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Opportunities for Collaboration in Heavy Ion Fusion*

Rudolf Bock
Gesellschaft für Schwerionenforschung
D-6100 Darmstadt, Germany

W. B. Herrmannsfeldt
Stanford Linear Accelerator Center
Stanford, CA 94309, USA

SUMMARY

The objective of research in thermonuclear fusion is to find an environmentally attractive technology for the production of electrical energy that is both universally available and economically competitive. The method of containing the hot, dense plasma known as Inertially Confined Fusion Energy (IFE) uses small targets containing the deuterium and tritium isotopes of hydrogen which are implosively compressed to achieve fusion conditions. Research to develop IFE has been conducted at a low level in a number of nations for about the last fifteen years. One approach, known as Heavy Ion Fusion (HIF), uses large, high energy accelerators based on concepts developed for basic research to deliver intense beams of ions to compress and ingnite the targets.

The recently released Final Report of the Fusion Policy Advisory Committee (FPAC)[1] of the USDOE, says that "Heavy Ion Accelerators are currently thought to be the most promising (drivers for IFE)." Because the driver is the most expensive element of an IFE system, research to develop lower cost, more efficient heavy ion drivers has the greatest potential payoff in the search for a practical approach to fusion energy.

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The FPAC report recommended that demonstration of ignition be the highest priority near-term objective of the U.S. ICF Program. Sufficient progress has been made on target physics that the FPAC recommended construction of a 1-2 MJ Upgrade to the Nova laser to demonstrate ignition.

There are aspects of target design that are classified, which inhibits full international collaboration. The international community was asked, at a recent International Symposium on Heavy Ion Fusion, to express its viewpoints on collaboration under some classification restrictions. The emphatic response was that both sides (those with and those without access to classified material) were being penalized by the restrictions. There was strong urging for better access so that a collaboration could be on an even basis. The Secretary of Energy, Admiral James D. Watkins, who heads the USDOE, has called for a review of ICF Classification, with the view towards removing unnecessary restrictions. This process has started, and some results are already appearing. It is quite possible that by the time the reader sees this paper, it will be possible to have a full and open interchange of ideas in the area of target physics.

Meanwhile, the subject areas associated with the accelerator drivers and the designs of reactors are all unclassified and are historically fruitful areas for international collaboration. It is especially notable that many of the problems for IFE have been the subject of ongoing research in MFE for many years. Issues of reactor materials, tritium handling and tritium breeding, blanket design, and balance of plant all have areas in common in the two approaches to fusion which are otherwise very diffent.

There are two basic accelerator technologies being studied for HIF applications:

1. An RF linear accelerator is used to fill storage rings with beams of heavy ions. When sufficient charge has been collected, the stored beam energy is quickly dumped into a beam line to carry the charge to a target. This method is being studied in Germany, Japan, and the USSR.

2. A single-pass linear induction accelerator is used to both accelerate and compress the beams of heavy ions, which are immediately focused onto a target. The linear induction accelerator technology has been selected for the U.S. HIF program.

In spite of the technical differences, there are many areas in common between these two approaches, including: final focus systems, beam transport of space charge limited beams, transverse and longitudinal stability, ion sources, longitudinal compression during the transport to the target, and many others. One specific recommendation of this report is that small inter–laboratory meetings should be held on specific issues of common concern. In the United States, work is beginning on a new concept that combines a circular design with linear induction accleration, to form a recirculating linear accelerator, that has elements of both technical approaches. The new approach to the design of RF accelerator systems is the use of non–Liouvillian beam manipulation to preserve brightness while stacking higher currents together in the same beam.

While the strongest efforts in HIF are in the U.S. and Germany, there is great interest in HIF among scientists in accelerator and fusion laboratories in Japan, the U.S.S.R., Spain, and Italy, to mention only a few of the many nations that have accelerator laboratories. Scientists everywhere are aware of the needs for society to achieve a secure source of energy for the future. This report finds that the capability, the technology, and the interest are all in place for an international cooperative effort in Inertial Fusion. The immediate objective should be a single facility with a driver capable of testing a large variety of target and reactor combinations. The driver should have the capabilities of energy and pulse repetition rate needed for a fully operative power plant. Only one such facility is needed in the world so that it is entirely appropriate for the leading laboratories in this field to combine their efforts.

INTRODUCTION

Beginning about fifteen years ago, with reports by Maschke[2] and Martin[3] accelerator scientists became interested in the prospects for energy production by Inertial Confinement Fusion (ICF) using the broad base of technology developed for particle accelerators for scientific research. Their ideas were to use intense beams of heavy ions to provide the energy, and high instantaneous power, necessary to implode the small capsules containing the light elements (typically the deuterium and tritium isotopes of hydrogen) which are then compressed and heated sufficiently to cause fusion ignition and burn.

Although high energy accelerators are commonly thought of in terms of the kinetic energy of their beams, in fact the stored energy in the beams can be substantial. (Several of the presently operating high energy accelerators have multi megajoule beams; the plans for the Superconducting Supercollider (SSC) indicate that it will have up to 500 MJ in the storage rings.) It is the ability to deposit this stored energy in a very small, precisely located spot that makes this technology appropriate to the ICF application. By comparison, the energy needed to implode an ICF pellet for power production is in the range 3 to 10 MJ.

The study of HIF has continued at a distressingly low level since the excitement generated by these early proposals. Yet there has been steady progress on a number of critical technical areas including:

1. experimental demonstration of the maximum current that can be carried in a periodic focusing system,

2. longitudinal current amplification,

3. development of scenario studies and cost optimization programs,

4. a large body of theoretical knowledge about beam stability,

5. construction of the large accelerator complex at GSI, Darmstadt, with facilities for doing accelerator and beam-target interaction experiments.

The various technical issues of HIF will be briefly reviewed in the following sections. It will be seen that there are numerous areas in common in all the approaches to HIF. In the recent International Symposium on Heavy Ion Inertial Fusion, the attendees met in specialized workshop sessions to consider the needs for research in each area. Each of the workshop groups considered the key questions of this report:

1. Is this an appropriate time for international collaboration in HIF?
2. Which problems are most appropriate for such collaboration?
3. Can the sharing of target design information be set aside until other driver and systems issues are better resolved, by which time it might be supposed that there could be a relaxation of classification of target issues?
4. What form(s) of collaboration are most appropriate, e.g., bilateral or multilateral?
5. Can international collaboration be sensibly attempted without significant increases in funding for HIF?

The authors of this report share the conviction that collaboration on a broad scale is mandatory for HIF to have the resources, both financial and personnel, to progress to a demonstration experiment. Thus, the ultimate objective of the international effort should be an international facility for HIF research. The objectives of this paper are to establish some of the technical base for the companion report from the Institute for Technical and Strategic Research as it examines preconditions that must be established for an international ICF program.

