LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-CONF-223792

Electromagnetic Confined Plasma Target for Interaction Studies with Intense Laser Fields

B. Zielbauer, U. Ursescu, S. Trotsenko, U. Spillmann, R. Schuch, T. Stohlker, T. Kuhl, S. Borneis, T. Schenkel, J. McDonald, D. Schneider

August 17, 2006

CAARI
Fort Worth, TX, United States
August 20, 2006 through August 23, 2006

Disclaimer

Electromagnetic Confined Plasma Target for Interaction Studies with Intense Laser Fields

B. Zielbauer, D. Ursescu, S. Trotsenko, U. Spillmann, R. Schuch[+],
Th. Stöhlker, T. Kühl, S. Borneis,
T. Schenkel*, J. McDonald**, D. Schneider**
GSI, Planckstr. 1, D-64291 Darmstadt, Germany
+ Univ. of Stockholm, Alba Nova, S-10405 Stockholm, Sweden
**Lawrence Berkeley Nat. Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, USA*
***Lawrence Livermore Nat. Laboratory, PO Box 808, East Ave., Livermore, CA 94551, USA*

Conference publication for CAARI06 (19th International Conference on the Application of Accelerators in Research and Industry)

Auspices Statement

This work was in part performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Abstract

The paper describes a novel application of an electron beam ion trap as a plasma target facility for intense laser-plasma interaction studies. The low density plasma target (~10^{13}/cm^3) is confined in a mobile cryogenic electromagnetic charged particle trap, with the magnetic confinement field of 1-3T maintained by a superconducting magnet. Ion plasmas for a large variety of ion species and charge states are produced and maintained within the magnetic field and the space charge of an energetic electron beam in the "Electron Beam Ion Trap" (EBIT) geometry. Intense laser beams (optical lasers, x-ray lasers and upcoming "X-Ray Free Electron Lasers" (XFEL)) provide strong time varying electromagnetic fields (>10^{12} V/cm in femto- to nano-sec pulses) for interactions with electromagnetically confined neutral/non-neutral plasmas. The experiments are aimed to gain understanding of the effects of intense photon fields on ionization/excitation processes, the ionization balance, as well as photon polarization effects. First experimental scenarios and tests with an intense laser that utilize the ion plasma target are outlined.

Introduction and Motivation

The interaction of strong time-varying electromagnetic (EM) laser fields with ionized matter are of intrinsic interest to “High Energy Density Physics (HEDP)” ($>10^{18}$W/cm^2) (1, 2). Several fundamental issues of photon-matter interaction physics can be studied with strong EM field pulses interacting with confined and well defined low density neutral or non-neutral plasmas. Low density plasmas ($\sim 10^{13}$ ions/cm^3) will allow to isolate and identify particular excitation processes (e.g. excitation/recombination) and to study them as a function of the laser interaction. This in turn provides bench mark data for the more complex case of dense matter under extreme conditions. Ionization/excitation are the primary mechanism by which photons deliver heat to a sample and create high density plasmas. High intensity laser interaction with plasmas produce electrons at high energies (keV to MeV) via various overlapping processes (e.g. plasma instabilities), which effect the ionization balance and “Equation of State (EOS)”. The interpretation of the EOS for hot dense plasmas requires data of the ionization stages to determine the specific heat contributions. A question of fundamental interest is for example, to what extent a low density, equilibrium or non-equilibrium photo-ionized plasma consisting of multiple ionized atoms can be created and be probed in the density-independent, radiation dominated regime (e.g. in relevance to neutron-star accretion disk physics).

In short pulsed laser interactions multiple-ionization of atoms, using intense optical fs lasers, has been studied experimentally and theoretically resulting in mostly qualitative data (3). Many surprises were found and models are modified revised continuously. From a sequential ionization (4), i.e. 2+ comes from 1+ and 3+ via 2+ etc., to the tunneling ionization model and above threshold ionization, to a re-scattering model of the ionized electron that causes multiple ionization (5). In these cases the strong electrical field modulates the Coulomb potential and subsequent ionization processes are responsible for the degree of ionization (Fig.1).

