

# The Tandem-RFQ Linac Booster at Sandia National Laboratories

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**Abstract.** A booster linac based on the Radio Frequency Quadrupole (RFQ) linac has been put into routine operation on the 6.5 MV EN tandem accelerator at the Sandia National Laboratories (SNL) Ion Beam Materials Research Lab (IBMRL) for Radiation Effects Microscopy (REM) experiments with high energy, heavy ion beams. The booster linac consists of two RFQ stages that accelerate heavy ions with  $m/q < 8$  from 0.25 MeV/amu up to 1.22 MeV/amu in the first stage and to 1.90 MeV/amu in the second stage to produce high Linear Energy Transfer (LET) ions for REM. This RFQ linac has a total length of 6.0 meters and is installed on a new experimental beam line at the SNL IBMRL to measure single-event upset (SEU) cross-sections of integrated circuits (ICs) and to perform radiation hardness research using REM with the associated Ion Electron Emission Microscope (IEEM). This paper presents the recent beam measurement results from operation of the RFQ linac with beams from silicon to gold and compares these results with theoretical beam dynamics calculations. It also describes the details of the experiments to measure SEU cross-sections and IEEM.

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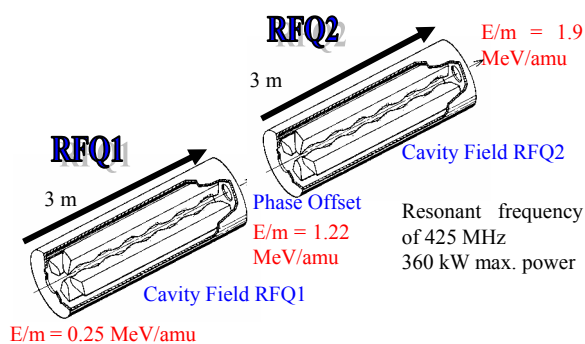
## INTRODUCTION

Electronics in spacecraft and satellites are exposed to high-energy solar, galactic, and inter-galactic cosmic radiation. In addition, terrestrial radiation can also affect earth-based electronics. To study the effects of radiation on integrated circuits (ICs) and to insure the reliability of electronic devices, cosmic and terrestrial radiations are simulated with ion beams from particle accelerators. The Sandia National Laboratories (SNL-Albuquerque, NM) Ion Beam Materials Research Laboratory (IBMRL) has used Radiation Effects Microscopy (REM) [1] for many years to study radiation-hardened ICs. For these radiation-hardened ICs, ions with extremely high charge deposition or linear energy transfer

(LET) [2] are needed to produce electronic malfunctions such as single event upsets (SEU). The SNL tandem Van de Graaff alone cannot accelerate the heaviest ions of interest to high enough energies to achieve these higher LETs [2]. Therefore, a new, higher LET acceleration system for heavy ions has been developed at SNL. Heavy ions from the 6.5 MV EN tandem accelerator at an energy/mass,  $E/m = 0.25$  MeV/amu are injected into a two-stage Radio Frequency Quadrupole Linear Accelerator Booster (RFQ linac), which accelerates the ions to  $E/m = 1.9$  MeV/amu. The  $E/m$  is proportional to the square of the ion velocity. For example, the RFQ-boosted tandem has produced 53 MeV  $^{28}\text{Si}$ , 120 MeV  $^{63}\text{Cu}$ , 241 MeV  $^{127}\text{I}$ , and 374 MeV  $^{197}\text{Au}$  ions that are used for IC upset studies.

