MEETING REPORT

SUMMARY OF LES HOUCHES PHYSICS WINTER SCHOOL ON INTENSE ION BEAMS AND TARGET PHYSICS FOR INERTIAL CONFINEMENT FUSION, LES HOUCHES, FRANCE, MARCH 13-17, 1995

INTRODUCTION

Fifty-five physicists spent a week (March 13-17, 1995) at the well-known Les Houches Physics Winter School, located at the foot of the highest mountain chain in the Alps. The basic motivation of this gathering was to present the state of the art of particle-driven inertial confinement fusion (ICF) to selected graduate students. After extensive international consultation, emphasis was agreed to be placed on the basic physics of intense ion beams, their coupling with a thermonuclear target, indirectly driven, in a reaction chamber designed for either energy production or ignition studies. One of the specific features of the winter school was the attention given to target chamber issues, considered as important as the more traditional issues pertaining to the driver or pellet compression. The timing proved rather favorable because declassification of the physics of indirectly driven targets had recently taken place. So, it was possible to discuss hohlraum results with a radiation temperature below 400 eV.

The format of the winter school consisted of 4 days of tutorial lectures (30 and 50 min each), followed by extensive interaction with the audience. An additional half-day was dedicated to roundtables featuring, respectively, intense ion beams {Chair: I. Hofmann [Gesellschaft für Schwerionenforschung (GSI), Darmstadt]}, target physics {Chair: M. Tabak [Lawrence Livermore National Laboratory (LLNL)]}, and reaction chambers [Chair: R. Moir (LLNL)]. In an afternoon session, the specific features of energetic ion-dense plasma interaction were discussed, primarily from an experimental point of view. Also, three talks were dedicated to opacity calculations.

TARGET PHYSICS

Nearly two full days were devoted to presenting every aspect of particle-driven ICF. The indirect drive approach was given the lion's share of attention. A specifically designed target that allows for driver X-ray conversion, photon confinement, and compression of an inner spherical pellet with the thermonuclear fuel in it were highlighted.

Most of the results came from numerical simulations in one and two dimensions. It appeared that much significant data are now produced in nonclassified and academic institutions.

Through the wealth of information thus provided, a strong incentive emerged for symmetry and stability requirements to achieve a realistic target gain.

S. Atzeni (ENEA, Frascati) presented the basic principles (methods, modeling, etc.) of simulations. Recent trends and open issues (such as radiative transfer in optically thin regions, the achievement of adequate spatial resolution, etc.) were also outlined. The degree of symmetry required for central ignition and several aspects of the Rayleigh-Taylor instability (RTI) were thoroughly discussed. The linear stage of ablative instability and the nonlinear and turbulent evolution of classical instability were also given due attention.

Starting from the gain model based on the self-similar solution for a contracting gaseous sphere, M. M. Basko [Institute of Theoretical and Experimental Physics (ITEP), Moscow] speculated that the main portion of deuterium-tritium (D-T) fuel must be imploded along a low adiabat with an entropy parameter $\alpha = 2$ to 3 and an implosion velocity $U_{im} = (3.2 \text{ to } 4) \times 10^7$ cm/s. As possible hohlraum configurations, he advocated (a) two-sided irradiation of relatively compact X-ray converters shielded by radiation screens (LLNL design) or (b) circular (2π) irradiation of two ring-band converters along the side walls of the hohlraum casing without radiation screens. The point was made that special attention should be given to eliminating the second and to suppressing the fourth Legendre asymmetry modes in the D-T fuel implosion.

J. A. Maruhn (Goethe Universität, Frankfurt) emphasized that a simple hohlraum layout with two converters on both sides of the capsule and enclosed by a casing produces asymmetries that are too strong. Therefore, he examined the feasibility of adding shields at certain positions to homogenize the irradiation. These configurations were studied in hybrid calculations combining a simple radiation model with one-dimensional multigroup radiation hydrodynamic simulations for the surfaces. Suppressing the expansion of the target component and maintaining the overall efficiency of the energy transfer are the two crucial points in producing a workable target.

