Proceedings of the 1984 Linear Accelerator Conference, Seeheim, Germany

USE OF HIGH DISPERSION ACCELERATING WAVEGUIDES IN LINEAR ELECTRON ACCELERATORS

Yu.P.Vakhrushin, V.M.Nikolaev, A.V.Rjabtsov, V.L.Smirnov
D.V.Efremov Scientific Research Institute of Electrophysical Apparatus, Leningrad, USSR

Summary

In this paper an optimization of S-band travelling-wave (TW) and standing-wave (SW) structures is made using the maximized energy gain as a criterion and the structure length and rf input power as parameters. It is shown that the maximized energy gains in both structures are comparable over the beam current range being considered. Dispersion of the optimized low beam current TW structure should be high. Using the measurement data, it has been found that these structures would be of about 1m or higher in length. This conclusion is illustrated by a number of linacs, which are currently in operation or under design.

Comparison of Optimum TW and SW Structures

Both the TW and SW structures are successfully used in pulsed electron linacs. Studies and operational experience accumulated to date make possible a comparison of their potentialities.

The normalized energy gain W_n^{TW} in the conventional TW structure of constant impedance design is given by the well-known formula[1]:

$$W_n^{TW} = (2/\tau)^{1/2}\cdot(1-e^{-\tau}) - i_n^{TW}\left(1-\frac{1-e^{-\tau}}{\tau}\right) \quad (1)$$

where

$$W_n^{TW} = W^{TW}\cdot(r^{TW}\cdot P^{TW}\cdot \ell)^{-1/2} \quad (2)$$

$$i_n^{TW} = i^{TW}\cdot(r^{TW}\ell/P^{TW})^{1/2} \quad (3)$$

The condition for maximum energy gain with respect to τ, while i_n^{TW} kept constant, is found to be:

$$i_n^{TW} = (\tau/2)^{1/2}\cdot\left(\frac{\tau}{e^{\tau}-\tau-1}-1\right) \quad (4)$$

where W(MeV) is the energy gain,
i(A) is the peak beam current,
r(MΩ/m) is the structure shunt impedance,
P(MW) is the rf input power,
ℓ(m) is the structure length, and
τ is the dimensionless attenuation parameter of the structure.

i_n^{TW} and τ values satisfying eq.(4) will be referred to as the optimal i_n^{TW} and τ values.

By analogy with the above equations, the normalized energy gain W_n^{SW} in the standing-wave structure may be written[2]:

$$W_n^{SW} = (2\beta^{1/2} - i_n^{SW})(1+\beta)^{-1} \quad (5)$$

where

$$W_n^{SW} = W^{SW}\cdot(r_{eff}^{SW}\cdot\ell\cdot P^{SW})^{-1/2}, \quad (6)$$

$$i_n^{SW} = i^{SW}\cdot(r_{eff}^{SW}\cdot\ell/P^{SW})^{1/2}, \quad (7)$$

r_{eff}^{SW} is the effective shunt impedance, β is the coupling coefficient of the structure to feeding waveguide and the rest denotations are quite analogous to those in the TW case.

Similarly, the condition of maximum energy gain with respect to β, while i_n^{SW} kept constant, is given by:

$$\beta_{opt} = \{i_n^{SW}/2 + [1+(i_n^{SW}/2)^2]^{1/2}\}^2 \quad (8)$$

Substituting eq.(8) into eq.(5), one obtains:

$$i_n^{SW} = (W_n^{SW})^{-1} - W_n^{SW} \quad (9)$$

Fig.1 shows the normalized energy gains at optimal τ and β values plotted against the normalized beam current for both the TW and SW structures. Tangents to these lines represent the beam loading characteristics.

