LEDA – A HIGH-POWER TEST BED OF INNOVATION AND OPPORTUNITY*

J. David Schneider, & Richard L. Sheffield,
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

The low-energy demonstration accelerator (LEDA) is an operational 6.7-MeV, 100-mA, cw proton accelerator consisting of an injector, radio-frequency quadrupole (RFQ), and all associated integration equipment. Achieving this unprecedented level of performance (670-kW of beam power) from an RFQ required a number of design innovations. We highlight a number of those more-significant technical advances, including those in the proton injector, the RFQ configuration, the RF klystrons, the beam stop, and beam measurements. In addition to identifying the importance of these innovations to LEDA performance, we summarize the plans for further testing, and the possibilities for addition of more accelerating structures, including the possible use of very-low-beta super-conducting structures. LEDA's current and upgradable configuration is appropriate for several future high-power accelerators, including those for the transmutation of radioactive waste.

1 INTRODUCTION

As an integrated accelerator, LEDA made impressive technical advances [1], possible only because several critical subsystems showed performance beyond those previously achieved. We address a number of those advances that were critically important for reaching this performance level.

2 DESIGN FEATURES

2.1 Injector

The LEDA injector was developed [2] and refined over a number of years, building directly on improvements learned from previous projects, capitalizing most significantly on the development of the microwave-powered ion source [3] from Chalk River Laboratories. We also made a number of changes to this injector that resulted in improved performance.

In the interest of simplification and improving reliability, we eliminated all electronics at high potential. This required designing a special foil-lined insulator (made of polypropylene) that isolates the high-potential ion-source chamber from the grounded ECR solenoid magnets. Success in this isolation also required that the gas feed to the ion source be at high (near-atmospheric) pressure to avoid breakdown and discharge along the gas feed tube. The microwave feed also includes an in-line waveguide break, where a spacer of about 3-mm thickness separates the grounded WG from the continuing feedline into the source chamber.

We've continued the tradition (begun on the FMIT test stand of 1978—1985) of using a precision-shaped emitter surface (spherically convergent Pierce) and a single-gap extractor. This configuration is mechanical simple and provides a high-quality, low-divergence beam. We've used both a triode and tetrode configuration for the electron-trap assembly. Although the triode provided more beam current, most of our operations have been with the tetrode configuration because of better protection of the electron trap, and improved beam quality and stability.

During tuneup and commissioning, it is convenient to operate with variable current levels and differing values of duty factor. For this, we first used a continuously variable collimator, and than an insertable unit with three different sized apertures. Both work, but the engineering challenge is to provide proper cooling (easier with the fixed-aperture device). There are some additional operational challenges because the insertion of an interceptive device (particularly upstream of the first LEBT solenoid) adversely affects extractor high-voltage reliability.

Variable beam pulsing required some development with this microwave ion source. The successful approach proved to be that of using a high-voltage current modulator in the anode circuit feeding the 2.45-GHz magnetron. This modulator provides completely arbitrary pulse lengths and duty factors, with short, clean transitions.

We recently completed a brief test of a circularly polarized waveguide feed into the ion-source chamber. This showed the expected improved coupling into the plasma, cutting in half (to 400—500 W) the microwave power needed for operation..

Even though the LEDA RFQ is designed to accept a less-convergent input beam (≈60 mrad) than previous RFQs, we find that very close spacing is required between the last LEBT solenoid and the RFQ input. Using an electron trap near the RFQ entrance gives benefits, including improvement of current measurement [4].

We've demonstrated sustained high-current, stable operation with well over 140 mA extracted from the ion source, coupled with high power and gas efficiency, and a most-impressive proton fraction (90%). Ion-source excitation with isolated microwave power at 2.45 GHz eliminates the troublesome and lifetime-limiting internal filament. The resulting stable, uniform, low-temperature

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plasma provides a low-emittance beam (<0.2 π mm mrad) appropriate for RFQ injection.

Simple restart algorithms allow the computer control system to perform fully automatic and rapid recoveries from the majority of infrequent beam faults.

