DEUTERON ACCELERATION IN THE C. L. A. (CERN LINEAR ACCELERATOR)*

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Acceleration of deuterons in the CLA using the 2π mode as employed for protons would require that the deuterons have the same velocity as the protons at every point along the linac structure. This would mean deuteron acceleration up to 100 MeV. This is far above any field level that is practically possible in the present machine. We can investigate the case where we use half the proton velocity in the 4π mode; so maintaining the same frequency of 202 Mc/s, the deuterons traverse one unit cell in two rf cycles. The alternating magnetic focusing properties are now identical for protons and deuterons, because the momenta of both particles are equal. Nonrelativistically speaking, this can be realized if the velocity of the deuteron is half the velocity of the proton; so the linac injection energy deuterons should be 270 keV instead of 540 keV for protons and linac final energy will be 25 MeV instead of 50 MeV for protons.

Approximately the energy gain for a synchronous particle per cell is:

$$W = e\bar{E}T L_n \cos \varphi_s$$

in which e = electron charge

$\bar{E}$ = mean accelerating field

T = transit time factor

L_n = cell length

φ_s = synchronous phase angle.

Thus, for deuteron acceleration, the transit time factor T_D should be half the factor T_H for protons, if the other quantities are identical for both particles; if $T_D > 1/2\ T_H$, one has to diminish E and if $T_D < 1/2\ T_H$, one must look for means of increasing E.

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*See: "A Theoretical and Experimental Comparison of Proton and Deuteron Acceleration in the CLA", CERN 64-22.

Courant (1962*) has calculated these ratios T_D/T_H for all gaps of the BLA, showing a reasonable drift tube geometry for deuteron acceleration.

Ratios of the energy gain per gap can be obtained by calculating the effective available voltage in the gaps for both particles, using theoretical values of the longitudinal electric field for the first cavity and experimental values for the second and third tanks:

$$R = \frac{\int_0^{\infty} E_x(x) \cos \frac{4\pi x}{\lambda}\, dx}{\int_0^{\infty} E_x(x) \cos \frac{2\pi x}{\lambda}\, dx} = \frac{\text{effective accelerating voltage for } D^+}{\text{effective accelerating voltage for } H^+} .$$

These ratios were evaluated for the first and last gap of each tank (see Table I). The results show a less optimistic situation compared with Courant's results for the BLA and they suggest, for deuteron acceleration, appreciable tilting of the electric field in each cavity.

TABLE I

Cavity I		Cavity II		Cavity III	
Gap 1	Gap 42	Gap 1	Gap 41	Gap 1	Gap 27
0.2625	0.5137	0.6345	0.3598	0.7613	0.4942

A more extended investigation of axial motion has been made by calculating linac phase acceptances for both particles as a function of mean accelerating field and tilt using a mercury autocode program for proton acceleration written by A. Carne of the Rutherford National Laboratory. The approximations in this program are: symmetric gap fields, constant drift tube radius in each cell and acceleration independent of radial excursions.

The phase acceptances have been calculated as follows: at first the ideal tilt factors of the first cavity have been determined so that phase oscillations around a given phase angle are as small as possible

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* E. D. Courant, "A Study of Possible Deuteron Acceleration", Conference on Linear Accelerators for High Energies, BNL, August, 1962.

($< 1^{\circ}$); then one searches for stable phase oscillations in the phase space. The tilt factors for the first cavity for synchronous deuteron acceleration compared to the tilt factors used for synchronous proton acceleration are shown in Fig. 1. Using these tilt factors, the linac acceptance for deuterons has been calculated for a stable phase angle of - 25 degrees, (see Fig. 2). On the basis of phase acceptance alone (so without radial loss), and a buncher peak voltage of 10 keV, deuterons are trapped for 80% between the initial phases 30° and 314°.

In practice, the flatteners in our cavities are fixed for synchronous proton acceleration and one can only impose from the outside a "linear" tilt gradient with tilt tuners positioned at the input and output end of each cavity. So it is more realistic to investigate deuteron acceptances with a linear change of electric field along the cavity.

