THE PROPOSED BROOKHAVEN ACCELERATOR-BASED NEUTRON GENERATOR*

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INTRODUCTION

The d-Li Neutron Source concept, which includes a high-current deuteron linac, is an outgrowth of attempts made to use the BNL, 200-MeV proton linac BLIP facility to do radiation damage studies. This concept was first proposed by BNL in 1973.[1,2] It included a 100 mA, 30-MeV deuteron linear accelerator and a fast-flowing liquid lithium jet, as the target. The latest design is not very different except that the current is now 200 mA and the linac energy has been raised to 35-MeV. Both parameters, were changed to optimize the effectiveness of the facility with respect to flux, experimental volume and match to 14-MeV neutron-radiation-damage effects.

It is not the intent here to delve into the utilization of this facility. For background information on the subject one can refer to a number of published papers.[3-6]

This paper describes the proposed Brookhaven Accelerator-based Neutron Generator,[7,8] with particular emphasis on the linear accelerator.

DESIGN CHOICES

The fundamental choice of the combination of the 35-MeV deuteron linear accelerator and its associated liquid-lithium target to produce an intense neutron source was motivated by the desire to find the best compromise between many factors: such as, cost, technical feasibility, operational reliability, flexibility, and not least, the desire to give the user a viable, large volume experimental facility. As it turns out, the drift tube linac is the only type of accelerator that can produce cw currents of the magnitude contemplated here (~200 mA).

The proposed design whose main characteristics are shown in Table I has not yet been optimized. It constitutes however, a conservative approach to a working design based on experience and scaling of existing operating facilities. In addition, the proposed accelerator-target system will provide some unique characteristics:

a) The deuteron beam delivery on the target will be flexible to allow the tailoring of the neutron flux and equiflux contours to meet the requirements of a given experiment.

b) Although the accelerator will operate cw, (dc beam on target), it will also be capable to operate in a pulsed mode to simulate pulsed fusion reactors (e.g. Theta-pinch type reactors).

c) The deuteron energy on the target will be available in discrete steps of ~5 MeV between 20 and 35 MeV to provide the user with a desired range of neutron energies. This will be done by deenergizing linac cavities at the high energy end of the machine.

Also, because the facility will be required to operate reliably at high current and for long periods, the choice of design parameters will be extremely conservative. All components will be overdesigned to guarantee long life, high plant-factor and minimize radiation losses around the accelerator.

Linac Design Parameters and Beam Characteristics

So far, short of detailed quantitative calculations, we have relied on experience with proton linacs to arrive at the preliminary design parameters for this machine. It is however clear that the acceleration of a high current, cw, deuteron beam presents some particular problems, especially at injection. These problems are related to the low β, cw aspect of the beam and are complicated by the potential production of 3.5-MeV neutrons by D-D reaction. Thus, the injection scheme is far from being optimized.

The injection system will consist of two 500 to 700 kV, 0.5-A, direct current generators. The second injector will be a stand by to provide the overall reliability required of such a facility. The ion source will be of the duoplasmatron type presently used as a proton source in the Brookhaven 200-MeV linear accelerator injector for the AGS. This source has operated at currents up to 0.5A in a pulsed mode.

The BANG proposal utilizing 500 kV injection energy is now being reviewed. It is clear that for injecting a 200 mA beam in the linac, a higher injection energy is desirable.[9] It is therefore likely that the final injection energy will be >500 kV. This requirement will necessitate a multielectrode accelerating column, something we were trying to avoid, based on the difficulties that the Chalk River people have had so far.

Figure 1 shows one version of an injection system. Each accelerating column will have a reentrant section housing a quadrupole triplet followed by beam diagnostic equipment to measure the beam quantity and quality. Also at this location, a dc chopper will deflect the beam away from the accelerator in the event of a malfunction and will divert the beam during the switching time of a high-energy chopper used for pulsed-beam operation. This will be followed by a second quadrupole triplet to focus the beam at the entrance to the electromagnetic buncher.[10] This device consists of two fundamental frequency bunchers separated by an analyzing magnet. Slits placed at the maximum dispersion point within the magnet will intercept those particles which are outside the linac energy-acceptance region and would not be accelerated to the final energy. If not intercepted in this low energy area, these particles would gain some energy in a nonsynchronous manner and eventually strike the walls of the drift-tubes giving

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*Work performed under the auspices of the U.S. Energy Research and Development Administration.

rise to unwanted gamma and neutron radiation.

