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ACRONYMS AND SYMBOLS

ACRONYM/SYMBOL	MEANING
AGEX	aboveground experiments
HE	high-energy
ICF	inertial confinement fusion
ISIS	a computer code
LANL	Los Alamos National Laboratory
LASNEX	a computer code
LLNL	Lawrence Livermore National Laboratory
MHD	magnetohydrodynamic (computer code)
MHRDR	Magneto-, Hydro-, Radiative Dynamics Research, computer code
MTF	magnetized target fusion system
NSLS	Brookhaven National Synchrotron Light Source
SHG	second harmonic generation
T_e	electron temperature
THG	third harmonic generation
TRAC-2	a computer code
VNIIEF	All Russian Scientific Research Institute of Experimental Physics
VUV	vacuum ultraviolet

Experimental Colliding Plasma

Mark Wilke, P-15,
Applied Physics Experiments and Imaging Measurements

April through June 1994

We continued the colliding plasma experiments in the April-to-June time frame with another set of experiments on Trident in May. The plasmas were again generated with 100 J, 0.5 ns, 2 ω laser pulses on tuna can targets, dual Au foils, dual CD-coated Au foils and CD-coated tuna cans. The main purpose was to fill in gaps in the existing data set, particularly with respect to Au-only targets, so the collaborative paper with the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) can be completed. Approximately 25 shots were taken on the Trident run in May. We also participated in Lawrence Livermore National Laboratory's (LLNL's) basic plasma physics experiment to observe ion waves for the first time in a laser plasma where the colliding plasma, Thomson scattering diagnostic was used to help measure the plasma temperature.

Improvements have been made in several diagnostic areas. The recording van, originally developed for use on Trident, has been improved and put in a configuration making it a valuable tool for general AGEX II applications as evidenced by its use on Procyon. The high-energy (HE), x-ray spectrometer was recalibrated at the Brookhaven National Synchrotron Light Source (NSLS), a time-resolved neutron diagnostic was added, and improvements were made to the ion spectrometer.

The gated x-ray imager (GXI) confirmed earlier conclusions about ISIS modeling of the Au vs. CD plasma collisions with dramatic images of, in particular, the Au plasma collisions. Sharp images of the Au collision and stagnation compared well with the LASNEX and ISIS prediction of well-defined stagnation within 0.5 ns of target irradiation. The CD images showed more diffuse late-time stagnation, which can only be modeled well with ISIS.

The neutron diagnostics were augmented with a time-compensated scintillator, microchannel plate, and photomultiplier tube detector to try to measure the burn time and Doppler broadening of the colliding D-D plasma. The still preliminary results indicate the CD-coated tuna-can style target produces neutrons that arrive later at the detector than those from CD-coated dual foils. The statistics are unsatisfactory, however, and we will be repeating these measurements.

The value of the electron temperature (T_e) is an important parameter. The value at the laser target interaction surface determines the energy of the ions that will collide. At the collision region, the value of T_e is a factor in the value of the mean free path and, therefore, the diffuseness of the collision region. Because of the importance at both the surface and collision region, we are pursuing three techniques to measure

T_e : the HE spectrometer and Thomson scattering, and we are now exploring the use of isoelectronic line ratios from doped targets.

The HE spectrometer is used to measure the electron temperature of the colliding plasma via the bremsstrahlung emission and, therefore, provide a measure of T_e that is independent from the Thomson scattering measurement. Measured temperatures have typically been lower than expected, leading us to suspect the spectrometer calibration. We expect temperatures of several keV and typically observe temperatures of 1.5 to 1.9 keV. The spectrometer has not been calibrated in several years. Calibration time was obtained on the Los Alamos National Laboratory (LANL) x-ray beam line at the NSLS. Initial evaluation of the calibration of the low-energy channel indicates some differences with the original calibration but not by enough to account for the lower than expected T_e .

The Thomson scattering diagnostic has been operational with the assistance of Bruno Bauer and Paul Drake of the LLNL Institute for Plasma Physics. The diagnostic should yield T_e by measuring the frequency broadening and shift of the coherent scatter of the 2w probe beam (C-beam) by ion acoustic waves. The broadening and shift yield the ion acoustic frequency of the plasma, which in turn can be used to infer T_e . Preliminary results were obtained in May, indicating a temperature above 2 keV. Because of the angle of the line of sight to the probe beam, we obtain little Thomson-scattered light into the spectrometer, so we are sensitive to light scattered from the target surfaces. We are, therefore, extremely sensitive to alignment errors, which we are working on to improve. We participated in Bruno Bauer's experiment to observe and measure the properties of ion waves in a laser plasma. The waves were apparently observed in Thomson backscatter, and the side-scatter station we ran provided the plasma temperature.

Isoelectronic spectra is the third method we plan on using to determine T_e . Calculations have been done by J. Abdallah that indicate that He- and H-like Ti and Cr will be useful in the range of several keV and up to several times $10^{21} \text{ cm}^{-3} N_e$ range, which is what we expect. Above about 10^{22} , the line ratios become density sensitive. Dual Au disk targets have been manufactured for the next set of experiments with 100 nm of Ti and Cr coating. Calculations are underway to determine if this coating will perturb the colliding plasma.

We continued to make improvements to the ion spectrometer. We now believe we understand the operation and the results. Data were taken on Bauer's Cu targets, and the Carbon and Hydrogen contamination lines are clean and well defined. It is evident that above a certain signal level, the individual charge state lines begin to merge as a result of space charge. The sensitivity to space charge may make it difficult to use the diagnostic on single-foil experiments because of the amount of ions present. The side-scattered ions are less intense and provide cleaner signals.

Although no new holographic interferometry data have been taken, EG&G has continued to work on the data reduction programs. Gerry Graham has a program now running, which is being checked against similar types of interferograms from a previous experiment at KMS Fusion.

We began planning for the next series of experiments to start in July. The main objective of this set will again be to fill in some holes in our data set so that we can complete the joint paper with our Russian collaborators. We also plan to try the isoelectronic T_e measurement technique.

