PHELIX – a Petawatt High-Energy Laser for Heavy Ion Experiments

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ABSTRACT

The unique combination of an intense heavy ion beam accelerator and a high energy laser opens the possibility of exploring new physics taking advantage of the synergy of both facilities. A variety of new fields can be addressed with this combination in plasma physics, atomic physics, nuclear- and astro- physics as well as material research. In addition, using CPA-technology (Chirped Pulse Amplification), laser pulses with a pulse power of up[1] to a petawatt opens the door to explore the regime of fully relativistic plasmas. Therefore the Gesellschaft für Schwerionenforschung (GSI) is augmenting the current high intensity upgrade of the heavy ion accelerator facility with the construction of PHELIX – a Petawatt High Energy Laser for heavy Ion Experiments. Designed with two pulse-generating front ends and send to multiple experimental areas PHELIX will serve as a highly versatile laser system for various applications[1]. In this report, we present the design of the laser system and some key experiments that can be performed with this combination for the first time.

Keywords: Laser, heavy ion beams, laser-plasma interaction, x-ray laser

1. INTRODUCTION

Worldwide, the majority of fundamental research in plasma physics, atomic- and nuclear physics, experimental astro physics and material research is based on either particle accelerators or lasers. Both are complementary in their specific capabilities. Whereas lasers are able to produce the highest temperatures and pressures (with exception of energetic nucleus-nucleus collisions) as well as short pulse x-ray flashes, particle accelerators are able to produce larger samples of homogeneously heated matter, create nuclear isotopes far off stability, and generate highly charged ions at energies tailored to the required experimental needs.

To take the advantage of both specific capabilities for the first time a combination of a highly developed particle accelerator with a high energy laser system will be set up at the Gesellschaft für Schwerionenforschung (GSI). In this configuration the ion beam and the laser beam are designed to work as the driver for experiments as well as a probe beam to diagnose the experimental parameters. After completion of the high current upgrade of the accelerator facility GSI can provide the highest heavy ion intensities world wide. The heavy ion beam energy deposition in matter is expected to increase up to 100 kJ/g leading to matter temperatures of up to 10 eV at solid state density. The high ion beam intensity also leads to the highest yields of highly charged heavy ions and exotic nuclei for precise measurements of their nuclear and atomic properties. The addition of the kilojoule high intensity laser system PHELIX will further extend the experimental capabilities. It will either serve as a driver to generate targets for ion beam matter interaction or as a diagnostic tool to probe the properties of matter generated by the ion beam. Therefore it was mandatory to design the laser system as versatile as possible to fulfill the different experimental requirements and to guide the laser beam to several experimental areas.

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2. DESIGN OF THE PHELIX LASER

The PHELIX system is designed to deliver several kilojoules of laser energy within a pulse in the nanosecond range as well as to generate pulses of highest intensities up to a petawatt power in a sub-picosecond pulse. Based on current technology and cost restrictions the system is designed to be a flash-lamp pumped, all solid state Nd:Glass laser in MOPA (master oscillator - power amplifier) geometry with two different front ends working either in a narrow bandwidth or CPA (chirped pulse amplification) mode. The laser geometry is designed to operate in double pass geometry to efficiently use the energy stored in the main amplifiers. The layout of the system is shown in figure 1. For the different requirements determined by the experiments described in chapter 3 the front ends were designed as follows:

