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1 GeV リニアック検討資料

1 GeV LINAC DESIGN NOTE

題目 (TITLE) The 1 - GeV Proton Linac for the Japanese Hadron Project

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概要 (ABSTRACT)

A proton linac for the Japanese Hadron Project(JHP) has been designed. It comprises a volume production-type H- ion source, a 432-MHz RFQ linac (3 MeV), a 432-MHz DTL(148 MeV) and a 1296-MHz high-b linac (1 GeV). The designed peak beam current is more than 20 mA (average of 200 mA), with a pulse length of 400 msec and a repetition rate of 50 Hz. The design of the linac was determined with special emphasis on the achievement of stable operation with a minimum beam loss in the high-energy part of the linac at a maximum beam current. Therefore, the main parameters of the linac, including both longitudinal and transverse acceptances, were carefully chosen on the assumption that the normalized beam emittance is to be 1.3 pmm.mrad(90%) at the entrance of the RFQ linac.

KEY WORDS:

Ion source, RFQ, DTL, CCL, Magnet, Monitor, Beam Dynamics,
Transport, Vacuum, Cooling
Klystron, Low level rf, High power rf, Modulator
Control, Operation, Radiation, Others

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THE 1-GeV PROTON LINAC FOR THE JAPANESE HADRON PROJECT

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ABSTRACT

A proton linac for the Japanese Hadron Project(JHP) has been designed. It comprises a volume production-type H^- ion source, a 432-MHz RFQ linac (3 MeV), a 432-MHz DTL(148 MeV) and a 1296-MHz high-β linac (1 GeV). The designed peak beam current is more than 20 mA (average of 200 μA), with a pulse length of 400 μsec and a repetition rate of 50 Hz. The design of the linac was determined with special emphasis on the achievement of stable operation with a minimum beam loss in the high-energy part of the linac at a maximum beam current. Therefore, the main parameters of the linac, including both longitudinal and transverse acceptances, were carefully chosen on the assumption that the normalized beam emittance is to be 1.3 πmm·mrad(90%) at the entrance of the RFQ linac.

1. INTRODUCTION

A 1-GeV proton linac will be constructed in order to inject proton beams into various ring accelerators of the Japanese Hadron Project(1-4). The parameters of the beams to be delivered by the linac are listed in Table I. The linac has three distinctive features: 1) high energy, 2) high average current and 3) high duty factor of an rf system, that should be carefully taken into account in designing the linac. It is also required that the linac can be operated with extreme stability.

Table I Design parameters of the H^- linac

Energy	1 GeV	Total length	~500 m
Peak current	20 mA	Repetition rate	50 Hz
Pulse length	400 μs	Average current	>200 μA

A fundamental scheme of the proton linac was proposed, as shown in Fig. 1. The linac comprises a volume production-type H^- ion source, a 432-MHz RFQ linac (3 MeV), a 432-MHz DTL(148 MeV) and a 1296-MHz high-β linac (1 GeV). Negative hydrogen beams are to be accelerated, since the injection efficiency is higher than the multi-turn injection of proton beams.

Among the various parameters of linacs, the accelerating frequency is one of the most important, since the cost and performance are strongly dependent upon the frequency. In general, both of the shunt impedances and the possible accelerating fields of the cavities with the same figure increase proportionally to a square root of the resonant frequency. However, as the frequency increases, the sizes of the accelerating cavities and klystrons decrease, so that the cooling of these RF parts becomes difficult and the beam acceptances of the cavities decrease. Thus, the nearly highest frequency should be chosen, as long as the cooling of the RF parts is feasible and the beam acceptance is sufficiently large. Another important condition arises from the available length of the space(less than 500 m). If the optimized beam dynamics are achieved within this length, a low accelerating field is desirable from the viewpoint of long-term stable operation. A calculation of cost optimization indicates a rather low accelerating field, below 4 MV/m. Taking these factors into account, we have chosen 1296 MHz for the frequency of the high-β linac and 432 MHz for those of the RFQ and the DTL. Average accelerating fields of 3 MV/m for the DTL and from 3.6 to 4.4 MV/m for the high-β linac have been chosen.

