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# OPERATIONAL RESULTS OF SIMULTANOUS FOUR-BEAM DELIVERY AT JEFFERSON LAB*

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*Abstract*

A concept for simultaneous beam delivery to all four CEBAF experimental halls from a single injector and a single main accelerator for the 12 GeV era was proposed in 2012. The original 12 GeV beam delivery plan was for a maximum of three experimental halls at a time as in the 6 GeV era. Therefore, the new concept increases the potential beam time for the experiments up to 33%. This change, although a major improvement in operational capabilities, required only limited modifications to the existing machine. The modifications were mainly timing and pattern changes to the beams in the injector, adding a fourth laser to the photo-cathode gun, and the addition of new RF separators to the highest pass of CEBAF. These changes are now complete and, for the first time, the full system is operating, producing four simultaneous beams through the accelerator to four different destinations. In this paper, in addition to presenting the results of the full system commissioning, we will discuss important details about the new configuration plus some of our operational challenges.

## BACKGROUND

The 12 GeV upgrade to the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab doubled the energy reach of the accelerator from 6 GeV. The upgrade also added a new experimental Hall D to the three existing Halls A, B and C (Fig. 1) [1].

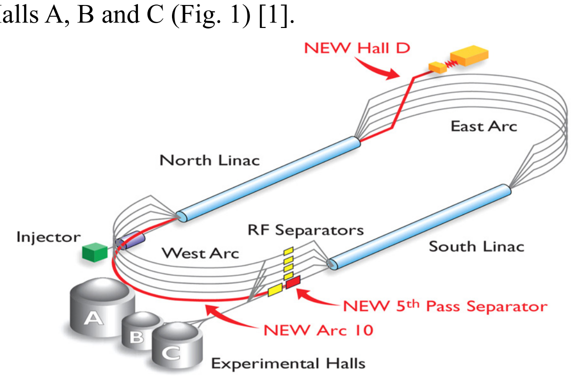


Figure 1: The 12 GeV upgrade doubles maximum energy from 6 GeV and adds a new experimental Hall D.

During the 6 GeV era, the CEBAF accelerator was capable of simultaneously delivering beam to up to three different destinations, Halls A, B and C, extracted at any of the five passes through the accelerator. This was done by generating three interleaving beams in a photo-cathode electron gun using three lasers pulsing at 500 MHz[1] each, one third of accelerating frequency 1.5 GHz[1]. These beams would be accelerated together through the machine to eventually be separated and directed to experimental halls by rf separators also operating at 500 MHz [2].

The same pattern with some upgrades, accounting for energy increase and extraction to the new hall, could have been used for the 12 GeV machine and in fact was the original plan. However, that would limit operation to three beams and three destinations at most. In other words, only three out of four halls would be receiving beam, and there would always be at least one experimental hall not receiving beam. In 2012, near the end of 12 GeV upgrade construction, a new beam pattern was proposed that allowed simultaneous beam delivery to all four halls [3].

This new pattern required modifications only to the injection and the extraction sections of the machine. The changes for the injection system were the addition of a fourth laser for Hall D and the addition of a new 250 MHz[1] pulse rate for beams. The rf separator extraction system for lower passes and for separating the beams for Halls A, B, C at the highest pass, remained at 500 MHz and only upgraded for higher energy. The major change in the extraction system was the addition of a new separator operating at 750 MHz[1] at the highest pass. This new separator, labeled "5th Pass Separator" in Fig. 1, separates the beam for Hall D to continue around Arc 10 to Hall D.

Different parts of the Four-Hall delivery system were constructed and commissioned piece-by-piece with minimal impact on the operations of the accelerator over several subsequent physics run periods. Full Four-Hall operation was first performed in January 2018 [4], and full Power Operations (900kW total beam power) to multiple halls was achieved in April 2018. Figure 2a shows all four beams downstream of the 750 MHz separator showing the D beam kicked to the right to continue Arc 10 and the A, B, and C beams on top of each other to the left for extraction. The A, B, and C beams are then separated from each other by a 500 MHz vertical separator to go to Halls A, B, and C (Fig. 2b).

