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Low Intensity Configuration at NTF for Microdosimetry and Spectroscopy

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0. Abstract

Additional circuitry has been developed to regulate beam delivery to Fermilab's Neutron Therapy Facility. This allows the number of protons on target to be reduced to a point that makes microdosimetry and spectroscopy possible. An introduction to the problem is presented. The modifications are described and results verifying their effectiveness are reported.

1. Introduction

For almost twenty years, Fermilab has contributed to the fulfillment of Robert R. Wilson's vision of heavy particle therapy for cancer through its support of the Neutron Therapy Facility (NTF). The high average current of the linac translates into favorable treatment times and its exceptional reliability has made operating in a non-hospital setting very reasonable. While this high average current is advantageous for treatment and the macroscopic biological studies that preceded patient treatment, it has proven to be quite frustrating for the microdosimetric studies that would enlighten us as to the actual physical processes that underlie the clinical results that are observed.

This paper describes a number of aspects of normal beam delivery to the Neutron Therapy Facility at Fermilab and shows how they can be easily modified to allow low intensity operation. The ability to alternate between normal and low intensity operation makes it possible to perform microdosimetry and time-of-flight measurements without interrupting high energy physics (HEP) operations. The methods developed here would also be useful should a 400 MeV experimental area be built. A number of experiments that might be conducted there would need similarly low intensity beam on a pulse-by-pulse basis so as not to interfere with normal HEP operations.

2. The Neutron Therapy Facility

The Neutron Therapy Facility was developed to treat cancerous tumors by taking advantage of the unused RF pulses in the Fermilab linac. The RF of the linac pulses continuously, yet beam is accelerated for high energy physics only about 3% of the time. NTF uses the RF pulses not used by high energy physics to accelerate protons which strike a beryllium target and generate neutrons. These neutrons are then collimated to the desired beam size and directed at the tumor. The biological effect of the neutron beam has been extensively measured[l-6]. These macrodosimetric measurements looked at the relationship between the biological effect and the total dose delivered to a volume of a few cubic centimeters. However, these measurements were of the gross beam effects and very little work was done to understand the microscopic dose or energy spectrum of the beam because of saturation effects in the detectors used for microdosimetry. Section 4 below describes the normal conditions of the NTF system. Section 5 describes the modifications necessary to produce the lower intensities.

3. Macrodosimetry vrs. Microdosimetry

In discussing the requirements driving the activities reported in this paper, it is important to recognize the difference between the two types of dosimetry.

Macrodosimetry, also commonly referred to as just dosimetry, deals with the relationship between dose to a macroscopic volume, on the order of a half a cubic centimeter or more, and response. Measurements are generally made using an ionization chamber placed in a phantom of material that mimics human tissue. The full intensity (40 mA) of the treatment beam is used. Neutrons are a form of indirectly ionizing radiation; they must produce electrons, protons, or alphas that then ionize a target material. In most of the volume of the phantom, an equilibrium exists between ionizing particles produced inside the detector volume and passing out of it, and particles produced outside and passing in. Under the high dose rate used for patient treatment, the chamber measures the total charge produced. These measurements are then correlated with the biological response, first in cell and animal studies and finally in human treatment.

Microdosimetry deals with measuring the *dE/dx* in individual interactions. It uses proportional chambers instead of ionization chambers. The characteristics of the proportional chamber allow it to mimic a volume of tissue of the order of a cubic micron.

The resolving time of a proportional chamber is 10's of nanoseconds compared to the 5 nsec period of the 200MHz beam. Likewise, the shortest elapsed time for a time-of-flight measurement at NTF would be on the order of 70 nsec. Therefore the dose rate must be low to avoid saturation in the detector. These measurements can provide information about the spectrum of the incident neutrons and identify the actual processes that give the dose response seen in the macrodosimetric measurements described above.

4. The Linac and NTF

The beam used to produce the neutrons used in treatment is derived from the Fermilab linac. The linac starts in one of two Cockcroft-Walton, 750 kV electrostatic accelerators. The beam passes through a Low Energy Transport Line (LEBT, the H- or I- line) and into the accelerating cavities of the linac. After the beam has been accelerated to 66 MeV in the first three accelerating cavities, and drifted through the fourth, it is diverted from the linac into the NTF beamline. Figure 1 shows the LEBT, Figure 2 illustrates the extraction to the neutron production target, and Figure 3 shows the target area.

4.1 The 750 keV Line (LEBT)

The H- line of the LEBT is the more complicated of the two lines so the following description will concentrate on it. The H- ion source within the Cockcroft-Walton accelerator operates at 15 Hz with a 75 μsec pulse length. An electrostatic chopper cuts the 75 μsec DC pulse into the length of macroscopic DC pulse desired for acceleration (57μsec for NTF). Once inside the H- line, the beam passes through two dipoles and a number of focusing elements.

4.1.1 Electrostatic Chopper

The circuitry of the chopper is shown in figure 4. The Cockcroft-Walton source is supplying DC beam that is being deflected by the 24 kV potential on the chopper plates. When the “ON” Thyratron fires, its deflecting plate is grounded and beam passes through undisturbed. Then the “OFF” thyratron fires, grounding the upper plate of the capacitor. The voltage change is AC coupled through the capacitor and drives the “OFF” plate to -24 kV, again deflecting the beam. The fire timing of the thyratrons is set by delay timers with 1 microsecond resolution. When the “ON” and “OFF” delay timers are set equal, about 300 nanoseconds of beam still manages to pass through. (This is presumably due to internal differences in the thyratrons as it is not seen in the trigger pulses.) Thus, the normal setup of the chopper system is capable of producing pulses of length .3, 1.3, 2.3, . . . μsec.

4.1.2 Aperture

Figure 5 shows a measurement of a 160 nsec pulse as seen through the beam position monitor (BPM) at NTF (fig. 3) . As an exercise to understand the falloff of the beginning and trailing ends of the pulse envelope a simulation was run to transport the beam through the 750 keV line. Figure 6 follows the beam from the H- source to the input of tank 1 (see fig. 1) for various amounts of voltage on the chopper plates. Figure 6 follows 210 "particles" on 5 concentric ellipses and tracks their positions at the center of 22 elements in the H- line. If the particle exceeds the aperture (the horizontal dotted lines) at that point, the trace stops. The ellipse in the lower right corner of some of the figures is the x-x´ phase space of the particles. The transverse emittance of the beam is 12.7 mm-mr (97%) in the x-x´ plane. If the particle passes all the way through the line, the point on the ellipse is marked with a box. The transition region between on and off occurs between 3 and 6 kV. Figure 7 shows the voltage change on the chopper plates when the thyratrons fire. The voltage change was measured to be approximately 200 V/nsec for the "ON" tube and 125 V/nsec for the "OFF" tube. This difference in voltage change determines the rate that the beam passes through the transition region of figure 7 leading to the rolloff seen in the leading and trailing edges of figure 5. As the time difference between firing of the tubes decreases, the two rolloffs meet. When this happens there is a natural reduction in amplitude along with the reduction in pulse length.

4.2 Buncher and Accelerating Cavities

Just upstream of the accelerating cavities, after the LEBT, is a buncher. The buncher varies the phase velocity of the particles in order to convert the DC beam to the 200 MHz RF structure of the linac. (Figure 8 shows a 57 μsec macropulse; Figure 9 shows the micropulses, or buckets, within the macropulse, defined by the 201.25 MHz RF frequency of the cavities.) The match of the phase between the buncher and the accelerating cavities can be varied to regulate the capture efficiency of the accelerating cavities. Therefore, this can be used to vary the intensity of the linac beam. The linac itself is made of Alvarez style drift-tube cavities.

