# COMPACT HIGH-TRANSMISSION ELECTRON LINAC STRUCTURES

J.-P. Labrie
Atomic Energy of Canada Limited, Research Company
Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0

## Abstract

Beam transmission through standing-wave linacs, designed with their electron gun mounted on the accelerator structure, is usually about 35%. Significant improvements in beam transmission through these devices can be obtained with a cylindrical cavity coupled at the front end of the linac structure. The accelerator section is then composed of a cylindrical buncher cavity electromagnetically coupled to shaped cavities for high rf efficiency. The device remains compact and is better adapted to high average beam power operation. Beam dynamics calculations have shown that beam transmission can be increased by 50%. Output transverse emittance and energy spread are 2 times greater than in conventional standing-wave structures. This degradation of the output beam characteristics is acceptable for use of these devices as high-power bremsstrahlung sources.

## Introduction

Industrial irradiators based on electron linear accelerators are well suited for high product throughput applications[1]. Linacs capable of producing high-power electron beams are required for bremsstrahlung x-ray irradiations because of the low conversion efficiency of electron beam power into photons at beam energies below the thresholds for material activation. The bremsstrahlung yield for 5 MeV electrons incident on an optimum 0.8 mm tantalum radiator is, for example, only 6.4%[2]. This means that a 5 MeV electron linac used for bremsstrahlung x-ray production may require average beam powers up to 250 kW. Such powerful devices, though technically achievable[3], impose severe demands on accelerator designers to make them sufficiently simple for application to industrial use.

Electron linear accelerators used for medical therapy, x-ray radiography and industrial irradiations usually have their electron gun mounted on the accelerator structure for simplicity and compactness of the device. Electrons are injected into the accelerator structure's capture section where they are accelerated and bunched into a series of micropulses synchronized to the rf fields for further acceleration in the following rf cavities. These accelerators have a beam transmission of about 35%. This low transmission is of little concern when average beam powers are low. Beam losses in the first cavities of the linac capture section and electron backstreaming can, however, trigger cathode poisoning in high-power devices and significantly reduce the machine availability. Good beam transmission rather than high beam quality is therefore preferable for high-power bremsstrahlung x-ray sources.

The computer code PARMELA[4], modified to account for backstreaming electrons in cavities, has been used to calculate beam characteristics at the output of standing wave on-axis coupled structures. The cavity field distributions used in the particle dynamics calculations were obtained from the cavity evaluation code SUPERFISH[5] for cylindrical and shaped 3 GHz cavities. The relative cavity field amplitude in the beam capture sections were determined from measurements with on-axis coupled cavity segments of appropriate length.

## Beam Characteristics in Electron Linac Structures

Comparison of the measured transverse beam characteristics at the output of electron linear accelerators show little variation among accelerators designed for the same output energy[6]. Indeed, the relationship between the measured transverse emittance and the beam current at the output of linacs is determined within a factor of 3 by the Lawson-Penner empirical scaling law, $\epsilon_n \approx 50\ I^{1/2}$ mm•mrad. The normalized emittance, $\epsilon_n = (\gamma^2 - 1)^{1/2}\,\epsilon$, where $\gamma$ is the ratio of electron energy to its rest energy, varies between 10 and 100 mm•mrad in linacs with beam energies up to 15 MeV. The corresponding normalized beam brightness, $B_n = I/\epsilon_n^2$, where I is the beam current, varies from $10^{-2}$ to $10^{-4}$ A/mm$^2$•mrad$^2$. This means that the rf fields in linac structures have small effects on beam transverse characteristics which are mainly determined at the electron gun.

Space-charge forces produce transverse and longitudinal defocusing of the beam during the bunch-forming process. At the low peak beam current considered in this paper for high average power devices, ≈ 100 mA peak, one of the main factors which determine an increase in transverse emittance is the phase extent of the bunches at the input to the accelerator capture section[6]. Space charge forces were not considered in the calculations.

The transverse acceptance of a linac structure is mainly determined by its beam aperture diameter; a large transverse acceptance requires a large-structure beam aperture diameter. Lower-frequency linac structures can be advantageous for high beam power devices since they can better accommodate larger beam aperture diameters with relatively less degradation of the structure shunt impedance. The transverse output beam emittance is mostly determined by the gun cathode area and does increase significantly with a larger-structure beam aperture diameter.

The longitudinal beam characteristics are determined to a great extent by the linac capture section. The input phase acceptance of an electron linac capture section is typically 125° and the phase extent of the accelerated bunch is usually reduced to about 60° after the first few cavities, see Fig. 1. The longitudinal output beam characteristics have a relatively small dependence on the injection energy. This is illustrated in Fig. 1 where the calculated output energy and phase of particles injected, at energies 20, 40 and 60 keV, in a 5 cavity capture section designed for an injection energy of 40 keV, are shown.

