LINACS FOR MEDICAL AND INDUSTRIAL APPLICATIONS

Robert W. Hamm
AccSys Technology, Inc.
1040 Serpentine Lane, Suite 208, Pleasanton, CA 94566

Summary

Linear accelerators for medical and industrial applications have become an important commercial business. Microwave electron linacs for cancer radiation therapy and high-energy industrial radiography form the bulk of this market, but these, as well as induction linacs, are now being offered for radiation processing applications such as sterilization of disposable medical products, food preservation and material modifications. The radio frequency quadrupole (RFQ) linac has now made the ion linac also practical for commercial applications in medicine and industry, including radiation therapy, isotope production, neutron production, materials modification, and energy transfer processes. Ion linacs for several of these applications will soon be commercially available. The market for both ion and electron linacs is expected to significantly grow in several exciting and important areas.

Introduction

Practical applications of linear accelerators were recognized shortly after their development as physics research tools, primarily for cancer radiation therapy but also for product irradiation. Because of its much simpler design and operation, the electron linac was adapted very quickly for these markets. Soon after the standing-wave side-coupled cavity linac was demonstrated at Los Alamos the compact electron linac began to replace Co-60 as the standard cancer radiation therapy technique. These linacs were later adapted for high energy industrial radiography.

An excellent early review of the historical development of the electron linac for radiation therapy was published by Karzmark and Pering[1] in 1973, with a recent update by Karzmark.[2] Since these reviews have presented such an excellent description of these machines and their development, that topic will not be covered here. Similarly, the recent review papers by Cleland[3] and McKeown[4] have presented an excellent detailed description of electron linacs developed for radiation processing. This review paper will therefore only summarize the present status of these markets and discuss the new products and growth areas for each.

The ion linac has been proposed for and utilized in several practical applications, as reviewed by Knapp[5] in 1976 and Blewett[6] in 1979. However, commercial availability of these machines was not achieved until the construction of the 45 MeV proton linac at New England Nuclear.[7] Although technically successful and innovative, this machine was still too large and expensive to be viable as a commercial product. However, the introduction of the radio frequency quadrupole (RFQ) linac has now made possible the replacement of these "conventional" ion linacs with a much simpler and more reliable system at a lower cost. Indeed, as these two visionary men predicted in their previous reviews, this new linac technology has now made ion linacs practical for medical and industrial applications, with systems soon to be available commercially. In fact, the growth in commercial ion linacs resulting from the development of the RFQ will be as rapid and as large as the growth of commercial electron linacs that resulted from the development of the side-coupled cavity linac.

Exciting new applications of both electron and ion linac technology and the commercial systems already unveiled for these applications will be discussed in this paper. The phrase "commercial linac application" refers to any process for which a linac system is or will be available commercially, as distinguished from the research applications of linacs at universities and national laboratories. Individual applications will not be described in detail, but the general beam requirements and unique linac features for that market will be given. Prospects for new products and market potential will be projected for existing applications. Finally, several exciting new linac applications which may have commerical implications will be outlined.

Electron Linac Applications

Medical

By far the largest single medical application for linacs is radiation therapy. As shown in Fig. 1, there are presently about 2500 world-wide medical installations of electron linacs for this purpose. The market for these machines and the ancillary equipment was recently reported to be nearly $250 million per year worldwide.[8] These machines range in energy from 4 to 40 MeV, with beam powers of about a kilowatt at duty factors of about 0.1% or less. Most machines offer treatment either with X-rays or electrons and deliver isocenter dose rates of several hundred rads per minute. Recent developments include the availability of dual X-ray energies from a single machine[9] and modifications for specialized treatment such as intraoperative radiation therapy.[10] The trend is toward computer control of the entire system, with integration of the linac into the entire radiation therapy process from diagnosis to final billing.

