

HIGHER FREQUENCY OPERATION OF LINEAR ACCELERATOR

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Summary

The high frequency operation of linacs is discussed and several trial designs for fusion material irradiation test facility in Japan are given. The size of linac namely the construction cost may be reduced by using 1 MW CW klystrons with the frequency of about 1 GHz. Preliminary results of the fabrication technique for the linac drift tube by copper coating are shown.

Introduction

The limitation of high energy accelerator construction is said a matter of cost rather than a technical problem. In general, the smaller construction leads to less expensive linac. The accelerator miniaturizing measures developed by PIGMI must be considered also in the future accelerator design. The miniaturizing can be ordinarily realized using high operating frequency. In present Japan, the development of a large klystron having a C.W. output power of 1 MW of 1~2 GHz oscillating frequency is proceeding for using the radio frequency heating of fusion plasma. We have tried the accelerator miniaturization using such a high frequency by referring to the FMIT² design.

Basically, the accelerator system is composed of RFQ and Alvarez linac. We have aimed at the total length of the accelerator system of less than 50 m. In the case of the accelerating particle of D⁺, the injection energy to the RFQ is 50 keV and the final energy at Alvarez linac is 35 MeV.

Design Principles

1. The RFQ operating frequency is selected from the range of the cell length for which the cell cutting can be easily performed. When the initial deuteron energy is 50 keV and the frequency is 80 MHz, the initial cell length is about 1.4 cm. No problem of the availability of high power source is raised at about 100 MHz.
2. Alvarez linacs driven by several different operating frequencies are prepared, and connected, in turn, to higher frequency linac, and finally the accelerator driven by operating frequency of about 1 GHz is realized.
3. In the accelerator for FMIT, a long-time continuous operation is required, so that good reliability must be maintained. For this purpose, it is better to design the average axial field E_0 at low value in order to avoid discharge. here, E_0 is 1 MV/m.
4. In each linac, initial gap spacing is selected to about 2 cm, and G/L is 0.25~0.35. The gap field is sufficiently smaller than 10 MV/m.

5. In the RFQ, the final energy is 1~2 MeV and the length is max. 6 m.
6. The concept of heat removal from tank wall is still flexible.

Accelerator System of High Operating Frequency

The schematic diagram of the first trial design of FMIT-Japan for a deuteron accelerator system whom high operating frequency is not used is shown in Figs. 1, 2 and 3. Fig.1 shows an example of construction when operating frequency is stepped up at two times that of 80 MHz in FMIT. RFQ operating frequency is 80 MHz and Alvarez linac in the next stage is operated at 160 MHz. This is possible because the longitudinal emittance of RFQ output beam is extremely narrow. Tables I, II and III show parameters for each accelerator design. E_0 is the injection energy to linac, g_i is the initial gap spacing of each linac section, g/L is the gap to cell length ratio, P_w is the power dissipation on the linac surface, P_w/S is the power density of P_w with no accelerating beam, Q_0 is unloaded Q factor of linac tank, and Q_0 for TM₀₁₀ mode is given by

$$Q_0 = \frac{1}{\delta_s} \frac{1}{\frac{1}{a} + \frac{1}{h}}, \quad (1)$$

where δ_s is the skin depth, a is tank radius, and h is tank length taken as 2~3 m. As the operating frequency increases, the thermal load tends to decrease. This is because the surface area decreases according to the miniaturization. However the thermal load per unit area is increased proportionally to \sqrt{f} .

Figures 2 and 3 show an example of the accelerator system for the final operating frequency of 1 GHz. Design 2 is an example of attempting the reduction of discharge in the gap as low as possible by broadening the gap spacing at low frequency. Design 3 is an example when the initial gap spacing g_i is unified to 2 cm similarly to design 1. However, the linac system operating at lower than 500 MHz is the same in design 2 and 3. In the 1 GHz linac, whether the Q magnet can be installed in the drift tube is a problem. For the tank, diameter $D = 12$ cm, and the drift tube diameter is 6.6~6.3 cm at the beam energy of 25~35 MeV. Therefore, the use of a permanent magnet quadrupole as in PIGMI must be considered.

The roughness of inside surface of the tank is usually made smaller than skin depth to approach Q to the theoretical value; therefore, at 1 GHz, the roughness of lower than about 2 μ m is required. The roughness was 7.4 μ m at 80 MHz; accordingly, the surface roughness better than this value becomes necessary. The problem of machining accuracy due to miniaturization becomes rather easy because $Q_0 = 120000 \sim 130000$ at about 100 MHz and $Q_0 = 50000$ at 1 GHz. In the system as frequency is increases in 2-times steps as the design shows here, the relative phase width increases when the linac operating frequency increases is a problem. When the frequency is increased to a factor of two, giving the same phase width to each linac injection is only to compress the phase width to 1/2 previously during each linac acceleration.

