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High-resolution time-of-flight mass spectrometry impulse-field focusing pulse generators

R. L. Miller, J. A. Browder, and G. Sanzone[a)]

Department of Chemistry, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

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Experiments have shown that the unit mass resolution of conventional Wiley–McLaren time-of-flight (TOF) mass spectrometers can be significantly improved using the technique of impulse-field focusing (IFF). Details of the circuitry used to test the IFF theory are presented. Generators of electrical pulses with nanosecond rise times and 100-V amplitudes are described.

INTRODUCTION

The mass resolution of time-of-flight (TOF) mass spectrometers having the conventional Wiley–McLaren configuration has been significantly improved with the use of a technique called impulse-field focusing (IFF).[1] The new technique involves the application of a time-dependent ion-draw-out field, as opposed to the time-independent field employed in conventional TOF spectrometers.

The previous study[2] showed impulse-field focusing increased the unit mass resolution of our conventional instrument by 140%. It should also be pointed out that the resolution was improved by 61%, solely by replacing the original ion-draw-out pulse (focus pulse) with an improved pulse of faster rise time (see Table I).

Due to the number of requests received since the appearance of the earlier paper, we are reporting the details of design and operational tests of the IFF electronics. These details should be helpful for those interested in improving the resolution of many conventional instruments now in use. The pulse generators described in this paper should also be useful in other experimental situations.

I. APPARATUS

In order to test the IFF theory, two time-coincident, relatively high-voltage pulses of short duration were required. One pulse, the focus pulse, was intended to have a variable amplitude of 0–400 V and a variable duration of 1–5 μs. The other pulse, the impulse-field (IF) pulse, was intended to have a variable amplitude of 0–400 V and a variable duration of 10–200 ns. Rise times of both pulses were to be $\leqslant 5$ ns. It was necessary that the pulses be generated synchronously, at a frequency of at least 10 kHz.

These specifications suggested the use of electron-bombarded semiconductor (EBS) devices,[3] which provide the voltage gain of electronic tubes and the rise times of transistors. The EBS devices used in this study (Watkins–Johnson 3684) are fast rise-time, grid-controlled amplifiers capable of producing output pulses of several hundred volts with nanosecond rise times. Basic components of this type of EBS device are the cathode, heater, grid, and semiconductor target. Operation of the device involves application of a negative-going input pulse to the cathode, resulting in an electron beam that strikes a reverse-biased semiconductor target.[4] The current produced in the target is multiplied to produce an amplified output signal. The EBS devices were incorporated into the pulse generator circuit, as indicated in Fig. 1.

The master clock pulse generator of the mass spectrometer, interfaced with the IFF pulse generator, was used to trigger the IF pulse and the focus pulse. Major components of the pulse generator circuitry are described below.

II. TOF INTERFACE

Both of the EBS devices required a bias voltage of 10 kV below ground, causing a large difference in potential between the original TOF chassis and the IFF electronics. This, in turn, required an interface, depicted in Fig. 2, capable of electrically isolating the original TOF circuitry from the IFF pulse generators. An optical isolator capable of withstanding the 10-kV differential was chosen to transfer the master clock pulse from the spectrometer to the IFF unit.[5] Supporting circuitry attenuates the master clock pulse to approximately 5 V, and then variably delays the pulse by means of a 74121 one-shot time delay. After the time delay, the signal is transmitted via the optical isolator to the timing control portion of the IFF pulse generators.

III. TIMING CONTROL

In the timing control circuit (see Fig. 1), the signal from the optical isolator is variably delayed by 1–10 μs using IC-A, a 74121 integrated circuit. This allows coincidence of ion-production cessation in the TOF and initiation of both the focus and IF pulses. From this time-delay circuit, the signal travels to IC-B and IC-C (both are 74123 circuits). Here, the signal triggers IC-B and IC-C to generate pulses that are logically combined using 74LS00 NAND gates.

In order to form the focus pulse, IC-B1 is used to generate a 40-ns fixed-width pulse that is logically added with a 1–

TABLE I. Time-of-flight mass spectrometer performance.

	Conventional	Improved focus pulse	Improved focus pulse with IFF
Unit mass resolution	280	450	671
Percent improvement	—	61%	140%

