A COMPACT HIGH-POWER PROTON LINAC FOR RADIOISOTOPE PRODUCTION*

H. Takeda, J. H. Billen, S. Nath, J. E. Stovall, R. L. Wood, and L. M. Young
Los Alamos National Laboratory, MS H817, Los Alamos, NM 87545, USA

Conventional designs for proton linacs use a radio-frequency quadrupole (RFQ), followed by a drift-tube linac (DTL). For higher final beam energies, a coupled cavity linac (CCL) follows the DTL. A new structure, the coupled-cavity drift-tube linac[1] (CCDTL) combines features of an Alvarez DTL and the CCL. Operating in a $\pi/2$ structure mode, the CCDTL replaces the DTL and part of the CCL for particle velocities in the range $0.1 \leq \beta \leq 0.5$. We present a design concept for a compact linac using only an RFQ and a CCDTL. This machine delivers a few mA of average beam current at a nominal energy of 70 MeV and is well suited for radioisotope production.

Accelerator System Design

A compact linear accelerator is a competitive source of beam power for the commercial production of radioisotopes. The linac we describe provides a beam of up to 2 mA of protons at energies of 30, 50, and 70 MeV. Linear accelerator designers try to minimize construction costs by optimizing the relative costs of the accelerating structure and the installed rf power. To first order, structure cost is proportional to length and the rf cost is proportional to the square of the accelerating gradient E_0. For a given structure power, accelerator length is inversely proportional to E_0. The rf costs are further constrained because rf power is available in quantized units of single klystron tubes. Usually, the minimum total cost occurs where the power cost equals the structure cost.

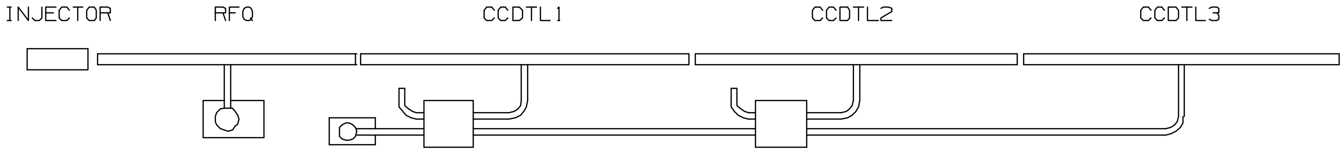

Figure 1. Schematic diagram of the radioisotope production accelerator.

A CCDTL can operate at higher frequencies than a conventional DTL because the focusing magnets are external to the rf structure. The designer can choose from a broader range of rf power sources. We have based our design on klystron tubes operating at 433 and 1300 MHz. Both of these tubes are available in models that deliver very high peak and average powers. Only one tube at each frequency is required, so cost minimization involves making the best use of the tubes' power capabilities in the linac design.

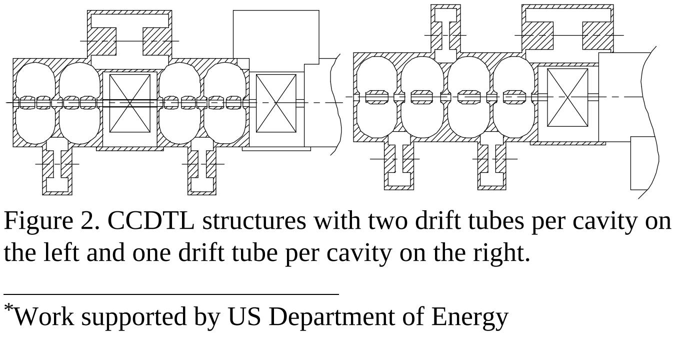

Figure 2. CCDTL structures with two drift tubes per cavity on the left and one drift tube per cavity on the right.

Figure 1 shows a layout of the accelerating structures. The 433-MHz RFQ accelerates the beam to 10 MeV. The 1300 MHz CCDTL comprises the bulk of the linac and accelerates the beam to a final energy of 70 MeV. The 1300-MHz frequency is the third harmonic of the RFQ frequency. Each structure is powered by a single klystron rf source.

