OVERVIEW OF HIGH-POWER CW PROTON ACCELERATORS*

J. David Schneider♣, LANL, Los Alamos, NM87545, USA

Abstract

Worldwide interest is increasing in high-current (>10-mA) high-power (>1 MW) proton accelerators. Applications vary, but most uses rely on production of spallation neutrons, with a nominal proton beam energy of about 1000 MeV. Several separate, but collaborative, programs are pursuing development and testing of the low-energy sections of these accelerators, and are proceeding with detailed designs of the full accelerators. Operational reliability and near-elimination of beam trips are more important than ever, especially for the accelerator-driven systems (ADS) that might feed a sub-critical reactor that produces energy and transmutes long-lived isotopes. Both linear accelerators and cyclotrons are considered for this power range. Super-conducting structures are preferred for high-power linacs. High-power RF systems, extensive cooling, and extremely low beam losses are common needs for these machines. This paper discusses several high-power accelerator projects, addressing specifically the commonality of their designs, mentioning the options under consideration, and then summarizing what has been achieved or learned in the setup and testing of each. Somewhat more detail will be given on LEDA (low-energy demonstration accelerator), where a 6.7-MeV RFQ is being characterized with a 100-mA, cw proton beam.

1 INTRODUCTION

There are now several planned uses for copious numbers of neutrons, with energy spectra different from what can be readily achieved in a reactor. Figure 1 shows that spallation neutron sources, in which approximately 1-GeV protons strike a high-Z target, are the most-efficient producers of these neutrons, and are capable of producing a neutron with an expenditure of only about 25—30 MeV (2.5×10^{11} n/J) on the incoming proton. Even with these efficiencies, intended applications require that we provide a few 10s of mA of proton currents at beam energies of approximately 1000 MeV. This results in a beam power of 10 to more than 100 MW, 1—2 orders of magnitude higher than present high-power proton accelerators.

Several developmental programs are underway to build, test, and demonstrate these accelerators, beginning of course with the more-difficult, but essential, low-energy portions of the linacs. One of these, the low-energy demonstration accelerator (LEDA) at Los Alamos, in the US, has already shown feasibility of using an RFQ to accelerate 100 mA of cw beam to 6.7 MeV [1].

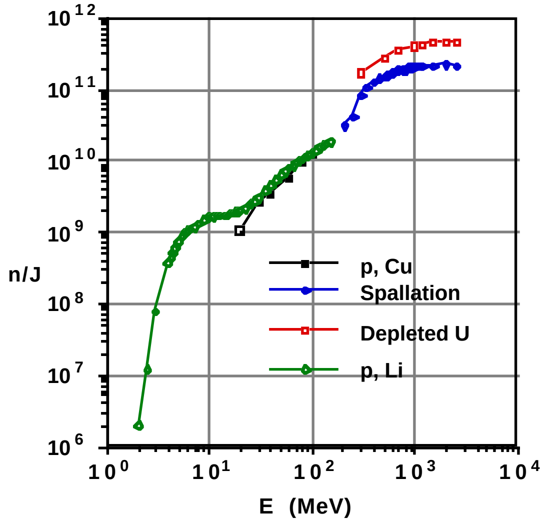

Figure 1. Efficiency of producing neutrons by energetic protons, showing different methods vs beam energy.

The major design issues are very similar on these different accelerators, even though the detailed implementation has subtle differences.

A variety of approaches were pursued on earlier attempts to develop a good cw accelerator; many of these were referenced in an earlier summary [2]. While these previous attempts did not reach all the design goals, they provided very valuable design data needed for the current linac programs.

2 TECHNICAL CHALLENGES

2.1 *Beam Formation*

Any successful accelerator requires a good ion source and injector of ions, with stable, long-term operation, and with a high-quality, low-emittance beam. Traditionally, ion injector run time has been limited by sparkdowns on the high-voltage column, and by filament lifetime inside the ion-source plasma chamber. In fact, injector beam interruptions and maintenance issues have contributed to a significant fraction of faults on most operational accelerators [3]. The operational test stands at both Los Alamos and Saclay [4, 5] are using similar injectors that are showing much-improved operational reliability.

