FOUR BEAM GENERATION FOR SIMULTANEOUS FOUR-HALL OPERATION AT CEBAF *

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Abstract

As part of the CEBAF 12 GeV upgrade at Jefferson Lab, a new experimental hall was added to the existing three halls. To deliver beam to all four halls simultaneous-ly, a new timing pattern for electron bunches is needed at the injector. This pattern change has consequences for the frequency of the lasers at the photogun, beam behavior in the chopping system, beam optics due to space charge, and setup procedures. We have successfully demonstrated this new pattern using the three existing drive lasers. The implementation of the full system will occur when the fourth laser is added and upgrades to the Low Level RF (LLRF) are complete. In this paper we explain the new bunch pattern, the challenges for setting and measuring the pattern such as 180° RF phase ambiguity, addition of the fourth laser to the laser table and LLRF upgrade.

BACKGROUND

For more than two decades the Continuous Electron Beam Accelerator Facility (CEBAF) has been delivering beam to three experimental halls: Halls A, B, and C. One of the unique features of the accelerator is its capability to deliver beam to all three halls simultaneously. This was achieved by producing three independent beams from a single photocathode, with interleaved micro-bunch trains, each at one third of the main accelerator frequency and 120° apart from neighbouring bunch trains. These beams were bunched, shaped and accelerated through a single beamline and delivered to the beam extraction system that directs the individual bunch trains to their designated hall lines. The frequency of CEBAF accelerating RF cavities is 1497 MHz (for simplicity 1500 MHz [1]) and producing three beams at the third sub-harmonic, 500 MHz, fills every accelerating bucket. The RF separator deflecting cavities operate at 500 MHz and are located at the end of each pass. This arrangement allows one of the three beams to be extracted at any pass to any of the experimental halls. At the highest pass, the fifth pass with highest energy, the RF separator can split all three beams to send them to their respective experimental halls [2].

The CEBAF upgrade increased the maximum beam energy from 6 GeV to 12 GeV. The upgrade also added a new hall, Hall D, to the machine [3]. In order to increase the availability of the accelerator, a new beam pattern and RF separator arrangement was introduced for simultaneous beam delivery to all four halls [4,5]. To add the new Hall D beam to the interleaved bunch trains, the repetition rate of the beam to one hall was reduced from 500 to 250 MHz, leaving half of the accelerating buckets empty. The new D beam could then occupy these empty RF cycles. Figure 1 illustrates the old and new beam patterns.

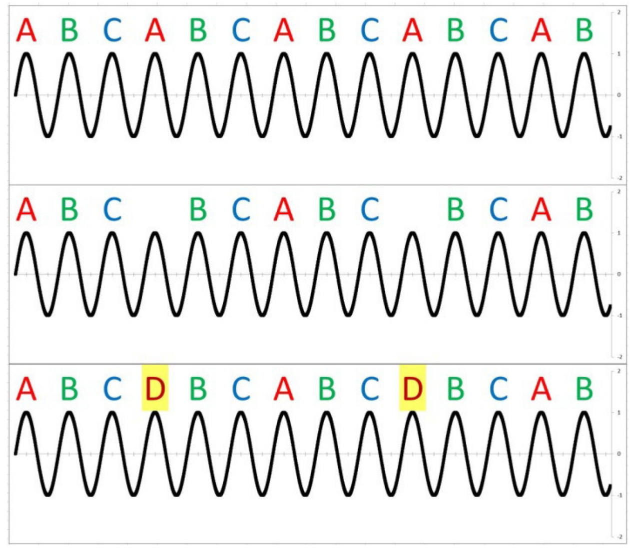

Figure 1: Each sine wave represents the 1500 MHz accelerating frequency. Top, three interleaved beams (A, B, and C) each at 500 MHz. Center, A beam at 250 MHz makes room for D beam. Bottom, A and D at 250 MHz and B and C at 500 MHz.

Since Hall D runs at the highest pass, only beams extracted at the highest pass need to have a 250 MHz structure. Experimental halls that ask for beam at lower passes can still use the 500 MHz structure. Therefore the electron gun needs to be capable of producing both 500 MHz and 250 MHz beams.

