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IMPROVEMENTS IN SYNCHRONIZATION OF THE PBFA-II ACCELERATOR WITH LASER-TRIGGERED GAS SWITCHES*

J. M. Wilson and G. L. Donovan
Sandia National Laboratories
Albuquerque, New Mexico 87185

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Abstract

PBFA II is a 36-module ion accelerator built by Sandia National Laboratories for inertial confinement fusion studies.[1] In the water-filled, pulse-forming section of the accelerator, each module is fitted with a 5.0-MV, SF_6-filled gas switch located between an intermediate storage capacitor and the first pulse forming line (Line 1). The intermediate storage capacitor is charged to 4.8-5.0 MV in approximately 950 ns by a Marx generator located in the oil section of the machine. The gas switch is required to close on command and transfer the stored capacitor energy to Line 1, a coaxial transmission line of 100 ns two-way electrical length. The switches are triggered by a single 3.0-J KrF laser located under the accelerator; a complex beam-splitting/distribution system is used to deliver 20-40 mJ, 35 ns FWHM beamlets to the individual switches.

In order to properly drive the experimental load on PBFA II, equal-amplitude pulses must be produced by each pulse-forming line with a module-to-module first-to-last timing difference (spread) of less than 20 ns. The gas switch, the last command-triggered point in the module, is the major determinant of total machine synchrony. To compensate for the additional (<3 ns) rms jitter of three sets of self-breaking water switches downstream of the gas switches, first-to-last timing spread of the 36 gas switches must be less than 15 ns.

At the last Pulsed Power Conference, we reported on prototype experiments in which four Rimfire switches were modified and tested, side-by-side, with four of the original PBFA II switches.[2] In these tests, the modified switches exhibited an rms jitter of less than 2 ns, and low prefire rate. The data taken on the modified switches were used in predicting a total 36-switch spread of less than 15 ns, and were the basis for proceeding with a complete retrofit of the PBFA II switch set. This retrofit was completed in the Fall of 1987.

Since the retrofit, several hundred machine shots have been taken at voltages ranging from 3.5 MV to 5.0 MV. Over this range of voltage, the rms jitter of each switch has been measured as less than 2 ns. The average firing times of the switches, however, is not identical; analysis of individual switch data reveals that each switch has an offset (either early or late) that is consistent shot-to-shot. These offsets range from 5.5 ns early to 4.0 ns late. The mechanical design of the laser optical system allows these offsets to be "tuned out" by adjusting the laser pathlengths of individual switches. Such "tuning" now results in 36-module switch spreads of less than 10 ns, and module spreads downstream of the water switches of less than 15 ns.

Gas Switch Configuration

The present and original Rimfire switch configurations are shown in Fig. 1. The present switch is made up of a triggered gap and sixteen series overvoltage gaps. Approximately one-fifth the total switch voltage appears across the triggered gap, and each overvolted gap supports approximately one-twentieth the switch voltage. The electrodes are supported within an acrylic housing by polycarbonate "hockey-puck" insulators pressed between the metal electrodes. This stacking method reduces stray capacitance ringing problems that occur when electrodes are extended through the acrylic housing and into the surrounding water. The switch electrodes are enclosed within a pressure housing made up of six acrylic rings separated by thin aluminum grading rings. The KrF-laser beam enters the trigger section through a hole in the anode end of the switch; the laser optics are designed to focus the ultraviolet light at the center of the trigger gap. The original Rimfire switch had a larger trigger gap and a stack of fifteen overvoltaged gaps.[3]

Figure 2 shows the electric field (E-field) distributions across the two switch versions, as calculated using JASON, a two-dimensional electrostatic solver code.[4] The E-field values were computed assuming a voltage across the switch terminals of 3.8 MV. This corresponds to a measured voltage of 4.3 MV at the center of the intermediate storage capacitor. The 500 kV difference is the result of (a) a 200 kV difference due to differences in the monitor and switch locations, and (b) capacitive precharge of Line 1 that raises the potential of the switch anode to approximately 300 kV. The 3.8 MV is the voltage at the time-of-arrival of the laser pulse in the trigger section of the switch. This results in a peak voltage of approximately 5.0 MV on the intermediate store at the time of switch closure, because of continued charging of the capacitor while the switch gaps are closing.

