

DEVELOPMENT OF THE HIGH-INTENSITY PROTON LINAC FOR THE JAPANESE HADRON PROJECT

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Abstract

The 1-GeV proton linac will be constructed for the Japanese Hadron Project (JHP). Our design concept and development program are based on the viewpoint of how to meet the requirements for the linac. The development includes the construction of a 10-MeV linac comprising a volume-production type ion source, a long RFQ (about four times as long as its wavelength) and a DTL with permanent quadrupole magnets. The test of an L-band high-power rf source had been successfully accomplished up to full power, and recently fed the power to a ten-cell cavity (annular-coupled structure) with a bridge coupler as designed. The present status of our development is described.

Introduction

A linac will be constructed to inject proton beams to the ring accelerator for the Japanese Hadron Project(JHP).¹⁻⁹ The optimum design of a specific linac is dependent upon required parameters as an injector. The requirements for the JHP linac are summarized in Table I. Low-emittance negative hydrogen beams are required for efficient injection to the ring. High energy is preferable in order to increase the space-charge limit of the current in the ring; our choice of 1 GeV is probably a reasonable one. A repetition rate not higher than 50 Hz is necessary for spallation neutron experiments. Keeping these constraints in mind we must design the proton linac that can accelerate a high-intensity beam of 400 μ A. Here, the high integrated-type beam current that is actually useful for experiments is required rather than the record current. In other words, we must design and develop a linac that can be operated with extreme stability and reliability. Design parameters that are to meet the above-mentioned requirements are presented in the next section together with a rationale for the chosen parameters.

Conceptual Design and Development Program

A high-energy, high-intensity proton linac immediately requires very high rf power. In general it is advantageous to reduce the number of rf sources by increasing the rf power of a single rf source, regarding cost performance, stable operation and easy maintenance. This is, however, very difficult in the JHP for the following reasons. The peak current of the low-emittance, high-duty negative hydrogen beam is relatively limited and probably around 20 mA for a 90 % normalized emittance of 1 π mm-mrad and a duty factor of a few percent. In order to obtain an average current of 400 μ A we require a rather long beam pulse length of 400 μ s for the repetition rate as low as 50 Hz. We must therefore prepare an rf pulse length of 600 μ s including a margin. In Fig. 1 the rf powers of available klystrons are plotted versus their pulse lengths. It can be seen that the available power rapidly decreases with increasing pulse length, since the discharging or sparking limit is a decreasing function of the pulse length. (The increasing power dissipation also has some effect.) Furthermore, the cost of a single rf source on the highest-power line in the graph is increased as the pulse is lengthened. Consequently, the rf power becomes very expensive for the JHP linac in comparison with shorter-pulse

TABLE I
Requirements for the Linac

Beam	H ⁻	
Energy	1	GeV
Repetition rate	50	Hz
Average current (without chopper)	400	μ A
Average current (with chopper)	> 200	μ A
Normalized emittance (90%)	~ 2	π mm-mrad

TABLE II
Design Parameters of the Linac

Total length	500	m
Beam pulse length	400	μ s
RF pulse length	600	μ s
H⁻ ion source		
Type	Volume-production	
Peak beam current	20	mA
Normalized emittance	1	π mm-mrad
RFQ		
Input energy	50	keV
Output energy	3	MeV
Frequency	432	MHz
Vane length	2.7	m
Minimum bore radius	0.24	cm
RF power	0.8	MW
Transverse emittance (Normalized, 90%)	1.1	π mm-mrad
Energy spread (90%, full)	0.03	MeV
Phase spread (90%, full)	15	deg
DTL		
Output energy	148	MeV
Frequency	432	MHz
Total length	83	m
Bore radius	0.5	cm
Number of cells	342	
Number of tanks	13	
RF power	12	MW
Transverse acceptance (90%, normalized)	8.9	π mm-mrad
Acceptable energy spread (90%, full)	1.4	MeV
Acceptable phase spread (90%, full)	88	deg
High-β linac		
Output energy	1	GeV
Frequency	1296	MHz
Total length	411	m
Tank length	303	m
Bore radius	1.5	cm
Number of cells	3568	
Number of tanks	152	
RF power	99	MW
Klystron output power	3	MW
Number of klystrons	36	
Transverse acceptance (90%, normalized)	29	π mm-mrad
Acceptable energy spread (90%, full)	3	MeV
Acceptable phase spread (90%, full)	87	deg

machines and the optimum design of the linac is strongly dependent upon reliable information regarding the power of a single source which can be obtained stably and reliably. This is the main reason why we started our program by developing an rf power source for the high- β linac that takes a large part of the linac. For our conceptual design we estimated a highest power of 6 MW and have decided to use it at 4 MW for improving reliability.