For the studies with optical lasers the competition between sequential, non-sequential (electron re-collisions) has been investigated and is interpreted on the basis of tunneling and many body S-matrix scattering theory as well as applying e.g. the Lotz formula. The presence of a high ac electric field requires the field to be treated as a strong perturbation; the Stark effect e.g. in atoms (resonant) can be described by coupled light-matter states (“dressed” states). In non-resonant cases, non-perturbative phenomena occur such as above-threshold ionization, higher-order harmonic generation, the laser assisted photoelectric effect. The non-resonant, non-perturbative effects occur when the applied field is at the transition between the classical and quantum regime (limit of single photon effect). A measure for the field strength that defines this regime is the pondemorotive potential, U_P (represents the averaged "quiver" kinetic energy of an electron in an ac electric field). U_P is given as: $U_P = (e^2A_0^2)/(4mc^2) = [(2\pi e^2)/(mc)]/(I/\omega^2)$ with I being the intensity of the electric field at the frequency ω and A_0^2 the amplitude of the electric field vector potential. If U_P is comparable to e.g. the ionization energy (E_{IP}) non-pertubative effects appear (see $\gamma = \sqrt{E_{IP}} / U_P < 1$ the Keldysch parameter(6). It is noted that the "quiver" energies can reach ~3MeV leading to relativistic degenerated electrons.

The majority of data has been obtained for neutral targets and clusters (7), where the later shows enhanced ionization probabilities. For clusters an important phenomena is the strongly increased energy absorption compared to the single atom case. The mechanisms, depending on the cluster size, are the enhanced ionization for small clusters, resonant coupling of the laser frequency to a collectively oscillating electron cloud in intermediate clusters, and the effective energy absorption by plasma oscillations resonantly coupled to the laser frequency in large clusters. Laser interactions with clusters or micro-plasmas can be viewed to some extend as an intermediate situation between the single atom case and complex plasmas.

Very little work has been done so far with optical high intensity lasers on the ionization of <u>ions</u> and particular highly charged ions as they are present in HEDP cases. So far only singly charged ions were investigated with strong laser fields. Recently data on singly and low charged ions have been published, showing a strong suppression of non-sequential processes. Evidence for the re-collision model has been found from the suppression of non-sequential processes using circular polarized fields and from analyzing the recoil ion momentum distribution (8, 9, 10, 11). In the re-collision process the electrons may occupy bound states of the parent atom and then release energy in form of short coherent EUV or x-ray bursts. The re-colliding electrons are "wiggling" in the Coulomb field of the parent atoms, generating higher harmonics potentially reaching very high harmonic numbers with multiply-charged ions depending on the laser determined re-scattering process and the ion species.

Future experiments will also utilize the XFELs in the x-ray regime (e.g. the LCLS at Stanford (12), XFEL at DESY (13)). The extreme peak power of XFEL beams creates new research opportunities in atomic physics. Here first experiments will produce and study atoms/ions in excited states never before accessible in the laboratory (e. g. by combining intense optical lasers as “pump” (ionization) and the XFEL as “probe” (excitation) or visa versa).

The intense upcoming photon sources (XFELs, petta-watt lasers (short/long pulsed)) where field strengths and photon energies become comparable to the electron binding strengths, make experiments on multiple charged ion plasmas possible, to obtain qualitative and quantitative data for the ionization stage evolution in the plasma. The XFELs provide for a high frequency (short wave-length) multi-cycle strong field modulation, where its photons cause “direct” ionization of the inner-shells as well as multiple-ionization (Fig.1). Here e. g. ionization/excitation in higher Z ions with high electron densities is of interest. With the XFELs, it will be possible to observe the behavior of atoms/ions that have absorbed many x-rays in rapid succession or that have been struck simultaneously by e.g. two x-rays. The ionization will be sufficient to ionize all the inner-shell electrons from an ion, producing "hollow" ions in exotic excited states. Such experiments are of key importance in understanding energy transfer and plasma energetics, they include studies of radiation and possibly lasing from an FEL highly excited plasmas. With pulses in the range of a few femto-second, it will be possible to study how electrons move within a highly excited atom as it transits from one state to another.

The paper describes the novel plasma target facility for the experimental investigation of interactions of strong electromagnetic fields with an electromagnetically confined neutral/non-neutral plasma at adjustable densities ($<10^{13}/cm^3$). The laser used for the first test experiments described here is the short pulsed lasers PHELIX (petta-watt) laser (14) at the GSI-Darmstadt.

