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RFQ-BASED, TRANSPORTABLE, HIGH-RESOLUTION, NEUTRON RADIOGRAPHY SYSTEM CONCEPT

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Abstract

A preliminary design for a high-resolution transportable neutron radiography system concept has been developed. The system requirement has been taken to be a thermal neutron flux of 10^6 n/(cm^2-sec) with an L/D of 100. The approach is to use an accelerator-driven neutron source, with a radiofrequency quadrupole (RFQ) as the primary accelerator component. Initial concepts for all of the major components of the system have been developed, and selected key parts have been examined further. An overview of the system design is presented, together with brief summaries of the concepts for the ion source, LEBT, RFQ, HEBT, target, moderator, collimator, image collection, power, cooling, vacuum, structure, robotics, control system, data analysis, transport vehicle, and site support. More detailed studies completed for the RFQ and moderator designs, and issues identified during the course of the work, are described.

1.0 Introduction

The utility of neutron radiography and radioscopy (NR) has been established for a number of applications [1]. Reactor-based facilities provide fixed installations that produce intense, high-quality thermal neutron beams used for examining aircraft parts and assemblies [2], nuclear fuel components [3], and a variety of research applications [1]. Transportable or mobile NR systems based on radioactive sources [4], D-T tubes [5], cyclotrons [6] and linear accelerators [7] have also been developed for several applications. Most of those transportable systems focused on applications with thermal neutron flux and/or collimation requirements that are somewhat below the parameters considered here. Other applications would be feasible if improved mobile systems were available. This paper describes the preliminary conceptual design for a transportable neutron radiography/radioscopy system (TNRS), based upon a radiofrequency quadrupole (RFQ) driven neutron source, capable of producing a thermal neutron flux of 10^6 n/(cm^2-sec) with an L/D of 100.

The approach taken in this work has been to cover, as completely as possible, all of the items that would be needed in order to field the TNRS. Concepts for the ion source, low energy beam transport (LEBT), RFQ, high energy beam transport (HEBT), target, moderator, collimator, imaging, power, cooling, vacuum, structure, robotics, control system, data analysis, transport vehicle, and site support have been developed. A continuous (CW) proton beam current of about 25 mA at 3.5 MeV generates a thermal neutron flux of 10^6 n/(cm^2-sec) with an L/D of 100. The design features a compact (24 foot long) configuration during transport.

2.0 The Transportable Neutron Radiography/Radioscopy System (TNRS)

2.1 Overview of the TNRS

The TNRS concept is a largely self-contained trailer-mounted device, that would be transported to user sites for extended operations. Each site is responsible for providing the power and cooling water, as well as the radiation shielding and/or an exclusion zone. The neutron production and radiographic imaging assemblies are mounted on the trailer during transport, but are deployed at the user site. Figure 1 illustrates the TNRS concept, showing one example for the deployed configuration. System operations personnel would be located in a separate instrumentation and control van (not shown in Figure 1).