4.3 The NTF Beam Line

The NTF beamline (figs. 2 & 3) starts with a bending magnet between linac tanks 4 and 5. The position of the NTF magnet was dictated by the relation between the tank 4-5 gap and a freight elevator that was converted for use in patient positioning. However, the magnet is not capable of bending 99 MeV protons produced by the acceleration through tank 4, so the beam is accelerated to 66 MeV and drifts through tank 4 to the magnet. The magnet bends the beam 58° and is energized only when beam is to be sent to NTF. Another bending magnet of 32° completes the bend. The beam then passes through the linac shield wall to the shielded target area. A p-n reaction on Beryllium produces the neutron beam.

4.4 Beam Control

The delivery of beam to the NTF target is regulated by three control systems, the accelerator control system (for all the accelerator complex), the linac control system, and the NTF control system. The time-line generator of the accelerator control system decides if there are otherwise unused linac cycles available for NTF and issues a permit. The NTF control system then issues a request for beam directly to the chopper control in the LEBT. The linac control system delivers beam to the NTF target as long as the request for beam is not removed by the NTF control system. The NTF request is removed when either the desired dose has been delivered or one of the monitored parameters has gone out of tolerance. Of the many parameters monitored, three ratios make sure beam is being delivered to the NTF target properly. These are the ratio of the two toroids (CTOR2/CTORl), the ratio of the two transmission chambers (X2/X1), and the ratio of the integrated charge in one of the toroids to the signal of one of the transmission chambers (QP/X1). (See figures 2 & 3.) The ratio CTOR2 to CTOR1 ensures that beam is not lost between the 58° magnet and the target. QP (whose integrated signal is CCHG2) over X1 makes sure the beam is targeted properly. X2 over X1 ensures the integrity of the transmission chamber which monitors the delivered dose.

5. The Need for Low Intensity

Numerous attempts at microdosimetry at NTF have resulted in failure because “the intensity was too high.” As alluded to above, the resolving time of the detectors require interaction rates to be one event per macropulse. This section tells how low intensity was produced and describes the modifications necessary for operation in the mode.

The peak current of the beam produced by the Cockcroft-Walton is 50-60 mA. After bunching and capture by the linac RF, 30-40 mA are delivered to NTF. The passage through the buncher increases the instantaneous intensity by at least a factor of five; the beam is converted to pulses of less than 1 nsec duration with a 5 nsec period. This gives as many as 1.25×10^9 particles per 200 MHz micropulse. NTF uses macropulses that are 57μsec long at a repetition rate of 15 Hz.

The conversion efficiency of the pin reaction is thought to be approximately 10^{-6} neutrons per incident proton. This means that approximately one thousand neutrons are produced within each sub-nanosecond micropulse.

Detectors used in microdosimetry are typically of the order of a half an inch in diameter. While the divergence of the neutrons is not known, it is estimated that the solid angle subtended by the detector is ~ 1×10^{-3} of the production angle. If the pulse length can be reduced to a single micropulse, event rates of the order of one event per pulse should be achievable.

5.1 Producing Low Intensity

The delay timers controlling the chopper have one microsecond resolution. A circuit was added to give a variable timing between the ON and OFF signals for the chopper. The circuit has two ten-turn potentiometers. A coarse adjustment is given by one of the potentiometers over a one microsecond range. The other potentiometer gives a fine adjustment over a 100 nanosecond range, giving sub-nanosecond control over the length of the pulse. As mentioned above, as the pulse length gets below 100 nanoseconds the rolloff of the rise and fall of the pulse meet and the amplitude of each micropulse starts to decrease. This amplitude reduction can be used in conjunction with the amplitude reduction produced by varying the linac buncher phase.

5.2 Effects of Low Intensity on Linac Operations

The linac RF system and the NTF control system required modifications to enable running with these low intensities.

The RF systems of the linac compensate for the beam loading whenever there is a beam pulse. Normally, NTF and HEP beam have the same peak beam current and the pulse lengths are of similar magnitude, so the beam loading is similar. When NTF is running in low intensity mode the beam loading is negligible. Since NTF runs at 15 Hz and HEP runs at .42 Hz, NTF would dominate the beam loading compensation algorithm. This would affect the stability of the energy of the beam delivered to HEP.

As mentioned above, the NTF control system monitors five signals to ensure that beam is being transported properly to the target. When the amount of beam is very low, these signals are indistinguishable from normal electrical noise levels and random fluctuations quickly drive the monitored ratios out of tolerance and inhibit beam.

5.3 NTF Low Intensity Beam Study Module

It was necessary to devise a way to accommodate low intensity running, while maintaining the integrity of patient treatment. A module, called the NTF Low Intensity Beam Study Module, was designed that allowed low intensity as a special mode of operation and defaulted to normal running conditions(figs. 10 & 11). When low intensity running is desired, the module intercepts CTOR1, CTOR2, QP, X1, and X2 and substitutes values equal to normal running conditions. Activating the system requires a configuration control key and two people to press a button in separate locations (fig. 10). Removing the key causes the system to revert to the normal mode. To guard against inadvertently leaving the system in low intensity mode, the portion of the safety system devoted to NTF is monitored. Opening the door to the treatment room interrupts the safety system and causes the low intensity module to revert back to normal running. The door must be closed for beam delivery to be enabled. If the system is somehow left in the low intensity mode, it will revert to normal when the door is opened to prepare for the next session of patient treatment.

Figure 11 shows how the low intensity module interacts with the monitored signals. The relay shown in figure 11 corresponds to the five relays in figure 10. Mechanical relays are used so that the normal mode is the default in the event the module fails.

The module also sends out a signal to the linac control system. This tells the beam loading algorithm to ignore NTF pulses as they do not measurably load the beam when in this mode.

6. Results

Figures 12 - 15 show the results of these procedures. Figure 12 is the normal 57μsec macropulse at full intensity. A fairly short bunch of 160 nsec length is shown in figure 13. Figure 14 shows a bunch that contains just 5 micropulses or RF buckets. The signal due to the beam is the negative going pulses which are followed by positive reflections of equal amplitude. Figure 15 shows the reduction in amplitude due to changing the phase of the buncher. The overall reduction between figures 12 and 15 is approximately 2.5×10^5. More importantly it means the the number of protons delivered on target is approximately 1×10^7 per macropulse. Assuming that the 10^{-6} neutron conversion efficiency and solid angle estimate are correct, this means that the number of neutrons incident on the detector is of order 1.

The neutron flux reduction was verified by measurements made with a carbon proportional chamber. The chamber essentially is a dE/dx detector. The chamber was run for 10 seconds at a time with various pulse lengths. The number of counts in the detector was recorded. A DC gamma background had to be removed from the readings as the measurements were done after patient treatment and the NTF target area was highly activated. (This will require careful attention in future measurements.) Figure 16 shows the results of these measurements. It displays the number of neutron counts in the detector as a function of pulse area. Since at short pulse lengths the amplitude is reduced we used the product of the amplitude and pulse length to characterize the number of protons on target. The first four points in the figure that are below 1 count per pulse are of pulses 40 nsec or less.

7. Conclusion

This paper has described the problems associated with trying to perform microdosimetry in intense beams such as exist at Fermilab's Neutron Therapy Facility. We have devised a method of greatly reducing the beam intensity so that detector rates are of the order of 1 event per pulse. Results have been presented that verify that we have succeeded in doing so.

8. Acknowledgements

The author would like to thank Larry Allen, Arlene Lennox, Chuck Schmidt, and Lester Wahl for their thoughts and assistance.

