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1 GeV LINAC DESIGN NOTE

題目 (TITLE) A PROPOSAL FOR A HIGH-INTENSITY, HIGH- ENERGY, CONTINUOUS-BEAM PROTON LINAC

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概要 (ABSTRACT)

The guiding principles used for the design of the proton linac for the Japanese Hadron Project (JHP) are presented explicitly. Applying the guiding principles to a high-energy proton linac with a high-average current we propose the use of a frequency of around 400 MHz for all of the high-b linac, drift-tube linac (DTL) and RFQ linac. Rationale for this choice is presented and the feasibility of this choice is discussed.

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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ABSTRACT

The guiding principles used for the design of the proton linac for the Japanese Hadron Project (JHP) are presented explicitly. Applying the guiding principles to a high-energy proton linac with a high-average current we propose the use of a frequency of around 400 MHz for all of the high-β linac, drift-tube linac(DTL) and RFQ linac. Rationale for this choice is presented and the feasibility of this choice is discussed.

1. INTRODUCTION

Among possible "High Mean Power Accelerators" we are going to discuss on high-energy proton linacs with high average beam currents in this report. We have made the conceptual design of a linac for the Japanese Hadron Project (JHP)[1], using the guiding principles[2,3] listed in the next section. We believe these guiding principles should be effective for a wide variety of proton linacs. Thus, it is interesting to see what results will arise from application of the principles to the high-energy proton linacs with high average beam currents. It is noted that the 90% normalized emittance is used throughout this report.

2. GUIDING PRINCIPLES

The principles are listed as follows.

1) The optimum design of a specific linac is dependent upon required parameters.

In other words we have to settle the parameters in order to make the optimum design of a specific machine. This is a kind of meta-principles, which we always have to follow. Nevertheless, some people are ignorant that the requirements for the beam current, time structure, emittance and so forth sometimes modify the optimum design drastically.

2) In order to obtain a high average current we require a long beam pulse length together with a high repetition rate and ultimately a continuous beam, since the peak current of the low-emittance beam is limited by various effects.

3) We have to take into account the cost of rf power sources more seriously for a long-pulse machine than for shorter-pulse machines, since the long-pulse rf power source becomes very expensive for the following reasons.

   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 power of a single rf source, regarding cost performance, stable operation and easy maintenance. However, the available power of a klystron rapidly decreases with increasing pulse length,[3] since the discharging or sparking limit is a decreasing function of the pulse length. The increasing power dissipation and stored energy also have some effects. Furthermore, the cost of a single rf source is rather increased as the pulse is lengthened.

4) If the rf power is relatively expensive, as in the present case, the length of a linac should be increased in order to save rf power by improving the total shunt impedance. (Of course, this is true for normal-conducting accelerating cavities. Discussion on advantages between normal- or super- conducting accelerating cavities is another matter, and should be discussed elsewhere.)

   Since the total shunt impedance is proportional to the cavity length, the total power dissipation is inversely proportional to the length. The optimum length is determined by the trade-off between the rf-power cost and the cavity cost, which, including the building, is roughly proportional to the cavity length. Thus, if the rf power is very expensive, it is worthwhile to save the rf power by increasing the cavity length. Even if the beam current is very high, the cavity should be lengthened, until the power dissipation becomes comparable or negligible in comparison with the beam loading.

So far we have been taking into account the cost of the rf power source only. In the case of the "High Mean Power Accelerators" the running cost or power efficiency is anther important factor which should be taken into account. Sometimes this can be more important than the initial investment including the costs of the rf power sources, cavities and buildings. Then, the high total shunt impedance becomes more important factor.

5) The nearly highest frequency should be chosen, as far as the cooling of the rf components is feasible and the beam acceptance is sufficient. If the cooling or the beam acceptance is an issue, we have to reduce the operating frequency.

   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. For the low-energy beam, the higher frequency is advantageous in order to suppress the emittance growth.[4](This will be discussed in more detail later.) 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.

6) 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 accelerator tanks in the high energy region. In order to ensure a sufficiently large transverse acceptance we have to choose a **large bore radius in the high energy region**, sacrificing the shunt impedance to some extent. In order to ensure a sufficiently large longitudinal acceptance we have to **decrease a ratio of the frequency of the high-β linac to that of the DTL and the DTL to the RFQ linac.**

We believe that everybody is agreeable to the six principles listed above. On the other hand the following statement may be controversial and thus should be refered as an assumption on which our design is based.

