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TITLE: **Update on the Commissioning of the LEDA Low-Energy Demonstration Accelerator (LEDA) Radio-Frequency Quadrupole (RFQ)**

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UPDATE ON THE COMMISSIONING OF THE LOW-ENERGY DEMONSTRATION ACCELERATOR (LEDA) RADIO-FREQUENCY QUADRUPOLE (RFQ)*+

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The LEDA RFQ is a 100% duty factor (cw) linac that delivers >100 mA of H^+ beam at 6.7 MeV. The 8-m-long, 350-MHz RFQ structure accelerates a dc, 75-keV, 110-mA H^+ beam from the LEDA injector with >90% transmission. To benchmark RFQ performance, beam measurements are made with low and high current beams for both pulsed and cw beam operation. Pulsed-beam currents of 110 mA and cw-beam currents of 100 mA have been achieved. The RFQ has operated continuously for as long as 56 min at the 90-mA output level.

1 Introduction

The LEDA RFQ [1] is a 100% duty factor (cw) linac capable of delivering >100-mA of H^+ beam at 6.7-MeV. The 8-m-long, 350-MHz RFQ structure [2] is designed to accelerate the dc 75-keV, 110-mA H^+ beam from the LEDA injector [3,4] with >90% transmission. The primary objective of LEDA is to verify the design codes, gain fabrication knowledge, understand beam operation, and improve prediction of costs and operational availability for the full 1000- to 1700-MeV APT accelerator. Even though the output energy is low (6.7 MeV), the average beam power (670 kW) of LEDA ranks it with the LANSCE accelerator as the two highest power proton linacs in the world. Clearly, radiation shielding and power handling are important design issues. Preliminary RFQ commissioning results for pulsed beams with low rep-rate and short pulse lengths are given in Ref. [5].

2 LEDA Configuration

The accelerator configuration for beam commissioning of the LEDA RFQ is shown schematically in Figure 1. The major accelerator subsystems are the injector [3]
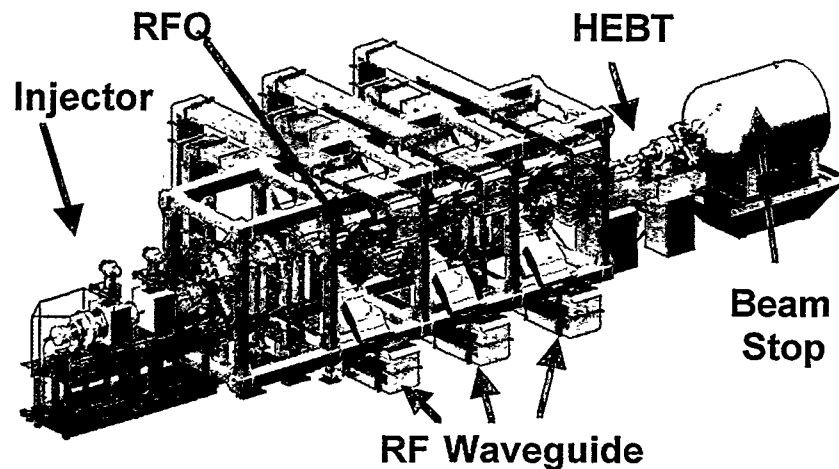
Figure 1. LEDA configuration for RFQ commissioning.

(source and Low Energy Beam Transport (LEBT)), RFQ [2], High Energy Beam Transport (HEBT) [6], and the beam stop [7].

The injector matches the 75-keV, 110-mA dc proton beam into the RFQ. A 2.45-GHz microwave proton source, a single-gap extractor, and dual magnetic solenoids provide this beam. The ion source requires only 500-800 W to create a suitable plasma from which a beam having >90% proton fraction and >30% gas efficiency is extracted [3]. The single-gap, spherically convergent extractor provides a beam with emittance <0.2 π mm-mrad (normalized). A microwave power modulator is used to provide beam pulsing [8] for commissioning and beam-tuning activities.