A partial commissioning of this new scheme was successfully completed during the spring and fall of 2015 and again in spring of 2016. Using the existing 6 GeV era three laser system two beams at 250 MHz were sent to Halls A and D at the highest pass, and a third beam at 500 MHz was sent to Hall B at a lower pass. A full commissioning of the system will be completed when a fourth laser is added to the drive laser table to produce four interleaved beams from the gun.

In the following sections we describe our experience creating the 250 MHz beams, the problems we encountered, the solution implemented, how the timing of the pattern can be measured, and the proposed system to add a fourth laser to the photocathode gun system.

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GENERATING 250 MHZ BEAMS

To prolong the photocathode lifetime, Jefferson Lab uses synchronous photoinjection which was first invented at the lab in 1996 and is well described in [6,7]. In a few words, the beam micro-pulse structure at the gun is synchronized to the main machine RF system. The electrons are only produced while they are used in the bunching and accelerating process. Since the electrons are produced when the laser light strikes the cathode, the photogun drive lasers must also emit picosecond optical pulses synchronized to the RF. Our first attempt to produce 250 MHz RF used a multichannel frequency prescaler "divide-by-two" circuit (Fig. 2). The main drawback of adding the frequency divider at the output of the Low Level RF (LLRF) [8] system was the 360° phase range at 500 MHz would become 180° at 250 MHz. Subsequent modification of the digital I&Q modulator increased the input phase shift range to 720° (of 500 MHz), but the output phase would still wrap around modulo 360°. The culprit was the phase locked loop (PLL) architecture of the frequency prescaler. Further modification of the digital modulator and the addition of an automated smooth phase ramping procedure to the operator requested phase setpoint eliminated this issue as well. Our plan is to develop a new four channel, dual frequency LLRF laser system to provide both 250 MHz and 500 MHz beams with full phase range.

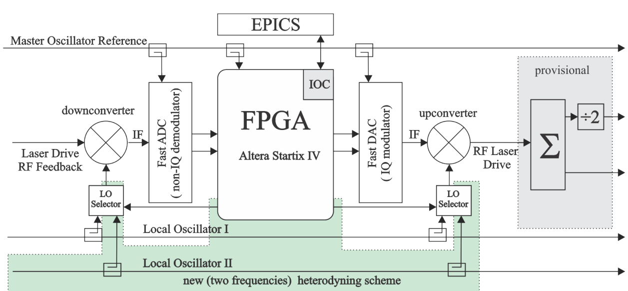

Figure 2: Architecture of the LLRF hardware for an individual laser. Signal processing involves mixing with the Local Oscillator to down and up convert RF signals, digital demodulation, Proportional-Integral control, and generating the Intermediate Frequency (IF) signal using a single Digital to Analogue Converter (DAC) [8]. The clocks for the FPGA and Fast ADC/DAC are derived from the Master Oscillator Reference. The Local Oscillators for the up and down conversions are coupled from the Local Oscillator lines. The green area shows the proposed addition to the LLRF to allow system operation at two frequencies while the grey is the present configuration.

MEASUREMENT OF BEAM TIMING

The CEBAF injector has a 500 MHz circular chopper. A DC beam would show as a circle in the middle of the chopper; therefore, in the past, it was relatively straightforward to use the chopper to set the phases of the 500 MHz beams. However, with this approach the phasing for a 250 MHz beam would have a 180° ambiguity. Take for example the two 250 MHz beams shown in Figure 1 (labelled A and D). At 250 MHz they are 180° or 2 ns apart. But in a 500 MHz chopper, the 2 ns is 360°, a full circle, which makes the A and D beams indistinguishable.

One can certainly wait until the beams are threaded to the extraction system at the end of the accelerator (5 passes) to determine if they go to the same hall or two different halls. However from the operational point of view, it is prudent to determine and correctly set the relative timing of the beams at the injector (early in the machine setup process). The problem boils down to determining if two 250 MHz beams have the same timing or are 2 ns apart. Once that is confirmed, other phases can be set by adding or subtracting RF phases. Two different ways to accomplish this at the injector are: 1) capitalizing on the space charge effect, and 2) measuring the relative timing of micro bunches in each beam using the existing Mott polarimeter [9]. Each method is discussed in detail in the two following subsections.

