DEVELOPMENT OF NEW TECHNIQUES FOR THE JHP 1-GeV PROTON LINAC

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Abstract

For a high-intensity, high-energy proton linac of the Japanese Hadron Project (JHP) we are developing various new techniques; a volume-production type ion source, a long RFQ (about four times as long as its wavelength), a DTL with permanent quadrupole magnets, and an axially symmetric annular-coupled structure, and long-pulse, high-power RF sources. The present status of our development is described.

Introduction

Various new techniques have been and are being developed for a proton linac of the Japanese Hadron Project (JHP).[1] These techniques should be useful in order to promote the recent trend toward the high-average-intensity, high-energy proton linacs[2] in addition to the JHP proton linac.

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 the beam loss would become a serious problem during long-term operation, limiting the possible beam current. In order to suppress the generation of the radioactivity we have to produce the low-emittance beam and to keep the emittances of the beam as low as possible during the acceleration, both transversely and longitudinally. The development of a volume-production type H^- ion source is the effort to obtain the low-emittance, high-intensity, high-duty H^- beam. In order to suppress the transverse emittance growth and to shape up the beam longitudinally an RFQ linac is an ideal accelerator owing to its strong focusing ability and adiabatic bunching. Our effort is concentrated on the development of an RFQ linac which is stronger against the emittance growth than conventional ones. For a drift-tube linac (DTL) various techniques have been and are being developed in order to use permanent quadrupole magnets which provide strong focusing in a limited space, being maintenance-free. For a high-β linac an annular-coupled structure was studied extensively and powered up to the designed acceleration field. The annular-coupled structure is unique for its axial symmetry, keeping the shunt impedance comparable to those of other high-impedance structures. The axial symmetry is one of the most important factors to accelerate the high-intensity beam without the emittance growth. Present status of these developments will be described in this report.

The long-pulse, low-repetition operation is more preferable than the short-pulse, high-repetition one, since a significant amount of the beam is lost during rise or fall of the beam pulses.[3] However, the available power per a single RF source rapidly decreases with increasing pulse length, since the discharging or sparking limit is a decreasing function of the pulse length. Development of reliable high-power RF sources is one of the most important items in our development program. An L-band RF source[4-6] thus developed was already used for the test of the high-β structure. A UHF-band power source is being prepared for the test of the DTL, the RFQ and the power source itself. The power source consists of a 2-MW klystron (THOMSON TH-2134), a hard-tube pulsar for the modulating anode, and a DC power supply for the cathode with a crowbar circuit. A full system will be tested in near future.

Volume-Production Type Ion Source

A volume-production type H^- ion source was promising in order to produce a high-intensity H^- beam with low emittance and high duty. At first we expected that we could eliminate cesium vapor which could reduce the breakdown voltage of the following RFQ. However, it was found that the introduction of a small amount of cesium vapor increases the current density by a factor of four or more.[7] In contrast to a naive expectation this phenomena suggests that the surface plays an important role even in the volume source. We have already 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 should be noted that the amount of cesium used in the volume source is significantly less than that in the surface source, probably causing no harm to the RFQ. Since the ionization process is being understood gradually, further improvement of the parameters is expected.

π-mode Stabilizing Loop for RFQ Linac

In order to realize a high-intensity, high-energy proton linac it is a key technique to construct a long RFQ linac in comparison with its wavelength for the following reasons. Since the space charge is most effective on the low-energy beam, the extraction energy from the ion source, that is, the injection energy to an RFQ linac, should be as high as possible in order to suppress the emittance growth arising from the nonlinear space charge effect. For keeping the adiabaticity in the bunching process for the high-energy beam the RFQ has to be lengthened. Also, the acceleration energy of the RFQ should be as high as possible in order to keep the beam from the emittance growth. Finally, the high operating frequency is advantageous regarding the acceleration of high-intensity, low-emittance beam.[8] All the above three requirements lead us to a 432-MHz, 2.7-m RFQ linac which is four times as long as its wavelength (50-keV injection, 3-MeV ejection). However, the long RFQ linac is difficult to realize for the following reasons.

