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MEBT LASER NOTCHER (CHOPPER) FOR BOOSTER LOSS REDUCTION*

D.E. Johnson#, T.R. Johnson, C. Bhat, S. Chaurize, K. Duel, P. Karns, W. Pellico, B.A. Schupbach, K. Seiya, D. Slimmer, Fermilab, Batavia, Illinois, USA

Abstract

In synchrotrons, beam extraction is accomplished by a combination of kicker magnets and septa which deflect the beam from one accelerator into another. Ideally the extraction kicker field must rise in a beam-free region in the synchrotron (aka "notch"), to avoid beam loss at high field during the extraction kicker rise time. In the case of the Fermilab Booster, which utilizes multi-turn injection and adiabatic capture, the notch is created in the ring at the injection energy using fast kickers which deposit the beam in a shielded absorber within the accelerator tunnel. This process, while effective at creating the extraction notch, was responsible for a significant fraction of the total beam-loss power in the Booster tunnel and created significant residual activation within the Booster tunnel in the absorber region and beyond. With increasing beam demand from the Experimental Program, the Fermilab Proton Improvement Plan (PIP) initiated an R&D project to build a laser system to create the notch within a Linac beam pulse at 750 keV, where activation in not an issue. This paper will discuss the loss reduction in the Booster, increased efficiency, and increased proton throughput, and its integration into the accelerator complex. We will also touch on other potential applications for this bunch-by-bunch neutralization approach.

INTRODUCTION

With the transition from the Collider Era to the Intensity Frontier in 2011, it became clear that, to meet the demands of the existing Neutrino and future Muon and Neutrino Experimental Programs as well as the Fixed target area programs, the Accelerator and its infrastructure needed upgrades. A series of task-forces and workshops were held [1-3] to define the necessary improvements and upgrades such that the Proton Source will 1) remain viable and provide reliable operation of the Linac and Booster through 2025, 2) assure beam operation of the Linac and Booster at 15 Hz and 3) double the proton flux (to 2.25E17 protons/hour) while maintaining the 2010 residual activation levels. These goals make up the essence of the multi-year Proton Improvement Plan (PIP) starting in 2012. At the start of PIP another project, “The 750 keV RFQ Injector Upgrade”, [4] was well underway as a project to replace the 40+ year-old Cockcroft-Walton pre-accelerator with a more modern and reliable radio-frequency quadrupole (RFQ) and associated source and transport line(s) for injection into Tank 1 of the Linac.

FERMILAB PROTON SOURCE

The Fermilab Proton Source is comprised of a dual ion source providing a continuous current of H^- ions, a low energy beam transport (LEBT) line, a 750 keV RFQ operating at 201.25 MHz, a medium energy beam transport (MEBT) line, to match between the RFQ and Tank 1 of the 15 Hz 400 MeV Linac which injects into the Booster.

The Fermilab Booster is a combined function synchrotron with magnet systems resonantly powered at 15 Hz. The synchrotron has an injection energy of 400 MeV and extraction energy of 8 GeV, with an acceleration cycle of ~33 ms. Injection into the Booster is multi-turn injection with adiabatic capture into stationary 38 MHz buckets. The RF harmonic number of the Booster is 84. The Linac pulse length is equal to the number of turns to be injected times the revolution period of the Booster (2.21 μsec) at injection.

To cleanly extract the beam at the top energy of 8 GeV, an 80 ns no-beam gap (notch) must be created in the Booster ring after adiabatic capture into the 38 MHz buckets, while at the injection energy. The 80 ns gap is required for the Booster extraction kicker rise time and is equivalent to sixteen 201.25 MHz Linac bunches. This has historically been performed by a series of fast kickers [5] which will remove three of the 84 bunches into an absorber inside the Booster tunnel.

Although this is only a small fraction of the beam in Booster, it represents about 30% of the total lost beam power. Fermilab’s administrative loss limit assures that the average loss around the ring does not violate the 1 W/m level. Obviously, the losses are not uniform around the ring, they are typically concentrated in the injection and extraction regions as well as the internal absorbers for collimation and notch production.

