SWITCHING MAGNET FOR HEAVY-ION BEAM SEPARATION*

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Abstract

We present a design for a complete switching magnet system capable of deflecting 8-25 MeV/u heavy-ion beams by 10 degrees. The system can produce flat-top pulses from 1 to 30 ms with rise and fall times of less than 0.5 ms at a duty cycle of 3-91% into a heavily inductive load. As determined by physics needs, the operational parameters of this magnet place it between fast rising kicker magnets with short duration and slow rising (or DC) resistive magnets which are optimized for efficiency and current-based power loss. This magnet must operate efficiently with over 91% duty factor and have a modestly fast rise time. The resulting design uses a resistive magnet scheme, to optimize the current-based losses, that is pulsed using a new circuit to control the applied voltage. The magnet has a laminated, iron dominated, H-shaped core. Directly-cooled copper pancake coils energize the magnet. The modulator employs a novel, proprietary, over-voltage topology to overcome the inherent inductance and achieve the fast rise and fall times, switching to a precision DC supply to efficiently maintain the flattop without requiring voltage in excess of ±3 kV.

INTRODUCTION

The planned upgrade of the ATLAS [1] exemplifies the need for sub-ms-transient-time switching magnets. Adding a fast beam switching capability behind the booster section of the linac enables multiplexing different beams between the various users' stations concurrently [2], and could essentially double the facility throughput. However, the rise and fall times of such a switching magnet are required to be well within the 1 ms time scale to avoid significant beam losses. Combined with the large load inductance and high field amplitude (>1 T), such a fast transient time requirement represents a significant technological challenge.

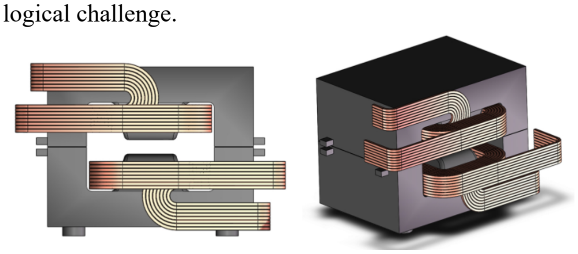

Figure 1: End-on and isometric views of the magnet

RadiaBeam Technologies has designed a fast switching magnet to address this need, integrated with a novel solid-state power supply, which mitigates the problem of large load inductance through modular IGBT-based architecture. This magnet system satisfies the needs of the Argonne Tandem Linac Accelerator System (ATLAS) upgrades, matching the temporal structure of the interlaced beam to enable simultaneous acceleration of stable and radioactive. To date, we have done the physical and conceptual engineering design of the magnet and of the power supply. RadiaBeam also successfully built and tested reduced-scale prototypes of both the laminated core and power supply to demonstrate proof-of-concept

MAGNET DESIGN

For this magnet design, we selected the target parameters consistent with the needs of the ATLAS facility, where the demand for such a magnet is most immediate.

Table 1: Target Parameters for the Magnet

Parameter	Target Value
Maximum physical length	55 cm
Magnet full gap	4 cm
Minimum good field width	6 cm
Field homogeneity requirement	0.1%
Maximum rise/fall time	<1 ms

Electromagnetic Design

At the initial stage of design, we selected an H-magnet frame shape, since these are lighter and more stable than C-magnets and do not require saddle coils [3]. The demand for sub-ms transient times requires that the core be laminated and that the laminations should be as thin as reasonable. From our experience, the minimum lamination thickness is 0.25 mm since thinner materials are easily deformed and are too expensive to process. Of the commercially available materials, AK Steel's DI-MAX HF-10 steel had both the best flux carrying capacity and the lowest losses of what varieties we could find, so it is an obvious choice in this context.

The width of the magnetic field must be flat (<0.1% deviation) across at least a 6 cm width of the gap. Such a good field region can be efficiently made by shaping the poles to include protruding tabs near the edges to force the field to remain "flatter" [4]. For this magnet, the tabs saturate sooner than the bulk of the pole and could not be used. We settled on a flat pole face with sides of circular radius. The longitudinal ends of the magnet are shaped with a Rogowski profile [5], which is shaped so that it follows an equipotential profile defined by magnetostatics and minimizes eddy current penetration through the laminations (as opposed to along the laminations, which is what we want). The main drawback of the Rogowski

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profile is that it reduces the mechanical length of the magnet's gap and therefore requires a stronger magnet to achieve the required integrated field of 0.45 T-m.