7) In order to eliminate the beam loss in the high-energy region the low-energy end of a linac should be optimized for suppressing the emittance growth. It should be reminded that the acceptance just necessary for the beam transmission is sufficient in the low-energy end where the beam energy is too low to activate the machine.

It is reasonable to believe that particles in the tail or halo predominantly contribute to the beam loss during the acceleration. Thus, the generation of the tail or halo should be suppressed as far as possible in order to eliminate the beam loss. This is as important as enlarging the acceptance in the high-energy region. Although the mechanism of the generation of the tail or halo has not been well understood, it is probably related to the emittance growth arising from the non-linear space-charge effect. Since the space charge is most effective on the low-energy beam, the suppression of the emittance growth is one of the most important factors to be taken into account in the low-energy end of linacs. As mentioned in 5) the operating frequency should be increased as far as the cooling is possible and the beam transmission is sufficient. It should be warned that too large acceptance of the low-energy end transmit the beam with the long tail or halo, possibly resulting in the large beam loss in the high-energy region.

3. PROPOSAL

Now let us follow the above principles. The principle 1) advises us to settle the parameters of a linac. However, no parameter was settled for so-called "High Mean Power Accelerators" at present. For the time being, consider a linac characterized by a set of parameters listed in Table I.

TABLE I **Requirements for the Linac**

Beam	H^+	
Energy	1	GeV
Average current	100	mA
Normalized emittance (90%)	~ 2	π mm·mrad

The principle 2) together with a proposed beam current of 100 mA leads us to use a continuous beam, since the maximum peak beam current at present obtainable with an emittance of 1 π mm·mrad is around 100 mA. The principles 3) and 4) tell us not to save the lengths of the cavities or the linac.

Then, considering the above guiding principles 5), 6) and 7) we came to the conclusion that we should use a frequency of around 400 MHz (UHF) for all of the RFQ linac, DTL and high-β linac for the following reasons. Let us consider the frequency of the high-β linac at first. It is interesting to note that the UHF band has been used for continuous beam machines, among which electron or positron storage rings are most popular. The reasons for this choice are common to both electron-positron storage rings and high-intensity proton linacs. First, the sizes of UHF cavities and klystrons are sufficiently large for their cooling under the CW (continuous wave) operation. Second, the bore radius should be sufficiently large in order to ensure long beam life of the storage rings or to eliminate the beam loss of the proton linac. Then, the increase in the frequency can hardly improve the shunt impedances. (The improvement is possible only if the same figure is kept.) Third, UHF is the practically lowest frequency for the use of klystrons, which we believe are more reliable than other power sources.

What about the frequency of the DTL? Which of 200 or 400 MHz should be chosen? It appears that the chice of 400 MHz is disadvantageous as compared with 200 MHz regarding the transverse acceptance(bore radius), the cooling and the use of electro-quadrupole magnets(EQM's). However, these apparent disadvantages should be reexamined as follows. The discussion are divided into two parts; the low-energy region(up to several MeV) and high-energy region. In the low-energy region where drift tubes are short and have no large space, the beam loss gives rise to neither radioactivity of materials nor radiation damage on permanent quadrupole magnets(PQM's). Thus, the large acceptance is unnecessary and the PQM's can be used. The cooling for power dissipation is eased by increasing the cavity length, since the power dissipation per length is decreased in inverse proportion to the square of the cavity length. In the high-energy region where the beam loss could cause serious problems, drift tubes are sufficiently long to allow the cooling and the use of the EQM's. Also the bore radius can be enlarged, since the focusing magnetic field weakened by enlarging the bore radius can be compensated by increasing the magnet length.

In contrast to the apparent disadvantages of the UHF version, its advantages are essential. First, the high-β linac can have the maximum longitudinal acceptance with respect to the longitudinal emittance of the output beam of the DTL. Second, the same power sources can be used for both the high-β linac and the DTL. As mentioned above, klystrons cannot be used for 200-MHz DTL's. Third, we can use a frequency of 400 MHz for the RFQ linac. This is advantageous regarding the emittance growth in comparison with RFQ's with the lower frequency.