To be able to increase the throughput of the Booster the loss associated with the production of the extraction notch in the Booster tunnel must be significantly reduced or eliminated. Moving this process out of the Booster tunnel to the 750 MeV MEBT, is expected to significantly reduce Booster total lost power allowing a proportional increase in accelerated beam intensity (throughput), a positive step in addressing the third goal in the PIP.

The PIP initiated an R&D project to build a laser system to create the required series of notches within a Linac beam pulse at 750 keV. The concept is that 80 ns sections of the Linac pulse at the Booster injection revolution period will be removed. As the Linac pulse is injected into the Booster these no-beam sections (or notches) will line up on top of one another thus creating a "ready-made" notch at injection. Assuming a 90% efficiency in the creation of the notch in the Linac pulse, the Booster kicker needs to only remove the remaining 10% of the beam into the absorber.

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#DEJ@fnal.gov

Figure 1 shows the 15 Hz Linac pulses in the top pane and a single Linac pulse segmented into sections at the Booster revolution period in the lower pane.

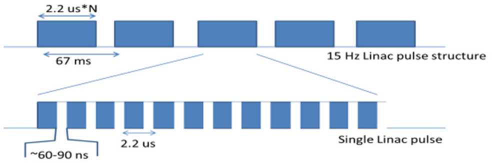

Figure 1: Schematic of Linac pulses at 15 Hz (top) and a single pulse showing multiple notch structure (bottom). The 201.25 MHz linac bunch structure is not shown.

LINAC NOTCHER CONCEPT

The technique employed to produce the notches in the Linac pulse is to remove the outer electron of selected H⁻ ions using photoionization [6]. There have been discussions on using lasers to create a notch in the Linac beam in the past [7-9]. The laser system developed under PIP was designed to minimize the peak laser pulse energy required for neutralizing H⁻ ion bunches exiting the RFQ, utilizing two techniques. First the laser pulses match the temporal structure (spacing and bunch length) of the ions exiting the RFQ. In addition, laser system operates in a burst mode at the Booster injection revolution frequency. Each burst contains a group of 201.25 MHz laser pulses, which in the current scenario is 16 pulses to create an 80 ns notch

At the early stages of design, the expected notch width was ~ 60 ns and the number of injected turns was 10-12. In the current operational scenario, with 18 turn injection, the laser system creates 19 bursts (one to sharpen the head of the Linac pulse and the rest of the 18 to create the required notches within the Linac pulse), each Linac cycle.

The second technique employed to minimize the required peak laser pulse energy is the utilization of a non-resonant interaction cavity with parallel mirrors. [10] The geometry of this cavity (mirror separation, separation between interactions, and laser injection angle) is adjusted such that the velocity of the laser advancing downstream on the axis between the parallel mirrors matches the ion velocity traveling through the cavity. This allows the laser to interact many times with the ion bunch as it progresses down the cavity [11]. The number of interactions depends on the beam line space available, the length of the optical cavity (in the present implementation the mirrors are only 27mm long) and the distance between successive interactions (currently ~1.1mm). We typically strive for 21 up to 27 interactions as the ions pass thru the cavity.

Estimation of Required Laser Energy

When the probability of interaction between the photons and electrons is high and the mechanism does not depend on the electron intensity [6], the fraction of electrons that are detached from the moving H⁻ ions is given by [12]

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

where f_{CM} is the flux of photons at the interaction point in the rest frame of the H⁻ [photons/cm^2/sec], σ(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

$$f_{CM} = \gamma\left(\frac{E_{laser}\lambda_{LAB}}{hc\tau_{laser}}\right)\left(\frac{1}{A_{laser}}\right)(1-\beta\cos\theta), \qquad (2)$$

where $\boldsymbol{E}_{\mathbf{laser}}$ is the laser pulse energy, $\boldsymbol{\lambda}_{\mathbf{LAB}}$ is the lab frame wavelength of the laser, τ_{laser} is the laser pulse length, $\boldsymbol{A}_{\mathbf{laser}}$ is the laser cross sectional area, γ and β are relativistic parameters, and θ is the interaction angle between the photons and H⁻

Given the vertical beam size of the ion bunch and the cavity geometry, we use Eq. 1 and 2 to calculate the neutralization as a function of laser pulse energy. We show three different calculations in Figure 2 to reflect the energy savings from the two energy-saving techniques. The three curves are: 1) a single 80 ns laser pulse is used to create a complete notch (red, solid line), 2) a single interaction with the 2 ns laser pulse, to match the ion bunch length) without utilizing the interaction cavity (blue, dot-dash), and 3) with a 2 ns laser pulse utilizing the interaction cavity with 27 interactions (black, dashed).

