EMERGING INDUSTRIAL APPLICATIONS OF LINACS

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Abstract

Three emerging linac market areas are discussed: contraband detection using tandem ion accelerators; x-ray sterilization of food using high-power electron linacs; and large volume material surface processing with radiation from superconducting RF accelerator-driven free electron lasers. The opportunities are described and simple economic models are applied to assess the viability of linac technology market penetration. The high cost of ownership is considered a potential problem for accelerator systems in the inelastic contraband detection market. However, the food sterilization and material processing markets appear to have sufficient headroom to permit successful accelerator technology penetration. Of these three areas, food sterilization is likely to be the application that could first experience significant growth early next century.

1 INTRODUCTION

Medical applications, particularly clinical x-ray systems, continue to dominate the industrial market for linear accelerators. However, several developments suggest that significant new markets may soon emerge.

Among these markets is food irradiation which for some time has been pushed within the technical community but has never developed sufficient market pull to secure a commercial foothold. Irradiation should benefit from the recent Food and Drug Administration (FDA) approval of x-rays for the cold pasteurization of red meat, poultry and pork.

Another growth area, driven by Federal Aviation Administration (FAA) and Department of Defense (DoD) funding, is contraband detection. In addition to airport hand baggage, inspection of large cargo volumes and containers at airports, seaports, road and rail border crossings and military bases is a growing market. The current market surge is dominated by advanced x-ray devices and chemical detection “sniffers”, but larger linac systems may have a niche in container inspection. Increasing terrorist activity is once again focusing a spotlight on higher performance explosive detection systems (EDS).

Further off in time, ultraviolet (UV) and infrared (IR) micromachining and surface material processing with high-power, linac-driven, Free-Electron Lasers (FEL) has the potential to evolve into a major and varied market. Many applications, principally in polymer and metal processing, are already established and their commercialization is limited only by the economics of available light sources.

The following three sections focus on Contraband Detection Systems (CDS) utilizing tandem ion accelerator-generated gamma-rays for resonance imaging, cold pasteurization of red meat using high-power electron accelerator-generated x-rays, and high-volume surface material processing with UV and IR radiation from a superconducting-RF FEL. The applications, their performance requirements and their economic potential to achieve market penetration are assessed.

We stress the platitudes that successful technology insertion requires market pull and not simply technology push, and that a technology cannot simply be thrown over the wall to thrive without nurturing. Economic considerations are almost always critical, but market infrastructure, operational simplicity, robustness, reliability, availability, maintainability, inspectability (RAMI or the “ilities”) and after sale support are all vital.

2 CONTRABAND DETECTION

A principal motivation for contraband detection systems is the increasing number of successful terrorist incidents. Most recently, the Nairobi and Dar es Salaam US Embassy attacks and the despicable incident in Omagh have again heightened awareness of terrorist activities. While we are all aware of the PanAm 103 and TWA 800 incidents, one of which was definitely caused by a bomb, it is not so widely known that there are hundreds of annual attacks at US bases abroad, though few are as severe as the recent al Khobar Towers incident.

Hence, there is a significant opportunity for contraband and explosive detection systems of various kinds: at seaports and airports to inspect hand baggage, cargo and to otherwise detect smuggling; for force protection of bases and embassies; and at border crossings to inspect trains and trucks.

The market characteristics are somewhat fickle with significant peak-to-peak funding oscillations and sales opportunities that often seem to parallel occasional tragedies. The market also remains largely inelastic due to the high cost of ownership (COO) of effective detection systems coupled with the low probability of incidents actually occurring in the first place or being prevented by the system.

InVision Technologies is the market leader with the \$1M CTX 5000 x-ray device that is deployed at airports worldwide and is the only presently FAA certified EDS for hand baggage. Lockheed Martin has recently introduced the cheaper L-3 system, while Vivid Technologies and others market simpler units. Thermedics is a leading supplier of competing chemical "sniffer" systems.

