PROGRESS REPORT ON DEVELOPMENT OF THE RING CAVITY FOR LASER-BASED CHARGE STRIPPING OF HYDROGEN IONS*

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Abstract

Charge stripping of hydrogen ions is the first stage of any high intensity proton accelerator. To achieve higher-charge proton sources, the stripping efficiency must be improved, especially in the context of the Spallation Neutron Source at Oak Ridge National Laboratory. A method based on laser-ion interaction has a great potential for increasing efficiency. The approach of this proposed project is to design a laser cavity based on the Recirculation Injection by Nonlinear Gating (RING) technique. This paper reports on the progress of the development of the RING cavity; in particular, the radiation hardness studies of the nonlinear crystal.

INTRODUCTION

Charge stripping of hydrogen ions is the first stage of any high intensity proton accelerator [1]. Use of carbon foils as strippers, introduces beam loss, hence limiting beam power in high intensity proton rings; also, the carbon foils have a short life time due to radiation damage, and activation makes them difficult to replace [2]. Recently, a method based on laser-ion interaction [3] has been successfully demonstrated [4]. The direct application of such a method, however, requires megawatts of average laser power in order to strip the entire ion beam. Laser beam recirculation is a natural step towards increasing the overall interaction efficiency of ion stripping while maintaining the average power of the drive laser within practical limits.

A novel, collinear laser recirculation scheme termed Recirculation Injection by Nonlinear Gating (RING) has been recently proposed and demonstrated [5]. This technique exhibits high enhancement factors, simplicity, and compatibility with both nanosecond and short-pulse laser sources, such as needed for a laser ion-stripper at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) [6].

BBO CRYSTAL RADIATION TEST

There is a high level of radiation present at ORNL SNS facility; hence, there is a concern over the performance of the nonlinear crystal and other optics, and ultimately their life expectancy in the high-radiation environment. Of particular importance is maintaining the reflectivity of mirrors, good performance of anti-reflection coatings on the nonlinear crystal, and the transparency of the crystal. The radiation is primarily due to energetic neutrons produced by (p,n) reactions. Such reactions result in the production of neutrons in the MeV energy range as well as some gammas. The irradiation dose present in SNS at the location at which the RING optical setup would be introduced is estimated to be in the order of 100 mrad per hour, or 500 rad/yr (5 Gy/yr). While the dose depends not only on the irradiation spectrum, but also on the absorber material, we have assumed that the dose absorbed in the BBO crystal would be of similar magnitude, and embarked on an experiment to simulate the radiation environment of SNS and its effect on the BBO crystal transparency. Our experimental goal was to study the crystal transparency at an irradiation level of several Mrad's (tens of kGy), or approximately 10,000 years of crystal irradiation at SNS.

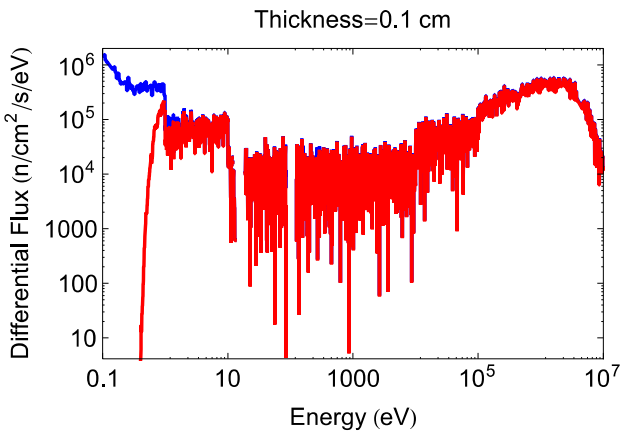

Figure 1: PTR R1 neutron spectrum: before Cd filter (blue); and with 0.1cm Cd filter (red). Slow neutrons are efficiently removed in the latter case.

