Operation of variable energy radio-frequency quadrupole linear accelerator systems to produce intense beams of neutrons for interrogation of cargo to identify illicit material.

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Abstract. Two radio-frequency quadrupole (RFQ) linear accelerator systems have recently been commissioned at Necsa, near Pretoria, South Africa. These accelerator systems are unique in their design, construction and mode of operation. Although of different design, both accelerator systems can operate over the same energy range, but with different intensities and duty cycles. To extract a variable energy ion beam a system consists of two RFQ acceleration cavities, which operate at a selectable phase between one another, thus facilitating an acceleration or deceleration of the ion beam within the second cavity.

H^+ or D^+ ions can be accelerated (1.5 to 2.5 MeV or 3.8 to 5.0 MeV respectively) and targets of deuterium gas or solid targets, such as a thin beryllium foil, have been used to generate a range of neutron distributions which, through appropriate selection criteria, can then be used to perform radiographic imaging of various objects. The primary focus of this work has been to set up a system producing intense ($>10^{10}$ n/s) beams of neutrons of pre-determined energy and energy spread, to interrogate typical cargo containers for traces of illicit material and/or explosives. The methodology has been to develop a neutron radiography system that can be used to scan large volumes, such as cargo containers in a relatively short time span and provide an indication as to whether the contents tally with the cargo manifest.

1. Introduction.

It is well documented that high energy X-rays and gamma-rays can be used to interrogate large volume containers to produce radiographic images of their content [1]. The difficulty still remains to interpret the content composition, especially in terms of organic and inorganic material. Dual, or multiple, discrete electromagnetic irradiation can facilitate the interpretation process, however it is not a simple process to generate mono-energetic X-rays or gamma-rays.

A prominent feature of explosives is that their bulk density is typically 1 to 2 $g.cm^{-3}$, which is markedly greater than most organic material and below that of metallic systems. Furthermore the fact that most explosives contain nitrogen is also a useful indicator. The segregation of a range of common cargo, and illicit material, by the ratio of carbon, nitrogen and oxygen has been well known for some time, see Figures 1 and 2 as examples. These elements can be detected by using fast neutron resonance reactions to generate contrast radiographic images. The process of generating intense beams of pseudo mono-energetic neutrons has advanced considerably in the past decade, the process driven primarily by the needs of industry. The process of adaptation of this accelerator based technology for cargo scanning, utilizing fast neutron resonance reactions is one of the functions of the research group, P-LABS, at Necsa near Pretoria, South Africa.

The purpose of this article is not to address the methodology of interpretation of fast neutron interrogation of cargo, but rather the technology needed to provide the appropriate radiation source and detection technique.

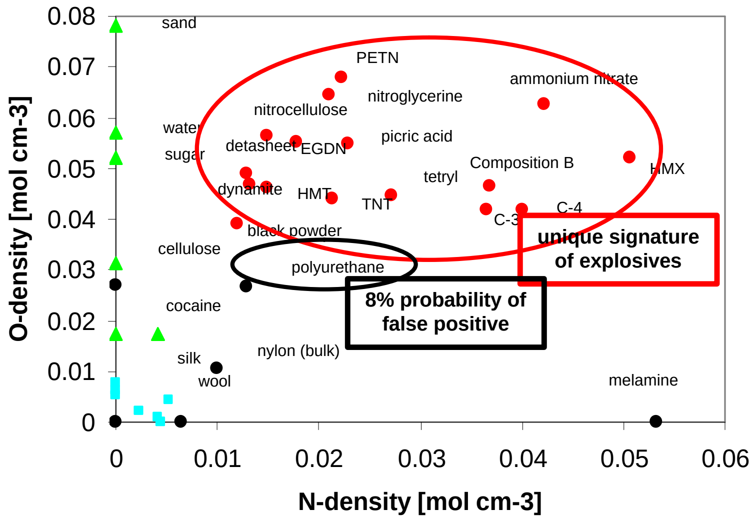

Figure 1. Oxygen versus hydrogen density ratios for common explosives and other materials.

