CHARACTERIZATION OF A VARIABLE ENERGY DEUTERON RFQ SYSTEM FOR NEUTRON PRODUCTION

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Abstract

A variable energy radio-frequency quadrupole (RFQ) linac system, the LANSAR™ Model DL-5, has been developed at AccSys Technology, Inc. as a fast neutron source. The energy variation is accomplished by coupling two RFQ cavities with an adjustable rf power phase shift between them to provide two modes of operation, beam acceleration or beam transport. The beam dynamics code PARMTEQ was used to model this system and calculate the output beam parameters as a function of phase shift between the two RFQs. Output beam measurements were performed using a Rutherford back-scattering (RBS) technique and beam scanner developed for this system. The results are compared to the calculations.

1 INTRODUCTION

A compact variable energy RFQ linac, the LANSAR™ Model DL-5, has been developed by AccSys Technology, Inc. for the production of fast neutrons for resonance neutron radiography. The system was designed to accelerate deuterium ions to two discrete energies for injection into a high pressure windowless deuterium gas target that employs a rotating shutter. Precise deuteron beam energies are required for the neutron radiographic imaging technique being employed. The beam size at the gas target must also be small as this determines the spatial resolution of the imaging system.

This system produces a deuteron beam in the selected energy range of 3.60–4.90 MeV by directly coupling two RFQ cavities with an rf power phase shift between them to provide two modes of operation, beam acceleration or beam transport. Depending on the relative rf phase shift between RFQ1 and RFQ2, RFQ2 can either add or subtract energy from the 3.94 MeV deuteron beam from RFQ1. However, the large bore and strong transverse focusing permits most of the particles to be transmitted through RFQ2, regardless of phase.

2 SYSTEM DESCRIPTION

The Model DL-5 linac system consists of a deuterium ion injector and two close-coupled RFQ resonators. Each RFQ is powered by an rf amplifier supplying up to 300 kW of peak rf power via a semi-rigid coaxial cable. The high energy beam transport system (HEBT), consists of a beamline, a toroid for monitoring the pulsed output beam current, two orthogonal steering magnets and a quadrupole triplet for beam focusing. The performance specifications of the LANSAR™ Model DL-5 system are presented below in Table 1.

Table 1. Model DL-5 Performance Specifications

Operating frequency	425	MHz
Injector output energy	25	keV
RFQ1 output energy	3.94	MeV
RFQ2 output energy via transport mode via acceleration mode	 3.90 4.86	 MeV MeV
Injector output current (pulsed)	12	mA
RFQ2 output current (pulsed)	6-8	mA
Maximum average current	0.1	mA
Linac total length	4.4	m
Maximum beam pulse width	90	µs
Repetition rate (variable)	20-200	Hz
RF power (RFQ1/RFQ 2)	280/160	kW
Maximum rf duty factor	1.5	%
Nominal beam transmission (RFQ1/RFQ2)	84/95	%
Nominal HEBT beam transmission	> 95	%

3 VARIABLE BEAM ENERGY

The beam dynamics code PARMTEQ was used to model the linac design. As shown in figure 1, the calculated beam dynamics indicates a strong periodic variation of the accelerator output energy as a function of the relative phase shift between the two RFQ structures.

The Rutherford back-scattering (RBS) technique was used to measure the output deuteron energy as a function of the relative rf phase shift between RFQ1 and RFQ2. A water-cooled, thick tantalum target was mounted at 45° to the beam direction. The scattered particles were counted with a silicon surface barrier detector which was calibrated using an ^{241}Am α-source and positioned at 90° to the beam direction.

Significant pile-up and detector dead-time were initially observed in the RBS measurements due to the linac's low duty cycle (1.5%), high peak current (6–8 mA), and low repetition rate (100–200 Hz). Significant beam de-focussing and collimation had to be employed in order to avoid the pile-up effects, resulting in an average acquisition time of ~15 min per RBS spectrum.

