Proceedings of the 1979 Linear Accelerator Conference, Montauk, New York, USA

DETUNING EFFECT IN A TRAVELING WAVE TYPE LINAC

S. Arai, K. Kobayashi, E. Tojyo, and K. Yoshida
Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo, Japan

Summary

A 15-MeV traveling wave type electron linac is used as the injector for the 1.3-GeV electron synchrotron at the Institute for Nuclear Study, University of Tokyo. The resonant frequency of this accelerator waveguide is 2758.00 MHz at 30°C. The performance of the linac, however, is improved when it is operated with a frequency which is higher than the design value by 200-400 KHz. It is shown that the detuning due to the beam loading is serious in such an accelerator waveguide in which the buncher and regular sections are combined, and the detuning effect can approximately be compensated by changing the operating frequency. The detuning effect in the traveling wave-type accelerator waveguide was studied both from experimental and theoretical aspects by using a short test waveguide.

Introduction

The microwave amplitude reduction due to beam loading results in decreasing the energy gain, while the microwave phase variation due to the detuning effect not only reduces the beam energy, but also deteriorates the energy spectrum by upsetting the synchronism between the electron bunch and microwave. The detuning effect has been studied by many authors for proton linacs, synchrotrons and storage rings. The traveling wave (TW) electron linac, however, has had little study except for the resistive beam loading effect.[1] In a linac used as the injector for an electron synchrotron, a narrow beam energy spread is required, so that the detuning effect is serious. A 15-MeV TW type electron linac[2] is the injector for the 1.3 GeV electron synchrotron at the Institute for Nuclear Study (INS), University of Tokyo. The INS linac consists of a single accelerator waveguide, which includes a buncher section and an accelerator section. In this case, the phase shift produced by beam loading in the buncher section is carried along. The beam loading in the accelerating section becomes reactive, and the detuning effect is severe. In designing the INS linac, the effect of resistive loading was considered but that of reactive loading was not.

Operating Characteristics of the INS Linac

The specifications and microwave characteristics of INS linac are summarized in Tables I and II. It has been confirmed by low power test that the accelerator waveguide was constructed with the resonant frequency within ±100 KHz of the design value. In the actual operation, however, it is found that the capture efficiency of injected beam, the energy gain and the energy spectrum of output beam are improved by setting the operating frequency higher than the design value of 2758.00 MHz, by 200-400 KHz. The above operating characteristics measured in relation with the beam current and operation frequency are shown in Figs. 1, 2 and 3. Since the difference between the optimum and design frequencies increases in proportion to the accelerated beam intensity, these phenomena seem to be due to the detuning effect in the accelerator waveguide. To examine the phase relation between the electron bunch and the accelerating field when the operating frequency is changed, the microwave phase shift caused by the beam loading in the accelerator waveguide has been measured. The phase shift is obtained by comparing the rf phases of the input-to-output rf with and without beam loading. The experimental result is shown in Fig. 4. It is seen from the behavior of the phase shift, that the bunch surmounts the crest of the accelerating field when the operating frequency is changed to higher values. And, it is also clear that the acceleration efficiency is best for the frequency that produces a phase shift slightly greater than zero.

Table I Specification of INS Linac

Length of accelerator structure	∿2.5 cm
Type of construction	semi constant gradient
Number of cavities in buncher section	9 (3 step)
Number of cavities in regular section	51 (4 step)
Accelerating mode	2/3 π
Frequency	2758.00 MHz (at 30°C)
Unloaded Q	12000
Total voltage attenuation	0.45 neper
Filling time	0.5 μsec
Input RF power	7 MW
Injection voltage	100 KV
Beam energy	15 MeV
Beam current	250 mA
Beam pulse length	2 μsec
Energy spread	5 %
Repetition rate	21.5 pps

Table II Dimensions and Microwave Characteristics of Accelerator Waveguide

	2a (mm)	2b (mm)	d (mm)	f_0 (MHz)	v_p/C	v_g/C	r_0 (MΩ/m)
B1	29.795	88.236	28.093	2758.069	0.7753	3.09×10^{-2}	29
BII	27.111	86.364	35.314	2758.027	0.9746	2.39	49
BIII	26.522	86.140	35.900	2758.059	0.9908	2.26	50
RI	25.534	85.842	36.233		1.0000	1.86	50
RII	24.049	85.469	26.233		1.0000	1.62	53
RIII	22.255	85.056	36.233	2758.005	1.0000	1.13	55
RIV	19.893	84.587	36.233	2758.027	1.0000	0.79	58

* B and R in the first column mean the buncher and the regular sections, respectively. f_0, v_g/C, and r_0 are experimental values.