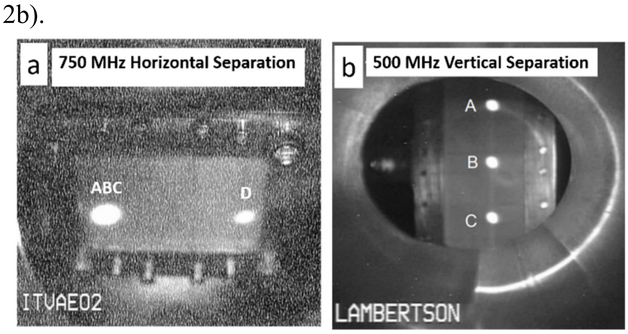


Figure 2: (a) Beam viewer downstream of the new 750 MHz 5th pass separator showing separation of the D beam. (b) Beam viewer downstream of the 500 MHz separator showing the vertical separation of the A, B and C beams.

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[1] The frequencies are rounded for ease of reading 1.5 GHz for 1.497 GHz, similarly sub harmonics 750, 500, and 250 for 748.5, 499, and 249.5

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In the following sections we discuss the modifications to the injection and extraction and present the operational results of the system.

## LLRF FOR LASERS

For the new beam pattern to work for all possible Hall combinations, the electron gun must produce four independent beams each with bunch rates of 250 MHz or 500 MHz. Note not all run configurations require the 250 MHz repetition rate for all four halls; some run configurations are compatible with 500 MHz operations for one or more halls. Because a photo-cathode is used to produce the electron bunches, the gun's drive laser pulses need to be synchronized with the required bunch rate frequencies of 250 MHz or 500 MHz [5].

To meet these new operational requirements, a "4-Laser" digital low level rf (LLRF) system was implemented to replace the older analog VME based 3-laser system. The 4-Laser LLRF system consists of four RF receivers and four RF transmitters allowing independent operation of four RF driven lasers [6].

The system is connected to the accelerator network via a PC104 controller running EPICS. Operators can set the amplitude, phase and one of the two possible beam frequencies for the laser RF drive signal. Expert level control screens provide detailed diagnostic and configuration tools. Selected signals are stored in the accelerator archiver and can be used for system troubleshooting. The relative rf phases of the beams were stable with no measurable phase drift between beams over the course of several days. All RF signal spurs remained below -50 dBc, well below requested -40 dBc.

## TIMING THE BEAMS IN INJECTOR

One challenge faced was how to set the order of the four beams in the injector to ease operational setup and reduce configuration errors. The four beams are created at a subharmonic of the accelerating frequency of the machine; therefore, they all will go through the same bunching and accelerating fields. However, their relative order (their relative rf phases or their timing) determines their final destinations. As mentioned, Hall D beam is separated from the other three at the new 750 MHz separator. Since all other CEBAF rf elements are based on either 1.5 GHz or its 1/3 harmonic, 500 MHz, distinguishing the D beam from the other three beams at these frequencies is not readily done in real time or non-invasively. Invasive measurements relying on measuring the bunch timing or on the space charge to determine the timing of individual beams was initially used, but was found to be cumbersome and required expert attention.

Instead, using an existing beam position monitor (BPM) in the injector, we created a real time minimally invasive diagnostic to readily determine the relative phasing between the Hall D beam and any of the three other beams. A small portion of the beam signal from one of the antennas of a BPM was coupled out. Considering only the 750 MHz content, if signals from D beam and another beam add, they are phased such that both would go to hall D (not desired); if they subtract, D beam goes to Hall D and the other beams go to the A, B, or C halls. This signal is called the Beam Destination Monitor signal, and it is available to operators non-invasively to monitor the relative phasing of the beams.

## LASER TABLE

The photo-cathode gun produces highly spin-polarized electron beams for the experiments. With four lasers, the design of the laser table for the gun becomes a challenging task. The laser table serves two functions. The laser optics combine beams making them collinear to shine on the same spot on the cathode, and additional table elements provide control for the polarization of the beams. A solution was achieved by combining laser light "A" (destined for high current Hall A) with laser "B" (destined for low current Hall B) using a reverse splitter mirror with one linear polarization state. In the same way laser "C" (high current Hall C) and laser "D" (low current Hall D) are combined, but with orthogonal polarization. Then the resulting pairs of laser beams were merged altogether using a polarizing cube to join all four lasers to a single path. This four-laser light is then passed through the elements needed for creating circularly polarized light. Figure 3 shows the schematic and picture of the 4-Laser table.