This bunching scheme has the additional advantage of localizing the dumping of the unwanted low energy beam on the slits which makes localized shielding at that point possible. Shielding will be necessary to protect against the 3.5-MeV neutron produced by the D-D reaction. This bunching scheme allows a very tight phase acceptance at the expense of efficiency. Although it is desirable to limit losses in the linac, it may be too wasteful in terms of ion source current. Other bunchers will therefore be examined.

For the linac itself, the design considerations for acceleration of a 200-mA deuteron beam in a cw configuration require a conservative choice of parameters, since the beam will be largely space-charge limited. Any significant beam loss along the accelerator will cause difficult activation problems. Specifically, this means strong transverse focusing (high quadrupole strength in a + - + - configuration), strong longitudinal focusing (high accelerating gradient), and a conservatively large drift-tube aperture. In turn, the choice of large aperture determines the transit time factor for a given frequency, hence the acceleration efficiency of the linac. For a large drift-tube aperture, it is therefore desirable to operate at low frequencies. At the same time, considerations of available rf power-amplifier systems for the large amount of power required, limits our choice of frequencies to the VHF region. With these considerations in mind, we have chosen a linac operating frequency of 50 MHz resulting in ~3.8 m diameter linac cavity. Table II lists the major cavity parameters as calculated at LASL with the Parmilla program. These parameters are far from being optimized, they will serve however to establish a design basis for the machine.

BEAM DYNAMICS

The major design parameters affecting the beam dynamics are as follows:

Injection energy	0.5 MeV-0.7 MeV
Injection $\beta=v/c$	0.023-0.027
Accelerated current (I)	0.2 A
Injected transverse emittance (ε)	$6\pi\times10^{-4}$mrad @ 0.7 MeV
Radio frequency (f)	50MHz ($\lambda=\frac{c}{f}$=6m)
Acceleration rate	1.0 MeV/m
Synchronous phase (ϕ_s) (Tank 1, -35°)	-30°
Initial drift tube bore diameter	4.8 cm @ 0.7 MeV

Transverse Focusing

A + - + - quadrupole configuration with a phase advance per magnet period, μ_{SF}, $5\pi/8$ is chosen in order to operate near the center of the widest possible stability diagram when space charge is included. If the quadrupole magnets in the beginning of tank 1 occupy about 1/2 of the cell length one finds that magnetic gradients must be approximately 3.0 kG/cm. It can easily be shown that under these conditions, taking into account the rf transverse defocusing and the longitudinal phase excursions, the operating region stays well within the transverse stability limits given by cos $\mu_{SF}=\pm1$.

For a constant phase advance per magnet period, the quadrupole gradient will vary as β^{-1} down the machine assuming a fixed ratio of magnet to cell length.

Matched Beam Sizes and Space-Charge Parameters

It is important to match the beam transversely as well as longitudinally to ensure minimum beam loss and transverse emittance growth.[11,12] In a high current linac, repulsive space-charge forces become comparable to transverse quadrupole focusing forces, and longitudinal rf focusing forces and space-charge effects have to be included in the calculation of matched beam sizes. Assuming that the beam bunch is a uniformly charged ellipsoid, space-charge forces are linear and can easily be incorporated in the beam envelope equations from which the matched beam sizes are derived.

With a being the average beam radius ($a=\sqrt{a_x a_y}$, and a_x and a_y are the half-widths of the beam in the x and y directions) and b the half-length of the bunch, one can calculate a from the equation (nonrelativistic approximation):

$$(k_t\beta\lambda)^2 a=\frac{(\beta\lambda\varepsilon)^2}{a^3}+\frac{45\Omega\ eI\lambda^3(1-\frac{a}{eb})}{M_o ab} \qquad (1)$$

Here k_t is the wave number of the transverse oscillation in the zero space charge approximation, given by $\mu_{SF}/2\beta\lambda$ and M_o is the deuteron rest mass in energy units. Assuming that the half length of the beam bunch, b, corresponds in phase spread to ϕ_s one finds a=1.10 cm for 0.2 A beam current. The flutter factor, which is space-charge independent[13] takes the maximum transverse oscillation amplitude to about 1.65 cm.

