Proceedings of the 1972 Proton Linear Accelerator Conference, Los Alamos, New Mexico, USA

LIMITATIONS OF ACCELERATION OF DEUTERONS IN ALVAREZ-TYPE PROTON LINACS*

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Introduction

A deuteron beam current of 17 mA up to 23 MeV in an Alvarez structured linac was obtained for the first time in 1964 at CERN,(1) stimulated by a paper of E. Courant.(2) Actual experimental programs with deuterons instead of protons are presently in progress with the 20-MeV injectors of the Dubna and Saclay proton synchrotrons.(3,4) Recently Argonne reported 1 mA deuteron acceleration in their 50-MeV proton linac,(5) while Brookhaven accelerated 18 mA deuterons in the first (10-MeV) accelerating tank with a trapping efficiency of 25%.

The above-mentioned machines are 20- to 50-MeV energy proton linacs. Their transit time factors and the available rf power are favorable to accelerate deuterons reasonably well in the 4π mode instead of the 2π mode for proton acceleration. In the new higher energy linacs of NAL, BNL, and LAMPF, the transit time factors in the later tanks form a serious limitation for deuteron acceleration.

Despite the rather encouraging results of deuteron acceleration in the first section of some proton linacs, there are also disappointments in the trapping efficiency. It will be shown that there exists a precarious balance among rf field, the injection energy and the injection phase for the optimum deuteron acceleration in a proton linac. Also, a proper choice of the quadrupole strengths in the first tank seems to be required to accommodate the wild phase oscillations.

Difference in Proton and Deuteron Acceleration

In the Alvarez-structured linacs acceleration of protons takes place in the first harmonic. That means that the protons progress one cell during one rf period. Particles are electrically shielded when the electronic field is in the decelerating direction. (See Fig. 1a.) For deuteron acceleration in this mode, the deuterons have to traverse each cell with the same speed as protons. The available rf power and quadrupole fields do not allow this type of operation. Another possibility is to accelerate deuterons with half the velocity across each gap and the energy gain for deuterons is then about one-half (at the low energy end) and lower (at the high energy end). The deuteron is then accelerated in the second harmonic $2\beta\gamma$ or 4π mode. (See Fig. 1b.)

In terms of Fourier analysis of the axial electric field $E_z(z)$, the first harmonic component is responsible for proton acceleration and the second for deuteron acceleration. For a gap length g and a cell length L, these components are proportional to

$$\sin(m\pi g/L) / (m\pi g/L) \qquad (1)$$

for a simple model and

$$J_0(m\pi g/L), \quad J_0 \equiv \text{Bessel function} \qquad (2)$$

for a somewhat better model of $E_z(z)$ in which the effect of a sharp boundary around the drift tube bore hole is taken into account.(6) Here $m = 1$ is for protons and $m = 2$ for deuterons. It is clear from these expressions that the rf accelerating field is less favorable to deuterons compared to protons. For a large value of (g/L), these quantities go to zero at

$$g/L = 1/2 \quad \text{or} \quad 0.383 \text{ for } m = 2$$

so that there is no acceleration in the cell, acceleration and deceleration canceling each other exactly. If (g/L) is further increased, the sign of these components changes and, in order to maintain acceleration, one has to switch the phase of particles (relative to rf field) by 180°.

Another difference, which is important at low energies, is in the effect of the size of the bore hole. The accelerating component of rf field on the axis $(r = 0)$ is proportional to

$$1/I_0(K_m a),$$

$$I_0 \equiv \text{modified Bessel function} \qquad (3)$$

where

$$a = \text{radius of the bore hole,}$$

$$K_m \simeq 2m\pi/L. \quad (L \ll \lambda).$$

The importance of this factor is evident in the following table.

	a(cm)	m=1	m=2
Original BNL, ANL	.635	.899	.673
LAMPF	.75	.864	.585
NAL, new BNL	1.0	.776	.414

(L = 6.037 cm, the first cell of linac)

Physically speaking, a larger bore size means less shielding of the undesirable rf field. Deuterons spend twice as much time compared to protons under the influence of this field, thereby getting less net acceleration. Above considerations show that acceleration of deuterons suffer:

a) from the effect of the size of the bore hole at low energy,

b) from large values of g/L at higher energies.

