COMMERCIAL ION LINACS

R.W. Hamm, J.H. Bower, K.R. Crandall, M.E. Hamm, and J.M. Potter
AccSys Technology, Inc., 1177 Quarry Lane, Pleasanton, CA 94566

SUMMARY

Transfer of linear accelerator (linac) technology utilizing the radio frequency quadrupole (RFQ) structure from the national laboratories to U.S. industry has led to their commercial development for a variety of practical applications. These include medical applications in isotope production and cancer therapy and industrial applications in nondestructive testing and ion implantation. This paper briefly describes several new commercial linacs and a proven new rf system that has been developed to power them.

INTRODUCTION

Ion linacs have been used for physics research since the invention of the drift tube linac by Alvarez in 1945.[1] However, unlike electron linacs, ion linacs were not quickly adopted for commercial use. Commercialization of ion linacs was restricted due to the larger size, and hence cost, of "conventional" systems, even though research linacs at large laboratories were used for practical applications as early as 1972.[2] The development of the RFQ structure and permanent magnet focusing has now made possible the replacement of conventional linacs with lower cost, much simpler and more compact systems that are better suited for commercial applications.

ION LINAC APPLICATIONS

With only a few exceptions where high current pulsed ion beams are required, the practical applications of ion linacs are the same as for other types of ion accelerators. These are generally classified as either medical or industrial. Medical applications include the production of radioisotopes for nuclear medicine and the irradiation of tumors by direct particle bombardment or by secondary particle (neutrons or pions) bombardment. Industrial applications include the production of neutrons for non-destructive testing (i.e., radiography or activation analysis) and ion implantation. In many of these applications, the advantages offered by the ion linac are compactness, reliability and current capacity.

COMMERCIAL SYSTEMS

Ion linacs are now being designed and fabricated for commercial applications by AccSys Technology, Inc., a U.S. company established for this purpose. Present products include a 2 MeV synchrotron-injector RFQ, an 11 MeV isotope production linac for positron emission tomography (PET), and a compact deuteron RFQ for neutron production.

The 2 MeV RFQ linac (Model PL-2) developed at AccSys is a conventional four vane cavity using a new resonant structure geometry which allows repeatable precision alignment of the vanes and resonator, while eliminating all but four of the rf joints in the cavity. The operating parameters are given in Table I, and the segmented resonator structure is shown in Fig. 1. This system, capable of accelerating either H^+ or H^- ions, has been tested with H^+ ions as the first stage of the 11 MeV PET isotope production linac, described below, and as the injector for the proton therapy synchrotron being constructed by Fermi National Accelerator Laboratory for the Loma Linda Medical Center in California.[3] A photograph of the Model PL-2 delivered to Fermilab is shown in Fig. 2.

Table I. Model PL-2 RFQ Linac Specifications.

Accelerated particle	H^+ (or H^-)
Operating frequency	425 MHz
Input ion energy	30 keV
Final ion energy	2.0 MeV
Acceptance (norm.)	0.116 π cm-mrad
Current limit	63 mA
Final synchronous phase	-30 degrees
Average bore radius	2.61 - 1.61 mm
Maximum vane modulation	2.3
Intervane voltage	65 kV
Maximum surface gradient	35 MV/m (1.75xKP)
Cavity rf power (w/o beam)	175 kW
Vane length	1.595 m
Total length	1.651 m
RF drive loop	3 1/8" coaxial
System weight (approx.)	1000 lbs.
Vacuum pump	8" cryopump
Beam transmission at 30 mA	>88%
Output emittance (norm.) (0.04 π cm-mrad input)	0.06 π cm-mrad
Output energy spread (90%)	$\leq\pm$20 keV
Output phase spread (90%)	$\leq\pm$15 degrees

Fig. 1. Segmented RFQ Resonator Assembly.