The layout of the low-energy beam transport (LEBT) beamline optics and diagnostics is shown in Figure 2. The beamline optics include two solenoids and two steering magnet pairs for proper matching and injection into the RFQ. The suite of diagnostics include two view screens (interceptive diagnostic intended only for low-power-density beams), three non-interceptive video profile diagnostics (VD1, VD2, & VD3), three DC current diagnostics (DC1, DC2, & DC3), and two pulsed beam current monitors (AC1 and AC3). The pulsed beam current monitors are located right after the source and directly before the RFQ. Multiple extended beam runs with this injector have shown it delivers the required current, emittance, and stability. Measured erosion rates show a predicted maintenance-free lifetime exceeding 400 hours. The LEBT physics design [4, 9, 10] is in good agreement with the mechanical design [11] and detailed measurements [12].
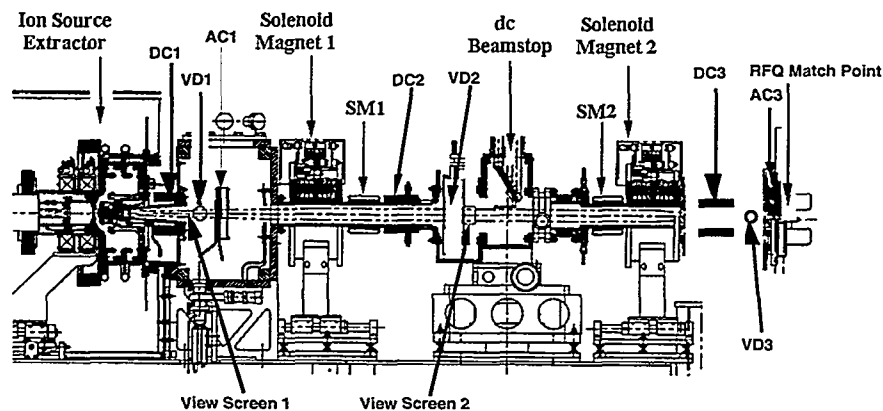
Figure 2. The LEDA LEBT beamline, including optics and diagnostics.

A photograph of the LEDA RFQ with the injector in the rolled-back position is shown in Fig. 3. The LEDA RFQ [2, 13, 14] is unique in terms of its long physical length (8 meters), high output energy (6.7 MeV), large beam power (670 kW), and cooling requirements (1.2 MW). It is constructed as an all-brazed, 100% copper (OFE) structure, and assembled from eight separate 1-meter-long sections [2]. When in operation, its only active resonance control is by modulation of the input water temperature.

Of the eight separate sections, two are used for 350-MHz RF power feed [15] via six 350-kW coupling irises and three sections provide vacuum pumping. Each section includes 16 static slug tuners, used only for tailoring the initial field distribution. A complete description of the LEDA RFQ, including the RFQ RF-field tuning procedure and beam measurement results, is given in Ref. 16.