Let us define acceptances in the energy phase plane as a product of the height of a bucket (stable energy range ΔE) and width of the bucket at mean injection energy (stable phase range $\Delta \varphi$), (see Fig. 3).

Figure 4 represents now proton and deuteron acceptances as a function of mean accelerating field for a set of negative tilts in the first cavity.*

The curves show that an increase in field level is necessary for deuteron acceleration in this drift tube structure and radio frequency and that tilt increase is more effective for deuterons than for protons. In practice, the increase in field level (which affects the whole cavity) is limited by radial losses, whereas the optimum tilt has not been reached.

The relation between acceptances, level and tilt for the second and third cavities are of less interest, because one can expect that the bunches can be captured in the respective buckets at appropriate level and/or tilt. Figures 5a and 5b show two typical deuteron buckets of the second cavity inside which an ellipse around an ideal deuteron bunch is drawn. Deuteron acceptances are here much less dependent on tilt compared with the first cavity.

Experimental deuteron acceleration has been investigated with a standard rf ion source assembly, producing deuteron beam currents up to 100 mA (10 μs pulse and 90% D^{+}). The beam performance for optimum machine conditions is given in Table II.

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*Tilt is defined as $\frac{\Delta E}{E}$ x 100% in which ΔE is the rf electric field at output end minus the electric field at the input end of the cavity.

TABLE II

Preinjector	Source current	100 mA
	Beam current after column	60 mA
	Total emittance ($\frac{\text{area}}{\pi}$)	20 cm-mrad
	Linac input current	40 mA
	Injection energy	268 keV
Linac	Output current after first cavity (4.9 MeV)	7 mA
	Output current after second cavity (14.6 MeV)	7 mA
	Output current after third cavity (22.9 MeV)	7 mA
Inflector	Total beam emittance (90%)	$<$3.0 cm-mrad
	Energy spread of 65% of the beam	$<$100 keV

In the first cavity, approximately 17% of the beam was trapped and no beam losses occurred in the second and third ones. The final deuteron energy was 23 MeV with an energy spread of around 60 keV for 65% of the beam. The remaining part had a wide energy spread concentrated around an energy of 7.2 MeV.

There are two reasons for low trapping in the first cavity:

a) Axial phase losses. The range of the tilt tuners is limited to - 14%. Increase of rf level (affecting the whole cavity) should also increase the axial phase acceptance, however an optimum was reached, which finds its origin in stronger radial defocusing forces across the accelerating gaps for higher electrical field; this could not be compensated with the quadrupole focusing.

NOTE: For deuterons, always stronger focusing than for protons is necessary; this can be explained by comparing the radial force constant across the accelerating gaps; this constant is - 1/2 the axial force constant ω_φ^2, which is the square of the frequency of phase oscillations per unit length (Smith and Gluckstern, 1955*). The first cavity yields $\omega_\varphi(D^+)/\omega_\varphi(H^+) \approx 1.5$, so the defocusing forces for deuterons across the gaps are somewhat more than twice as large as for protons under equal machine conditions.

b) Radial losses. An important part of the beam is lost by improper matching at injection due to a smaller instantaneous transverse

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*L. Smith and R. L. Gluckstern, Rev. Sci. Instr. 26, 220 (1955).

