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International Symposium on Heavy Ion Inertial Fusion Program and Abstracts

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INTERNATIONAL SYMPOSIUM ON HEAVY ION INERTIAL FUSION

DECEMBER 3–6, 1990

PROGRAM AND ABSTRACTS

Hosted by:
Lawrence Berkeley Laboratory

Sponsored by:
American Physical Society
U.S. Department of Energy

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

PROGRAM AND ABSTRACTS

INTERNATIONAL SYMPOSIUM ON HEAVY ION INERTIAL FUSION

December 3–6, 1990
Monterey Sheraton Hotel
Monterey, California

HOSTED BY:
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Sponsored by:
American Physical Society
U.S. Department of Energy

This publication was sponsored in part by the Director, Office of Energy Research, Office of Basic Energy Sciences, Advanced Energy Projects Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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GENERAL INFORMATION

Introduction

The International Symposium on Heavy Ion Fusion is being hosted by Lawrence Berkeley Laboratory. LBL is home to the Department of Energy-sponsored Heavy Ion Fusion Accelerator Research program, whose mission is to assess the suitability of heavy-ion accelerators (specifically, induction linacs) as igniters, or "drivers," for inertial-confinement fusion.

All sessions are being held at the Monterey Sheraton Hotel in Monterey, California. A map of the hotel is included at the end of this book.

Presentations are scheduled for Monday through Thursday, December 3–6.

Proceedings

The Proceedings will be published by Gordon and Breach as a refereed special issue (edited by Dr. David Judd of LBL) of the journal *Particle Accelerators.*

The registration fee includes one copy of the Proceedings, which will be mailed directly to the registrant. Extra copies may be ordered directly from the publisher.

Note to Authors: Please deliver your manuscripts to the Registration Desk on Sunday, December 2, or Monday, December 3 to be sure that they will be refereed in a timely manner and appear in the Proceedings. If you have any questions regarding manuscripts, come to the Conference Office in the San Francisco Room.

LOGISTICS

In addition to reading this section, please be sure to check for handouts at the Registration Desk and look at the bulletin boards for any late-breaking news regarding conference plans.

Registration

The Registration Desk in the North Foyer will be open from 3:00 to 7:30 p.m. Sunday, December 2. On Monday, December 3, it will be open from 7:30 a.m. to noon outside the San Carlos III room. The walk-in registration fee is $300.00 for the entire conference.

Guests who will not attend the conference, but who wish to participate in the special events (Sunday night reception, Tuesday afternoon field trip, and Wednesday evening banquet at the Monterey Bay Aquarium), may register for $75.00.

Beginning Tuesday, December 4, the Registration Desk will be located in the Conference Office in the San Francisco Room.

Conference Office: Information and Message Center

The conference office, located in the San Francisco Room on the hotel mezzanine, is open 8:00–5:30 daily. Feel free to ask any of the conference staff (who wear blue nametags) for assistance.

The message board is located near the door of the San Carlos III room, which is the main meeting room for the conference.

Messages: (408) 649-4234. To leave messages or get information, call (408) 649-4234, which is the main number for the hotel, and ask for the Heavy Ion Symposium Office. The hotel operator will connect you to the Conference Office.

SCIENTIFIC PROGRAM

The scientific program will be presented in three formats.

- **Oral Presentations.** Invited papers and selected contributed papers will be given in ten plenary sessions Monday through Thursday in the San Carlos III Room.

- **Poster Sessions.** Most contributed papers will be presented as posters. Two poster sessions are scheduled: Poster Session 1 (10:30–12:30 Tuesday, December 4) and Poster Session 2 (3:00–5:00 Wednesday, December 5). Posters will be displayed in the San Carlos I and II Rooms.

- **Workshops** held in parallel from 9:15 to noon on Wednesday, December 5:

  — Injectors and Ion Sources
  — Beam-Target Interaction and Targets
  — Driver Systems and Reactors
  — High-Current Beam Transport and Instabilities
  — Beam Transport, Pulse Compression, and Final Focus
  — Beam Diagnostics and Controls

  Fifteen-minute summaries of these workshops will be given in plenary session beginning at 3:00 on Thursday, December 6.

Abstracts for the oral and poster presentations are given later in this book. Below is a day-by-day schedule of events.

SUNDAY, DECEMBER 2

3:00–7:00 **Registration Desk open,** ***North Foyer****

6:00–7:30 **Welcoming reception for all participants and their guests,** ***North Foyer***

* Authors: Please bring your manuscripts to the Registration Desk on Sunday or Monday so that they can be refereed promptly.

MONDAY, DECEMBER 3

General

8:00–5:30 **Conference office open, *San Francisco Room***

7:30–noon **Registration Desk open, *outside San Carlos III Room****

7:30 **Continental breakfast, *outside San Carlos III Room***

4:00–6:00 **Set-up for Poster Session I, *San Carlos I and II Rooms***

Sessions, *San Carlos III Room*

8:30–8:45 **Opening Session**

Roger O. Bangerter and Henry L. Rutkowski

8:45–10:35 **Session 1, *San Carlos III Room***

10:35–10:55 **Break, *outside San Carlos III Room***

10:55–12:40 **Session 2**

12:40–2:00 **Lunch**

* Authors: Please bring your manuscripts to the Registration Desk on Sunday or Monday so that they can be refereed promptly.

Monday, December 3 (continued)

2:00–3:30 **Session 3**

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3:30–4:00 **Break, *outside San Carlos III Room***

4:00–5:15 **Session 4**

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TUESDAY, DECEMBER 4

General

8:00–5:30 **Conference office open, *San Francisco Room.* (Note: Registration Desk is in Conference Office beginning on Tuesday.)**

8:00 **Coffee service, *San Carlos I and II Rooms***

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Tuesday, December 4 (continued)

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12:45–5:00	**Field trip.** ***Box lunches provided. Buses leave promptly at 12:45***
7:00	**Poster Session 1 takedown**

WEDNESDAY, DECEMBER 5

General

8:00–5:30	**Conference office open, *San Francisco Room***
8:30	**Coffee service, *San Carlos I and II Rooms***
7:00–1:30	**Set-up for Poster Session II, *San Carlos I and II Rooms***

Sessions

8:30–9:15 **Session 6, *San Carlos III Room***

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Beam Acceleration Experiments on a Heavy Ion Linear Induction Accelerator (MBE-4)	Terry Garvey	32

9:15–12:00 **Workshops *(room assignments to be announced)***

- Injectors and Ion Sources
- Beam-Target Interaction and Targets
- Driver Systems and Reactors
- High-Current Beam Transport and Instabilities
- Beam Transport, Pulse Compression, and Final Focus
- Beam Diagnostics and Controls

12:00–1:30 **Lunch**

Wednesday, December 5 (continued)

1:30–3:00 **Session 7, *San Carlos III Room***

3:00–5:30 **Poster Session 2, *San Carlos I and II Rooms***

5:30 **Poster Session II takedown**

6:45–10:00 **Banquet at Monterey Bay Aquarium**
Buses leave promptly at 6:45.

THURSDAY, DECEMBER 6

General

8:00–5:30 **Conference office open, *San Francisco Room***

Sessions, *San Carlos III Room*

8:30–10:00 **Session 8**

10:00–10:30 **Break, *outside San Carlos III Room***

10:30–12:00 **Session 9**

Thursday, December 6 (continued)

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Committees

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Proceedings

D.L. Judd (Guest Editor, *Particle Accelerators*)
J.T. Chew (Assistant Editor)

Monday, December 3 **Sessions 1 through 4**

MONDAY, DECEMBER 3

7:30–8:30	Continental Breakfast
8:30–8:45	Opening Session
8:45–10:35	Session 1
10:35–10:55	Break
10:55–12:40	Session 2
12:40–2:00	Lunch
2:00–3:30	Session 3
3:30–4:00	Break
4:00–5:15	Session 4

THE U.S. FUSION PROGRAM

James Decker

HEAVY ION FUSION - PROGRESS AND PROSPECTS

Roger Bangerter, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, CA 94720

The heavy ion fusion concept was first suggested by A.W. Maschke in 1984. Since that time the program has made remarkable progress. Today heavy ion fusion is widely regarded to be the most promising approach to inertial fusion power production. A vigorous international program has put to rest many important questions relating to the physics and design of targets, accelerators and reactors. Progress in these areas will be reviewed.

There are still many areas that require additional research. These include final beam compression, focusing, transport in the reactor, accelerator cost reduction, further study of instabilities and emittance growth, and mass production of targets. These areas will be discussed.

HEAVY ION INERTIAL FUSION IN THE U.S.

Walter M. Polansky, Department of Energy, ER-16, Mail Stop G-356, Germantown, MD 20767

The objective of the U.S. heavy ion fusion program is to assess the suitability of using an induction linear accelerator as a driver for inertial fusion energy generation. Theoretical studies of beam transport, beam acceleration, and induction linac technology are in progress. The Single Beam Transport Experiment (SBTE), the Multiple Beam Experiment (MBE-4) and the multi-beam ion injector apparatus have provided the bulk of the relevant experimental data. However, to fully characterize the physics embodied in space-charge dominated non-relativistic beams of heavy ions and, thereby, complete the program objective further accelerator demonstrations are required. The Heavy Ion Fusion Accelerator Research (HIFAR) program, which presently serves as the cornerstone of U.S. heavy ion fusion activities, will be discussed in terms of accomplishments and future needs from a management perspective.

THE GERMAN HEAVY ION INERTIAL FUSION ACTIVITIES

R. Bock, GSI, Darmstadt

Problems of heavy-ion inertial fusion are investigated in the framework of a basic research program at German research laboratories and universities. The SIS/ESR facility at GSI became operational recently and will provide excellent conditions for studies on beam dynamics and beam/target interaction. In collaboration with other European laboratories, advanced accelerator scenarios are investigated which include concepts of non-Liouvillean beam handling techniques and indirect drive.

THE ITALIAN STUDY PROJECT FOR ICF DRIVEN BY HEAVY IONS

Renato Angelo Ricci, Laboratori Nazionali di Legnaro, IFN, and Departimento di Fisica, Universita Padova, Italy

Started beginning 1989 a study project has been pursued in Italy concerning ICF with heavy ions, in the frame of an agreement between ENEA (Ente Nazionale Energie Alternative) and the Italian Physical Society. The purpose was to perform theoretical and experimental investigations on the feasibility of thermonuclear processes based on the microexplosion on D-T pellets induced, directly or indirectly, by energetic and intense heavy ion beams accelerated following the non-liouvillian technique proposed by C. Rubbia.

Such a technique involves a study of an appropriate driving chain (acceleration, storage, bunching) where the ion beam (e.g. $^{+}$Bi) will be doubly ionized ($^{++}$Bi) by photo ionization with a Free Electron Laser, in order to achieve the required intensity and energy (10^{15} ions, $E \geq 5$ MJ, $\Delta t = 10$ ns, P=500 TW) at the interaction phase. The problem of the beam-target interaction and the question of direct or indirect illumination has been analyzed and a number of issues and possible computational and/or experimental investigation have been considered.

Such a study will be pursued in the frame of a bilateral collaboration between Italy and Germany. This agreement is now under definite proposal.

SOME PROBLEMS OF DRIVERS FOR HIF

D.G. Koshkarev, Institute of Theoretical and Experimental Physics, B. Cheremushkinskaja 25, Moscow 117259, USSR; V.M. Nazarov, JINR, Dubna, USSR; R. Bock, D.H.H. Hoffman, R.W. Muller, J. Vetter, GSI, Darmstadt

Some problems of heavy ion drivers based on proton synchrotrons planned for HIF investigation under low thermonuclear output have been examined.

It is shown that the transference of part of the phase volume from longitudinal to transverse motion may be useful for the attaining of a high value of radiation specific power. Such operation permits to get a high value of longitudinal beam compression needed for big radiation specific power of target.

Vacuum instability[1] puts certain limits on beam intensity under proton synchrotron used as a heavy ion driver. The estimations of possible limits of heavy ion beam energy are given based on last measurement results of sputtering matter values[2].

It is also shown that non-Liouvillian compression is possible in a proton synchrotron after certain modification of its magnetic system. The smallness of mass relative change of accelerated ions is a needed condition for this.