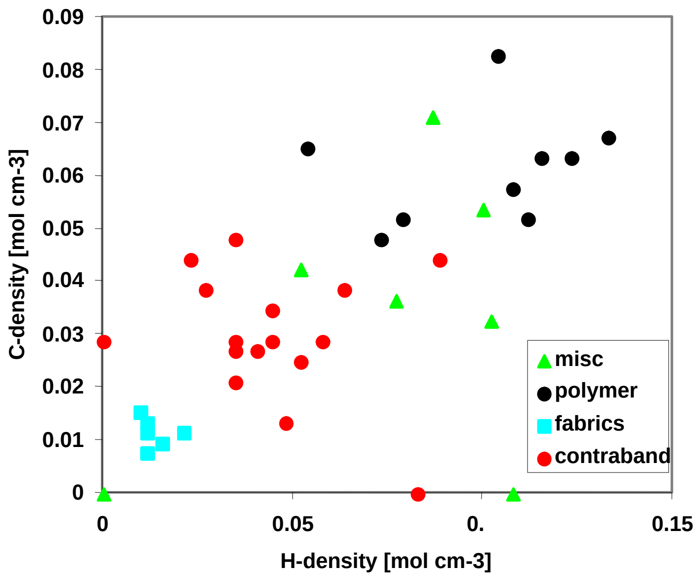

Figure 2. Carbon versus hydrogen density ratios for a range of polymers, fabrics and contraband.

2. RFQ accelerator systems.

RFQ accelerators have proven to be useful tools for generating intense beams of ions of specific energy. Two RFQ accelerator systems, specifically designed to accelerate deuterium ions, are presently operated at P-LABS and are referred to here as the ADM and D-100. Although the systems are similar, differences in their operation characteristics are illustrated in Table 1. 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 a deuteron, the other cavity capable of supplying a further 1 MeV of kinetic energy.

Features	ADM	D-100
operating frequency (MHz)	425	200
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
Neutron flux from D_2 target ($n.s^{-1}$)	10^{10}	10^{12}

TABLE I. Operating specifications of the two accelerator systems

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 range of mono-energetic deuterons (D^+) or hydrogen (H^+). Figure 3 illustrates the measured deuteron energy as a function of the relative RF phase for the ADM system, whilst Figure 4 illustrates the level of extra energy added to a hydrogen beam in the D-100 system, where not only the phase but the RF power itself plays a role in the acceleration of the ion, which is due to the structure of the booster cavity.

For the generation of neutrons, through the $d(d,n)^3He$ reaction, a combined spinning disc and differential pumping system is used to isolate a deuterium gas target from the main vacuum of the accelerator. Such a system removes the effect of energy loss and dispersion for a beam having to traverse a gas containment window. Dependent on the phase between the two RF systems of the accelerators and the radial location of the neutron detection system with respect to the incident beam direction, neutron beams of energy from 2 to 8 MeV can be generated with a total flux of 10^{10} $n.s^{-1}$ for the ADM and 10^{12} $n.s^{-1}$ for the D-100.

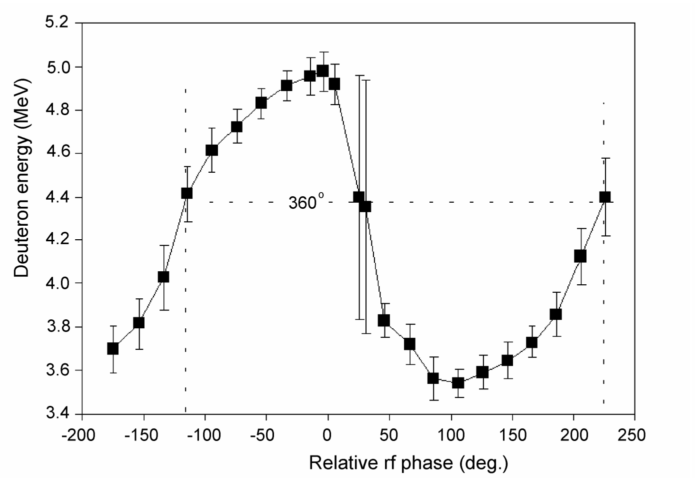

Figure 3. Measured deuteron energy as a function of the relative phase of the RF power in the ADM system.

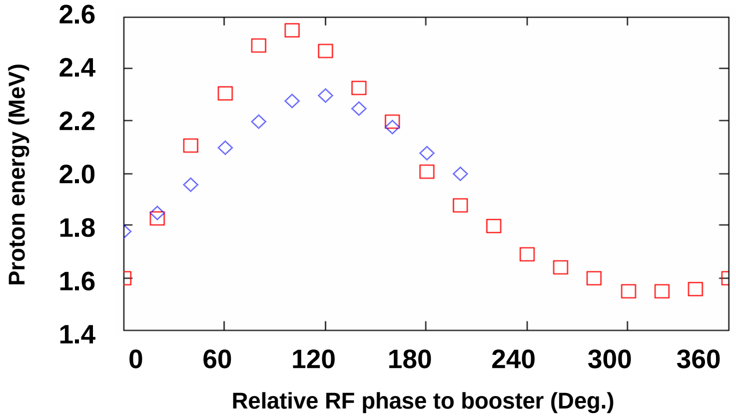

Figure 4. Extracted proton energy from the D-100 system as a function of relative RF phase for 35 kW (red square) and 10kW (blue diamond) booster power.

