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1 GeV リニアック検討資料

1 GeV LINAC DESIGN NOTE

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概要 (ABSTRACT)

Proposed design of the 1 GeV proton linac for the Japanese Hadron Facility is described together with rationale for the design parameters. The linac is composed of a volume production type H^- ion source, a 432 MHz RFQ linac (3 MeV), a 432 MHz DTL (150 MeV) and a 1296 MHz high-β linac (1 GeV). Problems expected in each part are discussed and possible remedies are also presented.

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 FACILITY

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Proposed design of the 1 GeV proton linac for the Japanese Hadron Facility is described together with rationale for the design parameters. The linac is composed of a volume production type H^- ion source, a 432 MHz RFQ linac (3 MeV), a 432 MHz DTL (150 MeV) and a 1296 MHz high-β linac (1 GeV). Problems expected in each part are discussed and possible remedies are also presented.

1. Introduction

A 1-GeV proton linac will be constructed to inject proton beams to various ring accelerators of the Japanese Hadron Facility.[1] 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) a high average current and 3) a high duty factor of an rf system, that should be carefully taken into account in designing the linac. Also, it is required that the linac can be operated in 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 high energy proton linac accelerating an intense beam with a limited length immediately requires very high rf power. Necessary rf power is further increased for the following reason. In the high intensity and high energy proton linac no beam loss is allowed at the high energy region of the accelerator, since radioactivity caused by the beam loss becomes a serious problem in a long term operation. Then sufficiently large beam acceptances are required for all of accelerator tanks. This requirement tends to increase bore radii of the accelerator tanks and shift synchronous phases further from the phase of the highest rf field, resulting in lower acceleration efficiency. Thus, the requirement of no beam loss also implies increase of the rf power.

A fundamental scheme of the proton linac was proposed as shown in Fig. 1. The linac will be composed of an ion source, an RFQ linac, a drift-tube linac (DTL) and a high-β linac. Negative hydrogen beams will be accelerated, since the injection efficiency is higher than the multi-turn injection of proton beams.

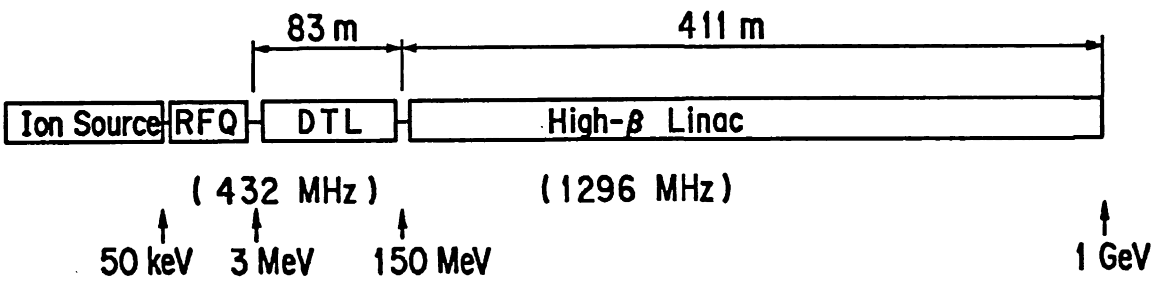

Fig. 1 The scheme of the proton linac.

Among various parameters of linacs, an accelerating frequency is one of the most important parameters, since cost and performance of the linacs will he strongly dependent upon the frequency. In general both of shunt impedances and possible accelerating fields of cavities with the same figure increase proportionally to a square root of the resonant frequency. However, as the frequency increases, sizes of accelerating cavities and klystrons decrease, so that cooling of these RF parts becomes difficult and beam acceptances of the cavities decrease, Thus, the nearly highest frequency should be chosen, so far as the cooling of the RF parts is feasible and the beam acceptance is large enough. Also, it is advantageous to choose the frequency, at which commercial klystrons are available. 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 RF quadrupole and drift-tube linac.

2. Ion Source

We are planning to use a volume production type H^- ion source rather than a surface plasma type multi-cusp ion source whose possible cesium vapor flow will reduce the breakdown voltage of the following RFQ. We have developed a test model of the ion source, whose typical parameters are listed in Table II.

