# ACCELERATOR FOR THE PRODUCTION OF TRITIUM (APT)*

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## Abstract

A collaborative study by Los Alamos and Brookhaven National Laboratories, supported by the Westinghouse Hanford Company, investigating a facility to produce tritium for the nation's defense needs indicates that a 1.6-GeV, 250-mA proton accelerator is required. A reference design of this accelerator starts with two parallel 125-keV injectors feeding 350-MHz radio-frequency quadrupoles (RFQ) that funnel at 2.5 MeV into a 700-MHz drift-tube linac (DTL). The DTL injects at 100 MeV into a 1400-MHz side-coupled linac (SCL). The accelerator will cost about $1.2 B and require 746 MW of electricity.

## Background

Tritium is an essential ingredient of modern nuclear weapons. Its 12.3-year half-life requires the continuous production of tritium to replenish the inventory in the weapons stockpile.

Recent national discussions concerning the viability of the historic sources of tritium have renewed interest in alternative production methods. In collaboration, a group from the Los Alamos National Laboratory and the Brookhaven National Laboratory, supported by the Westinghouse Hanford Company (WHC), has studied the scope of an accelerator-based facility that would produce the DOE goal amount of tritium. Los Alamos concentrated on the accelerator, Brookhaven on the target lattice assembly, and Westinghouse Hanford on the physical plant.

It has long been recognized that high-energy particles interacting with heavy nuclei will liberate copious quantities of neutrons that may be utilized for nuclear transmutations, including the production of special nuclear materials. Lawrence Livermore National Laboratory, Chalk River Nuclear Laboratories, Brookhaven National Laboratory (BNL), and Los Alamos National Laboratory (LANL) have been involved in a variety of studies, experiments, and prototype developments associated with the use of accelerators for isotope production.

Linear accelerator technology has made major advances with continuing new developments for the Los Alamos Meson Physics Facility (LAMPF) accelerator and with additional structures development funded by the National Cancer Institute, the Department of Energy (DOE), and the Strategic Defense Initiative Office Neutral Particle Beam (NPB) program. Equally impressive advances have been made in understanding the physics of beams and the behavior of accelerator structures, the ability to calculate performance, the creation of beam diagnostic instrumentation, and packaged control system software that contains tool kits to simplify applications programming.

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## The Concept

Lead was chosen as the primary spallation neutron-source material as it avoids fission waste, is inexpensive, abundant, and easy to fabricate. Neutrons from lead are absorbed by lithium, which splits to create tritium and helium. An aluminum lithium alloy was selected for the lithium source because of its well-characterized performance in the heavy-water reactors at the Savannah River Plant. Cooling water temperatures are kept low and there is no attempt to recover power from the target lattice.

The study indicates that 250 mA of 1.6-GeV protons will produce the desired quantity of tritium, if the beam is utilized 75% of the time.

## Accelerator Components

The fundamental frequency of 350 MHz was chosen for the linac because 1-MW cw RF tubes are commercially available at this frequency, permitting early testing of the low-energy accelerator structures. The linac starts with two parallel 125-keV proton injectors, each feeding 350-MHz RFQs that interlace or funnel RF bunched beams at 2.5 MeV into a single 700-MHz DTL. The DTL injects at 100 MeV into a 1400-MHz SCL.

A discrete-element, low-emittance-growth funnel is used to combine beams from two RFQs so that the low-energy portion of the system can generate a high-current beam with reasonably low transverse emittance and without significant space-charge limitations. Assigning only half the final current to each ion-source/RFQ combination allows the sources and RFQs to be designed for better performance and enhanced long term reliability. Attention to emittances and matching between sections permits a smaller aperture in the accelerator system and helps control halo formation, which could lead to excessive activation if not minimized.

Duoplasmatron- or plasma-cusp-field-type ion sources will be utilized. Backup sources will be poised to quickly replace the operating sources for enhanced beam availability.

A few RFQ design calculations were completed with the following example chosen (Table I) for system integration purposes. Each RFQ will be powered by its own 1-MW cw klystron.

