LA-UR-97-3626

CONF-9708134--

Approved for public release;
distribution is unlimited.

Title: Development of RF Linac for High-Current Applications

Author(s): K.C. Dominic Chan, APT/TPO
G.P. Lawrence, APT/TPO
J.D. Schneider, APT/TPO

Submitted to: 5th European conference on Accelerators
in Applied Research and Technology
August 26-30, 1997
Eindhoven, The Netherlands

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. The Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

Ref. Number: EC438

DEVELOPMENT OF RF LINAC FOR HIGH-CURRENT APPLICATIONS[†]

K. C. Dominic Chan^{*}, G. P. Lawrence, and J. D. Schneider

Los Alamos National Laboratory, MS H816, Los Alamos, NM 87544, USA

(Keywords: Accelerator, Tritium, Superconducting, Application; Classification Code: 29.17)

Abstract

High-current proton linacs are promising sources of neutrons for material processing and research applications. Recently, a linac design that makes use of a combination of normal-conducting (NC) and superconducting (SC) linac technologies has been proposed for the US Accelerator Production of Tritium Project. As a result, a multi-year engineering development and demonstration (ED&D) program is underway. In this paper, we will describe the design and merits of the NC/SC hybrid approach. The scope, technology issues, and present status of the ED&D Program, and the participation of industry will also be described.

1. Introduction

High-energy proton linacs have been proposed as drivers for neutron sources for different applications [1]. These applications include the transmutation of nuclear reactor waste, production of tritium and other special materials, and research in physics and material sciences. For many

[†] Work performed under the auspices of the US Department of Energy

^{*} Corresponding author: Los Alamos National Laboratory, MS H816, Los Alamos, NM 87545, FAX: 505-667-7443, Phone: 505-665-0376, Email: KCCCHAN@LANL.GOV

applications, proton linacs with multi-megawatt beam-power levels are required. Production of tritium using an RF proton linac is being actively pursued by the US Government. In the Accelerator Production of Tritium (APT) Project [2] of the US Department of Energy, a 170-MW CW proton linac has been proposed to produce tritium for maintaining the US nuclear stockpile. It has an average current of 100 mA and a beam energy of 1.7 GeV. This beam power is two orders of magnitude higher than the power of the highest power existing proton linac (1 MW), built in the 1960's at Los Alamos. The technology to build a multi-megawatt proton linac, though a reasonable extension of the present technology, needs to be demonstrated with a well-designed engineering development and demonstration (ED&D) program. The APT Project has initiated such a program, which consists of a Low Energy Demonstration Accelerator (LEDA) [3] and an ED&D Program [4] to develop SCRF accelerating modules.

2. APT RF Linac Design [5]

The APT RF linac design is shown in Figure 1. It has a front-end linac that accelerates the proton beam to 217 MeV using normal-conducting technology and a high-energy linac accelerating the beam from 217 MeV to 1700 MeV using superconducting technology. The CW beam current is 100 mA. Fundamental performance requirements for the linac include high availability, high efficiency, and low beam loss.

A NC/SC hybrid linac design provides optimum performance by fully utilizing the advantages of each technology. The NC front-end linac provides a high-density magnetic lattice and smoothly varying accelerating and focusing parameters, such that a high-quality high-current beam with minimum beam halo and beam loss is produced for further acceleration. Use of a SC high-energy linac provides high efficiency to minimize cost, large aperture to minimize beam loss, and a wide velocity acceptance for flexible operation.

2.1 Normal-conducting front-end linac

The front-end linac is built with normal-conducting copper accelerating structures. It consists of a radio-frequency quadrupole linac (RFQ), sections of couple-cavity drift-tube linac (CCDTL), and a couple-cavity linac (CCL). The front-end linac parameters are given in Table 1.

The APT RFQ (Figure. 2) [6] is 8 meters long, accelerating the 75-keV proton beam from the microwave ion source to 6.7 MeV. It will be the longest and highest energy RFQ built to date. Its length and energy are required to achieve a smooth beam dynamics match to the following CCDTL structure. In order to maintain the required RF electric field flatness and stability along its length, the RFQ will be built in four segments that are resonantly coupled. To reduce fabrication time and cost, the RFQ will be a completely hydrogen brazed structure.

The CCDTL structure (Figure 3) [7] accelerates the proton beam from 6.7 MeV to 100 MeV. It combines the well-established technologies of drift-tube linacs (DTL) and coupled-cavity linacs (CCL). In a CCDTL, drift-tubes are installed inside the cavities so that it has the high acceleration efficiency for low-velocity protons of a DTL, and the high field stability of a CCL.

The CCL structure [8] accelerates the proton beam from 100 MeV to 217 MeV. It uses side-coupled cavities like the well-understood linac at Los Alamos.