One can now calculate the transverse and longitudinal space-charge parameters μ_t^{sp} and μ_ℓ^{sp} equal to the ratios of the space-charge defocusing force to the external focusing force. They are given by:

$$\mu_t^{sp} = \frac{45\Omega\ eI\lambda^3(1-\frac{a}{3b})}{(k_t\beta\lambda)^2 M_o a^2 b} \qquad (2a)$$

$$\mu_\ell^{sp} = \frac{30\Omega\ eI\lambda^3}{(k_\ell\beta\lambda)^2 M_o ab^2} \qquad (2b)$$

where

$$k_\ell = \left[\frac{2\pi eET\sin|\phi_s|}{M_o\lambda\beta^3}\right]^{1/2}$$

is the longitudinal wave number in the zero space-charge approximation. Equations 2a and 2b give $\mu_t^{sp}=0.40$ and $\mu_\ell^{sp}=0.55$ demonstrating the importance of space-charge forces in the proposed linac. Under these conditions, experience gained from operating machines[14] as well as from computer simulations[11,13] indicates that some transverse emittance growth is to be expected in the low energy part of the linac. The drift tube bore having a 4.8 cm aperture at injection will most probably have to be enlarged continuously through tank 1 to allow for transverse beam growth. Because of the gradually increasing values of β this can be done without appreciably lowering the transit time factor T which is proportional to $[I_o(2\pi R/\beta\lambda)]^{-1}$. Further computer studies are required to determine the necessity for such a design feature.

As can be seen from Eqs. 2a and 2b, a constant value of μ_{SF} down the machine is ideally consistent with a constant transverse beam size except for a weak energy dependence of b (the half-length of the beam bunch).

Energy Spread

To match the beam longitudinally, it is required that the deuteron beam enter the linac with an energy spread given by

$$\Delta E = \pm M_o \beta^2 b\ k_\ell (1-\mu_\ell^{sp})$$

which with the present design parameters yields ±27 keV. This can be achieved with the bunching scheme described earlier. With the adiabatic $\beta^{3/4}$ growth in energy spread found to hold under space-charge conditions[13] a perfectly matched beam would have an energy spread of ±125 keV at 35 MeV.

A more pessimistic estimate for the output energy spread can be obtained if one assumes that an imperfectly matched beam will fill the bucket area that is calculated without space charge at injection. The energy spread of this bucket is

$$\Delta E = \pm M_o \left[\frac{2\lambda\beta^3 eET(\phi_s \cos\phi_s - \sin\phi_s)}{\pi M_o}\right]^{1/2}$$

and is ±60 keV in this case. Again, assuming a $\beta^{3/4}$-type growth one finds $\Delta E = \pm 275$ keV at 35 MeV.

HARDWARE DESIGN CONSIDERATIONS

The drift-tube structure will be of conventional, state-of-the-art design. It will be different, however, from existing modern proton linacs in that its duty factor will be 100%, hence particular attention will be paid to the thermal and radiation problems.

At 50 MHz and an acceleration rate of 1.0MeV/m, the total length of the machine will be about 35 meters, plus allowances for some drift lengths between cavities. These however will be kept short to avoid longitudinal debunching. In order then to limit the drift space between adjacent cavities, the eight cavities will be contained in a single vacuum tank. The tank will be constructed of copper-clad steel containing both vacuum and rf power in an integral envelope, like all modern proton linacs. Water-cooled copper-boundary plates will be mounted inside to provide the separation between the 8 radio-frequency resonators.

The 54 copper drift-tubes mounted on the axis of the accelerator will each contain a dc, water-cooled, electromagnetic quadrupole. The drift-tubes and the tanks will demand an efficient water-cooling system to dissipate the ~2.5 MW of excitation power and maintain a constant temperature. The accelerating cavities resonant frequencies will be maintained and adjusted by means of a servo system controlling the operating mean temperature. This scheme is being successfully used presently on the Brookhaven proton linac.