The FAA certification requirement for baggage inspection systems is a throughput of 450 bags per hour. False Alarm Rate (FAR) and detection rates are not public, but simple intuition suggests that values of FAR ≤ 10% and detection probabilities ≥ 90% are probably required to prevent significant transit delay. An interesting economic point is that the cost to install CTX 5000 systems in the 75 busiest airports is estimated at around \$2.2B [1]. This figure is greater than the entire 1995 airline industry profit and explains the COO market penetration difficulty of EDS, given the very few US airline bomb incidents to date.

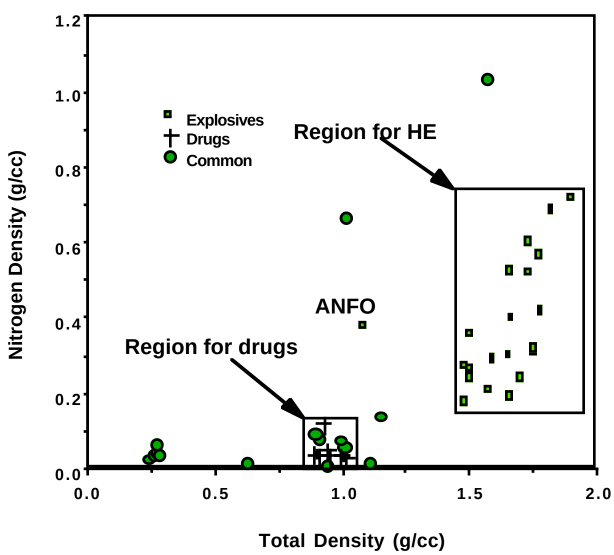

Figure 1: Nitrogen-based High Explosive (HE) identification using the gamma resonance CDS technique [2].

Gamma resonance imaging holds great promise as an EDS technology. Here 1.76 MeV protons impinging on a ^{13}C target produce γ-rays that are arranged to pass through an inspection target. A high-current tandem accelerator is selected for wall-plug efficiency reasons. At a particular detection angle, the γ-rays are resonant with ^{14}N. Hence, measuring the resonant γ-rays determines the sample nitrogen density, while the non-resonant γ-rays yield the total sample density. Figure 1 illustrates that these two simultaneous measurements provide excellent discrimination and the potential for high detection probabilities with corresponding low FAR for nitrogen-based explosives. Tomographic inversion leads to small voxel identification of suspicious material that in principle permits the identification of sheet explosives. Gamma resonance CDS is a relatively immature technology, which is projected to meet FAA throughput and performance targets, but at a higher cost than the competing systems.

In analyzing EDS systems, we have assumed a 15% cost of capital, a 5% of capital cost per annum maintenance expense, \$150K annual operating cost comprised of \$100K for operating personnel and \$50K for other costs and services over a 7 year system lifetime with straight line depreciation. This results in a net present COO of ~\$2.0M for a \$1M x-ray system and ~\$4.0M for a gamma resonance CDS. An interesting figure of merit is that 450 bags/hour, 18 hours a day, 350 days a year for 7 years result in a cost of 5¢/bag per \$1M COO. Even if gamma resonance technology matures and can outperform multiple units of other systems as is projected, the high COO will remain a problem in this market unless the driving forces change significantly.

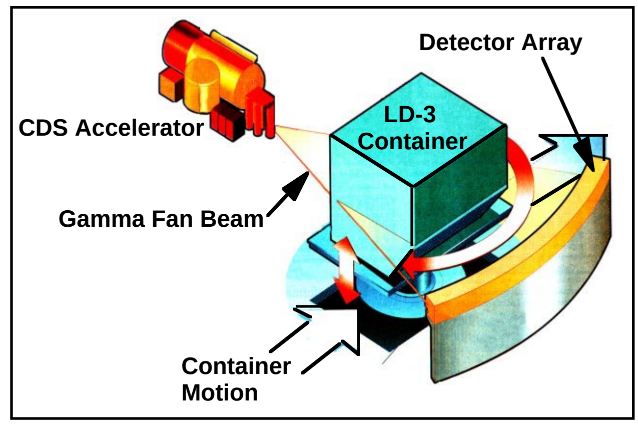

Figure 2: LD-3 airline cargo container CDS interrogation concept [2].