1 D.G. Koshkarev, *Particle Accelerators*, 16 (1984) 1.

2 N.A. Vasilyev et al., *Sputtering of Gold by Uranium Ions with Unilac Energies*, presented at this symposium.

ADVANCED DRIVER CONCEPT AND RELEVANT MACHINE EXPERIMENTS

I. Hofmann, GSI Darmstadt, 6100 Darmstadt, Germany

The status of an advanced driver scheme based on the rf linac/storage ring concept and on non-Liouvillean pulse compression by photo-ionization is given. Beam dynamics issues of the ion-photon interaction section are discussed, as well as the necessary parameters of an FEL to provide the photon beam. The goal of this scheme is to fulfil the requirements of indirectly driven targets (10^{16} W/g) and to create a larger safety margin with respect to emittance growth. Results of recent storage ring experiments with heavy ion beams of maximum phase space density (obtained by electron cooling) are presented. The relevance of these results to the realization of a heavy ion fusion driver and the next planned experiments is discussed.

HEAVY ION RECIRCULATING INDUCTION LINAC STUDIES*

Terry F. Godlove, FM Technologies,
Fairfax, VA 22032

A high-current, heavy-ion accelerator is now recognized as a leading contender for a driver for inertial fusion power plants. The cost of an induction linac driver for a 1 GWe plant is likely to be about $1 billion.[1] A multi-beam recirculating induction linac, while introducing serious new issues, could dramatically reduce the cost. In this paper some initial studies by a group at the Lawrence Livermore Nat. Laboratory with representatives from the Lawrence Berkeley Laboratory, and by F.M. Mako and myself at FMT, are reviewed.

Initial effort indicates that the following approximate parameters are appropriate: cycle time 1 msec; 4 to 8 beamlets; circumference 2 km. Transport stability is required for 30-40 turns. While fewer quadrupoles and cavities are needed, a large number of pulsed dipoles, with increased losses, and programmed, multi-pulsed, accelerating cavities, are necessary. Apertures, lattices and losses are calculated based on assumed quad strength and beam parameters. Approximate costs are being added to yield initial optimization. Various technical issues and optional geometries are reviewed.

1. Fusion Technology 13 (1988).

* Supported in part by the US DOE Small Business Innovation Research program.

PRELIMINARY DESIGN FOR A RECIRCULATING INDUCTION LINAC FOR HEAVY ION FUSION*

S.S. Yu, J.J. Barnard, G.J. Caporaso, A. Friedman, D.W. Hewett, H. Kirbie, M.A. Newton, V.K. Neil, A.C. Paul, L.L. Reginato, W.M. Sharp, Lawrence Livermore National Laboratory, P.O. Box 808, L626, Livermore, CA 94550

T.F. Godlove, F.M. Technologies, Inc., 10529-B Braddock Road, Fairfax, VA 20032

R.O. Bangerter, C.G. Fong, D.L. Judd, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, CA 94720

A substantial savings in size and cost over a linear machine may be achieved in an induction accelerator in which a heavy ion beam makes many (~ 25) passes through one or more racetrack shaped accelerators. We examine a point design for such an accelerator, consisting of four racetracks, each of which increments the energy by a factor of ten. We estimate the consequences of this design on emittance growth, longitudinal instability growth, vacuum requirements, pulser requirements, pulsed-magnet requirements, acceleration schedule, and cost.

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*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and at LBL by the Director, Office of Energy Research Projects Division, U.S. DOE under contract DE-AC03-76SF00098.

THE FIRST YEAR OF SIS/ESR OPERATION

D. Böhne, GSI, Darmstadt, WEST GERMANY

In January 1990 the new heavy ion synchrotron came into operation, followed by the storage ring in April. High Intensity performance was not yet required for the early experimental activities and the predominantly requested very heavy ions cannot be provided by the injector anyway. For machine studies light ions with decently high intensities were used and even multifold accumulation in the storage ring was achieved. Predicted intensity limits, however, were not yet reached. The ring components work very reliably, in contrast to the linac environment. Beam transfer from one ring to the other, as required for heavy ion fusion installations, work without problems. A program for bunch merging and compression is underway.

STUDIES OF THE MIRRORTRON ION ACCELERATOR CONCEPT AND ITS APPLICATION TO HEAVY-ION DRIVERS*

R. F. Post, L. A. Schwager, Lawrence Livermore National Laboratory, P.O. Box 5511, L-644, Livermore, CA 94550; S. R. Douglass, B. R. Jones, M. A. Lambert, D. J. Larson, Dept. of Applied Science, U. C. Davis/Livermore, P.O. Box 808, L-794, Livermore, CA 94550

The Mirrortron [1,2] ion accelerator is a plasma-based ion accelerator concept that, when implemented, should permit both higher acceleration gradients and higher peak-current capabilities than are possible with conventional induction-type ion accelerators. Control over the acceleration and focussing of the beam approaches that achieved in vacuum-field-based ion accelerators.

In the Mirrortron a low density (10^{10} to 10^{11} cm^{-3}) "hot electron" plasma is confined by a long solenoidal magnetic field capped by "mirrors". Acceleration of pre-bunched ions is accomplished by activating a series of fast-pulsed mirror coils spaced along the acceleration tube. The hot electrons, being repelled by mirror action, leave the plasma ions behind to create a localized region of high electrical gradient (up to 100 MV/m).

An experiment and analyses to elucidate the concept and its scaling laws as applied to heavy-ion drivers are underway and will be described.

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1) R. F. Post, Phys. Rev. Letters, **58**, 878 (1987)
2) R. F. Post, AIP Conference Proceedings **193**, Advanced Accelerator Concepts, Lake Arrowhead, CA, p. 298

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*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

HYLIFE-II ICF POWER PLANT DESIGN*

Ralph W. Moir
Lawrence Livermore National Laboratory, Livermore, California 94550

The HYLIFE-II inertial fusion power plant design uses a liquid fall, in the form of jets to protect the first structural wall and final beam components from neutron damage, x rays, and blast to provide a 30-y lifetime. HYLIFE-I used liquid lithium. HYLIFE-II avoids the fire hazard of lithium by using a molten salt composed of fluorine, lithium, and beryllium (Li_2BeF_4) called Flibe. Calculations for assumed heavy-ion beam performance show a nominal gain of 70 at 5 MJ producing 350 MJ. The nominal 1 GWe of power results at a repetition rate of 8 Hz. Such a high repetition rate requires fast re-establishment of the jets after a shot, which can be accomplished in part by decreasing the jet fall height and increasing the jet flow velocity. There is undoubtedly liquid splash that must be forcibly cleared because gravity is too slow, especially at high repetition rate. Splash removal can be accomplished by either pulsed or oscillating jet flows. The cost of electricity is estimated to be 0.09 $/kW·h in constant 1988 dollars, about twice that of future coal and LWR nuclear power of 0.04 to 0.05 $/kW·h. The driver beam cost is about one-half the total cost. One option to lowering the effective cost of the $1300 M driver direct cost is to switch to 4 chambers of 1 GWe power each (HIBALL-II option). Another option is to cut the cost per unit power by a factor of 4 of plant components principally the driver by innovation.

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory, contract W-7405-ENG-48.

THE FUSION-FISSION BURNER

Ronald L. Martin, Martin Energy Systems, Inc.,
901 S. Kensington, LaGrange, Il, 60525, U.S.A.

The 14 MeV neutron spectrum from Heavy Ion Inertial Fusion is unique in its ability to transmute the fission products of light water reactors with the n, 2n reaction. This transmutation would occur in an inner blanket of the reactor. Studies of fusion materials can also be done in this blanket more profitably than in accelerator facilities proposed for this purpose.

Since the 14 MeV neutrons induce fission in all actinides including ^{238}U and ^{232}Th they can produce fission energy from spent fuel rods of LWR reactors and from heavy ores (U,Th) in the concentrations mined. The actinide potential result is fission energy with no residual radioactive waste to be buried. Other advantages over existing critical fission reactors will be discussed. Generation of fission energy would take place in an intermediate blanket of the reactor.

Both inner blankets of the fusion-fission burner act as neutron multipliers. Breeding of tritium and fissile material can therefore be done in an outer blanket of the reactor.

Heavy Ion Inertial Fusion appears much more valuable for these applications than for the generation of energy alone.

MUON CATALYZED FUSION AT HIIF FACILITY

Johann Rafelski*, Department of Physics, University of Arizona
Tucson, AZ 85721

There are a number of common issues between muon catalyzed fusion and HI-inertial fusion. Generally, the physics of muon catalyzed fusion would be quite different in environments of temperature measured in eV and densities exceeding 10 times LHD, with the expectation that the fusion yield is substantially greater than the 150 fusions/muon reached today. However, the confinement time which is needed is about 10μsec, in view of the natural lifetime of the muon. But the conditions of temperature and density of interest here can be substantially lower than needed for burning without a catalyst. It would appear that the Heavy Ion Inertial Fusion facility would provide an ideal environment to set the limits on MuCF in extreme conditions, in particular to determine the fusion yield per muon beyond the 'room temperature and density' environment. The MuCF results suggesting such an approach are:

Hydrogen target density: The experimentally observed density dependence of the muon loss in deuterium-tritium fusion calls for MuCF studies in highest accessible density of hydrogen.

Plasma temperature: Calculations suggest enhanced muon regeneration (stripping of muons bound to the fusion product, the α-particle) at temperatures O(100 eV) which could substantially enhance the fusion yield per muon.

Accelerator requirements: Monte-Carlo studies of energy efficient muon production call for intense beams of neutron rich low Z nuclei at energies of about 3-8 GeV/c^2. Pulsed beam structure is of advantage.

*Supported by DOE under contract DE-FG02-88ER13858

PROGRESS ON IGNITION PHYSICS FOR ICF AND PLANS FOR A NOVA UPGRADE TO DEMONSTRATE IGNITION AND PROPAGATING BURN*

John D. Lindl, University of California, Lawrence Livermore National Laboratory, P.O. Box 5508/L-472, Livermore, California 94550

Very rapid progress on Nova experiments during the past year, coupled with a very successful modeling capability for these experiments has resulted in greatly increased confidence in our ability to predict the driver requirements and driver size for an ignition and gain demonstration in the laboratory. Progress has been sufficiently promising that both the Fusion Policy Advisory Committee (FPAC) and the recent NAS review of ICF supported construction of a 1-2 MJ upgrade to the Nova laser which could demonstrate ignition and burn propagation by the turn of the century. This recommendation is subject to completion of a series of technical objectives on target physics, laser technology, and target fabrication planned for the next few years. The recent progress, the proposed Nova Upgrade, and the technical objective will be discussed.

* Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48,

ANALYSIS OF HEAVY ION FUSION TARGETS

I. THE OVERALL COUPLING EFFICIENCY

J. Meyer-ter-Vehn and M. Murakami
Max-Planck-Institut for Quantum Optics
D-8046 Garching, Germany

The overall coupling efficiency of targets for heavy ion fusion is studied both analytically and numerically as the product of conversion efficiency, transfer efficiency, and hydrodynamic efficiency of the fusion pellet. Results are given for a reactor size target.

AN ANALYSIS OF THE IMPLOSION OF HEAVY ION DIRECTLY DRIVEN SIMPLE TARGETS

G. Velarde, J. M. Martínez-Val, C. González, M. Piera,
J. M. Aragonés, L. Gámez, J. J. Honrubia, E. Mínguez, J. M. Perlado,
P. M. Velarde
Institute of Nuclear Fusion, DENIM
J. Gutiérrez Abascal, 2. 28006 Madrid, SPAIN

Hollow targets made of a shell of DT coated only by lithium(1) are analyzed. This type of simple targets are selected to try to avoid hydro instabilities. They also present a very positive performance to reach ignition with a few MJ of driver pulse, if a perfect illumination uniformity is assumed.

The last phase of the implosion process is particularly analyzed. It is found that ignition can be achieved if fuel stagnation is avoided. Stagnation can appear if the fuel is unsuitably accelerated during the compression phase and the innermot layer of fuel reaches a speed much higher than those of the outer layers. The main parameter governing the compression acceleration is the dose rate delivered in the lithium by the driving pulse. Shocks waves and Marshack waves can be avoided by properly selecting the beam power and the lithium thickness. Neither pulse shaping nor voltage ramping(2) are necessary. Numerical simulations carried out with the NORCLA code(3) show that energy gains above 50 can be obtained with 1 mg DT targets and 2 to 3 MJ of driving pulse. Higher gains can be achieved with higher fuel mass, but the driving energy required also increases.

