A DEUTERON LINAC FOR A HIGH-INTENSITY NEUTRON SOURCE*

1976 Proton Linear Accelerator Conference

J. Staples, D. Clark, H. Grunder, H. Lancaster,
R. Main, F. Selph, L. Smith, F. Voelker, R. Yourd
Lawrence Berkeley Laboratory
University of California
Berkeley, California

Summary

The preliminary design of an accelerator suitable to meet the flux and neutron energy requirements of a CTR materials test facility is presented. The specifications of such a facility call for a neutron flux of 10^{14} n/cm^2-sec distributed over an area of about 10^2cm^2 with a neutron spectrum similar to that anticipated from a fusion reactor. A 30 MeV deuteron linac producing a CW beam of 125 mA, upgradable to 40 MeV at 250 mA at a later date, would produce the relatively broad spectrum of neutrons at the required intensity.

Beam dynamics at the required current dictate an injection energy of 750 keV and a frequency of 50 MHz. The average axial field of 1 MV/m results in a wall power density of slightly less than the Super-HILAC at full gradient and 30% duty factor. Each of the seven cavities will have its own 800 kW r.f. power source for a 125 mA beam intensity, expandable to 250 mA by doubling the number of r.f. sources. Attention to the low-energy beam intercept on the drift tubes and diffusive losses producing neutrons and attendant activiation problems are discussed.

Introduction

The primarily specifications of a national materials test facility for the CTR program call for a neutron spectrum that would produce radiation damage similar to that anticipated from a fusion reactor. This spectrum can best be approximated by stripping deuterons in a light target. The deuteron source would be a high-current Alvarez-type linear accelerator.

The neutron flux initially available from the proposed facility would be at least an order of magnitude below the fluxes anticipated in CTR fusion reactors. After a reasonable period of operation, it is inevitable that an increased flux would be desired. This could be accomplished by augmenting the beam intensity, the energy, or by a combination of both.

With our choice of 30 MeV as the initial operating energy, beam intensity is determined by estimating the maximum power that can be dissipated in the targets with a reasonable value being 125 mA. However, as experience is gained in this technology, we expect rapid improvements in target capability to raise the early power limitations. Consequently, we have designed the accelerator so that the beam intensity can be increased by up to a factor of four. Our design is such that a factor of two can be made with minimum disruption of the operating schedule.

For the proposed accelerator, neutron production and attendant component activation are problems, particularly at the high-energy end. In the injection system and early linac cells beam loss is substantial, resulting in beam interacting with implanted deuterium, producing relatively low-energy neutrons. In the high-energy end of the linac beam losses are small, but charged particle and neutron interactions are more severe. To control the losses we have incorporated sophisticated transport and bunching techniques for highest possible longitudinal acceptance in the linac, generous drift tube apertures to provide a large stay-clear region, precise alignment of the linac quadrupoles, in-cavity beam steering, and judiciously positioned beam scrapers along the entire length of the linac.

Because completion of the experimental program of the proposed facility is dependent on the routinely available beam current, it is vital that estimates of the current not be exaggerated. Ion sources exist that are capable of producing high-quality deuteron beams in excess of that required to saturate the linac entrance. However, performance is ultimately limited by linac acceptance of space-charged beams.

Choice of General Parameters

The deuteron linac is planned for 30 MeV output energy, with a provision for a 10 MeV add-on, if desired. The initial current level is 125 mA, but, in fact, the linac we propose is designed to accommodate a current of 250 mA. The critical parameters--once the output energy and current are set--are the frequency, injection energy and acceleration rate.

Principal parameters chosen are listed in Table 1; more detailed structure parameters are given in Table 2.

Quadrupole focusing is used with an N = 1 (+-+-) sequence. The gradients required are nominal, and the magnetic design of the quadrupoles will present no difficulty.

Beam dynamics considerations require that the transit time factor (TTF), which decreases with aperture and frequency and increases with injection energy, be maintained above about 0.70. This requirement influences the choice of frequency and injection energy. The injected beam is matched to the lattice structure to minimize transverse

*This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent soley those of the author(s) and not necessarily thos of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

oscillations of the beam envelope.