The Model PL-2 was initially developed as the injector for an 11 MeV drift tube linac for PET isotope production.[4] The operating parameters for this PET linac system are listed in Table II. It has been previously described[5] and all of the subsystems have now been prototyped. The PET linac is a descendant of medical linac technology developed at Los Alamos in the PIGMI program.[6] The 30 keV injector, which uses a duoplasmatron ion source, has been proven to be compact and reliable, but the low energy beam transport system, which uses a single einzel lens, is

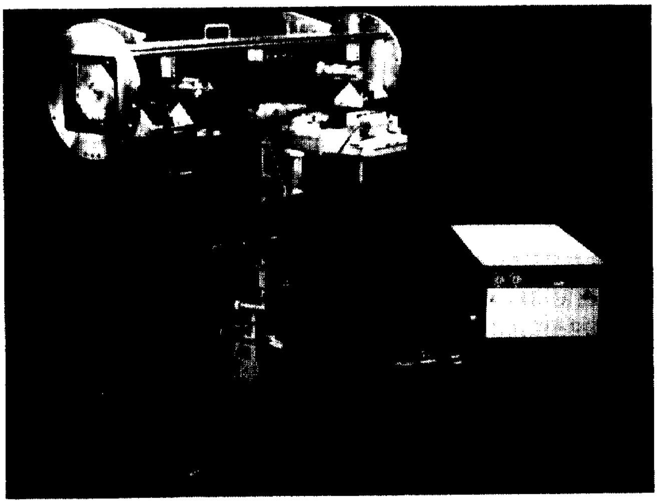

Fig. 2. Model PL-2 RFQ System.

unable to properly match the high current beam into the RFQ due to aberrations. An improved transport system is now being designed for use in future high current linac applications.

Table II. PET Linac System Specifications.

Accelerated particle	H^+
Operating frequency	425 MHz
Injector output energy	30 keV
RFQ output energy	2.0 MeV
Final linac energy	11.0 MeV
Ion source output current	>30 mA
Linac output current	25 mA
Beam pulse width	34 μsec
Beam repetition rate	1-120 Hz
RF pulse width	50-60 μsec
RF peak power (w/beam)	925 kW
Total length (w/injector)	5.36 m
Average structure power	4.7 kW
Total input AC power	25 kVA
System weight (approx.)	3000 lbs.

The PET system uses a standard post-coupled drift tube linac with permanent magnet quadrupole focusing. A full size model of the tank, first drift tube and post coupler is shown in Fig. 3. The drift tubes are precision mounted and removable post coupler adjustment tooling has been incorporated to allow easy tuning of the structure. Such innovations have resulted in lower fabrication costs and greater mechanical stability. The drift tube geometry was designed to optimize the rf efficiency. The drift tube bore is graduated to allow the use of conventional small bore samarium cobalt permanent magnets at the input to the linac, while making the bore larger at higher energies to avoid any beam spill that might arise from magnet misalignment. The accelerating gradient, while conservative with respect to demonstrated sparking limits, is a compromise between the rf power requirements and accelerator length. The single tank is maintained at the resonant frequency of the RFQ linac by the use of motor driven slug tuners mounted into the tank wall. The drift tube linac is powered by three 240 kW rf systems and the RFQ is driven by a single unit. The entire linac system is operated by a single microprocessor control system, based on the design of the secondary station from the National Bureau of Standards racetrack microtron control system.[7] This system allows the operator to easily control the start-up and operation of the linac. It has provisions for interfacing to a larger control system, or for the integration of target and chemistry controls. The system also has several operational layers, allowing more knowledgeable linac operators access to more complex data and controls, and at the highest level, to programming changes.

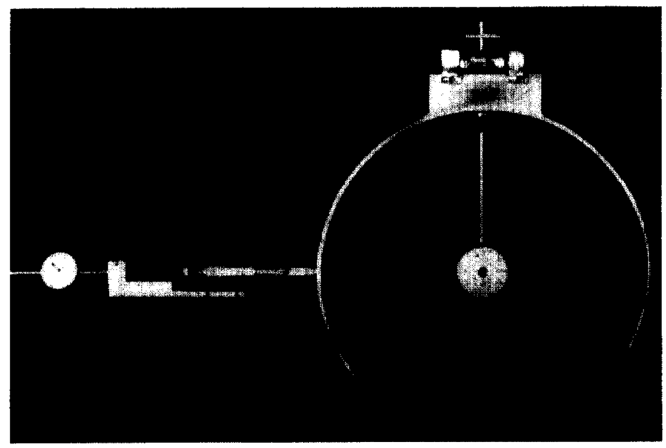

Fig. 3. PET Linac Drift Tube Structure.