In designing a high-intensity and high-energy proton linac, minimization of beam losses at the high-energy region of the accelerator plays an important role. Otherwise, radioactivity caused by the beam losses would become a serious problem in long-term operation.

It is noted that the beam quality deterioration, beam halos and an undue low-energy tail were observed along

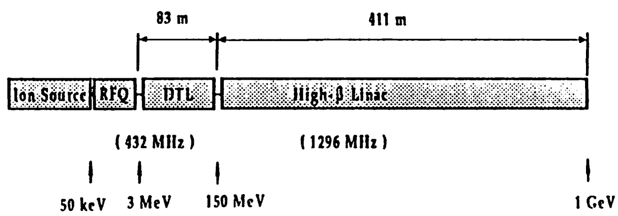

Fig. 1 The scheme of the proton linac.

with an increase in the beam intensity at LAMPF(5). At Fermi Laboratory a transverse emittance growth by a factor more than three has been observed in DTL acceleration from 750 keV to 200 MeV(6). It is reasonable to expect that these phenomena are closely related to the beam losses in the high-energy region. Thus, understanding of these phenomena is crucial in minimizing the beam losses.

The physics of emittance growth in the low-energy region has been studied extensively (7-9). The equipartitioning of the kinetic energy in six-dimensional phase space (10,11) is one of the useful methods to reduce the emittance growth. Also, a new design principle of the DTL was proposed(12), in which the accelerating field gradually increases keeping the longitudinal focusing force constant.

Keeping the results of the previous studies in mind the accelerating parameters were determined with emphasis on minimizing the beam losses as follows. First, the acceptances,both longitudinal and transverse, were made as large as possible for all accelerator tanks. Second, a matched and equipartitioned beam injection into the DTL was used. Here, it is noted that the beam is accelerated to the rather high energy (3 MeV) by the RFQ linac in order to improve the quality of the beam injected into the DTL. Third, we attempted to minimize the emittance growth, both longitudinal and transverse. In this context it is noted that the beam emittances have been represented in terms of rms values in the previous studies. However, in order to discuss the beam quality for minimizing beam losses the 90% values of the emittances that reflect the tail part of the beam will be sometimes more suitable measures than their rms values that reflect the core part. Thus, we will present both the 90% and rms values of the emittances. Details of the procedure are described in the following sections.

2. ION SOURCE

The volume-type of negative hydrogen ion source is going to be used. In order to produce an intense ion beam, it is necessary to use cesium to enhance the probability of forming an negative hydrogen ion in plasma. The volume ion source has a possibility to reduce the cesium consumption rate in operation compared with any other type of negative hydrogen ion sources and this would be very helpful for long term operation of the RFQ linac in eliminating sparking problems caused by cesium atoms. The typical parameters of the volume ion source under development are summarized in Table II. With feeding a very small amount of the cesium vapor into the plasma chamber, the beam current density of 45 mA/cm^2 and the normalized emittance of about 1 πmm·mrad (90 %) have been obtained.

Table II Typical parameters of the present volume ion source

Arc current	280 A	Arc voltage	130 V
Bias voltage	+ 8 V	Extraction voltage	1 kV
Acceleration voltage	40 kV	Extraction gap	6 mm
Acceleration gap	16 mm	H^2 flow rate	3.8SCCM

3. RFQ LINAC

The H^- beam from the ion source is to be injected into a 432 MHz four-vane-type RFQ linac at an injection energy of 50 keV and then accelerated to 3 MeV. The design parameters of the RFQ linac are listed in Table III; these were determined so as to obtain a normalized acceptance of 1.5 πmm·mrad for a beam current of 20 mA with the maximum electric field ($E_{s,max}$) of 1.8-times the Kilpatrick limit.

One of the important rf properties is the mode separation of other modes from the TE210 mode. From this point of view, the length of the cavity is very important and a proposed length of about 263 cm has been approved, in spite of increased fabricating difficulty and a decrease in the longitudinal stability of the tank. The RFQ linac with a small bore radius and a long vane will require rigid tolerance limits on dimensional errors; it is also difficult to machine, assemble and align the long vanes accurately. In consideration of a possible lack of fabrication techniques of such long vanes, the possibility of optional acceleration by two RFQ tanks was proposed and studied. If two rf-independent tanks (1.4-m length each) were placed with a 2-cm drift space, the decrease in the transmission efficiency would become about 10% for a 20 mA-1.5 πmm·mrad beam, which seems allowable. In addition, there remains no mode-mixing problems and no difficulties in the mechanical engineering of such short tanks. The longitudinal stability of the short tank will be also improved.