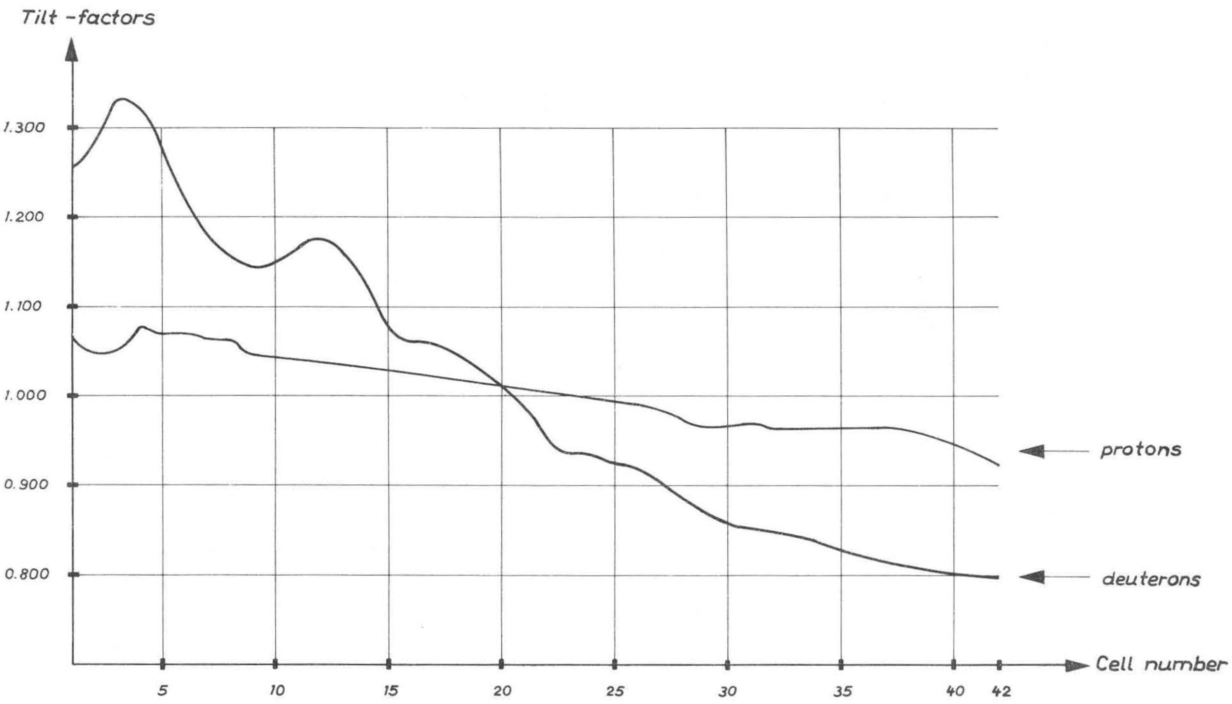

Fig. 1 Tilt factors for synchronous proton and deuteron acceleration in the first cavity.

