Fermi National Accelerator Laboratory

FERMILAB-TM-1957

Laser Stripping of Relativistic H^- Ions with Practical Considerations

R. Tomlin

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

December 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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.[1] 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 $H^{-} + \lambda \rightarrow H_0 + e$. 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:

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

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

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

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

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

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

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

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

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

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

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

$H = H_{init}$ t = 0 $\qquad$ $H = H_{init} - dH$ t = 10 ns

a → **b**

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

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

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

$H = e^{-\sigma I t} \cdot e^{c}$ *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.

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

$$I = 5.77\times10^{24} \frac{photons}{cm^2 \, second}$$

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:

$$E = \frac{hc}{\lambda} = \frac{6.626\times10^{-34} \, J\,s \cdot 2.998\times10^{8} \, m/s}{5\times10^{-6} \, m}$$

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

$Joule / sec = Watt$

$$Watts = 3.97\times10^{-20} \frac{Joule}{photon} \cdot 1.81\times10^{25} \frac{photons}{second}$$

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

$$Average\ power = 720{,}000 \, J/s \times 10\times10^{-9} s = 7.2 mJ$$

That means that the laser must deliver 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

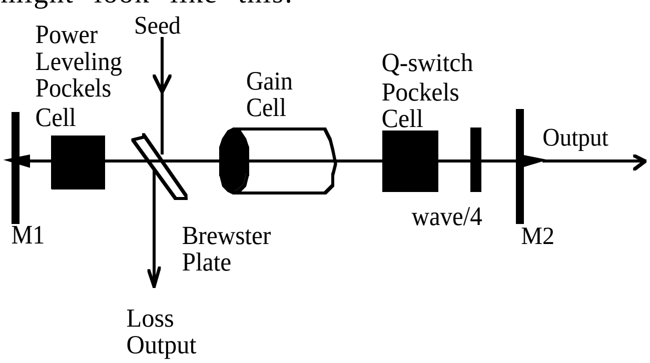
Watts Peak power	% stripped	Joules Avg power
15,871	5	0.00015871
32,602	10	0.00032602
69,048	20	0.00069048
110,367	30	0.00110367
158,067	40	0.00158067
214,484	50	0.00214484
283,532	60	0.00283532
372,551	70	0.00372551
498,016	80	0.00498016
712,500	90	0.007125
926,985	95	0.00926985
1,425,001	99	0.01425001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

Total power over area

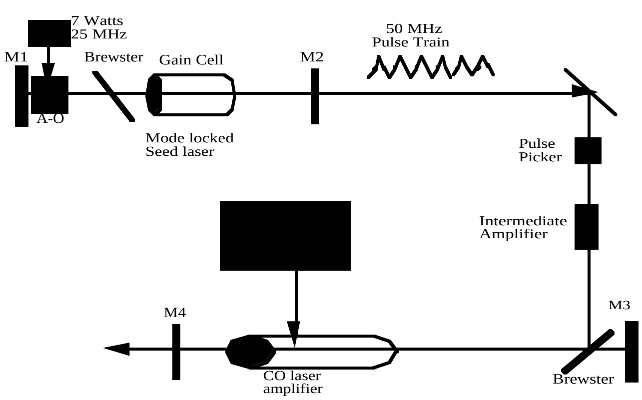
How to Generate The 5 μm Light

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 [2] 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[3] with good rise and fall times is possible and mirror/shutter pulse string generation[4] schemes exist. The pulses are best manufactured at low power. Pockels cells with pulse divers 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[5,6,7,8]. LSDI people say that LN2 would be used to cool a CO laser[9]. Pulse lengths of 2 to 4 ms have been observed[10]. An amplifier might look like this:[11]



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[12] and into X-rays[13], no one is generating 30MW peak power. CLBO can be used to generate 190 to 266 nm[14]. 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 [10,15,16] 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 1μm can be applied at 5 μm. Big differences appear in performance of materials. 1μm is mature and cheap. 5μm 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.

---

[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] Laser Systems Devices, Inc., Alexandria, VA. Tel: (703)-642-5758,

[3] ogorelsky et all, "Subnanosecond Multi-Gigawatt CO2 Laser", IEEE Journal of Quantum Electronics, Vol. 31, NO. 3, March 1995 pp 556-566.

[4]A.M. Sessler, LBL, in a talk at FNAL on gamma-gamma colliders, 7/13/95.

[5] Zhuang et all, "GW-level High Power CO2 Laser System", in Lasers and Particle Beams (1992), Vol., 10, NO. 3, pp. 413-419.

[6] P. Persephonis et all, "The Inductance and Resistance of the Laser Discharge in a Pulsed Gas Laser", IEEE Journal of Quantum Electronics, Vol. 31, NO 3, March 1995, page 573.

[7] P. Persephonis et all, "The Influence of the External Circuit on Arc-Discharge of a Spark Gap: Its Application to a Pulsed Gas Laser", IEEE Journal of Quantum Electronics, Vol. 31, NO 3, March 1995, page 567.

[8] Rupert Tkotz et all, "Pseudospark Switches-Technological Aspects and Applications", IEEE Journal of Quantum Electronics, Vol. 31, NO 3, March 1995, page 309.

[9] Svelto, Orazio, Principles of Lasers, 3rd ed. 1989, Olenum Press, N.Y.

[10] D.B. Cohn, "CO TEA Laser at 77 degrees K" Appl. Phys. Lett., Vol. 21, No. 8, 15 October 1972.

[11] One of many inputs by Alan Fry.

[12] "Novel dyes alter the frequency of light", Science News, June 3, 1995, page 343 and the June 1 NATURE.

[13] "Lasing turned upside down",Science News, September 30, 1995, page 223.

[14] Synoptics, Charlotte, NC., (704)-588-2340

[15] Conoptics makes fast modulator drivers (203)-743-3349

[16] New Focus makes fast modulators (408)-980-8883

Interaction makes Ge 25 MHz 5 μm A-O modulators (708)-547-6644

II-VI makes CdTe 5 μm E-O modulators, half-wave voltage is 2500V. Optically bias with external rotated waveplates. Dc bias not good for CdTe (412)-352-1504