LBL-25989

REPORT ON THE SYMPOSIUM ON HEAVY ION INERTIAL FUSION, DARMSTADT, GERMANY, JUNE 1988*

D. Keefe
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

Abstract

The Symposium hosted by GSI attracted about 130 participants from 12 countries. Progress in developments for high-current low-emittance heavy ion beams in both rf linacs and induction linacs has beem reported. Significant current amplification in a proof-of-principle multiple-beam induction linac was described. Experimental results from France and Germany show enhanced energy deposition by low-energy heavy ions in hot dense plasmas. The GSI heavy ion synchrotron (SIS) and the experimental storage ring (ESR) are under construction; when completed, the beams will be used for experiments to study hot dense plasma phenomena.

Introduction

Since the beginning of interest in using high energy accelerators for heavy ions to produce high intensity beams for inertial confinement fusion, it has been the practice for interested scientists to get together roughly at two-year intervals to exchange ideas and review progress. Early on, these interchanges took the form of workshops; later as ideas became explored in detail the workshop mode was abandoned in favor of Symposia of three or four days duration with invited and contributed papers. The most recent of these was held at Gesellschaft für Schwerionenforschung (GSI), Darmstadt on June 28 - 30, 1988.

The main attraction of the accelerator approach to Heavy Ion Fusion (HIF) is that the technology, which has a large development base, can offer a combination of features (repetition rate, efficiency, lifetime, reliability, and focussing at a large stand-off distance from the fusion pellet) that makes it seem very attractive for an electricity-producing plant based on inertial fusion (IF). Thus the issues lie in (a) cost, and (b) feasibility, especially in being able to generate the very high current (tens of kiloamperes) and small focal spot size (3-5 mm radius) needed at the fusion target. HIF has suffered an historical disadvantage, however, in being a late-comer to the inertial fusion field, where much larger programs using lasers or light-ion beams had been in place for some years. Laser and light-ion systems, at least in their present forms, may have serious disadvantages for electricity-generating systems, but could be adequate for the military applications which are their primary emphasis.

In discussing the U.S. inertial fusion program directed at the energy application, Polansky (DoE) described the only such undertaking, Heavy Ion Fusion Accelerator Research (HIFAR), which concentrates on exploring the application of heavy ion induction linacs to the problem.[1] A major fraction of this 6-M$-a-year effort is conducted at Lawrence Berkeley Laboratory (LBL) with other activities at Lawrence Livermore National Laboratory (LLNL), the Naval Research Laboratory (NRL), Stanford Linear Accelerating Center (SLAC), and Argonne National Laboratory (ANL). By contrast, the research on ICF managed by the Defense Programs part of DoE, is much larger (M$150/year); Kahalas (DoE) summarized these activities which include glass (e.g. NOVA), and gas lasers, the Particle Beam Fusion Accelerator-2 (PBFA-2), and a classified segment of research designated Halite-Centurion. (Two months after the Darmstadt Symposium, the U.S. DoE revealed that Halite-Centurion was a program on ICF experiments conducted underground in Nevada using nuclear explosives; results remain classified).

In his talk, Kahalas gave details of the DoE Defense Programs plan to construct a Laboratory Microfusion Facility, or LMF, which would satisfy the military application needs.[2] A specific driver technology would be chosen in 1991 or 1992. The LMF would have a very low repetition rate (< 1 shot per day) and a short lifetime (< 10^6 shots); efficiency is not of importance. Hence, one could choose a driver technology, e.g. glass lasers, which did not conform to the properties desired in a power plant driver. Since LMF is intended to produce a high yield per shot (higher than in a electricity-generator) with high confidence of success the beam energy is set at 5 to 10 MJ - higher by a factor of two or so than what is believed needed for power generation, and higher by a factor of 200 than the largest operating glass laser facility (NOVA).

2. Driver Research

2.1 Induction Linac: The February issue of *Fusion Technology* was devoted to the results of a Heavy Ion Fusion Systems Assessment study, a collaborative venture by industry and DoE laboratories to evaluate a broad spectrum of power plant options that used an induction linac as a driver.[3] Beam parameters that were varied included ion mass, ion charge, ion kinetic energy, total beam energy, and beam emittance. Four choices of reactor chamber and five choices of target design were also examined. Results indicated favorable electricity costs for a 1 GeV plant (5 - 5.5 cents/kWh). A 500 MWe plant, which would be more attractive for a utility company because of the lower buy-in price, gave an electricity cost of 9 cents/kWh; the price per kWh would drop at a future date if the utility were to add a second reaction chamber in an upgrade to 1 GWe. These electricity costs were quite stable over a wide range of variation in the accelerator parameters.

