

COMMERCIAL APPLICATIONS OF LINACS

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Abstract

Although research and development of new linear accelerators will continue, linac technology is already well accepted for commercial applications. Dedicated electron linacs have been used for almost 30 years to do cancer radiation therapy. Electron linacs are also being routinely used for high energy x-ray radiography, irradiation of products with x-rays or electrons, and free-electron lasers. The development of the Radio Frequency Quadrupole (RFQ) linac has now also made the ion linac a practical tool for commercial applications. Ion linacs are being commercially supplied for medical isotope production, particle radiation therapy, neutron activation analysis, high energy ion implantation, and neutron radiography. The demand for commercial linac systems is expected to significantly increase in this decade and well into the next century.

Introduction

Linear accelerators developed for physics research have resulted in practical systems for commercial applications. As the technology of these early linacs was improved by researchers, practical applications were developed using these machines. When the technology was proven, commercial companies began to build these linacs for specific markets. One example is the development of the standing-wave side-coupled-cavity linac. Soon after its demonstration at Los Alamos<sup>1</sup> in 1966, compact standing-wave electron linacs were designed for cancer radiation therapy.

The medical electron linac market has grown enormously since its beginning, as seen in Fig. 1. This success is due to these compact systems having no competition in operational reliability, size, cost and safety. Electron linacs now being developed for industrial applications in product irradiation and free electron lasers have similar advantages over competing technologies. Since elec-

tron linac applications have been thoroughly discussed in a previous review,<sup>2</sup> this paper emphasizes the more recent development of ion linacs for commercial applications.

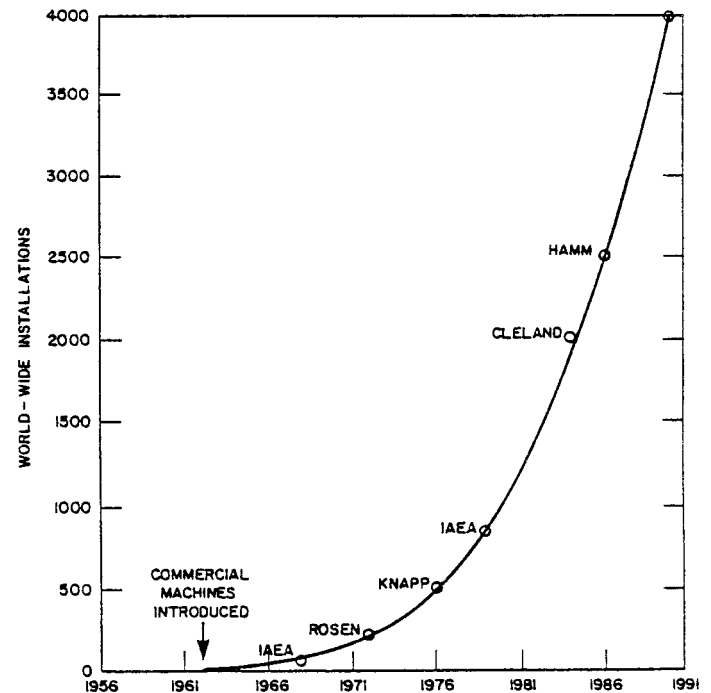


Fig. 1. Growth of electron linacs for radiation therapy.<sup>2</sup>

Just as the introduction of the side-coupled linac spurred the commercial development of electron linacs, the introduction of the RFQ has spawned commercial applications of ion linacs. The same attributes of compact size, operational reliability, cost and radiation safety have enabled the ion linac to become competitive for ion beam applications over a wide range of energies and currents. Low energy ion beam applications (up to several MeV) require only the RFQ, while higher energy beams require the use of a drift tube linac (DTL). Future applications of ion linacs at very high energies (>100 MeV) will even require the use of coupled-cavity linac structures.

For this review, a "commercial application" is defined as any process for which an ion linac system is or will be

available from a commercial company. It, therefore, does not cover research linacs constructed by universities and government laboratories, except where the system is used for a practical application or fabricated by an industrial company.