A poster presentation of the Trident colliding plasma experiment was given at the International Conference on Plasma Science in Santa Fe in June 1994. Charts were prepared for the June 28 review of AGEX II laser programs that was presented by Mike Jones of X-1. A proposal is being generated for FY95 AGEX II colliding plasma experiments. A visit to Arzamas-16 by X-Division members is planned for early August.

Capacitor Development for Atlas Marx Modules

W. A. Reass and W. M. Parsons

P-1, High-Energy Density Physics

The conceptual design of the Atlas Marx bank is based on a higher-voltage version of the 50 kV Pegasus II capacitor. The Pegasus II capacitor is $11 \times 14 \times 27$ inches, stores 30 kJ, and has a low-profile, Scyllac-style bushing. The Atlas design uses a similar 30 kJ capacitor, except with a 60 kV rating. However, the increased dielectric stress at 60 kV will not permit the same energy density as the 50 kV units. The increase in foil edge margins inside the capacitor will require a $12 \times 16 \times 28$ -inch case. This in turn increases both the individual capacitor and machine inductances.

Another shortcoming of the conceptual design relates to the complicated assembly of the capacitors into the system. First, four capacitors must be assembled into a specially designed metal box. Each of the boxes must then be stacked and interleaved with the transmission-line Mylar. This methodology requires *in-situ* assembly, test, maintenance, and repair. When components require service, the entire machine must be secured until the maintenance or repair is complete. This is particularly troublesome because periodic rail-gap maintenance will definitely be required. A modular approach, where the maintenance or repair can be accomplished "off-line" (while the system runs with a spare module), will greatly improve system availability.

We are designing a modular Marx bank based on capacitor technology developed by Maxwell Laboratories for the Defense Nuclear Agency ACE II machine. The capacitor style has been dubbed "FASTCAP," and each unit replaces two Pegasus-style capacitors. FASTCAP capacitors are plastic-cased with large 2×22 -inch bushings at each end. The rail-gap switch will mount directly on one end and attach to adjacent capacitor bushings to provide minimum inductance. Bushings on the opposite side will have flat interconnecting plates mounted to them and will become part of the output transmission line. An illustration of an ACE II Marx bank using similar capacitors is shown in Figure 1.

In the Atlas design, FASTCAP capacitors will be stacked in a plastic rack that can be removed from the system as a complete assembly. This design reduces the discharge current path and the machine height, thereby decreasing system inductance. This modular design will also facilitate construction and testing and will allow verification of a module's performance before installation. Units will be repaired or maintained in a separate test bay without affecting the machine operation schedule. Rail-gap maintenance will become part of a regularly scheduled preventative maintenance program as spare modules are rotated into and out of the machine.

Figure I. ACE II Marx bank with FASTCAP capacitors.

Computational Modeling of Magnetized Target Fusion Experiments

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ABSTRACT

The advent of 100-MJ-class flux compression generators^{1,2} has made it possible to consider driving fusion targets by direct magnetic implosion,³ with implosion kinetic energies far beyond those available with conventional fusion drivers. Computational studies have suggested that the optimal use of such energy is in a magnetized target fusion (MTF) system.⁴

An MTF system requires a means of preheating and magnetizing the thermonuclear fuel within the target before implosion. One means of obtaining a preheated and magnetized plasma is the recently reported "MAGO" concept.^{5,6} In "MAGO," an inverse pinch is followed by axial flow through a "nozzle" and is subsequently magnetically compressed and ohmically heated. D-T neutron yields in excess of 10^{13} have been reported.

We have begun computational modeling of the "MAGO" experiment, using a number of different multidimensional, magnetohydrodynamic (MHD) codes. In addition, other MTF concepts are being computationally and theoretically evaluated. The status of our modeling efforts will be reported.

I. INTRODUCTION

MTF is a relatively untried approach to fusion ignition, which uses a magnetic field within a fusion target to suppress thermal conduction losses while retaining the implosion heating and inertial confinement advantages of conventional inertial confinement fusion (ICF). The basic principles of MTF have previously been reported. Using a simple target model,⁴ including such phenomena as magnetic back pressure on an imploding pusher, magnetic reduction of thermal conductivity, magnetic diffusion and Ohmic heating, as well as the usual hydrodynamic and radiation phenomena, new regions in parameter space where significant thermonuclear fuel burn-up can occur were identified.

Operating in a density- and time-parameter range intermediate between ICF and magnetic confinement fusion, MTF offers distinct advantages over both of the more conventional approaches. When compared to ICF, the new regions are characterized

by very low fuel densities, very low implosion velocities, and most importantly, driver requirements reduced by several orders of magnitude. The magnetic field compressed along with the fuel may reach a value whereby charged particle energy deposition is enhanced. MTF does not require magnetic confinement: the plasma β (plasma pressure/magnetic pressure) of the imploded target can be much greater than unity with most of the plasma pressure supported by the confining pusher. Because the fuel is wall-confined, many of the instabilities that impede magnetic confinement are not expected to be as damaging, and simple magnetic field topologies can be considered, leading to easier plasma formation techniques.

An MTF system requires two elements: (a) a target implosion driver and (b) a means of preheating and magnetizing the thermonuclear fuel before implosion. Lasers and particle beam drivers optimal for conventional ICF targets are probably not optimal for MTF, although they could be employed. However, because of the reduced driver power and intensity requirements, MTF permits a complete rethinking of the entire driver/target configuration. Novel 100-MJ-class disk flux compression generators^{1,2} make it possible to consider direct magnetic implosion³ of fusion targets in a energy-velocity space simply inaccessible by any other laboratory means. Such energy-rich sources appear ideal for MTF, and consequently a demonstration of fusion ignition may be possible using MTF, without a major capital investment in unproven driver technology.

One possible way to obtain a preheated and magnetized plasma suitable for subsequent implosion is the "MAGO" concept,⁵ which was originated at VNIIEF and is currently the subject of a collaborative research program involving VNIIEF and LANL. The unique MAGO experiment consists of two cylindrical chambers joined by an annular "nozzle," with electrical current flowing in one chamber accelerating plasma flow into an implosion chamber. Up to 4×10^{13} D-T neutrons have been produced in a MAGO discharge experiment without implosion of the plasma chamber.