Table III Parameters of the 432-MHz H^- RFQ

Frequency			432	MHz
Input energy			0.05	MeV
Output energy			3	MeV
Vane length			263	cm
Number of cells			297	
Mean bore radius			0.33	cm
Minimum bore radius			0.21	cm
Cavity diameter			15.4	cm
Normalized acceptance	(100%)		1.5	πmm·mrad
	(90%)		1.0	
Normalized emittance at 3 Mev				
	(100%)		2.3	
	(90%)		1.0	
Kilpatrick factor			1.8	
Max. surface field ($E_{s,max}$)			361	kV/cm
Focusing strength			4.14	
Transmission	(0 mA)	98 %	(20 mA)	94 %

4. BEAM TRANSPORT BETWEEN RFQ LINAC AND DTL (BT)

The beam dynamics in the low-energy beam line between the RFQ linac and the DTL determines the beam behavior in the following tanks. There are three purposes in the BT. One is for matching the beam in the longitudinal phase space using both drift spaces and a bunching cavity. The second is matching the beam in the transverse phase space using quadrupole magnets. The third is chopping the beam in order to decrease the beam losses after injection into the following circular accelerator. The required rf pulse length for the chopper is 130 nsec with a 3-MHz repetition rate, as shown in Fig.2. One of the candidates for a fast beam chopper is a proposed rf deflecting cavity(13). Preliminary results of a beam-optics calculation (including two deflecting cavities and a buncher cavity) are shown in Fig.3. The focusing parameters were chosen in order to increase the efficiency of the deflecting cavities and to obtain a narrow beam around the buncher cavity. The deflecting cavities with a filling time of 14 nsec are to be driven by solid-state power amplifiers with a peak power of 11 kW.

The longitudinal phase spread at the entrance of the DTL is an important parameter from the viewpoint of achieving both matched and equipartitioned conditions. It has been shown by computer simulation that an injection phase spread at the entrance of the DTL can be related to beam losses in the high-energy part of the linac(14). Therefore, an rms half-phase spread below 15 degrees was chosen with a buncher voltage of 70 kV.

5. DRIFT-TUBE LINAC

A 432-MHz drift-tube linac (DTL) accelerates a beam from 3 MeV to 148 MeV. The parameters of the drift-tube linac are listed in Table IV. The DTL comprises 13 tanks, each of which are to be driven by a 1-MW klystron. The shunt impedances of the drift-tube linac are

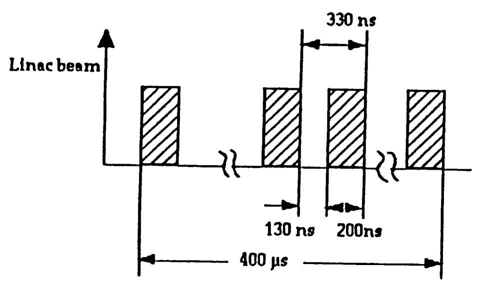

Fig.2 Required pulse structure for the linac beam.

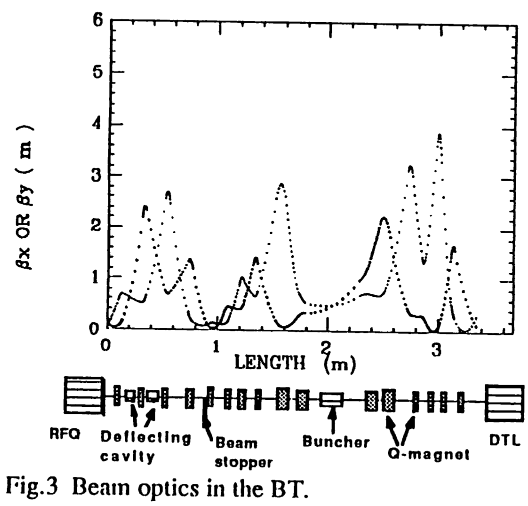

Fig.3 Beam optics in the BT.

