REVIEW OF THE APDF AND OTHER LOW-ß, HIGH-DUTY-FACTOR LINACS*

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Abstract

The Accelerator Performance Demonstration Facility (APDF) is being designed at Los Alamos to develop the "front end" of a cw accelerator suitable for Accelerator Transmutation of Waste (ATW), Accelerator Production of Tritium (APT), and Accelerator-Based Conversion of Plutonium (ABC). Each of these applications requires high-power linacs of about 1000 MeV and average currents in the range of 20-200 mA. The APDF will accelerate 200-mA funneled proton beams to 40 MeV using 7-MeV cw RFQs followed by two types of DTLs. The 75-keV injector and RFQ cold model are being tested. Other experiments in this class are the Chalk River RFQ1 project, Grumman's Continuous Wave Deuterium Demonstrator (CWDD), the JAERI Basic Test Accelerator (BTA), and MRTI's HILBILAC. Other high-duty-factor linac projects include superconducting designs for fusion materials testing and drivers for pulsed spallation sources.

Introduction

Accelerator-driven assemblies for producing fissile materials and tritium have been proposed for decades, but it has only been in the past few years that accelerator technology has advanced to the point where such devices are practical. Much of the early work started at Chalk River with the Zebra project [1], but in recent years Los Alamos and other laboratories have designed linear accelerators as drivers for APT [2], ATW [3], ABC, and Accelerator Generation of Energy [4,5,6]. Since the accelerator parameters for these applications [jointly called Accelerator Driven Transmutation Technology (ADTT)] are similar, Los Alamos has initiated a project to demonstrate the front-end of a high-current cw linac suitable for such applications. The name given to this project is the Accelerator Performance Demonstration Facility [7].

Although the feasibility of cw linacs has been extrapolated from pulsed versions, few experimental tests of such linacs with currents in the 50-200 mA range have been done. The largest body of data for operation of high-duty-factor linacs comes from the Los Alamos Meson Physics Facility (LAMPF) where 10% duty factor, 20 mA (peak) proton currents are routinely accelerated to 0.8 GeV. In contrast, the types of accelerators required for many of the new applications require 100% duty-factor operation at currents up to 200 mA, factors of 100 higher in average beam current than the LAMPF experience.

The earliest experimental verification that such high average currents could be produced in the critical low-energy part of a linac came in 1985 from the Fusion Material Irradiation Test Facility (FMIT) at Los Alamos. Although it operated only a short time, it accelerated 100 mA cw H_2^+ beam to 2 MeV. In 1988, Chalk River Laboratory's RFQ1 program succeeded in accelerating an 80 mA cw proton beam to 0.6 MeV [8]. Following an upgrade to 1.2 MeV and successful operation at 55 mA cw [9], RFQ1 was moved to Los Alamos and renamed CRITS (for Chalk River Injector Test Stand). At JAERI the BTA [10], which is designed to accelerate 100 mA to 10 MeV at 10% duty factor, has recently accelerated beam to 2 MeV. Although a high-duty-factor version has yet to be built, the HILBILAC idea was demonstrated at 1.5 MeV, 400 mA at low duty factor [11]. A review of high-current RFQs was given in 1991 by G. McMichael [12], and there have been recent reviews of high-current linac issues by G. Lawrence [13] and linac front ends by A. Schempp [14].

The Strategic Defense neutral particle beam (NPB) program also contributed to the development of high-power linacs, primarily through the Ground Test Accelerator (GTA) program at Los Alamos and the CWDD program led by Grumman Corporation. The GTA program proved high-peak current operation at low-duty factor, while the CWDD linac was designed for cw operation. The paper by E. Heighway at this conference [15] describes the legacy of the NPB program.

Accelerator Performance Demonstration Facility (APDF)

The APDF is an implementation of the first 40 MeV part of a 200 mA, cw linac (see Fig. 1). When completed, the APDF will allow a complete engineering and operational evaluation of the critical components, including ion source, injector, RFQ, funneling, and high-current drift-tube linac sections. The design phase currently underway is generating many ideas for component design that are appropriate for such a high-current device [13]. A crucial issue is control of beam loss, and methods to understand and control beam halo start with the critical low-energy region [16,17].

