KEK Report 97-3
JHF-97-1
May 1997
A

Proposal for Japan Hadron Facility

JHF Project Office

April 17, 1997

High Energy Accelerator Research Organization

II. 4. 200-MeV Linac

II. 4. 1. Overview

A 200-MeV proton linear accelerator for the JHF has been designed (Ref. [1]). It consists of a 3-MeV radio-frequency quadrupole linac (RFQ), a 50-MeV drift tube linac (DTL) and a 200-MeV separated-type drift tube linac (SDTL). A frequency of 324 MHz has been chosen for all of the rf structures. A peak current of 30 mA (H^- ions) of 400 μsec pulse duration will be accelerated at a repetition rate of 25 Hz. A future upgrade plan up to 400 MeV is also presented, in which annular-coupled structures (ACS) of 972 MHz are used in an energy range of above 150 or 200 MeV. One of the design features is its high performance for a beam-loss problem during acceleration. It can be achieved by separating the transition point in the transverse motion from that of the longitudinal motion. The transverse transition at a rather low-energy range decreases the effects of space-charge, while the longitudinal transition at a rather high-energy range decreases the effects of nonlinear problems related to acceleration in the ACS. Coupled envelope equations and equipartitioning theory are used for the focusing design. The adoption of the SDTL structure improves both the effective shunt impedance and difficulties in fabricating drift tubes with focusing magnets. An accurate beam-simulation code on a parallel supercomputer was used for confirming any beam-loss problem during acceleration.

II. 4. 2. Requirements for the JHF linac

The required main parameters for the JHF proton linac are listed in Table 1. The construction plan of the linac consists of two stages. In this paper, the first stage is mainly described. The main features of the parameters are the high average current and the high output energy compared with the existing proton linac at KEK.

II. 4. 3. Design criteria

Within the framework of satisfying the requirements, our criteria for designing of the linac are as follows:

1) Stable operation with minimum beam losses

The beam-loss issue during acceleration is one of the most important problems, since the peak and average currents are very high. The following procedures were adopted in order to achieve stable operation with minimum beam losses. Firstly, achieving good beam qualities in both the transverse and longitudinal phase spaces is very important. Secondly, the linac should be designed and constructed with appropriate margins in order to achieve a stable and reliable operation of the total system, including the accelerating structure, rf power supply, water-cooling system, vacuum system and monitor and control system.

2) Easy tuning for varied peak currents

One of the important problems in a high-intensity linac is to establish an effective tuning method in all parts of the linac for various peak beam currents, since the beam-loss problem often becomes serious when the peak current increases.

3) Minimum cost

A simple accelerator structure, both in rf properties and mechanical structure, is desirable, since it leads to reliable and stable operation with the total minimum cost finally.

II. 4. 4. The configuration of the linac

According to the criteria mentioned above, a 200-MeV proton linear accelerator has been designed. It consists of a 3-MeV RFQ, a 50-MeV DTL and a 200-MeV SDTL. A future upgrade plan up to 400 MeV is also included, in which a 972-MHz ACS are used in an energy range of above 150 or 200 MeV. The design is summarized in Table 2 and shown in Fig. 1. The effective shunt impedances for the three accelerating structures are given in Fig. 2. The features of the design are as follows:

1. A frequency of 324 MHz has been chosen for all of the rf structures up to 200 MeV.
2. An SDTL has been chosen in an energy range from 50 to 200 MeV.
3. A 3-MeV RFQ has been chosen.
4. A transition energy of 150 or 200 MeV from the SDTL to the ACS has been selected.
5. The klystrons are used for all of the accelerating structures.