The RFQ, CCDTL, and CCL provide stable accelerating fields and smooth beam-dynamic matches between structures. They also allow the use of a strong-focusing quadrupole lattice with quadrupoles installed between the accelerating structures for easy access and alignment. These properties insure that a high-quality beam will be produced with minimum halo and low beam loss.

2.2 Superconducting high-energy linac

The high-energy linac is a superconducting (SC) linac. It accelerates the proton beam from 217 MeV to 1700 MeV in two linac sections. Each section is made up of identical linac units optimized for different velocity (β) ranges. The medium- β and high- β sections are designed for β equal to 0.64 and 0.82 respectively. Figure 4 shows the high- β linac units, each consisting of a cryomodule and two RF systems. The cryomodules each contains 5-cell cavities made from solid Nb sheet that have elliptical cell shapes. These cavities operate with a field gradient near 5 MV/m and at a cryogenic temperature of 2 K. RF power from 1-MW klystrons will be split to supply multiple cavities. Two coaxial power couplers, with a power capability of 210 kW each, are used to supply power to a cavity. The parameters of the SC high-energy linac are summarized in Table 2. A superconducting linac is chosen for the high-energy linac for low operating and capital cost, low beam loss, and high availability [9].

The SC linac has a high power efficiency. RF power is a major cost item in APT linac because of its CW operation and high beam current. SC cavities have negligible RF loss in the cavity walls. The amount of RF power required for a SC linac, compared to a NC linac, is 30% less. The lower RF power requirement leads to less investment in RF power installation and less electricity use in operation. Even taking into account the added cost of providing the cryogenic requirements of the SC linac, the net savings have been estimated to be about 20% both in capital and operating cost.

The SC linac has lower beam loss. The RF power required to operate a SC cavity, unlike room-temperature structures, does not increase significantly with the aperture of the cavity. The aperture radii used in the medium- β and high- β SC linac sections are very large (6.5 and 8.0 cm respectively). For comparison, the largest aperture in an equivalent NC linac is 2.5 cm. With such a large aperture, the probability of intercepting halo particles and creating beam loss is much reduced for the SC linac.

The SC linac has high availability. The β -value of the proton beam changes significantly over the length of the APT linac. Because of the low field gradient and long length of room-temperature structures, an APT linac using NC technology can operate only with a designed beam-energy profile. On the other hand, with short cavities, a SC linac has large velocity acceptance. This provides flexible operation allowing a change of local or final beam energy changes if any of the accelerating units fails along the linac. The high-velocity acceptance also allows each linac section to be built with identical cryomodules. With only two types of cryomodule in the APT linac, production prototypes can be developed and tested thoroughly before production. It also allows a few ready-to-go spares to be provided to back up the entire high-energy linac. Flexibility in operation, thorough timely testing of prototypes, and ready-to-go spares all contribute to higher availability.

3. Low-Energy Demonstration Accelerator (LEDA) [3]

LEDA will construct and operate a prototype front-end linac at full power. The prototype linac will be virtually identical to the first 20-MeV of the APT linac. One of the few differences is that LEDA will have additional beam diagnostics to enable better characterization and measurement of the beam.

The front-end linac is the most challenging part of the APT linac because of the high space-charge forces in the proton beam. LEDA will provide measured output beam parameters to compare with beam simulations and an opportunity to investigate halo formation. The front-end linac is also challenging because of the RFQ and CCDTL linac structures. These structures, though using conventional technologies, are moderate extensions of the state of the art in these areas. They will be fabricated and tested to demonstrate CW high-power operation with high reliability and availability. Finally, development of beam commissioning procedures will be an important part of LEDA. LEDA provides the opportunity for bringing a CW beam to full power level.

LEDA activities will be conducted in four distinct stages with Stage 3a expected to be started early in year of 2000.

- Stage 1 - installation and testing of a 75 keV, 110 mA proton injector. This stage demonstrates the availability and beam quality of the injector.
- Stage 2 - addition of a 350-MHz RFQ linac to accelerate a 100-mA proton beam to 6.7 MeV. This stage demonstrates the output beam characteristics of the RFQ linac.
- Stage 3a - addition of a 700-MHz CCDTL section that accelerates beam to about 11 MeV. This step confirms the critical matching from the RFQ into a CCDTL section.
- Stage 3b - addition of a second 700-MHz CCDTL section to accelerate the 100-mA proton beam to about 20 MeV. This stage tests multiple 700-MHz RF systems and permits observation of the beam quality available for high-energy accelerating structures.