References

(1) G.R. Magelssen, Nuclear Fusion, **24**, 1527 (1984)
(2) G. Velarde et al., Nucl. Instr. Meth. Phys. Res., **A278**, 105 (1989)
(3) G. Velarde et al., Laser Part. Beams, **4**, 349 (1986)

Tuesday, December 4 **Session 5**

TUESDAY, DECEMBER 4

8:30–10:30	**Session 5**
10:30–12:45	**Poster Session 1**
12:45–7:00	**Field trip**
	Box lunches provided *Buses leave promptly at 12:45*

LONGITUDINAL INSTABILITY OF INDUCTION LINAC DRIVERS*

Edward P. Lee, Lawrence Berkeley Laboratory, University of California, 1 Cyclotron Road, Berkeley, CA 94720, U.S.A.

An induction linac accelerating a high current pulse of ions at sub-relativistic velocities is predicted to exhibit unstable growth of current fluctuations. This instability is driven by the interaction of the beam with the complex impedance of the induction modules. An overview is given of the mode character, estimates of growth rates and their application to an HIF driver. The present effort to understand and ameliorate the instability is described. This includes particle-in-cell simulations, calculation and measurements of impedance, and design of feedback controls.

*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy under contract No. DE--AC03--76SF00098.

STUDIES OF BEAM TRANSPORT AND LONGITUDINAL COMPRESSION AT THE UNIVERSITY OF MARYLAND*

Martin Reiser, Laboratory for Plasma Research, University of Maryland, College Park, Maryland 20742

At the University of Maryland, several experiments with electron beams are in progress that are relevant to Heavy Ion Inertial Fusion driver physics issues: (1) Transport of single and multiple beams through a long periodic solenoid channel and study of emittance growth due to nonlinear external and space-charge forces. This work has been in progress for several years and has now reached the point where excellent agreement with theory and simulation has been achieved. (2) Generation of short electron pulses with velocity shear (using an electron gun and induction acceleration module built in house) and study of longitudinal compression in the long solenoid channel. The electron gun and induction module have been put into operation this summer and the first results of beam measurements will be reviewed. (3) Study of resistive-wall instability effects of interest to induction linac drivers. This is a new proposed project, and first conceptual design studies will be reported.

* Research supported by U.S. Department of Energy

3D PARTICLE SIMULATION OF BEAMS USING THE WARP CODE: TRANSPORT AROUND BENDS*

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We describe WARP, a particle-in-cell code being developed and optimized for ion beam studies in true geometry. The code is being used to study drift-compression in the presence of misalignments in the strong-focusing lattice, transport around bends, and equilibration processes which lead to the transfer of thermal energy between longitudinal and transverse motions. In the future we hope to examine final focusing (during which the beam is not long and thin), multiple beamlet interactions, and other inherently 3d processes. We briefly describe the code architecture and techniques employed to enhance efficiency.

Recent improvements to WARP include a round pipe model (which applies a capacity matrix to each axial Fourier mode in turn) and an axially confining force (which replaces the "ears" incorporated in real accelerating pulses).[1] WARP now also contains an r, z model which is being used to study longitudinal stability, compression, and equilibration.[2]

In this paper we emphasize the physics of transport around bends. We have implemented a simplified (faster, but inexact) version of a bent-beam PIC algorithm described earlier.[3] The code follows the beam particles in a family of rotated laboratory frames, thus "straightening" the bends. The simplified algorithm folds the rotation of the velocity vector due to coordinate transformation into that already required by the magnetic force advance; it uses a simpler transformation for the position as well. Using this model, we have followed a space charge dominated beam around several circuits of a simple racetrack system. Results on overall dynamics and emittance growth are presented.

*Work performed in part under the auspices of the U.S. Dept. of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

[1] D. P. Grote *et. al.*, this conference.

[2] D. A. Callahan *et. al.*, this conference.

[3] A. Friedman, Proc. 13th Conference on Numerical Simulation of Plasmas (R. J. Mason, ed.), Santa Fe, NM, 1989 (Los Alamos National Laboratory; unpublished).

PHYSICS OF FOCUSING HIGH–CURRENT BEAMS FOR HEAVY–ION FUSION*

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I. Haber, Naval Research Laboratory, Washington, DC
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In heavy–ion fusion, kiloampere beams must be focused onto millimeter size pellets. Progress has been made toward understanding the physics of final focusing. We will discuss: (1) theory and simulation results for correcting geometric aberrations; (2) theory and simulation results for focusing variable–current beams using fixed strength quadrupoles and; (3) methods of reducing chromatic aberration induced by longitudinal velocity tilt and momentum spread.

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

CHAMBER PROPAGATION

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Propagation of a heavy ion beam to the target appears possible under conditions thought to be realizable by several reactor designs. In unneutralized propagation across the reactor chamber, photoionization of beam ions by thermal x-rays from the heated target has a defocusing effect. Since first results were reported at the 1988 meeting, this topic has been restudied with PIC modeling of the photoelectrons and more favorable parameters for final focus. In contrast to the results reported at the Darmstadt meeting, all but a few percent of the beam ions deposit in the intended spot of radius 3 mm. Photoionization remains an important aspect of chamber propagation, but propagation through very low densities still seems a conservative mode.

New results by Fawley, Stewart and Yu on pinch mode propagation, an attractive but more speculative mode, are reported in their poster at this meeting.

This work was performed under the auspices of the U.S. Department of energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

EXAMPLES OF HEAVY-ION ICF DRIVER SCHEMES FOR INDIRECT DRIVE

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Schemes for heavy-ion inertial fusion drivers are presented which use:

(a) indirect pellet drive

(b) non-Liouvillian processes for accumulation of the beams in the phase-space of the storage and buncher rings.

Examples for reactor drivers as well as for implosion test facilities are given.

Wednesday, December 5 **Sessions 6 and 7**

WEDNESDAY, DECEMBER 5

8:30–9:15	Session 6
9:15–12:00	Workshops: • Injectors and Ion Sources • Beam-Target Interaction and Targets • Driver Systems and Reactors • High-Current Beam Transport and Instabilities • Beam Transport, Pulse Compression, and Final Focus • Beam Diagnostics and Controls
12:00–1:30	Lunch
1:30–3:00	Session 7
3:00–5:00	Poster Session 2
6:45–10:00	Banquet at Monterey Bay Aquarium *Buses leave promptly at 6:45*

NON LIOUVILLIAN IGNITION DEVICES FOR INERTIAL FUSION

Carlo Rubbia, CERN, Switzerland

The possibility of Non-Liouvillian stacking for the accumulation of strong ion beams for indirect inertial fusion is discussed and a possible schedule is illustrated based on photo-ionization of heavy ions.

BEAM ACCELERATION EXPERIMENTS ON A HEAVY ION LINEAR INDUCTION ACCELERATOR (MBE-4)

T. Garvey, S. Eylon, T.J. Fessenden, and E. Henestroza, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720.

The evolution of the normalized rms transverse emittance of heavy ions in induction linacs depends on many factors including envelope matching, details of the acceleration waveforms, and beam misalignments within the focusing system. Present acceleration experiments on MBE-4 confirm the difficulty of fully resolving the explicit dependence of the emittance on these and other parameters. In this paper we discuss the most recent acceleration experiments on MBE-4 in which both the transverse and longitudinal beam properties are investigated in detail. These experiments utilize a beam of smaller current (5 mA) and smaller emittance (0.03 mm-mRad normalized K-V) than was used in previous MBE-4 studies. As before we find that acceleration is accompanied by more transverse emittance growth than predicted by our theoretical models. In addition to our work on transverse beam properties of accelerated beams, we report on progress in demonstrating longitudinal control of the beam via judicious application of the accelerating waveforms. Comparisons are made between our measured current and energy distributions and those predicted by our longitudinal dynamics code (SLID) and its upgraded version (SLIDE).

Work supported by the Director, Office of Basic Energy Research, Office of Basic Energy Sciences, Advanced Energy Projects Division, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

HEAVY ION PLASMA INTERACTION EXPERIMENTS AT ITEP

Boris Yu. Sharkov, Institute of Theoretical and Experimental Physics, B. Cheremushkinskaja 25, Moscow 117259, USSR

By using the ITEP Van-de-Graaf facility some important measurements in heavy ion atomic physics have been carried out during 1990 comparing the energy losses of protons and heavy ions in fully ionized hydrogen plasma as well as in a cold hydrogen gas target. The plasma-gas targets are prepared by focusing a powerful TEA CO2- laser pulse on a supersonic hydrogen jet. The on-line plasma density profile measurements along the ion tracks by means of a holographic interferometry system are reported.

The main experimental activities currently concentrate on investigation of interaction of heavy ions with plasmas having different temperatures and densities. The existing RFQ accelerator technique opens an opportunity to measure the stopping power dependence for Xe and Bi ions, with an energy 0.1 MeV/nucl, on the ratio of projectile ion velocity to that of free plasma electrons.

According to this purpose three types of plasma targets have been developed:

- super sonic gas jet, heated by a powerful laser pulse up to Te 40 eV;
- high density gas-puff Z-pinch with Te 200 eV;
- gas jet, heated by an intense ion beam up to Te 1 eV.

The recent results of the use of a new high-repetition laser source of multicharged heavy ions for the beam injection into the ITEP heavy-ion synchrotron are presented.

An important part of experimental activities is the development of plasma diagnostic tools, which are specific to heavy-ion induced plasma as well as to other short-lived plasma targets, prepared by means of powerful laser or low-inductive discharges.

DIAGNOSTICS OF PLASMAS CREATED BY HEAVY IONS AND LASER BEAMS

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A.A. Golubev, B.Yu Sharkov, A.V. Shumshurov, Institute for Theoretical and Experimental Physics, 117259 Moscow, USSR

Since intense heavy ion beams as well as high power lasers are considered to be suitable drivers for ICF we studied the response of targets to intense laser and particle beam irradiation. A CO_2 laser beam was used with an energy deposition of up to 10 J during 100 ns on the target. The material investigated was solid carbon. Optical spectroscopy served as a method of plasma diagnostics. C I to C IV lines in the UV region were identified. The free electron density was determined via Stark broadening to be $1 - 2 \cdot 10^{17}$ cm^{-3}. Results for the plasma temperature determined from line ratios are 30 - 40 eV, decreasing to about 3 eV for t = 900 ns after the laser pulse.

An optical diagnostic system was built up at the intense ion beam facility RFQ-MAXILAC at GSI Darmstadt. A Kr^+ beam of up to 5 mA intensity delivered 10 J to a solid Mg target during 500 μs. The spectroscopy was performed in the visible region down to UV. Time resolution was achieved by observing the spectrum with a streak camera. Space information was obtained by scanning the distance of the line of sight to the target surface from shot to shot. With the aid of a calibrated halogen lamp the sensitivity of the optical system was evaluated. Thus it was possible to determine the radiated power in different detected Mg I and Mg II lines time and space resolved.

ATOMIC PROCESSES AT THE END OF THE RANGE OF FAST IONS IN PLASMA

E. Nardi and Z. Zinamon, Weizmann Institute of Science, Rehovot, Israel

Experiments in which various ions are stopped in low density hydrogen plasma are used in several laboratories in order to study both the stoppinng power and charge state problems. In this work it is suggested that in existing experimental systems the parameters can be chosen such that the end of the range will occur inside the plasma column. The charge state and level populations of ion projectiles in hydrogen plasma are calculated. The predicted narrow region over which recombination occurs can be used as a check on stopping power theory and as a direct measurement of the range using spectroscopic diagnostics. The sensitivity of the results to the various cross sections was studied.

HEAVY ION CLUSTER STOPPING IN PARTIALLY DEGENERATE ELECTRON PLASMA.

C. Deutsch, GDR-918+, Université PARIS XI

The enhanced electromagnetic coupling of molecular ion clusters with cold material and fully ionized Hydrogen plasma is investigated for qualifying a potential driver for heavy ion driven ICF. A systemic analysis is eschiewed. Fragmentation processes are discussed within a geometric and universal framework. The diclusters interacting in a partially degenerate electron jellium are given a certain attention[1].

The resulting enhanced and harmonically correlated stopping is worked out for several electron temperatures.

+*Associé au CNRS.*

[1] C. DEUTSCH, Laser and part-Beam (1990).

Thursday, December 6 **Sessions 8 through 10**

THURSDAY, DECEMBER 6

8:30–10:00	Session 8
10:00–10:30	Break
10:30–12:00	Session 9
12:00–1:00	Lunch
1:00–2:30	Session 10
2:30–3:00	Break
3:00–4:30	Workshop Reports (15 minutes each)

BEAM EXPERIMENTS AT COOLER SYNCHROTRON TARN2

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TARN2 is an experimental facility for accelerator studies, atomic and nuclear physics with an electron cooler equipment as well as the function of beam acceleration. This cooler synchrotron has the maximum magnetic rigidity of 5.8 T.m, corresponding to a proton energy of 1.1 GeV and 370 MeV/u for heavy ions of charge to mass ratio of 0.5. The ring is hexagonal in shape with an average diameter of 24.8 m. Its circumference is 77.76 m, just 17-times that of the extraction orbit of the injector SF cyclotron. It has 6 long straight sections of 4.2 m length each, which are used for the beam injection system, an RF cavity, an electron cooling device, a slow extraction system, and an internal target. It takes 3.5 sec for the power supply to excite the whole magnet system to the full excitation. The flat top duration of magnetic field is variable and sufficiently long for beam cooling, extraction and internal target experiments.