ACCELERATOR ISSUES

There are two very important differences between an accelerator for research and an accelerator driver for fusion:

1. The high energy protons that are used in a machine such as the 20-TeV Fermilab accelerator must be replaced with ions of higher atomic weight

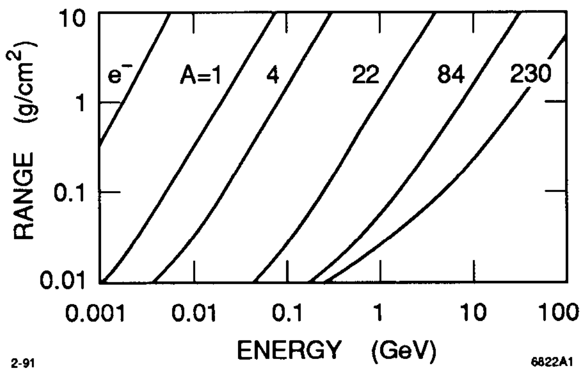

Figure 1. The range-energy relation for several ion species in hot matter (200eV). The ion range of interest for ICF is about 0.1–0.2 g/cm^2.

in order to decrease their range sufficiently to stop them within the ICF target. Most scenarios for HIF select ions with atomic number A in the range $A \geq 100$.

2. Both peak and average beam power need to be substantially increased. Especially in the case of storage rings (such as that at Fermilab or the SSC), the time during which the pulse can be delivered is determined by the size of the ring. Thus for the 1 km diameter main ring at Fermilab, this time is about 21 microseconds. By contrast, the desired pulse length for ICF is in the range 10 – 20 nanoseconds, corresponding to a bunch that is 1 – 2 meters long at the target.

The basic rationale for HIF is illustrated by the range-energy data shown in Fig. 1. To deposit the same power in a target using a proton beam, the peak beam intensity needed is about 1000 times greater than is required for heavy ions of A > 100.

Average beam power is primarily determined by pulse repetition rate, which is not significantly limited by technological constraints. Peak beam current is a much more fundamental issue for an accelerator. Therefore research has been conducted on a large variety of techniques to increase the beam power in HIF accelerators. Some of the more generally used of these approaches include:

1. Multiple beams: For beam transport reasons, there should be about twenty or more beamlets focussed through the reactor wall towards the target. This requirement is common to all approaches to ICF; lasers, light ions and heavy ions. Laser drivers, for example, may need several hundred beamlets, greatly complicating reactor design.

2. Current amplification: Because of space charge effects, much higher current can be transported at high kinetic energy than is possible at low energy. A wide variety of techniques are used for current multiplication:

   (a) Combining beams from different ion sources and pre-accelerators.

   (b) Longitudinally compressing the beam while it is being accelerated. This can be visualized as it is actually done in practice; that is push the long bunch from the back so that the tail is going faster than the head. This process can be adjusted so that the current just peaks as it hits the target. All ion accelerator schemes for ICF, light ion and all variations of heavy ion accelerators, use longitudinal compression, or alternatively, a non–Liouvillian stacking technique.

   (c) Storage rings: The most common method for increasing beam intensity is by stacking particles in a storage ring. The particles can then be accelerated, stored, switched to another storage ring, or directed towards a target. Storage rings are required with radio-frequency (RF) accelerator systems for HIF, as shown in Fig. 2, and are generally not used with Linear Induction Accelerators (LIA).

   (d) Non–Liouvillian Methods: Liouville's Theorem is a general precept in all types of optical systems. As applied to accelerator systems, it says that ordinary beam manipulations can only reduce the quality of a beam, never improve it. Thus all the manipulations referred to above exact a price from the quality of the beam. There must be an emittance

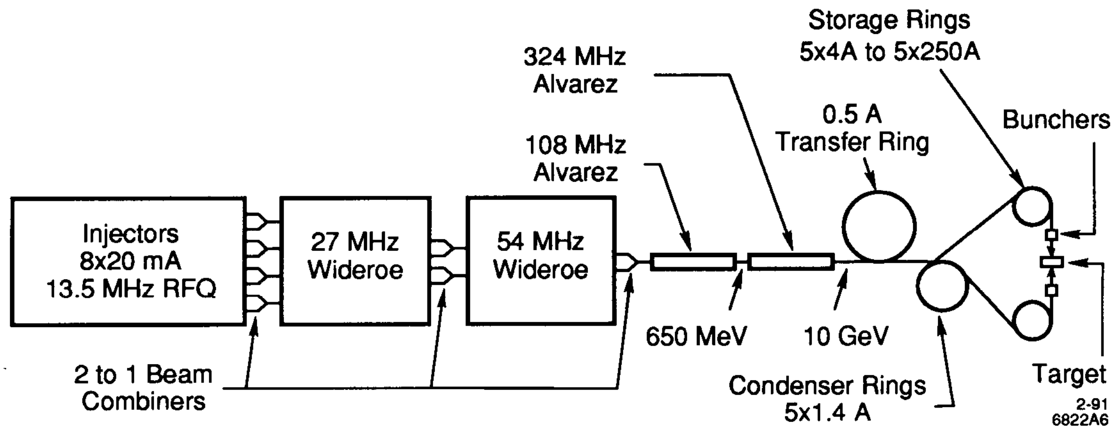

Figure 2. RF accelerator system with storage rings for current multiplication.

budget to ensure that the final result retains enough of the original source brightness to put a high percentage of the beam on the target. However, there have been a number of techniques invented, and some placed into routine application, which can improve the brightness of a particle beam, and are thus called "non–Liouvillian." One of these was proposed for HIF by Prof. Carlo Rubbia,[4] Director of CERN, who has taken a special interest in HIF. Usually these non-Liouvillian techniques involve some means of changing the charge of an ion beam at a critical point, such as when it is being loaded into a storage ring. Typically, a laser beam, probably from a free electron laser (FEL), is tuned to an atomic or molecular resonance to cause charge change or molecular dissociation.

There are a number of other requirements on a heavy ion accelerator for commercial power production:

1. Pulse repetition rate; typical scenarios for HIF show an optimum pulse rate around 10 pps for each chamber. If more than one reactor chamber is driven by the same accelerator, then the accelerator rate could be as much as 30 to 40 pps. Since typical accelerators of the type involved here, either RF or LIA, have operated up to 60 pps or more, this requirement is not expected to cause any special problems.

2. Efficiency; good efficiency in converting input power into beam on target is essential for an economic fusion power plant. High current and high average power accelerator system scenarios usually show an efficiency of about 25%. A driver (laser or accelerator) with efficiency less than about 10% has scant hope of making economical electrical power. Based on projected target gains, driver efficiency much above 25% does not significantly improve the economics, as will be discussed in the section on Ecoinomic Issues. This assumes that the conversion efficiency of thermal fusion power to electrical power is comparable to that usually found in nuclear reactors, i.e., about 33%.

3. Reliability; research accelerators must operate with about 80% reliability when in use. Typical machines spend a significant amount of time being modified for future experiments. Experience has been that reliability can significantly exceed 80%, especially when operational requirements do not constantly change.