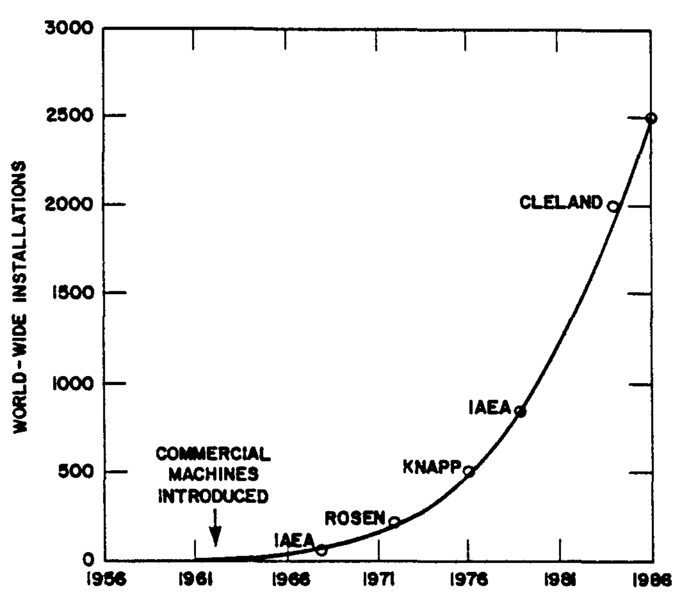

Fig. 1. Growth of Electron Linacs for Radiation Therapy

Industrial Radiography

The principal industrial application of the electron linac is high-energy X-radiography for nondestructive testing of thick metal parts, munitions and rocket motors. There are about 250 worldwide installations of these machines, ranging in electron energy from 1 to 16 MeV. Such systems are offered commercially by seven companies worldwide with about 20-25 machines sold annually. The beam power in these systems is at the level of approximately 1 kilowatt with X-ray dose rates at 1 meter from the target ranging from 20 to 10,000 rads per minute.

These systems were originally re-packaged versions of the medical linac described above but more recently have been developed specifically for radiographic applications. Recent developments include: (1) the design of compact portable systems at both S-band[11] and X-band[12] for field inspection of structures such as oil platforms, reactors and bridges; (2) the development of specialized high resolution industrial tomographic systems for rocket motor and jet engine inspection;[13] and (3) plans for add-on systems utilizing the (γ,n) reaction for neutron production.[14] Significant growth in radiographic inspection with high energy linacs may result from emphasis on quality and inspection in several heavy industries and the development of real time X-ray imaging systems.[15] In addition to radiography, a new market is developing for the radiation testing of electronic components, particularly computer parts, as "radiation hardened" electronic components become necessary for critical computer-control applications.

Radiation Processing

The use of high energy electrons and X-rays for the irradiation of food and medical products began soon after the electron linac became available for cancer therapy. However, regulatory restrictions and the advent of Co-60 irradiation has limited this linac application to less than 12 machines worldwide at the present time.[4] There are clear indications that the demand for radiation processing systems will increase in the future, with several new linacs having been recently developed for this market. The principal applications of radiation processing are sterilization of medical products and cosmetics, disinfestation of food, and materials modifications. The principal technique for irradiation of medical products, cosmetics and food is by gamma irradiation, using large radioactive sources of Co-60 or Cs-137. The list of currently irradiated products includes disposable medical products (surgical kits, syringes, gowns, gloves, sutures, etc.) bone and skin to be used in transplants, pet products, cosmetics, spices, and most recently, fruits and vegetables. After many years of controversy, these foods were approved for disinfestation with low doses of radiation (up to 100 kilorads) by the Federal Drug Administration.[16] Public opinion and recent isotope shortages have led to a renewed interest in using electron linacs for irradiation applications in place of or in addition to gamma irradiators. Most of the electron linacs presently or soon to be available commercially produce electron energies of about 5 to 12 MeV (the FDA has set a limit of 5 MeV for X-ray irradiation of food and a maximum electron energy of 10 MeV for electron irradiation). However, the beam power required in order to get a large throughput of irradiated products ranges from a few kilowatts to up to tens of kilowatts, depending on the product and the required dose.