Numerical Results for BNL and NAL

The energy gain of the synchronous particle in each cell of a linac is given by

$$\Delta W = eVT \cos(\phi_s) \qquad (4)$$

where

V = voltage across the gap,

ϕ_s = synchronous phase = -32°,

and

T = transit time factor = product of (1) and (3), or (2) and (3).

Some of the relevant parameters are given in Table I. The voltage across the gap is limited by the amount of rf power available and by the sparking. The synchronous phase may be reduced somewhat but this does not help much, cos (ϕ_s) being already 85% of the maximum value. Thus the crucial parameter for a successful acceleration of deuteron is the transit time factor T. Since expressions (1) and (2) are based on simple models for $E_z(z)$, they are not too reliable for our linacs with rounded drift tube corners. Fortunately, all field values (E_z, E_r, H_ϕ) have been calculated numerically using the computer program MESSYMESH for each cell. The accuracy of these field values should be better than a few percent in relative errors in view of the excellent result in the resonant frequency (≈0.1%).

The transit time factor is now given by

$$T_m = \int_{-L/2}^{L/2} E_z(z)\cos(2m\pi/L)\,dz \Big/ \int_{-L/2}^{L/2} E_z(z)\,dz. \qquad (5)$$

The effect of the bore is already included since $E_z(z)$ is the field on the axis. The voltage (or field level) required for deuteron acceleration relative to that for proton acceleration is then ($E \equiv V/L$)

$$V_2/V_1 \equiv E_2/E_1 = (\Delta W_2 \cdot T_1) \big/ (\Delta W_1 \cdot T_2) \qquad (6)$$

for the same value of the synchronous phase. Results are summarized in Table II and in Figs. 2-4.

Difficulties in cavities No. 4 to No. 8 are insurmountable. Even with an unlimited amount of power supply, one must switch the phase by 180° in cavity No. 6. The required field is already prohibitive near the end of cavity No. 3. However, one might be able to decrease ϕ_s in the last ten cells or so without losing the beam if the phase oscillation damping is normal. In cavity No. 1 the variation of E_0 up to cell No. 20 may not be easy to realize. There is also a discontinuity at cell No. 18 due to a change of the bore hole diameter starting with drift tube No. 18.

Injection Energy

The broken line in Fig. 2 is above the required average field for ϕ_s = -32° beyond cell No. 12. Near cell No. 18, it is slightly below for a few cells but this is not serious. The synchronous phase changes from -32° to -28° there and the resulting beam loss should be negligible. The major problem is how to keep the beam from the injection to cell No. 12. It should be remembered that, although the length involved is very short (0.82 m), the phase oscillation wavelength is also short and particles make one complete phase oscillation. If the beam is injected at 375 keV (one-half of the proton injection energy), it will be lost almost entirely before reaching cell No. 12. A detailed numerical calculation shows that, for the injection energy beween 370 keV and 380 keV, the entire beam is indeed lost before cell No. 12.

The synchronous energy of deuterons at the center of cell No. 12 is approximately 750 keV which is available from the present preaccelerator. In order for the beam to be captured in the stable area in cell No. 12 and be accelerated normally beyond, it is not necessary to have a net accceleration before this cell.(7) The problem is then reduced to one of finding an area in the longitudinal phase space that will be transformed to the stable area in cell No. 12. Particle motions are rather complicated and numerical calculation seems to be the only reliable way to find the solution. MESSYMESH values for E_z at 340 points along the longitudinal axis from the linac entrance to the center of cell No. 12 have been used to integrate phase and energy for a given initial condition $0 < W_i \lesssim 800$ keV and $-180° \leq \phi_i \leq 180°$. The calculation indicates that the collection of points (W_i, ϕ_i) that can eventually be captured in the stable area at the center of cell No. 12 makes a rather narrow, curved strip in phase space extending from slightly above 380 keV to almost 650 keV. The range in ϕ_i for a given value of W_i is generally very narrow ($\lesssim$15°) but there are two groups of points that look promising. These groups are shown in Fig. 5 as (A) and (B). Choice between (A) and (B) depends on the stability of the preaccelerator voltage. If the stability is better than ±1 kV at ~545 kV, (B) gives the largest phase acceptance (~150°). For a larger fluctuation, (A) is better in the overall acceptance, approximately 40° for 390 kV to 405 kV.

