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REPORT ON THE ENGINEERING TEST
OF THE LBL 30 SECOND NEUTRAL BEAM SOURCE
FOR THE MFTF-B PROJECT

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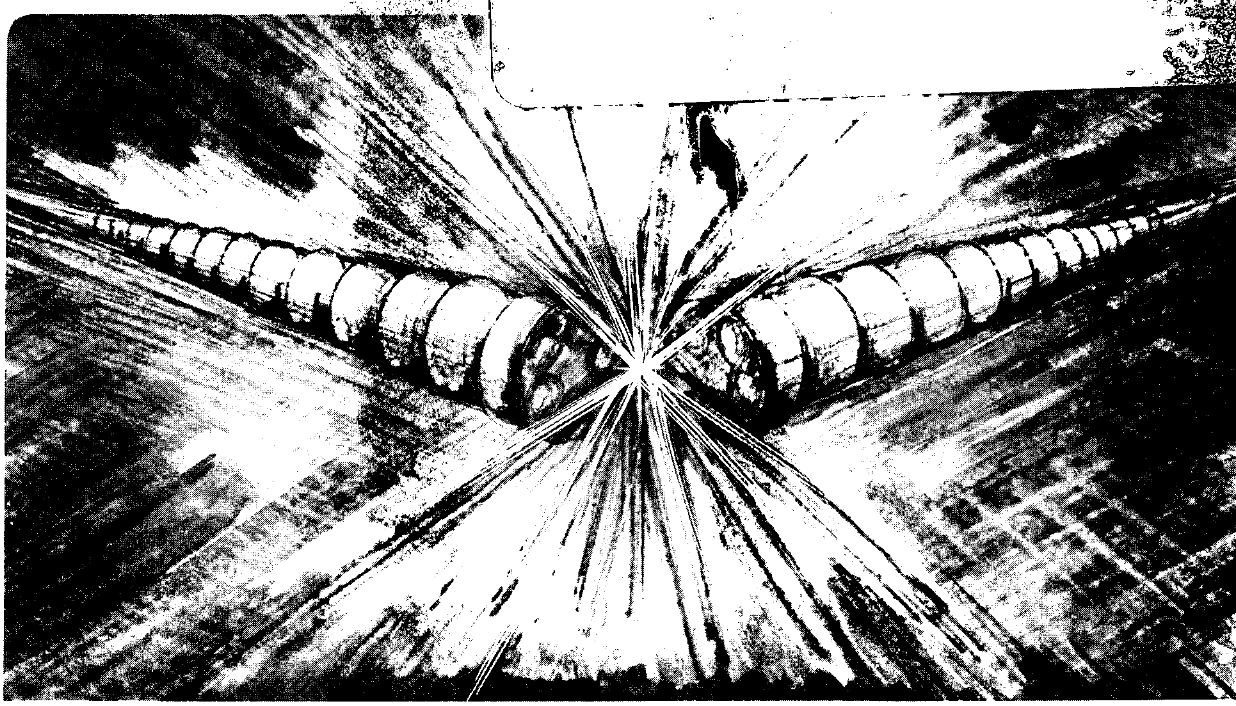
August 1984



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-17550

REPORT ON THE ENGINEERING TEST OF THE LBL 30 SECOND NEUTRAL BEAM SOURCE FOR THE MFTF-B PROJECT*

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* This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development & Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

CONTENTS

FIGURES

INTRODUCTION

Positive ion based neutral beam development in the U.S. has centered on the long pulse, Advanced Positive Ion Source (APIS). APIS eventually focused on development of 30 second sources for MFTF-B. The Engineering Test was part of competitive testing of the LBL and ORNL long pulse sources carried out for the MFTF-B Project. The Test consisted of 500 beam shots with 80 kV, 30 second deuterium, and was carried out on the Neutral Beam Engineering Test Facility (NBETF). This Report summarizes the results of LBL testing, in which the LBL APIS demonstrated that it would meet the requirements for MFTF-B 30 second sources. In part as a result of this Test, the LBL design was found to be suitable as the baseline for a Common Long Pulse Source design for MFTF-B, TFTR, and Doublet Upgrade.

A schematic of the NBETF beamline is shown in Figure 1. NBETF was chosen as a test site because of its extensive beam diagnostics, optical and calorimetric, and because it is the only test site with the radiation shielding required for long pulse deuterium operation. As tested, the LBL APIS consisted of a magnetic bucket plasma source, called the Long Pulse Source (LPS), mated to a water cooled, 10 x 39 cm accelerator, called the Long Pulse Accelerator (LPA). A picture of the source as mounted on NBETF is shown in Figure 2. In comparison with other long pulse sources, the most outstanding feature of the LBL accelerator is its perveance per unit area of extractor. With 60% grid transparency, it gives 50% to 90% more current per unit area than other designs, with excellent beam optics.

The LPA is a radiation hardened structure, designed for 150 kV operation in a reactor environment. The insulator stack is brazed ceramic and stainless steel, and the accelerator grids are water cooled molybdenum tubes. Design and construction of the LPA has been documented previously.[2,3] A picture of the LPA is shown in Figure 3. The first test of the LPA[4] was in 1982. A field-free plasma source was used initially, and, later, the LPS was used for testing up to two seconds. Pulse length was power supply and target limited at that time. The LPS plasma source is an arc in a magnetic bucket geometry, specifically designed to meet the 80% atomic fraction and extended lifetime requirements of MFTF-B. Development of the LPS for 30 second operation was done in the spring of 1983.[5]

In this Report, measured beam properties, such as, perveance and divergence are discussed, as well as source reliability. An Operating Manual for the LPA/LPS has also been prepared as a separate document.[1] LBL began MFTF-B testing on NBETF in May, 1983. The accelerator was gapped for 80 kV; the LPS had undergone development for deuterium operation. Beam characterization was carried out in June and July. Since this was the first long pulse operation of NBETF, some test stand development occurred, primarily with the beam target. Thirty second, 80 kV operation was achieved in August, 1983. The Engineering Test was carried out between November, 1983, and January, 1984, with a mid-test shutdown for the Christmas holiday.

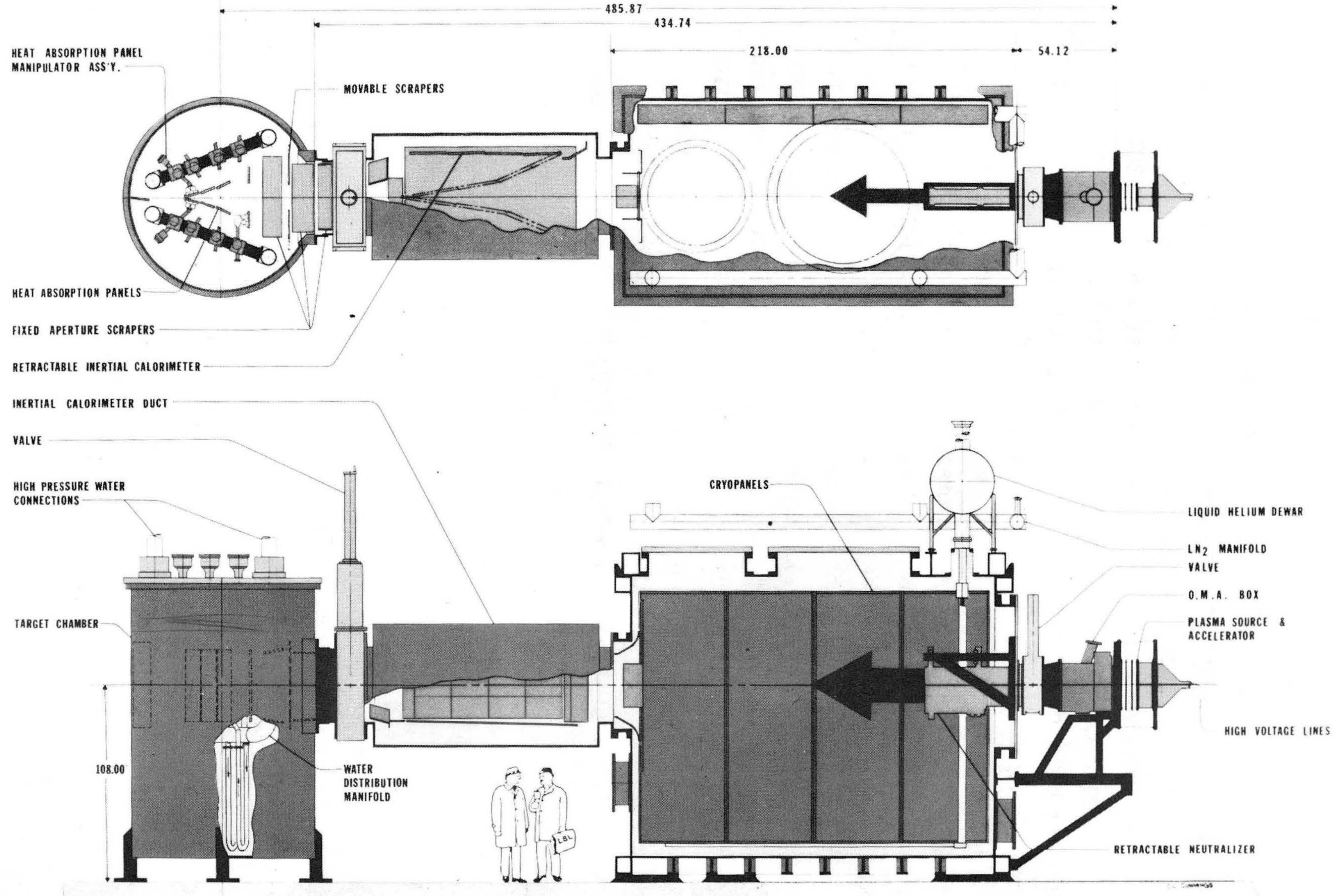
The parameters listed below illustrate that the LBL 10 x 39 cm LPA/LPS met the performance goals established for MFTF-B.

	Goal	Achieved
Pulse Length	30 sec	30 sec
Voltage	80	79 - 83 kV
Divergence, (1/e, half width)		
Total Beam	0.4° x 1.0°	0.35° x 0.95°
Full Energy		0.28° x 0.93°
Gas Flow	12 Tl	12 Tl/s
Atomic Fraction (OMA)	80	83%
Water Fraction (OMA)	Best Efforts	0% - 0.2%
Filament Lifetime	8000 shots	5000 shots (est.)
Interrupt Duration	≤ 10 msec	3 - 5 msec
Interrupt Limit (per shot)	10	5
Optimum Current	40 A, deuterium	40.7A, deuterium
Optimum Perveance		1.8 μpervs deuterium

The listed perveance is at the divergence optimum, 0.35° x 0.95° (1/e Gaussian half angle). Initial 30 second testing in the summer of 1983 was at a gas flow of 18 Tl/s. Based on 1982 operation on NBSTF, which had a separation magnet, this was known to be an equilibrium flow for the NBETF neutralizer. To correspond with the source pressure anticipated in the "pure beam" neutralizer under development for MFTF-B, 12 Tl/s gas flow was used for the Engineering Test; this was less than equilibrium flow on NBETF.

Including conditioning shots, the 500 shot average beam properties were: 80.8 kV, 40.3 A, or 1.76 μpervs, deuterium. The filament lifetime is projected on the basis of evaporation. The plasma source and accelerator were very reliable, and demonstrated 98.7% availability on the last day of the Test.

The 30 second shots counted as the Test are summarized in Section 2, called Shot History. Source reliability and general test stand conditions are discussed in Section 3. Beam properties and source operating parameters are presented in Section 4. Suggested design improvements are mentioned in Section 5. Brief operating experience with an LLNL supplied, oxygen contaminated deuterium bottle is mentioned in Appendix A. Five second, 80 kV hydrogen operation for Doublet Upgrade is discussed in Appendix B.



-NBETF-
NEUTRAL BEAM ENGINEERING TEST FACILITY

CBB 839-8010

Figure 1. A sketch of the Neutral Beam Engineering Test Facility (NBETF) is shown, with the major beamline sections identified.

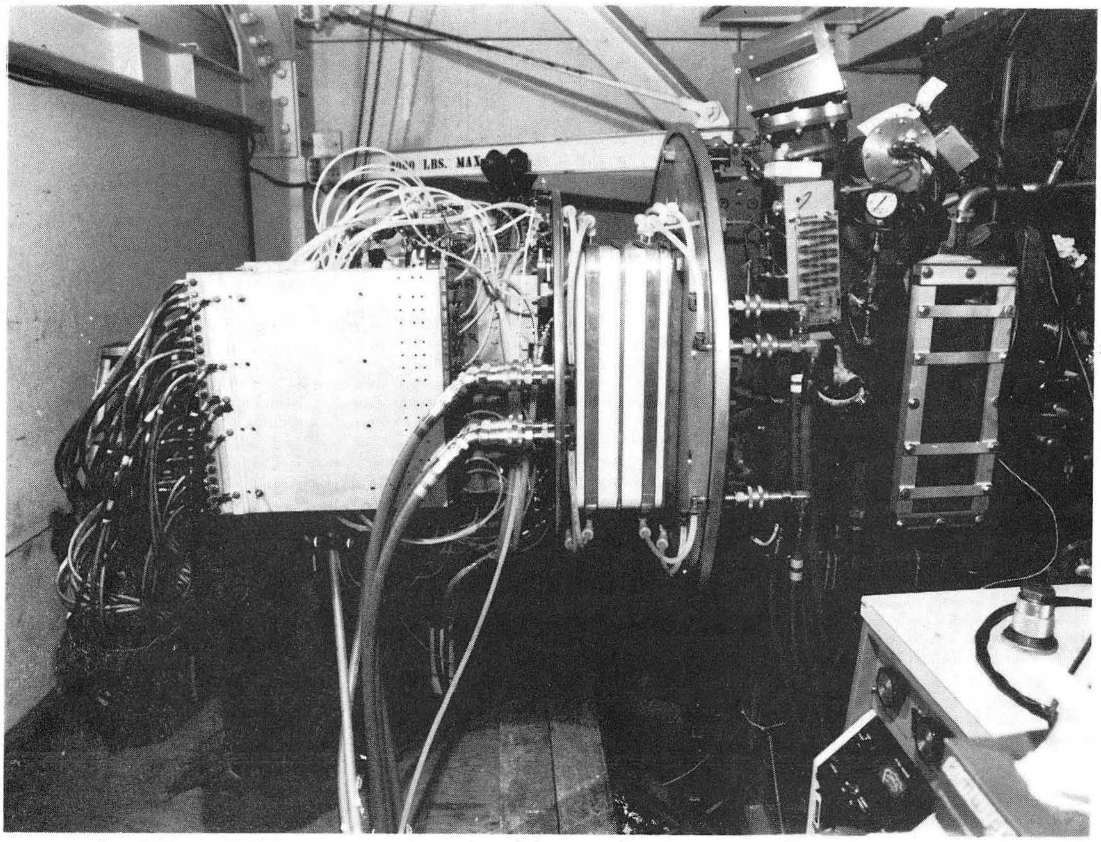


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Figure 2. A picture is shown of the LPA/LPS mounted on NBETF; the large plates at the rear are the (experimental) sheets used to carry filament and arc current.

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Figure 3. The Long Pulse Accelerator (LPA) is shown.

2. Shot History

A calendar overview of the Engineering Test is shown in Figures 4 and 5, which illustrate 30 second beam operations in December and January. A complete accelerator conditioning history is ruled out, since the LPA had been previously operated at 80 kV, in 1982 short pulse testing,[4] and in the summer of 1983 during 30 second testing for MFTF-B.

Starting October 26, 1983, the Test took 60 work days; most had two, and some three, shifts. November was occupied with mounting the source and system startup; short pulse beam at 60 kV was achieved by the end of the month. Water leaks in the target tank were also encountered. From the December overview, Figure 4, achievement of 80 kV, 30 second operation was paced by various problems with the target system, which was itself under development. By Christmas shutdown, December 22, 155 shots had been accumulated. Operation resumed on January 2, and the remaining 353 shots occurred from January 19 to 25. Best operation was on January 21 and January 25. Operation on these dates will be discussed in detail later.

Nine work days had 80 kV, 30 second operation, with 508 shots which are counted here. To be counted, a shot must have been $\geq$ 30 seconds, with an average accel voltage $\geq$ 78.6 kV, and must also have been included in the computer archive. The Engineering Test ended on the night of January 25, when operations switched to short pulse with an oxygen contaminated deuterium bottle, as preparation for Pure Beam testing later in FY84. Hydrogen was run for Doublet Upgrade until February 2. The electrical changeover for the Engineering Test of the ORNL source began on February 3, 1984.

In Figures 4 and 5, water leaks are indicated only for occasions which required significant time to repair. An underlying problem for evaluating source reliability is that nearly all 30 second shots were conducted with observable (on a gas analyzer) water leaks in the target tank. Target leaks had two effects: (i) source reliabilty deteriorated; and (ii) target calorimetry data were limited by noise on the thermocouple signals. For this reason, the source reliability demonstrated here probably represents a lower bound on source availability. Analysis of target calorimetry data is restricted to shots with clean data.

On December 20, an uncooled copper exit scraper and electrical switch were vaporized by the beam. This event is not noted on Figure 4, because

30 second operation continued. These data were counted in the shot total, although operation for the day was very erratic.

The target accident indicated in Figure 5 on January 21 was relatively serious for the source. Near the end of a 30 second shot, the high capacity water pump for the target dropped out, but a fault in the control system allowed beam to continue. After 5 seconds with no water flow, two of the target panels ruptured at braze joints. The beamline vacuum system valves closed, but both the arc and accelerator had to be reconditioned from low power. Arc reconditioning was accompanied by serious filament spotting, which will be discussed in Section 3.

Initial arc conditioning was carried out in one shift on November 14. Arc voltage and arc power for each shot of the day are shown in Figures 6 and 7. To avoid source damage, conditioning is done with the arc spot detector set to just allow operation. The basic strategy is to run at the lowest possible voltage, in order to avoid spotting. Arc voltage and power are raised as arc spot detector faults decrease. In this case, initial operation was with the back plate magnets removed, which gives field-free anode area and allows operation as low as 40 - 50V. The first shots were also restricted to 10 msec pulses and 15 kW, while the arc spot detector was setup.[1] The pulse length was later stretched to 0.5 sec. When arc power reached 80 kW at 80 V, the pulse was stretched to 4 seconds. The backplate magnets were then installed, and the source condtioned from 15 kW, 60 V to 70 kW, 70 V with 0.5 sec shots. Finally, the pulse was stretched to 2 seconds.