M. Murakami (Institute of Laser Engineering, Osaka) convinced us that the design of the irradiation system (two-sided, six-sided, or conic irradiation) is also crucial. Also, the effect of system imperfections such as power imbalance and the pointing error of the beams on the uniformity was given thorough attention.

Self-similar solutions for a stagnating hot spot have thus been used to parameterize its evolution. Experimental direct drive results obtained with the Gekko XII laser demonstrate that alpha-particle heating and bremsstrahlung are not significant before ignition. The smallest growth of RTI is at minimum implosion velocity.

A. R. Piriz (ENEA, Frascati) directed attention to the construction of relatively simple models for the phases of implosion, stagnation, and ignition for the calculation of target energy gain and the derivation of relevant scaling laws. The ablative implosion of a spherical shell driven by a rather general pressure pulse was then considered, and the process of entropy shaping was described. The resulting scaling laws for the ignition energy and for the limiting gain agreed well with the simulations reported in the literature. The model can be used for a parametric study of the target gain as a function of the constraints on symmetry, stability, and other physical quantities.

This presentation supplemented and overlapped constructively that of Basko, who also proposed a five-parameter analytic model to describe the main features of the stagnation phase. Hot debates thus took place within the appropriate roundtable session. Atzeni, Basko, and Piriz then warned us that a continuous and differentiable transition must be inserted between the cold fuel and the hot spot, a point already stressed by N.A. Tahir (GSI, Darmstadt) in 1984.

R. Ramis (Escuela Tecnica Superior de Ingenieros Aeronauticos, Madrid) looked at several target configurations for particle beam ICF that have been simulated with the MULTI 2D code. This code includes two-dimensional hydrodynamics, radiation transport, and beam deposition physics. The results include efficiencies of beam to X-ray conversion, radiation transfer, and hydrodynamic couplings. Also, the symmetry of the implosion has been studied. The influence of the geometry can be now quantitatively assessed. Ramis convinced us that in a one-beam illumination scenario, many photons get lost in a vacuum. He used a low-*Z* (aluminum) converter, as many other authors presently do.

In a masterly, two-session presentation, J. D. Lindl (LLNL) thoroughly reviewed all the basic features of indirectly driven ICF. He discussed every aspect of it starting with the first study performed at LLNL in 1976. He could elaborate his argumentation on the largest available combination of laser experimental results (NOVA laser) intertwined with the most complete and diverse body of numerical simulations in one, two, and even three dimensions. This impressive piece of knowledge allows one to qualify any new code begun to investigate indirect drive scenarios. Of course, the unique status of the LLNL results does not mean that every problem is solved or that target physics is now free of any surprise. A noticeable counterexample has been afforded by the hot debate about the influence of solid gold screens interspersed in the casing, between the converters and the inner pellet.

On that issue, the Frankfurt group of Maruhn could demonstrate how a static approximation is valid for only the first two or three initial nanoseconds of the target implosion.

Lindl provided many useful quasi-analytic results with rather straightforward physical insight. For instance, he showed why a minimum capsule size is required for a given implosion velocity.

Lindl also explained the National Ignition Facility (NIF) project (1.8 MJ/500 TW), which extrapolates the ongoing NOVA program. In that connection, he disclosed that hydrodynamic instabilities could be tamed with a 500- to 1000-Å surface finish.

Within this context, M. Novaro [Centre d'Etudes de Limeil (CEL)] gave a presentation on the French laser project, which looks very similar to that of LLNL (NIF). It will begin at CESTA, near Bordeaux. Both CEL and LLNL are already collaborating closely on both projects.

Because in indirect drive, hard photon confinement and pellet compression are driver independent, Tabak could elaborate on Lindl's presentation to begin a very thorough and impressive implementation of laser results to heavy-ion drive.

