A COMPACT 1-MeV DEUTERON RFQ LINAC*

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A compact 1-MeV deuteron radio frequency quadrupole (RFQ) linac has been designed and fabricated as part of an explosive detection system (EDS) for airport luggage surveillance. This system, based on the thermal neutron activation (TNA) technique, is capable of detecting high explosive materials in the midst of other materials with high probability. The role of the RFQ in this application is to accelerate deuterons for impact with a beryllium target, inside a neutron moderator, to produce intense bursts of thermal neutrons.

The thermal neutrons interact with a variety of nuclei in the luggage and produce characteristic high-energy gamma rays that are detected by an external array of detectors. The detector processing electronics converts the detected signals into pulses suitable for computer processing. If a predetermined set of conditions are fulfilled, such as a high count rate for nitrogen within certain spatial constraints, the system alarms to indicate the possible presence of an explosive threat.

The thermal neutron flux in the EDS should be high enough to satisfy a requirement for screening 6 or 7 luggage items per minute. Through extensive tests on EDS systems, developed by SAIC and tested at major airports, it has been determined that thermal neutron yields of 5×10^9 n/sec, in conjunction with suitable detectors and electronics, is needed for a production EDS.

Although tested extensively by SAIC, the neutron yield from commercially available 200 keV DD neutron sources are limited at about 1×10^9 n/sec. A significant increase in neutron yield is required for a production EDS.

A neutron source, based on a 1-MeV deuteron accelerator and a beryllium target, can easily produce the required neutron yield. The deuteron on beryllium (D-Be) reaction is favored over the D-D reaction from the point of view of neutron yield and energy spectra. Neutron transport calculations show that D-Be neutrons are more easily thermalized than D-D neutrons. The deuteron energy (1 MeV) and beam current (50 μA) are chosen to yield the desired neutron flux. Higher beam energy or current would increase neutron flux at the expense of an increased complexity of the system.

The commercial aspect of this application demands a compact, lightweight, low-power, reliable and inexpensive design. The RFQ linac, described in this report, meets all of these constraints. It was necessary to take some innovative steps, outside of the established RFQ parameter space, to arrive at this design. A list of the resulting parameters are given in Table I.

In the interest of compactness and reliability, the ion source, low energy beam transport (LEBT) system and RFQ linac are all housed in a single meter-long vacuum manifold. The entire system is evaluated by two turbomolecular pumps backed up by one roughing pump. No large aperture vacuum valves are employed. In order to achieve a lightweight design, most of the components are fabricated to aluminum, copper plated where necessary for conductivity.

RFQ Design Process

The RFQ design process, from the briefest description of the desired performance to the CNC milling machine instructions that put the delicate contours on the tips of the vanes, involves a series of interconnected computer-based design tools. In our case, these tools go by the names of RFQSCOPE, PARMTEQ, SUPERFISH, RFQVG, ME-10, and CAMp90.

TABLE I RFQ LINAC PARAMETERS

Particle Type	Deuterons
Frequency, nominal	425 MHz
Structure Length	64 cm
Input Energy	20 keV
Output Energy	1 MeV
Input Current	5.5 mA
Output Current	5 mA
Pulse Length	10 μs
Pulse Repetition Rate	1 kHz
Pulse Duty Factor	1%
Average Current	50 μA
Radial Aperture	0.15 cm
RF Drive Power, max	52 kW
Input Emittance, (norm)	0.005 cm-mrad
Output Emittance, (norm)	0.005 cm-mrad

RFQSCOPE helps the designer find the region of RFQ parameter space most likely to satisfy his design requirements. The process is fast and condusive to investigating large arrays of possible configurations. The designer is presented with arrays of numerical and graphical information describing the performance of specified configurations and data files to facilitate communication with more sophisticated beam dynamics programs.

PARMTEQ is the central tool for the design and analysis of RFQ structures. Starting from RFQSCOPE output files, it generates detailed descriptions of the RFQ geometry and its beam dynamical performance.

SUPERFISH provides the designer with information about the resonant frequency and electrical properties of the structure. With these data, he can select a transverse profile have the desired resonant frequency and can predict the rf power dissipation.

RFQVG, the RFQ vane geometry program, translates the RFQ geometry descriptions from PARMTEQ into detailed RFQ vane geometry descriptions. Practical consideration such as vane terminations and curve-fitting to facilitate machining are addressed. Data files from this program are transmitted by telephone from the SAIC VAX computer to the machinist's HP computer. There, these data are further massaged by his ME-10 and CAMp90 programs in preparation for machining the vane tips.