shown in Fig.4 as a function of β(v/c). Figure 5 shows the relation between the phase spread of the injection beam and the optimum accelerating field calculated with the equipartitioning theory, on the assumption that the zero-current transverse phase advance (σ_0^t) is 60 degrees and the beam current is 20 mA. If we choose a larger bunch length or lower σ_0^t, the optimum accelerating field decreases in order to satisfy the matched condition. However, a wide injection phase spread should be avoided from the viewpoint of beam losses in the high-energy part of the linac. A decrease in the transverse phase advance should also be avoided since it causes a decrease in the acceptance, causing more strict demand for the alignment of the quadrupole magnets and tanks. Then, for the main parameters of the DTL, we chose an accelerating field of 3 MV/m, a synchronous phase of 30 degrees for the first tank, a zero-current transverse phase advance of about 60 degrees and an rms phase spread of below 15 degrees for the 20 mA RFQ beam with a normalized transverse emittance (90%) of 1.5 πmm·mrad.

In order to study difference between flat-field type and inclined-field type for an accelerating field in DTL, a beam simulation including space-charge effects with a

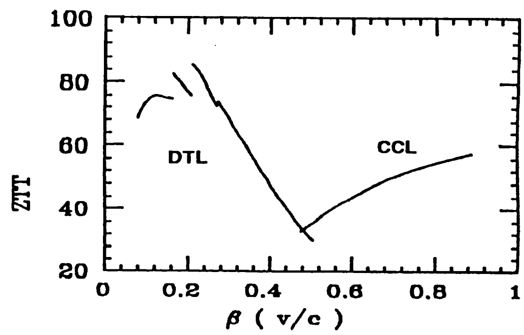

Fig. 4 Shunt impedances of the drift-tube linac and the annular-coupled linac as a function of β. The values in MΩ/m, as calculated with the SUPERFISH, are plotted.

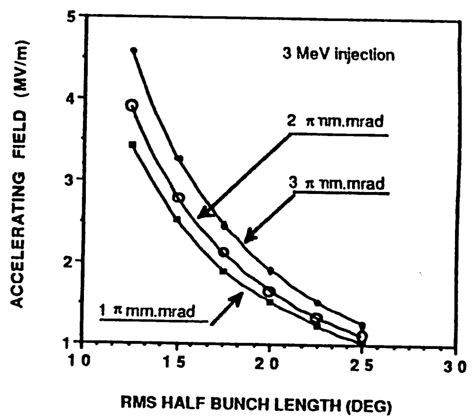

Fig. 5 Optimum accelerating field at the entrance of the DTL vs. the injection phase spread. I=20 mA and σ_0^t = 60°.

beam current of 20 mA was carried out with the aid of PARMILA for four kinds of distributions of the accelerating field (CASE-1 - 4). The accelerating fields were chosen to be constant (3MV/m) for CASE-1, changed from 1.85 to 3 MV/m for the first tank of CASE-2 and held constant for the other tanks of CASE-2, and changed from 1.85 to 8.5 MV/m for CASE-3 and CASE-4. The fields of CASE-3 and CASE-4 are approximately varied in order to keep the longitudinal focusing force constant. The zero-current transverse phase advance is held nearly constant at around 60 degrees. The injection particles for CASE-1, CASE-2 and CASE-3 were prepared by the codes for the RFQ, the buncher cavity and the drift space. The injection particles for the CASE-4 are prepared with a drift space of 1.7-m long after the RFQ acceleration for obtaining a wider phase spread in order to satisfy the matched condition. The normalized transverse emittances at the entrance of the RFQ have been assumed to be 1.3 πmm·mrad (90%). The injection phase of the DTL has been optimized in order to obtain the smallest longitudinal emittance at the exit of the DTL. The calculated results are listed in Table V. The longitudinal emittances at the exit of the DTL are shown in Figs.6-8. It can be seen that the longitudinal emittances with a high-inclined accelerating field become larger than those with a low-flat accelerating field. In addition, it seems no distinguishable differences in the transverse beam emittances at the DTL exit. Then, the flat-field type was chosen for an accelerating field in DTL.