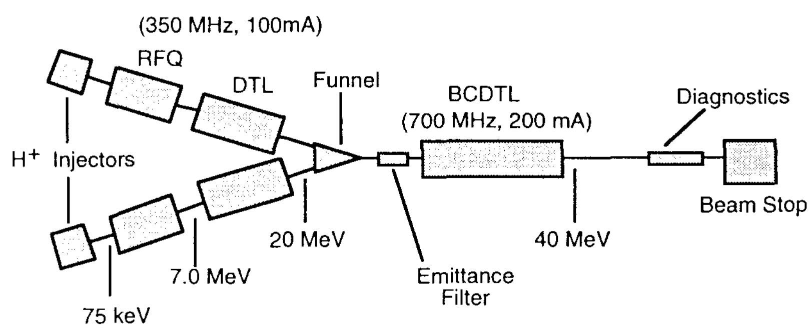

Fig. 1 APDF Accelerator Block Diagram.

The choice of a funneled system was based on the most demanding of the potential applications, APT, which could require up to 200 mA cw. However, even in applications with

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lower total beam power requirements, it is advantageous to use a lower frequency RFQ (for higher current limit) and double the frequency in the high-energy accelerating stages (for better efficiency). Funneling allows filling of all the rf buckets in the high-energy linac, thus potentially reducing emittance growth from space charge for a given current. Although several low-energy funneling experiments have proved the concept, the APDF was designed for a complete demonstration of funneling technology. To keep total costs reasonable, the 20-40 MeV Bridge-Coupled DTL segment is pulsed at 10% duty factor. All prior components operate at up to 100% duty factor.

Injector

The APDF injector uses a microwave proton source (also known as ECR source), developed for this application at Chalk River. Figure 2 shows the layout and Table 1 the parameters. A two-solenoid low-energy beam transport (LEBT) has been designed to provide proper matching into the RFQ. Non-intercepting beam diagnostics characterize the high-power beam. This injector has been fabricated, and an experimental program to study the beam characteristics and reliability has begun [18]. Tests using the CRITS facility, described below, will also contribute to reliability measurements of the microwave ion source.

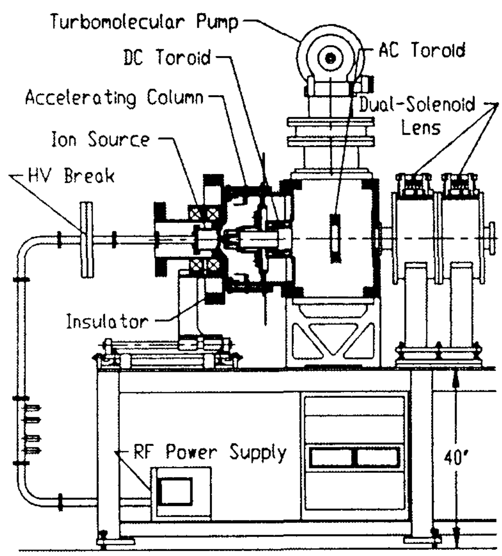

Fig. 2. APDF 75 keV injector with microwave ion source and dual-solenoid LEBT.

TABLE 1
APDF H$^+$ Injector Parameters

Source	Microwave Ion Source
Energy	75 keV
Extraction	Single gap
Current	110 mA (at RFQ input)
Emittance	0.2 π mm-mrad
Duty Factor	100% or pulsed

RFQ

At an output energy of 7-MeV and 8-m length, this will be by far the highest-energy, longest, and highest-power RFQ ever built. The high output energy allows better transverse and longitudinal matching to the DTL. At 7-MeV, the following DTL sections will have long enough drift tubes to use radiation-hard electromagnets instead of more compact permanent magnets that would be required if the RFQ ended at a lower energy. Resonant coupling between the 2-m-long sections is used to improve the longitudinal and transverse stability of the rf fields. Table 2 lists the RFQ parameters. An 8-m-long RFQ cold model has demonstrated resonant coupling and obtained a field flatness better than 2% with less than 2% dipole component [19]. A 0.5-m-long fabrication model has demonstrated the feasibility of hydrogen-furnace brazing as a cost-effective technique for joining the RFQ vanes [20].