One of the design characteristics is its high performance for a beam-loss problem during acceleration. It can be achieved by separating the transition point in the transverse motion from that of the longitudinal motion. The transverse transition at a rather low-

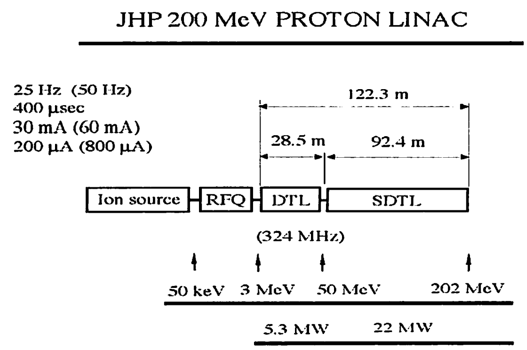

Fig.II.4.1 Schematic view of the JHP 200-MeV proton linear accelerator.

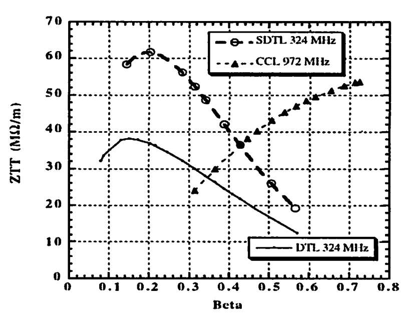

Fig.II.4.2 Effective shunt impedances used for the JHP proton linac.

energy range (50 MeV) decreases the effects of space-charge, while the longitudinal transition at a rather high-energy range (150 or 200 MeV) decreases the effects of nonlinear problems related to acceleration in the ACS. Therefore, the design has no longitudinal (frequency) transition up to the SDTL part. The characteristics mentioned above were confirmed using an advanced beam-dynamics simulation code (Ref. [2]), including both a more accurate electromagnetic field distribution in the acceleration process and a more exact three-dimensional space-charge calculation than ever used. A frequency of 324 MHz is selected for the following reasons:

1. The space-charge effects are greatly reduced compared with those at a conventional frequency of 200 MHz.
2. The electroquadrupole magnets for drift tubes can be fabricated on the assumption of a 3-MeV RFQ.
3. A 3-MeV RFQ of a single tank is possible.
4. A klystron is available with some modifications from that for a frequency of 350 MHz.
5. An ACS for a high-β structure can be fabricated assuming a frequency multiplication factor of three.

II. 4. 5. Brief description of each component of the linac

II. 4. 5. 1. The ion source and the RFQ (Refs. [3] and [4])

A volume-production type H^- ion source at the test stand at KEK could produce a 16-mA beam of 350 μsec pulse duration at a repetition rate of 20 Hz without cesium at a typical operation. The 90% normalized transverse emittance is 0.41 πmm-mrad. Since the designed acceptance of the 432-MHz RFQ linac was approximately 1 πmm-mrad and that of a 324-MHz structure can be further increased by a factor inversely proportional to the frequency ratio, it is reasonable to expect that one will obtain a peak current of more than 30 mA. It is also noted that the peak current is increased by a factor of approximately three by introducing some amount of cesium.

The 3-MeV, 432-MHz RFQ at the test stand at KEK accelerated a 13.2-mA beam with a transmission efficiency of 82.5% and with an emittance-growth ratio of 34%. The world-highest acceleration energy was realized by newly invented field stabilization method PISL(π-mode stabilizing loop)[3]. When the operating frequency is decreased from 432 to 324 MHz, the fabrication of the RFQ became easier. An output energy of 3 MeV is chosen for the following reasons:

1. The magnetic field gradient required for the injection part of the DTL becomes too high if a lower output energy is selected.
2. The length of the RFQ becomes too long to easily fabricate vanes as one unit within a tank if a higher output energy is selected.
3. A higher energy is not desirable from the viewpoint of radioactivity due to the lost beam by a fast beam chopper. It is also difficult to chop the beam with an energy higher than 3 MeV.
4. A configuration of two RFQ tanks, connecting successively via a beam-transport line in which a fast beam chopper is placed, is dismissed, since the tuning of the two tanks seems to be difficult.