The measurements were performed with the linac operating at two duty cycles: 0.32% (repetition rate of 80 Hz, beam pulse width of 40 μs) and 0.6% (repetition rate of 125 Hz, beam pulse width of 40 μs). The results of the RBS measurements are presented in figure 2. These measurements correlate very well with the calculations presented in figure 1 and display the calculated periodicity. The variations of the beam energy for the two selected duty cycles are within the measurement errors.

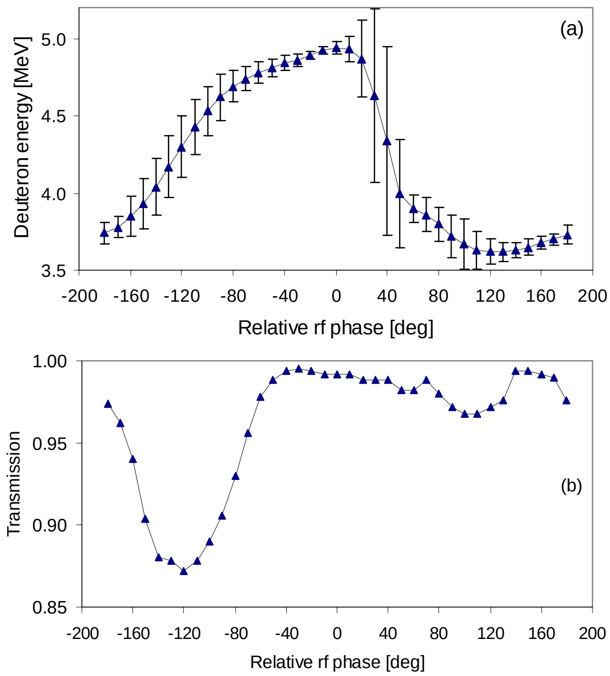

Figure 1. Calculated beam energy (a) and transmission (b) as a function of relative phase shift.

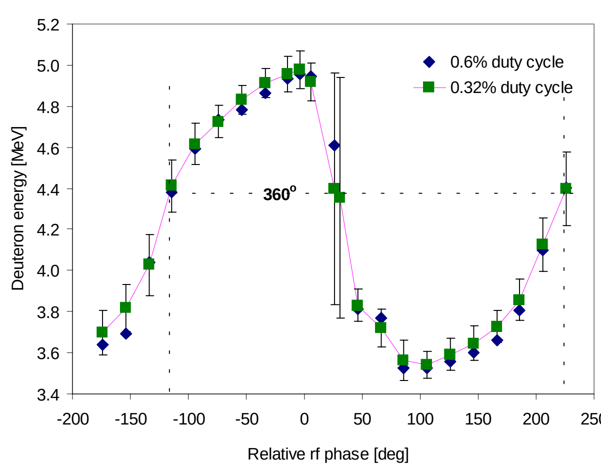

Figure 2. RBS measured beam energy as a function of relative rf phase shift at two beam duty factors.

The output deuteron energy is stable in the 4.7-4.9 MeV energy region over the relative phase range from 0° to –60° about the design synchronous phase of –28°. It is also stable over the 3.5 – 3.7 MeV energy range for relative input phases from 80° to 180°. The mean value of the output energy varies from 3.62 MeV to 4.93 MeV over the full 360° phase range. The exact amplitude and phase settings for operation in the dual energy mode depend on the operating duty factor, since the operating frequency and hence the phase relationship change slightly with the duty factor. However, for the two duty factors used for the RBS measurements, these changes were within the experimental measurement error.

The deuteron beam energy was also measured with RFQ2 switched-off, i.e. in the condition where the ions are only accelerated in RFQ1 but subsequently drift through RFQ2. The measured beam energy was 3.90±0.05 MeV.

