Reducing the Extraction Loss *via* Laser Notching the H^- Beam at the Booster Injection Revolution Frequency

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Abstract

With the requirement for more protons per hour from Booster, the radiation is a limiting factor. Laser notching the H^- beam at the Booster injection revolution frequency and properly aligning those notches on top of each other at the injection and relative to the trigger of firing extraction kickers can remove most of the extraction loss caused by the slow rise time of the kicker field.

Introduction

With the requirement for more protons per hour, the radiation could become a problem for Booster. It is important to make the unavoidable beam loss occur at relatively low energy for the purpose of reducing the radiation since the radiation dose increases with the increase of the beam energy.

The bunch-to-bunch space at the extraction is 18.9 ns, and the field rise time of extraction kickers is about 45 ns, which covers nearly two and a half beam bunches (BC). In the situation that the circulating beams go through extraction kickers when the kicker field is rising, those beams won't receive a proper kick and eventually will get lost in Booster. Presently, a beam notch with a width of the field rise time of extraction kickers is generated in the beginning of a Booster cycle, for the purpose of reducing the high-energy extraction loss. However, the low-energy beam notch still generates radiation losses, and it could become the limit for the maximum proton output from Booster in the future.

Since Booster accelerates protons (H^+) after the H^- beam injected from Linac is stripped to protons, the optimal solution is to create H^- beam notches in Linac, which have the Booster injection revolution frequency (f_0≈458 kHz) and a notch width of 65 ns. This requires that the H^- beam in Linac is properly notched at the injection revolution frequency and these notches are precisely aligned on top of each other after the injection and relative to the trigger of firing extraction kickers. Here, the field rise time of extraction kickers covers 2.5 rf periods at the extraction, and it is equivalent to 65 ns (=2.5×26 ns) at the injection since the injection rf period is 26 ns.

There are two approaches of creating H^- beam notches in the low-energy Linac at the Booster injection revolution frequency (458 kHz) with a notch width of 65 ns. The first approach is to pulse a electrical static deflector at the frequency of 458 kHz, a pulse width of 70 ns, and a gradient of 1400 volts to deflect the 20-keV H^- beam.[1] Present limits of this approach are:1st, the H^- beam notch is not so clean, and the maximum H^- beam reduction is 95%; 2nd, the ending edge of the H^- beam notch has a tail with a time constant longer than the notch width; 3rd, and the H^- beam right after the notch becomes unstable and oscillates. However, this approach is still being developed, and it is promising.

As a candidate, the second approach is laser notching the H^- beam in Linac at the Booster injection revolution frequency (458 kHz) with a notch width of 65 ns since an H^- beam notch can be generated *via* the photo-neutralization.[2,3] Since the neutralization efficiency of the H^- beam is inversely proportional to the transverse rms sizes of the H^- and laser beams,[2] the interaction region between the laser and H^- beams must be chosen at a place where the transverse H^- beam size is minimal. There is such a place in the 750-keV Linac,[3] where the transverse H^- beam waist is about 0.5 mm. And the transverse laser beam size can be adjusted to match the H^- beam *via* optical system.

There are several special requirements for the laser system of creating H^- beam notches in Linac. 1st, the intensity of each laser pulse must be sufficiently high to neutralize 90% (or more) of the H^- beam *via* the photo-detachment;[2-5] 2nd, the intercepting rate between the laser and H^- beams must be precisely locked to the injection revolution frequency (458 kHz); 3rd, the laser pulse must be long enough to cover the kicker field rise time. Here, the standard 12-turn injection is used as the design criteria for the laser system.

Laser System Design

Since we have already designed a laser system for notching the H^- beam at the Booster injection rf frequency in the 750-keV Linac,[3] the major differences between notching the H^- beam at the injection rf frequency and notching the H^- beam at the injection revolution frequency are:1st, the injection rf frequency is the 84th harmonic of the injection revolution frequency; the width of the H^- beam notch at the injection rf frequency is 5 ns, and the width of the H^- beam notch at the revolution frequency is 65 ns.

Taking these into consideration, the seeding laser for notching the H^- beam at the injection revolution frequency must have a pulse width of 65 ns, and a rep rate can be as high as the Booster rep-rate (15 Hz). There are two options of getting such a seeding laser:1st, Continuum corporation provides a Q-switched Nd:YAG customer laser with the energy of 1 J/pulse, the pulse width in the range of 3 ns to 200 ns, and the rep rate of 15 Hz;[6] 2nd, or using a pair of optical gratings to stretch the 5-ns laser pulse from the seeding laser of notching the H^- beam at the injection rf frequency to a pulse width of 65 ns.[7]

