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THE BROOKHAVEN RADIATION EFFECTS FACILITY*

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Abstract

The Neutral Particle Beam (NPB) Radiation Effects Facility (REF), funded by the Strategic Defense Initiative Office (SDIO) through the Defense Nuclear Agency (DNA) and the Air Force Weapons Laboratory (AFWL), has been constructed at Brookhaven National Laboratory (BNL). Operation started in October 1986. The facility is capable of delivering pulsed H^-, H^o, and H^+ beams of 100 to 200 MeV energy up to 30 mA peak current. Pulses can be adjusted from 5 μs to 500 μs length at a repetition rate of 5 pps. The beam spot on target is adjustable from 3 to 100 cm diameter (2σ) resulting in a maximum dose of about 10 MRads (Si) per pulse (small beam spot). Experimental use of the REF is being primarily supported by the SDI lethality (LTH-4) program. The program has addressed ionization effects in electronics, both dose rate and total dose dependence, radiation-sensitive components, and dE/dx effects in energetic materials including propellants and high explosives (HE). This paper describes the facility, its capabilities and potential, and the experiments that have been carried out to date or are being planned.

Background

Brookhaven National Laboratory is operated by Associated Universities, Inc. for the U.S. Department of Energy. Its primary missions are basic research in the hard sciences and the operation of large research facilities (e.g., nuclear reactors, particle accelerators) for scientific users, national and international. For 40 years the Laboratory has been especially prominent in the field of high energy physics because of its pioneering work in particle accelerators.

The 33-GeV Alternating Gradient Synchrotron (AGS) has been the workhorse in this field for the last 30 years. In the late 1960's a major upgrade of the AGS included the develoment of a new H^+, 200-MeV Linear Accelerator (Linac) injector for the AGS. Subsequently, in the mid-1970's, the machine's polarity was changed to accelerate an H^- beam. H^- injection in the AGS improves its performance. Figure 1 shows the Brookhaven National Laboratory with the AGS complex and its Linac injector clearly visible on the left. Figure 2 shows the 200-MeV Linac; it is 150 meters long, contains over 300 rf accelerating gaps and focusing magnets, and is powered by 45 MW peak rf power generated by an energy storage capacity of one Megajoule.

When the need arose for the construction of a dedicated Neutral Particle Beam (NPB) radiation facility in the energy range of 100 to 300 MeV, the choice of the Brookhaven Linac was logical. Although attaching such a facility to an existing accelerator complex constrains its performance parameters and operational scheduling, it was nevertheless the most cost effective and quickest way to get the SDI/NBP lethality program under way.

The REF construction project was funded in December 1984, and the first proton beam was delivered into the new facility in April 1986. As originally conceived and specified, the REF was to primarily address radiation damage to electronics. Thus the design specification called for operating parasitically to the main Linac user (AGS) with a maximum expected beam in the REF of 10^{16} protons/year. As will be seen below, demand has far exceeded expectations. In addition, beam delivery modes and flexibility have been under great pressure to meet the particular needs of a large number of experimental groups.

Facility Description

The high-energy end of the Linac was originally built with a beam switchyard allowing all excess beam pulses to be diverted into a beam dump especially designed to produce medical isotopes. Under normal operation, the AGS utilizes only 10% of the beam. Thus the remaining 90% is potentially available for other parasitic users.

When not required by the AGS, the beam is directed to the isotope production facility by operation of a pulsed dipole magnet. An identical pulsed dipole magnet has been inserted in the beam line to divert beam pulses to the REF on demand. The pulsed electromagnet designed for fast rise time operation for single pulse extraction, gives a 7.5° kick to the 200-MeV beam. Another dipole magnet, dc powered, bends the beam 30° to direct it out of the beam dump tunnel through a sleeve into a 200-foot long tunnel. The length of the transport allows partial longitudinal beam debunching and optimized target area location. The beam is kept focused on its way to the target by 13 quadrupole magnets. The last two quadrupole magnets are tunable over a wide range to change the beam spot size and shape on target as required. Algorithms are being developed for tuning the beam line optics to meet the experimental goals of flexibility and predictability.