The array of parameters investigated for this design included injection energies in the range of 20 to 40 keV, beam apertures in the range of 0.15 to 0.20 cm, vane modulation factors in the range of 1.4 to 2.0, and peak vane-tip surface electric fields in the range of 1.6 to 1.8 Kilpatrick. An injection energy of 20 keV, a beam aperture of 0.15 cm, a vane modulation factor of 1.8 and a peak vane-tip surface electric field of 1.6 Kilpatrick were chosen as the most appropriate compromise between the desire for a low injection energy, a short cavity length, a low peak power, and an adequate space charge limit. The resulting design has length of only 64 cm, a calculated cavity power of only 28 kW, and a space-charge beam current limit of 28 mA.

The surface electric fields on the tip of the vanes for a perfect quadrupole field is V/r_0, where V is the peak vane-to-vane voltage and r_0 is the vane-tip radius. In an actual RFQ, the maximum surface fields are higher than this value by some field enhancement factor, K. This field enhancement factor is tabulated for a wide range of RFQ geometries [Ref]. The field enhancement factor for this design varies from 1.30 at the beginning of the structure to a maximum of 1.40 in the region of cells 40-60 before dropping to 1.34 at the output end. This RFQ design is based on V/r_0 field valve of 1.6 Kilpatrick, corresponding to a maximum surface field value of 1.4*1.6 = 2.24 Kilpatrick.

The beam dynamics, as evaluated by PARMTEQ, is shown in Fig 1, where the upper portion shows the transverse profile of the beam and the middle and lower portions show the phase and energy spreads of the beam as it passes through the structure.

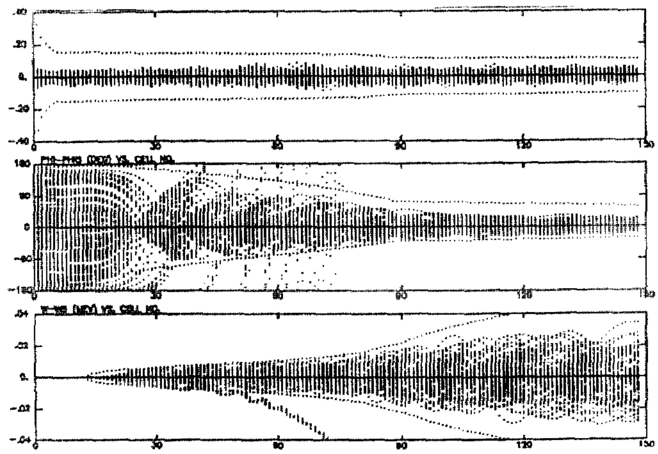

Fig. 1. X, Phase, and Energy Profiles by PARMTEQ.

The cross section of the cavity, as analyzed by SUPERFISH, is shown in Fig 2. It resonates at 425 MHz and has an inside diameter of 6.200 inches (15.748 cm), a radial aperture of only 1.5 mm, and constant vane-tip radius of 1.28 mm. The unusually small radial aperture had the advantage of reducing the rf power dissipation to an unprecedented low value. Although the small aperture is of some technical concern, it is worth noting that Los Alamos has recently chosen the same aperture for their next RFQ.

Mechanical Design, Fabrication, Assembly and Alignment

The mechanical design of the RFQ is based on the use of a heavy-walled aluminum tube (8"OD, 6"ID) as the main structural element of the assembly. After all welding on the assembly is completed, the assembly is stress relieved before final machining. The latter includes boring the inside of the cylinder to the precise diameter of 6.200 inches, and machining four precision flats on the outer surface of the cylinder. Extreme care is taken to insure that these flats are parallel to and equidistant from the axis of the interior surface, and parallel or perpendicular to each other.

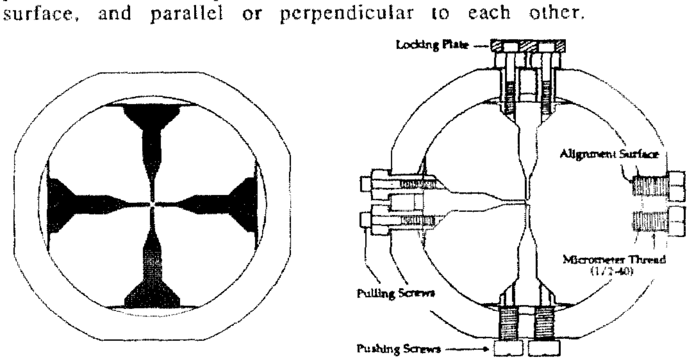

Fig. 2. RFQ Cross Section and Alignment Features.