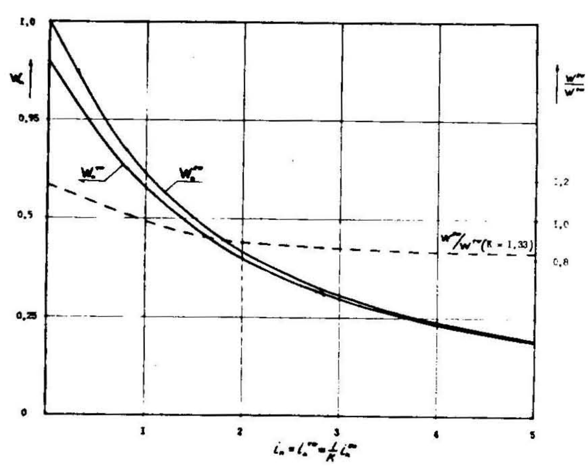

Fig.1. Comparison of maximum values of normalized energy gains (W_n^{TW} and W_n^{SW}) versus normalized beam currents (i_n^{TW} and i_n^{SW}) for the TW and SW structures (solid curves). Calculations were made at optimal values of τ and β at $K=1$. In addition, the non-normalized energy ratio W^{SW}/W^{TW} versus i_n^{TW} is plotted by a dashed line for $K=1.33$.

It is worthwhile to make a comparison of the TW and SW structures, evaluating, under some conditions, their normalized energy gains at the same accelerated beam currents. These conditions are: (i) optimal τ and β values, (ii) the same length of the structures, (iii) the same rf power P_s available from an rf source. The normalized quantities i_n^{TW} and i_n^{SW}, being taken at equal current $i^{TW}=i^{SW}$, are related by:

$$i_n^{SW} = \left(\frac{r_{eff}^{SW}}{r^{TW}} \cdot \frac{P^{TW}}{P^{SW}} \right)^{1/2} \cdot i_n^{TW} \equiv k \cdot i_n^{TW} \qquad (10)$$

Let us evaluate the parameter k using the data of S-band measurements.

For most of the SW structures, r_{eff}^{SW} is about 85 MΩ/m. Later on, it will be shown that the optimum TW structure (eq.(4)) should be high-dispersive at low beam currents having the ratio a/λ of about .1 or less where a is a disc hole radius and λ is the free-space wavelength. The $\pi/2$ mode r^{TW} value was measured to be 60 MΩ/m at a/λ =.1 and λ =10 cm.

Further, for the same rf source used, the power level at the input of the SW structure is different from that in the TW case because of direct power losses in an rf isolator inserted in the SW feeding line to eliminate the reflected power flow during the transients. These losses may amount to 30%[2]. On the other hand, for the TW structure, one can take $P^{TW} \simeq P_s$ or $P^{TW} \simeq .9\ P_s$ whether a klystron or magnetron are used. Therefore, one may assume $P^{SW} \simeq .8 \cdot P^{TW}$. Taking into account the above difference in shunt impedances, we obtain k=1.33.

A dashed line in Fig.1 represents the ratio $(W^{SW}(i_n^{SW})/W^{TW}(i_n^{TW}))$ as a function of i_n^{TW} at k=1.33 and $i^{SW}=i^{TW}$. Under above realistic assumptions, one can see that the SW structure provides higher energy gain at i_n^{TW} < .9 (which, e.g., corresponds to i < .2A at P/ℓ = 3 MW/m).

This SW energy gain margin obtains its 18% maximum value at zero beam loading. On the contrary, the TW structure becomes preferable for high beam currents showing about 18% energy gain margin over the SW one.

To make the comparison of the structures more adequate, the difference in their filling times should be involved into analysis. At low peak beam current, the filling time in the SW structure is longer than that in the TW one and, consequently, the average beam current $\bar{i}$, available for use will be higher in the latter case. Calculations were made at the operating frequency, f=3.2 GHz, and the rf pulse duration, t_{rf}=3.2 sec, to show that, at a given $\bar{i}$, the energy gain in the SW structure is only of about 10% higher than that in the TW one. Thus, energy gains in both structures are comparable at any value of $\bar{i}$.

Feasibility of Optimal Structures

The optimum operating conditions for a SW structure can easily be obtained by adjusting an appropriate β opt-value for a rated beam current. The β opt-curve as a function of i_n^{TW} is shown in Fig.2.

