Proof-of-principle demonstration of high efficiency laser-assisted H^- beam conversion to protons

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Thin carbon foils are used as strippers for charge exchange injection into high intensity proton rings. However, the stripping foils become radioactive and produce uncontrolled beam loss, which is one of the main factors limiting beam power in high intensity proton rings. Recently, we presented a scheme for laser stripping an H^- beam for the Spallation Neutron Source (SNS) ring. First, H^- atoms are converted to H^0 by a magnetic field, then H^0 atoms are excited from the ground state to the upper levels by a laser, and the excited states are converted to protons by a magnetic field. In this paper we report on the proof-of-principle demonstration of this scheme to give high efficiency (around 90%) conversion of H^- beam into protons at SNS in Oak Ridge. The experimental setup is described, and comparison of the experimental data with simulations is presented.

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I. INTRODUCTION

H^- ion laser stripping was initially proposed by Zelensky *et al.* in a paper [1] describing a 3-step stripping method: H^- conversion to H^0, H^0 excitation from ground to upper state, and finally $H^0$to p conversion using photoionization. Following this initial proposal of the method, modification of the first and third steps using Lorentz stripping was suggested [2]. For the second step it was proposed to utilize resonant Rabi oscillations for the hydrogen atom excitation. The main complication was outlined in [2]: the energy spread of the ions is too large to excite the entire beam. A variety of methods have been proposed to overcome this difficulty (see, for instance, [3]). Two of these proposals have become foundations for proof-of-principle (POP) experiments: (i) the frequency sweep excitation [4]; (ii) the broadening of the upper levels by a magnetic field, which is Lorentz transformed to an electric field in the beam rest frame [5].

We describe here the experimental realization of the first of these approaches.

If one uses a narrow-band laser with frequency equal to the transition frequency between the ground state and any of the upper states of the hydrogen atom, electrons are made to oscillate between the two states (so-called Rabi oscillations). For an H^0 atom, moving at speed $v = \beta c$, the laser angular frequency, ω_0, in the rest frame is related to the light frequency, ω, in the laboratory frame as follows:

$$\omega_0 = \gamma(1 + \beta \cos\alpha)\omega, \tag{1}$$

where α is the angle between the laser and the H^0 beam in the laboratory frame, and γ is the relativistic factor. For the $n = 3$ upper state the required wavelength is $\lambda_0 = 102.6$ nm, and the frequency is $\omega_0 = 2\pi c/\lambda_0 = 1.84 \times 10^{16}$ Hz. A fundamental problem in using this method for stripping is Doppler broadening of the hydrogen absorption line width due to the finite momentum spread of the beam. Since the neutral hydrogen beam inherits the energy spread of the H^- beam (its typical fractional value is of the order of 10^{-3}), each individual atom has its own excitation frequency in its own rest frame. The relative spread of frequencies is about the same as the spread of particle energies, and therefore its absolute value is $\sim 10^{12}$ s^{-1}. The achievable Rabi frequency is about 10^{11} s^{-1}. It has been shown (see, for example, Ref. [6]) that the upper state remains virtually unpopulated if the difference between the laser frequency and the transition frequency is larger than the Rabi frequency.

Our previous paper [4] presented a detailed calculation of the process along with a practical approach to a proof-of-principle experiment at the Spallation Neutron Source (SNS) project. It is summarized in Fig. 1. Stripping magnets are placed on either side of a laser-particle beam interaction point. The first magnet strips the first electron, and then the remaining neutral hydrogen beam is excited by a laser beam. By focusing the laser beam in the plane of the two beams, the angle of incidence of the laser light changes along the hydrogen beam path in the laser-particle beam overlap region. The laser frequency remains fixed but, because of the Doppler dependence of the rest-frame laser frequency on the incident angle, the frequency of the light in the atom's rest frame decreases as the angle increases. This introduces an effective frequency "sweep" as the hydrogen beam traverses the laser interaction region. This spread can be made large enough that all atoms within the spread of energies will eventually cross the resonant frequency and become excited.

