THE NBS LINAC

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Introduction

The NBS linear electron accelerator is a facility designed for a varied program in nuclear and radiation physics. Considerable attention has been spent in the design of the facility to the needs of experiments, the ability to rapidly (10-20 minute) switch the electron beam from one experimental area to another, and to providing experiments with high intensity electron beams having good energy resolution and stability.

The Linac

The NBS linac consists of 9 sections of L-band (1300 Mhz constant structure waveguide operating in the $2\pi/3$ mode. Each waveguide section is 2.5 meters long and has an unloaded energy gain of 23 MeV for 10 MW input power. A space equal to one waveguide section is left after the third section to allow addition of a future positron source, quadrupole triplet, and beam deflection magnet.

Forty liter per second ion pumps and ferrite beam magnitude and beam position indicators are located before the first accelerator section, after the last section, and between waveguide sections, to allow detection of loss of electron beam within the accelerator. Signals from the beam magnitude detectors are compared to detect loss of beam current in the accelerator for every beam pulse. If the current loss in any accelerator section is excessive, the section where loss occurred is indicated and the injector is automatically switched to a very low repetition rate (one pulse every 2 seconds) which is maintained until the first pulse where beam loss ceases. The injector then goes back to its normal repetition rate.

Longitudinal magnetic field is provided on all accelerator sections by means of aluminum, aluminum-oxide insulated coils. These are capable of providing up to 1000 gauss of longitudinal magnetic field on any waveguide section. Earth's field cancelling-steering coils are provided on each accelerator section.

Electron injection is provided by a gridded-Pierce type electron gun with oxide cathode operating at potentials of about 150 kilovolts. Focussed electrons are injected into the first $\beta=1$ waveguide section after passing through a low-Q klystron bunching cavity. Microwave power for the bunching cavity is derived from the rf power feed to the first accelerator section. Microwave chopping in the grid-cathode region of the injector is also provided to allow injection of chopped-bunched electron beams. While this chopping feature aids somewhat in obtaining better energy spectra, it adds significantly to the capacity which must be driven in obtaining few nanosecond length beam pulses, and we are now operating without this injector chopping feature.

Microwave power of 10 megawatt peak, 20 kilowatt average is provided for the first three accelerator sections with 5 megawatt peak, 10 kilowatt average for the last six sections. Rf pulse lengths of 7 microseconds maximum are provided, with pulse repetition rates up to a maximum of 720 pulses per second. For the higher repetition rates the rf pulse length must be decreased so as to maintain an rf duty of .002 maximum. Provision is included for a later expansion of the rf power source to 10 megawatt peak, 20 kilowatt average on all nine waveguide sections. Shielding, beam handling, etc. for the entire facility have been made with this later expansion in mind.

Figure 1 shows the designed beam loading curve for the NBS linac in its present configuration. The original unloaded design energy of the accelerator was 153 MeV. Due to lower rf losses than originally anticipated and the use of $2\pi/3$ rather than $\pi/2$ mode of operation, the actual observed unloaded energy is about 170 MeV. The shaded area indicates the region of the beam loading space which was considered acceptable performance in the original design. The actual performance exceeds design values for all energies and currents. The present maximum pulsed beam current for long beam pulses (6 microseconds) is about 350 milliampere (limited by beam blow-up) with 2 amperes peak for 0.1 microsecond or shorter beam pulses. Pulsed currents of about 250 milliampere are readily obtained for all energies from 10 MeV to the maximum allowed by the theoretical beam loading curve.

A view of the accelerator is shown in Figure 2 from a point near the high energy end of the accelerator. The accelerator tunnel is 156 feet long and located about 35 feet below ground. As much as possible of the accelerator instrumentation has been removed from this area for radiation damage and radioactivity reasons.

Directly above the linac tunnel and separated from it by 6 feet of concrete shielding is located a cooling room shown in Figure 3. Rf transmission waveguides pass through this room into the adjacent modulator room through 4 feet of additional concrete shielding. Water cooling systems for the linac are located in the cooling room. During linac operation the cooling room can not be occupied because of neutron flux penetrating the waveguide slots and because of short lived radioactivities generated in the cooling water systems (primarily the $O^{16}(\gamma,n)O^{15}$ reaction).

A separate cooling system is provided for each waveguide section. These systems operate with a completely pneumatic control regulator which uses a gas bulb thermometer built into the center of each waveguide section as its primary temperature sensing element. An outline of this waveguide temperature control system is shown in

Figure 4. With this system waveguide copper temperature stability better than 0.1°F is maintained. This is substantially better than can usually be realized when regulation is based on water temperature control since the water skin-drop is dependent upon the heat load. These waveguide temperature control systems have proved to be quite reliable and troublefree.