### Ion Linac Applications

The commercial applications of ion linacs can be divided into four separate areas: medical, industrial, military and research. The first three comprise the bulk of the commercial ion linac business, while the last one accounts for most of the ion linacs built to date. More than twenty large ion linacs have been constructed by universities and national laboratories worldwide for physics research and ten RFQs have been built as injectors for these linacs.<sup>3</sup>

#### Medical

The commercial applications of ion linacs in the medical field are cancer therapy and medical isotope production. Cancer therapy is performed with particle beams by bombarding the cancer directly with accelerated protons or heavy ions, or with secondary beams of neutrons or pi mesons created by bombarding a target with an accelerated particle beam. Such treatments have much better dose distributions than bremsstrahlung radiation as seen in Fig. 2, which is a comparison of the depth dose distributions of various radiation therapy treatments.<sup>4</sup> The sharp "Bragg peak" associated with charged particle therapy allows much better localization of the dose with less damage to the skin and healthy tissue surrounding a tumor.

Particle therapy is being performed at twelve research accelerators worldwide, but dedicated systems are now being developed at several facilities listed in Table I.<sup>5</sup> An ion linac will be the injector for many of these accelerators. An example is the 250 MeV proton synchrotron developed by Fermilab for Loma Linda University Medical Center, which is injected by a commercial 2 MeV RFQ linac.<sup>6</sup> In addition, a 250 MeV proton linac has now been proposed by AEA Industrial Technology of England as an alternative to the synchrotron for proton therapy.<sup>7</sup>

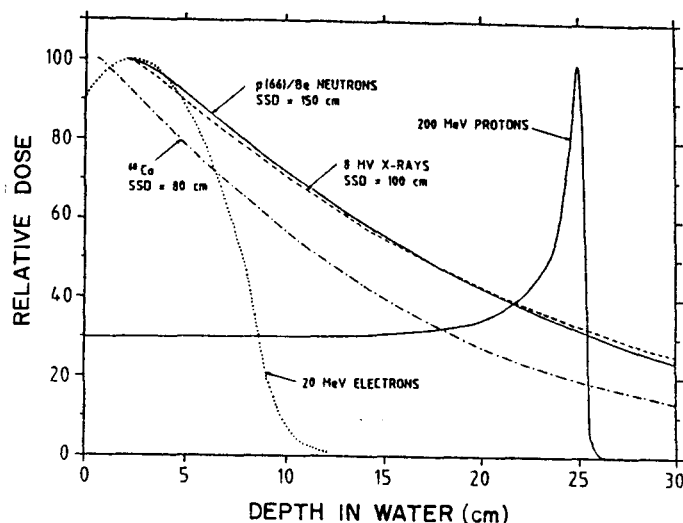


Fig. 2. Depth dose data from radiation therapy beams.<sup>4</sup>

TABLE I  
Dedicated Particle Therapy Facilities

COMPANY	COUNTRY	ACCELERATOR	PARTICLE	DATE
Loma Linda	USA	Synchrotron	p	1990
Orsay	FRANCE	Synchrocyclotron	p,n	1991
Nice	FRANCE	Cyclotron	p,n	1991
Chiba	JAPAN	Synchrotron	HI	1994
Chicago	USA	Linac	n,p	1995
EULIMA	EUROPE	Cyclotron	HI	199?
Tsukuba	JAPAN	Synchrotron	p	1995
Novosibirsk	USSR	Linac	p	1995

Neutron therapy has also been performed for many years with existing research accelerators, including linacs, and is being done now with seven dedicated cyclotrons. A dedicated 70 MeV proton linac facility for neutron therapy is planned in Chicago.<sup>8</sup> Pion therapy was performed with the Los Alamos Meson Physics Facility linac and new technology was developed at Los Alamos for a practical 600 MeV, 100  $\mu$ A proton linac to generate pions,<sup>9</sup> but the cost was prohibitive for commercial production.