TABLE 2
APDF RFQ Parameters

Energy	7.0 MeV
Frequency	350 MHz
Transmission	95.2%
Output Current	100 mA
Structure	4-vane
Segments	4, 2-m long
Gradient	0-1.75 MV/m
Structure Power	1.12 MW
Beam Power	0.70 MW
Total RF Power	1.82 MW
Efficiency	38.5%

DTL

The matching section from the RFQ to DTL contains rad-hard electromagnet quads and non-intercepting diagnostics to characterize the beam from the RFQ. The DTL is also designed with electromagnetic quads. Table 3 lists the DTL parameters. RF coupling will be by two 600-kW drive loops developed from the 80-MHz FMIT experience. The drift tubes are girder-mounted for ease of alignment and repair. There are 3 DTL modules to accelerate the beam in each leg from 7 to 20 MeV. Each module will be driven by a 1.1-MW rf station.

TABLE 3
APDF DTL Parameters

Energy	7.0-20.0 MeV
Frequency	350 MHz
Beam Current	100 mA
No. of Modules	3
Total Length	8 m
Lattice	FOFODODO
Gradient	1.04 - 2.80 MW/m
Clear Aperture	2.0 cm
Structure Power	1.153 MW
Beam Power	1.300 MW
Total RF Power	2.453 MW
Efficiency	53.0%

Funnel

The funnel section [21] provides frequency doubling, interleaving of beams from the two injection legs, and matching to the BCDTL. The design has evolved from a complicated interplay between physics (emittance control) and engineering requirements (space for bunching and focusing elements, diagnostics, and cooling). Novel elements are the two-beam quadrupole and buncher, and the deflector cavity. Current, centroid, and profile diagnostics are included to measure modulations caused by differences in the two legs so that feedback control can minimize the effects. The predicted emittance increase is 10-20% transverse and 1% longitudinal.

BCDTL

The Bridge-Coupled Drift Tube Linac (BCDTL) is proposed for this type of high-current linac where beam loss and efficiency are critical. Because the quads are in the gaps between tanks, the bores of the drift tubes can be increased to a larger diameter to minimize beam loss. The 19 tanks are connected by bridge couplers and grouped into 7 modules, each powered by a 1.1 MW rf station. Although the design of all components will be for 100% duty factor, the BCDTL will be pulsed at 10% duty factor. The rf power figures in Table 4 below, however, are for cw operation. A paper by J. Billen at this conference [22] describes an alternative type of structure, the Coupled-Cavity DTL, proposed for this energy range.

TABLE 4
APDF BCDTL Parameters

Energy	20.0-40.0 MeV
Frequency	700 MHz
Duty Factor	10%
Beam Current	200 mA
No. of Tanks	19 (7 $\beta\lambda$ each)
Total Length	23.8 m
Lattice	FDO
Clear Aperture	4.0-4.5 cm
Structure Power	1.74 MW
Beam Power	4.0 MW
Total RF Power	5.74 MW
Efficiency	70%

Chalk River Injector Test Stand

The Chalk River Injector Test Stand (CRITS) is the upgraded RFQ1 project, moved from Canada to Los Alamos to continue the cw evaluation program. Before the shutdown at CRL, the RFQ had operated with a new cw Klystrode rf system at the design energy of 1.2 MeV at 20 mA cw. In previous tests with lower-energy (0.6 MeV) vanes, 80 mA had been obtained. The purposes of the CRITS experiments at Los Alamos are to obtain additional cw experience, develop reliable rf and diagnostic components, measure beam limits and lifetimes of the microwave ion source and RFQ, and provide experimental data for code validation and APDF design. The microwave ion source is operating at 50 keV, 75 mA, and other subsystems are being checked out following the move and reinstallation. [23]. RFQ beam tests will begin next year.

JAERI Basic Technology Accelerator

As part of the OMEGA program for research and development on nuclide partitioning and transmutation, JAERI has proposed an Engineering Test Accelerator (ETA) with an energy of 1.5 GeV and an average current of 10 mA. The low energy part (up to 10 MeV) of this proton linac is called the Basic Technology Accelerator (BTA). Fig. 3 shows the layout of BTA, and Table 5 gives some of the specifications. BTA is designed to run at 10% duty factor with a peak beam current of 100 mA. The designers have chosen a multi-cusp ion source and two-stage extractor. Three rf amplifiers with 1 MW peak power are used for the RFQ and DTL. The ion source, RFQ, and RF power stations have been fabricated, and in initial beam tests, the 2-MeV RFQ accelerated 52 mA of protons at a 5% duty factor. The status of these tests is reported at this conference [24].