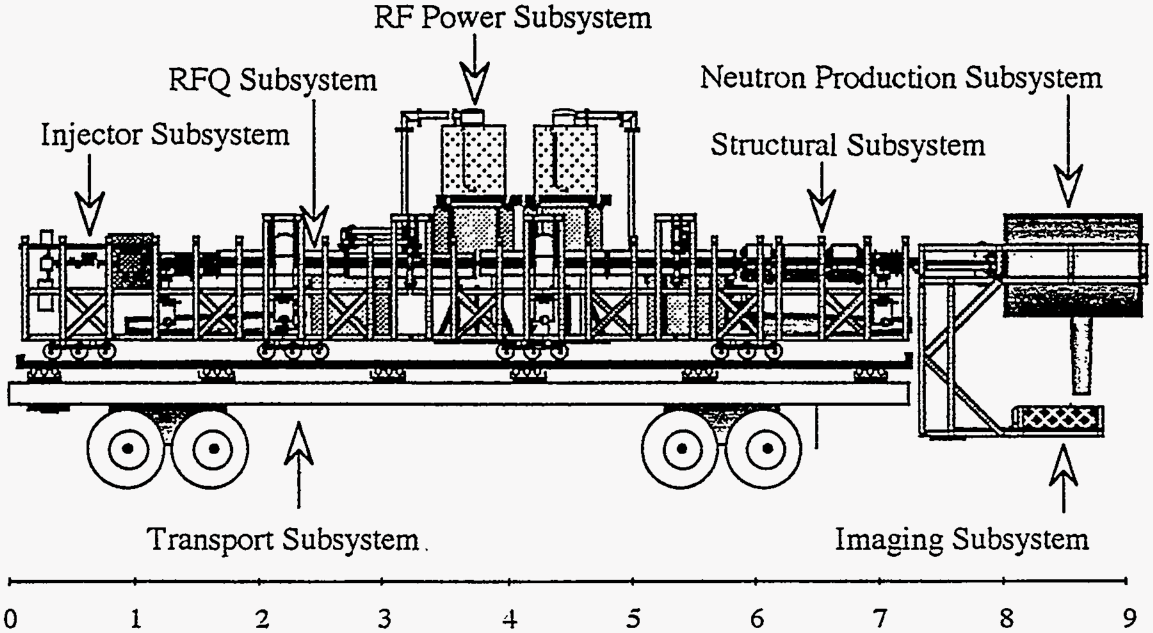

Figure 1. Transportable Neutron Radiography/Radioscopy System (TNRS) concept at 1/60 scale. The length scale is marked in meters.

The overall system has been divided into nine major subsystems. Seven of the subsystems are indicated in Figure 1. The two subsystems not appearing in Figure 1 are: instrumentation and control, the bulk of which would be located in the separate van with the operations personnel, and site support. Each subsystem has been further defined by identifying its major assemblies. One goal was to provide a description of the TNRS similar to that found in the first two levels of detail in a typical industrial work breakdown structure (WBS).

2.2 Accelerator Subsystems of the TNRS

The accelerator for the TNRS is composed of the injector subsystem and the RFQ subsystem. The injector is comprised of (1) an electron cyclotron resonance (ECR) positive hydrogen ion (H^+) source assembly and power supplies, (2) a dual solenoid low energy beam transport (LEBT) system, (3) a vacuum pump system, and (4) a deionized water system with interfaces for utility water to supply cooling for the ion source and solenoids. The ion source and solenoids are similar to those used previously at Chalk River [8] and Los Alamos [9]. The ECR source is capable of delivering high quality proton beams with very low molecular content [10]. The injector can produce a continuous beam of over 75 mA at 50 keV, more than is expected to be required by the TNRS.

The primary accelerator subsystem is that for the RFQ. The RFQ subsystem includes (1) a four segment vane-type RFQ, (2) eight radiofrequency (RF) power drive loop assemblies located at the second and fourth segments, (3) two vacuum manifold pump stations, one each at the first and third segments, and (4) a coolant manifold to supply water to the RFQ. Parameters for the RFQ are given in Table 1.

Table 1. RFQ Design Parameters.

Parameter	Value	Units
Frequency, f	352	MHz
Input Energy, E_{in}	50	keV
Output Energy, E_{out}	3.5	MeV
Intervane Voltage, V_o (input)	73	kV
V_o (output)	82	kV
Peak Surface Field, E_{max}	32	MV/m
Kilpatrick Factor, K_p	1.8	(none)
Aperture Radius, r_o (input)	2.9	mm
r_o (output)	3.1	mm
Final Synchronous Phase, ϕ_f	-28	degrees
Final Modulation, m	2.24	(none)
Cavity Power, P_{cavity}	400	kW

The RFQ is similar to concepts developed by Los Alamos and Northrop Grumman Corporation for the front end of an accelerator for the production of tritium [11]. However, the TNRS RFQ is designed for lower energy and somewhat lower current. The energy selected for the TNRS accelerator, 3.5 MeV, should be suitable for either a beryllium, lithium or lithium oxide neutron-generating target. We looked for an RFQ design that would give at least 25 mA of CW current for a total power (cavity plus beam) of about 500 kW, with the capability of significantly higher current if more RF power is available. Beam dynamics calculations were performed with a version of PARMTEQ [12,13] that uses an 8-term representation of the electric field between the vanes. Selected results are presented in Figures 2 and 3.

The current limit from PARMTEQ code calculations is greater than 75 mA and, as shown in Figure 2, the transmission is still 90% for an input current of 100 mA. The curves in Figure 2 are a based upon a simple fit to the PARMTEQ results. The RFQ current transmission efficiency, expressed as a fraction, can be approximated to within about 2% by:

$$\eta_{RFQ} = 0.98 \exp(-[I/2I_{lim}]^2) \quad ,(1)$$

where I is the input current, and I_{lim} is a limiting current. A fit to the calculated transmission points shown in Figure 2 gives a value for this limiting current of 160 mA.