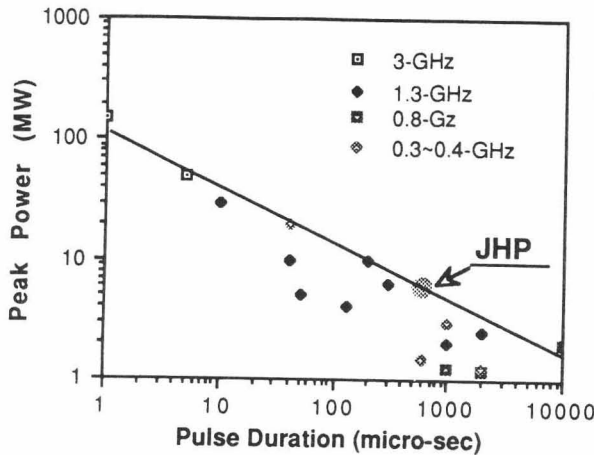


Fig.1. The rf powers of available klystrons versus their pulse lengths.

Since the total shunt impedance is proportional to the cavity length, the total rf power is inversely proportional to the length, if the beam loading effect can be neglected, while the costs of cavities and buildings are roughly proportional to the cavity length. Therefore, if the rf power is relatively expensive, as in the present case, the optimum length of a linac would tend to be increased in order to save rf power by improving the total shunt impedance. Although a total length of 500 m was primarily determined due to our available space, we believe that it is nearly the optimum length, taking into account various requirements for the linac.

In this context, the accelerating frequency is another important parameter. In order to save rf power a higher frequency is preferable, since the shunt impedance per unit length of a cavity with the same figure is proportional to the square root of the frequency. (The possible accelerating field is also proportional.) On the other hand, as the frequency increases, the size of the accelerating cavities and klystrons decreases, so that the cooling of these components become difficult and the beam acceptance of the accelerating cavities decreases. Therefore, the nearly highest frequency should be chosen, as far as the cooling of the rf components is feasible and the beam acceptance is sufficient. In this way we have chosen 1296 MHz for the frequency of the high- β linac, taking into account its relation to that of the drift-tube linac (DTL) and RFQ linac as follows.

In a high-intensity, high-energy proton linac beam losses should be eliminated at the high-energy region of the accelerator. Otherwise, radioactivity caused by beam loss would become a serious problem during long-term operation and limit the possible beam current. Thus, sufficiently large beam acceptances should be prepared both transversely and longitudinally for all accelerator tanks. In order to ensure a sufficiently large transverse acceptance we have chosen a rather large bore radius of 1.5 cm for the high- β linac, while sacrificing the shunt impedance to some extent.

In order to ensure a sufficiently large longitudinal acceptance we have chosen one third of the frequency of the

high- β linac for both the DTL and RFQ linacs. For the same reason, we use rather high transition energies of 3 and 150 MeV for the RFQ to the DTL and for the DTL to the high- β linac, respectively, since the debunching effect in the drift space inevitable for the transition is smaller for higher energy. The design parameters, thus determined, are listed in Table II. More detailed parameters and rationale can be found in Ref. 3.

Further optimization of the design of a highly stable machine with easy maintenance and operation requires both technical data and experience that can be accumulated only through the construction and operation of major components of the machine. Thus, we have formed a development program for the major components as follows.

Since one of the most difficult components of the proton linac is a high-power rf source (several MW) with a long pulse length (600 μ s),¹⁰⁻¹⁴ it is crucial to test the possibility and performance of the rf source for success of the project. Thus, a high-power test station was prepared, as shown in Fig.2. Second, we began to study and develop the high- β linac, since it also represents a large part of the linac. The power station is used to feed power to the high- β linac. Another important item in our development program is concerned with the front end of the linac. Obviously, the above-mentioned design was based upon various assumptions that must be confirmed empirically. The assumptions can be listed as follows:

- 1) The ion source can produce high-intensity, low-emittance beam as designed.
- 2) An RFQ can accelerate a 20 mA beam from 50 keV to 3 MeV.
- 3) An 432 MHz DTL of sufficient quality can be fabricated.
- 4) Emittance growth and generation of a halo can be properly suppressed from the ion source to the DTL, and the designed acceptances of the high energy section are sufficiently large to prevent the machine from being activated.