The target cave test cell is 20 x 30 feet and 10 feet high, allowing enough space for gamma and neutron spectroscopy. Five 70-foot long Time-of-Flight (TOF) tubes radiating from a single locus in the target cave, exiting at ground level, have been provided for spectroscopy experiments. Radiation shielding of the target area is provided by concrete and sand. Access to the target cave is from the control building basement via a 6-foot wide passage closed by a shielded door. A number of 8-inch sleeves are also provided for cables. A 10 x 10 foot aperture in the roof of the target cave, normally closed by concrete shielding beams, provides area access for larger objects.

A 40 x 50 foot control and service building is located adjacent to the target cave, separated by 13 feet of sand and concrete shielding. The ground floor contains the control room, mechanical services, and a staging area. The basement contains the power distribution system, vacuum and magnet power supplies and instrumentation, a counting room for dosimetry, and space for experimenters. Figures 3 and 4 show a plan view schematic of the facility and of the facility under construction. Figure 5 shows the beam line in the transport tunnel, and Figure 6 shows the target cave.

Facility Operation and Performance

The REF operation is supported by DNA through AFWL at a cost of about $3 million/year. Beam availability, parasitic to the high energy physics program, is about 15 weeks/year. Additional dedicated beam time can be purchased at about $100,000 per week (1988 dollars). During the parasitic mode of operation, the facility performance is very much tied to the available and fixed Linac parameters required for AGS injection. These are: a maximum beam current of about 25 mA, a pulse length of 450 μs, and a 5 pulse-per-second repetition rate. Within these constraints, we have added flexibility provided specifically for the REF on a pulse-to-pulse basis. Thus we can adjust current, rather coarsely, from nanoamps to the maximum available, pulse length from 5 to 450 μsec and pulse rate up to 5 pps. Additionally, beam size delivery on target can be tailored to suit the experimenter from ~3 cm spot to up to one meter. In the normal mode of operation, targets are set in air, thus the H^- REF beam exits the evacuated beam transport pipe through a window. In the process, the two electrons are stripped, and we are left with an H^+ beam. If required, H° and H^- beams can be made available to the experimenter providing the addition of a neutralizer and a vacuum chamber for the target.

When in the dedicated mode, operation of the REF gains in flexibility with continuous control on beam current and availability of energy as low as 93 MeV in steps of about 20 MeV.

Table I lists the REF parameters of interest in tabular form. It must be noted here that high-energy charged-particle beams have a Gaussian intensity profile which often does not satisfy the experimenter. Figure 7 shows the typical three-dimensional Gaussian beam profile delivered on target. This nonuniform distribution can be altered at the cost of flux on target by multiple scatter plates and collimation. This technique has been developed for electronic single-event-upset (SEU) experiments.

Table I
REF Beam Parameters

Particle	H^+, H^-, H°
Energy	200 MeV (93, 116, 140, 160, 180 MeV*)
Current	nanoamps to ~25 mA
Pulse Width	5 μs to 450 μs**
Repetition Rate	5 pulse/sec max
Max Fluence	10^{14} protons/pulse (macropulse)
Chopped beam Repetition Rate	<1 ns (200 MHz Linac micropulse) up to 100 kHz
Spot Size on Target	3 cm (min), 100 cm (max) (Gaussian 2 σ)

*All energies other than 200 MeV require dedicated Linac operation.
**Chopped-beam capability will be on line in FY'89.

Absolute measurement of total dose and dose rates as well as dose distribution are difficult. A major effort has been devoted to develop the dosimetry for the facility. A combination of beam current transformers and beam profile monitors readily give beam information in the beam line upstream from the target. This information is correlated with PIN diode-array and foil dosimetry. Albeit slow and laborious, foil dosimetry still provides for the best measurement of total dose and dose distribution on target. This technique consists of locating a carefully divided thin aluminum foil on the face of the target, then carefully measuring the residual radioactivity of each part of the foil to obtain the dose distribution. The range of 200-MeV protons in aluminum is 12 cm, therefore most targets look very thin compared to this range, so one is not normally concerned with dosimetry of the exit beam from the target.

Operation and Future Upgrade

Original funding for the REF was sufficient for a "bare facility." The intent was to instrument the beam line and experimental area properly as the program developed. This approach was sensible at the time since funds were limited, and it was difficult to instrument the facility for an, as yet, undefined detailed experimental program. However, we have had great difficulty in following through with this much needed investment. Two factors have affected the outcome of this projected plan: (1) funding never seems to be adequate to meet the need, and (2) demand for beam time immediately exceeded what was available, thus experimental pressures have precluded the usual shakedown/commissioning time usually required to bring such facilities to design performance. This breaking-in is taking place during actual operations as experimenters deal with their test specimens, and as instrumentation becomes available.