4. Durability; some accelerators operating today have been running for 30 or more years. The dispersal of components in a multistage accelerator results in acceptable component stress levels.

5. Cost; this is perhaps the most critical requirement of all. If cost were no object, enough is known about accelerators to build an experimental driver now. There have been several HIF scenario studies such as HIBALL[5] by West Germany and the University of Wisconsin, and the HIBLIC[6] study in Japan. A systematic evaluation of a variety of reactor and target systems was made for the Heavy Ion Fusion Systems Assessment[7] (HIFSA), led by Los Alamos with LBL, McDonnell Douglas, and others. These studies show that the accelerator driver is the most expensive component in an HIF power plant, as shown in Fig. 3. Thus the objectives of HIF Accelerator R&D are to achieve cost reductions while simultaneously preserving the advantages cited above, and also solving critical technical issues created by the need for very high intensity heavy ion beams.

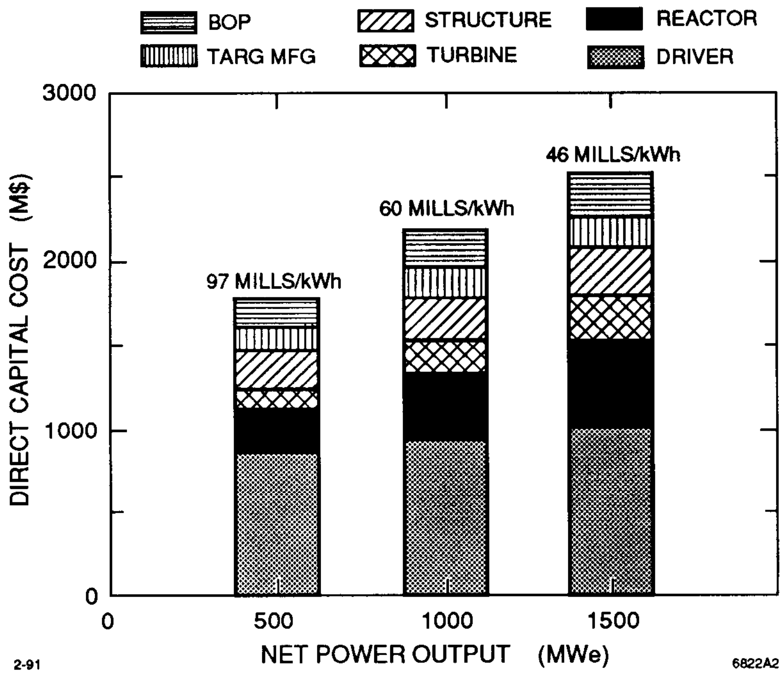

Figure 3. Results from the HIFSA[7] study showing the contributions of different components to capital cost and cost of electricity.

TARGET ISSUES

There has been remarkable experimental and theoretical progress in target physics during the past five years. Experiments have been performed at laser facilities such as Nova, Gekko, and Omega, and also underground at the Nevada Test Site. Taken together, these experiments along with the increased theoretical understanding have put to rest basic issues regarding the feasibility of ICF.

Nevertheless, targets are the most important part of an ICF energy system. As discussed in the recent report of the National Academy of Sciences Review of ICF,[8] target research is necessary to establish the feasibility of ICF.

The simplest targets consist of small (~0.5 cm diameter) spherical shells containing thermonuclear fuel, usually a mixture of deuterium and tritium. The shell surrounding the fuel may consist of several layers. In addition to confining the

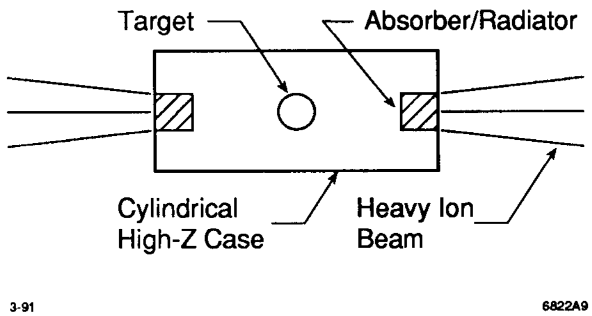

Figure 4. An indirect drive target configuration for heavy ion beams.

fuel, these layers serve as an ablator. Ion or laser beams heat the ablator to high temperature, producing high pressures ($\sim$100 million atmospheres) that implodes the fuel to about 1000 times solid density. The implosion process also heats the central part of the fuel to its ignition temperature which is about 5 keV. After ignition a thermonuclear "burn" propagates radially outward burning about 30% of the fuel and creating a small thermonuclear explosion. Calculations show that 1 – 10 MJ of beam energy must be delivered in about 10 ns to achieve an energy gain of about 100. (Gain is defined as the ratio of thermonuclear energy/beam energy.) It is very important to have nearly spherically uniform illumination. This method of illumination, which is known as direct drive, requires a large number of beams. Thirty two beams, oriented as the faces of a soccer ball is probably the minimum practical number for the targets described above.

In the approach known as indirect drive, the capsule containing the fuel is placed inside a cavity or "hohlraum." The driver beams produce radiation that fills the hohlraum and provides the energy to drive the implosion. Indirect drive relaxes the illumination uniformity requirements, particularly for ion beams. Illumination can be by one or two ion beams, or beam clusters, as shown in Fig. 4. These simpler illumination geometries greatly aid reactor chamber design. Indirect drive by lasers cannot use the cluster method and still requires illumination by a large number of widely spaced beams.

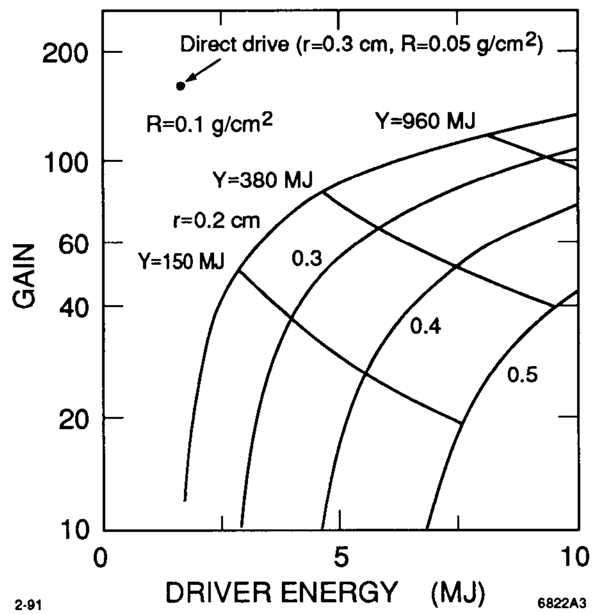

Figure 5. Gain predictions for targets with Range R=0.1g/cm^2 and spot radii from 1 to 5 millimeters.