Radiation damage considerations dictate that the accelerator be built excluding all organic materials. Rubber hoses, vacuum viton seals, electrical organic insulation, etc., will all be replaced by radiation hardened materials. Although these are design constraints, today, radiation hardening is standard procedure in new accelerator designs and the technology is well developed.

The dc quadrupole magnets will utilize hollow conductors for direct cooling and shunts will be used to achieve the required current distribution allowing the utilization of economically large and well-regulated power supplies.

The accelerator is expected to operate at a pressure of $\sim 10^{-7}$ torr. This low pressure parameter is common practice in all operating linacs and can be met with state-of-the-art commercially available equipment. The preliminary design is predicted upon the use of ion pumps. However, cryogenic pumping will be considered. The need to protect against radiation damage dictates that all vacuum seals be inorganic which inherently helps in producing a "clean" vacuum system and in minimizing the capital cost of the pumping system.

The heat dissipated in the tank walls will be carried away by the water cooling system. A water jacket designed to maximize the surface area in contact with the fluid will be welded to the tank's external surface. The cavities' resonant frequency is directly related to the dimensional stability of the system and it is therefore mandatory that the thermal stability be maintained to within a fraction of one degree. This is accomplished by the careful design of the water circuits to avoid large temperature gradients and by the proper choice of a control servo system to maintain the temperature constant during operation.

The rf excitation power dissipated in the tank walls and drift tubes will be ~2.5 MW. This power loss is high; it is a direct result of the 100% duty factor. To operate the cooling system efficiently it is planned to maintain the linac operating mean temperature between 40° and 50°C. The cooling system will consist of two closed loop circuits providing separate cooling for the rf cavities on the one hand and the drift tubes and quadrupole magnets on the other hand. The two circuits are the result of different requirements of flow, velocity and pressure drop in the two systems.

The rf system will be cooled by a separate loop circulating about 5000 GPM of low conductivity water. The rf system's losses to the water will be about 6 MW.

RADIO FREQUENCY AND CONTROL SYSTEM

The total rf power required is about 9.5 cw MW, or 1200 kW per accelerating cavity section at 50 MHz frequency. The choice of final amplifier-tube type and rf system configuration have forced a critical compromise among such factors as commercial availability, reliability, service life, wide band efficiency, ease of prototyping, costs, and others. Criteria for tube selection were:

1) The tube should be derated sufficiently to ensure performance with long life.

2) The tube should be available commercially and have a good enough history to evaluate anticipated performance with certainty.

3) The number of separate amplifier chains should be minimized consistent with performance, reliability, and cost.

With these criteria in mind we presently regard either Eimac 2170 or CFTH 537 coaxial tetrodes as possible final stage tubes in grounded-grid, grounded-screen concentric circuits at 300 kW cw output per tube. This rating is slightly less than half that allowed by Varian for Eimac 2170 in wide band service at frequencies up to 30 MHz.

Figure 2 is a block diagram of the rf power system for a typical (one of eight) accelerating cavity. Starting from a common low-potential master reference frequency bus, the cavity would be energized through four parallel 300 kW amplifier chains driving separate twelve-inch coaxial output lines with series phase adjustors and magnetic cavity coupling loops. If a high-power tube failed, the survivors would operate at 400 kW pending replacement. Fast phase and amplitude commands will be derived by comparing information from a cavity phase/amplitude scanning probe with the master reference frequency bus and injecting the difference signal at the common input of the four amplifier chains to provide drive-modulated closed loop control of cavity amplitude and phase. Matching each of the four amplifier chains to the cavity section and tracking them with each other will be accomplished by adjusting the phase shifters and the penetrations of the coupling loops. The sequence of amplifier stages preceding the final of each chain would preferably have ≥6 MHz open circuit bandwidth to ensure closed loop stability and rapid rise-time. Such a bandwidth is believed to be within the capability of commercially available 25 kW VHF TV transmitters; accordingly, they might be directly specified for this application. Well-known designs of voltage and current probes and directional couplers would be located appropriately to furnish frequency/phase/amplitude sensing data for the closed loops. The natural resonant frequency of the cavity section would be maintained the same as that of the master reference frequency bus through closed loop control of its coolant temperature. The master reference frequency bus itself will be energized by a temperature-stabilized low-frequency quartz crystal oscillator through varactor multipliers and buffering amplifiers.

