TO: Laser Chopping Study Group
Re: Design Requirements for Proton Drivers

Motivations of laser chopping at synchrotron RF frequency

1. Clean injection
Careful measurements and simulations of the FNAL Booster show that about 2% of the beam is lost to the adiabatic capture process. We propose to chop the H^- beam by stripping the first electron at 38 or 53 MHz intervals (frequency depends on the plan). If successful, we will reduce beam loss, and the associated activation of components, another 2%.

2. Beam observation at first turn in the synchrotron
Currently, and with new adiabatic capture systems, the first 10 to 20 turns of beam orbits are not seen or are unreliable. If the incoming beam were chopped at the RF frequency that the beam position monitors are looking for, the beam positions could be seen. That piece of information is critical to good operation of any high intensity, high through-put accelerator. The result is a better understanding of beam instabilities and another reduction of radiation to tunnel components, not merely at injection, but as acceleration proceeds.

3. Activation of tunnel components is a show –stopper for high through-put accelerators.

How do H^- light sabers work?

H^- ions can be neutralized by knocking off the first electron. The peak photodissotiation cross section is roughly $4 \times 10^{-17}\ cm^2$. It requires 1.5 eV photons or 780 nm. Our relativistic ion beams will see our laser wavelength in a "different light". So the applied wavelength needs to shift to roughly 780 nm in the beam frame for best efficiency. That can be done by adjusting the angle of colliding or "chasing" light.
As with other statistical processes, the more photons we pour in, the more ions get cooked. As with any reaction, the longer we cook it, more ions are stripped. If the H^- beam is physically smaller, it takes less photons to strip.

So we have two basic variables plus geometric constraints. We have wavelength (plus Doppler kinematics) and cooking time. Geometric considerations are things like zigzagging the laser pulse through the ion beam. The laser pulse has a finite duration, we want a notch of finite duration, and the beam sees the light in the interaction region for a finite time. All of these plus the physical width of the ion beam set the required laser power required to make a single notch.

What are the requirements for present and planned Proton Drivers?

The present FNAL Booster could benefit from 84 notches at 38 MHz. We have 84 beam bunches in 84 RF buckets in the ring. Each 84 buckets is called a "turn". We usually inject 12 turns. So 84 notches would reduce losses a little, and let us see our first turn on beam position monitors. To notch all of it, we need 12 times 84 notches.

FNAL modelers have determined that it is best to notch 30% of the forming 38 MHz bunches, so each notch needs to be ~8 nanoseconds wide.

The proposed synchrotron Proton Driver will have an upgraded UHF linac that will spill beam into the synchrotron for 45 turns or 90 microseconds, ~2 microseconds per turn. The synchrotron RF frequency is still ~38 MHz. So we need 3420 notches.

The proposed 8 GeV linac would spill 1300 MHz bunches into (existing) 52.815 MHz Main Injector buckets. It was discovered that by reducing the ion current in the linac by 80%, the number of klystrons is greatly reduced and machine reliability greatly increased. But since the beam current is only 8 milliamps, they want to spill beam for 3 milliseconds! For this arrangement we need ~158,000 six nanosecond pulses!

Two other important considerations.

Low velocity ion beams are more subject to space charge forces.
Stripping losses from beams are minimized when done at less than 10 MeV.
Stripping at 400 MeV, 600 Mev or 8 GeV will require a carefully designed beam dump for the neutral hydrogen.

How much power is that?

Approximately 1 mJ of photons is needed to make a 99% notch in an H^- beam that is 1 mm wide provided that the IR geometry is set up so than one gets 5 or 10 nanoseconds of cooking time.

For the present we would like 84 X 1 mJ, a perfectly reasonable laser. That allows us to see first turns in the Booster.
Better is 84 notches for 12 turns at 7 Hz; a 7 Joule laser, still OK.

For the synchrotron Proton Driver plan, we need 3420 notches, at 10 Hz, 35 Joule laser.

For the 8 Gev linac, we need 158,000 notches at 0.67 Hz (the 1.5 second Main Injector cycle), a 100 Joule laser! Serious optical power!

How are we going to do that?

There are two General schemes for notching.

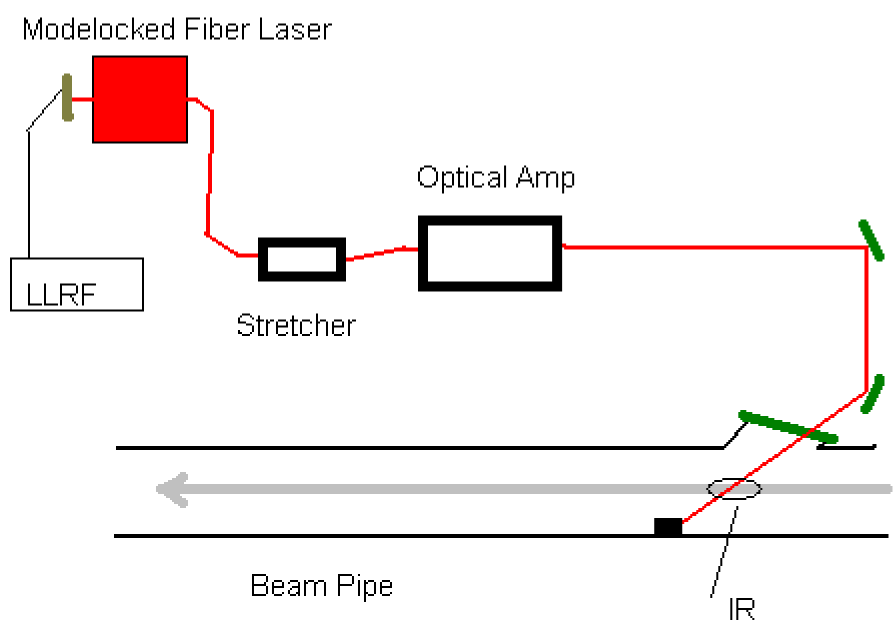
The first is an optical cavity with gain to offset losses. Since we are dealing with a billion times more photons than ions, we can reuse the laser pulse. If we suffer 10% loss per pass, we might guess that we need a gain of 1.10. So the 100 Joule laser might be a 10 Joule laser. We run a low power YAG at 15 Hz to feed a 158000 pass cavity. But how do we steer and retain optical beam quality for 158000 passes through ionized gasses (at ~10-7 torr)? The cavity length is 1/ 53 MHz. It is hard to steer invisible beams inside opaque beam pipes. This may be workable for the present Booster.

The second scheme is to generate single pulses for single passes. It takes more laser, but alignment, stability, and maintenance are greatly simplified. Some basic design goals are that this thing should operate unattended for weeks at a time, and repairs and realignment should be trivial.

A combination of multi-pass with no gain plus multiple amplifiers and perhaps multiple IRs would solve a lot of laser problems, but complicate ion beam optics.