9. References

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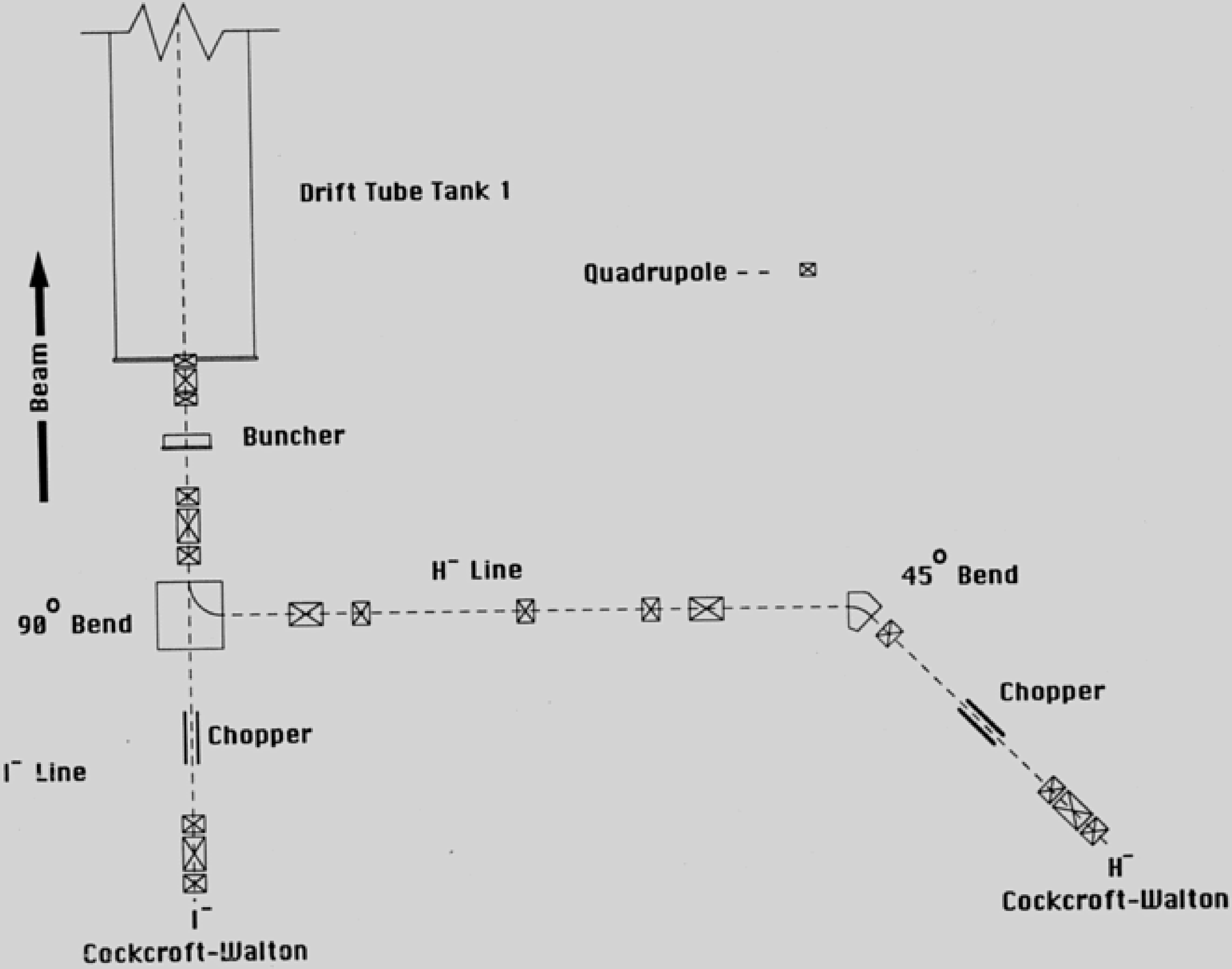

Figure 1. Linac beamline layout.

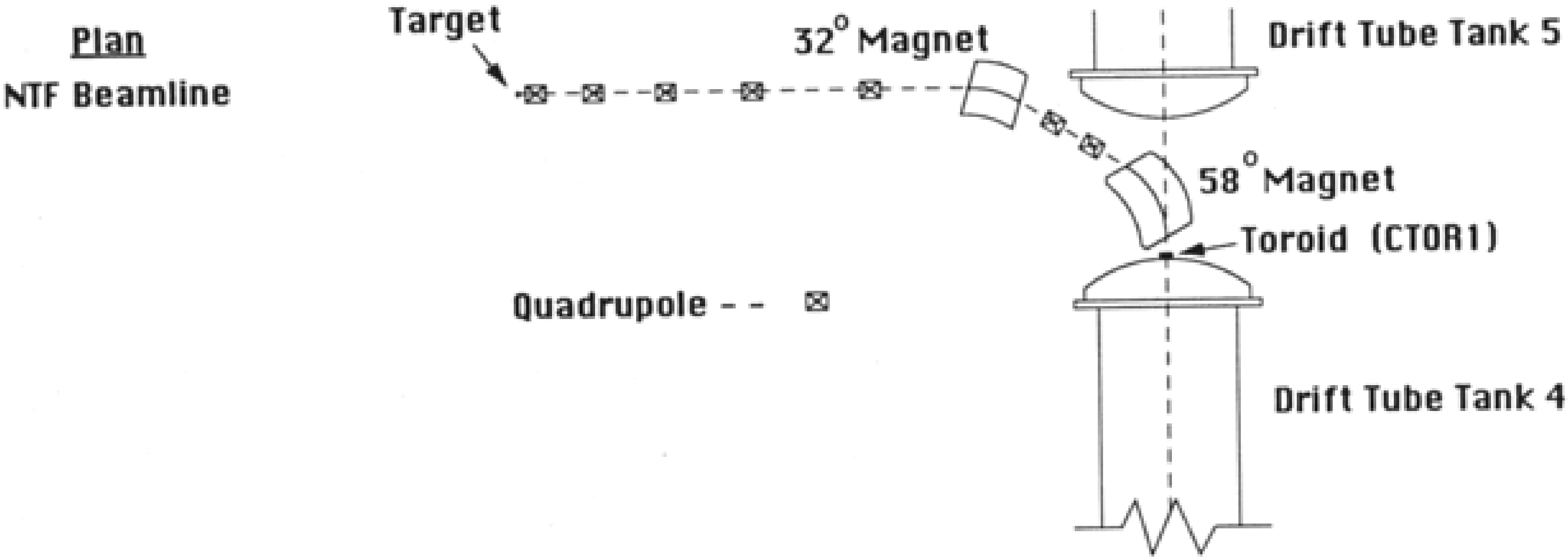

Figure 2. NTF beamline.