The original gas switch design did not meet the PBFA II timing requirements for individual jitter and system spread. It also exhibited an unacceptably high prefire rate. Typical switch rms jitters of the original switches were 4-8 ns, with corresponding 36-module spreads of 30-100 ns. Of note, in Fig. 2(a) is the skewed distribution, in the original design, of the E-field across the Rimfire gaps, as well as the relatively low field value in the trigger section. In tests on the DEMON accelerator, the self-break voltage of the switch was found to be dominated by the gaps nearest the cathode end of the switch.[5] The ratio of the field where the laser-induced spark is generated (on axis in the center of the trigger gap) to the peak field within the switch (in the Rimfire gap furthest from the trigger gap) was 0.57 in the original design. This implies the trigger section was required to fire with low jitter at E-field levels less than or near half the self-break field. The present switch design both reduces the peak field in the switch, and substantially raises the field in the trigger section. The ratio of minimum trigger section field to peak field in the Rimfire section is now 0.82.

The modification itself involved changing the trigger section electrode shapes and separation, changing the number and separation of the Rimfire gaps, and reshaping the field distribution along the switch column. The original anode trigger electrode was hemispherical in shape, with a large radius hole to allow the laser light to enter. The present anode electrode is a Rogowski profile insert with a smaller laser entry hole and smaller radius around that hole. The original cathode trigger electrode was similar to the anode electrode, with the hole allowing laser light to scatter in the first plastic "hockey-puck," thus producing more visible light in the switch during pre-shot "light-up" tests. The present cathode electrode is also a Rogowski profile without any hole on axis; the visible light level in the switch during "light-up" tests is reduced, but still identifiable. The present switch design reduced the trigger gap from 5.1 cm to 4.4 cm, and employs sixteen 0.95-cm Rimfire gaps, while the original switch used fifteen 1.15-cm gaps. The field distribution within the switch housing was altered significantly by a metal "hockey puck" placed between the trigger section and the first Rimfire electrode. This design forces more voltage onto both the trigger section and the first few Rimfire gaps.

The resultant E-field distribution of the present switch is shown in Fig. 2(b). The distribution across the Rimfire gaps is now flat, with the average field approximately 200 kV/cm (for the 5.0 MV nominal operating point). The trigger section field is 175 kV in the center, with peaks of 210 kV/cm and 230 kV/cm at the cathode and anode surfaces, respectively. Comparison tests of four original switches and four modified switches were completed in 1987 on PBFA II. The runtime (i.e., from time of laser arrival at the switch to closure viewed by a monitor at the center of the intermediate storage capacitor) of the modified switches was 70-80 ns, with rms jitters of less than 3 ns. The original gas switches operated with average runtimes of 90-110 ns, with rms jitters of 3-10 ns. More detailed analysis of the switch data, which removed shot-to-shot variations and constant offsets in runtime showed that, over the 20-shot series, the actual rms jitters of the modified switches was 0.5-2.0 ns, while the original switches had jitters of 2.0-5.7 ns.

The results of the comparison experiment were used to predict 36-module spread of the gas switch set of 20 ns if no corrections were made for consistent offsets in module runtimes. Constant offsets in a given switch can be caused by differences in Marx generator capacitance or inductance, intermediate storage capacitance, laser energy delivered to the switch, module optics, or mechanical tolerance build-up during switch fabrication. However, if such offsets could be tuned out, the predicted spread of the 36-module set decreases to 5 ns. These data, and the resulting predictions of low 36-module spread, were the bases for proceeding with a complete retrofit of the PBFA II gas switch set in late 1987.

36-Module Switch Set Performance

Since the retrofit of the gas switch set, over 300 shots have been fired. The majority of the machine shots (approximately 225) have been at the half-power level, which corresponds to approximately 3.5 MV on the gas switches. Damage to the accelerator (mainly vacuum and water PFL insulator tracking and breakage) at this voltage level is minimal, and allows a shot rate of greater than one per day. There have been approximately 55 shots at the three-fourths power level (4.1-4.3 MV), and only 21 shots at the full power (4.6-5.0 MV) level.

