A HIGH CURRENT TANDEM ACCELERATOR FOR GAMMA-RESONANCE CONTRABAND DETECTION

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Abstract

TRIUMF and Northrop Grumman have developed a new system for the detection of concealed explosives and drugs. This Contraband Detection System (CDS) is based on the resonant absorption by ^{14}N of gammas produced using $^{13}C(p,\gamma)^{14}N$. The chosen reaction uses protons at 1.75 MeV and the gammas have an energy of 9.17 MeV. By measuring both the resonant and the non-resonant absorption using detectors with good spatial resolution, and applying standard tomographic techniques, we are able to produce 3D images of both the nitrogen partial density and the total density. The images together may be utilized with considerable confidence to determine if small amounts of nitrogen based explosives, heroin or cocaine are present in the interrogated containers.

Practical Gamma Resonant Absorption (GRA) scanning requires an intense source of protons. However this proton source must also be very stable, have low energy spread, and have good spatial definition. These demands suggested a tandem as the accelerator of choice. We have therefore constructed a 2 MeV H$^-$ tandem optimized for high current (10 mA) operation, while minimizing the overall size of the accelerator. This has required several special innovations which will be presented in the paper. We will also present initial commissioning results.

1 INTRODUCTION

In recent years the ease with which high explosives can be concealed and then placed on public transport such as planes has caused major concern worldwide. There is also a growing demand to reduce the transit of illegal drugs through public transport systems including the postal service. In both cases because of the required throughput and privacy requirements there is a desire for non-invasive techniques for the detection of contraband. Normal x-ray systems rely on strong density differences for identification, and have proven very successful in the detection of weapons in carry-on luggage. However while most explosives have fairly high densities, they are difficult to distinguish from other items commonly contained in luggage, particularly given the ability to shape them and/or conceal them in appropriate materials. Therefore there have been many efforts to detect contraband using methods more dependent on the exact chemical composition.

When reviewing the composition of explosives it is immediately noted that they all have a large partial density of either nitrogen or chlorine when compared with most common materials. Various techniques have been developed to measure the quantities of key constituents such as carbon, oxygen and nitrogen. In fact many techniques that exploit the specific properties of these nuclei are being pursed and are reviewed elsewhere[1][2]. Perhaps the best known of these is neutron activation.

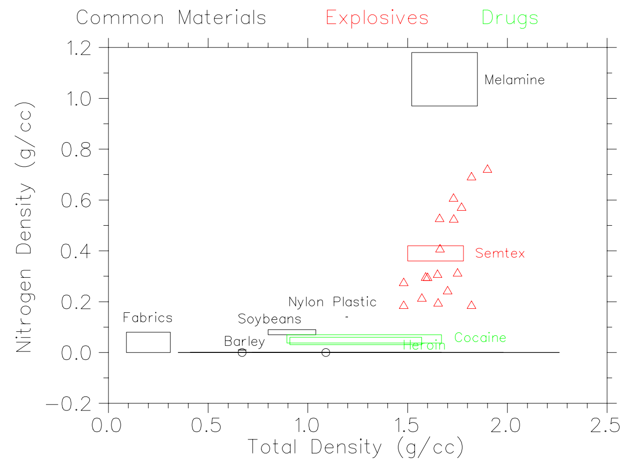

Figure 1: Explosives have a unique signature compared to common materials when nitrogen density is plotted against total density

In figure 1 the density and nitrogen partial density of a number of substances are shown. The clustering of the explosives in one part of the plot indicates how knowledge of the nitrogen partial density can lead to the identification of an explosive substance. The plot also indicates how a knowledge of both the partial nitrogen density and the total density together could be used to identify heroin or cocaine. Gamma resonant absorption (GRA) is a process that shows strong promise as a way to measure partial nitrogen (or chlorine) density.

