BLIP SCANNING SYSTEM POWER SUPPLY CONTROL*

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Abstract

In the Brookhaven LINAC Isotope Producer (BLIP) facility, a fixed target is bombarded by proton beam to produce isotopes for medical research and cancer treatment. This bombardment process causes spot heating on the target and reduces its lifetime. To mitigate this problem, an upgrade to the beamline has been made by spreading the beam on the target in a circular pattern, which allows the target to heat more uniformly. The beam is steered in a circular pattern by a magnet with orthogonal (X and Y) windings. Each of these two windings is independently powered as part of a resonant circuit driven by a power amplifier. This paper describes the hardware platform used as well as the software implementation of the resonant circuit design and its feedback loop.

OVERVIEW

The BLIP facility is faced with a high demand for isotopes. To increase the production, the target needs to be bombarded with higher current beam. Focused beam with increased beam current causes heat damage on the target. To prevent this, the heat has to be distributed within the target. This can only be achieved if the target is scanned by the beam in a moving pattern. A set of ferrite core windings was designed to generate a dynamic magnetic field that steers the beam in a circular pattern. Increasing the current into the magnet results in a wider circle. The magnet's two windings are physically perpendicular to each other and are independently powered by two power amplifiers. To minimize the power required to energize these windings, a resonant circuit was designed. Without the resonant circuit, an amplifier with a much higher apparent power would be needed to power each winding. As inherent with resonant circuits, the energy is transferred between the inductor (the winding) and the matching capacitors. The power amplifiers are needed to supply only the initial energy to charge the capacitors at start-up, as well as to make up for the losses in the system. A small portion of these losses is due to the magnet leads. The windings are placed around the beam pipe in the tunnel, about 18 feet in front of the target. Due to high radiation in the tunnel, the resonating capacitors are located in a remote control room. The connections between the resonant capacitors and the windings are made via Kapton insulated litz wires. Kapton was chosen because of its high tolerance to radiation; and litz wire was chosen to mitigate the AC skin effect. The long leads contribute to the resistive losses in the resonant circuit.

The windings and the components of the resonant circuits are required to run at a frequency of 4.9 kHz. This frequency was chosen to spread the beam on the target for specific number of turns (circles) per beam pulse. The pulse width of the beam that is sent to the BLIP facility is 450 µs. At approximately 5 kHz, the beam scribes two and a quarter turns on the target. The scanning system was designed to run continuously as opposed to a pulsed ringing circuit. This is advantageous in two ways. First, running continuously allows for continuous monitoring of proper operation of the equipment. In a ringing circuit, a misfire will not be known until after the beam has been sent to the target. Second, the beam distribution is precisely controlled in the continuous system by a lookup table. In a pulsed system, the only control would be the starting current.

To keep the power amplifier running with minimum power, the load – the inductor and the capacitors (LC) – needs to be matched to the impedance of the power amplifier. This is achieved by adding a transformer in parallel with the capacitors. The turn ratio of the transformer is determined by the ratio of the resistive losses of the resonant circuit to the power amplifier impedance. Since the impedance of the resonant circuit is higher than the power amplifier impedance, the transformer steps up the voltage. Having a matched impedance system ensures the amplifier supplies the minimum power required to run the system.

HARDWARE

As mentioned in the above section, all the components of the resonant circuit except the windings are located in a remote room. Interface chassis were built to house these components. Each winding has two interface chassis. The first chassis provides access to the litz wire leads and includes the resonant capacitors, while the second chassis contains the impedance matching transformer and connection point to the power amplifier. Each chassis also includes a dedicated current transformer and a dedicated voltage sensor to measure the magnet current and voltage, and the power amplifier current and voltage, respectively. These measurements are acquired by the power supply control system to regulate the feedback loops. A pair of interface chassis is shown in Figure 1.

National Instruments' PXIe hardware platform was chosen as the power amplifier controller. Each power amplifier is controlled by its own function generator module which has the capability to generate 20 MHz sine waves with 14-bit resolution (NI PXI-5402). These modules are configured to generate two separate sine waves. These outputs have adjustable amplitude and have a nominal 90° phase shift, as an input to each power amplifier. To read the current and voltage measurements, an oscilloscope/digitizer module is utilized. The PXIe-5105 is an 8-

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Dept. of Energy.
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ISBN 978-3-95450-177-9