The magnetization curve for AK Steel's DI-MAX HF-10 [6] was imported into CST Studio, and the magnetic length of the magnet was calculated along the central axis. From that, we determined that to exceed the desired field integral it will require approximately 380 A with 50 turns per coil or 19 kA-turns.

In addition to the total integral, we need to ensure that the magnet does not show significant saturation. Saturation has two adverse effects. First, a saturated core has higher reluctance, and this reduces the magnet efficiency. Second, if the pole face is saturated, the assumption of the pole face as an equipotential becomes worse (as compared to a magnet that is not saturated) and the field distribution becomes difficult to predict from pulse-to-pulse [7]. Our simulation (see Figure 2) shows that no part of the magnet goes into saturation and only a small part, far from the pole face, leaves the linear regime of the magnetization curve.

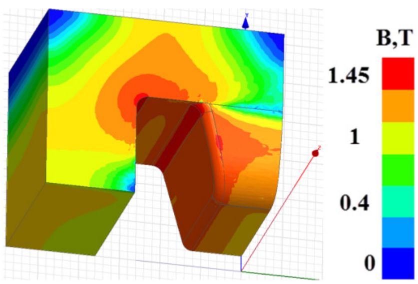

Figure 2: Surface magnetic fields using the realistic magnetization curve and excited with 19 kA-turns per coil.

Engineering Design

The preliminary engineering design of the magnet is shown in Figure 1. Manufacturing of the coils will adhere to the general practices for accelerator magnet fabrication with particular attention given to the high voltage transients the coils will experience.

The coils will be made of rectangular 3/8" hollow core copper conductor with a 3/16" diameter channel for direct water-cooling. These coils have a total current carrying area of 73 mm^2, and we estimate the coil length to be 1.6 m per turn. Combining these figures, we find the resistance of one coil is 21 mΩ, so the ohmic loss in each coil is 2.2 kW and the current density in the copper is 4.7 A/mm^2, well below the 10 A/mm^2 rule-of-thumb used in the design of water-cooled accelerator magnets. The steady-state DC power supply needs 7.1 V per coil to sustain the 340 A. Thermal performance of the coils was evaluated separately from the magnet core, consistent with a weak thermal connection between the two. With 51 PSI inlet pressure at the input and 3.5 l/m flow rate, the coil temperature increases less than 2°C from an assumed 22°C ambient temperature.

Losses in the steel core come from different sources, but all of these sources require a transient applied field since there are no DC losses in the core. Losses in a laminated core are generally described by the Steinmetz formalism wherein the losses are separated into three categories: hysteresis losses, eddy current losses, and excess losses [8]. The two most accessible sources of losses are eddy current losses and hysteresis losses, while the excess loss is an experimentally determined parameter.

For the AF Steel DI-MAX HF-10 material, we performed a transient simulation of the magnet in ANSYS Maxwell using data provided by the manufacturer. The results of the simulation are shown in Figure 3. These results show that core losses are constituted of roughly 40% due to eddy currents and the losses are approximately 65 kW during the transient period. Thus, the average loss rate for two transient periods of 200 μs per cycle is about 800 W.

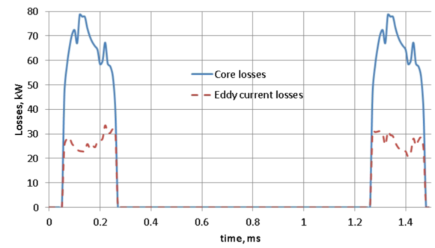

Figure 3: Input voltage and field strength in the magnet as a function of time (left) and transient losses in the core as a function of time as calculated by Maxwell (right).

Because of the very large surface area of the magnet, the losses in the core can be cooled by forced air blowing over the surface of the magnet. Simulation of the magnet in CST Studio assuming 10 W/(m^2-K) convective cooling by 22°C air on the magnet surfaces shows that motion of the magnetic gap is minimal and can be corrected at the time of installation.

POWER SUPPLY DESIGN

After establishing a baseline magnet design and its corresponding load characteristics, we studied the feasibility of various topologies for the power supply. The required operating regimes are challenging since the magnet system must operate both as a fast-pulsed magnet and as a pseudo-DC magnet. The power supply strategies for these modes of operation are very different.