Still sorely lacking are the algorithms necessary for beam tailoring to provide specific beam conditions an experimenter requires for his particular target. Another area of much needed improvement is the dynamic range of beam line instrumentation; original facility criteria called for 1 mA beam current and up, whereas experimental needs, especially in discrimination-related experiments, demand beam currents as low as 1 nanoamp. This is in the noise level of our present monitoring system. The dynamic range of the dosimetry techniques used are also being stressed by the wide range of flux available at the facility—eight orders of magnitude. These shortcomings have been a handicap during our first year of operation. However, they are being addressed as well as the usual early operational failures of power supplies, vacuum pumps, and other equipment.

In addition to improving operational reliability and dynamic range of the instrumentation, two major improvements are underway which will affect and broaden the REF capability:

1. Under the High Energy Physics program, the BNL 200-MeV Linac is getting a new injection system. The old Cockroft-Walton 750 kV power supply, H^- ion source, and electrostatic and magnetic optics are being replaced. A new, higher performance H^- ion source coupled to a 750-kV radiofrequency quadrupole (RFQ) accelerator will provide the beam into the 200 MeV Linac. This new system, if its performance matches that of the test bed, should increase the maximum current available at the REF by 50% to 35 to 40 mA (averaged over the macropulse).

2. Combined with the above injector improvement, a fast chopper, partially funded by the SDI program, is being integrated in the system. When operational, the chopper will allow the selection and acceleration of a single <1 ns micropulse at a frequency adjustable from 100 kHz to 1 Hz during the 450 μs macropulse. This micropulse is determined by the Linac fundamental frequency of 200 MHz. Instantaneous maximum current during the micropulse is of the order of 10^9 particles per pulse.

This short-pulse capability is being added to carry out Time of Flight (TOF) neutron and gamma spectroscopy for the SDI discrimination and target signature program. This capability also opens up interesting prospects for the study of SEU, transients, and other TREE[1] phenomena in electronics.

Experimental Program

In the design and construction of the REF, there was a great advantage in that many of the potential LTH-4 target concerns were already identified and known. This led, at the beginning of the program, to several workshops on facility design and operation in order to design the facility from the start to fit the program, rather than having to retrofit later, as is sometimes the case. The result has been a facility with emphasis placed on flexibility.

The scenario for the use of a Neutral Particle Beam in space defense is to engage ballistic missile boosters, post-boost vehicles, re-entry vehicles, and decoys, and because of that engagement, interdict the mission of that system. There are therefore several systems, components, and materials that are of obvious interest in the investigation of the vulnerability of ballistic missiles.

(a) High explosives and propellants

The initiation of high explosives (HE) might be an easily identifiable lethal interaction of the NPB with a target. This has been the impetus for several studies of proton interactions with several types of explosives, both primary and secondary. The issues being addressed are strictly thermal, due to the dE/dx of the beam traversing the HE, or whether the ionizing nature of the beam may be playing some role, either by charge deposition, and/or altering the chemistry of the materials. The varied nature of the types of HE with different chemistries makes for a wide diversity of possible results. If the NPB, through thermal or ionization effects, can alter the behavior of vehicle propellants (e.g., by raising the temperature after the burn rate, decompose and thereby render inactive some propellant) mission failure could be brought about. Again several types of propellants in varying mission configurations lead to many questions.

(b) Semiconductor electronics

The failure of many space assets such as satellites due to the interaction of natural space radiation with the electronics packages is well documented. The military has long been concerned with vulnerability of electronics to nuclear-detonation radiation also. Likewise, an NPB would be expected to be capable of creating damage in electronics components in missiles and RV's in a space engagement. From a standpoint of current knowledge, one would expect damage to the components at much lower total doses than those required for thermal effects in HE, for instance. Also, if one is to harden a particular technology, i.e., CMOS or GaAs, the detailed knowledge of the mechanism(s) causing the damage is required. It is for these reasons that an active program in high-energy-proton damage in various electronics components and subsystems has been carried out and is planned for the future. Several different agencies are involved with concerns from the standpoint of lethality, survivability, and vulnerability.

