Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research B 261 (2007) 106–109
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Picosecond ion pulses from an EN tandem created by a femtosecond Ti:sapphire laser

K.D. Carnes *, C.L. Cocke, Z. Chang, I. Ben-Itzhak, H.V. Needham, A. Rankin

James R. Macdonald Laboratory, Kansas State University, Department of Physics, Cardwell Hall, Manhattan, KS 66506, United States

Available online 3 April 2007

Abstract

As the James R. Macdonald Laboratory at Kansas State University continues its transformation from an ion collisions facility to an ultrafast laser/ion collisions facility, we are looking for novel ways to combine our traditional accelerator expertise with our new laser capabilities. One such combination is to produce picosecond pulses of stripping gas ions in the high energy accelerating tube of our EN tandem by directing ~100 fs, sub-milliJoule laser pulses up the high energy end of the tandem toward a focusing mirror at the terminal. Ion pulses from both stripping and residual gas have been produced and identified, with pulse widths thus far on the order of a nanosecond. This width represents an upper limit, as it is dominated by pulse-to-pulse jitter in the ion time-of-flight (TOF) and is therefore not a true representation of the actual pulse width. In this paper, we describe the development process and report on the results to date. Conditions limiting the minimum temporal pulse width, such as tandem terminal ripple, thermal motion of the gas and space charge effects, are also outlined.

PACS: 39.10.+j; 29.25.Ni; 52.59.Af

Keywords: Accelerator; Laser; Ion; Pulse

1. Introduction

The James R. Macdonald Laboratory is uniquely positioned to combine our longstanding expertise in ion sources and accelerators with our newly developed capabilities in state-of-the-art ultrafast, intense lasers. Over the last two years we have been developing a new experimental tool by using our femtosecond Ti:sapphire laser system to ionize stripping gas in our EN Tandem van de Graaff accelerator. Our ultimate goal is to achieve MeV ion bunches on the order of a few tens of picoseconds in width that are automatically synchronized to the laser. These energetic, narrow bunches of ions could find use in such areas as time-dependent charged particle diffraction [1,2], where the greater penetrating power and smaller de Broglie wavelength of light ions as compared to electrons would be beneficial. Very narrow time bunches of ions would also alleviate some of the duty cycle mismatch between ion and laser beam pulses that make laser-assisted charge transfer collisions so difficult to study experimentally [3,4].

2. Construction details

Our experience in delivering ion beams to various target areas in the laboratory has stood us in good stead in developing a distributed laser transport system. From a central laser room, the pulsed laser beam is already delivered to several experiments throughout the laboratory. It was therefore relatively straightforward to bring the laser beam to the tandem. A small optical table has been mounted on the 90° analyzing magnet stand which supports a mirror, irises and a variable neutral density filter to control the power and position of the laser beam as it enters the beamline through a quartz window on the 0° port of the analyzing magnet.

* Corresponding author. Tel.: +1 785 532 2662; fax: +1 785 532 6806.
E-mail address: kdc@phys.ksu.edu (K.D. Carnes).

0168-583X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2007.03.068

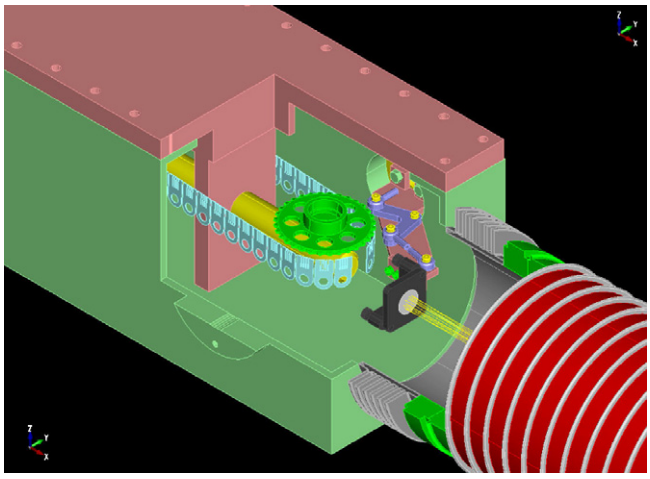

Fig. 1. Focusing mirror inside stripper box.

A focusing mirror was installed inside the stripper box at the terminal of the tandem (see Fig. 1). A remote-control linear motion feedthrough operates a gear assembly that either extends the mirror into the path of the laser beam or folds it back out of the way for standard tandem operation.