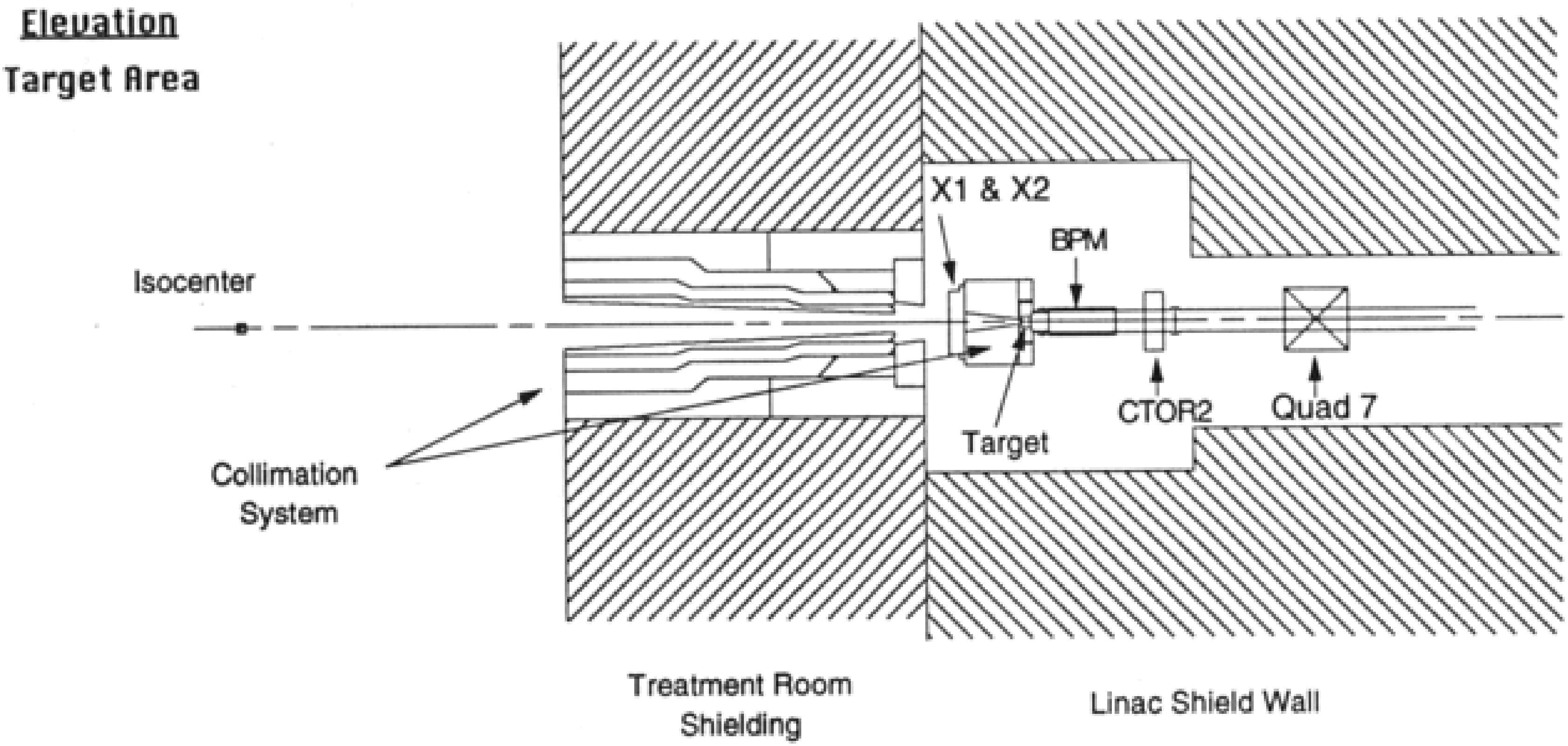

Figure 3. NTF target area. X1 and X2 are planes of a transmission chamber. BPM is a beam position monitor. CTOR2 is a toroid.

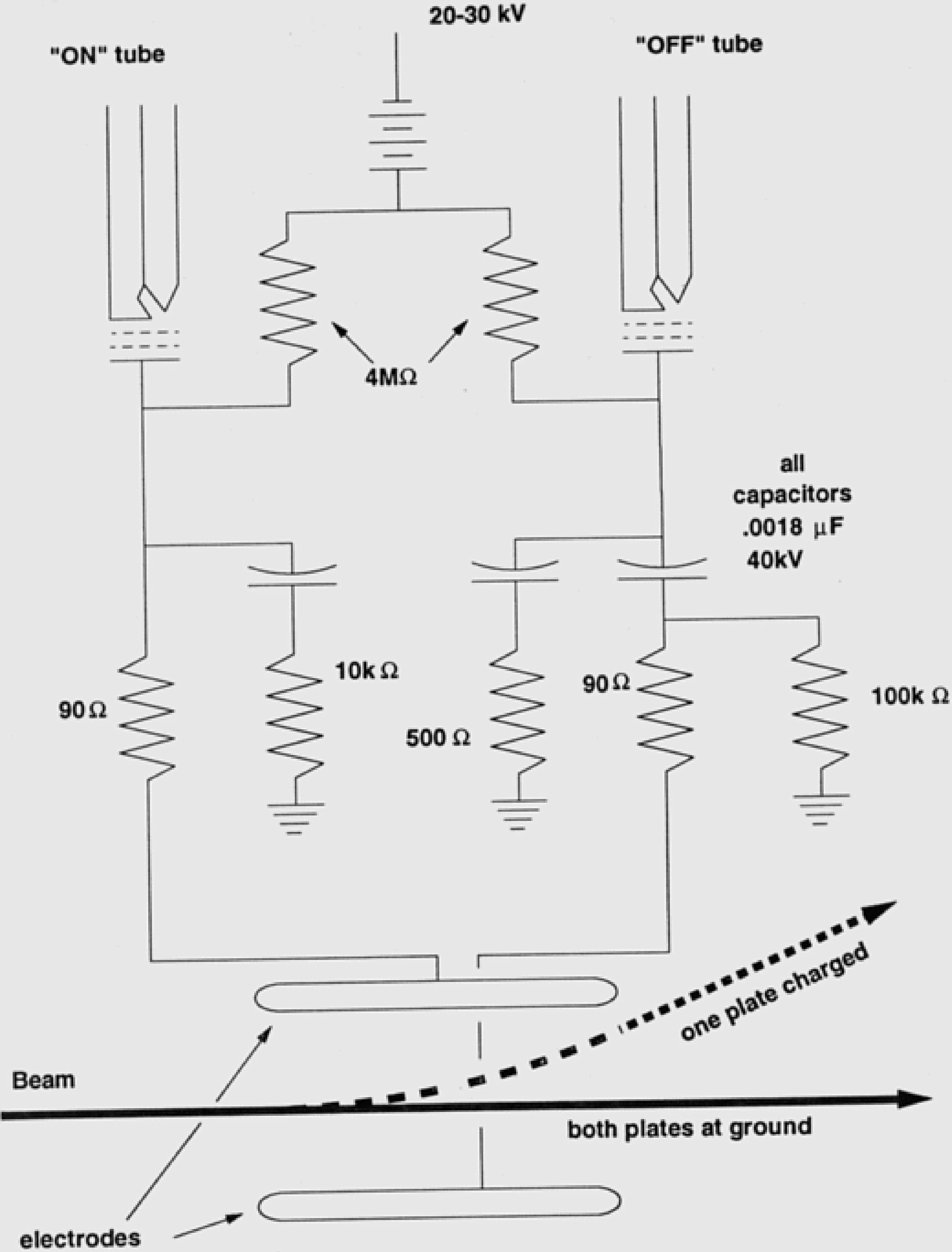

Figure 4. Linac chopper circuitry.