Figure 3 is a plot of the gas switch spread for all PBFA II machine shots since the first shot in 1985. Of note in the figure are the high values for spread before shot 39 - the time of the switch retrofit. The peaks in the figure seen after shot 39, which represent 36-module spreads of greater than 20 ns, are understood and are not attributed to prefires along the gas switch electrode column. The four peaks seen between shots 200 and 210 are the result of early firing of switch #15. Closer analysis of data and photographs revealed housing flashover that is believed to be the result of tracks created during previous shots at the full-power level. The six peaks seen at the three-fourths power level (shots 291-340) are definite housing flashovers prior to arrival of the trigger pulse; photographic evidence, post-shot discovery of heavy tracking, and occasional rupture of the housing provide the bases for this conclusion. These ten shots are the only observed instances of early modules in the 36-module spread distributions in over 10,000 switch firings. This implies an "early module firing" rate of one in every 28 machine shots. Because early modules are much more detrimental to the ion diode experiments than late ones, the gas switch set now exceeds its original specification of 90% reliability in delivering useful pulses to the accelerator load.

The remaining peaks in Fig. 3 are the result of late modules. The high spreads seen on shots 63 and 290 are the result of single Marx generators firing over 120 ns late, with the corresponding gas switches, triggered at 0.7-0.8 MV below the intended level, running approximately 40 ns late. The remaining peaks on the plot (shots 141, 147, 209, 225, and 301) are apparently the result of switches that received either no trigger pulse or the triggering light was misaligned and did not reach the trigger section *in toto.* On shots 141, 147, and 301, switches continued to hold off increasing voltage for several tens of nanoseconds and then switched out, presumably exceeding the self-break voltage of one or more gaps. On shots 209 and 225, switches fired 8-10 ns late. This could have been the result of low-energy light pulses, or the statistical (4-6 σ) tail of the jitter distribution.

As mentioned above, the comparison tests of 1987 were used to predict 36-module spreads of approximately 20 ns, assuming no adjustments were made to correct for offsets in individual switch firing times. Prior to the first series of 36-module shots, several 18-module shots were taken (shots 47-103 in Fig. 3). Throughout this series of shots, individual switch performance was monitored and a database was kept on switch firing time and jitter. Periodically, individual switch timing was adjusted by changing the optical pathlength to the switch trigger section, e.g., the optical path to a switch that was firing 3 ns early was lengthened by 3 feet. At the end of the series of 18-module shots, tuning adjustments had lowered the average 18-module spread to less than 10 ns.

Figure 4(a) is a plot of the runtime spread for the twenty-five 36-module shots at half power immediately following the series of 18-module shots. Over this series of shots, the runtime spread ranged from 9.0 ns to 15.7 ns, with a mean value of 11.8 ns. Figure 5 is a plot of the runtime offsets of the 36 switches over these same shots, and shows switch #20 running consistently 6.1 ns early and switch #29 running consistently 4.4 ns late, with several other switches running more than 1.5 ns away from the mean. Figure 6 is a plot of the individual switch rms jitters, around the offsets plotted in Fig. 5, over the same twenty-five shots. This shows average rms jitter of the gas switches as less than 1.5 ns. The aforementioned tuning resulted in actual 36-module output spreads of less than 10 ns on the subject shots, as shown in Fig. 4(b). The average 36-module spread over the twenty-five shots was 8.1 ns, with a maximum of 11.9 ns and a minimum spread of 6.3 ns.

Constant review and updating of the switch database allows adjustments to be made based on the previous shot series. The low jitter of each switch allows adjustments to be made on new or refurbished switches after only a few shots have been taken. Such new switches fire slightly early (2-4 ns) on their first 2-5 shots, but do not drift appreciably thereafter.

Low-spread operation at full and three-quarter power was verified on shots 178-193 and 291-335, respectively. At the full power level, the average runtime spread was 16.4 ns, with the tuned module spread averaging 11.9 ns over a 16-shot series. At the three-quarter power level, the average runtime spread was 11.6 ns, with tuning reducing the average module spread to 7.2 ns. It has been found that module spreads of less than 15 ns are required to obtain reasonable results in the ion diode experiments. Spreads greater than 15 ns complicate the ion diode results considerably, while spreads from 5 ns to 15 ns produce almost identical results.