It should be stressed that one needs to know the partial density of nitrogen in a selected volume, not the total amount of nitrogen in the overall container being inspected. For this reason it is important to have a spatially defined measurement technique, which in the case of high explosive reduces to a position resolution around 5mm. We have thus decided to combine GRA with high resolution tomography, similar to the combination of x-rays and tomography used in CAT scans. More details of the specific mission can be found in ref [3]

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Production Reaction	Proton Energy	Gamma Energy	FOM
$^{14}N(\gamma,p)^{13}C$	1.75	9.17	1000
$^{35}Cl(\gamma,p)^{34}S$	1.89	9.08	35
$^{35}Cl(\gamma,p)^{34}S$	2.79	8.21	76
$^{16}O(\gamma,p)^{15}N$	1.03	13.1	22
$^{12}C(\gamma,p)^{11}B$	1.39		10

Table 1: A comparison of potential gamma resonances in carbon, oxygen, nitroge and chlorine, using a Figure Of Merit normalized to 1000 for the $^{13}C(p,\gamma)^{14}N$ reaction.

2 GAMMA RESONANCE ABSORPTION

GRA makes use of the fact that for each element there are certain gamma energies that are strongly absorbed by the nucleus. Since the gamma energy at which this happens is specific to the target nucleus, a comparison of the absorption at the resonant energy with the absorption at an energy just off resonance will yield a measure of the sought after element. For example the reaction $^{13}C(p,\gamma)^{14}N$ has a large cross section at a gamma energy of 9.17 MeV, so by interrogating a container with gammas at this energy one could measure the nitrogen density.

From a practical point of view it is not easy to produce a near mono-energetic beam of gammas. At present the most promising approach is to use an inverse reaction to produce the gammas. For example the 9.17 MeV gammas can be produced using a beam of protons and the $^{14}N(\gamma,p)^{13}C$ reaction. Assuming favourable reaction kinematics, it is possible to find an outgoing gamma angle at which the gammas have been Doppler shifted by an amount that exactly compensates for the energy absorbed in the production reaction.

In 1994/95 the TRIUMF-Grumman team conducted an extensive study of GRA for the detection of concealed contraband. This study developed a figure of merit for evaluating various resonances. The figure of merit included factors for the strength of the resonance, the width of the resonance, gamma energy spread and other factors that affect the usefulness for imaging by tomography. The figure of merit was normalized to 1000 for the $^{13}C(p,\gamma)^{14}N$ reaction. Table 1 compares some of the considered reactions. From this the $^{13}C(p,\gamma)^{14}N$ reaction was found to be the most promising, however CDS has continued to maintain the option of using the lower energy $^{34}S(p,\gamma)^{35}Cl$ reaction, for the detection of chlorine based explosives, and the hydrochloride forms of cocaine and heroin.

One advantage of producing the required gammas using an inverse reaction is that gammas meeting the re-absorption criteria form a narrow conical fan. In the case of ^{14}N detection, the cone lies at 80.7 degrees, and is about half a degree wide. This results in a convenient inspection geometry as shown in figure 2. Gammas produced just outside this cone can be used to measure the non-resonant absorption, which can be used to normalize the resonant absorption for the calculation of nitrogen partial density, and for the calculation of total density.

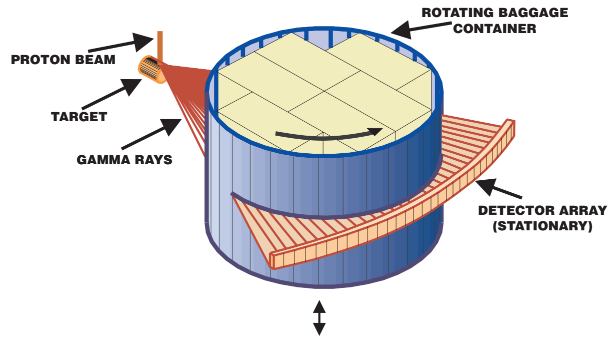

Figure 2: CDS detector and inspection geometry

3 ACCELERATOR REQUIREMENTS

For a practical inspection device there are several key elements affecting the choice of accelerator. They include image resolution, throughput, over all size and convenience of operation. The first two of these determine the number of gammas per second required and the quality of those gammas.