The Plasma Target Facility

A plasma target device based on the design of an “Electron Beam Ion Trap (EBIT)”, has the advantage that one can breed charge states and study photon field induced multiple ionization/excitation starting from different initial charge states. The studies can be performed by observing photon emission from the plasma in situ or by analyzing the extracted ion charge state distribution. Electron beam ion trap style sources have been used for years to produce low emittance, low kinetic energy beams of highly charged ions (15, 16, 17) for surface physics studies, for re-trapping and laser cooling of highly charged ions (18, 19) and for in-situ x-ray spectroscopy (20, 21). The specially designed electron beam ion trap (Fig.2) as an ion or ion/electron low density plasma ($<10^{12}/cm^3$) target facility, resembles an open cylinder Penning trap geometry (Fig.3), where an electron beam passes through three axial drift tubes as trap electrodes inside a cryogenic super-conducting 3T magnet. The plasma is produced and confined in the center drift tube. The ions are confined radial by the space-charge of the compressed, high density ($10^{12}/cm^3$) electron beam and magnetic field while axial confinement is provided by appropriate biasing the trap drift tubes; the trap biases are superimposed on a high voltage potential which determines the electron beam impact energy. The electron beam energy, intensity and the ionization time determine the achievable charge state distribution via successive electron impact ionization. The target facility provides selectively narrow charge state distributions of highly charged ions up to about U^{80+}. The base vacuum in the plasma region is maintained at 10^{-11} Torr. The ion plasma target is equipped with especially designed windows and apertures to allow the high power laser beams to interact with the plasma without distorting the vacuum or cause background effects. The plasma target device has an innovative design, using new cryogenic vacuum technology, which allows the trap core to remain at the nominal super-conducting operation temperature without relying on liquid gas cooling (22, 23) and allows easy access as well as transfer to different target locations. During testing and performance verification (22), highly charged Ar- and Xe-ions have been produced in a commercially available device temporarily used for testing at the Lawrence Berkeley Laboratory (19). In that device the ions were produced using up to a 15 keV electron beam energy at a beam currents of 50 to 100mA, a confinement time of 500ms and a saw–tooth extraction pulse with an extraction base width of 100ms. The extracted ions are, focused, momentum analyzed in a 90^0 analyzing magnet and detected with a multi channel plate (MCP) detector and Faraday cup. The measured ion yields for Ar^{18+} and Xe^{45+} ions are 10^7/sec in a less than 1mm spot 2.5 m from the trap; the emittance of the ion beams is 0.3π mm mrad.

To verify the time dependence of the extracted ion pulses from the center drift tube (trap), the pulse, which triggers the rise of center drift voltage above the top drift tube voltage, can be compared to the analyzed ion signal detected with the Faraday cup. The ion extraction can be accomplished in micro-seconds as reported in the literature (19). The measured time delay verifies that the ions are produced in the trap. The extracted Xe ions are momentum analyzed in an analyzing magnet (see e.g. Ref. 24).

Different experimental scenarios can be arranged for laser plasma interaction studies. Laser injection can be accomplished by focusing the laser through side windows on to the target. A coaxial laser arrangement with the plasma, along the magnetic field axis of the trap can be arranged as well.

Higher density target plasmas are generally obtainable by increasing the electron beam current and magnetic field. It is noted that these increases will significantly raise the plasma ion temperature prior to the laser interaction. The open trap geometry and electron beam space charge trapping can also be used to produce plasma targets from radial inserted solid microprobes or from a gas “puff” target.

Experiment Scenarios and First Tests

A scenario for the laser/plasma interaction studies has been tested in a first experiment at the GSI PHELIX laser. The EBIT used to produce the plasma target, has been provided temporarily by the University of Stockholm (Atomic Physics Department). For the tests a high intensity laser beam (10^{14} W/cm^2 has been focused onto the confined electron beam/ion plasma target ($e + Xe^{q+}$) through a side window (Fig. 2). The laser injection set-up and a ray tracing simulation is shown in Fig.3a. (e. g. rotation of the focusing mirror allows changing the circular point focus (e.g. 30 μm) to a well defined elliptical focus to match the target geometry).