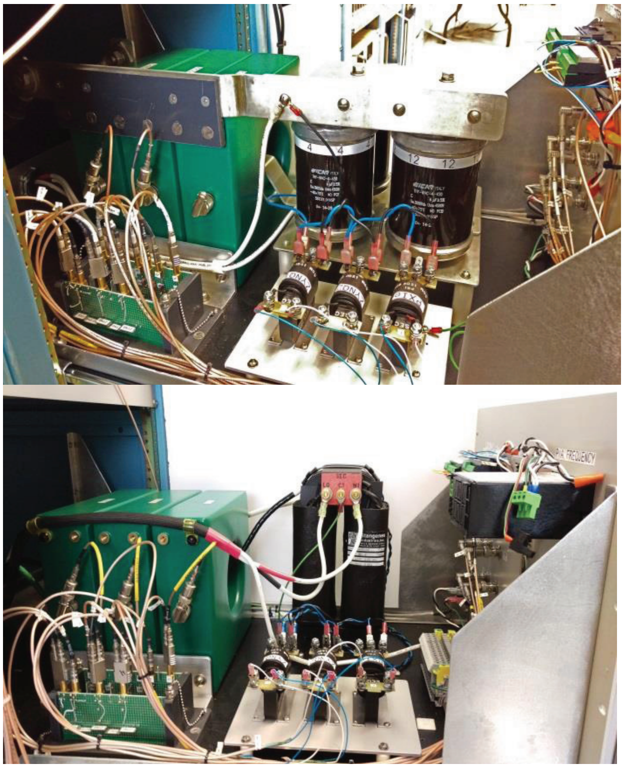

Figure 1: Two interface chassis: One with the resonant capacitors (top) and one with the matching transformer (bottom). The current and voltage transformers are shown in both.

channel, 12-bit analog to digital converter board with a 60 MHz real-time sampling rate. In addition, there are digital I/O boards used for interlock outputs and synchronization with beam pulse. For synchronization and fast interlock I/O, a PXIe-6341 providing 24 TTL I/O lines is used. For slow interlock outputs, such as relay switches, a PXI-6515providing 32 isolated channels at +/- 30 VDC is utilized. The controller, where all real-time computation is done, is a 2.3 GHz Intel Core i7 processor running a LabVIEW Real-Time Operating System (NI PXIe-8135). The program that is running on the processor and communicating with all the I/O modules is written in LabVIEW. LabVIEW is a graphical programming language from National Instruments and it stands for LABoratory Virtual Instrument Engineering Workbench. The PXIe chassis with all the modules is shown in Figure 2.

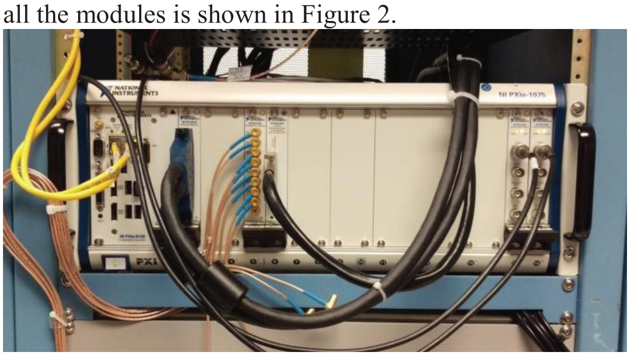

Figure 2: The National Instruments PXIe platform with 18-slot chassis and I/O modules.

SOFTWARE

To maintain the efficient transfer of the voltage between the windings and the capacitors, the system has to run as close as possible to its resonant frequency. The accuracy of the circular beam pattern on the target also needs to be maintained. The circular shape of the magnetic field is obtained by keeping the two sine waves of each amplifier 90° out of phase. On the other hand, the phase shift between the current and voltage of the same amplifier has to remain zero. The amplitude of both sine waves is also required to be tightly controlled in order to maintain a constant diameter for the circle being scanned onto the target. Both the frequency and the current can drift due to heat. Heat can also cause changes in inductance and/or capacitance. Therefore, feedback loops are necessary to maintain a stable system. A power supply control circuit was designed as seen in Figure 3. This design was implemented in software using LabVIEW.

As mentioned in the Hardware section, each system has its own readbacks via a current and a voltage transformer. Power amplifier current and voltage, as well as the magnet current and voltage measurements, are brought back to the 8 channels of PXIe system's digitizer board, 4 for each winding/power amplifier combination. These measurements are used to derive frequency, amplitude and phase information. The computation necessary for the feedback loops is done on this information.

As seen in the schematic in Figure 3, there are four main feedback loops: Two amplitude feedback loops, one frequency feedback loop, and one phase feedback loop. Each winding has its own amplitude feedback loop, but there is only one frequency feedback loop for both systems because the amplifiers are locked together in a master-slave configuration. The amplitude feedback loops are software implemented PI loops with gains. The frequency feedback loop also utilizes a PI loop, and it operates on the phase sum of the power amplifier sine waves. Phase data of the voltage and current measurements for each amplifier is extracted and summed with the other amplifiers phase data. The frequency of the sine waves is adjusted with this phase sum to keep the systems frequency locked and on resonance.

Subsequently, the amplitudes of the each sine wave are adjusted with the result of the amplitude feedback loops. These loops sum the difference between a given setpoint and the magnet current readback and integrate this difference. The results of these computations, which are in amperes, are then converted to voltage values that are appropriate for the power amplifier input.

