17th International Symposium on Heavy Ion Fusion

HIF2008

Tokyo Institute of Technology
Tokyo, Japan

August 4-8, 2008

Organized by
Research Laboratory for Nuclear Reactors,
Tokyo Institute of Technology
International advisory committee

Roger Bangerter, Lawrence Berkeley National Lab., USA
John Barnard, Lawrence Berkeley National Lab., USA
Mikhail Basko, ITEP, Moscow, Russia
Debra Callahan, Lawrence Livermore National Lab., USA
Ronald Davidson, Princeton Plasma Physics Lab., USA
Alex Friedman, Lawrence Livermore National Lab., USA
Dan Goodin, Gen. Atomics, San Diego, USA
Dieter Hoffmann, GSI Darmstadt, Germany
Ingo Hofmann, GSI Darmstadt, Germany
Kazuhiko Horioka, Tokyo Institute Technology, Japan
Shigeo Kawata, Utsunomiya University, Japan
Horst Klein, UAP, University Frankfurt, Germany
Edward Lee, Lawrence Livermore National Lab., USA
John Lindl, Lawrence Livermore National Lab., USA
Grant Logan, Lawrence Livermore National Lab., USA
Steven Lund, Lawrence Livermore National Lab., USA
Gilles Maynard, LPGP, Orsay, France
Kunioki Mima, ILE, Osaka, Japan
Osamu Motojima, NIFS, Japan
Katsunobu Nishihara, ILE, Osaka, Japan
Masao Ogawa, Komazawa University, Japan
Craig Olson, Sandia National Laboratories, USA
Patrick O’Shea, University of Maryland, USA
J. M. Perlado, DENIM, Madrid, Spain
Antonio Roberto Piriz, University of Castilla-La Mancha, Spain
Modesto Pusterla, INFN, Padova University, Italy
Hong Qin, Princeton Plasma Physics Lab., USA
Raphael Ramis, ETSI Aeronauticas, Madrid, Spain
Boris Sharkov, ITEP, Moscow, Russia
Peter Spiller, GSI Darmstadt, Germany
Vladimir Smirnov, JINR, Dubna, Russia
Max Tabak, Lawrence Livermore National Lab., USA
Naeem A. Tahir, GSI Darmstadt, Germany
Ken Takayama, KEK, Japan
Francis Thio, U.S. Department of Energy, USA
Tosihide Tsunematsu, JAEA, Japan
Giorgio Turchetti, Universita di Bologna and INFN Bologna, Italy
Vladimir Vatulin, VNIIEF, Arzamas 16, Russia
Guillermo Velarde, Instituto de Fusion Nuclear, Spain
Pavel Zenkevich, ITEP, Moscow, Russia
Zeev Zinamon, Weizmann Institute of Science, Israel
Scientific program committee

Masao Ogawa, Chair
Kazuhiko Horioka, Vice Chair
Yoshiyuki Oguri, Proceedings Editor
Mikhail Basko, ITEP, Moscow, Russia
John Barnard, LBNL, Berkeley, USA
Debra Callahan, Lawrence Livermore National Lab., USA
Ronald Davidson, Princeton Plasma Physics Lab., USA
Claude Deutsch, LPGP, Orsay, France
Jean-Pierre Didelez, Institut Physique Nucléaire, France
Irving Haber, IREAP, College Park, USA
Dieter Hoffmann, GSI Darmstadt, Germany
Ingo Hofmann, GSI Darmstadt, Germany
Shigeo Kawata, Utsunomiya University, Japan
Edward Lee, Lawrence Livermore National Lab., USA
Steven Lund, Lawrence Livermore National Lab., USA
Gilles Maynard, LPGP, Orsay, France
Arthur Molvik, Lawrence Livermore National Lab., USA
Masao Ogawa, Komazawa University, Japan
Craig Olson, Sandia National Laboratories, USA
Per Peterson, Nucl. Engrg. Berkeley, USA
Hong Qin, Princeton Plasma Physics Lab., USA
Boris Sharkov, ITEP, Moscow, Russia
Eric Sonnendrucker, University of Louis Pasteur, France
Naeem A. Tahir, GSI Darmstadt, Germany
Dmitry Varentsov, GSI, Darmstadt, Germany
Vladimir Vatulin, VNIIEF, Arzamas 16, Russia

Organizing committee

Takayuki Aoki, Tokyo Institute of Technology, Japan
Jun Hasegawa, Tokyo Institute of Technology, Japan
Toshiyuki, Hattori, Tokyo Institute of Technology, Japan
Noriyosu, Hayashizaki, Tokyo Institute of Technology, Japan
Kazuhiko Horioka, Tokyo Institute of Technology, Japan
Junichi Kaneko, Komazawa University, Japan
Toru Kawamura, Tokyo Institute of Technology, Japan
Shigeo Kawata, Utsunomiya University, Japan
Takashi Kikuchi, Utsunomiya University, Japan
Masakatsu Murakami, ILE, Osaka, Japan
Masao Ogawa, Komazawa University, Japan
Yoshiyuki Oguri, Tokyo Institute of Technology, Japan
Ken Takayama, KEK, Japan
General information

Registration
Registration of participants is open from 8:30 on August 4 (Monday) at “Digital Multi-purpose Hall”. The registration and information desk will be open during the symposium.

Oral sessions
Oral presenters are strongly recommended to use Microsoft PowerPoint or Adobe Acrobat Reader with a PC projector. They can use their own laptop computers or a Windows PC prepared for common use. By the beginning of the session, the compatibilities between the PCs and the projector should be checked. When using the common-use PC, the presenters should copy the presentation files to the hard drive of the PC.

Poster sessions
A poster session will be held from 16:10 to 17:40 on August 5 (Tuesday) at “Collaboration Room”. Poster presenters are required to display their posters by the beginning of the session.

Conference proceedings
The proceedings will be published as a special issue of Nuclear Instruments and Methods in Physics Research, Section A (NIM-A). Three copies of the manuscript and an electronic file (MS-WORD, CD / Memory Stick / Floppy Disk) should be submitted to the registration desk during the symposium.

Social programs
The symposium banquet and excursion will be held simultaneously as a "dinner cruise" on a "YAKATA-BUNE" on Tokyo bay on August 6 (Wednesday). The detailed information on the banquet is given in another document included in the conference wallet.
**OVERVIEW OF U.S. HEAVY ION FUSION SCIENCE PROGRAM*\**

B. G. Logan\(^1\), J. J. Barnard\(^2\), F. M. Bieniosek\(^1\), R. H. Cohen\(^2\), J. E. Coleman\(^1\), R. C. Davidson\(^3\), P. C. Efthimion\(^3\), A. Friedman\(^2\), E. P. Gilson\(^3\), L. R. Grisham\(^3\), D. P. Grote\(^2\), E. Henestroza\(^1\), I. D. Kaganovich\(^3\), E. P. Lee\(^1\), M. A. Leitner\(^1\), S. M. Lund\(^2\), A. W. Molvik\(^1\), P. Ni\(^1\), L. J. Perkins\(^2\), H. Qin\(^3\), P. K. Roy\(^1\), A. B. Sefkow\(^1\), P. A. Seidl\(^1\), E. A. Startsev\(^3\), W. L. Waldron\(^1\)

\(^1\)Lawrence Berkeley National Laboratory, USA  
\(^2\)Lawrence Livermore National Laboratory, USA  
\(^3\)Princeton Plasma Physics Laboratory, USA

During the past two years, the U.S. heavy ion fusion science program has made significant experimental and theoretical progress in simultaneous transverse and longitudinal beam compression, ion-beam-driven warm dense matter targets, high-brightness beam transport, advanced theory and numerical simulations, and heavy ion target physics for fusion. First experiments combining radial and longitudinal compression of intense ion beams propagating through background plasma resulted in on-axis beam densities increased by 700X at the focal plane. With further improvements planned in 2008, these results should enable initial ion beam target experiments in warm dense matter to begin within a year. We are assessing how these new techniques may apply to higher-gain direct-drive targets for inertial fusion energy. The success of strong transverse and longitudinal beam compression in neutralizing plasma enables the application of heavy ion beams to direct drive in the ablative rocket regime. A simple analytic implosion model with a heavy-ion dE/dx deposition model, together with hydrodynamic implosion calculations using both LASNEX and HYDRA, have been used to explore the characteristic beam requirements for heavy ion direct drive in the ablative regime, for small, 1 MJ-drive, DT targets as well as for larger, tritium-lean (> 90% DD) targets needing 5 MJ drive energy. Overall beam-to-compressed-fuel coupling efficiencies of 15%, twice as high as for laser direct drive, have been found in LASNEX calculations, and up to 25% in analytic calculations. A candidate modular induction driver for 1MJ heavy ion direct drive has been identified that may be able to meet direct drive target requirements for power, pulse shape and symmetry, ramping-up of ion range during the drive pulse, and final focus in neutralized chambers with focal spot sizes that zoom-in during the implosion drive.

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH1123 and DE-AC52-07NA27344, and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.
ACTIVITIES ON HEAVY ION INERTIAL FUSION AND BEAM-DRIVEN HIGH ENERGY DENSITY SCIENCE IN JAPAN

K. Horioka¹, T. Kawamura¹, M. Nakajima¹, T. Sasaki¹, K. Kondo¹,
Y. Oguri², J. Hasegawa², M. Ogawa³,
S. Kawata⁴, T. Kikuchi⁴, M. Murakami⁵, K. Takayama⁶

¹Department of Energy Sciences (DES), Tokyo Institute of Technology, Nagatsuta 4259, Yokohama 226-8502, Japan
²Research Laboratory for Nuclear Reactors (RLNR), Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo 152-8550, Japan
³Komazawa University, Setagaya, Tokyo 154-8525, Japan
⁴Department of Electrical and Electronic Engineering, Utsunomiya University (UU), Utsunomiya 321-8585, Japan
⁵Institute of Laser Engineering, Osaka University (ILE-Osaka), Suita 565-0871, Japan
⁶High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan

While there is no coherent program in Japan, a number of research groups are dealing with basic problems for heavy ion inertial confinement fusion (ICF). Dense plasmas driven by intense ion beams and/or a pulse powered device, are evaluated in a group of DES-TIT, concerning the researches on high-energy-density (HED) and warm dense matter (WDM) physics. A quasi-statically tamped target has been proposed to make a well-defined, warm dense state for equation-of-state studies based on ion accelerators. The results show that the target structure can exclude an unclear factor caused by the tamper hydrodynamics in dynamic tamper schemes and enables us to produce a well-defined, quasi-uniform warm dense state with long spatial scale. In the same group, dense plasmas are produced using pulse-power driven exploding wire discharges in water. Experimental results show that the wire plasma is tamped and stabilized by the surrounding water and it evolves through a warm dense state, which enables us to draw a conductivity scaling at the WD state. Beam-plasma interaction experiments and related theoretical studies are in progress at RLNR-TIT. In the study, a shock-heated hydrogen is used for the interaction experiments as a well-defined non-ideal-plasma target. A special emphasis is placed on an evaluation of non-linear effects on the stopping power in a beam-heated plasma target. A direct-indirect hybrid scheme of beam-driven ICF target has been proposed and discussed at UU. Core dynamics of the impact fusion are investigated both experimentally and numerically at ILE-Osaka. Evolutions in phase space during the longitudinal compression of intense beams are investigated at UU-TIT. Potentiality of new facility planned at KEK is evaluated by a collaborating group of TIT-UU-KEK, which can extend the achievable parameter regime for laboratory experiments to study properties of the matter under extreme conditions. We show the achievable parameter regime of the beam driven target in a density-temperature plane and discuss a possible method to make high pressure experiments for study on the beam-heated ICF target physics, HED physics and also for exploration of the planetary science.
Mo-3

ACTIVITIES ON HEAVY ION FUSION IN RUSSIA

B. Yu. Sharkov

ITEP-Moscow, Russia

Overview of ongoing Heavy Ion Fusion activities in Russia is presented. Special attention is played to development of integrated simulations of the chamber response to micro explosion of a cylindrical target irradiated by intense heavy ion beam. Progress in intensity upgrade of accelerator-accumulator ITEP-TWAC [1] required for High Energy Density in Matter research and respective experiments on beam-mater coupling are described. New capabilities of the facility for experiments on heavy ion fusion issues are discussed.

Reference

HIGHLIGHTS OF FUSION SCIENCE STUDIES IN JAPAN

Osamu Motojima

Director General and Professor
The National Institute for Fusion Science (NIFS)
National Institutes of Natural Sciences
Toki-shi, Gifu-ken, 509-5292 Japan

The sun’s power has lasted steadily and safely for about 5 billion years. Since most of the visible universe, more than 98%, is composed of plasmas and the energy source of stars is the fusion reaction, humans might be able to obtain an understanding of the evolution of the cosmos through the study of plasmas. Therefore, the interest in our fusion science area is unbounded; the high temperature plasmas produced by magnetic or inertial fusion experiments provide great opportunities to establish advanced knowledge of, e.g., physics events and their systematization, non-linear phenomena, non-local and nonequilibrium physics, complex system science, plasmas within an atomic nuclei, etc. One of the recent achievements includes the experimental confirmation of the dynamo process, i.e., generation of a structured and meso-scale magnetic field by microscopic turbulence. Now, we are involved in active international collaborations, contributing to the globalization of physics and engineering, and as a result contributing to the preservation of the global environment and global peace.

Presently, the Japanese fusion program is progressing based on the report “Future Direction of National Fusion Research” issued by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2003. This report proposes a newly defined grand design for Japanese fusion research, which encourages a paradigm shift of fusion research from a multilateral approach to a concentrated one with enhanced mutual collaboration. This was a necessary process in order to prepare for the new ITER era. In this report, LHD (helical, NIFS) and FIREX (laser, ILE Osaka) were nominated as the major science programs, and JT-60U (tokomak, JAEP) and IFMIF (fusion material development) as the major development programs. The latter two programs directly support the ITER program, whereas the former two programs aim at advanced fusion reactor concepts. The role of research in universities is recognized again as very important for providing the research basis of plasma physics, fusion science, and reactor engineering.

The LHD project in NIFS is contributing to the scientific demonstration of the viability of fusion energy by producing advanced level plasma parameters approaching the break even condition. LHD is the world’s largest superconducting device, which is a heliotron type, uniquely three dimensional, and net current-free toroidal magnetic confinement device. The current status of the LHD project is presented focusing on the experimental results and the recent achievements in plasma physics. Since its start in the year 1998, remarkable progress has presently resulted in the temperature of 13.5keV, the highest density of $1.1 \times 10^{21} \text{ m}^{-3}$ with the internal diffusion barrier (IDB), and the highest steady volume average beta of 5% and the
largest total input energy of 1.6 GJ during a 1 hour steady state discharge. The production of a super high density core (SDC) of more than the target of $10^{20} \text{m}^{-3}$ is the result of the edge control study with the Local Island Divertor (LID) and multiple hydrogen pellet injection. The impurity density is kept low and the turbulence of the plasma is suppressed in the IDB zone due to the induced radial electric field and zonal flow. This makes it possible to formulate a new ignition scenario for the self burning fusion reactor, DEMO, with an extremely high density and lower temperature core. As for high $\beta$ plasmas, they are stable enough to keep the energy confinement time scaling at the same level as that of low $\beta$ plasmas. LHD will contribute to the ITER/DEMO oriented class of physics based on fusion science studies. There are still important subjects, which are the demonstration of steady state operation, the understanding of plasma wall interaction in a divertor, the achievement of high $\beta$, clarification of the role of radial electric field and suppression of plasma turbulence. Finally, a perspective is given on the ITER Broad Approach program as an integrated part of ITER and the Development of Fusion Energy Project Agreement.

