INDUSTRIAL HIGH-CURRENT ELECTRON LINACS[1]

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Abstract

For electron-based industrial, environmental, and medical irradiation applications, we have designed a family of compact modular continuous wave linear accelerators (CW LINACs) that produce 50 mA beams with energies from 0.6 to 10 MeV in increments of 600 keV. Here we report on the performance of our 0.6 MeV/50 mA/30 kW one-section and the design of our 1.2 MeV/50 mA/60 kW two-section prototypes.

1 INTRODUCTION

Our CW LINAC family consists of ten accelerators each with beam currents of 50 mA and energies ranging from 0.6 to 6 MeV in increments of 600 keV with corresponding beam power of 30 to 300 kW. We have realized two of these accelerators in operational prototypes whose parameters are listed in Table 1.

Table 1: CW LINAC parameters.

	One-Section	Two-Section
Beam energy	0.6 MeV	1.2 MeV
Beam current	0 to 50 mA	0 to 50 mA
Maximum beam power	30 kW	60 kW
Length	0.8 m	1.3 m
Gun/klystron high voltage	15 kV	15 kV
Plug power consumption	~75 kW	~150 kW
Electrical efficiency	~40%	~40%

Our one-section CW LINAC [1] provided a 600 keV/10 mA/6 kW exit beam. However, at ~10 mA the gun vacuum degraded because our steel Faraday cup began to melt, suppressing the cathode emission. To obtain a 50 mA exit beam, we replaced the Faraday cup with a klystron collector designed to dissipate ~60 kW of beam power and installed a 500 l/min turbo-molecular pump to protect the gun from bad Faraday cup vacuum.

2 OBTAINING FULL BEAM CURRENT

2.1 Experimental Set-Up

Our modified one-section test stand is shown in Fig. 1 and differs from our original [1] in that the Faraday cup is now ~1 m from the structure exit, a distance that the 600 keV traverses with no focusing. Further we installed steering coils and swept the beam in one dimension over the cup that must dissipate 30 kW of beam power.

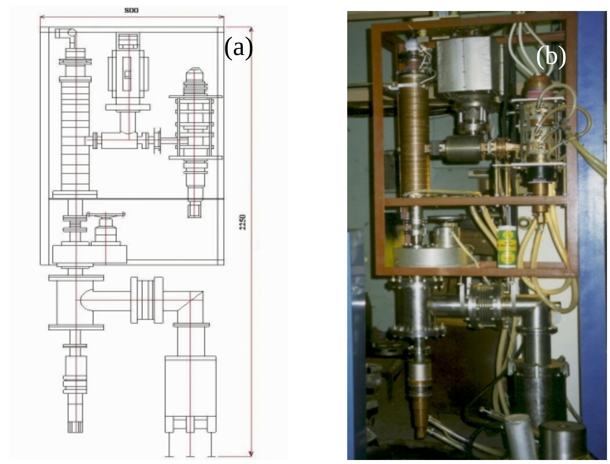

Figure 1: One-section (a) schematic and (b) test stand.

2.2 High Beam Loading Structure Coupling

We designed our accelerator to operate at 65% beam loading, with the klystron power shared 30 kW by the beam and 16 kW by the structure. With no beam the structure is over-coupled but with a 50 mA/30 kW beam it is critically coupled. The beam loaded structure steady state energy gain is

$$W = \frac{2\cdot\sqrt{\beta_0}}{1+\beta_0}\cdot\sqrt{P_{RF}\cdot R_{sh}\cdot L} - \frac{R_{sh}\cdot L\cdot I}{1+\beta_0}, \qquad (1)$$

where P_{RF} is the radio frequency (RF) source power, β_0 is the unloaded coupling factor, R_{sh} is the structure effective shunt impedance per unit length, L is the structure length, and I is the beam current. The first term is the maximum unloaded energy gain while the second contains the beam loading which can reduce the field amplitude. A tuned critically coupled structure at nominal beam current will be over-coupled with no beam present. The unloaded coupling factor that provides critical coupling with beam loading is

$$\beta_0 = \frac{P_{beam}}{P_{walls}} + 1, \qquad (2)$$

where P_{beam} is the beam power and P_{walls} is the power dissipated in the structure walls. For the design P_{beam} = 30 kW, the optimal dissipated power is P_{walls} = 16 kW while the transmission line-structure coupling is β_0 = 2.87.

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After successful beam tests with $\beta_0 = 1$ [1], we began to over-couple the structure in stages until we realized the design β_0 = 2.87. Up to $\beta_0 = 1.85$, we tuned the structure by cutting the central RF feed cell iris which reduced the structure resonant frequency causing an electric field to appear in the neighbouring coupling cells. To further increase the structure coupling in this manner could require additional central cell resonant frequency tuning, a tricky and complicated procedure in a brazed structure.