4 BEAM CURRENT PROFILES

A standard National Electrostatic Corporation beam profile monitor (Model BPM-45) was used to measure the output deuteron beam profile. In this BPM, a single wire formed into a 45° helix is rotated about the axis of the helix at a frequency of about 16 Hz. It sweeps across the beam in two independent directions in every cycle. The secondary electron current released from the wire as it intercepts the beam is a measure of the beam intensity.

The normal use of this BPM is not effective with the linac operating at a beam repetition rate of 100 Hz and beam pulse width of 100 μs. Primarily due to the frequency mismatch, the BPM's wire misses most of the beam pulses. In order to use the BPM more effectively the trigger signal generated by the BPM during every revolution (traditionally used as a trigger signal for the oscilloscope) was used to trigger the accelerator. By varying the delay of the trigger signal, the deuteron beam pulses were probed at different spatial positions, and the intensity of the beam was measured on a digital oscilloscope. Knowing the trajectory of the wire, its dimensions and rotation frequency, the trigger delay time was scaled into the linear extent of the beam.

The toroid, steering magnets and quadrupole magnets were removed from the HEBT to provide access to the beamline for the BPM. The beam spot dimensions were measured at several positions downstream from the exit aperture of RFQ2 at different settings of the relative rf phase, i.e. energy. A gaussian function was fit to all measured beam profiles and the FWHM was calculated. An example of the beam profiles obtained at 284 mm from the RFQ2 aperture, for the relative rf phases of -80° (E_d~4.65 MeV), 0° (E_d~4.90 MeV) and 160° (E_d~3.70 MeV), is presented in figure 3.

The results of measurements of the deuteron beam profiles as a function of the relative rf phase shift are presented in figure 4 for a distance of 284 mm and 404 mm from RFQ2 exit. The beam diverges in both planes as it travels down the beamline because the focusing elements have been removed. There are two regions of relative rf phase (deuteron energies) where the beam dispersion is small and varies little with small changes in the relative rf phase.

These regions are separated by a region of high beam dispersion, which corresponds to a transition region between high and low deuteron energy, as seen in figure 4. The large beam dispersion in this region is caused by the large deuteron energy spread within the bunch, which results in spatial de-focusing.

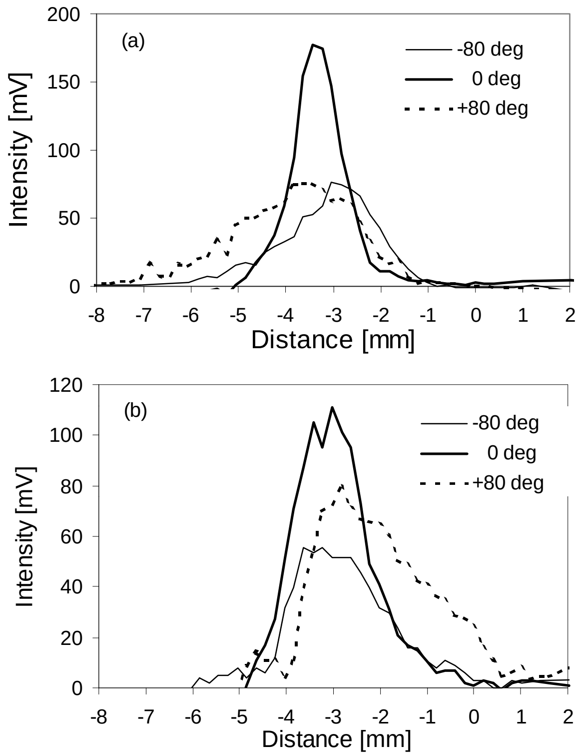

Figure 3. Measured x (top) and y (bottom) beam profiles at a distance of 284 mm from RFQ2 exit. The *x*-axis is the distance from the center of BPM's helix axis.