A photograph of the LEDA HEBT showing the location of beamline optics and diagnostics is given in Figure 4. Beam direction is from left to right. The function of the LEDA HEBT is to characterize the properties of the beam and transport the beam with low losses to a shielded beam stop. The beamline optics consists of four quadruples and two X-Y steering magnets. The HEBT beam diagnostics are described in [17]: they include 5 beam position monitors (BPMs) [18], 2 DC and pulsed toroids [17], 3 capacitive pickoff probes [17], and 2 profile monitors [19]. This set of diagnostics allow for measurements of beam current (pulsed beam, DC beam, and bunched beam), transverse centroids, longitudinal centroids (i.e. beam energy from time–of–flight and beam phase), and transverse beam profiles (wire scanner and video fluorescence).
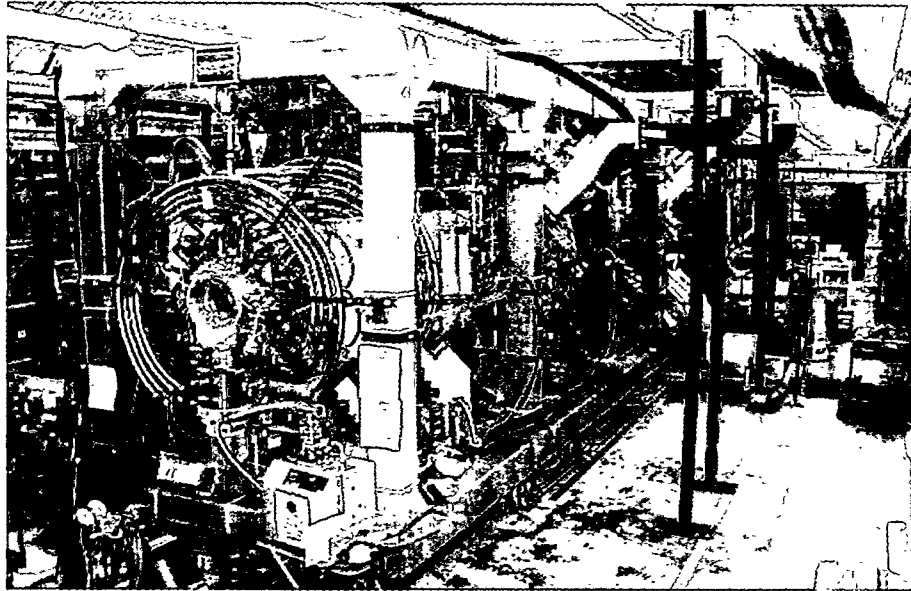
Figure 3. A photograph of the LEDA RFQ looking from the low-energy toward the high-energy end.
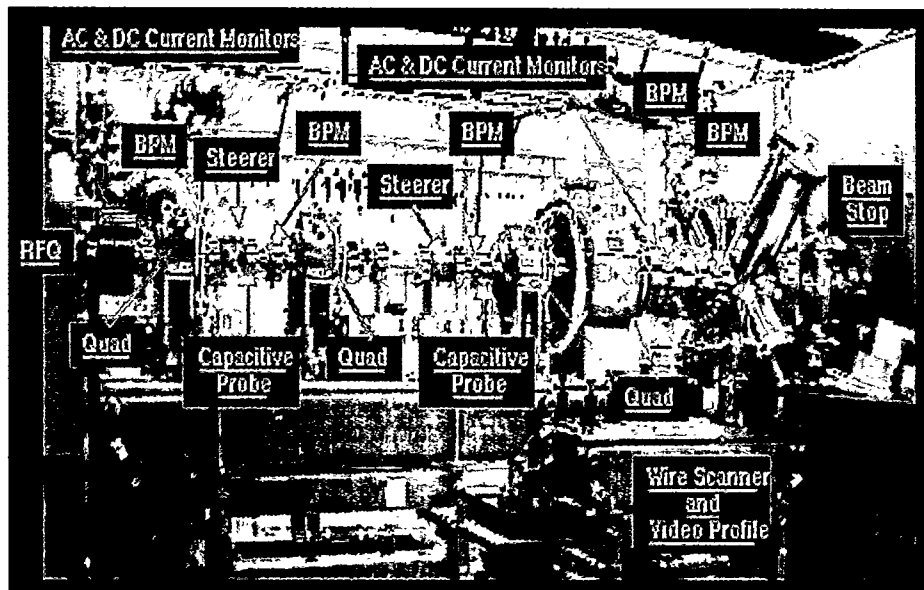

Figure 4. Layout of HEBT beamline optics and diagnostics. Beam direction is from left to right.
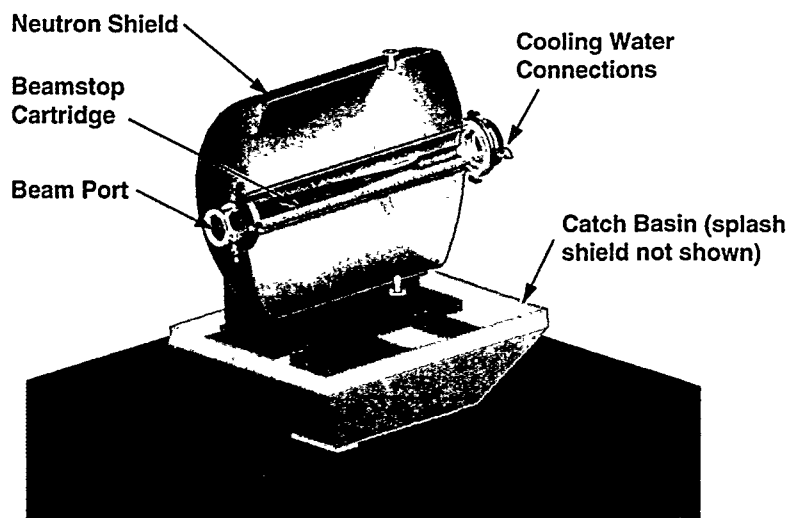
Figure 5. LEDA ogive beamstop. The beam enters from the left and impinges on the inside surface of the nickel beamstop cartridge.

The 6.7-MeV, 100-mA RFQ output beam impinges on a nickel ogive beamstop [7] that is mounted inside an aluminum vessel that contains water (Fig. 5) to shield against prompt neutrons.