OK, got any ideas?

Well, here is a simple plan for a start:



This is easy for a few pulses at ion velocities of 0.04c. The mode locked fiber seed laser is robust. Feedback to the 53MHz RF is something we do all the time. We typically see less than a few hundred Hz of drift per day. The stretcher broadens the pulse to save the amp and to give us the 6 nanosecond PW we want. If the amp is running at 1550 nm, we double it to 775 nm, the peak of the stripping cross section for 0.04c beam.

Can glass be doped with Nd and pulled to fiber for a mode locked fiber oscillator at 1 micrometer? That is up for discussion. We have been told that Er:glass is inefficient to pump. $5M worth of 980nm diodes is expensive.

Many people have proposed that the IR shown in the diagram can be fitted with two mirrors so that the light beam follows the ion beam, yielding a dozen passes that smears because the ion beam is moving through a prolonged (5 nsec) laser pulse. Each pass is only picoseconds of mixing time, so required photons increases, but multiple hits decreases photons required.

So now we begin to see how complex this can be. If we somehow manage to create 1 mm wide ion beams in the IR, the beam might be 10 or 20 mm wide in the other physical dimension. So the single pass IR is only that 10 to 20 mm, a very short cooking time.

The real key to high duty factor laser notching schemes is to make the H- cross section smaller than 1 mm. Then one must match kinematics and laser pulse width to obtain a desired notch length.

Here is a calculation from the early 1990's

FNAL TM1957

Laser Stripping of Relativistic H^- Ions
With Practical Considerations

R. Tomlin

This paper describes laser stripping of H- ions. Some applications are suggested for HEP including stripping 2GeV ions circulating in an accelerator with radius 75 meters where laser meets ion head on in a three meter interaction region.

Photoionization

Broad & Reinhardt calculated the photoionization cross section of H- ions.[i] Their work shows a broad photoelectric peak for 1.5 eV photons with a reaction cross section or area of $4 \times 10^{-17}\ cm^2$ for each ion. This is roughly half the area which can be calculated from the Bohr radius. In Joules it is:

$$1.5eV \times 1.602 \times 10^{-19}\ J/eV\ =\ 2.4 \times 10^{-19}\ J$$

That is the quantum energy required by a photon to kick the electron loose in the reaction $H^{-} + \lambda \to H_0 + e$. Note that the binding energy is 0.75451 eV but a more efficient reaction takes place at 1.5 eV. The "rest frame" wave length is hc/E:

$$\lambda = \frac{6.626 \times 10^{-34}\ J{\cdot}s \times 2.998 \times 10^{8}\ m/s}{2.4 \times 10^{-19}\ J}$$

$\lambda = 826nm$ for resting H- ions. Two GeV ions travel at 0.948 c. The wavelength required in the lab or laser frame for colliding beams is:

$$\lambda_{laser} = \lambda_{ion} \cdot \gamma(1 - \beta \cos\theta)$$

$$where \quad \cos\theta = 1$$

$$\beta = v/c, \qquad \gamma = 1\Big/\sqrt{1 - \beta^2}$$

$$826nm = \lambda_{laser} \cdot (3.132)(1 - 0.948)$$

$$\lambda_{laser} = 5042\ nm$$

Laser power calculation

Power calculation is a statistical game. Making something of the analogy to dice on a table, let

$$\sigma = 4 \times 10^{-17}\ cm^2,$$

the photo ionization cross section of an H- ion. If the die were n-sided, each side with area σ **,** and the area of the table top was A = nσ (analogous to the cross section of the interaction region) , the probability of the one photon landing on the one ion is: $P = \frac{\sigma}{A}$, $\quad N_\gamma = 1, \quad H = 1$

Lots of photons increases the odds of ionizing one H^{-}; $P = \frac{\sigma N_\gamma}{A}$

Lots of H^{-} ions increased the odds of interaction even more;

$$P = \frac{\sigma H N_\gamma}{A}$$

The longer one throws the dice, the more throws one gets and the better the odds;

$$P = \frac{\sigma H N_\gamma}{A}\ dt$$

Still one photon. Meanwhile the laser is delivering photons per second evenly over ion beam cross section A;

$$P = \sigma H \frac{N_\gamma}{A\,dt}\,dt$$

But laser power is defined as

$$I = N_\gamma \cdot cm^{-2} \cdot s^{-1}$$

So: $P = \sigma H I\, dt$ is the probability of stripping. The number of H^- remaining at any given time is proportional to the probability of stripping;

$dH = -\sigma H_{init} I dt$ *rearranging:*

$$\frac{dH}{H_{init}} = -\sigma I\, dt$$

To get from point **a** to point **b**:

$H = H_{init}$ $\qquad\qquad$ $H = H_{init} - dH$

t = 0 $\qquad\qquad$ t = 10 ns

→

a $\qquad\qquad$ **b**

with H = H^- left at any time t, integrate . . .

$$\int_a^b \frac{1}{H_{init}} dH = \int_a^b -\sigma I\, dt$$

$$\ln H = -\sigma I t + C$$

$$H = e^{-\sigma I t} \cdot e^{c} \qquad \textit{ions remaining}$$

H_{init} is about the only constant around, so:

$$\frac{H}{H_{init}} = e^{-\sigma I t}, \qquad \ln\left(\frac{H}{H_{init}}\right) = -\sigma I t$$

H is ions remaining. For 90% stripping $H/H_{init} = 0.10$. Nothing left to do but solve for photons per cm^2 second needed to strip 90% of the ion beam.

$$I = \frac{\ln(0.10)}{-\sigma t} = \frac{-2.303}{-4\times10^{-17} cm^2 \cdot 10\times10^{-9}\sec}$$

$$I = 5.77\times10^{24}\ \frac{photons}{cm^2 \sec ond}$$

To maintain that flux over $Area = \pi cm^2, \qquad I = \pi I_{init}$

$$I = 1.81\times10^{25}\ photons / cm^2 \sec$$

required to strip 90% of an ion beam with cross section pi cm squared.

At 5 μm each photon has energy E:

$$E=\frac{hc}{\lambda}=\frac{6.626\times10^{-34}\,Js\cdot2.998\times10^{8}\,m/s}{5\times10^{-6}\,m}$$

$$E=3.97\times10^{-20}\ Joule/photon$$

$$Joule/sec\ =\ Watt$$

$$Watts\ =\ 3.97\times10^{-20}\frac{Joule}{photon}\cdot1.81\times10^{25}\frac{photons}{second}$$ That means that the laser must deliver

$$Peak\ Power=720\,KW$$

$$Energy\ per\ pulse\ =720{,}000\,J/s\ \times10\times10^{-9}s$$

$$=7.2\,mJ$$

720KW at 5 μm for the 10 nsec that a bunch is in the 3 meter interaction region to get 90% stripping.