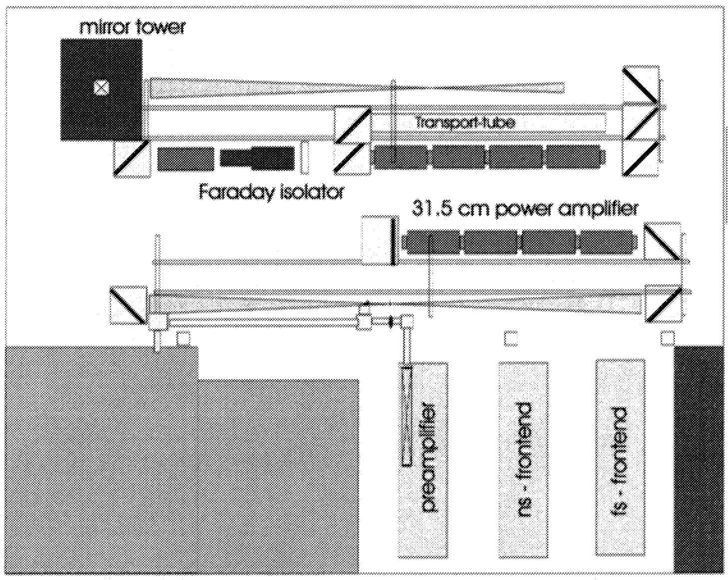

Figure 1: Layout of the PHELIX laser.

1. Nanosecond front end

The nanosecond front end is based on a diode pumped DFB-fiber laser. The cw laser light is then chopped by an acousto-optic modulator, amplified in a diode pumped, double pass fiber amplifier and send to a combination of an amplitude and phase modulator section. By generating arbitrary electrical signals it is therefore possible to obtain temporarily shaped laser pulses between 0.5 and 20 ns. The phase modulation of the laser light is sufficient to suppress SBS (Stimulated Brillouin Scattering) that might damage the larger optics as well as to allow modern beam smoothing techniques like SSD (Smoothing by Spectral Dispersion) to guarantee homogenous target illumination. The laser light is then launched into a ring-regenerative amplifier to be amplified up to a pulse energy of 20-50 millijoules. The front end was build in collaboration with the Lawrence Livermore National Laboratory (LLNL) similar to the latest design for the National Ignition Facility (NIF)[2]. It is capable to operate at a repetition rate of 0.2 Hz.

2. Femtosecond front end

Pulses within the femtosecond range require an oscillator, which is able to provide enough bandwidth for chirped pulse amplification. Therefore, a commercially available, all solid state Ti:Sapphire oscillator is used. Unlike similar systems the mode-locked laser is forced to work at the wavelength of 1053nm to match the gain profile of the Nd:Glass power amplifiers. The pulse is generated initially with a pulse duration of 130 fs and then stretched to 1.5 ns to reduce the fluence in the amplifier chain. Two regenerative Ti:Sapphire amplifiers boost the pulse energy up to the level of 20-50 millijoules similiar to the design of the Petawatt[3] laser system built and operated at LLNL. Both front ends are designed to be fed into the preamplifier section at the millijoule level to allow either the long or short pulse operation.

3. Pre-amplifier

The preamplifier increases the respective laser energy up to the Joule level by means of flash lamp pumped Nd:glass rod amplifiers. Two 19mm and one 45mm amplifier are used for that purpose. For the needs of certain experiments it was highly desirable to maintain a high repetition rate at this energy level. Therefore the 19 mm laser amplifiers are designed to work at a repetition rate of 0.2 Hz. In collaboration with the Max-Born Institute a novel, high repetition 45mm laser amplifier will be designed.

4. Main amplifier

The laser beam is inserted into the main amplifier section close to the center of the relay-imaging spatial filter shown in figure 1. For the amplification of the laser light up to the kilojoule level the PHELIX laser is using 31.5cm flash-lamp pumped Nd:glass amplifiers decommissioned at the NOVA and PHEBUS laser. Four amplifiers are double passed to reach at least one kilojoule within 10 ns pulse duration and about 600 J for the CPA design. An additional set of 5 booster amplifiers is used to further increase the output energy up to 4-6 kJ for the nanosecond option. Due to the limiting damage threshold of the compressor gratings the booster amplifiers are bypassed by the CPA pulse. Backreflected light will be isolated from the smaller optics by means of a full aperture Faraday isolator. Due to the gain narrowing of the pulse bandwidth during the amplification in the main amplifiers, the final pulse length is restricted to 450 fs.

