Utilization of Variable Energy Radio-Frequency Quadrupole Linear Accelerator Systems.

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Abstract. Radio-frequency quadrupole (RFQ) accelerators are utilized worldwide in a variety of applications but invariably are restricted in their individual diversity due to fixed energy and ion-species constraints. In collaboration with industry Necsa has been developing systems utilizing RFQ accelerators in such a way as to provide for greater diversification of applications.

A major development has been the routine operation of combining two RFQs in tandem and using the extracted beam to generate intense, pseudo mono-energetic, neutron beams with energies ranging from 3 to 8 MeV and energy spread of less than 600 keV. Such neutron beams are extremely useful when performing studies of materials with elements exhibiting resonance reactions in the applicable neutron energy range.

The greatest challenge in developing the neutron source has been the beam target. The only viable nuclear reaction to use for generating mono-energetic neutrons in the 3-10 MeV regime, is the d(d,n)^{3}He reaction. This necessitates the use of a gas target and the challenge then is how to inject an intense ion beam from the accelerator high vacuum environment into the gas target with minimal ion beam energy degradation. Two types of pseudo-differential pumping systems have been developed and their performance under various conditions proven.

With the systems in operation at Necsa a selected cluster of applications is being developed in collaboration with academia and international partners, so as to create a sustainable research and development environment having identifiable socio-economic impact.

1. Introduction.

The continual refinements taking place at all levels of accelerator development demonstrates the ongoing demand for these facilities for a wide range of applications. This is especially applicable, but not restricted to, developments of accelerators for the purpose of neutron generation in terms of neutron flux and facility size, ranging from the portable to entire research institutes. Off the shelf neutron generators, such as d-d and d-t tubes, that provide neutrons with energy of around 2.5 and 14 MeV respectively, are limited in terms of the maximum yield of around 10^8 to 10^{10} neutrons per second respectively as well as useful lifetime before suffering severe degradation in neutron yield.

The application of radio-frequency quadrupole (RFQ) accelerators for neutron generation and isotope production has been available for over a decade, however the development of applications using fast neutrons has been limited primarily due to the lack of development of suitable beam targets. The relatively successful development by Sowerby, et al, [1] of a dual energy neutron-photon radiography scanning system, where the signal is derived from the ratio of neutron and photon attenuation has provided new impetus to the possibility of applying RFQ accelerator systems to fast neutron radiography. It is generally accepted that fast neutron interrogation alone is not a tool for primary inspection, but rather for clearing false positives created by other techniques such as X-ray scanning. By extending the dual energy concept over several neutron energies sensitivity to carbon, nitrogen and oxygen becomes pronounced.

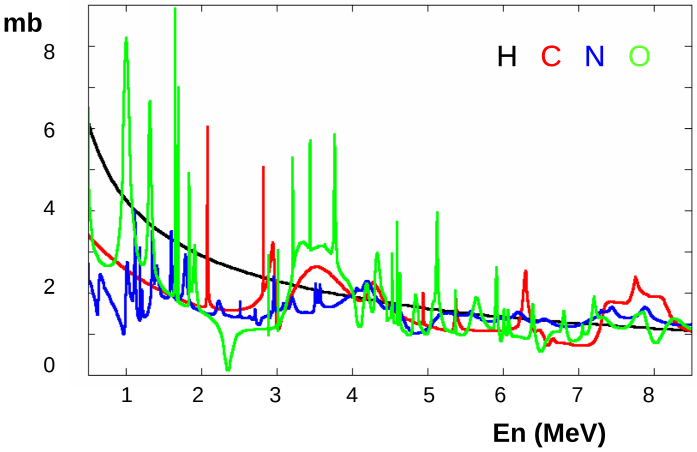

Figure 1. Neutron reaction cross-sections for carbon, nitrogen, oxygen and hydrogen.

