STATUS OF THE ACCELERATOR INDUSTRY IN NORTH AMERICA

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Abstract

Several projects for synchrotron light source facilities and medical accelerators are proposed in North America. Applications of accelerators for Homeland Security Systems and radioisotope production are also under consideration. Project X proposed for FNAL and the FRIB facility at Michigan State University are examples of large scale next generation accelerator projects. The current status of the accelerator industry in North America is reviewed

INTRODUCTION

Advanced accelerator designs and applications for the latest accelerator systems have been led for many years by research and development initiatives in North America. The R&D funding at the National Laboratories in the United States and Canada were the places that carried the torch for the largest developments. In more recent times a significant portion of this state-of-the art R&D is being driven by laboratories in Europe and Asia. That is not to say that there are not new projects in North America. It is more that the funding levels and expertise are more equal. There are large new projects in North America such as the Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Laboratory (SLAC)[1], the Facility for Rare Isotope Beams (FRIB) project at Michigan State University and the National Superconducting Cyclotron Laboratory (NSCL).[2] Also a high current proton accelerator facility extension presently called Project X is being planned at Fermi National Accelerator Laboratory.[3] The LCLS has recently become operational and is now producing results. In fact its second X-ray station began operation in early 2010. The Facility for Rare Isotopes and Beams (FRIB) at MSU is presently working on accelerator and subsystems designs and it will have its first critical design review by the end of 2010 which will be built for first beam operation in 2017. Project X is still in the proposal phase as an intense source of protons to be used for many challenging fundamental physics experiments. The accelerator industry in North America supports many of these large projects with various design capabilities, subsystems and construction talents.

Several firms supply these laboratory projects and upgrades with specialty systems and sub assemblies that are critical to the success of the projects. National laboratory projects and systems are often precisely tasked with very challenging specifications but a rather limited market opportunity which does not typically attract the interest of larger companies. Some example firms that work in this area from Canada are producers such as Mevex, Iotron, and Advanced Cyclotron Systems Inc. In the United States examples of manufacturers are Advanced Energy Systems (AES), Lyncean Technology, National Electrostatics, IBA/RDI, Wasik Associates, and Niowave.

There are several firms involved in large scale commercial accelerator production. Examples include larger firms such as such as Varian Medical Systems Inc (VMS), General Electric (GE) Medical, Siemens Medical, Accuray, Tomotherapy, and IBA. These companies supply linear accelerators for security applications, radiation treatment systems for oncology applications and medical isotope production.

NATIONAL R&D LABORATORY ACCELERATOR SYSTEMS

The FRIB system at MSU will be examining the forces that hold nuclei together and the rules that are used by nature for these building blocks of atoms. There are only ~260 stable isotopes found naturally in the earth but there are more than seven thousand isotopes that can be created theoretically. To date about 2500 of these isotopes have been created and identified. The reasons for this difference has been a major question for nuclear and astrophysicists for many years. The study of these rare isotopes will lead to new information on how stars evolve and on how we have been created in stellar furnaces. Studies will be conducted on the Equation of States of Nuclear matter. In addition there will be investigations of symmetry violations that can be enhanced by certain rare nuclei. There may also be a need to create new medical isotopes that can be used for labeling and medical imaging. At the new FRIB facility scientists will create new systems on the femtometer scale. This project is slated to deliver its first beams in 2018-2019.[2]

At SLAC the LCLS is taking intense X-ray physics to a new level. The system is operational and two of the experimental end stations have been commissioned. This system will allow X-ray images to be created on the time scale of approximately 100 femtoseconds while the X-ray burst traverses 0.03 mm or the width of a human hair. This system will be able to see motion on the atomic scales[1]

The last National project to be examined briefly is Project X that has been proposed by groups at Fermi National Accelerator Laboratory FNAL. The proposed system is a multi-megawatt proton beam accelerator that can be used for fundamental science studies such as improvement of neutrino experiments and for precision measurements of the properties of exotic particles like K and Mu mesons. This accelerator system design and implementation may also provide critical information on the necessary design parameters for a muon accelerator. The beam energy is 120 GeV and beam power is 2.1 MW at this particle energy. At this stage the primary goal is to have the basic R&D completed by 2012.[3] This would include a baseline science scope, costing and time-line estimates. Currently the baseline Project X design employs the 1.3 GHz design which is the same as the ILC.