In order to confirm these assumptions and to develop the fabrication technique we are going to construct a 10 MeV proton linac for the high-intensity beam tests within a few years.

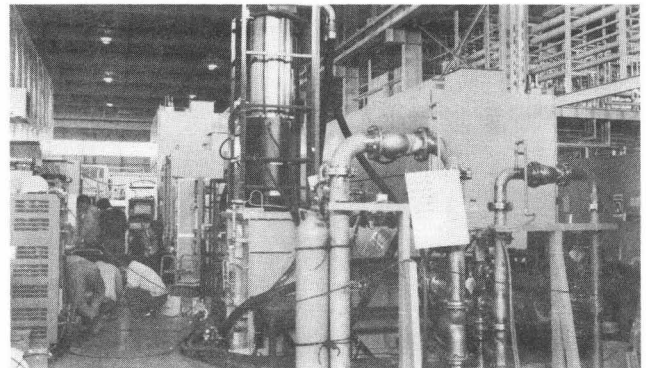


Fig.2 The high power test station showing the 5-MW klystron and the line-type modulator.

RF Power Source

A line-type modulator with an output power of 15 MW has been constructed. The line-type was chosen owing to its excellent stability with a de-Qing circuit and its high efficiency. At present, the pulse length of its pulse-forming network (PFN) is 400 μ s. An L-band 5 MW klystron (THOMSON TH2104A) with a pulse transformer (step-up ratio of seven) were installed in the station. Testing of the complete system has

been successfully accomplished up to full power with a repetition rate of 30 Hz.¹¹⁻¹³ A test at the designed repetition rate of 50 Hz will be performed after the acceptable average power of a dummy load is doubled. The pulse of the modulator will be lengthened up to the full length in the near future.

High-β Linac

A standing-wave coupled-cell linac operated at the $\pi/2$ mode will be used¹⁵ for the high-β linac rather than the $2\pi/3$ mode.¹⁶ Among the various possible candidates for the high-β structure, manufacturing techniques of an alternating periodic structure (APS)¹⁷ or an on-axis coupled structure (OCS) and a side-coupled structure (SCS)¹⁸ have been developed.⁴ The axially symmetric APS has advantages over the axially asymmetric SCS with respect to both mechanical simplicity and beam stability. However, the shunt impedance of the APS is much lower than that of the SCS, particularly in the low-β section, since the coupling cells of the APS are located on the beam axis and consume space that could otherwise be used for acceleration. In this context, the annular-coupled structure (ACS)¹⁹ became attractive, owing to its symmetric structure.

Although it had been reported²⁰ that a serious depression of the quality factor arises from the excitation of the coupling-cell quadrupole mode, we succeeded in improving the shunt impedance of the ACS by adopting four coupling slots.²¹ In order to show the effect of the coupling slots on the quality factor, the measured quality factors were divided by that of a single cell without coupling slots, and plotted versus the coupling factor (Fig. 3). Another important feature of the four coupling slots is that the dipole and quadrupole modes in the coupling cells are situated at higher frequencies than the passband of the accelerating mode. Thus, we have fabricated an ACS cavity with two 5-cell tanks²² connected by a 5-cell bridge coupler^{23,24} (Figs.4 and 5) and tested it up to full RF power. (An effective accelerating field is 3.6 MV/m and a power dissipation per cell is 30 kW.) Details of the fabrication and high-power test are presented in Refs. 22, 24 and 25.

A disadvantage of the ACS, compared with the SCS, is its large size, or heavy weight, that is inevitable due to symmetrization of the structure. We appreciate the advantages of the axial symmetry of the ACS rather than its disadvantage.