The numerous neutron resonances exhibited by carbon, nitrogen and oxygen, between 1 and 10 MeV, see Figure 1, makes the concept of utilizing fast neutron resonance based radiography extremely attractive, especially in applications such as explosives and contraband detection. Runkle et al [2] have recently reviewed extensively the potential for using fast neutrons for explosives detection, but it was also obvious from the article that care must be taken in selecting the appropriate resonance regions to use, especially when trying, for example, to distinguish explosives (such as Semtex-H) from magazines.

Versatile systems for generating intense beams of neutrons, for the purpose of fast neutron radiography, have been implemented at Necsa. This paper discusses the attributes of two similar, yet different, radio-frequency quadrupole (RFQ) accelerators, associated gas targets for neutron generation, and the detector systems that can be used for imaging. The research program in progress with these two systems include, but are not restricted to, detection of illicit material, explosives and minerals.

2. Accelerator systems.

Two RFQ accelerator systems are presently utilized at Necsa. Both systems function under the same basic principle, consisting of two independent radio-frequency quadrupole (RFQ) acceleration cavities, one cavity capable of adding 4 MeV of kinetic energy to an injected ion, the other cavity supplying a further 1 MeV of kinetic energy. The novelty of coupling the two cavities is encompassed in the selection of the relative phase of the RF power in the second cavity with respect to the first cavity. The effect is to retard, act neutrally, or accelerate the beam as it traverses the second cavity, resulting in a selectable range of mono-energetic ions, the ions in question here being deuterium or hydrogen.

The first system, referred to as the ADM (Advanced Demonstration Model), consists of a dual RFQ accelerator built by AccSys Technology Inc, USA, consisting of a 4 MeV RFQ accelerator with a 1 MeV RFQ accelerator coupled to the end [3]. Figure 2 is a photograph of the complete accelerator system in preparation for transit from its original research location to its present location at Necsa. Figure 3 illustrates the measured emitted deuteron energy as a function of the relative RF phase, which correlated well with predictions. Although beam transmission efficiency is degraded when the RF is out of phase for any ion energy between 3.5 and 5.0 MeV, a beam transmission of >96% is still achieved.

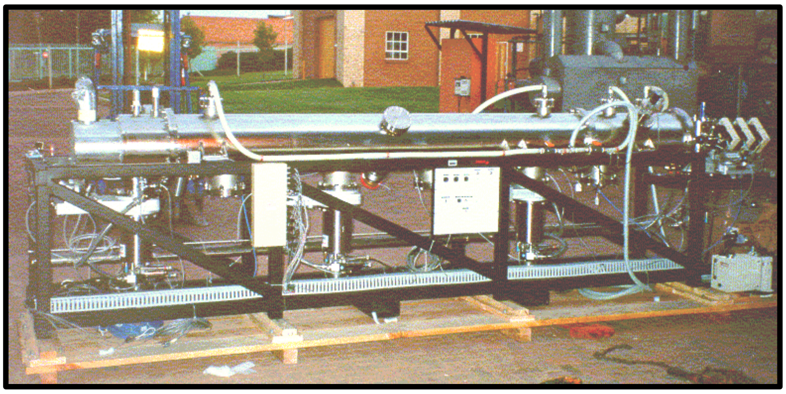

Figure 2. The AccSys dual RFQ accelerator system with ion source at left and high energy beam transport system to the right.

The second system, referred to as the D-100 was developed as a commercial prototype based on the proof of principal achieved with the ADM system. The specification was for a 100-fold improvement in performance, thus the acronym. The dual RFQ accelerator was designed and built by Prof. A. Schempp, Frankfurt am Main University, Germany. The second RF stage is a booster section which influences the emitted ion energy as a function both of the relative RF phase and the applied RF power. Beam energy measurements for hydrogen ions as a function of relative RF phase and booster RF power are presented in Figure 4. The respective performance of the ADM and D-100 accelerators are summarized in Table 1.

