A BEAT FREQUENCY RF MODULATOR FOR GENERATION OF LOW REPETITION RATE ELECTRON MICROBUNCHES FOR THE CEBAF POLARIZED SOURCE*

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Abstract

Fiber-based drive lasers now produce all of the spin-polarized electron beams at CEBAF/Jefferson Lab. The flexibility of these drive lasers, combined with the existing three-beam CEBAF photoinjector Chopper, provides a means to implement a beat frequency technique to produce long time intervals between individual electron microbunches (tens of nanoseconds) by merely varying the nominal 499 MHz drive laser frequency by < 20%. This submission describes the RF Laser modulator that uses a divider and heterodyne scheme to maintain coherence with the accelerator Master Oscillator (MO), while providing delay resolution in increments of 2ns. Some possible uses for such a beam are discussed as well as intended future development.

INTRODUCTION

Under normal operating conditions, the CEBAF photoinjector generates three interleaved electron beams, each having a repetition rate of 499 MHz, the third subharmonic of the acceleration cavities. This unique structure is achieved by using three individual photogun drive lasers to produce 40 ps bunches with 2 ns spacing. In CW mode, the drive lasers are synchronous with the rest of the machine, producing electron bunches that fill every RF period of the accelerator.

The CEBAF photoinjector chopper system sets the phase acceptance of the injector. It employs two 499 MHz TM210 cavities to deflect and recombine the electron beam after it passes through slits on a water-cooled copper mask. Only electrons within a 111 ps window (20 degrees at 499 MHz) pass through the mask. The chopping process is also synchronous with the accelerating cavities [1], [2].

Recent parity-violation experiments have requested longer bunch spacings to facilitate the separation of high-energy, elastically-scattered protons from lower-energy particles [3]. Early CEBAF injector configurations employed a separate 31 MHz (16^{th} subharmonic) mode-locked laser, resulting in 32 ns bunch spacing. Many hours were required to install and remove this dedicated laser system, and any attempts to automate the change were dismissed.

Although lower subharmonic drive laser frequencies appear attractive, it is difficult to maintain pulse symmetry and consistency for 100 MHz repetition rates and below. In addition, the optical cavity size for low repetition rates becomes large and intractable. An alternative solution involves unlocking the drive laser RF, and using the chopper as an analyzer, resulting in the creation of a heterodyne, or beat frequency, after the chopper mask [4]. This technique then allows the gun to continue to produce uniform bunches at near-499 MHz repetition rates, while the chopper output only contains bunches as defined by the beat frequency.

Concurrent with the recent run of the Hall C G_0 experiment, the JLab Electron Gun Group was evaluating the utility of high-power fiber lasers, which are prevalent in the telecommunications industry. The merits of these lasers are high peak power, relatively fast modulation speeds, and reliability. The fiber lasers are mounted in an accessible chassis, whereby optical fiber transmits the light to the tunnel, and ultimately to the photocathode. Most importantly, these lasers produce picosecond pulses via gain switching, a purely electrical technique that does not require changes to the laser cavity length or complicated feedback loops. And because the pulse repetition rate from a gain switched fiber based laser can be varied by simply changing the applied RF signal, these lasers are well suited for implementing the beat frequency technique.

MODULATION

Only certain frequencies applied to the fiber-based drive lasers will produce a periodic pulsetrain downstream of the chopper. Determination of appropriate frequencies for a given bunch-spacing requirement follows the equation:

$$T_{bunch} = \frac{1}{F_{chopper} - F_{laser}} = \frac{N}{F_{chopper}}$$

T_{bunch} = interval between bunches, seconds
$F_{chopper}$ = Chopper RF frequency, MHz
F_{laser} = Laser RF frequency, MHz

which yields

$$F_{laser} = \left(1 - \frac{1}{N}\right) \times F_{chopper}$$

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N is an integer > 1, and is equivalent to saying every Nth RF bucket contains an electron bunch.

A listing of parameters to achieve the demonstrated bunch spacings, with a Chopper frequency of 499 MHz, is given in Table 1.

Table 1: Selected laser drive frequencies for given bunch spacings and corresponding values of N.