The apparatus for an experiment called MBE-4 had been completed some months before at LBL.[3,4,5] See Figure 1. MBE-4 is a proof-of-principle accelerator with 4 separately focussed cesium ion beams. Twenty-four accelerating gaps raise the energy of the ions from 200 keV at injection to almost 1 MeV at the end. The induction core pulsers can provide shaped voltage waveforms, first, to speed up the end of the 1-m long beam bunch relative to its head thus initiating current amplification and second, to supply small correction acceleration/deceleration at the tail/head of the bunch to counteract the longitudinal spreading of the bunch ends due to space charge effects.

CBB 879-7734

Fig.1 The recently completed MBE-4 apparatus; the induction cores are housed in the square boxes.

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

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Current amplification proceeds from two effects. First, if the voltage waveforms on the accelerating gaps just after the injector are chosen correctly the length of the beam bunch can be held constant. Thereafter, flat-topped waveforms will maintain the length constant and the beam current will rise directly as the beam velocity (the pulse duration shortening inversely as velocity). In a driver this would amount to a factor (final energy/initial energy)$^{1/2}$ = (10,000 MeV/3 MeV)$^{1/2}$ = 58, but in MBE-4 only by a factor (1,000 keV/200 keV)$^{1/2}$ = 2.2. Additional current amplification is planned to take place in a driver by a second manipulation of the voltage waveforms causing the bunch length gradually to shorten by a factor of 4 leading to an overall amplification of 4x58 = 232. In MBE-4 an early experiment (so-called "aggressive accelerating schedule") accomplished an amplification of 9 (from 10 mA per beam to 90 mA per beam). See Figure 2. Thus, the bunch length was compressed by a factor of $9/2.2 \approx 4$, about the same as needed in a full-scale driver.

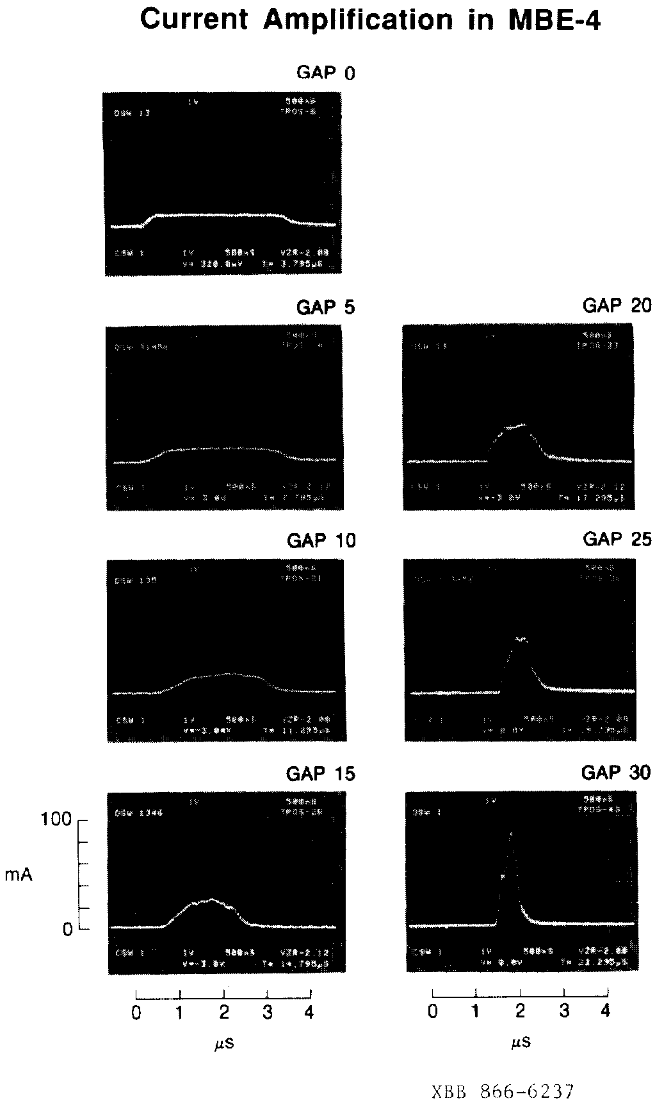

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Fig.2 Oscillograms for one of the beams in MBE-4 show the injected current trace (lowest amplitude, longest duration) at gap 0, and the amplified current traces after 4,8,12,16,20, and 24 accelerating gaps.