5. Petawatt

The stretched pulse from the fs-frontend is amplified up to at least 600 J by the main amplifier section. For the final pulse compression large aperture gratings are required. They will compress the pulse to approximately 450 fs to achieve at least one petawatt pulse power. To further reduce the pulse length the use of an acousto-optic programmable dispersive filter is projected, which may decrease the pulse length down to 250 fs. The large aperture compressor gratings will be installed in a vacuum compressor chamber close to one of the experimental areas. The area is shielded to contain the gamma ray flash as well as neutrons and other hazardous radiation expelled from the irradiated target. To maintain a beam quality sufficiently high to achieve on-target intensities exceeding 10^{20} W/cm^2 an adaptive optics will be integrated into the system.

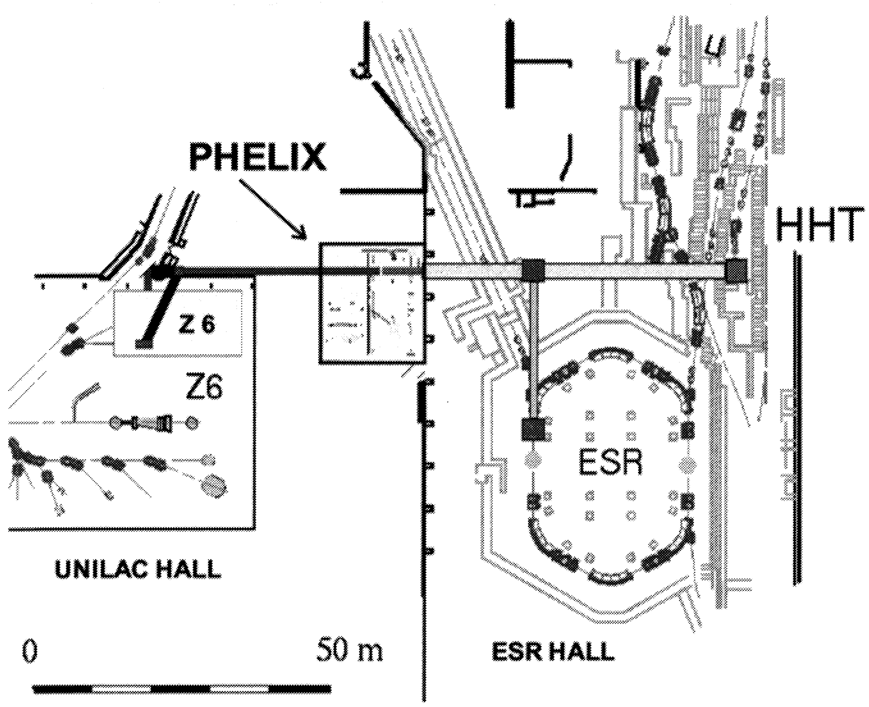

Figure 2: The PHELIX laser is integrated into the GSI accelerator structures to minimize the distance from the experiments and to keep the number of turning mirrors as small as possible.

6. Beamline

The laser light is lead to a mirror tower to be deflected upwards and to the different experimental areas. The target areas of the plasma physics group (named Z6 and HHT) and of the atomic physics group (at the ESR) will serve as the main users of both the ion and the laser beam. Vacuum spatial filters are used to suppress beam inhomogenieties caused by diffraction and will relay the beam to the experimental areas. The position of the laser has been chosen to keep the distances to the different experiments short as well as the number of required full aperture mirrors small. Figure 2 shows the integration of PHELIX into the accelerator structures at GSI.

3. EXPERIMENTAL PROGRAM

The experimental opportunities of this unique combination of a high energy heavy ion beam and a powerful laser system are numerous. The synergetic effects are shown in Figure 3. In this chapter some of the key experiments are presented.