The FIREX project (Fast Ignition Realization EXperiment) is recognized as a proof-of-principle level experiment, which is carried out by Osaka University (ILE). Now, ILE is conducting the first phase of the FIREX-I project and the construction of the laser system (LFEX laser) has been completed. The previous high compression of six hundred times liquid density and the recent fast heating of a compressed core to 1-keV temperature have provided proof-of-principle of the fast ignition concept, and these results significantly contributed to the promotion of the FIREX-I program. The goal of FIREX-I is to demonstrate fast heating of a fusion fuel up to the ignition temperature of 5-10 keV. Although the fuel of FIREX-I will not ignite due to the small amount of fuel, sufficient heating will provide the scientific viability to achieve ignition-and-burn by increasing the laser energy and thereby the fuel amount. The decision on FIREX-II to achieve the ignition-and-burn can be made, based on the results of FIREX-I. The FIREX program is being carried out by a collaboration between ILE and NIFS, including development of cryogenic targets, holistic simulation systems, and diagnostic equipment.

Since the National Institute for Fusion Science (NIFS) is a part of the Inter-University Research Institute Corporation, it is taking on increased responsibility for the coordination of collaboration among universities. An overview is given of fusion science studies in Japan.
Thermonuclear ignition and subsequent burn are key physics for achieving laser fusion. Laboratory ignition with very large laser systems is now anticipated with the National Ignition Facility (NIF) in the US and Laser Mega Joule (LMJ) in France. Fast ignition has a potential to achieve ignition and burn with about one tenth of laser energy required for these programs. With the fast ignition, the fuel compression and heating are separated, with ignition initiated by a short very high power laser pulse incident on the already compressed fuel. The fast heating of a compressed core [1], together with the scalability to high-density compression [2], has provided the scientific basis for the start of the Fast Ignition Realization Experiment (FIREX) project. The goal of the first phase (FIREX-I) is to demonstrate ignition temperature of 5-10 keV, followed by the second phase to demonstrate ignition and burn. Coupled with the achievement of central ignition on NIF and LMJ, the research focus would then move to the demonstrations of high gain and of the inertial fusion energy technology. These programs would converge onto a laser fusion test reactor that can deliver net electric power by 2030. We would expect the test reactor program as a truly international activity.

**Plasma Physics Progress since FIREX-I Approval**
Since the approval of FIREX-I, plasma physics study in ILE has been devoted to increase the coupling efficiency and to improve compression performance. We have designed an advanced target for FIREX-I as schematically illustrated in Fig. 1. The coupling efficiency can be increased by the following two ways:

1) **Double cone.** Electrons generated in the inner surface of the double cone will return by sheath potential generated between two cones. Our two dimensional PIC simulation indeed indicates the improvement of the electron confinement by a factor of 1.7.

2) **Low-Z plastic layer on the outer surface of the cone** may suppress the expansion of Au cone that flows into the interior of the compressed core. The 2D hydro-simulation PINOCO predicts that the target areal density increases by a factor of two if we employ this scheme.

**Laser Development**
The amplifier system of the heating laser LFEX is completed. The amplification test has demonstrated laser energy of 3 kJ/beam at 3nm bandwidth. The equivalent 12 kJ in 4 beams meets the specification of LFEX. The large format gratings for pulse compressor are completed. The fully integrated fast ignition experiment is scheduled on January 2009.
TOWARD A PHYSICS DESIGN FOR NDCX-II, A PLATFORM FOR STUDYING ION BEAM-HEATED MATTER

A. Friedman\textsuperscript{1,4}, J. J. Barnard\textsuperscript{1,4}, R. J. Briggs\textsuperscript{2,4}, M. Dorf\textsuperscript{3,4}, D. P. Grote\textsuperscript{1,4}, E. Henestroza\textsuperscript{2,4}, I. Kaganovich\textsuperscript{3,4}, M. A. Leitner\textsuperscript{2,4}, E. P. Lee\textsuperscript{2,4}, B. G. Logan\textsuperscript{2,4}, A. B. Sefkow\textsuperscript{3,4}, W. M. Sharp\textsuperscript{1,4}, W. L. Waldron\textsuperscript{2,4}, D. R. Welch\textsuperscript{5}, and S. S. Yu\textsuperscript{2,4}

\textsuperscript{1}Lawrence Livermore National Laboratory, Livermore, California, USA
\textsuperscript{2}Lawrence Berkeley National Laboratory, Berkeley, California, USA
\textsuperscript{3}Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
\textsuperscript{4}Heavy Ion Fusion Science Virtual National Laboratory
\textsuperscript{5}Voss Scientific, Albuquerque, New Mexico, USA

The Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL), a collaboration of LBNL, LLNL, and PPPL, has achieved 60-fold temporal pulse compression of ion beams on the Neutralized Drift Compression eXperiment (NDCX) at LBNL. In NDCX, a velocity “tilt” is imparted to the beam as it traverses an induction gap by a ramped voltage pulse; the beam’s tail then catches up with its head in a plasma environment that provides needed neutralization. The HIFS-VNL’s near-term mission is to study basic Warm Dense Matter physics in uniformly heated foils driven by ions near the Bragg peak energy; an emerging emphasis is on the novel properties of ion direct drive for inertial fusion energy. These goals will require an improved platform, labeled NDCX-II.

We describe progress toward, and planning for, NDCX-II. Development of this facility at modest cost was recently made possible by the availability of a number (~40) of induction cells and associated hardware from the decommissioned Advanced Test Accelerator (ATA) facility at LLNL. Our initial physics design concept accelerates a ~30 nC pulse of Li\textsuperscript{+} ions to ~3 MeV, then compresses it to ~1 ns while focusing it onto a sub-mm spot. It uses the ATA cells (with waveforms generated by simple passive circuits) to impart most of the final velocity tilt; smart pulsers provide small corrections. The ATA accelerated electrons; acceleration of non-relativistic ions involves more complex beam dynamics both transversely (because magnetic self-focusing does not significantly counteract the space-charge forces) and longitudinally (because ions at modest energy exhibit relative motions). We are using a combination of analysis, an interactive one-dimensional kinetic simulation model with optimizing capabilities, and multidimensional Warp-code simulations to develop the NDCX-II accelerator section. Both LSP and Warp codes are being applied to the beam dynamics in the neutralized drift and final focus regions, and the plasma injection process. These studies are described, and a status report is presented.

*This work was performed under the auspices of the U.S Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, by the University of California, Lawrence Berkeley National Laboratory under Contract DE-AC03-76SF00098, and by the Princeton Plasma Physics Laboratory under Contract DE-AC02-76CH03073.
SURVEY OF COLLECTIVE INSTABILITIES AND BEAM-PLASMA INTERACTIONS IN INTENSE HEAVY ION BEAMS

Ronald C. Davidson, Mikhail Dorf, Igor Kaganovich, Hong Qin and Edward A. Startsev*

Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA

Steven M. Lund**

Lawrence Berkeley National Laboratory, Berkeley, California, USA

This paper presents a survey of the present theoretical understanding based on advanced analytical and numerical studies of collective processes and beam-plasma interactions in intense heavy ion beams for applications to ion-beam-driven high energy density physics and fusion. The topics include discussions of the conditions for quiescent beam propagation over long distances; the electrostatic Harris instability and the transverse electromagnetic Weibel instability in highly anisotropic, one-component ion beams; and the dipole-mode, electron-ion two-stream instability (electron cloud instability) driven by an unwanted component of background electrons. In the longitudinal drift compression and transverse compression regions, collective processes associated with the interaction of the intense ion beam with a charge-neutralizing background plasma are described, including the electrostatic electron-ion two-stream instability, the multispecies electromagnetic Weibel instability, and collective excitations in the presence of a solenoidal magnetic field. The effects of a velocity tilt on reducing two-stream instability growth rates are also discussed. Operating regimes are identified where the possible deleterious effects of collective processes on beam quality are minimized.

* Research supported by the U. S. Department of Energy.
A SPACE-CHARGE NEUTRALIZING PLASMA FOR BEAM DRIFT-COMPRESSION EXPERIMENTS

P. K. Roy¹, P. A. Seidl¹, A. Anders¹, J. E. Coleman¹², E. P. Gilson¹, D. P. Grote⁴, J. Y. Jung¹, M. Leitner¹, S. Lidia¹, B. G. Logan¹, A. B. Sefkow³, W. L. Waldron¹, D. R. Welch⁵

¹Lawrence Berkeley National laboratory, Berekeley, CA 94720, USA
²Dept. of Nuclear Eng. University of California, Berkeley, CA 94720, USA
³Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451, USA
⁴Lawrence Livermore National laboratory, Livermore, CA 94550, USA
⁵Voss Scientific, Albuquerque, NM 87108, USA

Intense ion beams of low kinetic energy offer an attractive approach to heating dense matter uniformly to extreme conditions, because their energy deposition is nearly classical and shock-free. Simultaneous radial focusing and longitudinal compression of ion beams are being studied to heat matter to the warm dense matter, or strongly coupled plasma, regime (Temperature ~ 0.1 to 10 eV). Higher compression ratios can be achieved if the beam compression takes place in a plasma-filled drift region in which the space-charge forces of the ion beam are neutralized. In a recent simulation the compressed beam pulse reaches $10^{12}$ cm$^{-3}$ peak density ($n_b$) vs. a beam density of $\sim 2 \times 10^8$ cm$^{-3}$ entering for longitudinal compression (bunching gap). The longitudinal compression ratio peaks at 120 with a transverse spot $a_s = 1.3$ mm (edge radius) is expected (D. Welch et al, PAC 07 Proc., pp.3420). Thus, a target placed at the focus would receive peak deposition energy of $\geq 0.035$ J/cm$^2$ for a 300 keV 26 mA beam. Limitations of beam dynamics (emittance, chromatic aberration) and achieving a sufficiently high plasma electron number density ($n_p$) near the focal plane are the key issues. Recently, a system with four cathodic arc plasma sources (CAPS) has been developed and installed in the target chamber. A 10-cm long 8-T solenoid magnetic field, located upstream of the CAPS (distance between the solenoid center to the target plane is 19.3 cm), focuses the incoming ion beam, and its fringe field guides the CAPS plasma density on axis but also causes an expected mirroring. Axial and radial plasma density measurements near the target plane with 8T magnet operating condition will be presented to meet the challenge of $n_p > n_b$.

This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231, DE-AC52-07NA27344, DE-AC02-76CH-O3073 for Heavy Ion Fusion Sciences-Virtual National Laboratory (HIFS-VNL).
Tu-1

BEAM BEHAVIOR UNDER A NON-STATIONARY STATE IN HIGH-CURRENT HEAVY-ION BEAMS

T. Kikuchi\textsuperscript{1}, S. Kawata\textsuperscript{1}, K. Horioka\textsuperscript{2}

\textsuperscript{1}Utsunomiya University, Utsunomiya, Japan
\textsuperscript{2}Tokyo Institute of Technology, Nagatsuta, Japan

In Warm Dense Matter (WDM), High Energy Density Physics (HEDP), and Heavy Ion Inertial Fusion (HIF) studies by ion beams, the beam energy must be focused in a local volume of a target to make the higher energy density state. The input power is proportional to the production of the kinetic energy and beam current. The larger kinetic energy of the ion causes the longer stopping range in the target. From the requirement of the localized energy deposition, the kinetic energy is restricted to be as low as possible. For this reason, the high-current ion beams are needed for the above applications. The physics and dynamics of space-charge-dominated beams are crucial issues in WDM, HEDP, and HIF researches.

At the final stage of the particle accelerator system, the ion beam pulse should be longitudinally compressed to 10-100 ns. For the effective target experiments, we should compress and transport the ion bunch with the emittance growth less than an allowable level. In case of the intense ion beam propagation, particle dilution in the phase space can cause the emittance growth, because the collective relaxation from a non-equilibrium particle distribution to more thermalized state. Also, the process is carried out under a non-stationary condition.

In this study, we investigate the beam dynamics during the longitudinal bunch compression using multiparticle numerical simulations. Under the non-stationary situation of the beam parameters, the emittance growth and halo particle generation are reviewed.
Collective effects with strong coupling between the longitudinal and transverse dynamics are of fundamental importance for applications of high-intensity bunched beams in high energy density physics and heavy ion fusion. Analytically, the self-consistent Vlasov-Maxwell equations have been successfully applied to high-intensity finite-length charge bunches. However, when applying the standard delta-f particle-in-cell (PIC) simulation method to high-intensity bunched beams, we encounter two difficulties: (i) For bunched beams with anisotropic energy there exists no exact kinetic equilibrium, which is required by the standard delta-f method; (ii) For collective instabilities with coherent structures, wave-particle interaction may result in large weight growth for resonant simulation particles, which generates large simulation errors. To overcome these difficulties, we have developed a generalized delta-f particle simulation algorithm with smooth transitions between delta-f and total-f methods, and for bunched beams with or without energy anisotropy. A reference state in approximate dynamic equilibrium has been constructed theoretically, and a quasi-steady state has been established in the simulations for the anisotropic case. Collective excitations relative to the reference are then simulated using this generalized delta-f algorithm. When perturbation level is small, the simulation effectively makes use of the desirable low-noise feature of the delta-f method to accurately follow unstable mode structures. When the perturbation level becomes large during the nonlinear phase, the low-noise advantage of the delta-f method ceases to be significant and the simulation is switched smoothly to the total-f method to avoid the large noise induced by resonant simulation particles. This improved delta-f simulation method has been successfully applied to simulation studies of the electrostatic Harris instability driven by large temperature anisotropy in high intensity charged particle beams typical of applications in high current accelerators, including high energy density physics and heavy ion fusion.