Given the nature of the irradiation present at SNS and the availability of convenient irradiation sources for accelerated testing of the BBO crystal, we selected the Penn State Breazeale Nuclear Reactor (BNR) for our experiment. BNR is a 1 MW research nuclear reactor, which is frequently used for neutron activation analysis and isotope production and is fully equipped and convenient for this measurement. The fast and the thermal neutron flux is present in the reactor, along with the accompanying X-ray flux. In-core irradiation is available, which allows producing neutron irradiation conditions in which the ratio of fast to thermal neutron flux is significant. We have selected the PTR R1 in-core location for our experiment, which exhibits a favorable ratio of fast to thermal flux.

The sample was placed in a plastic container and wrapped with a 1-mm thick ^{113}Cd foil to reduce the thermal neutron flux and eliminate X-rays.

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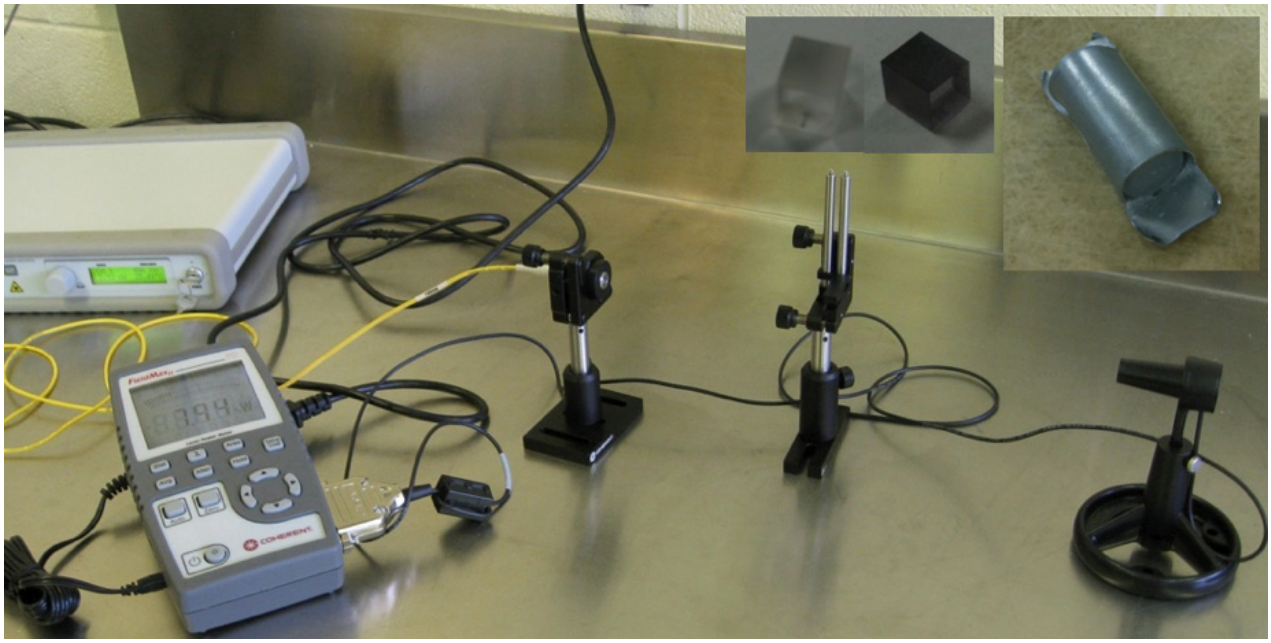

Figure 2: Experimental setup for transparency measurements. Thorlabs fiber-coupled cw diode laser station was used (808 nm, 658 nm, 406 nm); visible on the left. Inserts: the photographs of the BBO crystal before and after irradiation; the photograph of a plastic container that holds the BBO sample wrapped in 1 mm thick ^{113}Cd sheet.

This is of particular importance since the composition of BBO crystal is BaB_2O_4, i.e. contains a considerable fraction of boron, 10% of which is ^{10}B with very high thermal neutron cross section. If the thermal neutron flux were not reduced significantly, a considerable contribution to the dose would come from (n, α) reactions, which induce a different radiation damage mechanism than fast neutrons. The use of the ^{113}Cd foil efficiently removes the thermal flux (Figure 1).