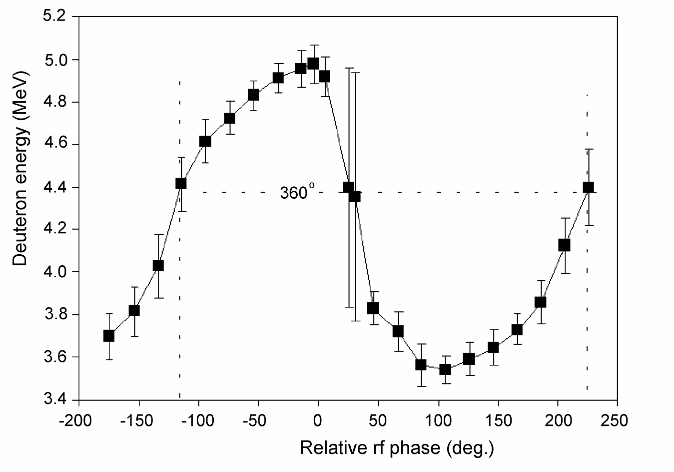

Figure 3. Measured beam energy from the ADM as a function of relative RF phase.

Features	ADM	D-100
operating frequency (MHz)	425	200
injection energy (keV)	25.0	35.0
D$^+$ output energy (MeV)	3.6 - 4.9	3.7 - 5.1
maximum beam pulse width (ms)	0.1	2
repetition rate (Hz)	20-200	20-100
maximum RF duty factor	1.2 %	20 %
pulsed RF power requirement (kW)	280/160	1000/200
linac length (m)	4.4	4.5
Average extracted beam current (mA)	0.1	10

TABLE I. Operating specifications of the two accelerator systems.

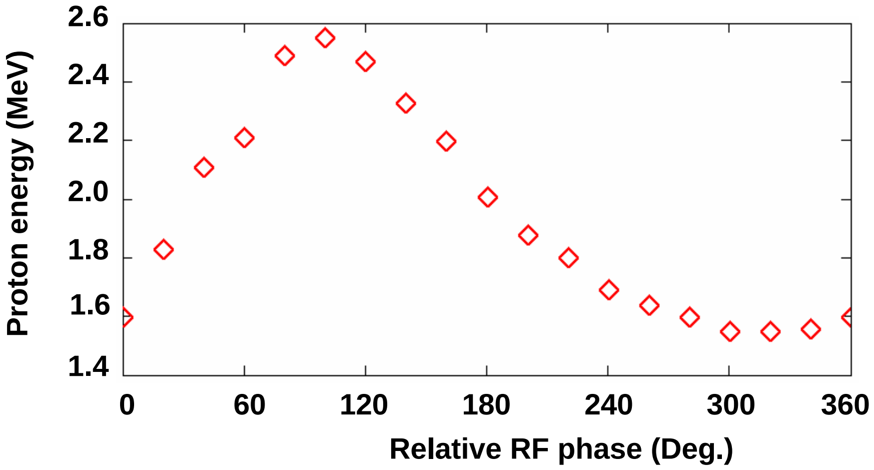

Figure 4. Extracted proton beam energy from the D-100 as a function of relative RF phase for 35 kW booster RF power.

3. Gas target

A key component of generating a pseudo mono-energetic beam of neutrons is the target configuration. To minimize energy dispersion, the target should be pure, that is, no other material present that could react with the beam, and have small longitudinal dimension to limit energy dispersion as the beam energy degrades traversing the target.

An optimum target for neutron production in the 2 to 10 MeV regime is deuterium, through the d(d,n)^{3}He reaction. Solid deuterium would be ideal but is logistically prohibitive. The next best alternative is a gas target, with the challenge being to contain the gas target within a high vacuum environment and yet meet the aforementioned prerequisites. A windowless gas target system has been successfully deployed on the ADM accelerator and is well described by J. Guzek, et al [4]. It is a combined rotating seal and differential pumping system that provides for a 3 cm long gas target at 3 bar pressure. Transmitted beam strikes a water cooled tungsten beam dump which minimizes unwanted production of lower energy neutrons and gamma-rays.

The D-100 system is similar to that used on the ADM, but has a more sophisticated gas handling system due to the higher duty cycle of the accelerator. Due to the much higher beam intensity a rotating tungsten beam dump is used to distribute the heat load over a larger effective area.