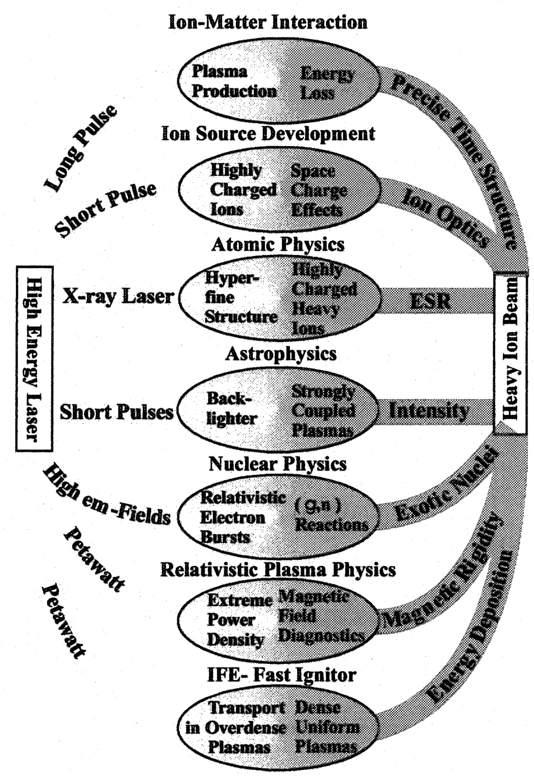

Figure 3: Synergetic experiments using high energy lasers and heavy ion beams

1. Plasma physics

Interaction processes of ion beams with matter have a wide range of applications to modify the material properties of the irradiated samples. If a multi-kilojoule beam is deposited in matter during a time span which is short compared to the hydrodynamic response time of the material, a state of high energy density is induced. In addition using expanding pusher targets, in planar and cylindrical geometry, states of high matter density can be produced in samples attached to these pushers. The yet widely unexplored region of the corresponding dramatic changes of material properties, like the metallization of condensed hydrogen or other molecular crystals, becomes accessible under reproducible conditions in the laboratory due to the now completed high intensity upgrade of the GSI accelerator facility[4]. Heavy ion beams are excellent tools for the generation of plasmas at solid state density because the deposition of the ion beam energy is well controllable and direct heating of a precisely known volume is achieved by its rather homogenous energy deposition. Thus they open new opportunities for the investigation of dense plasmas and will allow experiments with improved or complementary techniques[5].

To diagnose the equation of state of the samples detailed knowledge of the matter properties is required. To investigate the material parameters inside the sample x-ray backlighting techniques are a superior tool that can provide high spatial and temporal information. Because of the target size, line density and temporal evolution short bursts of energetic x-rays delivered from an almost point-like source are needed which can be generated by focusing a high energy laser pulse onto a high-Z target. PHELIX will be able to generate multiple, intense (>10^{15} W/cm^2) laser pulses as short as 500ps to avoid blurring from ion-beam target movement. The pulses can be chosen arbitrarily within a total length of 20 ns.

The investigation of interaction processes of high energy heavy ion beams with matter is a research topic with a long tradition at accelerator laboratories. At least for simple collision systems, a basic understanding of the dominant atomic and nuclear interaction mechanisms has been achieved. Since most of the matter, that constitutes our universe is in the plasma state, plasma are an interesting research object. Figure 4 shows a plasma map covering many orders of magnitude in temperature and density. Plasma targets used for experiments at GSI are shown in comparison with typical plasmas of astrophysical interest as well as fusion plasmas.