First, a field tilt in the long tank easily arises from a slight structure imperfection. Second, four cavities separated by the four vanes are coupled very weakly in an RFQ linac. Thus, a non-uniform distribution of the stored energy among the four cavities arises from a slight azimuthal asymmetry. Although a four-rod RFQ[9] or vane-coupling rings[10] for a four-vane RFQ were devised for solving this problem, the former is not suitable for a high-frequency RFQ, while the latter is hard to water-cool. The recently modified four-rod RFQ[11] is again hard to cool. In other words, these devices do not meet the requirements of high duty and high frequency. On the other hand, the uniformity in the field distribution can in principle be obtained by machining and fabricating an RFQ with infinite accuracy. (The beam loading is another matter.) Thus, we started our development program by attempting the extreme accuracy in machining and fabricating a cold model. The obtained field distributions without side tuners were uniform within ± 3.5%.[12] Together with the measured dispersion curves of the dipole and quadrupole modes shown in Fig. 1 we have obtained quantitative understanding of the mechanism which gives rise to the non-uniform field distribution. First, the machining and fabricating accuracies can be estimated from the small breaking of the degeneracy of the dipole modes seen from Fig. 1. Second, the accelerating quadrupole mode (TE210) is situated in between the two dipole modes (TE111, TE112); the separation between the quadrupole mode and the dipole modes are fairly large, implying a small mixing of the dipole modes. If the vane is shortened in this region of the length, the frequency of the TE111 mode is increased and becomes closer to the TE210 quadrupole mode, resulting in more mixing of the dipole modes. Paradoxically, a longer RFQ will be easier to fabricate than a shorter one in this region of the RFQ length.

Although the fairly uniform field distribution was obtained, we were still frustrated with the unstable mixing of the dipole modes. Thus, we were searching for a new field-stabilizing method that can be used for the high-duty, high-frequency RFQ. Finally, we devised a new field-stabilizing concept which implies a vane-coupling ring as a special case. The device referred to as a π-mode stabilizing loop (PISL)[13,14] stabilizes the field distribution by pushing up the dipole mode frequencies far from the quadrupole one. We have installed the PISL's (Fig. 2) to the existing cold model in order to study their effects empirically. The measured dispersion curve confirms the theoretical prediction as shown in Fig. 3. The measured field distributions are uniform within ± 0.75 %, indicating the drastical effect of the PISL's.[15] The fabrication of a high-power model of the RFQ with the PISL's is now under way.

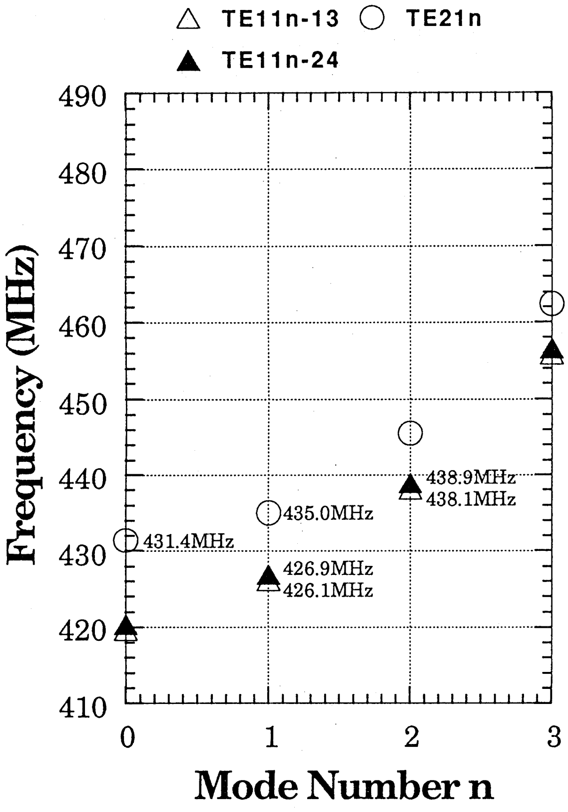

Fig. 1 Measured dispersion curves of the quadrupole and dipole modes in the cold model of an RFQ without PISL's.

