for preliminary beam studies that will lead to full implementation by 2016. This study focuses on the development of the of beam transport system extending from cathode to beam dump. A majority of the complexity involves the so called "combiner magnet" that acts as a high frequency-rotating dipole to bend each beam into the final common trajectory. Preliminary experiments into the feasibility of such a system are discussed.

BEAM CONSTRUCTION

A key technology in constructing a future heavy-ion collider lies in having a high average-current, high bunch-charge polarized electron source [1]. The injector currently in development at Stangenes Industries is illustrated in Fig. 1. The beam will have a diameter of 6mm with 5.3nC per bunch, a 2.3ns bunch length and a thermal emittance of 0.5μm/mm at 8mm. The 220keV beam begins on the surface of an array of 20 GaAs photocathodes in an XHV (10^{-12} torr scale) environment.

Each single cathode provides 2.5mA of beam current and are cyclically triggered in a “gatling gun” pattern of operation at 422 kHz. This unique operation prolongs the QE lifetime of the cathode by limiting the ion back-bombardment to which each cathode is subjected [2]. The beamlets from these cathodes are then focused and bent into a common trajectory producing 50mA of polarized electrons at an 8.44 MHz bunch frequency.

The redirecting of the 20 discrete beams into a common trajectory is accomplished by a novel rotating dipole magnet known as the combiner magnet [3]. The combiner magnet utilizes 10 sets of 2 dipole windings and and 10 sets of 4 quadrupole windings to bend and focus the beam through a diagnostic chamber and into a collector. Finely tuned resonant electrical circuits are utilized to generate the required rotating dipole and quadrupole fields. Simulated and experimental waveforms describe the efficacy of the magnet. It is worth noting that the focusing solenoids at the cathode and the initial bending dipoles are also developed at Stangenes Industries.

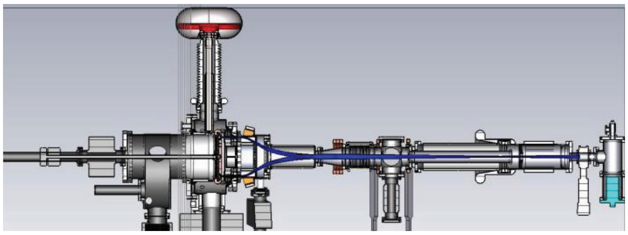

Figure 1: The injector assembly shows the beam in blue. The high voltage is brought to the cathodes through an insulator stack and corona ring (in red). The rotating dipole, or combiner magnet, bends the discrete beams back to a common trajectory.

COMBINER MAGNET

Figure 2 shows a detailed CAD layout of the combiner magnet. The magnet incorporates water-cooling in both the MN8CX ferrite and the copper windings to prevent the effects of temperature drift. Careful phase control and timing of the resonant circuits is necessary to maintain proper bending and focusing parameters. Each circuit incorporates a current transformer diagnostic to allow real-time monitoring of the current in each winding. A tuned feedback and feed-forward network will also be required but is beyond the scope of this analysis. The simulated waveform of the dipole windings is shown in Fig. 3.

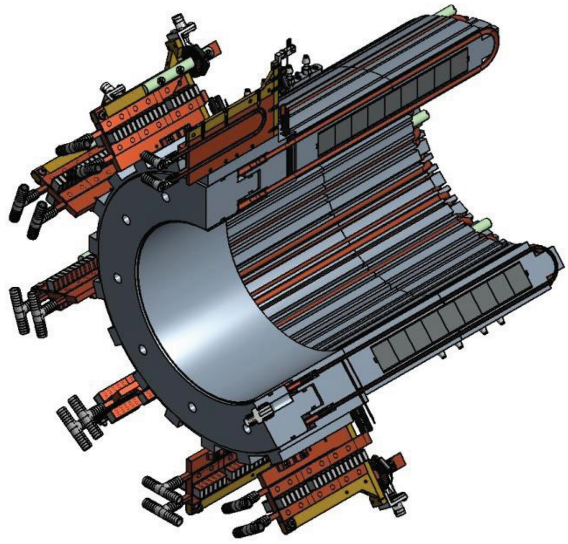

Figure 2: 7 out of 10 of the resonant circuits are shown mounted radially about the magnet in this cross-section view of the combiner. The darker cylinder is the ferrite encircled by the copper dipoles. The 10 quadrupole circuits are not pictured.