To date, the major concerns at the REF have been (1) correlation of "damage" due to protons with data bases of damage from other sources such as x-ray, γ-ray, electrons, and neutrons; (2) separating out the displacement-damage effects from those due to ionization, (3) single-event upset, and (4) investigating microscopic damage mechanisms, mostly in silicon-based junction devices. Figure 8 shows a typical test setup for in the REF. These tests were performed with beam pulse widths from ~5 μsec to 450 μsec. With the coming on line of the chopper in the BNL Linac, a new category of beam/electronics interaction involving very short pulses are available for investigation.

(c) Beam/target phenomenology

The demonstration of the ability for an NPB to discriminate between a massive RV and a light decoy has been one of the major objectives of the NPB program. This discrimination is based upon the ability to use some emanation from the object struck by the beam or a signature for the mass of the object and/or a verification that the object was indeed struck by the beam. The characterization of the nature of such target emanations becomes fundamental to this demonstration. The capability to characterize secondary neutrons in the REF was identified during the construction of the facility as a requirement. Consequently, five, 12-inch diameter neutron Time-of-Flight tubes were incorporated into the target-cave design at 12.5, 30, 45, 90, and 135°. These tubes have a common focus in the target cave and exit the ground at ~25 m from the focal point outside the target room. Thus TOF can easily be extended to 100 m if neutron energy resolution requires it. These assets, along with the short 1-nsec pulse provided by the new chopper/injector system, yield a capability for doing (p,n) and (p,γ) cross-section determinations to high precision. The ability also to obtain monoenergetic beams at 6 discrete energies between 93 and 200 MeV results in a world-class facility[2] to perform neutron and gamma-ray studies at intermediate energies, with excellent energy resolution. Figure 9 shows the New Time-of-Flight energy resolution as a function of neutron energy and flight path.

Besides discrimination based on neutron spectroscopy, another major issue is the hit-or-miss signature. This response must necessarily arise from a neutral beam interacting with a thin target. Such a return signal might lie in the spectral region from infrared to hard x-rays and will surely be materials dependent. Several different studies are going to address this issue and experiments have been conducted at the REF to detect emanations in this spectral range. Additionally, there are plans to install a foil stripper in the REF beam transport line in order to allow the study of H° surface interactions. Installed in the beam line in the target cave is an instrumented sample chamber. This chamber allows beam-on-target angles to be veered, and both entrance and exit surfaces of the thin targets to be viewed at several angles with detectors in vacuum. An eight-position target wheel operated by remote stepping motors allows sequential target selection without the necessity of breaking vacuum or even entering the target cave. This chamber and target wheel configuration has proven useful for damage studies of prospective neutralizer foils following high-dose/high-dose-rate H^- irradiations. Figure 10 shows the scattering chamber situated in the beam line with a vacuum-ultraviolet spectrometer attached to the left. The vacuum pump system is arrayed below.

(d) Other components

The list of the various components tested and scheduled to be tested is too long to be presented here. There are a few items, however, that will be delineated because of their nature and the unusual demands placed upon facility performance. The response of Inertial Measurement Units (gyros and accelerometers) to NBP engagement is of obvious interest. Tests have been run on these units and more are planned. Large-diameter beams (~15 cm) with maximum beam currents for long irradiation times are required with tests on the items being performed both during and after irradiation. An additional requirement was a "vibration free" environment. A two-foot-thick concrete floor of the target cave and Long Island's base of wet sand helped provide for the latter requirement. Other tests such as on various types of batteries demanded flexible beam shapes and required the highest beam currents that are available.

Summary

Since commencing operations in October 1986, the capabilities of the REF to conduct high-energy proton irradiations have expanded to provide a facility with high flexibility. From doses of ~5 MRad per pulse over a few cm^2 of target area down to a few Rads over an area of 10^4 cm^2 with good dosimetry over the whole dynamic range, the beam flexibility can fit almost any requirement. New capability of producing nanosecond pulse lengths with peak dose rates ~10^{11} Rad (si)/sec offer exciting new possibilities, especially for transient effects in submicrosecond-scale electronics.

References

[*] Work performed under the auspices of the Air Force Weapons Laboratory.

[1] "TREE Testing at the BNL Radiation Effects Facility (REF) Using Pulsed Beam," T. E. Ward and R. F. Lankshear, BNL/NPB-88-58, *Technical Note* #62, June 1988.