Alternatively, the arc could have been conditioned with the backplate magnets in place. This has been done in the past, but requires greater care on the part of the operator. In either case, the goal is to begin at the lowest possible voltage and power, with the spot detetctor set as close as possible to minimize spot damage. In the past, when filaments were conditioned with minimal spot damage, they have remained spot-free in subsequent operation with good vacuum.

Prior operation of the LPA rules out a complete accelerator conditioning history, but the Test shot history shows evidence of conditioning, and reconditiong. Computer averaged voltage, current and perveance for each of the 508 shots counted in this Test are shown in Figures 8, 9 and 10. In Figure 8, accel voltage is plotted vs shot number. The NBETF power supply is unregulated, and the shot average range is seen to be 78.8 - 84.6 kV. The variation of accel voltage over each shot was approximately ± 2%.

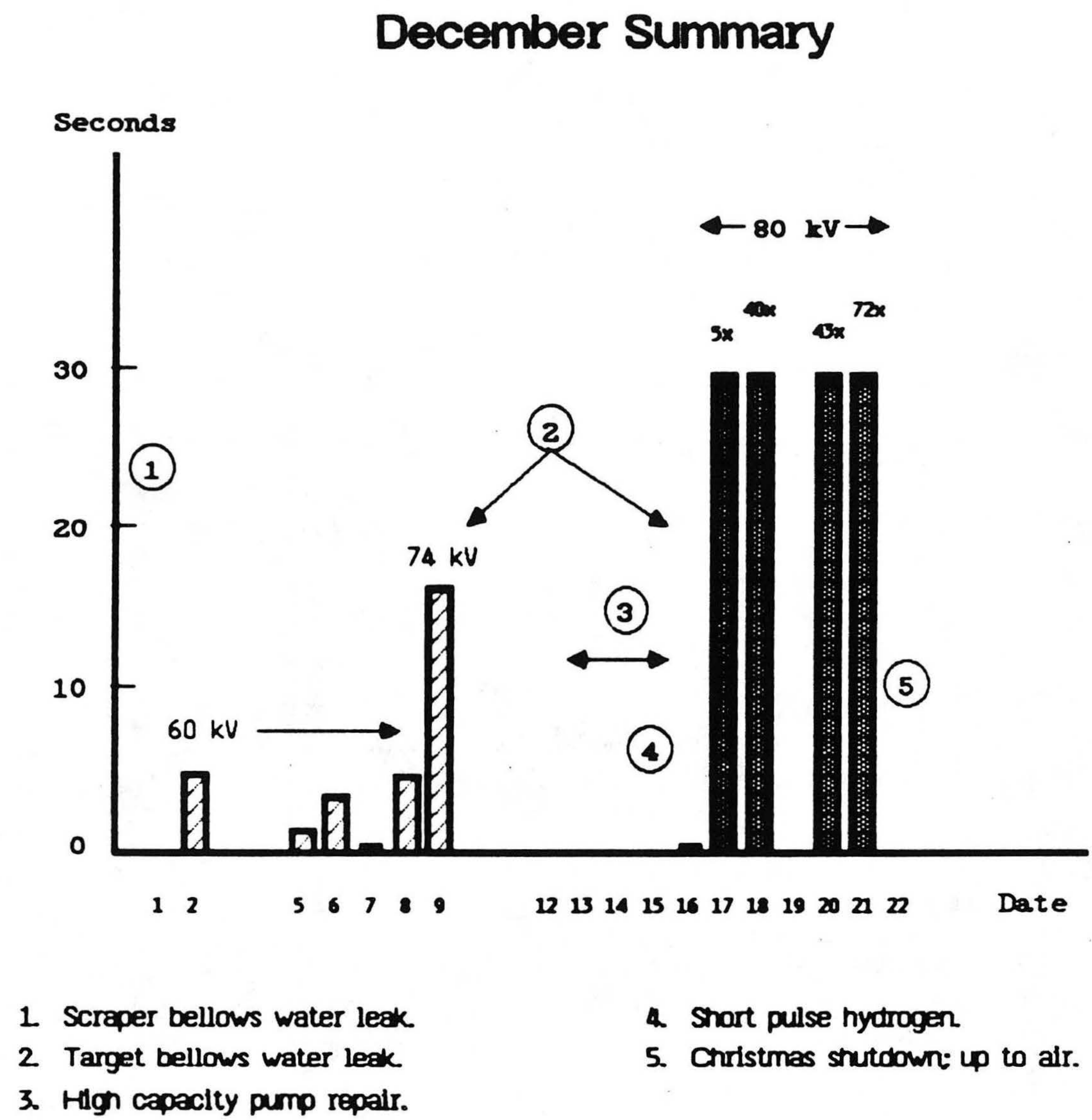
In Figure 9, accel current is shown for the same shot sequence; the range is approximately 35 - 43 A. Perveance is shown in Figure 10; the Test range was 1.4 - 1.9 μpervs. On all 30 second shots, arc feedback regulation[6,7] was used to maintain a constant accel current. The feedback system compared an input signal with a precision reference voltage, and phase controlled the arc power supply to maintain a constant input. During the Test, the input used was the saturated ion current read by a newly developed, 1/4" O.D. water cooled plasma probe, biased -22 V with respect to cathode. With arc regulation, the variation in accel current over a 30 second shot was determined by arc and filament power supply ripple, approximately ± 2%. Without regulation, beam operation up to 10 seconds required careful adjustment of the filament current; the stepper was used for filamenrt adjustment. Due to changing arc efficiency, variation in the unregulated arc level gave a gave an accel current which had a maximum/minimum difference of 10%.

Pictures of typical electrical waveforms are shown in Figure 11. As described in the Operating Manual,[1] the filament heater current was reduced, or "stepped", just as the arc was started. Arc turn-on was unregulated. The arc regulator was timed to start 1.5 sec after the start of arc operation, so that the operator could see the unregulated arc voltage on the scope waveform. The start of regulation is apparent in the flatness of the probe and , later, the accel current traces. The variation in arc voltage and current which can be seen is due to the combination of regulation and changing arc efficiency. The arc efficiency appeared to be affected by long thermal time constants in the filament sandwich.

The average number of interrupts per shot for January 21 and 25 is plotted in Figure 12. During the Test, interrupts decreased with conditioning from 40 to 5 per shot. Although the conditioning history is obscured by beamline downtime, the downward trend in interrupts on days of prolonged operation shows reconditioning, and suggests futher improvement.

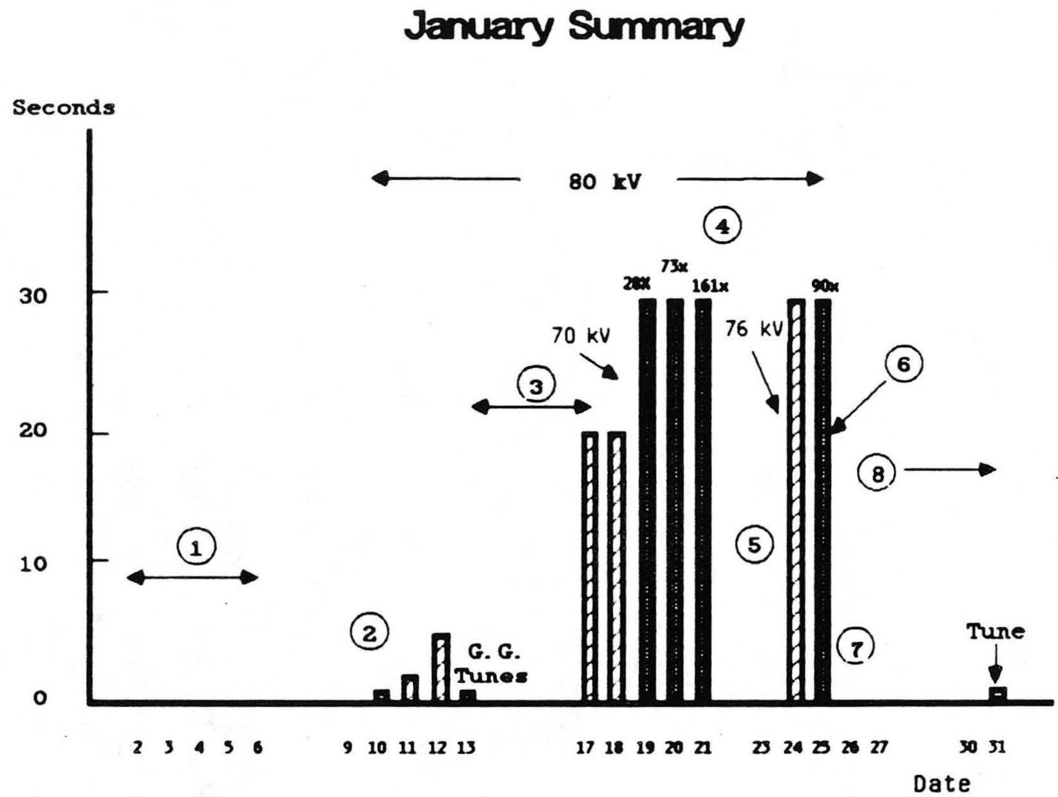
Several particulars about the NBETF power supplies merit note. The accel, arc, and filament power supplies are unregulated. Therefore, they drift with the local utility voltage. Since they have different coupling coefficients, they also drift with respect to each other. With feedback, the plasma level (and, therefore, the accel current) could be set by the operator, but perveance depended on the drift of the accel voltage. Since the filaments in the LPS are emission limited, the arc voltage was sensitve to the filament current, which also tended to drift. The filament supply was rated at 3% ripple, peak to peak, and the arc supply at 2%, for resistive load. The accel voltage ripple was approximately 0.5%. The arc feedback system was referenced to a precision reference voltage, AD584 ($\pm$0.1%). The feedback circuit was madeup of 1% precision components, and, during tests in which regulation was on arc power, the power was observed to be constant to $\pm$1%. The power supplies were designed for, and operated at, 10% duty cycle, which translates into a maximum of 12 full power 30 second shots per hour.

A complication of NBETF which affected the day shift is that the beamline has no ion separation magnet, and is near the 184" cyclotron. When the cyclotron is operating, stray magnetic field is a few Gauss in the injector tank (Ref. Figure 1), which causes significant deflection of the fractional energy ions. Since the target is 12 m from the source, the combined ion and neutral particle footprint could be fit onto the target only by reaiming the accelerator. This was done with short pulse shots whenever the cyclotron switched. The cyclotron field was primarily in the verticle direction, perpendicular to the slots. This deflected ions in the horizontal plane, and made target calorimeter measurement of parallel beam divergence meaningless during cyclotron operation. All references to inertial and target calorimeter divergence is for ions and neutrals, with the cyclotron OFF.



XBL 847-3100

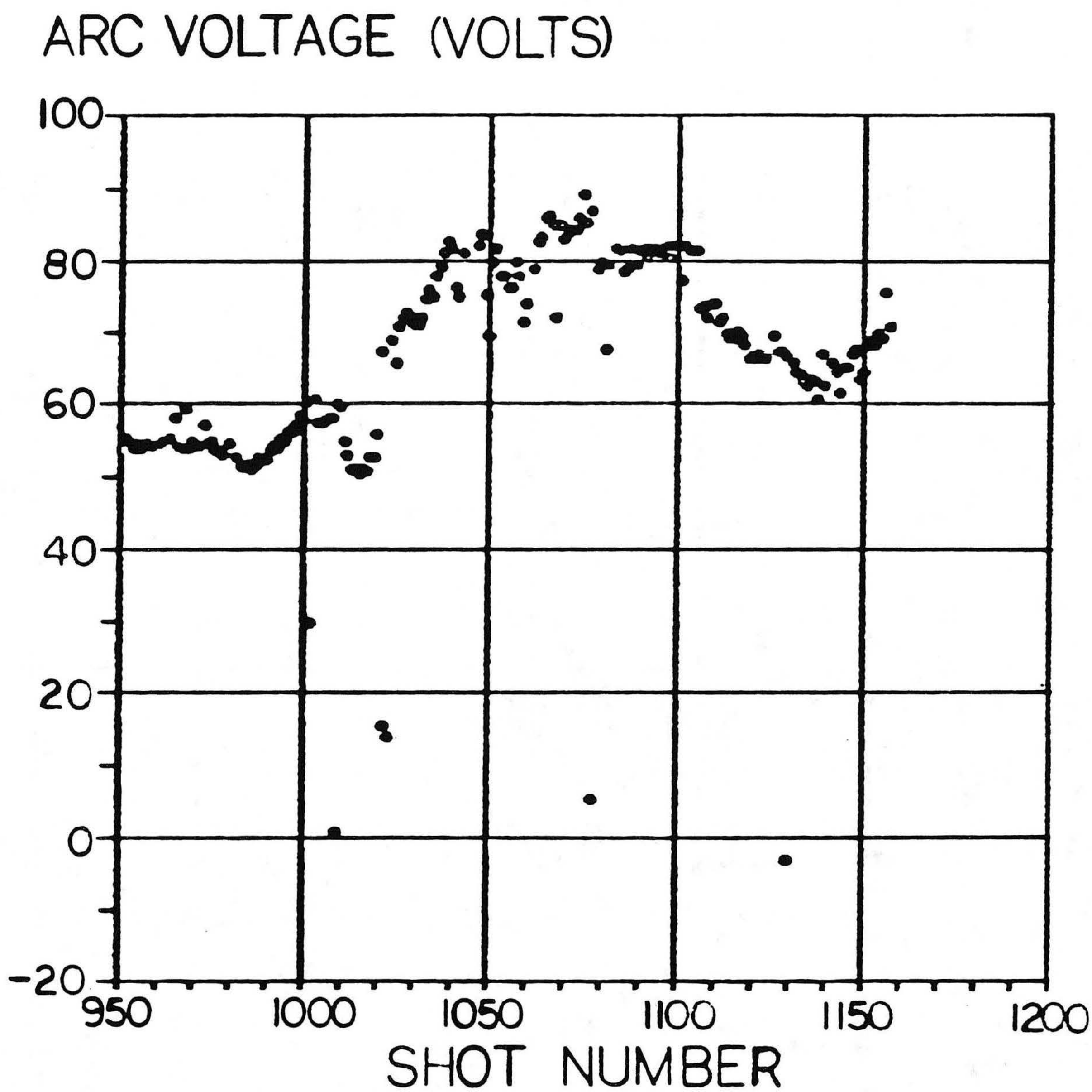
Figure 4. December beam operation is illustrated. Days with 30 second operation are shown as dark columns; the number of shots counted for the Test is shown above.



1. Repair cryo system. Replace one molybdenun shield in plasma source.
2. Arc conditioning after Christma shutdown.
3. Target bellows water leak.
4. Target accident.
5. Recondition plasma generator and accelerator.
6. Engineering test completion.
7. Contaminated deuterium test.
8. Hydrogen test.

XBL 847-3101

Figure 5. January beam operation is illustrated.



XBL 847-3102

Figure 6. The conditioning history of the Long Pulse Source (LPS) is illustrated. Arc voltage is plotted vs shot number.