2.3 β_0 = 2.85 Beam Tests

To tune the structure to β_0 = 2.85, we fixed a 5 mm diameter copper cylinder between the wide feeding waveguide walls which changed the klystron-structure match without disturbing the structure accelerating field or changing its resonance frequency. With our tuned β_0 = 2.85 structure, we measured the electron gun current (I_{gun}), the exit beam Faraday cup current (I_{out}), the power dissipated in the structure (P_s) which is the sum of the power dissipated in the structure walls (P_{walls}) and the beam loss power (P_{loss}), and the output beam power (P_{beam}) measured from the difference of inlet and outlet cooling water temperatures at the Faraday cup. We summarized the measured parameters at various gun currents in Table 2. Beam parameters derived from the measured ones are the beam energy (W = P_{beam}/I_{out}) and capture efficiency (I_{out}/I_{gun}).

Table 2: Beam parameters for β_0 = 2.85.

I_{gun} (mA)	I_{out} (mA)	I_{out}/I_{gun} (%)	P_{beam} (kW)	W (keV)	W eq. (1) (keV)
10	3.8	38.0	2.2	579	550
20	8.0	40.0	4.7	587	562
26	10.4	40.0	6.2	596	570
36	15.0	41.7	8.8	587	578
40	17.0	42.5	9.8	576	579
47	21.0	44.7	12.2	581	585
50	24.0	48.0	14.1	588	591
60	31.0	51.7	18.8	606	603
68	34.5	50.7	20.6	597	603
70	36.0	51.4	21.6	600	604
78	38.5	49.4	23.3	605	608
90	45.5	50.6	27.8	610	612
98	50.0	51.0	31.2	624	619

We compared the measured beam energy with that calculated from eq. (1). By only adjusting the electron gun current, we varied the beam current from several mA to 50 mA. The beam energy increased with increasing beam loading until it reached a maximum at I_{out} = 50.0 mA and P_{beam} = 31.2 kW, which corresponds to optimal beam loading when the structure becomes critically coupled with the beam.

From the measured power balance, we estimate the power and average energy of the beam lost in the structure, $I_{loss} = I_{gun} - I_{out}$. The lost beam power, P_{loss}, is the difference between the measured structure power and that dissipated in the walls, P_{walls} = 16.0 kW. With I_{gun} = 98 mA, I_{out} = 50.0 mA, and I_{loss} = 48 mA, P_{loss} = 2 kW, much less than the exit beam power. This corresponds to an average lost electron energy, $\langle W_{loss} \rangle$, of ~42 keV. The lost beam is distributed over the entire structure, consistent with beam dynamics calculations.

The beam test results are summarized in Fig. 2 as the dependence of exit current on gun current and beam power on exit current.

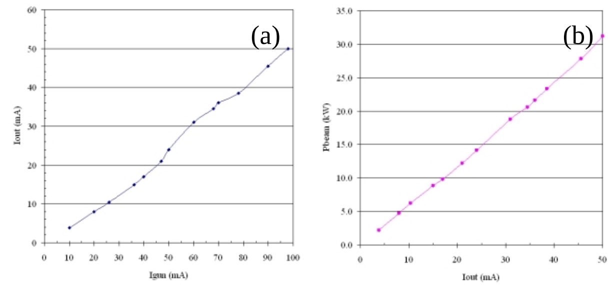

Figure 2: (a) $I_{out}(I_{gun})$ and (b) $P_{beam}(I_{out})$.

3 TWO-SECTION CW LINAC

3.1 Second Accelerating Structure

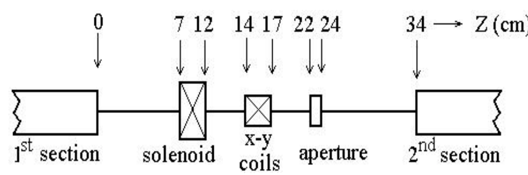

Figure 3: Intrastructure beam line.

In designing the 2nd accelerating structure, we simulated the beam dynamics in our two-section CW LINAC [2] using the measured 1st section parameters as input to the 2nd section. The resulting 51 cm long, 2nd accelerating section is a tapered-β structure with four β = 0.914 and five β = 0.945 accelerating cells. Fig. 3 shows the beam line between the 1st and 2nd structures.

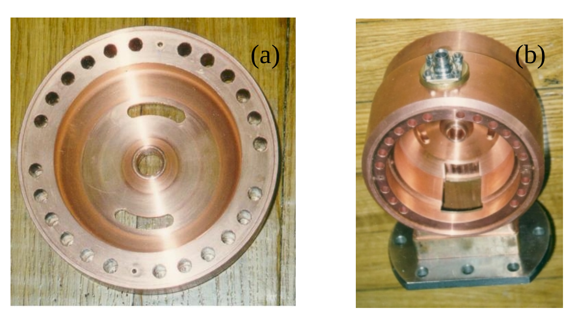

Figure 4: (a) Accelerating and (b) power feed cell.

At the 2nd structure entrance the ~3 mm radius beam is convergent and has a longitudinal phase space that can be compressed by injecting the bunch with a phase advanced with respect to the maximum RF acceleration phase. The maximum energy gain, Δ_{wmax}, is 693 keV, P_{walls} = 12.5 kW, and the injection phase, φ_{in}, is 60°, while the corresponding R_{sh} is 75 MΩ/m.

Table 3: Structure parameters with brazing.