CCDTL

The length of the CCDTL, which depends upon the choice for E_0, is limited by 1) the total amount of peak power available, 2) the average beam power required, 3) the peak surface electric field, and 4) the maximum local power density on the drift tubes. Figure 2 shows the two types of cavities used in the CCDTL. At the low-energy end, cavities have two drift tubes making three accelerating gaps. Gaps within a cavity are separated by $\beta\lambda$, where β is the relativistic proton velocity, and λ is the free-space wavelength of the resonant mode. Successive gaps between cavities are separated by $\beta\lambda/2$. The other cavity type has one drift tube per cell. Figure 3 shows the effective shunt impedance ZT^2 calculated by the 2-D code SUPERFISH[2] versus β. Based upon this data, we switch from two-drift-tube cavities to one-drift-tube cavities at $\beta = 0.28$, which corresponds to 40 MeV.

To estimate the linac length and power requirements, we correct these values of ZT^2 for the effect of the coupling slots. Each percent of coupling reduces ZT^2 by about 3%. Figure 4 relates the active structure length to the peak rf power required to excite the cavities. Points for a given length correspond to the same value of E_0. The lower curve is the structure power requirement without beam. The two upper curves include the power needed to accelerate 42-mA or 84-mA peak beam currents. For a beam duty factor of 2.4%, the corresponding average beam currents are 1 mA and 2 mA.

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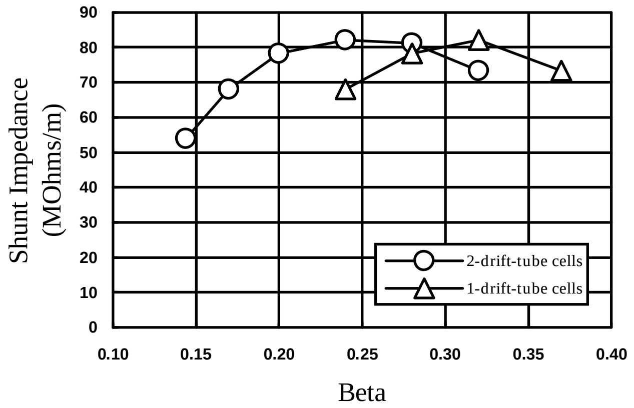

Figure 3. SUPERFISH shunt impedance versus particle velocity β for two types of 1300-MHz CCTDL cavities.

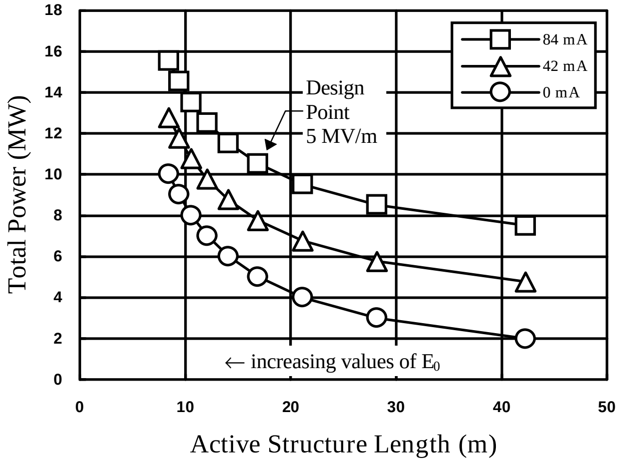

Figure 4. Peak power versus active structure length for nine values of E_0 between 2 and 10 MV/m.

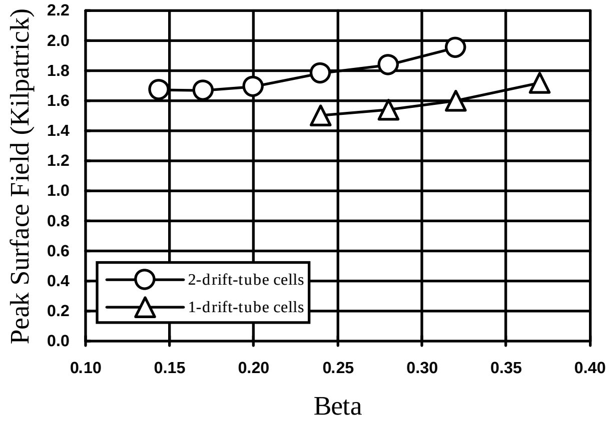

Fig. 5. Peak surface electric field expressed in terms of the Kilpatrick criterion versus β for CCDTL cells operating at E_0 = 5 MV/m.