2.2 RFQ

LEDA's RFQ is one of the first implementations of a fully brazed, all-copper (OFE) structure [5]. This gives a maximum Q, thus minimizing the RF losses (down to 1.2—1.5 MW for LEDA!). We also use only passive slug tuners, relying on precise control of cooling water temperature to maintain RF resonance during operation. Elimination of movable RF seals at high power greatly enhances reliability. A resonant-control cooling system provides precise control (<0.2 °C) of water temperature, and allows changing the balance among the four resonant segments to effect an optimum longitudinal field profile.

The length (8-m or 9.3-λ) of this structure suggests tuning and field-stabilization challenges. A good field profile is ensured by using four 2-m-long segments, capacitively coupled to facilitate power flow [6].

The very soft OFE copper structure dictates that we have a rigid (in this case a heavy-duty steel) support structure to carry the weight of the RFQ. A special mechanically elaborate suspension system is used to isolate the weight (nearly 2300 kg) of the RF window and waveguide feed assembly from the RFQ body.{See Fig 1}

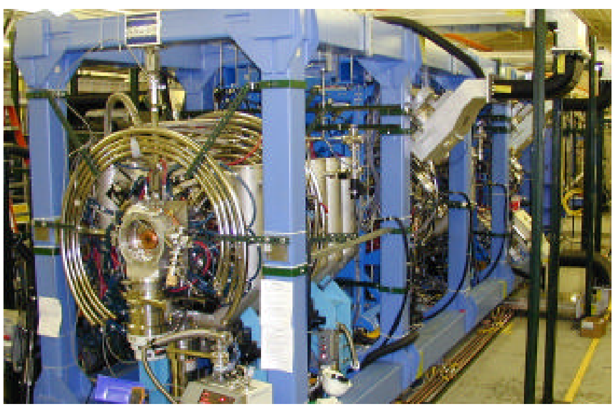

Fig 1. LEDA RFQ mounted in its support frame.

The only identified design flaw with this RFQ was the detail of the initial RF coupling irises that fed power into the structure. Wall current enhancement led to excessive heating at the ends of these slots [7], forcing us to replace the irises with a more-robust design.

2.3 CCDTL

The coupled-cavity drift-tube linac structure was invented [8] to capture the better characteristics of the more-conventional DTL and CCL structures. Although we are at least one year away from testing this 700-MHz CCDTL with beam, we have evaluated a number of cold models and have power tested five cavities of a hot model. It was more challenging that expected to provide adequate cooling and appropriate transient temperature control to the region of the coupling slot between the accelerating and coupling cavities. We observed a dramatic (almost 2 MHz) progressive shift in resonant frequency during the high-power testing and cycling of the hot model. This sensitivity indicates a need for better cooling and a more-sophisticated and detailed 3-D simulation of the critical coupling iris. Modifications, based on this experience, were made to the partially completed CCDTL structure and it will be fully instrumented and checked as a 'hot model' with RF power only before we install the structure onto the LEDA beamline.

2.4 Beam Stop

This beam stop [9] is a radical departure from conventional design, incorporating a small-diameter, integral water shield and very low trapped-air volume to enhance portability and shielding, and to ensure low air activation. We are able to use a small-diameter beam stop and neutron-shield assembly by expanding the beam in the longitudinal direction, rather than the transverse dimension. The near-total absence of air in the internal high-neutron environment, almost completely eliminates air activation. Additionally, the small-diameter internal beam-stop cartridge is easy to remove (by remote handling remotely if necessary) and store in a small cask. Audio sensors on the return water housing provide a simple means of detecting the onset of boiling and help prevent untimely burnout.

2.5 RF Power Systems

Although I/Q control has been used before, this is the first successful use at this high power under cw conditions. Use of highly adaptable PLCs and PLAs provided many variables with high-precision adaptability, crucial for supporting operations during all phases of RF and beam commissioning, as well as sustained operations.

The low-level RF control system uses a combination of analog and digital systems to provide an optimum mix of fast response and precision control for amplitude and phase control, equipment protection, and maintenance of structure resonance.