*Research supported by the U. S. Department of Energy.
This paper presents a survey of the present numerical modeling techniques and theoretical understanding of plasma neutralization of intense particle beams. For ion-beam-driven high energy density physics and inertial fusion applications it is critical to develop a basic understanding of the conditions for quiescent beam propagation over large distances, controlling pinching and filamentation effects, and minimizing the degradation of beam quality due to instabilities and particle loss. We previously developed a reduced analytical model of beam charge and current neutralization for an ion beam pulse propagating in a cold background plasma. The model made use of the conservation of generalized fluid vorticity. The predictions of the analytical model agree very well with numerical simulation results. The model predicts very good charge neutralization during quasi-steady-state propagation, provided the beam pulse duration is much longer than the electron plasma period. In the opposite limit, the beam pulse excites large-amplitude plasma waves. If the beam density is larger than the background plasma density, the plasma waves break, which leads to electron heating. The reduced-fluid description provides an important benchmark for numerical codes and yields useful scaling relations for different beam and plasma parameters. This model has been extended to include the additional effects of a solenoidal magnetic field, gas ionization and the transition regions during beam pulse entry and exit from the plasma. Analytical studies show that a sufficiently large solenoidal magnetic field can increase the degree of current neutralization of the ion beam pulse. However, simulations also show that the self-magnetic field structure of the ion beam pulse propagating through background plasma can be complex and non-stationary. Plasma waves generated by the beam head are greatly modified, and whistler waves propagating ahead of the beam pulse are excited during beam entry into the plasma. Accounting for plasma production by gas ionization yields a larger self-magnetic field of the ion beam compared to the case without ionization, and a wake of the current density and self-magnetic field are generated behind the beam pulse. Beam propagation in a dipole magnetic field configuration and background plasma has also been studied.

* Research supported by the U. S. Department of Energy.

Tu-4

DYNAMICS OF ELECTROMAGNETIC TWO-STREAM INTERACTION PROCESSES DURING LONGITUDINAL AND TRANSVERSE COMPRESSION OF AN INTENSE ION BEAM PULSE PROPAGATING THROUGH BACKGROUND PLASMA*

E. A. Startsev, R. C. Davidson and M. Dorf.

Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA

To achieve maximum energy density charged particle beam must be compressed radially and longitudinally while its space-charge is neutralized by background plasma. The beam propagating in plasma is subject to electrostatic two-stream instability and electromagnetic Weibel instability. The electrostatic two-stream instability may lead to longitudinal bunching of the beam pulse and eventual longitudinal beam heating. Consequently, this could degrade longitudinal compression of the beam. Similarly, the electromagnetic Weibel instability may cause transverse filamentation of the beam, which may degrade transverse compression. To achieve stronger transverse focusing, it has been proposed to pass the beam through a strong solenoidal magnetic field. The solenoidal magnetic field can extend long distance away from the solenoid into the neutralizing plasma where the beam is compressed longitudinally. In this paper, we review how transverse and longitudinal compression changes the dynamics of two-stream and Weibel instabilities. We also discuss how these instabilities are modified by the solenoidal magnetic field.

*Research supported by the U. S. Department of Energy
PERSPECTIVE ON THE ROLE OF NEGATIVE IONS AND ION-ION PLASMAS IN HEAVY ION FUSION SCIENCE

L. R. Grisham and J. W. Kwan

1Princeton Plasma Physics Laboratory, P. O. Box 451, Princeton, N. J., USA 08543
2Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, USA CA 97420

Since the suggestion some years ago that halogen negative ions [1] could offer a feasible alternative path to positive ions as a heavy ion fusion driver beam which would not suffer degradation due to electron accumulation in the accelerator and beam transport system, and which could be converted to a neutral beam by photodetachment near the chamber entrance if desired, experiments have demonstrated that negative halogen beams can be extracted and accelerated away from the gas plume near the source with a surviving current density close to what could be achieved with a positive ion of similar mass, and with comparable optical quality. In demonstrating the feasibility of halogen negative ions as heavy ion driver beams, ion—ion plasmas, an interesting and somewhat novel state of matter, were produced. These plasmas, produced near the extractor plane of the sources, appear, based upon many lines of experimental evidence, to consist of almost equal densities of positive and negative chlorine ions, with only a small component of free electrons. Serendipitously, the need to extract beams from this plasma for driver development provides a unique diagnostic tool to investigate the plasma, since each component—positive ions, negative ions, and electrons--can be extracted and measured separately. We will discuss the relevance of these observations to understanding negative ion beam extraction from electronegative plasmas such as halogens, or the more familiar hydrogen of magnetic fusion ion sources. We will also discuss the possibility and challenges of producing ion—ion plasmas with thin targets of halogens or, perhaps, salt, and we will discuss the remaining measurements which need to be done with an ion source and beam extraction to understand the properties and applications of ion—ion plasmas.


Research supported by U.S. DOE contract AC02-CH03073
Research supported by U.S. DOE contract DE-AC-76SF0098
RECENT ADVANCES IN THE PHYSICS OF COLLECTIVE EXCITATIONS AND TRANSVERSE COMPRESSION DYNAMICS IN THE PAUL TRAP SIMULATOR EXPERIMENT†

E. P. Gilson¹, M. Chung¹, R. C. Davidson¹, M. Dorf², P. C. Efthimion¹, A. B. Godbehere²
R. Majeski¹

¹Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
²Cornell University, Ithaca, New York, USA

The Paul Trap Simulator Experiment (PTSX) is a compact laboratory linear Paul trap that simulates the transverse dynamics of a charged-particle bunch coasting through a magnetic alternating-gradient (AG) transport system. The transverse dynamics of particles in the AG system in the beam’s frame-of-reference and those of particles in PTSX are described by the same sets of equations, including all nonlinear space-charge effects. Initial experimental results are presented in which the collective transverse symmetric mode (m = 0) and quadrupole mode (m = 2) have been observed in pure-barium-ion plasmas in PTSX with the intent of identifying collective modes whose signature will serve as a robust diagnostic for key properties of the beam, such as line density and transverse emittance. Additional results are presented from experiments in which the lattice period and lattice field strength are changed over the course of the experiment in order to transversely compress a beam with an initial depressed-tune $v/v_0 \sim 0.9$. Both instantaneous and smooth changes are considered. Emphasis is placed on determining the conditions that minimize the emittance growth and, generally, the number of halo particles produced after the beam compression. The results of PIC simulations performed with the WARP code agree well with the experimental data.

† Research supported by the U.S. Department of Energy.
RI ION BEAM PRODUCTION IN THE DIGITAL ACCELERATOR

Ken Takayama

High Energy Accelerator Researeh Organization (KEK), Tsukuba, Japan

Now the existing KEK 500 MeV proton synchrotron (Booster) is going to be converted to the digital accelerator (DA) called an all-ion accelerator [1], which is based on the induction synchrotron concept [2] and capable of providing any ions species including cluster ions, with their possible charge state. In addition, it has been realized that the DA is suitable for quick acceleration of radio isotope (RI) ions because of it unique characteristics of injector-free. Acceleration of a PET beam with a middle life time, such as C-11, or a beta-beam with a shorter life time for a future neutrino factory should be quite interesting. A production scenario integrating a proton driver and laser irradiation on a target including RI particles and their acceleration in the DA are presented at the conference, as well as the recent status of modification works.

Tu-8

SCALED ELECTRON STUDIES AT THE UNIVERSITY OF MARYLAND*

I. Haber, G. Bai, S. Bernal, B. Beaudoin, D. Feldman, R. B. Feldman,
R. Forito, K. Fiuza, T.F. Godlove, R. A. Kishek, P.G. O'Shea, B. Quinn,

Institute for Research in Electronics and Applied Physics,
University of Maryland, College Park, MD 20742

Recent experiments performed on the University of Maryland Electron Ring (UMER) have
demonstrated the advantages of using a scaled electron machine to economically investigate
the nonlinear physics of a space-charge-dominated beam. This physics is important to larger
and much more expensive machines, including accelerator systems for the study High Energy
Density Physics and Heavy Ion Fusion.
UMER has been successfully used for studying source and injector physics, developing
diagnostics, and for benchmarking WARP simulations under a wide variety of conditions, as
well as for investigating the special sensitivities of a space-charge-dominated machine to
small deviations from the nominal design parameters. A description will also be presented of
studies that utilize the downstream consequences of a controlled initial perturbation of the
beam distribution for the study of both longitudinal and transverse beam physics. Current
work to optimize ring operation will also be discussed.

*Work supported by the U.S. Department of Energy under contracts DE-FG02-02ER54672, DE-
FG02-92ER5178, and DEFG02-94ER40855
PROGRESS IN BEAM FOCUSING AND COMPRESSION FOR WARM- DENSE MATTER EXPERIMENTS

P.A. Seidl¹, A. Anders¹, R.H. Cohen⁴, J.E. Coleman¹², M. Dorf³, E.P. Gilson³, D.P. Grote⁴, J.Y. Jung¹, M. Leitner¹, S.M. Lidia¹, B.G. Logan¹, P.K. Roy¹, A.B. Sefkow³, W.L. Waldron¹, D.R. Welch⁴

¹Lawrence Berkeley National laboratory, Berkeley, CA 94720, USA
²Dept. of Nuclear Eng. University of California, Berkeley, CA 94720, USA
³Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451, USA
⁴Lawrence Livermore National laboratory, Livermore, CA 94550, USA
⁵Voss Scientific, Albuquerque, NM 87108, USA

The Heavy-Ion Fusion Sciences Virtual National Laboratory is pursuing an approach to target heating experiments in the Warm Dense Matter regime, using space-charge-dominated ion beams that are simultaneously longitudinally bunched and transversely focused. Longitudinal beam compression by large factors has been demonstrated in the Neutralized Drift Compression Experiment (NDCX) with controlled ramps and forced neutralization. Using an injected 30-mA K⁺ ion beam with initial kinetic energy 0.3 MeV, axial compression leading to ~100X current amplification and simultaneous radial focusing to beam radii of a few mm have led to encouraging energy deposition approaching, but still short of, the intensities required for eV-range target heating experiments. We discuss the status of several improvements to our Neutralized Drift Compression Experiment and associated beam diagnostics that are under development to reach the necessary higher beam intensities, including: (1) greater axial compression via a longer velocity ramp using a new bunching module with approximately twice the available volt-seconds; (2) improved centroid control via beam steering dipoles to mitigate aberrations in the bunching module; (3) time-dependent focusing elements to correct considerable chromatic aberrations; and (4) plasma injection improvements to establish a plasma density always greater than the beam density, expected to be >10¹³ cm⁻³.

This work was supported by the Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231, W-7405-Eng-48, DE-AC02-76CH3073 for Heavy Ion Fusion Sciences-Virtual National Laboratory (HIFS-VNL).
In order to verify direct plasma injection scheme (DPIS), an acceleration test was carried out using TiTech RFQ heavy ion linear accelerator and CO2 laser heavy-ion source of RIKEN in 2001. The accelerated carbon beam was observed successfully and the obtained current (9.2 mA of C$^+$) was much higher (about 10 times) than designed currents. To confirm the capability of the DPIS, we designed and fabricated a new RFQ to accommodate 100 mA of carbon beam collaboration RIKEN and Frankfurt University. We succeeded to accelerate very intense carbon ions with the DPIS in 2004. The peak current reached more than 60 mA. We believe that these techniques are quite effective for pulse accelerator complexes such as linear accelerator and synchrotron. Using the DPIS, we studied conceptual design of RF linac driver for heavy-ion inertial confinement fusion. A test accelerator was designed to accelerate 400 mA (4 beams) from 2 keV/u to 100 keV/u by an IH-RFQ type structure. A model of 4 beams acceleration cavity was designed and manufactured for proof of principle (POP) accelerator.
STUDY OF THE RESIDUAL ACTIVITY INDUCED BY URANIUM IONS IN CONSTRUCTIONAL MATERIALS

A. Fertman¹, G. Fehrenbacher², A. Golubev¹, R. Hinca³, I. Hofmann², H. Iwase², E. Kozlova², E. Mustafin², M. Pavlović³, D. Schardt², N. Sobolevskiy⁴, I. Strasik²,³, V. Turtikov¹, M. Zubanova¹

¹ITEP, Moscow, Russia
²GSI, Darmstadt, Germany
³FEI STU, Bratislava, Slovak Republic
⁴INR RAS, Moscow, Russia

Several laboratories in the world have started or plan to build new powerful ion accelerators. These facilities promise to provide very valuable tools for experiments in fundamental nuclear physics, physics of high energy density in matter and for Inertial fusion energy (IFE) research as well. Activation due to beam losses becomes an important issue for high-power accelerators. While beam losses on the level of 1 W/m are presently accepted for proton machines with beam energies of about 1 GeV, a beam-loss tolerance for heavy-ion high-power accelerators have not yet been quantified.

Results of an experimental study of the residual activity induced by high-energy uranium ions are presented. As a preparatory work for constructing the FAIR facility at Darmstadt, samples of stainless steel and copper were irradiated by ²³⁸U ions and depth profiles of residual activity were measured by gamma-ray spectroscopy. The isotopes with dominating contribution to the residual activity were identified and their contributions were quantified. Several long-lived isotopes with half-life larger than 200 days, notably ⁶⁰Co – 5.23 y, ²²Na – 2.6 y, ⁵⁴Mn – 312.5 d, ⁵⁷Co – 271.8 d, ⁶⁵Zn – 244.1 d were found in irradiated copper samples. Detailed depth profiling of residual activity of all identified isotopes had to be completed by measurements of individual target foils. The activity contributions were then obtained by integration of the depth-profiles.

The financial support of this work from the GSI – INTAS grant 03-54-3588 and RFBR-ROSATOM grant № 07-02-13658, is gratefully acknowledged.
PROGRESS ON HED MATTER EXPERIMENT DESIGN STUDIES FOR FUTURE FAIR FACILITY: HEDGEHOB COLLABORATION

N.A. Tahir\textsuperscript{1}, A. Shutov\textsuperscript{2}, V. Kim\textsuperscript{2}, I.V. Lomonosov\textsuperscript{2}, A.R. Piriz\textsuperscript{3}, J.J. Lopez Cela\textsuperscript{3}, D.H.H. Hoffmann\textsuperscript{4}, V.E. Forotv\textsuperscript{2}, C. Deutsch\textsuperscript{5}

\textsuperscript{1}GSI, Darmstadt, Germany
\textsuperscript{2}IPCP, Chernogolovka, Russia
\textsuperscript{3}UCLM, Ciudad Real, Spain
\textsuperscript{4}TU Darmstadt, Darmstadt, Germany
\textsuperscript{5}LPGP, Universite Paris-Sud, Orsay, France

Extensive theoretical work that involves analytic modeling and sophisticated 2D and 3D numerical simulations has been carried out over the past few years to assess the potential of the intense heavy ion beams at the future Facility for Antiprotons and Ion Research (FAIR) at Darmstadt to study the important field of High Energy Density (HED) physics. These studies have shown that one can access the entire phase diagram to study the thermophysical properties of HED matter using isochoric and uniform heating of large samples of solid as well as porous matter [1-3]. Moreover, using a multiple shock reflection scheme, it is possible to achieve low-entropy compression of a test material like hydrogen to generate physical conditions that are expected to exist in the interiors of the giant planets [4-6]. Problems of Rayleigh-Taylor and Richmyer-Meshkov instabilities in such a compression scheme has also been investigated [3,7,8]. It has also been shown that one can achieve a ramp type (shockless) compression of a test material that will allow one to study material properties like shear modulus and yield strength under dynamic conditions [9].