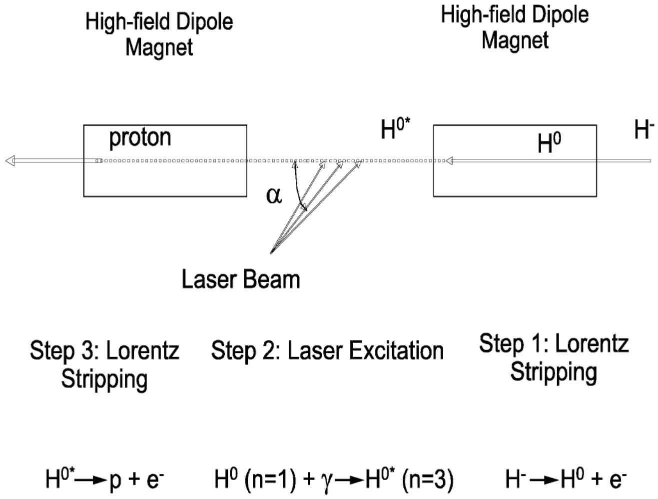

FIG. 1. General scheme of frequency sweep stripping.

II. EXPERIMENTAL SETUP

The designs of the magnets, the vacuum chamber, and the laser parameters were presented in Ref. [7]. The assembly was manufactured by Novosibirsk Institute of Nuclear Physics in 2005 and installed at the end of the same year in the SNS linac tunnel. Figure 2 presents the top view drawing of the assembly. One can see three magnets—the first one (2 T magnet) is for the first electron detachment, the second (small magnet) is for the interaction region shielding from the stray fields of two adjacent magnets, and the third (2 T) magnet is for the stripping of the last excited electron.

The third magnet was made a C-magnet to allow the laser beam to propagate from the windows with flanges (shown on the left bottom side of Fig. 2) to the interaction region. The laser beam piece of the vacuum chamber was made wide to provide flexibility to vary the incident angle if necessary. This proved to be very useful, because the energy of the ion beam from the linac was lower than the expected 1 GeV. The experiments were done at energies around 900 MeV with the lowest incident angle of 20 degrees, as compared to the initial design angle of 40 degrees for a 1 GeV beam.

The laser, a frequency tripled *Q*-switched Nd:YAG (Continuum Powerlite 8030) laser, was placed adjacent to the assembly and was coupled to the H^0 beam via mirrors and focusing optics. The 355 nm pulses had duration of 6 ns and peak powers up to 13.7 MW (in reality, maximal power of 10.25 MW was used, because a more powerful laser beam broke the vacuum chamber windows a few times during initial adjustment of the laser beam optics). A seed laser ensured a narrow laser spectrum and smooth temporal profile.

The proton beam current is measured by the wide bandwidth current transformer (Bergoz FCT-178) downstream of the third magnet. With all magnets unenergized, a beam of negative hydrogen ions passes freely to the beam dump inducing positive signal in the transformer. With the magnets energized, one electron is stripped from each negative ion by the magnetic field of the first magnet and then deflected to the vacuum chamber wall by the same magnet. The field strength in the third magnet is not sufficient for stripping neutral atoms in the ground state. The remaining beam of neutral atoms going to the beam dump does not induce any signal in the transformer. Now with all magnets energized and the laser on, the light crossing the neutral atom path between the first and the third magnet excites the remaining electron from the ground state to the $n = 3$ state. The magnetic field of the third magnet detaches the

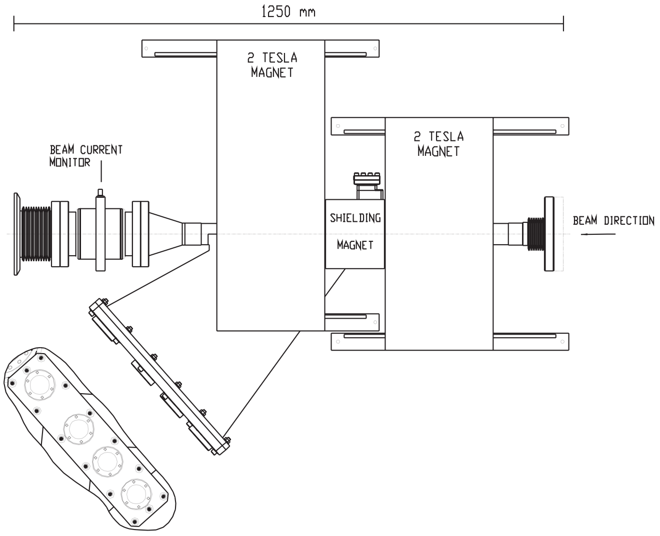

FIG. 2. Stripping assembly layout (top view). One can see two strong 2 T magnets with mechanical supports, the vacuum chamber with ceramic break and torroid on the left side of the assembly, and the laser window flange, with its top view at the bottom of the figure.