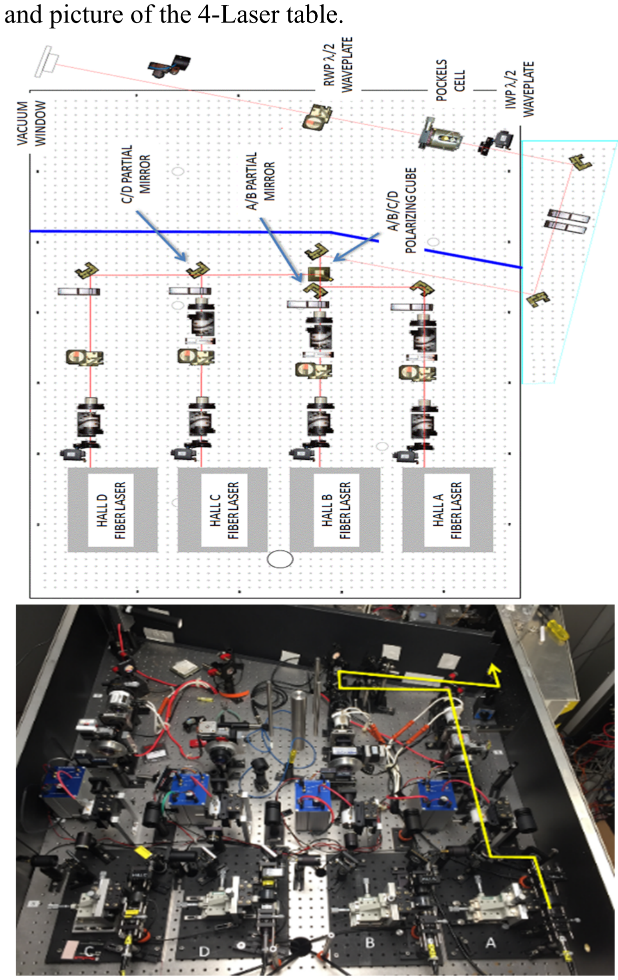


Figure 3: Four-Laser table. (Top) The laser paths from right to left are A, B, C, and D in the schematic. (Bottom) On the laser table C and D are switched.

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## RF SEPARATION

The 750 MHz rf separator cavities are similar to the 500 MHz cavities, only shorter in length [2,7]. They use a highly deflecting cavity design consisting of two parallel rods held at ends of cylindrical pillbox cavities with no accelerating field on axis (Fig. 4).

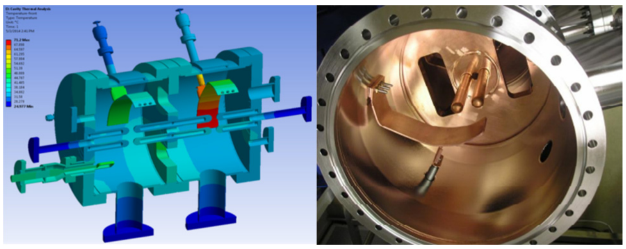

Figure 4: 750 MHz rf separator structure.

To achieve the required deflection four cavities were used. Three challenges for the operation of these cavities are worth mentioning:

- Higher sensitivity of resonance control for 750 MHz cavities compared to the original 500 MHz separators.
- Managing RF losses in the transmission system (high power phase shifters, long cable runs, circulators, etc.)
- Optimizing installation for maximum overhead.

The 750 MHz separation system was declared fully operational during the Spring 2018 physics run.

## INCREASE OF MULTIPLICITY

Multiplicity is defined as the number of experimental halls receiving beam at any given time. An obvious benefit of this Four-Hall operation is the increased multiplicity. With the 500 MHz system alone, the highest multiplicity we could achieve was 3. The maximum multiplicity for the new system is 4, an increase of 33% that is translating into greater science production.