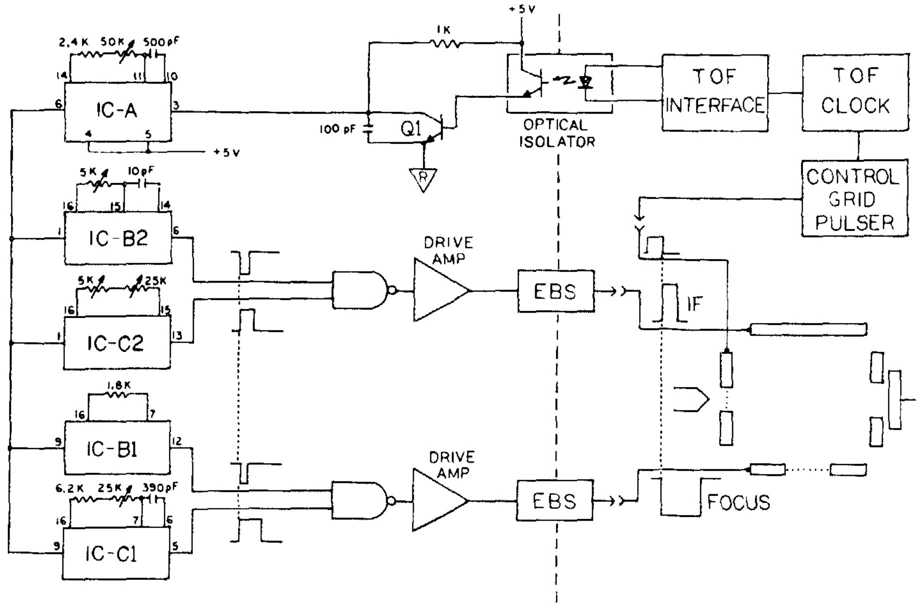

FIG. 1. Block diagram of entire circuit. IC-A is a 74121 integrated circuit and Q1 is a 2N2369 transistor. IC-B1 and IC-B2 represent two halves of the same 74123 integrated circuit. The same is true for IC-C1 and IC-C2. The reference voltage on Q1 is − 10 000 V, relative to ground.

5-μs variable width pulse from IC–C1. Since the pulse from IC-B1 is negative, while the one from IC-C1 is positive, combination of the two results in a focus pulse width that is the difference in time of the two pulses. This difference causes a 40-ns delay, which IC-B2 is adjusted to match. When the pulse from IC-B2 is combined with the one from IC-C2, a similar result yields an IF pulse that is variable from 50–250 ns. Essentially, IC-C1 is used to adjust the width of the focus pulse; IC-C2 is used to adjust the width of the IF pulse; and IC-B2 serves as a synchronization control on the production of IF and focus pulses. Following these timing controls and logic gates, the pulses are amplified by the drive amplifiers, and ultimately by the EBS units.

IV. DRIVE AMPLIFIERS

In the construction of the IFF electronics, two drive amplifiers are used, one each for the IF and focus pulses (see Fig. 3). Each is a three-stage, common-emitter amplifier offering fast switching and signal inversion at each stage. The amplifiers employ high-speed 2N5837 transistors with frequency cutoff in the gigaHertz range and typical switching times of 650 ps at 100 mA dc collector current. Their signal switching speed, combined with a storage delay of less than 10 ps, makes them quite attractive for amplification of the IF and focus pulses. The 2N5837 transistors are powered by a stable + 12-V dc power supply capable of supplying about 1.0 A dc to each drive amplifier.

Two other transistors (2N2369), chosen for their power handling capacity, were used to drive the EBS tubes. These transistors are carefully matched at a pulse current of 500 mA dc and selected for low collector leakage, as well as low gain, in order to provide their fastest possible rise time. Selection of the units was based on these criteria to prevent damage due to operator error. The 2N2369 transistors are powered by an adjustable 0–30-V dc supply (at 1.0 A dc) that is varied, as needed, to assure adequate rise-time characteristics of the EBS signal. Upon leaving these transistors, the IF and focus pulses are then amplified by the EBS devices and injected into the ion-draw-out region of the mass spectrometer.

V. EBS POWER SUPPLIES

Each EBS device requires three operating voltages: a large bias voltage of 10 kV dc at 100 μA; a smaller, 0–500 V dc, bias voltage; and a filament heating voltage. For the latter, a 0.8-A constant current supply, based on the LM337 National Semiconductor three-terminal variable voltage regulator, was chosen to avoid filament-damaging surge cur-

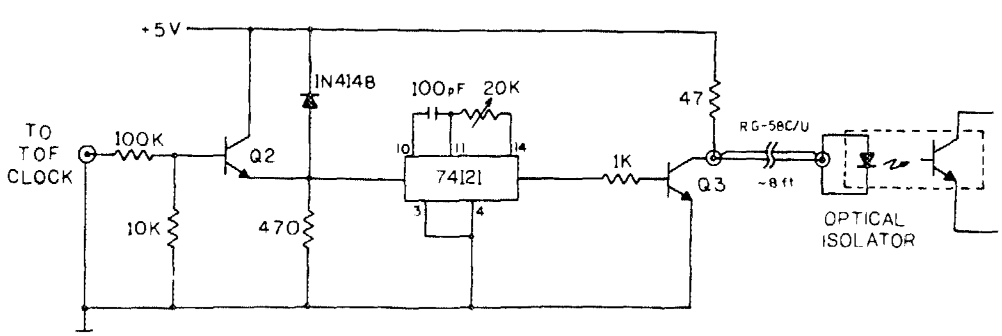

FIG. 2. TOF interface circuit. Q2 and Q3 are 2N2369 transistors.