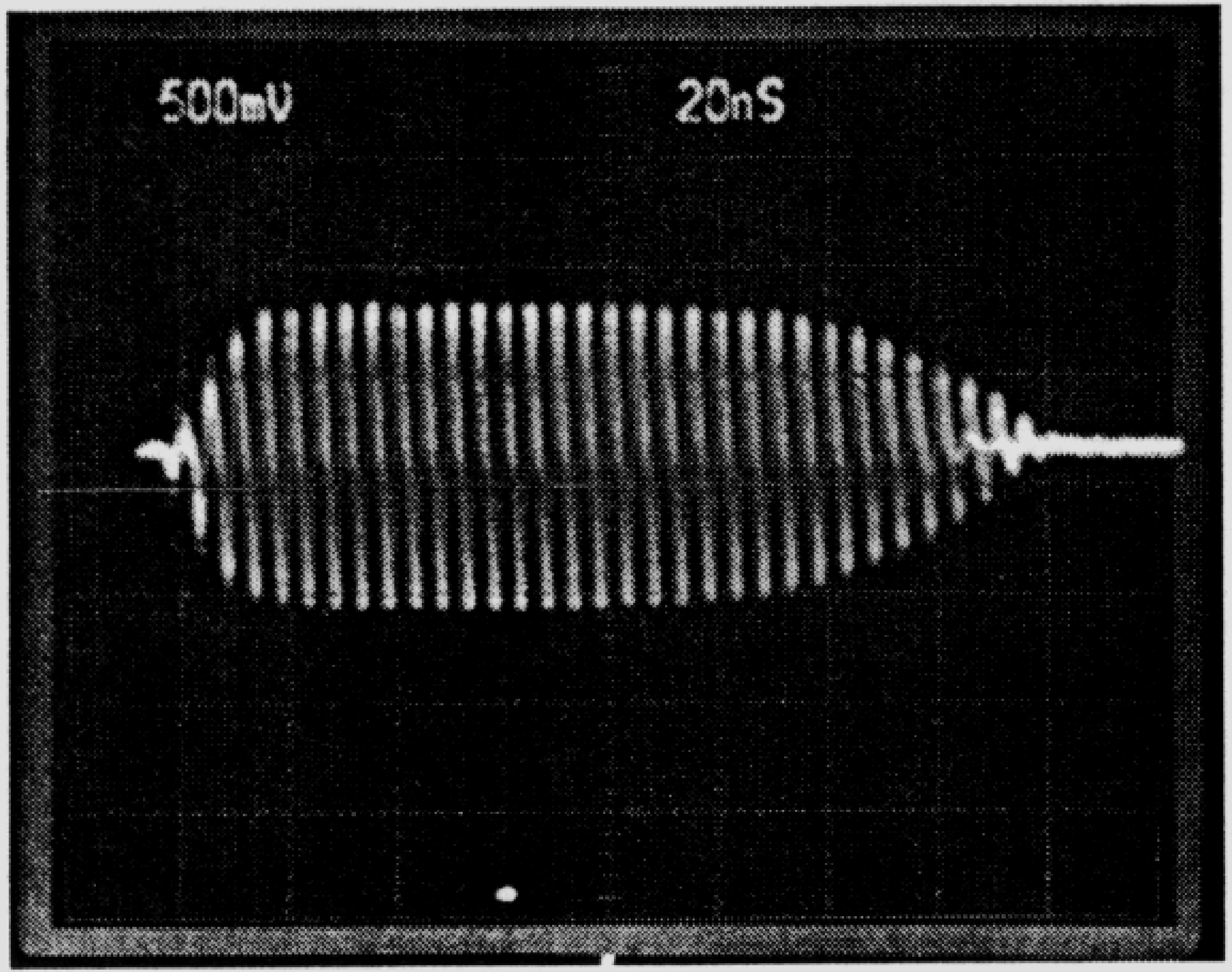

Figure 5.

BPM signal of 160 nsec macropulse. (Beam signal is negative with positive reflection).

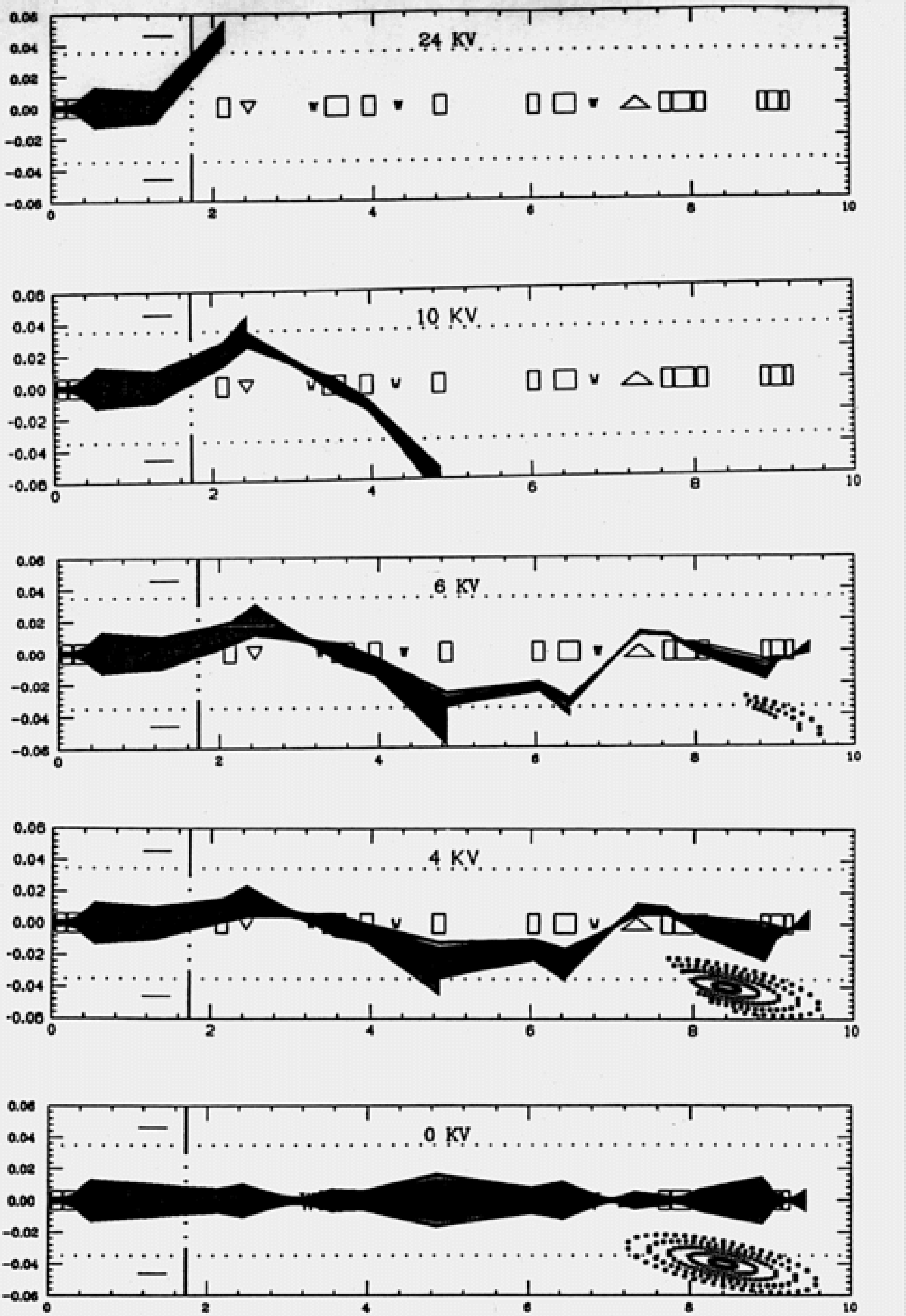

Figure 6. Simulation of transmission trajectories through H^- LEBT as a function of chopper voltage. X-axis is longitudinal dimension of beamline in meters; Y-axis is transverse dimension of beamline in meters.