A view of the modulator room is shown in Figure 5. This room can be occupied during all linac operations. There are 12 modulators for the entire accelerator (2 each for the first three sections and one each for the last 6 sections). The modulators are of the hard tube variety and are each capable of driving a 5 megawatt peak power, 10 kilawatt average power klystron operating with as low as 33 percent efficiency, and with microperveance as low as 1.65. Figure 6 shows a schematic diagram of one of these modulators. Slow overload protection is provided by means of overload relays on the incoming power lines. Fast protection is provided by means of two spark gaps and a fast vacuum relay. A view of the inside of one of these modulators, lifted out of its oil tank is shown in Figure 7.

The performance of these modulators has been relatively good. It was originally attempted to achieve a modulator pulse flatness during the pulse of about 0.3%. Under best operation we can achieve about 0.5% pulse flatness with a comparable fluctuation from pulse to pulse due to power line ripple. Slow variations in modulator output are effectively removed by a regulator circuit which compares the modulator output pulse with a dc reference signal. A correction signal is applied to the input pulses to the switch tube grid. Only one persistent cause of modulator failure remains to be resolved. This is the failure of windings on the charging reactors caused by saturation of the iron in these reactors during fault discharges. It appears that the addition of a current limiting diode in series with these charging reactors will cure this problem.

An outline of the microwave system for the linac is shown in Figure 8. A CW signal from a 2.5 Mhz oscillator is frequency multiplied to 1300 Mhz in a CW solid state multiplier chain. This signal is further amplified and distributed in a pulsed amplifier chain and applied to the klystron input cavities. The rf drive level to each klystron is independently adjustable from the linac control console by varying the final tetrode screen potential. For each of the first three waveguide sections, the output power from two klystrons is added in a hybrid tee, the unbalanced power being lost in a high power rf load. This has proved quite successful. Approximately 98 percent of the input power to the hybrid tee being sent to the accelerator.

The performance of this rf distribution system has proven suprisingly good. System failures are rare and phase and amplitude stability are excellent. Rf phase measurements indicate a general system phase stability of about 2 degrees over periods of 30 minutes or more. The long term phase stability has not yet been investigated.

No attempt has been made to incorporate an automatic rf phase control system on the NBS linac. Phase adjustment is accomplished manually by use of an rf phase bridge contained in the central control console. The input of one arm of this phase bridge can be an rf signal from any selected waveguide input, while the input to the other arm of the bridge can be an rf signal from any selected waveguide output. By rf phase comparisons with and without accelerated beam, phase adjustment of the accelerator is rapidly achieved, generally taking about 5 minutes to phase adjust the entire accelerator system.

A further and most valuable tool to study accelerator performance is the pulsed analyzing magnet, shown in Figure 9, at the end of the accelerator. Contained in the focal plane of this magnet is an array of 100 pulsed coaxial secondary emission monitors. The injector trigger is gated off during the rise and fall time of the magnetic field in this magnet with one beam pulse allowed in the accelerator during the time that the magnetic field is constant. The secondary emission monitors are pulsed on during the portion of this beam pulse which is under study. The collected charge from the detectors is then scanned by a rotating switch and displayed on a storage oscilloscope. One such display is shown in Figure 10. The spikes on this display correspond to signals from the various focal plane detectors. Successive channels of the display are separated by 0.5% in momentum.

A view of the main operating console of the NBS linac is shown in Figure 11. All linac controls normally used during a run are contained in this central console. Second class controls which must be adjusted during initial set up or for major changes in operating conditions can be seen behind the main console.

Facility Layout and Beam Handling

The layout of the NBS linac facility is shown in Figure 12. The beam from the end of the linac enters the magnet room from which it can be directed into any one of three experimental measurement rooms. With the present configuration, beams are available in two of these measurement rooms (number 1 and 2), with a third "straight ahead" beam available in the magnet room. Future additions to be completed in about one and one-half years will provide several beams in measurement room no. 3 and beams in a ground level area for a more extensive program of neutron time of flight experiments.