Defocusing action of each gap for the betatron oscillation is twice as large for deuterons as for protons if the same synchronous phase is maintained.(2) However, beyond cell No. 12 of cavity No. 1, there should be no major difference in the quadrupole strength since momentum is practically the same. Between cell No. 1 and No. 12, the phase motion is "wild" so that the optimum quadrupole strength must be found from a detailed study of the phase oscillation. None of these points has been investigated so far.

Experimental Results

Detailed descriptions of deuteron acceleration in other linacs are not available to the authors. In the laboratories of Dubna and Saclay deuterons are accelerated to 10 MeV and in the latter a beam current of not more than 4 mA has been obtained.(4)

A first trial of deuteron acceleration took place in August 1970 in the BNL 10-MeV accelerating tank. Main results of this trial are as follows:

Preinjector Voltage	390±10 kV
Preinjector Current ($D^+ + D_2^+$)	125 mA
Injected Current D^+ to Linac	70 mA
Accelerated Current:	
without Buncher	12 mA
with Buncher	18 mA
Final Energy	5 MeV

The quadrupole fields in transfer line and linac were kept the same as for proton acceleration. The rf level of the tank was at about the dotted line in Fig. 2. The buncher level was not recorded. The accelerated current was measured behind a momentum analyzer. The trapping efficiency without buncher was 17%, which is somewhat higher than the expected value of 11%. The use of the 25° analyzer excludes the possibility of current increase by lower energy particles. Neither the discontinuity at cell No. 18 nor the variation of E_0 seems to have a serious effect on the trapping efficiency.

References

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2. E.D. Courant, "A Study of Possible Deuteron Acceleration," Conf. on Linear Accelerators for High Energies, BNL (1962).

3. A.M. Baldin, et al., "Acceleration and Extraction of Deuterons from the JINR Proton Synchrotron," reprint P9-5442, Dubna (1971), (BNL-TR-431).

4. Levy-Mandel, private communication (1970).

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6. L. Smith, Handbuch der Physik 44, 341-389 (1959).

7. This scheme is essentially the same as one used at Dubna (Ref. 3). The current of the accelerated deuteron was increased by a factor of six.

* Work performed under the auspices of the U.S. Atomic Energy Commission.

† Operated by Universities Research Association, Inc. under contract with the U.S. Atomic Energy Commission.

TABLE I

VELOCITY, KINETIC ENERGY AND MOMENTUM
OF PROTONS AND DEUTERONS FOR NAL LINAC

Rest Mass	Protons 938.26 MeV			Deuterons 1875.6 MeV	
Cavity No.	β_{in}	W_{in} (MeV)	$(cp)_{in}$ (MeV)	W_{in} (meV)	$(cp)_{in}$ (MeV)
1	.0400	.750	37.5	.375	37.5
2	.1478	10.42	140.2	5.14	139.0
3	.2747	37.54	268.0	17.95	260.1
4	.3570	66.18	358.6	30.61	340.2
5	.4141	92.55	426.9	41.55	397.0
6	.4569	116.54	482.0	50.95	440.1
7	.4913	138.98	529.2	59.29	475.3
8	.5204	160.53	571.8	66.92	505.5
9	.5452	181.01	610.3	73.84	531.5
Final	.5665	200.31	645.0	80.09	553.9

TABLE II

AVERAGE FIELD REQUIRED FOR DEUTERON ACCELERATION

T_1 = transit time factor for protons on the axis
T_2 = transit time factor for deuterons on the axis
E_2/E_1 = average field required for deuterons relative to that for protons