Calculations of target gain for targets illuminated from two sides are shown in Fig. 5. These calculations, performed at LLNL, give target gain as a function of beam energy and beam focal spot radius. The gain also depends on ion range, as given by the kinetic energy. The curves shown correspond to a heavy ion (A $\simeq$ 200) with kinetic energy of about 10 GeV, as can be seen in Fig. 1.

POWER PLANT CONCEPTS

A complete ICF power plant will consist of a driver to implode and ignite the target, a target factory to manufacture and deliver the targets to the center of the reactor core, a reaction chamber in which the targets are burned, and the balance of plant in which the fusion energy is converted to electric power. The ability to transport heavy ion or laser beams over long distances without significant losses allows locating these drivers in a building that is separate from the reactor vessel itself. Furthermore, the interactions between the driver beams and the target take place in a small volume and are not very dependent on the surrounding environment. These facts bring several advantages:

1. There is great flexibility available in designing a reaction chamber and balance of plant.
2. Because the high technology components (i.e., the driver) are not near the reaction chamber radiation environment, their maintenance will be unaffected by radiation and their reliability should be greater.
3. Separability should reduce the required size of the containment structures.
4. Finally, one accelerator driver can service several reaction chambers, making modular construction possible and spreading the costs.

The functions of the reaction chamber are to contain the effects of the thermonuclear microexplosion, convert the released energy into a form more useable in the balance of plant for making electricity, and produce tritium (which is not found in nature) for future targets. The design flexibility allowed by the separability of the driver has resulted in a large number of different reactor designs being proposed in the U.S.A., Germany, Japan, and the Soviet Union. A review of most of these designs is given by Hogan and Kulcinski.[9] To produce the 2000 – 3500 MW of fusion power required for a 1000 MWe power plant, typical reactors must contain fusion explosions of 100 – 1000 MJ each at a rate of 2 – 20 times per second. High energy neutrons comprise about 2/3 of the energy of each explosion, the rest being X-rays and charged particle debris. The short range and short duration ($\sim$1 ns) of the debris mean that the first structural wall of an ICF reactor must either be at a very large distance to avoid ablation, or that this wall must be protected with a self-renewing sacrificial layer of some nonstructural material. Most reactor designs have been based on the latter method and include a fluid or granular first wall. Various reactor designs have considered the use of liquids such as lithium,[10,11] lead-lithium,[5] and FLiBe[12] (a molten salt consisting of flourine, lithium, and beryllium), or ceramic granules such as Li_2O and $LiAlO_2$.[13] In the HYLIFE-II[14] concept shown in Fig. 6, efficiency is improved by moving the

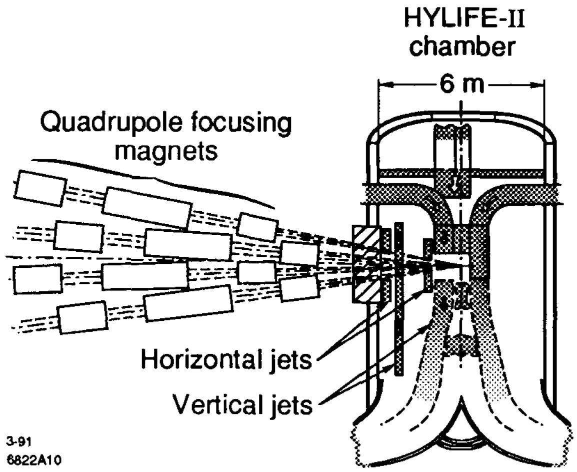

Figure 6. In the HYLIFE-II reactor design, the walls and all structural components are protected from blast and neutron damage by thick jets of liquid FLiBe (Li_2BeF_4) in order to make the components last the lifetime of the plant. In the configuration shown, 12 beams (in a 2-4-4-2 pattern) are directed to the target from one or two sides. Horizontal and vertical liquid jets are interwoven between the 12 beams in order to protect the walls around the beam apertures.

heat transfer and tritium production "blankets" inside the reactor structural wall. HYLIFE-II avoids the fire and toxicity hazards of lithium by using FLiBe.

In all of the liquid and solid first wall reactors, up to a few kilograms of the wall material will be evaporated with each pulse. The material just beyond the vaporized region is designed to be compressible so that large shocks will not be transmitted to the permanent structure. Recondensation of the vaporized material before the next pulse is necessary in all designs in order to reestablish the vacuum needed to inject and position the next target and also to propagate the beams to the target. The studies done to date have shown that self-renewing protective layers can be designed which would stretch the short energy pulse so that the peak loads on the structural walls are tolerable, reduce the radiation damage to the structural wall to the point that it would last the lifetime of the plant, and recondense the vaporized material in order to reestablish the environment in time for the next pulse. The research work necessary to put experimental results into all these studies is a large and fruitful area for international collaboration.

The existing studies have identified the requirements for many of the supporting reactor subsystems. The vacuum system must reestablish the vacuum needed for beam transport (10^{-4}–1 torr) for heavy ions, depending on the transport mode used. Tritium and some target debris must be recovered from the inner blanket material and recycled to the target factory. The target factory must make and transport high quality targets to the reactor at the rate of 2 – 20 targets per second. Targets must be injected at speeds of about 100 m/s and then tracked so that the beams can be brought to the target position with a precision of about 0.1 mm. Even in the storage ring and recirculating linac schemes, the beams are en route for only ~5 ms; thus the target is less than 1 m from the aiming point when the beams are initiated. Steering adjustments can be readily made based on tracking information. The driver/reactor interface along the beam lines must isolate the driver from the reactor phenomena but still allow the beams to reach the target at the appropriate time. Plausible conceptual designs have been proposed for many of the required subsystems, but virtually all of the development and demonstration work has yet to be done.

FINAL FOCUS AND TRANSPORT

Final focus is the name given to the ion beam transport system that focusses the multiple beams of heavy ions toward the target. The wide variety of options for final transport results from the variety of reactor environments that can be postulated. This subject area was extensively reviewed by Olson.[15]

Depending on the charge state of the beam, and the gas composition and pressure in the chamber, it is possible to consider vacuum transport, as usually considered for research accelerators, or transport in a plasma. Usually it is assumed that the incoming ion beam must be at least partially neutralized so that space charge forces do not excessively deflect the ions. As the target begins to heat up, it will emit a flux of X-rays which can photoionize particles in the incoming beam.

This subject has been studied by Langdon[16] who has calculated the probable percentage of the incoming beam that is likely to hit the target. A small percentage of the incoming ions will have their charge state changed, thus causing them to fall outside of a nominal 3 mm aiming spot on the target.

Although there is a large body of experience with transporting high intensity relativistic beams, final focus and transport tests under HIF conditions are generally not accessable to experiments with available facilities. Some issues may be addressed with the new experimental storage ring (ESR) at GSI.[17] The Induction Linac Systems Experiment (ILSE)[18] at LBL may also be able to test some final focus issues.