In designing the NBS facility it was necessary to make a basic decision as to whether time-sharing of the beam (ie. deflection of different beam pulses into different experimental areas) was to be provided or not. It was felt that for a nuclear and radiation physics laboratory where slow-cycle experimental equipment such as bubble chambers would not have great use, the important feature to provide was not time-sharing in the above sense, but rather a rapid (10-20 minute) switching of the facility from one experimental area to another, combined with the ability for experimenters in one area to work on their experimental equipment while the beam was in use on other experiments. The implications of this rapid change over from one experiment to another have proven to be very complex and involved, especially for a facility with large beam powers which can easily damage unprotected experimental equipment. We have systematically faced these problems and believe that rapid switching between experiments will be successful and valuable.

A block diagram of the beam handling system as it presently exists is shown in Figure 13 with a view of the equipment in Figure 14. In the input section is located a pair of quadrupoles to allow an optimum match of the optics of the beam leaving the linac to that required by the beam handling system. Two collimators are also located in the input section to define the horizontal and vertical dimensions of the beam respectively. These two collimators are imaged throughout the remainder of the system.

Two acromatic deflection systems are provided to allow beam deflection into different experimental measurement rooms. It is expected that beam momentum resolutions between .04 percent and 5 percent will be available in the 90 degree deflection system and between 0.1 percent and 10 percent in the 45° deflection system. The optics of the deflection magnets of the 90° system have been examined in detail using heavy-particle ion beams from a small Van de Graaff accelerator to insure that these resolutions will be obtained.

Provision is also made in the 45 degree system for deflection of the analyzed beam into a small irradiation cell for radioactivity and activation analysis studies and for dumping of the electron beam after a thin bremsstrahlung target.

The major technical difficulties in developing the beam handling equipment arise from the high beam currents for which it is intended. The system is designed to safely handle a one milliampere 100 MeV electron beam in a spot size as small as 5 millimeter diameter. Problems of metal fatigue due to pulsed heating by the beam and of boiling-burnout at water-cooled metal surfaces which the beam strikes are severe. Figure 15 illustrates how these problems have been handled in the region of the input collimator. (The same basic approach is used throughout the system.) The electron beam horizontal size is defined by a pair of rotating wheels of tungsten-tantalum alloy which will operate at a maximum temperature of 2300°C. These wheels are cooled by radiation to their surroundings. A similar arrangement collimates the vertical position. The aperture defined by these wheels is remotely adjustable from the control console. The function of these wheels is not to stop, but rather to heavily scatter the electron beam for subsequent clean up by other collimating elements. Following the rotating collimators are a pair of fixed aperture elements formed by thin walled (.020") copper tubing carrying cooling water at high velocity (45 feet per second). These serve to further scatter the beam. A final clean up of the scattered portion of the beam is made in a water cooled lead shield.

Figure 16 shows a view of the primary control console for the beam handling system. As much as possible this has been made a push-button operation to allow rapid switching of the system from one experimental area to another. The time to switch from one beam to another is about 10 minutes, which is determined by the time necessary for an automatic degaussing cycle of deflection magnets to be completed.

Summary

The NBS linac and beam handling system are now operational. The linac has been in use for an experimental program since March, 1966 with experimental set-ups at the end of the accelerator. While we still have problems typical of a new facility, the general operation has been quite good. Variation of beam energy from below 10 MeV to 150 MeV without loss of beam has proven extremely easy and fast by back-phasing the last sections of the accelerator. The highest beam currents at which we have operated have been 0.6 milliampere average with about 60 kilowatt of beam power.

At present we have operated with electron beam through the beam handling system into two of the experimental areas with beam powers of about 5 kilowatt. The power will gradually be increased as we gain experience and as needed by experiments. With 3 percent momentum slits approximately 90 percent of the beam leaving the accelerator appears in a well focussed spot in the experimental rooms. With slightly more than one percent momentum slits, 50 percent of the beam from the accelerator reaches the experimental area.

Acknowledgements

Any large accelerator is naturally the result of dedicated effort by a large number of people. The NBS linac facility is no exception. The physics design of both the linac and the beam handling system were done by NBS personnel. The linac was constructed by the Applied Radiation Corporation and the beam handling system by High Voltage Engineering Corporation.

DISCUSSION

J. Leiss, NBS

CITRON, Karlsruhe: Would you mind repeating the installed peak and average rf power?

LEISS: We have 12 klystrons, 5 MW peak power, 10 kW average power, so that we have 60 MW peak, 120 kW average. The machine will operate very close to its 0.002 duty-cycle design.

HENDRICKS, Univ. of Minnesota: Do you have any concern about erosion of your copper tubes in your collimators due to the extremely high water velocity; and have you any estimates of their lifetimes?