Cavity	Cell	T_1	T_2	E_2/E_1 $\phi_s = -32°$	E_2/E_1 $\phi_s = 0°$
1A*)	1	.644	.194	1.656	1.405
	2	.656	.206	1.594	1.352
	3	.668	.218	1.532	1.299
	4	.680	.230	1.476	1.252
	5	.691	.241	1.427	1.211
	6	.701	.253	1.384	1.174
	7	.710	.264	1.345	1.141
	8	.719	.275	1.303	1.105
	9	.728	.287	1.266	1.074
	10	.736	.297	1.231	1.044
	11	.743	.307	1.207	1.024
	12	.750	.317	1.179	1.000
	13	.756	.326	1.154	.979
	15	.767	.342	1.119	.949
	17	.777	.358	1.084	.919

TABLE II (continued)

Cavity	Cell	T_1	T_2	E_2/E_1	
				$\phi_s = -32°$	$\phi_s = 0°$
1B*)	18	.741	.303	1.212	1.028
	19	.747	.311	1.193	1.012
	27	.780	.359	1.078	.914
	35	.798	.386	1.025	.869
	45	.807	.395	1.006	.853
	56	.805	.380	1.036	.879
2	1	.860	.538	.776	.658
	15	.860	.530	.784	.665
	30	.849	.492	.818	.693
	45	.830	.436	.888	.753
	60	.808	.371	1.000	.848
3	1	.823	.413	.911	.773
	10	.805	.361	1.003	.851
	20	.783	.302	1.142	.969
	35	.750	.215	1.491	1.265
4	1	.747	.208	1.537	1.304
	15	.717	.136	2.199	1.865
	29	.687	.0668	4.153	3.522
5	1	.732	.169	1.739	1.475
	10	.714	.126	2.237	1.897
	24	.686	.0622	4.194	3.557
6	1	.684	.0581	4.504	3.820
	10	.668	.0223	11.13	9.437
	16	.657	-.0002		
	22	.646	-.0239	-9.808	-8.318**)
7	1	.643	-.0292	-8.009	-6.792
	10	.628	-.0589	-3.773	-3.200
	21	.611	-.0910	-2.323	- .1970
8	1	.608	-.0960	-2.199	- .1865
	10	.595	-.119	-1.686	-1.429
	20	.580	-.147	-1.301	-1.103
9	1	.577	-.152	-1.266	-1.073
	10	.566	-.169	-1.089	- .924
	19	.554	-.188	- .939	.797

*) In Cavity No. 1, the cell geometry changes at cell No. 18.

**) ϕ_s = 148° or 180° for $E_2/E_1 < 0$.

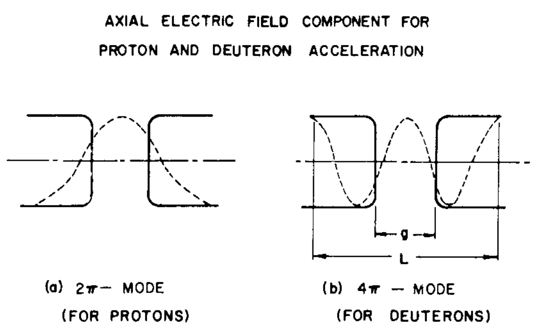

Fig. 1. Electric field for accelerating (a) protons and (b) deuterons.

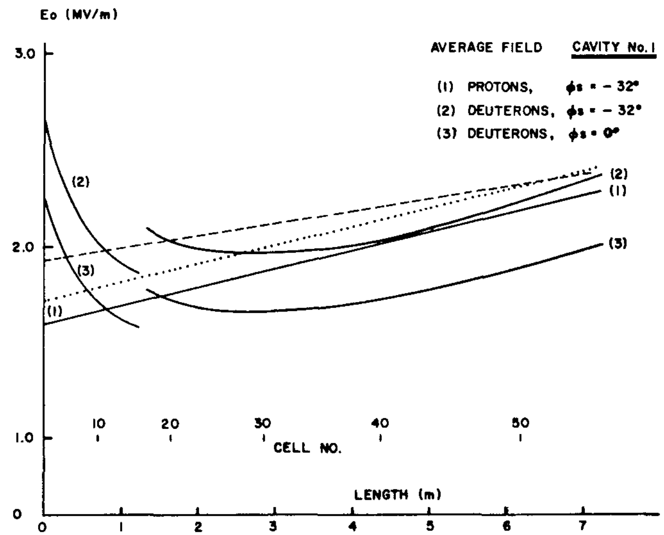

Fig. 2 Average electric field required in cavity No. 1 of BNL and NAL linacs. Broken line is suggested field variation for deuteron accelerations. Dotted line shows field level used at BNL.