In the first test experiments, low energy photon emission, x-ray emission and extracted ions have been detected with and without laser interaction. A solar blind photomultiplier was mounted behind a quartz window on top of the EBIT chamber to detect the emission of low energy photons perpendicular to the interaction region. The broad energy range of the photo multiplier of < 200eV is determined by the window's transmission and the multiplier detection efficiency. A small solid angle x-ray Si-detector (AMTEK) viewed the same interaction region as the photomultiplier through a Be window at another side port on the EBIT. Highly charged ions were extracted from the plasma in a pulsed mode by ramping the center drift tube potential with and with out laser interaction. The ions were momentum analyzed in a 30^0 bending magnet and detected with a position sensitive channel plate detector. Extracted ions were also analyzed via their emission of radiative de-excitation ("hollow" atoms) radiation following the surface interaction at a thin Be window on a straight through beam line port in the analyzing magnet; these x-rays were detected with Ge detector. The photon emission and ion extraction detection has been gated to the laser pulse timing and the data acquisition was done in event mode. The laser focus of e.g. 30μm diameter matches the ion volume in EBIT of nominal 60 μm diameter at 3T. Laser beams of 40ps pulses length of typical 10^{14} W/cm^2 power density from the PHELIX petta-watt laser (0.01 Hz) and of low power density (10^{12} W/cm^2) from the seed laser at 1Hz have been used. These first tests demonstrated the capability to focus a high power laser beam onto an electron beam/ion plasma target without distortion of the sensitive plasma confinement conditions (electromagnetic field, 4 K temperature, vacuum $<10^{11}$ Torr). Various tests have been performed to ensure that the laser intensity is focused onto the confined electron ion plasma target without scattering at the entrance slits at the center drift tube or any other aperture in the laser path. Through a variation of the electron beam energy and the time delays between ion extraction and laser pulse injection various tests have been performed which confirmed functioning of all the plasma confinement conditions (e. g. trapping potential). The confinement conditions can be varied in future experiments to enable studies of the effects on the ion charge state distribution and possibly of the plasma equilibration dynamics under well controlled and selected conditions.

The tests showed, e.g. from the low background condition, that it will be possible to observe (simultaneously or in coincidence) the x-ray emission and ion extraction from the confined ion plasma. The application of the different laser conditions will explore to what extend the strong time varying electromagnetic field pulses of the laser affect the ionization stages and their temporal development in the ion plasma. First evidence for significant effects on the photon emission from the plasma was observed which indicates the possibility to identify "signature" processes for this type of laser/plasma interaction. The relevant laser parameters are given in TABLE I together with the ion/electron plasma target parameters.

We summarize in the following some of the evidence for effects from the first laser/plasma interaction experiments:

1) Photon detection in photomultiplier on top view port:

Large photon (<200eV) bursts following the high power (HP) PHELIX laser beam interaction at >10^{14} W/cm^2 with an electron beam/Xe^{q+} ion plasma, are observed. No photon emission was observed, when the electron beam was turned of. The HP laser has a repetition rate of 3min. In between the HP laser pulses, a low power (LP) laser at 10^{12} W/cm^2 with a repetition rate of 2sec was turned on and smaller (factor 10) photon "bursts" were observed. These intensities appeared to decay exponentially over 3min (HP laser repetition rate). Each laser pulse is followed by an ion extraction cycle 150ms and "reloading" (300ms) of the trap.

This observation might be explained by the laser causing electron excitation into high n states in the 3T field (Landau states?) followed e.g. by laser induced radiative de-excitation. The decaying photon intensities may reflect the decreasing yield of highly excited electrons due to recombination (and cooling).

2) Highly charged Xe ions have been extracted and unanalyzed been used to bombard a thin Be window at the end of the straight beam line section in the analyzing magnet chamber.
The observation of radiative de-excitation x-rays confirme the extraction of highly charged Xe ions (not analyzed) centered around 44+ in agreement with earlier results. No effect from the laser interaction (e.g. energy shift due to change in the charge state distribution of highly charged Xe ions) could be seen due to low counting statistics. The charge state distribution could vary due to effects on the ion heating and an effective change of the trapping potential caused by the laser interaction.

3) For the momentum analyzed ions the overall yield of extracted ions seemed to be increased through the presence of the laser interaction (about 20%) which could be due to a temporary change of the effective trapping potential. This effect could be interesting if verified in future experiments for creating short pulsed HCI extraction with subsequent short pulsed x-ray emission following radiative de-excitation in a solid surface target.

At XFEL facilities higher photon energies, intensities and repetition rates are available, which enable the conductance of a new class of photon/confined multiple charged ion plasma interaction studies. It is possible to investigate the interaction of high intensity, short wavelength up to 8keV (0.15-1.5nm) photon beams (LCLS) with low density electromagnetically confined neutral/non-neutral multiple-charged ion/electron plasmas. Strong field and x-ray induced/assisted atomic multiple ionization/excitation processes, could possibly be investigated. For example it is expected to observe effects from the strong electromagnetic laser fields on the ion charge state distribution in the plasma with and without the presence of the electron beam. The effects will be detected by momentum analyzing the extracted plasma ions and by measuring the x-ray emission from the interaction region. Some expected XFEL (LCLS) parameters are given in TABLE I for comparison with the (PHELIX) laser parameters.