All rf, and other machine operation, including beam control and radiation monitoring, is to be effected by a common control system. This system will make use of local dedicated computers performing real time operations and receiving commands from and transmitting data to a large central control computer which will carry out computations and interact with an operation's console. CAMAC hardware will be used to interface with the local computers and to interact directly in a hard wired fashion with a malfunction and machine protection system for the linac. For the rf system in particular, power tube coolant loops, sequences of cathode turn-on and warm-up, grid, anode, and screen activation, and power supply overload and crowbar circuits must be arranged and monitored.

Because of the large potential for radiation, deuteron beam losses must be kept to a minimum and a radiation monitor system with various types of monitors including detectors in each drift tube of the high energy accelerator end will be an important diagnostic tool. Nonintercepting instrumentation will include dc beam transformers,[16] rf position[17] and bunch length detectors[18] and residual gas profile monitors.[19] At the low energy end conventional emittance measuring units,[20,21] may be employed.

THE BEAM TRANSPORT AND TARGET SYSTEM

The lithium targets will be separated from the accelerator complex by a drift distance of ~60m. This distance is required to debunch the beam rf structure to achieve the desired dc beam at the target. It also has the advantage that the expected lithium vapor generated in the targets will not migrate all the way back to the accelerator, but will be trapped at predetermined places in the beam channel.

The beam will be transported with a conventional system of quadrupole lenses properly aligned on the axis. A bending magnet will then direct the beam to its appropriate experimental cave and additional quadrupoles following the bending magnet will control the beam spot size and geometry at the target.

The target itself is a thick film (2 cm thick) of flowing liquid-lithium with a 12x12 cm area. The film will flow across the beam vacuum pipe and be supported on the sides, and on the back by a vacuum window. Figure 3 shows the conceptual design of the target. For a design power of 7 MW, the target velocity required is 15 m/s. The centrifugal force acting on the liquid at this velocity, due to the curvature of the window is 50 torr at the highest energy deposition point. This pressure keeps the liquid at that point below its saturated temperature of 1000° C, thus preventing the possibility of boiling.

The lithium loop necessary to circulate the hot lithium will utilize standard liquid metal technology. The bulk temperature of the lithium being ~300° C provides for an essentially corrosion free system. The hot lithium will be pumped utilizing electromagnetic pumps and the cooling will be done through a lithium-air heat exchanger. The system will contain the necessary heating elements for start-up and all safeguards required in case of accidental spills.

FACILITIES

Figure 4 shows a plan view of the 30 MeV deuteron linac facility. It could be located at Brookhaven, adjacent to the existing 200 MeV proton linac, allowing for efficient use of operating and maintenance personnel as well as use of laboratory space.

The accelerator will be housed in a 20-ft wide shielded tunnel with the beam height 5 ft below ground level. Adjacent to the tunnel a light structure will house the rf systems and adjoining assembly area. The control room which is located at the high energy end of the machine will monitor the experimental areas as well. With the use of local computers and CAMAC controllers, we expect to greatly diminish the need for a large number of cables.

Downstream from the accelerator the experimental building consists of a staging area with the necessary hot cells built on top of the target caves. The material samples to be irradiated will be transferred from the staging area to the targets through a duct system.

CONCLUSION

This proposed facility is a practical and efficient way of producing the intense, high energy neutron beams needed for CTR material studies. The accelerator and liquid-metal technologies are well proven, state-of-the-art technologies. The fact that no new technology is required guarantees the possibility of meeting construction schedules, and more importantly, guarantees a high level of operational reliability.