## RADIO FREQUENCY QUADRUPOLE LINEAR ACCELERATOR

The RFQ linac is a relatively new type of linear accelerator that derives its name from its use of radio frequency voltages and quadrupole focusing. Its development was a major innovation in the linear accelerator field. In 1970, two Russian scientists, I.M. Kapchinskii and V.A. Teplyakov, proposed a radio frequency (RF) linear accelerator (linac) design with a symmetry structure of an electric quadrupole [3]. The RFQ linac is especially well suited for accelerating ions in the velocity range of  $\sim 0.004$  to  $0.06$  times the speed of light. The electric fields of the RFQ, which accelerate and focus the ions, are produced by the RF fields applied to four vanes in a cavity structure in the original configuration proposed by Kapchinskii and Teplyakov [3], as shown in Figure 1. By using a potential function description, they discovered how to shape the four electrode vanes to produce the electric fields required to accelerate and focus the ions. This development of a practical way to apply velocity-independent electric focusing in a low-velocity accelerator gave the RFQ linac a significant strong-focusing advantage compared with conventional linacs that used velocity-dependent magnetic lenses. This allowed the RFQ linac's practical range of operation to be extended to lower velocities, therefore eliminating the need for large, high-voltage DC accelerators for injection of the ion beam into the linac.



**Figure 1.** SNL four-vane RFQ accelerator sections. The electrodes are modulated to produce longitudinal electric fields to accelerate low-velocity ions. The four electrodes are excited with quadrupole-mode RF voltages to focus the beam. The wavelength of the vane modulations increases as the ions gain energy.

The RFQ linac concept was experimentally verified by the Russians in 1974. The Western world did not

become aware of the new Russian RFQ linac design until 1977 when informal discussions were held at an accelerator conference in the USSR. A presentation by J.J. Manca at Los Alamos National Laboratory (LANL) in October 1977 led to intense activity to develop the Russian RFQ linac concept in the United States. At LANL, plastic models of the vane structure were fabricated and computer models were developed to simulate the effects of the perturbed quadrupole electric fields on the ion beams [4,5]. In 1979, LANL began construction of a proof-of-principle RFQ linac, which was successfully demonstrated in February 1980 [6].

### The SNL RFQ Linac

The RFQ linac at SNL is an accelerator structure composed of two AccSys Technology Inc. three-meter long RFQ resonators aligned end-to-end. The resonators are the compact four-vane structure shown in Fig. 1, operating at a resonant frequency of 425 MHz. The vane tips are precisely contoured for both accelerating and focusing a wide range of ion species with an RF electric field. Each RFQ linac is enclosed in a vacuum chamber and is equipped with a 3 1/8 inch coaxial drive loop and two high-vacuum ion pumps. The RFQ linac is mounted on a rigid support structure that is  $\sim 6$  m in length. Each RFQ resonator is connected to an AccSys Model 12TW360 RF amplifier, which is capable of providing 360 kW of peak RF power to each resonator. A PC computer control system is used for remote control and monitoring of the RFQ linac. Both RFQ resonators must be operated at the same resonant frequency. Since the resonant frequency depends upon the temperature of the RFQ linac, a re-circulating, water-cooling system controls the temperature of the RFQ linac during operation. The higher-energy resonator (RFQ2) uses a slug tuner and amplifier frequency control circuitry to maintain its resonant frequency exactly to that of the lower-energy resonator (RFQ1). In the RF amplifiers, internal phase, amplitude, and frequency control loops are designed to precisely control the electric fields in the two high-Q resonant cavities of RFQ1 and RFQ2.

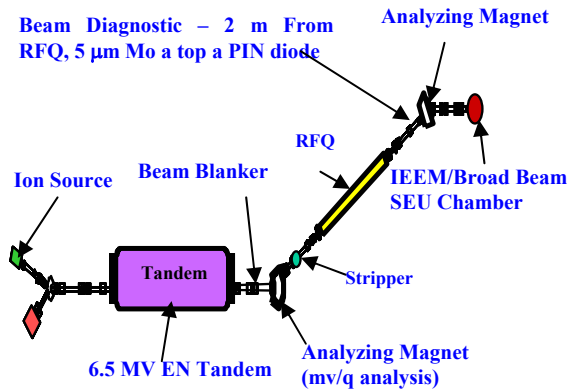
### High-Energy, Heavy-Ion Results with the SNL RFQ Linac