In this paper, we discuss our computational modeling of MAGO. Our objectives are to characterize the plasma, to compare our results with the diagnostics available, to understand the neutron production, and ultimately to evaluate the suitability of such a plasma for MTF. We also discuss, briefly, some other possible means for creating a magnetized target plasma.

II. COMPUTATIONAL DETAILS

This paper presents work done with two azimuthally symmetric two-dimensional MHD computer codes: MHRDR (Magneto-, Hydro-, Radiative Dynamics Research), at Los Alamos National Laboratory, and TRAC-2, at Lawrence Livermore National Laboratory. Both codes include resistive and thermal diffusion and

Figure 1. The two reported experimental MAGO geometries (solid and dashed lines) and the geometries used by the two codes (dotted lines).

optically thin radiation effects. Although MHRDR has an extensive diagnostic capability, it has limited geometric capability so the MAGO geometry can be represented only approximately. Shown in Figure 1 are the two reported experimental MAGO geometries and the geometries used by the two codes.

In principle, all gas within the discharge is initially at room temperature although the presence of tritium may lead to a nonnegligible initial ionization. If the gas is initially at room temperature, it will have a very high

resistance through which no current will flow, and the MAGO combined chamber will behave computationally like a fixed, large inductance. In the experiment, an initial, or bias, magnetic field is established by a 1.7-MA current that surrounds the entire chamber; this is followed by the main discharge current, which reaches a peak of about 8 MA in 4 μ sec. Neither code contains a breakdown model to account for the ionization of the gas as the discharge voltage is applied. In two-temperature (ion and electron) runs with both codes, an initial fully ionized D-T plasma of density 1.4×10^{-3} kg/m³ (corresponding to a D-T fill pressure of 5 torr) and temperature 2 eV is assumed; results with this assumption showed remarkably good correspondence to experimental measurements. However, the computed total current flow and computed current in the insulator chamber, as measured by experimental "B-dot" probes, did not match experimental values in detail. In one-temperature MHD runs with the MHRDR code, a more realistic initial condition was established: conducting paths with an initial temperature of 2 eV for a small region adjacent to the insulator and for a small region at the center of the nozzle, which connects the two chambers (the latter is used because the experimental results suggest that most of the current initially flows in the nozzle instead of along the insulator). All other gas is at room temperature, and ionization level/equation of state information for these runs is taken from the "SESAME" database. These runs did show better correspondence to experimental current measurements; we continue to seek computational parameters that more closely match the as yet incompletely reported experimental parameters.

III. COMPUTATIONAL RESULTS

The computations show that a relatively weak inverse Z-pinch forms at the insulator and moves radially outward. Concurrent with the inverse pinch, current that flows in the nozzle moves the gas ahead of it into the second chamber, compressing and heating it. The mass, which has accumulated in front of the inverse pinch is rapidly accelerated through the nozzle, thermalizing when it strikes the bulk plasma in the second chamber and producing neutrons. Although the neutron-producing portion of the plasma reaches the keV temperature range, this represents a low-density, relatively small part of the total plasma mass (Figure 2); the bulk of the plasma is in

the 100–500 eV temperature range (Figure 3) and is magneto-thermally insulated from the walls.

Computed peak neutron emission occurs between 2.5 and 3.0 μ s in agreement with experimental measurements. The neutrons are emitted by a toroidal volume surrounding the central conductor and also surrounding the bulk of the plasma, which has been compressed against the central conductor by essentially a Z-pinch. The computed location of the neutron-emitting region is consistent with the neutron "shadowgraph"⁵ obtained experimentally. Computed peak neutron production rates and total neutrons are within an order of magnitude of experimental measurements (in contrast to previously reported MHRDR results,⁶ which were three orders of magnitude short in neutron production. This was due to setting a cutoff density, below which plasma heating is disallowed to prevent unrealistically high and numerically disruptive heating of "vacuum" regions. This resulted in not heating plasma having density below about 3×10^{16} cm⁻³, plasma which Figure 2 indicates plays a major role in neutron production.

Figure 2. Electron densities above which 90% (A), 50% (B), and 10% (C) of neutrons are produced; superimposed is the neutron production rate.

Figure 3. Temperature range of the overall plasma mass: by 4 μ sec, 90% of the plasma is above 100 eV, 50% is above 300 eV, and approximately 10% is above 800 eV; at the time of peak neutron yield (2.5-3 μ sec), the corresponding temperature values are somewhat less.

IV. OTHER MTF POSSIBILITIES

In addition to our modeling of MAGO, we are investigating other MTF and implosion concepts. Deuterium or D-T fiber-initiated Z-pinch⁷ are one promising target plasma candidate, and another scheme involves "phi-target" integrated electron-beam-driven implosions.⁸ Another concept is the direct implosion of D or D-T cylinders (solid or gas) driven by a fast-rising current pulse (e.g., 10 MA in 40 nsec). Simulations⁷ indicate the possibility of obtaining kilovolt temperatures, high densities ($10^{21}/\text{cm}^3$), and high magnetic fields (6 MG) over a 2-mm radius. This approaches the MTF regime of enhanced magnetic insulation without the complication of an external liner to drive the implosion.

V. CONCLUDING REMARKS

Computations of the MAGO experiment now show reasonably good agreement to experimentally measured neutron production rates, timing, and location. As more diagnostic information becomes available in the United States/Russian collaboration involving these experiments, the computations will be refined. To the extent that the hot, low-density plasma is of interest, it would be desirable to

go beyond the collisional MHD model used here, although this would have a significant price in computing time and complexity. On the other hand, from an MTF standpoint, one may be more interested in the bulk plasma, which would be taken to fusion conditions by implosion; hence, the unique and interesting neutron production of the MAGO plasma could be considered of secondary importance. We have not yet determined the suitability of the MAGO plasma for subsequent MTF implosion, nor have we identified an optimal implosion driver.