Table II Typical parameters of the test H^- ion source of the volume-production type

Arc current	140 A	Arc voltage	150 V
Filament current	75 A x 4	Hydrogen gas flow	5 sccm
Anode bias	+ 5 V	Acceleration voltage	30 kV

In order to increase the beam current density we are planning to investigate its dependence on the volume of the ion source. It is expected that the density of the excited hydrogen molecules would be increased by decreasing the volume of the ion source at the same arc condition, resulting in increase of the H^- beam current.

3. RFQ Linac

The H^- beam from the ion source will be injected to a 432 MHz four-vane type RFQ linac at the injection energy of 50 keV and will be accelerated to 3 MeV. Design parameters of the RFQ linac are listed in Table III.

Table III Parameters of the 432 MHz H^- RFQ (four-vane)

Frequency	432 MHz			
Input energy	0.05 MeV	Output energy	3 MeV	
Vane length	269 cm	Number of cells	305	
Mean bore radius			0.340	cm
Minimum bore radius			0.236	cm
Cavity diameter			15.4	cm
Normalized acceptance		(100%)	1.5	πmm•mrad
		(90%)	1.0	
Normalized emittance at 3 Mev		(100%)	2.6	
		(90%)	1.3	
Kilpatrick factor			1.8	
Maximum surface field ($E_{s,max}$)			361	kV/cm
Focusing strength			4.0	
Transmission	(0 mA) 98 %	(20 mA)	94 %	

The parameters were determined to obtain a normalized acceptance of 1.5 πmm•mrad for the beam current of 20 mA with the maximum electric field $E_{s,max}$ of 1.8 times of the Kilpatrick limit . The RFQ linac with the small bore radius will require rigid tolerance limits on dimensional errors, and it is difficult to machine, assemble and align the long vanes accurately. To test a feasibility of the RFQ linac with these parameters a prototype RFQ linac is going to be fabricated. Modification of the parameters of the RFQ linac to make manufacturing of the RFQ easier, for example, by reduction of the accelerating energy and/or frequency, may require change of parameters of the following drift-tube linac.

4. Drift-tube Linac

A 432 MHz drift-tube linac (DTL) will accelerate the beam from 3 MeV to 150 MeV. Parameters of the drift-tube linac are listed in Table IV. The linac will be separated into 13 tanks, each of which will be driven by a 1 MW klystron. Shunt impedances of the drift-tube linac are shown in Fig.2 as a function of β(v/c). Three parameters of an inner diameter of tanks, an outer diameter and a corner radius of drift-tubes were approximately optimized to obtain the highest shunt impedances, keeping the maximum surface electric field within 75 percent of the Kilpatrick limit .

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	o.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°	

The 88° phase acceptance of the DTL will be large enough for the 30° phase emittance of the RFQ even with the drift space between the RFQ and DTL. Even if the frequency of the RFQ is halved to increase the bore radius of the RFQ, the DTL can longitudinally accept the beams from the RFQ. Therefore, it is worthwhile to investigate the possibility of the 216 MHz RFQ linac, although another type of a 216 MHz RF power source is required in this case. We are planning to use permanent magnets made of SmCo, since the permanent magnets require neither of wiring nor water-cooling for the magnets, that is, become maintenance-free and SmCo can produce a strong magnetic field, being rather stable against effects due to radiation. However, it is difficult to seal the drift tubes containing the SmCo, since the SmCo cannot stand the high temperature used for the silver brazing and the strong magnetic field produced by the SmCo inhibits conventional use of the electron-beam welding (EBW). At present attempts to seal the drift-tubes containing the SmCo are in progress by a few methods including EBW and laser welding, but results are not yet satisfactory. It will be another method to expose the SmCo to vacuum, and outgassing measurement of the SmCo in vacuum is in progress.

