7.1.5. Beam Notching with Lasers

When beam is transferred from machine to machine, it should be done synchronously so that bunches from the first land in buckets in the second. Approximately 2% of beam from an 8 GeV linac will be lost during capture in MI 53 MHz buckets. Laser chopping at 53 MHz can alleviate that source of beam activation of MI tunnel components. Laser chopping at 42 MHz can alleviate that source of beam activation of PD tunnel components. Existing BPMs in MI or a new proton driver would work at 42 or 53 MHz. Lasers can be used to chop beam at 42 or 53 MHz so that we can see the first turn on all BPMs. Laser chopping of injector beam to full synchrotron buckets also eliminates the need for LLRF adiabatic capture gymnastics.

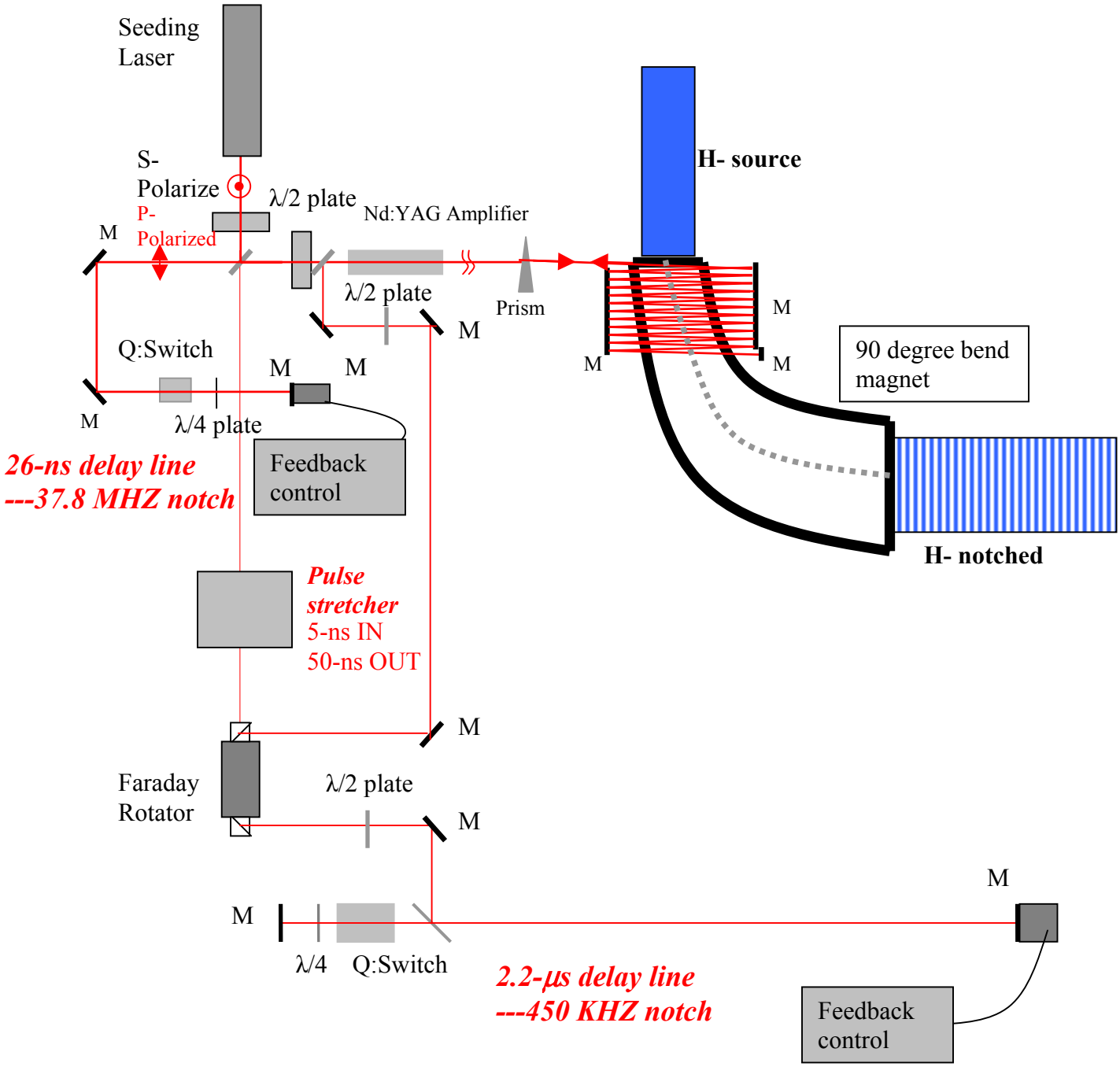
H^- ions have a broad photoejection cross section for photons in the range 500 to 1000 nm. The first electron is stripped, leaving neutrally charged, relativistic hydrogen. The laser "notched" beam is then subjected to bending magnets or accelerating electric fields where the neutral beam is lost and a physical notch remains. The reaction is $H^- + \lambda \rightarrow H^0 + e$. A proof of principle project demonstrated that this notching could be applied to the FNAL Linac and Booster. We made short notches with a laser that was tolerated by the unmodified Linac and Booster RF feedback systems.