MEDICAL ACCELERATOR SYSTEMS FOR CANCER THERAPY AND ISOTOPE PRODUCTION

Photon and Electron Treatment Systems

VMS, Accuray and Tomotherapy supply electron linear accelerators for cancer therapy and all their system manufacturing is performed in the United States. These use X-ray photons at energies ranging from 6-20 MeV. In the case of VMS the high energy accelerator system is also capable of delivering electron treatments. An example of a Varian Trilogy system is shown in Figure 1.

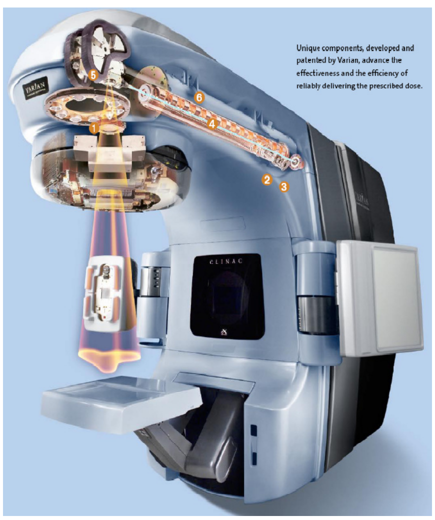

Figure 1: Clinac iX and Trilogy Beam Generation System.

In this system the electron beam strikes a target after being accelerated by an S-band linac and is then transported through a 270 degree achromatic magnet system. The treatment beams are shaped by tungsten and lead fixed and variable collimators. The final beam shaping is accomplished with a Multileaf Collimator system (MLC). The Accuray Inc[4] and Tomotherapy Inc[5] accelerator systems employ linacs with electron endpoint energies in the range of 6 MeV. Examples of the Tomotherapy and Accuray systems for cancer therapy are shown if Figures 2 and 3.

These systems also have collimation systems for shaping the beam profiles. Both VMS and Tomotherapy linac offerings are constructed from S-band accelerators and RF technology.

Figure 2: An example of a Tomotherapy HiArt Cancer Therapy System. (Image Tomotherapy brochure M-GEN-018-0908)

Figure 3: Example of Accuray Cyberknife system which uses a 6 MeV X-band accelerator (Image Accuray Inc Product brochure 500691.A)

The Accuray systems use a higher frequency X-band accelerator and RF source. This is due to the necessity of weight reductions in the accelerator and subsystems that are needed for operation on an industrial robotic arm.

Proton Accelerator Treatment Systems

VMS has supplied superconducting cyclotrons as the accelerator for the creation of 250 MeV proton beams. The first 250 MeV isochronous superconducting cyclotron was supplied to the Paul Scherer Institute (PSI) in Switzerland. PSI was responsible for the design and installation of the beam transport system and the treatment facilities. The second cyclotron was designed built and commissioned for use the Rinecker Proton Therapy Center (RPTC) in Munich Germany including the beam transport systems and patient treatment equipment. The RPTC system has four isocentric gantries for treatment and also has a low energy horizontal beam line that will be used for treatment of cancer near the optic nerve and other areas of the head. This system has a very high efficiency for beam extraction > 75%. An example of this cyclotron under construction at the VMS factory is shown in Figure 4.

