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Feasibility of a Fast Beam Chopper Using Laser Stripping of H^- Ions for the JHP

T. KATO
KEK, National Laboratory for High Energy Physics
Oho 1 - 1, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

The feasibility of a fast beam chopper of the photodetachment neutralizer type by means of a pulsed Nd laser was studied in order to realize a decrease in the beam losses after injection into a circular accelerator for the JHP (Japanese Hadron Project). A 54-kW peak-power laser of 400 µs in length and a fast external amplitude modulator are required in order to produce 130-ns H^0 pulses from H^- pulses in the beam line between the ion source and the RFQ. Several possible installation points for the chopper are discussed.

I. INTRODUCTION

It was reported that the photodetachment of electrons from an H^- beam by means of a Q-switched Nd laser can produce a 20-40-ns pulsed H^0 with near 100% efficiency [1]. Such a method is of interest from the viewpoint of a promising application to the fast beam chopper in a high-energy, high-intensity proton linac as the injector of a ring accelerator. First, a high beam quality for the charged portions of the beam passing through the chopper can be maintained, since a fast rise-time of the nsec-order for each laser pulse can be expected. Second, the neutralized beam can be immediately separated and damped into a fixed beam damp using a deflecting magnet. On the contrary, the conventional chopper of the beam-deflecting type [2,3,4] disperses the deflecting portion of the beam according to the deflecting angles. In particular, the portion of the beam deflected by the transient part of the force, corresponding to slow rise-times, causes an unexpected-random beam losses along the linac. The photodetachment chopper does not cause such effects on the transverse motion of the charged beam. Third, the photodetachment chopper can be used over a wide range of beam energies ranging from 50 keV to 1 GeV, since the relativistic electron-detachment cross sections are sufficiently large with a change in the optimum wavelength [5]. This provides a wide possibility of selecting the beam energy where a photodetachment chopper can be installed.

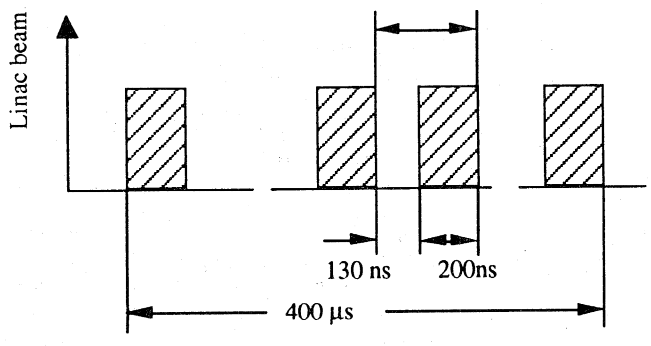

Fig.1 Required pulse structure for the JHP linac beam.

Figure 1 shows the required pulse structure of the linac beam for the Japanese Hadron Project (JHP) [6]. The required pulse length for the chopper is 130 ns with a 3-MHz repetition rate. The linac for the JHP comprises a 432-MHz RFQ (3 MeV), a 432-MHz DTL (150 MeV) and a 1296-MHz coupled-cavity linac (CCL, 1GeV). It accelerates a 20-mA H^- beam of 400 µsec pulse length at a repetition rate of 50 Hz from 50 keV to 1 GeV. Thus, there are two position candidates for installing the conventional deflecting-type chopper system: before or after the RFQ. The traveling-wave beam choppers [2,3] can be applied at both positions. In the former position, the space-charge effects are dominant in the energy range below 50 keV. In the latter position, a long structure and a high voltage are necessary, since the beam energy is as large as 3 MeV. A proposed rf chopper system using deflecting rf cavities [4], installed between an RFQ and a DTL, has a rise-time of more than 10 ns at a low rf power level. Recently, a high-power test of an rf amplifier with a 10 kW peak power and a rise-time of 15 ns was successfully performed (Fig. 2), resulting in a promising realization possibility for a chopper system with a carefully designed beam-transport line between the RFQ and the DTL. A laser-induced neutralization method using very narrow laser pulses has been already applied to measuring the longitudinal beam parameters of a bunched H^- beam [7,8].

In this paper, the feasibility of a fast beam chopper using laser stripping of H^- is considered. Some possible configurations are proposed based on the required laser equipment.

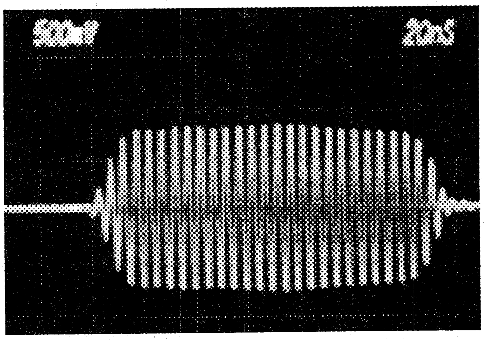

Fig.2 Measured rf pulse with a fast rise-time of about 15 ns and a peak power of 8.5 kW at a repetition rate of 3 MHz. The input CW rf power for the amplifier was amplitude-modulated with a fast pin diode. An rf frequency of 201 MHz was used in the experiment, 20 ns/div.