Experiment with a Test Accelerator Waveguide

In the actual linac, information about the detuning effect is obtained only from the output beam or the rf power to the dummy load, and the interaction of the bunch with the accelerating field along the waveguide cannot be directly observed.

In order to investigate the correlation between the TW accelerator waveguide and the detuning effect, a test accelerator waveguide was fabricated. As shown in Table III, the structure of the test waveguide was exactly the same as a part of the regular section of the INS linac. By passing the bunched beam from the INS linac through the test waveguide, the detuning effect was studied systematically and analytically. The measurement system is illustrated in Fig. 5. The microwave power to excite the test waveguide was distributed from the traveling wave tube amplifier in the rf system of the linac, so that the electron bunch and the microwave in the test waveguide were synchronous with each other. The phase relation between the bunch and the rf wave was determined by the line stretcher (A) which allowed various conditions of beam loading to be produced.

Table III Parameters of Test Accelerator Waveguide

Type of construction	constant impedance
Number of cavities	6
Diameter of disk hole (2a)	19.893 mm
Diameter of cylinder (2b)	84.587 mm
Distance between disks (d)	36.233 mm
Disk thickness (t)	5.000 mm
Accelerating mode	$2/3\ \pi$
Frequency	2758.00 MHz (at 30°C)
Normalized group velocity v_g/c	7.97×10^{-3}
Normalized phase velocity v_p/c	1.00
Unloaded Q	11400
Peak shunt impedance	58.0 MΩ/m

The variation of the output power and the phase shift due to the beam loading were measured by letting the bunch ride on the various phase of the external driving field. In this measurement, the INS linac was operated with the resonant frequency of the test waveguide without the beam loading. The results are shown in Fig. 6. The rf power released from the exit coupler varied sinusoidally with the phase on which the bunch rode, and the phase shift of the accelerating field varied most steeply when the bunch was near the crest of the accelerating field. These results are similar to that for the standing wave accelerator.[3]

Studies were made to see if the phase shift due to the reactive beam loading could be compensated by changing the frequency of the external driving field. The phase shifter was adjusted with the beam switched off to minimize the vector summation of two microwaves to the magic-T_{ee}. When the beam was switched on, the phase of the accelerating field shift due to the reactive beam loading, and the vector summation of the two microwaves, deviated from the minimum value. To minimize the vector summation again, the frequency of the external driving field was adjusted and the degree of the frequency change was recorded.

As seen from the experimental results in Fig. 7, the frequency must be changed to lower or higher value for the phase shift compensation when the bunch is before or behind the crest of the accelerating field, respectively.

Theoretical Analysis

The detuning effect in the test accelerator waveguide is analysed here by normal mode analysis for a microwave cavity, which has been developed by J.C. Slater, T. Nishikawa and others.[4-7]

The TW accelerator waveguide can be regarded as composed of a chain of unit resonant cavities. The wave equation in the unit cavity is represented as

$$\frac{d^2}{dt^2}\int \bar{E}\bar{E}_a^* dV + \frac{\omega_a'}{Q_0}\frac{d}{dt}\int \bar{E}\bar{E}_a^* dV + \omega_a'^2\int \bar{E}\bar{E}_a^* dV = -\frac{1}{\varepsilon_0}\frac{d}{dt}\int \bar{J}\bar{E}_a^* dV \quad , \tag{1}$$

where $\bar{J}$ is the current density of the electron beam, $\bar{E}$ is the electric field in the unit cavity, $\bar{E}_a$ is the a-th normal mode field in it, ω_a' is the resonant frequency of the unit cavity without the beam loading, Q_0 is the unloaded Q of the unit cavity and ε_0 is the dielectric constant of vacuum. $\bar{E}_a$ can be written as $\bar{E}_a = \bar{E}_{a0}e^{-jkz}$ in terms of the propagation constant of the microwave, k, and the amplitude of the normal mode field, $\bar{E}_{a0}$. In the TW type accelerator waveguide, the stored energy of the microwave is propagated with the group velocity v_g. It can, therefore, be considered that the unit cavity, for which eq. (1) holds, moves along the waveguide with the velocity v_g.