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Ultraviolet Ultrafast Pump-Probe Laser Using a Ti:sapphire Laser System

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ABSTRACT

An ultrafast spectroscopic pump-probe apparatus for detection of ultraviolet time resolved spectra is described. Frequency doubling of an 810-nm 0.3 TW Ti:sapphire laser system yields 15-mJ, 165-fs pulses at 405 nm. Pulse energies of 0.8 mJ are obtained by frequency tripling to 270 nm. An ultraviolet water supercontinuum extending from 200 nm to 600 nm is also generated from the frequency doubled 405-nm light. The system operates at a 5 Hz repetition rate and is useful for applications in deep ultraviolet pump-probe subpicosecond spectroscopy.

Recent reports of frequency conversion of ultrashort, terawatt class Ti:sapphire lasers have demonstrated their usefulness in producing femtosecond sources of light in the ultraviolet (UV)^{1,2} and near-vacuum ultraviolet (near-VUV)³ wavelength range. These sources are used to seed rare gas halide excimer amplifiers in the ultraviolet,^{1,2} and are used for the generation of wavelength tunable femtosecond pulses in the UV and near-VUV region.³ Other applications of femtosecond UV pulses include: subpicosecond UV kinetic spectroscopy,^{4,5} the study of electron-hole dynamics in wide-band gap semiconductors,⁶ and the determination insulator material dynamics.⁷ Such applications in time-resolved femtosecond pump-probe spectroscopy often rely on the absorption of a broadband probe continuum for the detection of a transient species spectral feature. Generally, the broadband probe is generated by an intense femtosecond source through supercontinuum generation in a gas or condensed phase medium.⁸ This paper describes a novel femtosecond pump-probe system useful for detection of photochemical UV transients that relies on frequency doubling and tripling an ultrashort-amplified Ti:sapphire laser to generate pump pulses at 405 nm and 270 nm. A synchronized UV probe continuum is produced by focusing intense violet femtosecond pulses at 405 nm in water to generate a continuum that spans a wavelength range of 200 nm to 600 nm. We believe that this is the largest spectral coverage achieved with an ultraviolet/visible continuum to date.

A 0.3 TW laser system based on chirped pulse amplification in Ti:sapphire is used to generate intense infrared ultrashort laser pulses before frequency conversion to the ultraviolet. The system is seeded with pulses from a commercial mode-locked Ti:sapphire laser operating at 810 nm and pumped by the 10-W, all-line output of an Ar-ion laser. These 70-fs, 15-nJ pulses have a spectral bandwidth of 9.6 nm. Before amplification, these pulses are temporally stretched using a grating pair pulse-stretcher configured to yield positive group velocity dispersion.⁹ Two antiparallel 2000-line/nm gold-coated holographic diffraction gratings are separated by 1.7 m, and a unit magnification telescope using 60-cm-focal-length achromatic lenses is inserted between the gratings. After two passes through the stretcher, the measured pulse duration is 440 ps. Next, the pulses transverse a

Faraday isolator. Losses in the beam up to this point (mostly in the stretcher) result in a 5-nJ/pulse energy to seed the amplifier chain.

The Ti:sapphire amplifier chain boosts the energy to 110 mJ and consists of a regenerative amplifier, a double-pass preamplifier and a final amplifier. All amplifiers are pumped using frequency-doubled Nd:glass/Nd:YAG oscillator/amplifier system.¹⁰ The intensity of these 110-ns, 0.53- μ m pump pulses are more than an order of magnitude smaller than those obtained from conventional Q-switched Nd:YAG lasers typically used to pump Ti:sapphire amplifiers, making the system more resistant to optical damage from the pump beam. The strategy used to increase the pump pulse duration is to utilize the low gain of Nd:glass in the oscillator to yield long-pulse-duration seed pulses at 1.062 μ m, and then use Nd:YAG, with its superior thermal properties, for amplification up to joule-level energies. The laser system, described in detail in Ref. 10, consists of a Q-switched glass oscillator, followed by three Nd:YAG amplifiers operating at a 5 Hz repetition rate. Frequency-doubling of the output with conversion efficiencies approaching 50% is achieved in two output arms using a 60-mm-long and a 100-mm-long KDP ($K_2H_2PO_4$) crystals.

The first amplifier is a regenerative amplifier using a linear cavity with one flat end mirror and one 3-m focal length end mirror separated by 145 cm to form a stable TEM_{00} mode with a waist size of 1.63 mm located at the flat end mirror. The 7-mm-diameter by 20-mm-long Ti:sapphire crystal with 0.15% Ti doping yields a small signal gain of 4 when pumped with 65 mJ of 532-nm light focused to a diameter of 2.0 mm. The seed beam is input via a Brewster's reflection off of the Ti:sapphire crystal. A combination of two Pockel's cells, a quarter wave plate and a thin film polarizer is used for pulse selection and switch-out. A 5-ns, 3.6-kV pulse from a pulse generator switches the Pockell's cell. A total of 20 round trips in the cavity is required to boost the pulse energy from 5 nJ to 7 mJ.

The pulse is then amplified up to the 60-nJ level in a double pass Ti:sapphire preamplifier. The 7-mm-diameter by 20-mm-long, 0.15% doped, Ti:sapphire rod is pumped with 250 mJ of 532-nm light focused to a 3.0-mm-diameter spot. After the first pass the output energy from the Ti:sapphire beam is 28 mJ, and after the second pass, the double pass gain is 8.6 to yield pulse energies of 60 mJ. At the output of the preamplifier, the diameter of the Ti:sapphire beam is 2.9 mm. In order to improve the spatial quality of the output from the Ti:sapphire preamplifier, an 1.5-times diffraction-limited vacuum spatial filter is placed between the preamplifier and the final amplifier. Typical energy throughput is 75%, including reflection losses from uncoated telescope lenses and vacuum port windows. The output energy after the vacuum spatial filter is 45 mJ. The telescope for the vacuum spatial filter is also used to expand the Ti:sapphire beam diameter to 4.2 mm before seeding the final amplifier.

The final amplifier consists of 12-mm-diameter by 20-mm-long, 0.15% doped, Ti:sapphire rod that is pumped with 400 mJ of green from the second output arm of the 532-nm pump laser. The single pass gain of the final amplifier is 2.6, yielding an output energy of 110 mJ for the Ti:sapphire beam. The beam diameters for the pump and the Ti:sapphire beam at this point are 4.4 mm and 4.2 mm, respectively.