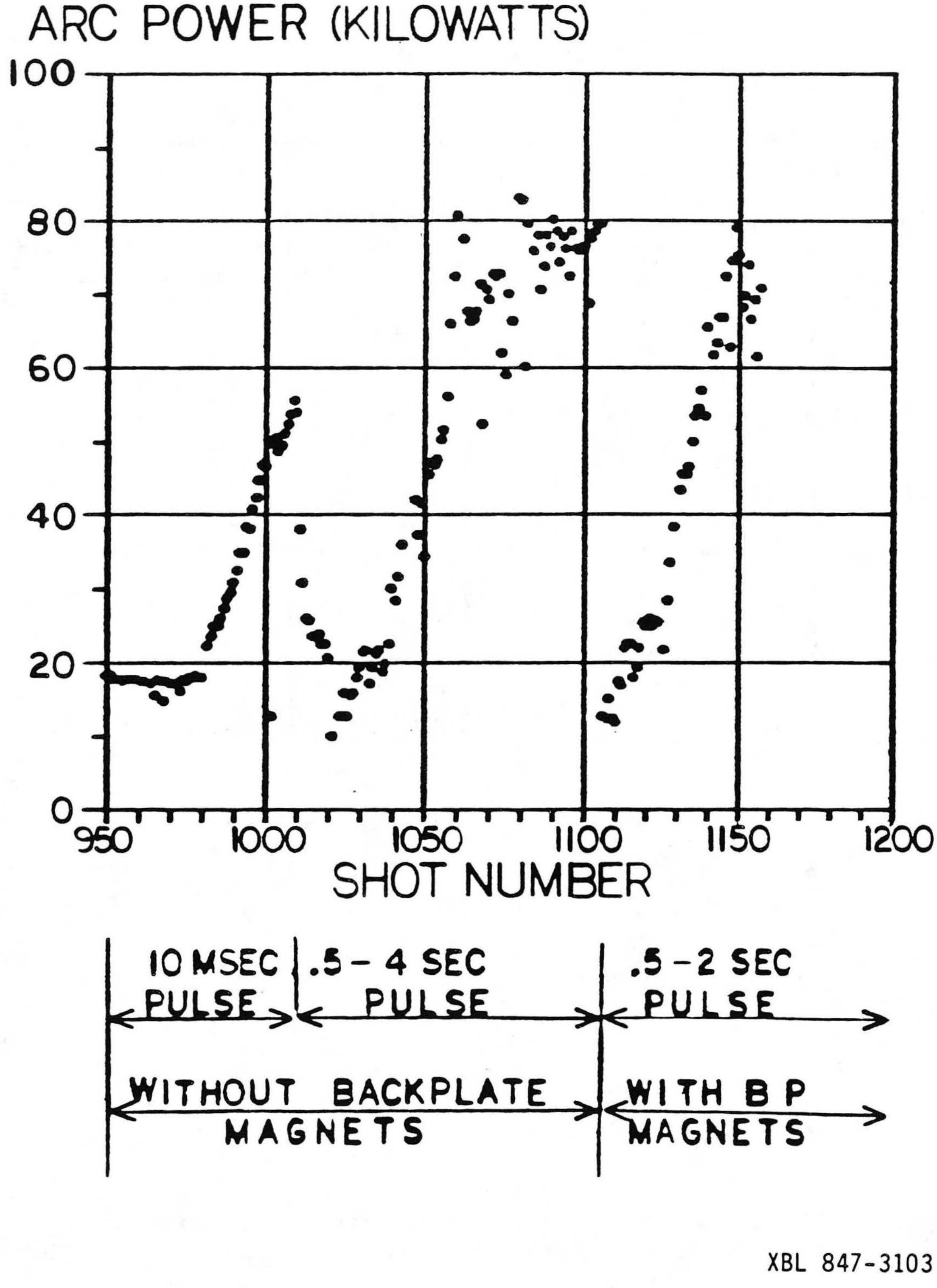
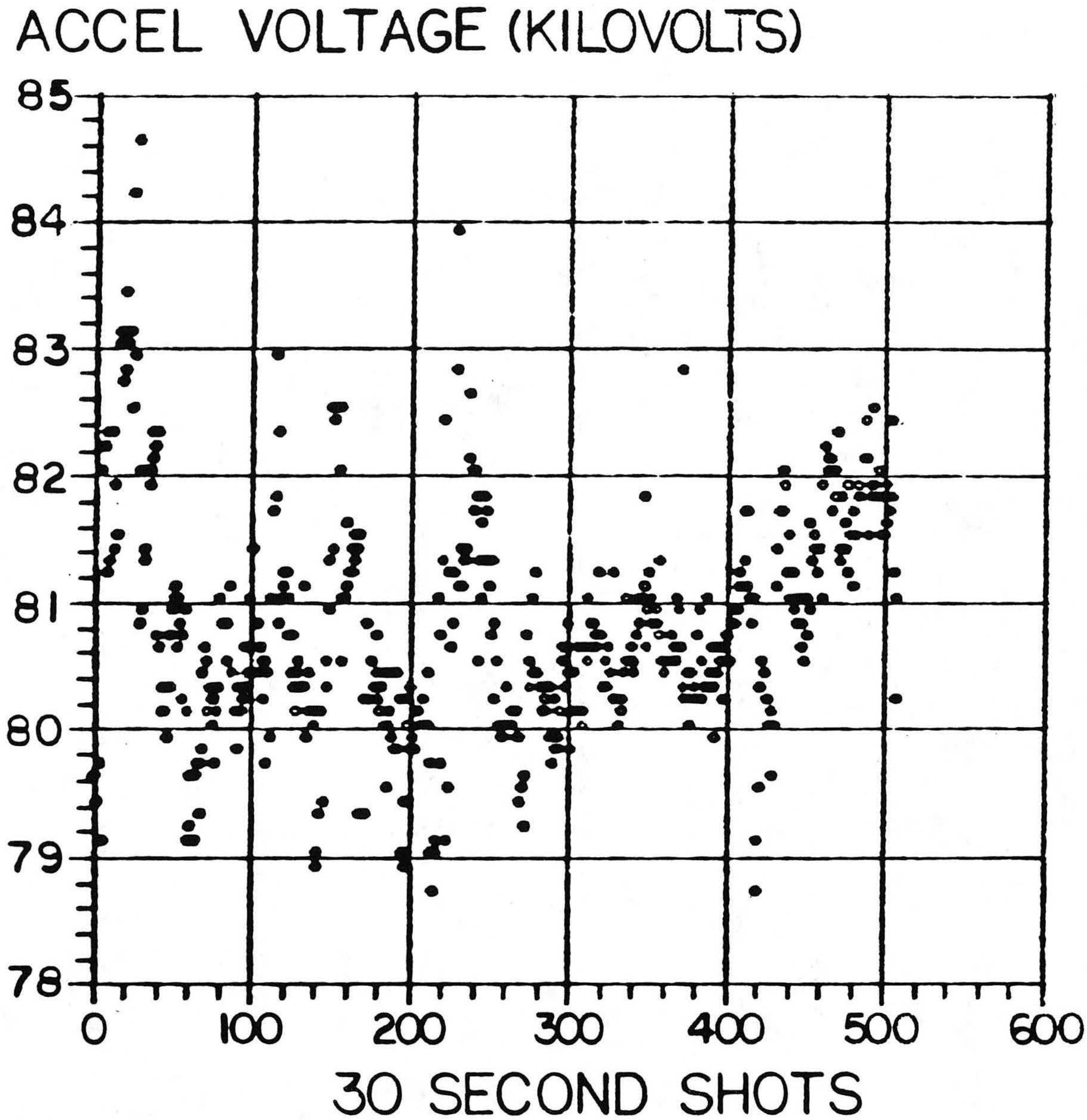
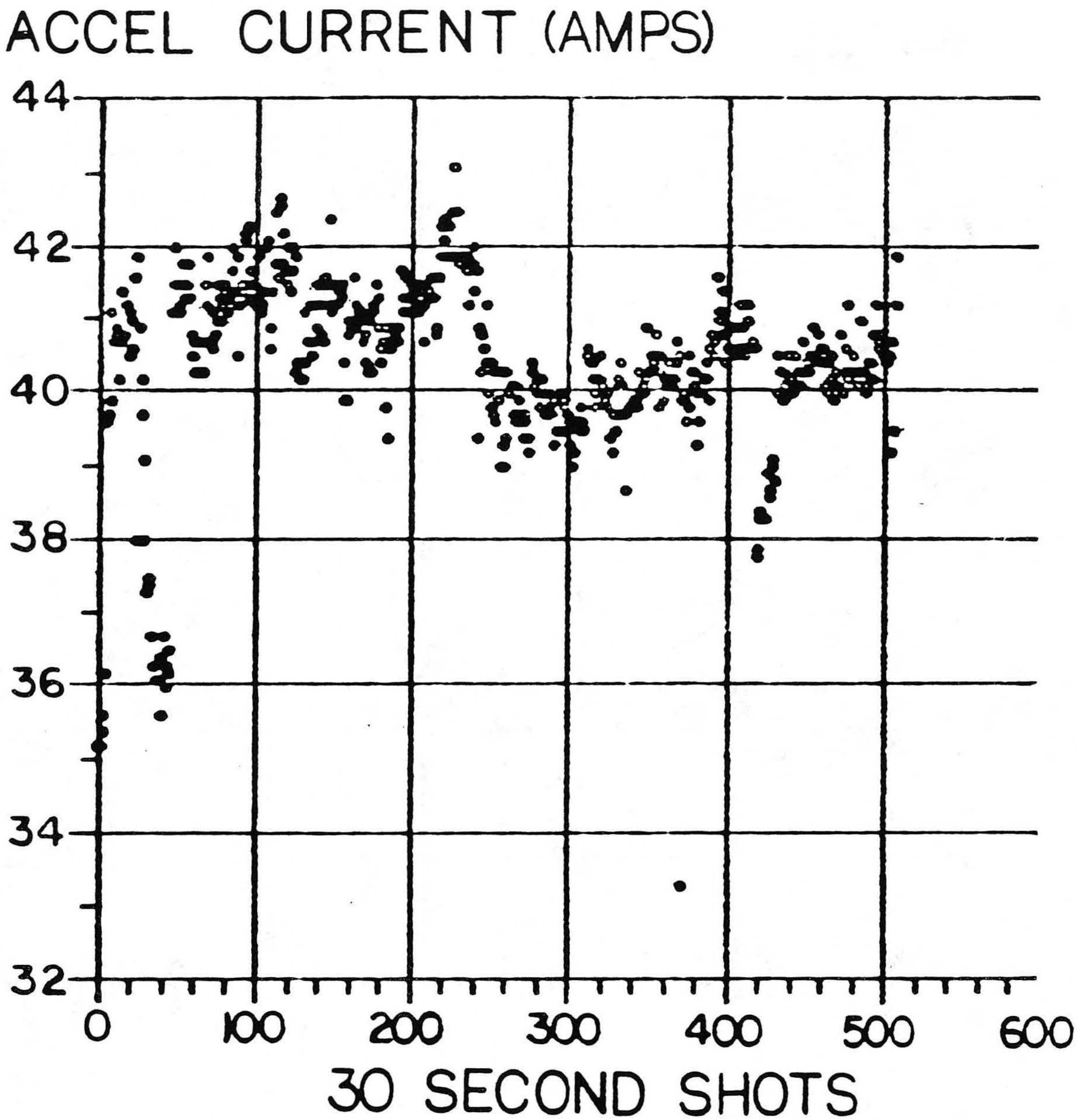


Figure 7. The conditioning history of the Long Pulse Source (LPS) is illlustrated. Arc power is plotted vs shot number.



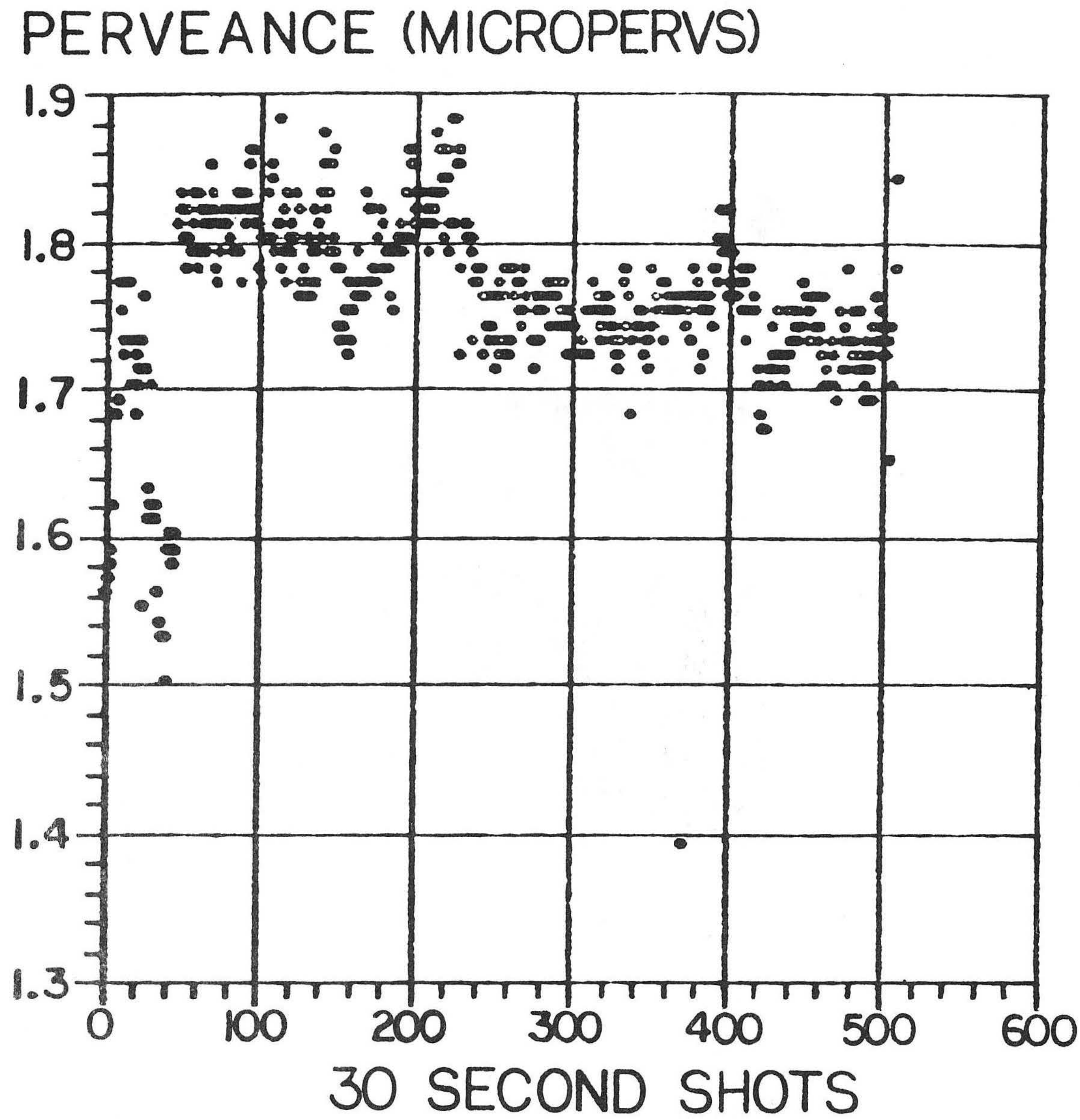
XBL 847-3104

Figure 8. The 30 second shot history of the Long Pulse Accelerator (LPA) is illustrated. Accel voltage is sequentially plotted for each shot counted in the Test.



XBL 847-3105

Figure 9. The 30 second shot history of the Long Pulse Accelerator (LPA) is illustrated. Accel current is sequentially plotted for each shot counted in the Test.

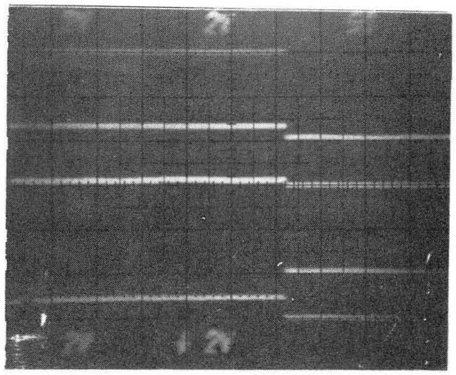


XBL 847-3106

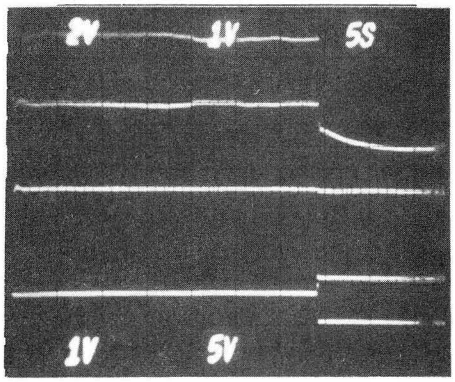
Figure 10. The 30 second shot history of the Long Pulse Accelerator (LPA) is illustrated. Accelerator perveance (μpervs) is sequentially plotted for each shot counted in the Test.

LPS/LPA

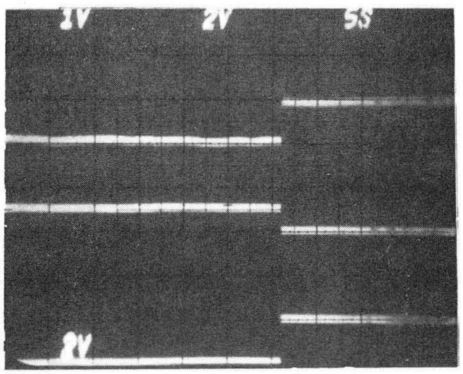
30 SECOND BEAM SCOPE TRACES
DURING OPERATION ON NBETF



V accel H.B. 20 kV/V
V 1-2 5 kV/V
I accel H.B. 10 A/V
I gg DC 100 mA/V



V arc 20 V/V
I arc 500 A/V
PROBE 100 mA/cm²/V
I fil 1 kA/V

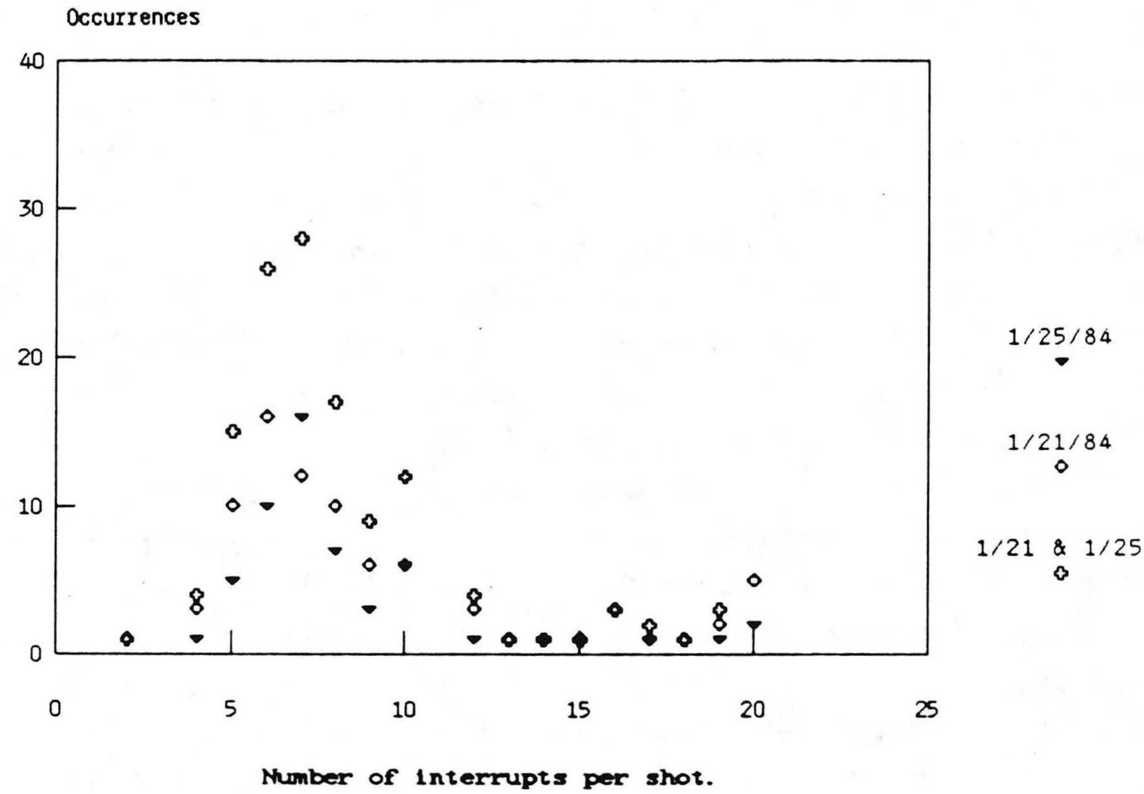


I gg DC 100 mA/V
I supp 2 A/V
V supp 1 kV/V

XBB 843-1704

Figure 11. Pictures of source electrical waveforms are shown for a typical 30 second shot.