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♣ Email: jdschneider@lanl.gov

2.2 Thermal Management

Without a doubt, the most-challenging engineering task for high-current cw normal-conducting accelerators is the several facets of thermal management. Power dissipation on the walls and other internal surfaces of normal-conducting structures are significantly increased by the desire to shorten linacs to reduce capital costs. Shorter structures require higher field gradients, with a resultant increase in surface currents and localized power densities. Additional localized increases in surface currents, often near support stems or RF coupling-iris edges, can easily cause serious power-density enhancement. Thermal gradients can be large, as can thermal transient effects.

Cooling demands, generally with high-velocity water, are exacerbated by a frequent need to maintain cavity resonance by control of the inlet cooling-water temperature. Precision resonance control typically requires cavity temperature regulation to 0.2 °C or better.

2.3 Low Beam Loss

To minimize the number of components that must be handled remotely during routine and special maintenance dictates that beam losses along the accelerator are kept to an absolute minimum. It appears that ‘hands-on’ maintenance is feasible only if average proton beam losses are less than about 1 nA/m, or a fractional per-meter loss of well under $1x10^{-8}$ of the beam current [6]. These low values dictate that extraordinary care be taken during design, construction, alignment, and operation to ensure that beam losses are kept at unprecedented low levels. Low beam losses demand good initial beam emittance, excellent matching along the accelerator and transport lines, and careful attention to beam halo formation and control [7,8].

2.4 Other Demands

Equipment protection becomes a more-critical issue simply because of the high beam power and the certainty of material damage if even a small fraction of the primary beam goes astray and strikes a beam tube or transport element. A related item is the development and incorporation of non-interceptive on-line diagnostics [9] for these high-power-density beams.

Because of the required very high beam powers and RF conversion efficiency, facilities demand many tens of Megawatts of power and cooling. Operational reliability, absence of unexpected beam trips, and beam control are exceptionally important, especially to avoid serious stress to the high-power targets. The operating costs, as well as the initial capital costs, are impressively large for these high-power accelerators.

Finally, there are the issues of international collaboration, financial support, and a long-term commitment by the sponsors. These topics are addressed to some degree by Hermannsfeldt [10].

3 PRESENT STATUS

General designs for these several accelerators have been progressing over the past several years, driven by a number of projects and interests and pursued semi-autonomously by several countries. Although the most common theme has been the interest in transmutation of radioactive waste [11], an active program of developing an alternative method for producing tritium was the major driver within the United States [12]. Within France, the impetus was largely for both tritium production and transmutation [13]. In the Japanese program, a broad range of objectives were listed, including also basic neutron science [14].

Some examples of the common design features of these different projects include:

- Use of either a microwave or volume ion source, to give long life, stable operation, and good reliability.
- Use of dual magnetic solenoids and space-charge neutralization for the low-energy transport line feeding into the RFQ.
- RFQ structures that are made of solid copper and brazed together, to achieve the best-possible cooling and thermal stability.
- RFQ operating frequencies near 350 MHz, to use the proven cw klystrons.

Nearly all projects plan to use superconducting structures for higher energies (>≈200 MeV). However, a variety of different structures are under consideration for the intermediate energies of 5—100 MeV.

4 TEST RESULTS

4.1 Testing on LEDA

The low-energy demonstration accelerator (LEDA) at Los Alamos has, in the past year, demonstrated its design-level performance at 100 mA. Its tested configuration was with a proton injector, a 6.7-MeV RFQ, transport line (HEBT), and beam stop, as depicted in Figure 2.