The innovative features of the PET system have been incorporated in the design of a compact deuteron linac system, the Model DL-1. This linac is one of two RFQ accelerators designed for the U.S. Federal Aviation Administration (FAA) as neutron sources for an airport explosives detection system. The other design is also being presented at this conference.[8] The pertinent operating parameters for the Model DL-1 are listed in Table III and a drawing of the prototype being funded for development at AccSys by the FAA is shown in Fig. 4. This RFQ uses the same injection system as the PET linac, including the einzel lens, since the required RFQ input current is only 10 mA. The segmented RFQ resonator structure is also used, but with a constant radius of curvature vane tip so that a ground cutter can be used to quickly and easily machine the vane tip modulations. The RFQ, as well as the vacuum system, will be constructed from aluminum to reduce the weight of the accelerator and the neutron activation. The rf amplifier will be a standard AccSys 60 kW unit. The accelerator, rf system, cooling system, vacuum system and injector control electronics will be modular units to allow flexibility in the use of the linac in the explosive detection system.

The RFQ resonator in the Model DL-1 has been optimized for minimum rf power in order to reduce cooling and average power requirements. In addition to using a low vane voltage, the resonator will incorporate resonant dipole mode couplers, instead of vane coupling rings, at the ends of the cavity to stabilize the field distribution from dipole modes. The low vane voltage not only lowers the required rf power but also minimizes the cavity rf electric surface fields, resulting in a much more conservative operating level. This allows a wider range of input power for routine operation with no sparking.

Table III. Model DL-1 System Specifications

Accelerated particle	d^+
Operating frequency	425 MHz
Input ion energy	25 keV
Final ion energy	900 keV
Acceptance (norm.)	0.04 πcm-mrad
Current limit	21 mA
Final synchronous phase	-28.0 degrees
Average bore radius	1.60 mm
Maximum vane modulation	2.26
Intervane voltage	45.0 kV
Maximum surface gradient	38 MV/m (1.92xKP)
Cavity rf power (w/o beam)	39.5 kW
Vane length	72.6 cm
Total length	1.016 m
RF drive loop	1 5/8" coaxial
System weight (approx.)	400 lbs
Vacuum pumps (2)	8" cryopump
Design input current	5-15 mA
Input emittance (norm.)	0.02 πcm-mrad
Beam transmission at 10 mA	>90%
Output energy spread (90%)	<±15 keV
Beam pulse length	5-15 μsec
Cavity fill time	5 μsec
Pulse repetition rate	1500 Hz
Total rf power	47.8 kW
RF duty factor (max.)	3.0%

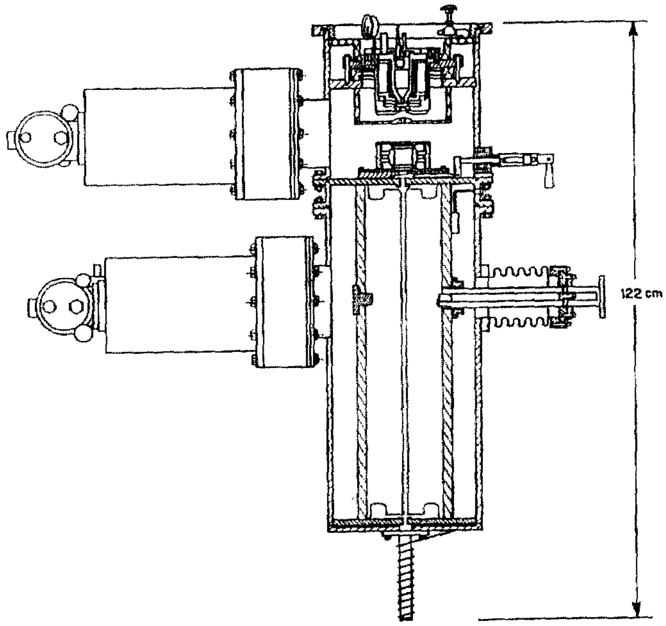

Fig. 4. Cross Section of Model DL-1 RFQ Linac.