Table 2

Structure Parameters

Cavity		1	2	3	4	5	6	7
Output Energy	(MeV)	3.74	8.18	12.70	16.92	21.06	25.57	30.40
Energy Gain	(MeV)	2.99	4.44	4.52	4.22	4.14	4.51	4.83
No. Cells		16	13	10	8	7	7	7
Cell Length	(cm)	17.5-37.1	38.5-55.1	56.5-68.7	70.0-79.3	80.6-88.4	89.7-97.3	98.6-106.0
D.T. Length	(cm)	13.6-27.4	29.4-40.9	41.8-49.7	50.3-55.9	56.2-60.6	61.5-64.9	64.6-68.6
Gap Length	(cm)	4.4-9.3	9.6-13.8	15.3-18.6	20.3-23.0	25.0-27.8	27.8-32.1	34.5-37.1
g/L		.25	.25	.27	.29	.31	.33	.35
a per radius r_a	(cm)	2.25-2.5	2.75-3	4	5	5	5	5
Inner corner radius r_c	(cm)	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Cavity Length	(m)	4.33	6.08	6.26	5.97	5.92	6.54	7.15
ϕ_s	(degree)	-30	-30	-30	-30	-30	-30	-30
TTF		.72-.84	.83-.86	.82-.84	.81-.82	.82-.81	.79-.82	.78
Quad Length	(cm)	10	20	30	40	40	40	40
Quad Strength B'l	(kG)	15.7	15.7	15.7	15.7	15.7	15.7	15.7
Z_{sh}	(MΩ/m)	31	33	35	35	36	36	37
Wall Power[1]	(kw)	240	250	250	240	230	254	270
Beam Power (125 ma)	(kw)	375	555	565	528	518	584	604
Total Power (125 ma)	(kw)	615	805	815	768	748	818	874
Total Power (250 ma)	(kw)	990	1360	1380	1296	1266	1382	1478

1 With end walls

To establish the injection energy and operating frequency, we plot in Figures 1 and 2 the matched beam size in the first cell in the "smooth" approximation[1] for 50 and 70 MHz. A focusing phase advance of $\pi/2$ per two-quadrupole periods, a constant normalized source emittance of 0.7π cm-mrad, and a bunch length of twice the stable phase is assumed. The bore necessary to contain the beam is taken to be larger by 40% for strong focusing flutter and an additional 35% stay-clear. When the transit time factor, deceases to 0.70, the curve is terminated. The inner bore radius r_c is held at 1.5 cm.

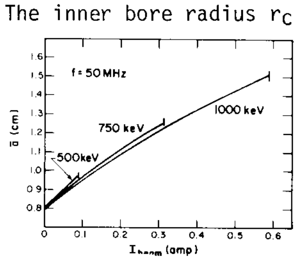

Fig. 1

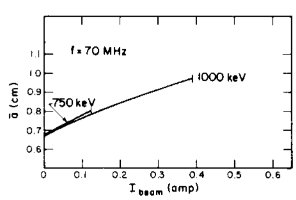

Fig. 2

The maximum achievable current is a strong function of the injection energy. The ratio of longitudinal space charge force to the rf restoring force at 250 mA is about 0.8.

We choose 50 MHz tank frequency and 750 kV injection energy on the basis of Figures 1 and 2, as well as on practical considerations. This injection energy corresponds to available high-current, high-voltage power supplies. The frequency is acceptable from the standpoint of achieving a reasonable tank diameter (~4 m) and obtaining suitable rf tubes. We note that the curves of Figures 1 and 2 are dependent on assumptions regarding the emittance and the detailed geometry of the drift-tube entrance and its influence on the TTF.

[1]Ohnuma and Vitale, NS-14, No. 3, p. 594, 1967.

Table I

GENERAL PARAMETERS

Output Energy (MeV)	30/40 variable in steps of 5 MeV
Output current CW (mA)	125 upgraded 250
Injection Energy (keV)	750
Normalized Emittance (Inj.) (cm-mrad)	0.84π (for 250 mA)
Minimum bore radius (cm)	2.25
Linac frequency (MHz)	50
Average axial E-Field (MV/m)	1
Acceleration rate (MeV/m)	.62-.74
Stable phase	-30^{0}
Drift Tube Quad. sequence	N = 1 (+-+-)
Integrated quadrupole strength (kg)	15.7
Total rf-power (MW)	5 (for 125 mA)
Number of cavities	7 (30 MeV)
Linac length (m)	46.5 (30 MeV)

The average acceleration rate is a compromise between many considerations, such as power density, total power, reliability, length and longitudinal space-charge forces. We adopt 1 MV/m as the average axial voltage gradient resulting in a gap field of 40 kV/cm and a wall-loss per unit length slightly less than that of the SuperHILAC.

Each of the seven cavities has its own 800 kW rf power source for acceleration of a 125 mA beam. To accelerate a 250 mA beam it is necessary to add one more tube per rf cavity.