Preliminary measurements for a less extreme example of amplification — by a factor of 3 — which is more amenable to accurate diagnosis, were reported by Meuth.[5] First results suggested a normalized emittance growth by almost a factor of two; significantly more than calculated. Since many instrumental effects can cause unnecessary emittance growth, e.g., incorrect tuning, imperfect matching, or a gradual drift in the operating point, a much more careful round of experiments is needed to establish how much of the growth is due to fundamental physics effects and how much to unsatisfactory tuning procedures.

LBL are also developing a pulsed 16-beam injector in preparation for future experiments. See Figure 3. The 2-MV high voltage is produced by an inductively graded Marx generator with gas insulation. The original design and partial fabrication was done at Los Alamos National Laboratory (LANL) and the apparatus moved to LBL in September 1987. A gated metal vapor vacuum arc source, developed originally by Humphries and Burkhart[6] and designed to give 500 mA of C^+ ions, is being optimized before the 16 sources for the injector are fabricated.

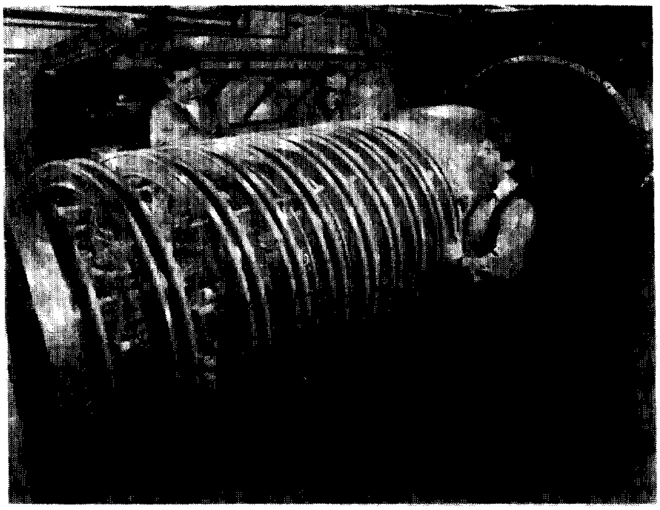

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Fig. 3 View of the partially completed inductively-graded Marx generator which is designed for gas insulation.

When complete, the 16-beam injector will be the first stage in a series of experiments to model many of the manipulations needed in a driver — beam combining in sets of four-to-one, magnetic transport, bending of space-charge-dominated beams, drift compression to remove energy tilt, and final focus experiments. Fessenden reported on the physics and engineering designs of the apparatus (called ILSE for Induction Linac Systems Experiment) to accomplish this program of experiments. Ho (LLNL) described results of 2 1/2 D particle-in-cell simulations of the beam behavior in the drift-compression section of a driver system, in which collective acceleration at the bunch head and deceleration at the tail remove the residual velocity tilt, $\Delta v/v$, as the beam leaving the accelerator drifts and bunches on its way to the target.[7]

Experiments on the behavior of space-charge-dominated beams are being conducted by Reiser's group using a low emittance electron beam transported through a sequence of solenoid lenses.[8] One experiment, in which the high-brightness beam is split into several beamlets which then mix and merge in the transport system, tests the theory that redistribution of electrostatic field energy feeds directly into a change in beam emittance. Several of the experimental observations are in good agreement with simulation work by Rudd et al.[9]

2.2 rf linacs/storage rings

While the US research is devoted to the induction linac approach, the study of rf linac/storage ring systems is being pursued in West Germany, the Soviet Union and Japan. A strong, broad program at GSI is moving forward on two fronts — the physics of high energy density by heavy ion beams and the accelerator physics issues in linac/storage ring systems. While initial experiments on the first topic have taken place with existing facilities — the new RFQ, for instance — the present construction program for the heavy ion synchrotron, SIS-18 and experimental storage ring, ESR, will lead to exciting opportunities in the next few years.[10,11] See Figure 4.