ECONOMIC ISSUES

The area known as "balance of plant" consists of facilities for tritium handling, target fabrication, containment buildings, power generation, heat exchangers and other similar components. Conventional nuclear power plants must include all of these except the target factory. Thus the costs and efficiencies of all except this one area are known.

A fundamental requirement for economic production of power is for the product $\eta G \epsilon \geq 3$, where η is the driver energy efficiency given by the ratio power-to-target/input power, G is the target gain (including blanket gains), and ϵ is the thermal to electric conversion efficiency (usually $\epsilon \simeq 0.3$). This product is the inverse of the fraction of power generated that must be recirculated to keep the driver operating. At the level at which this fraction is 1/3, as shown in Fig. 7, the cost of electricity used by the plant causes the price to consumers to increase by 50%, and it rises very rapidly for any higher fraction of recirculating power. Assuming the typical value of $\epsilon = 0.3$, this means we require $\eta G \geq 10$. Note that if we do much better, for example if $\eta G = 20$, the recirculating power drops to 16% and the cost to consumers is 20% of their power bill. Below this there is very little gain, so that most studies require $10 \leq \eta G \leq 20$. Choosing a midrange value

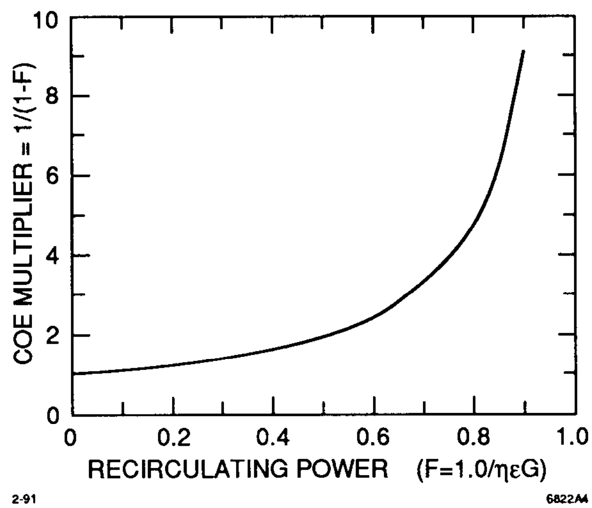

Figure 7. Effective cost of electricity as a function of the fraction of recirculating power $1/\eta G\epsilon$.

of $\eta G = 15$ and an overall efficiency of 25% for an accelerator driver, results in a need for a target gain of 60.

A typical laser driver with 5% efficiency, would require a target gain of 300 to achieve ηG=15. One cannot rule out inventions; a much more efficient laser or much higher gain targets. However, without assuming such an invention, a principal argument for heavy ions, and against lasers, is embodied in the above calculation. Other important arguments are the reliability and durability of the accelerator and focussing system. Protection of the final focussing magnets from neutron damage appears feasible; protection of the final optic elements remains a principal concern for laser drivers. As noted earlier, the illumination geometry is more favorable for heavy ion accelerators. Of course, all these arguments presuppose that the cost of an accelerator system is low enough to allow the economic generation of power, though it should be noted that accelerator beams can be switched from one chamber to the next sequentially, allowing one accelerator to serve up to about four or more chambers.

Other Applications: There is no question that the least economic use for a 14 MeV neutron is to convert its energy to hot water to spin a turbine generator. Other possibilities include:

1. Fission-fusion hybrids. Unenriched uranium or thorium can be used with the flux of neutrons from a fusion reactor to generate much more power than is possible just from the fusion reaction itself.

2. Fission fuel breeding. The supply of enrichable uranium will not support a large increase in nuclear power generation. That is why the complex breeder reactors were being developed some years ago, before the decline in the nuclear power industry. Because of the high flux of 14 MeV neutrons from a fusion device, some studies have shown that one ICF fuel breeder could supply fuel for more than ten conventional light water reactors.

3. Fission product transmutation. There have been a couple of recent studies about using accelerator generated neutrons for reactor waste transmutation. One of these, the Accelerator for Transmutation of Waste and Energy Production, (ATW), has been developed into a formal proposal.[19] In a recent paper, Dr. Ronald Martin (who was one of the pioneers of work on Heavy Ion Fusion) has shown how a fusion-fission burner could be used effectively for waste transmuting.[20] A single facility could conceivably process the waste from several light water reactors. He notes that only a small percentage of the funds now being spent on waste storage, guards, studies and burial projects, would be far more than is being spent on all of fusion, and could easily fund the construction of a prototype fusion-fission transmutation project.

Fusion scientists have never had much enthusiasm for mixing into the politics and technology of fission power. Both are very messy areas and the environmental desirability of pure fusion has always been a leading selling point. Nevertheless, the economics of pure fusion is difficult, and the fact is that large amounts of reactor waste do exist, and concern about waste is one of the principal impediments to wider development of nuclear power.[21] Thus one should consider carefully the proposal that Heavy Ion Fusion may have an important application here, especially if the requirements on accelerator driver and target performance are less demanding.

THE WORLD SCENE IN HEAVY ION INERTIAL FUSION

I. The U.S.A.

The Inertial Fusion Energy (IFE) Program in the U.S. depends on the larger ICF Program which is a defense program, for target development. There is a large ($\sim$ \$ 75 M/year) target physics effort at LLNL to determine the driver requirements for high gain targets. Although these experiments use laser beams, the capsule physics results with indirectly driven targets are believed to be applicable to heavy ion drivers as well. The proposed Nova Upgrade would investigate target ignition within the next decade.

The Heavy Ion Fusion Accelerator Reseach (HIFAR) Program, which is now in the DOE Office of Basic Energy Sciences, is being moved to the Office of Fusion Energy, (OFE). The HIFAR program has the purpose of determining if heavy ion accelerators can be used effectively for commercial energy production from ICF. The Inertial Fusion Energy (IFE) Program, as the new part of OFE will be known, will be an energy oriented program, building on the progress that has been made in target physics and driver development. Thus the HIFAR phase will be ended although not all of the experiments that were proposed will have been completed.

The main HIFAR program element is at the Lawrence Berkeley Laboratory. Smaller efforts (mostly theoretical) are at the Lawrence Livermore National Laboratory, Naval Research Laboratory, Stanford Linear Accelerator Center, University of New Mexico, and University of Maryland.