In order to maximize the efficiency of gamma production it is important that the energy spread of the beam be less than the target thickness. As well the lowest energy protons must have an energy at least as high as the resonance energy. Therefore the larger the proton energy spread, the higher the proton beam central energy that is required and the thicker the target that has to be used. This has a limit since we are interested in a target as thin as possible to avoid the excitation of other resonances which contribute only to the background. In addition, using too thick a target will affect the energy spread of the produced gammas, which in turn will decrease the resonance absorption signal.

The size of the beam spot on the target combines with the position resolution of the detectors to reduce the precision with which the flight path of each gamma is measured. Thus the larger the beam spot size the poorer the position resolution of the overall system. It is therefore desirable to choose a spot size that will make a negligible change in the image resolution given the resolution of the detectors.

Angular divergence of the proton at the target changes the angle of the produced gamma. Thus the proton beam's divergence creates an uncertainty as to the energy of a gamma ray even if its position at the detector is known precisely. Because of this uncertainty, some of the gamma rays that arrive at the detector on the locus of the resonant-energy conic section deviate from the resonant angle by an unknown amount up to the divergence of the beam. However these rays will not have meet the resonance condition when passing through the luggage. The effect of including off-energy gammas rays in the resonant image is to dilute the resonant absorption effect which causes an increase in the resonant image noise. The larger the proton beam divergence the greater the noise added to the resonant-energy image. Simulations were used to determine the beam di-

	$^{14}N(\gamma,p)^{13}C$	$^{35}Cl(\gamma,p)^{34}S$
Proton Energy (MeV)	1.75	1.89
Energy Spread (keV)	< 25	< 12
Spot Size (cm)	0.6 x 2.4	0.6 x 2.4
Divergence(mrad)	12	12
Current (mA)	10	12

Table 2: CDS accelerator requirements for the selected production reactions

vergence levels that would cause minimal increases in the false alarm rate.

Once an image resolution, a detection level, and false alarm rate have been chosen, then throughput determines the gamma flux requirement. Calculations show that in order to achieve throughput rates in the hundreds of bags per hour for the chosen configuration, the proton beam current must be in the 10 milli-ampere range.

A summary of the beam requirements as determined in the initial design study are summarized in table 3. The design study then performed a survey of methods for the production of protons up to 3 MeV. Accelerator options such as RFQs and cyclotrons were investigated. While RFQs looked very promising because of their compactness and high current capability they are not able to meet the other beam parameters. Electrostatic accelerators were really the only system capable of producing such high quality beams. However most electrostatic accelerators have two disadvantages for CDS, size and limited beam current. It was therefore decided to design a new tandem accelerator specifically for CDS. It should also be noted that a DC accelerator, when compared to a CW accelerator, creates a significantly lower instantaneous data rate in the detectors.

4 THE CDS SYSTEM

The layout of the CDS Proof-of-Principle system is shown in figure 3. This system has been designed to perform a laboratory proof of principle experiment and to allow for the testing and development of components that could be used in a commercial system.

The gamma production system begins with a high brightness H^- ion source coupled by a short matching section to the tandem. The tandem is followed by a beam transport section that analyzes the beam and produces the correct beam spot parameters at the target. At present the target consists of a fixed water cooled target coated with carbon-13. However in order to use the full beam current a rotating target will be constructed. The high energy beam line has been constructed so that the resonant gamma cone lies in the horizontal plane in the region of the baggage carousel.

In order to acquire tomographic information the objects to be inspected are located on a carousel that is capable of rotating and elevating. Behind the carousel is located a detection system that consists of a double deck arc of segmented BGO block detectors. The arcs subtend an angle of 53 degrees and contain 44 blocks each. Standard electronics is used to collect the phototube output which is then converted into gamma position information. Image reconstruction and interpretation is then performed in separate computers. At present we are using 7 detector blocks and offline data processing and a very simple carousel in order to assess the overall system performance. In a high throughput system the carousel would rotate and elevate simultaneously.

