A STUDY OF STORAGE RING REQUIREMENTS FOR AN EXPLOSIVE DETECTION SYSTEM USING NRA METHOD*

Tai-Sen F. Wang† and Thomas J. T. Kwan, LANL, Los Alamos, NM 87545, U.S.A.

Abstract

The technical feasibility of an explosives detection system based on the nuclear resonance absorption (NRA) of gamma rays in nitrogen-rich materials was demonstrated at Los Alamos National Laboratory (LANL) in 1993 by using an RFQ proton accelerator and a tomographic imaging prototype.[1,2] The study is being continued recently to examine deployment of such an active interrogation system in realistic scenarios. The approach is to use an accelerator and electron-cooling-equipped storage rings(s) to provide the high quality and high current proton beam needed in a practical application. In this work, we investigate the requirements on the storage ring(s) with external gamma-ray-production target for a variant of the airport luggage inspection system considered in the earlier LANL experiments. Estimations are carried out based on the required inspection throughput, the gamma ray yield, the proton beam emittance growth due to scatters with the photon-production target, beam current limit in the storage ring, and the electron-cooling rate. Studies using scaling and reasonable parameter values indicate that it is possible to use no more than a few storage rings per inspection station in a practical NRA luggage inspection complex having more than ten inspection stations.

INTRODUCTION

Most of the high explosives have high nitrogen content and concentration. This distinct characteristic accommodates a unique way of detecting high explosives by using the nuclear resonance absorption (NRA) process of $^{14}\mathrm{N} + \gamma \rightarrow {}^{13}\mathrm{C} + p$.[1] A schematic of utilizing the process is shown in Fig. 1. The technical feasibility of an explosive detection system based on the NRA method has been demonstrated at LANL in 1993[1,2]. The system employed an RFQ linac to produce the required protons and a tomographic imaging prototype to detect the transmission of gamma ray through airport luggage. However, the RFQ linac, though adequate for demonstrating the NRA method, was not capable to provide the required energy spread among protons at the desired beam current for a practical application. More study is needed for a practical implementation of such kind of explosive detection systems. The main challenge is to achieve the quality and intensity of the proton beam for generating sufficient gamma rays needed for the required inspection throughput and accuracy.

The recent direction of the study is toward a storage-ring-based approach. Electron cooling is being considered for reducing the emittance and the energy spread of the proton beam. In this study, we investigate the storage ring requirements based on a nominal case of luggage inspection. We limit our discussions to the use of external target for producing γ photons only.

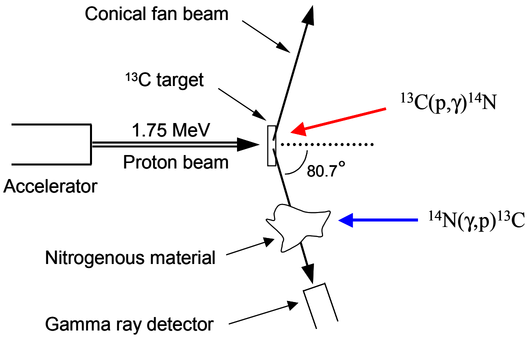

Figure 1: The NRA high explosive detection schematic.

BEAM QUALITY REQUIREMENTS AND NOMINAL CASE

At the target, the beam is required to have a spot size of 0.5cm in radius, a divergent angle less than 3mrad, and an energy spread $\Delta E/E \approx 1\times10^{-3}$.[2] Assuming the beam forms a waist near the target, we estimate that the upper limit of the transverse beam emittance ε_0, is about 15π mm•mrad.

In order to facilitate the investigation of storage ring requirements, a nominal case of the luggage inspection system is postulated here based on a variation of the 1993 LANL experiments.[2] In this nominal case, luggage bags are interrogated at inspection stations. At each inspection station, four luggage bags being interrogated are placed on a platform in a one-bag-per-quadrant arrangement. Each bag is placed on a turntable that can rotate the luggage in 90° intervals. The turntable is also movable vertically for four steps. For each vertical step, every luggage is scanned for four side views through four rotations of the turntable at the rate of one rotation per second. Taking an approximately 8s luggage loading time into account, the system is expected to achieve an inspection rate of one luggage bag every 6s.