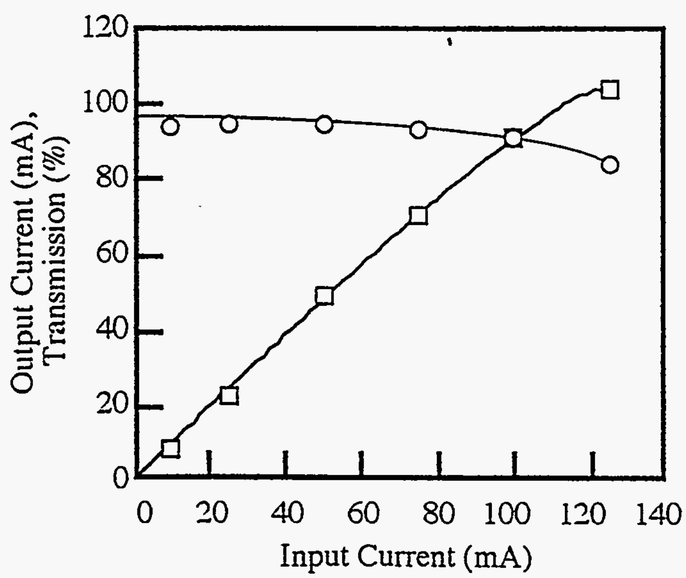

Figure 2. RFQ transmission.

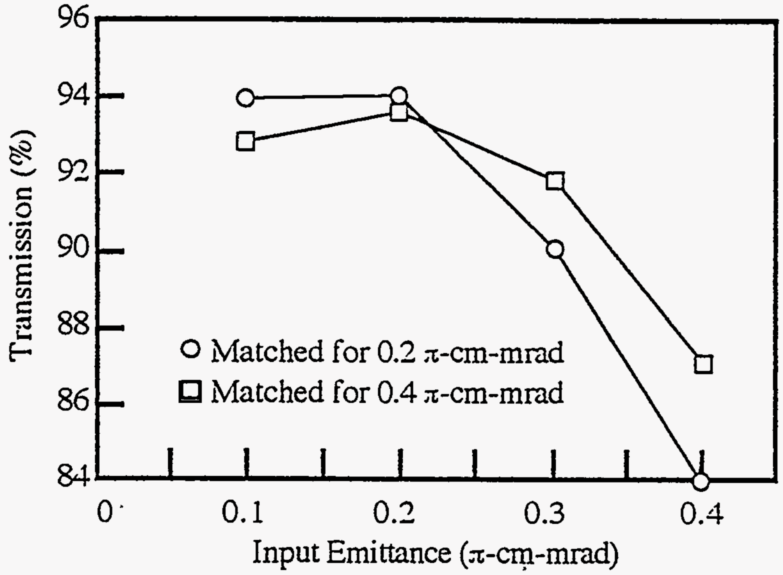

Figure 2. RFQ acceptance.

The acceptance of the RFQ is more than adequate for the expected source emittance of 0.15 π-cm-mrad (normalized, rms). Figure 3 shows the transmission as a function of input beam emittance for an input current of 75 mA, with the beam match optimized for an emittance of either 0.2 or 0.4 π-cm-mrad. For normalized, rms input emittances of 0.2 (π-cm-mrad) ±50%, the RFQ should transmit high current beams with an efficiency of 92% or more.

The cavity power dissipation (100 kW/m) and input energy (50 keV) are the same as that of the 267 MHz CW RFQ that was operated at Chalk River, Canada [14], for several years before being relocated to Los Alamos [15]. CW klystrode amplifiers able to produce 250 kW of CW RF power at 267 MHz are commercially available now, and it is expected that 500 kW CW klystrodes will soon be available to meet needs in the frequency range 250-425 MHz.

The RFQ should be further optimized, based on the eventual target and neutron flux chosen for the TNRS. For example, if a lithium target is employed, it may be desirable to lower the proton beam energy to about 2.5 MeV, the energy reached at the end of the third section (3 m point) in the RFQ described above. Alternatively, if 4 MeV protons are required, this could be achieved by increasing the length of each section from 1.0 to 1.1 m, or possibly by redesigning the vanes for higher voltage or greater modulation. While retaining a current limit in access of 50 mA, further reductions in length and power could be achieved by reducing the injection energy (to 35 or 40 keV).

2.3 Radiology Subsystems of the TNRS

The radiology (radiography and radioscopy) subsystems include those for neutron production and neutron imaging. The neutron production subsystem is comprised of four primary assemblies: (1) a neutron target, moderator and collimator, (2) a high energy beam transport (HEBT) line to transport and focus the proton beam onto the target, (3) a vacuum station, and (4) a cooling system. The neutron imaging subsystem is intended to support both electronic (radioscopy) and film (radiography) imaging and is comprised of two primary parts: (1) an image capture assembly and (2) a data analysis and archiving laboratory, which would be located in the instrumentation and controls van.

