Developments of LINACS for Accelerator-Driven Transmutation Technology in the USA

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Developments of Linacs for ADTT in the USA

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Abstract. Interesting developments in linear accelerators have been attained over the past 45 years. The
status of linear accelerators and future possibilities are described in context of demanding applications
and technology maturity. Features of industrial or ‘factory’-type applications are high availability,
economic operations, low investment cost and ease of running a facility. All features have been
demonstrated in one manner or another at large operating facilities for the research community; within a
different context that has been argued in the past to be not as demanding as for a ‘factory’ installation. In
addition, comments are made relative to intense beam power levels and choices that can be made for
power levels below 10 MW, on the assumption that a cw beam is required.

INTRODUCTION

Large and complex accelerators are moving more into the industrial, medical and
military environments based on technology developments and the high reliability achieved
at large accelerator-based research centers worldwide. For many years small accelerators
have demonstrated that they are reliable ‘workhorses’ and have shown that profitable
businesses can exist on accelerator performance -- be it for medical treatment and imaging,
radiation processing, isotope production or implantation systems. Comments heard many
times are that large accelerators are complicated devices with many components that can
fail and that the accelerators have not been designed with considerations for long-term
operations with high RAMI (Reliability, Availability, Maintainability, Inspectability). A
detailed investigation of the large accelerator-based centers that have operated for decades,
such as CERN, DESY, KEK, FNAL, SLAC, etc., will show just the opposite. Users of
these beams are very demanding and good operational results have been achieved for them.
Any complaints from users are usually associated with beam priority for a multiple-user
facility, or with committee approval for an amount of beam time less than requested.

At most facilities, linear accelerators (linacs) are usually the accelerator type for the
initiation of particles further accelerated in many of the complex devices used; the linac
need ranging from just a small injector to most of the facility accelerator. Advances in
linac technology have shown that pulsed and cw (continuous wave) accelerators are
reliable systems that can be used in a very demanding environment such as in that of an
intense spallation neutron source ‘factory’ for materials production, environmental
remediation, materials processing or basic research investigations. Most of the following
discussion will focus on aspects of linacs and future expectations.

Brief History of cw Linac Development

The use of high power cw linacs for materials production is not a new consideration.
A cw linac was considered more than 40 years ago for an application that would have
produced plutonium for the USA nuclear weapons program. Construction of a prototype
Mark I linac demonstrator for a $427M cw deuteron linac-based A-12 plant (1/2 A to 350
MeV with 400 MW of 12 MHz rf power) was finished in January 1952 by LLNL
(Lawrence Livermore National Laboratory). The 27 m length prototype linac, with a
diameter of 18 m and a vacuum port of 6 m, required 9 MW of rf power at 12 MHz. It
was completed for $13M and achieved a 33.5 MeV cw proton beam in May 1952 for an average accelerating gradient of 1.24 MeV/m. The 2 m diameter drift tubes were then rearranged to give better performance with an output beam of 22.5 MeV (accelerating gradient of 0.83 MeV/m). Shielding for the target was provided by 2.7 m of concrete. The 22.5 MeV cw proton accelerator operated for extended periods at 50 mA and for intermittent periods at 225 mA. The ion source/injector could provide 500 mA for several hours before the electrodes and focusing grids would burn out. The facility was shut down in December 1953 following the discovery of significant uranium ore deposits in the USA. A later 1954 proposal for C-50, that was not funded, was to be half the cost for a 320 mA, 500 MeV deuteron beam from a 50 MHz linac. Although the program was canceled, significant cw information useful today was obtained regarding electric field breakdown, operation of Alvarez drift tube linacs (DTL), rf coupling, beam transport, cavity design, injector operation, transients and beam diagnostics.

Chalk River Nuclear Laboratories (CRNL) initiated an Intense Neutron Generator (ING) project in the mid-1960s in order to have an intense spallation-based neutron source that could be used for a host of R&D programs of interest to Canada at that time. The design of the 65 MW proton beam facility was based on a 1 GeV beam impinging on a windowless liquid Pb/Bi target. Extensive work on liquid metal targets and accelerator technology were accomplished prior to the ING program being canceled in 1968. After extensive studies showed significant problems for a stacked separated-orbit cyclotron, a linac was selected for the beam delivery system based on the successful developments for LAMPF (Los Alamos Meson Physics Facility) at LANL (Los Alamos National Laboratory). Work on prototype cw electron machines at CRNL demonstrated that the coupled-cavity linac (CCL) could operate as required for intense beams in the π/2 mode with 1 MeV/m gradients for either a geometry with side-coupures or one with on-axis couplers.