Three 1.2-MW, 350-MHz, cw RF-power systems are installed to power the RFQ - one klystron feeds RFQ section B1 and two klystrons feed RFQ section D1. The six 350-MHz RF vacuum windows have been tested at power levels >950 kW [20]. During operation, these windows are run at power levels up to 400 kW each.

The LLRF controls system performs a number of functions including: set and maintain the proper phase and amplitude of the accelerating cavities [21], distribute reference signals along the beam line, monitor cavity resonance condition, and provide many field signals from cavity pickup loops.

LEDA is using a distributed control system based on EPICS [22, 23]. Many LEDA sub-systems have localized control with dedicated PLCs (programmable logic controllers), but all operational status and control commands are accessed through the EPICS operator interfaces. Eight EPICS stations in the control room are used to control the LEDA accelerator and its subsystems as well as to monitor the status of these devices. An automated control routine provides prompt, hands-off, full-beam recovery from injector high-voltage sparkdowns. The LLRF system, working through EPICS, provides prompt, hands-off, full-beam recovery from RFQ out-of-

frequency-lock excursions. The safety and protection systems are monitored using EPICS - in the case of the fast-protect system the beam is shut down within 10-20 μsec of an interrupt and the first fault is recorded by EPICS.

Operational run-permit is incorporated into the EPICS control system, with scores of interlocks to ensure that components and systems operate only when the risk of equipment damage is very low. A hard-wired fast-protect system ensures the near-immediate (10- to 20-μs) turnoff of the beam in event of beam spill as detected by either fast ionization chambers or by differential current loss detected by the beam toroids. Totally separate from both these equipment safety systems, a personnel access control system (PACS) ensures that all personnel are excluded from the beam tunnel whenever beam or high rf power is present. This PACS is very similar to the recently upgraded system in use at LANSCE.

3   Beam Commissioning

Beam commissioning of LEDA has followed a graded approach. Because beam operation was the first fully integrated test of all LEDA systems, commissioning proceeded cautiously. The assumption was that, in all likelihood, subsystems and their interfaces to other subsystems would not operate as expected. Initial beam commissioning of the RFQ was in pulsed rather than cw mode. To minimize or even eliminate beam related equipment damage, commissioning began in a pulsed low–power mode defined by short-pulse lengths (i.e. $\leq$ 500 μs), low-rep rate (i.e. 5 Hz), and low-beam current (i.e. $\leq$ 10 mA). Besides protecting equipment (e.g. RFQ, HEBT, and beam stop), beginning beam commissioning with short-pulse lengths, low–rep rate, and low-beam currents offers two other advantages. First, it allows for the operation of a wire scanner interceptive beam diagnostic that is unavailable at higher beam-power densities. Second, the most complete characterization of the RFQ can occur only when operating in a low-power pulsed mode.

4   Beam Commissioning Results

The initial RFQ pulsed beam commissioning results are reported in Ref. 5. At the time of that report, the RFQ output beam current and RFQ transmission of 40 mA and 95%, respectively, had been achieved. Also, the RFQ output energy had been measured by time-of-flight to be very close to the design 6.7 MeV [17].

The RF system configuration was changed before the start of cw beam commissioning. For low-duty-factor pulsed beam commissioning there were eight RF feeds into the RFQ, four from one klystron into RFQ section B1 and four from

120

100

80

Current (mA)

60

40

20

0

21-Jul-99 31-Jul-99 10-Aug-99 20-Aug-99 30-Aug-99 9-Sep-99 19-Sep-99 29-Sep-99 9-Oct-99 19-Oct-99
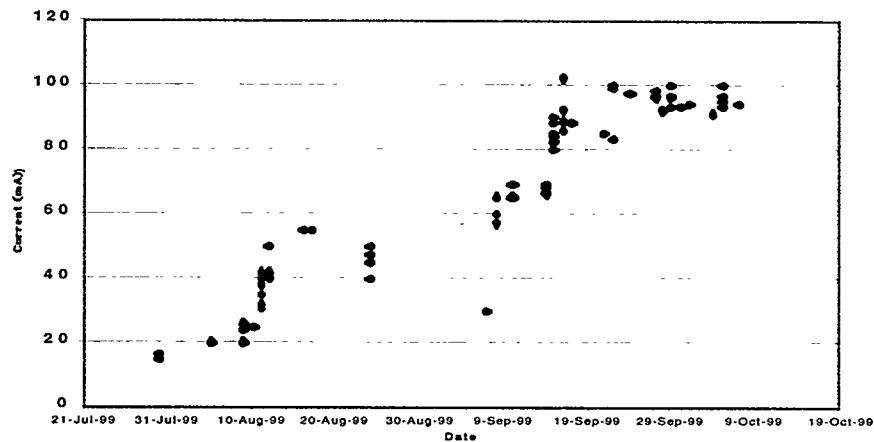
Date