At present, all the ring systems are completed and operated, including the extraction system. Electron cooling experiments are performed presently with use of 20 MeV proton and deuteron beams, and typical results of the experiments are as follows: the change of momentum spread of stored beam with cooling is observed in longitudinal Schottky spectra. The proton beam momentum spread was improved from 2×10^{-3} (after injection) to a value below 8×10^{-5} within a time of a few seconds. At the increased number of protons, Schottky spectra show a splitting. This behaviour is known as a transition from random to collective motion. The neutral atoms which result from recombination, are counted down stream from the cooler section. From the neutral beam size we obtained the cooled beam emittance as: 1 π mm·mrad (horizontal), 2.6 π mm·mrad (vertical). The proton beam radius at the cooler section is: 2.3 mm(H) and 1.7 mm(V). The longitudinal drag force of the electron beam on proton beam has also been measured.

In this paper the operational results of TARN2 from the points of view of accelerator technology and beam cooling will be presented.

A NEW APPROACH TO XUV: THE ρ COOLING TECHNIQUE

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We demonstrate that on resonance and for a fixed energy and wavelength, there is a maximum value of the fundamental FEL parameter ρ when the wiggler parameter is one. This circumstance maximizes the efficiency and minimizes the high gain effective energy spread $\Delta\gamma/\rho\gamma$. Furthermore, we show the possibility of "effective" beam cooling in the proposal of two wiggler scheme for coherent harmonic generation in the exponential gain regime. This consists of tuning the second wiggler to the n-th harmonics while changing simultaneously $\mathbf{B}_w$ and γ_w so that r increases and leads to a decrease of $\Delta\gamma/\rho\gamma$ in the second wiggler. This "ρ-cooling" technique can be relevant in many applications and, in particular,

i) it allows, in principle, the tapering of the second wiggler so that one can reach an efficiency larger than 10% for the harmonic generation;
ii) it allows one to relax the emittance requirement with a proper generalization of the Kim-Pellegrini criterion, in the case of bunched beams.

STOPPING OF ENERGETIC SULPHUR AND BROMINE IONS IN DENSE HYDROGEN PLASMA.

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C.Fleurier, D.Hong, LPGP Orléans
C.Deutsch, G.Maynard, LPGP Orsay.
(GDR 918 laboratories)*

The stopping power of sulphur and bromine ions traversing a fully ionized hydrogen plasma ($n_e.1 \sim 10^{19}$ $e^-.cm^{-2}$, $K_BT \sim 2-4$ eV), has been determined by coupling a plasma target to the heavy ion beam of the Orsay Tandem accelerator. This program initiated in 1986 has reached its first goal which was to demonstrate experimentally the enhanced stopping power of a plasma relatively to the cold matter. Recent measurements tend to improve the accuracy of the measurements, reducing plasma instabilities and cold gas corrections at the interface between the plasma target and the beam line.

Measured energy losses are well reproduced by the Standard Stopping Model (SSM)(1).The determination of mean effective charges during the stopping process will also be discussed in correlation with theoretical predictions.

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* Groupement de recherche CNRS

(1) *C.Deutsch et al Nucl. Instr. Meth. A278, 38(1989).*

IMPLOSION SYMMETRY REQUIREMENTS FOR HIGH GAIN ICF

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A key ingredient of high gain ICF is central ignition, whose attainment requires a highly symmetrical capsule implosion. This can be hindered by the growth of perturbations induced by irradiation asymmetries and/or by target defects.

We have studied the effect of long wavelength non-uniformities (modes with spherical mode number $\ell = 2 - 8$) of the pressure driving the implosion by means of 2-D numerical simulations /1/. These show the secular growth of the interface perturbations during the implosion, which are amplified at the collapse by the interaction with the reflected shock-waves. The mass displacement thus generated also seeds the Rayleigh-Taylor instability during the stagnation phase /2/. Control of the latter seems to be possible, but requires pulse shaping.

In agreement with a simple model of ignition in 2-D, our numerical simulations show that the tolerable non-uniformities depend critically on the specific target design, and in particular on the spark convergence ratio, on the '1-D ignition margin', and on the pulse shaping. 'Well designed' targets can tolerate peak-to-valley pressure perturbations as large as 6% for $\ell = 2$, 3% for $\ell = 4$, and 0.8% for $\ell = 8$ /1/. Work is now in progress to consider higher values of ℓ and multi-mode perturbations, and to better analyze the unstable stagnation phase.

The implications of the above results for the design of both direct-drive and indirect-drive heavy ion fusion targets are then discussed.

/1/ S. Atzeni, Europhys. Lett. 11 (1990) 639.
/2/ S. Atzeni, Laser Part. Beams, in press.

OVERVIEW OF DIRECTLY DRIVEN HIF TARGETS

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A straightforward theoretical approach to designing an optimal thermonuclear target is to define a certain class of targets characterized by a number of free parameters, and then to maximize the energy gain with respect to this parameters. Such an optimization has been carried out in the class of simple single-shell two-layer spherical DT targets driven by a perfectly symmetric heavy ion beam with a box pulse shape. The input energy was fixed at E_{in} = 6MJ. Calculations have been performed with a 3T 1D hydrodynamics code. It was found that the targets from this class ignite uniformly over the fuel volume and that the energy gains G $\simeq$ 100 can be achieved—provided that the beam power $P_{in} \geq 700$ TW.

Optimization in a more sophisticated class of DT targets with a low-Z absorber layer has revealed that with a 700 TW box-shaped pulse of 10 GeV Bi ions spark ignition can be obtained which, in the framework of our model, results in the optimum energy gain G=420.

Having performed the optimization in the class of single-shell D2 targets driven by a time-profiled 100 MJ pulse of 12 GEV Bi ions with a peak power of 10 TW, we obtained the maximum gain of G=10.

A possible way to reconcile the inherently cylindrical geometry of the ion-beam illumination with the spherical symmetry of the target is to adjust the thicknesses of various target layers to the beam penetration pattern—so as to still obtain an implosion with a good enough degree of spherical symmetry. Another approach is to develop a cylindrical target with magnetically suppressed electron thermal conductivity in the fuel. Two- and 1.5-dimensional simulations indicate that either approach can be feasible.

HIGH DENSITY COMPRESSION OF HOLLOW SHELL PELLET BY GEKKO XⅡ AT OSAKA

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C.Yamanaka; Institute for Laser Technology, Suita, Osaka 565 Japan

In inertial confinement fusion research it is essentially important to demonstrate 1,000 times liquid density with understanding of implosion physics of spherical hollow shell pellet. The ignition condition of laser fusion is estimated to be $\rho/\rho_s = 500 \sim 1{,}000$, $T = 5 \sim 10$ keV and $\rho R \sim 0.3 g/cm^2$[1].

High density compression of over 600 times solid density has been achieved by the implosion of a hollow shell pellet of deuterated-tritiated plastics (CDT) with the Gekko XⅡ green laser. This is the highest density of material which has ever been realized in a laboratory and corresponds to the density four times higher than the center of the sun.

The above results are caused by the improvements of laser irradiation uniformity and pellet quality, and by the sophisticated diagnostic techniques for ρR and implosion uniformity. The laser irradiation nonuniformity was reduced to 15% at target surface with a random phase plate. A rectangular laser pulse with 1.7ns FWHM was used. The sphericity and uniformity of shell theckness were better than 98%.

ρR measurements were mainly performed using a well developed silicon activation method. The sphericity of the imploding hollow shell target was measured by three x-ray multi-frame cameras with temporal resolution of 80ps.

[1] Laser Fusion Ignition Experiment "KONGOH" project: Report of Research Planning Committee at ILE Osaka

PARTICLE DYNAMICS IN A LOW FREQUENCY HIGH CURRENT RFQ PROTOTYPE*

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A new high current injector for all ions up to uranium is planned at GSI, the first part being a large RFQ operating at 27 MHz. A prototype corresponding to the low energy part of this RFQ (∿ 4 m, 190 cells) is being built at the Institut für Angewandte Physik for rf and beam tests.

Results of particle dynamics calculations and the status of the project will be discussed.

* Supported by BMFT under contract 06 OF 186I and GSI under contract FKLA

RFQ CONDITIONING BY GLOWDISCHARGES

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Electrical fields as high as possible are required for high current RFQs. The available field strengths however are limited by breakdowns. The limiting fields can be improved by conditioning. Glowdischarges in the critical electrode region of the RFQ are found as an effective conditioning method. Results of experiments are presented.

Work supported by BMFT under contract No. 06 OF 1861 and GSI under contract FKLA

THE BERKELEY INJECTOR*

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The injector being developed at Lawrence Berkeley Laboratory is a sixteen beam device which is to provide 500 mA C^+ beams at 2 MeV. The first half of the accelerating column has been tested at full operating voltage and beam experiments are underway. Information on column performance and source development is included.

*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy under contract No. DE-AC03-76SF00098.

EMITTANCE DEGRADATION OF INTENSE AND PARTIALLY SPACE CHARGE NEUTRALIZED ION BEAMS*

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Severe transverse emittance growth of intense and low energy ion beams in magnetic transport lines has been observed at different laboratories in the case of a partially space charge neutralized beam. This is unfavourable since magnetic systems are the common used transfer lines for the transport of high perveance beams as it is required for heavy ion inertial fusion drivers.

Rearrangement of the transverse charge density of the ion beam towards a uniform distribution is a known mechanism which leads to initial emittance increase at the front end of a transport system. In the presence of space charge compensating electrons the rearrangement of charge density affects ions and electrons as well. Unfortunately the electrons are not cold enough to be pinned exactly to the ions. The initial creation energy of the electrons, additional heating by the beam, and the quick process of thermalization lead to a non constant electron density even if the ion density would be homogenious. The finite electron temperature together with beam enveloppe and residual gas pressure variations along the beam line will cause continuous emittance increase.

Calculations using the tracking code PARMILA TRANSPORT including the influence of compensating background electrons have been carried out. First results will be reported and compared to experimental results obtained using a 10 keV, 3 mA, He^{+} beam in a magnetic transfer line.

* Work supported by BMFT under contract no. 06 OF 186I

PLASMA LENSES FOR HEAVY ION BEAM FOCUSING

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High energy density in matter can be produced by focusing a heavy ion beam on a target. Thus, a plasma is produced in parameter region which is relevant for ICF-research. At GSI the ion beam from the SIS accelerator with energies of typically 300 MeV/u will be used to achieve a specific deposition power in matter of about 10 TW/g. One key problem is the focusing of the beam. A plasma lens is presently considered for installation into SIS experimental area to significantly enhance the focusing power of the presently designed conventional quadrupole fine focusing system. A homogeneous current flow along the z-direction characterizes this cylindrically symmetric plasma lens. Here the plasma serves as a current carrying medium, almost transparent for high-energy charged ions. For a constant current density a constant magnetic field gradient is obtained reaching values of several 100 T/m.

For the first time a focusing experiment with a heavy ion beam and a z-pinch plasma was carried out at GSI. A 10 mm wide, 500 MeV Ar^{11+} beam was focused for ~200 ns to a spot size of ~2 mm within 10 cm from the pinch exit. This first successful demonstration of the focusing effect of a plasma lens on a heavy ion beam calls for further investigation of this superior focusing method which could at last allow us to design a final focus plasma lens for future SIS beam-target experiments.

Tuesday, December 4, 10:30–12:30

Poster Session 1

POSTER SESSION 1
Tuesday, December 4
10:30–12:45

HILDA: HEAVY ION LINAC ANALYSIS CODE*

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HILDA is a program which estimates the cost and finds an optimal design for HIF induction linac drivers. It can model near-term machines as well as full-scale drivers. Code objectives are: 1) A relatively detailed, but easily understood model. 2) Modular, structured code to facilitate making changes in the model, the analysis reports, and the user interface. 3) Documentation that defines and explains the system model, cost algorithm, program structure, and generated reports.