The funnel considered in this study was based upon experience gained preparing for the NPB funnel experiments at Los Alamos. The RFQs are angled at 20° to the final beam axis and have a 40-cm beam separation at the RFQ exits. The funnel has 28 permanent magnet quadrupoles and dipoles, 6 of which are adjustable-strength quadrupoles for fine tuning the match to the 700-MHz DTL input, and 6 of which are adjustable-position quadrupoles for beam steering. There are nine RF cavities: four 350-MHz rebunchers, four 700-MHz rebunchers for longitudinal focusing and matching to the DTL, and one 350-MHz RF deflector for merging the two 350-MHz beams from the RFQs into one 700-MHz beam for injection into the DTL. Each funnel RF cavity is frequency tuned by controlling its cooling water temperature, and each has its own 25 kW solid-state power supply. Beamline components are mounted on a baseplate and enclosed in a vacuum tank. The funnel is 1.5 m long. Considerable diagnostics and computer feedback controls are required to permit accurate adjustment of RF components, beam position, and beam match to the DTL. Transverse emittance growth in the funnel should be less than 20%.

TABLE I. RFQ Physics Design

| | |
|---|---|
| Frequency | 350 MHz |
| Injector energy | 125 keV |
| Proton current into RFQ | 165 mA |
| Proton emittance into RFQ | 0.020 $\pi$-cm-mrad |
| Vane length | 348.6 cm |
| Number of 350-MHz wavelengths | 4.07 |
| Beam transmission | 92.5% |
| Output energy | 2.5 MeV |
| Proton current out of RFQ | 152.6 mA |
| Transverse emittance (n,rms) | 0.0261 $\pi$-cm-mrad |
| Longitudinal emittance (n,rms) | 0.054 $\pi$-cm-mrad |
| | 0.2137 $\pi$-MeV-deg |
| Power absorbed in structure wall | 445 kW |
| Power to beam | 384 kW |
| Total RF power required | 829 kW |
| Beam loading | 46% |
| Maximum peak surface electric field | 1.81 Kilpatrick |
| RFQ longitudinal current limit | 290 mA |
| RFQ transverse current limit | 290 mA |

A DTL design (Table II) was chosen that lost no particles in simulations involving 1000 superparticles. This design had sufficiently rigorous input beam quality requirements that warranted the inclusion of funneled RFQs as the most prudent proton input beam.

The linac transitions from the DTL structure to a coupled cavity structure at 100 MeV. The SCL pioneered at LAMPF was used in this study (Table III) in the cw configuration developed for the National Bureau of Standards (NBS) microtron[1] by Los Alamos. A section of the NBS microtron SCL accelerator was successfully operated for many hours at cw power levels that produced structure wall heat loads higher than will be experienced in most of the APT SCL.

The APT SCL has 8646 accelerating cavities in 983 m as compared to LAMPF, which has 4276 cavities in 732 m. The APT SCL uses 450 klystrons, which is a bit less than twice Stanford Linear Accelerator Center's 244 klystrons. This indicates that a successful fabrication and operation base has been in place for over 15 years within these DOE Laboratories. In the past, the injector linacs at BNL, LBL, FERMI Lab, and CERN have been operated with more protons per bunch than required in APT.

TABLE II. DTL Physics Design

| | |
|---|---|
| Frequency | 700 MHz |
| Proton energy into DTL | 2.5 MeV |
| Proton current into DTL | 250 mA |
| Overall length | 51.3 m |
| Number of drift tubes | 466 |
| Quadrupole gradient | 240 T/m |
| Quadrupole length | 18 mm |
| Beam bore radius | 5 mm |
| Lattice | FOFODODO |
| Accelerating gradient (constant) | 3 MV/m |
| Energy gain | 1.9 MeV/m |
| Sync phase @ 2.5 MeV | -60° |
| Sync phase >20 MeV | -40° |
| Radius of 100% of beam | 3 mm |
| Power absorbed on structure wall | 4 MW |
| Power to beam | 24 MW |
| Total RF power required | 28 MW |
| Beam loading | 86% |
| Klystron overdrive | 10% |
| Klystron cw power | 1 MW each |
| Klystron efficiency | 65% |
| ac to dc conversion efficiency | 95% |
| ac power required | 46 MW |
| Number of klystrons required | 32 |
| Average spacing between klystrons | 1.6 m |
| Beam transmission | 100% |
| Output energy | 100 MeV |
| Proton current out of DTL | 250 mA |
| DTL Longitudinal current limit | 2.8 A |
| DTL Transverse current limit | 2.1 A |