Another class of experiments could utilize the extraction of HCI beams and their interaction with surfaces. Here the ions would act as “pump” for example. Large cluster emission has been reported from HCI impact and subsequent laser cluster interaction studies could be conducted on uniquely formed clusters such as $(SiO_2)_{22}$, $(UO_2)_{14}$ .Other studies could utilize the formation of dense rather hot micro-plasmas at the surface impact sites of HCIs. A probing laser beam focused onto the micro-plasma would allow to study correlation and inverse bremsstrahlung effects in such (strongly coupled, “warm dense matter”) plasmas.

Conclusion

We demonstrated the feasibility to use an electron beam ion trap as a plasma target facility for intense laser beam interaction studies. The laser experiments are aimed to gain understanding of the effects of intense photon fields on ionization/excitation processes, the ionization balance, as well as photon polarization effects on confined in charged particle plasmas. The low density plasma target ($\sim 10^{13}/\mathrm{cm}^3$) is confined in a cryogenic electromagnetic trap, with the magnetic confinement field of 1-3T maintained by a superconducting magnet. First experimental scenarios have been demonstrated and various tests have been performed, which confirmed functioning of all the plasma confinement conditions (e. g. trapping potential) during the intense laser interaction. The tests also showed that it will be possible to observe (simultaneously or in coincidence) the x-ray emission and ion extraction from the confined ion plasma during the laser interaction.

TABLE I

Electron/Ion Plasma Target:	
Magnetic Field	3 Tesla
Electron Beam energy	30 keV
Electron beam current	150 mA
Electron beam radius (trapped ion volume)	37 µm
Central current density	4 $\mathrm{kA/cm}^2$
Trap length	2 cm
Electron density	$10^{11}/\mathrm{cm}^3$
Ion density	$10^{11}/\mathrm{cm}^3$

PHELIX Laser	
Wave length	1054 nm
Energy	2.5 J
Focus	40 micron
Pulse duration	500 fs (Long pulse 10ns)
Repetion Rate	3 min
E-Field (V/cm):	1.7 10^{10}, B-Field: 5800T

LCLS (Linear Coherent Light Source)
Wave-length 0.15-1.5nm
Peak (average) brightness 10^{33} (average 10^{20}) photons s^{-1} mm^{-2} mr^{-2} $(0.1\%\text{bandwidth})^{-1}$
Pulse duration <230fs
Repetition rate 120Hz

References

1. Connecting Quarks with the Cosmos: Eleven Science Questions for The New Century (National Academies, 2003)
2. Frontiers in High Energy Density Physics – The X-Games of Contemporary Science (National Academies Press, 2003)
3. G. D. Gillen, M. A. Walker, and L. D. Van Woerkom, Phys. Rev. A **64**, 043413 (2001)
4. A. l'Huillier, L. A. Lompre, G. Mainfray, and C. Manus, Phys. Rev. A 27, 2503–2512 (1983)
5. J. B. Greenwood, I. M. Johnston, P. McKenna, and I. D. Williams, Phys. Rev. Lett., 88, 233001-1 (2002)
6. The Science and Applications of Ultra-fast, Ultra-intense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man (Report on the SAUUL Workshop, June 17-19, 2002)
7. Chr. Siedschlag and J. M. Rost, PRL 93, 4, 04302-1 (2004)
8. T. Weber, et al. Phys. Rev. Lett. 84, 443 (2000), D. N. Fittinghoff, P. R. Bolton, B. Chang, and K. C. Kulander, Phys. Rev. Lett. 69, 2642–2645 (1992)
9. P. B. Corkum, Phys. Rev. Lett. 71, 1994–1997 (1993)
10. R. Lafon, et al., Phys. Rev. Lett., 86, 2762 (2001), A.H. Chin, J. M. Bakker, J. Kono, Phys. Rev. Lett., 85, 3293 (2000)
11. R. Moshammer et al. Phys. Rev. Lett. 84, 447 (2000)
12. PHELIX (GSI) Ref.?
13. www.-ssrl.slac.stanford.edu/lsls/
14. http://tesla.desy.de/
15. D. Schneider et al., Phys.Rev.A, 44(5) 3119 (1991)
16. T. Schenkel, A. Hamza, A. Barnes, D.Schneider Prog. Surf. Sci. 61, 23 (1999)
17. T. Schenkel...D. Schneider, SPIE Proceedings, V4656 (Quant. Dot Devices and Computing)