Figure 4: A 250 MeV isochronous superconducting cyclotron at the VMS factory. (FDA 510 k pending)

Accelerators for Medical Isotope Production

Cyclotrons are the often used for medical isotope production. In North America there are three major suppliers of cyclotrons that are used for medical isotopes. These are GE, Siemens and Advanced Cyclotron Systems. The major use of these systems is in the supply of position emission tomography (PET). These systems use lower energy proton beams to manufacture PET isotopes such as ^{18}F which are typically made by irradiation of an ^{18}O enriched target with approximately 18 MeV protons. An RFQ accelerator for medical isotope production has been created by AccSys Technology Inc called the Pulsar. These systems operate at 7 or 10.5 MeV.[6]

Recently there has been quite a renaissance in the use of accelerators for the productions of the radioactive isotope ^{99}Mo which is the parent of ^{99m}Tc. ^{99m}Tc is the most widely used imaging agent after X-rays. There were more than 28 million procedures completed in the world in 2007 that used ^{99m}Tc as the imaging agent. The vast majority of these scans were performed for cardiac studies. The primary reason for this shortage is due the aging of the nuclear reactors in Canada and Europe that are used to make the ^{99}Mo from the fission of highly enriched uranium (HEU). These reactors are more than 40 years old and are approaching or have exceeded their original design lifetimes. There are several methods that have been proposed to create ^{99}Mo or ^{99m}Tc. The method that yields the highest specific activity for accelerator based solutions studies by VMS are the following reactions: The production cross section is on the order of 200 mb in the range from 10-17 MeV.[7,8]

$$\begin{aligned} &{}^{2}H + {}^{98}\mathrm{Mo} \rightarrow {}^{99}\mathrm{Mo} + \mathrm{n} \\ &{}^{2}H + {}^{98}\mathrm{Mo} \rightarrow {}^{99m}\mathrm{Tc} + \mathrm{p} \end{aligned} \qquad (1)$$

The energy required from the cyclotron is no more than 15-17 MeV with a beam power of up to 34 kW striking an enriched ^{98}Mo target. We estimate that the entire 6 day ~444TBq (12 kCi) current weekly need of the US for ^{99}Mo could be met by about 50 cyclotrons. ACSI has worked with Canadian hospitals and universities demonstrating that protons can be used to make ^{99m}Tc directly from ^{100}Mo targets using a TR19 cyclotron. The required energy is higher for short lived ^{99m}Tc. It would require higher energy to create the typical parent nucleus ^{99}Mo and the production cross section is smaller. Another group of researchers are working collaboratively with National Laboratories at Argonne and Los Alamos on a proof of principle system for making ^{99}Mo via the (γ, n) reaction. A 120-150 kW 20-40 MeV electron beam linac is required to make a reasonable amount of 99Mo from the ^{100}Mo. The issue here is that most of the electrons create photons that are not at the optimal energy of 14-15 MeV. Others have proposed very high current proton beams in the 250-500 MeV range creating a high flux spallation neutron source to fission LEU. All lead to a lower specific activity than the HEU fission process. All of these accelerator processes with the exception of the LEU spallation source would have a greatly reduced waste stream.

ACCELERATOR SYSTEMS FOR HOMELAND SECURITY AND NON DESTRUCTIVE TESTING (NDT) APPLCIATIONS

Accelerators for Homeland Security

Figure 5: Example of a VMS Linatron that could be used for NDT or cargo screening applications.

