Chapter 2 Beam Dynamics Design

2. 1 Linac

2.1.1 Fundamental design

A proton linear accelerator for the Joint Project has been designed. The linac consists of a 400-MeV normal conducting accelerator, to be used as an injector into the following 3-GeV rapid-cycle synchrotron, and an additional superconducting (400 – 600 MeV) accelerator for the accelerator-driven nuclear waste transmutation system (ADS). The design of the normal conducting linac is based on the 400-MeV proton linac for the JHF project [1-2]. It is also based on the accumulated knowledge of constructing and operating the 20-MeV linac at KEK since 1974, extending the energy up to 40 MeV in 1985, the research and development of a high-energy, high-intensity proton linac for both JHP since 1987 and the NSP since 1996 [3], and a large number of world-wide advances in beam-dynamics issues and accelerating structures during past three decades. The construction of the low-energy part up to 54 MeV has been almost finished at KEK [4], and the following part up to 400-MeV is under construction. The required main parameters for the linac are listed in Table 2.1.1.1.

Table 2.1.1.1 Required main parameters of the linac.

Particles	H^-		
Output energy	400	MeV	(600 MeV for ADS)
Maximum peak current	50	mA	
Beam width	500	μsec	
Repetition rate	50	Hz	
Chopping ratio	56	%	
Average current	700	μA	
Transverse emittance	~4	π−mm-mrad (99% , normalized)	
Momentum spread	± 0.1	%	

There are the following two additional requirements for the linac beam:

1) a chopped time-structure of the linac beam pulse (Fig. 2.1.3.1.1 in section 2.1.3.1) for reducing beam losses after injection into the ring, and
2) a change in the peak current, ranging from 10 to 50 mA.

The main features of the requirements for the linac are a high peak current, a high average current and a high duty factor. Therefore, the beam-loss issue along the linac becomes one of the main concerns during each stage of the design, construction and operation. An average beam loss power of 0.1 W/m along the linac is assumed. These parameters strongly require the best ability of the total system as well as each device of the linac. In addition, since it is to be used as an injector into the 3-GeV synchrotron, supplying beams for many kinds of scientific studies, stable operation with the required beam quality during many years is the most important and necessary characteristic of the linac. Therefore, the final design was determined not only based on the results of a beam-dynamics calculation, but also by careful studies of the accelerating structures, rf devices, and tuning and operation methods.

Design criteria

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

1. Stable operation with minimum beam losses

The linac should be designed and constructed with appropriate margins for beam losses in order to achieve a stable and reliable operation of the total system. An accurate beam-dynamics simulation code [5], including both an accurate electromagnetic field distribution in the acceleration process and a direct three-dimensional space-charge calculation, is used for determining the main parameters of the linac 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. Focusing along the linac is performed based upon the theory of the coupled envelope equations as well as equipartitioning theory [6]. It is a useful method from the viewpoints of obtaining good beam qualities with the space-charge effects and tuning the emittance growth in the transverse and longitudinal phase spaces (ref. [2] section 4.3.8). Here, a beam with balanced properties, between the core and halo part, and between the transverse and longitudinal qualities, is called a good one. One of the key issues concerning stable operation during a long period is to utilize sufficiently stable and reliable rf power sources. High performance of the high-power klystrons during long-period operation has been established in TRISTAN and B-factory at KEK.

2. Variable tuning for varied peak currents

One of the important problems in a high-intensity proton linac is to establish an effective tuning method for various peak beam currents, since the beam-loss problem often becomes serious when the peak current increases. In addition, although within the framework of the beam parameters and the assumed combined transverse and longitudinal focusing scheme, no serious beam instability is expected in the design, it is more reasonable to have a tuning knob during operation. Therefore, it is required to tune the transverse focusing forces freely for all rf structures in order to compensate for any space-charge effects, which in turn determines the highest possible frequency for the DTL structure. In order to satisfy these requirements, beam diagnostics systems, carefully prepared along the linac, are indispensable. Moreover, in order to obtain reliable measured beam data that can be compared with the calculated results, it is also indispensable for constructing accelerating structures and to align them within the required accuracy based on the calculation. It is thus pointed out that it is important to understand the fact that the accumulation of each part of the linac, accurately designed and fabricated, can make the linac reliable and stable.