Lastly, the phase feedback loop maintains the phase shift between the two sine waves (power amplifier outputs). This 90° phase shift determines the magnetic field pattern and subsequently, the path in which the beam is deposited on the target. Each power amplifier has its own independent function generator board in the PXIe system. Even though these boards are initialized as phase locked to each other in the software implementation, they each have their own on-board oscillator as clocks and as the

ISBN 978-3-95450-177-9

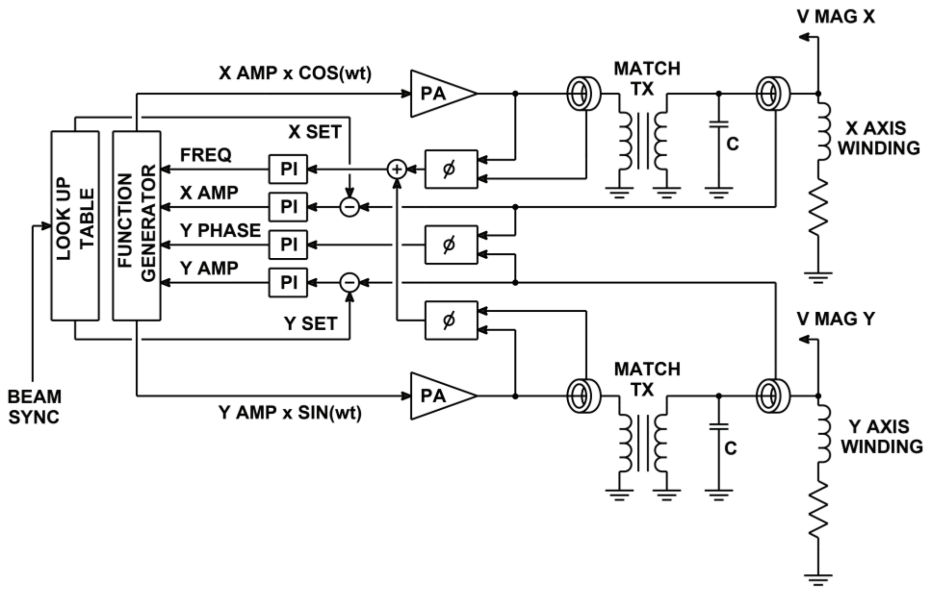

Figure 3: Schematic of the power amplifier control that is implemented by software.

frequency and amplitude of the sine waves get adjusted, the phase deviates slightly over time. The phase feedback loop corrects for this deviation to ensure the two sine waves stay 90° out of phase at all times.

Amplitude feedback is the most critical parameter and uses most of the computational resources. The amplitude feedback loop currently operates at a nominal 2 ms rate. Originally the goal was a 1 ms update rate, but hardware constraints within the PXIe could not accommodate that speed. Frequency and phase adjustments are not so time critical, and are made approximately every half second.

Coarse amplitude changes, or setpoints, (not to be confused with the feedback adjustments) can be made during operations in order to change the diameter of the circle being scanned onto the target. Concentric circles of specific diameters can be achieved with the use of a programmable setpoint table. This table is represented as the "Look Up Table" in Figure 3. However, these coarse changes should not be made while beam is present.

A beam pulse is received at the BLIP facility at a 6.67 Hz rate. This is roughly a period of 150 ms. However, the beam pulse width is only 450 µs. Since it is not desirable to make large changes to the magnetic field while beam is present, a timing signal is used by the PXIe system to provide the necessary synchronization. Settling time must be taken into account. An externally generated TTL pulse signals the arrival of the beam pulse. A software delay is added to this pulse to assure clearance from the beam and also allows for settling times before resuming feedback corrections to the windings which control the diameter of the circular pattern.

The 2 ms rate at which the amplitude adjustments are applied, is determined by the bandwidth required by the closed loop system. This bandwidth determines how fast the amplitude setpoints can be applied, and operate at that amplitude stably. The settling time of the power amplifier and the resonant circuit in between the amplitude changes is essential to keep the system stable. If the amplitude feedback loop adjustment is done too fast, the system can go unstable; and if it's done too slowly then the system won't be ready at the expected amplitude by the time the beam pulse arrives.

All aforementioned computations and feedback loops are done in one main while loop that iterates nominally every 2 ms. In addition to these calculations, the impedance of the windings are computed in this loop. The impedance value allows us to detect a short circuit in the winding. The main loop also determines under what conditions the power amplifiers should be shut down to prevent damage. In the case of an overcurrent – winding current exceeds the maximum value that could be handled by the entire magnet structure –, the resonant frequency and the impedance both going outside the allowed margins, the PXIe system interlocks the power amplifiers and beam is inhibited immediately. These statuses, along with some computational results, are sent back to a higher level custom accelerator interface via TCP/IP. The computational results include, but are not limited to, magnet current and voltage, power amplifier current and voltage, calculated impedance of the magnet, the interlock status, etc. These are reported to the user once per second. One issue was encountered during the data delivery process. When this reporting mechanism is enabled, the main loop unexpectedly can come to a brief halt, as often as 2 or 3 times a day. This obviously affects the feedback loops, making them go unstable due to large errors once the loop resumes. The cause of this is not fully understood and is currently being investigated in concert with National Instruments.

CONCLUSION

The resonant circuit and the PXIe system completed its first operational year [1]. The fundamental purpose of this beam scanning equipment was to increase the production of medical isotopes. Despite the minor control incon-

ISBN 978-3-95450-177-9

venience caused by disabling data reporting, this fundamental purpose has been successfully accomplished. The BLIP scanning system reliably boosts the production up to the limit of the beam production.

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ISBN 978-3-95450-177-9