Before injecting the amplified Ti:sapphire pulses into the grating compressor, the beam diameter is expanded and collimated to a diameter 9.3 mm with a dual lens telescope in order to minimize any potential for optical damage to the compressor gratings. After the telescope, the Ti:sapphire pulse energy is 95 mJ.

After the Ti:sapphire amplifier chain, the pulse width is compressed by a factor of 3200 with a parallel grating pair. The compressor consists of a pair of 2000 lines/mm gold-coated holographic gratings separated by 74 cm. Although compressed pulse widths of 110 fs are achievable, day-to-day operation of the system yields a typical compressed pulse width of 125 fs. The throughput energy efficiency of the grating pair compressor is 45%, and the output pulse energy of the compressed beam is 43 mJ. The measured spectral width of the compressed 810-nm beam is $\Delta\lambda = 8.8$ nm, and the time-bandwidth product is $\Delta\nu\Delta t = 0.443$. Upon measuring the output energy stability at a repetition frequency of 5 Hz, the pulse-to-pulse amplitude stability is approximately $\pm 5\%$.

Frequency conversion of the 810-nm Ti:sapphire laser pulses occurs in two stages. Type-I second harmonic generation (SHF) in a 1.5-mm-thick KDP crystal is used to produce intense 405-nm pulses, and type-I third harmonic generation (THG) in a 0.5-mm-thick KDP crystal is used to mix 810-nm and 405-nm pulses to obtain 270-nm pulses. The calculated group velocity mismatch between ω and 2ω is 80 fs/mm, and the calculated group velocity mismatch between ω and 3ω is 390 fs/mm. In order to avoid optical damage to the crystals, both crystals have 35-mm diameter apertures, and are Sol-Gel AR coated. Figure 1 shows the optical layout used for SHG type-I and THG type-I of the Ti:sapphire laser output. The first delay line is employed to optimize the THG output energy by

Figure 1. Optical layout used for SHG, THG, and supercontinuum generation of the ultrafast Ti:sapphire laser. A final delay line is used to control the timing between the 270-nm pump pulse and the probe continuum pulse.

compensating for the walkoff between the 810-nm and 405-nm pulses. For SHG, an output of energy of 15 mJ at 405 nm is achieved. The SHG energy conversion efficiency is 35%. For THG, an output energy of 0.8 mJ at 270 nm with a conversion efficiency is 2% is obtained. With an input energy fluence of 63 mJ/cm², the output energy fluences for SHG and THG generation are 22 mJ/cm² and 1.2 mJ/cm², respectively. Figure 2(a) displays the measured output spectrum at 405 nm after SHG. The spectral bandwidth for the 405-nm pulse is $\Delta\lambda = 3.0$ nm. The inset to Fig. 2(a) shows the intensity crosscorrelation between 810 nm and 405 nm. Deconvolution of the crosscorrelation trace with a 160-fs, 810-nm pulse reveals that the 405-nm pulse width is 165 fs. The time-bandwidth

Figure 2. Frequency converted Ti:sapphire output spectrum after: (a) SHG and (b) THG. The spectral bandwidths of the second and third harmonics are $\Delta\lambda = 3.0$ nm, and $\Delta\lambda = 1.5$ nm, respectively. The inset to (a) shows the intensity cross-correlation between the 810-nm and 405-nm pulses. The FWHM of the cross-correlation trace is 230 fs. After deconvolution, the pulse width at 405 nm is $\Delta t_{405} = 165$ fs. The 810-nm input pulse width is $\Delta t_{810} = 160$ fs.

product for the 405-nm pulse is $\Delta\nu\Delta t = 0.903$, which is twice the transform limit for Gaussian pulses. The measured 405-nm pulse width is determined by the input 810-nm pulse width. Calculations indicate that shorter 405-nm pulses should be attainable. Figure 2(b) displays the output spectrum for THG generation. The spectral bandwidth of the 270-nm pulse is 1.5 nm. Although we are yet unable to measure the pulse width at 270 nm, it is expected that these pulses are in the 200-fs regime since both inputs, 810 nm and 405 nm, each have pulse widths under 165 fs and since the calculated group velocity mismatch is expected to be ~ 195 fs for a 0.5 nm KDP-I crystal. It is worth noting that previous reports of frequency conversion of an ultrafast Ti:sapphire laser to the ultraviolet-produced pulses with an energy and pulse width of 5 μ J, $\Delta t \sim 100$ fs, at 248 nm (Ref. 1), and of 1 mJ, $\Delta t = 200$ fs at 248 nm (Ref. 2), respectively.

In addition to SHG and THG, Fig. 1 also shows an additional delay line inserted into the system after frequency doubling and tripling of the Ti:sapphire beam. For subpicosecond kinetic UV spectroscopy, the system is configured as a pump-probe apparatus. The 270-nm beam is utilized as an ultraviolet pump pulse, and after spectral filtering, the unconverted 405-nm light is used to generate an supercontinuum in water (H_2O) for the probe. The time delay between the pump

Figure 3. Plot of the water (H_2O) supercontinuum spectrum. The 405-nm input pulse energy and pulse width are ~ 5 mJ and 165 fs respectively. The H_2O cell transmission is 80% at 220 nm.

and the H_2O continuum probe is controlled using an optical delay line in the pump beam arm. Approximately 5 mJ of the 405-nm beam is focused into a quartz cuvette cell (path length = 5 mm) containing a static fill of H_2O with an $f = 7.5$ -cm quartz lens. Figure 3 shows the spectral extent of the generated supercontinuum. Centered at 405 nm, the UV continuum extends from below 200 nm to beyond 600 nm. This is believed to be the shortest wavelength generated with an H_2O continuum to date. The UV cutoff of the continuum is due to the absorption in the quartz cell. The threshold energy for generating continua at 275 nm was measured to be 200 μ J at 405 nm. Figure 4 displays the H_2O continuum spectra between 270 nm and 280 nm obtained with five successive shots when pumping with 5 mJ at 405 nm. It shows that the shot-to-shot intensity fluctuation in the continua is 20%. The high quality of the continuum is also demonstrated by the smooth structureless features that it displays. The smoothness of the continua throughout the 200 nm to 600 nm range is in contrast to the spectral modulation that may appear in ultraviolet supercontinua of rare gases.^{11,12} Moreover, no micro-filamentation is observed in the H_2O continuum beam, as is manifested in the good shot-shot amplitude stability.