Presented here is a HILDA generated intermediate facility design with a low repetition rate (1/10 Hz), moderate life span components (10^6 pulses), pulsed quadrupole magnets (1.0 ms) for beam focusing, and beam currents that lightly load (≅20 A/beam) the pulsers Cost estimates are based on near-term technology and prices.

*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy under contract No. DE--AC03--76SF00098.

VACUUM REQUIREMENTS FOR HEAVY ION RECIRCULATING INDUCTION LINACS*

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A. Faltens, Lawrence Berkeley Laboratory, One Cyclotron Road, Berkeley, CA 94720

We examine the requirements of the vacuum system for the LLNL/LBL recirculating induction linac concept. We reexamine processes, including beam stripping, background gas ionization, intra-beam charge exchange and desorption of gas molecules from the wall due to the incident ionized gas molecules and stripped ions, in the context of the proposed recirculator. We discuss implications for the vacuum system layout and estimate the cost of such a system.

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*Work performed under the auspices of the U.S. DOE by LLNL under contract W-7405-ENG-48 and at LBL by the Director, Office of Energy Research Projects Division, U.S. DOE under contract DE-AC03-76SF00098.

TIME DOMAIN ANALYSIS OF 1-D LONGITUDINAL BEAM DYNAMICS IN AN INDUCTION LINAC*

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In the study of longitudinal beam dynamics in an induction LINAC, the causal condition and the finite bunch length are the unique features to be considered. The causal condition insures proper wake fields and finite bunch length could limit the convective instability growth[1]. Also the accurate representation of complex longitudinal impedance $Z(\omega)$ in the low frequency domain below 100 MHz is crucial. At higher frequency, above the inverse of the radial transit time scale, impedance representation of the beam-structure interaction is not adequate and a full electromagnetic treatment should be used.

A simple time domain numerical analysis has been performed which incorporates the necessary causal condition as well as the complex $Z(\omega)$ for parameters relevant to the typical heavy ion fusion(HIF) induction driver. Since the beam residence time in a HIF driver is relatively short (~msec), the stability criterion can be relaxed to a growth rate small enough to be tolerated by the final focussing requirement of $(\delta v/v) \sim 0.001$ at the end of a driver. Initial calculations show the tolerable impedance limits in terms of circuit parameters for a presumed initial noise error level.

[1] Bisognano, J., Haber, I., and Smith, L., Proceedings of the particle accelerator conference, 1983.

*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy under Contract No. DE--AC03--76SF00098.

TARGET CHAMBER PROPAGATION OF HEAVY ION BEAMS IN THE PRESSURE REGIME ABOVE 10^{-3} TORR

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From the point of view of reactor design, it may be advantageous to operate the HIF target chamber at pressures exceeding 10^{-3} torr. At these densities, it is still possible to propagate the ions along essentially ballistic orbits, but perturbations due to the background gas become significant: a fraction of the beam is stripped to higher charge states, and the density of beam-produced plasma may be comparable with the beam density. In some regimes, virtually all stripped ions are expected to miss the target. At higher densities, one may consider the alternative of propagating the beam in a pinched state.

For the case of ballistic propagation, we have made preliminary numerical estimates of beam intensity on target, using the multiple envelope code HIMEC. This code uses stripping cross sections for U^{+1}-U^{+4} impacting Li atoms and ions to estimate the density of beam and plasma particles in each charge state as the beam propagates in z. Envelope equations are used to calculate the radius $R_n(z)$ for the n^{th} beam component. We have also begun to develop a more complete description of beam dynamics using the axisymmetric particle simulation code FRIEZR. Plasma electrons, which are included in FRIEZR, may partially neutralize the ion beam space charge.

We have also begun to evaluate the possibilities for propagation of a pinched ion beam. FRIEZR is also applicable here, particularly in the low pressure regime where plasma electrons are nearly collisionless. Various strategies will be discussed for setting up a pinch potential prior to arrival of the ion beam, and for rapidly stripping the beam to a high Z state, which is essential to maintain a tight pinch.

EXPERIMENTAL STUDY OF THE LONGITUDINAL INSTABILITY FOR BEAM TRANSPORT*

M. Reiser, J. G. Wang, W. M. Guo, D. X. Wang
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The induction linac is being studied in the USA as a driver for Heavy Ion Inertial Fusion. When the heavy ions are accelerated by the induction gaps, the beam sees a resistive impedance along the accelerated and transport channels. Theoretical study predicts that there is a resistive wall instability which is detrimental to the beam.

The analysis based on a simple model shows that the temporal growth rate of the resistive wall instability is expressed by

$$\Gamma \propto V_0 R \sqrt{\frac{q\lambda_0}{m}}$$

where V_0 is the initial beam velocity, R is the wall resistance, q and m are the charge and mass of the particles, and λ_0 is the line charge density of the beam. An experiment to study the instability with heavy ions would be costly because of the large mass of the ions which requires a long distance to observe the effect.

We plan to study experimentally the longitudinal instability with electrons. Specifically, an electron gun has been designed and constructed to produce a beam of 5 ns in width, up to 10 keV in energy, and a maximum of 100 mA in current. An induction linac following the gun will impart a small head-to-tail energy spread to the beam to balance beam expansion in the longitudinal direction. The beam is further matched to a resistive wall channel of a few meters in length with uniform solenoidal magnetic field. Various diagnostics will be used to determine the instability in this transport experiment. Comparison with simulation could provide useful information for ion induction linacs.

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

MEASUREMENTS OF SPACE CHARGE AND FINITE GEOMETRY EFFECTS ON EMITTANCE IN THE UNIVERSITY OF MARYLAND HIGH PERVEANCE ELECTRON GUN*

D. M. Kehne, M. Reiser, University of Maryland, College Park

Emittance measurements of the high perveance electron beam source used in the University of Maryland Electron Beam Transport Experiment have been performed. The gun is a 5:1 scaled down version of the SLAC klystron gun. The 240 mA, 5 keV beam is generated by a 1 inch diameter dispenser cathode and is compressed by a factor of two between the cathode and anode.

The emittance of the beam is measured 45 mm from the anode via the slit/pinhole technique. Since the beam current density is near its peak in this region, these studies focus on space charge induced errors present in emittance meters of this type. The finite slit effect is examined both analytically and experimentally by performing measurements with slits of various sizes. Finite pinhole effects are compensated for by numerical and analytical methods.

The emittances of the full beam (240 mA) and a smaller apertured beam (70 mA) are measured. Variation of emittance with cathode temperature is investigated. Beam profiles (Faraday cup) at the slit location and beam expansion data (phosphor screen) are also presented.

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

STUDIES OF SELF-PINCHED PROPAGATION OF A HEAVY-ION BEAM FOR P ≥ TORR*

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We have reexamined the use of the self-pinched and discharge-assisted propagation modes to confine and direct an intense heavy-ion beam toward an ICF target pellet. These modes are attractive both in allowing a simpler reactor design than vacuum transport and in possibly relaxing the constraints on transverse beam emittance and longitudinal energy spread. We have used several simulation codes to study pinch formation behind the beam head and to estimate the relevant erosion rates. Particular emphasis has been placed on improving the model of the beam-generated plasma channel.

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MODELING THE LONGITUDINAL WALL IMPEDANCE INSTABILITY IN HEAVY ION BEAMS USING AN R-Z PIC CODE*

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The effects of the longitudinal wall impedance instability in a heavy ion beam are of great interest for heavy ion fusion drivers. We are studying this instability using the R-Z thread of the WARP PIC code.[1] We will describe the code and how we model the impedance due to the accelerating modules of the induction LINAC as a resistive wall. The effects of this instability on the beam quality will be presented.

* Work performed in apart under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

1 A. Friedman, D.A. Callahan, D.P. Grote, A.B. Langdon, and I. Haber, Proc. of the Conf. on Computer Codes and the Linear Accelerator Community, Los Alamos, NM, January 21-25, 1990, R.K. Cooper and K.C.D. Chan, eds.

THE DEVELOPMENT OF COMPACT MAGNETIC QUADRUPOLE FOR HEAVY ION ACCELERATORS *

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Magnetic focusing is selected for the 4-MeV to 10-Mev section of Induction Linac System Experiments (ILSE). Compact current dominated magnetic quadrupoles are being developed to study transport of magnetically focused space-charge-dominated beams and to explore the engineering problems involved in accurate positioning of the magnetic fields in an array of quadrupoles. A prototype development program for such magnetic quadrupoles is currently underway.

In this design the traditional iron yoke is minimized so that the multiple beam-to-beam spacing is minimized. The overall accelerator diameter and its consequent impact on cost are then optimized. The design evolved from a cosine 2θ current distribution corrected for end effects. 2D field computations of this geometry including the magnetic properties of the silicon steel have been performed using the POISSON code. The field at the edge of the coils is 1 tesla and the magnet aperture is 86 mm. Each quadrupole, in an array of four, will be subjected to 1000 amp current with ≤ 12 kV voltage for 1 millisecond (Half sine curve). Current dominated magnets are used in a pulsed mode to allow higher current densities compared to standard dc water cooled conductors , resulting in closer stacking of quadrupoles.

The mechanical construction of this quadrupole is aimed at achieving location accuracy of the magnetic field center within $\pm$.001 inches of the mechanical center of the quadrupole.

* This work is supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy under contract No. DE-AC03-76SF00098.

3D SIMULATIONS OF AXIALLY CONFINED HEAVY ION BEAMS IN ROUND AND SQUARE PIPES*

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We have been using the 3D PIC code WARP6[1] to model the behavior of beams in a heavy ion induction accelerator; such linacs are candidates for an ICF driver. Improvements have been added to the code to model an axially confined beam using comoving axial electric fields to simulate the confining "ears" applied to the accelerating pulses in a real system. We have also added a facility for modeling a beam in a round pipe, applying a capacity matrix to each k_z in turn. These additions are described along with results, such as the effect of pipe shape on the beam quality degradation from quadrupole misalignments.

* Work performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

[1] A Friedman, Proc. 13th Conference on Numerical Simulation of Plasmas (R.J. Mason, ed.), Santa Fe, NM, 1989 (Los Alamos National Laboratory; unpublished).

WAKE POTENTIAL AND IMPEDANCE CALCULATIONS USING STIFF SUBRELATIVISTIC BEAMS*

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The calculation of longitudinal and transverse impedances of induction cells used in an HIF induction driver is an important step in understanding beam instabilities in these devices. Since the ions are subrelativistic through most or all of the accelerator, it is necessary to develop the computational capability to calculate wake potentials under conditions of $\beta < 1$. The relevant impedances are obtained by taking the Fourier transform of the wake potentials.

We present the mathematical formalism of subrelativistic wake potentials as it pertains to rigid beams in the $2\frac{1}{2}$-D, time-domain, electromagnetic simulation computer code AMOS. This formalism is a simple generalization of the $\beta = 1$ result. The approach is to divide the potential into "incident" and "scattered" parts, which correspond to the contributions of the undiffracted and diffracted beam self-fields, respectively. The potential due to the undiffracted beam field is simply a constant increment per unit distance. The impedance that corresponds to the scattered potential has a form identical to that of the $\beta = 1$ case, except that the dependence on the radial positions of the source and test charges has the form $I_m(\Gamma r)I_m(\Gamma r_Q)/I_m^2(\Gamma b)$, where $\Gamma = \frac{\omega}{c\beta\gamma}$, b is the beampipe radius, and r and r_Q are the radial positions of the test charge and the source charge, respectively.

The capability to compute wake potentials and impedances when $\beta < 1$ has been implemented in the AMOS code. Test cases will be presented which show correct behavior of the algorithm as $\beta \longrightarrow 1$. Calculation of impedances in conceptual induction cells for a heavy ion accelerator will also be discussed.

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* Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

3-D IMPEDANCE CALCULATIONS FOR STIFF $\beta < 1$ BEAMS USING THE PLATO CODE*

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Induction accelerators have been proposed as possible drivers for heavy ion inertial confinement fusion (HIF). Conceptual designs have induction cores of amorphous metallic glass, multiple subrelativistic beams passing in parallel through a single induction module, and possibly multiple accelerating gaps per module. Of interest for understanding beam instabilities in these devices is the coupling impedance of the ion beam to the cavity modes and to the pulse power feed lines. 2-D simulations on rotationally symmetric idealizations of this structure yield some insight, and provide a useful starting point. However, the pulse-power feeds and the multiple beamlines are manifestly 3-D features which must be modeled if accurate quantitative information is to be obtained about the module impedances.