The four RFQ vanes are mounted inside the heavy-walled aluminum tube (the vane housing) as shown in Fig 2. Electrical contact between the vanes and the vane housing is based on flexed fins at the base of the vanes, which are designed to produce a force of 100 pounds/inch, or greater against the vane housing. The range of fin flexure is designed to allow mechanical alignment of the vanes with a tolerable effect on this contact force.

Each vane is held in position by 6 pairs of concentric push/pull screw assemblies as shown in Fig 2. The pushing screws have a micrometer thread to the vane housing and form the vane-base alignment surfaces. The pulling screws serve to pull the vane bases against these alignment surfaces. The locking plates load the alignment screw threads to prevent accidental movement.

The RFQ vanes are designed in the conventional manner with the vane tips extending close to the end plates of the RFQ cavity with a cutout between the vane tips and the vane bases to allow the rf magnetic fields to wrap around the ends of the vanes. A sketch of the vane termination is shown in Fig 3. The gap between the vane tip and the end plate is 0.500 cm. The cutout has an area of about 13.2 cm^2. The vane base makes electrical contact with the end plate through a segment of spring ring in a groove in the end of vane base.

The vanes are fabricated from the aluminum alloy 7075, which has the best spring properties for the flexed fins. .The vane material is purchased as rectangular bars with gun-drilled cooling channels through their long dimensions. The bars, bolted to a rigid machining fixture, are machined to the desired cross section by conventional CNC milling machines. At this stage, the vane tip is still in the form of a rectangular blade 0.256 cm thick. The ends of the vanes are cut off and contoured by a computer-controlled wire electrical discharge machining (EDM) process. The last step in the machining of the vanes is to put the delicate contours on the vane tips.

The longitudinal vane-tip profile, evaluated by RFQVG, involves a numerical solution of the idealized RFQ potential function. Tables of such results are not the most convenient form of communication with the vane-tip machining process. Computer Aided Machining (CAM) processes translate most cutting processes into straight line segments and circular arcs. The standard vane-tip profile between a peak and an adjacent valley was translated into three segments, namely a circular arc, a straight line, and a circular arc, in such a way as to preserve the height and location of the peak, the depth and location of the valley, the slope at the midpoint between the peak and valley, and a smooth interface between all segments.

At the input end of the RFQ, the radial matching section is blended smoothly into the radial cut forming the end of the vane tip. At the output end of the RFQ, a circular arc, of one-centimeter radius, is appended to each vane, blending smoothly with the radial cut forming the end of the vane tip.

The constant vane-tip-radius design allows the use of a special shaped cutter for contouring the vane tips, which greatly reduces the cost of the vane-tip machining. RFQ designers are well aware of a constraint on the radius of this

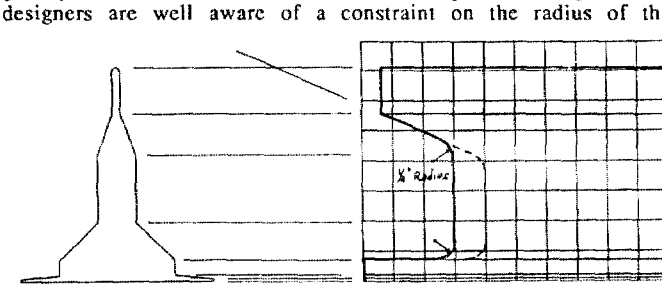

Fig. 3. Vane Cross Section and End Profile.

cutter coming from the geometrical details of the vane-tip profile itself. The constraint is simply that the tool radius must be smaller than the minimum concaved radius of the vane-tip profile.

This design, involving acceleration of deuterons at 425 MHz from an injection energy of 20 keV, represents the smallest concaved vane profile radii in the history of RFQ fabrication. The minimum concaved radius of this design is 2.883 mm. A cutting tool was designed with a radius of 2.794 mm. The tool has the form of a single flute cutter in a cylindrical holder. Both the tool and the holder were fabricated by the EDM process. This tool was tested and the results were satisfactory. Subsequently, a cutting tool with a radius of 2.54 mm was fabricated and used for the actual vane-tip machining.

The vane-tip machining process took only one hour per vane, including mounting the vane on the machining fixture, checking the alignment, making two preliminary passes and one final pass at the contour, and removing the vane from the fixture. Five vane-tips (including one on a spare vane) were processed in one afternoon. The same cutter was used for the entire process.