18. D. Schneider, D. A. Church, G. Weinberg, J. Steiger, B. Beck, J. McDonald, E. Magee, D.A. Knapp, Rev. Sci. Instrum. 64, 3472 (1994)
19. L. Gruber, J. Holder, D. Schneider, Physica Scripta ....(2004)
20. R. Marrs, P. Beiersdorfer, D. Schneider, Phys. Today 27 (1994)
21. P. Beiersdorfer, AIP Conference Proceedings No. 389 (AIP, New York, 1997), p. 121
22. R. Schuch (Plasma target set-up for laser interaction experiments at the University of Stockholm, Sweden 2004, private communication)
23. T. Schenkel (Highly charged ion applications for surface physics, Lawrence Berkeley National Laboratory 2004, private communication)
24. J. McDonald and D. Schneider, NIM B 241 (2005) 870

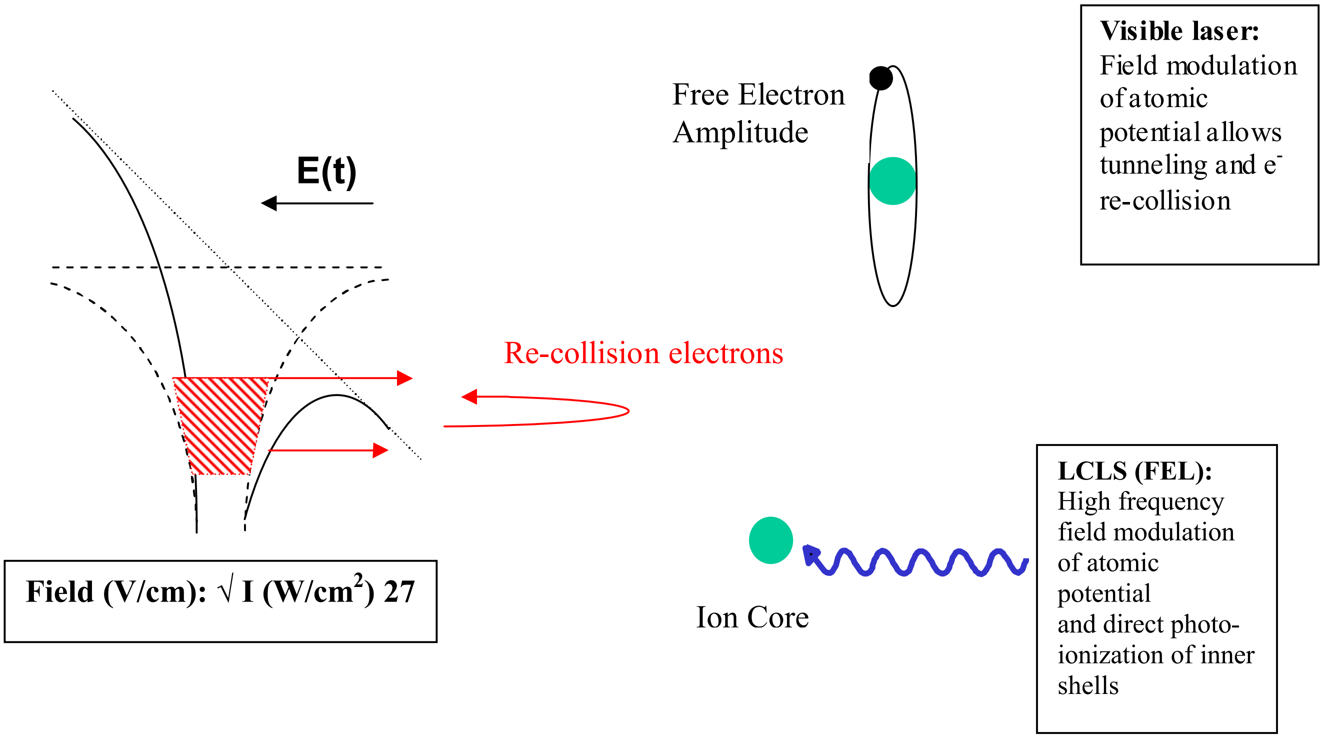