In this paper, the 3-D, finite-difference, time-domain (FDTD), electromagnetic simulation code PLATO is described. PLATO is an extension of the AMOS wakefield code, and it is equipped with an impedance calculation package which allows the computation of cavity impedances in the presence of stiff beams with $\beta \leq 1$ (for description of $\beta < 1$ wake potential formalism for stiff beams, see paper this conference). The mesh generation package for PLATO consists of a solid modeler, an automated mesh generator based on the output from the solid modeler, and a mesh viewing tool. Graphical postprocessing capabilities are under development, and the computational postprocessing package is quite similar to that in the AMOS code. Benchmark calculations, comparing PLATO results to analytic theory and to the AMOS code will be presented. Ongoing work to model conceptual induction cells for an HIF driver will also be discussed.

* Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

FIXED FIELD ALTERNATING GRADIENT* RECIRCULATOR FOR HEAVY ION FUSION

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Abstract

A heavy ion fusion driver is considered in which a beam is passed repeatedly through a LIA (linear induction accelerator) by recirculating with two spiral sector FFAG (Fixed Field Alternating Gradient) 180 degree bends. The driver consists of three such rings: a 10-100 MeV low energy ring, a 100-1000 MeV medium energy ring, and a 1-10 GeV high energy ring. Using a scaling field of 14 kG and taking the length of the straight sections to equal the path length in the bends, the circumference of the three rings would be 187, 590, and 1890 meters.

Four matching sections in each of the three rings provide the interface between the two straight sections accommodating the LIA and the FFAG bends. These matching sections consist of dipoles which provide a dispersion free match between the linear induction accelerator and the energy dependent equilibrium orbits of the FFAG ring.

The advantage in the use of the spiral sector FFAG over other recirculator concepts is that the fields are time invariant. This removes the problems associated with time dependent field penetration into the vacuum chamber and the large amount of energy which must be expended to change the magnetic field on the small time scale associated with the required pulse repetition frequency.

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ENVELOPE MODEL OF A HEAVY-ION RECIRCULATOR*

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A simple transport code has been developed to model the beam in a heavy-ion recirculating accelerator. The novel feature of the model is the treatment of the beam charge density as a Lagrangian fluid in the axial direction. In addition, the envelope and centroid equations include terms that account for the transverse self-force, image forces, and bend fields in the paraxial limit. The use of "compressible" beam slices makes the code suitable for designing the acceleration and compression schedules, and for studying such axial phenomena as the longitudinal instability. At present, the code is used primarily to design the lattice of the LLNL recirculator, and preliminary magnet configurations for that machine will be shown.

* Work supported by the U. S. Department of Energy under contract W-7405-ENG-48.

EMITTANCE VARIATIONS OF VERY COLD ION BEAMS DURING TRANSPORT THROUGH MBE-4

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We have been studying the transverse emittance variations of very low emittance (0.03 mm-mrad normalized K-V) Cs^+ beams drifting through the electrostatic quadrupole transport of the MBE-4 apparatus at the injection energy of 180 keV. Both experiment and simulation show that these strongly tune depressed ($\sigma = 7^o$) beams, when off-axis, interact with image charges and focus field non-linearities to produce a modulated emittance that grows with distance.The modulations appear at frequencies of approximately $(\sqrt{2}+1)\sigma_o$ where σ_o is the undepressed phase advance of the electrostatic focusing lattice. Experimentally, the extent of the emittance variation depends on the amplitude of coherent betatron oscillations induced by injection offsets and by transport alignment errors. At larger emittances and therefore less tune depression, the modulations and growth are reduced suggesting that these effects may saturate with distance in a long transport system. Simulations, verified by experiments, indicate that on-axis beams exhibit essentially no emittance variation or growth with distance.

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NUMERICAL SIMULATION OF HIGH-CURRENT ION BEAM ACCELERATION AND CHARGE COMPENSATION IN MAGNETOINSULATED SYSTEMS

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The physical processes occurring in the high-current ion beam induction linac [1] were numerically simulated by the use of a discrete model, based on the method of particle-in-cell (PIC), for open plasma configurations, in particular, for space-bounded systems with electron and ion injection and escape [2]. The dynamics of a collisionless plasma in self-consistent and external electromagnetic fields is described by a set of Vlasov relativistic equations for particle distribution functions and the Maxwell equations. The analysis is performed in the axially-symmetric geometry with the description of fields by scalar and vector potentials [3].

The undertaken simulation of the dynamics of simultaneous electron- and ion-beam propagation through an axially symmetric magnetoisolated accelerating gap has shown that: (i) in the high-current ion beam case, the charge and the current compensations take place in accordance with the mechanism suggested in [1]; (ii) the ion beam is stable for the time essentially greater than the reciprocal ion Langmuir and Larmor frequencies; (iii) under certain conditions the electric field applied to the gap efficiently accelerates the ion beam particles without disturbing stability, charge and current compensations of beam.

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NONLINEAR ANALYTICAL THEORY OF CHARGE COMPENSATION OF HIGH-CURRENT ION BEAMS IN AXIS-SYMMETRICAL MAGNETOISOLATED SYSTEMS

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Previously [1], we have suggested the mechanism and have formulated conditions [2] ensuring charge compensation of a high-current ion beam in an axis-symmetrical magnetoisolated accelerating gap. The main idea lies in that a specially injected neutralizing electron beam drifts through a cusp due to the magnetic self-field of the ion beam and the electric field resulting from the radial separation of electron and ion beams. For the case of tubular electron and ion beams and the time less than Ω_i^{-1}, ω_i^{-1} (Ω_i,ω_i-correspond to the plasma-and the cyclotron frequency of the ions) the problem is described by a set of nonlinear drift hydrodynamical equations and the continuity equation for particles of the electron beam and the Maxwell equations for polarized electric and azimuthal magnetic fields. Analytical expressions were derived for the scalar potential ϕ the azimuthal magnetic field H_y and the drift velocity V_{dz}. These expressions enable one to determine the degree of charge and current compensation of the high-current ion beam as a function of the system parameters and also the self-consistent electric fields giving rise longitudinal and radial spreads of the ion beams.

This analytical theory allows optimization of the parameters of the magnetoisolated accelerating systems and the electron beam for obtaining a high-current ion beam with prescribed emittance.

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STUDIES OF A SPACE-CHARGE NEUTRALIZED ION BEAMS INDUCTION LINAC FOR INERTIAL CONFINEMENT FUSION

V.I. Karas´, V.A. Kiyashko, E.A. Kornilov, Ya.B. Fainberg, Kharkov Institute of Physics and Technology, Ukranian SSR Academy of Sciences, 310108 Kharkov, USSR; O.V. Batishchev, Yu.S. Sigov, I.I. Silaev, M.V. Keldysh Institute of Applied Mathematics, USSR Academy of Sciences, 125047 Moscow, USSR.

Results are reported from experimental and theoretical studies and a numerical simulation of physical processes occurring in a high-current linear ion induction accelerator (IINDUS). Experiments were performed with an experimental model of IINDUS, comprising an injector of gas and metal ions and two induction sections with magnetoinsulating cusps in plasma-filled accelerating gaps, which ensured the following output beam parameters: 2-3 kA, 0.5 MeV, 0.5 μs.[1] Two most dangerous instabilities affecting the beam quality were investigated, namely, HF beam-plasma and filamentation instabilities.[2] To develop the high-power beam property diagnostics, we also studied the amplitude and shape of the acoustic pulse generated by particles in a metal target versus the beam parameters. The prospects for fusion applications of the proposed accelerators were estimated by means of 2.5-D electromagnetic codes which were used to numerically simulate the processes of ion beam acceleration, charge compensation and stability in the accelerator channel.

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MODEL EXPERIMENT TO SEARCH FOR EMITTANCE GAIN OF RECIRCULATING HEAVY ION BEAM*

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An experiment is underway to measure the increase in emittance of a 8.2 KeV, 10^{-4}A X_e^{131} beam in passing through the 30° bend of the LLNL ATA Beam Director. The experiment will model the proposed heavy ion recirculating rings in that the ratio of beam electric space charge potential to ion kinetic energy is comparable and the ratio of beam radius to ring radius is comparable. The ions execute one betatron oscillation in the 30° bend.

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

BEAM BEHAVIOUR DUE TO IMAGE FIELDS

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HIF acceleration usually starts with an RFQ driven under strong space charge conditions. However, fairly little regard has been given to image forces inherent with high beam currents as demanded by HIF.

The paper explains and demonstrates two-dimensional calculations of beam behaviour with respect to image fields, as caused by more or less deplaced beams within metallic quadrupole boundaries.

THE SINGLE-BEAM FUNNEL DEMONSTRATION: EXPERIMENT AND SIMULATION

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Accelerator concepts for heavy-ion fusion and for the transmutation of nuclear waste require small-emittance, high-current beams. Such applications include funnels in which high-current, like-charged particle beams are interlaced to double the beam current. The first experimental demonstration confirming the beam dynamics of the funnel principle (with contained emittance growth) was recently completed at Los Alamos National Laboratory. A single leg of a prototype 5-MeV, H^- funnel was successfully tested. This single-beam demonstration explored physics issues of a two-beam funnel. The experiment contained elements for emittance control, position control, and rf deflection. Diagnostics allowed measurement of beam intensity, position and angle centroids, energy and phase centroids, transverse and longitudinal phase-space distributions. Results of the experiments will be presented along with comparisons to simulations.

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POSTER SESSION 2

Wednesday, December 5
3:00–5:00

PROGRESS REPORT ON THE INS 25.5-MHZ SPLIT COAXIAL RFQ

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The development of split coaxial RFQ linacs at INS started in 1984. The cavity of the INS type is characterized by modulated vanes generating the RFQ field and its multi-module structure, composed of short cavities. After accelerating successfully protons through a 50-MHz, 2-m long RFQ, we are now working on a 25.5-MHz RFQ for heavy ions.

The prototype comprises three module cavities, each of which is 0.7 m in length and 0.9 m in inner diameter. Ions with a charge-to-mass ratio (q/A) greater than 1/30 will be accelerated from 1 keV/u to 45.4 keV/u. Through rf tests and conditioning so far conducted, we have obtained the following results: 1) the resonant frequency has been tuned to 25.5 MHz; 2) the unloaded Q-value measured before high-power tests was 6400; 3) the intervane voltage is flat over the vane length; 4) the field strengths between neighboring vanes are same within $\pm 0.6\%$; 5) an intervane voltage of 110 kV has been attained under a pulse operation of 70 kW in peak and 0.9% in duty (the design voltage for $q/A = 1/30$ ions is 109 kV, 2.2 Kilpatrick).

The issues of tests from now on are increase of the duty factor up to 10%, examination of voltage break-down, and acceleration of N_2^+ ions.

NUMERICAL MODELING OF THE SWITCH MESH IN HIF SOURCES*

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The requirements of HIF place severe restrictions on the operating parameters of the ion source. In addition to the usual requirements of high brightness, constant current and energy/nucleon are the need to switch the ion flow on abruptly with enough ion flux so that the full HIF pulse current requirement can be met without the flow becoming source limited. Present techniques[1] use a group of control girds that are biased with an electron-confining potential that stops ion flow until the grid voltage is overpowered by the abrupt application of the extraction voltage. The plasma feed must satisfy various criteria so that the plasma electrons neutralize the flow to this switch grid, but no further. Space charge limited flow, between the switch and extraction grid, is essential to providing the constant current required by the HIF accelerator. Our modeling of the plasma-grid interaction with the PIC code GYMNOS shows that the plasma source must provide density and flow rates within a small parameter window so that all the criteria can be satisfied. We are reexamining our conclusions with respect to several plasma sources.

[1] *Review of Scientific Instruments*, **61**, No. 1, 553 (1990).

* Work performed under the auspices of the U.S. Department of energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

CLUSTER BEAM ACCELERATION USING A TANDEM VAN DE GRAAFF

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Cluster beams such as C_n and Si_n (n > 1) have been accelerated using a 1.7 MV NEC 5SDH-2 tandem Van de Graaff. A SNICS-2 sputter type negative-ion source was used to generate negatively-charged clusters of carbon and silicon. We have determined parameters which maximize the transmission of injected cluster beams.

A beam of accelerated clusters is one of the new tools for fundamental study of fusion reactions. We have investigated a possibility of cluster beam generation by using a tandem Van de Graaff equiped with a sputter-type negative-ion source. The key issue is the efficiency of transmission through the charge exchanger located in the high-voltage terminal. The charge exchanger is a canal filled with nitrogen gas. The nitrogen-gas feeding rate, accelerating voltage and pumping speed of nitrogen from the charge exchanger are the factors which have been investigated in this work. We have injected a beam of C_n^- or Si_n^- (n > 1) into the tandem to measure the intensity of accelerated clusters with m atoms (m = 1 - n). As an example, the transmission of C_2 through the tandem was 1%.