Ion Source

When our development started, no ion source existed that met our requirements. It was, however, expected that a volume-production type H⁻ ion source could produce a high-intensity H⁻ beam with low emittance and high duty, an attractive feature being that it would be free of cesium vapor that could reduce the breakdown voltage of the following RFQ. Thus, a test volume source²⁶ was constructed in order to study the mechanism of volume production. We have obtained a beam current of 20 mA with an anode hole diameter of 7.5 mmφ, where the normalized 90 % emittance was 1 πmm·mrad at 30 keV and the pulse length is 400 μs. It is interesting to note that the introduction of a small amount of cesium vapor increases the current density, even in the volume source, by a factor of four or more. It should be emphasized that the amount of cesium used in the volume source is much less than that in the conventional surface source. This amount of cesium will probably not cause any harm to the RFQ. Further development of the volume source is in progress.

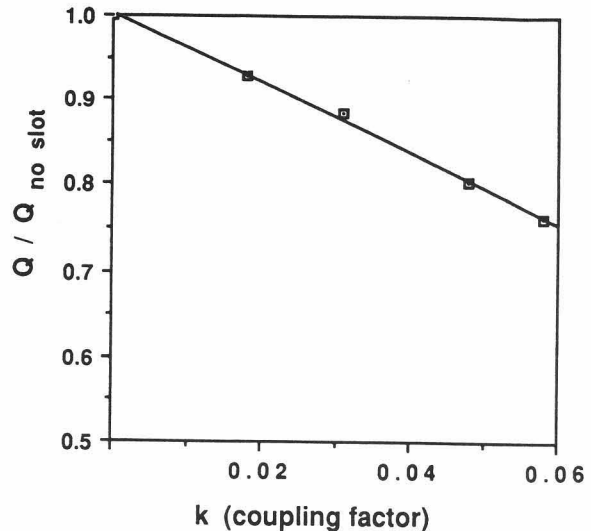


Fig.3 Measured coupling-factor dependence of the Q-value of the four-slot ACS divided by that of a single cell without slots. The 5% coupling will be used.

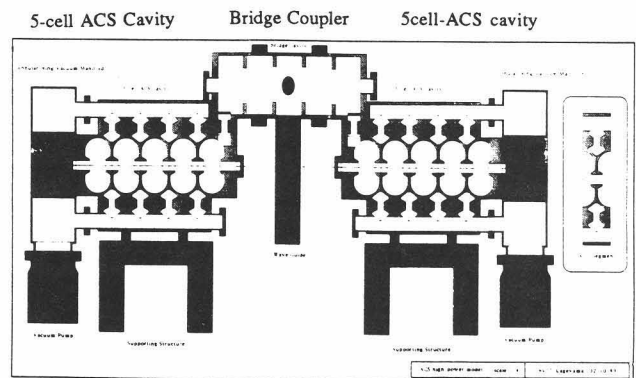


Fig.4 A high-power ACS model comprising two five-cell ACS cavities and a five-cell bridge coupler.

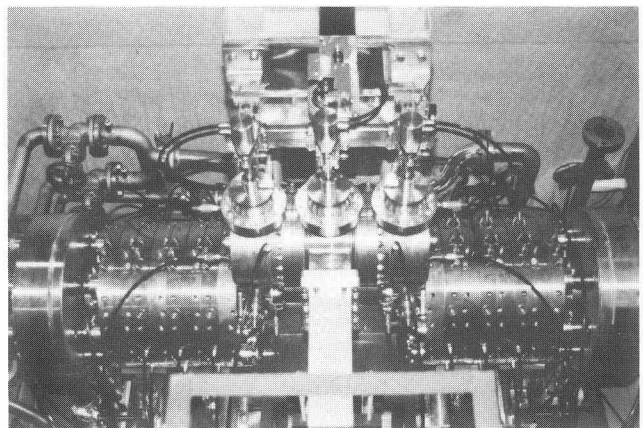


Fig.5 Photograph of the high-power ACS model.

RFQ Linac

A 432-MHz RFQ linac will accelerate a beam from 50 keV to 3 MeV. A design study for the beam dynamics has indicated that its vane length should be 2.7 m (about four times as long as the wavelength).^{27,28} We have developed a new beam-dynamics design procedure,²⁸ taking into account the space-charge effect in the bunching process more realistically. It is, in general, difficult to fabricate a conventional four-vane RFQ linac that is long compared with the wavelength for the following reasons. First, a slight structure imperfection easily gives rise to field tilt in the long tank. Second, an RFQ linac consists of four cavities separated by the four vanes; these four cavities are coupled very weakly. Thus, a slight azimuthal asymmetry gives rise to a non-uniform distribution of the stored energy among the four cavities. (The effect is closely related to the mixing of the dipole modes with the quadrupole mode.) As a result severe specifications are required for the structural dimensions. It has been believed that the specifications become more severe for a longer RFQ. On the other hand accurate machining naturally becomes more difficult for longer vanes.