Light tracking of the acrylic housing has been observed on switches when operated for 50-100 shots at the half-power (3.5 MV) level, with few catastrophic failures. No prefires and no degradation in performance with time have been observed. At the three-quarter (4.4 MV) and full (4.8-5.0 MV) power levels, increasingly heavy tracking, that eventually leads to catastrophic flashover and/or rupture, is observed. Damage to the Mallory 1000 copper/tungsten alloy trigger inserts is substantial after repeated firings, but effects of such wear are not noticeable in the shot-to-shot data. Inspection of electrodes after 50-100 shots shows pits in the cathode trigger insert approximately 1 cm in diameter and 0.3 cm deep. Erosion of the edge of the laser entry hole in the anode insert is also observed, with the radius of the hole increased from the machined value of 0.5 mm to an irregular radius of 2-3 mm. Damage to the rimfire electrode surfaces is minimal, with no apparent loss of material and only slight discoloration of the electrode surfaces; the lack of damage is undoubtedly due to multiple current channels around the circumference of the electrodes. Light tracking (i.e., without carbonized roots) is observed routinely on the inside surface of the acrylic housings upon inspection, but does not appear to present a failure mechanism. Tracking of the outer surface of the acrylic housing, however, does often lead to catastrophic flashover and fracture of the housing. There is some evidence that tracking on one surface (inner or outer) may cause the tracking on the other surface (outer or inner), and that any tracking will eventually lead to failure of the switch. Neither studies to determine such cause/effect relationships, nor destructive tests of lightly tracked insulators have been attempted as means to answer these questions.

Conclusion

A modification to the original PBFA II gas switch set has resulted in a new set of switches that operate with low jitter and spread at voltages up to 5.0 MV. Each switch operates with rms jitter of less than 2 ns. The individual switches are tuned by adjusting specific pathlengths from the triggering laser, so that the first-to-last spread of the 36-switch set is routinely less than 10 ns. The reliability of the switch set is a strong function of the operating voltage. At operating voltages above 4.5 MV, flashover results in early modules and ruptured housings on approximately one-fourth of the shots. At lower voltages, these failure mechanisms are not observed. The low gas switch set spread, coupled with the 2-3 ns rms jitter of water switches used for further pulse-compression in the accelerator modules, result in routine 36-module asynchrony of less than 15 ns. This level of symmetry in the power flow has allowed Sandia's inertial fusion program to proceed with critical ion-beam generation and focussing experiments on PBFA II.

References

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FIGURE CAPTIONS

Figure 1. Comparison of Original (Top) and Present (Bottom) Gas Switch Designs.

Figure 2. JASON-Derived Plots of the PBFA II Gas Switch E-Field Distribution. Curve (a): Original Configuration. Curve (b): Present Modified Configuration.

Figure 3. Plot of Gas Switch Spread (First-to-Last) on All 18- and 36-Module Shots since the Initial Shot in December 1985.

Figure 4. Plots of Runtime Spread (Curve A) and Tuned Gas Switch Spread(Curve B) for PBFA II Shots 1747-1804.

Figure 5. Plot of the Runtime Offsets for the Individual Gas Switches Operated on PBFA II Shots 1747-1804.

Figure 6. Plot of the RMS Jitter of the Individual Gas Switches Operated on PBFA II Shots 1747-1804.

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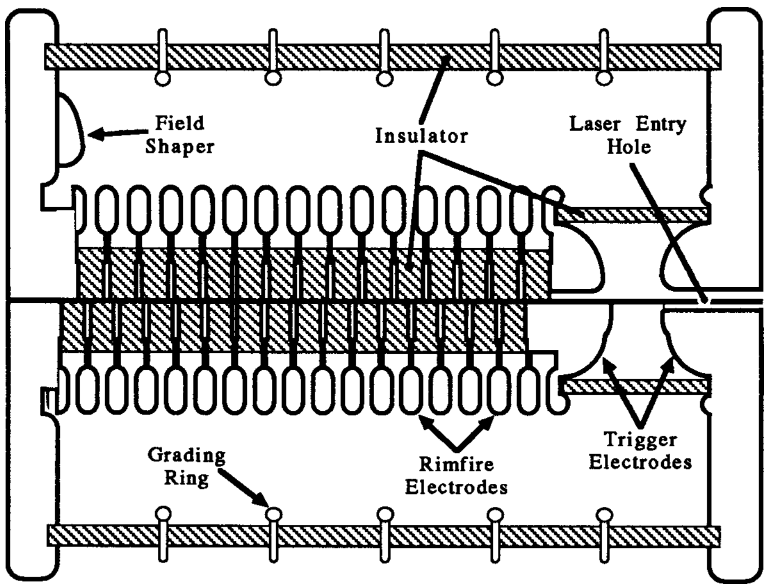