[2] "New Neutron Time-of-Flight (NTOF) Facilities at the Brookhaven 200 MeV Linac," T. E. Ward et al., BNL 41048, Pres. Spin Observables of Nuclear Probes Conf., *Telluride*, OH, April 1988.

Figure Captions

1. Brookhaven National Laboratory aerial view showing Linac and REF locations.

2. Brookhaven 200-MeV Linac.

3. REF schematic plan view.

4. REF during construction.

5. REF beam line tunnel.

6. REF irradiation target cell.

7. Typical three-dimensional beam on target.

8. Target chamber and vuv spectrometer positioned in the beam line.

9. Neutron Time-of-Flight energy resolution parameterized for various flight distances.

10. Typical experimental setup for small-components testing showing beam line, collimator, and target setup with camera for viewing fluorescent flag.

Figure 1

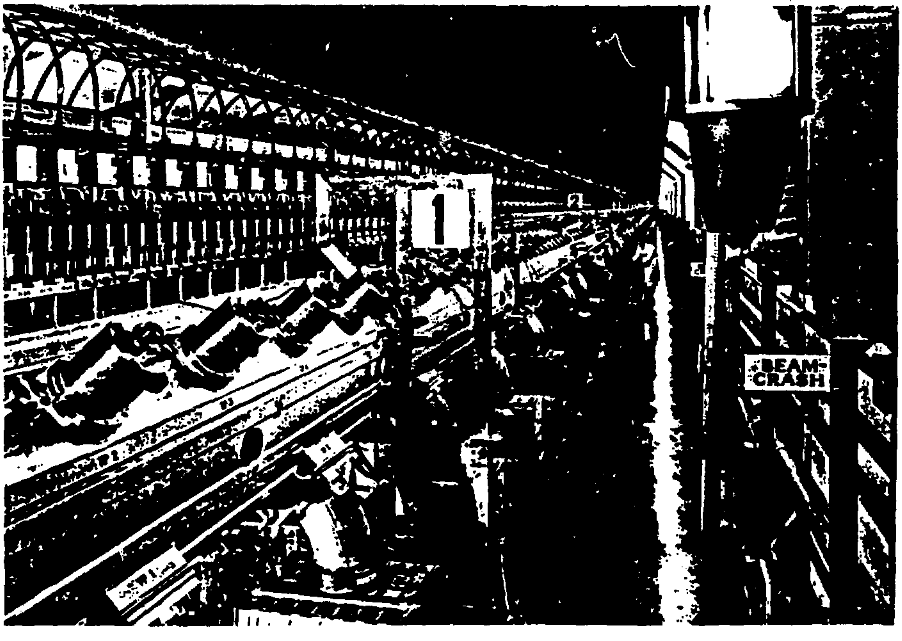


Figure 2

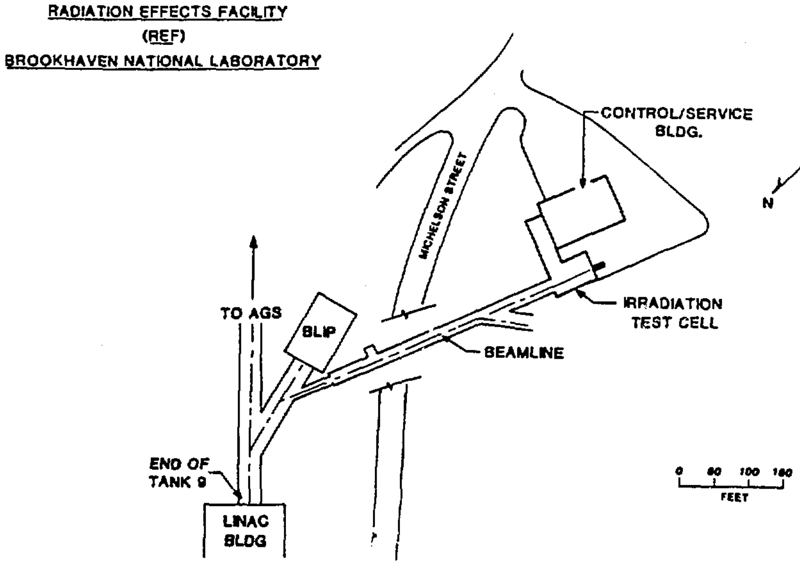
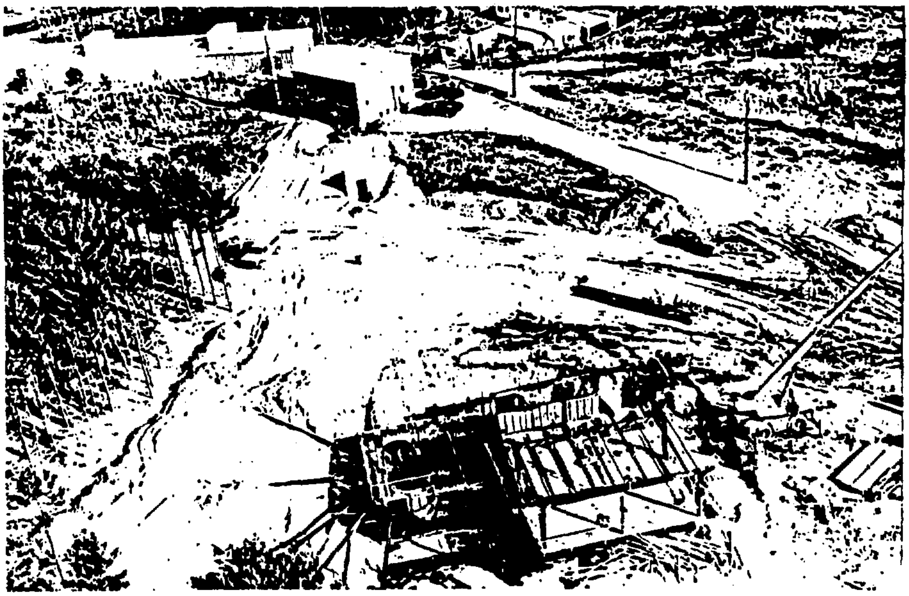


Figure 3



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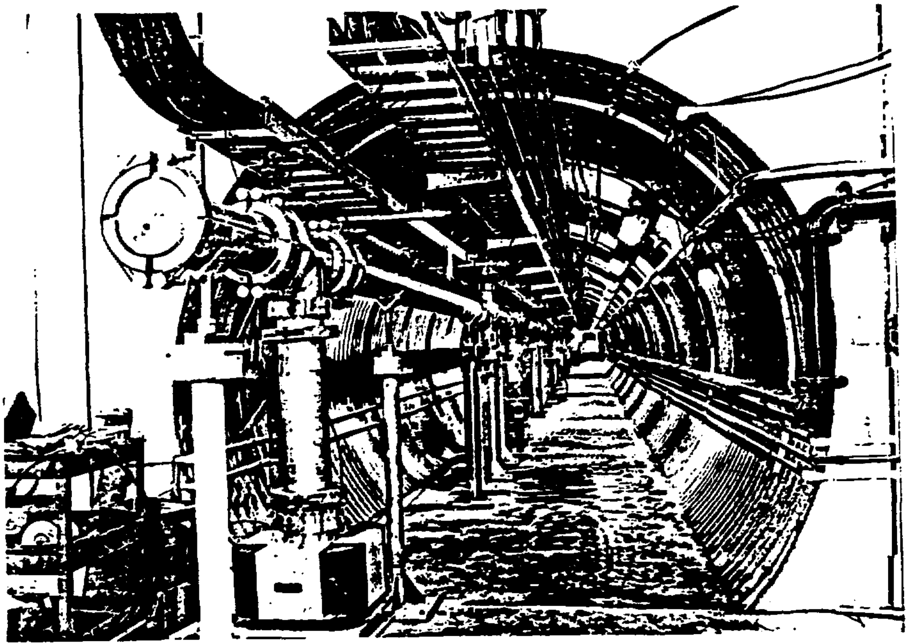