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In the phase width $\Delta\phi$, the following proportional relation exists:

$$\Delta\phi \propto (\gamma_s \beta_s)^{-\frac{3}{2}}$$

where $\beta_s = v_s/c$ (v_s is synchronous particle velocity) and $\gamma_s = 1/\sqrt{1-\beta_s^2}$. In the non-relativistic range, approximately can be expressed as

$$\Delta\phi \propto V^{-\frac{3}{4}} \quad (2)$$

Therefore, in a linac, if the ratio of final energy V_f to initial energy V_i (that is, V_f/V_i) is 2.52, the phase is compressed to 1/2. In design 1, the compression of $\Delta\phi$ by the increase of V_s in each linac is larger than 1/2; therefore, shifting to the linac of 2-times frequency is easy.

In designs 2 and 3, the phase compression in the 500 MHz linac is a little insufficient; however, since the phase width of the beam from RFQ is sufficiently narrow, no problem will be raised. The total length of the accelerator system including the RFQ is about 39 m in designs 1 and 2, and about 37 m in design 3. However, the length of RFQ is about 6 m in designs 1 and 2, and about 3 m in design 3. In each design, the condition of 50 m or shorter is satisfied and the length is almost the same as that of FMIT. Therefore, diameter reduction becomes advantageous.

At present, the availability of high power source for each operating frequency has sufficient feasibility except 250 MHz and 320 MHz. Table IV shows the ratings of the 500 MHz 200 kW CW klystron (E 3774) and now developing 1.7 GHz 1.4 MW semi-CW klystron (E 3778). In 100 MHz region, the high power tetrode or triode has already been manufactured.

When considering the input power increase to supplement the field reduction by beam loading, the surface heat loading becomes larger. If the average beam current becomes 0.1A, the power loss density of 1 GHz linac may reach about ten times of the tubulated value.

Test Cavity Measurement

We have investigated the method of fabricating TM_{010} cavity to be used for high frequency linac. We have manufactured a cylindrical cavity of TM_{010} mode when the operating frequency is 500 MHz to 1 GHz. The cavity size is as shown in Fig. 4. We have tried to manufacture a cavity by coating Cu on the inner surface of an iron pipe of 295 mm in inner diameter and 20 cm in length. The Q factors measured to several coating thickness are shown in Fig. 5. when no Cu coating is applied, the Q factor is $Q \sim 1600$ and when the coating thickness is more than skindepth at Cu coating, it is $Q \sim 28000$. On the other hand, the unloaded Q estimated from equation (1) regarding the TM_{010} mode is $Q_0 = 35000$, where frequency is 780 MHz. The variation of Q factor obtained when changing the measuring probe length is shown in Fig. 6. L_n is the projection length of the probe into the cavity. The extrapolated value, when $L_n = 0$, is $Q_0 \sim 30000$. This value is approximately 89% of the theoretical value. In this experiment, the cylinder is merely forced to the end plate. Nevertheless, it is greatly worth notice that the Q factor of 89% of the theoretical value has been obtained. It is obvious, therefore, that the Q factor of more than 90% of the theoretical value can easily be obtained.

As stated above, manufacturing of a cavity by coating is considered to be an extremely attractive method.

Problems and Conclusion

The construction of the accelerator system using the operating frequency higher than 80 MHz is realizable except several problems.

The major problems are (1) difficulty of obtaining a high power source at 200~300 MHz and (2) the dimension of the drift tube diameter at 1 GHz. Regarding (2) it is necessary to perform a trial for avoiding cooling problems by adopting a permanent magnet. Regarding (1), since TH515 (max. frequency 200 MHz) is provided, it is sufficient to use the system by lowering its output efficiency or since R&D of 250 MHz high power vacuum tube is considered not to be so difficult. For the designs 2 and 3, therefore, it is supposed that no problem will arise regarding the RF source. In any case, the several hundred MHz region is a "missing link" region in high power source. To avoid this difficulty, it is considered to be a method to adopt such a system that it has the frequency of 100 MHz-200 MHz - 600 MHz - 1.2 GHz. However, in connecting from 200 MHz linac to 600 MHz linac, since the relative phase width is widened three times, it is necessary to compress the phase width in the output of 200 MHz linac and it is not easy to perform the connection.

As the accelerator system of FMIT-Japan at present, the design 2 or the design 3 is considered to be a basic model and further detailed discussions are required.

According to the result of measuring Q of preliminary Cu coating cavity, the present manufacturing method has possibility of obtaining more than 90% of the theoretical value easily and manufacturing of a linac by means of Cu coating is considered to be very promising.

Reference

1. T.J. Boyd et al., "THE PIGMI TECHNOLOGY", LA-UR-80-3561
2. M.V. Fazio, H.P. Johnson, W.J. Hoffert, and T.J. Boyd, IEEE Trans. on Nucl. Sci., vol. NS-26, No.3, P.3018 (June 1979)

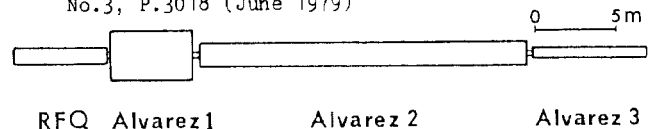


Fig.1 FMIT-Japan design 1

	Alvarez 1	Alvarez 2	Alvarez 3
f (MHz)	160	320	640
g_j (cm)	2	2	2
g/L	0.25	0.25	0.25
A.L.L. (m)	5.2	21.1	7
P_w/S [$\frac{KW}{m^2}$]	4.2	5.9	8.4
Q_0	110000 2 tanks	87000 7 tanks	66000 2 tanks
E_{inj} (MeV)	1.7	6.9	8.