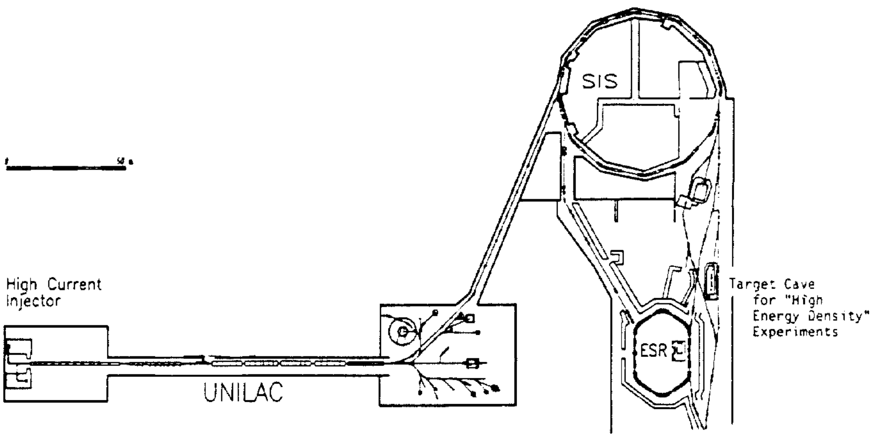

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Fig.4 The SIS/ESR heavy ion facility with UNILAC as the injector. SIS and ESR are to be commissioned in 1989 but the high-brightness injector will not be operational before 1991.

Several other institutions in West Germany are collaborating in the theoretical and proposed experimental program - MPQ-Garching, Frankfurt, Aachen, TH-Darmstadt, Giessen, among others. Much of the present activity is related to the planning and design of experiments on heavy-ion induced plasmas, and to some fusion target calculations. One accelerator experiment, however, on electron cooling of partially stripped heavy ions produced by the UNILAC is soon to take place.[12] This is in the nature of a preliminary evaluation of the method in anticipation of the use of electron-cooling in the ESR when it is completed late in 1989. In ESR it is hoped that the emittance can be reduced by a factor of 10 below the SIS emittance.

At the time of the Symposium, SIS-18 was nearing completion and ESR was about half complete. The invited paper by Boehne at the present Conference reports that commissioning the accelerator is already under way.[13] I. Hofmann described the main areas of study in preparation for the use of SIS/ESR to evaluate the problems of a fusion driver system.[14] Among these were (a) the three-dimensional space charge effects during multi-turn injection which can cause emittance dilution both transversely and longitudinally; (b) an interesting experiment on the longitudinal microwave instability in which SIS will be filled with Ne^{+2} ions and, after acceleration and stripping, Ne^{+10} ions will be injected into ESR to exceed the Keil-Schnell limit by a factor of 25; and (c) fast bunching to amplify the current while using electron cooling to keep $\Delta p/p$ adequately small.

Schempp et al. at Frankfurt are developing a high-current spiral RFQ in the right parameter range for HIBALL.[15] Calculations show that, operating at 27 MHz, it should accelerate 25 mA of U^{+2} ions from 2.5 to 25 keV/amu. High-power models have already been built for sparking tests.

A rf/ring driver system under study at ITEF (Moscow) would use Bi^{+2} ions at 20 GeV and a beam energy of 6 MJ.[16] A bismuth ion source is operating at 25 mA. Funnelling is envisioned at the front end to achieve high current in the main linac. They have already constructed an impressive 6 MHz RFQ which has undergone beam tests. Now they are examining the possibility of modifying the 9 GeV proton synchrotron to accelerate heavy ions. A beam energy of 1 kJ is achievable which if bunched to 10 nsec could provide an interesting experiment. Koshkarev was concerned that the well-known ion-gas instability (named after him and Zenkevich) could be a problem for heavy ions in a storage ring since the desorption coefficient for a heavy ion lost to the walls may be rather large. This is directly related to the "black cloud" concern identified some years a go, namely that vapor emission due to a small amount of beam loss on an injection septum could thwart attempts to stack multiple turns in a storage ring. An experiment is planned at ITEF to study the desorption coefficient by means of a H_2^+ probe beam. See Figure 5.