There are so many more photons than ions that photon depletion is not a problem. This photon flux will strip 90% of any intensity ion beam obtainable. The intensity profiles of the colliding laser and ion beams are assumed to be similar. The same flux of chasing photons would be required to strip 90% of the ions. The wavelength required is 133 nm.

Care must be taken to define the interaction region and pulse length so that ions don't see photons in magnetic fields.

Power can be reduced by lengthening the IR or increasing the number of times the ion beam comes round through the IR.

Power levels required vs % ions stripped per πcm^2 are given in the following table:

Table I

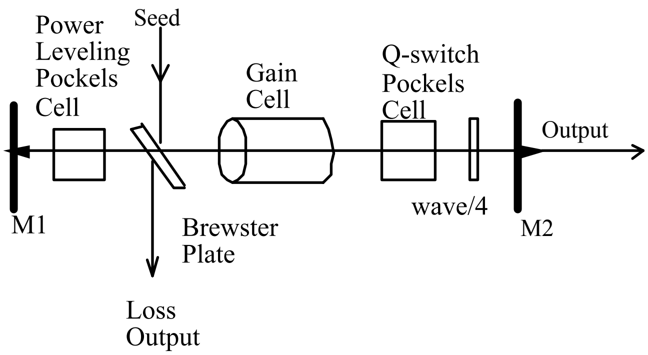
Watts Peak power	% stripped	Joules Avg power
15,871	5	0.00015871
32,602	10	0.00032602
69,048	20	0.00069048
110,367	30	0.00110367
158,067	40	0.00158067
214,484	50	0.00214484
283,532	60	0.00283532
372,551	70	0.00372551
498,016	80	0.00498016
712,500	90	0.007125
926,985	95	0.00926985
1,425,001	99	0.01425001
2,137,502	99.9	0.02137502
4,275,005	99.9999	0.04275005

Total power over area

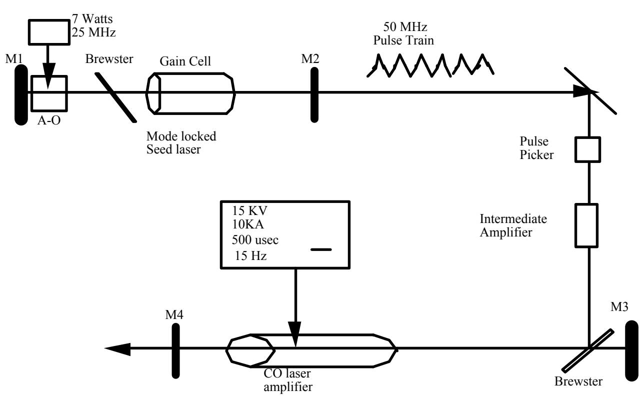
How to Generate The 5 μm Light

In a practical application up to 50% of the beam power could be lost in optics and overhead needed to maintain 90% stripping power level for 10 nsec. High average powers requirement arise because there may be 84 to 100 bunches every 67 milliseconds. Even more average power is required if one wants to extract any combination of bunches, or do 99% stripping. Experts [ii] who build big custom lasers say these power levels, PW = 500 usec, PRF = 15 Hz, are achievable. The long PW is made possible by enriching the gas mixture with nitrogen to enhance the nitrogen tail. Output is not flat over long pulses so some power overhead must be built in.

The generation of very fast pulses[iii] with good rise and fall times is possible and mirror/shutter pulse string generation[iv] schemes exist. The pulses are best manufactured at low power. Pockels cells with pulse drivers exist which can gate in 18 nsec and run continuously at 20 MHz at 1 to 2 microns. 100MHz units are expensive. 5 μm units should be achievable. The seed pulses are then fed to a large CO laser. Much work has been done on gas lasers. There are several usable articles in the literature[v],[vi],[vii],[viii]. LSDI people say that LN2 would be used to cool a CO laser[ix]. Pulse lengths of 2 to 4 ms have been observed[x]. An amplifier might look like this:[xi]



The whole system might look like this:



A more efficient system may be a mode locked seed driving an amplifier.
The seed oscillator would be programmed to provide only the pulses required. The high power stage does not need to sustain megawatts for 500 usec. Pulses can be shaped with EO devices or mirrors whose reflectivity is altered with a second laser.

While an IR laser works for colliding beams, 135 nm is required to chase a 2 GeV beam. While some work is being done there[xii] and into X-rays[xiii], no one is generating 30MW peak power. CLBO can be used to generate 190 to 266 nm[xiv]. 150 nm Lasers seem to be the limit in 1995.

The laser beam must collide or chase the proton beam at zero degrees in order to pick the portion of particle phase space desired. If the laser crossed the proton beam all of some space would be stripped. A μm laser could be used but would require 187mJ per bunch.

The 5 μm laser requires only 7.2 joules per bunch (90% stripping)

Laser Practice

Applications for laser stripping of ions exist at FNAL today.

Quality of 400 MeV beam can be determined with a laser. We don't have an easy or accurate way to assess LINAC beam quality today.

Partial Booster batches could be created by stripping at 750 KeV.

Beam diagnostics are possible at the 66 MeV NTF port.

Beam synched laser pulse provides the ability to kick out any bunch in the machinebefore injection to make a hole for extraction kicker rise time. We presently smear 1.5 bunches on the extraction septa, limiting the integrated beam which can be provided to MR while staying within RAD safety limits. This can be accomplished with a commercial 1 μm [10],[xv],[xvi] laser at a cost less than gap preserving RF cavities.

Lasers can be applied to these four applications at a cost less than a high end oscilloscope.

Development of one of the smaller systems would train us to manipulate light in a bigger way. Many techniques and modes of thinking developed at 1 μm can be applied at 5 μm. Big differences appear in performance of materials.
1 μm is mature and cheap. 5 μm has seen very little developement.

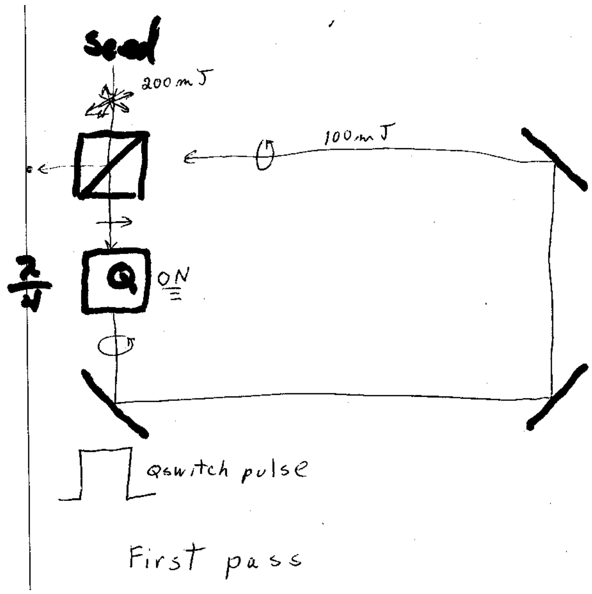
Is emittance carving possible?