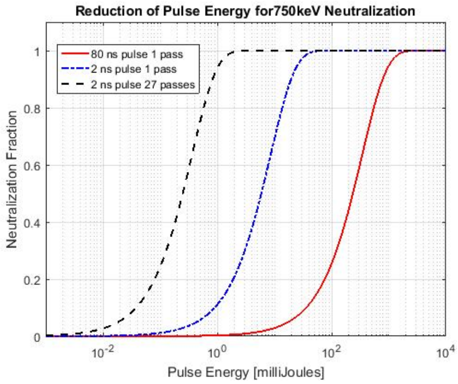

Figure 2: Neutralization of a single bunch with and without the use of a multiple interaction cavity.

To neutralize 99% of an ion bunch, it would require 47 mJ in a single pass interaction while only 2 mJ for a cavity with 23 interactions. For 95%, it would be 25 mJ vs 1 mJ per bunch.

LASER SYSTEM DESIGN

The laser system may be characterized as a flexible hybrid burst-mode laser system with a master-oscillator-power-amplifier (MOPA) architecture. The spatial properties of the final amplifier output are controlled to match the vertical dimension of the ion beam, which in our case we require the spatial cross section of the laser to be 1 mm × 7 mm vertically. Figure 3 shows a block diagram of the laser system. The MOPA architecture indicates starting with a low power diode laser and impressing the desired laser pulse structure on this seed source. This is then amplified through a series of CW pumped fiber amplifiers, a pulsed pumped fiber amplifier, brought into free space with the final amplification from two dual pass diode pulse pumped

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solid state laser amplifiers. After the final amplifier the transverse spatial profile is modified to create a roof-top profile and a cylindrical telescope is used to create a narrow horizontal profile at the entrance of the cavity.

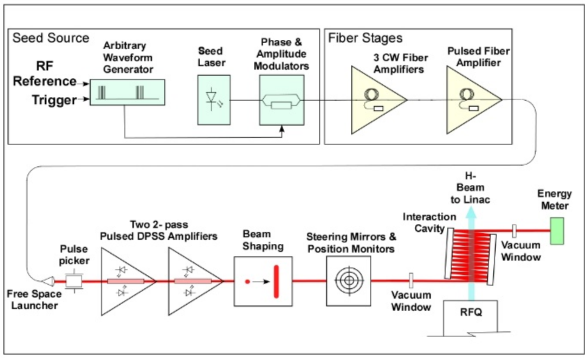

Figure 3: Block diagram of the laser system and optical transport to the interaction cavity.

Instrumentation

To tune and monitor the operation of the laser system and injection into the interaction cavity several commercial instruments and several Fermi designed/built pieces of instrumentation are utilized. The instrumentation falls into a few categories to measure, 1) average power, 2) pulse amplitudes, 3) total laser pulse energy each 15 Hz Linac cycle, 4) laser positions in transport to the interaction cavity, and 5) IR capable video camera to monitor the laser bounce spacing inside the interaction cavity.

Controls

The LabView front-end software that is used to monitor and control all the amplifiers, Data Acquisition system, and associated hardware. The program is a flexible queue driven state machine composed of independent tasks such as the 1) GUI interface, 2) main accelerator controls system interface for operational monitoring and control, 3) hardware monitoring, and 4) a very flexible waveform creation for the laser pulses. All communication with hardware is via USB. Since the laser system is in a very noisy electrical environment, a significant effort was required to minimize interference with hardware communication. In addition, automatic recovery routines for identified hardware communication errors have been implemented. Accelerator Operations interface to the front end is via a Java Graphical Monitoring page, closed circuit video channels, and standard parameter pages, and alarm monitoring. Figure 4 shows the image of the main page LabView front-end GUI interface. Other functions such as piezo-electric mirror control and Optical Beam Position Monitor positions of the laser trajectory into the optical cavity, parameter setting limits, DAQ configuration, and alarm configuration are accessible through tabs at the top of the GUI. Access to the flexible waveform generation is through a "button" at the bottom of the page.