The LBL program of driver research using induction linacs has been carried out during the last decade by Keefe[22] and his group. Following the untimely death of Denis Keefe in 1990, the HIFAR program is being led by Roger Bangerter. With Induction linacs, the basic idea is to inject a long bunch of high intensity ions and to achieve current amplification by ramping the inductive acceleration fields

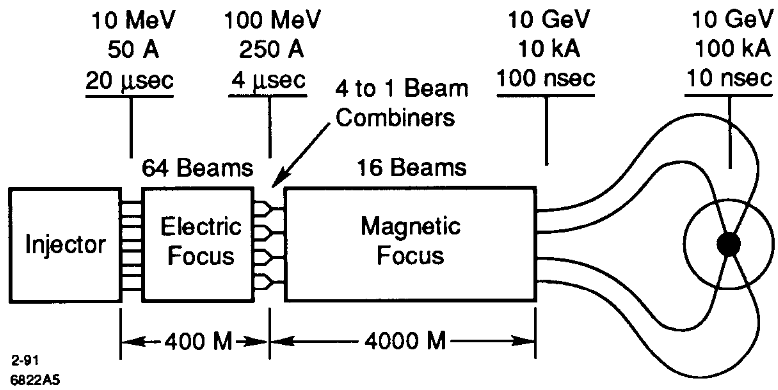

Figure 8. Linear Induction Accelerator Driver with typical parameters.

as the bunch passes. By this procedure the pulses have to be compressed from $\sim$20 μs at injection down to $\sim$10 ns at the target, the current being increased from amperes to kiloamperes. An important conceptual improvement was the splitting of a single high-intensity beam into a large number of parallel beamlets, each of them being separately focussed inside the same accelerating structure. This concept has improved focussing because of smaller emittance and has shown to be cost effective if the number of beamlets is in the range of 8 to 16. One concept for a driver starts with 64 beamlets at injection which are quickly combined, each 4 beamlets into 1, to a final number of 16 beams. For a 3^+ charge state of bismuth, the whole length of the accelerator is about 5 kilometers, as shown in Fig. 8.

Until recently, work at LBL has concentrated on the Multiple Beam Experiment (MBE-4), consisting of 4 beamlets. MBE-4 is the first experimental test of the multiple beam concept. In spite of being limited to low energies, MBE-4 allows many important issues to be investigated because the injector and the initial pulse formation sections are the most critical parts of an accelerator.

As a next step, an "Induction Linac System Experiment (ILSE)" has been proposed[23] which is intended to address all key issues of a full scale driver, including transport of space-charge dominated beams, combining and bending of beams, compression and pulse-shaping as well as final focussing. ILSE has been recommended to be funded in the near future. Fabrication should be finished within 4-5 years. It would be necessary to have another step in between before a full-scale driver can be designed and constructed. In addition, a new concept is being considered; the "Recirculating Induction Linac"[24] in order to reduce the cost for such a driver.

Some of the most important accomplishments of the LBL program include:

1. Experimental measurement of the maximum current that can be transported in a periodic strong-focused beam line.
2. Development of ion sources for up to 1 A of heavy ions (cesium).
3. Assembly of the Four-Beam Accelerator MBE-4.
4. Demonstration of current multiplication in a linear induction accelerator in MBE-4.
5. Development of cost optimization programs LIACEP and HILDA.
6. Development of efficient induction modules using Metglas.
7. Assembly of a 16-beam, 2 MV injector for ILSE.
8. Heavy Ion Fusion Systems Assessment (HIFSA) surveyed economics of power production with different combinations of reactor, target and accelerator parameters.[7]

II. European IFE Potential and National Activities

1. General Situation

Fusion Energy Research in Western Europe is funded in the framework of a multinational program by the European Community (EC), not on a national basis. There is a strong MFE program but nearly no European IFE program, mainly because classification of ICF in France and the United Kingdom has prevented a concerted EC effort. There are however, very substantial national IFE-related activities with laser and heavy ion beams. Classification in France and the U.K.

might become less severe, but still is a serious impediment for international collaboration. In some other European countries there are increasing interest and increasing activities in heavy ion inertial fusion (HIF), mainly funded as basic research programs by national agencies.

Accelerator Research in Europe is based on a large and experienced physics community, with major research centers in Switzerland (CERN and PSI), Germany (GSI and DESY), France (SATURNE and GANIL), Italy (Legnaro and Trieste), and the Soviet Union (Serpukov, Protvino, Dubna, Moscow, and Novosibirsk). In addition there are smaller facilities located at various laboratories and universities and there is an established educational effort, providing highly qualified young scientists in accelerator physics and technology.

Target Physics is – apart from military ICF research – a growing basic research activity in several countries, particularly in Italy, Germany and Spain. Objectives are the physics of hot dense plasmas, beam target interaction, and target physics for IFE, both for direct and indirect drive.

2. Research Activities

The programs and research activities in IFE with heavy ion beams, reviewed in this section are basic research programs with institutional or governmental funding. There is an increasing tendency for international collaborations and in some cases cooperation with bilateral agreements.

a) Germany

There has been an established program on IFE related research since 1979. It is funded by the Federal Ministry of Research and Technology in the framework of basic research. Objectives are the investigation of key issues of ICF with heavy ion beams; in particular investigations of accelerator scenarios and the development of accelerator components for high intensities including beam handling techniques, the generation of beams with high phase space density, beam target interaction and the physics of dense plasmas.

Major achievements were:

- a conceptual design study for a heavy ion driven power plant based on an RF linear accelerator with storage rings (HIBALL).
- construction of an accelerator facility (SIS/ESR), a synchrotron/storage ring facility for heavy ion beams which will open in the near future excellent opportunities for dedicated research on ICF key issues both in the field of driver and target physics.
- development of ion sources and low-velocity accelerator structures (RFQ), and other specific beam handling devices such as fine focussing and plasma lenses.
- determination of IFE-relevant cross sections e.g. for intrabeam scattering in storage rings and of other basic parameters for beam/plasma interaction, e.g. stopping power.

Present direction of work includes:

- studies of indirectly driven targets. In the past two years considerable progress has been achieved in the study of these targets.[25] The enhanced driver power requirements that resulted from this work have been shown to be achievable by introducing the non–Liouvillian stacking technique into the accelerator design.
- extensive accelerator experiments are continuing at the GSI synchrotron (SIS) and experimental storage ring (ESR).[26]

Present research is structured as follows:

1. GSI is the center for accelerator physics and for experiments with heavy ion beam/plasma interaction. A strong group at Frankfurt University and a group at Giessen University has made substantial contributions as well as the Fraunhofer Institute in Aachen (Z-Pinch for plasma interaction experiments).

2. The Max-Planck Institute for Quantum Optics is the leading laboratory for target physics. Contributing laboratories are the Technische Hochschule Darmstadt (dense plasmas) and a small group at Frankfurt University (hydrodynamics, compression physics, Rayleigh-Taylor instabilities).
3. Investigations on ICF relevant atomic physics are carried out at the GSI facilities by groups of Stuttgart and Munich Technical Universities, and with a crossed beam technique at Giessen University.

Collaborations on some of these investigations exist with groups in France, Italy and in the Soviet Union. Close contacts exist in the field of accelerator research with U. S. laboratories. The new facility SIS/ESR at GSI will open new and unique opportunities for beam target interaction. The ESR cooling device allows the generation of beams with high phase space density and, therefore, provides opportunities for investigations on beam instabilities.

b) Italy

Research on target physics has a long tradition in Frascati. Recently theoretical investigations on target design and on compression physics are carried out using 2D codes on symmetry and stability issues for directly and indirectly driven targets.