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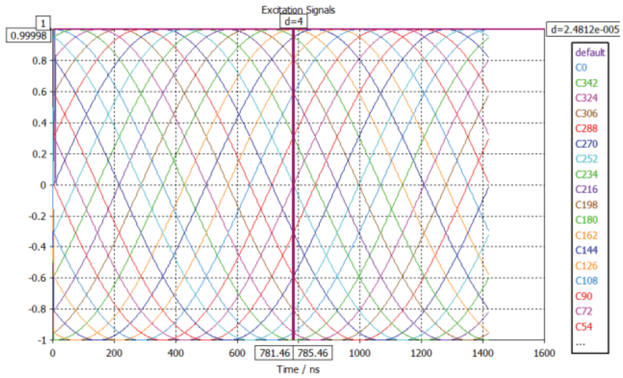


Figure 3: 20 beamlets are bent by the dipole fields generated by 10 resonant circuits which are 36º out of phase with each other.

CIRCUIT SIMULATIONS

The circuit of Fig. 4 is responsible for generating the resonant dipole field. A modified ALC Model AL-300-HF RF amplifier generates the required electrical drive. The 640.5 kHz frequency was found experimentally by fixing the value of the larger C2 capacitor and then adjusting the frequency until resonance was achieved. The capacitor C1 was then tuned until the efficiency was maximized. The capacitors were delivered by Advanced Technical Ceramics. Figure 5 shows the simulated waveforms.

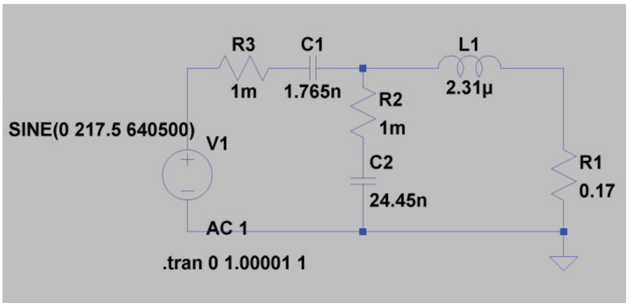


Figure 4: The resonant circuit consists of a RF source operating at 640.5 kHz. The two capacitors, C1 and C2, form the resonant circuit that drives the magnet represented by the components L1 and R1.