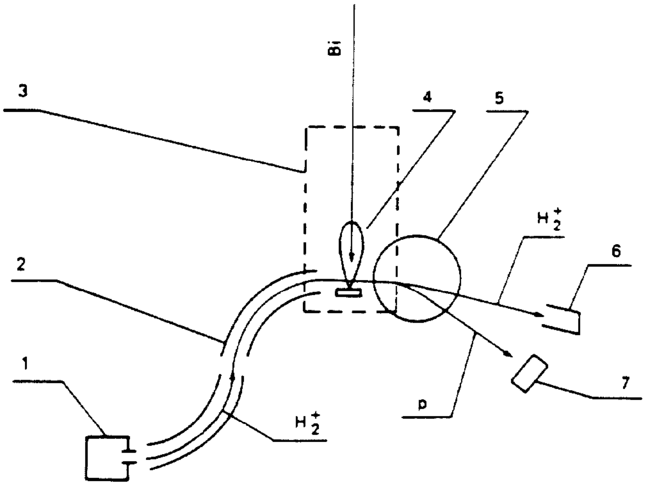

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Fig. 5 Schematic of ITEF experiment to measure gaseous desorption coefficient for normal impact of bismuth ions. Gas density is inferred by measuring dissociation of $H^+{}_2$ beam.

Katayama (INS) discussed a proposed experiment on heavy ion cooling that is planned for the TARN-2 ring.[17] This 400 MeV/amu synchrotron has been completed and is in the process of being commissioned about now.[18] One of the straight sections includes a 10 ampere electron cooling system which will be operated on the flat top of the magnet pulse. Accelerating structures suitable for low-energy heavy ions are under study in Tokyo. S. Arai and colleagues have tested a proton model of a split coaxial RFQ which offers some simplification of fabrication.[19] Satoh et al., have tested two types of interdigital H-mode (IH) structures suitable for low-β acceleration and report that operation is extremely sensitive to a number of parameters especially drift-tube capacitance.[20]

Finally, Martin reported preliminary measurements at the ISIS accelerator that addressed the question of the threshold for the longitudinal microwave instability in a bunched beam — a critical piece of design information for an IF driver.[21] ISIS is a high-intensity synchrotron with a proton injection velocity closely matching that of the heavy ions near the end of a driver. Martin and collaborators did indeed observe the growth of a longitudinal instability in a coasting beam at the injection energy. This was observed as a 202.5-MHz signal (showing that the debunched beam still had some memory of the linac frequency) which saturated quickly and then decayed in a few hundred microseconds. Whether this stabilization is accompanied by a gross increase in momentum spread or generation of relatively weak momentum tails as suggested by Hofmann,[22] could not be determined. If more ISIS time can be scheduled, this clearly is a unique facility for further fruitful investigation of coasting and bunched beam instabilities.

2.3 Other Driver Ideas

In characteristic style, Rubbia pointed out that there were many tools developed for high-energy physics machines that could be deployed in imaginative ways to solve the driver problem.[23] He gave some examples. A possible driver configuration could consist of two rings that are tangential at a long straight section. The first is a synchrotron containing a high-brightness Bi^+ beam (derived by charge-exchange injection of a Bi^- beam). A high-power FEL shining 17-eV photons along the shared straight section is used to convert the Bi^+ ions to Bi^{+2} which are stored in the second ring. Such an injection scheme avoids the large emittance-dilution factor arising from multiturn injection with a septum; in fact it greatly increases the density in phase-space. Also, it eliminates the "black-cloud" problem inherent in septum-injection and, further, allows a strategy of stacking several rings with minimum beam residence time per ring which helps circumvent longitudinal instability problems. Tuning to other approaches and observing that the beamstrahlung phenomenon at the interaction region of an e^+e^- linear collider leads to a very high-power burst of hard photons, Rubbia encouraged examination of a driver based on a high-energy electron accelerator. The technology is well-understood and such an accelerator in the multi-GeV range could be designed for high electrical efficiency. If the beam can be focussed to a spot size of the order of a micron and sent through a gas a pinch field in the megagauss range could be realized and photon emission would occur because of the betatron motion. Alternatively, Rubbia suggested that a collective undulator might be made by creating a wiggled line of ions.