II. LASER STRIPPING OF H$^-$ IONS

The laser stripping process is

$$\gamma + H^- \rightarrow H^0 + e^-, \qquad (1)$$

which has a threshold at a photon energy of 0.78 eV [9], and a broad peak at 1.5 eV, corresponding to laser wavelengths of 1.6 and 0.83 µm, respectively. The maximum electron detachment cross section (Fig. 3), except for the narrow resonances [12, 13], is about 4.2×10^{-17} cm^2 [14,15]. It is noted that the narrow resonances with a large peak has some possibility of the chopper application. However, it is not considered in this paper.

III. REQUIRED LASER PARAMETERS

The formula for the number of events produced in a colliding beam for which one of the particles is a photon is [1]

$$N = \sigma(1+\beta\cos\alpha)\, c\int \rho_a\rho_b dVdT, \quad (2)$$

where σ is the cross section, T the time interval, V the intersection volume, ρ_a and ρ_b the particle densities, βc the velocity of the massive particle beam, c the speed of light, and α the laboratory angle between the two beams (defined so that α=0 when the collision is head-on). The charge (Q) released by a laser pulse of N photons crossing an H$^-$ beam of current (I) was derived [1] based on the assumption that ρ_a and ρ_b are constants during the interval T and over an intersection volume defined by the intersection of two circular beams of radius R. It is written as

$$Q = \frac{16\sigma N\,I}{3\pi^2 Rc}\,\frac{1+\beta\cos\alpha}{\beta\sin\alpha}. \qquad (3)$$

Bryant et al. obtained a calculated Q of 1.06×10^{-13} with a 15-mJ laser pulse, a 4-µA H$^-$ beam, a beam radius of 0.3 cm and 12-times reflections of the laser pulse in the parallel mirrors at the intersection place [1]. The experimental value was half the calculated one. Their results suggest that a safety factor of about three for the laser power is desirable in order to achieve photodetachment with 100% efficiency. The parameters for a pulsed 20-mA beam in the JHP linac and the required laser properties for the photodetachment were calculated from eq. (3) and are listed in Table 1 for beam energies of 50 keV and 3 MeV. As a result, the requirements for the laser are summarized as follows:

1) pulse energies of 7 to 63 mJ, depending on both the number of reflections and the beam energy (without a safety factor of three),
2) a 130 ns short pulse at a repetition rate of 3 MHz within a pulse duration of 400 µs,
3) a repetition rate of 50 Hz for a 400 µs pulse, and
4) a wavelength around 1 µm.

In order to fulfill the above-mentioned requirements, a Nd:YAG laser (1.064 µm) under normal-pulse operation with a pulse length of 400 µs and a repetition rate of 50 Hz is promising. An external fast amplitude modulator of the electro-optical type with a rise-time of 2 ns can produce a pulse structure satisfying the above-mentioned requirement of (2). As for a high-power laser, it has been reported that a Nd:YAG laser with a pulse length of 0.1 - 20 ms, a repetition rate of 500 Hz, an output energy of 150 J/pulse, and an average power of 3 kW has been realized using normal-pulse operation [16]. If the peak laser power is not sufficient, there are three ways of increasing the photon target thickness: (1) using an optical resonator [17], (2) using multiple reflections [1] between two parallel mirrors in the intersection point, and (3) using many lasers simultaneously or successively with time. The last method is also desirable from the viewpoint of the micro-pulse structure of the laser pulse in the normal-pulse operation. A fast modulator with a high-power operating range is also crucial. Since the average handling power of the commercial E-O modulator is not very large, some modification and development may be required in order to fulfill the specifications.

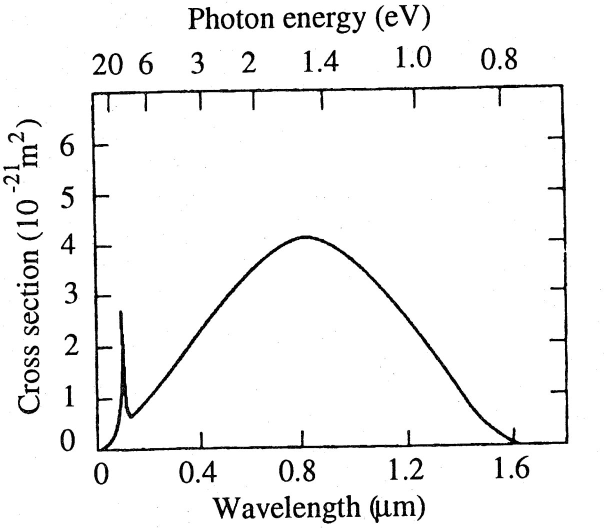

Fig. 3 Photodetachment cross section of negative hydrogen. (Adapted from Ref. 10 and originally in Ref. 11)

IV. DESIGN OF A LASER STRIPPING CHOPPER

The laser stripping chopper (LSC) comprises a high-intensity pulsed laser with an external fast amplitude modulator, an optical resonator or two parallel reflecting mirrors (either of them is used for increasing the photon target thickness), and some optical elements for laser-beam handling. The LSC mentioned above can be installed into any section along the 1-GeV proton linac (Fig. 4), since there is no restriction arising from the energy dependence of the laser-stripping process. An LSC in the low-energy part of the linac is desirable in connection with the beam-loading problem. A decrease in the beam loading by 30% results in various good effects on the beam quality, beam handling, and both the construction and operation costs. However, the deflecting magnets just after the LSC inevitably introduce a momentum dispersion. This additional degradation of the beam quality is not desirable in connection with the beam-loss

Table 1 Parameters of the H⁻ beam and the laser stripping chopper.