Figure 4: Laser Notcher front-end GUI.

Installation

The complete laser system and the free space optics is contained in a custom 19 inch electronics rack with the free space amplifiers and free-space optics in a light tight optics box sitting on top of the electronics rack. The centerline elevation of the beam line is 41 inches above the floor. The elevation of the free space optical path must match the beam line elevation.

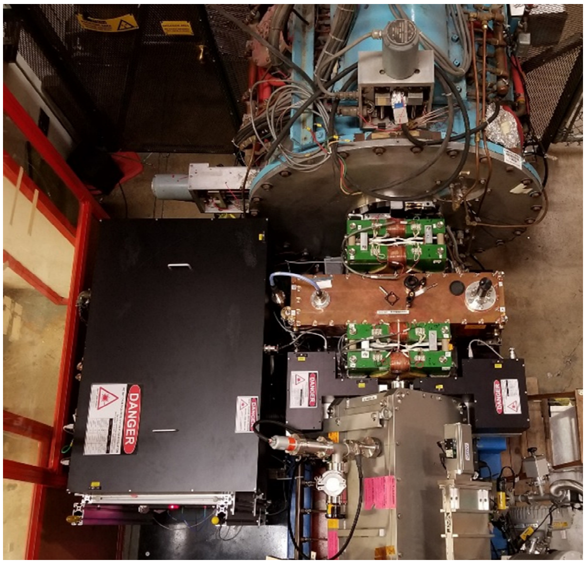

Figure 5: Installation of Laser Notcher in the Linac.

A light tight transport enclosure and a light tight laser dump enclosure are used to transport the laser from the optics box, through the interaction cavity, and finally to a dump energy meter to measure the laser energy after the interaction cavity.

The complete system is portable and can be rolled in and set in place. The optics box is aligned so that the laser output trajectory is perpendicular to the ion beam trajectory and at the correct elevation. The interaction cavity is built into the output flange of the RFQ. Figure 5 shows the laser system installed between the RFQ and tank 1 of the Linac.

Comparison of Neutralization Measurements with Estimates

We utilize a resistive wall current monitor (WCM), located midway down the Linac, to monitor the individual

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201.25 MHz bunch intensities for each Linac cycle and a fast photodiode (PD) to monitor the laser pulse amplitude out of the final amplifier. The top pane in Fig. 6 shows the WCM and PD for an entire Linac cycle (magenta) and the laser bursts (green) responsible for each notch. The bottom pane shows an expanded view of the first notch along with the laser pulses that neutralized each bunch within the notch. On either side of the 80 ns notch are the un-affected bunches.

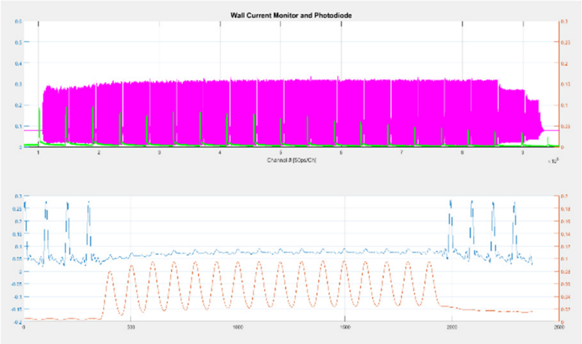

Figure 6: Wall current monitor and photodiode signal showing the burst spacing (top pane) and the detail of the first notch (bottom pane).

We compare the bunch intensity of the bunches 'in the notch' that have been neutralized by the laser to the nearest 'un-affected' bunches to determine the level of neutralization (see bottom pane in figure 6).