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Table I Principal Characteristics of the Accelerator-based Neutron Generator

BEAM CHARACTERISTICS

1) MAXIMUM ENERGY 35 MeV
2) AVERAGE ACCELERATION RATE 1.0 MeV/m
3) ENERGY VARIABLE ABOVE 20 MeV IN STEPS OF ABOUT 5 MeV (20, 25, 30, 35 MeV)
4) BEAM MICROSTRUCTURE, 4-nsec PULSES SEPARATED BY 20 nsec AT 50 MHz
5) TIME STRUCTURE AT THE TARGET, BEAM DEBUNCHED AT TARGET ESSENTIALLY DC WITH MAXIMUM 5%, 50 MHz FLUX MODULATION
6) AVERAGE CURRENT 200 mA ($\sim 2 \times 10^{18}$ DEUTERONS / SEC)
7) BEAM DUTY CYCLE 100% (CW OPERATION)
8) AVERAGE BEAM POWER 7 MEGAWATTS
9) BEAM PULSING POSSIBLE

ACCELERATOR PHYSICAL CHARACTERISTICS

1) TOTAL LENGTH OF ACCELERATOR 40 m MADE UP OF 8 CAVITIES, EACH ABOUT 5 m LONG AND 3.8 m DIAMETER
2) INJECTORS 2 X 500 KV, 0.5 A POWER SUPPLIES
3) TOTAL RF POWER ~ 9 MEGAWATTS
4) STRONG FOCUSING UTILIZING ELECTROMAGNETIC QUADRUPOLES

TARGET CHARACTERISTICS

1) TARGET MATERIAL, 220°C FLOWING LIQUID LITHIUM
2) TARGET SIZE, 12 X 12 cm X 2 cm THICK
3) FLOW RATE, 15 m/sec (130 m^3/hr)
4) OPERATING BULK TEMPERATURE, 220° – 300° C
5) DEUTERON BEAM AREA ON TARGET, VARIABLE FROM 1 cm^2 TO ~ 10 cm DIAMETER

Table II Basic Linac Parameters

CAVITY	1	2	3	4	5	6	7	8
INPUT ENERGY (MEV)	0.70	4.26	8.61	12.59	17.04	21.26	25.94	31.08
INPUT $\beta\gamma$	0.027	0.067	0.096	0.115	0.134	0.149	0.165	0.180
OUTPUT ENERGY (MEV)	4.26	8.61	12.59	17.04	21.26	25.94	31.08	35.52
CAVITY LENGTH (m)	3.53	4.38	3.79	4.48	4.24	4.70	5.16	4.45
INPUT CELL LENGTH (m)	0.16	0.41	0.58	0.70	0.81	0.90	0.99	1.08
NUMBER OF CELLS	13	9	6	6	5	5	5	4
INPUT GAP/LENGTH RATIO (g/L)	0.20	0.24	0.26	0.27	0.29	0.30	0.32	0.33
INPUT DRIFT TUBE LENGTH (m)	0.13	0.31	0.43	0.51	0.58	0.63	0.68	0.72
DRIFT TUBE DIAMETER (m)	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
DRIFT TUBE APERTURE (m)	0.048	0.06	0.06	0.08	0.08	0.08	0.08	0.08
QUAD. FIELD STRENGTH (kG/cm)	3.0-0.7	0.6-0.4	0.4-03	0.25	0.23	0.21	0.19	0.16
TRANSIT TIME FACTOR	0.7-0.8	0.8-0.85	0.85	0.80	0.80	0.80	0.80	0.80
STABLE PHASE ANGLE	35°	30°	30°	30°	30°	30°	30°	30°
CAVITY EXCITATION POWER (kW)	373	306	276	318	300	345	372	322
BEAM POWER FOR 200 mA (kW)	712	868	796	890	844	937	1028	888
AVERAGE SHUNT IMPEDANCE (MΩ/m)	32	36	36	37	37	37	37	37