II. 4. 5. 2. Beam-transport line between the RFQ and the DTL (Refs. [5] and [6])

The beam-transport line between the RFQ and the DTL has two main purposes: one is to match the beam both transversely and longitudinally to the DTL acceptances using flexible tuning parameters and monitoring systems and the other is to chop the beam by a

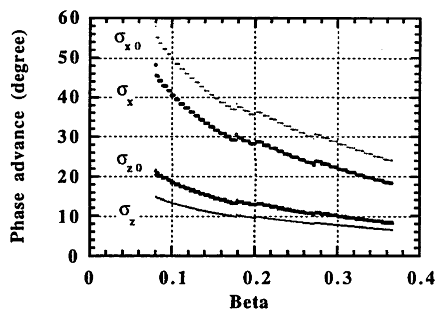

Fig.II.4.3 Phase advances in both the transverse and longitudinal phase spaces along the DTL. A peak current of 30 mA is assumed.

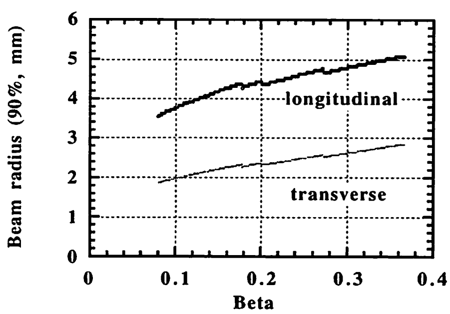

Fig.II.4.4 Variation of the beam size along the DTL.

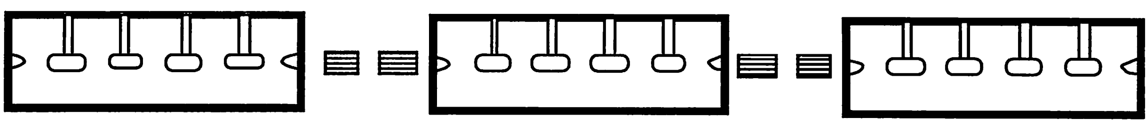

Fig.II.4.5 Schematic view of the SDTL structure. The focusing magnets are indicated by squares.

fast beam chopper in order to decrease the beam losses after the injection into the following ring.

II. 4. 5. 3. The DTL

The DTL accelerates the beam from 3 to 50 MeV with three tanks. Each tank is stabilized with post couplers (Ref. [7]) in order to suppress the effects of perturbations due to both beam loadings and fabricating errors. Coupled envelope equations and equipartitioning theory are used for the focusing design (Ref. [8]). The typical focusing parameters along the linac are shown in Figs. 3 and 4. Then, the transverse beam radius becomes larger than that with the constant phase-advance focusing method. It is also a good choice from the viewpoint of space-charge effects, since the density of the bunch decreases. By using this focusing method, it becomes possible to suppress the emittance growth due to the space-charge effects as well as the emittance transfer between the transverse and longitudinal motions.

II. 4. 5. 4. The SDTL (Ref. [9])

The SDTL accelerates the beam from 50 to 200 MeV with 31 tanks. Each tank consists of five unit cells. The typical configuration is shown in Fig. 5. The comparison between the DTL and the SDTL is given in Table 3. The SDTL has several merits as follows:

1. It contributes to the good beam qualities by separating the transition point in the transverse motion from that of the longitudinal motion.
2. A higher effective shunt impedance can be achieved for the total accelerating system.
3. The fabrication and alignment of the drift tubes and tanks become easier compared with those of a conventional DTL, resulting in a reduction in the construction cost as well as a reduction in the number of focusing magnets.
4. Since a unit tank of the SDTL consists of several unit cells, stabilizing devices are not necessary, resulting in a more simple structure compared with the DTL.

It also has demerits as follows:

1. The number of unit tanks increases.
2. The number of drift spaces between two adjacent unit tanks increases.
3. The number of tuning parameters increases.

The results of the beam simulation show that the degradation in the longitudinal beam quality due to the additional drift spaces mentioned above is about 10%, being negligibly small.

II. 4. 5. 5. The ACS (Ref. [10])

An ACS of 972 MHz is used in an energy range of above 150 or 200 MeV. The fundamental rf-structure issues were already solved and a high-power rf test using the 1296-MHz model cavity was successfully performed. Therefore, the future extension using a 972-MHz ACS will be possible with some efforts of modification.