Figure 1. Comparison of Original (top) and Present (bottom) Gas Switch Designs

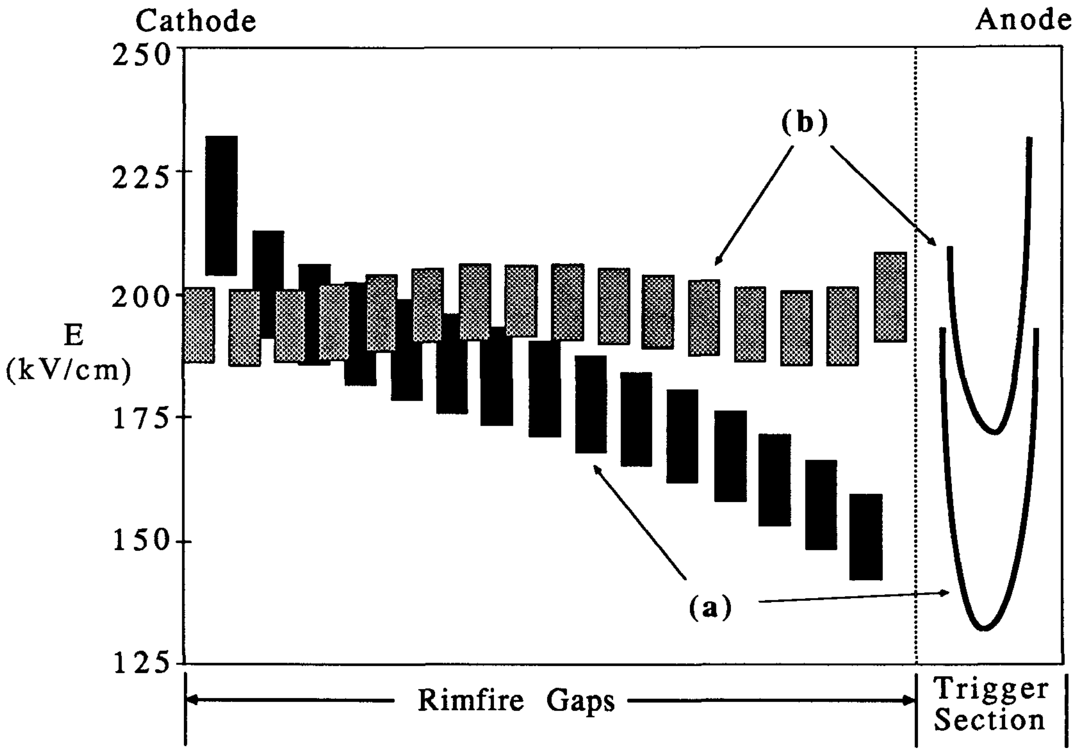

Figure 2. JASON-Derived Plots of the PBFA-II Gas Switch E-Field Distribution. Curve (a): Original Configuration. Curve (b): Present Configuration