Figure 6. Progression of LEDA RFQ cw output current during commissioning.

a second klystron into RFQ section D1. To provide the power needed (2.1 MW) for full cw current beam commissioning, the addition of a third klystron, with four more RF feeds into RFQ section C1, was planned. However, the ridged-waveguide sections between the RF windows and the RFQ multipacted at RF power levels up to 100 kW per feed. Because 1.2 MW is needed to condition the RFQ to the design vane voltage, multipacting would likely occur with twelve RF feeds. Thus, the RF system was rearranged to feed the power from one klystron into RFQ section B1 through two RF feeds, and to feed the power from two klystrons into RFQ section D1 through four RF feeds. To achieve the design RFQ vane voltage without beam (1.2 MW) the power through each RF feed is 200 kW: to achieve the nominal RFQ field level with beam (2.1 MW), the power through each RF feed is 350 kW.

As the performance of all systems was verified, commissioning proceeded in a stepwise fashion to the full cw high–power mode, 100% duty cycle and full current (100 mA). The progress in raising the cw RFQ output beam current from 16 mA in late July, 1999 to >100 mA in mid September 1999 is illustrated in Fig. 6.

The LEBT configuration was changed during the course of cw beam commissioning. As discussed in Ref. 16, it became obvious that RFQ output currents above ~90 mA were not achievable with ~30 cm between LEBT solenoid #2 and the RFQ match point. A LEBT model that included beam deneutralization just before the RFQ predicted that 100 mA RFQ output currents could be obtained if the distance between LEBT solenoid #2 and the RFQ match point were to be shortened to ~15 cm (allowing an increase of the beam injection angle into the RFQ) and an electron trap were to be included just in front of the RFQ (to minimize the length of the

space-charge deneutralized beam channel just in front of the RFQ). These changes, made in early September, 1999 required the removal of DC3 and VD3 (Fig. 2). The shortened LEBT configuration has resulted in pulsed RFQ output currents up to 110 mA and cw RFQ output currents of >100 mA. See Ref. 16 for details.

For a tetrode extraction system [3] and the injector parameters adjusted to give the best combination of RFQ output beam current and RFQ transmission, values of 100 mA and 93-94%, respectively, for these parameters are achieved (Fig. 7). The RFQ transmission is determined using AC toroids (AC3 at the RFQ entrance [Fig. 2] and an AC toroid at the RFQ exit [Fig. 4]) for both pulsed and dc beams. In the absence of a DC toroid just in front of the RFQ (DC3 was removed when the distance between LEBT solenoid #2 and the RFQ match point was shortened to ~15 cm), the RFQ dc beam transmission is measured by switching from cw to "high-duty-factor mode" where the pulse length is 99.7 msec and the pulse repetition rate is 10 Hz – the resulting 300 μsec hole in the beam allows using the AC toroids for the transmission measurement. The HEBT transmission is determined using the AC and DC current monitors at the RFQ exit and the HEBT exit (Fig. 4). Typically the HEBT transmission is >99% for both pulsed and CW beams.
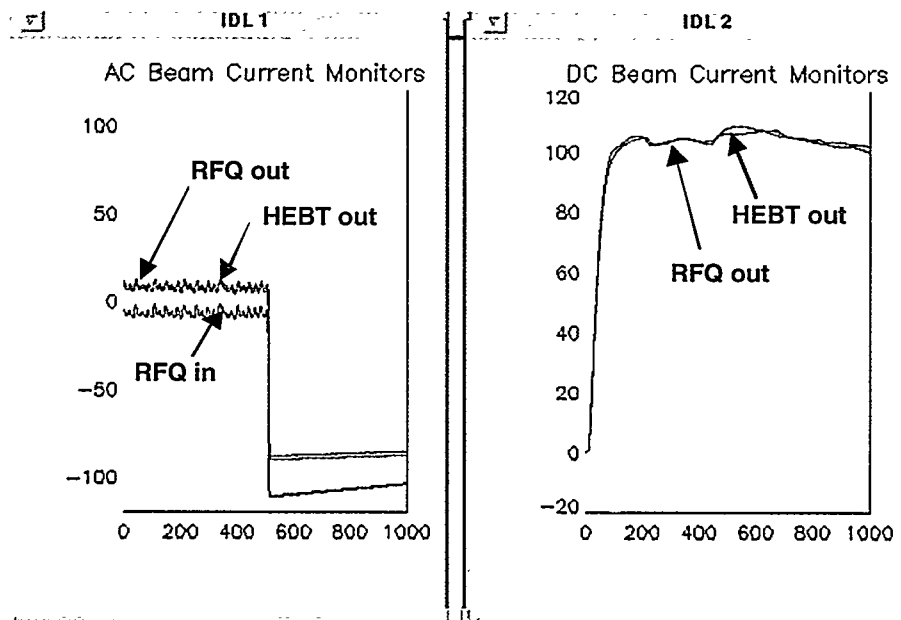