II. 4. 5. 6. Debuncher

In order to satisfy the requirement for the energy spread of the output beam, a debuncher located downstream of the exit of the linac is necessary. A voltage ranging from 1 to 1.5 MV is required when the rf field errors are taken into account during acceleration.

II. 4. 6. Beam simulations

We have used several kinds of beam-simulation codes. The LINSAC code[2] recently developed in KEK has been used for confirming the main parameters of the linac, such as the frequencies, type of accelerating structures and transition energies from the viewpoints of not only the rms properties of the beam, but also the behavior of the halo-like particles around the core-part of the beam. The code is highly vectorized up to a vectorized ratio of more than 99.9% in order to make the best use of the parallel supercomputer.

II. 4. 7. RF sources

The RF power requirements for the JHF accelerating tank units are 0.8 MW for an RFQ, 1.6 MW to 1.8 MW for DTL's, 1.3 MW to 1.8 MW for SDTL's and 0.5 MW for a debuncher. The total number of klystron power stations are nineteen. One has to take into account the 10 percent power loss through transmission lines and RF components such as a circulator and a power divider. Furthermore, the klystron should be operated at an unsaturated power region in order to control the output power by adjusting the input power. This is necessary for maintaining the proper accelerating field under varying beam loading. For this reason we have to choose the klystron working point 1.3 times as high as the required power, where the working point is determined by the cathode and modulating anode voltages. In total the klystrons to be used for the JHF linac should have the capability to produce an output power of more than 2.5 MW.

An anode-modulation type klystron is preferable regarding the cost of the cathode power supply. On the other hand, it is disadvantageous regarding the voltage breakdown problem at the cathode area, which is continuously at the high voltage level in contrast to a cathode-modulation type klystron. We have been using this type of klystrons (Thomson TH 2134) as RF power sources for the JHF test linac, the frequency and maximum power of which are slightly different: 432 MHz and 2 MW, respectively. Parameters for a new 324-MHz klystrons are summarized in Table 4, which are scaled up to 2.5 MW and

3.0 MW(objective) on the basis of those of the TH 2134. It is expected from the experience of the stable operation of the above klystrons that neither the cathode voltages of 102 kV or 110 kV assumed for 2.5 MW or 3.0 MW will not give rise to any serious breakdown problems. For more stable and reliable operation at 2.5 MW one should develop a klystron capable of generating 3 MW output power.

At present we are considering the klystron output port with a structure configuration comprising a loop coupler, a coaxial window, a coaxial (WX-203)-to-rectangular (WX-2300) waveguide transition. The waveguide system is composed of a Y-junction circulator, a 2- or 3-way power divider and rectangular-to-coaxial waveguide transitions. The divided power is transmitted through a penetration from the klystron gallery to the tunnel.

Since the RF power required for klystrons widely ranges from 0.7 MW to 2.5 MW depending upon accelerating structures, cathode DC power supplies with different output voltages are prepared. Dividing the power range into three groups in such a way as less than 1.0 MW (2 klystrons), 2.2 MW to 2.0 MW (7 klystrons) and 2.0 to 2.5 MW (10 klystrons), we will prepare three kinds of power supplies, the voltages of which are 72 kV, 95 kV and 102 kV, respectively. Two to several klystrons are connected to one DC power supply, in order to reduce the cost of the power supply system. Each power supply should be equipped with an AVR for gradually increasing voltage application at turn-on process and for conditioning a klystron. A crowbar circuit is another important component for klystron protection.

The anode of each klystron will be individually modulated by a pulse modulator which allows the step-wise adjustment of the output voltage by changing a voltage divider ratio. In this way all the klystrons can be operated at about 80 percent of the saturated RF power, although the output RF powers of the klystrons are widely distributed as mentioned above.

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Table II. 4. 1 Required main parameters of the linac.

	Initial requirement	Final goal	
Particles	H^-	H^-	
Output energy	200	400	MeV
Peak current	30	60	mA
Beam width	400	400	μsec
Repetition rate	25	50	Hz
Average current	200	800	μA
Length	<150	~220	m
Momentum spread	± 0.1	± 0.1	%

Table II. 4. 2 Parameters of the JHF 200-MeV proton linac.