3. Adoption of new ideas and devices

A long time has passed since the first-generation high-energy proton linacs were constructed. During this long period, many new ideas for proton linacs have been proposed and tested. Although many of them were dismissed, some proved to be valid for future linac technology. Therefore, it is a reasonable way to take these new ideas and devices into our design positively. One of the most important and valuable technologies utilized in constructing the DTL-type structure is an advanced process of copper electroforming by periodic reverse (PR) electrolysis for producing the lining [7]. Its high performance concerning discharge issues allows us to adopt a rather high accelerating-field design in DTL-type structure, even under long-pulse, high duty factor operation.

According to the criteria mentioned above, a 400-MeV proton linear accelerator has been designed. It consists of a 3-MeV radio-frequency quadrupole linac (RFQ), a 50-MeV drift tube linac (DTL), a 190-MeV separated-type drift tube linac (SDTL)[8], a 400-MeV annular-coupled structure (ACS)[9] and three kinds of beam-transport lines (MEBT1, MEBT2, L3BT). The main parameters are summarized in Table 2.1.1.2 and shown in Fig. 2.1.1.1.

Choice of the operating frequencies

In the framework of a peak beam current of about 50 mA, our major concern is how to obtain the required beam stably without beam losses, instead of finding the maximum current in the linac. Therefore, the emittance growth as well as a beam-halo formation in both transverse and longitudinal motion along the linac becomes a main beam-dynamics issue. The choice of the operating frequency is closely related to the above-mentioned issues via space-charge effects. Based on a comparison of the accelerator parameters for various operating frequencies [ref. [2] section 4.3.2], a frequency of 324 MHz was selected for the following reasons:

1. the space-charge effects are greatly reduced compared with the case of using a conventional frequency of 200 MHz,
2. quadrupole electromagnets with sufficiently strong focusing strength installed into the drift tubes of the DTL are possible based on the assumption of a 3-MeV RFQ,
3. the shunt impedance increases as the frequency increases,
4. a 3-MeV RFQ having a single tank can be constructed,

5. a klystron is possible with some modifications from that at a frequency of 350 MHz, and
6. an ACS for a high-β structure with minimum beam losses is possible, assuming a frequency multiplication factor of three.

In conclusion, the choice of 324-MHz for the fundamental frequency combined with a 3-MeV RFQ satisfies the major requirements: variable and sufficient transverse focusing in the DTL structure, efficient suppression of the space-charge effects, and the adoption of klystrons as rf sources.

Table 2.1.1.2 Parameters of the 400-MeV linac.

	RFQ	DTL	SDTL	ACS	
Output energy	3	50	191	400	MeV
Frequency	324	324	324	972	MHz
Total length	3.1	27.1	91.2	108.3	m
Structure length	3.1	26.7	65.7	68.2	m
Number of tank	1	3	32	46	
Number of cell		146	160		
Number of Klys.	1	3	16	23	
Accelerating field		2.5~2.9	2.5~3.7	4.2~4.3	MV/m
Stable phase	-30	-30	-27	-30	deg
Vane voltage	82.9(1.8KL)				kV
Drive power	0.336	3.3	16.6	33.3	MW
Beam power	0.148	2.4	7.0	10.5	MW
Total power	0.484	5.7	23.6	43.8	MW