Using Space Charge Effect

Normally, the beams leaving the photocathode, if left untreated, exhibit some space charge related degradation. The beam bunches become flattened and elongated, and in the transverse direction, the beam spots become larger resulting in some beam loss. Knowing this, determining the relative timing of two pulses becomes easy. With both 250 MHz beams ON, if their pulses have the same timing, then they experience more space charge-induced growth, leading to longer pulses and lower peak current compared to when their timings are different.

Figure 3 shows the results of this technique. Two beams, A and D, each have ~45 µA and 250 MHz structure. In both traces, the baseline shows the A beam alone going fully through the 500 MHz chopper slit registering ~45 µA of beam at a downstream Faraday cup in the injector. With the A beam ON, the D beam pulse was scanned across the same slit. In the left trace, the A and D pulses are 2 ns apart showing no degradation of the peak current. For the right-side trace, bunches are coincident exhibiting lower peak current.

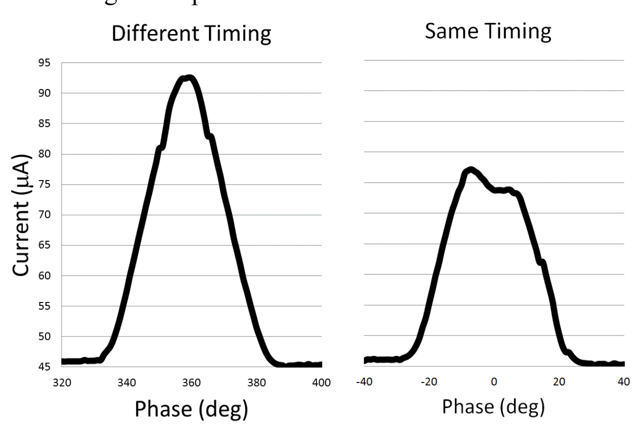

Figure 3: Total current from two 250 MHz beams each at 45 µA peak. Left: the beams are 2 ns apart in time. Right: the two beams have simultaneous pulses showing signs of higher space charge.

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Using Mott Polarimeter System

The beams downstream of the chopper may be directed to a Mott-scattering polarimeter to measure their spin polarization. Electrons elastically scatter from a thin target foil and deposit their energy in plastic scintillators. The scintillator pulses and a copy of the injector RF are provided to a TDC in a fast data acquisition system. Therefore the arrival time of an electron bunch relative to the RF can be measured with very good precision (200 ps).

Thus while the phases between two 250 MHz beams are indistinguishable as viewed at the chopper chamber e.g. by a view screen, the Mott polarimeter will clearly detect if their difference is really 0 ns or 2 ns (Fig. 4).

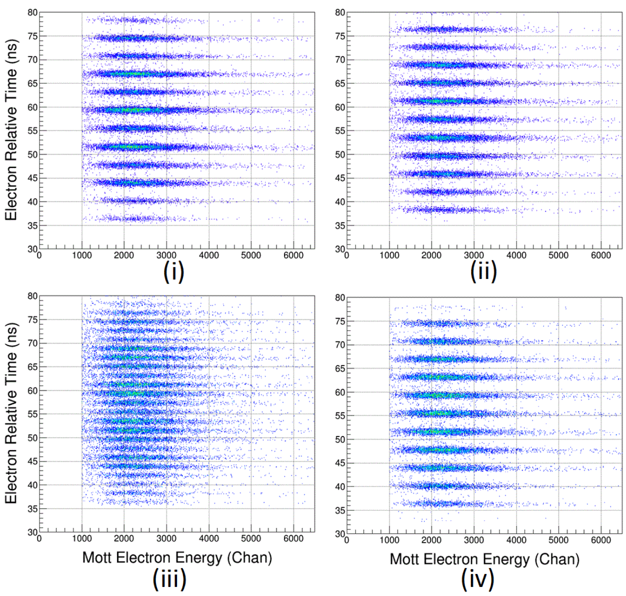

Figure 4: Timing of 250 MHz beam bunches measured in Mott polarimeter (i) Beam A only, (ii) Beam D only (note bunches shifted in time by 2 ns), (iii) A+D 2 ns apart, (iv) A+D 0 ns apart after D timing changed to match A.