Materials modification using electrons is a large market primarily dominated by large electrostatic accelerators. Linac applications in this market include: (1) crosslinking of polymers, particularly for thicker parts that require energies greater than 5 MeV for adequate penetration; (2) modification of semiconductor characteristics, e.g. to tailor transistor switching speeds;[17] and (3) irradiation of gemstones to enhance their color and appearance.[18]

Recent systems developed for radiation processing include a compact standing-wave linac from Varian,[19] the large triode-driven Cassitron from CGR-MeV,[20] and the conventional induction linac from Ford Labs.[21] Other linac concepts developed previously include the Russian self-excited resonant cavity[22] and the CW standing-wave accelerator at Chalk River.[23] Presently, at least one contract irradiator company offers radiation processing on a commercial basis using an electron linac.[24] The present perception of many commercial experts is that there will be a large market in the future for radiation processing with electron linacs. It is certain that the radiation processing business will continue to grow as the regulatory environment requires a decrease in the use of harmful chemicals in the medical and food industry and encourages alternative processes.

Radiation processing applications which may develop in the future include the sterilization of waste products and the expansion of the FDA regulations to include higher dose irradiation of food for shelf life extension. Regulations could be approved by the FDA in the near future for higher dose levels for the pasteurization of approved poultry, hamburger and seafood (several other countries have approved these dose levels already). A long-term possibility is the approval of very high dose rates for the preservation of meat. The realization of either of these will result in a large commercial market for electron linacs.

Radiation Sources

There are several large development programs in progress in the national laboratories to provide electron linacs for sources of radiation and, although no commercial programs exist at this time, these sources could be useful in other applications. These include the development of linacs for replacement of isotopic sources in analytical systems, such as oil well borehole logging.[25] Other areas that could benefit from linac technology include the generation of coherent tuneable light from the free electron laser and the generation of synchrotron radiation. The free electron laser has applications in processing pharmaceuticals for medicine and chemical processing for industry, in addition to its use in isotope separation and directed energy.[26] Synchrotron radiation has applications in semiconductor fabrication[27] and medical imaging.[28] Another application of linac-based radiation sources is the generation of positron beams for material analysis.[29]

Ion Linac Applications

Medical

The medical applications of ion linacs include isotope production and radiation therapy. Existing research linacs are being used for commercial production of medical isotopes,[30,31] with the New England Nuclear 45 MeV proton linac being the first commercial linac built for this purpose.[32] A powerful new linac for the production of medical isotopes has been proposed by Los Alamos,[33] and a compact proton linac for the in-hospital production of short-lived positron emitting isotopes is being constructed by

AccSys Technology, Inc.[34] As stated earlier, these linac systems are now very practical because of the development of the RFQ, particularly when combined with new rf source technology being discussed at this conference.[35]

This RFQ linac technology can be used to build practical ion linacs for radiation therapy with protons, neutrons, heavy ions or pions. The medical results from the therapy research programs underway around the world at various medical centers will determine the relative effectiveness of these different modalities with respect to conventional X-rays. Once the most effective treatment techniques have been determined, these new linacs will be able to provide the most cost effective radiation source for this medical application. The use of the linac for radiation therapy has already been proven with existing research linacs,[36,37] so the economics of the linac compared to other types of accelerators will be the determining factor in its clinical use, provided that particle radiation therapy becomes a common treatment.

Industrial

The two major industrial applications for ion linacs will be neutron analysis and ion implantation. Neutron analysis includes neutron activation analysis, neutron radiography and neutron bombardment of materials. The use of the RFQ to generate neutrons for these applications has been suggested already.[38,39] Since this technology can provide a compact, intense source of electrically generated thermal neutrons, analysis of chemical impurities or contamination using neutron activation at processing plants is now realistic. Similarly, as suggested by IRT,[39] such a system can be used for off-site neutron radiogrpahy of aluminum and carbon composite structures. Finally, solid-state, biological and material analysis can be performed using linac-generated fast neutrons, although these applications will probably not be large enough to justify dedicated machines.

Ion implantation of semiconductors using high-current heavy ion beams generated by ion linacs at energies of a few MeV has been proposed.[40] Applications for this technique include retrograde wells, buried grids, ROM programming, cryogenic germanium devices and buried interconnects.[41] MeV ion implantors now in use employ electrostatic machines, but an rf linac utilizing independently phased cavities is now being built and tested by Eaton Corporation.[42] This machine, which will be available commercially, will accelerate boron, phosphorous, arsenic and antimony ions from 100 keV to about 1 MeV for singly charged ions. The maximum ion beam current is several hundred microamperes for all but the heaviest ion, antimony. It will accelerate doubly charged ions also, but at reduced current levels since a standard 80 kV electrostatic ion implantation system is used for the injector.