Neither a four-vane RFQ with vane coupling rings nor a four-rod RFQ for curing the above-mentioned problems can easily meet the present requirements of high duty and high frequency. On the other hand, the above-mentioned difficulty regarding the four-vane RFQ was not understood quantitatively enough to make a final decision for a choice of the RFQ parameters. Thus, a cold model^{9,29} (Fig. 6) was fabricated in order to develop a machining method for the severe specifications and to study the effect of possibly harmful dipole modes. Silver was added (0.2 percent) to vacuum-melted oxygen-free copper in order to strengthen the material mechanically.

The results of the measurements on the cold model are described in detail in Refs. 9 and 29. The field distributions are uniform within $\pm 3.5\%$. Although the geometries of the vane ends and the end plates were adjusted in order to obtain this uniformity, no side tuners were used.

The measured dispersion curves of the dipole and quadrupole modes shown in Fig. 7 indicate that the accelerating quadrupole mode (TE210) is located just at the middle of the dipole modes (TE111, TE112). Separation is fairly large, implying a small mixing of the dipole modes. Also, good machining accuracy is seen from the small breaking of the degeneracy of the dipole modes. It is noted that more mixing of the dipole modes is expected for the shorter RFQ, since the frequency of the TE111 mode is increased and becomes closer to the TE210 quadrupole mode if the vane is shortened in this region of the length. In other words, a longer RFQ will be easier to fabricate than a shorter one.

During the course of development we devised a new field-stabilizing concept, referred to as a π -mode stabilizing loop (PISL)^{30,31} (Fig. 8) that pushes up the dipole mode frequencies far from the quadrupole one. A three-dimensional calculation indicates that the loop is quite promising for stabilizing the RFQ field, increasing the dipole mode frequencies by an amount of several 10 MHz. We will thus substantiate the feasibility of the PISL empirically with the existing cold model and continue development, including studies of the effects of the matching section, vane modulation, input coupler and tuning plungers in order to obtain the necessary data for the final design of a high-power model of the RFQ.

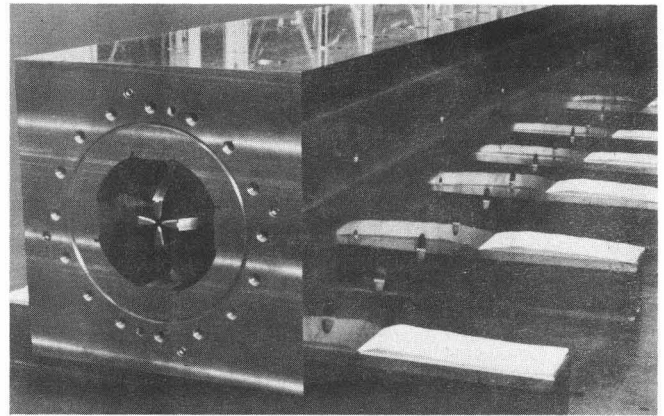


Fig.6 Cold model of the 432-MHz 3-MeV RFQ linac.

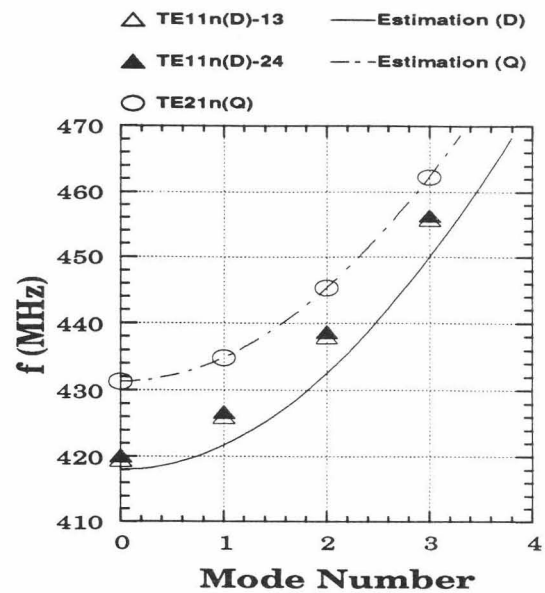


Fig.7 Measured dispersion curves of the quadrupole and dipole modes in the present RFQ.