The right hand side of eq. (1) represents the external force of the forced oscillation and can be expressed as

$$-\frac{1}{\varepsilon_0}\frac{d}{dt}\int \bar{J}\bar{E}_a^* dV = -j\,\frac{2FI_0E_{a0}\omega}{\varepsilon_0}\,e^{j(\omega t+\phi_b)} \quad , \tag{2}$$

where ϕ_b is the phase of the external field on which the bunch rides, F is the form factor of the bunch and I_0 is the peak beam current. F is assumed here to be unity.

The relation between the amplitude of the normal mode field E_{a0} and the peak shunt impedance r is given by the equation,

$$r = \frac{2Q_0E_{a0}^2}{\varepsilon_0\omega_a'} \quad . \tag{3}$$

When the axis of the accelerator waveguide is defined as the z-axis, the entrance of the waveguide being the origin of the coordinates, the electric field at z is obtained by substituting the relation, $t = z/v_g$, into the solution of eq. (1), as:

$$E(z) = \{E_0 e^{-\frac{\omega}{2v_g Q_0}z} - I_0 r e^{j\phi_b}(1-e^{-\frac{\omega}{2v_g Q_0}z})\} \cdot e^{j(\omega t - kz)} \quad , \qquad (4)$$

where E_0 is the electric field amplitude at $z = 0$ and $t = 0$. The first and second terms of the right hand side in eq. (4) represent the attenuation of the external field and the build-up of the beam induced field, $E_b = I_0 r$, respectively.

The phase shift of the accelerating field is regarded to be the result of the detuning of the accelerator waveguide due to the beam loading. The wave equation in the unit cavity, eq. (1), is rewritten by using the relation, $\int E E_a^* dv$ = constant $\cdot e^{j\omega t}$, as:

$$j\left(\frac{\omega}{\omega_a'} - \frac{\omega_a'}{\omega}\right) + \frac{1}{Q_0} = \frac{j}{\varepsilon_0 \omega \omega_a'} \frac{\frac{d}{dt}\int \bar{J}\bar{E}_a^* dV}{\int \bar{E}\bar{E}_a^* dV} \quad . \qquad (5)$$

The imaginary part in the right hand side of eq. (5) represents the reactive component of the beam loading and its contribution to the resonant angular frequency shift, $\Delta\omega = \omega - \omega_a'$ is:

$$\Delta\omega_i = \frac{\omega_a'}{2Q_0} \frac{-E_0 T E_b \sin\phi_b}{E_0^2 T^2 + E_b^2(1-T)^2 - 2E_0 T E_b(1-T)\cos\phi_b} \quad , \qquad (6)$$

where T represents the attenuation of the microwave in the accelerator waveguide, $e^{-\frac{\omega}{2v_g Q_0}z}$. The real part represents the resistive component, and gives the beam quality factor, Q_b:

$$\frac{1}{Q_b} = \frac{1}{Q_0} \frac{E_0 T E_b \cos\phi_b - E_b^2(1-T)}{E_0^2 T^2 + E_b^2(1-T)^2 - 2E_0 T E_b(1-T)\cos\phi_b} \quad . \qquad (7)$$

The total Q, Q_T, is given by $Q_T = Q_0 Q_b/(Q_0+Q_b)$, and the contribution to the resonant frequency shift is :

$$\Delta\omega_r = \omega_a'\left(\sqrt{1 - \left(\frac{1}{2Q_T}\right)^2} - 1\right) \quad . \qquad (8)$$