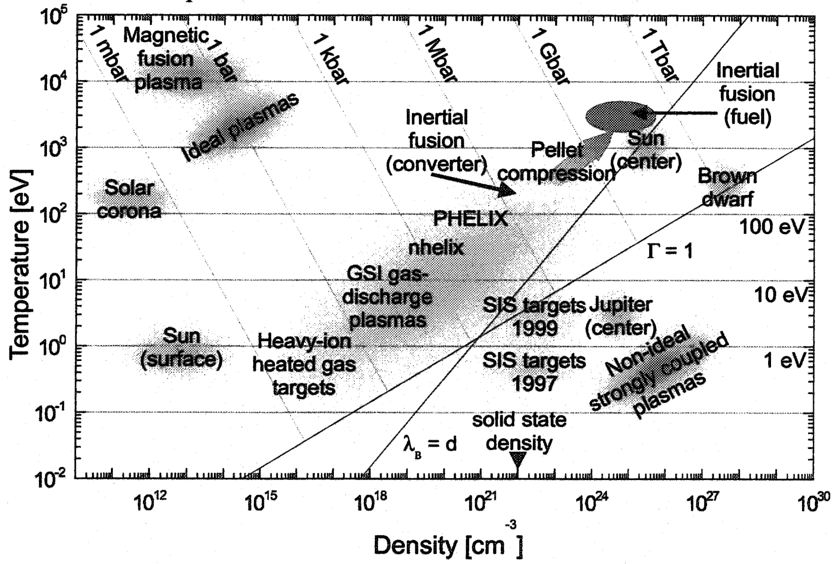

Figure 4: Astrophysical and laboratory plasma covering many orders of magnitude in density and temperature. The present and future experimental capabilities of GSI are shown.

Externally generated plasmas by means of gas discharges and laser produced plasmas were used to investigate the energy loss and charge state evolution of heavy ions in partially and fully ionized plasmas. With laser produced plasmas generated by the nhelix (nano-second high energy laser for heavy ion experiments) laser it was possible to generate temperature and density conditions close to those relevant for a heavy ion fusion scenario. The nhelix laser system (Nd:Glass laser 100 J, 8 ns) allows to generate carbon plasma targets for beam plasma interaction experiments with densities up to 10^{21} cm^{-3} at a temperature of 60 eV. The experimental set-up and results are shown in Figure 5. In the right part of the figure the results for the energy loss measured by a time of flight method are plotted as a function of the particle bunches caused by the rf acceleration. The first four bunches represent the constant energy loss in the cold matter followed by the enhanced energy loss in the plasma ignited by the onset of the laser pulse.

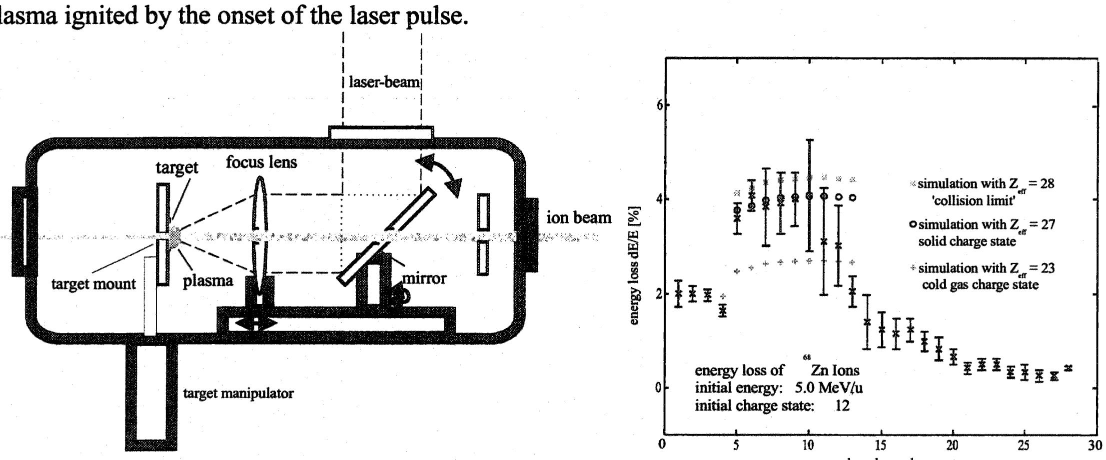

Figure 5: Heavy ion beam – plasma interaction experiments. Left: experimental setup. Right: energy loss measurement. After the constant energy loss in the cold matter (first 4 bunches), the enhanced energy loss is clearly visible. After 7 bunches (63ns) the energy loss is reduced due to hydrodynamic expansion of the target matter.

The following drop in energy loss is caused by the hydrodynamic expansion of the plasma. The experimental results could be reproduced by numerical calculations only assuming an increased effective charge state not observed in plasmas at lower density[6]. This has been confirmed by measurements of the resulting charge state distribution using a magnetic spectrometer.
At this point the limited energy delivered by nhelix does not allow a further increase of the target parameters temperature and density. Also fully ionized plasmas of higher atomic number are not achievable with the current laser system. PHELIX will serve as a driver for plasma targets closer to conditions that occur in heavy ion inertial fusion converters. The investigation of density effects of the stopping power of heavy ions in plasmas can then be extended by orders of magnitude.