VMS is also a leading supplier of electron linacs that are employed in non destructive testing (NDT) and Homeland Security applications. This includes inspection of munitions, solid rocket motors and pressure vessels for flaws as typical examples. In the last 10 years there has been a significant increase in the use of X-ray linacs for cargo container screening at ports and border crossings. One example of a linac used for this application is shown in Figure 5. The typical range of energies used for cargo inspection systems range from ~ 4 MeV for mobile cargo screening applications up to 9 MeV for large fixed site installations. An intermediate system that is relocatable with some effort on the part of the customs agency is the gantry type systems which operate around 6 MeV. The dose rates and filtration used by suppliers varies but system operational parameters vary from a 2.5 cGy/min at 1 meter for mobile cargo applications up to 30 Gy/min for a fixed site inspection system at 9 MeV. The highest energy bremsstrahlung X-rays are needed if one wants to examine all areas of trucks and containers for contraband. An example of a 9 MeV X-ray image of an automobile is shown in Figure 6. In this image there is no part of the engine or transmission that is not revealed for inspection. For lower energy X-ray systems these areas can be problematic and could be exploited by smugglers. Recently there has been a large push to look at methods to detect contraband items such and high explosives and other dangerous goods such as Special Nuclear Materials (SNM). For this case, the X-ray or neutron beams must cause a secondary nuclear or chemical reaction that is then detected after the beam passes through the container or vehicle. For SNM detection there typically is the need to induce fission, examine the ratio of attenuations at multiple energies or other methods like nuclear resonance fluorescence. Programs to build linacs with adjustable pulse widths of 1-10 ns are under consideration. These systems could be used to look at prompt radiation signatures from both SNM and explosive materials.

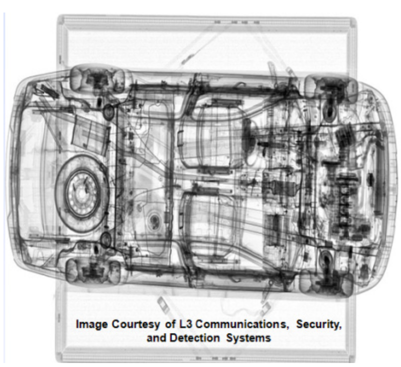

Figure 6: Radiograph of an automobile at 9 MeV. (Image Courtesy L3 Security and Detection)

An example of an accelerator for explosive detection system that was constructed by National Electrostatics Corporation (NEC) and Rapiscan Systems is display in Figure 7. This unit employed a 3 MV tandem DC accelerator that used a chopped and bunched deuteron beam to strike a deuteron target. This yielded up to 8.5 MeV neutrons that were pulsed on a nanosecond time scale. The neutrons induce gamma rays in the container. One can then detect characteristic gamma rays and attempt to identify explosives by looking at ratios of carbon, nitrogen and oxygen.

Figure 7: Ion source, injection beam transport with chopping and buncher section shown. The 3 MV tandem is at the far right of the photo. (Image Courtesy NEC)

There is also great interest in looking at systems that can be very compact and operate under extremes of temperature humidity and vibration. VMS and others have been working in this area. Figure 8 displays a small X-band accelerator that operates at 9.3 GHz and has an endpoint energy approximately 1 MeV.[10] This was originally designed by SLAC and then transferred to Radiabeam Technologies which is currently working on commercializing the design. X-band sources offer the ability to reduce the accelerator system size by about 60%. The sizes of the RF network and RF power sources are also reduced. The size of the target shielding is still the same as in the S-band or DC case since the radiation yield determines the radiation shielding requirements.

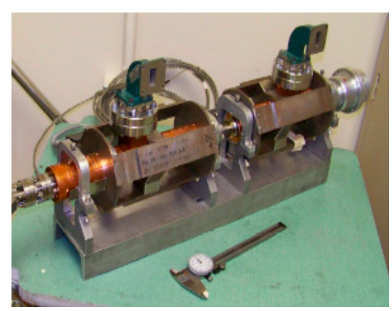

Figure 8: An example of a 1 MeV X-band accelerator. (Image Courtesy of Radiabeam Technologies)