References

ION BEAM HEATED TARGET SIMULATIONS AND ANALYSIS FOR WARM DENSE MATTER PHYSICS AND INERTIAL FUSION ENERGY

J. J. Barnard¹, J. Armijo², D. S. Bailey¹, A. Friedman¹, F. M. Bieniosek², E. Henestroza², I. Kaganovich³, P. T. Leung⁵, B. G. Logan², M.M. Marinak¹, R. M. More², S. F. Ng⁵, G. E. Penn², L. J. Perkins¹, P. Stoltz⁴, S. Veitzer⁴, J. S. Wurtele², S. S. Yu⁵, A. B. Zylstra²

¹Lawrence Livermore National Laboratory, Livermore, CA 94550 USA
²Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA
³Princeton Plasma Physics Laboratory, Princeton, NJ 08543 USA
⁴Tech-X Corporation, Boulder, CO 80303 USA
⁵Chinese University Hong Kong, Hong Kong, China

Hydrodynamic simulations have been carried out using the multi-physics radiation hydrodynamics code HYDRA³ and the simplified one-dimensional hydrodynamics code DISH§. We simulate possible targets for a near-term experiment at LBNL (the Neutralized Drift Compression Experiment, NDCX) and possible later experiments on a proposed facility (NDCX-II) for studies of warm dense matter and inertial fusion energy (IFE) related hydrodynamics and beam-target coupling. Simulations of various target materials (including solids and foams) will be presented. Analysis of target evolution in the two-phase regime, including the evolution of droplets and bubbles, will be reported. Experimental configurations include single pulse planar metallic solid and foam foils, and double-pulsed and ramped-energy pulses on cryogenic targets. Heavy ion fusion direct drive capsule simulations with efficient beam-target coupling will also be presented, showing the relevance of NDCX II experiments to IFE.


*Work performed under the auspices of the U.S. Department of Energy under contract DE-AC52-07NA27344 at LLNL, and University of California contract DE-AC03-76SF00098 at LBNL and contract DEFG0295ER40919 at PPPL.
ELECTRICAL CONDUCTIVITY OF HEAVY IONS INDUCED HED MATTER: NEW EXPERIMENTAL APPROACHES AND RESULTS

S. Udrea\textsuperscript{1}, N. Shilkin\textsuperscript{2}, J. Ling\textsuperscript{1}, A. Fertman\textsuperscript{4}, V.E. Fortov\textsuperscript{2}, D.H.H. Hoffmann\textsuperscript{1}, A. Hug\textsuperscript{1,3}, M.I. Kulish\textsuperscript{2}, J. Menzel\textsuperscript{1}, N. Müller\textsuperscript{1}, V. Mintsev\textsuperscript{2}, S. el Moussati\textsuperscript{1}, D. Nikolaev\textsuperscript{2}, B.Yu. Sharkov\textsuperscript{4}, N.A. Tahir\textsuperscript{3}, V. Ternovoi\textsuperscript{2}, V. Turtikov\textsuperscript{4}, D. Varentsov\textsuperscript{3}

\textsuperscript{1}Institute of Nuclear Physics, Technical University, Darmstadt, Germany
\textsuperscript{2}Institute of Problems of Chemical Physics, Chernogolovka, Russia
\textsuperscript{3}Gesellschaft für Schwerionenforschung, Darmstadt, Germany
\textsuperscript{4}Institute for Theoretical and Experimental Physics, Moscow, Russia

The high intensity heavy ion beams provided by the accelerator facilities of the Gesellschaft für Schwerionenforschung (GSI) Darmstadt are an excellent tool to produce large volumes of high energy density (HED) matter. Thermophysical and transport properties of HED matter states are of interest for fundamental as well as for applied research. During the last few years development of new diagnostic techniques allowed for a series of measurements of the electrical resistivity of heavy ion beam generated HED matter. These experiments provide us with the basis for future measurements in the frame of the HEDgeHOB collaboration.

In this report we present the most recent experimental results for the electrical conductivity obtained by the four point measurement technique as well as the design of and preliminary results achieved by a non-contact radio frequency technique.

The experiments on which we report have been performed with targets consisting of wires and foils of different metals. Uranium and Tantalum beam pulses with durations of a few hundred ns, intensities of up to $5 \times 10^9$ particles/bunch and an initial ion energy of 350 AMeV have been used as a driver. An energy density deposition of about 1 kJ/g has been achieved by focusing the ion beam to a few hundred micrometers FWHM focal spot size.

The authors would like to acknowledge the financial support through the INTAS-GSI grant 06-1000012-8707.
RICHTMYER-MESHKOV INSTABILITY IN ELASTIC-PLASTIC MEDIA

A. R. Piriz\textsuperscript{1}, J. J. López Cela\textsuperscript{1}, N. A. Tahir\textsuperscript{2}, D. H. H. Hoffmann\textsuperscript{3}

\textsuperscript{1}E. T. S. I. I., Universidad de Castilla – La Mancha, 13071 Ciudad Real, Spain.
\textsuperscript{2}Gesellschaft für Schwerionenforschung, Plankstrasse 1, D-64291 Darmstadt, Germany.
\textsuperscript{3}Institut für Kernephysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany.

Hydrodynamic instabilities are an issue of great importance in the LAPLAS (Laboratory of Planetary Sciences) experiment that is being designed for the study of high energy density states of matter in the framework of the FAIR (facility for Antiproton and Ion Research) project. [1-3]

During the implosion of the LAPLAS cylindrical target Richtmyer-Meskov (RM) instability occurs when a shock is launched into a material pusher with elastic and plastic properties that determines the physics of the instability evolution. [4, 5]

We have studied the evolution of the interface from which the shock is launched as a consequence of the RM instability. For this we have developed an analytical model and we have performed extensive two-dimensional numerical simulations in order to validate the model results. Model and simulations show the asymptotic stability state in which the interface oscillates elastically around a mean value that is higher than the initial perturbation amplitude. Such a mean value is determined by an initial plastic phase.

Applications to the measurement of the yield strength of materials under extreme conditions are foreseen. [6, 7]

EXPERIMENTAL ACTIVITIES ON WDM AT ITEP

A.Golubev\textsuperscript{1}, V.Abramenko\textsuperscript{1}, M.Basko\textsuperscript{1}, A.Fertman\textsuperscript{1}, K.Gubskyi\textsuperscript{2}, V.Demidov\textsuperscript{1}, E.Demidova\textsuperscript{1}, A.Drozdosvyki\textsuperscript{1}, D.Iosseliani\textsuperscript{1}, A.Kantsyrev\textsuperscript{1}, A.Kuznetsov\textsuperscript{2}, T.Kulevoy\textsuperscript{1}, Yu.Novozhilov\textsuperscript{1}, A.Hudomjasov\textsuperscript{1}, N.Markov\textsuperscript{1}, S.Minaev\textsuperscript{1}, O.Pronin\textsuperscript{2}, P.Sasorov\textsuperscript{1}, B.Sharkov\textsuperscript{1}, A.Smolyakov\textsuperscript{1}, G.Smirnov\textsuperscript{1}, V.Turtikov\textsuperscript{1}, V.Yanenko\textsuperscript{1}

\textsuperscript{1}Institute for Theoretical and Experimental Physics, Moscow, Russia
\textsuperscript{2}Moscow Engineering Physics Institute (State University), Moscow, Russia

In preparations of the experimental campaign on TeraWatt Accumulator (ITEP-TWAC) facility special attention is paid to the development of special diagnostic methods required for investigation of thermodynamic properties of dense, strongly coupled plasma with high temporal resolution comparable with the hydrodynamic time scale for the expansion of the beam-heated target material.

Results of experimental tests on proton radiography employing special magnetic lenses and studies on the feasibility of the Bragg-peak contrast ion radiograph for the HEDP experiments with heavy ion beams are presented as well.

For advanced experiments on high energy density physics the hollow cylindrical target combined with cylindrical geometry of the energy deposition region is required. This combination will be capable of providing extremely high densities and pressures on the axis of imploding cylinder. A new method for RF rotation of the ion beam is applied for reliable formation of the hollow beam of ~2 mm in diameter. In order to obtain hollow beam geometry on the target the beam delivered by TWAC will be transformed by means of fast rotation around a cylindrical axis. The specified RF system consisting of two deflecting cavities is under development for this purpose now. The cavities operating frequency has been chosen 300 MHz, which appears to be sufficient for uniform target illumination at power deposition level about 10 TW/g. The RF rotation system will be placed in the beam transport line at the distance from the target equal to quarter wavelength of transverse beam oscillations. The design of the rotation system and layout of the target – rotation system and focusing elements are presented.
MODELLING THE SCATTERING OF X-RAYS
IN WARM DENSE MATTER

D.O. Gericke, K. Wünsch and J. Vorberger

Centre for Fusion, Space and Astrophysics, Department of Physics,
University of Warwick, Coventry CV4 7AL, UK

X-ray scattering is one of the few potential methods to probe dense systems like warm dense matter or ICF plasmas that are opaque in the visible. The scattering spectrum usually shows two distinct features: a large peak around the incident wave length (ion feature) and one or two frequency-shifted peaks associated with the collective scattering from free electrons (plasmon peaks). Theoretical predictions for both features are needed to obtain all plasma properties from the measured scattering spectrum. However, such theoretical predictions for the scattering signal sets a number of theoretical challenges since the matter under consideration is characterized by partially to highly degenerate electrons and strongly coupled ions.

The free electron contribution is rather easily described by the random phase approximation (RPA) since the electrons are in most cases only weakly coupled. Degeneracy effects on this level are standard. This feature can be used to obtain the electron density and temperature. In highly degenerate system, only the density can be obtained and the plasma temperature has to be inferred otherwise. The ion charge state and the ion temperature might be obtained from the ion feature (electrons associated with the ions). We use first principle quantum simulations (DFT-MD) and multi-component hypernetted chain (HNC) solutions to calculate both the ionic structure and the electron cloud around the ions. The HNC calculations show a strong dependence on the applied quantum potential which strongly limits their applicability to diagnostics of warm dense matter. However, simple one component calculations using the well-known linear screening model for the strongly coupled ions predict the ionic properties rather well compared the full quantum simulations. The DFT-MD results agree well with measurements and also allow to extract information on the charge state and short range interactions. They also give insights in the structure of the bound states in a dense, highly correlated medium showing strong deviations to bound states in isolated atoms. The last effect can be strong enough to considerably change the expected x-ray scattering spectrum.
HIGH ENERGY DENSITY PHYSICS EXPERIMENTS
WITH INTENSE HEAVY ION BEAMS

F.M. Bieniosek$^{1,2}$, J. J. Barnard$^{1,3}$, J.E. Coleman$^{1,2}$, E. Henestroza$^{1,2}$, M. A. Leitner$^{1,2}$, B. G. Logan$^{1,2}$, R. M. More$^{1,2}$, P. A. Ni$^{1,2}$, P. K. Roy$^{1,2}$, W. L. Waldron$^{1,2}$, P. A. Seidl$^{1,2}$

$^1$HIFS-VNL
$^2$LBNL, Berkeley, CA, USA
$^3$LLNL, Livermore, CA, USA

The US heavy ion fusion science program has developed techniques for heating ion-beam-driven warm dense matter (WDM) targets. The WDM conditions are to be achieved by combined longitudinal and transverse space-charge neutralized drift compression of the ion beam to provide a hot spot on the target with a beam spot size of about 1 mm, and pulse length about 1-2 ns. As a technique for heating volumetric samples of matter to high energy density, intense beams of heavy ions are capable of delivering precise and uniform beam energy deposition \(dE/dx\), in a relatively large sample size, and the ability to heat any solid-phase target material. Initial experiments use a 0.3 MeV K+ beam (below the Bragg peak) from the NDCX-I accelerator. Future plans include target experiments using the NDCX-II accelerator, which is designed to heat targets at the Bragg peak using a 3-6 MeV lithium ion beam. The range of the beams in solid matter targets is about 1 micron, which can be lengthened by using porous targets at reduced density.

We have developed a WDM target chamber and a suite of target diagnostics including a fast multi-channel optical pyrometer, optical streak camera, VISAR, and high-speed gated cameras. Initial WDM experiments will heat targets by compressed NDCX-I beams and will explore measurement of temperature and other target parameters. Future experiments are planned in areas such as dense electronegative targets, porous target homogenization and two-phase equation of state.
AN IMPLICIT “DRIFT-LORENTZ” PARTICLE MOVER FOR PLASMA AND BEAM SIMULATIONS

R. H. Cohen¹, A. Friedman¹, D. P. Grote¹, and J.-L. Vay²

¹Lawrence Livermore National Laboratory, Livermore, CA, USA
²Lawrence Berkeley National Laboratory, Berkeley, CA, USA

In order to efficiently perform particle simulations in systems with widely varying magnetization, we have developed a “drift-Lorentz mover”, which interpolates between full particle dynamics and drift kinetics in such a way as to preserve a physically correct gyroradius and particle drifts for both large and small ratios of the timestep to the cyclotron period.[1]. In order to extend applicability of the mover to systems with plasma frequency exceeding the cyclotron frequency – such as one may have with fully neutralized drift compression of a heavy-ion beam – we have developed an implicit version of the mover. A first step in this direction, in which the polarization charge was added to the field solver, was described previously[2]. Here we describe a fully implicit algorithm (which is analogous to the direct-implicit method for conventional particle-in-cell simulation[3]), a stability analysis of it, its implementation in the WARP code, and several tests of the resultant code. The fully implemented version is electrostatic; we are beginning development of an electromagnetic version, and describe also the status of that effort.


* Work performed for the U.S. Department of Energy by LLNL under contracts W7405-ENG-48 and DE-AC52-07NA27344 and by U.C. LBNL under contract DE-AC02-05CH11231.
STUDY OF PROTON AND HOT ELECTRON CHARACTERISTICS FOR FAST IGNITION

Kazuo A. Tanaka

Graduate School of Engineering & Institute of Laser Engineering, Osaka University, Suita Osaka 565-0871 Japan

Hot electrons and protons are currently under intense studies as candidates for fast ignition heat carrier [1]. We show our latest results of proton and hot electron characteristics produced with an ultra-intense laser (UIL) pulse. MeV protons [2] and up to 600 MeV electrons [3] are reproducibly produced at UIL facilities. Proton focusing resulted in heated black body temperature 80 eV within a solid target. The proton focusing was achieved by using a tea cup shape target irradiated from the convex surface with a peta watt (PW) laser energy 170J. The xuv image is shown in Figure 1 where the cup is indicated with the white line shape. The small bright spot indicates the spot focused with protons created at the inner, concave surface of the cup.

Hot electrons are studied in terms of UIL pulse duration dependence on slope temperature. As known well our Nature paper [4] indicated a compressed core heated with hot electrons of a slope temperature 1-2 MeV. In this experiment UIL pulse width was less than psec with a PW peak power. In order to achieve a higher heated temperature up to 5 keV, FIREX laser system will be used, which is supposed to deliver 10 kJ in 10 psec with a PW peak intensity. Under a relatively long pulse UIL irradiation, we need to study the characteristics of hot electrons. Long UIL pulses will prepare a plasma formation which could supply a field for UIL to be self-focused in under dense plasmas. We have examined this dependence using an UIL pulse up to 5 psec at relativistic laser intensities and will report the details.