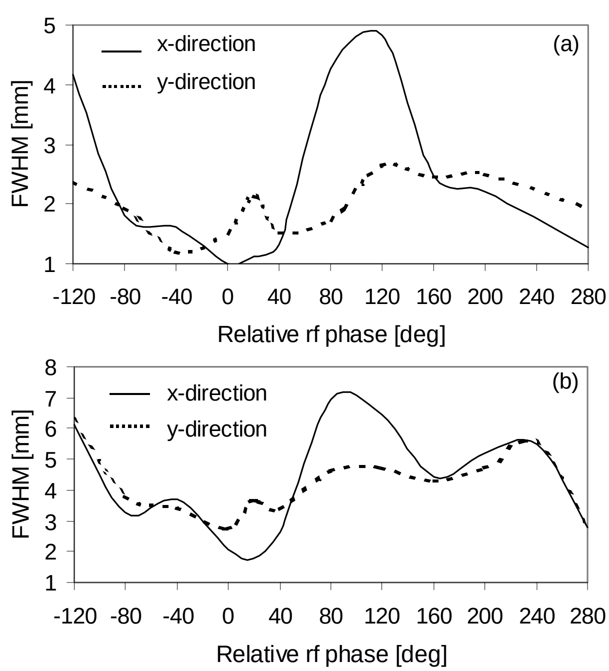

Figure 4. Measured beam dimensions at 284 mm (top) and 404 mm (bottom) distance from RFQ2 exit.

The calculated output beam size is shown in figure 5. There is good agreement between the measurements and the calculations. The smallest beam size is both predicted and observed in the high energy range, and is half the minimum value in the low energy range. The calculations indicate that at the maximum beam energy, the beam diameter is <1 mm at the exit of RFQ2.

The measurements indicate that the operation of the linac is very stable in the "acceleration" mode, where the beam has a well-defined energy with the smallest spatial dispersion. When operating with the relative rf phase outside these conditions, RFQ2 has both accelerating and decelerating modes as the beam passes through it. This results in significant beam energy spread and a larger beam spot size on the target.

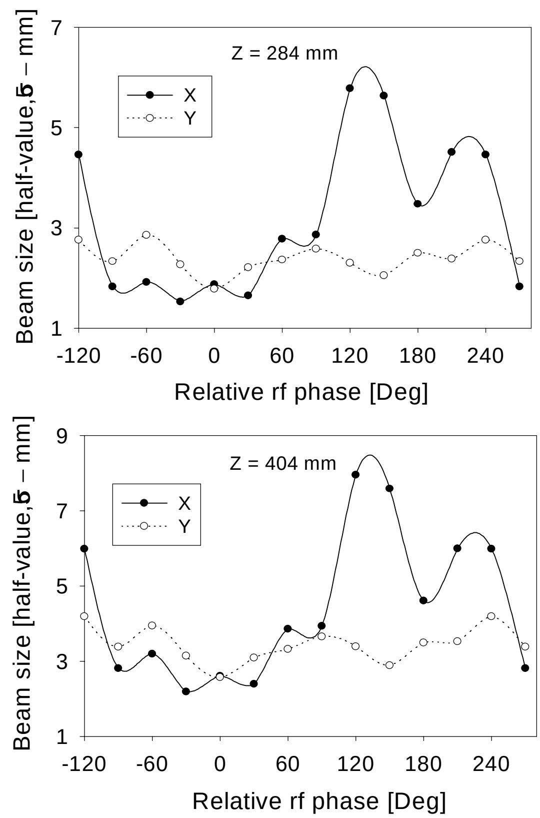

Figure 5. Calculated output beam dimensions at 284 mm (top) and 404 mm (bottom) from RFQ2 exit.

5 CONCLUSION

Output beam measurements on the LANSAR™ Model DL-5 variable energy RFQ linac have been performed and compared to PARMTEQ calculations. The experimental measurements are in good agreement with the beam dynamics calculations and prove that the system performance does indeed satisfy the stringent requirements imposed upon it as a dual energy neutron source. The system was installed in the spring of 1997 in a radiographic test facility in South Africa and has been in routine use for more than one year.