LEISS: Yes. It wasn't done absolutely blindly. Some tests were made at higher water velocities for around 1000 hours. The samples were examined microscopically and no sign of erosion was seen. We are still concerned about this. We have paid very careful attention to the corrosion problems that go along with such high water velocities, and the pulses fatigue, and heating questions, and things like this. The one place that we could really get into trouble is if the erosion tests were completely wrong.

LOEW, SLAC: I noticed with a certain amount of pleasure that, when you showed your spectrum display, you also have some negative spikes which we all know are not positrons. We have never been able to explain them to our satisfaction.

LEISS: Are you sure? Yes, I can explain them much easier than you can explain yours. There's leakage on some of the detectors. The way these detectors work is that they are coaxial geometry devices and are biased on pulse-wise during a burst and then biased off. The charge is stored on a cable and you always have a little bit of a leakage of this charge out of the cable and a little bit of a leakage of your bias voltage onto the cable. Those that go negative are ones where the balance is unfortunate.

BITTNER, BNL: I thought you mentioned something about ferrite beam position monitors; if so, could you say a word about those, please.

LEISS: I don't think they're anything unique and I'm not sure how well these particular devices are going to work. We don't have good enough circuitry on them at the moment. What they are (I believe it was developed first at Argonne) are four rods of ferrite with coils on them. Now in this arrangement, you have such low inductance that you have to add circuitry on them or else you just get a transient ring. We have added difference amplifier circuitry on them. It looks like they tell position, but we really haven't proved it yet. We're working on a number of other devices that we hope will work better than these, but I wouldn't like to talk about this.

LEBOUTET, CSF: Could you comment more on the last curve? Do you have experimental evidence now of the bigger drop of energy for the first pulses? And I have a second question: Could you comment about the misalignment effect on the beam blowup as SLAC indicates?

LEISS: On the first question: We do not have experimental evidence. If you will look at the operation that you can get for any machine I know of, you really can't tell whether these effects are there. We may be wrong in the quantitative value of what current you can get; however, it remains an inescapable fact of physics that you cannot take all of the energy out of a cavity instantaneously. The type of effect that we are talking about is there. It's only a question of whether some of the parameters are more important than we think they are. The second point about the misalignment: We really don't understand this. I think we have proven it--that the place where beam blowup sets in on our machine depends upon how well the machine is aligned. We believe we at one time aligned the machine to 0.010 in. down its entire length. When we did this, the beam breakup started at 1/4 A in the pulse. Originally we found that the sections were all due to some jigging problem in the couplers, pointing upward 1 mm, systematically. Then the beam blowup was occurring at very close to the 1/2 A level. That was the original situation. We lined it up. and we found blowup occurring at the 1/4 A level. We then misaligned the first three sections and found that the current went up to about 350 mA. We can get it back up to the 1/2 A, I believe, by remisaligning the last 2/3 of the machine. We really can't justify this; there aren't presently experiments that want to use this much current. With the present alignment we can run from 8 or 10 MeV to 150 MeV. We can just switch energy up and down. We don't have to touch focusing or steering and just back phase sections. It's a 3 or 4 minute job to give people any energy they want. When the accelerator is misaligned, it's not so easy, and we can't justify doing it.

HAIMSON, MIT: You mentioned, regarding the waveguide design, uniform gradient. Did you mean uniform impedance, or constant gradient?

LEISS: Uniform impedance, I'm sorry. It's a constant structure guide, $2\pi/3$. I'd like to comment that it's quite interesting that if you take the magic formulas, we still come within a factor of 2 of where people say we should get blowup.

LEBOUTET: What group velocity?

LEISS: I'd have to figure it out for you. It's about 0.048 C. Our sections are 2-1/2 m long; filling time is 1.7 μsec.

SEVERNS, LASL: You mentioned when you talked about the modulators that you had some difficulty with fast feed-back loop, which you apparently abandoned. What was the difficulty?

LEISS: Well, first our maximum pulse lengths are, say, 7 μsec on the modulator. What you get into are time delay problems. The time delay problems come in two forms. One is just the normal time delays around the loop through pulse transformers and so forth. These are anticipated. Another, less apparent, source of time delay, and one that's very difficult to do anything about and often forgotten, is that you have switch tubes and various things that are in a cut-off position. In getting them up to the conducting position, there are substantial time delays in any driving circuitry. These add on into the total loop time delay and make a closed loop control (without bad things at the beginning of the pulse) quite difficult. For longer pulses, if I had 15 μsec or more, it would be quite feasible.