Bunch Spacing (nsec)	N	Laser Frequency (MHz)	Bunch Frequency (MHz)
10.0	5	399.2	99.8
16.0	8	436.625	62.375
20.0	10	449.10	49.9
32.1	16	467.8125	31.1875
40.1	20	474.05	24.95
50.1	25	479.04	19.96

Note that frequencies derived from many of the N-integer values result in repeating decimals. This is problematic when using a separate synthesizer having finite dividers. It causes the bunches to precess around the mask, thereby creating slow beam intensity modulations.

Initial Tests

Initial proof-of-concept experiments at 31.1875 MHz involved a HP8662 synthesized RF source as the drive laser signal, synchronized to the 10 MHz Master Oscillator. Although bunches possessing the proper spacing were produced, excessive tails and asymmetries were observed by the incoherence of the beat frequency as a result of absence of true phase lock of the synthesizer time base reference to the MO, as well as residual phase noise within the synthesizer. Only those values of N resulting in laser frequencies of less than 5 decimals were investigated, due to the repeating decimal problem. A viewer located at the Chopper mask was used to qualitatively examine the resulting N-1 spots on the mask, as shown in Figure 1. Although the first experiments provided proof-of-principle, the resulting transported beam quality was not acceptable to the users.

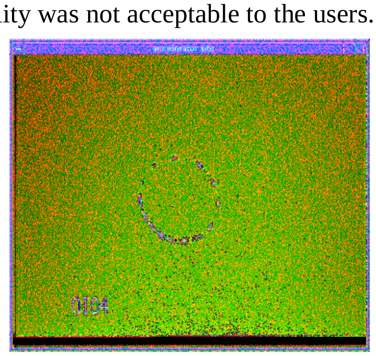

Figure 1: Chopper mask viewer for 40 uA beam, N=16 32 ns delay, showing the creation of 15 (N-1) microbunches. Irregularities and tails are evident due to lack of true phase lock within the HP8662.

Modulator Development

A dedicated G_0-beam modulator was constructed, requiring only 499 MHz input from the Low-Level RF Module (LLRF) as a reference. This topology, using a combination of frequency division and heterodyning, was inherently synchronous to the rest of the accelerator. The modulator produced a 32ns bunch spacing, without introducing drift or excessive phase noise. The schematic is shown in Figure 2.

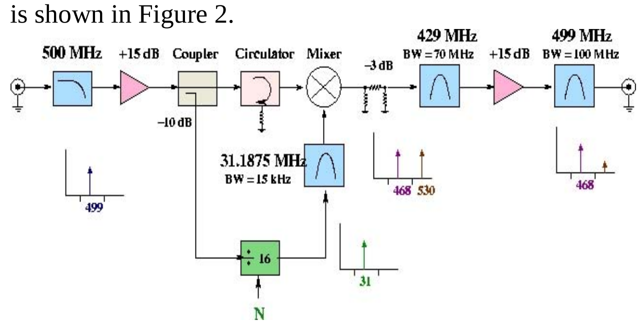

Figure 2: Schematic diagram of Beat-frequency laser modulator and related spectra. Divider and filtering are selected for required bunch spacing.

Results of the modulator provided better uniformity of bunches, especially when aided by the application of electron pre-bunching. User-quality beam with 32 ns spacing was successfully delivered to the experimental halls although modest residual low frequency intensity modulation was present (Figure 3), a result of inadequate output filtering of the 436 MHz sideband produced from LO leakage on the mixer.

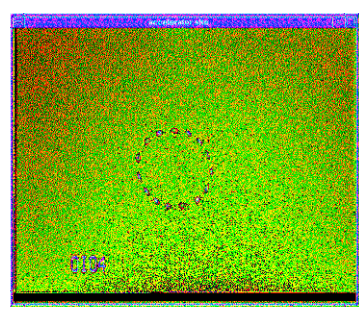

Figure 3: Chopper mask viewer showing modulator-produced beam. Better uniformity is observed, but a low-frequency component is still present. Beam current = 40uA.