Accelerators for Non Destructive Testing

NDT applications use accelerators in the range from 1 up to 16 MeV. The required dose rates are determined by the energy of the accelerators and by the imaging systems that are used where specifications range from 0.1Gy/min at 1 meter to more than 150 Gy/min at the highest energies. The lowest energies are used for mobile and small part inspections while high energy systems that operate from 9 to 15 MeV are used to inspect thick sections on items such as pressure vessels, rocket motors and other large and dense objects. For mobile applications X-band technology can use much smaller packaging that increases the type of inspections that could be accomplished. Focal spots on these systems are an important imaging parameter and range from 1-3 mm full width at half maximum (FWHM). Digital imaging technology is well on the way to replacing film as the media for acquiring and storing X-ray images. The ability to immediately store an image and process it without any need for chemicals for example makes this technology very viable for a higher production environment. The medical community is leading the way and the industrial NDT community must adapt as well. This brings about some issues that the NDT community needs to address. The first is that the ease of creating NDT images with digital imagers means that accelerators will be operating more frequently for longer periods of time. In the case of automotive inspection, discussions are in process to make transmission and engine inspections an inline production process and not just a quality control tool. Linear diode arrays (LDA) and flat panel imagers permit Computed Tomography and Cone Beam Computed Topographic images to be collected. A three dimensional part rendering of a CBCT image is shown in Figure 9 for a gas turbine blade. These data were collected at the VMS Security and Inspection facility using an M9 operating at 6 MeV. The imager was a VMS manufactured amorphous silicon flat panel array with a gadolinium oxysulfide ceramic scintillator and a copper build up plate that converts X-ray photons into electron-positron pairs for signal generation. This imaging was a joint effect by Hytec Imaging and Sensors which is now part of 3M Inc and VMS.[11]

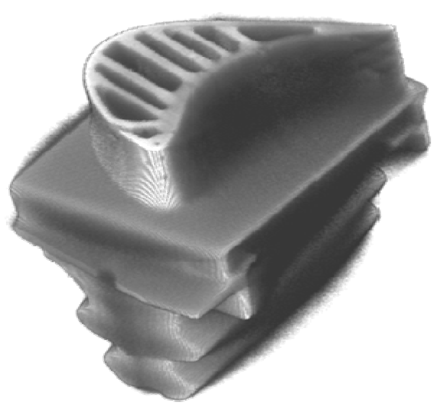

Figure 9: A CBCT rendering of gas turbine blade inspected at 6 MeV. See text for details.[11]

Accelerators for replacement of radioactive sources

There are other groups that are exploring the use of accelerators to eliminate the use of radioactive sources such as ^{192}Ir, ^{137}Cs and ^{60}Co. These radioactive isotopes are used in NDT inspection systems for detection of cracks, voids and other flaws in welds on bridges and pressure vessels for example. Cancer therapy systems use ^{60}Co or ^{192}Ir. Medical sterilization applications use ^{60}Co and ^{137}Cs. The use of compact (d, d) or (d, t) generators is being studied as possible field replacements for neutron sources such as ^{252}Cf, PuBe and AmBe. These radioactive sources are often used in oil well logging applications as a source of high energy neutrons. Providing robust and reliable designs that can work on oil drilling rig is challenging. There is also a need in oil well applications for compact X-ray sources to probe down the borehole and examine piping and welds. There are extremes of temperature, vibration and pressures that need to be considered. These radioactive isotope systems could be replaced with the use of high current high electron energy accelerators. Linacs with higher duty factors can be utilized as various compact DC topologies are being considered. Cost and system complexity is a very significant portion of the equation and is coupled with requirements for high reliability and ease of operation.

CONCLUSION

The accelerator systems that have been discussed here only begin to examine the large number of projects that are ongoing in North America at this time. There has been no mention of accelerator technology that is used in radiation processing, or sterilization of food or medical goods. There are accelerators that are used in semiconductor processing and manufacturing, with Ion implantation systems and ion milling systems are just two examples. There are new accelerator designs that create high energy monochromatic photons via inverse Compton scattering from electrons and intense laser pulses. These are being used to study the chemical structures of drugs and proteins for example. Accelerators have found important applications in the medical community and industry. Many items we use in our everyday life may have been processed using an accelerator. It is certain that they will have a part in technology developments in years to come as a spin off tools or as important parts in the production of goods and services.

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