References

Acknowledgement: The experiments are under the collaboration with U.S. fast ignition, China, and Indian groups.

Figure 1 XUV image of Al target heated with proton beam generated with a PW laser 170 J.
IONS ACCELERATION BY PETAWATT CLASS LASER PULSES AND PELLET COMPRESSION IN A FAST IGNITION SCENARIO

C. Benedetti\textsuperscript{1}, P. Londrillo\textsuperscript{2}, T. V. Lyseykina\textsuperscript{3}, A. Macchi\textsuperscript{4}, A. Sgattoni\textsuperscript{1}, G. Turchetti\textsuperscript{1}

\textsuperscript{1}Dipartimento di Fisica Università di Bologna, INFN sezione di Bologna, Italy
\textsuperscript{2}Dipartimento di Astronomia Università di Bologna, INAF and INFN sezione di Bologna, Italy
\textsuperscript{3}Institute for Computational Technologies, SD-RAS, Novosibirsk, Russia
\textsuperscript{4}polyLAB, CNR-INFM, Pisa, and INFN, sezione di Pisa, Italy

Ions drivers based on standard accelerations techniques have faced up to now several difficulties. We consider here a conceptual alternative to more standard schemes, which are still beyond the present state of the art of particle accelerators even though the requirements on the total beam energy are lowered by fast ignition scenarios. The new generation PW class lasers open new possibilities: acceleration of electrons for the fast ignition and eventually light ions acceleration for compression. The pulses of CPA lasers are too short for direct adiabatic compression but allow electrons and ions acceleration with a high repetition rate. We analyze the possibility of accelerating light ion bunches by interaction of a circularly polarized pulse with an ultra-thin foil. The advantage would be compactness and modularity, due to identical accelerating units. The laser efficiency and intensity needed for inertial fusion are still far from the presently achievable values, whereas the conversion efficiency is already good and grows with the intensity. We have developed a Maxwell-Vlasov code ALADYN for the PLASMONX experiment at Frascati where the 0.3 PW laser FLAME will accelerate electrons and protons. We present the results of some simulations and parametric scanning for the acceleration of light ions. Circularly polarized laser pulses with intensity above $10^{21}$ W/cm$^2$ on sub-micrometric foils accelerate ions in the GeV range with a very small energy spread and up to 30% efficiency. The number of ions can reach $10^{12}$ per bunch if the focal spot is large enough. The bunch parameters presently achieved, the beam quality and efficiency may be interesting for other applications.
One of the most promising applications of intense femtosecond laser pulses is a concept of a compact laser-driven accelerator of charged particles, [1]. A femtosecond laser pulse with the electric field several times greater than the atomic unit can produce in plasmas a long-living collective electric field with magnitude greater than TV/m. An efficient generation of fast ion beams with unique properties has been recorded in experiments on the interaction of terawatt-petawatt laser pulses with solid targets, [2]. In these experiments, electrons are accelerated up to several hundred MeV while energies of the fast ions amounted up to several tens of MeV/nu.

Numerous applications require ion beams of high quality. For example, for hadron therapy in oncology the relative energy spread should be as small as 2% and the transverse emittance should be of the order of 0.1 mm·mrad, in order to guarantee an eradication of a malignant tumor while simultaneously ensuring an acceptable level of the irradiation of the surrounding healthy tissues. Using special shapes of the laser pulse and certain configurations of the target one can control the properties of the accelerated ion spectra. The proposed double layer target [3] is capable of producing ion beams suitable for the hadron therapy.

The scaling laws of the ion acceleration driven by a terawatt-petawatt laser pulse from a double layer target are obtained with multi-parametric Particle-in-Cell (PIC) simulations, [4]. For targets with a wide range of thickness and density, at given laser intensity the highest ion energy gain occurs at certain areal density of the target, which is proportional to the square root of intensity. In the case of thin targets and optimal laser pulse duration, the ion maximum energy scales as the square root of the laser pulse power. When the radiation pressure of the laser field becomes dominant, the ion maximum energy becomes proportional to the laser pulse energy and can reach several GeV, [5]. In this regime, the efficiency of the acceleration, which is the ratio between the energy of accelerated particles and the energy of the laser pulse, is near 100%.

LASER ION SOURCE FOR LOW CHARGE HEAVY ION BEAMS.

Masahiro Okamura\textsuperscript{1}, Alexander Pikin\textsuperscript{1}, Vladimir Zajic\textsuperscript{1}, Takeshi Kanesue\textsuperscript{2}, Jun Tamura\textsuperscript{3}

\textsuperscript{1}Brookhaven National Laboratory, Upton NY, USA  
\textsuperscript{2}Kyushu University, Fukuoka, Japan  
\textsuperscript{3}Tokyo Institute of Technology, Tokyo, Japan

As a part of Relativistic Heavy Ion Collider (RHIC) Electron Beam Ion Source (EBIS) project, a laser ion source (LIS) development for low charge state ion beams has been started. In this program, a stable ion beam generation using a Nd-YAG laser was demonstrated. A laser power density on the source target materials were carefully adjusted to provide long pulsed ion beams with low damage to the target surface. The ion beam emittance was measured with a pepper pot detector and time dependent emittance data are presented. This method of generating a high quality ion beams can be utilized for direct injection scheme (DPIS) which enables us to capture high current beam in an radio frequency quadrupole linear accelerator (RFQ). The combination of a LIS with low charge state and an RFQ could be a strong candidate for an injection part of HIF complex.
IMPACT FUSION IGNITION AND IMPLICATION TO HIF

M.Murakami¹, H.Nagatomo¹, H.Azechi¹, and A.Velikovich²
¹Institute of Laser Engineering, Osaka University, Osaka, Japan
²Naval Research Laboratory, Washington DC 20375, USA

The Thermonuclear ignition has been a long-awaited goal in laser fusion research. Ignition are expected to be achieved at National Ignition Facility in the US and at Laser Mega-Joule facility in France based on central spark ignition scheme. Meanwhile, fast ignition has the potential to reach this goal with about one tenth of the laser energy required in these other programs. The concept of fast ignition is to separate fuel compression from ignition, which is attained by injecting an extremely intense and short laser pulse into pre-compressed fuel. However, fast ignition still has many intractable physical problems to solve relevant to complex laser-matter interactions, such as the transport of the absorbed energy via hot electrons or energetic ions to the dense compressed fuel. Impact ignition eliminates this complexity while keeping the compactness advantage of fast ignition.

In impact ignition scheme [1-3], the compressed DT main fuel is ignited by impact collision of another fraction of separately imploded DT fuel (impactor), which is accelerated in the hollow conical target to super high velocities beyond 1000 km/s. Its kinetic energy is directly converted into thermal energy corresponding to temperatures > 5 keV on the collision with the main fuel, and this self-heated portion plays the role of ignitor. Simple physics, potential for high gain designs, and low cost - these are the crucial advantages of the present scheme. A preliminary experiment has demonstrated a highest velocity, 650 km/s, ever achieved in use of a planar target, which was ablatively driven.

We have also done experiments with an integrated target, which is composed of two deuterated polystyrene (CD) semispherical targets bonded by the gold cone. Both the main fuel and the impactor were irradiated by Gaussian-shaped lasers characterized by a wavelength of 0.53 µm and a pulse duration of 1.3 ns at full width at half maximum. In these experiments, it has turned out that the neutron emissions were isotropic and they were accompanied with no energy shift. Thus they indicate that the neutrons were generated by thermonuclear fusion due to the collision effect by the impactor. The increase of two orders of magnitude in neutron yield at the right timing of the impact collision indicate the high potential of impact ignition for future fusion energy production.

In this paper we show that the scheme of the Impact Fusion Ignition can be extended for Heavy Ion Fusion research.

References
ROBUST HYBRID FUEL TARGET IN HEAVY ION INERTIAL FUSION

S. Kawata\textsuperscript{1}, Y. Iizuka\textsuperscript{1}, T. Kikuchi\textsuperscript{1}, A.I. Ogoyski\textsuperscript{2}

\textsuperscript{1}Utsunomiya University, Utsunomiya, Japan
\textsuperscript{2}Technical University of Varna, Varna, Bulgaria

Nonuniformity of heavy ion beam (HIB) illumination is one of key issues in HIB inertial confinement fusion (HIF): fuel implosion symmetry should be less than a few percent in order to compress a fuel sufficiently and release fusion energy effectively. In this paper a new HIB illumination scheme is presented in order to realize a robust illumination scheme against a displacement of a direct-driven fuel pellet in an ICF reactor. It is known that the HIB illumination nonuniformity is sensitive to a little pellet displacement from a reactor chamber center; a pellet displacement of only 50-100 \textmu m was tolerable in conventional HIB illumination schemes. In this paper by three-dimensional computer simulations a new robust HIB illumination scheme was found, in which a 200-300 \textmu m displacement is allowed. In addition, in this study a direct-indirect hybrid implosion mode is also discussed in HIF. In the direct-indirect hybrid mode target, a low density foam layer is inserted, and the radiation energy is confined in the foam layer. In the foam layer the radiation transport is expected to smooth the HIB illumination non-uniformity in the lateral direction. We study the influences of the foam thickness and the inner Al density on the implosion uniformity. In conclusion, two-dimensional fluid simulations demonstrate that the hybrid target with the optimal HIB illumination scheme contributes to the HIB non-uniformity smoothing and releases a sufficient fusion energy output in HIF.
We re-studied the historical impact fusion concept, and proposed a new approach, which is closed related to fast ignition concept, but without pre-compression. It is a fast ignition version of impact fusion. In this approach, a hypervelocity (500 to 2000 km/s) millimeter size macro particle is shot to a passive centimeter size target, to ignite and burn the target. The macro particle size is much smaller than adopted in previous impact fusion schemes, so the argument ruling out the electrostatic acceleration is no longer valid. DT compounds with light elements such as Lithium, Boron, Carbon, are used as fusion fuel, instead of common DT ice. The compounds have denser DT concentration than DT ice. Other elements act as catalysts, help in stopping and keeping the energy of the alpha particles produced in fusion, and transfer the energy to DT ions. In typical temperatures, these elements capture about 10 times more alpha particle energy than DT ions, but they are still in low energy regime, which will theromolize only with DT ions. This increase of DT heating is vital in the burning process. The larger size of the target means much more DT is burned, and produces more fusion energy than other ICF schemes. In our approach, the fusion fuel is tossed to the reaction chamber, and device or component has to be near the fusion point, which means it is free of the notorious "stand-off" problem of ICF. In addition, this concept provides a way of concentrating a large amount of energy into solid density materials, and can be explored as another experimental tool for studying high energy density physics in laboratory.
PROSPECTS FOR HEAVY ION BEAM PUMPED VUV/XUV-LASER EXPERIMENTS

A. Adonin$^1$, D.H.H. Hoffmann$^2$, J. Jacoby$^1$, A. Ulrich$^3$, J. Wieser$^4$

$^1$Johann Wolfgang Goethe Universität, Frankfurt/Main, Germany
$^2$Technische Universität, Darmstadt, Germany
$^3$Technische Universität, München, Germany
$^4$Coherent GmbH, München, Germany

Intense heavy ion beams are an excellent tool for producing strongly coupled plasmas and to measure the properties of matter under such extreme conditions. The quantitative determination of an equation of state e.g. requires a precise knowledge of the specific energy deposited by the ion beam in the target. This can be determined from three parameters: beam intensity, beam profile and stopping power. If possible these parameters should be measured directly in order to obtain an accuracy of the specific energy deposition on the order of 1 %. For the projected heavy ion facility FAIR at GSI the available beam intensities will be enhanced by several orders of magnitude in comparison with the existing synchrotron SIS-18 and will reach values up to $10^{11}$ U-ions per pulse. The diagnostics of such a high beam intensity focused onto a target with sub-mm spot size will require a non-destructive and precise diagnostic method which is presently not yet available.

As one approach for such a diagnostics we propose to produce and study laser effect induced by the heavy ion beam in a dense gas target. Excimer lasers of the pure rare gases for example require very high pumping power densities and may be used for that purpose. The stimulated intensity enhancement in the target gas develops above a certain specific energy deposition and has a non-linear response with respect to beam intensity. This should lead to a high accuracy when this effect is used for beam diagnostics.

In 2005 the first successful operation of a heavy ion beam pumped UV excimer laser has been demonstrated at GSI and laser effect for a KrF$^*$ excimer laser at 248 nm had clearly been demonstrated [1]. As a next step the laser wavelength will be extended to the VUV region with a correspondingly enhanced specific deposition power. The laser systems which will be used for that purpose are the excimer laser transitions of the pure rare gases: Xe$_2^*$ ($\lambda=172$nm), Kr$_2^*$ ($\lambda=146$nm), Ar$_2^*$ ($\lambda=126$nm), Ne$_2^*$ ($\lambda=83$nm) and He$_2^*$ ($\lambda=80$nm). For the presently available beam intensities of SIS-18 laser action can be predicted for Xe$_2^*$ and Kr$_2^*$ in an optical cavity for an improved experimental set up. Short wavelength lasers at FAIR may then be designed as single pass amplified spontaneous emission (ASE) lasers.

Precise knowledge of heavy ion stopping in warm/hot matter is essential to determine beam-energy-deposition profiles not only in heavy-ion-fusion targets but also in targets for accelerator driven warm-dense-matter experiments. Increase in the target temperature due to high-power-beam irradiation leads to the excitation and the ionization of the target atoms, which change the mean excitation energy, i.e. the stopping power of the target. These temperature effects on the stopping power are predicted to become more particular for low energy projectiles having “Bragg peak velocity”, which corresponds to the averaged bound/free electron velocity in the target.

To examine the energy loss of low-energy heavy ions in various temperature targets, we have developed a shock-produced plasma target using an electromagnetically driven shock tube[1,2]. By controlling the initial gas pressure and the shock speed, we produced well-defined density and temperature states behind the shock front. The temporal and spatial profiles of the target density and temperature were examined by spectroscopic measurements and compared with results of one-dimensional simulations. The energy loss of low-velocity heavy ions (~100 keV/u) in the shock-produced warm gas/plasma targets was also measured by a combination of a fast beam kicker and a silicon semiconductor detector.

The results on the shock-produced plasma targets are presented and their applicability to the interaction experiments is discussed. The reliability of stopping power formulae in the Bragg-peak-velocity regime is also discussed based on the results of the energy loss measurements.