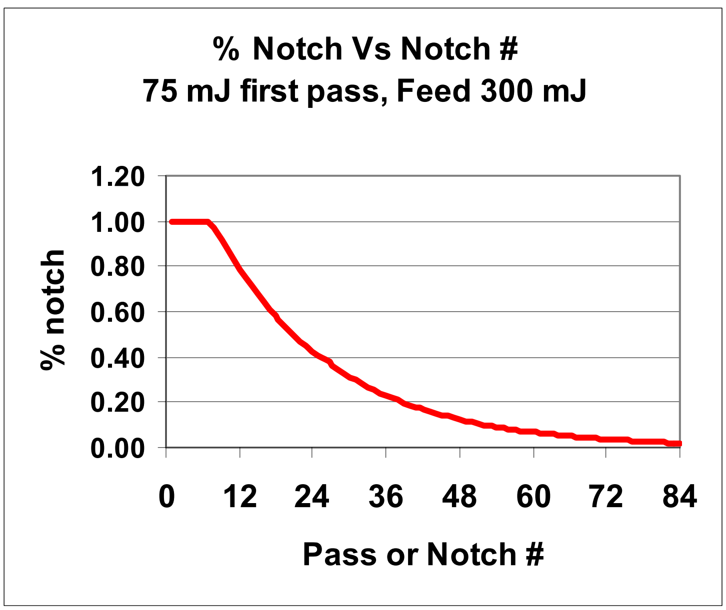
Stripping a single bunch is easy; 14 mJ. Stripping 84 bunches can be done at some expense; 1.2J. Stripping 84 bunches in any combination (every 7th) at 15 Hz needs power levels not easily attainable at 5 μm.

This is the upstream end of the FNAL linac. One can see the beam through the window. The plan is to recirculate a ~100mJ laser pulse through the beam via a 7.8 meter optical cavity. The cavity would be folded to the right of the window and lay right on the blue linac RF cavity.

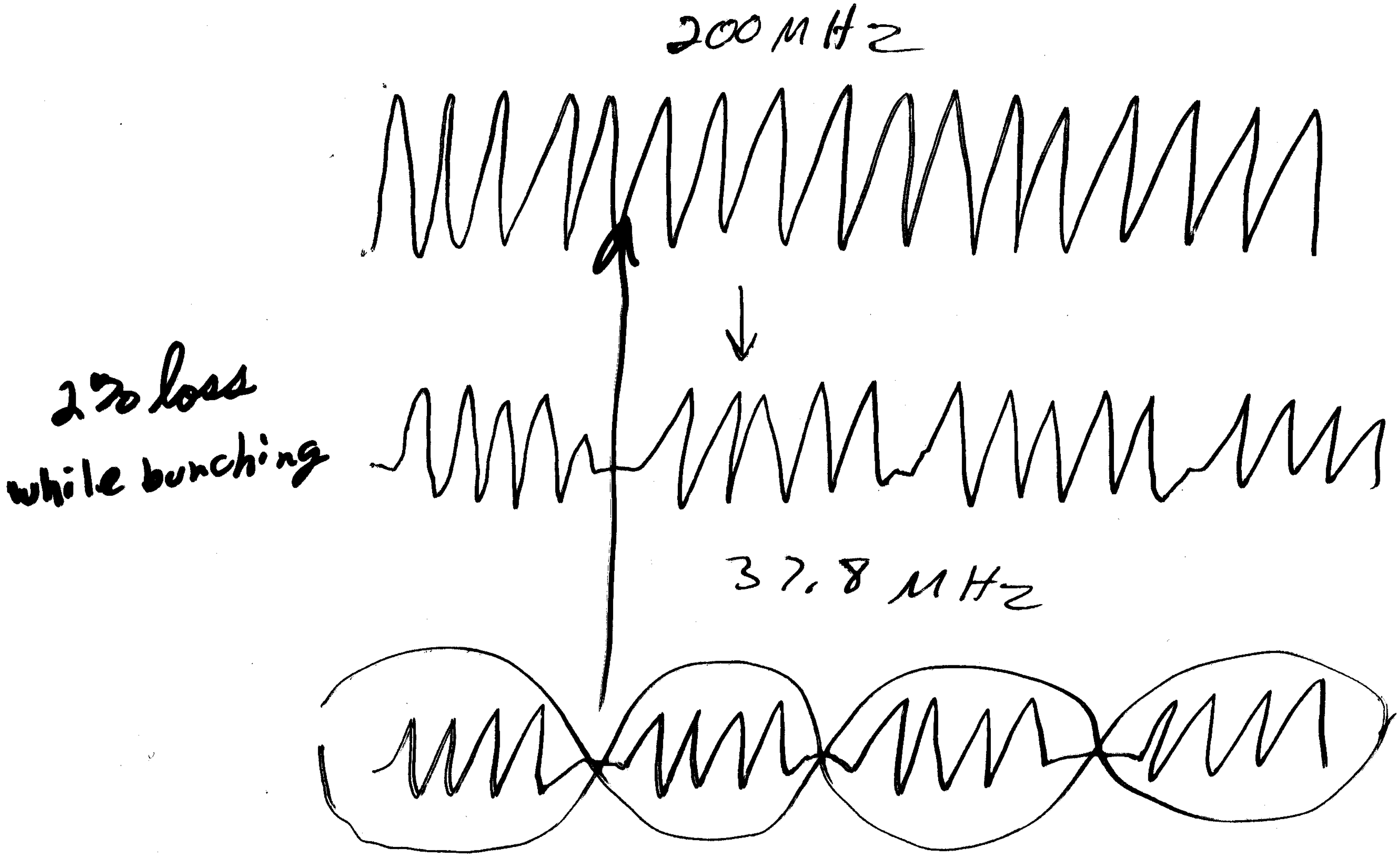
A simple way to wake up the Booster BPM's on the first turn would be to make 40 to 80 notches in the linac beam at PRF = 37.95 MHz.