The RFQ linac at SNL is a booster linear accelerator designed to accelerate a variety of ion species from  $0.25$  MeV/amu to  $1.22$  MeV/amu with one resonator and to  $1.9$  MeV/amu with both resonators. After magnetic momentum/charge

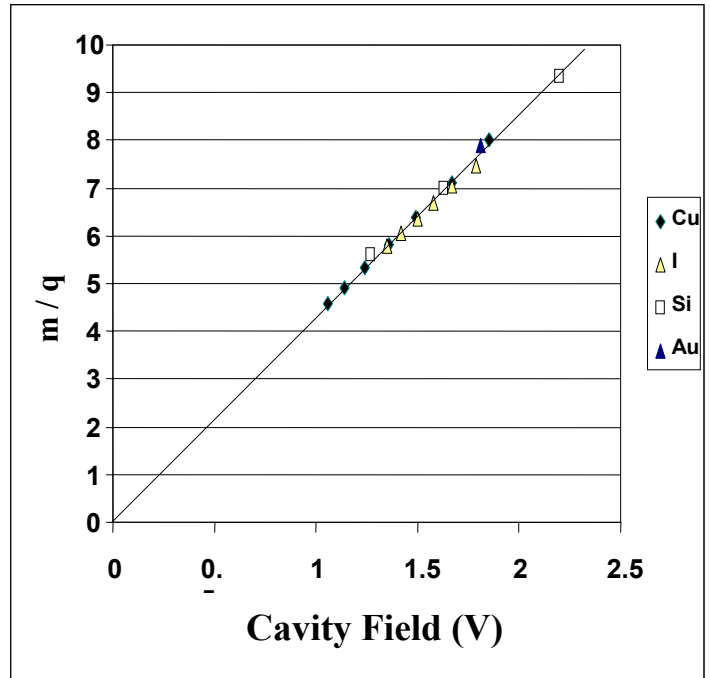
analysis, the 0.25 MeV/amu DC ion beams from the 6.5 MV EN tandem accelerator are injected into the RFQ linac. See Fig. 2. Since only a limited number of ions are needed for SEU measurements, the RFQ linac is usually operated at 100 Hz with a pulse width of 50  $\mu$ s for a duty cycle fraction of 0.005. Since the RFQ linac is designed for ions with a mass to charge ratio of  $m/q \leq 8$ , the 0.25 MeV/amu ions from the tandem accelerator are passed through a stripper foil before injection into the RFQ linac. The cavity electric field necessary to accelerate different  $m/q$  ions is directly proportional to the  $m/q$  of the ion. Figure 3 shows the required RFQ1 cavity field versus  $m/q$  for Si, Cu, I, and Au ions in different charge states. Figure 4 shows the accelerated  $^{127}\text{I}$  ion intensity versus cavity field for RFQ1. The peaks in Figure 4 correspond to the different charge states of the  $^{127}\text{I}$  ions and therefore to the different data points for  $^{127}\text{I}$  in Figure 3. To accelerate ions through both RFQ1 and RFQ2 to 1.9 MeV/amu, both RFQ cavity fields and the phase offset between the two RFQs have to be set at certain values. Figure 5 shows the accelerated  $^{197}\text{Au}^{25+}$  ion intensity versus the cavity field of RFQ2 for a fixed cavity field for RFQ1 and a fixed relative phase set between the two RFQs. This figure shows that once you filter the different charge state beams with RFQ1 by setting the cavity field, that chosen charge state is favored in RFQ2.