Injection energy	3.0	MeV
Output energy	202.5	MeV
Frequency	324	MHz
Particles	H^-	
Peak current	30	mA
Beam width	400	μsec
Repetition rate	25	Hz
Average current	200	μA
Total length (structure only)	92.9	m
Total length	122.3	m
Total rf driving power	21.3	MW
Total rf power (30 mA)	27.3	MW
Number of klystrons(*)	19	

(*)includes for RFQ and debuncher

<u>RFQ</u>

Frequency	324	MHz
Injection energy	50	keV
Output energy	3	MeV

<u>DTL</u>

Frequency	324	MHz
Injection energy	3	MeV
Output energy	50.06	MeV
Number of tank	3	
number of cells	150	
Total length	28.51	m
Power dissipation (*)	3.92	MW
Beam power (30mA)	1.41	MW
Total power (30mA)	5.33	MW
Number of klystron	3	
Acceptance		
Ax (normalized 90%)	43	π mm-mrad
Ay (normalized 90%)	41	π mm-mrad
Az (normalized 90%)	9.3	π MeV-deg
Focusing method	Equipartitioned focusing	
Stabilization	Post-stabilized	

DTL details

DTL Tank number	1	2	3	
Injection energy	3.0	19.196	35.407	MeV
Output energy	19.196	35.407	50.058	MeV
Tank length	10.36	8.87	7.81	m
Number of cells	80	41	29	
Power dissipation (*)	1.16	1.36	1.40	MW
Beam power (30mA)	0.49	0.49	0.44	MW
Total power (30mA)	1.64	1.84	1.84	MW
Accelerating field	2.5	2.7	2.9	MV/m
Stable phase	-30	-26	-26	
Drift space	4	3	0	$\beta\lambda$
	0.737	0.742		m

(*)including a factor of 1.3, which is estimated with an ample margin for the difference between the shunt impedance calculated by the SUPERFISH and the real one.

SDTL

Frequency	324	MHz
Injection energy	50.058	MeV
Output energy	202.488	MeV
Number of tank	31	
number of cells	155	
Structure length	65.9	m
Total length	92.4	m
Power dissipation (*)	17.4	MW
Beam power (30mA)	4.6	MW
Total power (30mA)	22.0	MW
Number of klystron	14	
Accelerating field	3.86	MV/m
Energy gain	2.86 - 1.92	MeV/m
Drift space (**)	0.67-1.03	m
Acceptance		
Ax (normalized 90%)	21.3	π mm-mrad
Ay (normalized 90%)	18.6	π mm-mrad
Az (normalized 90%)	40.4	π MeV-deg

(*) including a factor of 1.2.
(**) shorter length is possible.

Table II. 4. 3 Typical parameters of the DTL and SDTL structures at a frequency of 324 MHz and an energy of 50 MeV (β=0.31).

	DTL	SDTL	
Tank diameter	56	52	cm
DT diameter	13	9	cm
Bore radius	1.3	1.5	cm
Outer corner radius	2.5	2.2	cm
Inner corner radius	1.0	0.5	cm
Z	78.2	75.9	MW/m
T	0.703	0.830	
ZTT	38.6	52.3	MW/m
Esurface peak	4.02	5.87	MV/m

Table II. 4. 4 324-MHz Klystron Specifications

		Maximum rating (Objective)	Operated (Saturation)	TH-2134 (Test Linac)
Structure		5 cavities, horizontal position		
RF window and connection		coazial, WR-2300		pill box, WR-1800
Frequency	MHz	324		432
Peak output power	MW	3.0	2.5	2
Average output power	kW	98	81	65
Pulse width	μs	650		650
Repetition rate	pps	50		50
Duty	%	3.25		3.25
Beam voltage	kV	110	102	95
Beam current	A	50	45	40
Mod. Anode voltage	kV	93	86	80
Efficiency	%	55		55
Gain	dB	46		46