Injection System

A plan view of the proposed injector system is shown in Figure 3. We have specified two injectors and a single power supply. We consider that duplication of ion source and high-gradient column is advisable in a facility of this nature because these components are likely to require frequent maintenance, at least at first.

When allowance is made for D_2^+ beam and for linac acceptance losses, the ion source must provide 225 mA for total ion output, upgradable to 450 mA later, at 100% duty factor. Among existing ion sources most promising for this application are those being developed as injectors for CTR reactors at Livermore[2], Oak Ridge[3] and elsewhere. These sources now produce up to 1-2 amperes of hydrogren ions with 80-90% H^+ fractions.

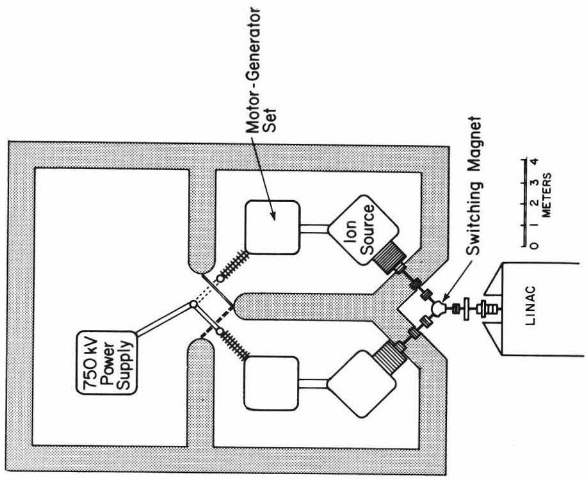

Fig. 3

The MATS III source at Livermore, for example, is a multiple-aperture reflex design, developed from a duoplasmatron geometry. This source currently produces 1 ampere of deuterium ions with 65% d^+ fraction at 29 keV. At a beam diameter of 6 cm the normalized emittance ($\frac{\beta\gamma A}{\pi}$) is .22 cm-mrad for 700 mA at 14 keV. Allowing for some emittance blowup in the column, low-energy beam transport and buncher, this production level becomes a reasonable match to the linac brightness requirements.

In order to handle the 225 mA ion current and the backstreaming electrons, a 750 kV 500 mA Cockcroft-Walton power supply will be provided. For an upgraded ion current of 450 mA we assume a method can be found to suppress most of the backstreaming electrons.

The output voltage of a Cockcroft-Walton power supply is given by the following approximate equation for a full-wave C-W voltage multiplier:[4]

$$V_{dc} \sim nV_o - \frac{i_L}{4fC} \frac{n^3}{12} + \frac{n^2}{8}$$

where n = number of decks
f = frequency of driving source
i_L = load current
C = capacitance per stage
V_o = voltage per deck.

As the load current increases, it is necessary to lower n or increase f. Two approaches are either to develop very high-voltage decks, which require high-voltage, high-current rectifiers and capacitors, or to push the frequency up and develop large high-frequency generators and transformers. Haefely and Co.[5], for example, have taken the first approach and have successfully built 2.5 MV/200 mA and 2.2 MV/200 mA C-W power supplies.

The accelerating tube selected is a 750 keV high-gradient column of the type used successfully for several years at BNL, LBL and other laboratories. A modular design of 3 to 6 sections is chosen to facilitate assembly, alignment, accuracy and module replacement, if necessary. The electrodes and all other metal in the column are made of titanium alloy to reduce field emission, suitably shaped to shield the beam from charges on the insulators.

Additional cooling is provided in the terminal to handle power dissipation from backstreaming electrons. Tests with LBL's existing 750 keV high-gradient column will further clarify the backstreaming problem and aid the design process.

Due to the high average power in the beam, particular attention is given to beam transport and buncher arrangement. The 750 keV beam from the ground end of the column is transported approximately 5 meters through a buncher to the first gap of the linac by a system of 4 quadrupole triplets and a ± 45° switching magnet (see Fig. 4). A double-gap harmonic buncher[6,7] is preferred to the double-gap fundamental buncher because it not only gives over 80% acceptance, but also places more of the beam in the central part of the phase-acceptance area of the linac.

Linac Structure

The proposed linac will operate at a frequency of 50 MHz. Its dimensions are approximately 4 m diameter and 46.5 m long, divided into seven electrically independent cavities, separated by diaphragms.

Some of the quadrupoles may have to be of the mineral-insulated conductor variety.[8] Initial investigations, however, show maximum neutron doses

[2] J.E. Osher and G.W. Hamilton, An Intense 1 kV Ion Source for Controlled Fushion Research, Proc. of the Symposium on Ion Sources and Formation of Ion Beams (1971).

