FERMILAB LINAC LASER NOTCHER*

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Abstract

Synchrotrons or storage rings require a small section of their circumference devoid of any beam (i.e. a "notch") to allow for the rise time of an extraction kicker device. In multi-turn injection schemes, this notch in the beam may be generated either in the linac pulse prior to injection or in the accelerator itself after injection. In the case of the Fermilab Booster, the notch is created in the ring near injection energy by the use of fast kickers which deposit the beam in a shielded collimation region within the accelerator tunnel. With increasing beam powers, it is desirable to create this notch at the lowest possible energy to minimize activation. Fermilab has undertaken an R&D project to build a laser system to create the notch within a linac beam pulse at 750 keV, where activation issues are negligible. We will describe the concept for the laser notcher and discuss our current status and future plans for installation of the device.

MOTIVATION

The current Fermilab Booster utilizes multi-turn injection and adiabatic capture to populate all RF buckets in the ring. To minimize losses from the rise time of the 8 GeV extraction kicker, a portion of the beam (about 60 ns. out of 2.2 µs.) in the ring is removed by fast kickers at low energy into an absorber. This empty section of the circumference is called a "Notch". On Booster cycles that are ultimately injected into the MI for the Neutrino program this process takes place at approx.700 MeV. At the completion of the Proton Improvement Plan (PIP) these losses are expected to contribute approximately 300 W of the total administrative limit of 525W. Moving this process out of the Booster tunnel to the 750 keV Medium Energy Beam Transport (MEBT) of the linac is expected to reduce the loss to 17 W, assuming a 90% efficiency in the Linac Notch creation and 10% clean-up in the Booster ring.

LINAC & BOOSTER BEAM

At the completion of PIP, the Fermilab Booster will be operating at 15 Hz. The length of the linac pulse injected into Booster is $N*\tau$ where N is the number of injected turns and τ is the Booster revolution period at injection. Creating a notch in the linac pulse requires removing a number sections of the linac beam at the Booster revolution period, where the number of sections to be removed is N-1. The spacing between these removed sections should guarantee that when the H- is injected into the Booster, the empty sections fall on top of one another in the ring producing a single notch in the Booster. This

process is shown in Fig. 1. The top pane shows the 15Hz linac pulses to be injected into Booster. The bottom pane shows a single linac pulse with 60 ns notches created within the pulse separated by ~2.2 µs, the Booster revolution period. Not shown is the 200 MHz bunch structure in the linac pulse.
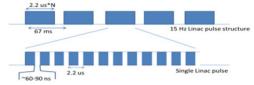

Figure 1: Linac pulse showing the notch structure for a single linac pulse.

LASER NOTCHER CONCEPT

The technique employed to produce the notch is to remove the outer electron of the H- ion using photoionization for the appropriate beam sections. There have been discussions on using lasers to create a notch in the linac beam for some time. [1-3] This technique was demonstrated in 2000. [1] The photoionization cross section has a broad peak centered at 1.51 eV (λ=821 nm) photon energy in the center-of-mass frame of the electron with a cross section of 4.2×10^{-17} cm^2. [4] The choice of the lab frame photon energy is dependent of the H- energy and the interaction angle through the standard Lorentz transformation. The laser technology for both solid state (Nd:YAG) and Yd doped fiber with a laser wavelength of 1064 nm has matured significantly over the last decade such that it is the natural choice for the laser system. The cross section for these photons with CM energy 1.165 eV is 3.66×10^{-17} cm^2, only 13% off the peak. When the probability of interaction between the photons and electrons is high and the mechanism does not depend on the electron intensity, the fraction of electrons that are detached from the moving H- ions is given by

$$F_{neut} = N/N_0 = (1 - e^{-f_{CM}\sigma(E)\tau}),$$

where f_{CM} is the flux of photons at the interaction point in the rest frame of the H- [photons/cm^2/sec], $\sigma(E)$ is the photoionization cross section for photon energy E, and τ is the interaction time of the photons and electrons. The center of mass flux can be expressed in lab frame parameters as

$$f_{CM} = \gamma \left(\frac{E_{laser}\lambda_{LAB}}{hc\tau_{laser}}\right)\left(\frac{1}{A_{laser}}\right)(1 - \beta \cos\theta),$$

where E_{laser} is the laser pulse energy, λ_{LAB} is the lab frame wavelength of the laser, τ_{laser} is the laser pulse length, A_{laser} is the laser cross sectional area, γ and β are the usual relativistic parameters, and θ is the interaction angel between the photons and H-. Figure 2 shows the "single pass" neutralization fraction as a function of laser pulse energy to neutralize a single 60 ns section of the 750 keV H- linac pulse, assuming a 90° interaction angle.
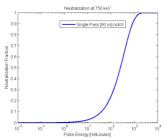
Figure 2: Single pass neutralization fraction for a 60 ns laser pulse.