Figure 5

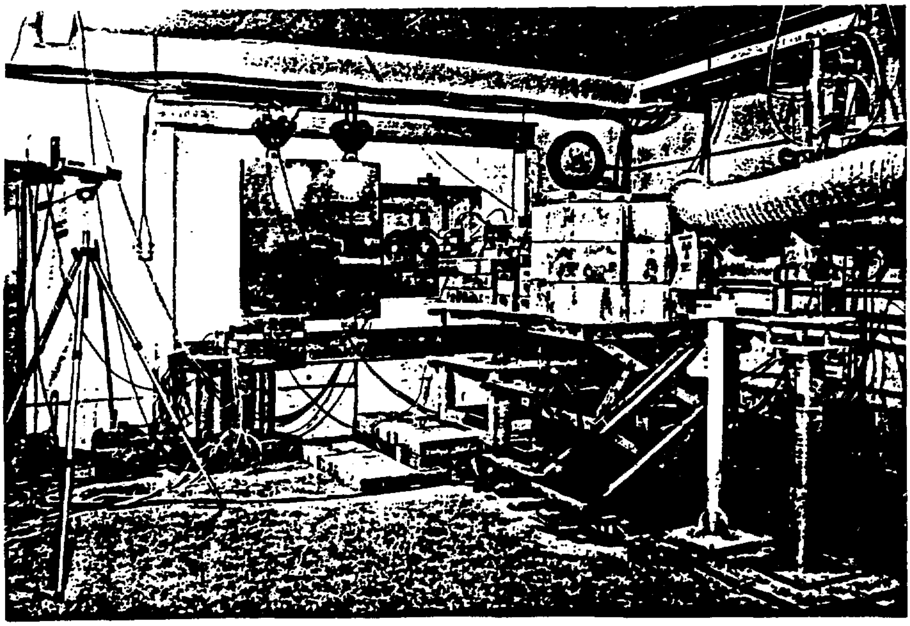

Figure 6

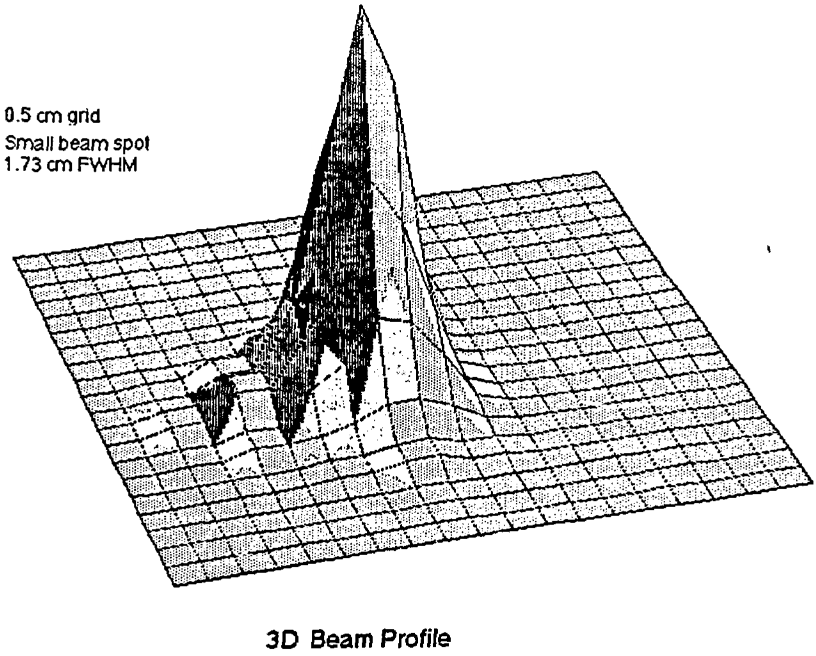

Figure 7

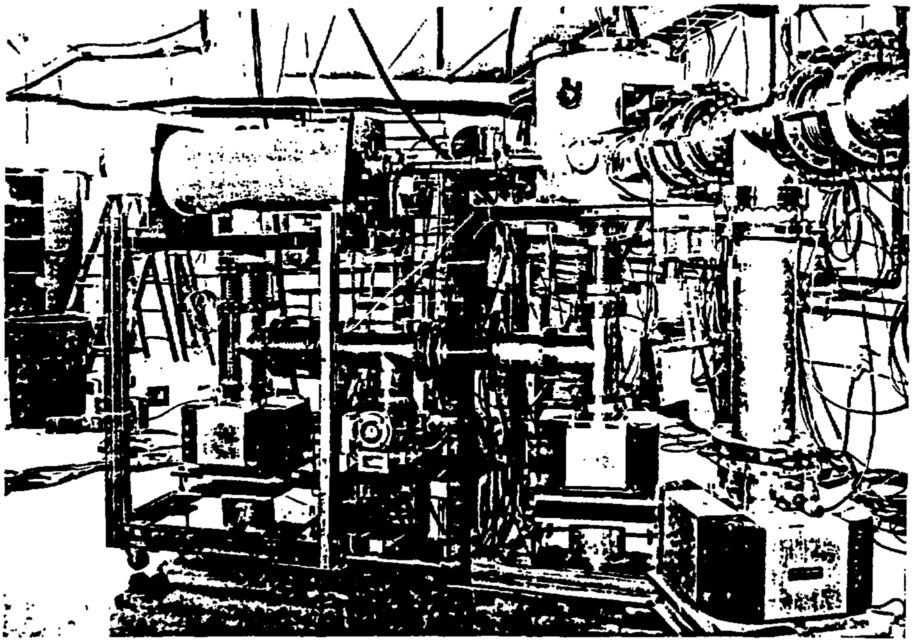

Figure 8