Force protection and airline cargo examination, as indicated in figure 2, have been projected as possible niche markets for the higher potential performance of gamma resonance CDS. Heimann Systems already markets static and transportable x-ray systems, based on conventional electron linac technology, that are used to inspect trucks and other cargo. However, despite strong DoD and Congressional interest, until the recent Embassy bombings, US action on force protection was proceeding conventionally and somewhat slowly, and the need for airline cargo inspection was again being questioned. US Customs interest for train and road border crossings, airframes and sea containers continues to lag DoD, State Department and FAA interest.

Thus, we are forced to conclude that the present outlook for market insertion of accelerator-based gamma-resonance CDS is mixed. However, the rapid swings in attention and funding within this market place suggest that the situation could again quickly reverse in the future.

3 COLD PASTEURIZATION

The motivation for cold food pasteurization is strong and receiving increasing recognition. The US Department of Agriculture (USDA) estimates that \$30B in annual hospitalization costs and lost earnings result from contaminated food. The Council for Agricultural Science and Technology (CAST) estimates greater than 33 million annual US cases of food contamination illness and more than 9000 deaths. Recently, the National Academy of Science, asked by Congress to review the situation, estimated 81 million annual cases of food contamination illness, higher than CAST, and expressed the need for a more centralized and modern Government food safety administration.

In addition to illness, radiation treatment reduces spoilage and adds shelf life of up to a month. This results in additional home market value added and opens new overseas markets because of the economic opportunity for seaborne transportation of US produce.

The FDA has recently approved x-ray cold pasteurization in addition to γ-ray and electron sterilization of red meat, poultry & pork. USDA radiation dose and packaging guidelines are imminent with a 30 to 60 days public review period to follow. We have chosen here to focus on x-rays because they permit significantly more uniform irradiation of thicker product. Within the permitted dose range, direct electron irradiation, while possible at tens rather than hundreds of kilowatts, is limited to boneless product such as ground beef patties.

An important paradigm changes is the recent emergence of a significant fraction of consumers (> 20%) who are willing to pay a premium for safe meat and the impending availability of economic, high-power electron accelerators. This yields the opportunity for near term market insertion shortly after the year 2000 because of the existence of value added headroom through market acceptance of a premium product. This leads to the price elasticity that was missing in the previous EDS market and opens the door for the introduction of a new accelerator product.

We have long been promised that the medical and food sterilization markets have been ready to explode. However, although imported spices have been irradiated for years, only 1B lbs of food is presently irradiated annually worldwide. Of interest is Food Technology Services in Florida, which already produces the premium brand "Nations Pride" poultry with cobalt source irradiation. However, radioactive sources cannot be turned off like accelerator-based sources, have a high environmental disposal cost and issues associated with high throughput.

Similarly, in the more accessible, lower throughput, higher value added medical sterilization market, Impela devices, Titan Scan systems, and most recently the Ion Beam Applications Rhodotron, have been competing for a limited number of orders. The continual drive towards the "greening" of processing technologies suggests that present chemical sterilization will continue to be displaced.

In evaluating the market economics, we assume a service provision business structure for the plant and present year money throughout. A 0.5 MW electron accelerator can generate 40 kW of x-rays that deliver a 1.8 kilogray exposure to 200 metric tons of red meat per 8 hour accelerator shift. At 50 mils/ kW-hour and greater than 50% wall plug efficiency, this leads to a $200K annual cost of electricity and other services. Splitting the mark up that consumers have indicated a willingness to pay for a safe premium product, yields ~ 5¢/lb added cost for irradiation to the service provider, plus a further 10-15¢ for the meat processor and retailer for around 5% of the final product cost. We baseline a $7.5M plant capital cost for the high-power accelerator, conveyor system, shielding and support systems, a 15% cost of capital, 2.5% of capital cost per annum maintenance expense, $100K annual personnel operating cost for a 7 year system lifetime with straight line depreciation.