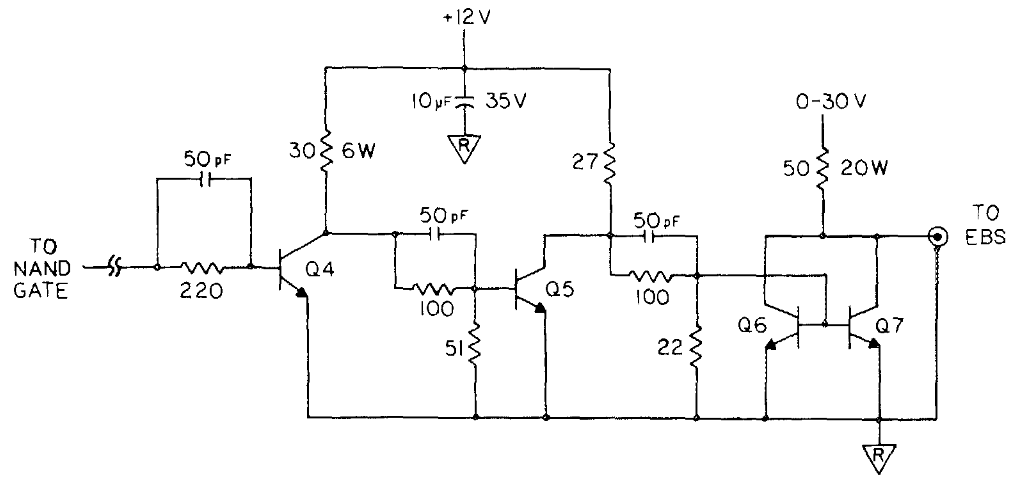

FIG. 3. EBS drive amplifier circuit. Q4 and Q5 are 2N5837 transistors and Q6 and Q7 are selected 2N2369 transistors (see text for selection criteria). Reference voltage is − 10 000 V, relative to ground.

rents. The other voltages were provided by separate power supplies, chosen for maximum stability and minimum noise. An additional 0–30 V dc variable power supply was required for each drive amplifier.

Each time the power supplies are turned on or off, stability of the EBS device requires a very systematic procedure. Turn on starts with a 3-min EBS filament warmup. Then, only 15-V potentials are applied to the EBS units from the 0–500-V supplies. Next, the high-voltage bias is applied to the EBS and supporting circuitry, and increased slowly from 0 to − 10 kV dc. At this point, the 0–30-V drive amplifier supply voltages are gradually increased to levels that afford good signal shapes. Finally, the 0–500-V supply voltages are raised to levels that provide the desired IF and focus pulse amplitudes.

The turn-off procedure is the reverse of the above turn-on procedure.

VI. RESULTS AND DISCUSSION

The circuitry described above was coupled with a Bendix model 12 TOF mass spectrometer. Both the IF and focus pulses showed rise times in the range of 3–5 ns, well within the 5-ns limit specified at the beginning of the experiment. Pulse amplitudes as high as 140 V and durations as brief as 10 ns were used. Higher amplitudes were obtainable, but there was significant deterioration of the signal shape at higher voltages. Although actual amplitudes fell short of the 400-V specification, the pulses generated were judged adequate for the purposes of this study.[6]

Noise levels of both pulses were found to be within acceptable limits. A certain amount of ringing was present in the pulses (see Fig. 4), but did not significantly affect final experimental results. In future studies, improved wire dress and component placement could reduce the ringing.

Overall performance of the IFF electronics was satisfactory. The pulse generators were sufficiently flexible to allow adequate variation of pulse amplitudes and durations for test of the IFF theory.

Results of the experiment showed that impulse-field focusing could be successfully used to increase the unit mass resolution of a TOF spectrometer by at least 140% over the resolution obtainable with a conventional instrument. The data also suggested that still greater improvement might result from the use of higher voltage IF pulses. Furthermore, the experiment confirmed the major trends predicted by the IFF theory.

In short, we found the IFF technique to be useful for resolving heavier masses with a TOF instrument and we found the pulse generators described above to be useful devices for producing the high-voltage, short-duration pulses dictated by the IFF theory. Units similar to the one used in this study could prove useful in molecular beam studies, other types of mass analysis, ion-kinetic analysis, and a number of other applications.

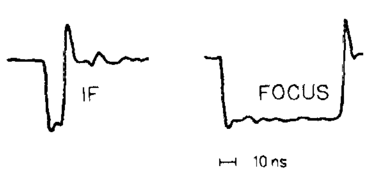

FIG. 4. IF and focus pulses generated using described electronics.

[a] Author to whom correspondence should be sent.

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[4] R. I. Knight and D. J. Bates, "Characteristics and Capabilities of the Modulator EBS," IEEE Conference Record of 1973 Eleventh Modulator Symposium, 18–19 Sept. 1973.

[5] A Monsanto MCT5-25 optical isolator was used in the original apparatus but is no longer manufactured.

[6] The EBS units employed were below specification, used units, graciously provided by Watkins–Johnson for this research.