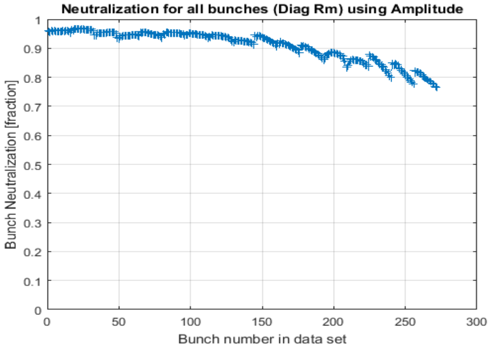

Figure 7: Measured neutralization of every bunch within the 17 notches created in a Linac pulse for 18 turn Booster injection.

Looking at Figure 7, one can clearly see that the first half of the bunches are neutralized to the 90 to 96% level and slowly tails off to the 75% level for the 17th notch as the current configuration lacks the stored energy necessary to maintain this number of uniform pulses. Using the fast photodiode monitoring the output of the last amplifier and an energy meter located in the laser dump, we calculate the pulse energy of each 201.25 MHz laser pulse.

Correlating the level of neutralization for each bunch within all notches with the laser pulse energy allows us to compare the neutralization as a function of energy. Figure 8 shows the results of the latest neutralization measurements and the neutralization estimation as a function of energy for 27 interactions

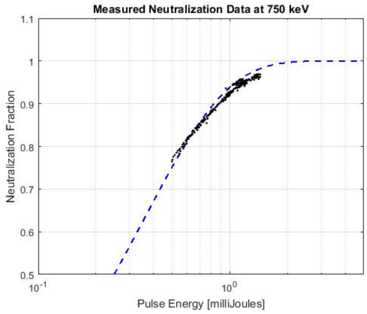

Figure 8: Comparison of measured neutralization with the predicted neutralization for 27 interactions.

BOOSTER INJECTION

The current injection process into Booster is known as Early Injection Scheme (EIS) [13] where the start of injection occurs on the decreasing dipole magnetic field 200 µs before its minimum is reached. The goal of this scheme is to increase the number of Booster turns (BT) for injected beam and provide more time for adiabatic capture of the beam to preserve longitudinal emittance of the beam at injection. However, the revolution period during the injection process is not constant. It is, therefore, important to adjust the spacing of the notches in the Linac beam so that all the notches line on top on one another through injection and retain 80 ns gap in the injected beam after the completion of the injection process. During injection a small amount of the Booster 38 MHz RF voltage is present. Once injection is finished, the amplitude of the 38 MHz RF is adiabatically increased to capture the bunches within the 38 MHz bucket. The center of the notch must line up with one of the 38 MHz buckets to keep the notch symmetric.

Longitudinal beam dynamics simulations carried out by including 80 ns notch in each BT beam convincingly show that the particle leakage into the notch during beam capture is less than 1-2% if beam capture commences immediately after the beam injection. However, in the current operation we observe ~15% of beam particle leakage by the end of the capture. In any case, we have greatly benefited in reducing the beam loss in the Booster ring due to the Laser notcher.

IMPACT ON OPERTIONS

The motivation for developing the laser notcher system was loss reduction in the Booster tunnel. As mentioned earlier, the process of creating the notch at injection energy was effective, but it contributed about 30% to the total loss power budget of the Booster. When the Booster and its notching process is "well" tuned up, without the laser notcher, the throughput for Booster is about 2.0-2.1 E17/hour with the Booster losses remaining within the 1W/m loss level. With the application of the laser notcher in combination with the current Booster notcher (to provide cleanup of the notch, the throughput rises to the level of 2.4-2.5 E17/hour with the Booster losses remaining within the 1W/m level, about a 20% increase in throughput.

When running with the laser notcher system on, we observed an increase in the amount of beam that can be accelerated in the Booster. Figure 9 shows the impact on Booster intensity (magenta) and extraction losses (cyan). The plot on the left (laser off) shows the Booster cycle intensity of 4.7E12 protons per Booster cycle (ppBc) for the NuMI cycles (on the left) and 3.4 E12 for the BNB cycles (on the right). The right plot (laser on) shows the reduction of the NuMI extraction losses by ~40% for the same intensity and a ~40% increase in the beam on the BNB cycles with the same extraction loss level.