A cw proton injector installation demonstrated the acceleration of a 2 MeV beam through a 270 MHz DTL from a 750 keV Cockroft-Walton (C-W) injector. Work on the injector showed that the maximum cw proton beam from the conventional C-W injector was limited to 35 mA because of ceramic charging and breakdown associated with UV and soft x-rays generated by the beam interacting with the residual gas. Operation in a pulsed mode allows for higher current operation because of the opportunity to deplete the charge on ceramics between pulses. It was also determined that higher cw currents could be obtained if the DC voltage was reduced -- for 400 kV it was possible to have cw currents in excess of 150 mA.

After cancellation of the ING project, CRNL focused on accelerator breeding activities with a 300 mA, 1 GeV cw proton linac as the reference accelerator driving a suitable target assembly. Again, many cw technological demonstrations were completed including operation of a cw 270 MHz RFQ (Radio Frequency Quadrupole) with a 75 mA, 1.2 MeV proton beam, development of a more efficient cw rf tube (Klystrode), development of suitable high-efficiency high-current proton injectors, and cw electron beam prototype measurements to demonstrate control of >80% beam loaded room-temperature CCL structures. These high power activities were put on hold by the Canadian government in 1983, in recognition of decreased sales of CANDU reactors worldwide and the fact that uranium prices dropped on the world market because of increased mining and new ore discoveries.

LANL was involved with the cw FMIT (Fusion Materials Irradiation Test) project in the early 1980s with design for a 80 MHz, 100 mA, 35 MeV deuteron accelerator that would drive a flowing liquid lithium target to produce the desired neutrons. A 80 MHz, 2 MeV RFQ operated cw with H₂⁺ beams demonstrating important issues associated with rf heating and structure cooling. Following cancellation of the FMIT program, significant improvements in beam dynamics issues, beam dynamics codes and rf structures were
realized for the Neutral Particle Beam (NPB) program within the Strategic Defense Initiative (SDI) directed-energy initiative. These developments and experimental demonstrations showed that pulsed beams could be transmitted from an RFQ to a DTL with essentially no emittance increase for 100 mA, 1 ms H beams. It was also demonstrated that 400-800 MHz was a better frequency regime for beams of this intensity than the previously considered 80 MHz (DTL permanent magnet quadrupoles replaced the expensive electromagnets and their associated power supplies, engineering was improved, and cost and assembly were reduced considerably). The 100 mA, 5 MeV beam from the 425 MHz DTL showed good beam performance characteristics for a system employing permanent magnet quadrupoles, a 2 MeV, 425 MHz RFQ as injector, and diagnostics suitable for the small emittance beams -- 0.015 π-cm-mrad rms normalized.

Operations at storage rings worldwide, such as those at CERN, DESY, KEK and SLAC, show that cw room temperature and superconducting rf cavities from 200 to 1000 MHz can operate for large beam currents with excellent reliability based on the many years of experience accumulated. Aspects of rf control, feedback and required maintenance are important associated developments that have had major impacts on current machine design philosophy.

**ADDT (ACCELERATOR-DRIVEN TRANSMUTATION TECHNOLOGIES) APPLICATIONS**

An interesting phenomenon seen today in many applications requiring intense neutron beams is that the spallation-produced neutron system is being seen and used as a reasonable alternative for conventional nuclear reactors. Some of the reasons for this change have to do with the neutron spectrum created, the less heat generated per neutron produced, the other particles generated for a host of other research applications, the relatively small amount of radioactive waste generated, and the simplicity relative to operations and power requirements. Other reasons realized over the past decade include the economics of a linac-based system, the intense particle fluxes that can be generated, the possibilities for accelerating intense high-energy proton beams, the development of suitable target materials and configurations, and the safety associated with fast shut-down of the associated targets and their residual heat. These latter reasons are the result of investments in linac and target technology for a variety of different projects over the past decade.