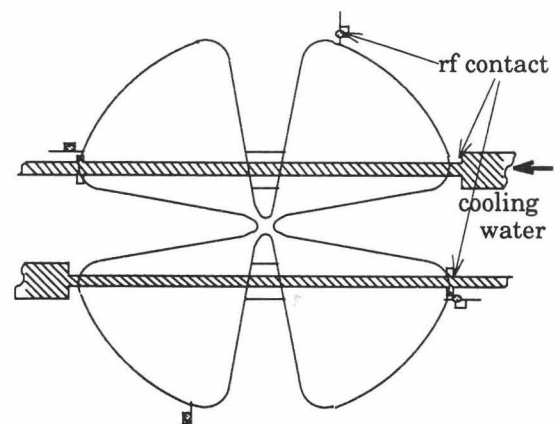


Fig.8 Example of π -mode stabilizing loops.

Drift-Tube Linac

For the 432-MHz drift-tube linac (DTL), permanent quadrupole magnets, such as SmCo and NdFeB, will be used since they require neither electrical wiring nor water-cooling and become maintenance-free. We have recently succeeded in fabricating NdFeB quadrupole magnets (Fig. 9) with a field center that coincides to their mechanical center within 20 μm . It should be emphasized that this was realized without any shuffling of magnet pieces, but with elaborate quality control in both machining and production. On the other hand, it is difficult to seal drift tubes containing these permanent magnets, since the magnets cannot stand high temperature during silver brazing; also, the strong magnetic field of the permanent magnets bends the electron beam for the electron-beam welding (EBW).

Thus, the electroforming method⁵ has been applied to seal the drift tubes from vacuum, since electroplating is carried out at room temperature. A drift tube and a NdFeB permanent quadrupole magnet were assembled and successfully electroformed. The EBW of drift tubes with the permanent magnets was also successful by shielding the electron beam from the strong magnetic field. At present we are developing a method³² using cold shrinking that will be more suitable for mass production.

A cold model (3 to 8 MeV, 35 cells, 2.6 m)^{33,34} made of aluminum for half of the first DTL tank has been fabricated in order to obtain necessary data for the final detailed design.³⁵ Without post couplers, a field flatness within 1.2 percent was obtained throughout the tank. It is noted here that the β -dependence of the effect of stems was corrected by adjusting the gap lengths between the drift tubes in order to make the frequencies of all cells uniform. In order to test the effectiveness of the post coupler, a field tilt was intentionally produced by frequency tuners; it could be eliminated by adjusting the positions of the post couplers.³² The effect of the number of post couplers was extensively studied regarding field stability.³³ Based upon these developments, the fabrication of the 5.3 MeV DTL is now under way, as shown in Fig.10.

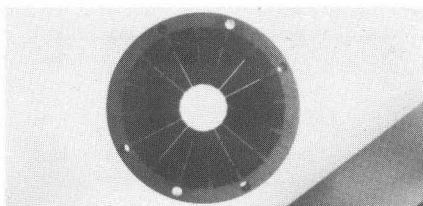


Fig.9 NdFeB quadrupole magnet.

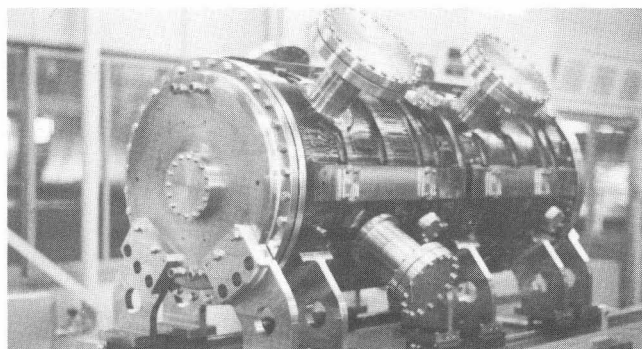


Fig.10. Hot model of the 5.3 MeV DTL.

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