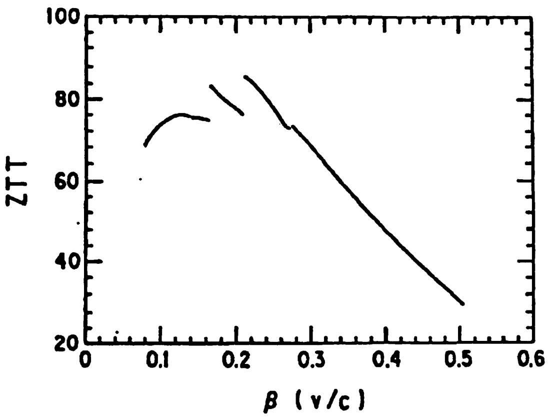

Fig. 2

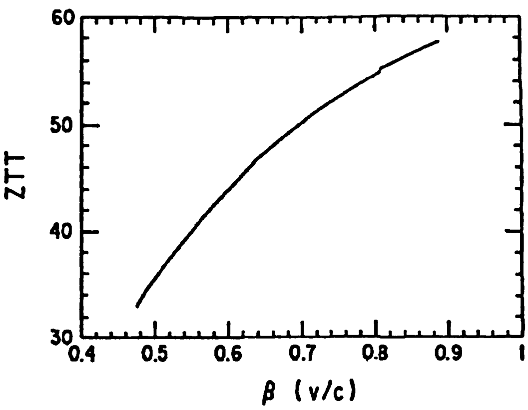

Fig. 3

Shunt impedances of the drift-tube linac (Fig.2) and the side-coupled linac (Fig.3) as a function of β. The values in MΩ/m as calculated with the SUPERFISH are plotted.

5. High-β Linac

Standing wave linacs are more advantageous than traveling wave linacs, if RF pulse widths are longer than filling times (~ a few μs typically) . The π/2 mode operation of a multi-cell cavity is necessary to keep 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 alternating periodic structure (APS) without nose cones or coupling slots, alternating periodic structure with nose cones and coupling slots, side-coupled structure (SCS), disc-and-washer structure (DAW) and annular-coupled structure (ACS).

For the annular-coupled structure it was reported that serious depression of a quality factor is arising from excitation of a coupling-cell quadrupole mode.[2)] Although a possible remedy was proposed,[2)] extensive study will be necessary to solve the problem. In the disc-and-washer structure a TM1 passband crosses the accelerating frequency. A method to keep the TM1 passband away from the accelerating frequency decreases a shunt impedance seriously.[3)]

Both of the alternating periodic structure and side-coupled structure are free from these troubles. Moreover, in the alternating periodic structure coupling cells are located on the beam axis, consuming space for accelerating cells, and space for the coupling cells is relatively limited compared with the side-coupled structure. Therefore, a shunt impedance of the alternating periodic structure is lower than that of the side-coupled structure, and a quality factor of the coupling mode of the APS is lower than that of the SCS resulting in more strict requirement for manufacturing accuracy [4]. On the other hand the axially symmetric structure of the APS, in particular, without coupling slots has the following advantages. The field of the TM0 mode of the APS is more symmetric. Machining and assembling of the APS are easier, allowing a more variety of assembling methods. Also, we have lots of experience in manufacturing and operation of the APS that is used in the TRISTAN rings. Therefore, we decided to develop both of the side-coupled structure and alternating periodic structure in parallel for the time being. In the following paragraphs, however, results of computation with the SCS are presented as an example. Shunt impedances of the SCS calculated with a computer program SUPERFISH are shown in Fig.3 as a function of β. A rather large bore radius of 1.5 cm as 1296 MHz structure was chosen to obtain a large transverse acceptance. The gap length was adjusted to optimize the shunt impedance. The sizes of the coupling slot was determined to obtain a coupling constant of 5 percent with a three dimensional computer program MAFIA[5].

A proposed typical configuration of the high-β accelerating tanks is shown in Fig.4. The drift space between two tanks have space enough for two quadrupole magnets and either of a steering magnet or a beam monitor. Shorter tanks will be used in the low energy side to increase transverse acceptances. Transverse and longitudinal acceptances thus obtained are shown in Table IV.

