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Design of an RFQ-Based Neutron Source for Cargo Container Interrogation [*]

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Abstract

An RFQ-based neutron generator system is described that produces pulsed neutrons for the active screening of sea-land cargo containers for the detection of shielded special nuclear materials (SNM). A microwave-driven deuteron source is coupled to an electrostatic LEBT that injects a 40 mA D^+ beam into a 6 MeV, 5.1 meter-long 200 MHz RFQ. The RFQ has a unique beam dynamics design and is capable of operating at duty factors of 5 to 10% accelerating a D^+ time-averaged current of up to 1.5 mA at 5% duty factor, including species and transmission loss. The beam is transported through a specially-designed thin-window into a 2.5-atmosphere deuterium gas target. A high-frequency dipole magnet is used to scan the beam over the long dimension of the 5 by 35 cm target window. The source will deliver a neutron flux of $1 \cdot 10^7$ n/(cm^{2}s) to the center of an empty cargo container. Details of the ion source, LEBT, RFQ beam dynamics and gas target design are presented.

INTRODUCTION

The "Nuclear Carwash" concept [1] exposes a cargo container suspected to contain shielded SNM to a pulse or a pulse train of neutrons and observes the characteristic fission signature of a delayed gamma above 3 MeV with half-life of up to 100 seconds and delayed neutrons. The shielding may consist of high-Z materials such as lead, or low-Z materials such as a hydrogenous cargo (water, wood, fruit, etc.) to disguise the SNM. A preliminary design report [2] has been drafted by the above authors in which the details of a neutron-based interrogator are presented.

This method is likely to be applied as the second tier of port security, examining containers whose SNM load cannot be dismissed by other interrogation techniques, and must exhibit a false positive rate of less than 10^{-3} and a detection probability of at least 95%. A forty-foot (12 meter) cargo container is scanned in less than 1 minute by being pulled along a beam of neutrons, directed either from the bottom or the side, surrounded by an array of gamma detectors.

The interrogating neutrons are produced by the $\mathrm{D(d,n)^3He}$ reaction in a 2.5 atmosphere gas target by a 6 MeV pulsed deuteron beam generated by a microwave ion source and accelerated by an RFQ.

To ensure a good signal-to-noise ratio of the signature gamma response for any reasonable low or high-Z shielding configuration surrounding the SNM, a neutron flux of $1 \cdot 10^7$ (n/sec cm^2) at 2.5 meters from the production target is required.

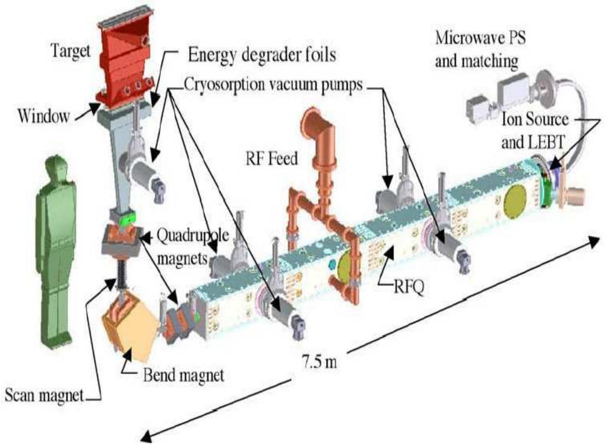

Figure 1: (color) Ion Source, RFQ, Scanner and Gas Target

The upper neutron energy is limited by interfering reactions, the strongest of which is the $^{16}\mathrm{O(n,p)}^{16}\mathrm{N}$ reaction with a threshold of 10.2 MeV, which would create a false positive indication of SNM.

ACCELERATOR SYSTEMS

The accelerator comprises a microwave-driven positive ion source, a two-lens electrostatic LEBT, followed by a 6 MeV 200 MHz RFQ.

The overall parameters are shown in Table 1.

Table 1: Overall Parameters

Parameter	Value	Unit
Beam species	deuterium	
Ion Source Intensity	40	mA
Ion Source Energy	60	keV
RFQ Output energy	6	MeV
Duty Factor	5	%
RFQ Length	5.1	m
Pulse Length	278	μsec
Time Average Current	1.5	mA
Pulse Rate	180	Hz
Neutron Flux at 2.5 m	$2 \cdot 10^7$	n/sec-cm^2

Ion Source and LEBT

The ECR ion source delivers a 40 mA D^+ beam to the electrostatic LEBT in 278 microsecond pulses at a rate of

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180 Hz. Up to 1 kW of RF from a 2.45 GHz magnetron is coupled into the plasma chamber from ground through a high-voltage break through an aluminum nitride window. The solenoidal ECR field is about 900 Gauss to produce an ECR resonance inside the extraction aperture. The walls of the plasma chamber are lined with boron nitride, which raises the D^+ species fraction to better than 90%. The output current with a 60 kV extraction system has been routinely measured at 55 mA, more than sufficient for this application. The source rise time is about 300 microseconds, so the beginning of the pulse is discarded by delaying the RFQ RF excitation.