Other ion implantation applications include bombardment of metals and plastics, techniques presently being developed using the heavy ion linac at GSI.[43] However, these applications require very high energy machines and are not large enough for dedicated machines at the present time, but would benefit from other commercial heavy ion linac applications such as radiation therapy.

Directed Energy

Directed energy applications for ion linacs include neutral particle beam weapons,[44] plasma heating in magnetic confinement fusion,[45] pellet ignition in heavy ion inertial fusion,[46] and nuclear fuel breeding.[47] Although each of these applications is still very much in the research stage, all have benefited tremendously by the development of the RFQ and offer large commercial linac market possibilities. Linacs for these applications are being developed at national laboratories under federally-funded defense and energy programs. The technology being developed in these programs will also provide a base for future medical and industrial applications. The challenge to the accelerator designers will be to effectively transfer this technology to industry for all of these applications.

Conclusion

The intent of this review has not been to discuss the detailed implementation of linac applications or to repeat the description of present or proposed linacs, but rather to update previous reviews on the status of these linacs and their applications, as well as to introduce new linacs and applications. Unless referenced, the projections and opinions given in this paper are attributed solely to the author. The data reviewed in this paper indicate that the "era of the linac" as suggested by Knapp[5] has indeed arrived.

References

1. C.J. Karzmark and N.C. Pering, "Electron Linear Accelerators for Radiation Therapy: History, Principles and Contemporary Developments", Phys. Med. Biol., 18, No. 3, 321 (1973).

2. C.J. Karzmark, "Advances in Linear Accelerator Design for Radiotherapy", Med. Phys. 11(2), 105 (Mar/Apr 1984).

3. M.R. Cleland, "Applications of Linear Accelerators in Industry," Proc. 1984 Linear Acc. Conf., GSI-84-11, 496 (1984).

4. J. McKeown, "Radiation Processing Using Electron Linacs", IEEE Trans. Nucl. Sci. NS-32, No. 5, 3292 (1985).

5. E.A. Knapp, "Applications of Linear Accelerators," Proc. 1976 Proton Linear Acc. Conf., AECL-5677, 115 (1976).

6. J.P. Blewett, "Applications of Linear Accelerators", Proc. 1979 Linear Acc. Conf., BNL 51134, 1 (1979).

7. W.G. Mourad and R.F. Lankshear, "Status of the 45 MeV Proton Linac at NEN", IEEE Trans. Nucl. Sci. NS-30, No. 2, 1421 (1983).

8. Varian 1985 Annual Report, 12 (1986).

9. J.A. Purdy and D.A. Goer, "Dual Energy X-ray Beam Accelerators in Radiation Therapy: An Overview", Nucl. Instr. method B10/11, 1090 (1984).

10. P.J. Biggs, "The Physics of Intraoperative Radiotherapy Using High Energy Electron Beams", ibid, 1102.

11. Varian Model X2PLUS Linatron[R] brochure.

12. R.G. Schonberg, H. Deruyter, W.R. Fowkes, W.A. Johnson, R.H. Miller, J.M. Potter, and J.N. Weaver, "Portable, X-band, Linear Accelerator Systems", IEEE Trans. Nucl. Sci., NS-32, No. 5, 3241 (1985).

13. C. Rain, "Uncovering Hidden Flaws," High Technology, 49 (Feb. 1984).

14. Radiation Dynamics, Ltd., Technical Information Bulletin.

15. R. McMaster, "A Look Ahead at Nondestructive Testing," World Congress on NDT, Las Vegas, Nev. (Nov. 1985).

16. Federal Register, April 18, 1986.

17. E.P. Bondos, "Quit Doping and Use A Linac", Research and Development, (May 1985).

18. G.R. Rossman, "Glitter: Gems or Gyps?," Engineering and Science, Cal. Tech., 26 (March/April 1978).

19. Varian Megaray™ Electron Beam Source brochure.

20. H. Leboutet and J. Aucouturier, "An Electron Accelerator for Irradiation: Cassitron," Rad. Phys. Chem. 22, Nos. 3-5, 403 (1983).