3. Limitations on achievable pulse widths

Several factors limit the minimum temporal pulse width we can achieve with the current configuration of our EN tandem. Our initial goal is to achieve these limits before affecting any major changes in the accelerator to further reduce the time spread. In the calculations that follow, a test case of helium stripping gas with 3 MV on the tandem terminal will be used, since it is likely that some of our first experiments will involve helium ions. Our laser beam has a 790 nm central frequency, and we currently use a 25 cm focusing mirror, which means that the focal point is approximately 20 cm into the third accelerating tube. Given a 1 cm diameter of the unfocused laser beam, the radius of the beam at the focus is 12.4 μm and the Rayleigh range is 0.62 mm. The ion TOF is measured at a detector 11 m downstream from the exit of the final tandem acceleration tube.

At room temperature, the $\frac{1}{2}kT$ energy of the stripping gas along the beam direction is ~13 meV. This produces a spread in the ion pulse TOF of about ±42 ps for He. The length of the focal volume along the beam is generally taken to be twice the Rayleigh range, i.e. the confocal parameter. The effect of this extended source can be removed by setting the drift length of the ions to twice the acceleration length. For the particular position of our detector, which is not quite at this optimal location, we can expect a temporal pulse spread due to the extended focal volume of about ±26 ps.

We have been unable to calculate a reliable estimate of the space charge effect on temporal pulse width. A simulation using SIMION [5] indicates that the TOF spread will be less than that due to thermal broadening if fewer than 200,000 ions are produced in each pulse. On the other hand, a modification of a time-dependent fluid model developed by Qian and Elsayed-Ali [6] indicates a time spread proportional to the number of ions, with 100,000 ions giving rise to a spread of several hundred picoseconds. We will have to examine this experimentally, looking for a variation of the jitter with laser intensity or gas pressure.

Currently, the largest known contribution to temporal pulse width is from the terminal-voltage ripple of the tandem. The ripple is roughly 800 V_{p-p} and gives rise to a pulse-to-pulse jitter of about ±100 ps. We will ultimately need to find some way to either remove or compensate for this jitter. Since the primary ripple has frequencies at 60 Hz and 400 Hz, this jitter only shows up between pulses of our 1 kHz laser. Single-shot measurements of the pulse width should not be affected.

4. Effect of the Dowlish spiral inclined field tubes

Early on in our development we used SIMION simulations to confirm that the existing accelerating tube configuration in our tandem was unsuitable for accelerating ions produced at rest. The Dowlish spiral inclined field tube in which the ions were produced has a transverse electric field, giving the ions enough transverse velocity to cause them to collide with the tube wall before successfully exiting the tandem. We replaced our #3 (out of 4) Dowlish tube with one of the HVEC inclined field tubes removed from the tandem in 1990 when the Dowlish tubes were installed. The first 22 planes of the old #1 inclined field tube are non-inclined and thus suitable for accelerating ions from rest. SIMION simulations predicted that the combination of an inclined field tube in the #3 position and a spiral tube in the #4 position should both allow us to extract the ions and not adversely affect the acceleration of normal ion beams from the negative ion sources. This has turned out to be the case, although now our maximum tandem voltage is 6 MV instead of 7 MV due to the age and different composition of the old HVEC tube.

5. Status

We have obtained a large ion yield for a number of different ion species, identified by their different TOF's to a silicon surface barrier detector placed just before the analyzing magnet. We inserted the detector into the beamline far enough to detect ions (steered to one side of the beam pipe) but not so far as to block the laser beam traveling upstream towards the terminal mirror. The amplified and discriminated detector signal was fed into a CAEN V1290 VME multi-hit time-to-digital converter (TDC), which has 25 ps/channel resolution. The zero time reference signal was obtained from a photodiode mounted on our optical table detecting reflected laser light. The multi-hit nature of the TDC was critical because of the numerous different ions produced by each 400 μJ laser pulse. Our