A converter that absorbs 2.5 MJ of 5- to 10-GeV lead ions was thus discussed together with the considerations and constraints leading to this design. A hohlraum driven by two of these converters was then described together with a view factor analysis of the symmetry of the radiation field driving the fuel capsule. Effects beyond those thus treated (material motion and intervening materials) were described as well as models featuring the capsule implosion and its symmetry requirements. Figures of merit were related for a high-gain heavy-ion target together with those for the NIF point design. This could show that successful capsules at NIF will put to rest fears about the implosion symmetry of radiation-driven heavy-ion targets.

Tabak also advocated a low-*Z* converter (Hyades code) to minimize the hydro expansion, as well as C_v and range-shortening effects. He discussed optimized transport properties, radiation smoothing, and leakage of converter material inside the hohlraum.

A crucial point also alluded to is the use of the fill to prevent plasma collisions arising from casing and pellet ablation during the confining phase.

P. Velarde (DENIM, Madrid) explained the dependence of the hydrodynamic evolution of the fuel on the conditions reached at the end of acceleration. Particularly, the speed and density radial profiles are fundamental variables to tailoring the compression phase. The effect of shock multiplexing and final tampering are also critical in this context. Velarde discussed the various numerical methods (PPM codes, etc.) employed to simulate such effects. He insisted, among other things, on border effects that facilitate the penetration of the outer parts of the ion beam.

N. Tahir asserted that it is possible to use a fuel composition with a much-reduced content of tritium, for example, that having 75% deuterium and 25% tritium. Such a mixture would still provide sufficient power output to operate a fusion reactor. As a result of this, one should be able to substantially reduce the tritium inventory in the reactor system. This would improve the overall safety of the power plant. Also, a much higher fraction of the tritium is burned in low-level tritium targets compared with equimolar D-T targets. Therefore, a much smaller mass of tritium will be left in the reactor chamber with the target debris, which will make the evacuation process much cleaner. This presentation elaborated on a suggestion put forward by G. Miley

(University of Illinois) and others in 1989 for the use of tritium-depleted thermonuclear fuel.

ION/PLASMA INTERACTION

Z. Zinamon (Weizmann Institute of Science, Rehovot) presented two selected topics. First, he demonstrated the existence of a vicinage effect on the stopping of ions in matter in the case of the interaction of ion clusters and ^{60}C molecules with plasma and with cold solids (Lindhard electron gas). The calculation includes the charge state evolution of the ions, the cluster disintegration dynamics, and the interference effect of neighboring ions on the energy loss. Next Zinamon discussed some issues, recently raised in the literature,[1] concerning the energy deposition by energetic ions in ICF fusion D-T plasma.

At this point, there were three talks on the experimental projects dedicated to energy deposition of fast heavy ions in dense plasma. We first heard from D. Gardès (Institut Physique Nucléaire, Orsay) about the first project that uses a dense linear column of fully ionized hydrogen synchronized with a bunched ion beam on a linear tandem accelerator. This is the well-known Stopping Plasma Quantitatively Reinforced II project presently dedicated to the investigation of simultaneous energy loss and projectile stripping while interacting with a dense and classical plasma target ($n_{el} \sim$ a few 10^{19} e/cm^2). A certain emphasis was put on projectiles Cl^{17+} and Cl^{16+}.

J. Jacobi (GSI, Darmstadt) presented a closely related program developed at GSI. The intense heavy-ion beams of the MAXILAC radio-frequency (rf) accelerator were used at ion energies of 45 keV/u to produce the first heavy-ion-driven plasma and to study the hydrodynamic reactions of this plasma. Similar experiments have now proven to be successful with the SIS heavy-ion synchrotron, where ion energies of 300 MeV/u have been used. Understanding and modeling ion-beam-driven plasmas require precise knowledge of the stopping power in a plasma. Thus, parallel to ion-beam-driven plasmas, the stopping power of heavy ions in a plasma was investigated by experimentally testing an energy range of 45 keV to 10 MeV/u at plasma densities from 10^{16} to 10^{19} cm^{-3}. The stopping-power experiments revealed the new stopping behavior of ions in a plasma. Compared with cold, nonionized matter, increased stopping in hydrogen plasma up to a factor of 35 was thus determined.