Boron neutron capture therapy (BNCT) is a new mode of radiation therapy in which a tumor is loaded with a boron-doped compound and then irradiated by epithermal neutrons. The high capture cross-section of the boron results in a preferential energy deposition in the tumor over the surrounding healthy tissue. The high flux of epithermal neutrons requires a reactor or an accelerator with a high beam power. A 2.5 MeV proton RFQ bombarding a molten lithium target with a 10 mA beam has been

proposed in the USA,<sup>10</sup> while a 30 MeV proton cyclotron bombarding a beryllium target with a 100  $\mu$ A beam has been suggested in Europe.<sup>11</sup>

The largest potential medical application for ion linacs is radionuclide production. This includes short-lived isotopes for Positron Emission Tomography and long-lived isotopes for nuclear medicine. Linacs at Los Alamos National Laboratory and Brookhaven National Laboratory have been used for many years to generate long-lived isotopes, but cyclotrons have been the work-horse of commercial isotope production, with approximately thirty-two machines in routine operation worldwide. With the development of the RFQ, ion linacs are now competitive with cyclotrons for this application. Three ion linacs for production of PET isotopes are being developed to compete with the small cyclotrons currently used. The parameters for these systems are given in Table II. A large linac for producing nuclear medicine isotopes has been proposed,<sup>12</sup> with an even larger linac for tritium production being presented at this conference.<sup>13</sup>

TABLE II  
Proposed PET Isotope Production Linacs

	AccSys	AccSys	SAIC
	Model PL-11	Model DL-3	<sup>3</sup> He RFQ
RF structure	RFQ + DTL	RFQ	RFQ
Ion specie	H <sup>+</sup>	D <sup>+</sup>	<sup>3</sup> He
Final energy (MeV)	11.0	3.5	8.0
Peak current (pA)	25.0	15.0	7.5
Beam pulse length ( $\mu$ sec)	67	167	167
Average current (pA)	100	300	150
Accelerator length (m)	4.6	3.0	3.4
Peak beam power (kW)	275	52	120
Peak rf power (kW)	1250	245	360
Average rf power (kW)	7.5	4.9	7.2

### Industrial

The primary industrial applications of ion linacs are ion implantation and neutron activation analysis, with a smaller market being neutron radiography. The largest industrial application is high energy ion implantation, for which Fig. 3 shows the required beam energies and ion doses.<sup>14</sup> At the present time, at least five companies worldwide have high energy ion implantation systems available or under development, as listed in Table III. All are designed to accelerate singly or

doubly charged heavy ions such as boron, nitrogen, phosphorus arsenic, and antimony. Most of these linacs are four-rod type RFQs with two exceptions, as detailed in Table III. Several of the RFQs are variable frequency so that variable energies and ions can be achieved. The Eaton linac is a phase and amplitude controlled independent-cavity system for this same reason. These variable frequency heavy ion RFQs are described by A. Schempp.<sup>15</sup>