Since the number of photons used to create an H^- beam notch is negligible,[3] the rest of the photons in the laser pulse can be stored in a laser cavity and reused to create H^- beam notches for the purpose of covering the entire injection. The laser cavity for notching the H^- beam at the injection rf frequency can be modified for notching the H^- beam at the injection revolution frequency, and the following changes should be made:1st, the intercepting place between the H^- beam and the laser beam is outside the storage cavity, since the intercepting rate for notching the H^- beam at the injection revolution frequency is eighty-four times slower than the intercepting rate for notching the H^- beam at the injection rf frequency; 2nd, beside the Q-switch Pockels cell (PC1), which is used for trapping the seeding pulse inside the storage cavity, a second Q-switch Pockels cell (PC2) will be used to switch the laser pulse between the storage cavity and the interaction cavity; 3rd, the round-trip time of the storage cavity should be a multiple of the injection rf period, and also, it should be greater than the sum of the laser pulse width (65 ns), the switching time of a PC (<10 ns), and the time of the pulse traveling from the PC to the nearby cavity mirror and coming back to the PC (<3 ns); 4^{th}, and the round-trip time of the storage cavity should be equal to the round-trip time of the interaction cavity. The combination of the 3^{rd} and 4^{th} requirements is for the purpose of locking the intercepting rate between the laser and H^- beams to the injection revolution frequency. Besides, the 3^{rd} requirement is set in such a way that the situation of the laser pulse passing through a PC when the PC is switching can be avoided.

The diagram of the laser system for notching the H^- beam at the injection revolution frequency is shown in Fig.1. The round-trip time of the storage and interaction cavities is chosen to be 78 ns (=3×26ns ≥ 65ns+10ns+3ns), and an injection revolution period is equal to 28 round-trips. The storage cavity is indicated by the red dashed line in Fig.1, and the interaction cavity is indicated by the blue dashed line. A zoom-lens system (matching optics) is used to optically match the output of the seeding laser to the storage cavity fundamental mode. In the situation that the seeding pulse is p-polarized, two mirrors (steering mirrors 1 and 2) are used to steer the seeding pulse through a static half-wave plate into the laser cavity, where the now s-polarized pulse reflects from a Brewster plate.[7] In the case that the seeding pulse is s-polarized, the half-wave plate isn't needed.

The storage cavity contains two Q-switch Pockels cells, PC1 and PC2. PC2 has a zero-wave bias, and PC1 has a $\lambda/4$ static bias to prevent the laser cavity from free-lasing. After the seeding pulse making two passes through PC1, the pulse is p-polarized and passes through the Brewster plate. At this time, a variable-width gate pulse (Gate1) changes the bias of PC1 to zero wave before the circulating pulse comes back, the pulse is trapped in the cavity when Gate1 is on, and Gate1 is on during the rest of the injection time. Right after the captured pulse makes 27 round trips through PC2, a variable-width gate pulse (Gate2) changes the bias of PC2 from zero wave to $\lambda/4$. After the pulse making the 28^{th} round trip through PC2, the pulse rotates to s-polarization such that it reflects off the Brewster plate into the interaction cavity. After the pulse intercepting the H^- beam, reflecting off the Brewster plate, and making one round-pass through PC2, the pulse rotates back to p-polarization; and right after the pulse passing through PC2, Gate2 is off and changes the bias of PC2 from $\lambda/4$ to zero wave. The pulse is trapped in the storage cavity again. The H^- beam notches at the Booster injection revolution frequency will be created after repeating the above process N times. Here, N is the number of the injection turns. The biases of PC1 and PC2 *vs*. the injection time are shown in Fig.2. The time starts when the seeding pulse reflects off the Brewster plate in the first time.

Comment

Since the round-trip time of the storage and interaction cavities for notching the H^- beam at the Booster injection revolution frequency is three times the round-trip time of the laser cavity for notching the H^- beam at the Booster injection rf frequency, the total number of round-trips for covering the 12-turn injection decreases to 336 instead of 1008. The requirement for the cavity Q will be slightly relaxed. Besides, the interaction cavity is separated from the storage cavity and the total number of the laser pulse passing through the interaction cavity is equal to the number of injection turns, such as 12 (instead of 1008 (=12×84)), so a multi-pass interacting configuration between the laser and H^- beams can be used without any degradation in the Q-factor of the storage cavity. As a result, the decrease in the photon density, which is caused by the longer pulse length (65 ns instead of 5 ns), can be largely removed by a multi-pass configuration, as shown in Fig. 3.

The reason why the multi-pass configuration hasn't been proposed for the laser cavity of notching the H^- beam at the Booster injection rf frequency is because the imperfect reflectivity of a mirror will be multiplied by the number of the passes and contribute to the round-trip loss. Especially, the intercepting rate for notching the H^- beam at the Booster injection rf frequency is 84 times higher than that for notching the H^- beam at the Booster injection revolution frequency.