At each inspection station, a gamma ray detecting system having 64 detector units per quadrant is set up to surround the platform for tomographic imaging. The proton beam enters the inspection station on the center axis of the platform to impinge on a carbon foil target placed about 40cm above the platform to produce gamma rays. The resonant gamma rays, fan out from the target in a cone approximately 81° from the central axis, will pass

---

*Work performed under the auspices of US DoE (NNSA-NA241) by the University of California under contract No. W-7405-Eng-36.

†twang@lanl.gov

through the luggage before reaching the detectors. In the absence of any nitrogen-rich material, each detector is expected to receive about 400 γ photons for one side view of the luggage. Hence for every 90° rotation of the luggage, we need at least 1.024×10^5 γ photons to be produced by passing a proton pulse through the carbon foil. At the yield of 0.63×10^{-8} γ photons per proton, this requires a proton beam that can deliver approximately 1.6×10^{13} protons per pulse. Note that during the one-second interval of rotating the turntable, most of the time is spent in positioning the luggage.

Protons are initially injected into the storage ring(s) from an accelerator such as a cyclotron or an RFQ. The proton beam is then stored and cooled to the required emittance and energy spread by electron cooling. When both the luggage positioning and the beam quality are ready for interrogation, protons are ejected from the storage ring and transported to the target for gamma ray production. The interaction of protons with the target introduces emittance growth and energy degradation to the proton beam. After passing the foil, protons are circulated back to the storage ring, accelerated, and cooled for the next interrogation.

The increase of the transverse beam emittance after traversing the target foil is estimated using the relation $\delta\varepsilon \approx \pi\beta_0\sigma_c\langle(\delta y')^2\rangle\, n\widehat{t}$,[3] where $\beta_0 \approx 1.667$m is the beta function at the target, n is the atomic density of the foil, $\widehat{t}$ is the foil thickness, σ_c is the effective total cross section for a collision between a beam proton and a target nucleus, and $\langle(\delta y')^2\rangle$ is the mean square angular deviation of the proton trajectory due to the scattering. For a carbon foil of 20μg/cm², $n\widehat{t} \approx 1 \times 10^{22}$ atom/m², and $\sigma_c\langle(\delta y')^2\rangle \approx 1.9 \times 10^{-27}$(m•rad)²/atom has been computed in Ref 4 for the 1.75 MeV protons. The increase of the transverse beam emittance per foil transit is then evaluated as $\delta\varepsilon \approx 3.17$ πmm•mrad $\approx 0.2\varepsilon_0$.

STORAGE RING REQUIREMENTS

Model Storage Ring

A conceptual design of a model storage ring is considered here for estimation purpose. Figure 2 shows the layout of the major ring elements. The rectangle-shape ring, 10m in circumference, has two 1.8-m-long and two 1.6-m-long straight sections. The beam focusing is accomplished by four combined-function bending magnets having a field intensity of 0.375T, a field index of –1.58, and the end pole faces normal to the beam line. The horizontal and vertical betatron tunes are 1.63 and 1.24, respectively. The lattice functions, computed using the program MAD-X[5], are shown in Fig. 3. Space is reserved in the straight sections for up to four 10-cm-long trim quadrupoles. The cooling section, located in one of the two 1.8-m-long straight sections, has a 0.9-m-long solenoid for providing an axial magnetic field up to 1kG.