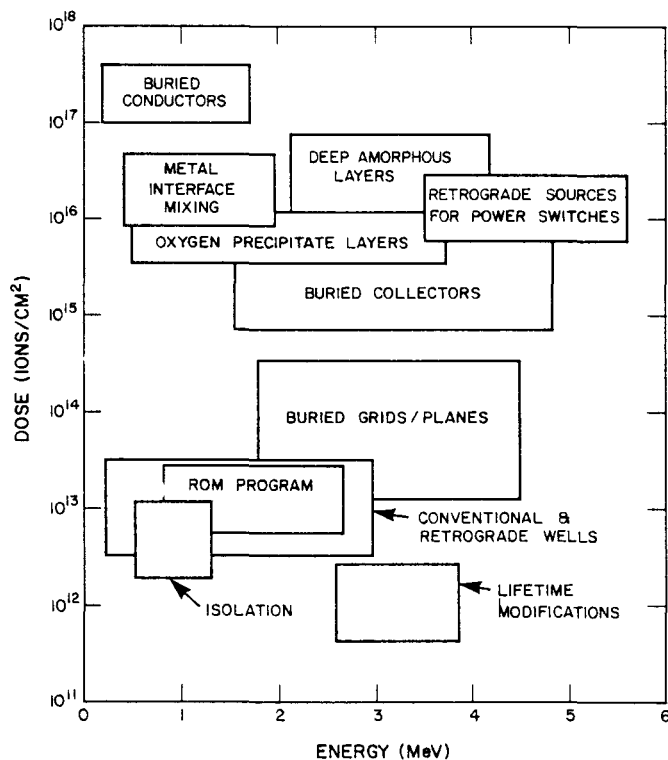


Fig. 3. Applications of High Energy Ion Implantation.

TABLE III  
High Energy Ion Implantation Linacs

Company (Origin)	RF Structure	Length (m)	Frequency (MHz)	B <sup>+</sup> Energy (MeV)	Present Status
Eaton (US)	Ind. Cavity	2.4	6.8	1.0	Prod.
AccSys (US)	RFQ-Rod	2.4	15-100	1.5	Dev.
P.E.T. (Germany)	RFQ-Rod	1.2	81.4	1.0	Proto.
Shimadzu (Japan)	RFQ-Vane	1.85	70	1.012	Proto.
Hitachi (Japan)	RFQ-Rod	N/A	var.	1.0	Dev.

The second industrial application of ion linacs is the production of neutrons for neutron activation analysis. The high beam current capability of the RFQ makes it a prolific source of neutrons from the



Be(d,n) reaction, which produces neutrons with energies of a few MeV. For most applications in neutron activation, thermal neutrons are required. Most existing sealed neutron tubes utilize the T(d,n) reaction which produces 14.1 MeV neutrons. These are much harder to shield and moderate to thermal energies than those from Be(d,n). An RFQ is much safer than radioactive sources that produce fission neutrons at approximately the same average energy, since it can be turned off. Since ion linacs span a wide range of ion energies and currents, ion linac neutron generators can cover a wide range of neutron outputs.<sup>16</sup>

Although neutron activation analysis has already been used for industrial analysis of contaminants, such as sulfur in coal,<sup>17</sup> the first application of an ion linac in this field is for the detection of explosives in aircraft passenger baggage. A small RFQ developed for this (shown in Fig. 4) produces a neutron flux of up to  $10^{10}$  neutrons/sec from a thick beryllium target using a 0.9 MeV  $d^+$  beam. It is pulsed at a high repetition rate (up to 1500 Hz) with an rf duty factor up to 0.0225, resulting in a quasi-continuous thermal neutron flux.

The detection of explosives in airline baggage can be accomplished by a number of nuclear techniques. As reviewed by L. Grodzin,<sup>18</sup> these include not only thermal neutron activation, but fast neutron activation, gamma ray resonance absorption, and neutron backscattering and absorption. Many of these techniques can employ ion linacs as neutron and gamma ray sources. At the present time, the only technique being deployed for actual airport use is the thermal neutron activation system, with the five first systems fielded containing  $^{252}\text{Cf}$  fission neutron sources. The final choice of the technique to be used in production units must await the results from these and several new systems under development.

A smaller industrial market for ion linacs is neutron radiography. This nondestructive testing technique was proposed as a use of the RFQ soon after the testing of the first one at Los Alamos in 1979.<sup>19</sup> Linacs for this application are much more powerful than the neutron activation analysis systems. Typically, they accelerate proton or deuteron beams

to energies of several MeV to tens of MeV, with beam currents from several hundred microamperes to one millampere or more. Neutron fluxes range from  $10^{11}$  to more than  $10^{13}$  neutrons/sec. The principal application for such systems is to replace radioactive sources and small reactors for neutron radiography of munitions and aircraft parts. For example, a 4 MeV proton RFQ is being developed for the U.S. Navy for realtime neutron radiography at China Lake Naval Weapons Center.<sup>20</sup>