References:

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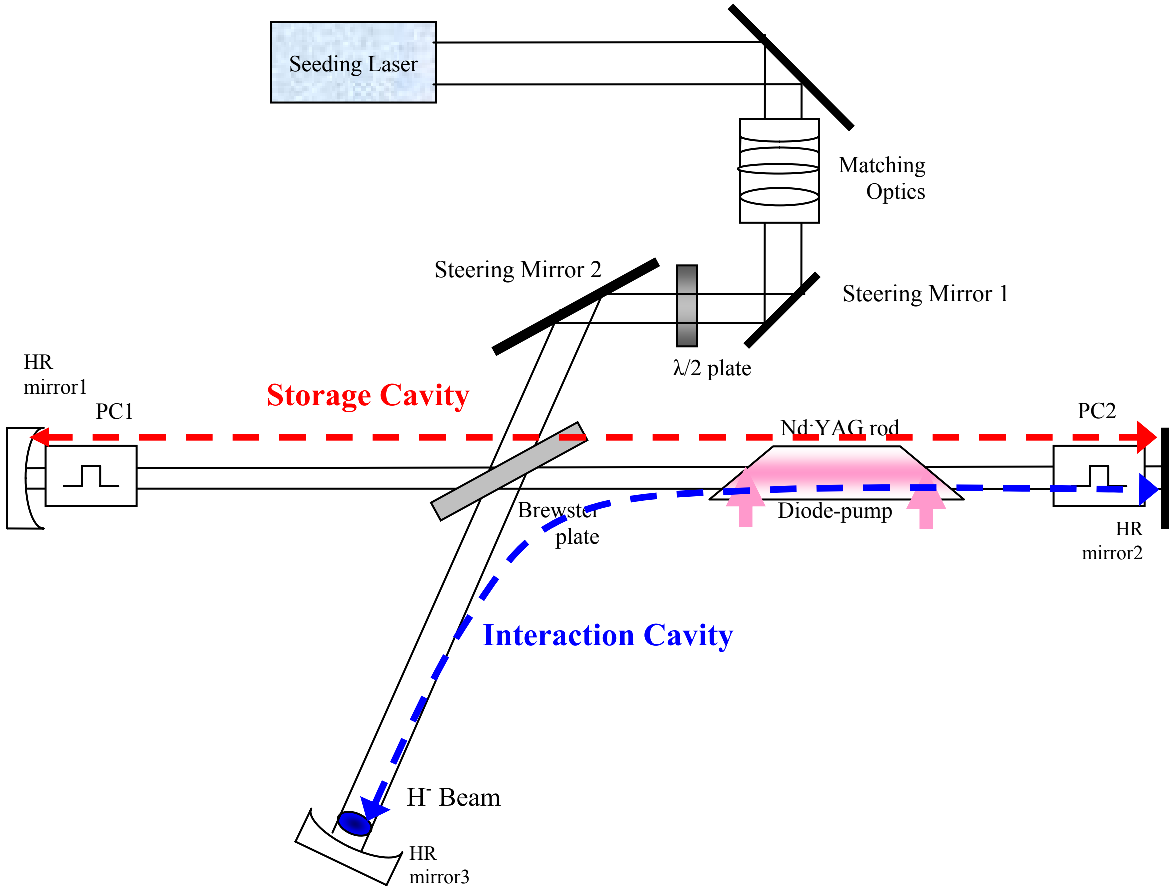

Fig. 1

Fig. 1 the diagram of the laser system for creating H^- beam notches at the Booster injection revolution frequency.

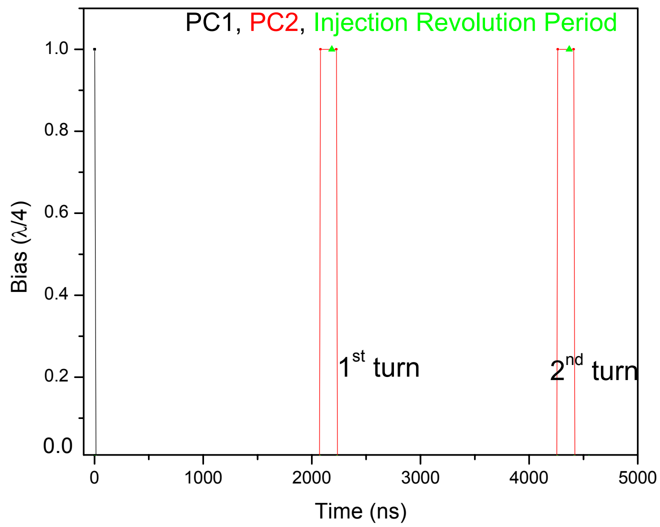

Fig.2

Fig. 2 the bias of PC1 *vs*. the injection time is shown as the black curve, and the bias of PC2 *vs*. the injection time is shown as the red curve. The revolution period is indicated by the green point.

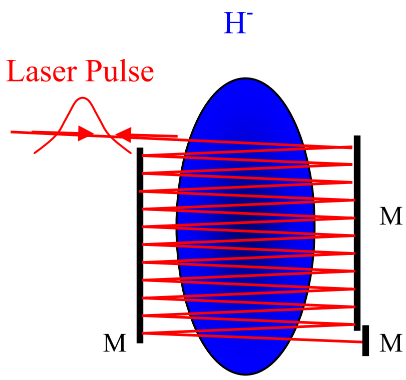

Fig. 3 a multi-pass configuration of the interception between the laser and H^- beams.