LOW ION VELOCITY SLOWING DOWN IN A STRONGLY MAGNETIZED TARGET PLASMA

Claude Deutsch and Romain Popoff

LPGP(UMR-CNRS 8578), Université Paris XI, Orsay, France

Ion projectile stopping at velocity smaller than target electron thermal velocity in a strong magnetic field, is investigated within a novel diffusion formulation based on Green-Kubo integrands evaluated in magnetized one-component-plasma models, respectively framed on target ions and electrons. Analytic expressions are reported for slowing down orthogonal and parallel to an arbitrarily large and constant magnetic field, which are free from the usual uncertainties plaguing standard perturbative derivations. Magnetic and target temperature dependences of the low velocity slowing down are thoroughly detailed for dense plasmas of fast ignition ICF concern and also ultracold plasmas as well.
QUASI-STATICALLY TAMPED TARGET FOR WARM DENSE MATTER EXPERIMENTS BASED ON ALL ION ACCELERATOR

Toru Sasaki\textsuperscript{1}, Takashi Kikuchi\textsuperscript{2}, Mitsuo Nakajima\textsuperscript{1}, Tohru Kawamura\textsuperscript{1}, and Kazuhiko Horioka\textsuperscript{1}

\textsuperscript{1} Department of Energy Sciences, Tokyo Institute of Technology, Yokohama, Japan
\textsuperscript{2} Department of Electrical and Electronic Engineering, Utsunomiya University, Utsunomiya, Japan

We propose a quasi-statically tamped target to make a well-defined, warm dense state based on All Ion Accelerator: AIA. AIA has attractive features; it can accelerate any ion species with any charge state, and has precise waveform controllability.

The target is composed of two layers, in which the inner material is set to be low-Z and low density, and the outer layer is formed with a dense high-Z material. The structure can exclude an unknown factor caused by the tamper hydrodynamics in dynamic tamper schemes. In order to evaluate uniformity of the large-scale target, we calculated the hydrodynamics of the target with two dimensional, cylindrical r-z geometry.

We compared behaviors of a solid target and a monolayer target to that of the tamped target driven by AIA. Results show that though both those targets can reach a warm dense state, only the tamped target can produce a well-defined, quasi-uniform warm dense state with long spatial scale. We show the achievable parameter regime of the beam driven target in warm dense state and discuss a possible method to make high-pressure experiments for exploration of the interior structure of Jupiter.
DEVELOPING ACCELERATION SCHEDULES
FOR NDCX-II*

W. M. Sharp, A. Friendman, D. P. Grote

Lawrence Livermore National Laboratory, Livermore, CA, USA

The Virtual National Laboratory for Heavy-Ion Fusion is developing a physics design for NDCX-II, an experiment to study warm dense matter heated by ions near the Bragg-peak energy. To minimize the cost of this facility, induction cells and other hardware from the decommissioned Advanced Test Accelerator (ATA) at Lawrence Livermore National Laboratory will be reconditioned and reused. Present plans call for using about thirty ATA cells to accelerate 30 nC of Li+ ions to an energy in excess of 3 MeV before neutralized drift-compression. To heat targets to useful temperatures, the beam must be compressed to a sub-millimeter radius and a duration of about 1 ns, a longitudinal compression factor of more than 600.

Developing a suitable acceleration schedule for NDCX-II is challenging for several reasons: (a) The limited floor space constrains the number of acceleration cells to forty or fewer; (b) budgetary considerations necessitate the use of passive circuit elements to shape waveforms; (c) the applied waveforms must compensate for the beam longitudinal space charge and impose a head-to-tail velocity tilt, in addition to accelerating the beam; (d) the large ATA beam pipe (6.7 cm radius), unless reduced with apertures or sleeves, causes the gap fields to spread out axially to nearly a full lattice period; and (e) the need for extreme longitudinal and transverse compression requires minimal emittance growth and halo formation during acceleration.

A combination of analysis, 1-D particle-in-cell simulation, and detailed, multidimensional modeling with WARP is being used to develop NDCX-II acceleration schedules. Simple calculations demonstrate that a suitably chosen pair of acceleration waveforms can add or subtract a velocity variation along a beam that is linear along the beam length. This result has been verified using an interactive 1-D particle-in-cell code that optimizes the cell parameters. With the addition of gap fringe fields, a 1-D electrostatic field solver, and a library of realizable analytic waveforms, this code has also been useful in working out full acceleration schedules for NDCX-II. WARP runs are then used to verify these schedules, to add appropriate transverse focusing, and to compensate for 3-D effects. Results from this work are presented, and ongoing work to replace the analytic waveforms with output from a circuit model is discussed.

* This work performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
EMITTANCE EVOLUTION DURING LONGITUDINAL MANIPULATION OF PARTICLE BEAMS

Sota Kinoshita, Masashi Kobayashi, Mitsuo Nakajima, and Kazuhiko Horioka

Department of Energy Sciences, Tokyo Institute of Technology, Yokohama, Japan

In order to make an energetic particle beam, bunch compression using longitudinal beam manipulation is essential. However, the bunching process is inevitably accompanied by emittance growth, because of a space charge effect, inaccurate bunching voltage, fluctuation in the beam transport line, and others [1].

To simulate the longitudinally modulating process in a small laboratory, we constructed a small accelerator which is composed of an electron beam injector, induction voltage modulators, and a beam transport line with 2m in length, in which an electron beam is accelerated, longitudinally modulated, and transported for beam bunching. The bunching waveform is synthesized using the induction modulators with voltage adder configuration.

Evolutions of the beam emittance are estimated by images of a pepper-pot beam detector. We discuss the emittance evolution including the correlation between transverse and longitudinal emittance as a function of the beam parameter, the transport distance and the bunching factor.

SIMULATION OF HIGH FREQUENCY MODES AND THEIR EFFECT ON INSULATOR BREAKDOWN IN THE PULSE LINE ION ACCELERATOR

C.Y. Ling¹, E. Henetroza², S. Yu¹,²

¹The Chinese University of Hong Kong, Hong Kong, China
²Lawrence Berkeley National Laboratory, Berkeley, California, USA

The Pulse Line Ion Accelerator (PLIA) produces a traveling EM wave by applying a voltage pulse to one end of a helix that accelerates and axially confines the heavy ion beam pulse. An anomalous flashover phenomenon has been observed on the vacuum-insulator surface which limits the amplitude of the accelerating field. It has been suspected that a small component of high frequency modes in the input pulse may be the cause of the breakdown. Simulation using MAFIA (MAxwell’s equations by Finite Integration Algorithm) was conducted to investigate the fields on the insulator surface. A scaling law was proposed to reduce substantially the computational time in simulation. It is based on the hypothesis that the pattern of EM field for a given wavelength is independent of the wire spacing provided that the wavelength is much longer than the inter-wire spacing and the termination resistors are adjusted to maintain impedance matching. Simulation shows that at low frequencies (ka << 1, where k is the wave number, and a the pipe radius) the field strengths on axis as well as on the insulator grow linearly with frequency. At high frequencies (ka >> 1), the field on axis nearly vanishes, while the field on the insulator continue to grow at a rate faster than linearly with frequency. At medium frequencies and above (ka >~ 1), we see clear signs of reflections from the terminating resistors, which are impedance matched only at low frequencies. These wave reflections, which are consistent with experimental observations, lead to further enhancements of the fields on the insulator surface. On the basis of these numerical simulations, we conclude that high frequency modes, even at very low amplitudes, may indeed lead to the observed insulator flashover.
MULTIBEAM LINAC STRUCTURE FOR HEAVY ION FUSION

Noriyosu Hayashizaki, Taku Ito, Takuya Ishibashi, Toshiyuki Hattori
Research Laboratory for Nuclear Reactors,
Tokyo Institute of Technology, Tokyo, Japan

Both linear accelerators (linac) and induction accelerators have been considered as drivers for heavy ion fusion (HIF). The linear accelerator system for HIF is required to accelerate high intense heavy ion beam of ion mass about 200 amu up to 50-75 MeV/amu. In the low energy region, the funneled tree system of linear accelerators (RFQ, IH and Alvarez) is adopted to avoid space charge effect. Then, a multi-beam linac that accelerates the multiple beams in an acceleration cavity has advantages for downsizing and cost reduction of the linac system. However, the configuration of electrodes of the multi-beam linac is more complicated than that of single beam type, and so it influences the resonance frequency. A minimum of cavity diameter is restricted by the volume of electrodes, which depends largely on the numbers of beams. The relation between the numbers of beam and the acceleration structure is studied with electromagnetic simulation and the feasibility of the multi-beam linac for HIF will be discussed.
Plasmas are a source of unbound electrons for charge neutralizing intense heavy ion beams to focus them to a small spot size and compress their axial length. The source should operate at low neutral pressures and without strong externally applied fields. To produce long plasma columns, sources based upon ferroelectric ceramics with large dielectric coefficients have been developed. The source utilizes the ferroelectric ceramic BaTiO$_3$ to form metal plasma. The drift tube inner surface of the Neutralized Drift Compression Experiment (NDCX) is covered with ceramic material. High voltage (~ 8 kV) is applied between the drift tube and the front surface of the ceramics. A BaTiO$_3$ source comprised of five 20-cm-long sources has been tested and characterized, producing relatively uniform plasma in the $5 \times 10^{19}$ cm$^{-3}$ density range. The source was integrated into the NDCX device for charge neutralization and beam compression experiments, and yielded current compression ratios ~ 120. Present research is developing multi-meter-long and higher density sources to support beam compression experiments for high energy density physics applications.

Research supported by the U.S. Department of Energy.
Po-6

STUDY ON TARGET STRUCTURE FOR DIRECT-INDIRECT HYBRID IMPLOSION MODE IN HEAVY ION INERTIAL FUSION

Y. Iizuka\textsuperscript{1}, T. Kikuchi\textsuperscript{1}, S. Kawata\textsuperscript{1}, A.I. Ogoyski\textsuperscript{2}

\textsuperscript{1}Utsunomiya University, Utsunomiya, Japan
\textsuperscript{2}Technical University of Varna, Varna, Bulgaria

In inertial confinement fusion (ICF) driven by heavy ion beams (HIBs), key issues include a particle accelerator system as an energy driver, a reactor chamber design, an efficient HIB transport, a beam-target interaction, and so on. There are two implosion schemes for ICF, that is, direct- and indirect-driven designs. Each design has some advantages and disadvantages. The direct-driven scheme has a simple structure of the fuel pellet, although the scheme may be sensitive for the illumination non-uniformity of HIBs. On the other hand, the indirect-driven scheme may be robust against the illumination non-uniformity with the lower number of the HIBs. However, the fuel pellet structure is complicated. To realize an effective implosion of a fuel pellet, the beam illumination non-uniformity and implosion non-uniformity must be suppressed to less than a few percent in the azimuthal direction.

In this study, a direct-indirect hybrid mode is researched in ICF driven by HIBs, in order to release sufficient fusion output energy in a robust manner. In the target pellet with a direct-indirect hybrid mode, a low-density foam layer is introduced into the pellet structure, and radiation energy is confined in the foam layer. In the foam layer, the radiation transport is expected in the lateral direction for the illumination non-uniformity smoothing of the heavy ion beams.

Two-dimensional implosion simulations are performed, and the simulation results indicate that the illumination non-uniformity of the heavy ion beams can be smoothed well. The pellet gain and the implosion non-uniformity depend on the thickness of the inserted foam layer.
DIGITAL ACCELERATION SCHEME OF THE KEK-ALL ION ACCELERATOR

Tanuja S. Dixit\textsuperscript{1}, Taiki Iwashita\textsuperscript{2}, Yoshio Arakida\textsuperscript{2}, Ken Takayama\textsuperscript{1,2}

\textsuperscript{1}The Graduate University of Advanced Studies (GUAS), Hayama, Japan
\textsuperscript{2}KEK, 1-1 Oho, Tsukuba, Japan

R&D works to realize an all-ion accelerator (AIA)\textsuperscript{*}-capable of accelerating all ions of any possible charge state, based on the induction synchrotron concept, which was demonstrated using the KEK 12 GeV-PS in 2006\textsuperscript{**}, is going on. In the induction synchrotron, unlike an RF synchrotron, operational performance is not limited due to the frequency bandwidth, since the switching power supply to energize the induction acceleration system is triggered by signals obtained from the bunch monitor. For a POP experiment of AIA, argon ions will be accelerated in the KEK-500MeV booster ring, a Rapid Cycle Synchrotron (f=20Hz) and the RCS requires a dynamic change in the acceleration voltage. Since the induction acceleration voltage per pulse is fixed, a novel technique combining the pulse density control and intermittent operation of multi-acceleration cells has been proposed. The acceleration scheme of the AIA fully employing this technique was verified by computer simulation and demonstrated at our test facility, where a new induction acceleration cell generating an acceleration voltage pulse of 2microsec long was triggered by a beam simulator to mimic a circulating Ar beam in the KEK-AIA.

TWO-BEAM TYPE IH-RFQ LINAC FOR HEAVY ION INERTIAL FUSION

Takuya Ishibashi\textsuperscript{1}, Noriyosu Hayashizaki\textsuperscript{1}, Toshiyuki Hattori\textsuperscript{1}, Taku Ito\textsuperscript{1}, Jun Tamura\textsuperscript{1}, Lu Liang\textsuperscript{1}

\textsuperscript{1}Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, N1-25 2-12-1 O-okayama Meguro-ku, Tokyo 152-8550, Japan

The defocusing force of space charge effect is proportional to the beam current and to the inverse square of the beam velocity. In order to suppress the defocusing force on Heavy-Ion Inertial Fusion (HIF), an idea has been proposed to divide a single, high intensity beam into several beams, and integrate these beams into a single high intensity beam with higher energy. However, this scheme needs huge system, especially RFQ linac section.

Therefore, we have developed a two-beam type Radio Frequency Quadrupole (RFQ) linac with an Interdigital H-mode (IH) structure for high intensity heavy-ion beam acceleration. The two-beam type IH-RFQ linac, which has two beam lines in one cavity, could save the space and the operational cost in the RFQ linac section of the heavy ion inertial confinement fusion driver system.
An extensive WDM experimental program is scheduled at LBNL where NDCX induction linear accelerator is used as a driver for heating metallic targets. The target diagnostic in these experiments must be capable of precise measurement of temperature in the range from 1000 K to 5000 K, pressure in kbar region, and expansion velocities up to several km/sec. The volumetric heating occurs on a nano-second time scale, during which the sample remains in a solid state.

Low temperature (i.e. low level radiation of ~1 mW in VIS-NIR) probing with a sub-nanosecond temporal resolution is a challenging task, and for this purpose a unique fast, high-sensitivity optical pyrometer operating at 750 nm and 1100 nm is being built, with a possibility to be upgraded up to 7 channels in the future.

An absolutely calibrated streak-camera-based-spectrometer working in 450 nm to 850 nm is also being developed. Apart from the conventional discrete-channel pyrometer, this instrument will lead to determination of both, physical temperature and surface emissivity of the sample. However, due to lower sensitivity of the instrument (compared to the 2-channel pyrometer) it is planned to be used in experiments with higher target temperatures, starting from 5000 K.

Expansion velocity of a target’s surface (that is in turn related to pressure), will be measured by a Doppler-shift diode-laser interferometer (VISAR) with 50 ps temporal resolution and 20 m/s velocity resolution.