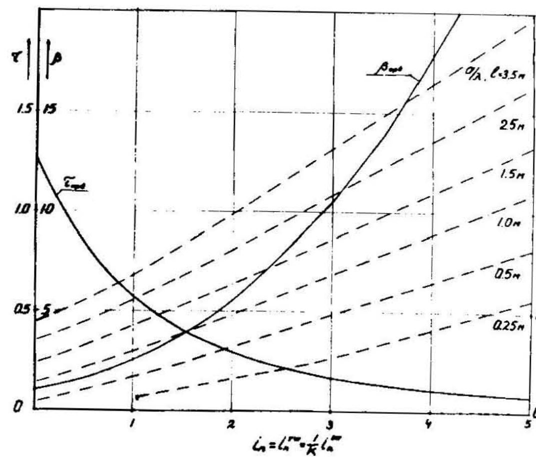

Fig.2. Optimal values of τ and β (solid curves) versus normalized beam current (i_n) plotted at k=1. The dashed lines represent the TW structure parameter (a/λ) versus i_n^{TW} found at τ opt, f=3.2 GHz and at various ℓ values.

To perform an optimal TW structure, it is necessary to provide an optimum attenuation parameter τ opt, in accordance with eq.(4). The dependence of τ opt (i_n^{TW}) is also plotted in Fig.2 (note that τ opt=1.26 at i_n^{TW}=0).

By definition

$$\tau = \frac{\pi \cdot f \cdot \ell}{v_g \cdot Q_o} \qquad (11)$$

where Q_o is the unloaded quality factor, and v_g is the group velocity which is strongly dependent on the structure parameter a/λ.

Substituting τ opt into eq.(11) and using the measurement data,[2] one can plot a family of a/λ curves versus i_n^{TW} with ℓ as a parameter. These curves shown by dashed lines in Fig.2 were calculated for $\pi/2$ mode, f=3.2 GHz, and t/λ =.038 where t is the structure disc thickness.

In most of the existing TW linacs, the structure parameter a/λ is not less than .1. This choice is mainly made because of an enchanced sensitivity of high-dispersion waveguides to frequency variations, tuning problems and danger of voltage breakdown at high fields. It is seen from Fig.2 that, at a/λ > .1, the low current optimal TW structure would be of about 3 m in length.

This situation has significantly changed with the recent progress in accelerator technology. At present, it seems quite realistic to move down the .07 structure parameter, thus obtaining an essential increase in the shunt impedance. However, the available experimental data show that the further reduction of the a/λ parameter would not influence the shunt impedance, while the waveguide tuning appears to become a serious problem[3].

Improved performances of the high dispersion linacs have been confirmed by a number of machines designed and fabricated at NIIEFA. Table 1 shows some TW structures with a/λ < .1 which are used in linacs for medical and industrial applications. Some basic characteristics of structures I and II, of the same .7m length, are given in Fig.3.

TABLE I

$\pi/2$ HIGH DISPERSION TW STRUCTURES USED AT NIIEFA LINACS[4]. RF POWER IS AVAILABLE FROM MAGNETRON: P=3-8 MW, f=3.2 GHz, t_{rf}=3 sec

Type	Total Length (Buncher +Main Cells) m	a/λ (Main Cell)	rf Input Power MW	Rated Energy Gain MeV	Rated Peak Beam Current A	Linac Model	Application
I	.2+.5	.0927	3	5	.1	LUE-5-500D	radiography
II	.2+.5	.0725	5	8	.1	LUE-8-2000D	radiography
III	.8+1.7	.105-.0927	7	19.6	.035	LUE-15M	medicine
III				15	.17	LUE-15-15000D	radiography
III				15(8-22)	.17	LUE-15A	activation analysis
III				30(8-40)*	.035	LUE-22A	activation analysis

* 40 MeV energy gain is obtained by twofold acceleration with the beam recirculation system.

Each structure begins with an identical, 2λ long, bunching section and ends in a collinear rf load.

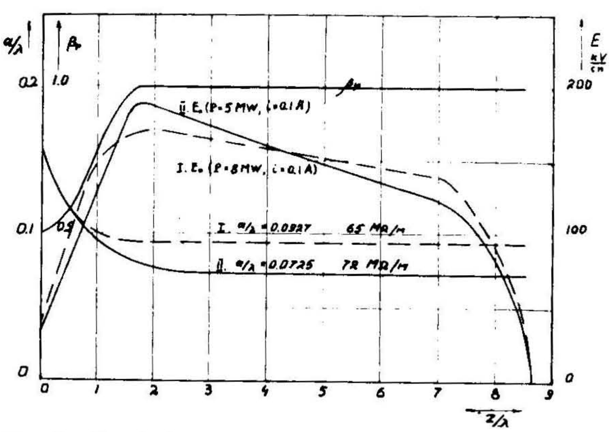

Fig.3. Variations of phase velocity (β_φ), the TW structure parameter (a/λ), and the accelerating field gradient (E) through the disk-loaded waveguide