INTERRUPTS DURING 80 KV, 30 SECOND OPERATION



XBL 847-3107

Figure 12. The number of times that a particular number of faults occurred on a 30 second shot is plotted for the best days of operation, January 21 and 25.

3. Reliability and Projected Filament Lifetime

The source demonstrated excellent reliability during periods of good beamline vacuum. Source reliability is discussed here in terms of arc faults and accelerator faults. The NBETF fault protection system had ten accel monitors, e.g., current, gradient grid current, dV/dt, etc., plus arc power supply protection, arc spot detector, and interlocks.[1] For present purposes, the only information tracked is the number of accel faults (all types) on a 30 second shot, and the number of times an arc fault was noted in the logbook. System problems, e.g., power supply, are excluded from consideration, as are shift changes, cyclotron switching, etc. Significant source conditioning occurred at the start of 30 second operation, immediately following the repair of target leaks indicated in Figures 4 and 5, and following the target accident on January 21. Although target water leaks were apparent throughout, stable operation was achieved for extended periods on January 21 and 25. These periods are analyzed for arc and accelerator reliability.

Reliable source operation occurred during an 84 shot interval on January 21, and a 66 shot interval on January 25. The longest interval of successive 30 second shots was 42, on January 21; with a 10% duty cycle, this represents over four hours of operation. The number of accel faults on each 30 second shot is shown in Figure 13 for the 21st, and in Figure 14 for the 25th. On both days, a target bellows water leak was apparent from the target ion gauge and RGA. The leak had a large transient during switching of the high capacity target pump. The 84 shot sequence achieved on January 21st occurred immediately after the pump was set for continuous operation, in order to reduce the water pressure in the target tank during the beam shot. Operations on the 21st were halted by the target accident mentioned in Section 1. The shot interval selected on the 25th begins where the source was judged to be reconditioned after the target accident ($\leq$ 10 interrupts), and ends with completion of the Test.

Arc reliability on these two days is illustrated in Figure 15. The number of occurrences of arc faults is plotted vs the number of shots between misses (A miss is any shot less than 30 seconds). System availability for MFTF-B is defined as delivered ontime divided by requested ontime, e.g., a miss which delivered 15 seconds of beam corresponds to 50% system availability. Counting both arc spots and accel faults, system availability for the selected January 21 interval was 95%, and 98.7% for January 25. Availability was primarily determined by shot termination due to arc spots. An accel fault caused a beam interrupt of 5 msec, and had only a small effect on system availability. Since spot- free operation had been experienced in previous testing under good vacuum conditions, improved availability can be anticipated.

Accel reliability for January 21 and 25 is illustrated in Figure 12, where the occurrence of a given number of interrupts is plotted. The peak of the distribution is at 6 or 7 interrupts per shot. The nonstatisical features on the tail suggest another variable in addition to accelerator conditioning. During testing, a tendency for bursts of interrupts associated with target leaks was apparent, and would account for these features. At the end of the Test, the accelerator appeared to still be conditioning.

After removal from NBETF, the accelerator passed a helium leak check. Visual inspection without disassembly indicated no sign of deterioration. A picture of the LPA source grid is shown in Figure 16. The area around the accelerator grid shows the effect of plasma cleaning and beam conditioning. The darkened area around the outside was covered by the probe plate, and remains in original condition.

The LPS was disassembled just after testing. A schematic of the source is shown in Figure 17, and pictures are shown in Figures 18 and 19. Several noteworthy and related features were apparent. First, the hand-fit molybdenum shields which covered the filament sandwich were warped. Second, three of the screws used to locate the shields had fallen out; one of these shorted to a spacer plate. Third, small particles had collected on the magnetic cusp lines. Fourth, some of the filaments were pitted by arc spotting.

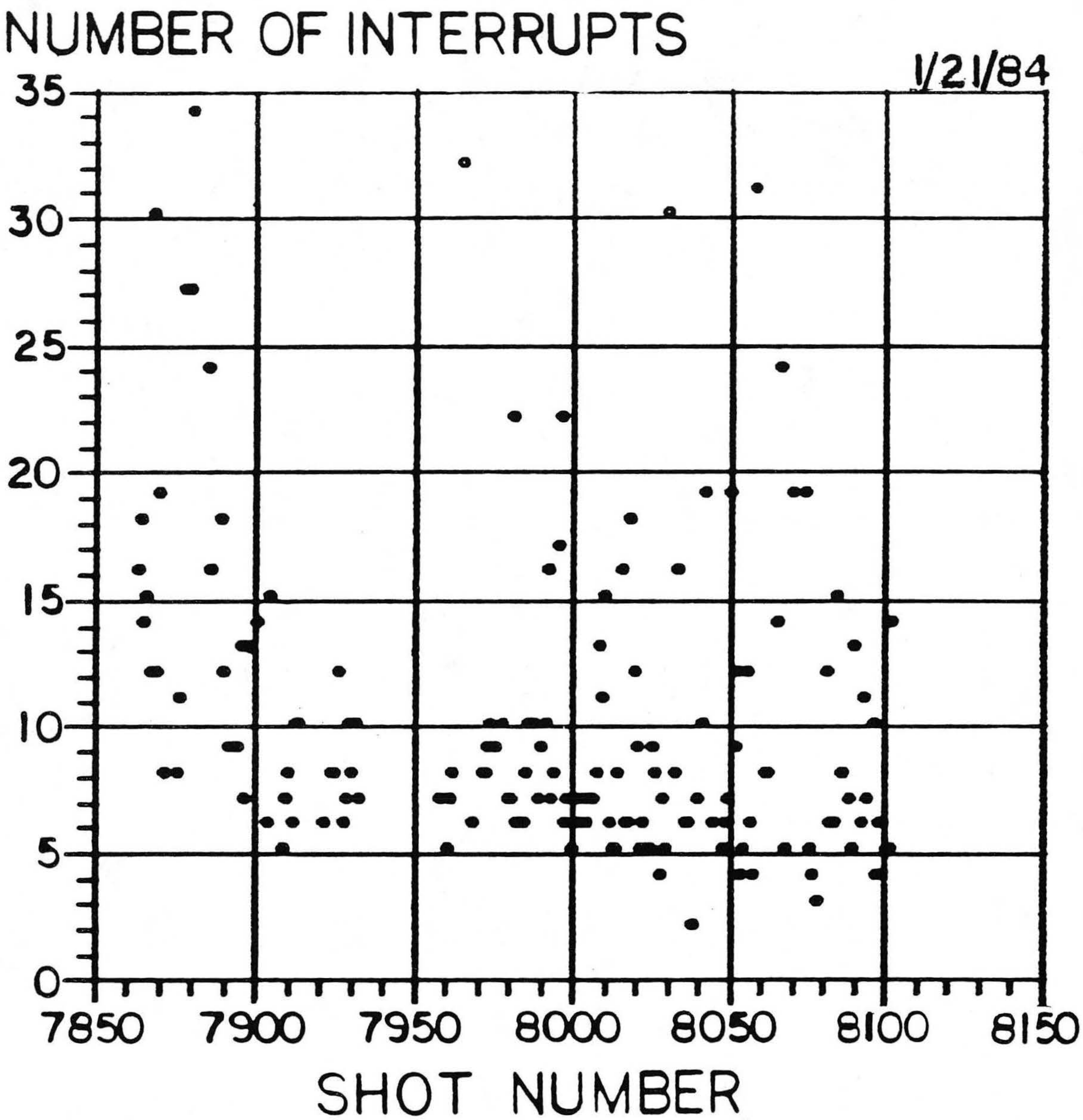
The molybdenum shields were developed in the Spring of 1983, as a hand-fit patch. Under good vacuum conditions, the shields essentially eliminated arc spotting, but, as installed, they were only radiatively cooled. They are believed to be effective for two reasons. First, they keep plasma off of the copper surface in the filament sandwich, which is at cathode potential. Second, they keep plasma out of the insulator gaps. Since they make good contact only at the mounting screws on the filament positive plate, the shields experience extreme thermal cycles. During beam shots longer than five seconds, the shields began to warp, and shorted to the spacer plates, bringing them to cathode potential. Warping was a runaway effect, since any part of the shield which curled into the plasma received even more heat. Eventually, warped shields reduced arc efficiency, and caused spotting in the gap between the spacer plates and anode, which is shown in Figure 20 and 21. A design fix which functionally replaces the shields is suggested in Section 5.

The loose screw is symptomatic of a related problem with the shields. Each shield was held down with a single moly screw, plus two locating screws which fit into slots. As a result of the thermal expansion and contraction cycles associated with testing, the screws had a tendency to ratchet. Some became loose, others tightened. Those which tightened caused buckling of the shield. One screw which fell out appears to have fallen between a shield (cathode), the forward spacer, and the foward anode. The resulting short melted enough of the screw to eliminate the short, Figure 22, but the spacer was damaged.

The dust which collected on the cusp lines (Ref. to Figure 19) had never been observed in previous operation and was found to be ferromagnetic. This rules out material in the plasma source and accelerator. Speculation is that a large pressure transient during the target accident carried the dust from the main tank into the plasma source. This loose material could have contributed to the spotting experienced after the accident.

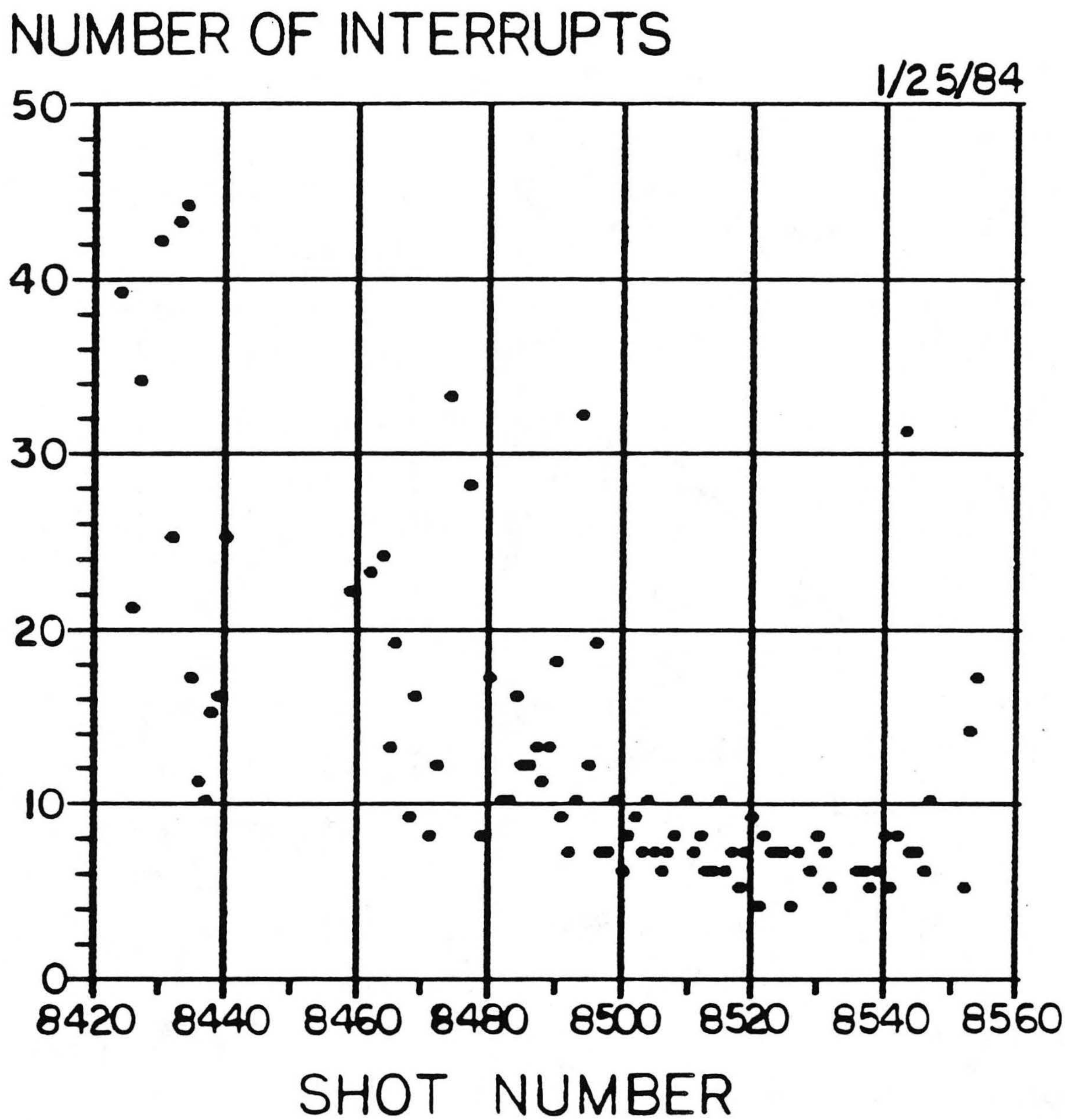
In general, arc spotting can occur in a number of situations. The simplest case involves cathode conditioning. Filament conditioning appears to involve removal of chemical contaminants, particularly nonconductors from the surface, plus voltage conditioning. During the Test, most spotting appeared to be associated with water leaks in the target. Some spotting was due to the shields shorting to the spacers, bringing them to cathode, which meant conditioning a larger area. A soft metal, such as copper, exposed to plasma at cathode potential is very prone to spotting. The shields were originally developed to cover the copper for this reason. The conviction that water was the principal culprit during the Test comes from the fact that reliable beam operation began on January 21 only after the target pump was kept on between shots. This was done to reduce the water transient in the target associated with pump switching. After the target accident, severe arc spotting was encountered, which required reconditioning the arc from low power. The best source availability, 98.7%, was achieved on January 25, the last day of the Test, which was also the day which had the best target vacuum.

Since essentially spot-free operation was obtained during periods of good vacuum, projected filament lifetime is based on evaporation. After 500 shots at 80 kV, 30 seconds, measured evaporation was 0.5 mil, out of 60 mil. Without taking conditioning and reconditioning shots into consideration, this gives an estimate of a 5000 shot filament lifetime. Limited test stand availability ruled out a demonstration of filament lifetime, but the estimated lifetime is in the ballpark of the MFTF-B operating goal.



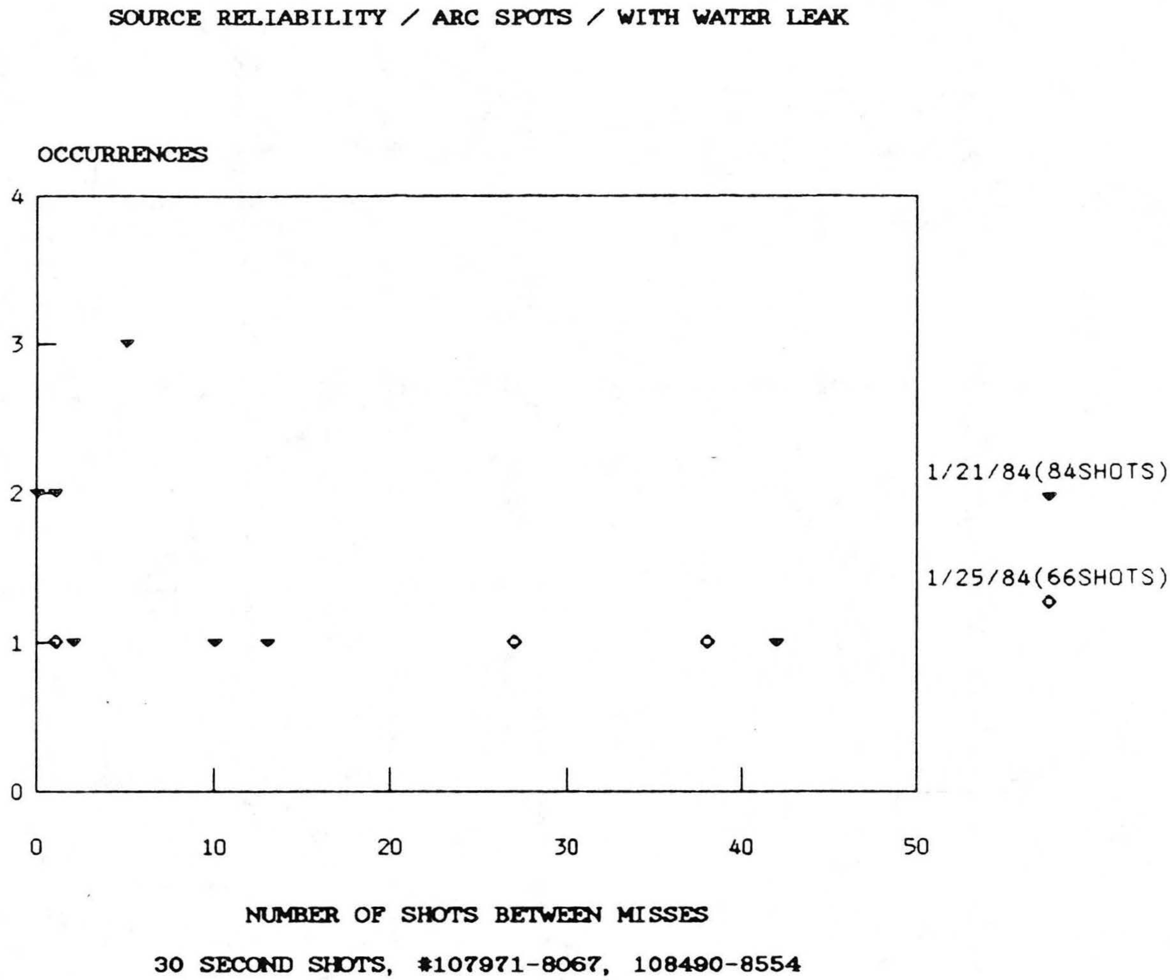
XBL 847-3108

Figure 13. The interrupt history for January 21 is shown; the number of interrupts on each 30 second shot is plotted vs shot number.



XBL 847-3109

Figure 14. The interrupt history for January 25 is shown; the number of interrupts on each 30 second shot is plotted vs shot number.



XBL 847-3110

Figure 15. The number of times that a particular number of arc spots occurred is shown for the two best days of operation, January 21 and 25.