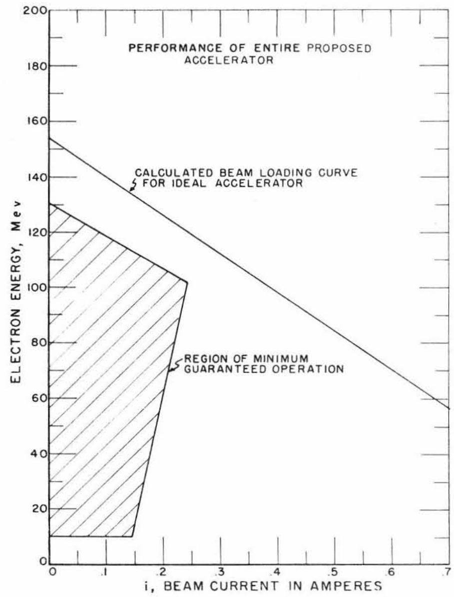

Fig. 1. Beam loading curve for NBS linac as originally proposed. Solid curve calculated from expected waveguide parameters. Dashed area represents region where operation was considered necessary. Actual operation exceeds these predictions both in energy and current.

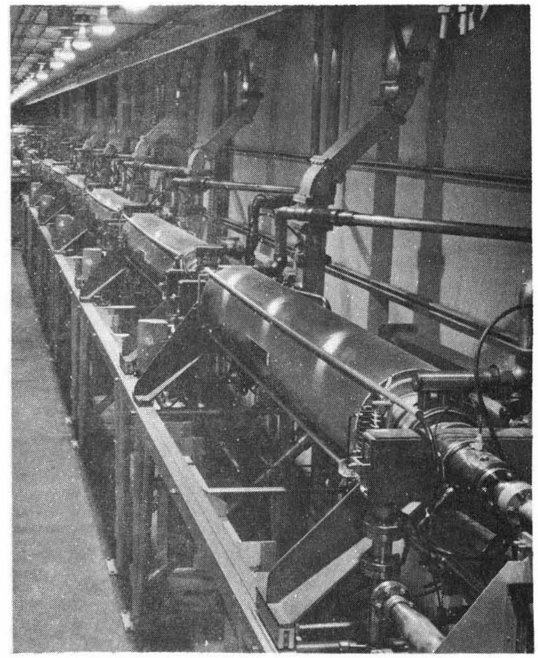

Fig. 2. View of accelerator waveguide from near end of last accelerating section.

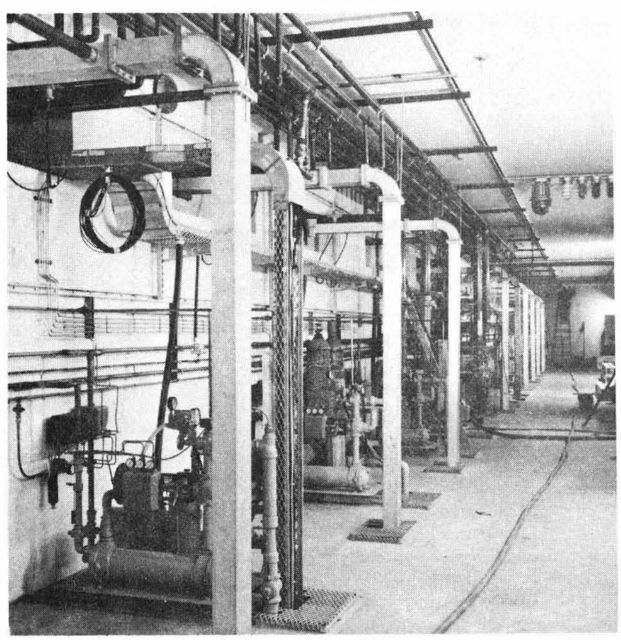

Fig. 3. View of cooling room from near injector end. Room is directly above accelerator and separated from it by 6 ft of concrete. Aluminum rf transmission waveguides pass through this room on way from modulators to accelerator. All accelerator water cooling systems located in this room.

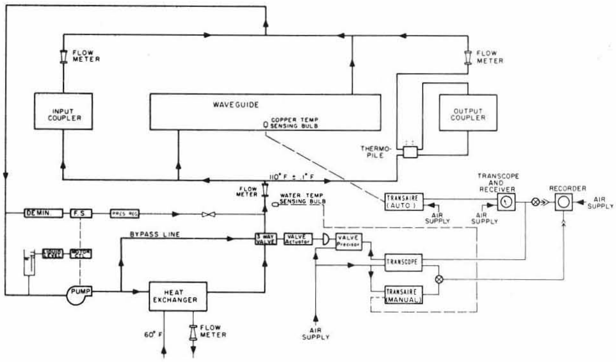

Fig. 4. Accelerator waveguide cooling and temperature control system schematic. Copper waveguide temperature sensed by gas-bulb thermometer in accelerating waveguide. Pneumatic control system maintains temperature at 110°F with temperature stability better than 0.1°F.