The whole resonant angular frequency shift due to the beam loading is given by eqs. (6) and (8) in the following form,

$$\Delta\omega = [\{\omega_a' - \frac{\omega_a'}{2Q_0} \frac{E_0 T E_b \sin\phi_b}{E_0^2 T^2 + E_b^2(1-T)^2 - 2E_0 T E_b(1-T)\cos\phi_b}\} \cdot \sqrt{1-\left(\frac{1}{2Q_T}\right)^2} - \omega_a'] \qquad (9)$$

When the resonant frequency of the accelerator waveguide changes by Δf, the phase velocity of the accelerating field is, assuming the group velocity to be constant around the resonant frequency, given in the form,

$$v_p = \frac{v_g \lambda_g f_0}{v_g - \lambda_g \Delta f} \quad , \qquad (10)$$

where λ_g and f_0 are the guide wavelength of the accelerating field and the original resonant frequency.

The phase difference between the accelerating fields with and without the beam loading can be written as

$$\Delta\phi = 2\pi f_0 L\left(\frac{1}{v_{p0}} - \frac{1}{v_p}\right) \quad , \qquad (11)$$

where v_p is the phase velocity without the beam loading and L is the length along the accelerator waveguide passed by the waves. The rf power at the position z is expressed in terms of the electric fields as

$$P(z) = P_0(z)[1+\{\frac{E_b(1-e^{-\frac{\omega}{2v_g Q_0}z})}{E_0 e^{-\frac{\omega}{2v_g Q_0}z}}\}^2 - 2\frac{E_b(1-e^{-\frac{\omega}{2v_g Q}z})}{E_0 e^{-\frac{\omega}{2v_g Q_0}z}}\cos\phi_b] \quad , \qquad (12)$$

$$P_0(z) = \frac{v_g Q_0}{r\omega} E_0^2 e^{-\frac{\omega}{v_g Q}z} = P_{in} e^{-\frac{\omega}{v_g Q_0}z} \qquad (13)$$

where P_{in} is the input power to the accelerator waveguide and $P_0(z)$ is the rf power at z, without the beam loading. Numerical results are shown in Fig. 6.

Finally, the subject of compensating the phase shift due to the beam loading by changing the operation frequency will be discussed. As seen in eq. (9), the resonant frequency varies with the position along the accelerator waveguide. Therefore, when the operation frequency is changed to make the phase shift zero at the exit of the waveguide, the new frequency is a certain mean of the resonant frequencies of the cells in the accelerator waveguide.

The value of frequency change for the compensation as defined above has been calculated as a function of the beam current and the phase of the external field on which the bunch initially rides. The calculated result is compared with the experiment in Fig. 7. It is seen that both results agree well with each other.

Analysis of the Operating Characteristics of INS Linac

A program for tracing the beam based on the above mentioned theory of the detuning effect, has been developed in order to analyze the operating characteristics of INS linac. In the beam trace calculations to date, the rf power loss due to the beam loading and the wall resistance of the accelerator waveguide have been taken into account, but the detuning effect due to the beam loading has not been considered.

In the calculation, the following assumptions are used: 1) the group velocity of the microwave remains constant when the resonant frequency varies due to the beam loading, or the operating frequency is changed from the resonant frequency of the accelerator waveguide; 2) since the frequency passband of the TW linac is wide, the rf reflection due to the detuning of the accelerator waveguide can be neglected; 3) the value of the phase shift due to the beam loading, when the linac is operated with the frequency different from the resonant frequency as determined from the mechanical dimensions, is obtained by the same method as for the case of operating with the resonant frequency.

Calculated results, together with the experimental results of the output beam current and the beam energy, are shown in Figs. 1 and 2, respectively. The calculation of the energy spread is shown in Fig. 8. The calculated results of the microwave phase shift due to beam loading by passing through the whole accelerator waveguide are indicated in Fig. 4, with the experimental results. Since the present program gives a good explanation of the experimental results at the exit of waveguide, it is concluded that the methods of the analysis and the calculation are both correct. The state of detuning inside the accelerator waveguide, which cannot be directly measured, has been estimated. The results of the resonant frequency shift, the phase shift due to the beam loading, and the effective loading angle of the bunch, are indicated in Fig. 9.

Conclusion

From the experimental results and the theoretical analysis, it has been confirmed that the detuning effect on the accelerating field deteriorates the acceleration performance of the linac which performs bunching as well as the beam acceleration in a single accelerator waveguide.