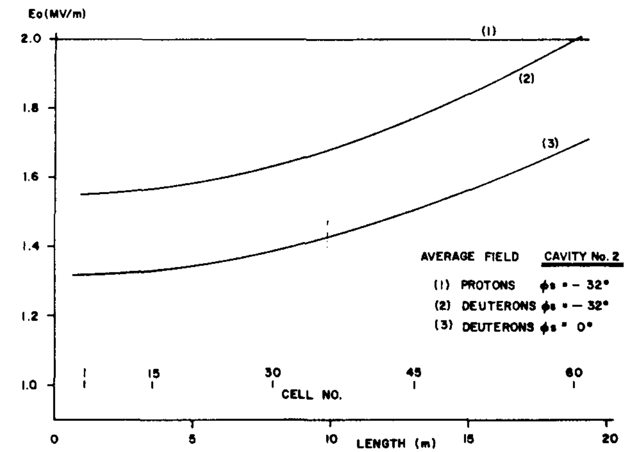

Fig. 3 Average electric field required in cavity No. 2 of BNL and NAL linacs.

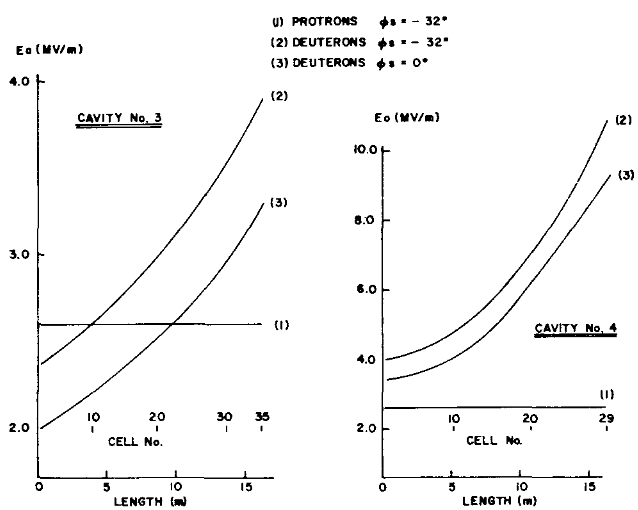

Fig. 4 Average electric field required in cavity Nos. 3 and 4 of BNL and NAL linacs.

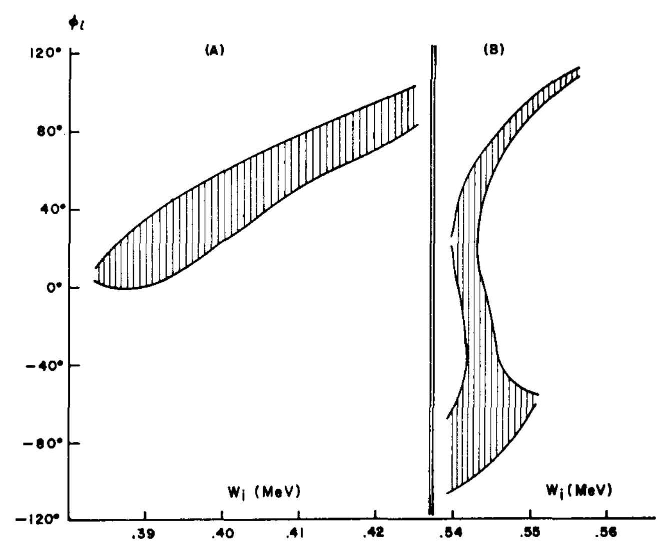

Fig. 5 Favorable range of the injection energy and the injection phase for a deuteron acceleration in BNL and NAL linacs. Average electric field assumed given by Fig. 2 broken line.