Figure 4. Water supercontinuum spectra obtained in the 270-nm-to-280-nm region. Five successive single-shot spectra are displayed. The spectra illustrate good shot-to-shot amplitude with no spectral modulations.

Finally, since this pump-probe system operates at a repetition frequency of 5 Hz, pulse-to-pulse signal averaging should improve the minimal detectable absorption sensitivity to under a few percent.

In this Letter an ultrafast, ultraviolet pump-probe apparatus based on frequency doubling and tripling a Ti:sapphire laser is described. The 0.3-TW, 125-fs output of the Ti:sapphire laser yields a frequency doubled output at 405 nm of 15 mJ with a pulse width of 165 fs. After tripling the Ti:sapphire wavelength to 270 nm, an output energy of 0.8 mJ is attained, sufficient for use as an UV photolysis source of molecules in a subpicosecond pump-probe apparatus. A synchronized broadband, probe source is demonstrated via supercontinuum generation in water using the unconverted 405-nm light after frequency tripling. The continuum extends from below 200 nm to beyond 600 nm, and appears to be smooth and free of any spectral modulation. The system should be useful in detecting UV photochemical transients in the subpicosecond time domain.

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High Resolution X-Ray Spectroscopy of a Subpicosecond Laser-Produced Silicon Plasma

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ABSTRACT

The Los Alamos Bright Source laser was used to create a silicon plasma by irradiation of a solid target. A very high resolution curved crystal spectrograph was used to detect the emitted x-rays. The satellite lines due to the decay of doubly excited states that accompany the Lyman $-\alpha$ were observed. The $2p3l - 1s3l$ radiative transitions in He-like Si were identified for the first time. In addition, all the components of the $2l\ 2p\ 3p - 1s2l\ 3L$ transitions were resolved. The spectra were compared to various collisional radiative calculations with good results.

Plasmas created by ultrahigh-intensity, subpicosecond laser pulses are very convenient sources for the investigation of radiative transitions from the autoionizing levels of multicharged ions.^{1,2} In these dense plasmas, satellite lines are produced by the radiative decay of the autoionizing levels into a 1-s vacancy. Autoionizing levels are generally populated by inner shell excitation, inner shell ionization, and dielectronic capture. Since satellite lines are generally excited-to-excited transitions, they are optically thin, and in principle should provide excellent diagnostics of density and temperature because the radiation is unperturbed by the surrounding plasma. However, these lines are weak compared to resonance lines, and they have very complicated structures. Spectrographs of very high resolution are required to separate structures into component lines, and very accurate calculations are necessary to identify individual lines.

The interaction of laser pulse with solid targets³⁻⁵ produces high-temperature plasmas, having high values of the electron density (up to solid density), and containing highly stripped ions. Because some of the transitions, the initial doubly-excited ionic states are relatively intense. These states that have small autoionization rates are populated in the plasma not predominately by dielectronic capture, but by several other populating mechanisms: 1) collisional mixing with strongly

autoionizing levels and 2) direct excitation of ion inner shell by electron impact. The first process is effective only in a dense plasma; the second, in a underionized plasma. In the case of subpicosecond laser-produced plasmas both processes mentioned are effective. This results in doubly excited levels that have large populations and, consequently, the satellite spectral lines caused by radiative decay of these levels have relatively high brightness.

The subpicosecond laser-produced plasmas are, of course, very bright x-ray emitters; but since the pulse length is short, the total energy of emitted photons can be small. Therefore, it is necessary to have a sensitive spectrograph to observe spectral lines from doubly excited levels. Additionally, this spectrograph must have very good spectral resolution $\lambda\Delta\lambda \geq 5000$ because the large number of satellite lines are concentrated in a very narrow spectral region near the appropriate resonance line. Such spectrographs, called FSSR-1D, were constructed in the past few years at MISDC.⁶ They use spherically bent mica crystals to disperse and to focus, with a spectral resolution of up to $\lambda\Delta\lambda \approx 10000-20000$.

Using a FSSR-1D spectrograph to observe subpicosecond laser-produced plasma allowed us for the first time to observe and identify the resolved satellite lines caused by the $2p3l - 1s3l$ radiative transitions in He-like Si XIII ions and also to resolve all components of the $2p2l^3P - 1s2l^3L$ transitions. Comparison of the intensities of observed spectral lines with time-independent calculations showed that the emission of these lines mostly occurs at plasma electron density $N_e \approx 6 \cdot 10^{22} \text{ cm}^{-3}$ and plasma electron temperature $T_e \approx 460 \text{ eV}$.

The experiment was performed at the Los Alamos Bright Source II facility. The excimer XeCl laser system was used to create high-temperature plasma. A frequency doubled seed pulse generated with a synchronously pumped dye laser oscillator/amplifier combination is amplified with transversely pumped XeCl amplifiers. The detailed performance of the laser is described in Ref. 7. The laser operates at a wavelength of 308 nm, produces a 300-fs pulse containing 0.25 joules, at a repetition rate of 1 Hz. When focused on a silicon target, with $f/1.9$ optics, it generates irradiances exceeding $4 \cdot 10^{19} \text{ W/cm}^2$. The amplified stimulated emission (ASE) from the amplifier generates a prepulse plasma in front of the target with which the main pulse interacts.

The plasma emission spectra in the x-ray region was measured by FSSR-1D spectrographs with mica crystals curved into a spherical surface with a radius $R=100 \text{ mm}$. The crystal was positioned in a spectrographic scheme with vertical focusing.⁸ In our case, the spectra near the resonance line of the H-like ion Si XIV was measured in third order. The spectrograph was very sensitive and the plasma emission was intense so the spectra could be recorded in a single laser shot.

An example of the plasma emission spectrum in the region $\lambda = 6.16 - 6.27 \text{ \AA}$ near the Ly_α line of the H-like Si XIV ion is shown in Fig. 1(b). For comparison in this figure we also present analogous spectra observed earlier in a plasma heated by a 2 ns-pulse from a Nd-laser⁸ (a) and in a X-pinch plasma⁹ (c). We see that spectrum (b) contains a number of resolved spectral lines having significant intensities.