Table IV Parameters of the drift-tube linac and high-β linac

	DTL	High-β linac	
Frequency	432	1296	MHz
Input energy	3	148	MeV
Output energy	148	1017	MeV
Accelerating field	3	3.6 ~ 4.4	MV/m
Synchronous phase	-26°	-30°	
Tank length	75.7	303.0	m
Total length	83.3	410.9	m
Bore radius	0.5	1.5	cm
Number of cells	342	3568	
Number of tanks	13	152	
Total wall loss	9.0	81.7	MW
Beam loading	2.9	17.4	MW
Total power	11.9	99.1	MW
Number of klystrons	13	36	
Klystron power	1.0	3.0	MW
Normalized acceptance			
Ax,n (90 %)	8.9	29	πmm·mrad
(100%)	10.0	36	πmm·mrad
Ay,n (90 %)	8.8	26	πmm·mrad
(100%)	10.0	34	πmm·mrad
Acceptable			
Input energy spread	0.30	3.0	MeV
Output energy spread	1.44	8.8	MeV
Acceptable			
Input phase spread	88°	87°	
Output phase spread	24°	32°	

All of the tanks will be stabilized with post-couplers in order to obtain a finite group velocity(15). Before stabilization with post-couplers, the field of the tank is perturbed according to the distribution of the resonant frequency of each cell(16). In order to reduce the difference in the frequency shift by the stem between the first cell and the last cell for the first tank, the diameter of the stem is partially increased from 15 to 20 mm (Fig.9). As a result, it decreases from 167 to 78 kHz, as shown in Fig.10. We then tried to tune the resonant frequency of each cell to the same value, including the perturbation by stems in the SUPERFISH calculation. The reason of the fine correction of each cell frequency is to minimize the excitation of the post modes after tuning of the post-couplers(17). The post modes have large deflecting electric fields on the beam axis, which have no good effect on the beam motion.

We are planning to use permanent magnets made of Nd-Fe-B, since such magnets require neither wiring

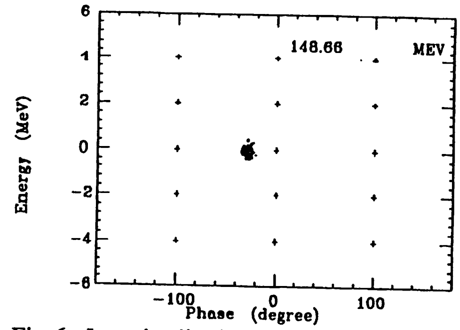

Fig.6 Longitudinal emittance at the exit of CASE-1. E_0=3MV/m. $\Delta\phi_{in}$(rms)=8.6°.

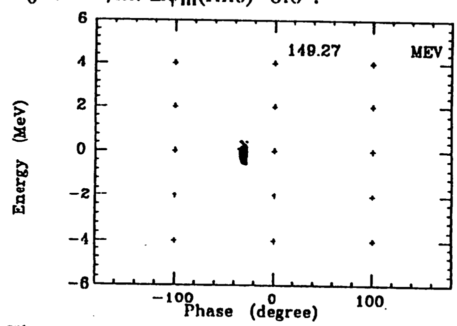

Fig.7 Longitudinal emittance at the exit of CASE-3. E_0=1.85-8.5 MV/m. $\Delta\phi_{in}$(rms)=8.6°.

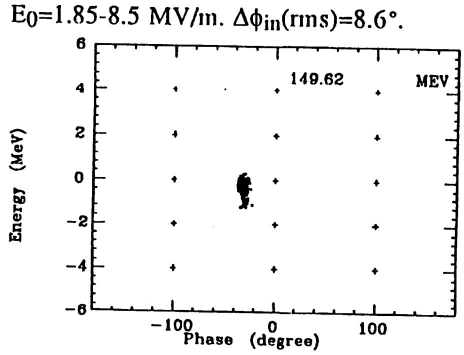

Fig.8 Longitudinal emittance at the exit of CASE-4. E_0=1.85-8.5MV/m. $\Delta\phi_{in}$(rms)=19.6°.