The detuning effect can be compensated fairly well by taking the operating frequency higher than the design value.

The disks and the cylinders of the waveguide can be machined with an accuracy of a few μm, and the accuracy of the phase advance in the accelerator waveguide is better than three degrees. This mechanical accuracy has been regarded to be of major importance in providing an electron beam with as narrow energy spread as possible. Even if the accelerator waveguide is constructed with extreme mechanical accuracy, however, it is of little use unless the detuning effect due to the beam loading, which causes the phase shift amounting to some tens of degrees, is taken into account.

The ideal design for the future accelerator waveguide including a buncher section should be as follows: when very narrow energy spread is required, as in the case of an injector for a synchrotron, each cavity of the accelerator waveguide should be designed so as to resonate at the operating frequency under the expected beam loading conditions. However, it is complicated and not practical to make an accelerator waveguide with cavities having different resonant frequencies. It is better to design the cavities of the waveguide to yield the phase advance which is correct when the beam loading exists. Although such a linac is, to be exact, for a specific amount of beam loading, the average performance will be much better than that for no beam loading. The phase advance for each cavity can easily be determined by the beam loading detuning theory presented in this work.

Reference

1 J.E. Leiss, "Beam Loading in Linear Accelerators", IEEE Trans. on Nucl. Sci. NS-12, 566 (1965).

2 T. Katayama, S. Arai, K. Yoshida and J. Tanaka, "The Construction of 15-MeV Linear Accelerator as Injector for INS Electron Synchrotron", INS-Report 240 (1975).

3 S. Arai, T. Katayama, E. Tojyo and K. Yoshida, "Beam Loading Effects in a Standing Wave Accelerator Structure", INS-TH-118 (1978).

4 J.C. Slater, "Microwave Electronics", Reviews of Modern Physics, 18 441 (1946).

5 T. Nishikawa, "Normal Mode Analysis of Standing Wave Linacs - Field Excitation and Beam Loading in Linac Cavities", BNL Accelerator Dept. Internal Report AADD-87 (1965).

6 R. Beringer and R.L. Gluckstern, "On the Normal Modes in Linac Structures", Yale Univ. Internal Report Y-9 (1964).

7 M. Bell, "Normal Mode Analysis of Standing Wave Linacs and the New Linac", CERN/MPS/DL 75-3 (1975).

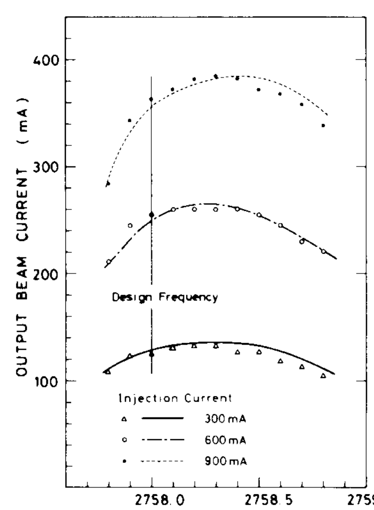

Fig. 1 Frequency dependence of the output beam current of the linac for the injection currents of 300 mA, 600 mA and 900 mA. The curves are calculations.

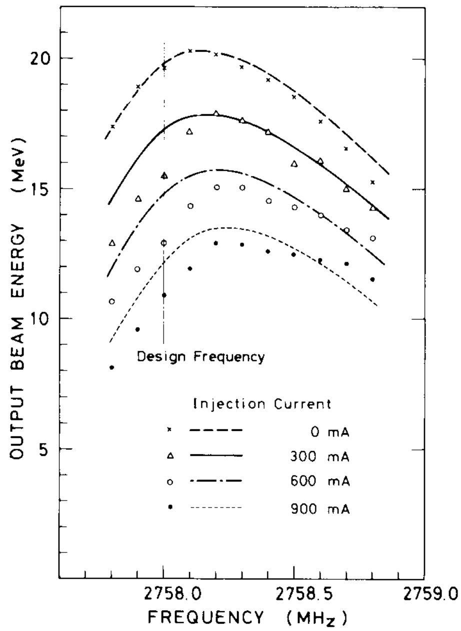

Fig. 2 Frequency dependence of the output beam energy of the linac.