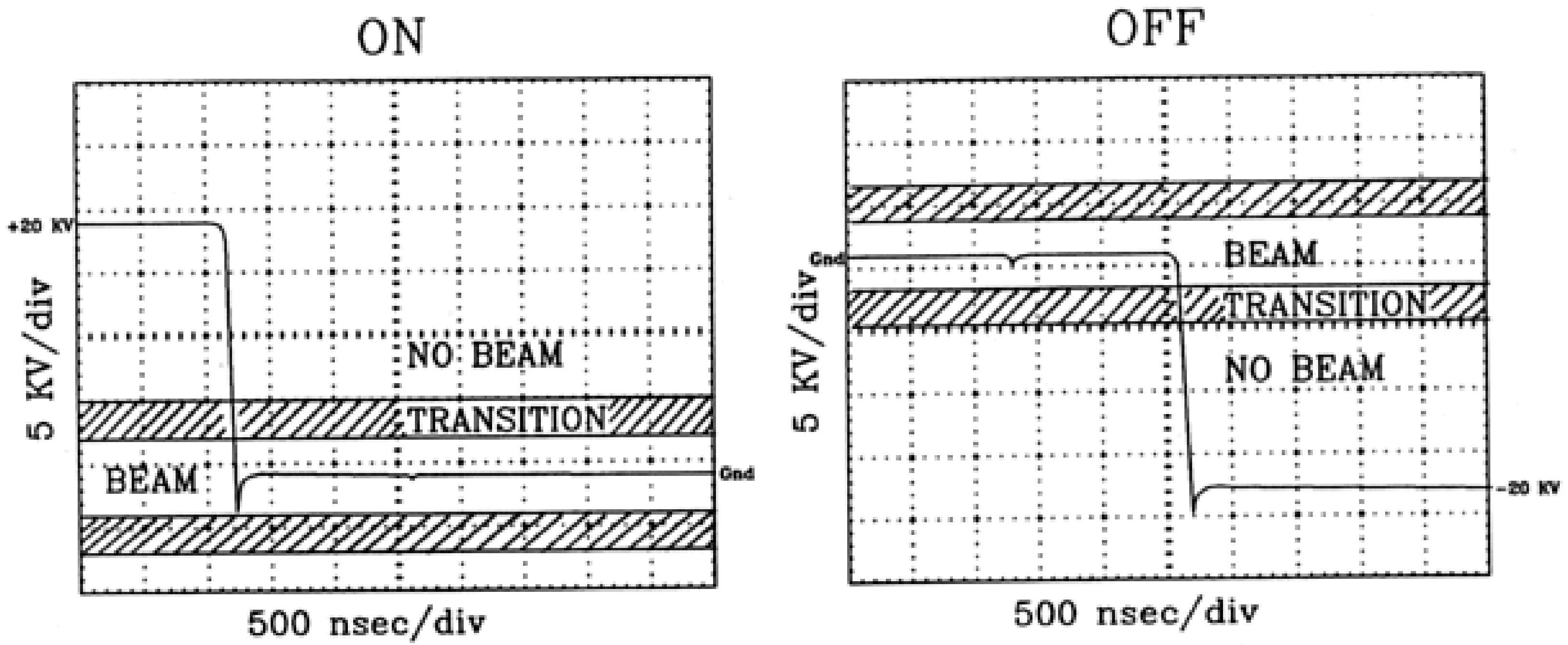

Figure 7. Waveforms of "ON" and "OFF" chopper thyratrons.

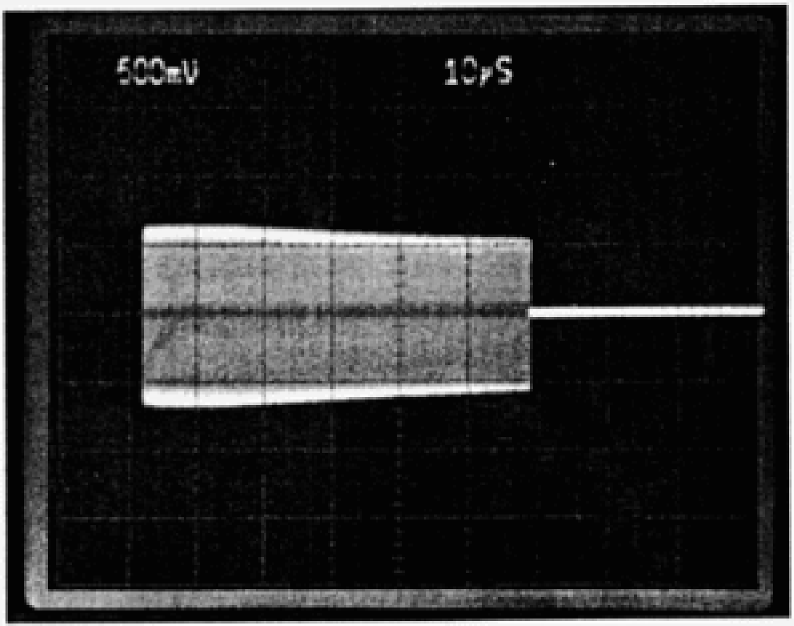

Figure 8.
BPM signal for normal 57μsec macropulse.

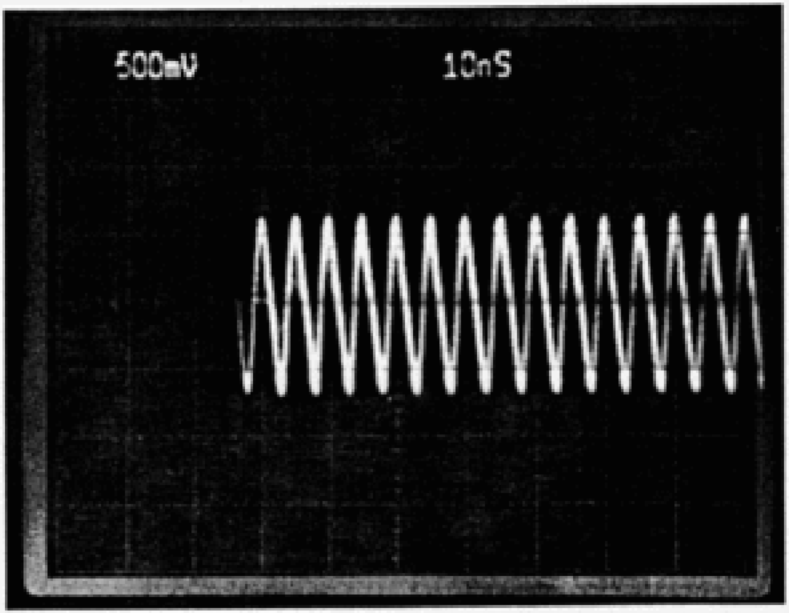

Figure 9.
Normal macropulse with expanded time scale to show 200 MHz structure.

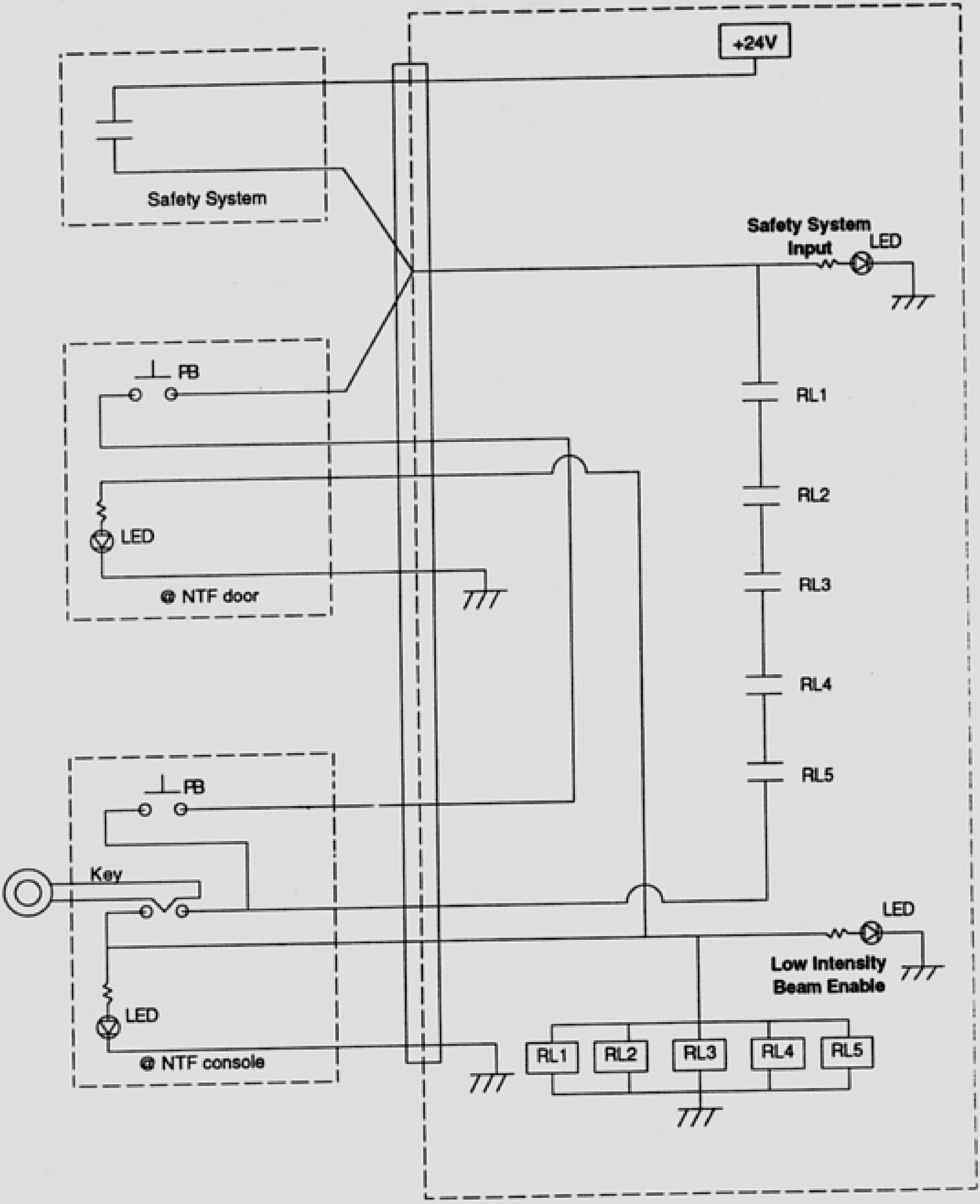

Figure 10. Signal path of the Low Intensity Beam Study Module.