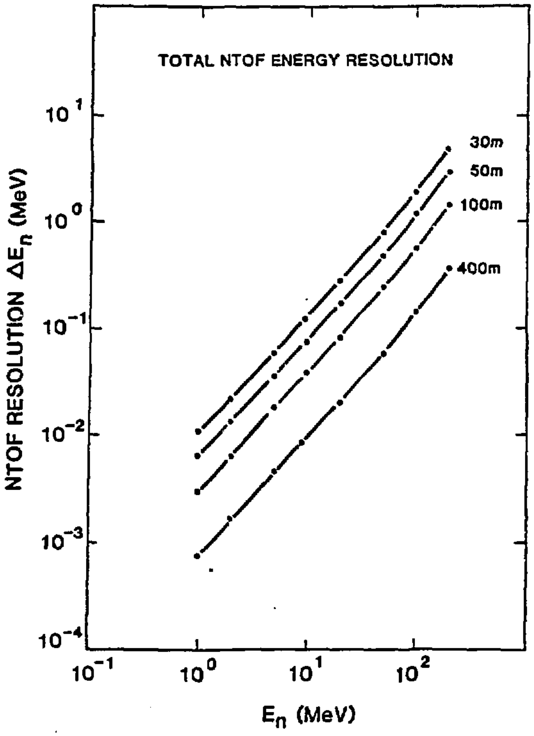

Figure 9

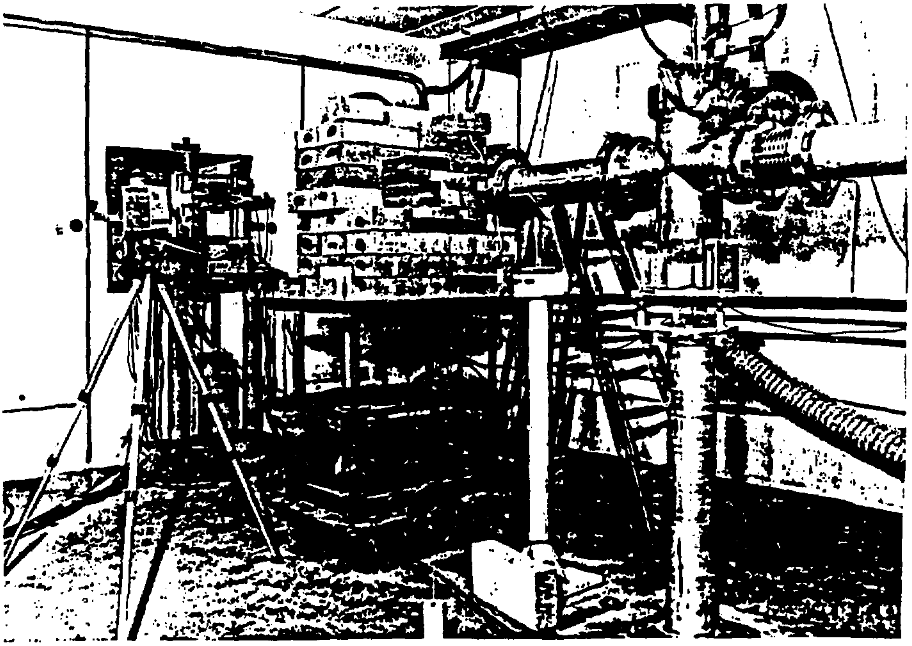

Figure 10

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