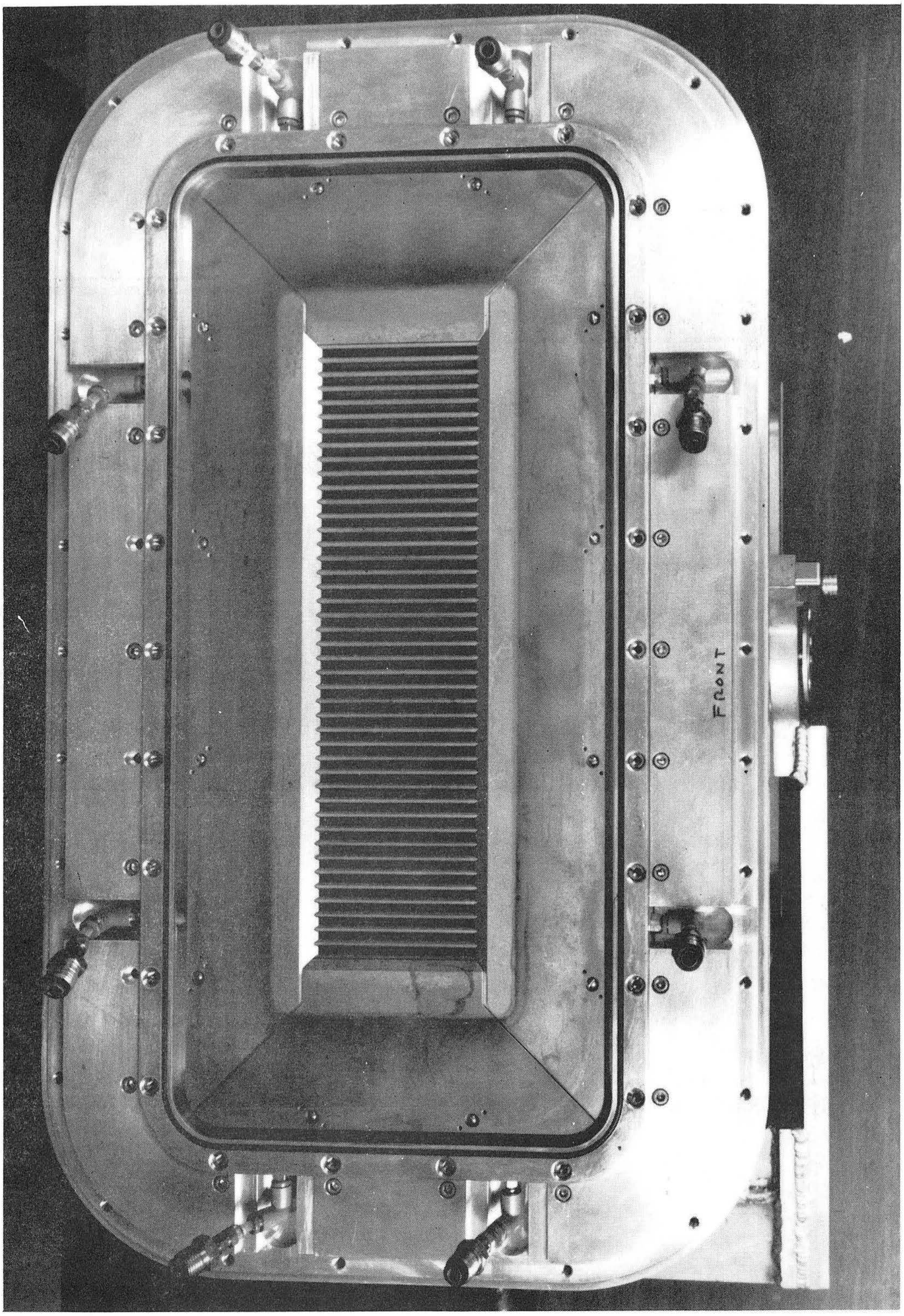


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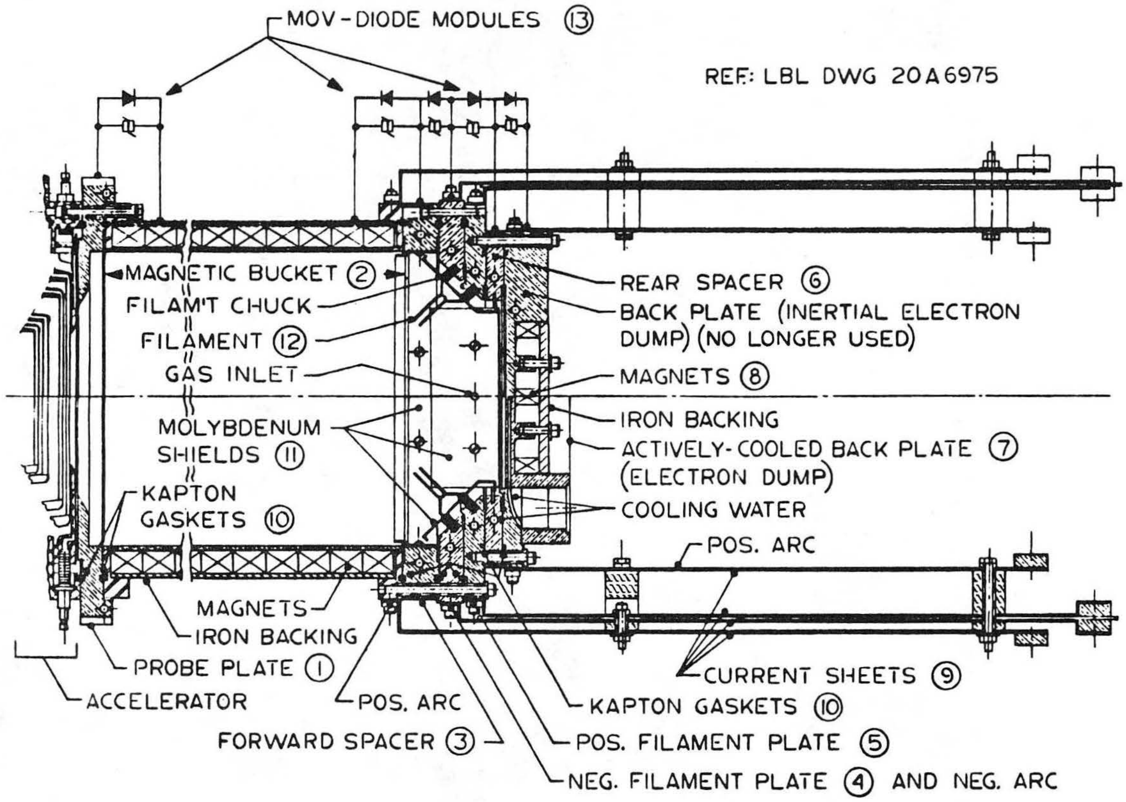
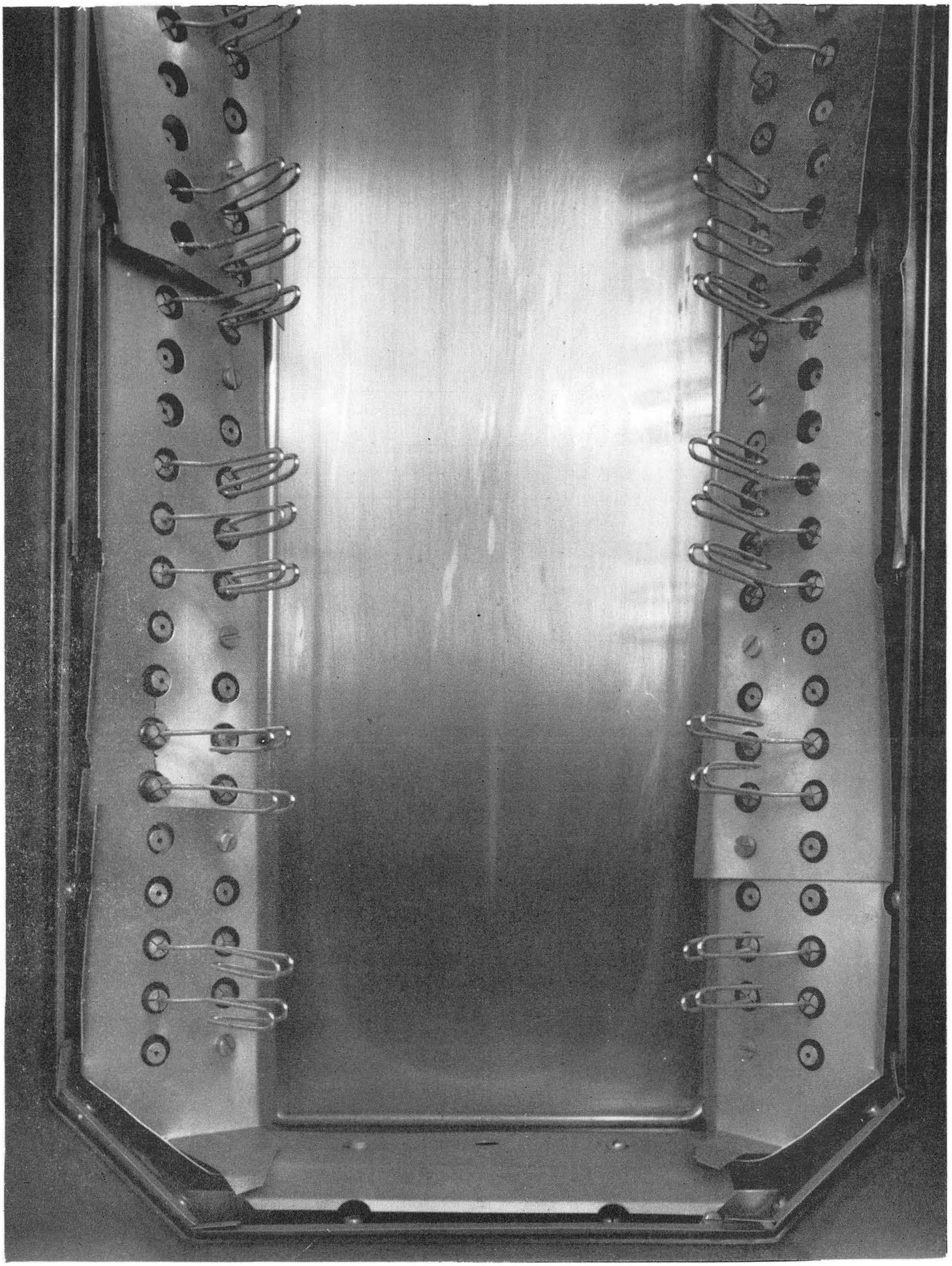
Figure 16. A picture of the accelerator source grid is shown following the Test. The dark area surrounding the grid is the area shadowed by the probe plate.



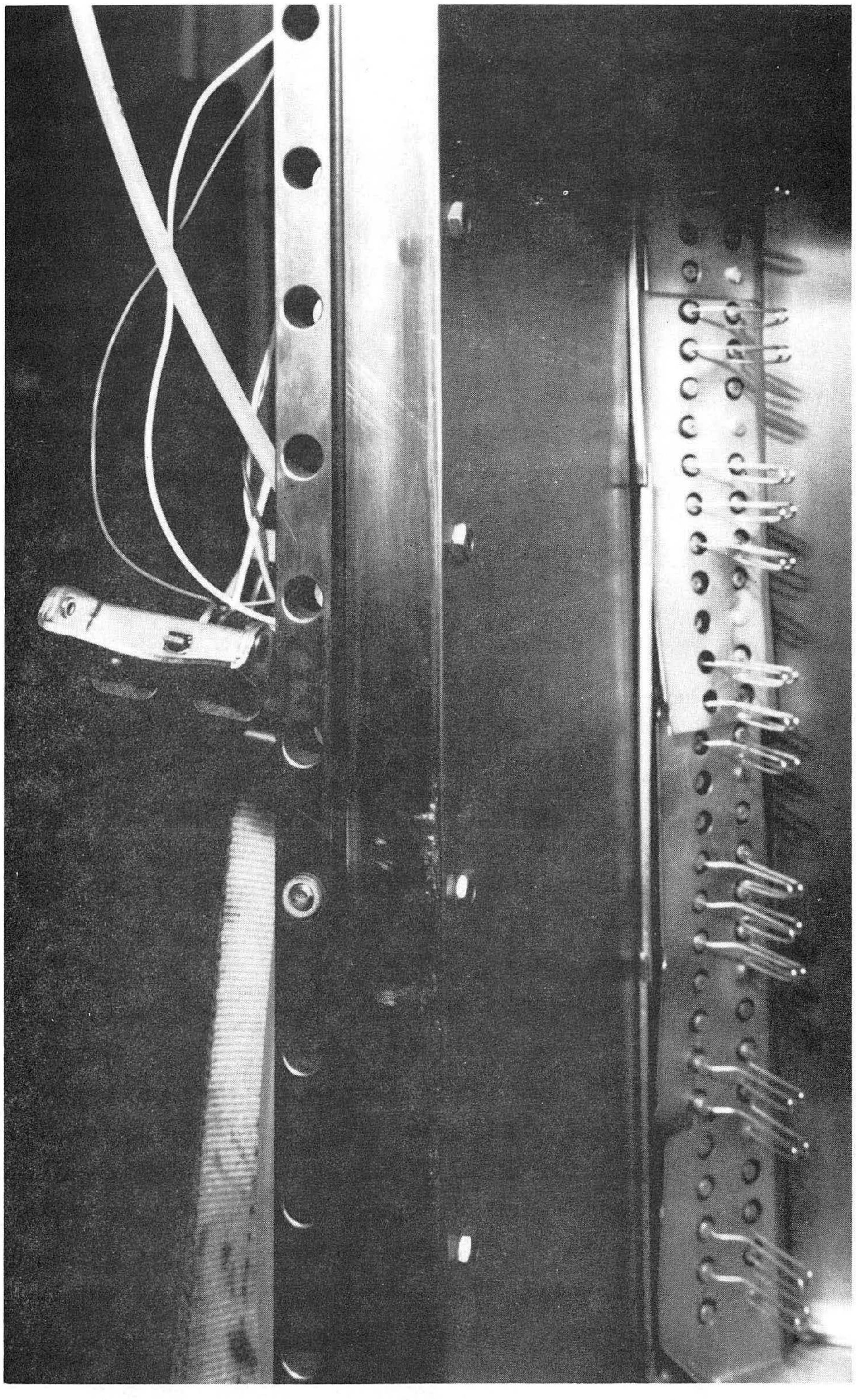
XBL 847-3111

Figure 17. A schematic of the Long Pulse Plasma Source (LPS) is shown; the major components are identified.



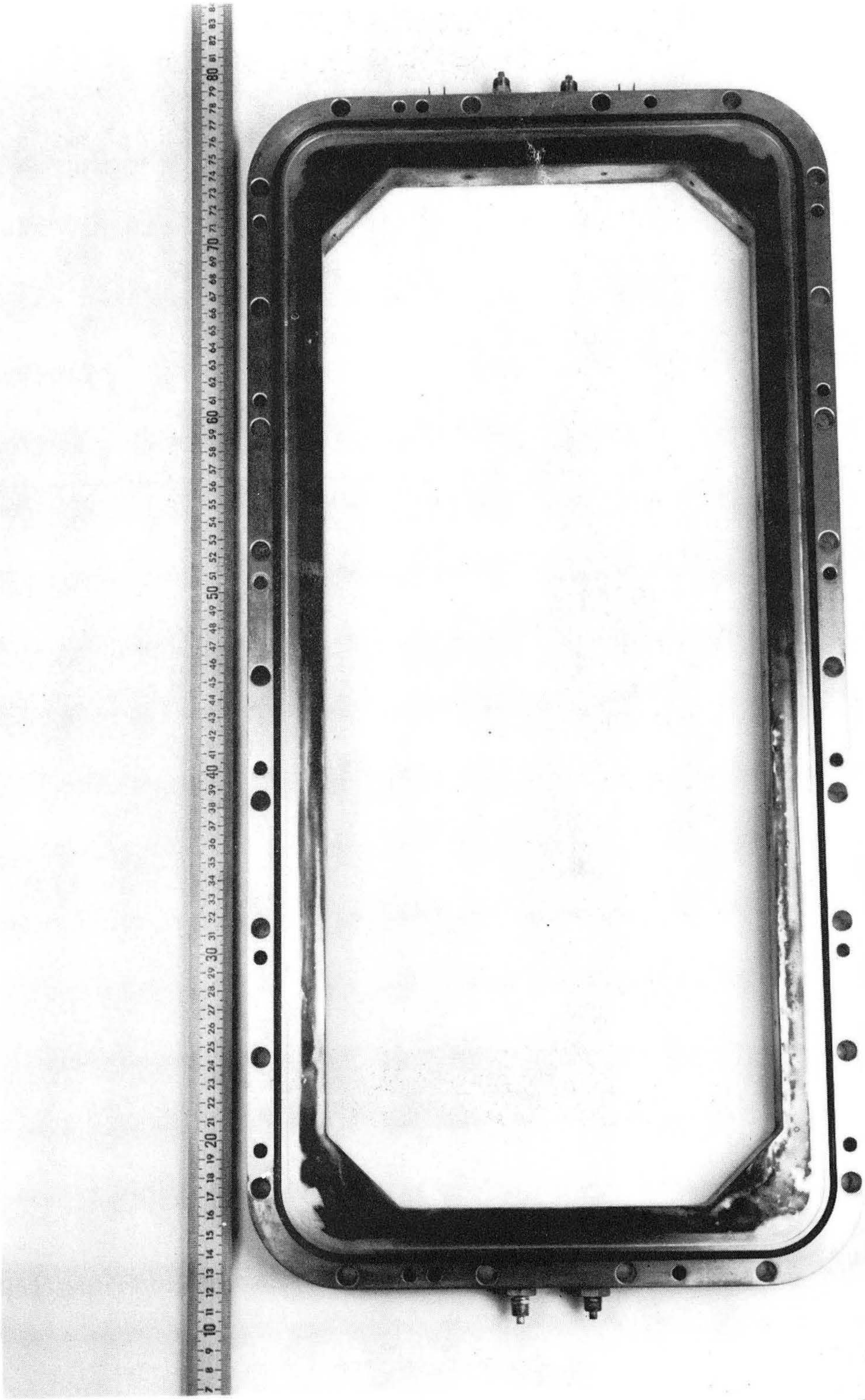
XBB 842-862

Figure 18. A picute of the Long Pulse Plasma Source (LPS) is shown following the Test. The molybdenum shields over the filament sandwich have been warped by the plasma heat.