The 3 GHz capture section cavity parameters used in this calculation are given in Table 1. The accelerating gradients are typical for S-band structures. The longitudinal phase acceptance increases slowly with injection energy but there is little variation in the output energy and phase spread. These results are essentially the same for linac structures operating at other frequencies when the energy gain per cavity is kept the same, i.e. when the accelerating field is scaled by the ratio of the linac frequencies and the cavity length relative to the wavelength, $\beta_c/2$, is the same.

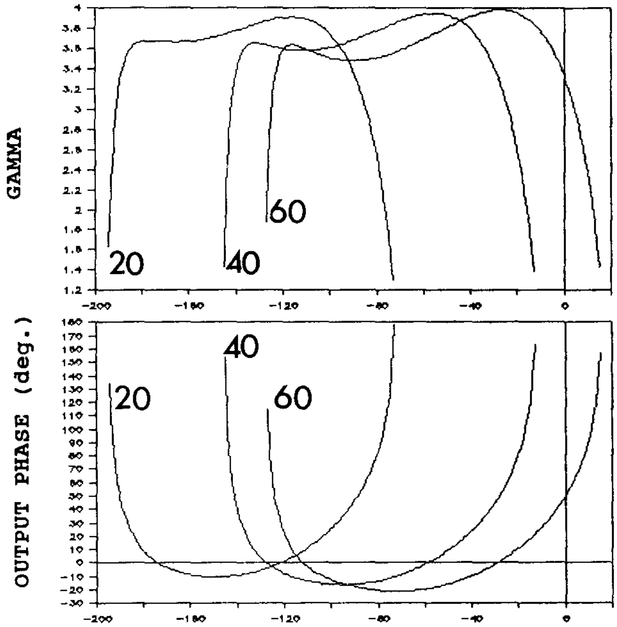


Fig. 1. Longitudinal beam characteristics at the output of a 5 cavity on-axis coupled 3 GHz capture section for beam injection energies of 20, 40 and 60 keV.

The longitudinal density distribution of the injected beam bunch, the gun cathode area and the beam aperture diameter of the structure are the dominant factors in determining beam transmission. Phase compression of the beam to match the longitudinal acceptance of the structure can be achieved in various ways. Beam transmission from the electron gun can be increased to 70% with a fundamental buncher section located upstream of the linac structure[7]. The phase extent of beam bunches after velocity modulation of the dc beam from the gun with a buncher section located at a distance L from the linac structure is given by[8]

$$\Delta\phi = \frac{2\pi L}{\beta\lambda}\,\frac{1}{\gamma(\gamma+1)}\,\frac{\Delta W}{W} \qquad (1)$$

Table 1

Buncher Cavity Parameters

| Cavity | $\beta_c$ | Accelerating Field (MV/m) | Transit Time Factor | Type |
|---|---|---|---|---|
| 0 | 0.617 | 6.00 | 0.800 | cylindrical |

Capture Section Cavity Parameters

| Cavity | $\beta_c$ | Accelerating Field (MV/m) | Transit Time Factor | Type |
|---|---|---|---|---|
| 1 | 0.617 | 7.77 | 0.853 | shaped |
| 2 | 0.818 | 8.85 | 0.832 | shaped |
| 3 | 0.902 | 9.17 | 0.824 | shaped |
| 4 | 0.941 | 9.29 | 0.820 | shaped |
| 5 | 0.993 | 9.34 | 0.815 | shaped |

Beam aperture diameter of the 3 GHz cavities is 10 mm.

where $\beta\gamma = (\gamma^2 - 1)^{1/2}$, W is the electron kinetic energy and $\Delta W$ is the maximum energy gain across the buncher section. This means, for example, that electrons injected at 40 keV, receiving a ± 40 keV energy modulation in the buncher section, will undergo a phase compression from 360° down to 125° after a 30 mm drift between the buncher section and the input to a 3 GHz linac structure.

Compact designs can be achieved with the buncher section installed very close to the linac structure but the main disadvantages of a buncher section separated from linac structure come from the added complexity of the rf phase and resonance control of two structures whose resonant frequencies must be matched to the rf drive frequency. These added controls are likely to reduce the system availability. A single structure linac has the advantage that AFC (automatic frequency control), with the rf power source tracking the structure resonant frequency, can be used. This allows for rapid corrections of the rf drive frequency to compensate for resonant structure frequency shifts from temperature changes during run up to high power.