LEDA has been making progress in the last two years. The LEDA injector has operated in a test-stand configuration, where it demonstrated full design current of >130 mA, at 75 keV, and with good beam emittance. Five of the total eight RFQ sections have been brazed. All are leak-tight, mechanically aligned, and showing excellent RF tuning. The first HVDC power supply has been installed and hookup is complete. All connections were made on the first transmitter. Three of the 350-MHz klystrons have been received and installed. Nearly all full-height 350-MHz waveguide has been connected, including all circulators, switches, and dummy loads. High-power testing should begin before the end of August.

4. SCRF ED&D Program [4], [9]

The SCRF ED&D Program plans to build prototype linac units of the high-energy linac (Figure 4). It consists of several distinct stages (Figure 5). Components, including cavity and power coupler, will be designed, fabricated, tested and integrated in a cryomodule. The cryomodule will be tested

with a 1-MW RF system as a linac unit. The results of the development and testing will provide final information for the design of the production cryomodules.

There are two major technical issues that will be addressed by the SCRF ED&D Program. They are the cell shape of the $\beta < 1$ cavities and the power capability of the power coupler. An elliptical cell shape has been used by most of the electron linacs. In particular, they have been used recently by the linacs at the Thomas Jefferson National Accelerator Facility (TJNAF) and the LEP-II upgrade at CERN. Table 3 shows statistics of elliptical cells in existing SC electron linac. They perform well at accelerating field gradient level of 5 MV/m without multipacting. The APT SC linac also uses an elliptical cell shape, but compressed longitudinally because of the lower β . With the sidewalls being closer than those for $\beta = 1$ cavity designs, there is a chance that multipacting could occur, which would prevent the APT cavities from reaching design gradient. Coaxial couplers with a maximum power capability of 210 kW are required to supply RF power to the cavities. A conceptual design of such a coupler is shown in Figure 6. Table 4 shows the current test results of RF power couplers at different laboratories. It shows power capabilities with beam operation up to 168 kW, which is close to but lower than the APT requirement. On the other hand, all the couplers were operated on test stands at power levels higher than the APT requirement. In most cases, the power transferred with beam operation is limited by the amount of current accelerated and not the performance of the coupler.

By the end of year 2000, the SCRF ED&D Program plans to have demonstrated performance of $\beta < 1$ multicell cavities, 210-kW power couplers, and integrated cryomodule performance.

Throughout the ED&D Program, the Project will work to demonstrate the fabrication capability of APT SCRF cavities and cryomodules in industry such that the production capability of APT linac is established.

Steady progress has been made in the SCRF ED&D Program since early summer, 1997.

Conceptual designs of cavities, power coupler, and cryomodule are close to completion. We are starting the fabrication of single and multicell cavities with industrial participation. Single-cell cavity tests have shown promising results. The APT field performance requirement of 5 MV/m with a Q_0 of 5×10^9 has been obtained. No multipacting has been observed.

5. Industrial Participation

The production of the APT linac is a very large undertaking that places a high demand on industrial production capability. This is particularly true in the case of the SC high-energy linac.

Fortunately, with the production of the TJNAF and the LEP-II linacs, a knowledgeable industrial base does exist. During the APT ED&D Program, the APT Project will establish a working relationship with industry. Industry will be invited to participate in early ED&D activities that include cryomodule design workshops and in providing fabrication services. In the final stages of the program, industry will build complete prototype cryomodules. The goal is to have industry ready to produce cryomodules when APT linac component procurement starts in the year 2001.

6. Summary

High-intensity proton linacs are promising drivers of spallation neutron sources for applications in transmutation technologies, research, and material sciences. A hybrid NC/SC linac has been designed for production of tritium. In this linac, room-temperature linac technology is used for the front-end to produce a high-quality proton beam. Superconducting linac technology is used for the high-energy linac to provide high efficiency, high availability, and low beam loss. Engineering development and demonstration programs are now underway to address technical issues of such a linac.

References

- [1] C. D. Bowman, et. al., Nuclear Energy Generation and Waste Transmutation Using Accelerator-Driven Intense Neutron Source, NIM in Phys. Res., (Sec. A), Vol. A320, Nos. 1 and 2, August 15, 1992, pp. 336-367.
- [2] P. W. Lisowski, The Accelerator Production of Tritium (APT) Project, to be published in the Proceedings of 1997 Particle Accelerator Conference, Vancouver, BC, Canada (May 1997).
- [3] J. D. Schneider and K. C. D. Chan, Progress Update on the Low-Energy Demonstration Accelerator (LEDA), *ibid.*
- [4] K. C. D. Chan and B. Rusnak, Applying Superconducting Accelerator Technology to High-Current Proton Linac, Los Alamos National Laboratory Report LA-UR-3258 (1997).
- [5] G. P. Lawrence and T. P. Wangler, Integrated Normal-conducting/Superconducting High-Power Proton Linac for the APT Project, to be published in the Proceedings of 1997 Particle Accelerator Conference, Vancouver, BC, Canada (May 1997).
- [6] D. Schrage, A 6.7-MeV CW RFQ Linac, *ibid.*
- [7] J. H. Billen et. al., A Versatile, High-Power Proton Linac for Accelerator -Driven Transmutation Technologies, Proceedings of 1995 Particle Accelerator Conference, Dallas, p. 1137.
- [8] D. E. Nagle, E. A. Knapp, and B. C. Knapp, Coupled resonator Model for Standing Wave Accelerator Tanks, Review of Scientific Instruments, Vol. 38, 11, p. 1583, November, 1967.
- [9] K. C. D. Chan, Conceptual Design of a Superconducting High-Intensity Proton Linac, Proceedings of the 18th International Linear Accelerator Conference, 25-30 August, 1996, Geneva, Switzerland, pp. 580-584.