UPGRADE TO THE LASER TABLE

As mentioned above four independent lasers are needed to generate four electron beams in the photogun. During the 2016 scheduled accelerator maintenance period, a fourth laser will be added to the laser table, where laser beams are combined (Fig. 5) and directed along a common trajectory toward the entrance window of the electron gun vacuum system. This will be accomplished using partially reflecting mirrors and a polarization-sensitive beam combining optic. Specifically, the A (high-current) and B (low-current) laser beams have the same linear polarization and are combined using a partially reflecting mirror. Similarly the C (high-current) and D (low-current) laser beams are combined using another partially reflective mirror. These laser beam pairs have orthogonal laser polarization allowing the four beams to be combined using a polarizing cube which can be thought of as a reversed beam splitting polarizer.

CONCLUSION

Production of four independent beams with the option of 250 MHz or 500 MHz structure at the injector is essential for achieving four-hall operation capability at CEBAF. Significant progress has been made during the last year toward achieving this goal. We have already operated physics quality beams with the new 250 MHz beam structure and the beams have been directed to the appropriate experimental halls under the new separation system. The future plan is to add a fourth drive-laser to the existing three and make further improvement to the low level RF system for those drive-lasers.

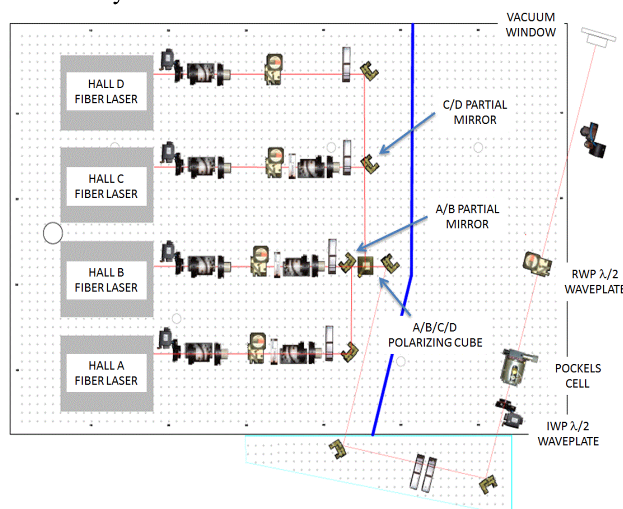

Figure 5: The 4-laser configuration. Once the four laser beams are combined, all four traverse the same Pockels cell and waveplates which are used to convert the linearly polarized lasers into circularly polarized lasers prior to reaching the entrance window to the electron gun vacuum system.

REFERENCES

[1] The RF frequencies have been rounded to the nearest 10 MHz; all references to 1500 MHz, 500 MHz and 250 MHz are more precisely 1497 MHz, 499 MHz and 249.5 MHz.

[2] R. Kazimi, et al., “Test of a new RF separator for CEBAF”, in *Proc. 1992 Linear Accelerator Conference*, pp. 244-246.

[3] L. Cardman, et al., "The JLAB 12 GeV energy upgrade of CEBAF for QCD and hadronic physics", in *Proc. PAC’07*, pp. 58-62.

[4] R. Kazimi, et al., “Simultaneous four-hall operation for 12 GeV CEBAF”, in *Proc. IPAC13*, pp. 3502-3504.

[5] R. Kazimi, et al., “Source and extraction for simultaneous four-hall beam delivery system at CEBAF”, in *Proc. IPAC13*, pp. 2896-2898.

[6] M. Poelker, in *Proceedings of the 12th International Symposium on High-Energy Spin Physics (SPIN 96)*, p. 723.

[7] M. Poelker and J. Hansknecht, Proceedings of the Workshop on Polarized Gas Targets and Polarized Beams, in *AIP Conference Proceedings 421*, p. 270 ,1997.

[8] C. Hovater, et al., “A New RF System for the CEBAF normal conducting cavities”, in *Proceedings of 22nd International Linear Accelerator Conference*, pp. 456-458 , 2004.

[9] M. Steigerwald, "MeV Mott polarimetry at Jefferson Lab", *in AIP Conference Proceedings 570*, p. 935, 2001.