In the same vein, B. Y. Sharkov (ITEP, Moscow) reported the first successful experimental attempt to directly measure the Coulomb logarithm in ionized matter. Gathering a large Russian team to work at the nuclear physics institute at Alma Ata (Kazakhstan), he used 1-MeV proton beams to obtain an accurate 5-keV energy loss in dense hydrogen plasma ($n_e \sim 10^{17}$ e/cm^3). This was achieved by cleverly neutralizing the plasma lens effect in the target plasma. A salient feature of that experiment was very precise nuclear diagnostics of the proton beam through the $^{27}\mathrm{Al}(p,\gamma)^{28}\mathrm{Si}$ reaction. Plasma diagnostics were obtained through a Mach-Zender interferometer operating at two wavelengths. The reported ratio of Coulomb logarithms for free and bound electrons is

$$\frac{L_{fe}}{L_{be}} = 2.9 \pm 0.6 \quad \text{with} \quad L_{fe} = 13.4 \pm 2.8 \ .$$

C. Deutsch (Laboratoire de Physique des Gaz et des Plasmas, Orsay) reported on correlated and enhanced stopping in fully degenerate electron (jellium) targets and hot and dense classical plasmas, of ion debris resulting from the fragmentation of cluster ions impinging on a gaseous or solid target. Such calculations are preliminary to an experimental program envisioned at Orsay and elsewhere, making use of C_{60}^{n} $(-2 \leq n \leq 7)$ and Au_n^{p+} $(p = 1,2)$ clusters linearly accelerated at several tens of kilo-electron-volts per atomic mass unit. Deutsch also advocated intense cluster ion beams at those low velocities to drive efficiently an ICF target through direct and also indirect compression.

OPACITY CALCULATIONS

In view of the emphasis put on the indirect drive scenario, having technical expositions on opacity numerical codes was appropriate. T. A. Blenski (Ecole Polytechnique Fédérale de Lausanne, Lausanne) discussed the case of plasmas in local thermodynamic equilibrium (LTE). He reviewed different approaches to opacity calculation and atomic models used for that purpose. He spoke about the average atom model, detailed configuration accounting, and detailed term accounting. The role of term structure is illustrated by a comparison between measured and calculated spectra. The importance of statistical approaches such as the unresolved-transition-array and super-transition-array methods was emphasized. The present approaches are still lacking a firm theoretical basis to include plasma and free electron effects, which can become important at higher densities.

Nonetheless, the displayed methods allow one to retrieve, within a factor of <2, through a rather moderate number of transitions (≅30 000), the ion opacities measured at 25 eV by Da Silva and his group at Los Alamos National Laboratory.

Opacities in dense non-LTE plasmas were addressed by A. Rickert (Max-Planck-Institut für Quantenoptik, Munich), who had also recently hosted a workshop dedicated to a comparison of 14 numerical benchmarks.

A remarkable achievement featured among many is the elegant adaptation of the so-called Green-Sellin-Zachor potential for computing bound level properties of arbitrarily ionized atoms, through a numerical solution of the Dirac equation (more stable than Schrödinger).

A model was represented within the framework of the collisional-radiative model that describes state distribution and radiative opacities for these plasmas. It takes into account deviations from local thermodynamic equilibrium as well as nonideality effects. The influence of free electrons on the atomic potential is treated within the homogeneous free electron gas approximation. The results of the model for average ionization degrees, distribution of ionization stages, and extinction coefficients were discussed.

Y. K. Kurilenkov (Institute for High Temperatures, Moscow) discussed strong coupling effects and their influence on opacities of dense hydrogen. He disclosed a theoretical program based on a Green's function formalism. He also advocated astrophysical interests, as well as recent shock tube measurements performed at the University of Paris VI and University of Florida at Gainesville.

There was general agreement that direct observations of a genuine plasma effect on Rosseland opacities (the most common ones) are very scarce these days.