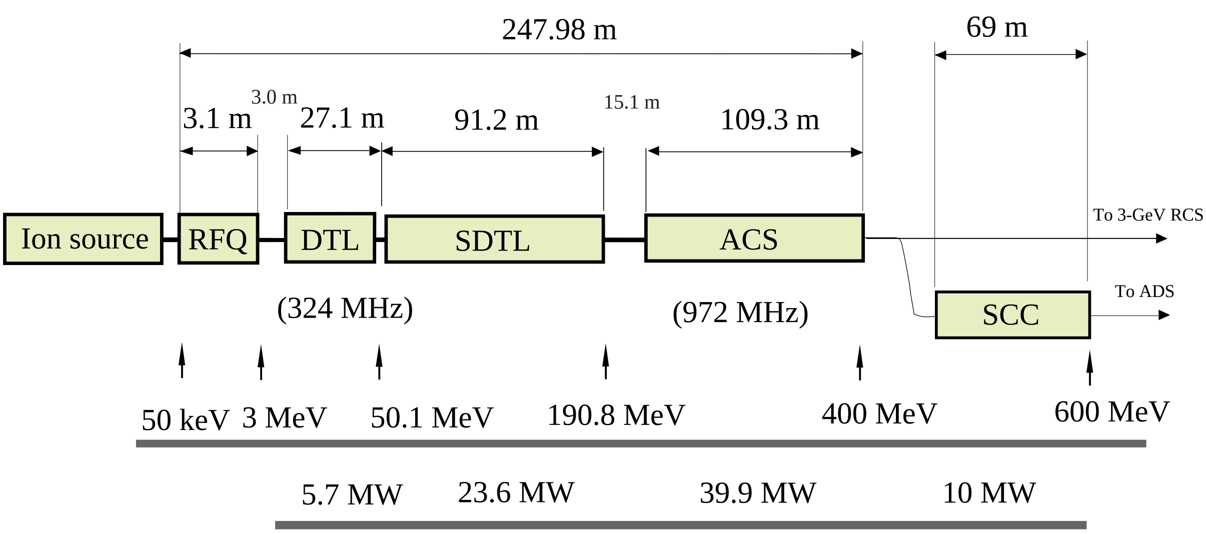

Fig. 2.1.1.1 Layout of the proton linear accelerator.

Choice of rf-structure type and transition energies

It is widely accepted that an accelerator complex, an RFQ followed by a DTL, is very effective for acceleration in the low-energy region of a high-intensity, high-energy proton linac. The main reason for changing the accelerating-structure type along the linac is to improve the accelerating efficiency (Fig.2.1.1.2-3). From this point of view, the SDTL was utilized in intermediate acceleration from 50 to 190 MeV. A transition energy of 50 MeV from DTL to SDTL was chosen by the following reasons:

1. a lower transition energy is desirable from the viewpoint of the total higher shunt impedance,
2. a lower transition energy is not desirable from the viewpoint of a possible perturbation due to the transition combined with space-charge effects,
3. an SDTL tank length with a very low transition energy seems to be too short, assuming an equal number of cells for all tanks and the rf excitation of two adjacent tanks by a klystron.

A detailed discussion about properties of the SDTL structure is reported [ref. [2] section 4.3.10].

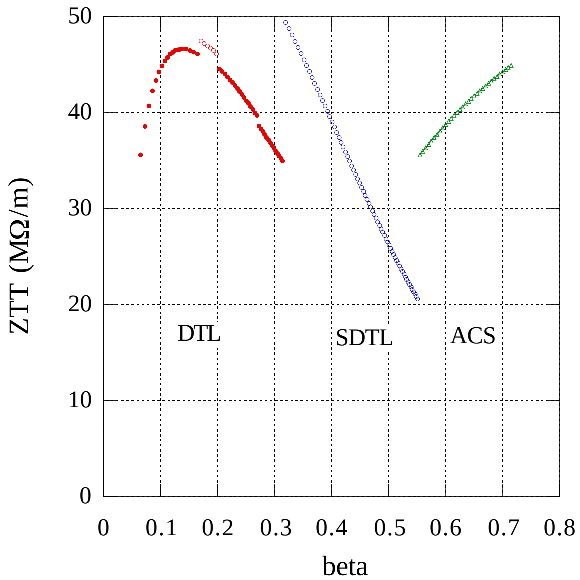

Fig.2.1.1.2 Calculated effective shunt impedances with SUPERFISH for three kinds of rf structures (DTL, SDTL and ACS). No corrections due to stems, coupling holes etc. are added.

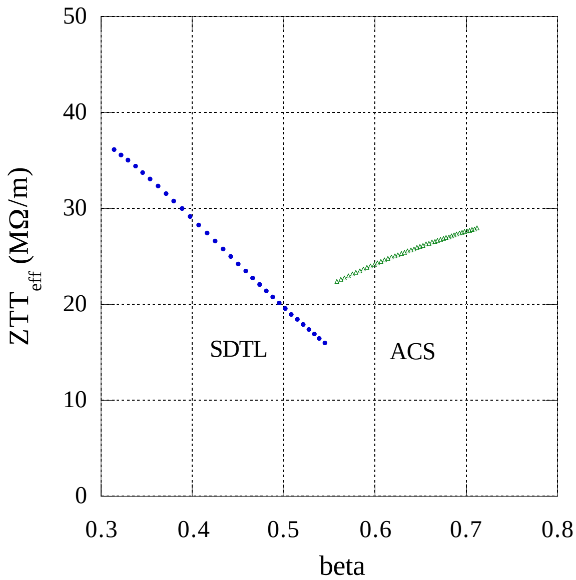

Fig. 2.1.1.3 Calculated effective shunt impedances for the SDTL and the ACS. Realistic corrections due to stems, coupling holes, surface imperfections etc. are added.