	Before	After
Frequency, f (MHz)	2,450.77	2,450.20
Loaded quality factor, Q_L	3,700	3,940
VSWR	2.36	2.60
β_0	2.36	2.60
Unloaded quality factor, $Q_0 = Q_L \cdot (1 + \beta_0)$	12,400	14,200
Coupling constant, k	0.05	0.05

We next optimized and tuned the 2nd structure cells [3] after which we produced engineering drawings and manufactured the 18 structure half-cells, one of which, together with the central power feed cell, is shown in Fig. 4. The structure parameters before and after brazing are listed in Table 3, and the accelerating field distribution after brazing is shown in Fig. 5.

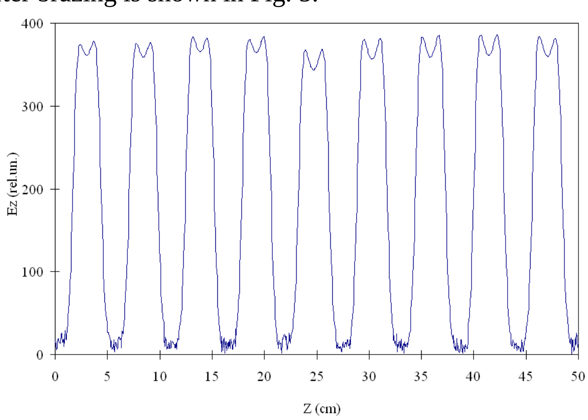

Figure 5: On-axis E_z after brazing.

3.2 Two-Section Beam Experiments

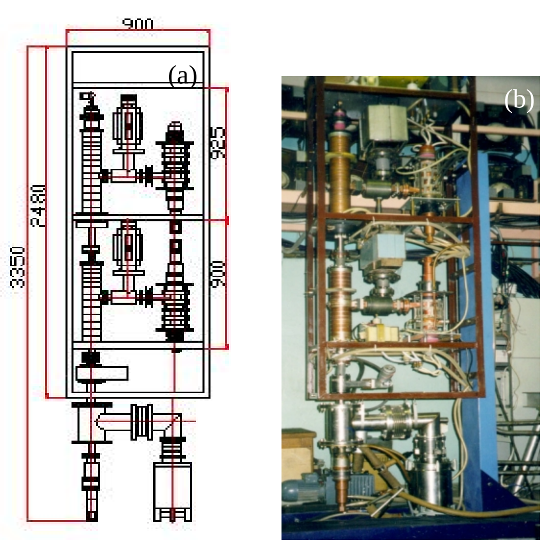

Figure 6: Two-section (a) schematic and (b) test stand.

We assembled the two-section CW LINAC shown in Fig. 6 with its corresponding sub-systems. As both accelerating structures operate in a self-excited positive klystron/section feedback loop without a circulator, they must be phased with each other since their frequencies are similar but unequal and their relative phase varies randomly. We accomplished this by using an external signal mixed in a positive feedback loop between the accelerating structure and the klystron. We let our first auto-oscillating accelerating section provide the reference signal for the second section, thus eliminating the need for a stable synchronizing oscillator.

We began beam tests after assembling our accelerator and sub-systems, using our existing industrial programmable logic controller based system to control the structures and Faraday cup water flow and inlet/outlet cooling temperatures, the RF power dissipated in the structures walls, the beam power absorbed by the cup, the beam current at the cup, and the electron gun current. We should soon obtain a 1.2 MeV/50 mA/60 kW electron beam, proving our initial design principles.

4 CONCLUSION

We have constructed one- and two-section CW LINACs, the first in our new family of industrial electron accelerators. In the one-section beam tests, we achieved the design 600 keV, 50 mA, 30 kW electron beam at a 98 mA gun current, thus demonstrating a 50% capture efficiency. The two-section accelerator tests are now in progress. With the successful phasing of the two accelerating structures using self-excitation and obtaining the 1.2 MeV/50 mA/60 kW exit beam, we will have completed the validation of our design ideas.

REFERENCES

[1] A.S. Alimov, D.I. Ermakov, B.S. Ishkhanov, E.A. Knapp, V.I. Shvedunov, and W.P. Trower, “A Compact Industrial High-Current Continuous Wave Electron LINAC”, in *Proc. 1999 Particle Accelerator Conf.*, A. Luccio and W. MacKay, eds. (IEEE Piscataway, 1999) p.2555, and A.S. Alimov, E.A. Knapp, V.I. Shvedunov, and W.P. Trower, “High-Power CW LINAC for Food Irradiation”, App. Rad. Isotopes, in press.

[2] Originally developed by K.R. Crandall - PARMELA code.

[3] R. Klatt, F. Krawczyk, W.R. Novender, C. Palm, T. Weiland, B. Steffen, T. Barts, M.J. Browman, R. Cooper, C.T. Mottershead, G. Rodenz, and S.G. Wipf, “MAFIA - A Three-Dimensional Electromagnetic CAD System for Magnets, RF Structures, and Transient Wake-Field Calculations”, in *Proc. 1986 Linear Accelerator Conf.*, SLAC-303 (1986) 276.