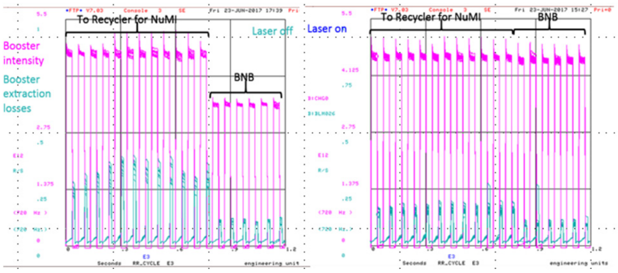

Figure 9: Comparison of Booster cycle intensity and extraction losses with the laser notcher on and off.

HE PATH FORWARD

Since we embarked on the R&D project to create a bunch-by-bunch H^- neutralization system for notch creation in the existing Linac beam pulse, various other applications of this technique have surfaced. This concept of bunch-by-bunch interaction with the laser system coupled to our non-resonant interaction cavity has led to proposals of creating laser systems for other applications such as arbitrary bunch chopping, transverse and longitudinal collimation, extraction of various bunch intensities from H^- transport line, etc. One such proposal is to create a laser transverse collimation system for complete Linac pulses. This was successfully tested last summer for a Linac pulse with a length of about 2.2 µs, a single Booster turn.

To accomplish this, we utilized 1) our flexible waveform generation program to create a waveform of 440 201.25 MHz laser pulses (each 2 ns long) to interact with every bunch in the Linac pulse and 2) our patented beam shaping device to redistribute the total energy of the pulse, i.e. change the spatial profile from a single roof-top profile to a pair of laser spots separated by 4-5 mm, thus, only neutralizing the tails of the vertical spatial profile as shown in the right hand picture of Figure 10.

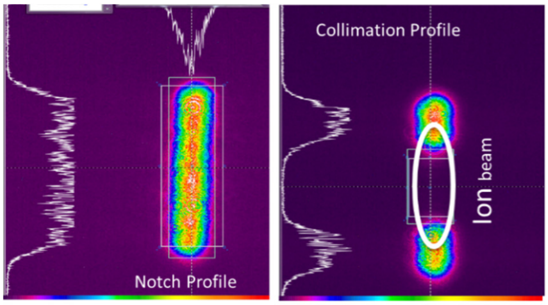

Figure 10: Transverse profile of laser pulse used for notching (left) and the one used for vertical transverse collimation (right).

Although the impact of the laser on the vertical profile could not be discerned on a multiwire in the injection region, the reduction of bunch intensity for all bunches in the Linac pulse could clearly be seen on the WCM and the losses in the injection region showed a clear reduction when the laser was turned on.

Another potential utilization of this technique is momentum collimation in a Linac. Currently, it has been conceived that reduced momentum spread of the beam from the Linac at injection might improve the beam capture efficiency. It has been proposed that the laser system could be set up to collimate in longitudinal phase. This may be accomplished by creating two laser pulses for each bunch by splitting a single laser pulse and directing one through a variable optical delay line and re-combining. The temporal spacing of the recombined pulse can be adjusted to vary the extent of neutralization of the head and tail of the bunch.

For applications requiring interaction with all bunches in a Linac pulse (high duty factor), the amplifier system must be capable of providing 1) enough stored energy for uniform energy extraction by all seed laser pulses, or 2) a fast gain media pumping to allow uniform amplification of all laser pulses. Because of the advancement in specialty large mode area gain fibers and the large peak and average power handling capability these gain media, these media are becoming more attractive as final amplifier stages. Even though these fiber gain medias do not suffer thermal lensing and wedging issues found in solid state gain media (c.f. Nd :YAG) due to non-uniform temporal pulsing, they have their own limitations due to non-linear instabilities at high peak powers. Currently, fiber amplifiers are available with 300 kW peak and ~ 200 W average power capabilities. Progress continues in the development of even higher peak power capability.

CONCLUSION

We have developed the first of its kind bunch-by-bunch H^- neutralization system for the purpose of loss reduction in the Fermilab Booster. This is being utilized to create the Booster extraction gap or notch in the Linac pulse. The system has successfully led to a significant increase in proton throughput.

We continue to understand and improve the operation of the system in the Linac. We continue to develop and improve the non-resonant interaction cavity. We continue the R&D to develop a quasi CW amplifier system that will be compatible with long pulse operation required for collimation applications and other applications.

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