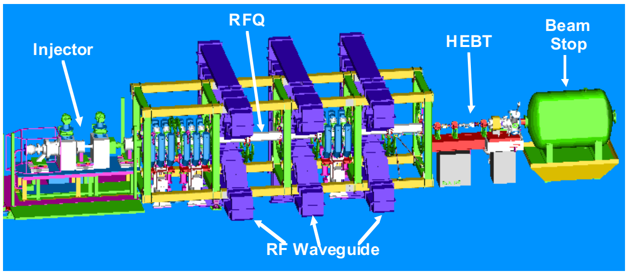

Figure 2. As-tested configuration of the LEDA beamline

The LEDA proton injector is described in an RSI paper [4]. Mechanical design of the RFQ [15], the HEBT [16], and the beam stop [17] were described at Linac98.

Initial testing was with lower-current pulsed beams, and those results were reported at PAC99 [18,19]. Damaged RF coupling irises were replaced in May of 1999, and testing then focused on demonstrating the acceleration of design current levels of 100-mA under cw conditions [20, 21, 22]. After more than eight hours of cw operation at 100 mA or above, we concentrated in January—April of 2000 on detailed characterization of the RFQ output beam. The first brief summary of this beam characterization is given in a companion paper [1] at this conference. That paper also identifies the more-detailed summaries that will be presented at LINAC2000.

Table 1 Parameters of the LEDA RFQ

Operating Frequency	350.00 MHz
Input Beam	75-keV, 110-mA, 0.2 π mm-mrad, (rms norm.) protons
Output beam	6.7-MeV, 100-mA, cw
Peak Surface Field	1.8 x Kilpatrick, 33 MV/m
Structure Power Loss	1.2—1.5 MW
Total RF Power	1.9—2.1 MW, from three klystrons, six windows & irises
Surface Heat Flux	11 W/cm^2 ave, 65 W/cm^2 pk
Structure Configuration	4 resonant segments, 8 brazed sections, each 1-m long
Structure tuning	Static: 128 slug tuners. Dynamic: water temperature

Another companion paper [23] describes the instrumentation used to measure beam properties in the output transport region. The HEBT (high-energy beam transport) line was designed [16] to be as simple as possible and to include only a minimum of components, including diagnostics. The HEBT's primary purpose was to carry the 670-kW beam to the beam stop. A single dual-axis carbon slow-wire profile monitor was used with short pulses and very low duty factor to make the majority of beam-quality measurements.

Off the LEDA beamline, we completed a series of high-power RF testing on a structure consisting of representative cavities for the coupled-cavity drift-tube linac (CCDTL) structure [24]. A persistent plastic deformation and detuning (by more than 1.4 MHz during the test phase) of this structure shows that we need to modify and improve the thermal control around the coupling slot of this new structure. The indicated modifications are being incorporated into the actual LEDA CCDTL accelerating structure, and we hope to test this structure at high RF power near the end of 2000.

The LEDA beam line is presently being reconfigured to add a string of 52 additional quadrupole magnets in a transport lattice immediately after the RFQ. A deliberate mismatch can be selectively introduced [25] at the beginning of this lattice, and special diagnostic gear will be used to measure and compare the induced beam halo with computer simulations [26].

4.2 Accelerator Studies and Testing in France

An excellent summary of the French program was given by Lagniel [13] at LINAC98. Although several different agencies are involved in many projects, the IPHI project at Saclay is actively involved in the construction of a 100-mA, 10-MeV, cw prototype.

The Saclay team has completed and tested a highly reliable [5] 100-mA, 95-keV, microwave-driven injector (SILHI) and are starting fabrication of a 5-MeV, 8-m long, 352-MHz RFQ, which has a design somewhat different from the LEDA 6.7-MeV 350-MHz RFQ. Optimization of vane-tip geometry [27, 28, 29] on this new RFQ indicates an expected transmission in excess of 99%.

Later additions to the IPHI may include a special DTL structure to less than 20 MeV.

A comparison of the main parameters of the LANL and Saclay RFQs is given in Table 2.