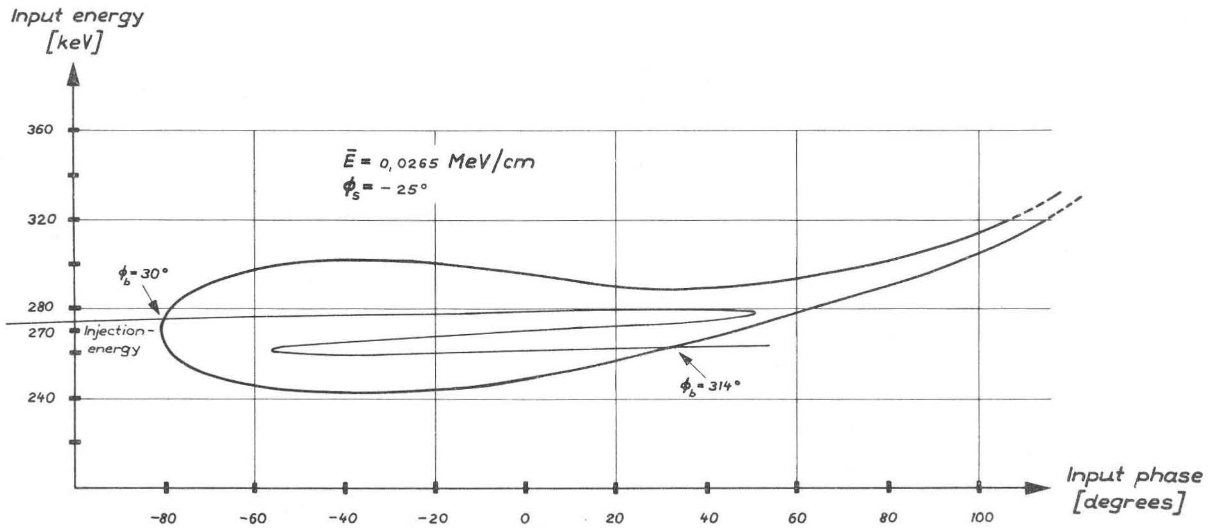

Fig. 2 Linac phase acceptance for deuterons with ideal tilt factors and a phase trapping curve for a buncher peak voltage of 10 keV. ϕ_b are particle phase angles at buncher position.

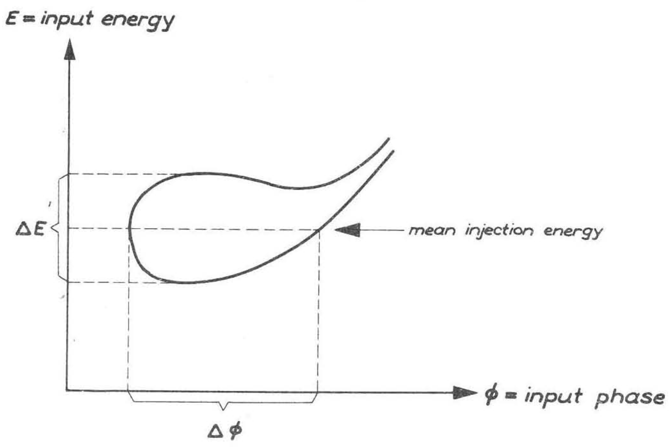

Fig. 3 Acceptance definition ΔE . Δφ

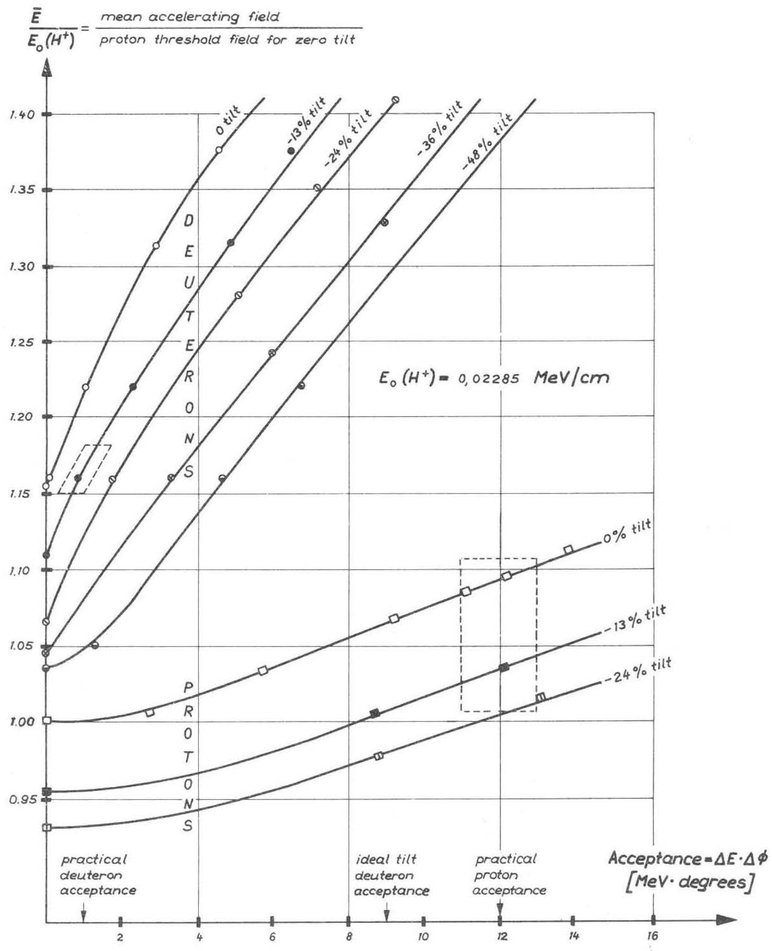

Fig. 4 Proton and deuteron acceptances as a function of accelerating field and linear negative tilt gradients in the first cavity. The parallelograms are actual working regions.