Table I.
Parameter
of design 1

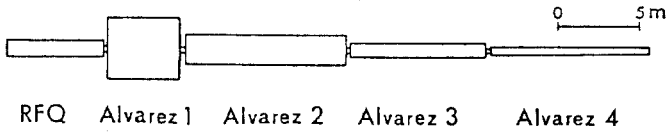


Fig.2 FMIT-Japan design 2

	Alvarez 1	Alvarez 2	Alvarez 3	Alvarez 4
f (MHz)	125	250	500	1000
g _i (cm)	2.8	2.5	2	1.7
g/L	0.25	0.25	0.25	0.35
A.L.L. (m)	4.5	10.3	8.2	9.9
P _w /S [kW/m ²]	3.7	5.2	7.4	10.5
Q ₀	110000 2 tanks	93000 4 tanks	70000 4 tanks	53000 3 tanks
E _{inj} (MeV)	2.05	6.56	16.9	25.1

Table II. Parameter of design 2

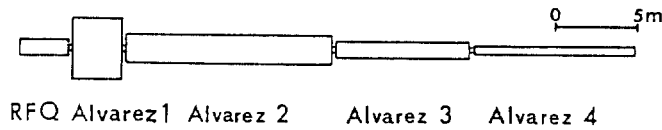


Fig.3 FMIT-Japan design 3

	Alvarez 1	Alvarez 2	Alvarez 3	Alvarez 4
f (MHz)	125	250	500	1000
g _i (cm)	2	2	2	1.7
g/L	0.25	0.25	0.25	0.35
A.L.L. (m)	3.1	12.7	8.2	9.9
P _w /S [kW/m ²]	3.7	5.2	7.4	10.5
Q ₀	120000 1 tank	93000 5 tanks	70000 4 tanks	53000 3 tanks
E _{inj} (MeV)	1.05	4.19	16.9	25.1

Table III. Parameter of design 3

	E 3 7 7 4	E 3 7 7 8
Frequency (GHz)	0.5	1.7
Output power (MW)	0.2	1.4
Beam voltage (kV)	4.4	8.7
Beam current (A)	7.4	3.1
Total length (m)	2.46	2.9

Table IV. Ratings of E3774 and E3778

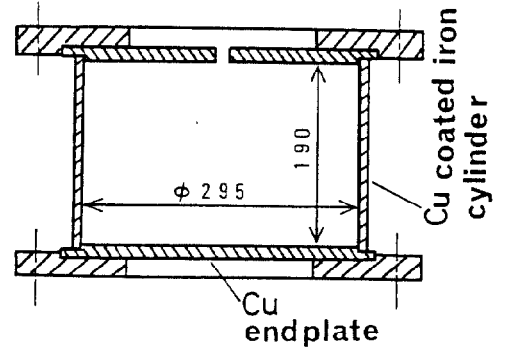


Fig.4 Test cylindrical cavity

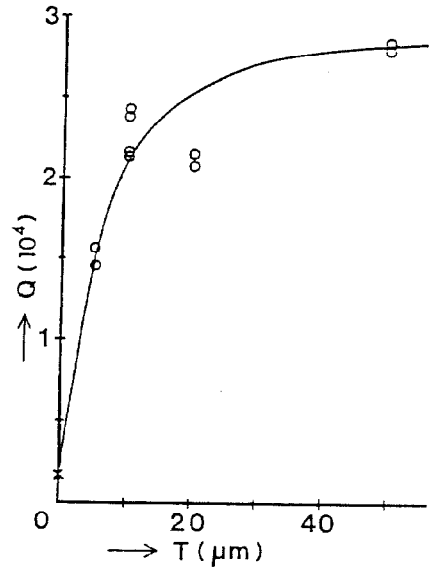


Fig.5 Q factor for some coating thickness

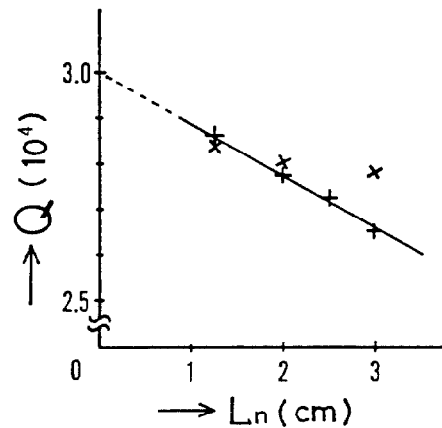


Fig.6 Effect of probe length to Q factor