5 THE CDS TANDEM

As discussed above, the CDS requires an electrostatic accelerator capable of a very high beam current, while maintaining the smallest practical size. Using a tandem allows the terminal voltage to be halved thus reducing the demands on the voltage generator, and the amount of space required to hold voltage. The trade-off is the requirement for a stripper located in the terminal that is capable of handling the current. Since the proton beam energy at the terminal will be below 1 MeV, the energy loss in a stripping foil would be quite large. Calculations show that expected foil lifetimes would be perhaps a few minutes at the design intensities. We therefore chose to use a vapour stripper. Design of this element has concentrated on providing good differential pumping between the stripper cell, and the acceleration columns. A schematic of the system is shown in figure 4. Pressure in the acceleration columns is particularly important because interactions between the residual gas and the beam will produce free electrons that will then be accelerated and generate x-rays. Significant production of high energy x-rays could lead to voltage breakdown and constitute a radiation hazard external to the accelerator. Testing to date has shown that with the stripper operating above design pressure, the pressure in the columns is in the low 10^{-7} range.

Obviously the overall size of a tandem can be reduced by increasing the electric fields, particularly in the acceleration region. However voltage holding problems rise steeply with electric field so we have chosen to remain at a fairly conservative 50 kV/inch in the acceleration region. By pressurizing the containment vessel to 60 PSI with SF_6 the distance between the vessel and the terminal has been reduced by factor of almost 10 over using unpressurized nitrogen (air). Keeping the terminal compact has also helped to reduce size. As well as the vacuum equipment for the stripper, the terminal contains two magnetic quadrupole triplets for matching beam between the acceleration regions and the stripper cell. Considerable effort has been devoted to making this region compact while still using commercial power supplies and controllers. Communication between ground and the terminal is achieved using fiber optics.

Of particular importance to CDS is a suitable power supply. In order to produce a 10 mA, 2 MeV beam, the power supply must be able to supply at least 20 mA at 1MV, meaning it must be capable of a power output greater than 20