Figure 7. Left: The RFQ input (black), RFQ output (red) and HEBT output (blue) pulsed current at the end of the 40-msec, 10-Hz, 100-mA current pulse as measured with the AC toroids. The horizontal scale is 2 μsec/pixel. Right: The RFQ output (red) and HEBT output (blue) current at the start of the 40-msec, 10-Hz, 100-mA current pulse as measured with the DC toroids. The horizontal scale is 25 μsec/pixel.

The changes outlined above, plus improvements in the LLRF system and in the injector, allowed continuous operation of the RFQ at the 90-mA RFQ output current level for as long as 56 min without faults. RFQ transmissions of 92-93% are typical for these dc beams. The archived data for a 50 min continuous run is shown in Fig. 8. The squares are the RFQ output current (92-90 mA) measured using the DC toroid at the RFQ exit. The diamonds in are the beamstop power and the triangles are the RF power into the RFQ, both determined calorimetrically. Because the beam energy is 6.7 MeV, the beam current is estimated from the beamstop power (590 kW) and from the net power into the RFQ (670 kW) to be 88 mA and 100 mA, respectively.

The HEBT (Figs. 4 and 9) and beamstop (Figs. 5 and 10) designs allow safe dissipation of the proton beam power on the inside surface of the beamstop. The TRACE 3-D and LINAC (3D) codes are used to design the HEBT [6]. The input to these codes is the PARMTEQM output beam from the RFQ. The 1-σ and 5-σ
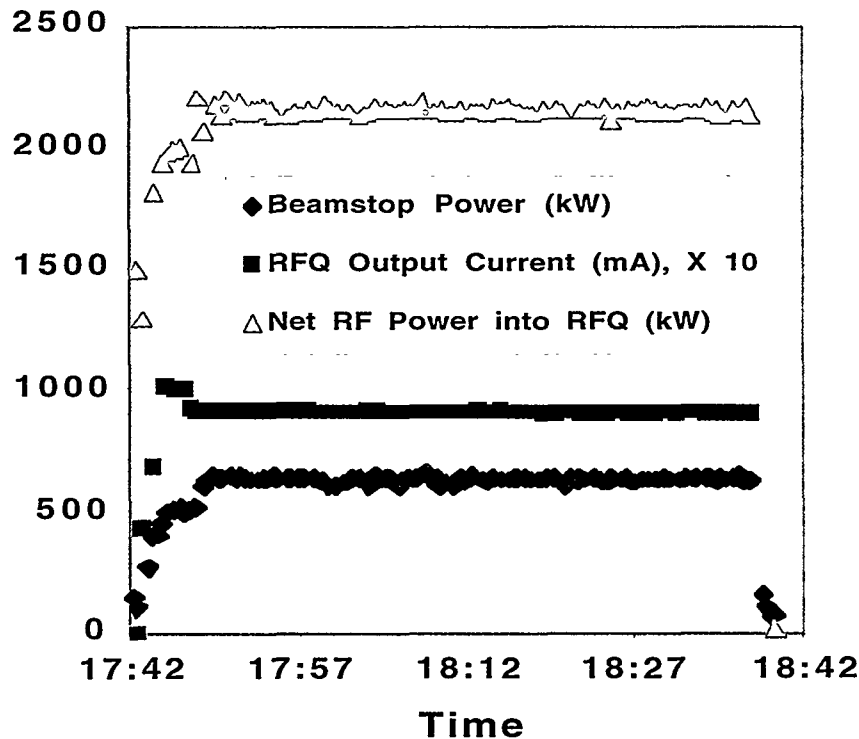