Target and moderator performance impact the optimum choice for the proton beam energy and current. For carrying out system-level trade studies, it is useful to have analytic parameterizations for the neutron yields and thermalization factors as a function of beam energy and current. Lone and Chidley [17] developed parameterizations for the effective neutron yield and thermalization efficiency that are useful in this regard. The performance of the target is defined in terms of its total neutron yield, Y_n, and the average energy, E_n, of the neutrons produced. The average neutron energy is used in the parametrization of the moderation efficiency, discussed below. Y_n is a function of the accelerator beam energy, E (in MeV), and is proportional to the accelerator beam current, I (in Amperes), whereas E_n only depends on E. Table 2 summarizes the Lone and Chidley [17] thick target parameterization for the ^{9}Be(p,n) reaction. The neutron yield given by their formula agrees with the thick target results of Hawkesworth [16] at a proton beam energy of 2.8 MeV, rises slightly above Hawkesworth's curve (Figure 4 in [16]) as the energy increases, and is about 15% higher at 6 MeV. Their average neutron energy agrees well with measurements in the forward direction on range-thick targets for proton beam energies from 12 to 23 MeV [19].

Table 2. Parameterization of Be(p,n) thick target performance, after [17].

Parameter	Formula	Inputs
Neutron Yield, Y_n (neutrons/sec)	$Y_n = 10^{12}[1-1.4E+0.4E^2]I$	E in MeV, I in mA
Average Neutron Energy, E_n (MeV)	$E_n = 0.25(E+Q)$	$Q = -2$ MeV

Lone and Chidley suggest that the effective moderator efficiency, η_{th}, may be parameterized as

$$\eta_{th}\ (\text{cm}^{-2}) = a\,(E_n)^{-b} \quad . \tag{2}$$

Several calculations have been performed to determine the utility of this model. Neutron thermalization data for selected accelerator-driven and radioisotope sources in a light water moderator are given in Table 3. The neutron flux was calculated using the radiation transport code MCNP [18] for locations inside an infinite moderator, and for finite spherical moderators of various radii. The results for the infinite moderator agree quite well with the original parameterization for the thermalization efficiency of Lone and Chidley, i.e. using $a = 0.0174$ and $b = 0.715$ in Equation (2). This set of data corresponds to the best that one can expect for an ideal moderator, free of the perturbing effects of structure and penetrations. At the other extreme is the thermal flux available from the surface of a small (5 cm radius) spherical moderator. For this case, the thermal flux is from twenty to fifty times smaller than the maximum thermal flux available from the interior of an infinite moderator. A fit to Eq. (2) for this data gives $a = 0.000652$ and $b = 0.95$.

Table 3. Neutron thermalization performance limits for light water moderators.

E_n (MeV)	η_{th} (cm^{-2}) - small	η_{th} (cm^{-2}) - infinite	Neutron Source
0.354	1.11×10^{-3}	2.72×10^{-2}	Li (p,n) @ 2.5 MeV
0.851	7.02×10^{-4}	1.68×10^{-2}	Be(p,n) @ 3.5 MeV
1.06	6.19×10^{-4}	1.57×10^{-2}	Be(p,n) @ 4.0 MeV
1.99	6.12×10^{-4}	1.47×10^{-2}	AcBe
2.31	4.28×10^{-4}	1.16×10^{-2}	Cf^{252}
2.45	2.26×10^{-4}	8.01×10^{-3}	d(d,n)
4.29	2.36×10^{-4}	7.55×10^{-3}	AmBe
14.0	2.95×10^{-5}	1.73×10^{-3}	t(d,n)

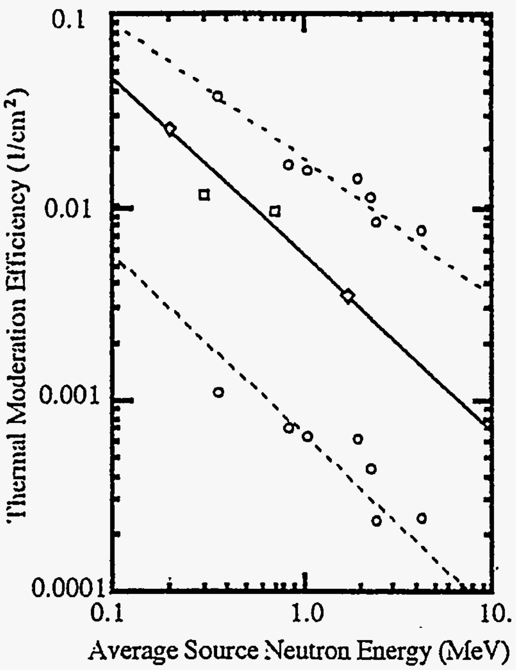

Figure 4. Parameterization of the effective thermalization efficiency for light water moderators.