Figure captions:

Figure 1: Architecture of the APT NC/SC hybrid linac.

Figure 2: APT RFQ linac.

Figure 3: APT CCDTL linac section.

Figure 4: APT high- β linac unit.

Figure 5: Flow diagram of the APT SCRF ED&D Program

Figure 6: A conceptual design of a APT power coupler.

Table captions:

Table 1: Normal-conducting front-end linac parameters.

Table 2: Superconducting high-energy linac parameters.

Table 3: Statistics of existing elliptical cavities.

Table 4: Test results of power couplers in different laboratories.

Figure 1: Architecture of the APT NC/SC hybrid linac.

APT/LEDA RFQ SCHEMATIC

Figure 2: APT RFQ linac.

Figure 4: APT linac unit for $\beta=0.82$ section.

Figure 5: Flow diagram of the APT SCRF ED&D Program

Figure 6: A conceptual design of a APT power coupler.

Table 1: Normal-conducting front-end linac parameters.

Parameter	RFQ	CCDTL	CCL
Structure gradient (MV/m)	1.38	1.1-1.6	1.6-1.5
Average gradient (MV/m)	1.38	0.4-1.2	1.2-1.3
Length (m)	8.0	102.3	104.3
Synchronous phase (deg)	- (90-33)	- (60-30)	-30
Shunt impedance (M Ω /m)	—	18-52-33	33-37
Phase-adv./period (deg)	—	80	80-35
Quadrupole lattice period	—	$8\beta\lambda$	$8\beta\lambda$
No. of quadrupoles	—	234	125
Quadrupole G•L prod. (T)	—	2.6-2.2	2.2-2.0
Trans emitt. (π mm-mrad)*	0.160	0.163	0.163
Long emitt. (π mm-mrad)*	0.405	0.44	0.45
Aperture radius (mm)	2.3-3.4	10-17.5	17.5-25
Aperture : beamsize ratio	—	6.5-14	14-17
Copper rf losses (MW)	1.26	5.0	6.8
Number of klystrons	3	21	27

* Normalized rms emittance

Table 2: Superconducting high-energy linac parameters.

Parameter	$\beta=0.64$	$\beta=0.82$
Structure gradient (MV/m)	4.24 - 4.85	5.4 - 6.4
Avg. gradient (MV/m)	1.26	2.25
Peak surface field (MV/m)	13.1 - 15.0	14.0 - 16.6
Section length (m)	249	649
No. of (5-cell) SC cavities	102	304
No. of klystrons (1-MW)	34	152
Synchronous phase (deg)	-30 to -35	-29
Coupler power (kW)	123.5	210
Power per klystron (kW)	741.2	840
Trans. phase adv./period (deg)	83 - 67	81 - 32
No. of quadrupoles	102	152
Trans. emittance (π mm-mrad)*	0.17 - 0.18	0.18
Long. emittance (π deg-MeV)*	0.34 - 0.33	0.33 - 0.39
Aperture-radius/rms-beam-size	37	65

* Normalized rms emittance

Table 3: Statistics of existing elliptical cavities.

Startup Year	Freq. (MHz)	Accelerator	Gradient (MV/m)	Installed (MV)	Total Hours
1988	508	TRISTAN	3 - 5	200	33,000
1990	3000	Darmstadt	4 - 10	50	10,000
1991	500	HERA	3 - 5	75	23,000
1995	1500	TJNAF	4 - 14	800	14,000
1995	350	LEP-II	5 - 6	1500	>5000

Table 4: Test results of power couplers in different laboratories.

No Beam

Laboratory	Frequency (MHz)	Power (kW)
SLAC	476	500
CERN*	352	300
DESY*	500	300
Cornell	500	300
KEK*	500	850

With Beam

Laboratory	Frequency (MHz)	Power [†] (kW)
DESY*	500	100
Cornell	500	155
KEK*	500	168

[†]Power levels are not coupler limited

*Coaxial couplers