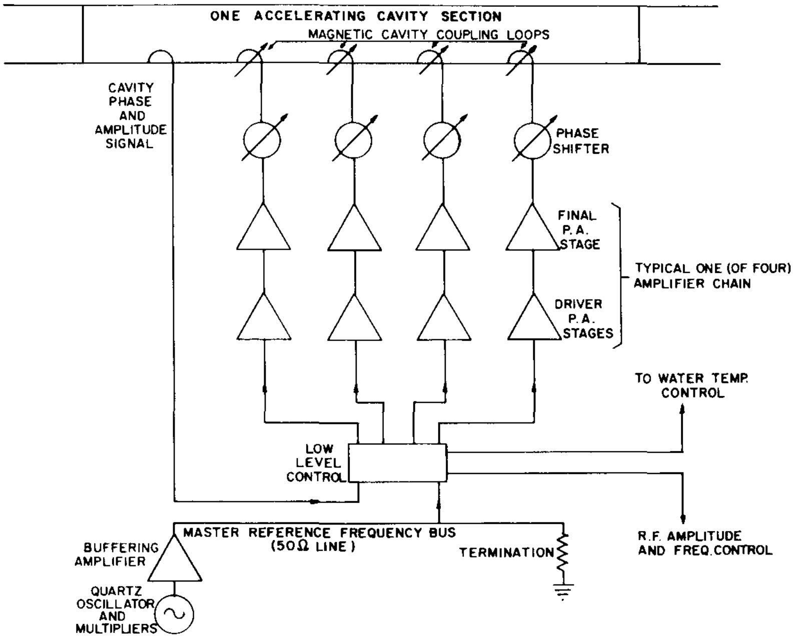

Fig. 2 Typical RF System

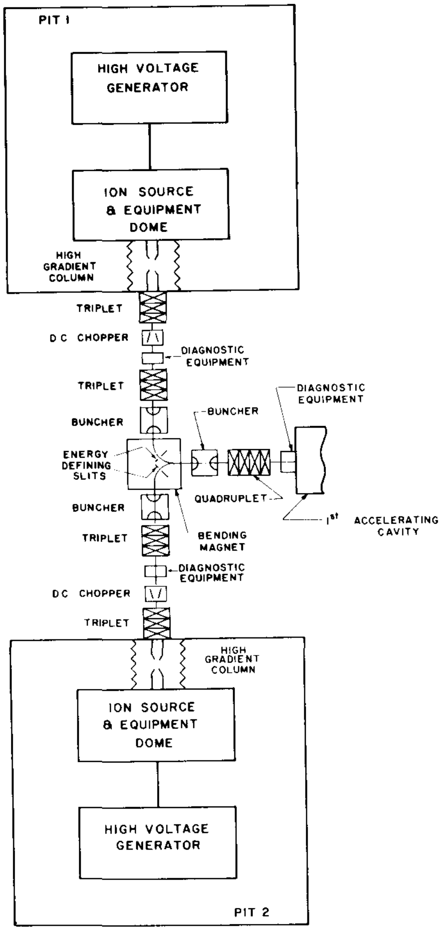

Fig. 1 Injection System

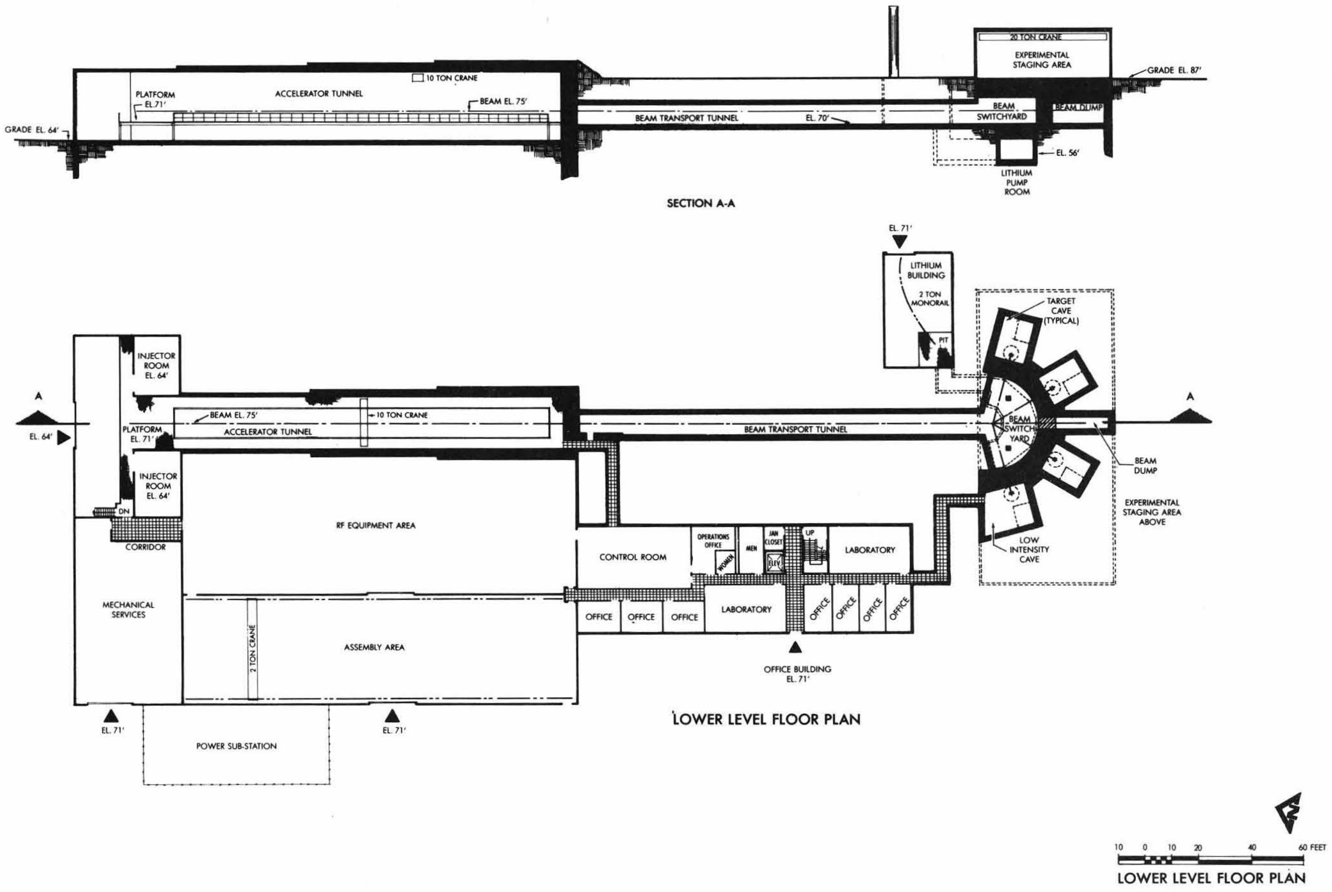

Fig. 4 Plan View of Facility

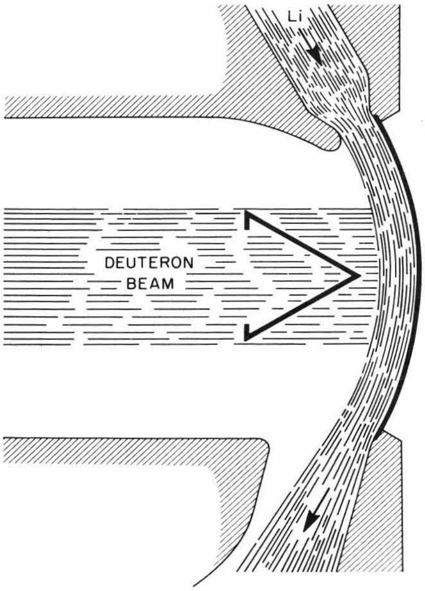

Fig. 3 Schematic of Liquid-Lithium Target

DISCUSSION

J.E. Vetter, Karlsruhe: Are the targets served simultaneously by the beam?

Grand: No, only one target is in operation at any time. The other caves are for standby and the setting up of other experiments while irradiation takes place in another target cave. The possible addition of a d^- beam however might make the simultaneous operation of two targets practical.

N.D.West, RHEL: Have you looked at the problem of the untrapped beam in the first tank?

Grand: Yes, we have been concerned with the problem. The bunching scheme proposed was chosen for that reason. In principle it should make 100% trapping in the linac possible.