This shows that to neutralize 95% of the ions would require a laser with ~ 1 Joule pulse energy and 60 ns pulse length which corresponds to a 16 MW/ pulse peak power, a significant laser. To create multiple notches in the linac this laser would have to have a repetition rate of 450 kHz. Such a laser system is beyond what is technically feasible for this project.

Reduction of Pulse Energy

To reduce the laser pulse energy, two techniques are utilized. First, instead of a single pass interaction, we introduce an optical zig-zag cavity [5] made up of two parallel mirrors such that as the laser traverses the cavity it will interact with the ions M times, where M is the number of times the laser crosses the mid- point of the cavity (i.e. ion trajectory). The diameter of this cavity and the angle at which the laser is injected are matched to the ion velocity through the cavity. Second, the laser pulse length is matched to the ion bunch length, otherwise the temporal section of the laser pulse between bunches is wasted and only contributes to the average power of the laser system.

Optical Cavity

The optical cavity is installed in the 750 keV MEBT where the loss of the neutralized ions by the laser do not contribute to activation of any accelerator components. The optical cavity is built into the downstream RFQ flange and just upstream of the first quad in the MEBT. Figure 3 shows a model of the installation with the flange removed to illuminate the geometry of the optical cavity.
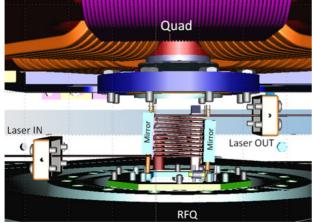

Figure 3: The laser notcher optical cavity between the RFQ and first MEBT quad.

The end of the RFQ is shown at the bottom and the first quad in the MEBT is at the top of the picture. The cavity is seen between these two devices. The laser enters from the left of the picture, traverses the cavity, and exits on the right. Viewports with an Anti-Reflective coating used to bring the laser into the vacuum cavity are seen on the left and right. The H- traverses the cavity from bottom to top, on the cavity axis. Due to the severe longitudinal space constraints the maximum length of the zig-zag cavity allowable is 25.4 mm which allows for 21 interactions of the laser with the same group of H- ions. Figure 4 shows the neutralization fraction for a multi-pass cavity (with M=21) and a laser pulse length matched to the ion bunch length (2 ns).
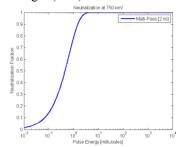

Figure 4: Multi-pass neutralization fraction for a 2 ns laser pulse.

Laser Requirements

The second technique to reduce the laser pulse energy is to match the laser temporal structure to the linac bunch structure out of the RFQ. Figure 5 shows the 200 MHz bunch structure out of the RFQ, the laser pulse structure, and the resultant linac bunch structure to be accelerated in the linac and injected into the Booster.
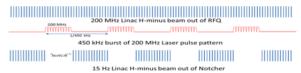

Figure 5: Result of laser pulses on a continuous 200 MHz bunch pattern.

The laser system must be capable of generating a 450 kHz burst of 200 MHz laser pulses each with a pulse length of about 2 ns (equal to the bunch length out of the RFQ) each 15 Hz linac cycle. The minimum number of bursts each 15 Hz is N-1, where N is the number of turns injected into Booster. Since we would like to neutralize nearly 100% of the ion bunch, all ions should see the same photon density thus leading to uniform temporal and spatial profiles. The laser pulses must be synchronized with the 200 MHz bunch structure and the burst must be times so the notches line up once injected into Booster.