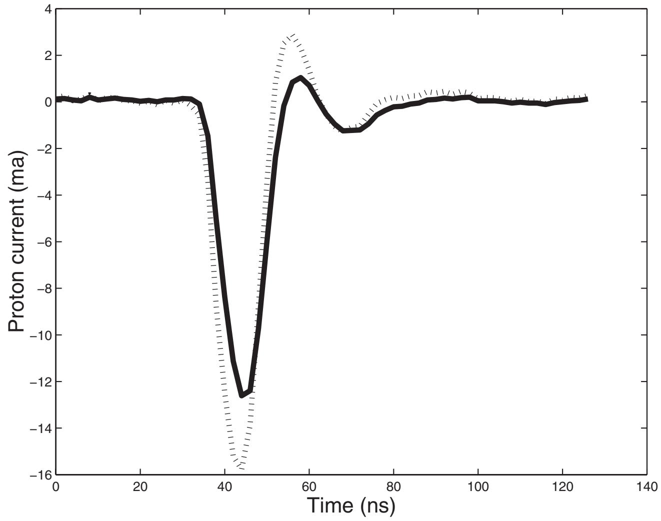

FIG. 3. Proton signal from the stripped H^- atoms as recorded by digital oscilloscope (solid line), and restored original signal from beam current monitor (dashed line).

excited electron from the proton and deflects it to the vacuum chamber wall. The much heavier proton is only slightly deflected by the same magnetic field, and it proceeds to the beam dump, exciting negative signal in the transformer (see Fig. 3).

III. EXPERIMENTAL RESULTS

The first stripping was observed in March, 2006, and 50% efficiency was attained before operations were halted because of a leak in the vacuum chamber near the laser beam absorber. The results of these measurements were presented in [8]. Higher efficiency was obtained in two later runs carried out in August and October, 2006, discussed below.

The stripping efficiency is given by the ratio of the negative pulse amplitude (stripped proton current) to the positive pulse amplitude (incoming ion current). In the ideal case, these amplitudes can be taken directly from the fast transformer. In our setup, however, the short laser pulse strips only a 6 ns (FWHM) slice of a much wider (~ 700 ns) incoming ion beam pulse. The bandwidth of the measuring system, including the transformer and the 85 m long cable, is sufficient for accurate measurement of the amplitude of the 700 ns incoming beam pulse but insufficient for accurate measurement of the 6 ns stripped pulse amplitude. The signal pulse width increases and the amplitude decreases due to dispersion in the long cable. We used the measured transfer function of the cable to restore the pulse shape [9]. Comparison of the raw and restored signals is shown in Fig. 3, where a ~25% amplitude reduction due to cable dispersion is observed. The transformer itself had a limited bandwidth and a resonance at frequency around 20 MHz (see the decaying oscillations at the end of the proton pulse in Fig. 3). We did not have the possibility to measure the transfer function of the transformer, and therefore our reported numbers for stripping efficiency still could be several percent lower than the actual values due to the uncorrected effect of the limited bandwidth of the transformer. The reported efficiencies were calculated by dividing the peak current from the restored signal (in the case of signal from Fig. 3 it is 16 mA) by the original current (18.9 mA). This gave efficiency of 85% ± 10%. This efficiency was obtained in the third experimental run in August, 2006. In addition to the described systematic error in the current measurements, we had pulse to pulse variations in beam current of around 5%. To reduce this noise, we averaged signals 10 times. We were able to do it because our timing had low (less than 1 ns) jitter. There was also a slow drift of the incoming current. Altogether, we estimate that the total accuracy of the stripping efficiency measurement (systematic and nonsystematic) is 10%.