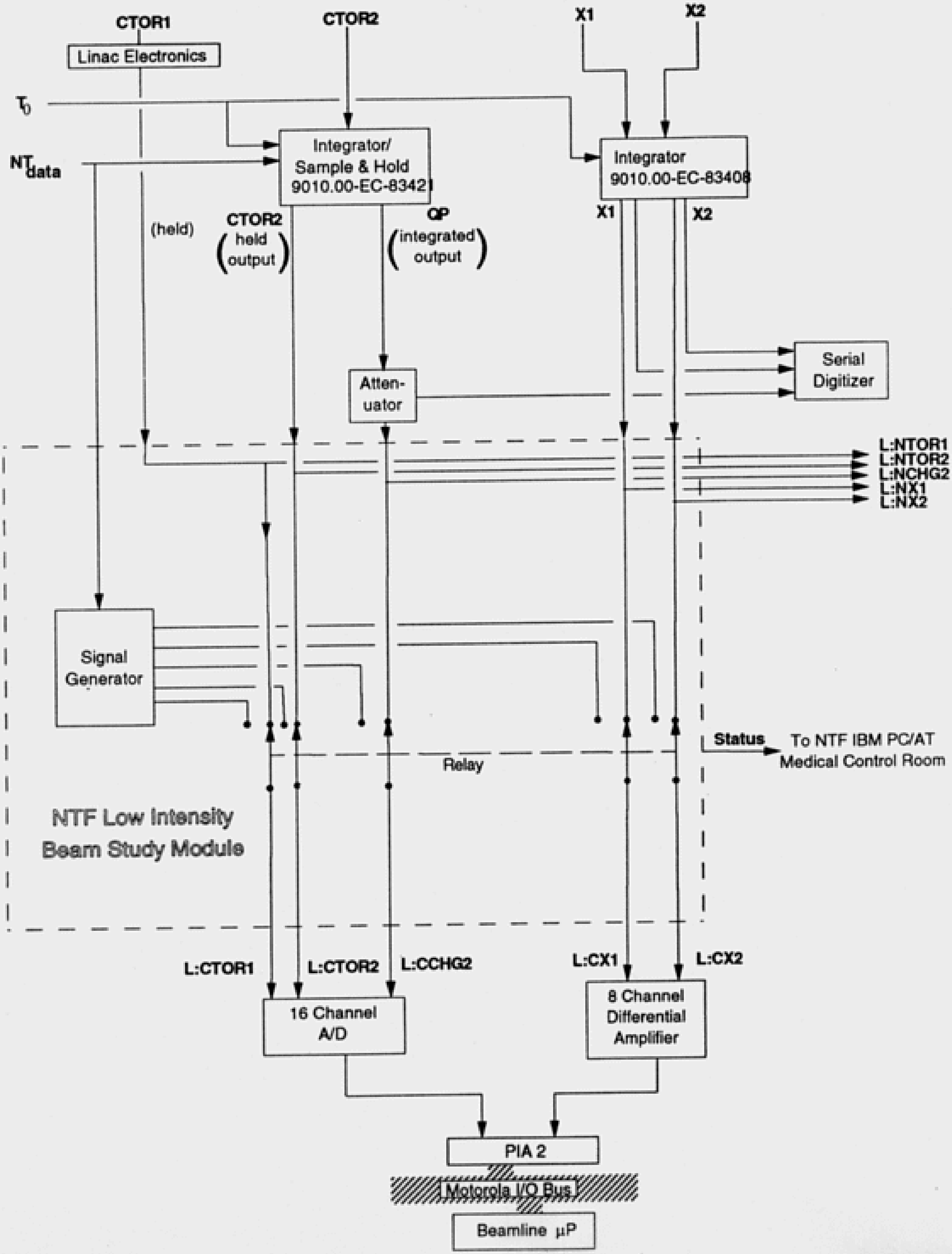

Figure 11. Interlock system of the Low Intensity Beam Study Module.

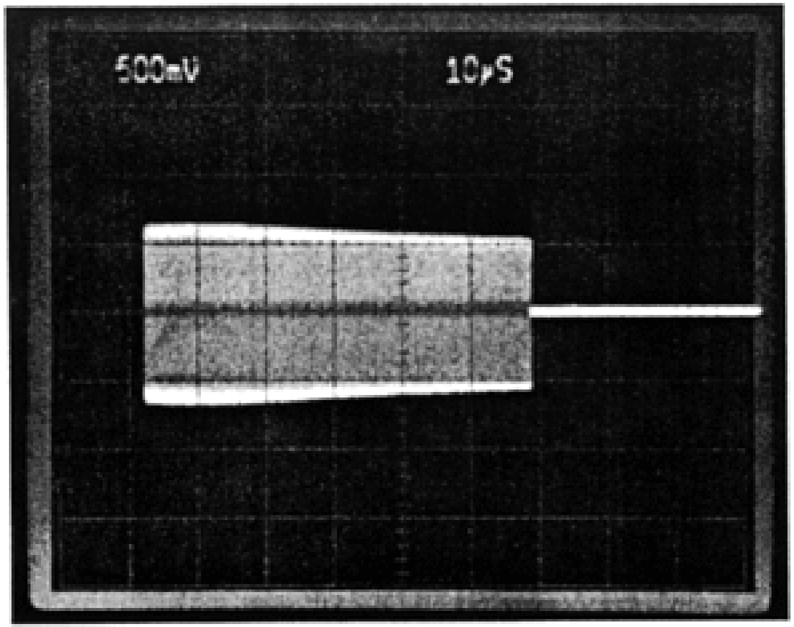

Figure 12. BPM signal for normal 57μsec macropulse (reprint of Fig.8).

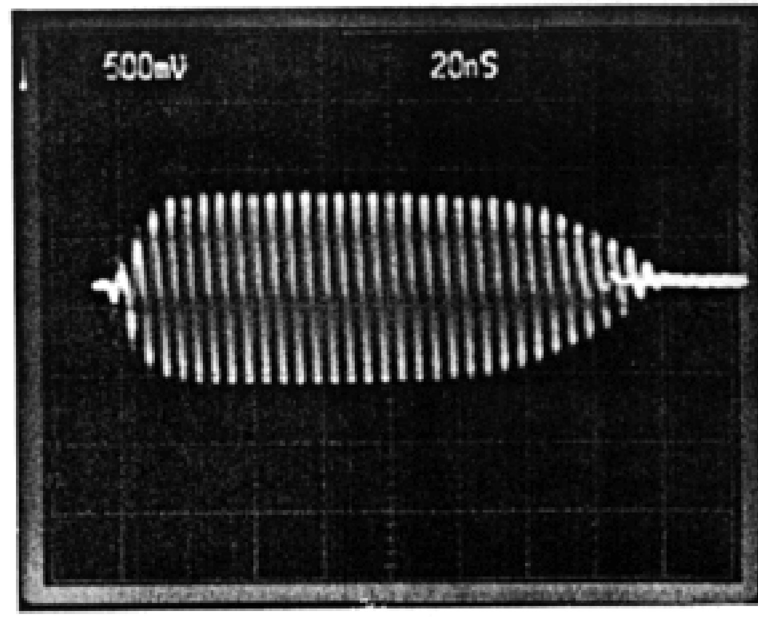

Figure 13. BPM signal of 160 nsec macropulse (reprint of Fig. 5).