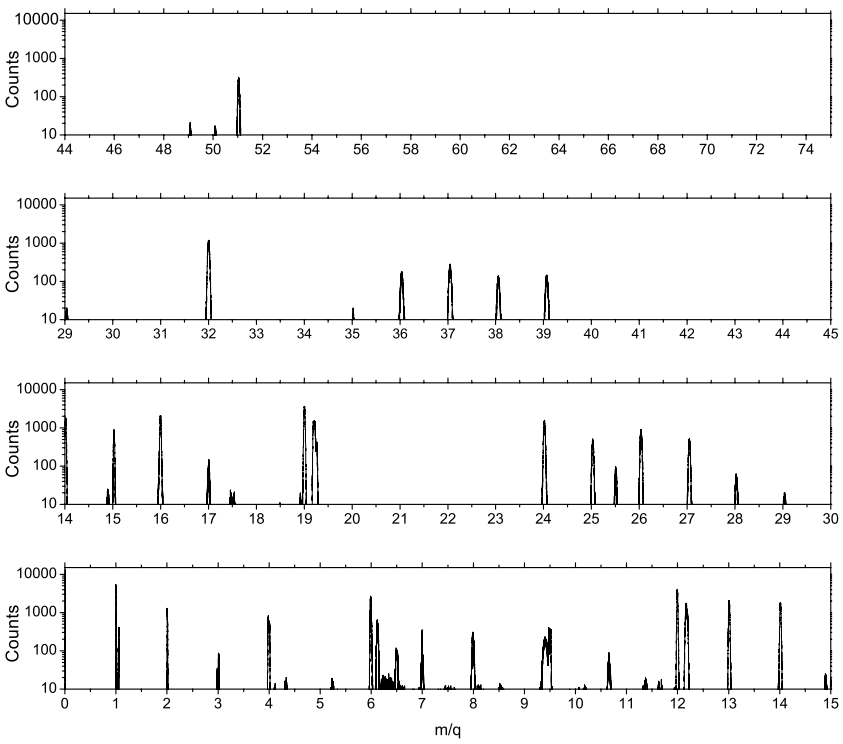

Fig. 2. Four hundred microJoule laser on background gas. Double peaks at $m/q = 12$ and 19 are instrumental effects due to signal amplitude.

event-mode data acquisition software was able to histogram a composite TOF spectrum of all (up to the maximum of 16) ions for each pulse.

The resulting spectrum is shown in Fig. 2. Our background gas contains air, sulfur hexafluoride and hydrocarbons which are being dissociated by the laser pulse. The

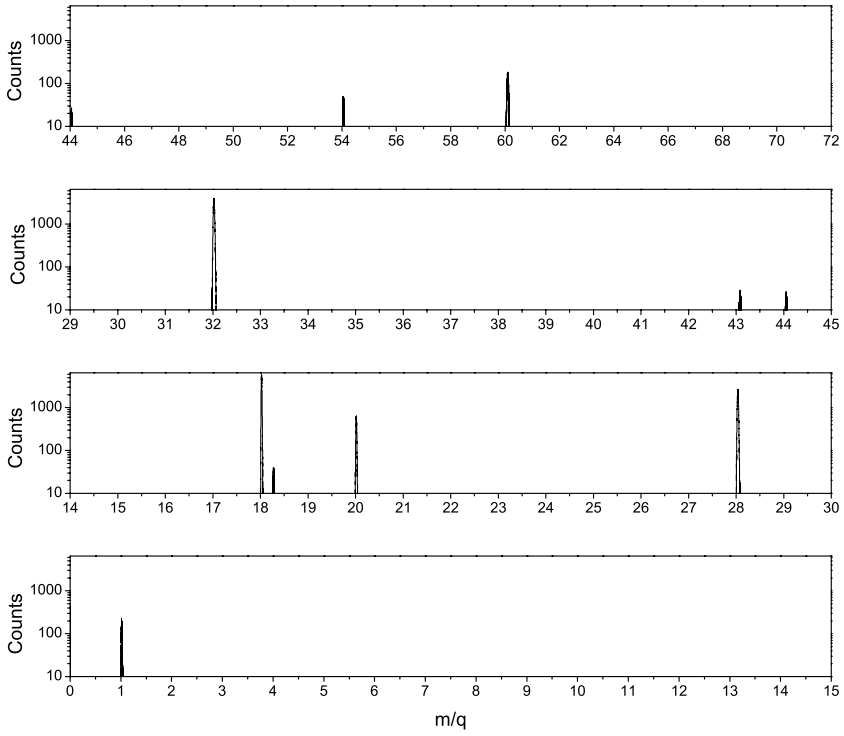

Fig. 3. Four hundred microJoule laser on neon stripping gas and background. The discriminator has been set to eliminate multiple triggering on large amplitude signals.