LASER SYSTEM DESIGN

The laser system is a Master Oscillator Power Amplifier (MOPA) configuration which takes a low power seed laser and amplifies it to the required power. Transverse polarization is maintained through the entire laser and

optical system. Figure 6 shows a block diagram of the laser and optical system. Since we want uniform temporal pulses, we utilize a CW diode seed laser and a wave-guide modulator to create the required temporally uniform laser pulse pattern (both at the 200 MHz and 450 kHz frequencies) at low pulse energies (pJ) for each linac cycle. This pulse pattern is amplified using a three stage fiber amplifier system to increase the pulse energies to the 5-10 µJ level. The laser is brought out into free space where it is further amplified by double passing through two diode pumped solid state (DPSS) amplifier modules delivering the desired pulse energy of 2 mJ. The pre-amp and fiber amp 1 operate CW while fiber amp 2 and both DPSS modules operate at 15 Hz. A system of Faraday isolators and wave plates are used for polarization control to allow double pass operation of the DPSS amplifiers. Several optical telescopes are used to match between the DPSS amplifiers and into an optical system to create a roof-top spatial profile. After exiting the final amplifier, the Gaussian laser profile is focused onto an optical system which splits the single Gaussian beam into 8 beamlets of alternating polarization thus creating a roof-top spatial profile. A final horizontal and vertical cylindrical telescope modify the profile to create a beam with horizontal width of 0.5 to 0.8 mm and vertical height of 10 mm to match the vertical dimension of the ion beam out of the RFQ.
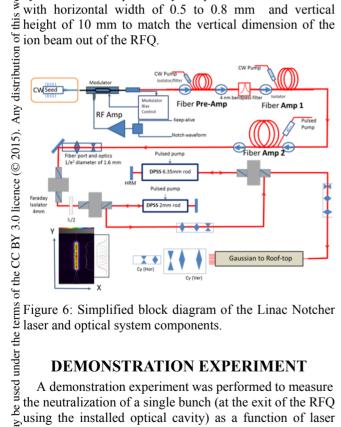

Figure 6: Simplified block diagram of the Linac Notcher laser and optical system components.

DEMONSTRATION EXPERIMENT

A demonstration experiment was performed to measure the neutralization of a single bunch (at the exit of the RFQ using the installed optical cavity) as a function of laser pulse energy and compare with neutralization predictions. Because the laser system (this work) is under development, the demonstration experiment performed with a 100 mJ Q-switched Nd:YAG laser with a FWHM temporal profile of 10 ns. and operated at 15 Hz. The laser pulses were locked to a 200MHz RF pickup from the RFQ. A programmable delay line allowed precise

timing of the laser pulse to align the peak amplitude of the laser with the selected bunch. The bunch signal from a Wall Current Monitor (WCM) in the high energy end of the linac was used to measure the neutralization of the single bunch as a function of laser pulse energy. The WCM response to a section of the linac bunch train, including the bunch hit by the laser, is shown the left plot of Fig. 7. Each curve corresponds to different laser pulse energy. The area under the curve of the bunch being neutralized was compared to the average of the areas of the near unaffected bunches. The ratio of these areas gives the neutralization factor. The data points in the plot on the right of figure 7 show the measured neutralization as a function of the laser pulse. The error bars are a rms value of the baseline of the WCM response (~5%) and the uncertainty in the WCM pulse amplitude (~5%). The predicted curve is based upon a 1.5 ns bunch length and 0.8 mm H laser profile and 10 mm laser vertical profile.
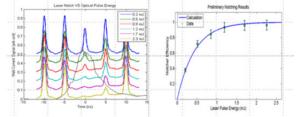

Figure 7: Waterfall plot of the neutralization of a single 200 MHz bunch with the laser pulse shape overlaid in black(left) and the measured neutralization fraction as a function of pulse energy compared with predictions.

REFERENCES

[1] R. Tomlin, "Ion Beam Notcher Using a Laser", proceedings of the 2001 Particle Accelerator Conference, page 3912.

[2] Xi Yang and C. Ankenbrandt, "Design Report of the Laser System for Notching H- Beams at Booster Injection RF Frequency in the 750 keV Linac", Fermilab FN-0765-AD (April 2005).

[3] Xi Yang and C. Ankenbrandt, "Reducing the Extraction Loss via Laser Notching the H- Beam at the Booster Injection revolution Frequency", Fermilab FN-0767-AD (May 2005)

[4] H.C. Bryant and E.P. MacKerrow, "Accelerator-Based Atomic Physics Techniques and Applications", ed. S.M. Shafroth, J.C. Austin, (1997) chapter 6, page 183.

[5] R.E. Shafer, Laser Diagnostics for High Current H-Beams", Proc. 1998 Beam Instrumentation Workshop (Stanford). A.I.P. Conf. Proceedings, (451),191.