3.0 Beam-Target Interactions

Langdon and coworkers using simulation codes examined several effects that can occur in the reactor environment.[24] Charging-up of the target by the deposition of the positive ions appears not to be a problem — positive ion emission from the target plasma or electron-capture following photo-ionization of the residual gas in the chamber make the effect negligible. Electrons accelerated to the target in this process do not contribute any significant pre-heat to the fuel. Also, they examined the possibility that electron anisotropy caused by streaming instabilities might convect energy rapidly away from the deposition zone. Transverse instability growth, driven by such anisotropy, is too small to be damaging. Likewise, the ion-electron two-stream mode seems to pose no problem. One effect examined for the first time, however, turned out to be of considerable significance; the x-rays emitted from the hot target, Doppler-shifted by the ion motion, can cause significant photo-ionization of the incoming ion beam. In high-vacuum, at least, the shift upward in average charge-state of the ions will cause transverse beam expansion and result in some half of the particles lying outside the desired focal spot. This is an important effect to study in more detail since the real situation must include the other species present — hot ions and electrons from the target, cold ions and electrons from the residual gas, and possibly, co-injected electrons — which will have to be included in the calculation.

Direct rather than indirect drive is inherently a more efficient implosion method and, if practicable, could result in significantly reduced driver requirements. Rather than the bipolar illumination geometry usually assumed, direct drive requires a high degree of symmetry for the impinging beams. In continuing to study the possibility of direct drive, Mark, using 2-D codes, has shown how the effect of asymmetries can be reduced while maintaining a manageable number of beams.[25]

A number of reports addressed the opportunities that will be presented when SIS-18 and ESR are operating to study the physics of hot dense matter. Topics to be examined include the beam-plasma interaction, hydrodynamics, and plasma radiation. A set of experiments discussed by Hoffman and Meyer-ter-Vehn would use the SIS high energy beam, 100 MeV/amu, bombarding a solid target either planar or some millimeters in length.[26] See Figure 6. For high energy ions at relatively high charge state (e.g., Xe^{+44}) a focal spot radius of 0.1 mm can be achieved so that a columnar plasma can be formed along the axis of the target. Over time, as the beam intensity and other conditions are improved, the plasma temperature and pressure could be increased from 1 eV, 1 Mbar, to some 100 eV, 100 Mbar. Low-temperature (1 eV) solid density plasmas have already been produced in a target by the 15 kW beam from the new high-current RFQ for SIS.[27] The range shortening that occurs for ions when stopped in a plasma rather than cold matter continues to be the object of experiments by Deutsch at both Orsay and GSI.[27,28] The effect is quite large – a 50-percent reduction in range – for low energy ions in the region of 1 MeV/amu, but is expected to be under 10% for the more energetic ions (50 MeV/amu) appropriate to a driver.

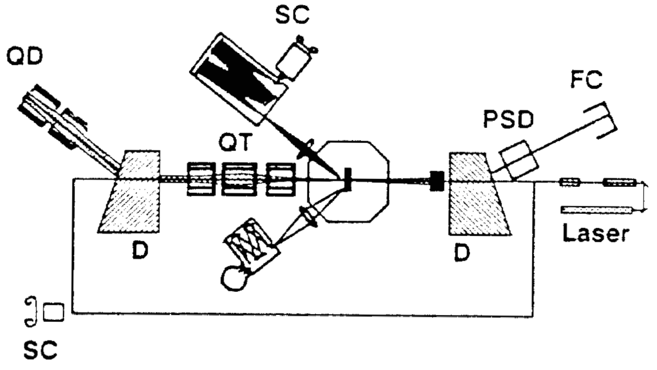

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Fig. 6 Conceptual design for a GSI experiment on a hot, high-density plasma produced by a neon beam.

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At the time of writing, the Proceedings of the Heavy Ion Fusion Symposium (Darmstadt, 1988) is not yet published. It will appear as a special issue of Nuclear Instruments and Methods, edited by R. Bock, I. Hofmann and J. Meyer-ter-Vehn (1989). Most of the references below will be found in that issue.

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