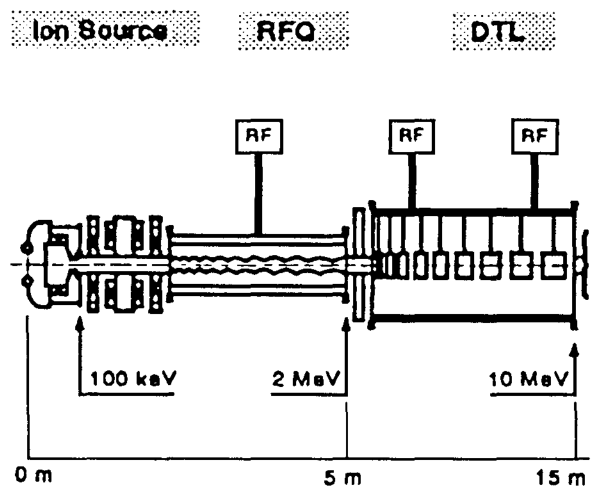

Fig. 3 JAERI Basic Technology Accelerator Layout

TABLE 5
BTA Parameters

Injector	H^+
Ion Source	Multi-cusp
Injection Energy	100 keV
Current	140 mA
Emittance	0.5 π mm-mrad
LEBT	Two-solenoid
RFQ	4-vane type
Energy	2.0 MeV
Frequency	201.25 MHz
Peak Beam Current	100 mA
Duty Factor	10%
Vane Length	3.35 m
DTL	EM Quads
Energy	10 MeV
Frequency	201.25 MHz
Clear Aperture	2.0 cm
Length	5.65 m

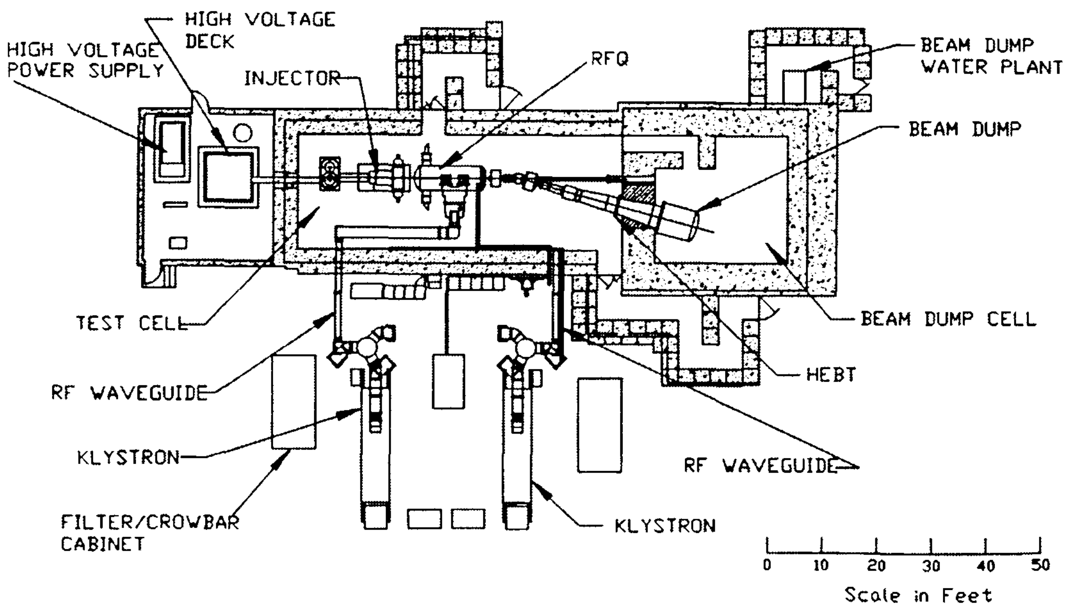

Fig. 4 Argonne CW Linac Installation

Argonne CW Linac (ACWL)

Formerly called CWDD (for Continuous Wave Deuterium Demonstrator), this facility is being converted from a defense mission to demonstrating high-current linacs for ADTT and other applications, such as neutron radiography and boron neutron capture therapy. [25]. A layout of the present facility is shown in Fig. 4. The 200 keV injector, built by Culham Laboratory, has produced 20 mA D^-.