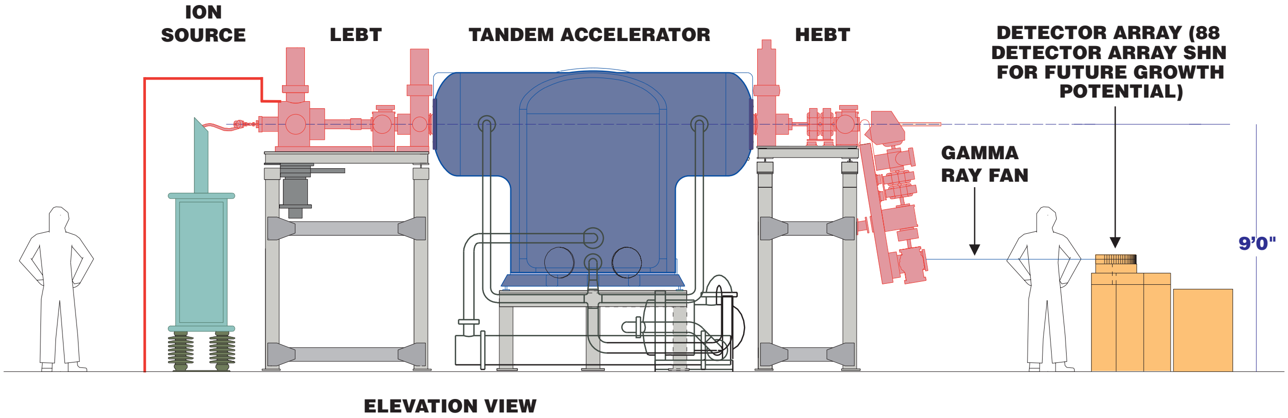

Figure 3: Side elevation of the CDS proof-of-principle device

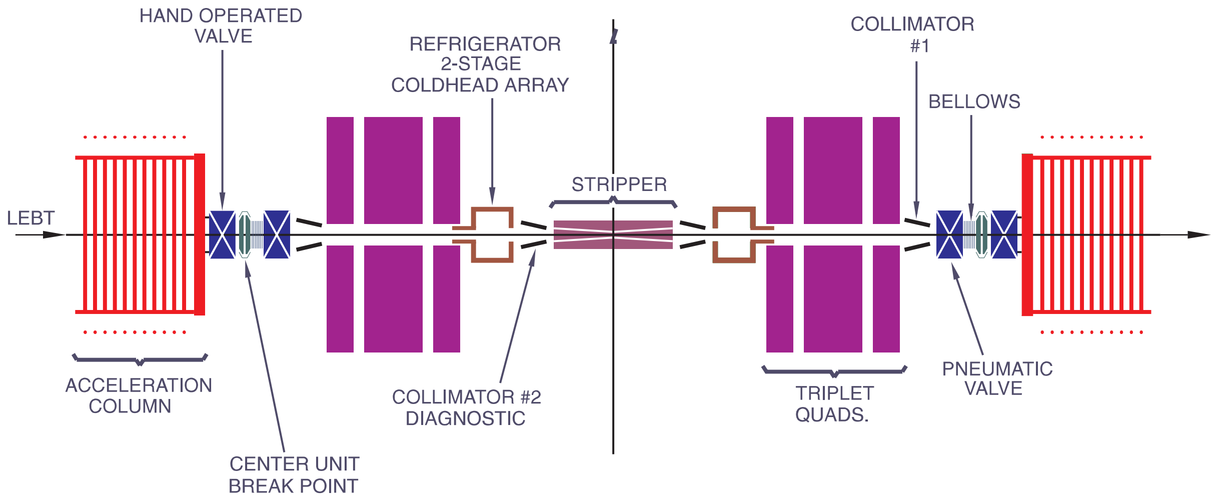

Figure 4: Schematic layout of the terminal vacuum system

kW. The preliminary CDS design study showed that most conventional power source were incapable of providing the necessary current, and those that had produced currents in the milli-Ampere range were extremely bulky. However the design study also identified a novel power supply development at the University of Waterloo that was able to meet the CDS requirements in a compact volume. Basically this system uses a high frequency isolated core transformer to couple a large number of voltage doubler circuits that are then connected in series to develop the necessary voltage. The high frequency allows relatively small conventional components to be used, with the secondary tracks and doubler circuits mounted on normal circuit boards. This supply occupies a space less than 300 in^2 and is under 36 inches high. In the tandem the supply sits under the terminal between the support insulators and is insulated by the SF_6. In the region of the voltage generation the average field is 50 kV/in. Tests of the supply using a water load have demonstrated outputs of greater than 26 kW at 1 MV.

Fine control of the power supply voltage is achieved by varying the primary frequency, allowing rapid changes. As well since the capacitance of the doublers is small, the stored energy of the supply is small when compared to the overall tandem capacitance. Tests at 860 kV without beam have shown that even with no voltage stabilization the system shows less than a ± 5 kV variation. We have implemented a system that will adjust the frequency based on the terminal voltage. This appears to take care of basic beam loading effects. Eventually we expect to use feedback from the high energy beamline to adjust this loop.

At present all of the system sub-components have been tested. A resonant image has been observed with the detectors using gammas produced with a proton beam of a couple of micro-amperes on a vanderGraff. The ion source and low energy beam transport emittance has been fully characterized at 10 mA. The tandem has undergone a series of voltage tests up to 900 kV on the terminal, including full operation of the stripper while at 865 kV. Initial tests at

25 μA have indicated that the beam spot at the stripper location is as specified. On the first attempt to run beam 100 μA at virtually 100% transmission was extracted. Beam current was limited to this level by target restrictions. We are now working on parametrization of the beam and expect start basic tomographic scans of realistic phantoms in the near future.

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