TABLE III. SCL Physics Design

| | |
|---|---|
| Frequency | 1400 MHz |
| Proton energy in | 100 MeV |
| Proton current in | 250 mA |
| Length | 982.5 m |
| Number of accelerating cells | 8646 |
| Bore radius | 7.5 mm |
| Accelerating gradient | 2 MV/m |
| Average energy gain | 1.53 MeV/m |
| Power absorbed in structure wall | 52 MW |
| Power to beam | 375 MW |
| Total RF power required | 427 MW |
| Beam loading | 88% |
| Klystron cw power | 0.95 MW each |
| Klystron efficiency | 65% |
| ac to dc conversion efficiency | 95% |
| Total ac power | 696 MW |
| Number of klystrons | 450 |
| Average spacing between klystrons | 2.2 m |

## Control and Diagnostics

Current developments are providing nonintercepting beam diagnostics capable of accurate and rapid beam characterization. Control systems are evolving into transportable packages that also provide *toolkits* for easy applications programming. Automatic element correction based on interpretation of diagnostic data will be utilized to enhance reliability and reduce activation.

## Accelerator Facility

The APT linac length totals 1051 m. The power lost to the accelerating structures, which must be removed in carefully controlled cooling circuits, is 57.6 MW. An additional 250 MW of coarser cooling are required for the klystrons. The ac power needed, to provide the required 457.6 MW of RF power, is 746 MW. The remainder of the plant requires about 25 MW, for a total facility need of

770 MW. For a 75% utilization factor and a 32-mils/kW-h rate, the estimated electrical costs are $162 M/yr. Electricity availability and low rates can be found within the large hydropower grids of the Bonneville Power Administration or the Tennessee Valley Authority.

The capital cost of a complete APT facility as developed in this study was about $2.3 B and is comparable with that quoted for a new production reactor. The operating cost of the APT ($270 M/yr) with its dominant electrical bill is balanced by the cost of supporting the infrastructure of a new production reactor with its fissile-fuel reprocessing plant.

The accelerator and RF systems are made from a large number of similar parts that can be mass-produced in many factories and shops throughout the country and brought to centralized locations for assembly into clusters and for testing. Installation will be very rapid as the components will have been designed for ease of replacement and the length of the accelerator facility provides ample room for many installation activities to occur simultaneously. Facility construction will be rapid in that the long tunnel and surface buildings may advance in numerous sections independently. The lattice (beam stop/T-production volume) building is smaller and lighter than a reactor containment building as no fissile materials or stored energy are present. The decay heat of the APT lattice is about 0.4% of that of a new production reactor (NPR) core producing a comparable amount of tritium. The inventory of radioactive materials in the lattice is only 0.4% (growing to 2% at 1000 years) of those in an NPR. Therefore, it is believed that the construction time and the licensing requirements should be less for an APT than for an NPR.

## Design Considerations

Accelerator parameters should be optimized to minimize life-cycle costs, which are dominated by power consumption and electrical equipment capital cost. A significant cost driver is the efficiency of electrical power conversion from ac to RF. One percentage point change in efficiency equates to an electrical cost change of $1.7 M/yr and a $4 M change in the amount of electrical equipment required.

Control of beam loss is essential. Activation of the accelerator or beam transport elements would severely hamper maintenance. The growth of beam halos or off-energy tails must be suppressed or scraped, and a beam-breakup-resistant structure should be utilized.

High availability requires a well-integrated facility, a design philosophy that stresses reliability and maintainability, and good quality assurance in fabrication and installation. Component over-capacity and redundancy must be combined with convenient modular system replacement.

## Future Work

New production reactors are planned for the Savannah River Plant and the Idaho National Engineering Laboratory. Alternative sources, such as APT should be evaluated for their viability as a contingency in case the reactors encounter licensing, design, or construction difficulties. Such a study for APT should include the construction of an engineering demonstration to validate performance.

An engineering demonstration would include the low-energy portion of the proton accelerator and a representative section of the high-energy portion. The injector, RFQ, funnel, and a portion of the DTL should be operated as a system. The high-energy SCL structure could be constructed as an electron machine to test the proper beam loading, as adequate proton currents with sufficient energy are not available.

## References


1. L. M. Young and J. M. Potter, "CW Side-Coupled Linac for the Los Alamos/NBS Racetrack Microtron," *IEEE Trans. Nucl. Sci.* **30** (4), 3508, August 1983.


Two additional documents form the official report of this study: "Accelerator Production of Tritium (APT)," BNL/NPB-88-143, March 1989, and "Preliminary Assessment of Accelerator Production of Tritium," Los Alamos National Laboratory report DEW-89:20, in preparation.

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