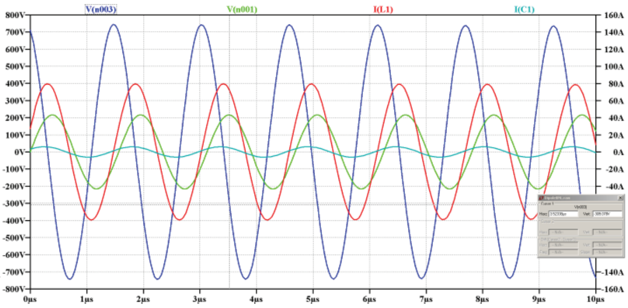


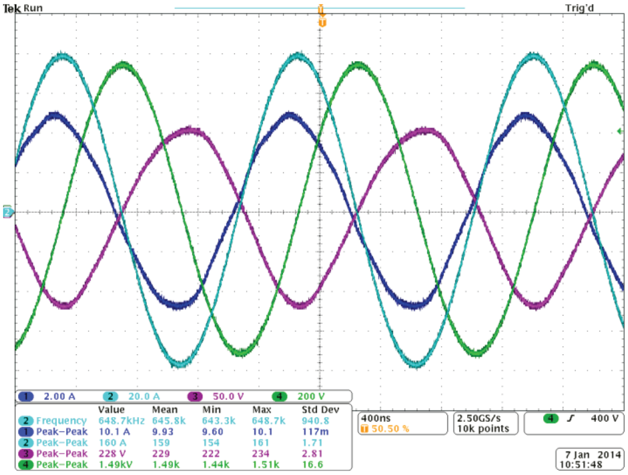
Figure 5: The simulated waveform shows resonance at 640.5 kHz. The output voltage across the magnet is the dark blue line. The input voltage is the green line. The light blue and red lines represent the input and output current, respectively.

For these efficacy tests the operational frequency was not important as the required frequency was not decided until after the conclusion of these tests. However, adhering to 422 kHz will be vital in the final circuit as the project moves into the next phase. The lower frequency circuit will require capacitors with more capacitance but a lower rated voltage.

EXPERIMENTAL WAVEFORMS

The circuit simulations matched the experimental waveforms of a single dipole winding. The experimental waveforms of Fig. 6 demonstrate the feasibility of the resonant circuit. The peak-to-peak input and output voltages are 456V and 1500V, respectively. The peak-to-peak input and output currents are 10.1A and 160A, respectively.

The voltage and current values give us an input and output impedance of 45.14Ω and 9.38Ω, respectively. Additional tuning of the circuit parameters would bring the input impedance closer to 50Ω, increasing the efficiency of the circuit. The results indicate an input power of 575.7W. The circuit was run up to 240A peak-to-peak with an input power of 1424W before tripping the amplifier.



	Value	Mean	Min	Max	Std Dev
② Frequency	648.7kHz	645.8k	643.3k	648.7k	940.8
① Peak−Peak	10.1 A	9.93	9.60	10.1	117m
② Peak−Peak	160 A	159	154	161	1.71
③ Peak−Peak	228 V	229	222	234	2.81
④ Peak−Peak	1.49kV	1.49k	1.44k	1.51k	16.6

Figure 6: The experimental waveforms are pictured above. The output voltage across the magnet is the green waveform. The input voltage is the purple line. The input and output current are the dark and light blue lines, respectively.

The dipole windings are connected via litz cables to mitigate the heat generated by the eddy currents at high frequency. The litz used was the equivalent to #6 gauge wire with 48 bundles of 5x5x6 strands of 44 gauge copper provided by New England Wire. The temperature of the litz remained below 50C for all of the testing. The capacitor assemblies will be mounted on chill plates to manage thermal drift of the capacitance. Maintaining a constant steady state is vital to the operation of the combiner magnet.

DISCUSSION

The feasibility of a resonant network to drive a high frequency rotating dipole field is investigated. Preliminary results on a single dipole winding indicate that it is possible to drive a dipole circuit with a resonant network with a high degree of stability. The stability of the resonance is vital in maintaining exactly 36º of separation between the dipole fields. Precise bending is necessary to ensure that the beamlets from the 20 cathodes combine to form a perfect representation of a beam produced by a single cathode.

FUTURE WORK

As the project moves into the next phase, the effect of all 10 of the dipole circuits and quadrupole circuits operating simultaneously must be studied extensively. Calculations regarding the heat loss in the ferrite must be validated with experimental observation to ensure that the magnet remains thermally stable. Feedback and feed-forward networks to maintain 36º of phase shift between the resonant fields must also be explored.

The current phase of the project has two objectives. The first is to discover whether the operation of two cathodes in a common XHV environment is possible. This is soon to be tested at a 2 Hz rep-rate using 5 pairs of dipole windings driven by an alternating DC source to bend two beamlets from two radially opposite cathodes. The beam current for these tests is very low (<1µA) to ease radiation concerns. The second objective is to determine the feasibility of a resonant circuit to drive the dipole field. The experimental data relayed in this report will be supported by additional data after the completion of the beam tests and installation of the capacitor chill plates and water-cooling of the dipole windings.

REFERENCES

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