The value of 3 or 4 is the maximum value; however, in practice, the average facility multiplicity also depends on the availability of the rest of the machine. The largest contributors to reduced CEBAF availability are the rf trips in the accelerating cavities of the two linacs. Therefore, the average multiplicity is usually lower than the maximum by about 10% which means the average multiplicity should be compared to 3.6 (90% of 4). Figure 5 is a graph of CEBAF multiplicity and beam currents during the 2018 Spring run. It shows that as the run progressed the multiplicity graph is reaching the 3.6 level.

## IMPACT ON EXPERIMENTAL HALLS

Besides increasing the multiplicity, there is another advantage of Four-Hall operations, and that is ease of scheduling. Dedicated beams for the four halls makes them mostly independent as far as scheduling beam time. There are exceptions: One is the lasers produce a small amount ~few nanoamps of beam at the wrong phase which can propagate to other halls. This is mostly problematic for the low current halls B and D. The condition can be mitigated at the injector for most operational configurations, but not always, and is a factor in scheduling. Another challenge is operating a high current hall at 5th pass with Hall D, where the high current hall must operate at 250 MHz (instead of 500 MHz), doubling the bunch charge. This requires greater effort in the injector setup and it may cause event pile up in the experimental detector systems. The latter has not been an issue.

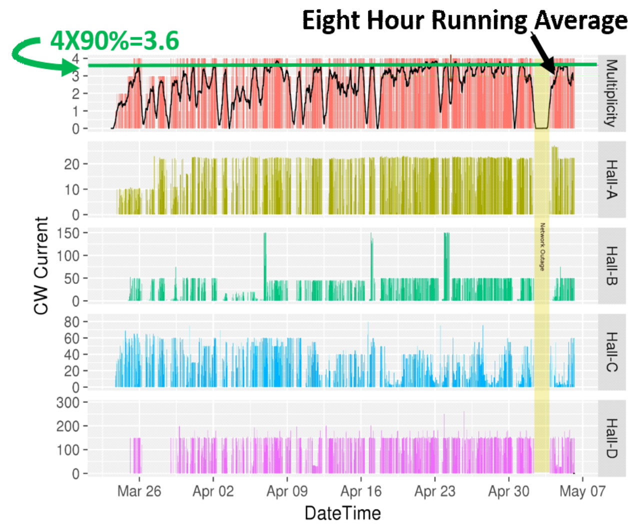


Figure 5: (Bottom four histograms) instantaneous cw current at four CEBAF experimental halls. (Top histogram) the multiplicity calculated as the number of halls receiving cw beam simultaneously. The black line is the 8 hour running average. The green line marks the 3.6, maximum multiplicity for 90% accelerator availability. Periods of zero multiplicity lasting several hours are typically off time for maintenance or beam studies.

## CONCLUSION

The Four-Hall beam delivery system which was proposed as an addition to the 12 GeV CEBAF upgrade, has become operational. The system has already demonstrated in an increase of more than 30% beam time for physics experiments at our facility. The users supported this increase in capabilities and have applauded this achievement for the laboratory.

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## REFERENCES

[1] L. S. Cardman and L. Harwood, "The JLab 12 GeV Energy Upgrade of CEBAF for QCD and Hadronic Physics", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper MOZBKI03, pp. 58-62.

[2] R. Kazimi, *et al.*, "Test of a New RF Separator for CEBAF", *1992 Linear Accelerator Conference*, pp. 244-246.

[3] R. Kazimi, "Simultaneous Four-hall Operation for 12 GeV CEBAF", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPFI091, pp. 3502-3504.

[4] M. F. Spata, "12 GeV CEBAF Initial Operational Experience and Challenges", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1771-1775. doi:10.18429/JACoW-IPAC2018-WEYGBD1.

[5] J. Hansknecht and M. Poelker, "Synchronous photoinjector using a freq.-doubled gain-switched fiber-coupled seed laser and ErYb-doped fiber amp.", PRST-AB **9** 063501 (2006).

[6] T. E. Plawski *et al.*, "CEBAF Photo Gun RF System", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 236-238. doi:10.18429/JACoW-LINAC2018-MOPO115.

[7] H. Wang, G. Cheng, L. Turlington, and M. J. Wissmann, "Cavity Design, Fabrication and Test Performance of 750 MHz, 4-Rod Separators for CEBAF 4-Hall Beam Delivery System", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3548-3550. doi:10.18429/JACoW-IPAC2015-WEPWI029.