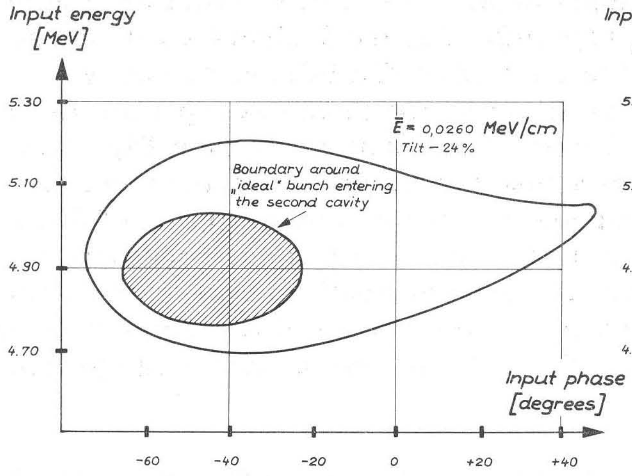

Fig. 5a Deuteron phase acceptance for the second cavity with positive tilt.

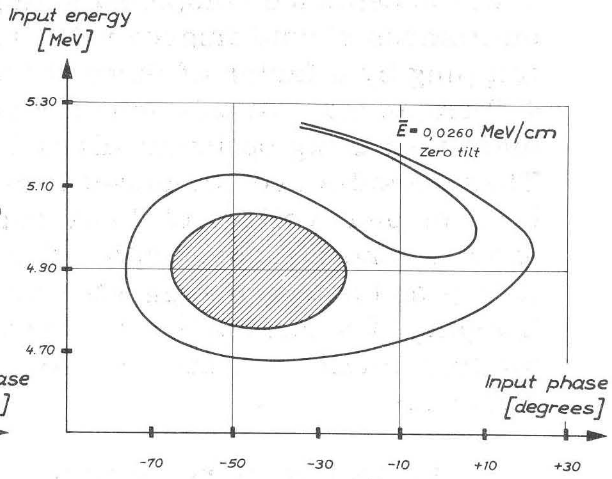

Fig. 5b Deuteron phase acceptance for the second cavity with flat field.

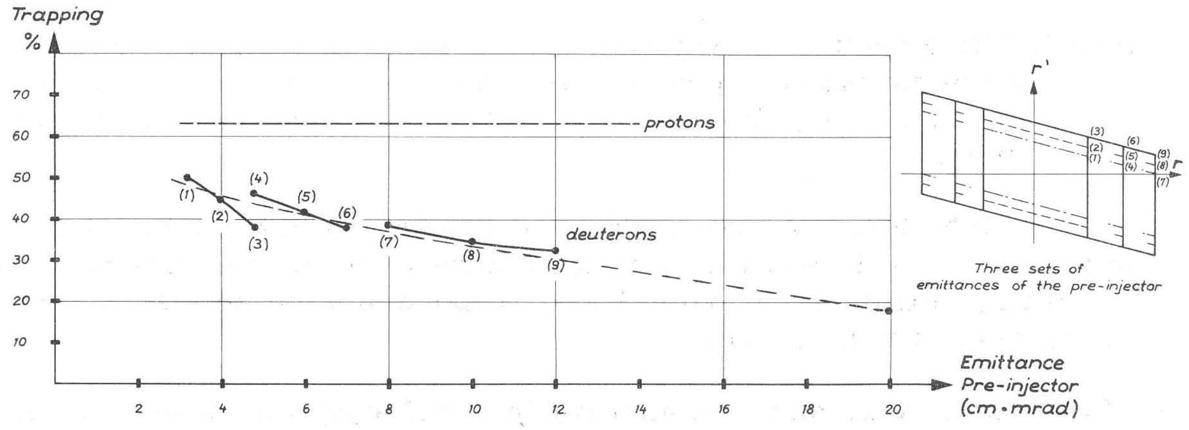

Fig. 6 Trapping for protons and deuterons as a function of injector emittances.