Today's mode locked fiber lasers and microcrystal lasers can provide seed pulses at rates approaching a GHz. The seed pulses would be switched to optical power amplifiers as needed and applied to the H^- ion beam. An amplified light pulse would be generated for each required notch and "wasted" rather than recirculated to make many notches. Recirculation schemes are technically unwieldy due to laser beam degradation and optical alignment problems. Also, recirculation schemes can require two windows on the vacuum chamber rather than one window, each window taking up to 4 inches of beam pipe.

Optical power is a prime consideration in optical notcher design. Simple redesigns of the beam line optics make optical notching feasible. Given the cross section of the 0.75 eV electron beam, the percent of ions stripped depends on the number of photons per unit area per unit time. So 99% stripping of an H^- beam that is just 1 mm across requires two orders of magnitude less photons than 99% stripping of an H^- beam that is 1 cm across. The number of ions stripped also depends on how long they "cook" in the photon flux. Some factors that determine the cooking time are the laser pulse length and application of the pulse in the geometry of the interaction region.

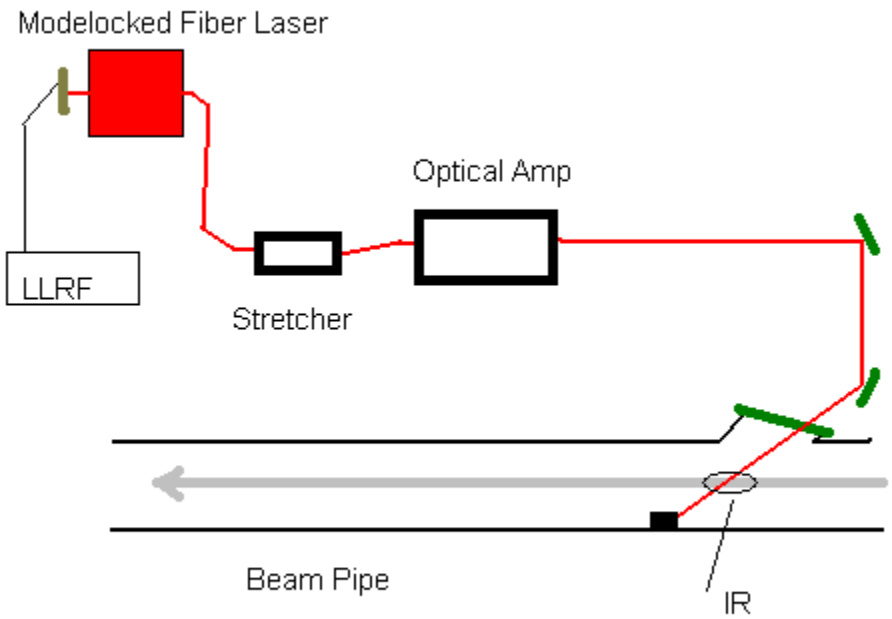
There may be many ways to do laser notching. The ion accelerator should be designed with a stripping interaction region designed to minimize laser power. So a region where the ion beam is focused to a ribbon with physical dimensions 1 mm x 12 mm for 50 millimeters might be ideal. Space charge is a concern, so we would narrow the ion beam at higher than 0.02c. Component activation is a concern, so it is best to strip

ions at less than 0.05c. A bending magnet might follow to reject the neutrals. The next figure depicts a typical recirculation scheme developed by Xi Yang and myself. It might be difficult to maintain.