Probably, one of the most controversial points is the use of 400 MHz for the RFQ. As stressed repeatedly, the acceptance and the cooling are most important factors to be taken into account in the "High Mean Power Accelerators." Then, lower operating frequency appears to be favorable. Roughly speaking, the transverse acceptance of the RFQ is inversely proportional to the square of the frequency, if the maximum surface electric field divided by the Kilpatrick limit is constrained. Definitely, the lower operating frequency should be chosen, if one wants the high current at the exit of an RFQ. It should, however, be reminded that what we want is not the current of 2- or 3-MeV protons, but that of 1-GeV protons. Then, it is quite possible that the maximum current is limited by the beam loss in the high energy region of the linac rather than the physically acceleratable current. Even if the high current can be emitted from the RFQ, the beam with the long tail or halo could not be accelerated up to high energy, since the particles in the tail or halo will be lost during the acceleration, giving rise to the radioactivity. If the tail and halo are closely related to the emittance growth arising from the non-linear space-charge effect, the emittance growth should be suppressed as far as possible. Since the emittance growth in a higher-frequency RFQ is smaller than that in a lower-frequency RFQ, the higher frequency is advantageous regarding the suppression of the beam loss. It is true that the mechanism of the generation of the tail or halo is not well understood. We know that we just pointed out the possible advantage of the use of the higher frequency for an RFQ, but we believe that the possibility is quite high.

Needless to say we are assuming that we can obtain 100-mA proton beam with the transverse emittance lower than the acceptance of the RFQ which is around 1 π mm·mrad. Also, it is very difficult to cool a 400-MHz CW RFQ. In order to overcome these problems it is interesting to note that a recently devised PISL(π-mode stabilizing loop)[5,6] can suppress the mixing of dipole modes. In contrast to VCR's, PISL's can be easily cooled, being useful for the CW RFQ. In other words we can neglect the mixing of the dipole modes, when we want to lengthen a CW RFQ or when we consider the effect of a thermal detuning. The field tilt induced by the structural imperfection or thermal detuning can be compensated by the tuning plungers. Now we can lengthen the RFQ, we can inject the high-energy beam, for example the 100-keV beam, into the RFQ, enhancing the possibility of the high-intensity, low-emittance beam. (It may sound paradoxical that the high-energy injection requires a longer RFQ. This is, however, true, since the same number of periods is necessary in order to accept the beam adiabatically, while a wavelength is increased by the high-energy injection.) Another problem is if it is possible to cool the RFQ down to, for example 80°C. Preliminary thermal analysis[7] indicates that this is possible by boring many cooling-water channels.

Finally, we would like to point out that the axial symmery of the accelerating structure is probably important to accelerate the high-intensity, low-emittance beam without the beam loss, that is, the emittance growth. This is the reason why we concentrate our effort on the development of the annular-coupled structure(ACS)[8-12] for the JHP. Unfortunately the ACS becomes considerably large for the UHF band. Then, anther symmetric structure, that is, alternating-periodic structure (APS)[13] should be used, but without the coupling slot, that is, without the nose cone for the following reason. (This structure is sometimes refered to as an on-axis coupling structure (OCS).) When the nose cones are machined in order to improve the shunt impedance, the electrical coupling through the beam pipe becomes too small. Then, in order to improve the coupling we have to machine coupling slots, the number of which is typically two. The two coupling slots together with the high-intensity beam may generate uncontrollable quadrupole field, resulting in the emittance growth. Therefore, the APS without the coupling slots or the nose cones is preferable.

It is noted that the large bore radius to be used for the large acceptance increases the coupling through the beam pipe. Another disadvantage of the APS as compared with other structures like the ACS, SCS (side-coupled structure)[14] and DAW (disc and washer structure)[8] is its low shunt impedance. However, the differences in their shunt impedances are decreased by using the large bore radius and the disadvantage can be compensated by increasing the cavity length. Finally, it is noted that the totally 300-m APS cavities[15-18] have been used under the high-power CW operation in the TRISTAN main ring for several years. Probably this structure has been the most used under the CW operation among the π/2-mode structures, which are required for their excellent stability of the field.