The four-m-long RFQ, built by Grumman Corporation, accelerates the beam to 2.0 MeV. Although designed for cryogenic cooling, it is being converted to water cooling. RF power dissipation at design fields will be 600 kW. The ramped-gradient DTL accelerates the beam from 2.0 to 7.5 MeV. The 353-MHz rf power system has two 1 MW cw klystrons, one for the RFQ and one for the DTL. The controls and diagnostic systems are completed, but the RFQ has not yet been operated at power. The 46 drift tubes for the DTL have been fabricated, but the DTL assembly is incomplete.

A staged commissioning plan has been proposed for completion and testing of ACWL [26]. This includes stability and sparking studies, accelerating 20 mA D^- through the RFQ, changing the injector from D^- to D^+ and accelerating up to 90 mA D^+, and modifying the RFQ vanes to change from 2.0 MeV deuterons to about 3.0 MeV protons.

HILBILAC

At the Moscow Radiotechnical Institute, developers have proposed a different type of High-Intensity, Low-β Ion Linac (HILBILAC) for acceleration of beams of 1 A and higher. The HILBILAC consists of a resonator with drift tubes placed inside a bore of a superconducting solenoid. Thus the focusing is external to the accelerating cavity, even for the crucial first stages of acceleration. High values of accelerating and focusing fields enable beams of low emittance. Figure 5 shows the HILBILAC design. A cw HILBILAC with beam energy of 20 MeV and current of 250 mA is being designed [27] with tests proposed as shown in Table 6.

TABLE 6
HILBILAC Parameters

Accelerator	CW	TEST
Injection Energy	150 keV	100 keV
Output Energy	3.0 MeV	1.5 MeV
Frequency	352 MHz	352 MHz
Resonator Length	3.0 m	1.2 m
Field (Solenoid Temp.)	7.0 T (4.2 K)	7.0 T (4.2 K)
Transverse Emittance	1.2 π mm-mrad	1.2 π mm-mrad
Capture Efficiency	>90%	>85%
RF Power	760 kW	370 kW
Resonator Temperature	300 K	77 K

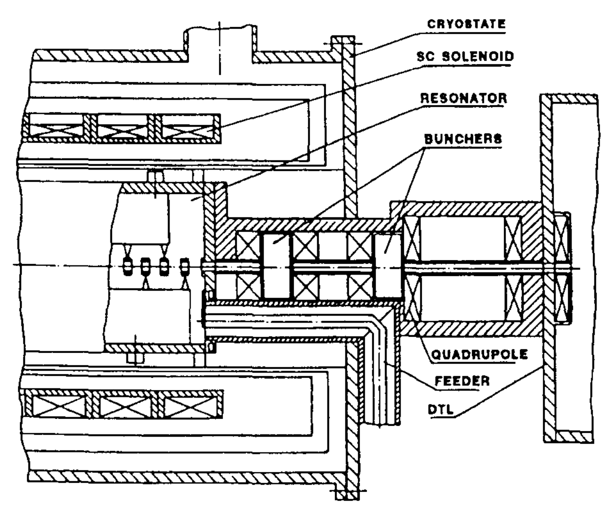

Fig. 5 The HILBILAC and matching section

Other Proposals

Several US labs have generated a preliminary design for a 35-MeV, cw deuterium linac for fusion materials testing using superconducting rf cavities [28], and there is interest in Japan in an energy-selectable linac for the same application. Funding is currently being sought for an international collaboration for materials testing called IFMIF (International Fusion Materials Irradiation Facility) [29].

Proposals for next-generation neutron spallation sources in the US and Europe have included high-duty-factor linacs with peak currents in the 100 mA range as injectors into compressor rings. The low-β part of the Los Alamos proposal (called LANSCE II) draws on the APDF design, but with the added complications of H- ion sources and beam chopping. This could be combined with an upgraded LAMPF accelerator to obtain 1-5 MW beam power [30]. The European Spallation Source (ESS) design [31,32] is similar, but with funneling at 5-7 MeV (after the RFQs). Both LANSCE II and ESS propose several options for the chopping, including two RFQs in each leg with a traveling wave chopper in between (at about 2 MeV). Other possibilities are chopping in the ion source or the LEBT, but these have not been proved.

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