The total power figures for these curves include a 15% control margin. A 10 MW klystron would support a family of interesting linac designs. For example, a 12-m-long linac operating at 7 MV/m could deliver 1 mA at full energy. Another one operating at 4 MV/m would be 21 m long and could deliver 2 mA. Longer linacs can provide even higher beam currents.

For higher values of E_0, we approach other limits. Figure 5 shows the peak surface electric field in the CCDTL versus β for E_0 = 5 MV/m. The ordinate is relative to the Kilpatrick field E_K, which is 32.1 MV/m at 1300 MHz. Kilpatrick made his measurements[3] when clean surfaces and good vacuum were difficult to achieve. Experience has shown that we can exceed the Kilpatrick's criterion by an amount often called the "bravery factor." We typically design for peak fields up to 1.8 E_K. We expect little or no sparking below this value. In a 2-drift-tube CCDTL, the peak field increases with β, reaching 1.8 E_K on the drift-tube nose at β = 0.25 (31 MeV).

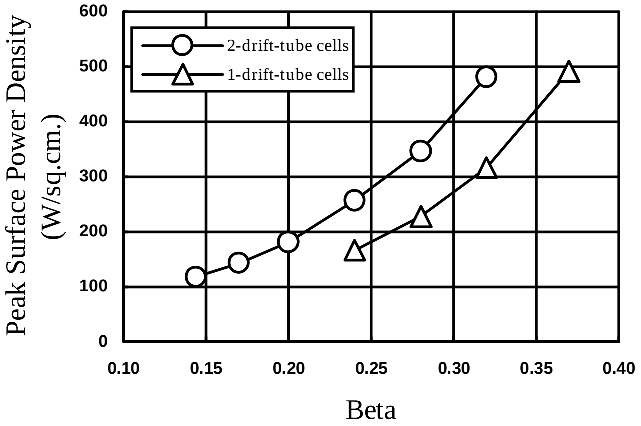

Fig. 6. Peak surface power density versus β for CCDTL cells operating at E_0 = 5 MV/m and 100% duty.

Figure 6 shows that as the cells get longer with increasing β, the peak power dissipation increases. The hottest spot is at the longitudinal midpoint of the drift tubes. Power densities increase in proportion to E_0^2. The plot is for 100% duty factor (i.e. cw), so for a duty factor of 2.5%, the maximum power density is about 12.5 W/cm^2 on the longest drift tube. At this power level all of the drift tubes are simple to build, easily cooled, and inexpensive.

Table 1. Linac Design Parameters.

Linac Parameter	RFQ	CCDTL		
		1	2	3
Injection energy (MeV)	0.075	10	30	50
Final energy (MeV)	10	30	50	70
Length (m)	6.7	9.1	7.1	7.0
RF frequency (MHz)	433	1300	1300	1300
No. of accelerating. cavities	--	50	56	45
No. of quadruples	--	25	14	11
Transmission (%)	85	100	100	100
Accel. Gradient (MV/m)	2.75*	5*	5	5
Peak Cu Power (MW)	2.4	1.43	1.44	1.5
Peak beam power (MW)	0.8	1.6	1.6	1.6

* Corresponds to the exit of the RFQ and the entrance of the CCDTL; the field ramps up to 5 MV/m in the CCDTL.

Based upon these cavity properties we have chosen to operate the CCDTL at E_0 = 5 MV/m. Table 1 summarizes the properties of the 70-MeV linac. It is 23 m long and contains 151 accelerating cavities. Including the nominally unexcited coupling cells, the accelerator has a total of 299 resonant cavities in the three tanks. A total of 50 electromagnetic quadrupole (EMQ) lenses provide the transverse focusing. These magnets mount outside the rf cavities and the vacuum system. The FODO lattice has a period of 16 $\beta\lambda$ at 1300 MHz. The EMQs are 6 cm long and they can achieve a field gradient of 50 T/m. With no adjustment of the focusing strength, they provide excellent confinement of the beam for peak currents of 82 mA over a wide range of energies. At full energy this linac can deliver 2 mA of average beam. At reduced energies, even higher currents are available without raising the peak current by simply increasing the pulse repetition frequency. This scheme takes advantage of the full average power available from the klystron.