Figure 8. The cw output current from the RFQ (red squares), power deposited into the beamstop (blue diamonds), and RF (forward) power delivered to the RFQ (green triangles) for a 92-90 mA, 6.7 MeV beam.
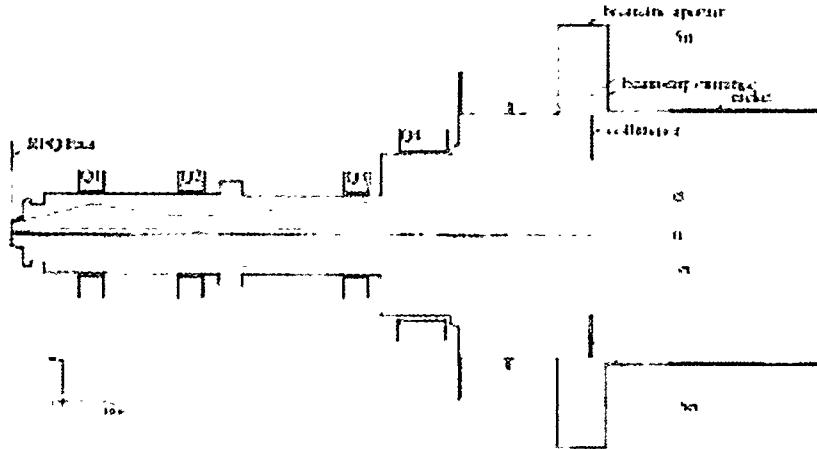
Figure 9. The 1-σ and 5-σ HEBT beam profiles for the standard tune.

HEBT beam profiles for the standard tune is shown in Fig. 9 (Fig. 2 of Ref. [6]). The standard tune rms beam size is <1/5 of the HEBT bore.

The ogive beamstop design codes used approximate LINAC (3D) profiles, with the beam being treated as a point source in the last HEBT quadrupole. The calculated axial heat flux profile in the x (horizontal) plane is shown in Fig. 10 (Fig. 4 of Ref. [20]). When the full 100-mA, 6.7-MeV beam is dissipated on the ogive surface the maximum heat flux is calculated to be <175 W/cm^2, allowing the temperature of the nickel ogive to be kept <180 °C, thereby preserving its structural integrity.
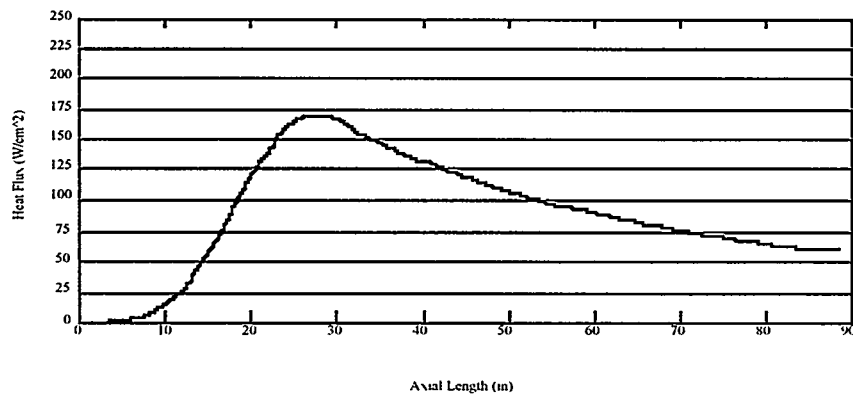

Figure 10. The axial heat flux profile in the beamstop in the x plane. The beam enters from the left.
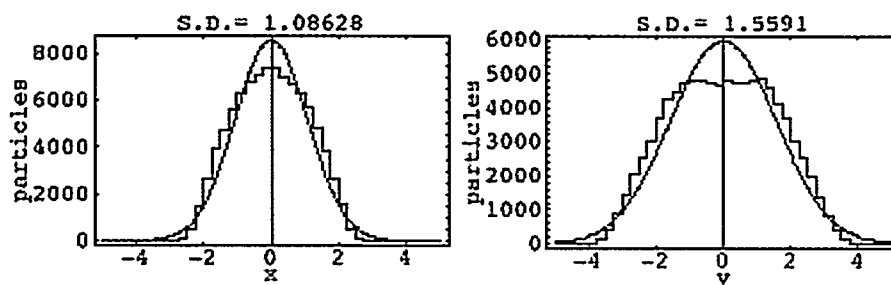
Figure 11. The LINAC (3D) calculated beam profiles at the wire scanner for the standard tune. The horizontal scales are cm. The widths from the Gaussian fits are 10.8 and 15.7 mm, respectively.