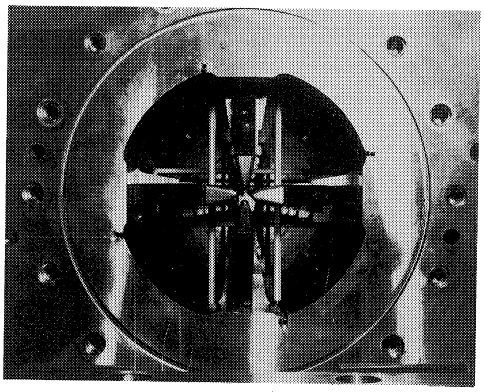

Fig. 2 The PISL's installed to the existing cold model.

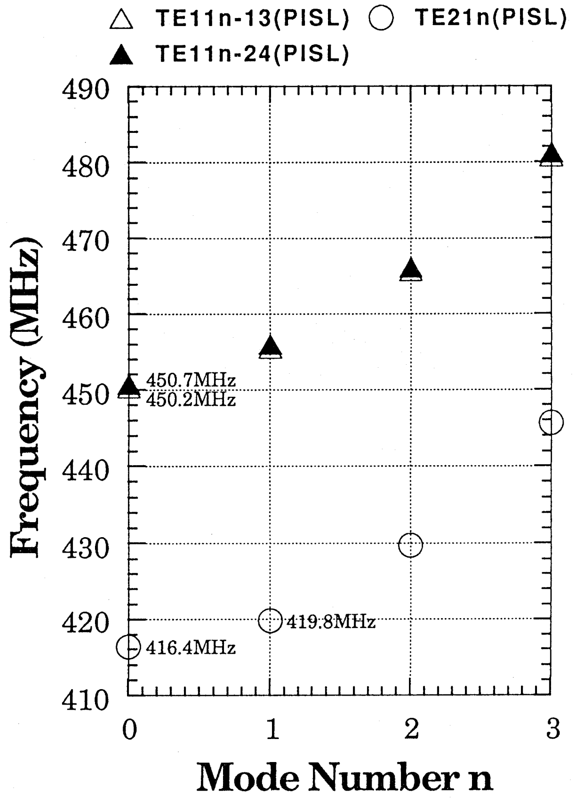

Fig. 3 Measured dispersion curves of the quadrupole and dipole modes in the cold model of an RFQ with PISL's.

Drift-Tube Linac with Permanent Quadrupole Magnets

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. By use of the permanent magnets we obtain not only maintenance-free but also strong focusing device within a small space. As mentioned repeatedly both the strong focusing and mechanical accuracy are important in order to obtain the quality beam.

We have already produced and machined NdFeB quadrupole magnets with a field center that coincides to their mechanical center within 20 μm.[1] This was realized with elaborate quality control in both machining and production. In order to assemble the magnets into the drift tube we are now developing the following method.[16] First, we insert sixteen magnet pieces into the drift-tube inner cell to form a quadrupole magnet. Figure 4 shows the magnet thus formed in the dummy inner cell with an assembling jig. In the figure the accuracy of the assembly was being tested by measuring the deviation of the magnetic center from the mechanical center. Second, the magnet pieces are held tight to the inner cell against the magnetic force by welding one band to another. Third, the inner cell with the permanent quadrupole magnet is inserted into an outer cell heated up to over 65°C and finally shrinkage-fitted together. Fourth, the drift tube thus assembled is accurately mounted to a tank by use of a taper-fitting method, where both the stem of a drift tube and the opening of a tank should be tapered with extreme accuracy.