Table 2 – Comparison of two RFQ Designs

Parameter	**IPHI(Saclay)**	**LEDA (LANL)**
Output energy	5.0 MeV	6.7 MeV
Input energy	95 keV	75 keV
Peak surface field	1.7 x Kilpatrick	1.8 x Kilpatrick
Computed transmission	99.3 %	95 % (94% exp)
Vacuum pumping	6 sections	3 sections
Length	8 meters	8 meters
Average wall-power loading	11 – 15 Watts/cm^2	11 Watts/cm^2
Status	In fabrication	Tested with beam

4.3 JAERI/KEK Accelerator Complex

A complex and ambitious two-phase program [14] is planned for this complex, where the original intent was to address needs of the ADS, but is now focused primarily on spallation neutron science.

The Japanese project, supported jointly by Monbusho and STA (Science and Technology Agency), will provide beams for basic physics research, materials science with spallation neutrons, and serve as a demonstration test bed for ATW technology. The new joint project represents a merging of the Neutron Science Project at KEK, and the OMEGA Project at JAERI, both of which have evolved separately for a number of years. The machine configuration includes a 600-MeV proton linac (that may have a second implementation stage taking the beam energy to 1500 MeV), a 3-GeV synchrotron, and a 50-GeV final synchrotron. The linac will initially be a 400-MeV normal-conducting system, and will supply a 333 μA pulsed beam (25 Hz) to a transmutation R&D area. In a second stage, a 200-MeV section of super-conducting linac will be added to bring the beam energy up to 600 MeV. The plan is to complete the $1.5 B Phase I construction by the end of 2005.

A 324-MHz RFQ was tested [30] with 70 mA at 10% DF, and a peak current of 100 mA at 1% DF.

4.4 Status at INFN/Legnaro

The National Institute of Nuclear Physics (INFN) at Legnaro in Italy is pursuing the TRASCO project [31], that is designed to create and test a 100-MeV, 30-mA CW H+ beam. A 3-m cold-model of the planned 5-MeV RFQ has been tested [32], and design of the accelerating cavity is underway. Additional development work is underway on superconducting cavities to be used immediately after the RFQ. Part of their team is also considering the possibility of a superconducting RFQ.

4.5 Status at KOMAC

A similar RFQ is being developed [33] at the Korea Multipurpose Accelerator Complex (KOMAC). This RFQ has a cross-sectional structure very similar to that used on LEDA, but will be used to accelerate about 20 mA of either H+ or H- ions. Its 3.24-m length should provide an output energy of 3 MeV. Cold models of both the RFQ and the CCDTL structure [34] were described at PAC99.

5 FUTURE DIRECTIONS

We can expect that projects such as transmutation of waste will need linacs with about 1000 MeV beam energy, and currents of 10—60 mA. Advantages of the linac approach are the relatively straightforward extension in energy and current, and the proven feasibility of the low-energy proton launcher.

However, questions persist about the beam loss from halo, achievable operational beam-trip rates, total availability, fabrication and maintenance costs, and achievable functional accelerating gradient (length).

For the current region where they can compete, cyclotrons promise advantages in terms of relative compactness, simplicity, and ease of operation. There is the proven performance of the PSI cyclotrons [35] at 1.8 mA at 590 MeV, and the several commercial IBA cyclotrons at a few mA up to 18 MeV. There are proposals that these simpler, and lower-cost circular devices can be upgraded to beam currents of 5—10 mA, with output energies of 500—1000 MeV. However, unknowns include the successful low-loss beam extraction, maximum achievable currents, activation due to unpredicted beam loss, and the proper accounting for internal beam dynamics (as the transport codes for circular machines are somewhat more complex than those for linacs).

By comparison, we believe that it should be relatively straightforward to extend the performance of linacs to several 10s of mA of beam current, and energies to any desired energy, up to a few Gev. However, these structures are likely to be expensive, rather long, and have mostly unproven operational reliability in this high-current regime.