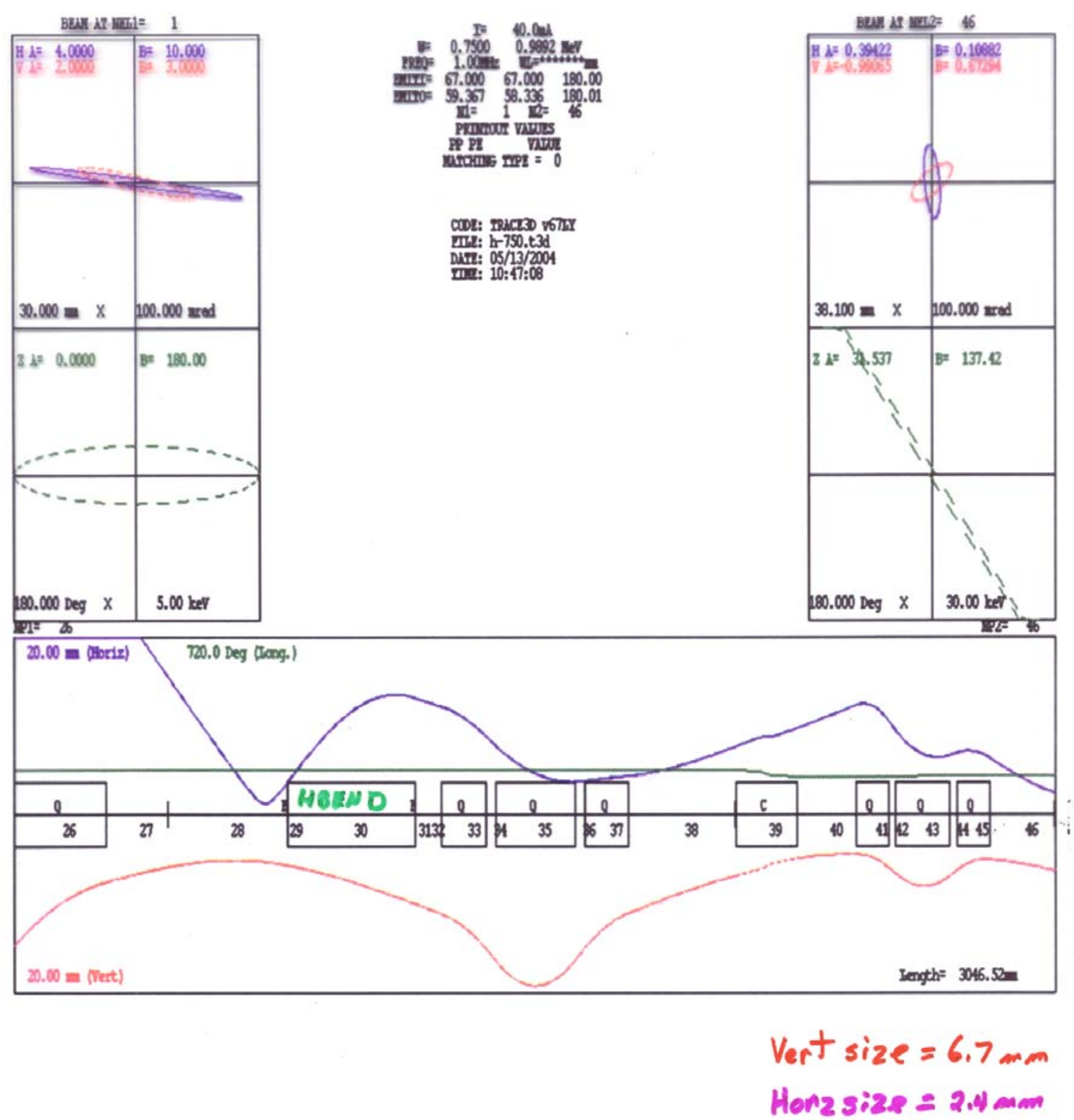
The basic optical cavity is as follows; A seed pulse is injected via a cube beam splitter, The Q-switch is on. The Q switch turns off once the 6 nsec laser pulse clears it. The laser pulse is captured in the cavity.





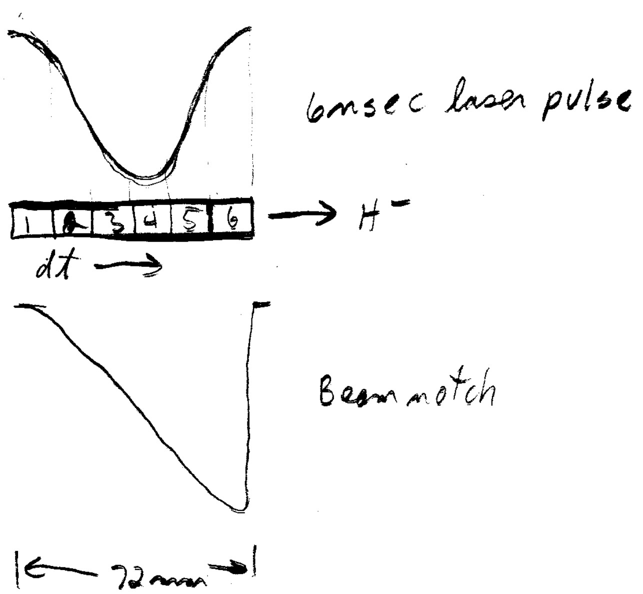
Without an intracavity optical amplifier, the Notch depth would decrease due to losses on cavity optics, assumed to be 5% here. It is felt that this circuit alone would allow Booster BPMs to see the first turn, and thus allow closure. That would reduce higher energy losses in the Booster.
Cavity losses could likely be cut in half in practice, even with focusing optics, and all 84 bunches would be clear.

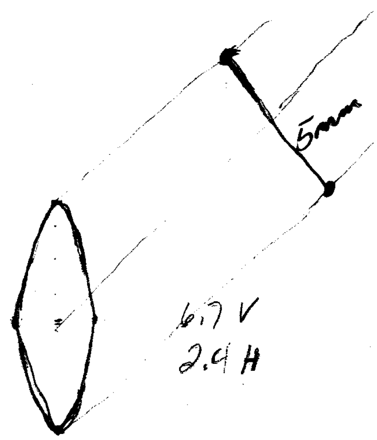

200 MHz
2% loss
while bunching
37.8 MHz



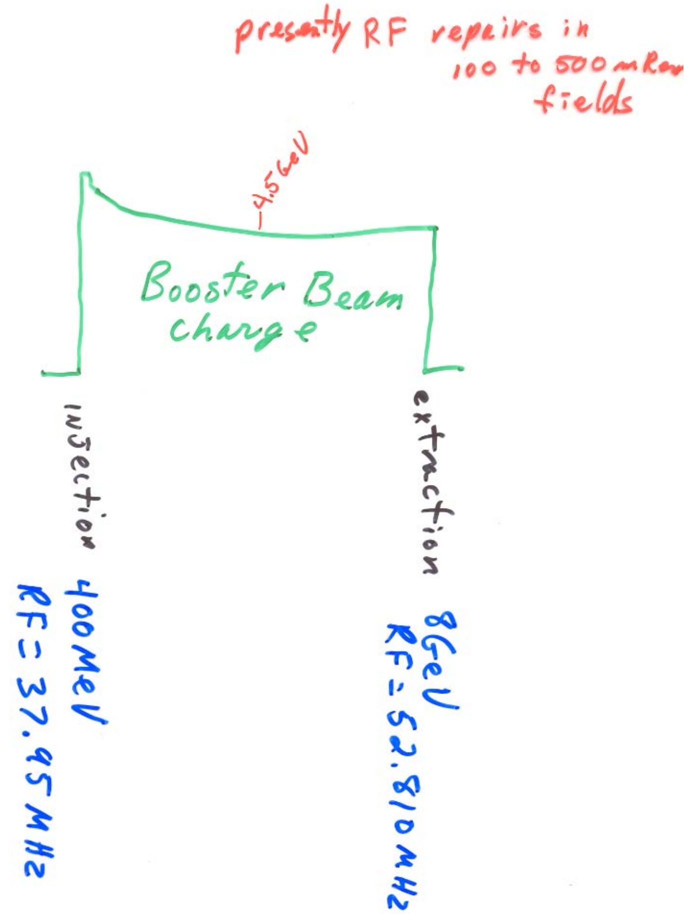
This is our best guess of beam sizes at 750 KeV, Courtesy of M. Popovich. The farthest right is the beam as it enters the first linac DTL, and is the size where the laser IR would be.