All these techniques are being developed in parallel. Since our ultimate goal is to align all magnetic centers in a tank within several ten microns without adjustment, the accuracy of each process should be within a few ten microns.

The effect of the number of post couplers was extensively studied regarding field stability.[17] Based upon these developments, the fabrication of the 5.3 MeV DTL is now under way.

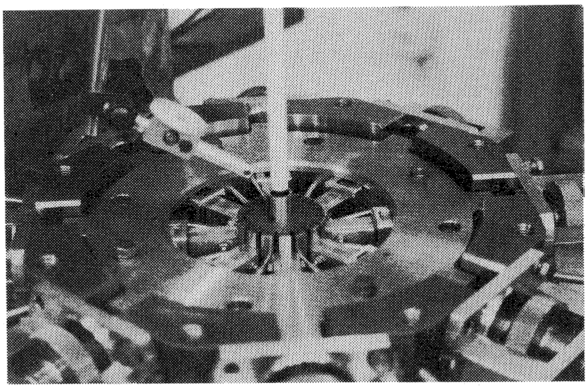

Fig. 4 Assembling test of permmanet quadrupolet magnet in a dummy inner cell. Magnetic center was being measured with respect to the mechanical center of the dummy cell.

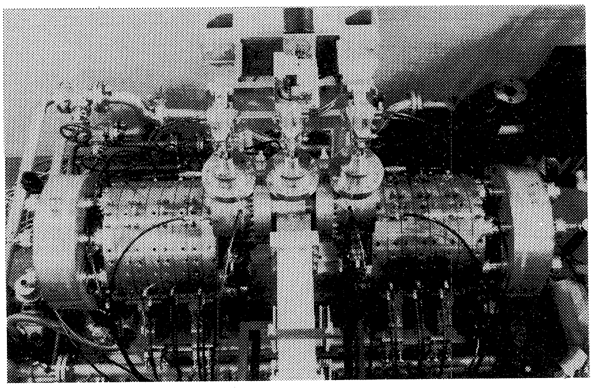

Fig.5 Photograph of the high-power ACS model.

Annular-Coupled Structure for High-β Linac

A standing-wave, coupled-cell linac operated at the π/2 mode should be used for the high-β linac in order to keep a high degree of stability of the accelerating field against effects due to heavy beam loading and manufacturing imperfections.[18] Possible candidates for the high-β structure are an alternating periodic structure (APS)[19] or an on-axis coupled structure (OCS), a side-coupled structure (SCS),[20] a disc-and-washer structure (DAW),[21] and an annular-coupled structure (ACS).[21] 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 the DAW a deflecting TM1-mode passband crosses the accelerating frequency. Methods to keep the TM1 passband away from the accelerating frequency decrease a shunt impedance seriously.[22] In addition the separation between the accelerating mode and the TM1 passband is around 2 per cent[23] which is of the same order as that between the dipole and quadrupole modes of a short RFQ linac. Since the asymmetry is introduced by stems and slots, the mixing of the deflecting mode to the accelerating mode can still be significant.

In this context, the annular-coupled structure (ACS) became attractive, owing to its symmetric structure. However, it had been reported that a serious depression of the quality factor arises from the excitation of the coupling-cell quadrupole mode.[24] Even worse is that the frequencies of the dipole and quadrupole modes in the coupling cells are drastically lowered by increasing the coupling between the accelerating and coupling cells and ultimately intrude into the accelerating passband, resulting in the serious distortion of the passband.[25] We have extensively studied the reasons for these shortcomings both empirically and theoretically, and finally succeeded in solving these two problems of the ACS by adopting four coupling slots.[26] Thus, we have fabricated an ACS cavity with two 5-cell tanks connected by a 5-cell bridge coupler (Fig. 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. 27-30.

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. However, we recommend the ACS for the high-intensity machine, since the axial symmetry can be one of the most important factors in order to suppress the possible emittance growth or beam blow-ups.

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