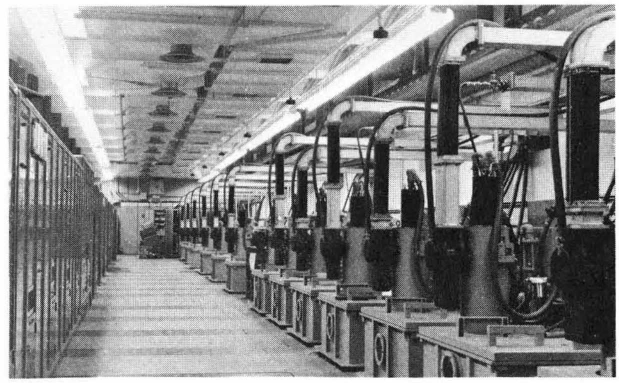

Fig. 5. View of modulator room from near injector end of accelerator. Racks on left contain rf distribution system, power supplies, and pulsing equipment. Twelve modulators on right sit in insulating oil tanks extending 30 in. below floor level. Special lifting rig used for modulator maintenance.

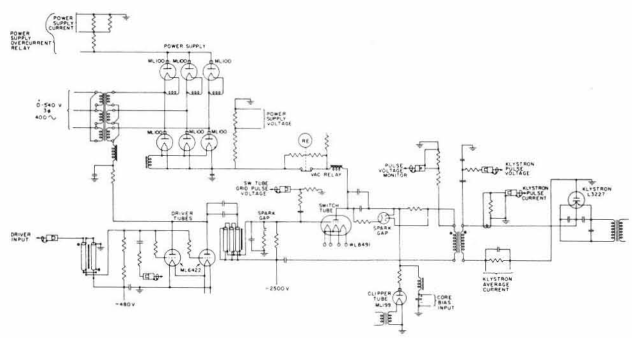

Fig. 6. Schematic of power and hard tube modulator for one klystron. Amplitude and slope of input driver pulse to modulator can be varied from control room to obtain desired modulator performance. Vacuum relay opens whenever power supply voltage is $<\frac{1}{2}$ normal value of 60 kV. This protects power supply from sudden severe overloads during operation and turn-on transients.

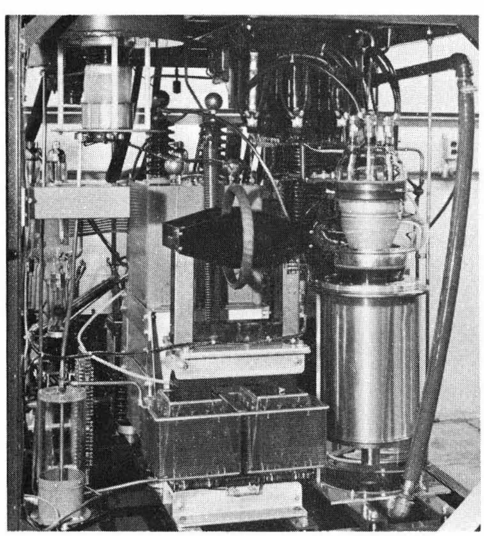

Fig. 7. View of modulator lifted out of oil tank.

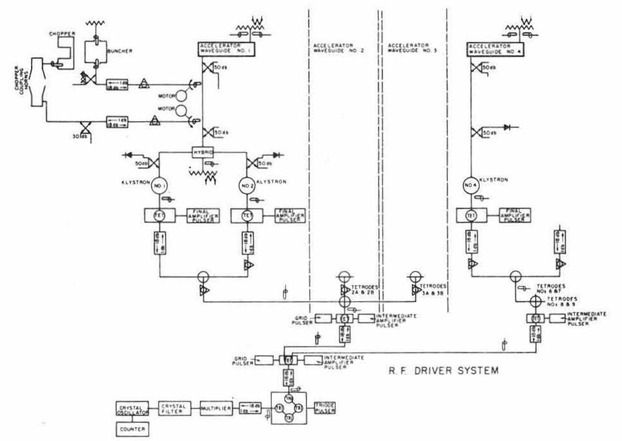

Fig. 8. Schematic of rf system. A stable CW 2.5 MHz crystal oscillator is frequency multiplied to 1300 MHz, further amplified, and distributed in pulsed amplifier chain. On first 3 accelerating sections, output of klystrons is added in a hybrid tee. For each of last 6 accelerator sections, only one klystron drive is used.