To validate the flux experimentally, an Al-Au wire sample was inserted into the reactor core together with the sample and its activation was measured approximately 72 hours after the irradiation experiments. Using the ^{27}Al (n, α) ^{24}Na with a 7-MeV threshold, fast flux (>7 MeV) was measured to be $1.01\text{x}10^{11}$ cm^{-2}s^{-1} for the reactor working at 300 kW this corresponds to fast flux of $6.8\text{x}10^{12}$ cm^{-2}s^{-1} full spectrum (100 keV to 20 MeV) at full power (1 MW), in accordance to what was expected. Our neutron spectrum was appropriately normalized for this measured flux, and used to estimate the absorbed dose.

A Mathematica code was developed for the purpose of calculating the deposited dose in the sample. The dose calculation is especially tailored to the geometry and the known conditions of the irradiation experiment, including the reactor neutron spectrum and the relevant energy-dependent cross section of the ^{113}Cd shielding and the BBO constituents. The absorbed energy in the sample per unit volume is estimated by calculating the rate of energy deposition by nuclear recoil in elastic scattering, for each isotope present in the substantial quantity in the BBO crystal, and integrated over the entire spectrum:

$$E_{dep} = \int_0^\infty dE \frac{d\Phi}{dE} E \sum_i \left(1 - \exp(-\sigma_i N_i \Delta x)\right) f_i \quad (1)$$

where $d\Phi/dE$ is the neutron spectrum appropriately attenuated by ^{113}Cd shielding, σ is the microscopic cross section, N is the number density, Δx is the sample thickness, $f = ((1\text{-}A)/(1+A))/2$ is the average fraction of the energy of the incident neutron that is transferred to the recoiling nucleus with atomic mass number A. The sum is taken over the following nuclei in BBO: ^{137}Ba, ^{10}B, ^{11}B, and ^{16}O. Note that the fast neutrons contribute considerably more to the dose due to the high nuclear recoil energy in their collisions with the BBO nuclei. Since we are neglecting any exothermic slow neutron interactions, the actual deposited dose may be somewhat greater than calculated by this method. When combined with the actual experiment, this approximation in fact leads to a pessimistic threshold for radiation damage, i.e. a threshold which is somewhat lower than the real threshold.

The rate of energy deposition per unit volume is appropriately converted into dose, and the irradiation time is calculated to reach the required dose. The total dose to the sample is estimated to be 4 Mrad (40 kGy) over our 3 experimental runs. The crystal has visibly darkened following the experiment (Figure 2). The crystal transparency is measured using a laser system operating at three wavelengths: 406 nm, 658 nm, and 808 nm. The transmitted power is measured using a silicon photodetector, before and after irradiation. In Table 1 we show the crystal absorption after all three runs, at three

wavelengths (after the Fresnel loss on two uncoated crystal faces were accounted for).

Table 1: Crystal Absorption After Irradiation

Wavelength	Crystal Absorption after Irradiation
808 nm	11%
658 nm	21%
406 nm	26%

We have experimentally obtained the worst-case estimate for the loss of transparency for the BBO crystal in SNS-like radiation environment, taking into account only the fast neutron dose, and neglecting the dose due to exothermic neutron-induced nuclear reactions, gamma-rays and X-rays. The displayed behavior of absorption increase being inversely proportional to the wavelength is very typical for a number of materials and radiation species. This is due to the fact that the defects created by radiation have different absorption bands whose density and efficiency are higher for shorter wavelengths [7].

With a simple extrapolation, one can conservatively estimate a loss of transparency on the order of 30% -40% at 355 nm for a 4 Mrad (40 kGy) dose.

SUMMARY

After an absorbing a dose of 4 Mrad which is equivalent of irradiation for over 8,000 years in normal operation at SNS, a BBO crystal shows adequate transparency, thus making it an excellent choice for the RING cavity to be used for hydrogen ion stripping.

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