As shown in figure 3, this leads to a 2.5¢/lb earned value break-even point. Earned value is defined to be the net present value of the free cash flow over the lifetime of the plant. In the vicinity of the nominal 5¢/lb charge, which is removed from the break-even point, there is relative insensitivity to interest rate, plant capital cost and electrical efficiency, which influences the choice of drive accelerator. It is this insensitivity that suggests there is a high probability of successful technology insertion at price levels the market will tolerate. However this also implies that early on in the development of the market, competition for the large available sales volume, which will expand beyond premium brands, will drive the acceptable processing cost for the customer much closer to break-even. Here, sensitivity to efficiency and plant capital cost will become critical discriminators in obtaining adequate margin and the successful accelerator technology will have to be both very affordable and highly efficient.

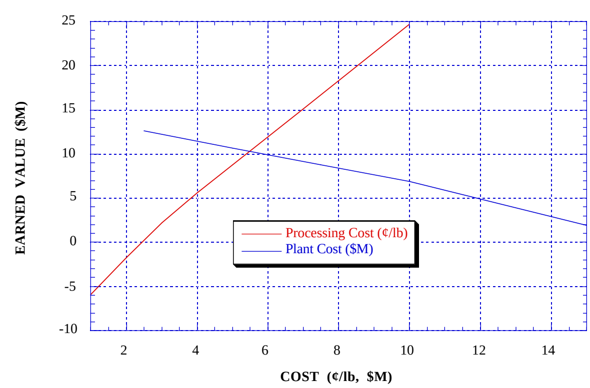

Figure 3: Earned value as a function of plant cost ($M) and unit processing cost (¢/lb).

4 FEL MATERIAL PROCESSING

The third area we consider is large volume material processing with an IR or UV FEL. A superconducting-RF accelerator driver has been assumed because of the high wall-plug efficiency at the very high power level projected. The envisaged system is based on the Jefferson Lab IR FEL that recently set the FEL power record of 311W [3], and is pushing on towards kW power levels to provide market evaluation quantities from some of the processes described below.

The motivation in this case is that future US prosperity is strongly linked to on-shore manufacturing strength. Radiation processing offers the opportunity to widen product value and choice by surface modification, can reduce resource intensity by optimal use of prior investment, may provide near real-time response to consumer demands and leads to reduced environmental impact over competing chemical processing by minimizing waste and improving efficiency.

Many of the metal and polymer applications are proven and patented [4], and the issues for deployment are the available power level and the economics at the desired wavelength. Excitation is vibrational in the IR and electronic in the UV. For instance, many of the processes have already been demonstrated with conventional lasers or lamps, but the cost of these radiation sources is too high and their power levels are too low for practical application. In particular, UV excimer lasers have opened the way to surface modification via transform chemistry, morphology or topography changes dependent on fluence, irradiance and wavelength.

On the other hand, the vacuum lasing medium of the FEL still promises to yield very efficient, high-power lasing, while the wide tunability leads to versatility with respect to processing applications and permits matching to narrow-band absorption. The ultra-short and intense pulse structure gives rise to optimum surface coupling, very high peak powers, as well as the highest heating and cooling rates available for surface modification. In addition, the short pulses minimize collateral damage due to bulk heating and the dry chemistry enables increasingly economic "green" processing.

Polymers are a huge, highly cost sensitive business. 1994 US synthetic fiber production was 9.5 B lbs, while the 1993 World artificial fiber production was 40 B lbs. 1994 US resin production was 5.7 B lbs for food packaging within flexible packaging sales of 14.7 B lbs, but this is dwarfed by the huge food packaging potential in the Third World.