Beam energy	0.05	0.05	3	3	MeV
Beam current	20	20	20	20	mA
Beam pulse length	130	130	130	130	ns
Charge/pulse	$2.6\text{x}10^{-9}$	$2.6\text{x}10^{-9}$	$2.6\text{x}10^{-9}$	$2.6\text{x}10^{-9}$	C
Number of H^-/pulse	$1.6\text{x}10^{10}$	$1.6\text{x}10^{10}$	$1.6\text{x}10^{10}$	$1.6\text{x}10^{10}$	
β	0.01	0.01	0.08	0.08	
Beam radius	0.5	0.5	0.3	0.3	cm
Beam length	40.1	40.1	312	312	cm
Beam volume	31.5	31.5	88.2	88.2	cm^3
Beam density	$5.1\text{x}10^{8}$	$5.1\text{x}10^{8}$	$1.8\text{x}10^{8}$	$1.8\text{x}10^{8}$	cm^{-3}
Laser pulse length	130	130	130	130	ns
Laser wavelength	1.06	1.06	1.06	1.06	µm
Photon energy	$1.87\text{x}10^{-19}$				J
Laser energy/pulse	0.014	0.007	0.063	0.032	J
Peak power	107	53.5	488	244	kW
Number of photons	$7.4\text{x}10^{16}$	$3.7\text{x}10^{16}$	$34\text{x}10^{16}$	$17\text{x}10^{16}$	
Number of reflection	12	24	12	24	
Crossing angle	70				degrees
Cross section	$3.9\text{x}10^{-17}$				cm^2

Note 1. A uniform distribution for a 3-MeV beam is assumed.
Note 2. A beam radius of 0.5 cm is used for a 50-keV beam.
Note 3. Constant cross section is used for both energies.
Note 4. A safty factor of 3 is not tanken into account.

problem in the high-energy part of the linac. A deflecting magnet after the LSC is not always necessary; however, the neutralized beam loss along the linac cannot be ignored if the beam energy is sufficiently large for making the cavity wall radioactive. It cannot be ignored, either, if the chopper is installed before an RFQ, since the possibility of an rf discharge in the RFQ increases. The LSC located after the 1-GeV linac shows reversed properties: heavy beam loading in the linac and no dispersion arising from the bending magnet before acceleration. However, the required energy for each laser pulse increases linearly as the beam energy increases, based on the assumption that the beam size and the cross section are constant. In conclusion, the LSC in the low-energy part with a carefully designed beam line is promising from the viewpoint of the operation of the linac and the total costs required for both the construction and operation. In addition, a smaller laser power is desirable not only for a laser, but also for related optical components, such as a modulator and a polarizer, even if high-power laser technology is advanced day by day.

V. REFERENCES

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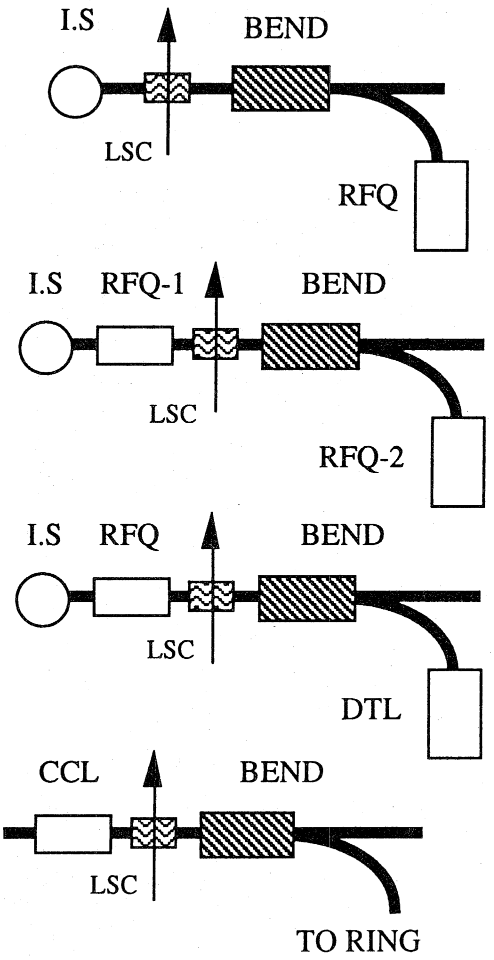

Fig. 4 Four possible configuration of the laser stripping chopper (LSC) in the JHP proton linac. The bending magnet for distinguishing particles is not always necessary.

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