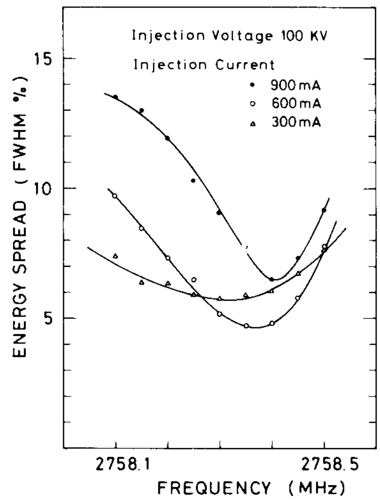

Fig. 3 Frequency dependence of the energy spread of the output beam. The solid lines are the best fit curves to the experimental values.

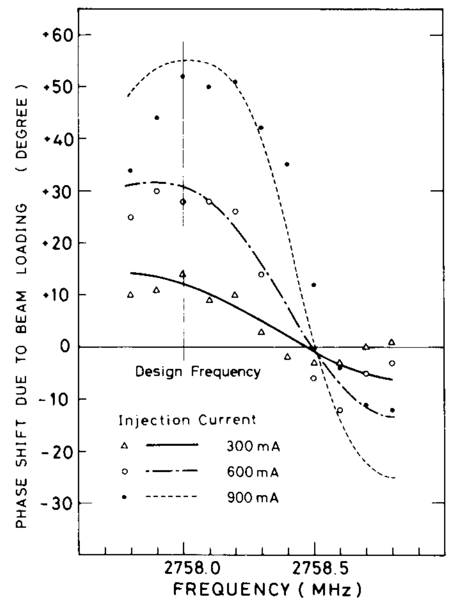

Fig. 4 Frequency dependence of the phase shift due to the beam loading.

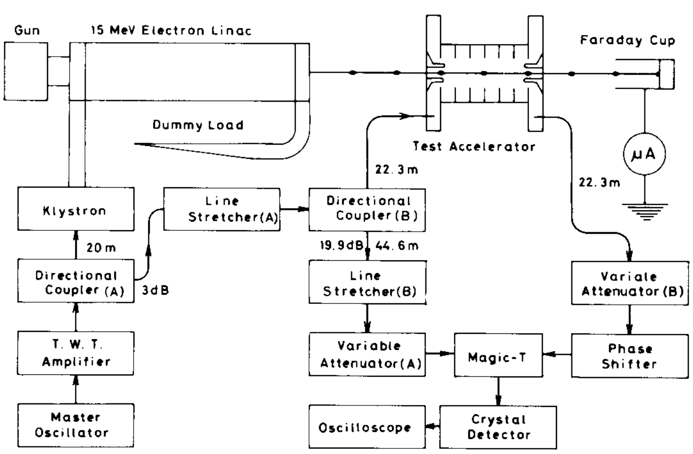

Fig. 5 Experimental setup for investigating the detuning effect in the test waveguide.

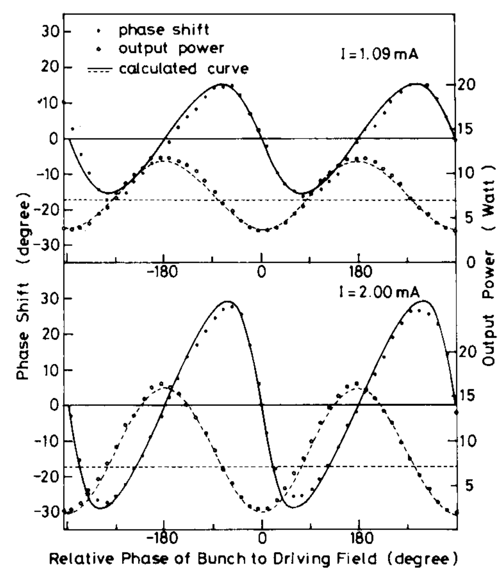

Fig. 6 Phase shift and output power of the microwave riding the bunch on the various phase. Input power is 8.2 Watt.