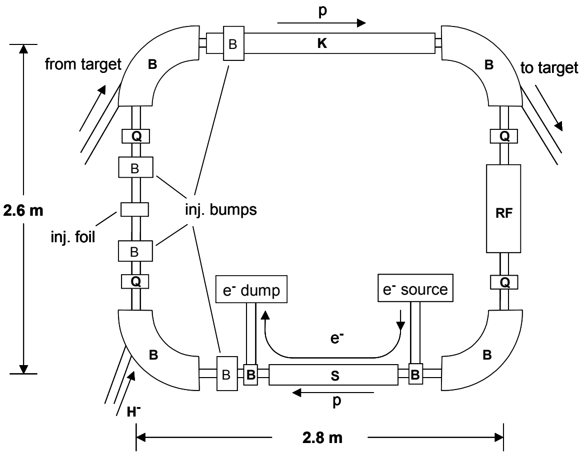

Figure 2: Layout of the model storage ring.

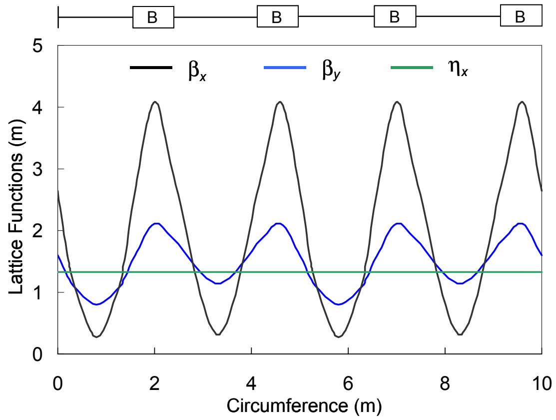

Figure 3: The lattice functions of the model storage ring.

A 1.5-m-long fast kicker, located in the other 1.8-m-long straight sections, is to be operated at 5kV per plate for a total voltage of 10kV for beam extraction and injection. The H⁻ injection method is used to accumulate the protons in the ring. The injection foil is situated in one of the two 1.6-m-long straight sections. Four injection bump magnets are inserted to facilitate the H⁻ injection. A dual-harmonic rf cavity is placed in the other 1.6-m-long straight section. The ferrite-loaded rf cavity is expected to operate at the first and the second harmonics of the proton revolution frequency (1.835MHz and 3.67 MHz) with maximum voltage of 300V and 100V, respectively. The second harmonic rf is added to reduce the proton density and the transverse space-charge force in the middle of the bunch.

Electron Cooling

Cooling time is estimated using the program BETACOOL[6] for 0.2A of electron beam current and 5kG of solenoid field in the model ring lattice structure.

For the increments of 20% in the transverse beam emittance and 100% in energy spread due to the beam-foil interaction ($\Delta E \approx 1.9$KeV per foil traversing for the 20 μg/cm^2 carbon foil), BETACOOL gives about 0.004s to cool the transverse emittance back to 15πmm•mrad and about 0.02s to cool the energy spread down to $\Delta E/E \approx 1\times10^{-3}$ as shown in Fig. 4. The corresponding averaged cooling rate is about 35s^{-1}. Thus the time needed for the longitudinal cooling limits the maximal repetition rate of the storage ring to 50Hz. Note that the cooling estimation here is rather crude because the BETACOOL computation does not include the longitudinal effect due to the second harmonic rf field.

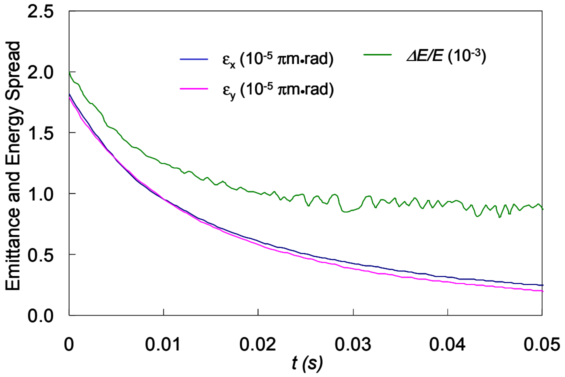

Figure 4: The emittance and the energy spread of the proton beam during the first 0.05s of cooling.