The LEBT continues the successful LBNL tradition of short, electrostatic beam transport systems and comprises two einzel electrodes, separated by a grounded electrode containing steering plates. The entire LEBT is 19.3 cm long, and is housed in a chamber with a large pumping port and electrical feed-throughs for the lenses and steerer, as shown in Figure 2.

The 1-times rms normalized beam emittance is 0.05 π cm-mrad at the RFQ entrance.

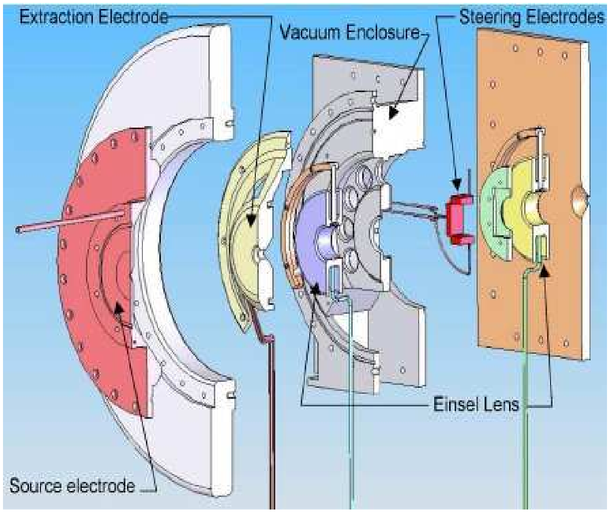

Figure 2: (color) 60 kV LEBT

RFQ

The RFQ is a 200 MHz machine of rather unusual beam dynamics design. Instead of the traditional four-section (RM,SH,GB,AC) approach, a kick buncher following the radial matcher is followed by a drift, a transition section and an accelerating section [3]. This is similar to the zero-current design used in the IUCF injector RFQ [4], modified to provide 90% transmission at 40 mA D^+ input current. This design results in a significantly shorter RFQ (5.1 m) than a conventional design, which would be up to 2 meters longer.

The frequency selection is dominated by the cost of RF power, 1 MW at 200 MHz being significantly less expensive than the same power at 400 MHz. Although the RFQ is slightly longer than a 400 MHz design and has twice the transverse dimensions, the higher acceptance for deuterons, the lower wall power density for a 5% duty factor and looser manufacturing and assembly tolerances favor the lower frequency. The gridded-tube based 200 MHz amplifier is more compact than a 400 MHz klystron-based system of the same power.

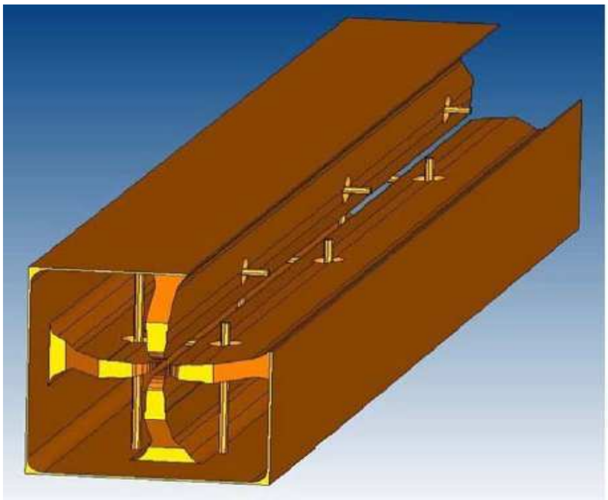

Figure 3: (color) RFQ Section with Pi-Mode Stabilizers

The beam dynamics design of the RFQ is calculated ”by hand”, as there is currently no code that optimizes the kick-buncher design for significant space charge defocusing. A starting design for zero space charge [3] is modified empirically for high space charge, while keeping the vane transverse radius parameter along the structure constant or piecewise continuous for easy manufacturability. Figure 4 shows the evolution of m and a, the modulation index and minimum beam aperture along the RFQ as a function of z. Note a small ”blip” of m at the beginning, which starts the bunching process, followed by a piecewise continuous increase of m to its final value of 2.45. The aperture a and other parameters are selected for maximum transmission at 40 mA as well as providing a constant local resonant frequency along the structure with a piecewise constant (within each of the four modules) of the transverse vane tip radius $\rho_\perp$.