21. Frank Ford, Ford Laboratories, private communication.

22. V.L. Auslender et. al., "Radio-Frequency Electron Accelerator" U.S. Patent No. 4,140,942 (Feb. 20, 1979).

23. J. McKeown, R.K. Elliott, L.W. Funk, S. Gowens, J.P. Labrie, C.E. Langlais and D.G. Logan, "Design of a High Power Electron Linac," Proc. 1984 Linear Acc. Conf., GSI-84-11, 186 (1984).

24. Committee on Radiation Applications, INFO, p.2 (May 1986).

25. W.E. Stein, "Electron Linacs For Laser and Radiographic Applications," IEEE Trans. Nucl. Sci. NS-30, No. 2, 1434 (1983).

26. J.M. Watson, "Free-Electron Lasers and Related Topics," Proc. 1984 Linear Acc. Conf., GSI-84-11, 256 (1984).

27. Leybold Heraus Synchrotron Light Source.

28. H. Wiedemann, "Pulsed X-ray Source for Non-Invasive Digital Subtraction Angiography," IEEE Trans. Nucl. Sci., Ns-32, No, 5, 3308 (1985).

29. R.H. Howell, M.J. Fluss, I.J. Rosenburg and P. Meyer, "Low-energy, High-intensity Positron Beam Experiments with a Linac", Nucl. Inst. Meth. B 10/11, 373 (1984).

30. L.F. Mausner and P. Richards, "The Production of Spallation Radionuclides for Medical Applications at BLIP", IEEE Trans. Nucl. Sci. NS-30, No. 2, 1793 (1982).

31. H.A. O'Brien, "Accelerator Preparation of Radioisotopes for Medical Applications", 1979 American Nuclear Society Winter Meeting, San Francisco, (Nov. 1979).

32. D. Comastra, Industrial Research and Development, (Sept. 1981).

33. J.E. Stovall, L.D. Hansborough and H.A. O'Brien, "Radioisotope-Production Linac", Proc. 1981 Linear Acc. Conf., Los Alamos Report LA-9234-C, 344 (1981).

34. R.W. Hamm, K.R. Crandall, M.E. Hamm, L.D. Hansborough, and J.M. Potter, "A Compact Proton Linac For Positron Tomography," this proceedings.

35. D.W. Reid, "RF Power Sources for 1990 and Beyond", this proceedings.

36. L. Cohen and M. Awschalom, Appl. Radiol. 5, 51 (1976).

37. Los Alamos National Laboratory 1981 Annual Report, LALP-81-68, 42 (Feb. 1982).

38. B.G. Chidley, G.E. McMichael and S.O. Schriber, "CANUTRON-a Clean Accelerator Neutron Generator," Nucl. Inst. Meth. B10/11, 888 (1984).

39. J.A. Stokes, L.A. Parks, C.A. Preskitt, and J. John, "Performance of Neutron Radiography Systems Using Particle Accelerators," IEEE Trans. Nucl. Sci. NS-30, No. 2, 1623 (1983).

40. C. McKenna, C. Russo, B. Pedersen and D. Downey, "Applications for MeV Ion Implantation," Semiconductor International, 101 (April 1986).

41. P. Burggraat, "Ion Implanters: Major 1986 Trends," ibid, 78.

42. Eaton Corporation Model NV-1000 High Energy Ion Implantation System brochure.

43. 1981 GSI Scientific Report, GSI 82-1 (Mar. 1982).

44. G. Yonas, "Strategic Defense Initiative: The politics and science of weapons in space," Physics Today 28(3), 24 (June 1985).

45. L.R. Grisham, D.E. Post, and D.R. Mikkelsen, "MeV Light Atom Beams For Heating and/or Diagnostics of Tokamak Plasmas," IEEE Trans. Nucl. Sci. NS-30, No. 2, 1179 (1982).

46. R. Bock, "Heavy Ion Fusion," IEEE Trans. Nucl. Sci. NS-30, No. 4, 3049 (1983).

47. P. Grand and H. Takahashi, "Breeding Nuclear Fuels with Accelerators - Replacement for Breeder Reactors," Nucl. Inst. Meth. B 10/11, 454 (1985).