2. Atomic physics

With the upgrade of the accelerator, which is in the commissioning phase at present, GSI can provide the highest yields of highly charged heavy ions worldwide. With the Experimental Storage Ring (ESR) these ions can be stored, cooled and their energy precisely be tailored for experimental studies of their atomic and nuclear properties. Beside nuclear masses (or binding energies), nuclear charge radii, spins, and nuclear moments are key information on ground state properties of atomic nuclei. They can be obtained by atomic spectroscopy. Such measurements are especially favorable at GSI, where all elements up to uranium can be obtained in a specific charge state (bare, hydrogen-like, helium-like and so on). A large number of radioactive isotopes are available at the fragment separator (FRS) by fragmentation or fission. Although the information on nuclear ground-state properties extracted from a study of hyperfine structure and isotope shift are model independent, it is hampered in complex neutral atoms by the accuracy with which the electron wave functions are known at the site of the nucleus. In that respect, it is highly advantageous to measure these effects on highly charged heavy ions, where the electron wave function can be calculated very precisely. Lithium-like ions are most suited for the experiments presented here since they represent a good compromise between the request for reliable calculations of the electronic factor and low atomic excitation energy.
The development of new x-ray lasers by the use of high power lasers is a very interesting subject in itself for laser physics as well as for atomic physics. For the study of hyperfine structure and isotope shift in lithium-like systems up to uranium, lasers capable to deliver photons in the energy range of 100 eV are required. The combination of a nanosecond laser pulse followed by a sub-picosecond laser pulse has been shown to be an efficient table top x-ray laser.[7] Using such a scheme, lasing has been reported for example in a Ni-like palladium plasma at 14.7 nm [8]. The 10 J chirped pulse front end of PHELIX will be an ideal pump source for such an x-ray laser.

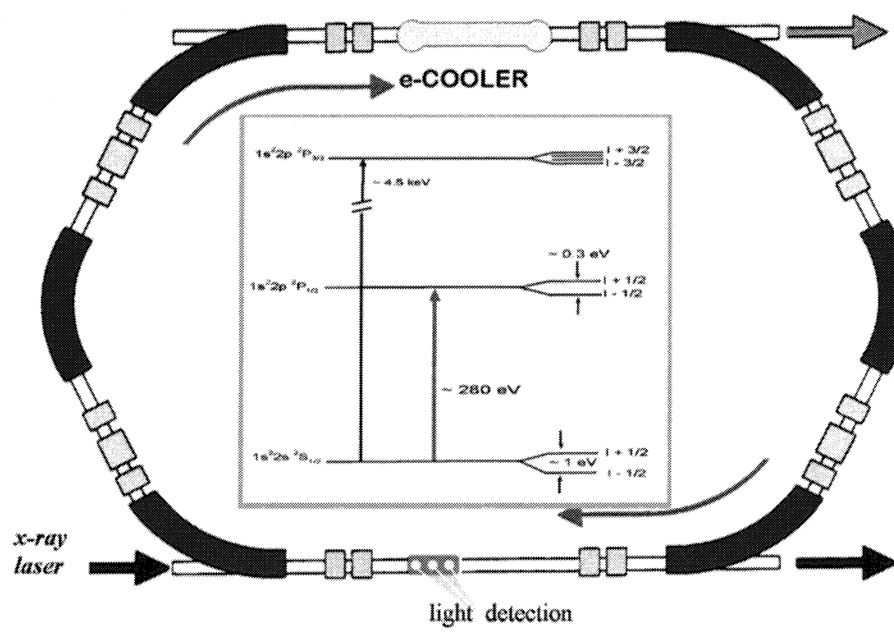

Figure 6: X-ray laser spectroscopy on highly charged heavy ions in the ESR. Due to the Doppler shift the photon energy can be matched precisely to the hyperfine transitions for example in lithium like uranium.