PHYSICS OF INTENSE ION BEAMS

Physics of intense ion beams was the other major topic highlighted at the winter school. It was structured around a few highly didactic presentations [A. Friedman (LLNL), I. Hofmann, and T. A. Mehlhorn (Sandia National Laboratories)], each given in two parts by the same speaker.

Friedman presented the basics of numerical beam simulation through particle-in-cell (PIC) codes. In particular, he detailed his WARP three-dimensional code, making use of a leapfrog algorithm. This enables him to treat nonlinear forces, which are mostly responsible for the transverse emittance growth. Bend effects must also be included. Moments models (fluid description, envelope equation, etc.) were very clearly presented. Gradient alternating dynamics was also discussed.

In his second presentation, Friedman examined the recirculator project. This is essentially a three-ring adaptation of the heavy-ion induction linac currently being developed at Lawrence Berkeley Laboratory (LBL). This concept really interpolates between the induction linac concept and the rf linac-storage ring concept advocated in Europe and Japan. It allows for accelerating a low-velocity projectile. An experimental and small-scale recirculator is currently being developed at LLNL.

In his first presentation, Hofmann stressed the fundamentals of space-charge effects in the final transport of intense heavy-ion beams in the reaction chamber. The main issue is the sensitivity of the focal spot location to beam space charge, which varies in strength both in time and space. Different neutralizing schemes have also been compared as well as final focusing for the European ignition facility. Then the crucial issues are the relationships between driver energy and target spot size.

The longitudinal momentum spread arising from resistive instability was thoroughly covered in Hofmann's second presentation. He made use of basic theoretical arguments, Schottky effect measurements, and numerical simulation.

Light-ion-beam physics was introduced by Mehlhorn, who first emphasized beam generation through the pulse-power technology, now widely used. Nanosecond pulses involving energy storage, pulse-forming lines, multimodule synchronization, vacuum power flow, and magnetically insulated transmission lines have been shown to underlie the concentration of electric energy in space and time to trigger the magnetically insulated diodes that produce the requested intense ion beams. Limitations encountered in producing and focusing high-brightness ion beams were shown to arise from ion divergence and parasitic loads. The latter effect is now unambiguously ascribed to cathode surface contamination. This might be circumvented through bake-out and discharge cleaning (compare CERN and Fermi Laboratory).

In his second presentation, Mehlhorn turned his attention to ballistic ion transport through solenoidal focusing and self-pinching. Then he addressed the all-important issues of symmetry, synchronicity, power, and energy in a multimodule LMF/ETF environment. The results of proton and lithium beam target experiments on Particle Beam Facility II must be related to the requirements of a high-gain target. The future was disclosed of the ion-beam-target program, which includes sophisticated diagnostics and the near-term use of alternate radiation sources to investigate internal pulse shaping, radiation smoothing, and flow.

Turning to very high-energy (giga-electron-volt) proton beams, we heard from D. Möhl and R. Cappi (CERN, Geneva) about transverse space-charge effects in the CERN proton synchrotron (CERN-PS). Experiments to test beam behavior under extreme space-charge conditions have been run with a tune shift $\Delta Q = 1 \ldots 16$ and $Q = 0.3 \ldots 0.4$ for several milliseconds, the number of turns being inversely proportional to the tolerable space charge.

G. Plass (CERN, Geneva) discussed the European project for a heavy-ion-driven ignition facility at small gain ($G \sim 2$ to 10) operated through indirect drive and a small (1-m-diam) reaction chamber in a vacuum with a few shots per week repetition rate. This project essentially consists of a 2500-m-long rf linac followed by a 150-m-diam storage ring. It is expected to deliver a few kiloamperes of lead or uranium beams at a fiducial energy of 50 keV/nucleon. Plass also determined that the CO_2 rate in the atmosphere is likely to increase by a factor of 2 by the year 2050, compared with its value at the beginning of the industrial era.