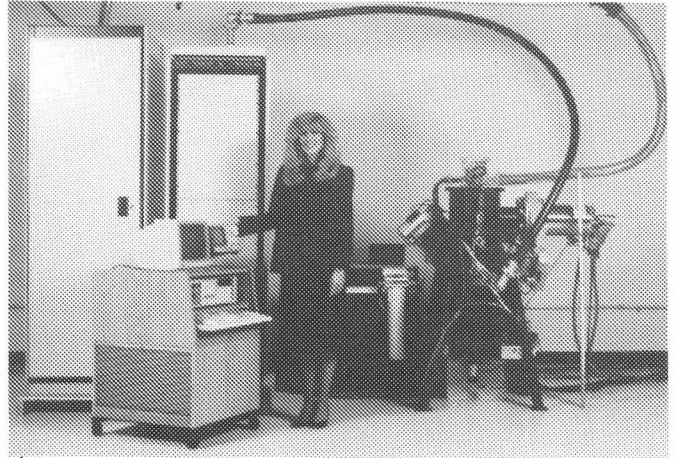


Fig. 4. Model DL-1 RFQ Linac neutron source for Explosive Detection.

### Military

The principal military applications of commercial ion linacs are neutron radiography, as described above, and neutral particle beam (NPB) weapons. The latter is not presently a "commercial" application, since this program is still very much in the development phase. However, industrial participation in the NPB development program at Los Alamos has resulted in the commercial production of accelerators, such as the small 1 MeV RFQ linac flown aboard a test rocket last year.<sup>21</sup> This industrial participation is continuing in several more recent NPB programs, with complete linac systems now being built as demonstration units by commercial aerospace companies.<sup>22</sup>

### Research

As described earlier, this application accounts for the bulk of the ion linacs built to date, but has involved



very little commercial participation with the university and laboratory groups who have built them. However, prior to the commercial availability of RFQ linacs (and even today in Europe), many of the RFQs in use at research laboratories worldwide originated from only a few research groups. Ten RFQs have been built for other research facilities completely by or in cooperation with Los Alamos and Lawrence Berkeley Laboratory in the U.S. and University of Frankfurt in Europe. Although ion linacs will continue to be developed for research applications by university and national laboratory groups around the world, an increasing number will be procured from commercial companies as the technology matures.

One example is the L3 Calorimeter Calibration RFQ shown in Fig. 5. This system will be mounted onto the large L3 detector in LEP at CERN. It will provide a pulsed  $H^0$  beam (10mA at 1-3  $\mu$ sec) to bombard a Li target at 1.85 MeV in order to provide intense pulses of radiative-capture gamma rays to calibrate 12,000 BGO crystals in the calorimeter. A new rf-driven  $H^-$  ion source has been developed to provide a 25 mA beam pulse for injection into the RFQ with a long source lifetime, even when operating at 150 Hz.<sup>23</sup> A gas neutralizer will strip the  $H^-$  beam to a neutral  $H^0$  beam for injection through the magnetic field of the L3 solenoid.

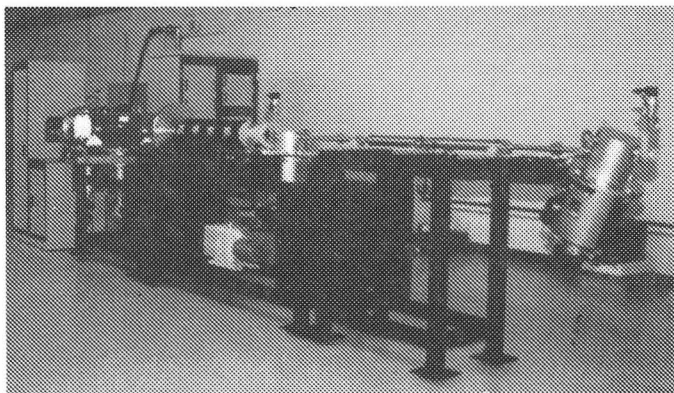


Fig. 5. L3 Calorimeter Calibration RFQ.

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