Fig.1 Long- and short-wave-length laser/atom interactions

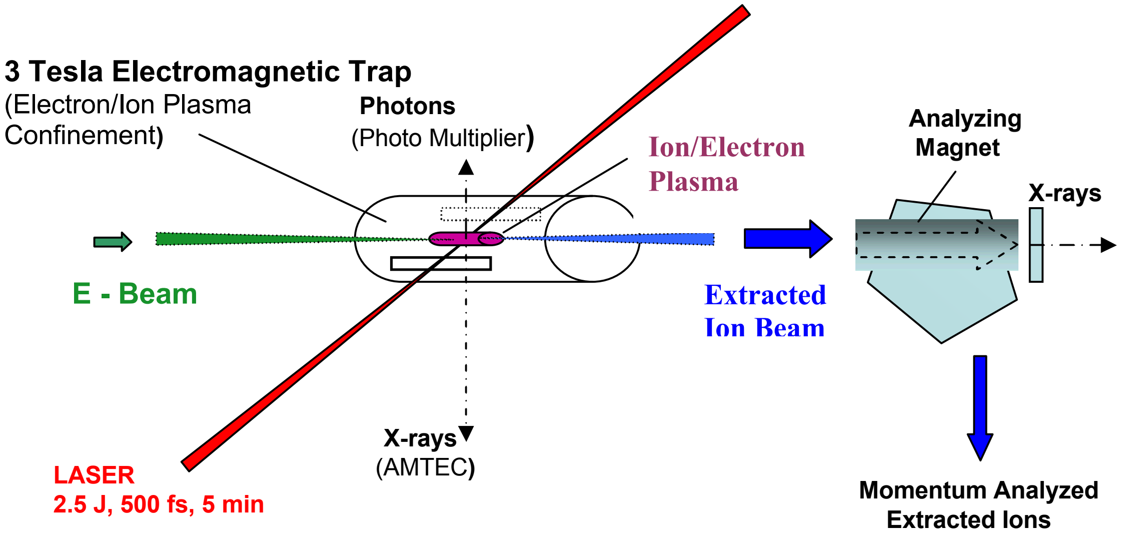
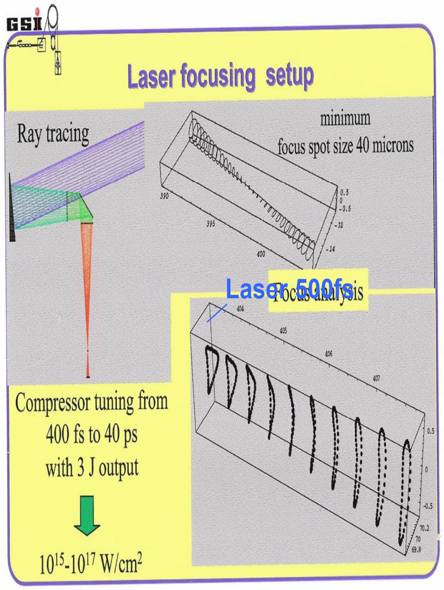
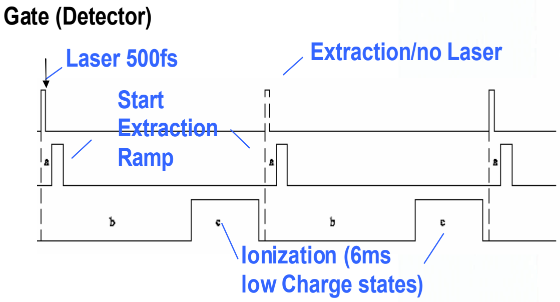


Fig.2 Schematic of experimental set-up

Laser Beam/Confined Plasma Interaction Studies

-Laser Focus- Timing Pattern -





Gate (Detector)

Laser 500fs

Extraction/no Laser

Start Extraction Ramp

Ionization (6ms low Charge states)

(e.g. a:1ms; b:41ms; c:6ms, TL – TL: 100ms; TL – TNL:50ms)

(other experimental „modes“ e.g. e$^-$ off during laser; DR measurements and fast switching to resonances)

Fig.3a) Ray-tracing results of focusing the laser beam onto electromagnetically confined ion or electron/ion plasma.

Fig.3b) Timing structure for ion injection, laser pulse injection, and extraction