Using such an x-ray laser on highly charged heavy ions, absolute radii can be determined instead of only changes in charge radii between two isotopes due to the well known electron wave function. Furthermore in combination with measurements of the matter radius, neutron radii can be determined. This adds a new quality to studies of hyperfine structures and isotope shifts. The layout of the ESR is shown in figure 6 together with a level scheme of lithium-like uranium. For the $^2S_{½} \rightarrow ^2P_{½}$ transition in uranium a photon energy of 280 eV is required. At ESR energies, photon energies in the laboratory frame of 110eV would be sufficient to induce this transition due to the Doppler shift.
Since the emitted photon after the laser excitation again will be Doppler shifted, high detection sensitivity and a good suppression of scattered light can be reached. Since tuning can be done via the Doppler shift in the ESR, a fixed-frequency laser can be used.

3. Ion source development

Conventional accelerator technology relies on ion sources where low intensity ion beams are extracted in general also at low charge states. At present GSI is using an ECR (Electron Cyclotron Resonance) ion source as a high charge injector. A petawatt-class short-pulse laser may produce a high number (10^{12}) of ions with low ion temperature (100 eV), a low momentum spread and a charge state distribution that can be narrowed down to essentially a single charge state. These conditions are ideally suited to explore the effects of space charge on ion beams, a problem which has to be addressed with respect to future high current facilities.
Another possibility is to use the high electric field of the sub-picosecond laser pulse to field-strip pre-accelerated, low-charge heavy ions into a higher charge state to increase the efficiency of heavy ion accelerators.
Finally, recent experiments at the Petawatt Laser at LLNL, direct ion acceleration has been shown, that results in a well collimated beam of ions at MeV energies. These ions were accelerated due to an electric sheath separation field in laser solid target experiments. Figure 7 shows the basic idea of the acceleration drawn by Wilks [9].

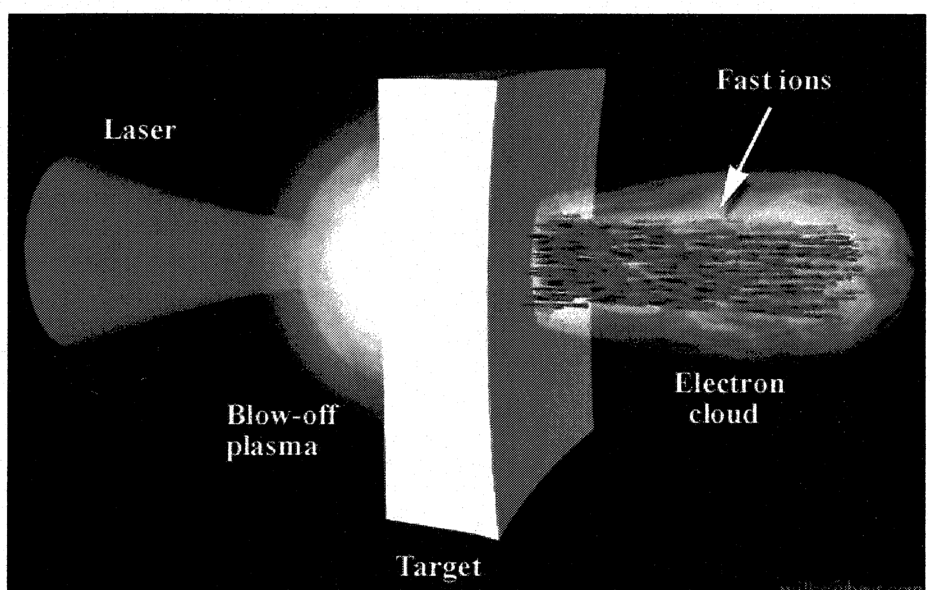

Figure 7: Sketch of the proton acceleration (by Wilks). The main laser beam is interacting with the blow off plasma produced by the pre-pulse. A large number of hot (several MeV) electrons are produced that penetrate the target and form an electrostatic acceleration sheath at the rear surface, where a steep density gradient results in accelerating fields of MV/μm.