Scaling Relation for Storage Rings

Here, we estimate the number of storage rings, like the model storage ring proposed here, needed for the nominal explosive detecting system under study. We first estimate the maximum number of protons can be stored in a ring by using a crude relation inferred from the incoherent tune shift formula:

$$\frac{(N_p)_1}{(N_p)_2} \approx \frac{\gamma_1^3 \beta_1^2 \varepsilon_1 / G_1}{\gamma_2^3 \beta_2^2 \varepsilon_2 / G_2} , \qquad (1)$$

where N_P is the maximum number of beam particles in the ring, $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$, v is the speed of a beam particle, ε is the beam emittance, and G depends on the ring lattice and the bunching factor. The subscripts 1 and 2 in Eq. (2) denote one of the NRA rings and the machine to be scaled from, respectively. Taking the approximation $G \approx 1$, and applying Eq. (1) to scale from the storages rings MIMAS, PSR and the storage ring at BINP, we conclude that it is reasonable to assume the maximal possible protons can be stored in our model ring is between 10^{10} and 10^{11}.[4] If we also assume a 20μg/cm^2 carbon foil is used for the target and 0.02s is needed for beam cooling, we estimate that 4 rings are needed to achieve a 1.6×10^{13} proton/second average beam current at the target. From these results and the conditions postulated in the nominal luggage inspection system, we formulate a crude scaling relation for the smallest number of storage rings per inspection station needed to yield the required γ photon production rate:

$$\begin{aligned}&\text{Number of storage rings} \approx (10^{11}/\text{protons per ring}) \times \\ &(\text{vertical slice views per luggage}) \times (\text{rotations per slices}) \times \\ &(\gamma \text{ counts per detector unit}/400) \times (\text{cooling rate}/35\text{s}^{-1}) \times \\ &(\text{carbon foil thickness in } \mu\text{g per cm}^2/20)\ /(4 f_i N_r) , \qquad (3)\end{aligned}$$

where $N_r f_i \leq 1$, f_i is the fraction of one second for imaging, N_r is the maximal number of stations a storage ring serves, and it is also assumed that a storage ring can serve more than one inspection station in a time-sharing manner. As an example, if only two side views per vertical slice are required in the luggage inspection, and if the cooling rate is about 50s^{-1}, $N_P \approx 7\times10^{10}$, $f_i = 0.1$, $N_r = 10$, and a 20μg/cm^2 foil is used for target, then two storage rings are needed for each inspection station.

CONCLUSIONS

We have discussed the storage ring requirements for an explosive detection system that uses the NRA method based on a postulated nominal case of luggage inspection. The proton beam emittance growth due to scattering with the target was estimated. We also formulated a scaling relation for the number of proton storage rings required in the nominal case. Our study is limited to the use of external target for producing gamma rays and our investigation has not considered the proton beam intensity limitation in the storage rings due to collective instabilities. Studies based on scaling and reasonable parameter values indicate that it is unlikely a single storage ring will be capable to provide the required proton beam intensity. Possibilities of using an electrostatic accelerator or collimating the proton beam from a high intensity accelerator should be explored. Nonetheless, we found that if a 20μg/cm^2 or a thinner carbon foil is employed as the γ-photon-production target, it is possible to use no more than a few storage rings per inspection station in a practical NRA luggage inspection complex having more than ten inspection stations.

REFERENCES

[1] R. E. Morgado et al., SPIE Conf. Proc. 2092, 1993, p. 503.
[2] R. E. Morgado et al., Los Alamos National Laboratory Report LA-12776-MS, 1994.
[3] H. Bruck, "*Circular Particle Accelerator*," English translation, LANL Report LA-TR-72-10 Rev., 1972, p. 144.
[4] T. F. Wang and T. J. T. Kwan, Los Alamos National Laboratory Report LA-UR-04-5457, 2004.
[5] See MAD-X website at http://mad.home.cern.ch/mad.
[6] A. Smirnov, A. Sidorin, and G. Trubnikov, "Description of software for BETACOOL program based on BOLIDE interface," JINR report, 2004.