Legnaro is the central nuclear physics laboratory with experience in accelerator physics and development. It is conceived as the center of future activities. In addition, accelerator physicists at the synchrotron light source now under construction at Trieste, are participating in accelerator design studies for a fusion driver and for a free electron laser (FEL) to be used for the recently proposed non-Liouvillean injection of heavy ion beams into storage rings. An example of an accelerator scheme using laser induced charge changing to assist injection into a storage ring is shown in Fig. 9.

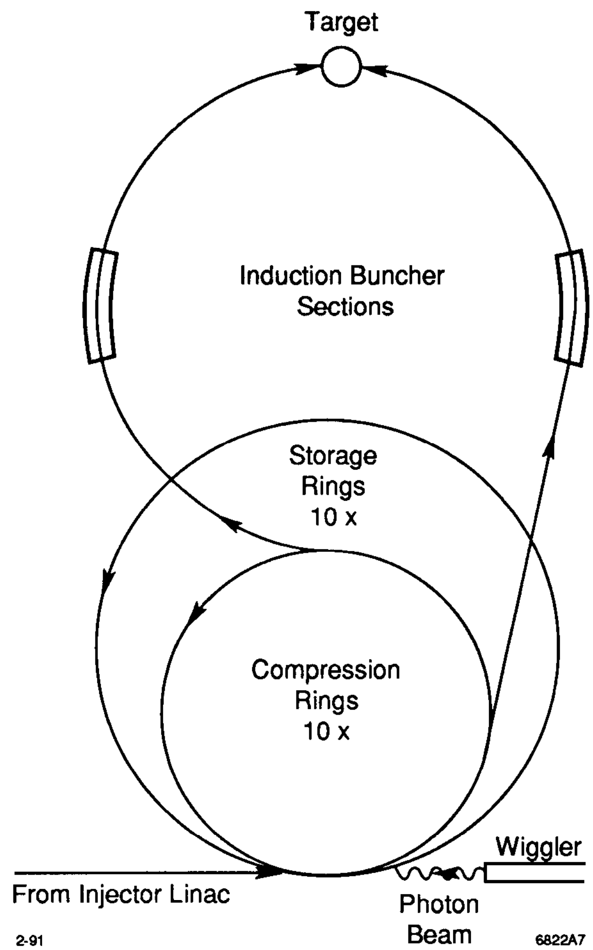

Figure 9. An accelerator/storage ring system using an FEL to cause charge changing at the point of injection into the Compression Ring.

c) Spain

The Institute of Nuclear Fusion in Madrid is concentrating on the theory of target design and target dynamics. During the last decade the group has developed a number of hydrodynamic codes including all kind of atomic and plasma physics issues, primarily concentrated on conditions for direct drive targets.

d) Soviet Union

Activities on ICF relevant research in the Soviet Union are wide spread and diversified. There are many institutes with laser facilities and with a broad experience in accelerator physics, target physics, physics of dense plasmas. A large dedicated group for heavy ion inertial fusion is at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow, working on both accelerator and target problems (including a bilateral agreement with GSI). They have heavy ion accelerators in operation but not dedicated facilities. The group of Kapchinski is famous for the RFQ high-current structure development. Traditionally the Kurchatov Institute has big installations for electron linacs (Angara 5) and at Lebedev Institute and at a number of other institutes (e.g. Institute of Chemical Physics) ICF related activities exist. There is a growing interest in the physics of highly compressed plasmas.

3. Contours of a future European Program

During the past years an increasing effort has been made for more collaboration between the European groups in two areas: Driver Accelerators and Target Physics. Study groups have been established in order to discuss the key problems and possible scenarios and to define the directions of future research. The goals discussed at present for a near term program could be summarized as follows:

1. The new 2-ring accelerator at GSI will be a unique facility for the investigation of many key issues, in particular in the fields of beam dynamics and beam matter interaction. It will provide a testing ground for the study of many driver issues. The concept of non-Liouvillean beam manipulations and research on all related techniques, such as FEL development shall be pursued.

2. Ten years after the HIBALL concept has been proposed, it is urgent to elaborate a new concept including the new achievements and new ideas for driver scenarios.

3. It is planned to develop a strategy for building an HIF Demonstration Accelerator which should enable significant beam-target experiments, a feasibility proof of accelerator technology and non–Liouvillean stacking. Either a dedicated test facility (e.g. with low repetition rate) or the first stage of

a larger facility might be considered, it should however be based on the new technology.

For the realization of such programs a stronger collaboration between some European countries is envisaged, in particular between Germany and Italy.

III. Japan and Others

There are a few isolated scientists interested in HIF in nations that have not been mentioned. One that comes to mind is Heinrich Hora of Australia.

Even though Japan has a strong laser-based ICF program, the activity in HIF is limited. The IAEA Topical Meeting on Drivers for Inertial Fusion will be held in Osaka in April 1991. The 1984 Symposium on Heavy Ion Fusion was held at the Institute for Nuclear Science. In addition to the target physics work, it is likely that the Japanese programs in MFE will contribute to related problems in IFE. There are many related areas in material science, tritium handling, and blanket design to mention only a few.

INTERNATIONAL COLLABORATION

The recent International HIF Symposium provided an opportunity to sample the attitudes of scientists from seven countries. The symposium agenda included specialized workshops in areas such as Injectors, Beam Stability, Energy Systems, etc. The attendees met in specialized workshop sessions to consider the needs for research in each area. Each of the workshop groups considered the key questions of this report:

1. Is this an appropriate time for international collaboration in HIF?
2. Which problems are most appropriate for such collaboration?
3. Can the sharing of target design information be set aside until other driver and systems issues are better resolved, by which time it might be supposed that there could be a relaxation of classification of target issues?

4. What form(s) of collaboration are most appropriate, e.g., bilateral or multilateral?
5. Can international collaboration be sensibly attempted without significant increases in funding for HIF?

There was certainly general support from each of the groups for the concept of working together. One would hardly expect anything else from an International Symposium. The nature of this collaboration, as envisioned by the respondants, ranged from large, formal arrangements to more inter-laboratory exchange visits. There is general recognition that the field is not mature enough to define a large, central facility that could become the focus for a large team approach similar to the International Thermonuclear Experimental Reactor (ITER), that has been studied for Magnetic Fusion.

The previous sections of this report have discussed numerous areas in which the research interests of different laboratories in different nations complement each other. These are areas widely recognized by the workshop participants as appropriate for collaborative research. The general vision of team research would be to informally coordinate work on a problem of mutual interest, with the work concentrated at one of several principal centers. With somewhat better program support, laboratory directors can typically be expected to welcome visiting scientists and provide suitable facilities.

The suggestion that issues of target design information could be set aside for a time, was not generally accepted. There are two important reasons for this feeling:

1. Many technical decisions depend critically on target specfications.
2. A true collaboration must be based on mutual opportunity and mutual understanding of all of the scientific issues.