$.95^{84} = .0135 \Rightarrow 2.7\,mJ$ on 84th notch

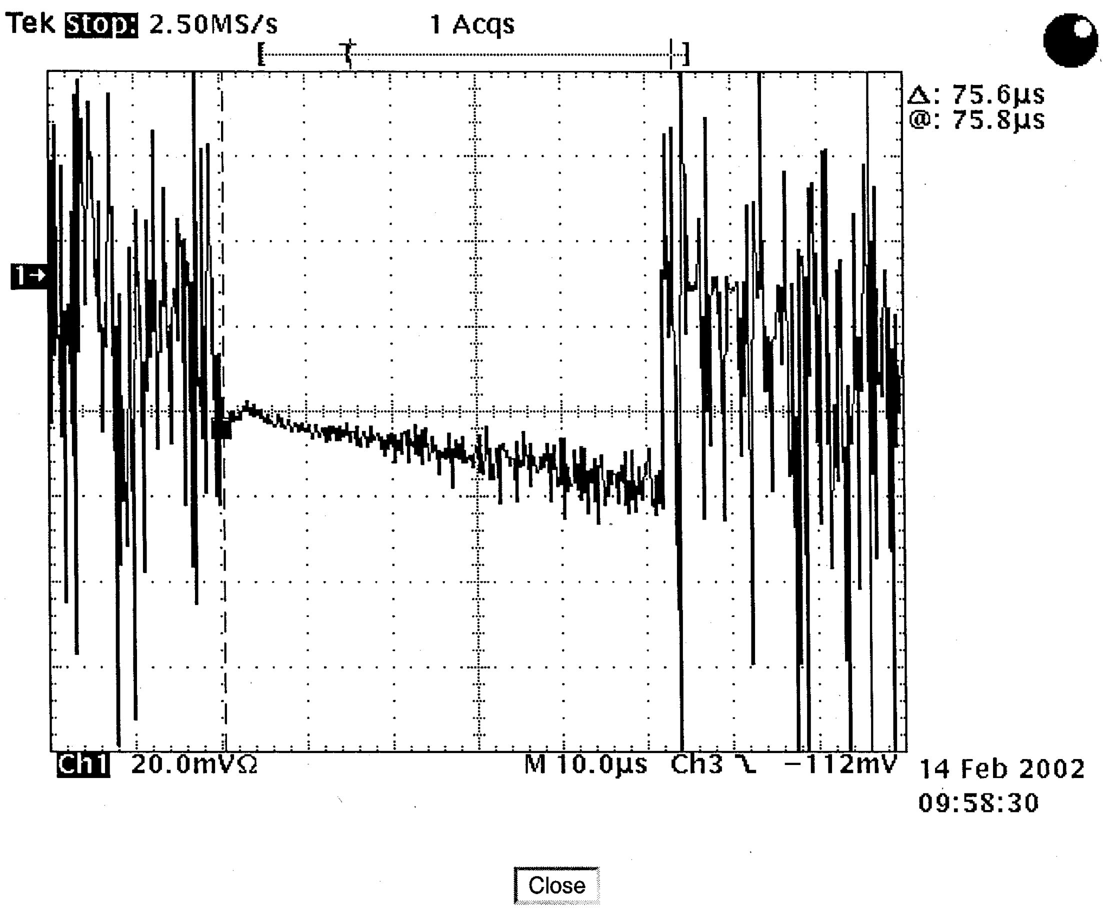




We would hit the H- beam at 45 degreess, yielding a 5 mm ross section.



200 MHz linac bunches are injected to Booster and captured into 37.95MHz bunches with a ~2% beam loss.



Horz BPM TANK 2 OUT

A worry to long pulse length linacs is the fast transverse motion shown here during a typical FNAL Linac spill. Vacuum instability causes these oscillations to become objectionable by 50 microseconds. This could be serious for 0.1 to 3 millisecond spills.