Accelerator driven transmutation technologies are being considered for a number of different applications requiring intense neutron beams. These spallation-based neutron applications include materials production, materials destruction, treating radioactive waste, and energy production. Materials production includes the production of tritium, as well as the conversion of fertile material to fissile material. Materials destruction includes the important aspect of dealing with the plutonium resource legacy that exists in the world from nuclear weapons programs as well as from the larger amount of plutonium being generated as a by-product in commercial reactors worldwide. Treating radioactive waste could accommodate waste from both defense and commercial nuclear reactors, with the main advantage being the conversion of long-lived radioactive waste to either stable or short-lived material. This application addresses the radioactive waste problem now, rather than passing it on to future generations. Electrical energy production from a suitable spallation target is possible with enough energy being produced to provide power for the accelerator as well as competitive power for the electrical grid, with a minimal radioactive waste stream because the accelerator-based system can be designed to burn most of its own radioactive waste.
What all of these applications need are reliable components related to accelerating high-power proton beams through a high-energy proton linac. Most applications described above require proton beam powers within a range of 20 to 300 MW. Accelerator layouts for these high average power regimes obviously require well thought-out systems designs that have adequate safety and operating margins to allow for unforeseen difficulties and gradual component degradation. Costs, power requirements and operating efficiency are important aspects for an economic facility design and especially for one with an anticipated lifetime in excess of 30 years. From a beam operations point of view it is very important to pay attention to all aspects of low-noise intense-beam generation, beam transport with proper matching between transitions, availability of appropriate diagnostics and interactive displays, and above all, minimal beam spill. Particular attention must be paid to matching of the beam (over the complete range of zero to full current) between different segments of the accelerator to ensure that beam oscillations, halo and off-normal beam characteristics are not generated.

Three critical issues for high-intensity linacs are therefore:

1. Life-cycle costs including all capital and operating expenses. The optimum cost for a spallation-based facility usually occurs for an output energy of the proton linac between one and two GeV, with this energy range having the general characteristics of a broad minimum. To some extent, the broad minimum allows selection (within a small energy band) of an operating point on the basis of other factors which will impact facility operation and performance.

   In order to achieve high electrical efficiency for the accelerator, careful attention must be paid to all steps in the ac-to-rf conversion process and to the selection of rf structures which maximize the conversion of rf power to beam power within the different energy regimes of the accelerator (such as the coupled-cavity linac choice).

2. Availability should be greater than 85%. The major elements that impact availability are ion sources, rf power tubes, power supplies and items experiencing radiation damage over time associated with unexpected beam spill at specific locations. Replacement and/or repair time can have a big impact on availability and an adequate monitoring program should be instituted in order to note changes in component characteristics before a catastrophic failure occurs. Enough redundancy should be built into the system to provide versatility; however this feature needs to be implemented without seriously impacting overall costs.

3. Operability requires consideration of simple operating techniques in a cost effective manner, without the need for a large operations and maintenance staff. One important aspect that could assist efficient operations is the use of diagnostics to ensure achievement of very low beam loss, such as using effective types of aperture and halo control procedures. Another important aspect is use of a precision rf system control that can accommodate high- to low-beam currents. Finally, there must be adequate capability for controlling turn-on procedures, for handling fault/transient/interruption recovery, and for assuring protection of equipment, staff and the public.

An rf linac is not the only type of accelerator that can be considered for delivery of the required beams. A LANL-sponsored workshop was held December 1995 in Santa Fe, NM to discuss high power possibilities for a cyclotron-based spallation source. Experts from the world attended and helped to determine technology status and possible impacts for the near future. Outcome of the meeting indicated that for 1-2 MW cw proton beams, the cyclotron appeared to have many attractive features. A fair amount of technology development and demonstration would be required to attain a 5 MW level, requiring the correct investments in cyclotron resources, facilities and funding. Above 10 MW it appeared that the linac was the appropriate choice and that linac technology appeared to be in hand for beams up to about the 200 MW level. In addition, investments in demonstrations and linac technology improvements could lead to cost savings and possible
operations improvements. At about 10 MW it appeared that significant developments were required for a cyclotron and a reasonable time frame would be required in order to demonstrate capabilities of such a device.

The following discussion will describe an APT (Accelerator Production of Tritium) system in more detail, as an example of how linac technology has developed and the implications for future systems. An induction linac is not considered because as stated by the proponents, the technology is not as mature as the linac or cyclotron, nor is it possible to demonstrate significant operation or cost advantages at this time for ADTT applications.

APT AS A TYPICAL SYSTEM

The APT system is a good example to use for discussion purposes because it is typical of an accelerator-based application requiring a high-power linac, and because it is a program that is presently funded for engineering development activities in order to place the technology on a firmer foundation of acceptability and understanding. A firmer foundation is required to assist with an end of 1998 calendar year decision on what technology will be used for future tritium production in the USA.