The HEBT is tuned by adjusting the measured pulsed-beam profiles to the design profiles and by centering the beam in the HEBT The beam profiles predicted by LINAC (3D) at the wire scanner location are shown in Fig. 11. These profiles are calculated using LINAC (3D) with the PARMTEQM RFQ output file that was used
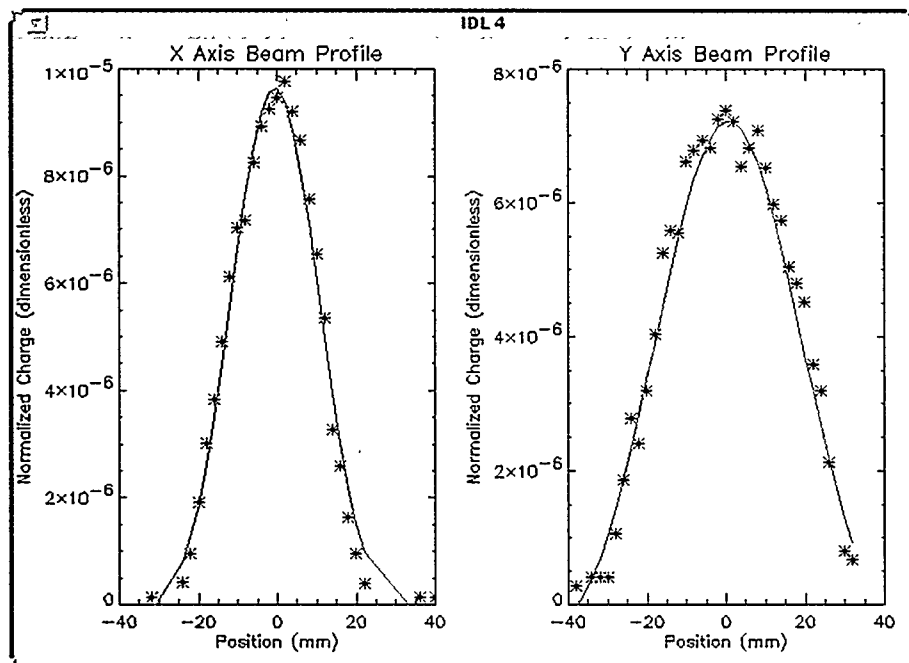

Figure 12. The measured beam profiles for a 85-mA, 5-Hz, 100-μsec pulsed beam. The measured data (astericks) are compared to Gaussian profiles.

in the HEBT design (Fig. 9). The predicted x and y widths are 10.8 and 15.7 mm, respectively.

Because of the very high beam power, the initial beam tuning is done with low-duty-factor pulsed beam, typically 10-Hz, 20-msec, 100-mA current pulses. The HEBT quadrupoles are set at the values for the standard tune [6]. In order to measure the beam profile, the pulsed beam duty factor is reduced to <1%, with the limit being set by the beam power density. For 100 mA, we restrict the beam pulse length to 100 μsec at 5 Hz. The beam profile for a 85-mA, 5-Hz, 100-μsec pulsed beam is shown in Fig. 12. The widths are 9.1 and 13.9 mm in x and y, respectively. These widths are intentionally adjusted to ~90% of design to protect a collimator placed just in front of the beamstop.

Once the beam tune through the RFQ and HEBT into the beamstop is verified with the wire scanner and the beam position monitors, the repetition rate is set to 10 Hz and the pulse length is increased to ~80 msec in 20-msec steps, with minor adjustments in ion source, LEBT, and, if necessary, HEBT parameters after each step. Once a satisfactory tune is achieved at 10 Hz and 80 msec, the pulse length is then increased to 99.7 msec and the tune adjusted again, making sure that the RFQ transmission is >92%, before switching to cw operation. This procedure has allowed safe, reliable tuning of the cw, 100-mA, 6.7-MeV proton beam.

5 Summary and Conclusions

The integrated performance of the LEDA injector (ion source and LEBT), RFQ, HEBT, beamstop, HPRF, LLRF, and control systems is encouraging. RFQ output pulsed-beam currents of 110 mA and cw-beam currents of 100 mA have been demonstrated at 92-94% RFQ transmission. Observed RFQ transmission and output current is consistent with PARMTEQM simulations based on PARMELA modeling of the present injector configuration. Long-term operation at 100-mA cw will be demonstrated before detailed RFQ characterization measurements begin.

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