[3] R.C. Davis, et al., A Multiampere Duopigatron Ion Source, Review of Scientific Instruments, Vol. 43, #2 (Feb. 1972).

[4] G. Reinhold, J. Seitz and R. Minkner, Advanced Development of the Cascade Generator, 67, p. 258-265, Basel, Switzerland, 1959.

[5] G. Reinhold, Ultra-high Voltage D.C. Power Supplies for Large Currents, Emil Haefely & Co., Ltd., Technical Report E4-19.

[6] Blashke and Friehmelt, UNILAC Report No. 1-69.

[7] Bru and Weiss, NS-20, No. 3, p. 963, 1973.

[8] K. Mirk, SuperHILAC Vacuum System, Lawrence Berkeley Lab. LBL-1329, October 1972.

to the drift-tube magnet structure of 7 x 10^9 rads/year. Consequently, adequate lifetimes possibly could also be guaranteed using the SuperHILAC tape quadrupole methods[9] and a mineral filled epoxy with lifetime approaching 10^{11} rads.[10]

The drift tube design provides access for easy servicing and removal through large tank ports.

To minimize activation of the linac drift tube surfaces, removable collimators are inserted at frequent intervals (∿5 MeV, at diaphragms) to scrape off the beam halo resulting from gas and other scattering. In the latter part of the tank, above 10 MeV, the bores for the drift tubes contain an easily removable sleeve for quick disposal during tank and drift tube maintenance periods.

Radiofrequency System

There are seven rf stations, each composed of a 50 MHz amplifier chain, amplitude and phase control loops, cavity tuning control, and power supply.

The rf amplitude and phase of each cavity is independently adjusted by control loops similar to those presently used on eight cavities at the SuperHILAC.

A separate DC power supply for each amplifier consists of two conventional three-phase solid-state converters in series connected for 12-pulse operation, followed by a filter to remove fast transients coming from the converter. A crow-bar protects the final tubes in case of a fault. A switching system between these power supplies and the final tubes allows the linac to be run at reduced energy (last cavity off) in case one of the power supplies fails. The possibility of having an additional spare power supply in the switching network is clearly attractive.

Space is provided to expand the rf system for 250 mA beam loading. The amplifier chains and power supplies would then be paralleled on each cavity.

The beam passes through drift tube gaps in a pulse approximately 30° out of phase with the peak of the electric field in the gap. The energy to accelerate the beam is stored in the fields and the gap. Since much more energy is stored than extracted, only the fundamental Fourier component of beam current needs to be considered in calculating beam loading.[11] In this linac the fundamental component of the beam current is several times larger than the copper loss component.

The resulting load on the final amplifier is reactive and can be handled successfully in one of three ways: (1) The amplifier can supply the reactive load, which increases the tube dissipation and so reduces the power it can deliver. (2) A phase shift can be introduced between the amplifier and the cavity. This is satisfactory during steady state, but may introduce high voltages in the drive line during transient conductors. (3) The cavity can be tuned slightly off resonance when beam loading is present, so that the reactive energy required by the beam is just compensated by the reactive energy unbalance in the cavity.[12] Under these conditions, the amplifier sees a resistive load.

Control System

The accelerator control and monitor functions will use a radially distributed control system architecture. Sets of localized signals are interfaced to a process control terminal. Some number of process control terminals are linked to a real time computer. The real time computers in turn are linked to a central computer which interfaces all the signals to the operators.

Since the computer system requirements for control of the accelerator and the experimental test facility are quite different, a separate computer system should be used for the latter. The two systems should be identical to facilitate maintenance and operating systems support.

Interlocks required for personnel safety are hard-wired, with only monitoring being done by the computer. Protection circuitry required to prevent expensive machine components (rf, drift tubes, etc.) from damage are also hard-wired.

Beam Monitoring

The beam intensity is monitored using induction and pick-ups at the linac entrance, exit and between between-tank diaphragms. These detectors are used primarily during startups. To detect beam loss at less than 1%, sensitive loss monitors (neutron detectors) are installed inside drift-tubes at several positions along the linac. Continuous monitoring of these detectors by the computer alarms the operator or shuts the machine down if a preset loss limit is exceeded.

Nondestructive beam profile monitors, probably of the residual gas ionization type, are specified in the injection transport line to facilitate matching injector emittance to linac acceptance. Additional profile monitors in the transport system from the linac exit to the target serve as an aid in tuning quadrupoles and steering magnets for lossless transport.