The proposed scheme is shown in Fig. 1 and Table II. The cavity length was optimized, assuming the cost of the 1-MW power source is six times as high as that of 1-m cavity. Accidentally this length makes the beam loading roughly identical to the power dissipation, which sounds a reasonable choice. Also, the relatively high acceleration field as the CW machine is roughly the same as already tested by using the cavity of the Photon Factory (3 MV/m).[19, 20]

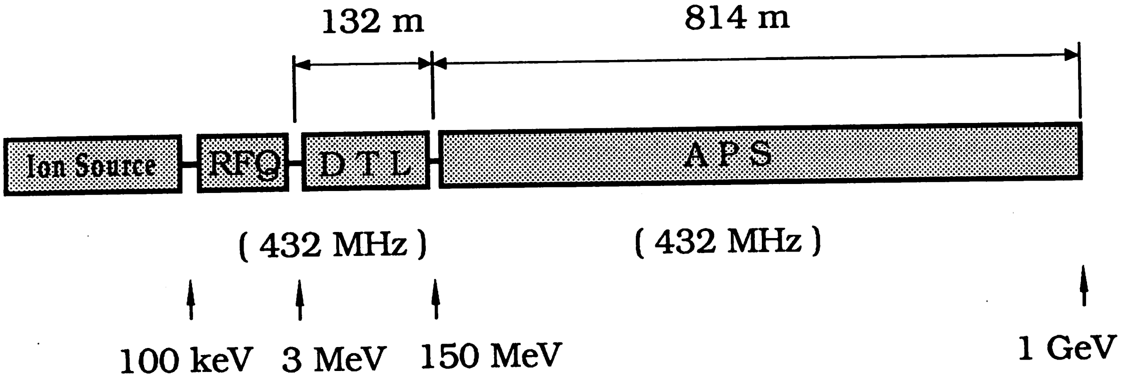

Fig. 1 The scheme of a proposed 1-GeV, 100-mA, continuous-beam proton linac.

TABLE II Design Parameters of the Linac

Total length	1000 m
Beam pulse length	continuous beam
RF pulse length	continuous wave
<u>Ion source</u>	
Type	Duoplasmatron
Peak beam current	100 mA
Normalized emittance	1 πmm·mrad

RFQ

Input energy	100	keV
Output energy	3	MeV
Frequency	432	MHz

DTL

Output energy	148	MeV
Frequency	432	MHz
Total length	132	m
Number of cells	593	
Acceleration Field	1.7	MV/m
Power Dissipation	5.1	MW
Beam Power	14.5	MW
Total RF power	20	MW

High-β linac

Output energy	1	GeV
Frequency	432	MHz
Structure	APS (OCS)	
Total length	814	m
Tank length	590	m
Bore radius	5	cm
Acceleration Field	1.7 - 2.5	MV/m
Power Dissipation	117	MW
Beam Power	87	MW
Total RF power	204	MW
Klystron output power	1	MW
Number of klystrons	204	
Transverse acceptance	320	πmm·mrad

4. CONCLUSIONS

We propose the use of an operating frequency of around 400 MHz for all of an RFQ linac, a DTL and a high-β linac. It should be noted that the advantage of this scheme is based upon the following assumptions.

a) The generation of the tail or halo is a phenomenon closely related to the emittance growth and both can be suppressed by a high-frequency RFQ better than by a low-frequency RFQ.

b) The ion source together with the LEBT can inject 100-keV proton beam into an RFQ with an emittance of 1 π mm·mrad and a current of 100 mA.

Although we believe the feasibility of this scheme is quite high, it should be confirmed by testing the cooling of the CW 400-MHz RFQ.

REFERENCES

1. M. Kihara, "Present Status of the Japanese Hadron Facility", Proc. Advanced Hadron Facility Accelerator Design Workshop, 1988, Los Alamos, LA-11432-C p.4.
2. Y. Yamazaki, S. Anami, H. Baba, S. Fukumoto, T. Kageyama, T. Kato, M. Kihara, Y. Mori, A. Takagi, E. Takasaki, A. Ueno, S. Arai and N. Tokuda, "The 1 GeV Proton Linac for the Japanese Hadron Facility," Proc. Advanced Hadron Facility Accelerator Design Workshop, 1988, Los Alamos, LA-11432-C p. 80 ; KEK Preprint 87-159.
3. Y. Yamazaki and M. Kihara, "Development of the High Intensity Proton Linac for the Japanese Hadron Project," Proc. 1990 Linear Accel. Conf., 543 (1990); KEK Preprint 90-91.
4. R. A. Jameson, "Accelerator-Based Intense Neutron Source for Materials R&D," Proc. 2nd Int. Symp. on Advanced Nuclear Energy Research, 1990, Mito, p. 34.
5. A. Ueno and Y. Yamazaki, "New Field Stabilization Method of a Four-Vane Type RFQ," Nucl. Instr. Meth. A300, 15 (1991); KEK preprint 90-38.
6. A. Ueno, T. Kato, and Y. Yamazaki, "The π-Mode stabilizing Loop for Four-Vane Type RFQ," Proc. 1990 Linear Accel. Conf., 57 (1990); KEK Preprint 90-106.