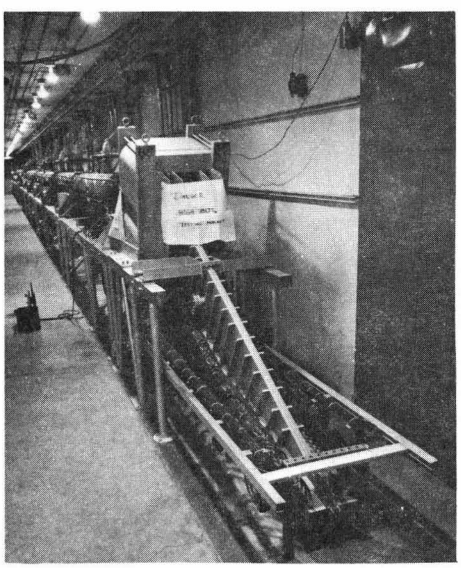

Fig. 9. View of pulsed energy analyzing magnet at end of accelerator before connection of linac and beam handling system. Rise and fall time of magnetic field is 10-15 msec, determined mainly by eddy current losses in vacuum chamber. The 100 secondary emission monitors in focal plane of magnet are of cylindrical geometry. Each detector covers 0.2% momentum bin. Detectors are spaced 0.5% on centers.

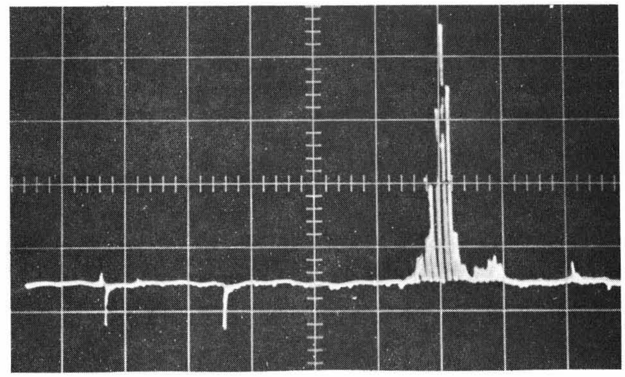

Fig. 10. View of accelerator beam energy spectrum as displayed on storage oscilloscope of energy analyzer magnet system. Example shown is for a 6 μsec, 140 MeV beam pulse with 160 mA in beam.

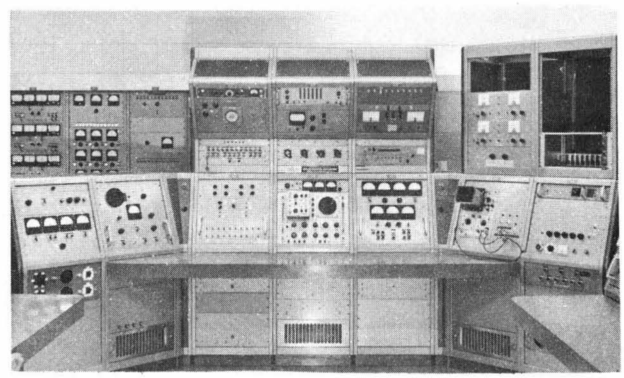

Fig. 11. View of main accelerator control console.

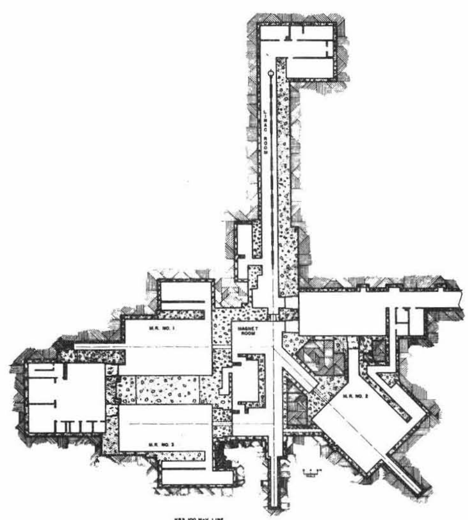

Fig. 12. Layout of NBS linear accelerator facility showing accelerator, magnet room, and three measurement rooms. Shielding is nominally 12 ft of concrete, primarily for high-energy neutrons.