phase acceptance compared with protons. Therefore, smaller injector emittances should improve the trapping. Figure 6 shows an increase of trapping by a factor of three if the emittance diminishes to below 4.0 cm-mrad. At this injector emittance, the phase acceptance has been measured using optimum tilt and mean field conditions (see Fig. 7a). These results are compared with a theoretical phase acceptance. A buncher peak voltage of 7 keV suggests a theoretical trapping of 56%. In practice one measures 46%. The reasonable correspondence between theory and practice suggests that the present machine has an optimum trapping of around 50% for a preinjector emittance of around 4.0 cm-mrad; for this small emittance and low rf levels the radial focusing system is sufficient.

At the low energy side of the machine the radiation from deuteron interaction was 1 mrem/h or 7 n/cm^2/sec. This is a lower level than found from proton interaction with twice as much beam current. At the output end of the linac, a maximum dose rate of 20 mrem/h was measured.

SHAYLOR: I am very impressed with the fact that your ion source went well. We have a very elementary rf ion source in our Birmingham synchrotron and we started to accelerate deuterons about two years ago. Please don't ask me why. We had great trouble with the ion source; we had to get our witch doctor to say all sorts of interesting spells and to this day we don't really know why we cannot use commercial deuterium gas in it, but we have to use electrolyzed D_2O.

SLUYTERS: We have used commercial deuterium gas and normal operation of the source as if it were hydrogen gas except for the automatic flow control which was switched off.

SHAYLOR: I don't know why commercial gas would not work for us. Our injector is like your preinjector. We did not have trouble with the synchrotron, although it does not have beam control so we had to reprogram rf.

VAN STEENBERGEN: The emittance of the beam in the theoretical limit should be mass dependent. Was the emittance of the deuteron beam from the preinjector different from the corresponding emittance for an identical intensity of proton current?

SLUYTERS: Normalized to energy, the emittance was about twice as large as normal.