We expect to see increased emphasis on accelerator operational reliability and automatic fault recovery, particularly when accelerators are used to drive sub-critical reactors as waste transmuters. Target/blanket and subsequent power-producing systems appear to be less tolerant [36] to beam interrupts than the more-traditional science applications of accelerators.

The extension of super-conducting structures down to lower energies is likely to continue, as SCRF promises significant operational advantages, expecially for cw beams. For this low-beta regime, we must demonstrate cavity configurations different from the traditional elliptical niobium structures.

Understanding and reducing beam losses, particularly in the higher-energy sections, remains a top priority. Improvements in simulation codes and the use of parallel computers for modeling with 100 Million (or more) particles promises to provide a better understanding of the formation and growth of beam halo. Dedicated experiments are planned for the fall of 2000 on LEDA to measure the characteristics of beam halo caused by a deliberate mismatch immediately after the RFQ.

There is a need to design new high-power targets and beam stops, because proton beam powers of tens of MegaWatts are unprecedented. These beam targets represent a very challenging thermal design issue, as well as a severe radiation environment. But properly exploited, these high-power targets might offer an opportunity for experiments that can utilize an interesting neutron environment.

SUMMARY

Based on extensive development work done in the last few years, the technology of high-power proton accelerators looks very promising. The use of high-average-current proton accelerators offers exciting prospects for a new method of producing clean power and reducing the levels and volumes of radioactive wastes.

Feasibility of the low-energy part of the accelerator is proven, based on beam testing at LEDA and on SILHI. Demonstration of this technology should be advanced even further by additional work scheduled for the near term.

However, some development work needs to be done on:

- Improving accelerator operational reliability, to reduce the frequency and duration of unscheduled beam trips.
- Reducing capital and operational costs. Today’s accelerator designs represent predominantly a modification of lower average current research accelerators that have been modified to have improved cooling. As such, they may be over-engineered and more expensive in some respects.
- Controlling beam losses, such that hands-on maintenance is ensured for the majority of the accelerator and transport components.

REFERENCES

[1] H. V. Smith, “Commissioning Results from the Low–Energy Demonstration Accelerator (LEDA) Radio–Frequency Quadrupole (RFQ),” this conference.

[2] J. D. Schneider, “A Review of High Beam Current RFQ Accelerators and Funnels,” Proc. of EPAC’98, p.128—132.

[3] C. M. Piaszczyk, ”Accelerator as a Repairable System,” Second Workshop on Utilisation and Reliability of High Power Proton Accelerators, Nov, 1999 (to be published).

[4] J. D. Sherman *et al*., “Status Report on a dc 130-mA, 75-keV Proton Injector,” Rev. Sci. Instrum. **69** (1998) p.1003—8.

[5] R. Gobin, *et al.*, “Reliability of the High-Power Proton Source SILHI,” Second Workshop on Utilisation and Reliability of High Power Proton Accelerators, Nov, 1999 (to be published).

[6] T. P. Wangler, *et al*., “Basis for Low Beam Loss in the High-Current APT Linac,” Proc. of LINAC98.

[7] G. Haouat, “Experimental Results on Beam Halo,” PAC97.

[8] P. L. Colestock, *et al*., “The Beam Halo Experiment at the LEDA Facility: a First Test of the Core-Halo Model,” Proc. LINAC2000 (Monterey, 21—25 August 2000) (to be published).

[9] P. Ausset, *et al.*, “Beam Diagnostics for High-Intensity Accelerators,” Second Workshop on Utilisation and Reliability of High Power Proton Accelerators, Nov, 1999 (to be published).

[10] W. B. Hermannsfeldt, “Considerations for very-high-power accelerators,” Nucl. Instruments and Methods in Physics Research A 415 (1998) 256—262.

[11] G. P. Lawrence, *et al.*, “High-Power Accelerator Design for ATW Systems,” Report of Accelerator Technical Working Group ATW Roadmap. LA-UR-99-3225.

[12] K. C. D. Chan, *et al.*, “Development of RF linac for high-current applications,” Nucl. Instruments and Methods for Physics Research B 139 (1998) p 394—400.