A tritium production system consists of an accelerator, a high energy beam transport, a target/blanket and a tritium processing system. The APT program will have four major technology activities to provide necessary engineering demonstrations. The four items are:

1. Demonstration of cw linac reliability at high power for the front end of a typical accelerator.
2. Demonstration of tritium production efficiency at full engineering scale.
3. Determination of the lifetime for suitable materials in the target/blanket system.

The first demonstration component will be discussed in more detail below. The following material will not describe the beam expander associated with item two above; an expander capable of providing very flat ‘table-top’ beam distributions onto the target over areas in excess of a square meter, from a pseudo-gaussian beam exiting the linac with dimensions less than a centimeter in diameter. Development of higher-order optics capabilities under the SDI program sponsorship allowed for this advanced innovation.

Two different concepts for the APT linac are under study. One uses a conventional room-temperature linac for the entire length of the machine and the other uses a superconducting linac above 100 MeV. Both concepts were designed for 2 kg per year production with a potential for upgrading to 3 kg per year. The conventional room temperature linac concept for 2 kg per year production consists of a 100 mA, 1300 MeV cw proton beam (130 MW) requiring a linac of 1186 meters in length and a plant ac power of 426 MW. The linac consists of a 75 keV injector; a 7 MeV, 350 MHz RFQ; a 100 MeV, 700 MHz CCDTL (Coupled-Cavity Drift-Tube Linac) with a break point at 20 MeV and a 700 MHz CCL that accelerates beam to 1300 MeV. The funneling breakpoint at 20 MeV was selected on the basis of a compromise between beam dynamics, and the engineering and rf complexity associated with the funneling process. To achieve the 3 kg per year upgrade, two 67 mA beams are funneled at the 20 MeV point of the CCDTL. The combined 134 mA beam is then accelerated to 1300 MeV (beam power 174 MW) requiring a plant ac power of 510 MW.

The interesting second concept, which is gaining more acceptance as the preferred option, is based on a 700 MHz superconducting linac from 100 MeV to 1300 MeV with the same beam characteristics and the same front end as the room-temperature linac. In this case, the linac is 1288 meters in length and the plant ac power is 317 MW. To provide an upgrade to 3 kg, the energy of the superconducting linac would be increased to 1700 MeV.
was one of the considerations for the accelerator breeder DTL at CRNL in the 1980's, with a further restriction that the rf fields would not penetrate to the location of the bore-hole liners. Outgassing measurements and a determination of assembly methods were completed before the end of their accelerator breeder project.

LANSCE Operations

Operation of the 1 MW proton beam linac for LANSCE (Los Alamos Neutron Science Center) over the past 24 years has provided invaluable information on limitations and possibilities for accelerator-based spallation facilities. The linac (part of the facility formerly called LAMPF -- now called LANSCE), has shown improved performance over the past three years because of investments that have been made in the drivers for the 201 and 805 MHz tubes, in improved maintenance and monitoring procedures, in improved operations, and in an increased emphasis on long lifetime for components. See Table 1 for a detailed list of characteristics and operating statistics over the past few years. The 800 MeV proton beam with 15 mA peak current has the highest beam power of any accelerator worldwide in this energy regime and has operated as a proton production factory (3000-4000 hours/annum) for more than 15 years with a demonstrated availability (fraction of scheduled beam time) of 85%. Program funding levels restricted beam operation to less than one half of the year. Beam losses and activation levels are very low for most parts of the linac. Total losses are carefully restricted during machine tuning by a fast loss-detector diagnostic system.

A detailed study of beam loss for the accelerator following extended beam operations (after a 2 hour cool-down period) has shown a number of interesting features subsequently duplicated in a computer code designed to analyze the physical and beam parameters for the beam region of the 800 MeV, 1 km linac. See Figure 1 for more details of the losses along the length of the linac. Total fractional beam loss was usually 0.0002 (2×10⁻⁷/m) with some ‘tunes’ for operation having a factor of four less loss. Fast time-response beam-
good efficiency. This source was based on the very successful work on a similar ion source developed at CRNL that was used for their 270 MHz RFQ demonstrations. The CRNL injector and 270 MHz, 1.2 MeV RFQ were shipped to LANL following a shutdown of the CRNL ion linac program in 1990 and has been successfully operated as CRITS (Chalk River Injector Test Stand) for gaining experience on issues associated with accelerating and diagnosing high power cw proton beams.