The ADM and D-100 systems were originally designed for the generation of 10^{10} and 10^{12} neutrons per second respectively at either 7.2 MeV or 8.2 MeV, primarily in a 30° forward cone. The neutron energy spread in the region of interest is less than 600 keV. By varying the relative RF phase, neutrons between 6.6 and 8.2 MeV can be produced in the incident ion beam direction. Neutron beams as low as 2 MeV can be utilized by moving away from the incident beam direction, albeit at lower intensity.

4. Neutron detection

Efficient detection of fast neutrons has in the past been one of the limiting factors against more general use of fast neutron radiography. This limitation is rapidly eroding, thanks not only to aforementioned improvements in neutron beam intensity, but also to advanced developments in efficient photon collection and amplification techniques, namely charged coupled devices, more commonly known as CCD cameras.

A CCD system has been successfully utilized for several years on the ADM system. Further improvements, in terms of spatial resolution and timing are currently being investigated using amorphous silicon devices coupled to scintillation fibre bundles. The use of scintillating fibre bundles has been employed in a novel dynamic detection system for the D-100 facility. The light emitted by the bank of scintillators is split by a pyramid mirror, the light from each quadrant traversing an image intensifier coupled to a pair of cooled CCD cameras, see Figure 5. The detection bank is used to dynamically image the samples passing the interrogation zone on a conveyor belt, with the accelerator booster switched on and off to provide two distinct neutron energy beams.Thus one camera is triggered for high energy and the other for low energy events.

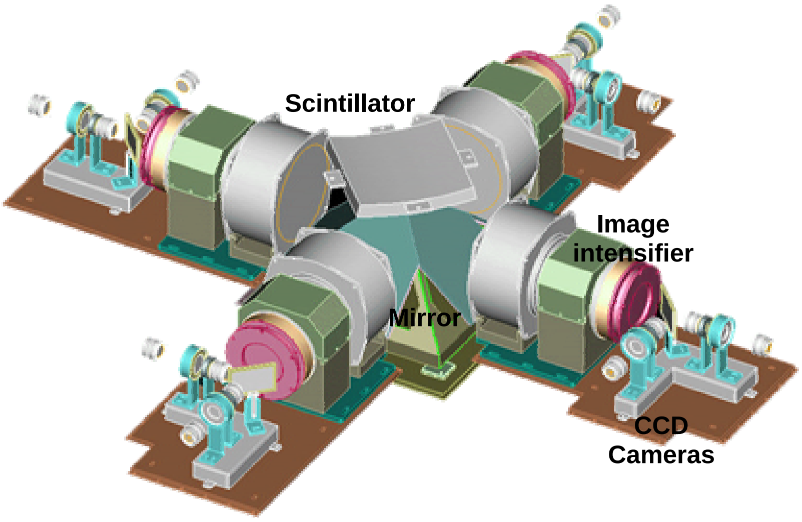

Figure 5. Dynamic imaging system, showing the scintillator, pyramid mirror and CCD camera systems for collecting high energy and low energy images.

5. Applications

The accelerator systems described were originally constructed for a specific radiography application. They are now being developed further for a range of applications, namely:

i) Mineral detection (e.g. gold and platinum group minerals).
ii) Explosives and contraband detection in cargo containers.
iii) Contaminant detection in wool bales.

Of special interest is to extend the radiography process to fast neutron tomographic analysis of objects.

Due to the high beam currents attainable another obvious application for the accelerators is radio-isotope production, and of specific interest to Necsa is the development of short lived radio-isotopes for radio-pharmaceutical applications, for example ^{195m}Pt through the ^{195}Pt(n,n')^{195m}Pt reaction.

6. Discussion

We have described two unique accelerator facilities available for national and international use for research and development investigations. To summarize this facility provides for:

- Training of scientists and engineers in RFQ accelerator science and technology.
- Isotope production.
- Novel vacuum/high pressure gas interfacing systems.
- Novel fast neutron detection techniques.
- Imaging software development.
- Novel non-destructive analysis science and technology applications in materials science.

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