CAVITY-RECIRCULATED LASER CHARGE STRIPPING OF HYDROGEN IONS*

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Abstract

High-intensity proton accelerators such as those at the Oak Ridge National Laboratory's Spallation Neutron Source require an intense, robust, reliable, and low-cost source of hydrogen ions. Laser-based charge stripping is a promising, high-efficiency method that could meet the requirements of present and future facilities. We are seeking to improve the efficiency of hydrogen ion stripping by an order of magnitude using laser recirculation. In our approach we recirculate a high-power laser using the technique termed recirculation injection by nonlinear gating, with a frequency-doubling nonlinear crystal as an efficient switch that allow pulse injection into the cavity. We present our progress on cavity development and the preliminary experimental assessment of cavity performance in high-radiation environment. Our experimental studies were conducted by irradiating the nonlinear crystal used in the laser cavity by fast neutrons in a research nuclear reactor and measuring its change in transmissivity.

INTRODUCTION

Charge stripping of hydrogen ions is the first stage of any high intensity proton accelerator [1]. Typically, carbon foils are used as strippers, but they introduce uncontrolled beam loss. In addition, carbon foils have short life expectancies due to radiation damage, and the activation makes them difficult to replace [2]. To achieve higher intensity outputs from proton sources, the stripping efficiency must be improved. Recently, a method based on laser-ion interaction [3] has been successfully demonstrated [2] as an efficient and non-destructive approach to ion stripping.

A 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 drive laser average power within practical limits. A novel, collinear laser recirculation scheme termed Recirculation Injection by Nonlinear Gating (RING) has been recently proposed and demonstrated [4]. This technique is based on the use of intracavity frequency conversion (such as frequency doubling) to achieve efficient, energy-scalable injection of laser pulses into cavity without the need for interferometric alignment.

A critical requirement for achieving high enhancement factors with a recirculation cavity is low loss. When placed in a high-radiation environment such as that present at the Spallation Neutron Source (SNS), degradation of the performance of any of the RING optics could ensue, resulting in the loss of enhancement. A typical high-radiation environment of SNS consists of spallation fast neutrons, which are accompanied by gamma-rays, with a typical measured dose of 5 Gy/yr.

In the absence of the convenient ability to experimentally measure the loss of transparency of the nonlinear crystal in SNS, we present the results of a surrogate irradiation test designed to mimic the expected conditions at SNS. We report the measurements of transparency of a beta-barium borate (BBO) crystal when irradiated in a nuclear reactor, accompanied by a Monte Carlo analysis of the radiation dose delivered to the crystal in our experiment. The results allow prediction of the performance degradation of a RING cavity in typical SNS conditions.

EXPERIMENTAL RESULTS

We have selected a BBO (BaB_2O_4) crystal for our experiments. BBO is a nonlinear optical crystal of choice for this RING implementation. The selected crystal dimensions are 5x5x6 mm^3. Our surrogate experiment to irradiate the BBO crystal in SNS-like conditions has been conducted at the Pennsylvania State University's Breazeale Nuclear Reactor (BNR). BNR is a 1-MW research reactor with available in-core irradiation tubes, allowing irradiation of samples with large fast neutron fluxes. Large fast-to-thermal neutron flux is important in this surrogate experiment, as SNS conditions are consistent with large fast-to-thermal neutron flux.

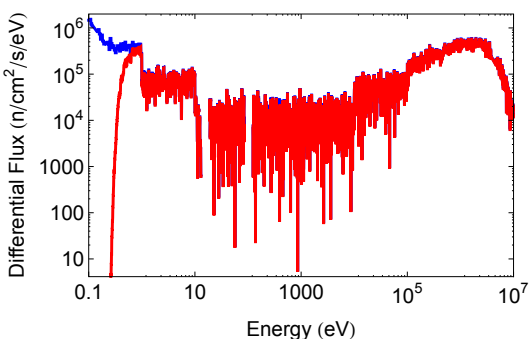

Figure 1: The neutron spectrum of the Penn State BNR at PTR R1 location (black). The red line shows the spectrum after attenuation by 1.27 mm-thick sheet of cadmium, which was used to irradiate the BBO crystal. The neutron flux has been normalized to the operating power of 300 kW.

The neutron spectrum at the location of irradiation experiment is shown in Fig. 1. The sample was wrapped with a 1.27 mm-thick natural Cd sheet to reduce the thermal neutron flux and eliminate any X-rays, and then

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placed in a thin (1 mm thick) polyethylene container. If the thermal neutron flux were not reduced significantly by use of the Cd sheet, a considerable contribution to the dose would come from (n,α) reactions. The use of the Cd foil efficiently removes the thermal flux, which is also shown in Fig. 1. Using the ^{27}Al (n,α) ^{24}Na reaction with a 7-MeV threshold, fast flux >7 MeV was measured at a 300 kW reactor power and used to normalize the total flux and neutron spectrum (Table 1).