Most commercial isotopes are presently made at energies of 30, 50, and 70 MeV. The three separate sections of CCDTL provide a simple and reliable way of producing beams at these energies without multiple rf-power tubes. The same tube drives each tank separately through power splitters connected to a common waveguide Three independent tanks have fewer cavities per rf module than one long tank, resulting in no appreciable field droop or power-flow phase shift within the rf structures. The machine produces different beam energies by selectively turning off rf power to the downstream accelerating tanks. By building tuning devices into some of the coupling cells we can achieve even finer energy variability.[4]

RFQ

The RFQ operates at the third subharmonic of the CCDTL. There are two commercial klystrons that offer high powers at 433 MHz. Table 2 shows that the RFQ peak-power requirements match the specifications of the TH2120 and the TH2118. The average power and pulse length are best matched by the TH2118.

The RFQ consists of four coupled resonant sections, each one 1.7 m long. The rf power couples into the high energy section through a waveguide iris. In the high-energy part of the RFQ, we specially tailor the vane-tip modulation to reduce the phase width of the exit beam. The CCDTL can directly capture this RFQ output beam and does not require a separate matching section. The first four cells of the CCDTL do little acceleration. Instead, these cells mainly bunch the beam to ensure capture of 100% of the beam into the rf "bucket." Following this capture section is a quasi-adiabatic ramp in both the synchronous phase and the field amplitude. The first few quadrupole lenses in the CCDTL match the beam from the RFQ in the transverse plane.

RF Power and Duty Factor

Table 2 shows that for E_0 = 5 MV/m the CCDTL is well matched to the TH2104U klystron. The design takes advantage of both the peak and average power available from this tube without exceeding safe limits for either cavity fields or power densities. To match the power requirement for 2-mA operation to the tube we have assumed only a 9% rf control margin at full energy. We believe further cavity optimization will reduce the power requirements enough to allow a full 15% control margin within the 10 MW available.

Table 2. RF Systems Parameters.

Parameter	RFQ	TH 2120	TH 2118	CCDTL	TH 2140U
Frequency (MHz)	433	433	433	1300	1300
Total rf power (MW)	3.2	--	--	9.17	--
Control margin (%)	15	--	--	9	--
Peak power, MW	3.7	4.0	6.0	10	10
RF pulse length* (μs)	208	10^4	220	208	250
Duty factor(%)	2.5	8	3.3	2.5	2.5
Average rf power (kW)	93	500	200	240	250
Klystron efficiency (%)	--	55	58	--	45
Total ac power (kW)	--	185	176		593

*assumes 8 μsec cavity filling time

Both sections of the linac run with a pulse-repetition frequency of 120 Hz synchronized with the line. The beam pulse is 200 μs long for a beam duty factor of 2.4%. The cavity filling time adds another 8 μs. This scheme takes advantage of the entire power capacity of the CCDTL klystron. We estimate that a total ac power of 800 kW is needed to produce 140 kW of beam power. An equal amount of cooling capacity would be required.

Conclusion

We have outlined a new design for a compact proton linear accelerator suitable for radioisotope production. A single 433-MHz klystron rf source powers the RFQ, and a single 1300-MHz klystron powers all three tanks of the CCDTL. The accelerator can provide beam currents up to 2 mA average at essentially any energy between 20 and 70 MeV.

References

[1] J. H. Billen, F. L. Krawczyk, R. L. Wood, and L. M. Young, "A New RF Structure for Intermediate-Velocity Particles," Proceedings of the 1994 International Linac Conference, Vol. 1, p. 341 (August 21-26, 1994).

[2] K. Halbach and R. F. Holsinger, "SUPERFISH -- A Computer Program for Evaluation of RF Cavities with Cylindrical Symmetry," Particle Accelerators 7 (4), p. 213-222 (1976).

[3] W. D. Kilpatrick, "Criterion for Vacuum Sparking Designed to Include Both rf and dc," Nuclear Instruments and Methods **28**, p. 824 (1957).

[4] L. M. Young, "A Method of Changing the Final Energy in a CCL or CCDTL," Los Alamos National Laboratory internal memorandum AOT-1:94-159 (August 18, 1994).