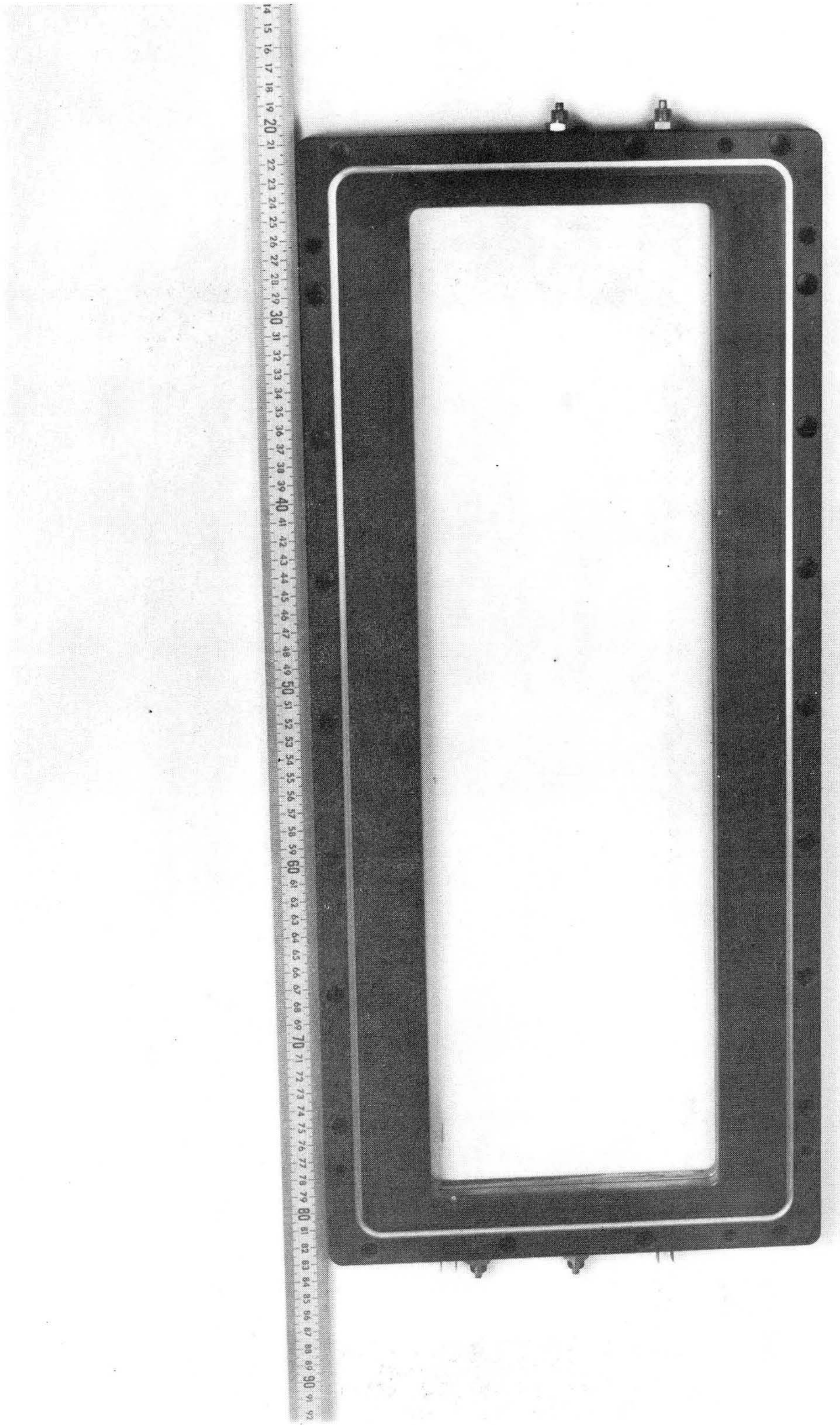
XBB 842-863

Figure 19. A picture of the Long Pulse Plasma Source (LPS) is shown following the Test. The magnetic dust collected on the cusp lines is visible.



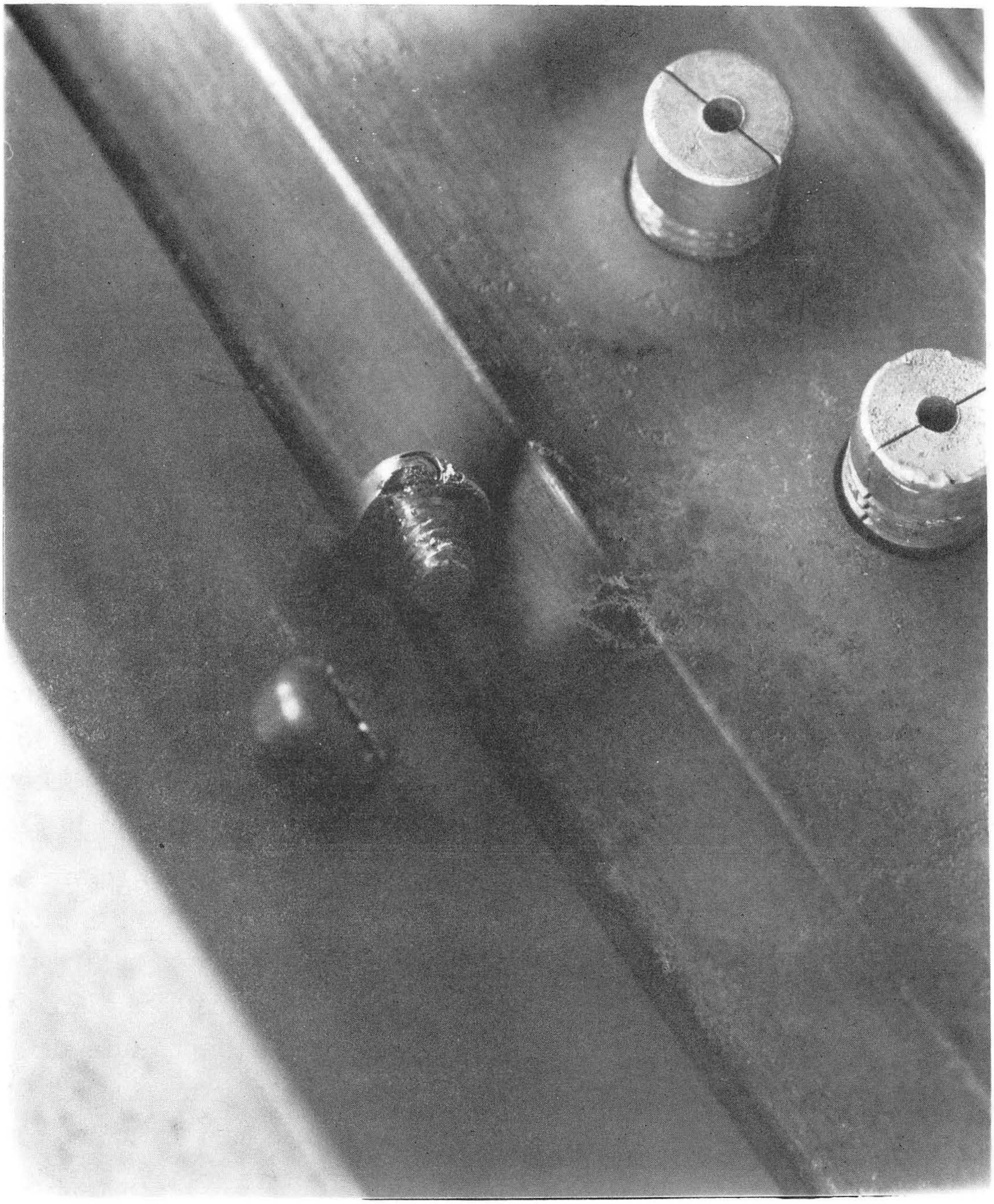
CBB 842-1287

Figure 20. A picture of the foward spacer between the filament sandwich and the bucket is shown following the Test.



CBB 842-1265

Figure 21. A picture of the rear spacer between the filament sandwich and the back plate is shown following the Test.



CBB 842-1277

Figure 22. A picture is shown of a molybdenum screw from one of the shields; several worked loose due to thermal cycling.

4. Operating Parameters and Beam Properties

During the Test, the LBL source demonstrated all of its performance goals for beam properties. These were compared with Test performance of the 10 x 39 cm LBL APIS in Section 1. Typical source operating parameters are now discussed, along with the beam properties and the measurement techniques used on NBETF.

Thirty second beam operation at 80 kV was first achieved in August, 1983, at which time an equilibrium gas flow for the NBETF neutralizer was used, 18 Tl/s. For the Engineering Test, LLNL requested operation be at a source pressure anticipated for the pure beam neutralizer under development. Based on monte carlo calculations, the pressure anticipated at the exit grid by LLNL was 1.3 mT. On NBETF, this was found to correspond to 12 Tl/s gas flow, by extrapolating the pressure measured by an ion gauge in the main injector tank and a barocell in the OMA box (Ref. Figure 1). The barocell was 1.3m from the exit grid, and the measurements were made before the cryo system was cooled down.

The NBETF high voltage supply is basically unregulated. On a given shot, accel current was stable, with peak to peak ripple of approximately 2%. Accel current stability is due to the arc feedback; the variation in accel current is consistent with the specs for ripple in the arc and filament power supplies. Typical accel and arc electrical waveforms are shown in Figure 10. The feedback controller[6,7] compared the input signal with a reference voltage, and phase controlled the arc power supply. For the Test, the input was a voltage proportional to saturated ion current, as measured by a 1/4" O.D. water cooled plasma probe, biased at - 22V with respect to cathode. From shot to shot, the plasma level, and, therefore, the accel current, were made reproducible. Over a period of time, the accel voltage drifted with the utility line voltage, with a corresponding drift in perveance. Including early conditioning shots at 1.5 μpervs, average parameters for all 500 shots were: 80.8 kV; 40.3 A; 1.76 μpervs deuterium.

At 80 kV, optimum accel current was 40.7 A, which corresponds to a plasma ion current density of 170 mA/cm^2 at the source grid. The arc was normally run at about 80 V, with a usable range of 70 - 100 V. If the arc dropped below 70 V, the LPS had a tendency to flip into an iefficient mode when notched for beam turn-on. The upper limit for arc voltage is not sharply defined; conditioning is always required when first running at higher levels. For example, if the arc had been operated routinely at 80 - 90 V, an hour or two of operation might be required to run without spots at 100 V. Typical 12 Tl/s operating parameters are listed below.

	40 kV	60 kV	80 kV
Filament Voltage	6.65 Volts	6.69 Volts	6.66 Volts
Filament Current	3.35 kAmps	3.30 kAmps	3.10 kAmps
Gas	12.0 TL/S	11.7 TL/S	12.3 TL/S
Arc Voltage	70.0 Volts	68.9 Volts	80.8 Volts
Arc Current	340 Amps	615 Amps	859 Amps
Arc Power	24.0 kWatts	42.4 kWatts	69.4 kWatts
Probe Level	60 mAmps/cm2	110 mAmps/cm2	170 mAmps/cm2
Probe Profile	<1.15 max/min	<1.15 max/min	<1.15 max/min
Accel Voltage	40 kVolts	59.1 kVolts	79 kVolts
Accel Current	13 Amps	25.4 Amps	40.5 Amps
Perveance	1.7 μpervs	1.77 μpervs	1.81 μpervs
Gradient Grid Voltage	34 kVolts	48.1 kVolts	65.7 kVolts
Gradient Grid Current	50 mAmps	31 mAmps	75 mAmps
Suppressor Voltage	-1.0 kV	-1.5 kV	-2.0 kV
Suppressor Current	2.0 Amps	2.4 Amps	2.5 Amps

Beam divergence was measured in two of the three ways which were tried: short pulse inertial calorimetry; OMA spectral diagnostic; and active target calorimetry. The global optimum divergence was located by doing inertial calorimeter "tunes". A tune is done by sweeping through a range of perveance around the optimum, at a nominal accel voltage. For example, once setup at 80 kV, the accel current may be lowered, then raised, on successive shots by varying the arc power. Since the accel supply is not stiff, the accel voltage changed by approximately 3%, for a 15% change in perveance.

The global optimum divergence was found from inertial calorimeter tunes with different gradient grid bias, from 82% - 85% of the accel voltage. Each gradient grid setting has a slightly different optimum, i.e., minimum, divergence. The lowest optimum divergence was found at 1.80 μpervs with an 83.5% gradient grid, and had 1/e half angles of 0.38° (parallel to the slots) x 0.95° (perpendicular). This measurement represents an upper bound on neutral beam divergence, since it includes both ions and neutrals. An 83.5% tune with the inertial calorimeter is shown in Figure 23; this gradient grid bias was used for most of the Test.

The inertial calorimeter is "V" shaped, about 1 m deep, with the apex about 8 m from the exit grid. It is indirectly cooled, and was limited to 75 msec of beam at 80 kV. Based on five shot statistics at optimum perveance, it had a standard deviation of $\pm$ 13% in the parallel view, and $\pm$ 2% perpendicular. The inertial calorimeter has 110 thermocouples, with line of sight resoulution to the accelerator grid of $\pm$ 0.15° parallel, and $\pm$ 0.45° perpendicular. The relatively large parallel variation reflects the difficulty of resolving the small parallel beam footprint with the finite mesh calorimeter. Divergence is calculated by comparing a fit to the thermocouple data with data expected for a beam with a given Gaussian 1/e half angle. Chi-squares indicate a confidence level of $\geq$ 95% for typical data.

Long pulse divergence was measured in two ways, OMA and target water flow calorimetry. The Optical Multichannel Analyzer (OMA) spectral diagnostic looks at Doppler shifted spectral lines from beam deuterium atoms. It has a precision of $\pm$ 0.2%, and has been described elsewhere in detail.[8] The OMA required a minimum of 300 msec beam for useful data. The period during which OMA data was taken was varied up to 30 seconds, and no variation of divergence or species with pulse length was observed. Typically, the OMA was setup to read data during the first 15 seconds of a beam shot, so that data was obtained in the event of a short shot. Based on the observed variation in data, the OMA had a standard deviation of approximately $\pm$ 0.2% in species, and $\pm$ 0.2° divergence.

The actively cooled target has thermocouples which read the change in water temperature in each of its 80 panels. Since it is 12 m from the exit grid, the target has intrinsically lower resolution than the other two diagnostics, $\pm$ 0.17° x $\pm$ 0.92°. The active target was developed as a backup diagnostic, to protect the beamline on long pulse shots. During the Test, data from the active target thermocouples were strongly affected by rises in target pressure due to water leaks, probably due to electrical noise carried by plasma generated by the beam. This problem has since been corrected by carefully shielding all thermocouple leads. For 30 second, 80 kV shots, the OMA divergence (RMS weighted for species) is compared with target divergence in Figure 24, using data selected at random throughout the Test. The OMA data compare very well with the inertial calorimeter tune discussed previously, indicating the same optimum, with parallel and perpendicular standard deviation of ± 1%. Due to electrical noise, the unedited target data were obviously unreliable. Five shots near optimum had a perpendicular standard deviation ± 81%. Selected shots with good target data are also shown; the five shot standard deviation was 1.6%, indicating good performance potential for the target as a diagnostic tool.

The total accel power on the active target could be obtained in two ways, by reading the thermocouples in the water manifolds, or by summing the data from the individual subpanels. Total power data from the manifolds was more reliable than detailed data from the subpanels, as illustrated in Figure 25. The median power fraction on the target 12 m downstream is 85% - 95%, which supports the excellent divergence data from the other diagnostics. Based on overall beamline power accountability, the aberrant beam power is estimated to be about 5%. Data in Figure 25 are unfiltered for 184" cyclotron operation, which decreased the on target fraction by a few percent. The effect of the 184" can be seen in Figure 26, which shows target isotherms with the cyclotron on and off. The tightness of the beam in the parallel direction is obvious.

The OMA species on 30 second shots are illustrated in Figure 27. The 12 Tl/s data were picked at random throughout the Test; the 18 Tl/s data were obtained August 12, 1983. At one time, the goal for atomic fraction was 90%, but the "pure beam" concept reduced the goal to 80% atomic. In comparison with previous LBL field free sources, the LPS deuterium species are relatively insensitive to arc power. Arc efficiency is comparatively high; 80 kV beam requires 65 - 70 kW arc power. The double data points correspond to parallel and perpendicular views, which differed slightly, although the standard deviation of each was ± 0.2%. Water was barely observable during long pulse operation, with an indicated fraction of 0.15% ± 0.05%. Typical OMA data are shown in Figure 28.

The interrupt duration was determined by the existing electrical system on NBETF. LLNL requested less than 10 msec, and 3 - 5 msec was used throughout. The goal for the number of interrupts per shot was ≤ 10. Conditioning was still evident at the end of the Test, and, during periods of good vacuum, 6 interrupts per shot was typical.