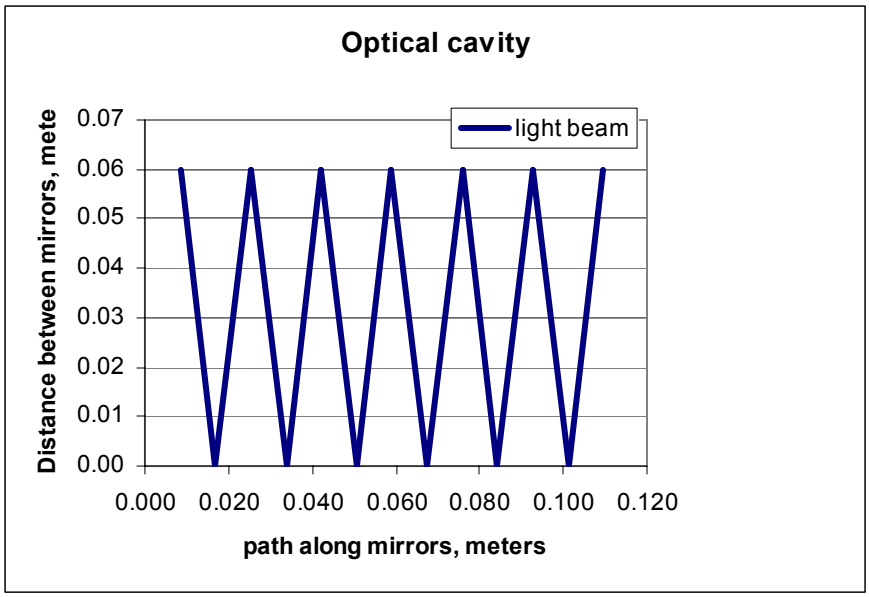
A suggested MOPA (mode locked optical power amplifier) SHG (second harmonic generation), that is easily serviceable in a hostile environment, follows.

We begin with a tunable mode locked fiber laser operating at "eye safe" 1550 nm. It is phased locked to the RF frequency of the accepting synchrotron. A short fiber delivers the 53 MHz bursts to a grating pulse stretcher which may be physically mounted on a box floating at high voltage potential, a hostile environment. The gratings operate well below damage threshold and increase the pulse length to about 5 nsec. The stretched pulse is amplified to approximately 1 mJ by two multipass optical amps. The mJ pulses (still eye safe) are applied to a SHG crystal to obtain a 775 nm wavelength optimum for the H^- photoejection cross section. The photon beam diameter is maintained at roughly 1 mm diameter in the MOPA and SHG. It is then applied to the ion beam in a multiple reflection IR where ion beam has one dimension that is 1 mm wide.



Microchip lasers are another emerging alternative. They are miniature diode pumped Nd crystals. They can operate with YLF and be amplified with Glass amps. The 1 micron wavelength is not eye safe, but can be rendered safe by suitable safety engineering.

An optical cavity may be installed in the beam pipe. The IR is set up so that the reflecting laser pulse keeps pace with the ions. If it is close, one gets a notch complicated by the kinematics of the ions and the multi-reflected 5 nsec laser pulse. For two flat 1-in × 4-in mirrors spaced a couple inches apart at beta = 0.04 (750 KeV), one gets about a 99% 3.5 nsec notch with 1 nsec rise and fall times. The ions move about 60 mm during the 5 nsec laser pulse.



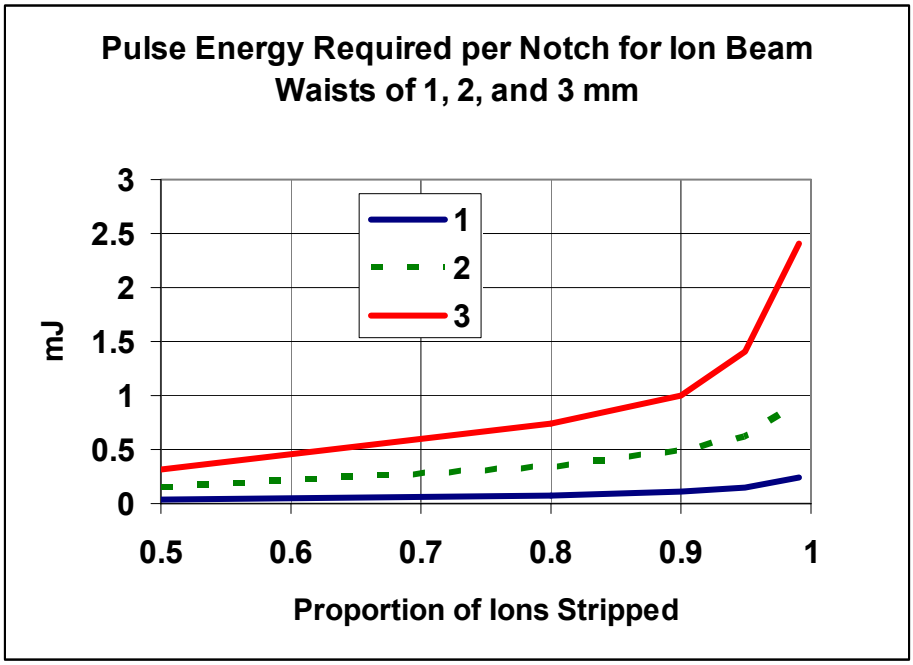
One might conjecture that when mirrors are separated by 60 mm, light is passing through a 1.2 cm high ion beam only 20% of the time, so laser power goes up by five for a given stripping efficiency calculation. However, it must be kept in mind that the 5 nsec pulse is streaming through the region for 5 nsec. The power multiplication factor comes only from the bouncing laser beam traversing some of the ions unevenly because of the 60 mm motion of the ions during the 5 nsec laser pulse.