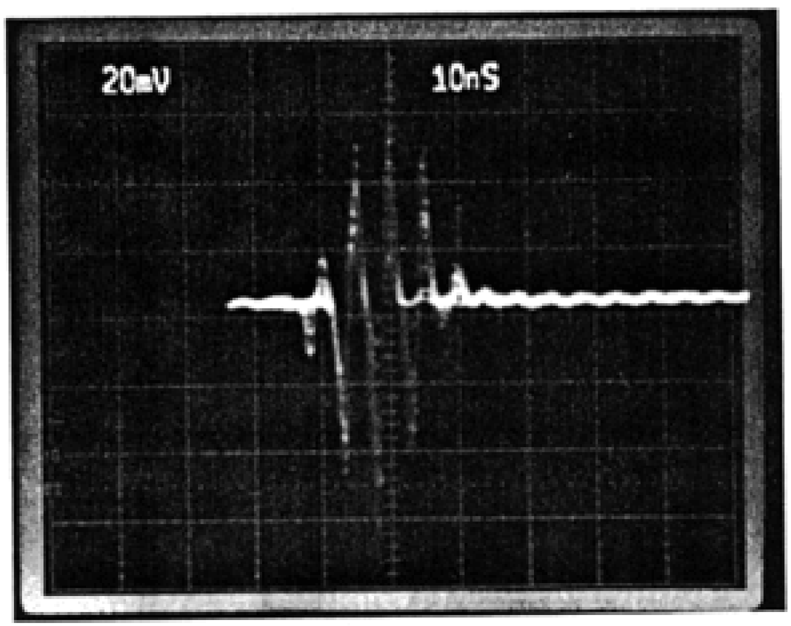

Figure 14. Shortest macropulse, 20 nsec (Beam signal is negative with positive reflection).

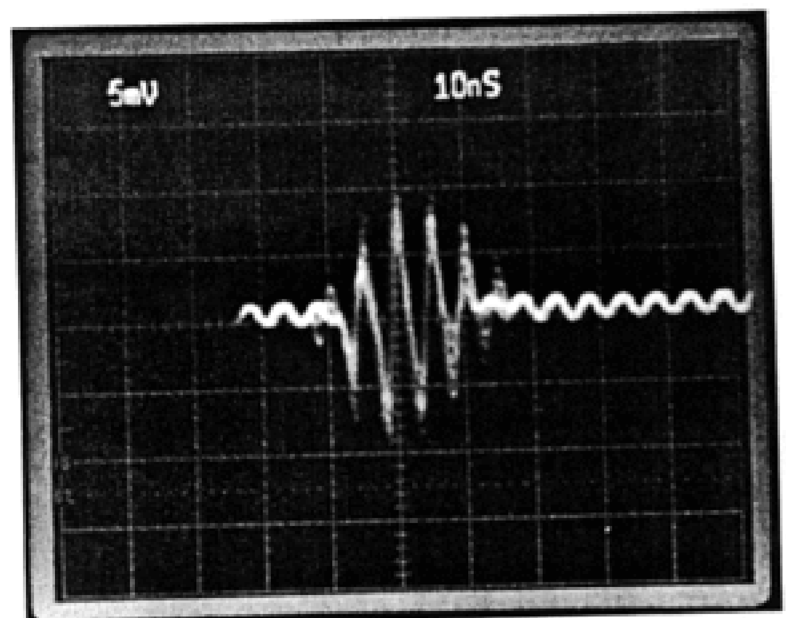

Figure 15. Shortest macropulse with buncher phase set to debunch for reduced amplitude.

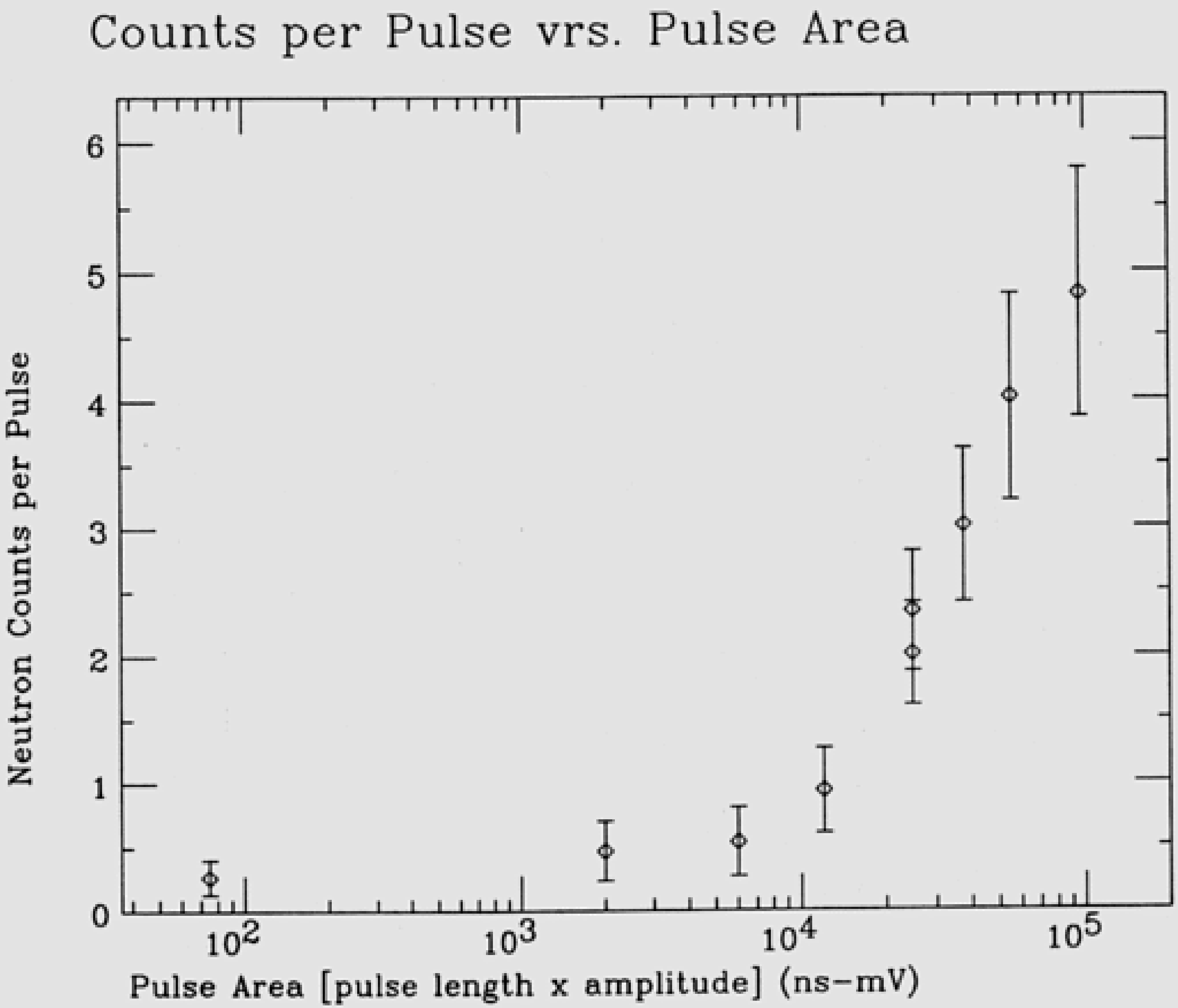

Figure 16. Neutron counts in carbon proportional chamber ($\frac{dE}{dx}$) versus pulse area. Pulse area is defined as pulse length times amplitude with no correction for roll off. No adjustments to buncher phase were made for these measurements. Results show that the goal of one event per pulse has been achieved.