Figure 6 shows the calculated and experimental transmission of 1.9 MeV/amu  $^{28}\text{Si}^{4+}$  ions through RFQ2 as a function of the cavity field. The calculated values are for beam at the exit of the RFQ, while the experimental values are measured  $\sim 2$  m downstream with a  $3.6 \times 3.6 \text{ mm}^2$  PIN diode. As seen in the transmission of the  $^{197}\text{Au}^{25+}$  ions in Figure 5, the transmission of the  $^{28}\text{Si}$  ions to the detector  $\sim$  two meters away from the end of RFQ2, is affected by the output beam divergence that occurs as the different charge state ion beams exit the RFQ2. Hence, the beam current measured at the detector is a maximum only at the design value of the RFQ2 for the chosen  $m/q$ , where the beam divergence is lowest and the most beam can drift to the detector. This change in the output beam divergence is also the reason why the peaks appear in Figure 4 for the  $^{127}\text{I}$  beam. Each individual charge state has a minimum output beam divergence at the cavity field values given in Figure 3, and at the centroids of the intensity peaks plotted in Figs. 4, 5 and 6. At cavity fields below that value, the charge state is not being accelerated, and above that cavity field, the charge state has a divergent output, which causes beam losses downstream. The calculations shown in Figure 6 are at the RFQ2 exit, so the output beam divergence does not affect the transmission.

Therefore, the calculated transmission reaches a maximum value and does not fall off like the experimental values.



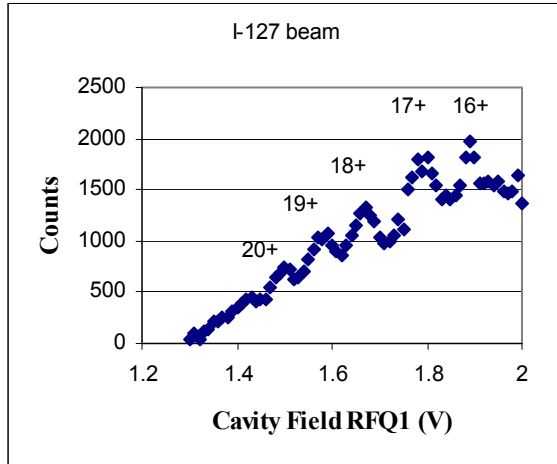
**Figure 2.** Schematic of the 6.5 MV EN tandem plus RFQ linac booster and the Ion Electron Emission Microscopy system.



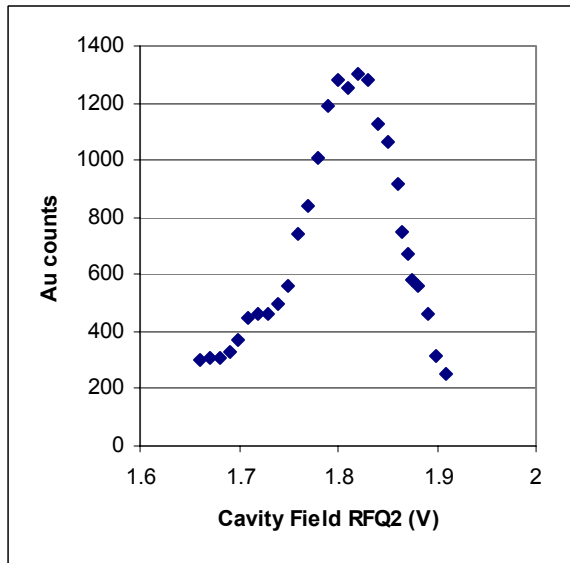
**Figure 3.**  $m/q$  versus cavity field for Si, Cu, I, and Au ions accelerated by the 6.5 MV EN tandem accelerator and RFQ1.

In order to be able to maximize the intensity of the 1.22- or 1.9-MeV/amu ions after the RFQ linac, a 5  $\mu$ m Mo range-out foil is used to stop the 0.25 MeV/amu ions that are not accelerated and just drift through the RFQ. The energies of the 1.22- and 1.9-MeV/amu ions are then measured in a PIN diode following the Mo foil and the cavity fields and

relative phase are adjusted. The beam diagnostic is then removed and the 1.22- or 1.9 MeV/amu ions are magnetically analyzed and passed into the scattering chamber for the broad-beam SEU, Ion Beam Induced Charge Collection (IBIC), and Ion Electron Emission Microscopy (IEEM) tests.