To determine the voltage breakdown level both structures have been tested at rf input powers up to 8 MW and under normal vacuum conditions. In structure II operating in the TW mode, a 20 MV/m average energy gradient was measured, while a maximum accelerating gradient of 30 MV/m and a maximum surface electric field of 40 MV/m were obtained in the first main accelerating cell. Structure I has also been tested in the standing wave mode at rf input power up to 3.8 MW (the 20 dB available isolator was not sufficient to ensure stable operation of the magnetron at higher power levels)[5]. In this case a maximum electric field exceeding 50 MV/m is necessary to produce an energy gradient of 10 MV/m.

Structures have been fabricated with standard machining and brazing techniques developed and used at NIIEFA. No sign of voltage breakdown has been detected in both structures over long runs except for occasional sparking during the preliminary rf conditioning. Thus, voltage breakdown tests, together with long-term operational experience of NIIEFA high-dispersion linacs, lead to conclusion that optimal low current TW structures of 1 m length or longer are prospective for use (see Table I). In these cases the potentialities of the TW and SW structures are comparable. However, the SW low current structure remains preferable, when it should be very compact or when the beam recirculation system is used[6].

A new series of electron linacs for industry and medicine is now under development at NIIEFA. A 5 MW, 2.45 GHz, low-potential klystron has been specially designed as an rf power source. Both the TW and SW structures are intended to use. To compare the main features of these structures some design parameters of the linacs are listed in Table II.

TABLE II

DESIGN PARAMETERS OF SOME TW AND SW LINACS (f=2.45 GHz)

Type	Total Length (Buncher +Main Cells) m	a/λ (Main Cell)	Shunt Impedance MΩ/m	Optimal Peak Beam Current A	Rated Peak Beam Current A	Rated Energy Gain MeV	Zero Current Energy Gain MeV	Application
TWI	.25+.85	.074	62	.47	.23	9.0	11.2	radiography
SWI	.15+.85		75	.23	.23	9.5	13.9	radiography
TWII	.25+.75	.074	62	.47	.5	6.4	11.2	radiation technology
SWII	.15+.85		75	.5	.5	6.1	10.6	radiation technology
TWIII	.25+1.35	.074	62	.19	.05	15.8	16.9	medicine
SWIII	.15+1.45		75	.05	.05	17.6	20.0	medicine

Beam parameters in Table II were calculated at the 4.5 MW rf input power for the TW linacs, and at 3.6 MW for the SW ones. The shunt impedances of the TW structures are given for a $\pi/2$ operational mode. A choice of an on-axis coupled structure for the SW linacs was made as a result of extensive design and experimental work done at NIIEFA, Moscow Institute of Physics and Engineering, and at the USSR Academy Institute of Nuclear Research.

References

1. R.B.Neal, Design of Linear Electron Accelerator with Beam Loading, J.of Appl. Phys., 29, No 7, 1019 (1958).
2. K.Irie, Y.Minowa, S.Sawada, A Compact Electron Linac Using Side-Coupled Structure, Jap.J.of Appl.Phys., 12, No 2, 277 (1973).
3. O.A.Valdner, N.P.Sobenin, B.V.Zverev, I.S.Shchedrin, Handbook on Disc-Loaded Waveguides, Atomizdat, (1977).
4. Yu.P.Vakhrushin, Electron Linacs for Medicine and Industry, Atomnaja Energija, 55, No 6, 429 (1983).
5. O.A.Volchkov et al., High Voltage Tests of Disc-Loaded Waveguides for Electron Linacs, Proc.of VIII All-Union Meeting on Charged Particle Accelerators, JINR, Dubna, v.II, 22 (1983).
6. T.Taylor, G.VanDyk, THERAC 25: A New Medical Accelerator Concept, IEEE Trans. Nucl.Sci., NS-30, No 2, 1768 (1983).