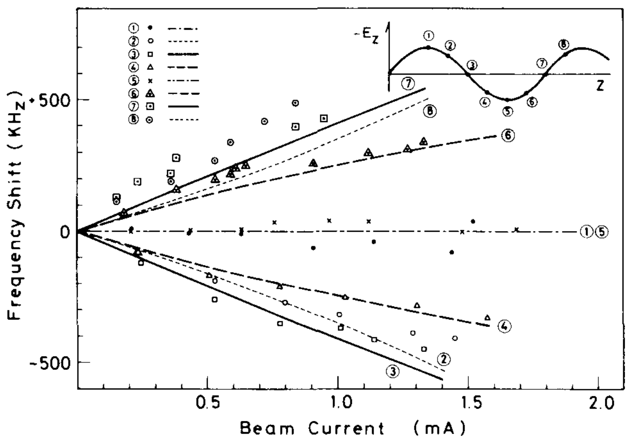

Fig. 7 Frequency change needed in compensating the phase shift due to the beam loading. Input power is 8.7 Watt.

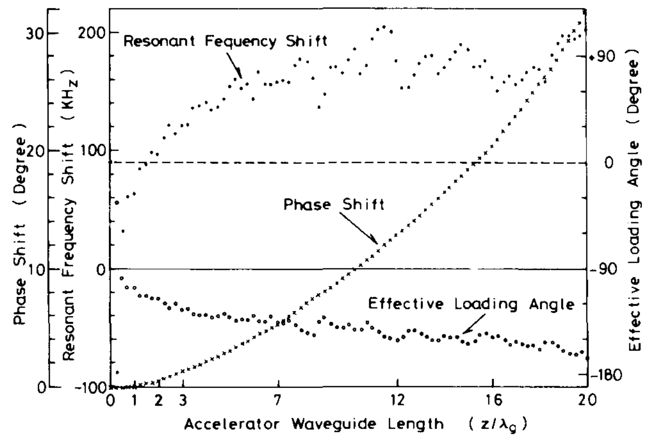

Fig. 9 Calculation of phase shift, resonant frequency shift and change of the effective loading angle along INS linac for the operation frequency of 2758.00 MHz.

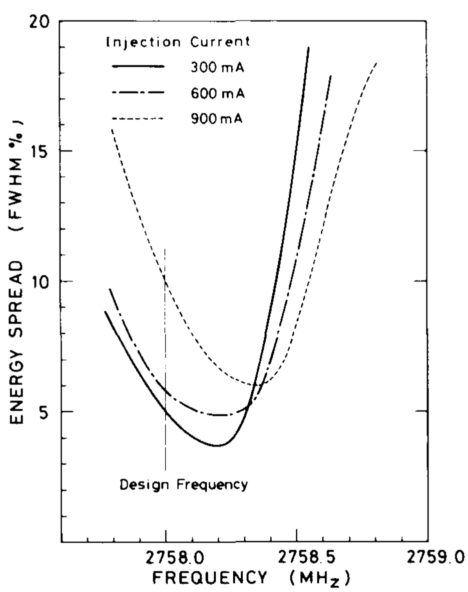

Fig. 8 The calculated result for the frequency dependence of the energy spread.

Discussion

Miller, SLAC: I believe J. Haimson has worked on this same problem and many have reported on his work in one of the IEEE Particle Accelerator Proceedings, or perhaps in the linear accelerator book edited by Septier.

My question is this: since the phase detuning is dependent on beam intensity, doesn't it make sense to correct for the phase detuning by adjusting the operating frequency as you have done?

Arai: The designed beam current of the INS linac is about 200 mA.

Miller: Or can one perhaps pick an intermediate current over the range of which you want to run and then have a pretty good design over a wide range?

Leiss, DOE: Of course with a single cell machine you have, not only possible beam dc tuning, but also the bunching and stable phase angle depend on current, so it is very complicated in a one section machine.

Miller: In a multiple section machine you can always correct for this effect by appropriately phasing the downstream sections. And I think it does not have a striking effect on the bunching itself, rather on the phase with which the beam rides after it essentially reaches the velocity of light. This occurs because the bunching occurs very early in the structure.

Arai: I agree with your opinion.