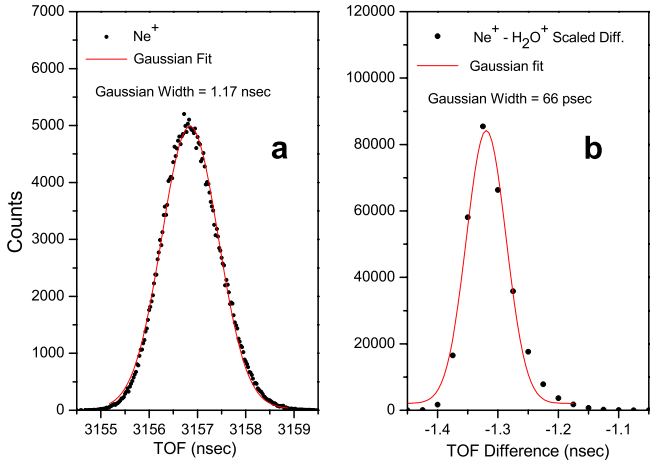

Fig. 4. (a) Neon TOF width. (b) Ne^+–H_2O^+ scaled time-of-flight difference.

various fragments are accelerated by the high energy tandem tubes and appear as discrete TOF peaks. The ion beam was tuned (using the high energy electrostatic steerers) so as to maximize the total number of detector pulses.

Tuning for the maximum number of pulses has the effect of maximizing the dissociated molecular ion fragments, which have a larger transverse velocity due to their initial Coulomb explosion energy. This reduces the measured yield of non-dissociated molecular ions, such as $m/q = 18$ (H_2O^+) and $m/q = 28$ (N_2^+). Fig. 3 shows a spectrum obtained by re-tuning the beam while maximizing the signal on an oscilloscope at the expected time position of the H_2O^+ peak. Some neon stripping gas from the terminal leak has also been introduced into the system. Now the H_2O^+, O_2^+, N_2^+ and Ne^+ peaks are clearly dominant, as expected. Most of these main peaks are saturated or nearly saturated, meaning there is at least one such ion produced for each laser pulse.

The width of the $^{20}Ne^+$ peak is 1.2 ns, as shown in Fig. 4(a). If our estimates of the various contributions to pulse width are correct, we have not yet achieved the minimum width possible with our current configuration. The measured width should be dominated by tandem terminal ripple, as described above, which adds pulse-to-pulse jitter but does not effect time spread within a pulse. Since we are accumulating the TOF data on an event-by-event basis, it is possible for us to construct a spectrum from the TOF difference between two molecular ion peaks from the same pulse. The TOF is proportional to the square root of the ion mass number for singly charged ions, so we must divide the TOF by this quantity when comparing two different ion species. We chose Ne^+ and H_2O^+. Doing the scaled subtraction of TOF's should remove the effects of voltage ripple from the equation. The result is seen in Fig. 4(b), with the two spectra taken at different laser intensities. The scaled width of 67 ps is encouraging, compared to SIMION simulations for the same quantity of roughly 55 ps.

6. Future plans

We would like to find another way to measure the temporal spread of the ion pulse for each laser shot that is not so dependent on signal processing electronics. Fortunately, we have in-house a streak camera that is capable of measuring time spreads down to a few picoseconds [7]. The ion pulse impinges on a thin foil and creates an electron shower, which is deflected electrostatically by a very fast set of deflection plates. The plates can be gated at a particular time so as to only deflect a certain range of TOF's. The dispersed electron pulse (the "streak") is imaged by a CCD. This will give us a good measurement of the single-shot pulse width. Once that value has been determined, we will need to do the hard work of compensating for some of the sources of pulse broadening and jitter (such as using the terminal-voltage ripple signal to control some sort of laser delay to better match the pump ion pulse with the probe laser pulse).

Acknowledgements

We thank the following members of the J.R. Macdonald Laboratory for their contribution to this project: Professors Pat Richard and Brett DePaola and technical staff Mike Wells and Bob Krause. We are funded by the Chemical Sciences, Geosciences and Biosciences Division, Office of Basic Energy Sciences, Office of Science, US Department of Energy.

References

[1] B.J. Siwick, J.R. Dwyer, R.E. Jordan, R.J. Dwayne Miller, Science 302 (2003) 1382.
[2] H. Ihee, B.M. Goodson, R. Srinivasan, V.A. Lobastov, A.H. Zewail, J. Phys. Chem. A 106 (2002) 4087.
[3] T. Kirchner, Phys. Rev. Lett. 89 (2002) 093203.
[4] T. Niederhausen, B. Feuerstein, U. Thumm, Phys. Rev. A 70 (2004) 023408.
[5] D.A. Dahl, SIMION 3D, Idaho National Engineering and Environmental Laboratory.
[6] B.L. Qian, H.E. Elsayed-Ali, J. Appl. Phys. 91 (2002) 462.
[7] J. Liu, J. Wang, B. Shan, C. Wang, Z. Chang, Appl. Phys. Lett. 82 (2003) 3553.