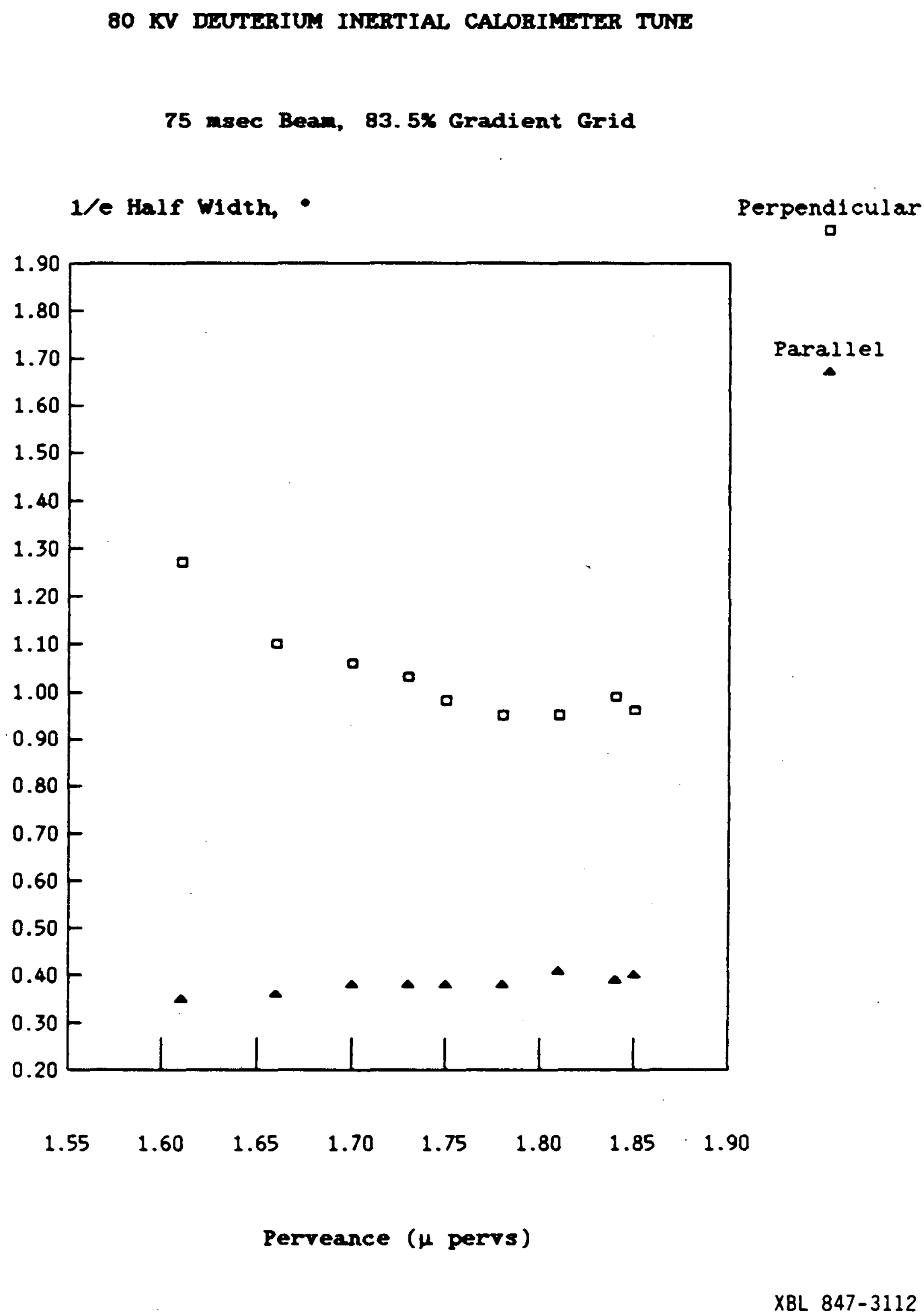
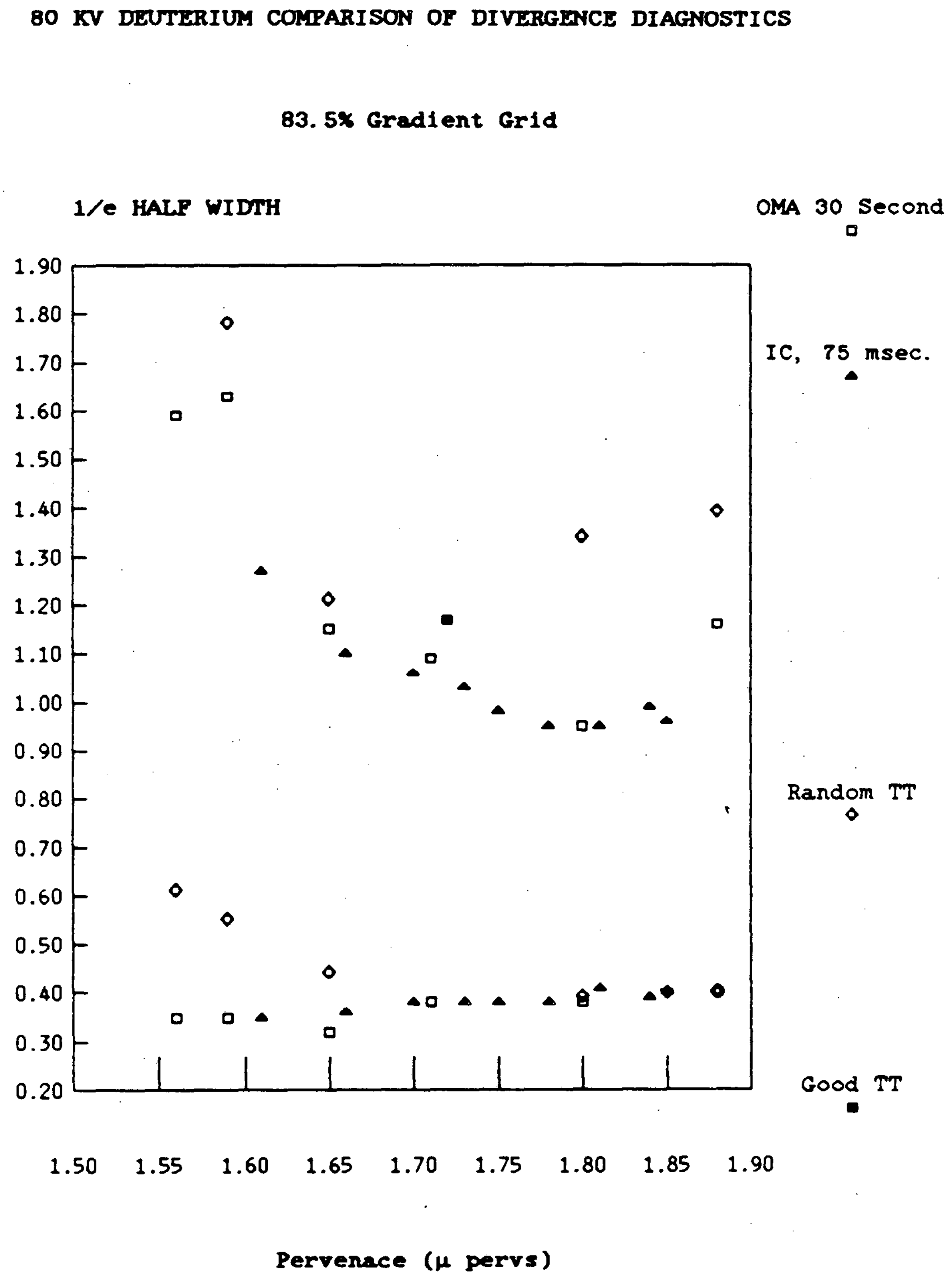
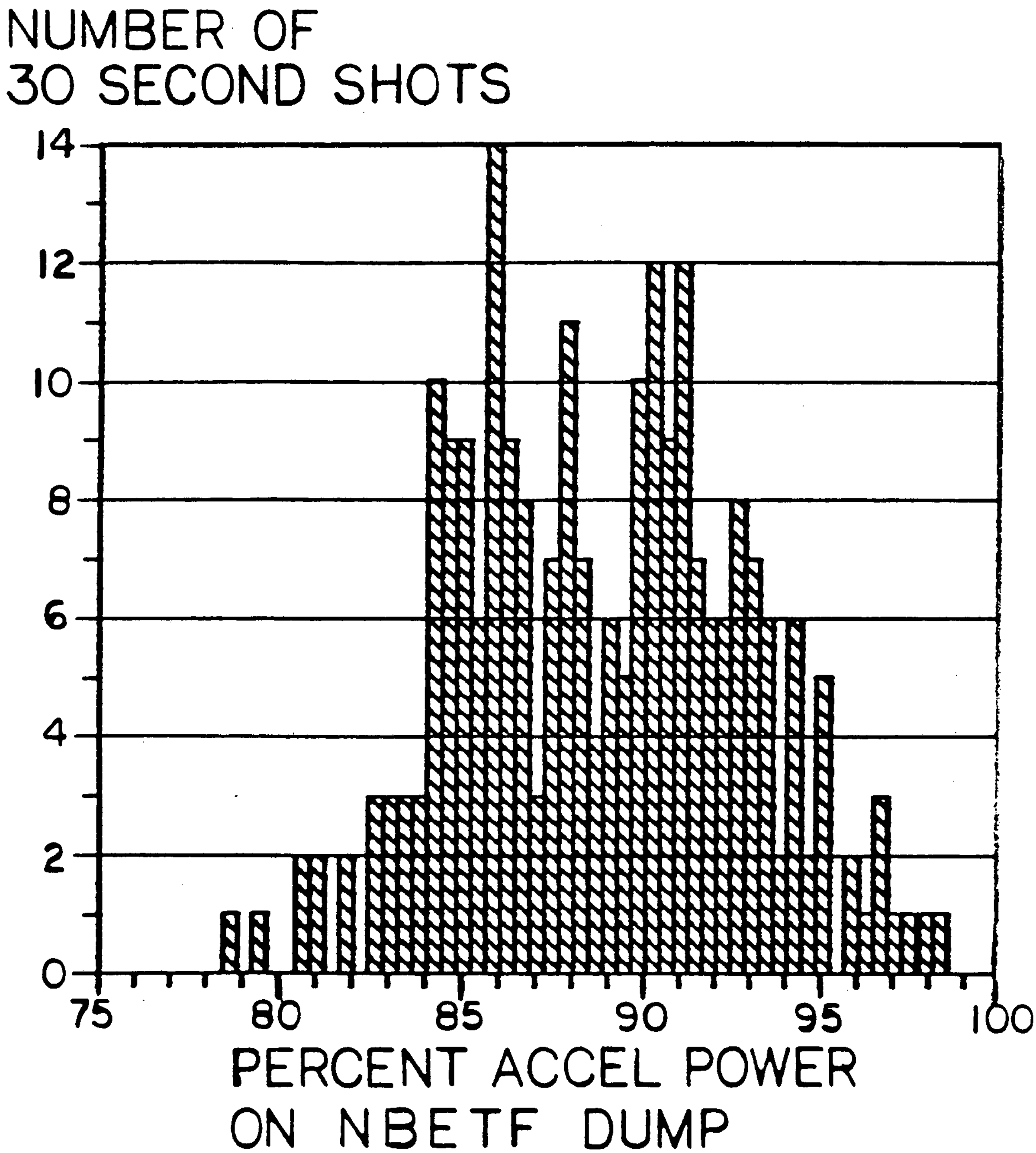


Figure 23. A tune on the inertial calorimeter is shown; divergence is plotted vs perveance for 75 msec shots with 83.5% gradient grid bias.



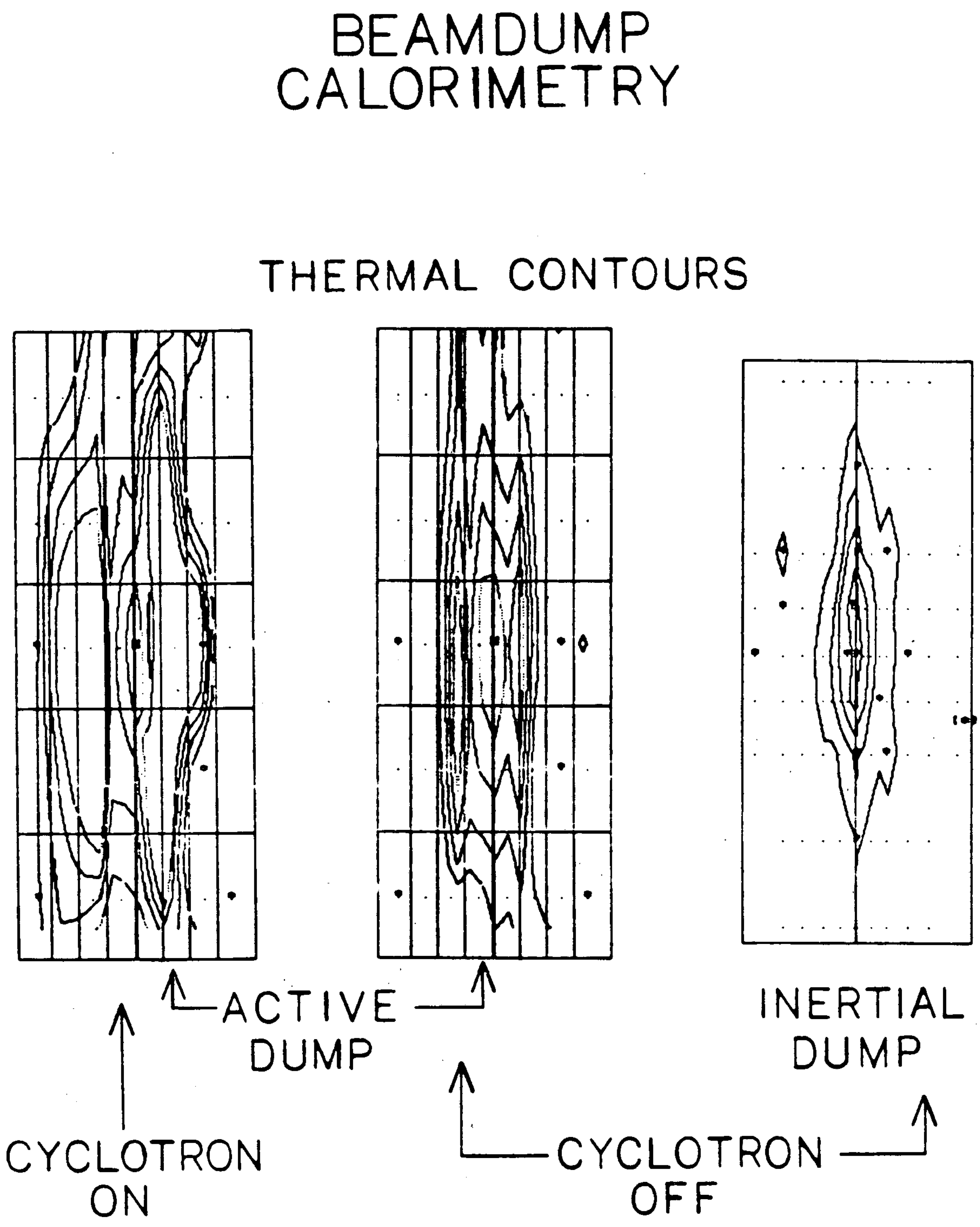
XBL 847-3113

Figure 24. A comparison of beam divergence diagnostics is shown. Inerital calorimeter results from 75 msec shots is plotted, along with 30 second shot divergence using OMA, and the active target. Beam divergence is plotted vs perveance.



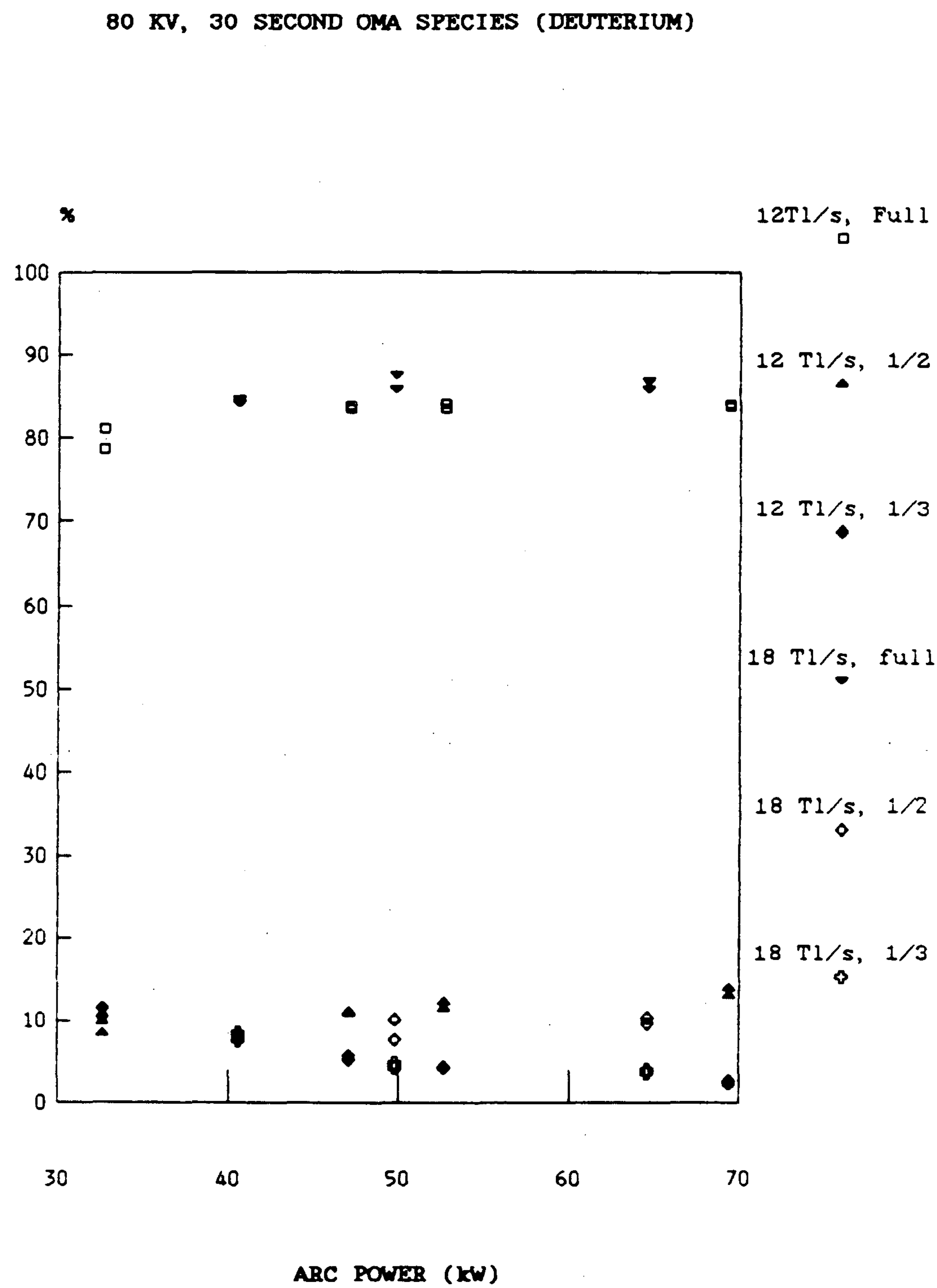
XBL 847-3114

Figure 25. A histogram is shown of the power fraction measured on the active beam target. The number of 30 second shots is plotted vs the percentage of power on the target.