[13] J-M Lagniel, “High Intensity Linac Studies in France,” LINAC98.

[14] Y. Yamazaki, *et al*, “Accelerator Complex for the Joint Project of KEK/JHF and JAERI/NSP,” Proc. of PAC99, p 513—517.

[15] D. Schrage *et al*., “CW RFQ Fabrication and Engineering,” LINAC98, pp 679—683.

[16] W. P. Lysenko, *et al*., “High-Energy Beam Transport Beamline for LEDA,” LINAC98.

[17] T. H. Van Hagan *et al*., “Design of an Ogive-Shaped Beamstop,” Proc. LINAC98, pp.618—620.

[18] J. D. Schneider, “Operation of the Low-Energy Demonstration Accelerator: The Proton Injector for APT,” PAC99, p503ff.

[19] K. F. Johnson, *et al.*, “Commissioning of the Low-Energy Demonstration Accelerator Radio Frequency Quadrupole,” PAC99.

[20] J. D. Schneider, “Initial Testing of the LEDA RFQ and Related Equipment,” Second Workshop on Utilisation and Reliability of High Power Proton Accelerators, Nov, 1999 (to be published).

[21] H. V. Smith, Jr., *et al.*, “Update on the Commissioning of the Low-energy Demonstration Accelerator (LEDA) Radio Frequency Quadrupole (RFQ),” Proc. 2nd ICFA Advanced Accelerator Workshop on the Physics of High-Brightness Beams (Los Angeles, CA) (in press).

[22] L.M. Young, *et al.*, “Low–Energy Demonstration Accelerator (LEDA) Radio–Frequency Quadrupole (RFQ) Results,” Proc. 2nd ICFA Advanced Accelerator Workshop on the Physics of High-Brightness Beams (Los Angeles, CA) (in press).

[23] J. D. Gilpatrick, *et al.*, “Beam Diagnostic Instrumentation for the Low-Energy Demonstration Accelerator (LEDA): Commissioning and Operational Experience,” this conference.

[24] R. L. Wood, *et al.*, “Status of Engineering Development of CCDTL for Accelerator Production of Tritium,” :LINAC98.

[25] T. P. Wangler, “Beam Halo in Proton Linac Beams,” Proc. LINAC2000 (Monterey, 21—25 August 2000) (to be published).

[26] J. D. Gilpatrick, *et al*., “Beam Diagnostics Instrumentation for a 6.7-MeV Proton Beam Halo Experiment,” Proc. LINAC2000 (Monterey, 21—25 August 2000) (to be published).

[27] R. Ferdinand, *et al.*, “Optimization of RFQ Design,” EPAC98.

[28] R. Ferdinand, *et al.*, “Field Description in an RFQ and its Effect on Beam Dynamics,” LINAC 98.

[29] B. Bondarev, *et al.*, “CW RFQ Designing Using the LIDOS.RFQ Codes,” LINAC98.

[30] M. Mizumoto, *et al*., “ A Proton Accelerator for Neutron Science Project at JAERI,” APAC98.

[31] Web Address:
http://trasco.lnl.infn.it/basic.htm#I.The program

[32] G. V. Lamanna, *et al.*, “Test of a Radio-Frequency Quadruple Cold Model,” PAC99.

[33] J. M. Han, *et al.*, “Design and Fabrication of the KOMAC RFQ,” PAC99.

[34] Y. S. Cho, *et al*., “Design and Cold Model Test of KOMAC CCDTL,” PAC99.

[35] Th. Stammback, *et al*, “The Cyclotron as a Possible Driver for ADS Systems,” Second Workshop on Utilisation and Reliability of High Power Proton Accelerators, Nov, 1999 (to be published).

[36] B. Giraud, “Preliminary Engineering Requirements on Accelerators for ADS,” Second Workshop on Utilisation and Reliability of High Power Proton Accelerators, Nov, 1999 (to be published).