Some of the lines (lines 1-8) are the satellites caused by $2p2l - 1s2l$ transitions in the Si XIII ion (for the spectroscopic notation for these lines see below in Table I). It should be noted that only lines 1.4.6-8 were identified earlier in Nd-laser-produced plasma, because it is necessary to have a dense plasma with $N_e \gg 10^{21} \text{ cm}^{-3}$ to observe the weakest components of the triplets $2l2p^3P - 1s2l^3L$ (lines 2.3 and 5). It will be shown below that other lines contained in spectrum (b) are caused by $2p3l - 1s3l$ transitions in Si XIII.

Table I. Dielectronic Satellites Caused by Radiative Transitions in He-like Ion Si XIII.

Ne	Wavelengths, Å			Transitions
	(exper.)	(theor. Ref. 10.13)	<exp.theor.>, mÅ	
1	6.2654*	6.2654**(6.2626)***	—	$2p^2 1D_2 - 1s2p^1P_1$
2	6.2564	6.2560(6.2552)	0.4	$2p^2 3P_1 - 1s2p^3P_2$
3	6.2549	6.2550(6.2541)	-0.1	$2p^2 3P_0 - 1s2p^3P_1$
4	6.2532	6.2532(6.2523)	0.1	$2p^2 3P_1 - 1s2p^3P_1$
		6.2530(6.2521)		$2p^2 3P_2 - 1s2p^3P_2$
5	6.2517	6.2525(6.2510)	-0.8	$2p^2 3P_1 - 1s2p^3P_0$
6	6.2501	6.2502(6.2491)	0.8	$2p^2 3P_2 - 1s2p^3P_1$
		6.2497(6.2490)		$2s2p^3P_0 - 1s2s^3S_1$
		6.2481(6.2474)		$2s2p^3P_1 - 1s2s^3S_1$
7	6.2447	6.2446(6.2438)	0.1	$2s2p^3P_2 - 1s2s^3S_1$
8	6.2296*	6.2296(6.2278)	—	$2s2p^1P_1 - 1s2s^1S_0$
9	6.2221	6.2238(6.2231)	-1.7	$2s3p^1P_1 - 1s3s^1S_0$
10	6.2186	6.2165(6.2166)	2.1	$2p3p^1P_1 - 1s3p^1P_1$
11	6.2117	6.2119(6.2118)	-0.2	$2p3p^3D_1 - 1s3p^3P_0$
12	6.2095	6.2097(6.2096)	-0.2	$2p3p^3D_2 - 1s3p^3P_1$
13	6.2080	6.2078(6.2076)	0.2	$2p3p^3D_3 - 1s3p^3P_2$
14	6.2039	6.2042(6.2034)	-0.4	$2p3d^3F_2 - 1s3d^3D_1$
		6.2043(6.2035)		$2p3d^3F_2 - 1s3d^3D_2$
15	6.2003	6.2019(6.2009)	-0.5	$2p3d^3F_3 - 1s3d^3D_2$
		6.2015(6.2012)		$2p3p^1D_2 - 1s3p^1P_1$
		6.1991**(6.1992)		$2p^2 1S_0 - 1s2p^1P_1$
16	6.1986	6.1993(6.1999)	-0.6	$2p3d^1D_2 - 1s3d^1D_2$
		6.1992(6.1982)		$2p3d^3F_4 - 1s3d^3D_3$
17	6.1963	6.1974(6.1976)	-0.6	$2s3p^3P_2 - 1s3s^3S_1$
		6.1963(6.1972)		$2s3p^3P_0 - 1s3s^3S_1$
18	6.1948	6.1952(6.1961)	-0.4	$2p3s^3P_1 - 1s3s^3S_1$
19	6.1928	6.1928(6.1928)	0.0	$2p3p^1D_2 - 1s3p^3P_2$
		6.1928(6.1935)		$2p3s^3P_2 - 1s3s^3S_1$
20	6.1677	6.1676(6.1676)	0.1	$2p3d^1P_1 - 1s3d^1D_2$
21	6.1650	6.1644(6.1640)	0.6	$2p3p^1S_0 - 1s3p^1P_1$

* – reference lines.

** – shifted by 0.005 according to calculation in Ref. 11 for the energy of $1s2p^1P_1$ level.

*** – numbers in parenthesis are LANL calculations.

The most intensive lines $2p^2\ ^1D_2 - 1s2p\ ^1P_1$ and $2s2p\ ^1P_1 - 1s2s\ ^1S_0$ (lines 1 and 8) were used as reference lines to measure the wavelengths of others. For these lines, we used the calculated wavelength values¹⁰ and shifted by 0.0005 Å according to a more precise treatment¹¹ for the energy of $1s2p\ ^1P_1$ - level. The relative accuracy of our wavelength measurements is about ± 0.0008 Å, with the absolute accuracy not known exactly, but we believe that it is better than ± 0.0015 Å.

X-ray spectroscopic methods are used in the present paper to estimate laser-produced plasma parameters. Since we observed plasma emission spectra without time and spatial resolution only average values of the plasma parameters can be obtained. To determine the electron plasma temperature we used the integrated line intensity ratio of the satellite $2p^2\ ^1D_2 - 1s2p\ ^1P_1$ to the resonance Ly_α line (see, for example, Ref. 8). Comparing the experimental value of this intensity ratio with theoretical ones, we found $T_e = 460$ eV. The actual value of the temperature may be somewhat higher than this value due to the optical depth and possible saturation of the Ly_α line.