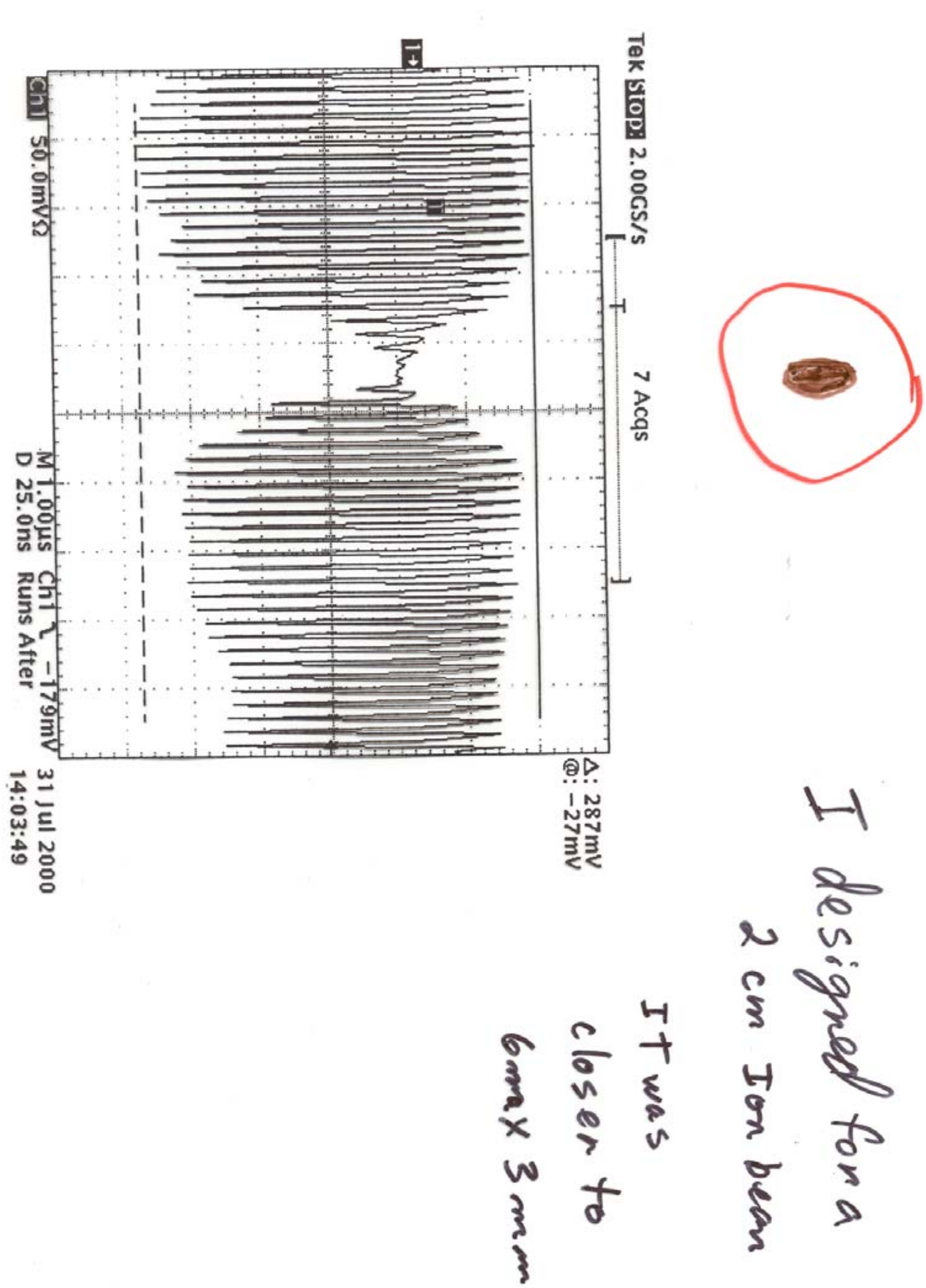


Figure 2: 200 MHz bunch signal from a BPM plate at the end of RF tank two in FNAL Linac shows a 99% notch. This is a 200 mJ, 5 ns pulse crossing at an angle.

This is an actual notch, courtesy of R.Tomlin The 2.4 cm 200 mJ laser beam is overkill. If all the laser had been sized to fin into the beam cross section, the required enegy would have been close to the calculated value of 69 mJ. This notch was created at approximately point # 38 in the Trace-3D plot shown above.

The PAC01conf paper follows. It is basically a repeat of TM1957 from 1995.

Ion Beam Notcher Using A Laser

R. Tomlin, FNAL, Batavia, IL60510, USA

Abstract

The FNAL LINAC will soon be asked to produce beam at 7.5 Hz. FNAL LINAC extraction involves sweeping the H-minus beam over a Lambertson magnet. The higher repetition rates are expected to activate the Lamberston magnet. A pulsed laser has been installed to make a notch in the beam so that beam will not sweep over the magnet.

1 INTRODUCTION

The first electron on H^- has a binding energy of approximately 0.74 eV. We use an Nd:Yag laser having 1.165 eV photons, $\lambda = 1064\,nm$, to ionize hydrogen ions that are streaming out of the 750 Kev source at 0.04c.

2 GEOMETRY

2.1 General Layout

The H^- ions are separated from photoionized H^0 by steering through a subsequent magnetic field. In this case we use a 90 degree dipole. Doglegs are ideal design tools for these reactions because the light can be made to collide or chase relativistic beam. That affords the option of wavelength shifting the laser to the particle frame, allowing a wider range of laser options.

2.2 The Interaction Region

Laser interactions with relativistic beams or beams that will be accelerated can be thought of as statistical chemical processes. Stripping is directly proportional to time that the ion beam remains in the light and the number of photons in the interaction region. For beam with velocity 0.04c the mixing time is essentially the laser pulse width. One can then run the laser pulse along a desired ion beam path by shooting across the ion beam or the ion beam can be "four-bumped" and the laser applied in colliding or following mode. The following mode allows the laser and the H^0 to share a common dump. The colliding mode was used in this application. The inside surface of an existing multiwire can serves the laser dump. H^0 land on the vacuum window that admits the laser pulse.

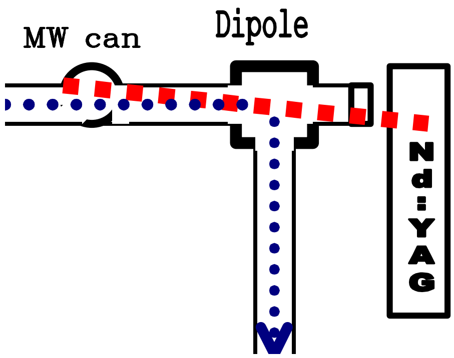


Figure 1

2.2 The light

A Surelite I-20 laser fires 400 mJ, 5 nanosecond pulses at 15 Hz. Pulse peak power is more than 80 megawatts and average power is 6 watts. It is mounted on a 2 x 3 foot optical table. The 6 mm diameter beam is directed with two 1 inch mirrors to a 4X expander on an X-Y stage. The expanded beam is routed via 3 motorized mirrors through a coated vacuum window. These 2 and 3 inch mirrors can change the horizontal position, horizontal angle and vertical angle of the laser beam. The expanded is about 24 mm in diameter to cover the largest ion beam width found in the interaction region.

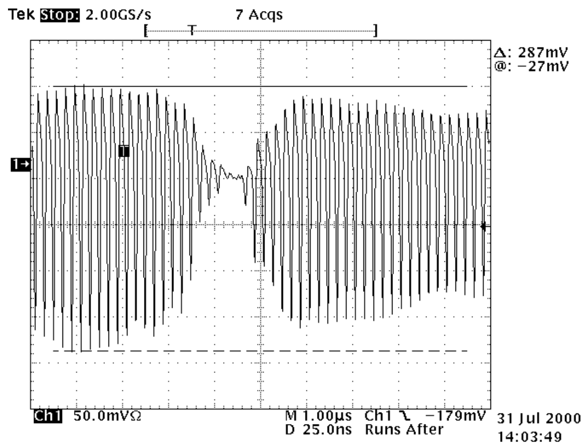
2.3 Alignment

Optics were assembled and tested in an interlocked laser lab. The range of angles vs. stepper motor counts was measured over a 4 foot path. The beam was set midrange in all three motor axis. The installation is in a public area and is completely shrouded. No laser beam can be used for spotting or alignment. The shrouded unit was then coupled to the vacuum window on the beam line and aligned with a ruler and dead reckoning. A 88% notch was seen on the beam on the first try.