A second modulator was built using an Analog Devices AD9511 Clock Generator IC evaluation board. Features of this IC include extremely low additional jitter and phase noise, multiple USB-programmable dividers, choice of logic families, and software-variable output delay [5]. The primary benefit of the AD9511 is to minimize re-configuration time, and provide computer control. In addition, IF and output filtering were optimized to reduce the unwanted sidebands to improve bunch consistency, as well as provide reasonable flexibility for other values of

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N. The beam quality with 32 ns bunch spacing was improved considerably, as indicated by the chopper slit scan in Figure 4, comparing results with new and old modulator. Clean beat frequency beam is indicated by large contrast between peaks and valleys and an indication of good isolation between consecutive beat-beam pulses.

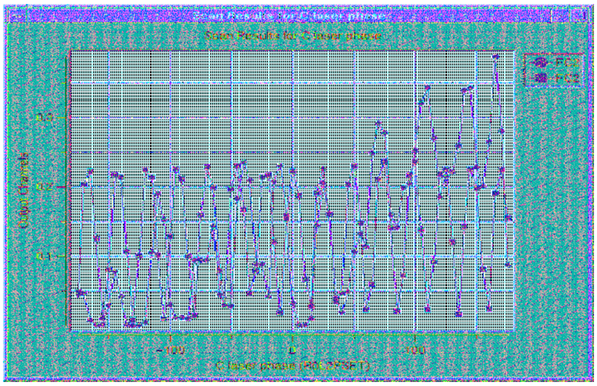

Figure 4: Chopper mask slit scan of modulator-produced beam, and related scan. Better uniformity is observed, but a low-frequency component is still present. Beam current = 40 uA.

As a demonstration of flexibility, rapid configuration changes were made to 40 uA CW beam for N=5,6,8, and 16, requiring only minutes to complete. Figure 5 demonstrates beam spacings of 10ns and 12ns, (N=5 and 6, respectively). The 12ns condition results in a repeating-decimal drive frequency of 415.833... MHz, and is easily handled by the modulator.

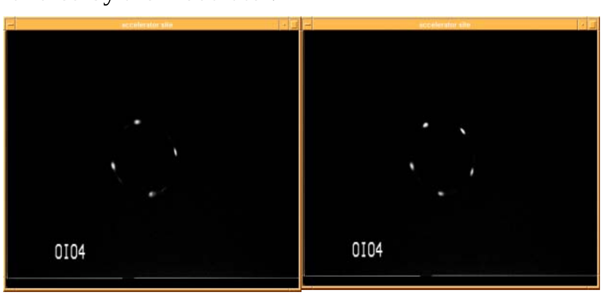

Figure 5: Chopper mask views of 10 ns (N=5) and 12ns (N=6) bunch spacings, I=40 uA. Demonstrated uniformity, ease of configuration, and ability to create run-on decimal frequencies.

CONCLUSION

Already, many experimenters have requested this new CEBAF beam structure, for example, to identify sources of background, detector calibration and polarimeter systematic studies. Figure 6 demonstrates clear pion and electron separation at the Hall C Cerenkov detector, data that could not have been obtained using normal CEBAF beam with 2 ns bunch spacing [6]. The versatile CEBAF photoinjector, including the Chopper and fiber laser systems, provides this capability. The new modulator described above has demonstrated synchronous beam production possessing 2*N ns bucket delay times for any N, using only 499 MHz as a reference. Beat frequency beam is clean, stable and adequate for many user applications. Future modulator boards will utilize band-switched filters, as well as comb filtering, facilitated by the AD9511 variable-delay output.

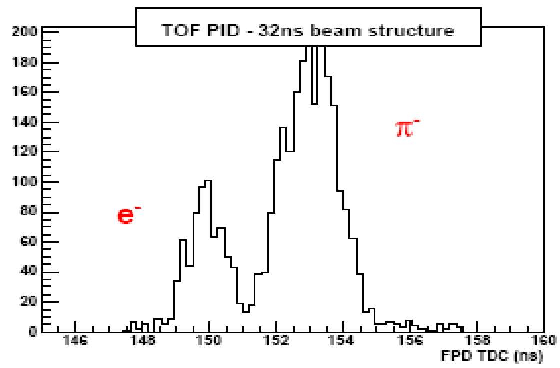

Figure 6: Electron-pion spectrum, demonstrating utility and user-quality of beat-frequency beam.

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