RF Structures

Superconducting technology has been studied extensively since the early 1970s. World-wide research efforts exist at major laboratories (CEBAF, CERN, Cornell University, DESY, KEK, Saclay) and numerous smaller efforts exist at other universities and laboratories. To give an idea of the acceptance of superconducting technology in operations, the number of accelerating cavities at various facilities are 338 at CEBAF, 250 at CERN, 16 at DESY and 32 at KEK. These cavities are all for electron acceleration and are designed for a beta (ratio of velocity of particle to the speed of light) of 1.0. The APT linac design was optimized without utilizing a continuous gradation in the length of the cavities, even though protons for the APT linac have a beta that changes from 0.43 at 100 MeV to 0.88 at 1300 MeV. The design employs only three cavity designs; in other words, design has constant beta sections of beta = 0.48 from 100 to 216 MeV, beta = 0.64 from 216 MeV to 506 MeV and beta = 0.71 from 506 to 1300 MeV. The design is based on four-cell independently-phased cavities that have a large velocity acceptance. Two cavities per cryomodule will be used with a quadrupole doublet between cryomodules. The superconducting design has many desirable features including large aperture, easy upgrade capability and a flexible operation parameter space. Uncertainties exist in the low-beta cavity shape performance and in degradation from proton irradiation effects. A development program is underway to resolve these superconducting cavity issues by November 1996.

The CCDTL is an efficient accelerating cavity for intermediate velocity particles that combines features of the Alvarez DTL with features of a coupled-cavity linac (CCL). This new structure has good shunt impedance compared to other structures in the velocity range with beta from 0.2 to 0.5. The CCDTL concept consists of either a two gap or a three gap system, depending on the particle velocity.

RF Systems

The highest leverage systems in terms of costs, performance and reliability are the rf power systems. Improvements in efficiency; control; feedback; protection and monitoring; operating constraints such as voltage, module size, limits and layout; and waveguide/coax components will have enormous impacts on any high power rf system. For these reasons a fair amount of investment in any of these areas will have payoffs that will assist sponsors, designers, installers, commissioners and operators. Hence, the investment in improving rf tube dc-rf efficiency for cw high power tubes from present day 70% to devices with greater than 80% efficiency. At the same time one has to ensure that reliability and lifetime are not compromised. In addition, complexity from size requirements for systems less than a GHz leads to an opportunity to re-engineer some of the typical rf drive line components and their performance with attention to impedances, modhg, reflections and possible phase shifts under operating conditions.

Many high power accelerators are now requiring better rf system control (approaching 0.1 degree and 0.1% amplitude) in order to maintain stringent beam performance criteria.
including emittance, halo, energy spread and possible oscillations in these parameters – either within a single beam bunch or between bunches

Other Considerations

Diagnostics for these high power accelerators should be non-intercepting and non-invasive, robust, low maintenance, and reliable. High sensitivity is required in order to track beam tails and to provide information on critical alignment issues. A good rule to follow is "When in doubt, install diagnostics because this will save time and operating costs in the long run."

A formal conduct of operations program should be employed for the facility and this program should include:

1. Well developed and understood tuning procedures.
2. Operations procedures for normal and abnormal conditions.
3. All-inclusive interlock test procedures.
4. Extensive training of staff and operations personnel.

A layered approach is recommended as the philosophy for equipment and personnel protection systems. All probable accident scenarios should be incorporated into this philosophy. Systems employed in the complex should be robust and designed for configuration control. In addition, consideration should be given to making the system as simple as possible. An important aspect of protection systems is accurate beam transmission and spill monitors with a fail-safe, fast beam-off response.

The design and operation of any accelerator can be aided by the following considerations:

1. With intense beams, what you can’t see can get you in trouble.
2. Modularity and ease of replacement need to be emphasized.
3. Systems should be simple and reliable.
4. Ability to fully test systems is a necessity.

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I would like to thank the many scientists, engineers, technicians and administrators who in one way or another made it possible for the many contributions over the years to accelerator development and experimental demonstrations; ‘opening the doors’ for others to consider ADTT applications. Their contributions have been numerous, timely and important. The technical advances and operations improvements have shown that large accelerators in the market place can make significant changes to the way we manage our resources, protect our environment and contribute to societies well-being. Personally it has been a pleasure to work with those I could, to discuss capabilities and advancements with many of them and to have benefited from many of their investigations. Developments in the accelerator arena have been based on international activities that benefited from a special community that helps each other.

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A list of acknowledgments would be too long to include here. No references have been included because it was felt more important to provide the content of the developments without losing pages because of the numerous references that would have to have been used for completeness. There are other places from which to obtain the references and I’d be willing to assist anyone who requires additional material.