Accelerator Shielding and Residual Activation

The neutron shielding requirement is for 0.25 mrem/hr at 6 meters from the beam axis for a design current of 125 mA of 40 MeV deuterons.

The injection shielding would be 134 cm of 2.4 gm/cm^3 concrete, also adequate to shield against bremsstrahlung radiation from 200 mA of back-streaming electrons of 750 keV peak energy. The neuteron shielding along the linac varies in thickness from 125 cm to 280 cm of 2.4 gm/cm^3 concrete, assuming point losses of 125 mA of beam at 10 to 40 MeV along the linac. Neutrons yields range from 1.7 x 10^{12} n/sec at 10 MeV to 7.6 x 10^{13} n/sec at 40 MeV.

[9] A. Harvey, Radiation-Hardened Magnets Using Mineral Insulated Conductors, Proc. Fourth International Conf. on Magnet Technology, 1972.

[10] H. Brechna, Effect of Nuclear Radiation on Organic Materials, Specifically Magnet Insulations in High Energy Accelerators, SLAC-40, March 1965.

[11] R. Main, Alignment of Drift Tube Lenses Using a Pulsed Wire, Lawrence Berkeley Laboratory LBL-1224, September 1972.

[12] P.N. Lapostolle and A.L. Septier, Linear Accelerators, p. 809-829.

Residual induced activity in the injector and first cavity area is not present, as deuteron energies are below the coulomb barrier. Activation along the rest of linac is expected to be up to 2 rem/hr after an 8-hour cooling period, neglecting self-shielding of the magnet structure. The dose rate from the last drift time (40 MeV) alone under the above assumptions is 0.5 rem/hr.

To stop incident deuterons, we incorporate easily removable sleeves inside the drift tubes, and collimators between cavities. A large fraction of the residual activity would then be contained in these sleeves and collimators.

If 0.1% of the beam were to be lost uniformly among 52 drift tubes, 2×10^{11} n/sec/μA would be produced. The dose deposited in the copper shell has been calculated to be 6×10^{12} rads/year--well below the threshold for damage ($\sim 10^{19}$ rads). The dose to the magnet structure could reach 7×10^{9} rads/year, depending somewhat on sleeve and collimator material.

Transport to the Experimental Area

Because a failure of the target, or some portion of the experimental area equipment, may result in the release of large amounts of radioactive materials into the vacuum system, it is essential to isolate conductance beam line, provided with high-speed vacuum pumping and fast valves. This line also allows the beam to debunch.

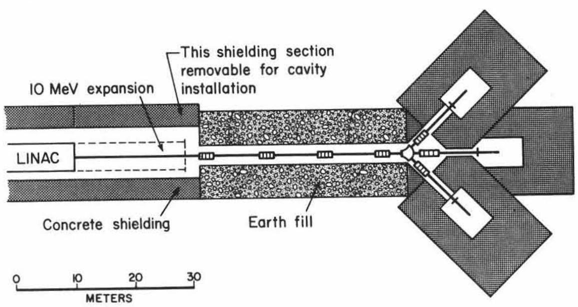

Fig. 4

In addition to this isolation and debunching drift space, approximately 15 m has been reserved within the accelerator enclosure to allow for the future installation of linac cavities to increase the maximum energy of the accelerator to 40 MeV. (See Fig. 4).

Two experimental areas are proposed, a ± 45° from the primary beam axis, as well as a beam dump on the axis. The beam dump is used mostly during tune-up, but is designed for easy removal should the experimental areas be expanded.

Doubling the Maximum Beam Intensity

We conclude with an innovative though admittedly speculative option for another doubling of the maximum intensity. The 250 mA limit is imposed already by acceptable pre-injector voltages and drift-tube bore radius rather than rf power availability. However, two independent beams could be provided by placing two quadrupoles side-by-side in the drift tubes and doubling the rf power. One more high voltage set is placed in the space allotted in the pre-injector area, and the two ion sources would provide simultaneous beams through two low energy beam transport systems.

This arrangement offers additional benefits in that two irradiation caves can be used simultaneously without the use of a septum or two beams can be combined to give a higher flux or larger uniform volume in one cave. The failure of one ion source will not interrupt an irradiation.

This concept has no obvious flaws and appears to be a workable method in providing beam currents of up to 0.5 ampere.

Additional people who contributed to this effort are V. Elischer, W. Lamb, G. Lambertson, E. Lofgren, J. McCaslin, W. Patterson, R. Richter, R. Thomas, C. Van Atta, C. Weber and E. Zajec.