2.4 The optics

Mirrors have 1064 nm coatings rated for 10 J/cm^2. The beam expander is rated at 8 J/cm^2. The laser has a 6 mm rod that produces diffraction rings of 30% depth in the near field. The net result is that we burned diffraction patterns in mirror coatings while testing at 450 mJ in 4.5 nsec pulses at 20 Hz. The fix was to reduce power, go 15 Hz, and rotate a good spot on the mirror into the beam.

The vacuum window is one inch BK-7 glass AR caoted for 1064 nm and mounted with O-rings in a 3 inch I.D. vacuum flang.



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3 WAVE LENGTH AND POWER CALCULATIONS

3.1 Laser wavelength calculation

Broad & Reinhardt calculated the photoionization cross section of H- ions. [1] Their work shows a broad photoelectric peak for 1.5 eV photons with a reaction cross section or area of $4\times10^{-17} cm^2$ for each ion. This is roughly half the area which can be calculated from the Bohr radius. $0.7545\ eV \times 1.602\times10^{-19}\ J/eV = 1.2\times10^{-19}\ J$

That is the quantum energy required by a photon to kick the electron loose in the reaction $H^- + \lambda \rightarrow H_0 + e$. Note that the binding energy is 0.75451 eV but the reaction becomes more efficient nearer 1.5 eV. The "rest frame" wave length is hc/E:

$$\lambda = \frac{6.626\times10^{-34}\ J\cdot s \times 2.998\times10^{8}\ m/s}{1.2\times10^{-19}\ J}$$

$\lambda = 1643\ nm$ for resting H- ions. 750 KeV ions travel at 0.04 c. The wavelength required in the lab or laser frame for colliding beams is:

$$\lambda_{laser} = \lambda_{ion} \cdot \gamma(1-\beta \quad \cos \quad \theta)$$

$$where\ \cos\theta = 1$$

$$\beta = v/c, \quad \gamma = 1\Big/\sqrt{1-\beta^2}$$

$$1643\ nm = \lambda_{laser} \cdot (1.008)(1-0.04)$$

$$\lambda_{laser} = 1579\ nm$$

A 1064 nm laser will work.

3.2 Laser power calculation

Power calculation is a statistical game. Making something of the analogy to dice on a table, let $\sigma = 4\times10^{-17} cm^2$, the photo ionization cross section of an H- ion. If the die were n-sided, each side with area σ**,** and the area of the table top was A = nσ (analogous to the cross section of the interaction region), the probability of the one photon landing on the one ion is:

$$P=\frac{\sigma}{A}, \quad N_\gamma=1, \quad H=1$$

Lots of photons increases the odds of ionizing one H^-; $P=\frac{\sigma N_\gamma}{A}$

Lots of H^- ions increased the odds of interaction even more;

$$P=\frac{\sigma H N_\gamma}{A}$$

The longer one throws the dice, the more throws one gets and the better the odds;

$$P=\frac{\sigma H N_\gamma}{A}dt$$

Still one photon. Meanwhile the laser is delivering photons per second evenly over ion beam cross section A;

$$P=\sigma H\frac{N_\gamma}{Adt}dt$$

But laser power is defined as

$$I = N_\gamma \cdot cm^{-2} \cdot s^{-1}$$

So: $P=\sigma H I dt$ is the probability of stripping.

The number of H^- remaining at any given time is proportional to the probability of stripping;

$dH = -\sigma H_{init} I\, dt$ rearranging :

$$\frac{dH}{H_{init}} = -\sigma I dt$$

To get from point **a** to point **b**:

$H=H_{init}$ $H=H_{init}-dH$

t = 0 t = 5 ns

a **b**

with H = H^- left at any time t, integrate . . .

$$\int_a^b \frac{1}{H_{init}}dH=\int_a^b -\sigma I dt$$

$$\ln H=-\sigma I \quad t+C$$

$H=e^{-\sigma I t}\cdot e^{c}$ ions remaining

H_{init} is about the only constant around, so:

$$\frac{H}{H_{init}}=e^{-\sigma I t}, \qquad \ln\left(\frac{H}{H_{init}}\right)=-\sigma I t$$

H is ions remaining. For 90% stripping $H/H_{init}=0.10$. Nothing left to do but solve for photons per cm^2 second needed to strip 90% of the ion beam during a 5 nanosecond laser pulse.

$$I=\frac{\ln(0.10)}{-\sigma t}=\frac{-2.303}{-4\times10^{-17}cm^2\cdot 5\times10^{-9}\sec}$$

$$I=1.15\times10^{25}\frac{photons}{cm^2 second}$$

To maintain that flux over an area covering a 2 cm circle:

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

$I = 3.62 \times 10^{25}$ photons/ cm^2 sec

are required to strip 90% of an ion beam with cross section pi cm squared.

At 1 μm each photon has energy E:

$$E=\frac{hc}{\lambda}=\frac{6.626 \times 10^{-34}\ J\,s\cdot 2.998 \times 10^{8}\ m/s}{1\times 10^{-6}\ m}$$

$E = 1.88 \times 10^{-19}\ Joule / photon$

Joule/sec = Watt

$\text{Watts} = 1.88 \times 10^{-19}\ \frac{Joule}{photon} \bullet 3.62 \times 10^{25}\ \frac{photons}{second}$

Peak Power = $6.8\ MW$

Energy per pulse $= 6795998\ J/s \times 5 \times 10^{-9}\ s$

$= 34\ mJ$

That means that the laser must deliver 6.8MW at 1 μm for the 5 nsec that a laser pulse bathes the interaction region to get 90% stripping.

There are so many more photons than ions that photon depletion is not a problem. This photon flux will strip 90% of any intensity ion beam obtainable. The intensity profiles of the colliding laser and ion beams are assumed to be similar.

Care may be taken to define the interaction region and pulse length so that ions don't see photons in magnetic fields.

Multiple reflection cavities tend to be unstable. Very careful consideration must be given to system geometry, keeping in mind that to get more stripping, the ions must remain in the photon brew longer or the photon brew must be stronger.

Laser pulses can be reused if stored until needed. We have proposed a storage time of 2.22 usec in a four pass bow-tie cavity some 665 meters long. Large Pockel's cells would shuttle the pulse to and from the delay line. A disk gain section would restore optical losses. The 15 Hz YAG could then drive our desired bursts of 12 pulses at 15 Hz.

Power levels required vs. % ions stripped per πcm^2 are given in the following table:

Table 1: Laser power vs. stripping

Peak Watts	**% Stripped**	**millijoules Average Energy**
671182	20	3
2084883	50	10
13851665	99	69
20777498	99.9	103

REFERENCES

[1] John T. Broad & William P. Reinhardt, "One and two electron photoejection from H-: a multichannel J-matrix calculation" Phys. Rev. A, Vol 14, N0. 6, Dec 1976, page 2159.

[2] Ray Tomlin, "Laser Stripping of Relativistic H^- Ions With Practical Considerations" FNAL TM1957.