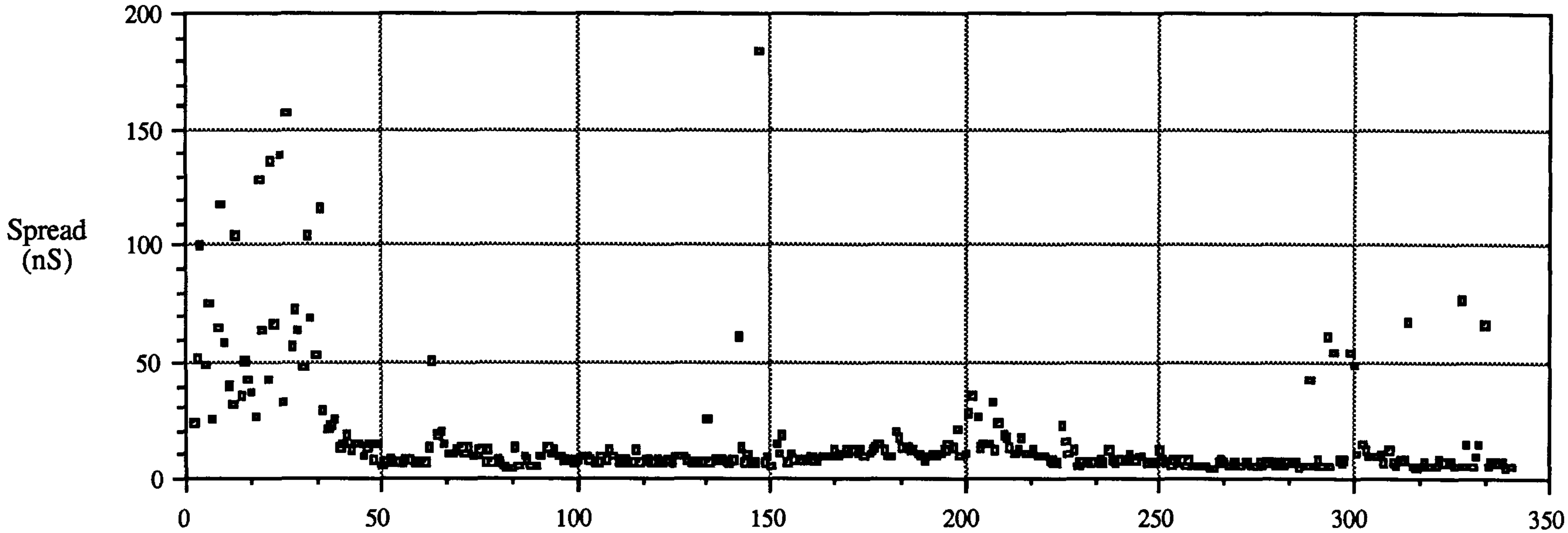

Figure ~~4~~ 3. ~~Histogram~~ Plot of Gas Switch Spread (First-to-Last) on All 18 and 36 module Shots Since June 1986.

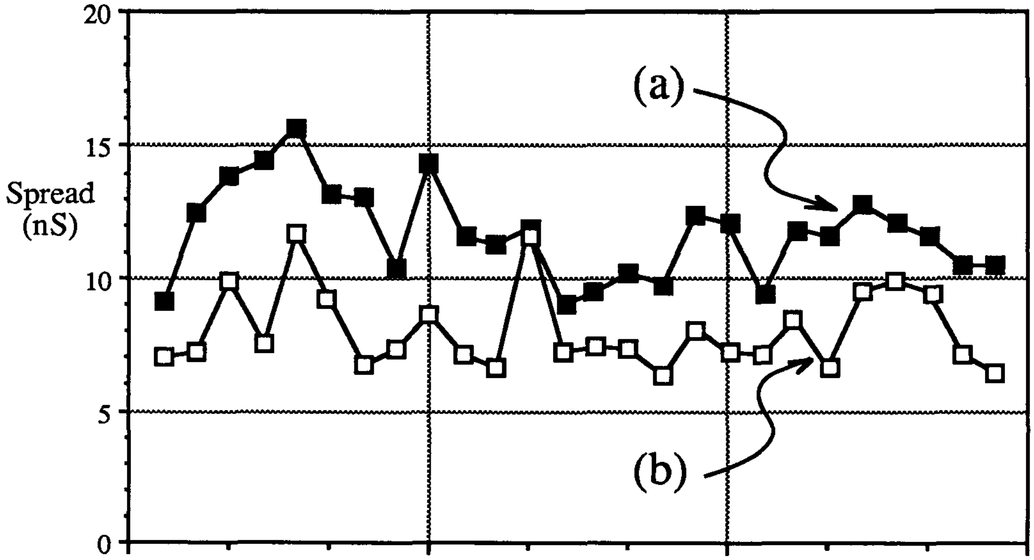

Figure ~~5~~ 4. Plots of Runtime Spread (Curve A) and Tuned Gas Switch Spread (Curve B) for PBFA-II Shots 1747-1804