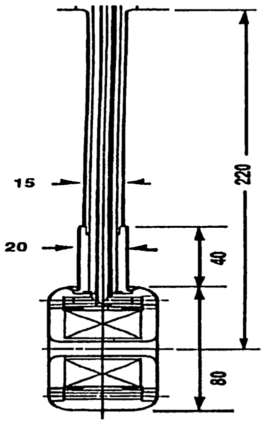

Fig. 9 Drift tube with a modified stem.

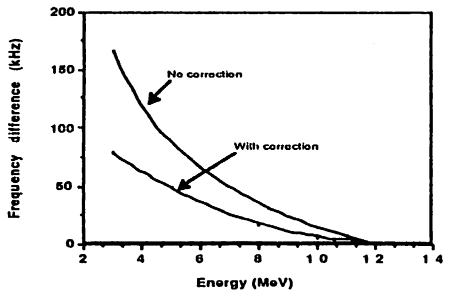

Fig.10 Difference in the shift of the cell-frequency between cells with the modified-stem and those with a straight-stem.

nor water-cooling: that is, they are maintenance-free and Nd-Fe-B can produce a strong magnetic field required for the first tank. At present, we have succeeded in sealing the drift-tubes by two methods. One is to use electron-beam welding (EBW) with a magnetic shield plate and a large heat mass around the drift-tube. The other is to use copper-electroplating of 0.1 mm in thickness. Since EBW near the beam hole is difficult, due to its small size, the sealing point has been moved to the outer part of the beam-hole corner by expanding the diameter of the end part of the inner pipe with a pipe-expander. A rise in the temperature of the magnet with EBW is suppressed within 20 degrees.

6. HIGH-β LINAC

Standing-wave linacs are more advantageous than traveling-wave linacs, if RF pulse widths are longer than the filling times (~ a few μs typically). The π/2 mode operation of a multi-cell cavity is necessary to maintain a high degree of stability of the accelerating field against effects due to heavy beam loading and manufacturing imperfections. Then, possible candidates for the high-β cavity structure are an alternating periodic structure (APS)(18) without nose cones or coupling slots, an alternating periodic structure with nose cones and coupling slots, a side-coupled structure (SCS)(19), disc-and-washer structure (DAW)(20) and an annular-coupled structure (ACS)(21).

Table V Comparison of the longitudinal emittances at the exit of DTL among four kinds of acceleration

	CASE-1	CASE-2	CASE-3	CASE-4	
Accelerating field	3	1.85-3	1.85-8.5	1.85 - 8.5	MV/m
At the entrance					
rms phase spread	8.6	8.6	8.6	19.6	degree
At the exit					
rms phase spread	2.11	2.12	1.36	1.56	degree
rms emittance	0.123	0.148	0.137	0.327	MeVdeg
90% emittance	0.457	0.651	0.716	2.265	MeVdeg

Extensive computational (with the code MAFIA(22)) and experimental studies were carried out in order to obtain an optimized geometry of the ACS(23). Then, a new ACS cavity was designed to keep the TM-dipole mode away from the passband of the π/2 accelerating mode and to suppress excitation of the TM-quadrupole mode in the annular coupling cavity, resulting in a 5 - 10% inferiority of the quality factor, with a coupling constant of 5% compared with the SCS .

The shunt impedances of the ACS calculated with code SUPERFISH are shown in Fig.4 as a function of β. A rather large bore radius of 1.5 cm as a 1296-MHz structure was chosen so as to obtain a large transverse acceptance. The gap length was adjusted in order to optimize the shunt impedance.

It can be seen in Table IV that the normalized transverse acceptances of the high-β linac are about 3-times those of the DTL and 10 ~ 15-times those of the RFQ. However, it should be noted that the acceptances were computed only for synchronous beams. It has been found by the computer calculations that the transverse acceptances are reduced to 60% of those of synchronous beams if the beam phase at the injection is located near the separatrix(3). Although the beam velocity becomes large in the high-energy part of the linac, an rf defocusing force has a large effect on the beam dynamics, since there are many rf defocusing impulses during a focusing period. The transverse phase advance under such rf impulses (μ') is related to those without rf impulses (μ) as ,