SPUTTERING OF GOLD BY URANIUM IONS WITH UNILAC ENERGIES

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The sputtering yield of gold foils by uranium ions in the energy range between 1.5 and 5.5 MeV/u was investigated experimentally with UNILAC beams. These experiments were begun in connection with the necessity of acceleration and storage of high-intensity heavy-ion beams in ring machines.[1] The experimental results, obtained by us, are essentially different from the predictions of existent theories.[2,3] We proposed a new possible mechanism of sputtering for the pair U-Au. According to this mechanism the elastic scattering is responsible for sputtering of gold, but under conditions where the electron system of gold in the cylindrical region (r 25A) around a uranium ion trajectory has a high temperature. The life time of this region is 10 s. During this time the binding potential of the atoms in gold is below V, the binding potential in cold matter. In this case the surface atoms with energy <eV have a finite probability to leave the metal. That is why the experimental sputtering yield (10-20 atoms/ion) is more than the sputtering yield (<1 atom/ion) corresponding to the cascade mechanism. For checking our hypothesis a special experimental program is planned. Besides that, a sputtering yield of constructive materials by heavy ions in the inelastic region of interaction should be measured.

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ALKALI-METAL-VAPOUR RARE-GAS MIXTURES EXCITED BY HIGH DC CURRENT HEAVY-ION-BEAMS †

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† supported by the BMFT

Alkalimetal vapours were produced in an electric heatable furnace filled with rare gases as buffer gas. High power heavy ion beams of the Stuttgart DYNAMITRON accelerator were used to excite the vapour-gas mixture.

The gas pressure was adjusted to stop the ion beam completely in the furnace and was varied between 1–20 kPa depending on the buffer gas. Spectroscopic investigations of the light emitted by the excited gas-vapour mixture showed narrow emission continua in the VUV when the alkali metal was vaporized.

The emission is assigned to a new class of ionic excited molecules $(RgA)^+$ formed by combination of different rare gas ions Rg^+ with different alkali atoms A. 18 new ionic excimers could be identified with emission wavelengths reaching from 76.5 nm (NeK^+) to 189.9 nm $(XeLi^+)$. Observed fine structures could be explained by emission from different electronic states. The fluorescence intensity was strongly enhanced with rising alkali vapour pressure while emission from atomic lines was suppressed. Ionic excimers are an ideal storage media for shortwavelength lasers. Experimental details and spectroscopic results are presented and discussed.

Spectroscopy of VUV and X-Ray Emission from Heavy Ion Beam Induced Plasmas

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Spectroscopy of VUV and x-ray emission is a very important tool to diagnose dense plasmas induced by interaction processes of intense heavy ion beams with matter. A unique facility to provide intense heavy ion beams for beam target interaction experiments is still the RFQ Maxilac accelerator at GSI Darmstadt. We used the Kr + beam of 45 keV/u to irradiate solid targets and gas targets. Plasmas were induced in these experiments on the surface of the solid targets and inside the volume of a closed gas target. Measurements to obtain information on the spatial distribution of the beam heated plasma region was deduced from pinhole camera photographs. The aim of the experiment is to measure the amount of beam energy that is converted into radiation in the wavelength regime ranging from VUV to x rays of 1 keV.

Electrical Potential of a Spherical Target Irradiated by an Intense Heavy Ion Beam

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A spherical, metallic target ($\phi = 1$ cm) was irradiated by an intense Kr^+ beam. The beam was provided by the RFQ-Maxilac accelerator at GSI-Darmstadt with a particle energy of 45 keV/u and a total beam current of 4-5 mA, which amounts to a maximum beam power of 19 kW.

The change of electrical potential of the target induced by the intense beam pulse was measured and the maximum value determined to be 8o kV. This is considerably smaller than the calculated maximum of 240 kV. The difference is explained by the existence of a particle flux originating from the target, and the source is a plasma layer created on the target surface by the impact of the intense pulse of heavy ions.

The observed time dependence of the target potential is in agreement with a model calculation assuming ion emission from the surface plasma according to Child-Langmuir's law.

Intense-beam target interaction experiments with heavy ions

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Intense heavy ion beams are now widely regarded as a very promising candidate as a driver for inertial confinement fusion (ICF) targets. At GSI we have introduced a research program to study the applicability of intense heavy ion beams for ICF. With the completion of the new accelerator facility at GSI excellent conditions exist to engage in fundamental research for beam plasma interaction phenomena. The goal of the current research program is directed towards the goal of high current target experiments to study matter under extreme conditions of pressure and temperature. Recent experiments have clearly demonstrated an enhanced stopping power of hot, ionized matter for heavy ions. In first experiments with an intense beam from the RFQ accelerator we succeeded to heat small samples of matter to high temperatures and develop plasma diagnostic methods specifically for beam induced plasmas.

ENERGY LOSS AND CHARGE STATE OF HEAVY IONS IN A HYDROGEN PLASMA

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The stopping power of a hydrogen plasma for heavy ion beams from 1.4 to 5.9 MeV/u has been measured. A 20 cm long z-pinch constructed by the Fraunhofer-Institut für Lasertechnik in Aachen has been used as plasma target. It provides fully ionized hydrogen plasma with densities from 10^{17} to more than 10^{19} cm^{-3}. The energy loss of the heavy ions was measured using a time of flight method. We find an enhancement of the plasma stopping power compared to that of cold gas. The measured enhancement factors (up to 3) are in good agreement with the standard stopping power theory.

For the first time a direct measurement of the charge state of heavy ions after passing through a hydrogen plasma has been performed. The different ion charge states were separated in a magnetic dipole and then detected with a fast scintillator in combination with a streak camera. We find that in the plasma the ions are stripped to higher charge states than in cold gas. This result has been predicted theoretically and is due to the smaller capture cross sections for free electrons than for bound electrons.

HEAVY ION BEAM INTERACTION WITH CYLINDERICAL TARGETS*

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Recently, the heavy ion fusion group at GSI, Darmstadt, West Germany has measured the range of heavy ions in a hot (~ 10 eV), dense (~ $10^{17} cm^{-3}$) plasma created by a Z-pinch and obtained favorable comparisons with theory. They are also studying the interaction of their intense RFQ heavy ion beam with gas puff targets and, in the future, will irradiate solid cylinders with a beam of much higher energy.

In this paper, we compare our theoretical predictions of ion range shortening with these new experimental results. We also study the interaction of heavy ions with solid cylinderical targets and characterize the resulting plasmas.

* Work supported by the Department of Energy

2-D STUDY OF THERMAL X-RAY GENERATION FROM ION BEAM HEATED 'CONVERTERS'

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Recent analytical and 1-D numerical studies /1/ show that thermal X-rays suitable for driving ICF implosions can be generated by depositing a specific power of the order of 10^{16} W/g for a time $\Delta t \approx 10$ ns in a stretched cylindrical converter with radius $R_0 \approx 1$ mm. Low density, high-Z materials (e.g. Gold foams) appear to be the best material choice.

With the guidance provided by the above results, a 2-D study of converters heated by heavy ions with energy $E_0 \simeq 50$ MeV/amu has been performed, by using the 2-D, three temperature code DUED /2/ (including accurate opacities and EOS data, and an ion stopping routine).

The effects due to the finite ion range and to the space and time dependence of the stopping power have then been investigated; in particular the competing roles of range shortening and beam digging in the expanding plasma are clarified. The effects depending on the intrinsic 2-D geometry of the converter (end effects, converging geometry) and also of some realistic irradiation patterns have been considered.

A concept for a high efficiency converter for indirect drive ICF is also illustrated, in which backward radiation losses are minimized and direct irradiation of the ICF capsule is avoided.

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RECOMBINATION OF PARTIALLY STRIPPED HEAVY IONS WITH FREE ELECTRONS*

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During acceleration of heavy ions to energies needed for HIF, electron cooling of partially stripped heavy ions may be considered as a tool to increase the phase space density. The cooling by electrons, however, provides a loss mechanism for the ions stored, if these electrons recombine with the partially stripped heavy ions through radiative electron capture (REC) or by dielectronic recombination (DR).

In order to determine cross sections for these loss processes for ions available from the UNILAC, we have set up an electron target as a merged beams experiment. A dense electron beam (up to 10 A/cm^2, 660 mA, 8 keV) is merged with the UNILAC beam over an interaction length of 45 mm by means of suitably bent magnetic flux lines.

In contrast to ion storage rings, we also are able to measure REC, if ions and electrons travel at zero relative velocity. First experiments have shown, that cross sections for REC are significantly higher than theoretical predictions.

* Supported by BMFT under contract nr. 06 OF 304

PRESSURE IONIZATION AND LOWERING OF IONIZATION POTENTIAL OF PARTIALLY-IONIZED DENSE HYDROGEN-LIKE PLASMAS

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In this study the pressure ionization and the lowering of ionization potential of partially-ionized dense hydrogen-like plasmas at different electron degeneracies is considered in the framework of:

1° - Spherical cell self-consistent-field model (average atome);
2° - Thermodynamic approach, using the mass action law and the modified Saha ionization theory.

Finally an attempt is made to establish the connection between these two approaches.

HEAVY ION BEAM AND REACTOR CHAMBER INTERFACE DESIGN*

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The design of the beam lines as they approach and enter the HYLIFE-II reactor chamber must provide for final focussing quadruple pairs, neutron shielding, fast shutters, vapor condensation and pumping, thermal insulation, structure and other features. The smallest half angle encompassing all the beams as they strike the target might be ±14° for an array of 4x4 beams. The target gain drops considerably from the zero degree published values due to this finite angle. We further assume another drop due to one–sided irradiation. One–sided irradiation reduces the number of bending magnets needed. A yield of 350 MJ might be achieved with a 6 MJ driver (gain of 58), which results in a nominal 1000 MWe net power with a repetition rate of 8 Hz. For either lower rep rate or lower gain we need to increase the yield by increasing the driver energy. The beam ports are protected from radiation by an intricate array of vertical and horizontal, neutronically–thick, liquid jets.

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory, contract W-7405-ENG-48.

RM/D1

A STUDY OF INERTIAL FUSION TARGET IMPLOSIONS USING HEAVY ION CLUSTER BEAMS

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The use of relatively low energy (few tens of keV/n) and momentum rich heavy-ion clusters as driver for ICF pellets has recently been suggested.[1] One can have as many clusters as necessary with each of them having typically up to 200 atoms, for example of gold. These clusters can be accelerated in a multi-aperture column and made to converge at the centre of a spherical chamber where the pellet may be placed. It has been shown[2] that such an ion acceleration configuration is unstable and the growth of instability is Z^2/M where Z is ion charge and M the ion mass. In a cluster one can make Z/M — 0 which suggests that the beam transport instability may be eliminated. Moreover, the range of these driver ions is extremely small in target material,[1,3] and therefore ablation can be neglected. In such a scheme, the target is driven by the direct application of large beam momentum. The problem of energy deposition and material ablation is thus replaced by application of a strong pressure pulse at the target surface. This implies that one can use a very simple target made of a solid DT shell. It has also been shown[3] that the driver to fuel coupling efficiency, η in such a configuration is ~80% whereas in other conventional schemes[4,5] η is ~5-10%. It is therefore possible in this former scheme to achieve high energy output using 0;.25 MJ to 0.50 MJ input energy. In this paper we present simulations of compression and burn of two targets with 100 μg and 1 mg DT fuel, respectively. An input energy $\leq$0.5 MJ is used and a gain of 25-75 has been obtained. These simulations have been carried out using a 1-D, 3-T code MEDUSA-KAT.[6]

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PELLET IMPLOSION IN ION-BEAM ICF

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In the paper several nonuniformity-smoothing effects on a pellet implosion symmetry are studied in the ion-beam inertial confinement fusion(ICF): First we present a study for the nonuniformity-smoothing effect of the radiation transport by a 2-dimensional implosion simulation. Then the Rayleigh-Taylor (R-T) instability is studied by a self-consistent linear analyses under the influences of the nonuniform acceleration field and the radiation transportation.

The detail analyses described above show the following valuable results: 1)The 2-dimensional simulation presents that the initial nonuniformity introduced by impinging ion beams can be smoothed out well during the implosion phase of ion-beam pellet. For example the initial nonuniformity of 6% is smoothed down to 0.07% during the implosion phase. 2-a)The nonuniform acceleration field in space does not change the growth rate(γ) itself of the R-T instability. However this nonuniformity of the acceleration may suppress the growth of the R-T instability. b)The radiation may reduce the growth rate (γ).