Practical moderator systems will have a thermal moderation efficiency that lies between the "small" and "infinite" data of Table 3. Figure 4 summarizes several results for the effective thermalization data for a H_2O moderator. The boxes are based on the previously reported design results of Imel, et. al. [20] for a cylindrical moderator, and the diamonds are for measured results reported by Hawkesworth [16]. The circles are from Table 3. The solid line is a fit to Equation (2) with $a = 0.0056$ and $b = 0.93$. The dashed lines are the fits to the small and infinite performance limits described in the preceding paragraph. These results show that the extracted thermal flux for the Imel, et. al. design is approximately one-third that of the infinite moderator. We believe the differences between the Lone and Chidley parameterization and the moderator results reported by Imel, et. al., are due to the inclusion of the structure and penetrations required for the moderator, and are not associated with the differences in the proton beam energy range considered, as previously speculated [20].

The net thermal neutron flux Φ, at an image plane which is a distance L from the collimator entrance with an aperture diameter D, is then given in terms of the total neutron yield, Y_n, and the effective thermalization efficiency, η_{th}, by

$$\Phi \text{ (neutrons/[cm}^2\text{-sec])} = (1/16)(D/L)^2 \, \eta_{th} \, Y_n \quad . \tag{3}$$

Equation (3), together the formulae given in Table 2 and Equation (2) with $a = 0.0056$ and $b = 0.93$, can be used to model the thermal neutron flux as a function of the accelerator beam current and energy. For the TNRS requirement of $\Phi = 10^6$ n/(cm²-sec) with L/D = 100, this parameterization predicts that 11.5 mA of 3.5 MeV protons is required (for a Be target). If the average neutron energy from Table 3 (0.851 MeV) is used, rather than the value obtained from the formula in Table 2 (0.375 MeV), then this parameterization predicts that 24.6 mA is required. We adopted the latter, more conservative estimate, as the basis for the RFQ design.

2.4 Other TNRS Subsystems

Other subsystems include those for the structure and robotics, transportation, and RF power. The structure and robotics subsystem provides (1) a space frame for the structural support of the accelerator, (2) a detachable (for transport) C-shaped frame for the target/moderator/collimator and radiograph imaging assemblies, and (3) a remotely controlled two-axis translation table that permits scanning over a one square meter area. It is anticipated that the C frame, and the layout of the target/moderator/collimator and imaging assemblies, will be custom designed for specific applications. The transportation subsystem consists of two trailer vehicles: (1) the neutron radiography (NR) system vehicle and (2) an instrumentation and control (I&C) van. The NR system vehicle, with robotic table and support structures, is illustrated in Figure 1. Radiographers and support personnel remotely operate the TNRS from the I&C van.

The RF power system is composed of five primary elements: (1) two power amplifiers, (2) two circulators with dummy loads, (3) the RF power distribution system, (4) a low level RF drive with controls, and (5) a cooling system. The 500 kW of CW RF power could be supplied by a single commercially available klystron, but klystrode amplifiers similar to those developed for the Chalk River 267 MHz RFQ [14] would be more compact. Two klystrodes will meet the requirements, and this is the concept shown in Figure 1. Alternatively, if 500 kW CW klystrodes become available at 350 MHz, then a single klystrode would be able to supply the needed power, simplifying the TNRS design.

3.0 Summary

A preliminary concept for a high-resolution, transportable neutron radiography system has been developed that uses an accelerator-driven neutron source. The system utilizes a CW RFQ as the primary accelerator component. Initial concepts for all of the major assemblies of the system have been developed, and selected key parts, such as the RFQ and target-moderator, have been examined further. Parameterizations of the target and moderator performance have been developed to support trade studies needed to optimize the overall concept. Work to date indicates that a continuous (CW) proton beam current of about 25 mA from a 3.5 MeV RFQ, impinging on a Be target surrounded by a light water moderator, generates an image-plane thermal neutron flux of 10^6 n/(cm^2-sec) with an L/D of 100. Future trade studies are planned, using a computer code originally developed for studying high-energy linear accelerator systems [21], that should further optimize the system.

4.0 Acknowledgement

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