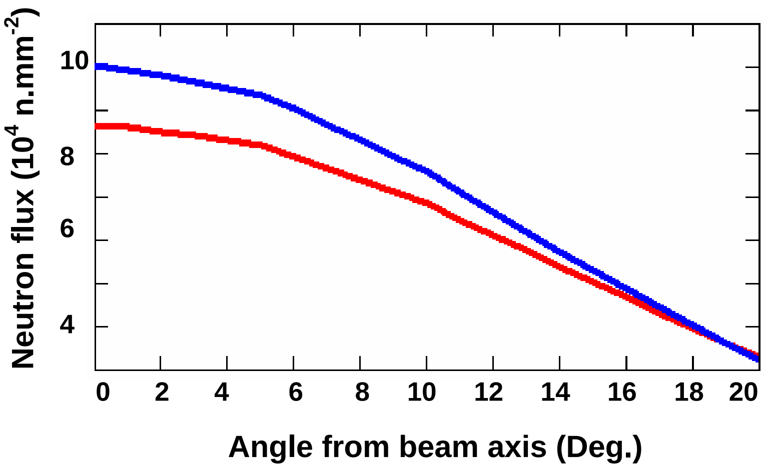

Figure 5. Neutron flux at 4 (red) and 5 MeV (blue) incident D^+ beam on a 3 cm 3 bar deuterium gas target

Figure 5 illustrates the neutron flux emanating from the ADM when operated at 100 microAmps at 4 and 5 MeV incident D^+ beam energy, interacting with a 3 cm deuterium gas target at 3 bar pressure.

3. Detection systems

Since the application of the system is for neutron radiography, several methods of image capture have been developed. In the first system a mirror reflects light from a neutron scintillator onto a CCD camera, thus protecting the CCD camera from the full intensity of the primary neutron beam. This system has operated reliably for many years.

With improvements in semiconductor based photon collection devices, an alternative imaging system was developed. Earlier studies with a 20 x 25 cm amorphous silicon flat panel detector indicated potential viability [2]. Drawbacks were encountered due to the use of a low efficiency scintillator material as well as degradation of the electronics associated with the detector readout which was in line of sight with the primary neutron flux. A larger amorphous silicon array was acquired from Perkin Elmer where the readout electronics are situated at the edges of the panel. This amorphous silicon panel has a sensitive area of 410 mm by 410 mm and pixel size of 400 microns. A specially made combination of Bicron scintillating fibre blocks was mounted directly onto the panel. Each fibre block (10 mm x 10 mm) consisted of 289 BCF-28 fibres of diameter 0.25 mm single cladding. The depth of the block is 70 mm. Each block of fibres was specially produced such that when combined to the full array, the fibres extended a focal length of 980 mm.

In the detection process neutrons induce an optical signal in the scintillator fibre. The fibre also adds its own noise (N_s) component which is proportional to the signal. The system signal to noise ratio (S_t/N_t) following neutron detection becomes:

$$\frac{S_t}{N_t} = \frac{S}{(N + S.N_s)}.$$

In the amorphous silicon panel there is a further gain step (G_p) plus a noise contribution (N_p) independent of the signal. Thus the system signal to noise ratio becomes:

$$\frac{S_t}{N_t} = \frac{S}{(N + S.N_s)}.G_p + N_p$$

Another fibre scintillation block array is also used on the D-100 system which relies on the use of an array of CCD cameras to collect the scintillation light from the 40 x 40 cm^2 detector area. The light from the array is effectively split into four segments by using a multiple mirror in the shape of a pyramid. The light from each mirror is amplified by an image intensifier and split by a semi-mirror to be detected by two CCD cameras. One camera is triggered for high energy mode of operation of the accelerator, whilst the second is triggered for the low energy mode. The images collected by the eight cameras are reconstructed by computer to provide a high/low energy contrast image. The added advantage of this system is that it is able to reconstruct an image of a moving target, thus it is possible to scan a large container moving through the field of view of the detector.

4. Discussion

Two novel accelerator based neutron detection systems have been described. They both have potential applications for cargo interrogation for detection of a variety of materials through the ability to vary the neutron energy used for inspection.

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References

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