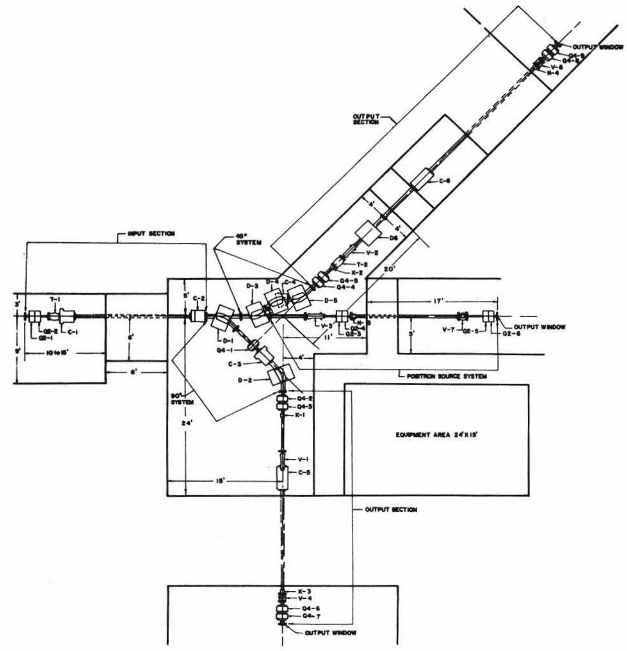

Fig. 13. Schematic of present beam handling equipment for NBS linac. Identification of elements of system: Q-quadrupole magnet, T-target assembly, C-collimator assembly, D-deflecting magnet, V-all-metal vacuum valve, K-steering coil.

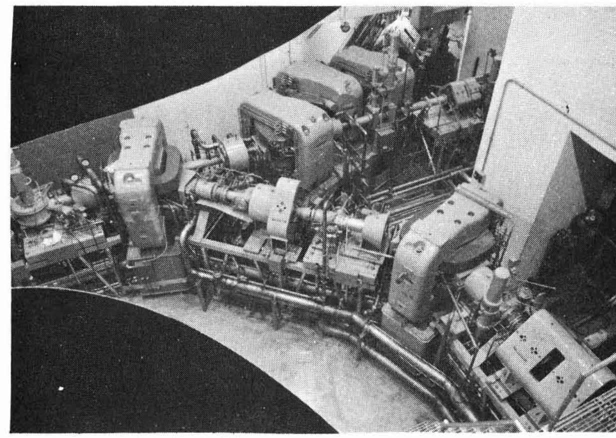

Fig. 14. View of beam handling equipment in the magnet room.

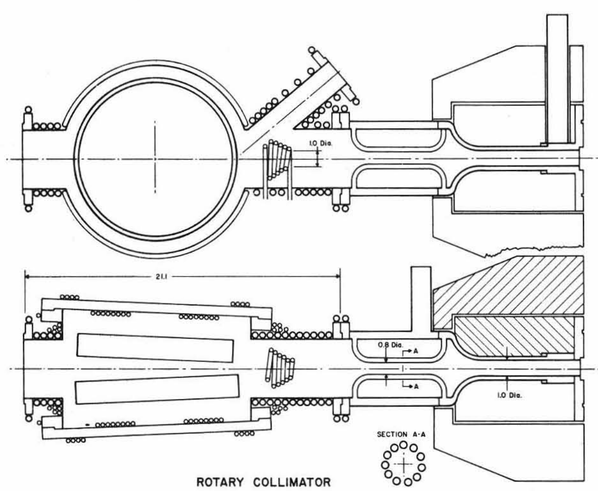

Fig. 15. Schematic of rotating collimator assembly. Rotating collimators are protected by magnetic pickups to insure rotation and by infrared temperature sensors viewing the beam "hot-spot".

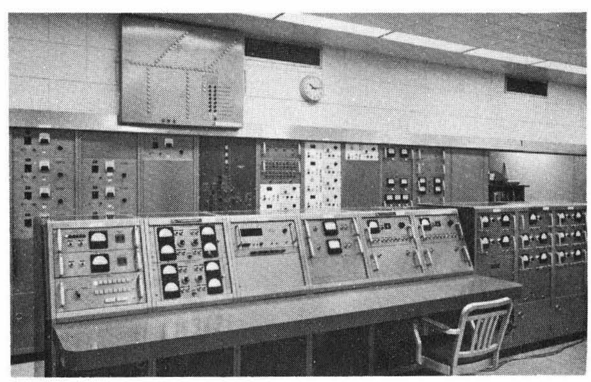

Fig. 16. View of beam handling system control console.