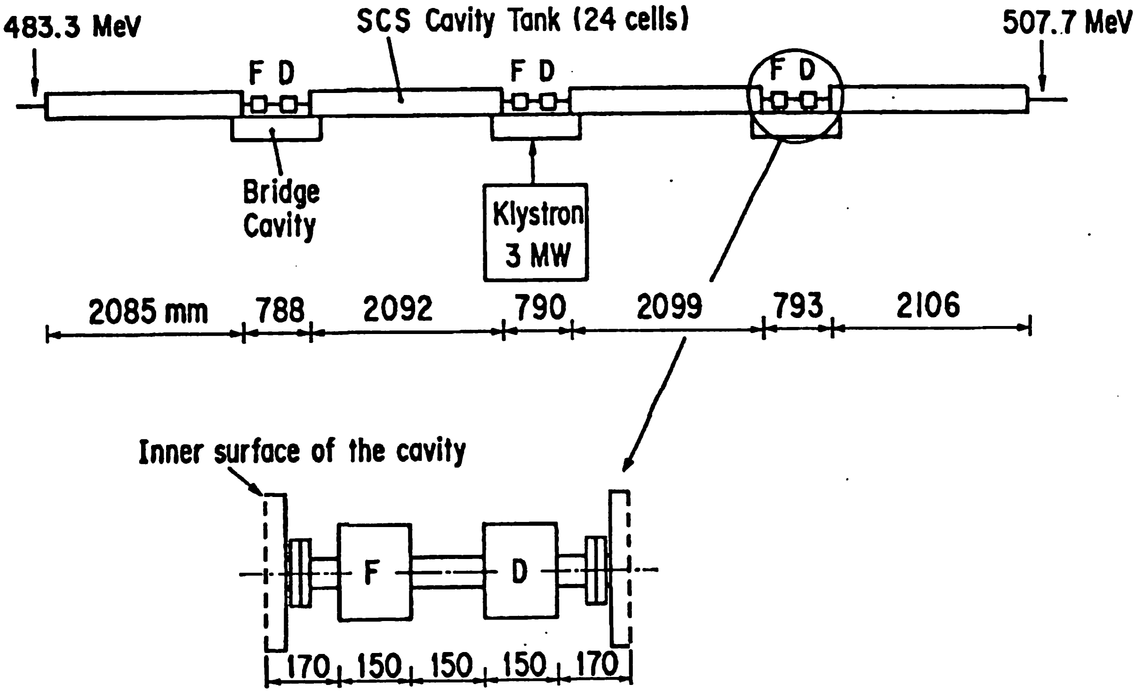

Fig. 4 A typical configuration of the high-β linac.

It is seen that the normalized transverse acceptances of the high-β linac is about 3 times of those of the DTL and 10 ~ 15 times of those of the RFQ.

However, it should be noted that the acceptances were computed only for the synchronous beams. It is found by the computer calculation that the transverse acceptances are reduced to 60 percent of those of the synchronous beams, if the beam phase is located near the separatrix. Thus, more detailed study will be necessary, including study of effects due to possible imperfect alignment of the cavities and quadrupole magnets, to decrease the bore radius of the cavities. For detailed design of the high-β linac including tuning method and so on it is required to estimate machining and assembling errors and to find the best method of welding or brazing. Thus, attempt is being made to fabricate the cavities using silver-brazing, electron-beam welding, electroplating welding and diffusion welding.

6. Modulator

One of the most difficult parts of the proposed 1-GeV proton linac will be a high power modulator that drives the 3 MW klystron with a long pulse (600 μs) and a high duty factor (3 %). Also, it should be operated with extreme stability and reliability. We decided to develop a line-type modulator rather than the other types, for example, a hard-tube modulator for the following reasons. First, we have some experience for line-type modulators. Second, line-type modulators provide stable pulses with relatively simple circuits whose behaviors can be easily understood. Third, efficiencies of line-type modulators are better than hard-tube pulsers. Finally, running costs will be less expensive, since no replacement of the tubes is necessary. Power-grid tubes used in hard-tube modulators are very large and expensive, while their life time cannot be expected to be long.

We have designed a prototype modulator for a 6 MW klystron rather than the 3 MW klystron for the following reason. In order to obtain klystrons that can be stably operated at 3 MW in unsaturated region, it is necessary to develop klystrons With the power capability of 5 or 6 MW. Development of the 6 MW klystrons requires a modulator with an output power of 15MW for a klystron efficiency of 40 %, and successful development of the modulator will directly lead to development of stable modulators for 3 MW klystrons at the same time. Parameters of the modulator designed for the 6 MW klystrons are listed in Table V.

Table V Parameters of the test modulator for a 6 MW klystron

Peak power	15 MW	Average power	450 KW
Output voltage	20 kv	Output current	750 A
PFN impedance	26.7Ω	Load impedance	26.7Ω
Pulse width (half value)		600 μs (flat top)	520 μs
Pulse rise time	<30 us	Flatness	<0.5%
Repetition rate	50 pps		
Pulse voltage stability		(short term)	<0.2%
		(long term)	<0.5%h

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