The theoretical expectations for our setup were in the vicinity of 90%. In the August run, we had maximal efficiency in the vicinity of 80%. In a special, October 2006, experiment, dedicated to achieving record stripping, we reached 90% level. The higher efficiency was obtained by reducing the vertical size of the ion beam (roughly, to 0.6 mm) by moving the vertical beam waist using an upstream quad, and by moving the vertical beam orbit to get maximal overlap of the ion and the laser beams. In addition, the ion beam distribution had fewer halo particles (the measured transverse distribution was essentially a Gaussian in the last experiment). Further squeezing of the laser and ion beams was not possible because of the risk of laser-induced damage to the vacuum windows.

To obtain a more quantitative prediction of the stripping efficiency, we carried out numerical simulations based on our theory of stripping, described in [4], taking into account the full 6D distribution of the ion beam and the real profile of the laser beam. To compare our theoretical understanding to the experimental observations, we performed an efficiency study versus some of the laser and the ion beam parameters. The ion beam and the laser beam parameters were measured after the experiments and are summarized in Table I.

The largest uncertainty in these parameters was the ion beam vertical size. For its measurements, we used a wire scanner located about 2 m away from the interaction point and varied upstream quadrupoles to calculate the beam Twiss parameters and emittance. The numbers for the restored beam size varied from 0.5 to 1.0 mm depending on the varied quadrupole settings. This number for the ion beam size s was enhanced due to the stripping process in the first 2 T magnet—the new size after the first magnet became $\sqrt{s^2 + (0.25)^2}$ mm. Therefore, we believe the ion beam had a Gaussian distribution with sigma ranging from 0.55 to 1.05 mm.

Figure 4 shows experimental data (dots with error bars) for an energy scan performed in August 2006 with peak laser power 6.25 MW, 2 mm FWHM vertical laser beam

TABLE I. Laser and ion beam parameters.

Parameter	Value	Units
Ion beam		
Energy	~870	MeV
Vertical size	0.55–1.05	mm
Vertical emittance	~0.5	mm mrad
Horizontal size	3	mm
Horizontal emittance	~0.5	mm mrad
rms energy spread	5×10^{-4}	
Laser beam		
Wavelength	355	nm
Incident angle	21.8	degree
Peak power (max)	10.25	MW
Vertical size, FWHM	2–4.5	mm
Horizontal size, FWHM	4	mm
Horizontal divergence, FWHM	6–8	mrad

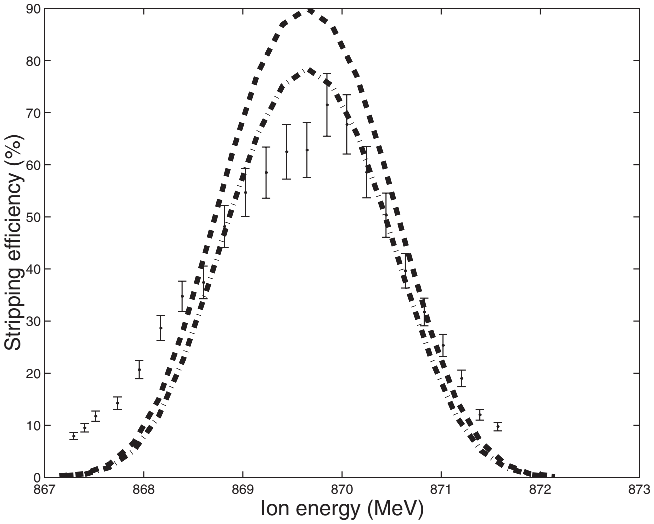

FIG. 4. Experimental points (dots with error bars), and calculated dependencies (dashed and dash-dotted lines) of stripping efficiency on ion beam energy. The dashed line represents the case with the ion beam vertical size of 0.55 mm, and dash-dotted line represents the vertical size of 1.05 mm.

size, and calculations for 0.55 mm (dashed line) and for 1.05 mm (dash-dotted line) vertical ion beam sizes, respectively. One can see that the experimental points are slightly lower than the calculated values. One interesting feature of the experimental data is that the points are not symmetric with respect to the maximum, and the stripping is higher for the large energy deviations from the optimal stripping energy. This is probably an indication of existing tails in the ion beam energy distribution.

We also performed studies of stripping efficiency versus laser peak power. Figure 5 shows the experimental dependence (dots with error bars) and the calculated curve (dashed line). The experimental points deviate from the predicted values for the stripping efficiency for low values of peak power. This can be attributed to the fact that the laser beam quality degrades as we go to lower pulse energies and the laser beam area increases with the power decrease.