HYDRODYNAMIC FLOW IN CYLINDRICAL TARGETS IRRADIATED WITH HEAVY ION BEAMS

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A two-dimensional hydrodynamic code was used for studying the interaction of heavy ion beams with cylindrical targets. It includes a realistic treatment of the energy deposition of the beam, radiation transport in either the volume radiation or thermoconduction approximation, and an equation of state based on the SESAME tables where available or the Saha equation. For all calculations detailed density and temperature profiles are presented.

The first set of simulations deals with experiments using the RFQ accelerator at GSI to irradiate Argon and Xenon gas targets. It is shown that two-dimensional flow effects are very important for the determination of the maximum density and temperature values reached and cause a number of interesting structures that should be observable. The peak temperatures are limited by either expansion or radiation cooling and are in agreement with the experimental observations.

A second set of simulations is devoted to beam deposition powers of 40 TW/cm^2, which will be available with the SIS/ESR facility at GSI. The targets in this case are Aluminum cylinders with or without a cavity, and irradiation with hollow beams was also considered. It is found that in all cases hydrodynamic flow may lead to cylindrical convergence effects which lead to the achievement of higher densities and temperatures on the axis of the cylinder. Even for a solid target, the rarefaction of the target near the outer boundary of the original beam deposition region leads to a further penetration of the beam in an annular shape, which in turn generates a cylindrically converging shock.

"HIGH REPETITION RATE PULSER CONCEPTS FOR A RECIRCULATING LINAC HIF DRIVER"*

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Recently a study on recirculating induction linac drivers for HIF was initiated to address feasibility and cost. One of the major engineering issues associated with designing and building a recirculating induction accelerator is the method used to drive the accelerating cells. High repetition rate pulsers (<50 kHz) are required to accelerate the ion beams in a recirculating scheme. Different accelerating schemes have been evaluated to reduce cost and technical risk in the pulser design. This paper will describe the pulser requirements and the pulser concept for each of the rings of a three ring recirculating linac. The issues of cost, efficiency and feasibility will be addressed.

*The work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

"CONCEPT FOR POWERING THE DIPOLE MAGNET IN A RECIRCULATING INDUCTION ACCELERATOR FOR HIF"*

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In a recirculating induction accelerator, the high energy ring is required to have bending fields which ramp from 0.6T to 2T in 0.8ms. These fields keep the 1 to 10 GeV heavy ions at a 200m radius. This corresponds to a stored energy of 40 MJ for two semicircular bends. In an accelerator which has a repetition rate of ten Hertz, this would amount to an unacceptable power loss. It is absolutely necessary not only to design the magnets with minimum of energy loss but to recover the remaining energy for the next cycle. A pulser is under study which uses the least expensive switching devices (SCRs) and the least expensive energy storage capacitors (electrolytic) in an energy recovery scheme which could be 90% efficient. The electrolytic capacitors and the dipole magnet form a ringing circuit which provides a sinusoidal ramp of current for the duration of the acceleration period. At the peak of the current pulse (zero voltage crossing) the switches are commutated off and the current flowing through the magnet is diverted back to the capacitor bank, recharging it with the same original polarity. The paper will describe this concept in more detail.

*The work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

TECHNIQUES FOR HIGH CURRENT ION BEAM DIAGNOSTICS*

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Sophisticated transport and acceleration of low energy, high current ion beams are necessary for a heavy ion inertial confinement fusion driver. Field nonlinearities produced by the accelerator system and the space charge of the beam have to be investigated and minimized to allow for only small degradations of beam quality.

During the last three years several techniques for destructive and non destructive beam diagnostics have been further developed and tested at the Institut für Angewandte Physik, Frankfurt:

- retarding field spektrometers and a 127^0-electrostatic energy analyzer as tools to measure the integral or differential energy spectra of residual gas ions created and expelled from the beam (non destructive) to allow for the evaluation of the transverse space charge potentials of unneutralized and space charge compensated beams.

- a transverse electron beam probe (typically 1 keV, 1 μA) for non destructive determination of the radial charge density distribution of uncompensated and neutralized beams.

- a multifunctional profile and emittance measurement system with 2-dimensional slit-to-slit and 3-dimensional point-to-slit operating mode. The latter allows for an improved imagination of the real 4-dimensional transverse phase space of intense beams at low energies.

The properties of the different devices and operation experience will be reported.

*Work supported by BMFT under contract no. 06 0F 186I

SCALING EXPERIMENT FOR HEAVY-ION FUSION FINAL FOCUSING*

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D.D.-M. Ho, Lawrence Livermore National Laboratory, Livermore, CA

A scaling experiment will be performed to test the feasibility of proposed solutions to several problems associated with the final-focus system in a heavy-ion driver. The experiment will be conducted at the Lawrence Berkeley Laboratory using a 120 keV Cs^+ beam. The experiment will test the proposed techniques for correcting geometric aberrations and for focusing variable-current beams using fixed strength quadrupoles.

* This work is supported by the U.S. Department of Energy under SBIR Grant No. DE-FG03-90ER81706.

THEORETICAL AND NUMERICAL STUDIES OF FINAL FOCUSING SYSTEM FOR HIF

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Progress has been made on understanding the physics of focusing high-current beams. In this poster, we present the detailed theoretical and numerical studies, on the physics of final focusing, that is not covered in the talk given by Ho et al., in this conference.

NONUNIFORM HEAVY-ION BEAM TARGET INTERACTIONS

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The two-dimensional numerical studies of the hydrodynamic stability of a direct-driven planar ICF target irradiated by a heavy ion beam are presented. The particle-in-cell/FLuid Implicit Particle (FLIP) method was chosen for this study because of its natural ability to handle the distorted flows in the target interfaces. The FLIP method represents mass, position, velocity, and energies of electrons and ions. Three cases of the beam-target interactions are studied: i) an initially uniform HIBALL-like target imploded by a normally incident, 10 Gev Bi^+ beam with a spatially uniform, time-dependent intensity, ii) a uniform target imploded by a normally incident, intensity-perturbed 10 GeV Bi^+ beam in a direction lateral to the beam propagation, and iii) an initially non-uniform target imploded by a normally incident, 10 GeV Bi^+ beam with a uniform intensity.

Numerical results obtained with the FLIP indicate that the beam intensity perturbation wavelengths close to target shell thickness and the initial target surface perturbations irradiated by a uniform beam at the tamper/absorber interface were found to be mostly disastrous. Computed average perturbation amplitudes of various quantities including density, deposition front, etc. as function of time will also be discussed.

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Appendix A — Index by Title

Appendix A
Index by Title

Appendix B — Index by Principal Author

Appendix B
Index by Principal Author

Appendix C **At Deadline**

Appendix C
At Deadline

The following changes have been made in the program:

- R. Bonifacio, "A New Approach to XUV: The ρ Cooling Technique," has moved from Session 8 on Thursday to Session 3 on Monday. It will follow D. Böhne, "The First Year of SIS/ESR Operation."
- Richard F. Post, "Studies of the Mirrortron Ion Accelerator Concept and its Application to Heavy-Ion Drivers," and Johann Rafelski, "Muon Catalyzed Fusion at HIIF Facility," have been moved from Session 3 (Monday) to Session 8 (Thursday). They will follow Gardès, "Stopping of Energetic Sulphur and Bromine Ions in Dense Hydrogen Plasma."
- B. Stautz, "RFQ Conditioning by Glow Discharges," has been moved from Session 10 to Poster Session 2.
- In Session 10, the order of presentation has been rearranged such that T. Weis, "Emittance Degradation of Intense and Partially Space Charge Neutralized Ion Beams," appears just after Horst Deitinghoff, "Particle Dynamics in a Low Frequency High Current RFQ Prototype."

Modeling of Switching Ferrite Cores for Induction Accelerators

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In order to design cells for induction accelerators, we have undertaken development of the capability for modeling switching of ferrite cores in EM codes like AMOS[1]. We have implemented a version of M. Hodgdon's rate-dependent, non-linear hysteresis model[2] for ferrites on our SUN network and have adapted C. Boley's core simulator[3] to represent LLNL experiments[4] conducted on the ferrite PE11BL. With these tools, we have found the modeling parameterization appropriate for this ferrite, which is used extensively in the LLNL accelerator ETA II. In order to examine quickly the numerical treatment to be used in AMOS, we have written a 1-D test-bed and have displayed EM wave propagation with this non-linear ferrite model. Furthermore, since the drive cabling to induction cells is intrinsically 3-D, we have developed an algorithm to permit an equivalent drive source modeled with the 2-D version of AMOS without the introduction of spurious scattering sites.

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*Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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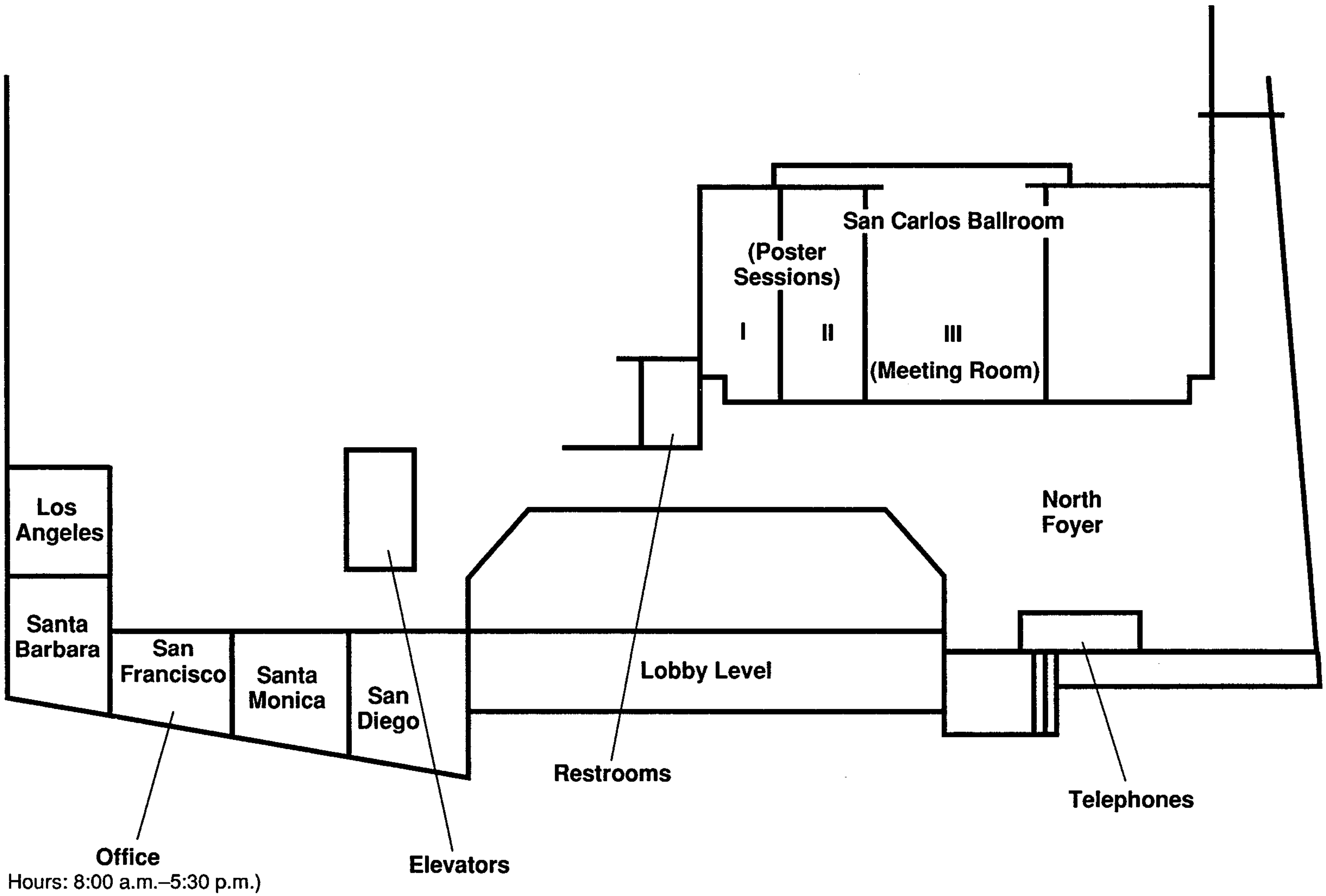

MEZZANINE LEVEL—MONTEREY SHERATON HOTEL

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