NEW LINAC RF POWER SYSTEMS

Auxiliary subsystems are of major importance in the operation of a complete linac system. In the commercial linacs described, all of the subsystems but the rf power have been directly transferred or scaled from large linac programs. After studying all of the available rf systems in the frequency range and power needed for compact commercial ion linacs, AccSys made the decision to commercially develop the parallel planar triode system that had been proposed and tested at Los Alamos.[9] A 240 kW version has successfully powered both the prototype Model PL-2 RFQ for the PET linac and the second Model PL-2 built for Fermilab. AccSys is currently building 60 and 480 kW versions of the planar triode amplifier. Operating parameters for the three systems are given in Table IV. These specifications are representative of the design flexibility available. All have gentle degradation, with multiple rf tubes allowing the larger units to be operated at reduced power with one or more tubes disconnected. The operating parameters for these systems are well matched in power, pulse length and duty factor to the commercial ion linacs described in this paper. The operating frequency can be designed from about 300 MHz up to above 800 MHz, with little change in efficiency and output power. These amplifiers are designed for operation with resonant structures and have phase and amplitude control built in, as well as fast protection circuits for cavity breakdown. In addition, all systems are supplied with high power phase shifters to allow optimum coupling of the amplifier to the resonant structure.

Table IV. AccSys Planar Triode RF Amplifier Specifications.

Parameter/Model	4TW60	12TW240	24TW480
Frequency (MHz)	425/850	425	350
Output power (kW)	60	240	480
Tuning range (MHz)	±20/±40	±20	±20
No. tube stages	2	3	3
No. tubes total	5/6	17	29
Tube efficiency	50%	50%	50%
Bandwidth (MHz)	±5/±10	±5	±5
Max pulse (μ sec)	250	120	100
Duty factor (%)	0.125	1.0	1.0
Output coax (EIA)	1 5/8"	3 1/8"	3 1/8"
Amplitude control (%)	±0.5	±1.0	±1.0
Phase control (°)	±0.5	±0.5	not used
Cooling	closed loop deionized H_2O		

REFERENCES

1. L.W. Alvarez, "History of Proton Linear Accelerators," 1986 Linear Accelerator Conf., SLAC-Report-303,3 (Sept. 1986).
2. K. Batchelor, "Operation of the BNL 200 MeV Linac," 1972 Proton Linear Accelerator Conf., LA-5115, 12 (Nov. 1972).
3. F. Cole, P. Livdahl, F. Mills and L. Teng, "Design and Application of a Proton Therapy Accelerator," 1987 Particle Accelerator Conf., IEEE No. 87CH2387-9, 1985 (Sept. 1987).
4. This work was supported by PHS Grants 1R43CA37512 and 7R44CA43915, awarded by the National Cancer Institute, DHHS.
5. R.W. Hamm, K.R. Crandall, M.E. Hamm, L.D. Hansborough and J.M. Potter, "A Compact Proton Linac for Positron Tomography," 1986 Linear Accelerator Conf., SLAC-Report-303, 141 (Sept. 1986).
6. L.D. Hansborough (compiler), "PIGMI: A Design Report for a Pion Generator for Medical Irradiations," Los Alamos Report LA-8880 (Sept. 1981).
7. R.L. Ayres, N.R. Yoder, E.R. Martin, R.E. Trout and B.L. Wilson, "NBS Racetrack Microtron Control System," IEEE Trans. Nucl. Sci. NS-32, No. 5, 2086 (Oct. 1985).
8. D.A. Swenson, "A Compact 1-MeV Deuteron RFQ Linac," this proceedings.
9. D.W. Reid, "RF Power Sources for 1990 and Beyond," 1986 Linear Accelerator Conf. Proc., SLAC-Report-303, 29 (Sept. 1986).