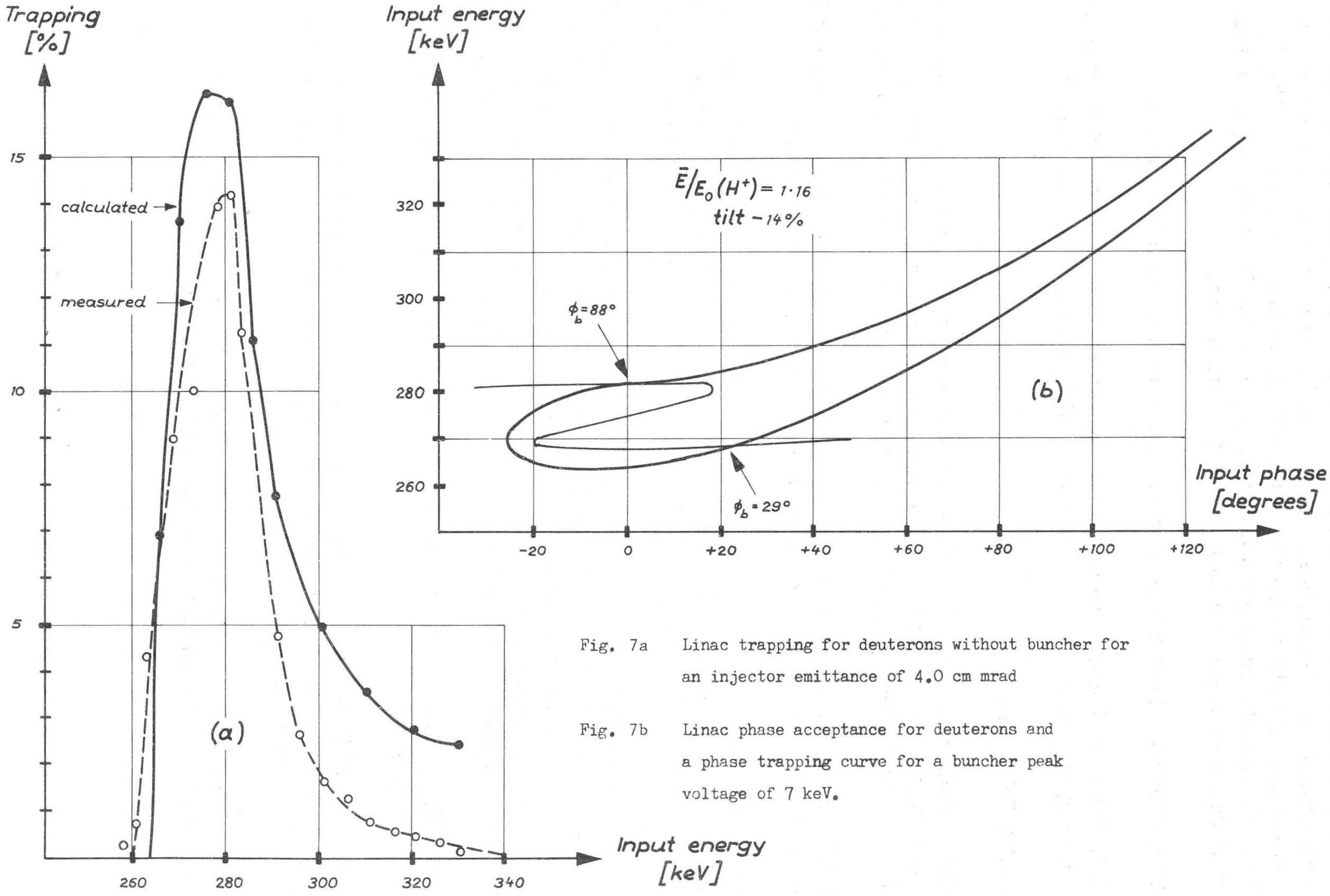

Fig. 7a Linac trapping for deuterons without buncher for an injector emittance of 4.0 cm mrad

Fig. 7b Linac phase acceptance for deuterons and a phase trapping curve for a buncher peak voltage of 7 keV.

VAN STEENBERGEN: The next question is regarding the longitudinal acceptance for deuterons. The calculated curve as shown here at a higher energy shows up the high energy acceptance tail in the fish diagram. The observed curve goes down to zero at the high energy end suggesting that you do not have a tail in the fish diagram.

SLUYTERS: There was a tail, but it was very low in intensity.

WADDELL: I was interested in your low background, when you were running the deuterons. I wonder, did you look for neutrons?

SLUYTER: Yes.

WADDELL: Then, does this not suggest that all of the loss was occurring essentially as one entered the machine, because certainly at energies of 4 or 5 MeV, the numbers of neutrons produced would have been very high.

BLEWETT: I think with protons the main capture loss is about 5 MeV, so with deuterons it should be about 1 MeV, should it not?

SLUYTERS: Yes. The main loss is during the first 10-15 drift tubes; this corresponds roughly with 1 MeV for deuteron acceleration. But, nevertheless, the background was much lower than we should expect.

FEATHERSTONE: I noticed in the first slide you showed us that the change of tilt required in going from accelerating protons to accelerating deuterons seemed to be in one sense in the first tank and in the opposite sense in the other two tanks. Do you use a constant g over ℓ ratio all the way through the machine as in the early Alvarez structures?

CARNE: In the first tank it is constant. Then the second two tanks have a varying g over ℓ .

FEATHERSTONE: So perhaps the fact that one had to change the tilt one way in the one tank and the other way in the other tanks is a reflection of the difference in design of the cavities.

SLUYTERS: In theory and in practice, the tilt has not an important influence on the capture as one can observe in Fig. 5.