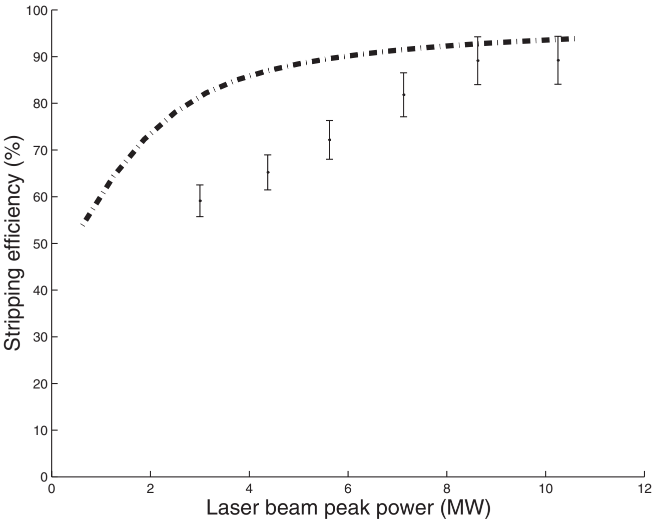

FIG. 5. Measured (dots with error bars), and calculated (dashed line) stripping efficiencies versus laser pulse peak power. The calculated efficiency reaches 99% for 20 MW laser peak power.

In the final, October 2006, experiment we compared the stripping efficiencies for two different laser bandwidths: the narrow (10^{-7} relative width) spectrum used in the measurements described above; and a broader (by a factor 300) spectrum obtained by turning off the seed laser. The stripping efficiency for these two cases showed the same dependence of stripping versus energy, within the accuracy of the experimental data. The difference was in the absolute values—the stripping efficiency dropped 25% (from 85% to 60%) for the case of unseeded laser operation, or the relative width of the laser spectrum of 3.5×10^{-5}. An attempt was made to keep all other parameters the same but, in the process of switching the laser from one mode to another the SNS linac was turned off, and some magnets were turned off as well. Therefore, we cannot claim that there was no uncontrollable change of some laser or ion beam parameters, for instance, the vertical sizes. However, we allege that lasers with larger bandwidths can be used for stripping, as well. Moreover, 25% reduction of the stripping efficiency is equivalent to a factor of 2 of reduction in the laser beam power (see Fig. 5).

The high stripping efficiency obtained using an unseeded laser can be explained by the fact that, even though the spectrum width increased by factor of 300, its relative spread value of 3.5×10^{-5} is smaller than that of the energy spread (and the transition frequency spread), which is of the order of 10^{-4}. This means that the light frequency spread due to excited harmonics in the unseeded laser is smaller than the Doppler spread due to the laser beam divergence, and the excitation process still can be considered as adiabatic. At the same time, we think the light signal irregularities are responsible for the reported 25% reduction of the stripping efficiency. More accurate calculations of the excitation process require more precise knowledge of the electric field of the unseeded light, which is not available to us at the moment and is beyond the scope of this paper.

IV. OUTLINE OF THE SNS LASER STRIPPING DEVELOPMENT

The goal of the proof-of-principle experiment described herein was to use a novel frequency sweep technique to understand if high excitation is achievable and if laser-assisted H^- stripping is a viable alternative to conventional foils. The positive result has encouraged us to proceed in developing a real scheme for SNS stripping. Such a system will need to reach an efficiency of 98%, similar to that of conventional graphite foils [the remaining 2% are directed to the 100 kW injection dump, specially designed to intercept unstripped ions outside the ring area where they will not contribute to uncontrolled beam loss (see how the SNS ring injection area is designed to minimize beam loss and to dump stripped electrons in, e.g., [10])].