Table 1: Experimentally measured fast neutron flux of the BNR at the PTR R1 location at 300 kW power.

Fast Flux (> 7 MeV)	Total Flux
1.01×10^{11} cm^{-2} s^{-1}	2.05×10^{12} cm^{-2} s^{-1}

The crystal was irradiated and the crystal transparency was measured using a laser system operating at three wavelengths: 406 nm, 658 nm, and 808 nm. The absorption in our crystal calculated from these transparency measurements is shown in Table 2.

Table 2: Post-irradiation absorption of the BBO crystal. Absorption was measured on a 0.5 cm-thick crystal, yielding the absorption coefficient.

Wavelength	Absorption	Absorption coefficient
808 nm	11%	0.23 cm^{-1}
658 nm	21%	0.47 cm^{-1}
406 nm	26%	0.6 cm^{-1}

MONTE CARLO SIMULATION

In order to determine the dose in our irradiation experiment and correlate it to the conditions at SNS, we constructed a simple Monte Carlo simulation. The simulation yields detailed information for each reaction, including the reaction location, reaction type, and energy deposition. These can then be used to determine both the total deposited dose and the contributions to the dose from different reaction types. A simple geometry of the problem is chosen, using a 5x5x6 mm^3 prism of BBO, shielded on one side by natural cadmium with a thickness of 0.05" (1.27 mm). Incident neutrons were simulated as a beam incident onto the cadmium shield, with the energy spectrum based on the known spectrum of the Breazeale Reactor.

Table 3: Results of the Monte Carlo simulation of the BBO irradiation experiment.

Quantity	Value
Neutron flux (300 kW)	2.05×10^{12} cm^{-2}s^{-1}
Dose/neutron	5.2×10^{-2} MeV g^{-1}
Neutron dose rate	5.13 Gy s^{-1}
Neutron dose	7.18 kGy
Gamma dose	10 kGy
Equivalent time at SNS	3400 years

The simulation provides the average energy absorbed per incident neutron with the energy spectrum of BNR. This information is combined with the experimentally determined neutron flux and experimental exposure times in order to determine the total dose that the BBO crystal received during the irradiation experiment. The results of the simulation are summarized in Table 3. The first result of interest is the energy deposition rate during the experimental trial. Energy deposition was found by combining the energy deposition per incident neutron with the total neutron fluence over the course of the experiment, which had been determined experimentally using Al-Au wire activation. The resulting dose associated with neutron irradiation in our experiment is 7.18 kGy. An estimated 10 kGy was also deposited due to gamma-rays, which was determined by scaling the previously measured gamma dose rate at this location to our experimental reactor power and irradiation time.

Table 4: Fractions of different neutron interactions occurring in the experiment and contributions of different interactions to neutron dose.

	Elastic scattering	Inelastic scattering	Neutron capture
Reactions	92%	6%	2%
Dose	66%	6%	31%

The simulation was also used to determine the contributions of different interaction modes of neutrons with the crystal to energy deposition in the sample. As can be seen from Table 4, elastic scattering dominates the number of neutron interactions with the crystal, as the fraction of neutron captures has been successfully reduced by the use of Cd shielding. However, while the neutron captures are relatively rare in our experiment, they constitute a relatively large fraction of the dose. This was an important consideration, as the morphology and effects of the radiation damage in the crystal depend on the type of interaction, and not only the total energy deposited. We also note that in the location in the BNR used in the experiment, it was not possible to conveniently reduce the gamma-ray flux, and thus the contributions to the total dose from fast neutrons and gamma-rays are of the same order in our surrogate experiment.

EXPECTED EFFECTS ON RING

The experiment allows to make a first-order estimate of the degradation of the performance of RING in SNS-like conditions. To this end, the radiation dose received by the BBO crystal in our experiment can be compared to the typical dose rate at SNS and correlated to the measured increase of absorption in the BBO crystal to predict the RING performance in SNS-like radiation environment. The primary source of uncertainty in this prediction is the dependence of the magnitude of absorption on the radiation dose, which has to be interpolated to lower doses on the basis of the single absorption measurement performed at a relatively large dose. The second cause of uncertainty is related to the significant contribution of gamma-rays to the radiation dose in our experiment, and

the unknown contribution of gamma-rays to the dose at SNS. An additional source of uncertainty are the differences of the neutron energy spectrum at SNS and our BNR experiment; however, this difference is expected to be less important since in both cases the interaction is dominated by elastic scattering. Since the RING design for SNS calls for recirculation of 355 nm light and absorption at this wavelength has not been directly measured in our transmission measurements, an estimate of linear absorption at this wavelength is also needed. Finally, BBO also exhibits nonlinear absorption which is wavelength and intensity dependent, and it could also vary considerably with dose. The nonlinear absorption is not considered in this study, since it can be appropriately reduced by reducing the pump intensity compensated by the increase in crystal length [4].