The interior surface of the vane housing and the majority of the vane surfaces are copper plated (UBAC-R1 process) for electrical conductivity. The vane tips are left unplated as a precaution against possible problems with copper plating in the region of high field and critical geometry. The exterior of the vane housing and flanges are anodized black to provide a smooth stable surface for precision alignment measurements.

After all the parts were readied, the installation and preliminary alignment of the four vanes took only four hours. Precision alignment of the four vanes took another four hours.

The installation process starts with the installation of the 48 micrometer-thread pushing screws that form the alignment surfaces and the 24 locking plates that restrict their motion. The pushing screws are initially set to their nominal position relative to the flats on the exterior surface of the vane housing. The vanes are installed to their nominal positions, one at a time, in any order. They may be aligned as they are installed or the alignment may be postponed until several or all have been installed. After the vanes are installed, the position of the vanes are adjusted by moving the pushing and pulling screws to achieve the desired gap spacing. The counteracting forces from the pushing and pulling screws keeps the vane position under positive control and contributes to the alignment accuracy achievable from this design.

All of the measurements required to align a vane, or check its alignment can be made at any time without regard to the status of the other vanes. The primary reference for all alignment measurements are the four flat surfaces accurately machined on the outer surface of the vane housing. The vane alignment is based on depth-micrometer measurements from these flats through holes in the housing and the vanes, to selected flat portions of the vanes.

Although test results do not indicate the need, field stabilization techniques could also be employed in this design at a later time to stabilize the quadrupole fields. Many techniques are available to stabilize the fields, including resonant end tuners, resonant azimuthal tuners and resonant longitudinal tuners. Vane coupling rings of the Lawrence Berkeley Laboratory design could also be added, but at the cost of increased structural complexity.

The cooling of the RFQ structure is accomplished by running a circuit of water through each vane and along the outside of each quadrant of the vane housing. The temperature of the structure is controlled to 1° C.

The vacuum requirement is enormously simplified by surrounding the entire RFQ assembly with a simple vacuum manifold, thereby eliminating hundreds of vacuum seals that would otherwise be required. The pressure in the RFQ end of the vacuum enclosure will be held to 1×10^{-6} Torr or better.

Low Power RF Measurement Results

The following low-power rf measurements were made on the completed RFQ structure: the resonant frequency of the quadrupole mode, the resonant frequency of the nearest dipole modes, the electrical quality factor (Q) of the structure, and the rf field distribution in quadrupole mode.

The resonant frequency of the quadrupole mode was measured to be 426.59 MHz. Although there is no necessity to do so, this could easily be tuned to design value of 425.0 MHz.

The nearest dipole mode is at 422.79 MHz. This is far enough from the quadrupole mode (3.8 MHz) to preclude problems of mode mixing which can shift distribution of field energy.

The electrical Q was determined to be 6108, which is 61% of the theoretical value. This excellent performance, by RFQ standards, can be attributed to the small number of electrical contacts (two per vane) through which the quadrupole mode currents flow in this design.

The field distribution in the quadrupole mode was measured by the "plunger" perturbation technique. In this technique, certain resonant properties of the quadrupole mode were monitored with great accuracy while a metallic plunger was inserted a fixed distance into each of 10 half-inch-diameter holes in each of the four quadrants.

The data so obtained indicates a small end-cell tuning error and a small vane alignment error. These errors are readily correctable by a minor change in the end cell tuning and a small adjustment in the position of the vanes relative to each other. The uniformity of these data for the cavity, as aligned mechanically, is excellent by RFQ standards and speaks well for the cavity design and alignment procedure.

Completion of the Linac System

The first phase of funding for this project covered the design of all the components of the system, but limited the fabrication to the linac structure itself. Contributing to the compactness of the entire system are several innovative features of the ion source, low energy transport system (LEBT), and rf power systems.

The ion source will be a commercial duoplasmatron unit, operated on deuterium gas and modified to mount inside the cover plate of the vacuum housing. Advantages can be taken of the low operating voltage (20 kV) and the vacuum environment to reduce the size of the insulating structure.

The LEBT will employ an RFQ lens in a new and innovative way that results in a substantial increase in lens strength and a very compact interface between the ion source and the RFQ linac.

The rf power will be supplied by close-coupled Eimac planar triodes, mounted inside the vacuum housing directly on the vane housing and operated in a grounded grid fashion. Services to this power system are reduced to 8 kV anode power, tube heater power, 6 kW of rf drive power, and cooling water.

The resulting package is extremely compact, as required by this commercial application, with the ion source, LEBT, RFQ, and power amplifiers of the rf system all located inside the 0.3-m-diameter by 1-m-long vacuum housing. More information on these auxiliary components will be published on completion of the system.