There exists a situation within the U.S. program that is comparable to that which would exist if classified information is not exchanged. Many of the scientists in the HIFAR program, especially the younger ones at LBL, do not have security clearances and must accept the target design parameters as given. In fact, the level of detail that is classified is really only of much concern to specialists in target design, and those whose duties are concentrated in accelerator specialties would generally not require more information than is unclassified.

In fact however, the above argument does not satisfy the scientists from either the classified or the unclassified communities. There are, as is well known, active and highly competent groups studying target issues in several other nations, notably Japan, Germany, Italy, and Spain. Rather than being satisfied that they can supply the needed target data, it is the members of these groups who are among the most insistant that target information should be shared in a collaboration. They are disturbed that their studies and reports cover areas that are better understood by workers in classified programs, and that they might be viewed as less informed and less competent. The inverse problem disturbs scientists in classified programs who cannot claim credit for their work, and frequently must listen to reports of discoveries that they may have made previously.

There is another potential impediment to international collaboration that could most simply be given the NIH (not invented here) label. Different laboratories follow different lines of research and are reasonably convinced that their own approach is best. If they were not so convinced, then logically they would change their methods. In the present scene, as was discussed earlier, the U.S. program is concentrated on the Induction Linac approach while the programs in all other countries are based on RF linacs filling storage rings.

A new feature of the U.S. program is interest in the recirculating induction linac. Although there are still many technical issues to be resolved, the recirculating LIA provides a possible area of common ground between the U.S. LIA approach and other nation's RF linac/storage ring approach. A recirculating induction linac would use rapid recycling of the induction modules, but would require fewer such modules. A system of bending magnets would create several different stages of "induction synchrotrons" in a configuration as shown in Fig. 10.

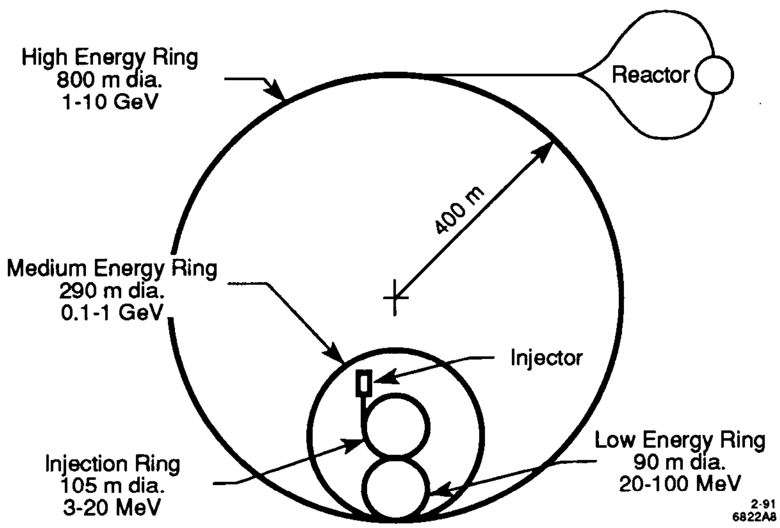

Figure 10. Recirculating linear inducation accelerator.

Even without something like the recirculating LIA, there are many areas in common, as has been illustrated earlier. In addition, most of the storage ring scenarios use induction linac modules in the final stages of pulse compression.

Most of the scientists at the HIF Symposium would prefer informal, or at most bilateral, collaborations at the present time. The question regarding funding can fairly be applied to all of fusion. Even the ITER project, in the much larger International MFE program, is a very questionable undertaking at current budget levels.

Even at current budget levels, there is one positive thing that should be started. There should begin to be inter–laboratory meetings on special topics to share information and provide detailed program guidance. There are numerous areas in which such activities could be useful, including examples such as:

- new and innovative ion sources,

- ion–ion and ion–gas charge exchange cross sections,

- ionization in the final transport in the reactor chamber,
- space charge issues in bending magnet systems.

Opportunities for International Collaboration.

The ultimate need in HIF/IFE is for a large, multimegajoule heavy ion driver that can be used to test a large variety of target and reactor configurations. It is clear that only one such facility is needed in the world, at least until after many research questions have been resolved. The primary goal of international collaboration should be to point the way towards the means of achieving such a facility.

As has been noted repeatedly, the subject area of accelerator research is unclassified. Highly competent accelerator designer teams exist in many countries, especially Canada, China, France, Germany, Great Britain, Italy, Japan, Switzerland, U.S.A. and the U.S.S.R.

There are already bipartite agreements in place for accelerator research (for basic research facilities) between the U.S. and China, U.S and Japan, USSR and Germany, in addition to international laboratories at CERN and Dubna. Accelerator communities are used to working together, primarily because goals have usually been basic research with little if any commercial interest.

There are numerous areas in reaction chamber phenomenology, materials evaluation and development, and reactor subsystems development that are candidates for international collaboration. Many of these areas, e.g., materials, tritium handling, etc., are common to MFE, which opens up a new community of potential contributors.

Target Issues:

(a) Target classification may be more of a psychological issue than an issue of needing certain information. It will be years (probably ten or more) before a facility exists to test targets with heavy ions. However, an important unanswered question remains; "can people collaborate without sharing all relevant information?" Is it enough if some people in the program have the full picture?

(b) All workers in the field know the key parameters, e.g., the need for 3–5 megajoules in pulses about 10 nanoseconds long, with pulse shaping so that first part of pulse is at low intensity. Beams must focus to about a 3–5 mm diameter spot. For reactors, this focussing must be from final focus magnets that are 3–10 meters away from the target.

(c) Target design is ongoing in Spain, Poland, USSR, France, U.S., Germany, Japan, England, and probably other places such as China and Israel. Especially with changes in the world scene, it seems unnecessary to classify concepts that are already common knowledge. Engineering data could well remain controlled, just as it would if there were corporations involved and the data were considered "company proprietary."

Guidelines for International Collaboration in HIF Driver Research:

(a) It is important to avoid splintering and duplication of efforts. Today the U.S. has about ten toroidal confinement systems in MFE in at least nine different institutions. There are countless more world wide. Yet none is large enough, or has the right physics, to achieve ignition of a plasma.

(b) In HIF accelerator research, the U.S. made a "down select" early to the Linear Induction Accelerator. This was done to concentrate limited resources. The choice was made to favor the approach that appeared simpler, less risky, and potentially less costly.

(c) In Europe and elsewhere, greater familiarity with RF systems, and applications of technology to ongoing research work, has maintained interest in the RF approach.

(d) The greatest technological need is to find lower cost solutions to HIF driver design.

(e) A big induction linac is expensive, probably close to \$1 billion to do high-gain target experiments.

(f) New designs of RF systems from Europe are interesting, but seem unlikely to be less expensive.

(g) The recirculating induction linac has elements of both approaches and the potential of reducing costs by half. This may be the common ground for international collaboration.

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