For a diagnostic of the electron plasma density, we used the density-sensitive dielectronic satellites $2p^2\ ^3P - 1s2p\ ^3P$ and $2s2p\ ^3P - 1s2s\ ^3S$. At first, we compared the experimental values of the intensity ratio $I(p^2\ ^3P_{0,1,2} \rightarrow 1s2p\ ^3P_{0,1,2})/I(2s2p\ ^3P_{0,1,2} \rightarrow 1s2s\ ^3S_1)$ with calculations of Ref. 12 and found $N_e = 6 \times 10^{22}$ cm⁻³. After that we used the results of Ref. 12 and this N_e value to calculate the intensities of all components of these triplets separately and to simulate plasma emission spectra in the region $\lambda = 6.24 - 6.26$ Å. Analogous procedures were also carried out for the cases of the Nd-laser-produced plasma and X-pinch plasma. Results obtained are shown in Figure 1 (a,b,c). In all cases, the correspondence between theoretical and experimental data is very good. It confirms the reliability of 1) this diagnostic method and 2) the value $N_e = 6 \times 10^{22}$ cm⁻³ obtained for the case of our subpicosecond laser experiment. It should be noted also, that the experimental Stark width of the Si XIV Ly_α line is consistent with the calculated Stark width due to electron and quasistatic ions¹³ at $N_e = 6 \times 10^{22}$ cm⁻³.

As can be seen from Figure 1b, the observed plasma emission spectra contains some lines in the spectral region 6.16-6.23 Å (these lines are marked by numbers 9-21 in Figure 2). The results of wavelength calculations from Ref. 14 allows us to suppose that these lines (all or some of them) are caused by the radiative decay of $2\beta l'$ levels of the Si XIII ion. Actually, the comparison of their experimental wavelength values with theoretical ones shows that all observed lines correspond to some $2l\ 3l' - 1s3l'$ transitions. However, the comparison of their intensities with line intensities in the coronal limit shows that the theoretical values strongly differ from the experimental ones (see Fig. 2b, which shows the plasma emission spectra calculated with the help of a coronal kinetic model). This disagreement is expected because a coronal model is not applicable in the case of a high-density plasma with $N_e = 6 \times 10^{22}$ cm⁻³. In reality, for such dense plasma, collisional mixing of double-excited ion states is even more effective than noncollisional decay, and a general radiative-collisional kinetic model must be used to calculate the level populations and, consequently, spectral line intensities. Such calculations were carried out in the present paper and the results obtained for plasma with $N_e = 6 \times 10^{22}$ cm⁻³, $T_e = 460$ eV and for Lorentz

Figure 1. Silicon plasmas emission spectrum in the region $\Delta = 6.16 + 6.27 \text{ \AA}$ observed in different plasma sources: a) Nd-laser-produced plasma (obtained in Ref. 8 for 5 shots), b) XeCl-laser-produced plasma (obtained in present work for 2 shots), c) X-pinch plasma (obtained in Ref. 9 in 1 shot), and (below) the results of theoretical calculations for $2l2p^3P - 1s2l^3L$ lines.

line shapes are shown in Fig. 2. Now we see that the correspondence of theoretical line intensities with experimental data is excellent. It allows us to identify lines 9–21 as satellites caused by $2l3l' - 1s3l'$ transitions in the He-like ion Si XIII. The results of our identification and wavelength measurements are presented in Table I.

As an independent check, a collisional radiative model was constructed using Los Alamos atomic physics codes, which are based on the semirelativistic Hartree-Fock method of Cowan.¹⁵ The model included configurations of the type $1s^2$, $1s2l$, $1s3l$, $2l2l'$, $2l3l'$, and $3l3l'$ for the He-like ion stage. The values of l and l' range over all possibilities for the given value of principle quantum number. The model also includes all configurations through $3d$ for the H-like ion stage. The corresponding detailed fine structure levels, including intermediate coupling, spin-orbit coupling, and configuration interaction, were used in the modeling calculations. Oscillator strengths were calculated for all dipole allowed transitions. Distorted wave collision strengths were calculated for all transitions starting in the $1s^2$, $1s2s$, and $1s2p$ levels to all upper levels. Plane-wave-born collision strengths were used for all

Figure 2. a) Silicon subpicosecond laser-produced plasma emission in the region 6.16 – 6.23 Å; b) plasma emission spectra calculated by both coronal and collisional-radiative kinetic models.

other transitions. Collisional ionization and photoionization cross sections were calculated for transitions between the appropriate levels in the adjacent ion stages. Auger rates were calculated for all autoionizing levels in the He-like ion.

The steady-state model¹⁶ included collisional excitation, deexcitation, spontaneous radiative decay, autoionization, dielectronic recombination, collisional ionization, three-body recombination, and radiative recombination. The atomic data

discussed above were used to calculate rate coefficients and solve the kinetics equations at $T_e = 460$ eV and $N_e = 6 \times 10^{22} \text{ cm}^{-3}$. The resultant populations were used to compute the spectra shown in Figure 3. The results correlate well with this experiment shown in Figure 1 and the Russian collisional-radiative model shown in Figure 2. The calculations also show that all satellite lines are optically thin assuming a 10 micron plasma size for the present experimental conditions.

In conclusion, the use of a subpicosecond laser-produced plasma and the high-resolution, high-luminosity FSSR-1D spectrograph allowed us for the first time to observe and identify the satellites to the Ly_α Si XIV resonance line caused by $2p3l - 1s3l$ radiative transitions and to measure their wavelengths with a relative accuracy of $\pm 0.008 \text{ \AA}$ and an absolute accuracy of $\pm 0.0015 \text{ \AA}$. For improvements of the absolute measurement accuracy, we need to exclude the uncertainties in the wavelengths of the reference lines. This can be done in the future, both experimentally and by using modern quantum electrodynamic *ab initio* methods, for wavelength calculations of the reference lines $2p^2 \text{ } ^1D_2 - 1s2 \text{ } ^1P_1$ and $2s2p \text{ } ^1P_1 - 1s2s \text{ } ^1S_0$.

In addition, we have found the average plasma temperature and density to be approximately 460 eV and $6 \times 10^{22} \text{ cm}^{-3}$, respectively, for the case of a plasma formed by the 400 fs pulse of a XeCl-laser with a flux density $q_e \pm 4 \times 10^{18} \text{ W/cm}^2$. The small value of electron temperature and the large value of electron density (greater than critical density for $\lambda_l = 308 \text{ nm}$) indicate that in our experiments, the X-ray plasma emission occurs mostly in the spatial region between the critical point and the solid surface.

Figure 3. The plasma emission spectra calculated using a Los Alamos-based collisional-radiative model.

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