The efficiency of converting the laser light into accelerated ions was found to be as high as 7% leading to a total yield of more than 10^{13} ions (protons) [10]. The investigation of these ion beams is a highly interesting topic for an accelerator laboratory, especially to address the question of capture and further acceleration of the ejected ions.

4. Fast ignitor research

The concept of fast ignition was introduced by Tabak[11] to reduce the requirements for the primary driver and to enhance the gain in inertial confinement fusion. The idea is to compress a deuterium-tritium filled microsphere by irradiating the outer surface and by conservation of momentum to compress the inner part. In contrast to the conventional central spark ignition the fast ignitor scenario attempts to compress the nuclear fuel relatively cold and to ignite the compressed pellet at the moment of highest density by an externally generated hot spot. The hot spot then launches a burn wave through the fuel as shown in figure 8.

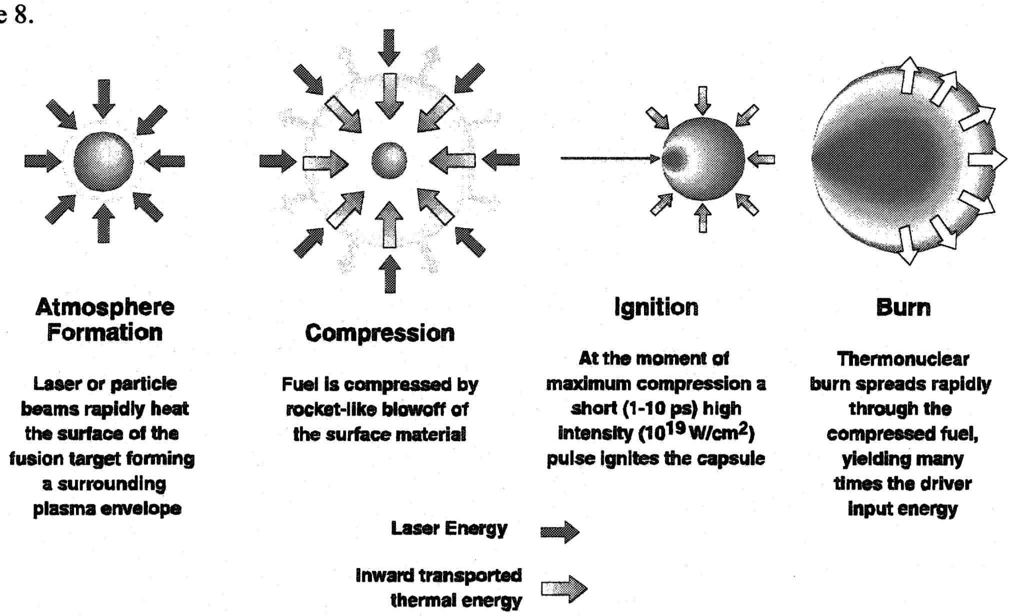

Figure 8: Diagram of Fast Ignition concept in inertial confinement fusion.

To ignite the fuel the required amount of energy has to be delivered in a time shorter than the disassembly time of the pellet, which is in the order of picoseconds. The investigation of the concept of fast ignition was the main motivation to build the first petawatt laser system at LLNL. A variety of questions could be addressed by the experiments performed at this laser, but some key questions are still to be answered. One of the most important question is if the laser generated hot electrons, which are supposed to transport the energy into the compressed fuel beyond the point the laser light is able to reach, are able to maintain a collimated beam to deposit the energy into the hot spot. The propagation of petawatt pulses into strongly overdense plasma can ideally be explored by the use of heavy ion generated plasma. These plasma are macroscopic, homogenous, at solid state density (or even higher) and generated without a lot of radiation which increases the signal to noise ratio and allows the precise measurement of the electron propagation.
Furthermore due to the discovery of the intense proton beam emerging from the rear surface of solid targets irradiated by petawatt class lasers, also the investigation of proton driven fast ignition can and will be addressed.

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