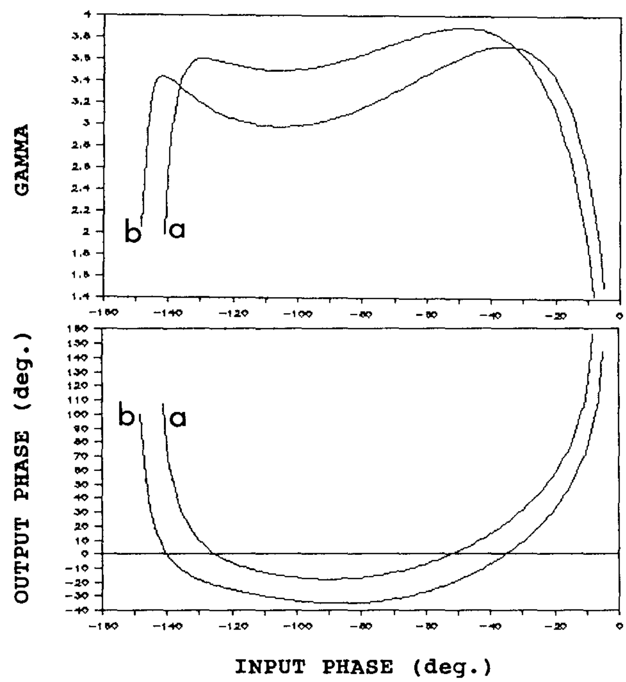


Fig. 2 Longitudinal beam characteristics at the output of 5 cavity on-axis coupled 3 GHz capture sections with the following cavity gradings: (a) $\beta_c$ = 0.60, 0.80, 0.90, 0.95 and 0.993 and (b) $\beta_c$ = 0.62, 0.72, 0.83, 0.94 and 0.993.

## Capture Section Design

The longitudinal beam characteristics at the output of capture sections, see Fig. 2, show a ratgher weak dependence of the output energy and phase spread and of the phase acceptance to small variations in the grading of the cavity lengths. These calculations were made for 40 keV electrons injected into 3 GHz capture sections with the relative field amplitudes in the cavities deduced from measurements with on-axis coupled cavities. The relatively low sensitivity of the longitudinal beam characteristics to small variations in the cavity lengths in the capture section allows for a simple design criterion for high-transmission capture sections: The length of each graded-beta cavity be made equal to the average value of the velocities of the transmitted electrons calculated at the input and at the output of each cavity. This design criterion can be written as:

$$\beta_c^2 \approx 1 - \frac{1}{\left(\frac{\gamma_{in} + \gamma_{out}}{2}\right)^2} \qquad (2)$$

where $\gamma_{in}$ and $\gamma_{out}$ are the ratio of electron energy to rest mass energy calculated at the input and output of the cavities. The following relationship is deduced from above:

$$\left(\gamma_{in} + \frac{\beta_c \lambda\ E(\beta_c)\ T(\beta_c)}{4\ m_o c^2}\right)^2 = \frac{1}{1 - \beta_c^2} \qquad (3)$$

where $E(\beta_c)$ and $T(\beta_c)$ are the field amplitude and transit time factor of the cavities and $\lambda$ is the cavity wavelength. Table 1 gives the cavity parameters of a capture section calculated from eqn. 3. Note that, as expected from Fig. 1 where large variations in the beam injection energy produce small changes in the longitudinal beam characteristics, the accelerating voltage in eqn. (3) is a slowly varying function of the beam injection energy. Furthermore, the accelerating voltage of the linac cavities is then set by the length of the first cavity in the beam capture section.

## Buncher Section Design

Several methods of improving the longitudinal acceptance of capture sections by adding a buncher section electromagnetically coupled to the capture section have been suggested[9,10,11]. Calculations have shown that in some cases, essentially 100% acceptance could be achieved[9]. These devices usually require a delicate tailoring of the buncher section cavity length and coupling to achieve the desired field distribution at the proper phases.

A compromise solution, which maintains the linac structure simplicity and compactness, is to add a cylindrical cavity electromagnetically coupled to the input of the capture section. This cavity produces some phase compression of the beam from the electron gun mounted on its input and is used to better match the injected beam to the longitudinal acceptance of the capture section.

The amplitude of the field in the cylindrical buncher cavity and its length are interdependent. They are constrained to allow for a large acceptance of the buncher cavity and to ensure synchronism of the bunched beam at the output of the cylindrical cavity with the following shaped cavities. The field amplitude and length of the cylindrical buncher cavity and the beam characteristics at the output of a capture section have a strong dependence on the injection energy as for conventional systems consisting of a buncher section and a drift space [7].