7. K. Yoshino, "Thermal Analysis of Cooling System of High Power Model of RFQ," 1 GeV Linac Design Note, PLA-90-50.(in Japanese)
8. V. G. Andreev, V. M. Belugin, V. G. Kulman, E. A. Mirochnik, and B. M. Pirozhenko, "Study of High-Energy Proton Linac Strucrures," Proc. 1972 Proton Linac Conf., 114 (1972).
9. T. Kageyama, Y. Yamazaki and K. Yoshino, "A New Annular-Coupled Structure Suppressing Higher Order Modes' Mixing with the $\pi/2$ Coupling Mode", Proc. of the XIV International Conference on High Energy Accelerators, 1989, Japan; Part. Accel. 32, 33(1990); KEK Preprint 89-94.
10. T. Kageyama, Y. Yamazaki, Y. Morozumi, and K. Yoshino, "A High Power Model of the ACS Cavity," Proc. 1990 Linear Accel. Conf., 150 (1990); KEK Preprint 90-102.
11. K. Yamasu, T. Iwata, M. Hamaoka, T. Kageyama, Y. Yamazaki, Y. Morozumi, and K. Yoshino, "Fabrication Technique of ACS Cavity for the JHP," Proc. 1990 Linear Accel. Conf., 126 (1990); KEK Preprint 90-110.
12. Y. Morozumi, T. Kageyama, and Y. Yamazaki, "Multi-Cavity Bridge Coupler," Proc. 1990 Linear Accel. Conf., 153 (1990); KEK Preprint 90-120.
13. T. Nishikawa, S. Giordano, and D. Carter, "Dispersion Relation and Frequency Characteristics of Alternating Periodic Structure for Linear Accelerators," Rev. Sci. Instr. 37, 652 (1966).
14. E. A. Knapp, B. C. Knapp, and J. M. Potter, "Standing Wave High Energy Linear Accelerator Structures," Rev. Sci. Instr. 39, 979 (1968).
15. T. Higo, S. Inagaki, Y. Yamazaki, and K. Takata, "Development of the APS Cavity for TRISTAN $e^+ e^-$ Storage Ring," Proc. 5th Symp. Accel. Sci. Tech. 114 (1984).
16. T. Higo, Y. Yamazaki, T. Kageyama, M. Akemoto, H. Mizuno, and K. Takata, "Development of an APS Cavity for TRISTAN Main Ring," IEEE Trans. Nucl. Sci. NS-32, 2834 (1985); KEK Preprint 85-11.
17. K. Akai, M. Akemoto, S. Araki, H. Baba, E. Ezura, H. Hayano, T. Higo, S. Inagaki, S. Isagawa, T. Kageyama, H. Mizuno, Y. Morozumi, H. Nakanishi, M. Ono, H. Sakai, M. Suetake, T. Takashima, K. Takata, Y. Takeuchi, Y. Yamazaki, and M. Yoshida, "RF System with Room Temperature Cavity of the TRISTAN $e^+ e^-$ Storage Ring," Proc. 13th Int. Conf. on High Energy Accelerators 303 (1986); KEK Preprint 86-54.

18. T. Higo, M. Akemoto, T. Kageyama, Y. Morozumi, H. Sakai, H. Mizuno, Y. Yamazaki, and K. Takata, "RF Cavity for TRISTAN Main Ring," Proc. 1987 IEEE Part. Accel. Conf. 1945 (1987); KEK Preprint 87-4.
19. Y. Yamazaki and K. Takata, "RF Cavity of KEK-PF Storage Ring," Proc. 3rd Symp. Accel. Sci. Tech. 225 (1980).
20. S. Tokumoto, M. Izawa, H. Kobayakawa, and S. Sakanaka, "Improvement on Accelerating Cavities and High Power Test at the Photon Factory Storage Ring," KEK Internal 88-6.(in Japanese)