Topologies and Simulations

We initially identified three possible topologies for the modulator based on common technology seen in accelerator facilities. Our basic design requirements (rise/fall times, stability, etc) and system goals (modern components, low cost, high reliability, etc) pushed us towards a modified resonant transfer topology [9].

The resonant transfer design uses high voltage capacitors to achieve the rise/fall times, and a conventional, constant-current DC supply to supply and regulate the current during the flat-top. The design phase then focused on how to achieve the switching needed to implement this mode of operation in a practical circuit. Treating the system as two coils, and thus two loads, basic circuit analysis of an inductive load with finite resistance shows that approximately 25 kV is required to achieve the rise/fall times, and approximately 50 V to sustain the flat top. Switches that can open and close, while holding off that voltage are expensive or difficult to control. Moreover, the high voltage of 25 kV makes insulation, water cooling, and personnel safety difficult.

To address these challenges, we developed a novel topology to address the difficulties of either the high voltage or high current approach. An arrangement of solid-state half-bridges allows each coil to be "boosted" by a modest voltage capacitor and then be driven by a conventional DC power supply. The largest voltage relative to ground for any point in the power supply is on the order of a few kV, so much less insulation is required, and a single commercial IGBT is sufficient to handle the voltage and the current, reducing complexity and cost [10].

Starting with the parameters yielded by the magnet design, we generated a schematic for the power supply we could study via simulations. To reproduce the transient behaviour, it was critical to include the parasitic parameters present for each component. We also included elements to simulate core losses and other magneto-dynamic effects that although subtle, still have an impact on the performance of the system. Using ANSYS's Simplorer simulation suite, we conducted several simulations, and iteratively optimized the design.

The simulation results showed we could achieve a rise and fall time of approximately 370 µs (see Figure 4). We consistently observe a small overshoot (<1%) in the current when switching between the capacitors and the DC power supply. However, the overshoot occurs only very briefly, and the current does not ring so that all the transient behaviour still occurs well with the required 1 ms.

Figure 4: Important features of the simulation results are the 370 µs rise and fall times in the current (top) and that the largest potential to ground anywhere in the system is only 1.62 kV (bottom).

Reduced Scale Testing

Since the topology of our power supply is a unique development, we built a small prototype to demonstrate proof-of-concept. Using a small-scale magnet (and thus smaller inductance) allowed us to scale down the voltage and current required so that readily available IGBTs with commercially available drivers could be used, while still observing the performance of the design.

Our initial pulses showed a distinct crossover problem during the transition from the rising regime to the flattop. The rising edge would reach a higher current than the DC supply would start driving current at. We spent significant effort trying to understand the cause of the discontinuity. Our primary concern was that the slew-rate of the bulk DC supply was too slow to suddenly go from zero amps to the operating coil of the current. We tried using lead-acid batteries instead but found little difference. Ultimately, we discovered that it is an issue of finely tuning the charge voltage of the booster capacitors and rise time to eliminate the overshoot and obtain a stable flat top.

We took an extensive amount of data to characterize the prototype, with our best result is shown in Figure 5. In this plot, we demonstrate a 1 ms flattop with rising and fall times of 0.5 ms. These experiments also generated some other ideas to explore such a providing a feed-forward signal to the DC power supply, shunting some current before switching, or obtaining a fast response and high slew rate DC power supply to improve the waveform.

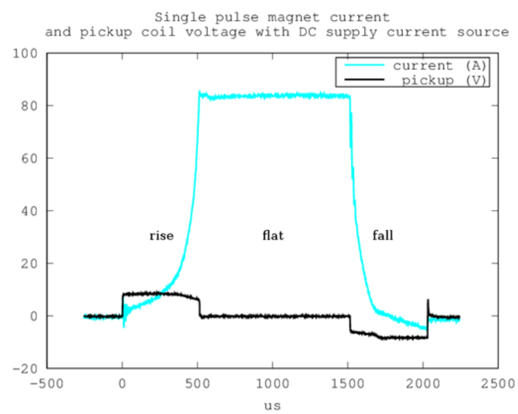

Figure 5: Our best complete waveform to date. Despite slightly saturating the core, we still obtained a stable flat top with tiny discontinuity during the crossover between the rise and flat regimes.

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