In the scheme described above, this would require a peak laser power of more than 10 MW, and maintaining this power level over the entire duration of the H^- pulse train would require an average laser power level of more than 1 MW. Clearly, the present scheme is not scalable in a straightforward way. However, it is possible to reduce the required average laser power through: (i) a specially tailored dispersion function to reduce the absorption line width at the interaction point; (ii) control of the H^- beam optics; and (iii) careful design of the laser system. The first of these ideas is described in detail in [4] and is briefly repeated here. The trajectory of a particle with relative momentum deviation, dp/p_0, is displaced by an amount $x = Ddp/p_0$ and has an angle $x' = D'dp/p_0$ with respect to the reference trajectory, where D is the dispersion function, and D' is the derivative of the dispersion function with respect to the longitudinal coordinate. The frequency of the laser light in the hydrogen atom rest frame is given by Eq. (1). The angle α between the laser beam and the particle trajectory is $\alpha = \alpha_0 - x'$, where α_0 is the angle for the reference energy particle. From $x' = D' \frac{dp}{p_0}$ and $d\alpha = -x'$ we have $\frac{d\alpha}{d\gamma} = -D'/\beta^2\gamma$. When we equate the derivative of the rest-frame laser frequency in (1) with respect to γ to zero, we find the dispersion derivative requirement for elimination of the spread of transition frequencies due to energy spread:

$$D' = -\frac{\beta + \cos\alpha}{\sin\alpha}. \tag{2}$$

For complete cancellation, this expression yields a dispersion derivative of $D' = -2.57$ for a 1 GeV ion beam ($\beta = 0.865$) and an incident angle of $\alpha = 39.7$ degrees, as determined by Eq. (1) for a wavelength of 355 nm. In the proof-of-principle experiment and throughout SNS linac, the dispersion is zero. However, the required dispersion can be easily achieved near the SNS ring injection area, because the SNS transfer line from the linac to the ring has a 90 degree bend with the large dispersion in it. This type of dispersion derivative tailoring is estimated to yield a factor of 10 reduction in the transition frequency spread and a correspondingly similar reduction of the laser power required for a given stripping efficiency.

An additional reduction in the required laser power can be achieved by reducing the vertical size of the H^- beam (a factor 2–3 is attainable for the SNS beam optics near the injection area) This makes possible a proportionally smaller laser beam spot which means that less power is needed to achieve the same optical intensity. These modifications are predicted to reduce the peak laser power required for 99% stripping efficiency from 20 MW to less than 1 MW, assuming the other parameters, such as ion beam horizontal size, bunch length, etc., remain unchanged.

Further improvement will be realized by more closely matching the temporal profile of the laser light to that of the ion beam, i.e., 50 ps duration, 402.5 MHz repetition rate, and 6% duty cycle. To use the laser light more efficiently, we propose to pass each pulse through the interaction region several times, with either a Fabry-Perot resonator matched to the SNS bunch repetition rate or else a simpler multipass configuration. In either case, the mirrors will be spaced so as to return the laser pulse to the interaction region every 2.5 ns. The optics will be designed so that the laser beam spot sizes on the mirrors are large enough to avoid damage to the coatings and the laser light will be absorbed in a laser dump outside the interaction region. The effectiveness of these techniques will be limited by a number of factors—space constraints in the case of the multipass scheme and mirror coating technology in the case of the Fabry-Perot resonator. However, we conservatively estimate ten passes through the interaction region for each pulse. Hence, the repetition rate of the laser system can be reduced from 402.5 to 40.25 MHz.

Taking all of these factors into consideration, the final estimate of the required average laser power P_a is obtained from multiplication of the above parameters (the laser peak power, the pulse duration, its repetition rate, and the duty factor):

$$P_a = 10^6\ \mathrm{W} \times 50 \times 10^{-12}\ \mathrm{s} \times 40.25 \times 10^6\ \mathrm{Hz} \times 0.06 \approx 120\ \mathrm{W}.$$

Although this would require a complex laser system, it can be realized with existing technology. We are now in the planning stages for a long pulse efficient stripping demonstration making use of the ideas described in this section.

V. CONCLUSION

We have experimentally demonstrated high efficiency (about 90%) laser-assisted H^- beam conversion into protons at SNS. The experimental results agree fairly well with our theoretical calculations. We believe that discrepancies are related to our limited knowledge of the beam parameters. More accurate beam data require a substantial improvement of the experimental setup, which we plan to implement at the next stage of laser stripping experiments with long linac pulse stripping. Once long pulse stripping is demonstrated, the replacement of graphite foils with lasers will be an immediate reality. The fact that the protons interact very weakly with the laser light can be used to make a special injection painting for the proton beam that will give sophisticated halo-less self-consistent 3D space charge distributions similar to those presented in [11], to advance the high power proton accumulators to yet another level of intensities.

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