Commercially important polymer applications include improved adhesion for forming multi-component film products or composite structures, more effective fibers for use in filters, and improved feel and appearance of synthetic fiber fabrics. Other applications would yield more easily recyclable food packaging, more durable and attractive carpeting, stronger and more versatile composite materials, and antimicrobial surfaces for shipment or storage of food without the need for refrigeration. As with food sterilization, the latter application has great potential impact in the Third World.

Figure 4 shows an electron micrograph of a polyester fabric surface microroughened with exposure to ultraviolet light from a conventional laser that illustrates the effects of surface texturing. This processing leads to improved look, feel and dye uptake that translates into value added that can be successfully charged to the consumer.

The present hierarchy of polymer processing can be expressed in energy density order as follows. Enhanced adhesion of amorphized PET with UV radiation occurs at 25 mJ/cm^2. Surface roughening of PET leading to enhanced feel, look, mechanical interlock, dye uptake or enhanced filtration via rapid thermal processing with UV and IR radiation occurs at 0.5 J/cm^2. Finally, photochemical anti-microbial surface activation of nylon with 193 nm radiation requires 2.5 J/cm^2. An equivalent suite of high-power metal applications, and micromachining at 2-10 kW, exist but are not described here. In all cases, the true need for FEL-specific properties, as opposed to a tailored, cheaper and smaller conventional laser, must be fully considered.

Figure 4: Excimer-treated polyester fiber showing surface roughening for improved look and feel [5].

We again assume a service provider business structure and present year money. In this case, the FEL power level is 100 kW and 80% annual availability is postulated. A $175K charge is applied for other services plus the annual cost of electricity at 50 mils/ kW-hour and a 20% overall wall plug efficiency. A 3.5 mils/kJ radiation cost, $20M plant capital cost, 15% cost of capital, 2.5% of capital cost per annum maintenance expense, $400K annual personnel operating cost, 10 year system lifetime and 7 year straight line depreciation are also nominally assumed.

This leads to a 2.2 mils/kJ earned value break-even point where plant capital cost is a key parameter in this case. Economics competition considerations similar to sterilization will likely move the system parameter choice from 3.5 mils/kJ towards break-even, thereby determining the accelerator choice and other factors. For this reason we believe that a superconducting-RF-driven linac is the FEL driver of choice. Again, there is clear market opportunity and head room, if accelerator plant cost targets can be met.

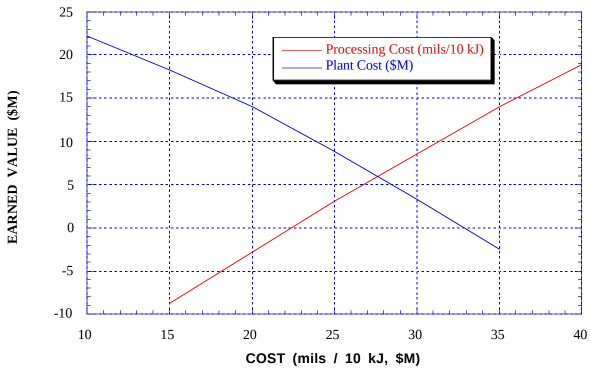

Figure 5: Earned value as a function of plant cost ($M) and unit processing cost (mils/10 kJ).

5 SUMMARY

New linear accelerator product opportunities seem to be immanent. In developing these new products, market and economic forces must always be recognized and observed. Contraband Detection has great potential, but sales are highly politicized and thus the market future is unclear. Sterilization has true and significant market potential and is finally almost here. FEL Material Processing is a potentially huge opportunity worldwide, but is still a few years off

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[5] Reproduced courtesy of M. J. Kelly from the Jefferson Lab Laser Processing Consortium at "http://www.jlab.org/fel/lpc/index.html/".

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