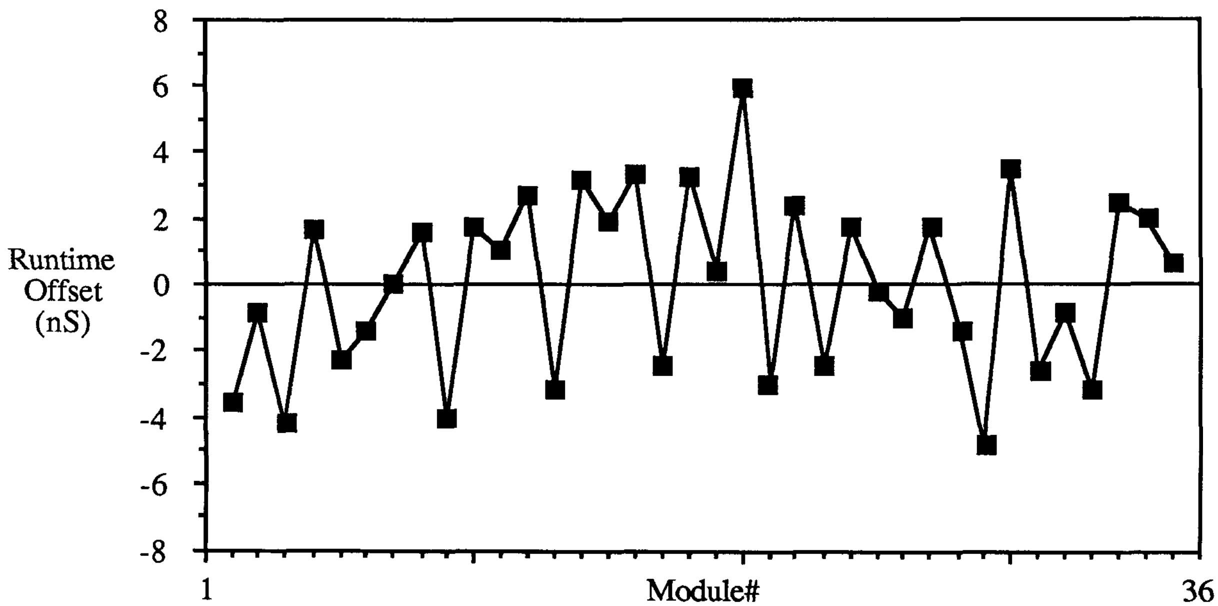

Figure 5. Plot of Runtime Offsets for Individual Gas Switches Operated on PBFA-II Shots 1747 through 1804

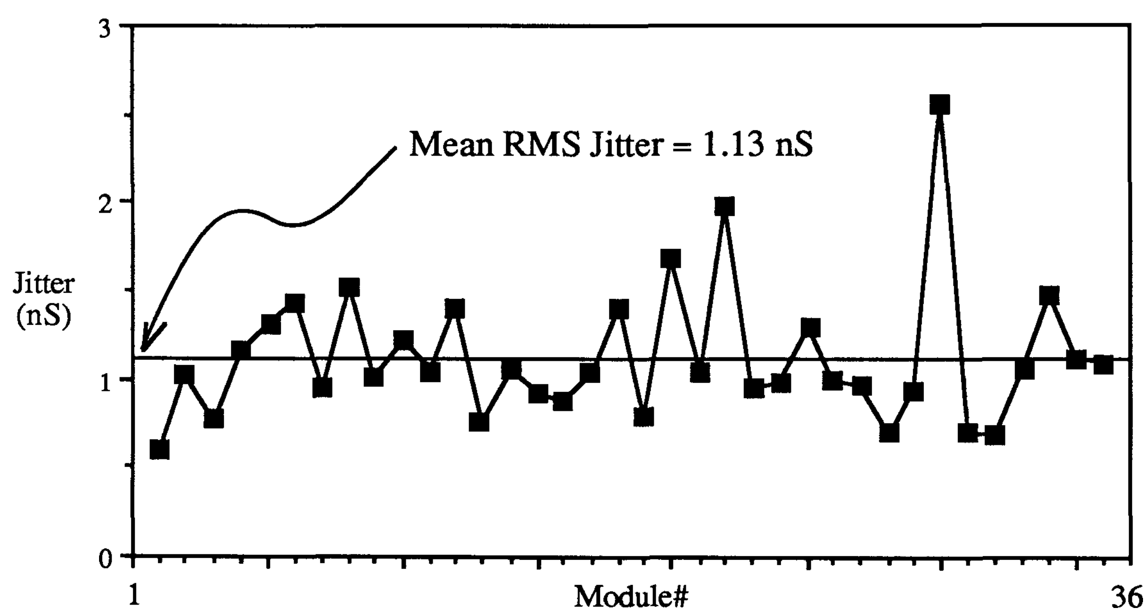

Figure 6. Plot of the RMS Jitter of the Individual Gas Switches Operated on PBFA-II Shots 1747 through 1804