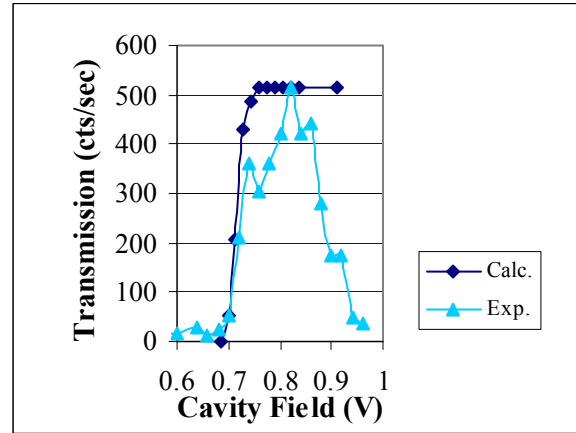


**Figure 4.** Intensity of the  $^{127}\text{I}$  beam after acceleration by the tandem accelerator and the first RFQ linac (RFQ1) and passed through the range-out foil. The peaks correspond to the different charge states of  $^{127}\text{I}$ .



**Figure 5.** Intensity of the  $^{197}\text{Au}^{25+}$  beam after acceleration by the tandem accelerator and both RFQ accelerator sections. The peak corresponds to the Au counts versus the cavity field of RFQ2 for a set cavity field of 1.95 for RFQ1 and a set relative phase between the two RFQs of  $-2.4$ . The differences in cavity fields for RFQ1 and RFQ2 for

maximum transmission is due to slightly different diode detectors for the two RFQs.



**Figure 6.** Calculated and experimental transmission through RFQ2 of  $^{28}\text{Si}^{4+}$  ions at 1.9 MeV/amu. The calculated values are for beam at the RFQ exit, while the experimental values are measured  $\sim 2$  m downstream with a  $3.6 \times 3.6 \text{ mm}^2$  PIN diode. The structure in the experimental data is due to poor statistics of just a few hundred counts per second.

## SEU CROSS SECTION MEASUREMENTS

Recent experiments utilizing the tandem and the RFQ linac to measure SEU cross sections in integrated circuits (IC) were made with 241 MeV  $^{127}\text{I}$  and 374 MeV  $^{197}\text{Au}$  ions. See McDaniel et al. [7] in this proceedings for details. For the memory chips studies, a pattern is written into the memory and the chips are irradiated with a known fluence of ions. The memory is read out to determine the number of errors. Repeating for different ions with different LETs allows the SEU cross sections to be determined as a function of LET and therefore the threshold determined for single event upsets in different ICs. For the I measurements, the ion flux was  $3.5 \times 10^3$  ions/cm<sup>2</sup>/sec and was uniformly spread over a spot size of 1.3 cm x 2.5 cm. The LET of the  $^{127}\text{I}$  ions was 58 MeV/mg/cm<sup>2</sup> at the surface of the IC and 55 MeV/mg/cm<sup>2</sup> 5.6  $\mu\text{m}$  deep through the active circuit and to the substrate. Measured SEU cross sections were  $3.5 \times 10^{-3} \text{ cm}^2$  to  $7.4 \times 10^{-4} \text{ cm}^2$  for different circuits for the 100 s experimental runs. To measure lower cross sections, ion fluxes can easily be increased by factors of 5-10 if necessary by increasing pulse width and the number of transmitted ions. Different LET values can be obtained simply by rotating the IC so that the ion beam impinges at an angle to the surface of the IC.

## ACKNOWLEDGEMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000. Work at UNT supported in part by the National Science Foundation, the Office of Naval Research, Texas Advanced Technology Program, and the Robert A. Welch Foundation.

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