A desire to keep the load presented to the ac grid largely unaffected by variable RF power output requires the 1.3-MW klystrons [10] to include a full-power (1.9-MW) electron-beam collector. During initial LEDA operation, we inflicted moderate, but non-catastrophic, damage to several of our klystron collectors, due to some beam non-uniformities and uneven water flow. The tube vendor has incorporated a collector redesign to correct these deficiencies.

2.6 Diagnostics and Beam Transport

On-line diagnostics [11] must be limited to non-interceptive devices, because of the high beam powers. AC and DC toroids, beam-position monitors (BPMs), and capacitive or resistive wall-current monitors provide most of LEDA's cw measurements. Wire scanners are used at low duty factors for detailed measurements of beam profiles. Development is underway on a residual-gas excitation video-profile monitor. In the interest of simplicity, the high-energy beam transport includes a minimum of transport elements and diagnostics to carry the beam from the RFQ into the beam stop.

3 SUMMARY OF TEST RESULTS

LEDA has demonstrated [12] two important aspects of 6.7-MeV beam operation.

- Many hours of steady 90--100-mA beam operation demonstrated feasibility of the injector, RFQ, RF systems, controls, diagnostics, beam stop, and utility system integration and suggest optimism for higher-energy beam operation as well.
- In addition, a three-month period of testing with pulsed beam verified the excellent output beam quality, close to that predicted for this unique RFQ.

Most significant on LEDA is the integration of systems at high power levels and with many first-of-a-kind features incorporated into its first use.

These systems have been integrated, checked out and used extensively to show overall feasibility of this concept and detailed design. Much of the unique challenge with the LEDA beam has been the high beam power (0.67 MW). This, combined with the extreme peak power densities (exceeding 10 MW/cm^2), demands precise steering and focus control, and leaves little margin for any beam impingement.

4 FUTURE WORK

The LEDA is in a condition and position to support follow-on programs that need a high-power cw beam, in at least the following areas:

- Provide tests of beam halo. In addition to the beam characterization and high-current demonstrations done last year, we will make detailed measurements [13] of beam halo in the next year. {See Fig 2} An array of 52 quadrupole magnets are installed after the RFQ, and a deliberate mismatch in the first two quadrupoles should create a measurable halo. The measured halo will be compared with the predictions of the beam-simulation codes.

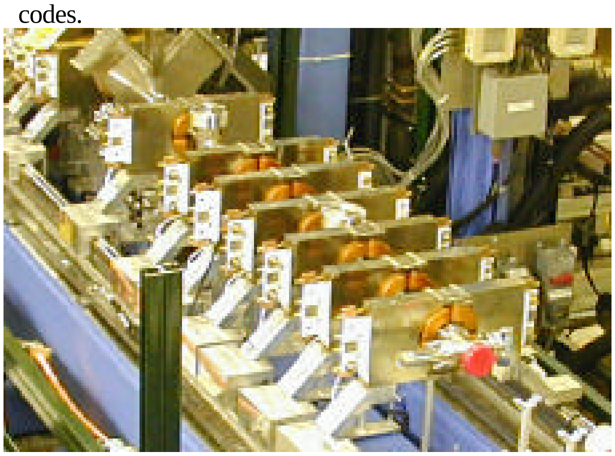

Fig 2. First 7 of the 52 quadrupole magnets in a 11-m section of beamline following the LEDA RFQ.

- Demonstrate operational reliability. Several months of planned operation with repeated start-ups, interspersed with periods of extended steady operation should provide much-needed and valuable data on the weak points, the nature of failures, time to recover, and identify effective repairs.
- Demonstrate performance of new accelerating structures. The available facility space, utilities, and other infrastructure at LEDA make it an excellent test bed for possible installation of additional accelerating structures, that can extend the energy beyond 8 MeV. Possible candidates include more CCDTL structures or spoke-resonator super-conducting structures.
- Facilitate refinement of procedures, operator training, and design confirmation.

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