A transition energy of 190 MeV from SDTL to ACS, combined with an operating frequency of three times the fundamental one, was chosen from the viewpoints of both a total improvement in the shunt impedance and a reduction of beam-loss possibility due to a longitudinal transition [1]. The ACS type was adopted, since we believe that it is the best choice at present over the side-coupled structure (SCS), the on-axis coupled structure (OCS), and the disc-and-washer structure (DAW). The ACS is the one which has balanced characteristics of both the shunt impedance and the field symmetry [10]. Recently, there have been noticeable advances in the rf-structure design of the ACS [11].

Design features

One of the design characteristics is its stable operation with high performance for a beam-loss problem during acceleration. There are five reasons for the above mentioned characteristic:

1. First, it can be achieved by adopting an SDTL for a medium energy structure. Here, the frequency of SDTL is the same as that of DTL. Considering a complex of DTL, SDTL and CCL (coupled cavity linac) of a multiplied frequency, there is a transverse transition from DTL to SDTL and a longitudinal (frequency) transition from SDTL to CCL. On the contrary, both the transverse and longitudinal transitions occur at the same place for a complex of DTL and CCL. It is normally considered that the rate of phase damping in CCL is larger than that in SDTL because of a difference in the energy-dependence of the transit time factor. Therefore, the volume of the bunch in SDTL is larger than that in CCL, assuming the same transition energy from DTL. Thus, the space-charge effects in SDTL are weaker than that in CCL. In addition, a longitudinal transition in a complex of DTL, SDTL and CCL occurs at a rather higher energy (190 MeV). Therefore, the bunch length of the SDTL output beam is sufficiently short that the effects of nonlinear problems related to acceleration in the CCL decreases in comparison with a complex of DTL and CCL.
2. Second, the equipartitioning focusing method, combined with variable transverse focusing forces and the focusing scheme of FD (in the DTL) and doublet (in the SDTL), is used, resulting in the following three features in beam behavior. First, a smaller amount of emittance growth in longitudinal phase space can be expected (ref. [2] section 4.3.8), compared with that in constant transverse phase advance focusing. Second, a smaller ratio of halo formation can be expected (ref. [2] section 4.3.8). Third, a transverse rms beam size does not change abruptly at the transition from DTL and SDTL, since the rms beam size becomes larger at the end of the DTL in the equipartitioning focusing, which can be smoothly connected by the transverse matching section.

3. Third, a sufficiently large longitudinal focusing force at the DTL injection point, compared with the transverse focusing force, is achieved by selecting a rather high accelerating field for the DTL injection point (ref. [2] section 4.3.9).
4. Fourth, a sufficiently large longitudinal ACS acceptance compared with the beam emittance from SDTL can be obtained by selecting a three-times operating frequency and a transition energy of 190 MeV.
5. Fifth, the rf structures have some stabilizing features (RFQ, DTL and ACS) or relatively shorter tank length (SDTL) which has high performance for any perturbation on the field.

It should be point out that acceleration along the linac first begins with a stable and high-performance (in a maximum current and emittance) negative-hydrogen ion source. So far, the volume-production type ion source without Cesium has not satisfied the requirements for the maximum peak current, and that with Cesium has successfully produced a peak current as high as 70 mA [12]. However, from the viewpoint of an accelerator complex of the ion source with Cesium and the RFQ, several issues to be solved are expected for achieving stable operation during a long period. Thus, further improvements and innovations concerning the performance of the ion source and the RFQ complex are one of the key issues to satisfy the requirements for the linac beam delivered to the 3-GeV synchrotron.

A long beam-transport line (L3BT) from the exit of the ACS to the ring is important in the sense that it determines the final beam parameters into the ring. Here, both the strong space-charge effects at the beginning part of the transport line in connection with the operation of two debunchers and the control of the beam emittance with the aid of both longitudinal and transverse scrapers are the main beam-dynamics issues.

The technology for producing a superconducting rf cavity for a proton linear accelerator has been greatly developed recently. Therefore, a superconducting proton linac in a high-energy region seems to be even more attractive. It was reported [13] that two distinct features of a sc proton linac design (a very high accelerating field and acceleration with a small number of equal cell-beta structures for a wide energy range) require very accurate control of the accelerating field in order to satisfy the severe requirement for the injection beam into the following rapid-cycling synchrotron. In addition, there are some peculiar issues concerning pulsed operation of the superconducting proton linac: perturbation on the accelerating field in connection with both a rather long time constant and the mechanical properties of the rf structure. From the viewpoint of satisfying the severe requirements for the beam injected into the synchrotron, further experimental studies on the above-mentioned issues are needed. Thus, it was decided that a sc proton linac is utilized for ADS; the requirements for the injection beam are much milder.

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