The field amplitude and length of a 3 GHz cylindrical buncher cavity optimized for the shaped cavity-capture section described above and for an injection energy of 40 keV, are given in Table 1. The buncher cavity and the first cavity of the capture section have the same length but the field in the buncher cavity is reduced by increasing the coupling between these cavities by 30%.

A comparison of the beam characteristics of a 5 MeV, 3 GHz linac structure with and without a cylindrical buncher cavity was made. The transverse acceptance of linacs varies with the input phase angle. The transverse acceptances of both types of structures, calculated with PARMELA assuming a beam aperture diameter of 10 mm, are similar and greater than 100 mm•mrad over the transmitted input phases angles. Beam dynamics calculations were done with input beams of 40 mm•mrad and an injection energy of 40 keV into the capture sections described in Table 1. Beam transmission through a 5 MeV linac with and without a buncher are shown in Fig. 3. Beam losses in the first cavities of the capture section are significantly reduced by the buncher cavity and become comparable after the third cavity. Beam transmission with the buncher cavity is increased by 50%.

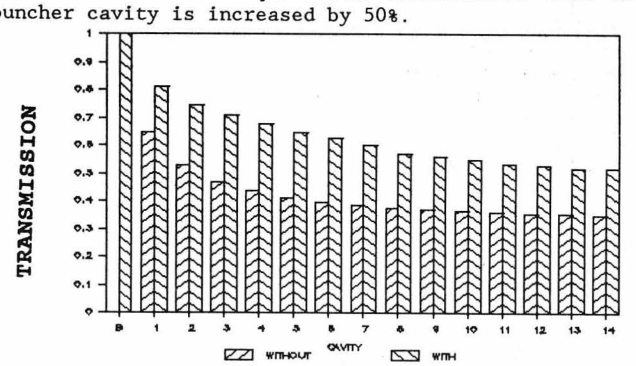


Fig. 3 Beam transmission through a 5 MeV linac structure with and without a cylindrical buncher cavity.

The increased beam transmission due to the cylindrical buncher cavity leads to some degradation of the output beam characteristics which are not critical for the production of 5 MeV bremsstrahlung. The energy spectra from the 5 MeV linacs are compared in Fig. 4. The energy spread and the calculated transverse rms emittance at the output of the linac with a buncher are about 2 times greater.

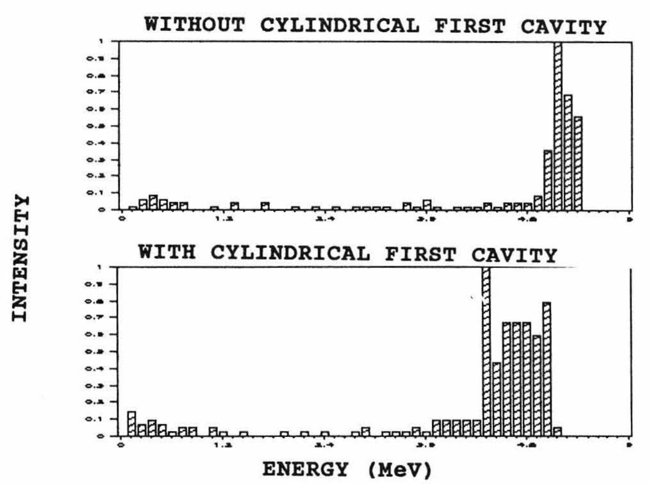


Fig. 4 Beam energy spectra at the output of a 5 MeV linac structure with and without a cylindrical buncher cavity.

REFERENCES

1. J.-P. Labrie, L.W. Funk, S. Gowans and J. McKeown, Nucl. Instr. and Meth. A242(1986)359.
2. K.C.D. Chan, M.A. Lone, S.E. Adams and P.Y. Wong, Nucl. Instr. and Meth., B10/11(1985)419.
3. J. McKeown, R.K. Elliot, L.W. Funk, S. Gowans, J.-P. Labrie, C.E. Langlais and D.G. Logan, Proc. of the 1984 Linear Acc. Conf., GSI-84-11(1984)186.
4. K.R. Crandall, private communication.
5. K.H. Halbach and R.F. Holsinger, Particle Accelerators, 7(1976)213.
6. V.A. Polyakov and I.S. Shchedrin, Sov. Phys. Tech.Phys., 27(2)(1982)250.
7. J.-P. Labrie and R.T.F. Bird, AECL-9112(1986).
8. J. Haimson, IEEE Trans. Nucl. Sci. NS-9(2)(1962)32.
9. L.W. Funk, Nucl. Instr. and Meth. b10/11(1985)896.
10. D. Tronc, Proc. of the 1986 Linear Acc. Conf.,SLAC -303(1986)472.
11. D. Tronc, Nucl. Instr. and Meth. 105(1972)335.