Probing of temperature and pressure is carried out simultaneously by the same collection optics, based on two-off axis parabolic mirrors or VIS-NIR corrected hyper-spectral lens. Finally, two fast-gated CCD cameras will be used for precise positioning and instant imaging of heavy-ion beam heated samples.
SIMULATIONS FOR WARM DENSE MATTER DRIVEN BY INTENSE HEAVY ION BEAMS

A. Grinenko, D.O. Gericke and J. Vorberger

Centre for Fusion, Space and Astrophysics, Department of Physics, University of Warwick, Coventry CV4 7AL, UK

Ion beams are one of the most efficient drivers for experiments in the warm dense matter region. Here, experimental and theoretical investigations concerning thermodynamic, structural and transport properties continue to break new ground. The focus is here on hydrogen for compression studies and heavy elements needed for the converters in indirect drive fusion scenarios. Simulations of designated experiments can serve two purposes: they can be used to predict the interesting regions and they may yield information about the equation of state (EOS) by direct comparison. For ion beam driven experiments, the EOS is needed over a very wide range of temperature and density crossing several phase boundaries as the melting line and the creation of a highly ionized plasma state. In this contribution, we investigate the capability of a new type of ion beam compression experiment, to be carried out at the FAIR facility at the GSI-Darmstadt, to observe the metal-liquid phase transition in molecular hydrogen at high pressures. The hydrodynamic simulations indicate that the new experimental facility is able to probe solid and fluid molecular region of hydrogen around the melting line at the high pressures near its maximum. A wide range equation of state for hydrogen employing first principles and experimental data was constructed for these simulations. Calculated structure factors in the vicinity of the high-pressure solid-fluid phase transition suggest that Thompson scattering diagnostic can be employed to distinguish between crystalline solids and the fluid hydrogen.
SONOLUMINESCENCE TEST FOR EQUATION OF STATE IN WARM DENSE MATTER

Siu-Fai Ng, P. T. Leung, S. S. Yu

Physics Department, The Chinese University of Hong Kong, Hong Kong SAR, China

Single-bubble Sonoluminescence (SBSL or SL), which was discovered in 1989, is a phenomenon of periodic light emission by an oscillating gas bubble trapped in the pressure anti-node of a standing ultrasound wave in water. Several experiments have shown that the width of the emitted light pulse is of the order of 100 ps with peak power of the order of 10 mW. Experiments also show that the pulse width and the emission time are nearly independent of wavelength.

It is generally believed that the bubble is heated to temperatures of a few eV in the collapse phase of the oscillation. Our hydrodynamics simulations also show that the density inside the bubble in the collapse phase can go up to the order of 1 g/cm$^3$, and the electron density due to ionization is $10^{21}$/cm$^3$. So the plasma coupling constant is found to be around 1 and we believe that the gas inside the bubble is in the WDM regime in the collapse phase.

We use an optical model that uses the thermal radiation and takes the finite opacity of the bubble into consideration to simulate the light emission of sonoluminescence and the numerical results obtained are compared to the experimental data. We find that the numerical results are very sensitive to the equation of state used.

As the equation of state, as well as the opacity data, in WDM regime is still very uncertain, we propose here that sonoluminescence may be a good and cheap experimental check for the EOS as well as the opacity data for matter in the WDM regime.
HIGH ENERGY DENSITY ISSUES IN SUPER-FRS AND ANTIPROTON PRODUCTION TARGETS AT FAIR

N.A. Tahir\textsuperscript{1}, V. Kim\textsuperscript{2}, A. Shutov\textsuperscript{2}, I.V. Lomonosov\textsuperscript{2}, A. Matveichev\textsuperscript{2}, A. Ostrik\textsuperscript{2}, A.R. Piriz\textsuperscript{3}, J.J. Lopez Celaz\textsuperscript{3}, D.H.H. Hoffmann\textsuperscript{4}

\textsuperscript{1}GSI, Darmstadt, Germany
\textsuperscript{2}IPCP, Chernogolovka, Russia
\textsuperscript{3}UCLM, Ciudad Real, Spain
\textsuperscript{4}TU Darmstadt, Darmstadt, Germany

Future Facility for Antiprotons and Ion Research (FAIR) will deliver a very intense bunched beam of particles of different species from protons up to uranium. In addition to dedicated High Energy Density (HED) physics studies, numerous other interesting experiments will be carried out at this facility. For example, for production and separation of radioactive nuclear isotopes, a superconducting fragment separator (Super-FRS) is being designed [1]. Another planned experiment is production and collection of antiprotons.

It is to be noted that in case of HED experiments, the target is destroyed in a single experimental shot. In case of the above two experiments, on the other hand, the target must survive over a long period of time, which is not a simple problem in case of high intensity beams that will be available at FAIR. Using a two-dimensional, computer code, BIG2 [2] and a three-dimensional code, PIC3D [3], we have carried out extensive numerical simulations to design viable targets for the Super-FRS and Antiproton production experiments. Solid as well as liquid targets using different beam and target geometries have been considered [4,5].

References

POTENTIAL OF THE CERN SUPER PROTON SYNCHROTRON TO STUDY PHYSICS OF HIGH ENERGY DENSITY STATES

N.A. Tahir¹, R.Schmidt², M. Brugger², A. Shutov³, I.V. Lomonosov³, A.R. Piriz⁴, D.H.H. Hoffmann⁵, V.E. Fortov³, C. Deutsch⁶

¹GSI, Darmstadt, Germany
²CERN-AB, Geneva, Switzerland
³IPCP, Chernogolovka, Russia
⁴UCLM, Ciudad Real, Spain
⁵TU Darmstadt, Darmstadt, Germany
⁶LPGP, Universite Paris-Sud, Orsay, France

Super Proton Synchrotron (SPS) at CERN will preaccelerate protons to an energy of 450 Gev before they will be injected to the Large Hadron Collider (LHC). Several SPS cycles will be required to fill the LHC whereas at present each cycle is comprise of 288 bunches while each bunch contains $1.1 \times 10^{11}$ protons. Bunch length be 0.5 ns and two neighboring bunches are be separated by 25 ns, so that the total beam duration is of the order of 7 µs. The total number of protons in the entire beam is $3 \times 10^{13}$. Although the total energy stored in one SPS batch is less than 1 % of that in 7 TeV/c LHC beam, still it is high enough to cause considerable damage to the equipment in case of an uncontrolled release of the beam. To assess the damage caused in case of such an accident, we have employed a two-dimensional hydrodynamic computer code, BIG2 [1], to study the thermodynamic and hydrodynamic response of solid targets made of different materials irradiated by the SPS beam. These simulations show that targets made of solid tungsten and copper will be destroyed by the SPS beam. An interesting outcome of this study is that the SPS facility can be used to study High Energy Density states in Matter [2].

References

HYDRODYNAMIC SIMULATIONS OF THE NDCX1 TARGET EXPERIMENTS

E. Henestroza\textsuperscript{1,2}, F.M. Bieniosek\textsuperscript{1,2}, J. J. Barnard\textsuperscript{1,3}

\textsuperscript{1}HIFS-VNL
\textsuperscript{2}LBNL, Berkeley, CA, USA
\textsuperscript{3}LLNL, Livermore, CA, USA

Initial experiments on ion-beam target heating will use a 0.3 MeV K\textsuperscript{+} beam from the NDCX1 accelerator at LBNL. NDCX1 will deposit \(~3\) nC on a spot size of about 1 mm, and pulse length about 1-2 ns on the target providing a fluence of \(~0.1\) J/cm\textsuperscript{2}. We will present hydrodynamics simulations of the target experiments including dependence on equations of state, two-phase transition, energy deposition (dE/dx), and solid vs. porous target material.

*This work was performed under the auspices of the U.S Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and by the University of California, Lawrence Berkeley National Laboratory under Contract DE-AC03-76SF00098.*
ENERGY-DEPOSITION PROFILE IN WARM DENSE TARGETS DURING IRRADIATION BY IONS WITH BRAGG-PEAK ENERGIES

Y. Oguri and J. Hasegawa

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Tokyo Japan

Concerning production of warm dense matter using the Bragg peak of heavy ion beams, change of the energy-deposition profile in sub-range targets during irradiation was numerically investigated. The pulse duration of the beam was assumed to be so short that the hydrodynamic motion during irradiation was ignored. A combination of Na (Z = 11) projectile and Al (Z = 13) target was assumed for the calculation. The projectile incident energy was varied from 10 keV/u to 10 MeV/u. A finite-temperature Thomas-Fermi model was employed to calculate the electron density / velocity distribution in the target atom at given temperatures and densities. We integrated differential scattering cross sections corresponding to the energy transfer from the projectile to target electrons with an isotropic velocity distribution to calculate the stopping cross section. The lower limit of the energy transfer was approximated by the plasmon energy calculated using a local plasma approximation. Nuclear stopping and Pauli exclusion in the energy transfer were included in the calculation. The projectile charge was evaluated by a simple Thomas-Fermi scaling taking into account the relative velocity between the projectile and the target electrons. We have verified that, for cold solid Al target, the shape of the calculated Bragg curve agrees well with that from the SRIM2006 data. For a foam target with a density of 1% of the solid density, we found that the stopping cross section increased with the temperature, especially at projectile energies below the Bragg peak. As a result, the Bragg peak moved toward the low energy side. Degradation of the homogeneity of the energy deposition profile along the whole target thickness is discussed in relation to the above effects.
LOCAL FIELD CORRECTIONS VS. MERMIN DIELECTRIC FUNCTION ON PROTON STOPPING IN PLASMAS

Manuel D. Barriga-Carrasco

E.T.S.I. Industriales, Universidad de Castilla-La Mancha, 13071, Ciudad Real, Spain

The energy loss of charged particles in a free electron gas is of considerable interest to actual slowing-down problems. This is a topic of relevance to understand the beam-target interaction in the contexts of particle driven fusion. The energy losses of ions moving in an electron gas can be studied through the stopping power of the medium. Large number of calculations of the stopping power of ions and electrons in plasmas has been carried out using the random phase approximation (RPA) in the dielectric formalism.

The RPA is usually valid for high-velocity projectiles and in the weak coupling limit of an electron gas. But for partially coupled plasmas, which are subject of much interest for current studies of ICF, RPA it is not sufficient and electron collisions have to be taken into account. In this report electron collisions will be treated through two different ways: the Mermin function or the local field corrections (LFC).

Mermin [1] derived an expression for the dielectric function taking account these electron collisions and also preserving the local particle density. On the other hand, LFC can be included in dielectric function. Mostly static approximations (SLFC), have been proposed in the past, as it was considered that greater part of the local field corrections will succeed for the static limit, \( \omega = 0 \), [2]. This latter approximation is used in our calculations.

LFC produce an enhancement in stopping at velocities smaller than the velocity at maximum but recover rapidly the RPA values after it. On the other hand, Mermin dielectric function also produces a enhancement at velocities smaller than the velocity at maximum but much higher than the one produced by the LFC. Besides, Mermin values decrease significantly below RPA ones at the velocity at maximum and higher velocities. Evidently all of them tend to the Bethe limit at high velocities. Differences between Mermin dielectric function and LFC could achieve 20% at higher velocities than the velocity at maximum.

References
APPLICATION OF ITEP TWAC ACCELERATOR BEAMS FOR DIAGNOSTICS OF FAST PROCESS

V.I. Turtikov\textsuperscript{1}, A.A. Golubev\textsuperscript{1}, A.D. Fertman\textsuperscript{1}, V.E. Fortov\textsuperscript{2}, D.H.H. Hoffmann\textsuperscript{3}, V.S. Demidov\textsuperscript{1}, E.V. Demidova\textsuperscript{1}, S.V. Dudin\textsuperscript{2}, S.B. Kolerov\textsuperscript{1}, S.A. Kolesnikov\textsuperscript{2}, V.A. Korolev\textsuperscript{1}, V.B. Mintzev\textsuperscript{2}, N.V. Markov\textsuperscript{1}, D.N. Nikolaev\textsuperscript{2}, A.V. Kantsyrev\textsuperscript{1}, G.N. Smirnov\textsuperscript{1}, B.Yu. Sharkov\textsuperscript{1}, D.V. Varentsov\textsuperscript{4}, A.V. Utkin\textsuperscript{2}

\textsuperscript{1}Institute for Theoretical and Experimental Physics, Moscow, Russia
\textsuperscript{2}Institute of Problems of Chemical Physics, Chernogolovka, Russia
\textsuperscript{3}Institute of Nuclear Physics, Technische Universität, Darmstadt, Germany
\textsuperscript{4}Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany

The radiography diagnostic method based on the using of the hadron beams gives an opportunity to obtain direct information about basic physical properties of matter under extreme conditions of high energy density, and in particular, of the so-called warm dense matter (WDM). Protons can be used to probe with high spatial and temporal resolution the interior structure of investigated systems. Using of the heavy ions beams for radiography diagnostic is also available. Developments of proton and adron radiography diagnostics are also essential for the realization of future high-energy density physics (HEDP) experiments at the FAIR facility.

In this report we present the parameters of the proton radiographic facility which constructed on the ITEP TWAC accelerator facilities of the ITEP, Moscow for diagnostic static objects and fast process. Time structure of ITEP TWAC accelerator beam is able to make a diagnostic of dynamic process with characteristic speed up to 20 km/s. The results of the facility spatial resolution simulation on the sharp edge of the dense object and the first experimental results are reported.
MEASUREMENT OF ENERGY LOSS OF LOW-ENERGY IONS IN A SHOCK-PRODUCED HYDROGEN PLASMA


RLNR, Tokyo Insititute of Technology, Tokyo, Japan

For observation of non-linear stopping of low-energy heavy ions in non-ideal hydrogen plasmas, we have developed a system to measure the energy loss of projectiles in a shock-driven plasma target. For the interaction experiment, we constructed an electromagnetically-produced shock tube, which produced a cold dense non-ideal plasma target. By one-dimensional calculations using SESAME equation of state, we estimated the following plasma-target parameters with a shock speed of ~60 km/s: electron density of \( \sim 10^{18} \) cm\(^{-3}\), temperature of \( \sim 1 \) eV, and a plasma coupling constant \( F \sim 0.1 \). We have so far achieved a beam-plasma coupling constant \( \gamma \sim 10^{-3} \), which is one order of magnitude higher than that of previous experiments.

The energy loss of \( \sim 100\text{-keV/}u \) oxygen ions accelerated by a 1.6-MV tandem pelletron accelerator at RLNR was measured by a time-of-flight method. Experimental data were compared with a numerical analysis taking into account the effective charge of projectile ions in the plasma target. The measured stopping power in the plasma target was larger than that in cold matter, although large discrepancies from the numerical values were observed.

*Present address: Tokyo Metropolitan Industrial Research Institute, Tokyo, Japan
MEASUREMENT OF CAPTURE AND LOSS CROSS SECTION FOR THE SYSTEM O$^0$+N$_2$ AT INTERMEDIATE AND HIGH VELOCITIES

M. M. Sant'Anna, B. F. Magnani, P. R. L. Alves, F. Zappa, L. F. S. Coelho

Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

Measurements of capture and loss cross sections are fundamental to model and plan the beam transport in Heavy Ion Fusion (HIF), because they can quantify the interaction between the projectile and the residual gas in the path from the ion source to the fusion chamber. In this path, intermediate-velocity and high-velocity data are, respectively, useful to model the regions close to the ion source and close to the fusion chamber.