The kinematics and the mixing time can make design of the notch length and stripping percentage difficult. An easier alternative is to find a straight piece of beam transport pipe of length equal to the ion velocity times the duration of the notch required. The ions can be thought of as just sitting there (0.04c) while a 5 nsec laser pulse rips through them and strips, say, 90 cm of them. At 750 KeV, one gets a 75 nsec hole suitable for a Booster extraction notch. Laser power requirements can be held down by carefully designing the interaction region so that the ion beam has a waist or one narrow transverse dimension. The cooking time for any ion in such an IR is easy to think about; it is the length of the laser pulse. Calculation of power is simplified.

For 99% stripping where the mixing time is 5 nsec and the cross section for 775 nm photons is rho:

$$I = \frac{\ln(0.01)}{-\sigma t} = \frac{-4.605}{-4\times10^{-17}\,cm^2 \cdot 5\times10^{-9}\,\sec}$$

$$I = 2.3\times10^{25}\frac{photons}{cm^2\,\sec ond}$$



If the beam waist is reduced from 1 cm to 1 mm, and 775 nm photons are used:

$$\text{Area} = \pi cm^2, \quad I = \pi r^2 I_{init}$$

$$I = 1.8\times10^{23} \text{ photons}/\, cm^2 \sec$$

Each photon has energy:

$$E = \frac{hc}{\lambda} = \frac{6.626\times10^{-34} Js \cdot 2.998\times10^{8} m/s}{0.775\times10^{-6} m}$$

$$E = 2.56\times10^{-19} Joule/photon$$

Joule/sec = Watt

$$\text{Watts} = 2.56\times10^{-19}\frac{Joule}{photon}\cdot 1.8\times10^{23}\frac{photons}{\sec ond}$$

$$\text{Peak Power} = 47 KW$$

$$\text{Energy per pulse} = 47000 J/s \times 5\times10^{-9} s$$

$$= 0.24 mJ$$

Assuming 50% SHG, remembering that 775 nm is more energetic than 1550 nm, and allocating a very generous factor of 2 for geometry and mirror losses, approximately 0.5 mJ at 1550 nm is needed for each 99% notch. Given a high current 600 MeV linac feeding an h = 84 proton driver, less than 2 Joules are needed for each 45 turn injection. Current off the shelf technology can do that at 15 Hz. So this is relatively easy to do.

However, if a low current 8 GeV linac is chopped at 53 MHz for 218 turns, the total light needed is 64 Joules, a burst of 128,184 × 0.5 mJ laser pulses. There may be some relief, however. Current ion sources in use at FNAL bend the beam 90 degrees right after a 1 mm x 1 cm slit that defines the beam size. Some R&D effort is being put into reducing the bend to around 5 degrees to preserve a notch made right at the slit. If the slit can be narrowed to 0.5 mm and most of the geometry factors reduced, the 8 GeV linac needs only 6.4 Joules per MI load. In addition, these 0.05 mJ pulses might be delivered by fiber optics. All of the laser equipment then operates in an equipment rack and only a SHG crystal would live in an extreme environment.

Other R&D efforts are taking place to reduce photon requirements further. Work is being done to see if the production of ions can be enhanced or depopulated inside the source itself. The work function of materials inside the source is within the range of photon wavelengths achievable.