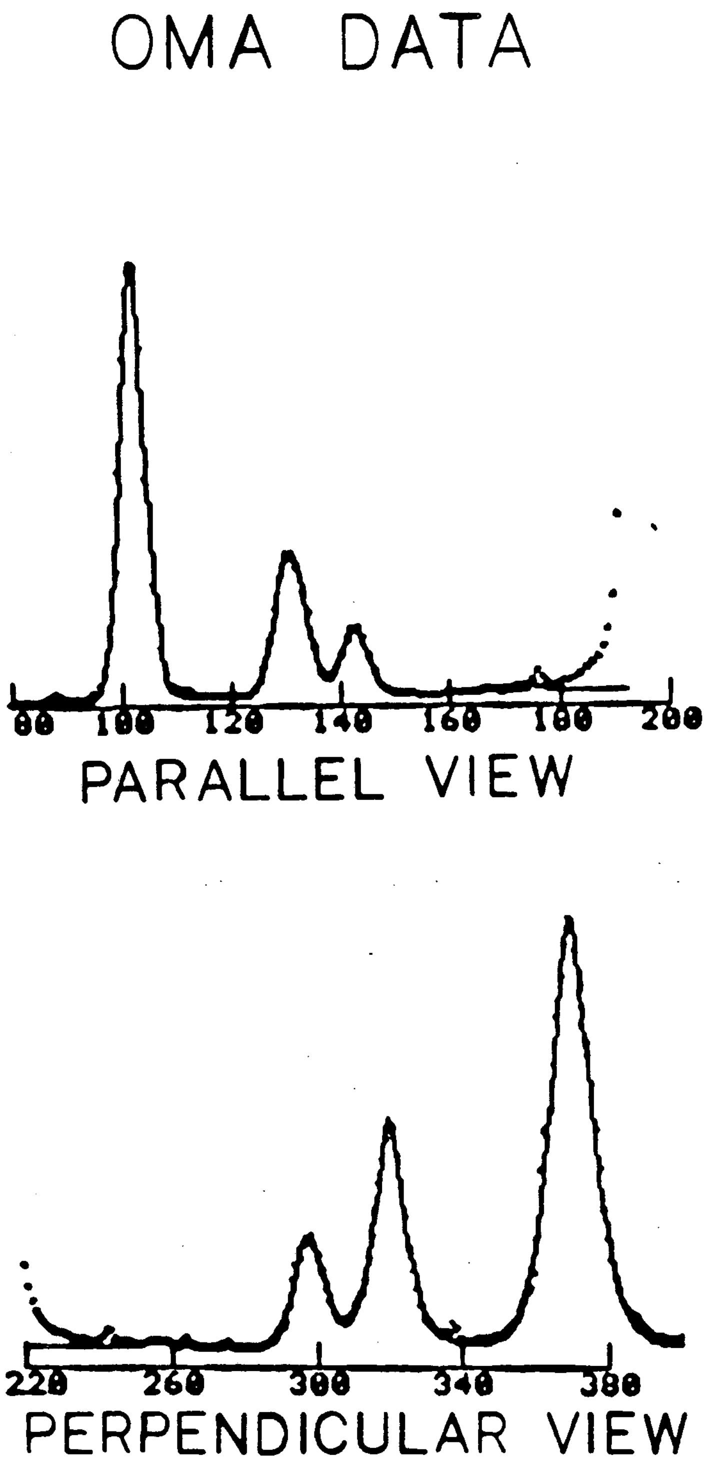
XBL 847-3115

Figure 26. Isotherms are shown from the inertial calorimeter and the active target. The active target is shown with the cyclotron ON and OFF.



XBL 847-3116

Figure 27. OMA species is plotted vs arc power at 12 and 18 Tl/s gas flow.



XBL 847-3117

Figure 28. Typical OMA data from a 30 second shot are shown.

5. Suggested Design Improvements

Based on accumulated operating experience, several design changes for the LPA/LPS are mentioned here which could reduce costs, or improve operability. Most apply to the LPS plasma source. The LPS was designed without the benefit of experience with a long pulse prototype, and performed surprisingly well. The accelerator design benefitted from extensive development testing of a 7 x 10 cm prototype, and its performance was excellent.

The LPS plasma generator is the first long pulse magnetic bucket developed at LBL. It was designed with limited information about the magnitude of the back streaming electron power from the accelerator, or its distribution. The Test confirmed the soundness of the basic design, particularly in regard to atomic fraction, which was higher than expected. Based on 80 kV operation, the electron dump appears to have excess cooling capacity, which could be an area for cost savings. The electron dump was designed to handle 3% of the accel power at 120 kV, 57 A, assuming peak power loading of 2 kW/cm^2. From water flow calorimetry, total back electron power was only 0.7% of accel power, of which half went to the dump.

The LPS was originally designed with water cooled, anodized aluminum insulators for the filament sandwich. These were in direct contact with the plasma and developed serious spots during initial arc testing in 1982. Water cooled copper spacer plates, captured in kapton insulators, were designed as replacements, but only the forward spacer plate was ready in time for the Test. The rear anodized plate was captured in kapton and used. Because of the mechanical fragility of kapton, alternative insulator materials are being considered.

Functional alternatives for the hand fit moly shields in the filament sandwich are being considered. As mentioned in Section 2, the shields eliminated spotting under good vacuum conditions. Their function is to shield both the copper in the filament sandwich (which is at cathode potential) and the insulator gap from the plasma. However, the shields are only radiatively cooled, and the mounting arrangement caused many to buckle under thermal stress. Two possible solutions are thicker, stress relieved molybdenum plates, or tungsten coated copper. The basic idea is to have a relatively spot resistant metal in contact with the plasma. In both cases, the redesign should have an edge overlapping the insulator gap to shield line of sight plasma. Thick molybdenum plates have been used as anodes in field-free LBL sources. The molybenum anodes experience much higher heat loads than the shields, and have been run up to 23 seconds at 70 kV. Tungsten plated copper should be less costly to fabricate, but has yet to be tried in this application. A third possibility is to eliminate the sandwich design by using individual filament feedthrus of the type used on the LBL negative ion source, which runs dc.

The perveance, divergence and reliability characteristics of this accelerator were outstanding. In comparison with short pulse sources, conditioning was relatively painless. Once conditioned up to 80 kV, it was routinely started every day at 80 kV without conditioning at lower voltages. After Christmas shutdown, it was brought up to air, then restarted at 80 kV, also without reconditiong at lower voltages. The principal area in which the accelerator could be improved is cost reduction. The insulator is a brazed alumina stack, which could be replaced with epoxy. Further savings might be obtained in the corona rings, which serve as water manifolds and were brazed stainless steel assemblies. Smaller savings can be found in redesigning the details of the grid assembly.

In conclusion, the LBL APIS met the development goals for MFTF-B 30 second neutral beams. Refinement of the plamsa source design is recommended for industrialization, and cost engineering of the accelerator.

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Acknowledgements

Long pulse source development at LBL has been a seven year effort. The results reported here represent the work of a group too large to mention individually. Design of the plasma generator was led K. W. Ehlers and A. F.Lietzke, who were especially helpful during this test program. The accelerator concept and optics are the work of a team led by O. A. Anderson and W. S. Cooper. The mechanical design and fabrication of the source was led by K. H. Berkner, J. A. Paterson, and J. T. Tanabe. Much of the construction, fabrication, and repair was done in the shop managed by L. A. Biagi. The authors gratefully acknowledge the quality of their work.

Completion of this test program required tireless effort on the part of the entire NBETF crew, directed by K. H. Berkner. Electrical support was managed by H. M. Owren, mechanical support by J. A. Paterson, and test stand operations by J. W. Roberts. The authors appreciate their perseverance.

Appendix A. Oxygen Contaminated Deuterium Test

In the LLNL Pure Beam test scheduled for NBETF, the plan is to use deuterium with a known oxygen contamination. Since the usual calorimetry diagnostics will be unavailable, operating experience with this gas mix beforehand was considered desirable. LLNL supplied a deuterium bottle with 2.4% oxygen which was tested on January 25, immediately after completion of the 500 shots.

The primary diagnostic for this test was OMA Doppler shifted spectroscopy. Species and divergence data were obtained with a 1 second OMA perveance sweep, or "tune", at 80 kV. The divergence is shown in Figure A.1, which indicates a perveance optimium at 1.72 micro pervs. The atomic fraction was about 85% for these shots, slighly higher than with only deuterium at 12 Tl/s. The seven shot average water fraction was 1.1% $\pm$ 0.3% in the parallel view, and 0.8% $\pm$ 0.2% perpendicular. However, the 4.4% reduction in perveance (from 1.80 to 1.72 μpervs) suggests a beam content of 6% oxygen. These results may be consistent, since the OMA sees only hydroxides and no direct measurement of oxygen has been made.

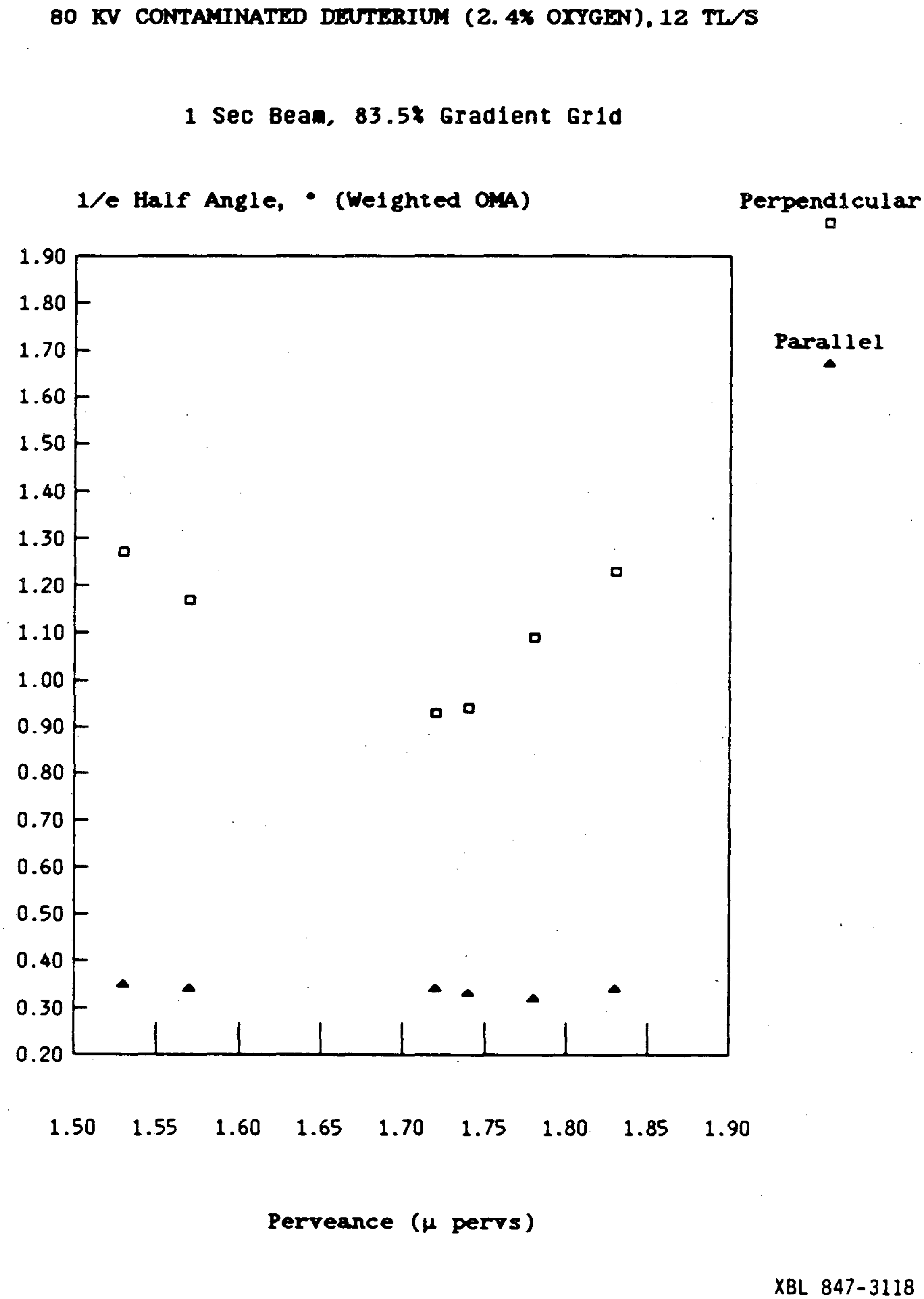

Figure A.1. OMA beam divergence (RMS) is plotted vs perveance during testing of the LLNL oxygen-contaminated (2.4%) deuterium bottle at 80 kV.

Appendix B. 5 Second, 80 KV Hydrogen

Before removal from NBETF, 5 second hydrogen beam was run at 80 kV, to obtain operating data for Doublet D-III. The LPS was specifically designed with minimum anode area to maximize both the deuterium atomic fraction and filament lifetime. Hydrogen operation without benefit of source development presented special problems. The plasma profile was unknown, which precluded making changes in the backplate magnets on NBETF. The options were either to remove the backplate magnets completely, or to use the probe plate as anode. After some trials, the probe plate was connected to anode with 80mΩ of series resistance; this reduced the current to the probe plate to about 15% of the total arc current. The resistance was determined by minimizing the heat imbalance on the upper and lower grid halves (from grid water flow calorimetry). In this configuration, the atomic fraction was reduced to 65% - 75%. The beam heat imbalance on the grids was barely acceptable, 15% max/min, which suggests that the plasma profile could be improved. Nominal arc efficiency in this configuration was 0.55 A of accel per kW of arc. Typical arc parameters were 77 V and 1300 A, with filament heater at 7 V and 2.9 kA.

An 80 kV perveance sweep, or tune, was done on the inertial calorimeter using 75msec beam. The results are shown in Figure B.1. Optimum divergence was 0.53° x 1.1° (1/e half width) at 2.50 µpervs, or 56.6A. The divergence is not as good as with deuterium, which also suggests profile problems. Due to the lower atomic fraction, the hydrogen perveance was slightly lower than had been expected based on deuterium operation. Plasma source development might result in improved divergence and species. Before shutdown, interrupt-free 5 second operation was obtained.

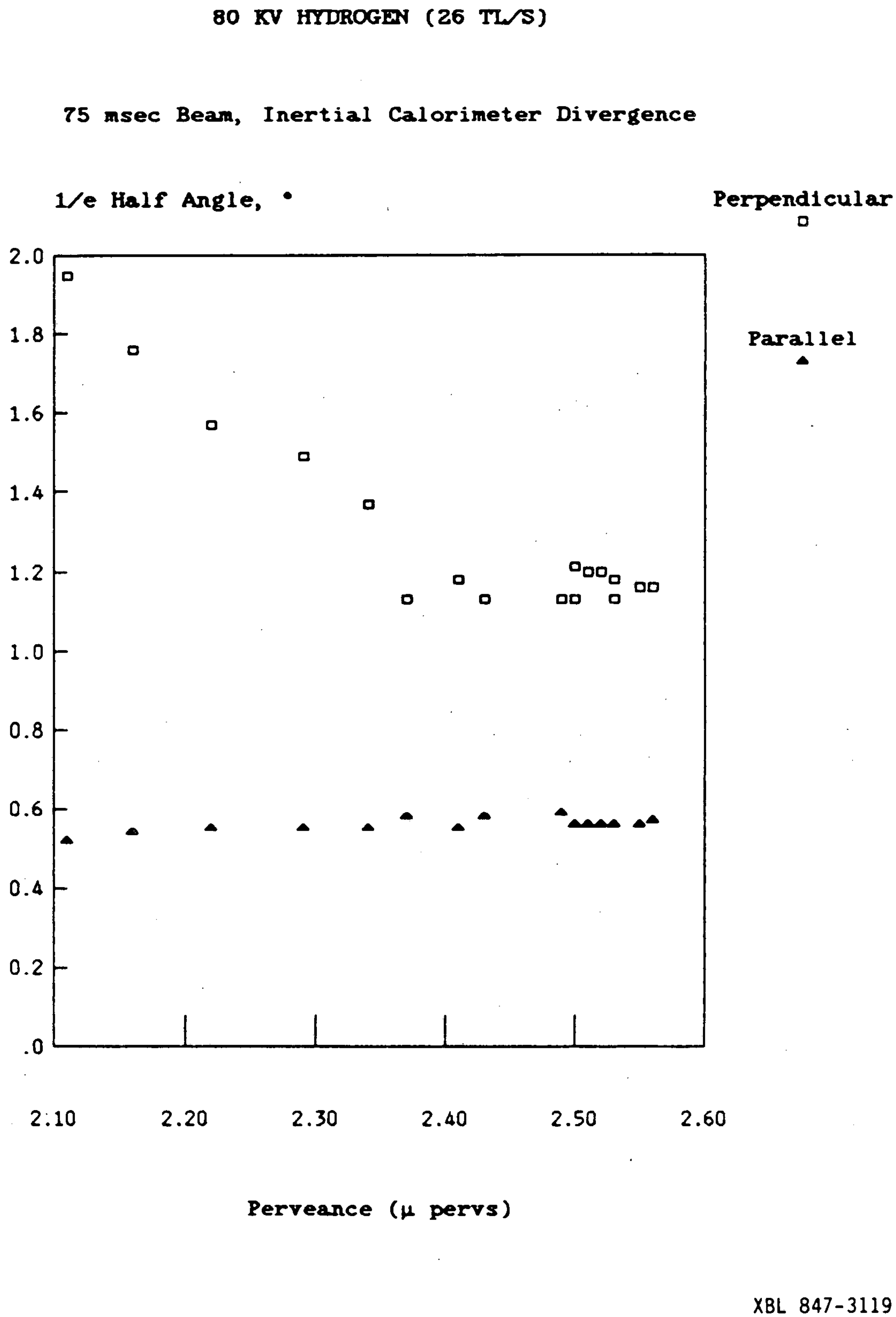

Figure B.1. Inertial calorimeter beam divergence is plotted vs perveance for hydrogen at 80 kV; the beam pulse was 75 msec.

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