Measurements of cross sections related to neutral projectile at intermediate and high velocity are very scarce in the literature, contrasting with low velocity data. The reason for this asymmetry is the difficulty to prepare a good quality neutral beam at high velocity, while at low velocities it is possible to create intense neutral beams by neutralizing positive ions in a gaseous chamber. This method, however, is not practical at high velocities since capture cross-sections decrease very sharply with projectile velocity.

To overcome this problem we use the gaseous stripper of a 1.7 MeV Pelletron-Tandem accelerator at LaCAM (UFRJ) as a collision chamber. The charge transfer occurs in that gas cell, placed at the high-voltage terminal at the center of the accelerator [1]. To obtain a neutral beam the pressure at the gas cell, which is crossed by an initially negative beam, is varied. Inside the cell, the initial beam loses an electron through a first collision and collides at least once more with other atoms in the gas cell. In order to obtain the cross section values we measure the emerging beam fractions for different charge states (e.g.: O$^-$, O$^0$, O$^+$, O$^{2+}$, O$^{3+}$…) as functions of the gas pressure in the collision chamber [2]. The analysis of these fractions allows obtaining the detection efficiencies, essential to determine the cross section values for neutral projectiles.

In this work, we experimentally determine the total loss and capture cross sections for the system O$^0$+N$_2$ with energies between 30 keV and 1 MeV, which are typical values of energy in the first stage (close to the ion source) of acceleration in HIF.

References:
SLOWING DOWN OF HEAVY IONS AT LOW VELOCITY IN A MULTICOMPONENT AND DENSE PLASMA

BekBolat Tashev\(^1\), Claude Deutsch\(^2\) and Patrice Fromy\(^2\)

\(^1\)Department of Physics, KazNu Tole Bi 96, 480012–Almaty, Kazakhstan  
\(^2\)LPGP(UMR-CNRS 8578), Université Paris XI, 91405-Orsay, France

We focus attention on the low ion velocity stopping mechanisms in a multicomponent and dense target plasmas built of quasi-classical electron fluids neutralizing binary ionic mixtures such as deuterium-tritium of current fusion interest, proton-Helium-like iron in the solar interior or proton-Helium ions considered in planetology, as well as other mixtures of fiducial concern in the heavy ion beam production of warm dense matter at Bragg peak conditions. The target plasma is taken in a multicomponent dielectric formulation la Fried-Conte. We stress out the occurrence of projectile ion velocities (so called critical) for which target electron slowing down equals that of a given target ion component. The corresponding multi-quadrature computations, albeit rather heavy, can be monitored analytically through a very compact code operating a PC cluster. Slowing down results are systematically scanned w.r.t target temperature, electron density as well as ion composition.
ENTANGLEMENT PRODUCED FROM ELASTIC COULOMB SCATTERING

R. Berezov, S. Böttger, J. Jacoby, J. Schunk, T. Rienecker

Institut für Angewandte Physik, Johann Wolfgang Goethe - Universität
Frankfurt / Main, Germany

Elastic coulomb scattering is a basic interaction process in plasma physics. Starting from binary collisions a many body process like stopping power or the behavior of strongly coupled plasmas can be modeled. Fundamental quantum properties have to be considered, if symmetric elastic scattering of e.g. electrons with electrons (Moeller scattering), protons with protons or helium with helium is considered [1]. In these cases spin entanglement appears if two particles scattered to a CM-angle of 90° are indistinguishable. Similar to the Pauli principle for bound electrons, the scattering of indistinguishable fermions to 90° is forbidden, whereas for identical bosons the scattering cross-section at that angle is twice as big as the one for distinguishable particles. We set up an experiment to test this entanglement for the symmetric process of quasi elastic scattering of electrons with electrons.

In order to proof the spin entanglement, the aim of our experiment is to determine the spin direction of two coincident Moeller electrons. The usual method to determine the electron polarization is based on an asymmetric scattering experiment at a high Z target. This scattering may yield an asymmetry due to a different spin-orbit coupling of the electrons. The main problem in polarized electron studies at keV-particle energy is the low efficiency of usual spin polarimeters. This low efficiency impedes or prevents electron spin resolved coincidence measurements because of the necessarily induced random coincidences. We present here the design and performance of a compact mini-Mott spin analyzer and the results obtained for the coincidence measurements. Due to the compact small size the cylindrical-electrode Mott polarimeter achieves a high detection sensitivity. In turn, the increasing sensitivity improves the figure of merit and opens a path for a new class of experiments, where fundamental quantum properties of free charged particles at large distances are measured.

Po-22

ATOMIC PROCESS IN ELECTRO-MAGNETICALLY DRIVEN STRONG SHOCK WAVE

K. Kondo, M. Nakajima, T. Kawamura, K. Horioka

Department of Energy Sciences, Tokyo Institute of Technology, Nagatsuta 4259, Yokohama, Japan 226-8502

Strong shock waves were driven in a compact pulse power device with a pair of conical electrodes, which enable us to observe the atomic process of rapidly heated high-Z materials in a well-defined condition [1]. We discuss ion-electron, ionization relaxation, radiation transport and also their interplay in the strong shock wave under the simplified condition.

When we drove an electromagnetic pulse in the pulse power device with peak current of 200kA, the shock Mach number reached 200 in Xe gas with number density of $10^{15}$[cm$^{-3}$]. The structure was investigated by a fast framing camera and a streak camera with spectrometer. Streak images of spectral line emissions from the shock layer bring us the information of the evolution of ion abundance as a function of distance from the shock front. We also estimated the relaxation length of Xe ions in the shock-heated region with an ionization relaxation model under a steady, one-dimensional condition. The comparison showed the effect of ionization process and radiation transport on the formation of relaxation layer, which indicates the existence of precursor region in the shock wave.

We discuss the atomic process, radiation transport, and the structure of the shock-heated high-Z gas, based on the comparison between the experimental results and the numerical calculations.

PIC CODE WITH MONTE CARLO COLLISIONS FOR HEAVY ION-PLASMA INTERACTION MODELLING

I. V. Roudskoy

Institut for Theoretical and Experimental Physics, Moscow, Russia

The most universal model describing a wide variety of plasma targets is based on Vlasov-Boltzmann equation. One of the most relevant numerical approaches to simulate an interaction of heavy ions with such targets seems to be a Particle-In-Cell method with Monte Carlo collisions (PIC-MC). This work presents the 2D3V numerical code PICSIS realizing the PIC-MC method and some results of simulation.

Plasma targets are supposed to consist of electrons and different kinds of ions of all charge states, which are represented by respective distribution functions. The electrons and ions of plasma and projectile ions are assumed to interact via electric fields, static magnetic fields and binary collisions. The neutral matter (if it is there) is treated as a uniform background of atoms or molecules with a constant temperature.

The following collisions are included into consideration: elastic electron-electron, electron-ion and electron-neutral collisions; inelastic ionizing and exciting collisions of electrons with neutrals and ions; elastic ion-ion, ion-neutral and charge exchange collisions. The collision events are modeled using a Monte Carlo technique, where random numbers are used to choose a time between collisions, to pick a particular event and to define post-collision velocities. To shorten consumption time an ad hoc table of collision frequencies is generated in the beginning of simulation.

Elastic collisions with neutrals are regarded in hard sphere approximation. For inelastic collisions the respective analytical or experimental differential cross-sections are applied. To speed up the calculations, binary collisions of charged particles are regarded in the following way. The simultaneous interaction of all possible collision pairs is approximated by the only one randomly selected pair at a given time step. The post-collision momenta of particles in each selected pair are determined with the help of the Spitzer equation for small-angle scattering probabilities and kinematics relations of binary collisions.
Symposium Participants List

John J. Barnard  
LLNL, USA  
jjbarnard@llnl.gov

Manuel D. Barriga-Carrasco  
UCLM, Spain  
manueld.barriga@uclm.es

Carlo Benedetti  
Dep. of Physics University of Bologna and INFN, Italy  
benedetti@bo.infn.it

Rustam Berezov  
Universität Frankfurt, Germany  
(Jacoby@Physik.Uni-Frankfurt.De)

Frank Bieniosek  
LBNL, USA  
fmbieniosek@lbl.gov

Luiz Felipe de Souza Coelho  
Universidade Federal do Rio de Janeiro, Brazil  
coelho@if.ufrj.br

Ronald Cohen  
LLNL, USA  
rcohen@llnl.gov

Ronald C. Davidson  
Princeton Plasma Physics Laboratory, USA  
rfdavidson@pppl.gov

Claude Deutsch  
Université Paris XI, France  
claude.deutsch@ppp.u-psud.fr

Philip Efthimion  
Princeton Plasma Physics Lab, USA  
peftthimion@pppl.gov

Akira Endo  
Gigaphoton Inc, Japan  
ak END@nifty.com

Timur Zh. Esirkepov  
Kansai Photon Science Institute Japan Atomic Energy Agency, Japan  
timur.esirkepov@jaea.go.jp

Emeka Emmanuel Eze  
Simpleandlogic, South Africa  
phillipnortey@yahoo.com

Alexander Davidovich Fertman  
Institute for Theoretical and Experimental Physics  
Moscow, Russia  
alexander.fertman@itep.ru

Alex Friedman  
LLNL & HIFS-VNL, USA  
af@llnl.gov

Dirk O. Gericke  
CFSA Department of Physics University of Warwick, United Kingdom  
D.Gericke@warwick.ac.uk

Erik P. Gilson  
Princeton Plasma Physics Laboratory, USA  
egilson@pppl.gov

Alexander Golubev  
ITEP Russia  
alexander.golubev@itep.ru

Alon Grinenko  
CFSA Department of Physics University of Warwick United Kingdom  
A.Greenenko@warwick.ac.uk

Larry Richard Grisham  
Princeton University Plasma Physics Laboratory, USA  
lgrisham@pppl.gov

Irving Haber  
University of Maryland, USA  
haber@umd.edu

Jun Hasegawa  
Tokyo Institute of Technology, Japan  
jhasegaw@nr.titech.ac.jp

Toshiyuki Hattori  
Tokyo Institute of Technology, Japan  
thattori@nr.titech.ac.jp

Noriyosu Hayashizaki  
Tokyo Institute of Technology, Japan  
nhayashi@nr.titech.ac.jp
Enrique Henestroza  
LBNL, USA  
EHENESTROZA@LBL.GOV

D.H.H. Hoffmann

Kazuhiro Horioka  
Tokyo Institute of Technology, Japan  
khorioka@es.titech.ac.jp

Yoshifumi Iizuka  
Utsunomiya University, Japan  
mt076603@cc.utsunomiya-u.ac.jp

Takuya Ishibashi  
Tokyo Institute of Technology, Japan  
ishibashi.t.a@m.titech.ac.jp

Taiki Iwashita  
KEK, Japan  
iwashita@www-accps.kek.jp

J. Jacoby  
Universität Frankfurt, Germany  
Jacoby@Physik.Uni-Frankfurt.De

Saebyeok Jeong  
Seoul National University, Republic of Korea  
genideal@naver.com

Igor D. Kaganovich  
PPPL, USA  
ikaganov@pppl.gov

Shigeo Kawata  
Utsunomiya University, Japan  
kwt@cc.utsunomiya-u.ac.jp

Takashi Kikuchi  
Utsunomiya University, Japan  
tkikuchi@cc.utsunomiya-u.ac.jp

Seongmin Kim  
Seoul National University, KOREA  
2001-k-sm@hanmail.net

Sota Kinoshita  
Tokyo Institute of Technology, Japan  
Kinoshita.s.ac@m.titech.ac.jp

Kotaro Kondo  
Tokyo Institute of Technology, Japan  
kotaro@es.titech.ac.jp

Yian Lei  
School of Physics Beijing University, China  
lei@phy.pku.edu.cn

Chi-yeung Ling  
The Chinese University of Hong Kong, China  
antelopeling@gmail.com

Grant Logan  
LBNL, USA  
bglogan@lbl.gov

Stanislav A. Medin  
Institute of High Energy Densities, Russia  
sabsam@m9com.ru

K. Mima  
ILE Osaka, Japan  
mima@ile.osaka-u.ac.jp

Osamu Motojima  
The National Institute for Fusion Science, Japan  
motojima@lhd.nifs.ac.jp

Masakatsu Murakami  
Institute of Laser Engineering, Japan  
murakami-m@ile.osaka-u.ac.jp

Siu-Fai Ng  
The Chinese University of Hong Kong, China  
siufai_hk2002@yahoo.com.hk

Pavel Alexander Ni  
LBNL, USA  
pani@lbl.gov

Suguru Nishinomiya  
Tokyo Institute of Technology, Japan  
06d19064@nr.titech.ac.jp

Yoshiyuki Oguri  
Tokyo Institute of Technology, Japan  
yoguri@nr.titech.ac.jp

Masahiro Okamura  
BNL, USA  
okamura@bnl.gov

Antonio Roberto Piriz  
University of Castilla-La Mancha, Spain  
oroberto.piriz@uclm.es

Modesto Pusterla  
PADOVA UNIVERSITY-PHYSICS-INFN, Italy  
pusterla@pd.infn.it
Hong Qin  
Princeton Plasma Physics Laboratory, USA  
hongqin@princeton.edu

Igor Roudskoy  
ITEP-Moscow, Russia  
Igor.Roudskoy@itep.ru

Prabir Kumar Roy  
LBNL, USA  
PKRoy@LBL.GOV

Marcelo Martins Sant’Anna  
Universidade Federal do Rio de Janeiro, Brazil  
mms@if.ufrj.br

Toru Sasaki  
Tokyo Institute of Technology, Japan  
(khorioka@es.titech.ac.jp)

Peter Seidl  
LBNL, USA  
paseidl@lbl.gov

Boris Sharkov  
ITEP-Moscow, Russia  
boris.sharkov@itep.ru

William Sharp  
LLNL, USA  
wmsharp@lbl.gov

Edward Startsev  
Princeton Plasma Physics Laboratory, USA  
estarts@pppl.gov

Naeem A. Tahir  
GSI Darmstadt, Germany  
n.tahir@gsi.de

Ken Takayama  
KEK, Japan  
takayama@post.kek.jp

Kazuo A. Tanaka  
Grad. School Eng. Osaka University, Japan  
katanakap@eei.eng.osaka-u.ac.jp

BekBolat Tashev  
KazNu Tole Bi 96, Kazakhstan

Giorgio Turchetti  
University of Bologna, Italy  
turchetti@bo.infn.it

Vladimir Ivanovich Turtikov  
ITEP-Moscow, Russia  
Vladimir.Turtikov@itep.ru

Serban Udrea  
Technical University Darmstadt, Germany  
S.Udrea@gsi.de