The RFQ comprises four modules, each about 130 cm long. Each module consists of two major vane/cavity sections and two minor vane/cavity sections which are bolted together with a canted spring ring RF contact. A unique 3-D O-ring with the geometry of the edges of a cube provides the vacuum barrier. This technique was used successfully in a proton RFQ produced by LBNL [5] that featured a design that could be economically produced in large numbers. No brazing is required, so hard OFHC copper may be used as a structural material for the cavity. The vane-tip is fly-cut, and the tuners are fixed during initial tuning. The frequency shift from zero to full power of less than 200 kHz is followed by the RF system. Gun-drilled passages along the cavity walls provide water cooling.

The field stabilization is provided by pi-mode rods [6],

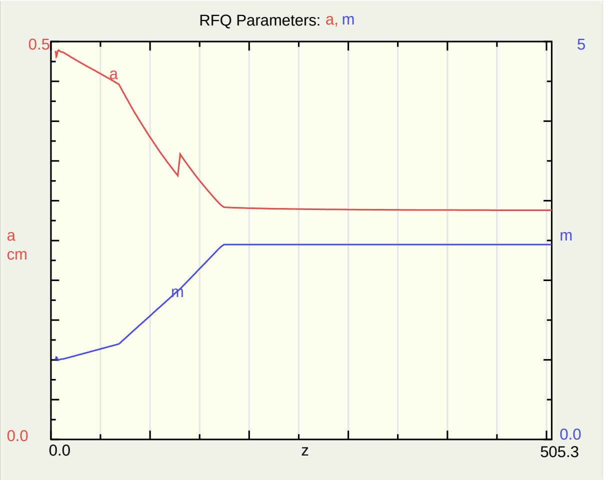

Figure 4: (color) Evolution of a(red) and m(blue) vs z.

also used in the SNS RFQ [7], which separate the quadrupole and dipole modes by up to 7%, significantly easing mechanical tolerances and tuning. The pi-mode stabilizers are designed to be conduction-cooled.

The RFQ cavity has been modeled in detail using CST Microwave Studio [8], including all details of the pi-mode stabilizers, vane end cutouts and end sections. The validation of Microwave Studio on a similar RFQ with pi-mode stabilizers is reported in these proceedings [9].

TRANSPORT SYSTEMS

The 6 MeV D^+ transport system includes an active scanner which spreads the beam along the long dimension of the 4 by 35 cm target window.

HEBT and Scanner

For a single neutron production target, the RFQ is located close to the target. The default configuration buries the accelerator below grade level and a 90° magnet directs the beam upward into the scanner. An air-core, ferrite-loaded magnet sweeps the beam from -25 to +25 milliradians into a defocusing quadrupole, which amplifies the angular sweep by a factor of five, for a total sweep of 14 degrees. The target window is located 1.4 meters from the pivot point, and the beam centroid is swept over the 35 cm long dimension of the window.

The 30 cm long sweep magnet ramps from -420 to +420 gauss in 278 microseconds, which is provided by a modest pulser. The defocusing quadrupole following the sweep overfocuses the beam in the transverse direction and provides a spot size at the target that covers the 4 by 35 cm window area with a few percent tail outside the window.

RF SYSTEM

The RF system is a primary cost driver for the frequency selection. RFQs were designed for both 200 and 400 MHz, and a peak RF power of nearly a megawatt, including beam loading, was required. The cost and physical form factor were significantly in favor of the 200 MHz system, and the RFQ, although larger, had larger acceptance and decreased manufacturing and assembly tolerances. Also, operation in the field will be more tolerant of tuning errors and operating parameter degradation for the 200 MHz option.

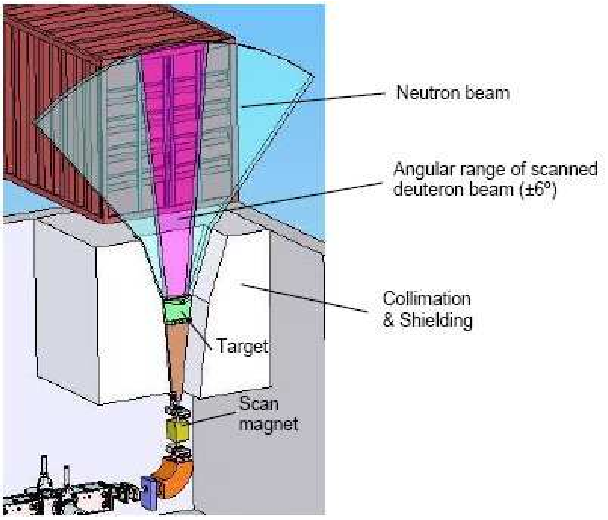

Figure 5: (color) Scanner and Neutron Delivery Configuration

The 200 MHz technology is now available as an ”off the shelf” item in this power and duty factor range, having been developed by more than one manufacturer and delivered in large quantity for industrial and medical applications.

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