$$\cos\mu' = (1 + n^2 L_c\xi/6)\cos\mu + (n^2 L_c\xi/3)\cos\theta\cosh\theta ,$$

$$\theta = kL_c , \quad k^2 = ecB'/m_0c^2\beta\gamma ,$$

$$n = L_2/L_c , \quad \xi = -e\pi E_0 T \sin\phi / (2m_0c^2\beta^2\gamma^3) ,$$

where L_2 is the length of a tank, L_c the length of a unit cell, L_Q the length of a quadrupole magnet, B' the field gradient of the quadrupole magnet, E_0 the average accelerating field, T the transit time factor, φ the synchronous phase, and ξ the rf defocusing force. Here, m_0,e,c,β and γ express the usual kinematic parameters. The assumption is made that n>>1 and one can neglect the length between the two neighboring magnets. Figure 11 shows the calculated results of the transverse acceptance with rf defocusing divided by those with no rf defocusing versus β, where L_2=1.2 m, E_0=4 MV/m, φ=-30° and μ=60°. Figure 12 shows similar parameters versus the tank length (L_2), where E_0=3.6 MV/m, φ=-30° and μ=60° and the beam energy is 150 MeV. As can be seen from Figs.11-12, the decrease in the acceptance becomes large when the beam energy is low and the tank length becomes longer. Thus, 16 sets of short (1.1-m long) tanks are adopted for the initial part of the linac, while the lengths of the other tanks range from 2.0 to 2.2 m. Then, the transverse acceptance increases by 80% with the short tanks. The longitudinal acceptance decreases with the introduction of short tanks because of the increase in the total drift space between the tanks. However, a decrease of 25% is allowable since the beam energy is chosen to be sufficiently high and the phase acceptance is relatively large (the number of frequency multiplications between the DTL and the high-β linac is three).

The bridge coupler of a multi-cell type has been studied and a model for high-power tests is under construction(24). The bridge coupler combines two adjacent tanks. The four tanks with three bridge couplers make a unit module. Since the module has many unit cells, the rf properties, tilts of the accelerating field and rf phase due to beam loading or manufacturing imperfections of the cavity, become very important for stable operation. The field stability of the standing-wave structure was studied(25) using a coupled resonator model. A computer simulation based on the analysis mentioned above is under way for finding the limit of the allowable perturbation given by the accelerating structures and the operating parameters.

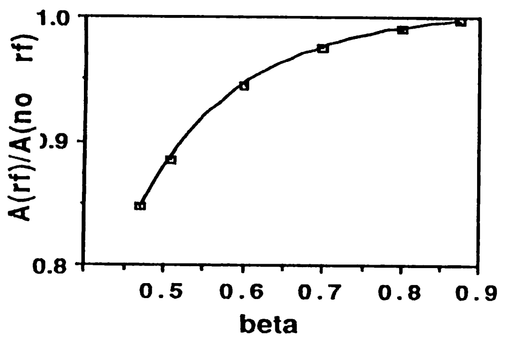

Fig. 11 Decrease in the transverse acceptance with an rf defocusing force versus β. A tank length of 1.2 m is assumed.

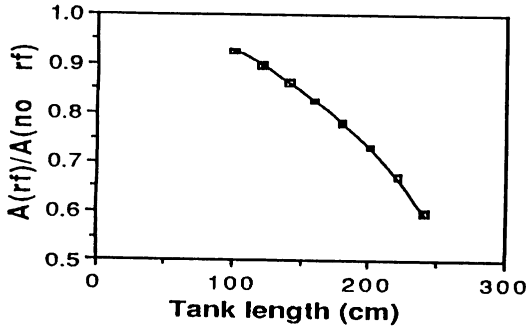

Fig. 12 Decrease in the transverse acceptance with an rf defocusing force versus tank length at an energy of 150 MeV.

7. RF POWER SOURCE

The RFQ and the DTL require 14 klystrons with an output power of 1 MW at a frequency of 432 MHz. The high-β linac requires 36 klystrons with an output power of 3 MW at a frequency of 1296 MHz. An rf test-stand with a 6 MW klystron (Thomson,TH2104A) and a 15 MW line-type modulator was constructed in 1988. An rf test-stand for a DTL is under construction. The design of the rf system and an initial performance of the test stand are reported in the literature(26-30).

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