We linearly extrapolate the experimentally measured absorption coefficients to 0.67 cm^{-1} at 355 nm. For a 6.5 mm-thick crystal needed for RING at SNS, this would result in absorption of 35.3% in radiation conditions equivalent to our experiment. To conservatively estimate the range of effects of SNS conditions on RING, we correlate the loss of BBO transparency to the dose rate only due to neutrons in our experiment (7.18 kGy), or to both neutrons and gammas (17.18 kGy). To address the most important uncertainty associated with the interpolation of the absorption to low doses based on the measurement conducted with large dose, we consider three characteristic models for dose-effect dependence: (1) linear model - absorption increases linearly with dose, (2) quadratic model - absorption increases as a square root with dose, and (3) logarithmic model - absorption increases logarithmically with dose. In this order, these models range from the most optimistic to most conservative in terms of the RING resistance to radiation.

We define the SNS-equivalent time associated with our experiment, defined as the time it would take for the BBO placed at SNS to receive the same dose as in our experiment. Given the typical SNS dose of 5 Gy/yr, the SNS-equivalent time associated with our experiment conducted at BNR is in the range of 1300-3400 yrs. By assuming that the dependence of absorption with dose follows one of the three characteristic models, the experimentally measured loss of transparency in conjunction with the SNS-equivalent time can be used to determine the time needed for the enhancement of the RING cavity to drop significantly. We chose a 10\% drop of enhancement from its nominal value as a characteristic time for RING cavity degradation. In Fig. 2 we show the expected enhancement degradation of a RING cavity with a modest enhancement factor of 10.

For a cavity with an initial enhancement of 10, the expected degradation time is on the order of 1000 years for the linear model, 10 years for the quadratic model, and as short as 1 month for a logarithmic model for absorption dependence on dose. Even in the case of the very conservative (logarithmic) damage model, it can be predicted that the RING is sufficiently robust for operation in SNS-like radiation environment. For much higher initial enhancement (on the order of 100 or 1000), the RING degradation time is likely to be much shorter, and a more detailed experimental study would be needed to qualify RING for long-term operation without maintenance.

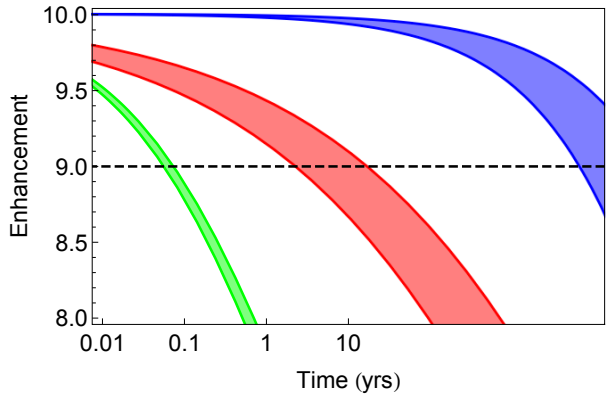

Figure 2: Expected variation of the enhancement factor for a RING cavity with pre-irradiation cavity loss of 10, for linear model (blue), quadratic model (red), and logarithmic model of damage (green). Shaded is the range of the expected enhancement, reflecting the uncertainty associated with mixed irradiation by fast neutrons and gamma rays. Dashed lines indicate the enhancement factor drop of 10% from its pre-irradiation value.

CONCLUSION

An experimental measurement of BBO crystal transparency change in fast neutron and gamma irradiation has been presented, with a goal to assess the potential of this crystal to withstand high-radiation environment typical of SNS and to allow continuous operation of a RING cavity for hydrogen ion stripping with minimum maintenance. It has been found that the BBO crystal is sufficiently resilient to SNS-like conditions, and will allow the operation of the RING cavity with <10% degradation of enhancement over a period of >10 years for an initial enhancement factors on the order of 10. This is a significantly better performance compared to that currently observed with carbon foils where the lifetime of the foil is measured in days. Even in situations where only a small degradation of performance of RING can be tolerated, the replacement of the BBO crystal is not a major concern, and we expect this technology to be a major contender for hydrogen ion stripping applications.

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