P. Seidl (LBL) discussed issues related to beam merging into a smaller number of transport channels. This question bears obvious relevance to induction linac drivers. The technical objective is to carry out the merging operation with acceptable emittance growth and beam loss. He proposed beams with sharply defined edges. He showed how the so-called stonehenge arrangement of elliptic beams constrained by focusing electrodes is accurately supported by numerical simulations. Finally, he recalled that the low-energy lattice MBE-4 built on four beams may be used as an injector.

J. M. Loiseaux (Institut Sciences Nucléaires de Grenoble) lectured on the experimental determination of the fission energy generated in nuclear cascades by a high-energy proton beam from CERN-PS at several kinetic energies from 600 MeV to 2.75 GeV (Ref. 2). An extant, subcritical arrangement made of natural uranium and water moderator was exposed to a low-intensity ($\approx 10^9$ proton/pulse) proton beam. The energy delivered by the hadronic cascade induced by the beam in the device was measured by the temperature rise of small sampling blocks of uranium located in several different positions inside the device and by counting the fissions in thin probe foils of natural uranium. The CERN team obtained typically $G \approx 30$ in reasonable agreement with calculations, where G is the ratio of the energy produced in the device to the energy delivered by the beam. This result paved the way to realization of the so-called energy amplifier, a practical device for producing energy from thorium or depleted uranium targets exposed to an intense high-energy proton beam. Results showed that the optimal kinetic energy is ≥ 1 GeV, below which G decreases but is still acceptable in the energy range explored. Loiseaux thus advocated with C. Rubbia (CERN) the use of thorium ore in the nuclear fission industry.

TARGET CHAMBER: PHYSICS AND DESIGN

D. Callahan and B. Langdon (LLNL) estimated the intense ion beam propagation in a real reaction chamber containing the thermonuclear capsule. They stressed that space-charge–dominated beams may be transported nearly ballistically in a low-density gas ($n_g \sim 5 \times 10^{13}$ cm^{-3}), in agreement with the HYLIFE-II reactor design. Even then, beam stripping is important. Simulations show that it can considerably increase the spot size on the target. They also simulated transport through an axisymmetric electromagnetic PIC code that includes beam stripping by the background gas and collisional ionization of the background gas by the beam as well. Simulations show that partial neutralization reduces the space-charge forces considerably, which results in a much-reduced spot at the target.

Turning to chamber design for power reactors, R. Moir advocated a target chamber that can be protected with 0.5 m of liquid Flibe (Li_2BeF_4 at 2 g/cm^3), a material compatible with stainless steel, to withstand radiation damage over a 30-yr period. The accelerator required must be low cost, i.e., less than \$600 million (direct cost) with $G \geq 47$, and have a spot size ≤ 3 mm on the target.

Target injection scenarios were discussed. An efficient gunlike device can accelerate targets at 1000 to 10 000 m/s^2. Cost of electricity and chamber cleaning were also examined.

Economical target fabrication was discussed featuring a glueing procedure of 11 basic subparts. Hohlraum cost is expected to stay below 3% of the total target cost.

A one-side two-beam illumination geometry was recommended to reduce the target chamber complexity. The two beams do not need to stay parallel to each other.

U. von Möllendorff (Forschungszentrum Karlsruhe) more generally discussed heavy-ion-beam-driven power plants, which are simultaneously economically competitive and ecologically acceptable. He noted that the recirculating power within the system should be less than ~15% of the gross power. He recalled the typical distribution of the produced nuclear energy, X rays (22%), neutrons (72%), ions (5%), endoenergetic nuclear reactions (1%), and its consequences for chamber design. He also contrasted, during the roundtable session, the requirements of the target chamber for an ignition facility with those in a power station.

CONCLUSIONS

The participants agreed that the winter school was productive as far as the dissemination of basic concepts and their comparison and validation are concerned. The winter school was also valuable in that it brought many of the most dedicated scientists in the field into contact with each other. Many participants suggested that there soon be a follow-up of Les Houches sessions dedicated to progress in particle-driven ICF.

As a final note, thanks are due the members of the permanent Les Houches staff for their warm welcome and their technical support, which contributed to the success of the winter school.

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