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# Inertially Confined Fusion Using Heavy Ion Drivers*

# Energie de fusion à confinement inertiel utilisant des Accélérateurs d'ions lourds

# Energía de Fusión Confinada Inercialmente Usando Aceleradores de Iones Pesados

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# 1. INTRODUCTION
# INTRODUCTION
# INTRODUCCIÓN

Beginning about fifteen years ago, with reports by Maschke[1] and Martin[2] 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 multimegajoule 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. Ultimately it may be possible for a single driver with the energy, power, focusibility, and pulse shape to satisfy the needs of the international community for target physics research. Such a facility could service multiple experimental chambers with a variety of beam geometries and target concepts.

## 2. ACCELERATOR ISSUES
## QUESTIONS D'ACCÉLÉRATEURS
## ASUNTOS SOBRE LOS ACELERADORES

There are two very important differences between an accelerator for particle physics 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 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 $\mu$s. By contrast, the desired pulse length for ICF is in the range 10–20 ns, corresponding to a bunch that is 1–2 m long at the target.

The basic rationale for HIF is illustrated by the range-energy data shown in Fig. 1. To deposit the same specific power in a target using a proton beam, the peak beam particle 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:

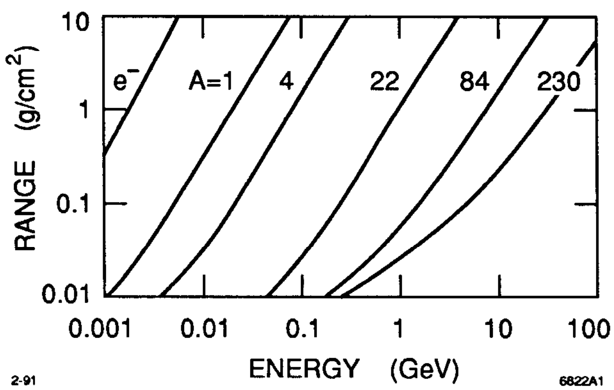


**Figure 1.** The range-energy relation for several ion species in hot matter (200 eV). The ion range of interest for ICF is about 0.05–0.2 g/cm$^2$.

**Figure 1.** La relation parcours-énergie pour plusieurs espèces d'ions dans de la matière chaude (200 eV). En ICF, la distance parcourue qui nous intèresse est de l'ordre de 0,05–0,2 g/cm$^2$.

**Figura 1.** La relación alcance-energía para varias especies de iones en materia caliente (200 eV). El alcance de los iones que interesa a la ICF es más o menos de 0.05 a 0.2 g/cm$^2$.

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).

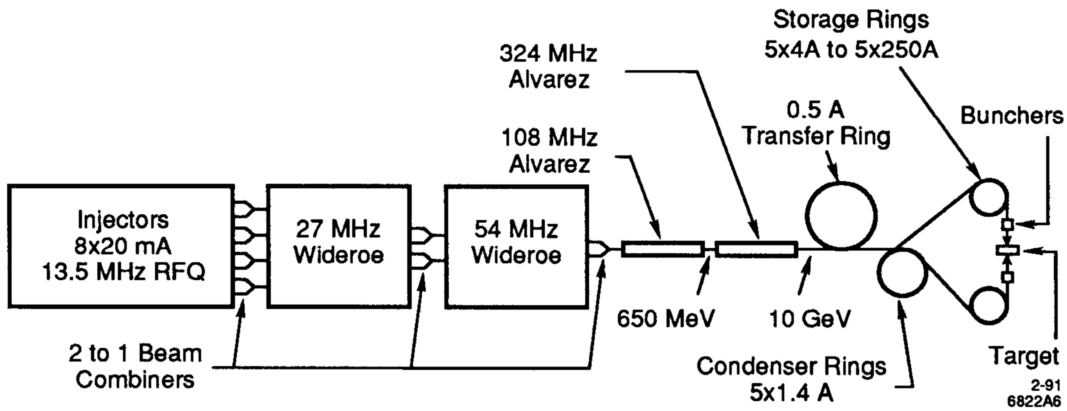


**Figure 2.** RF accelerator system with storage rings for current multiplication.

**Figure 2.** Système d'accélérateur H.F. avec anneaux de stockage pour la multiplication du courant.

**Figura 2.** Sistema de acelerador de alta frecuencia con anillos de almacenamiento para la multiplicación de la corriente.

(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 a budget to ensure that the final result retains enough of the original source quality 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 quality of a particle beam, and are thus called "non-Liouvillian." One of these was proposed for HIF by Carlo Rubbia,[3] Director of CERN, who has taken a special interest in this subject. 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

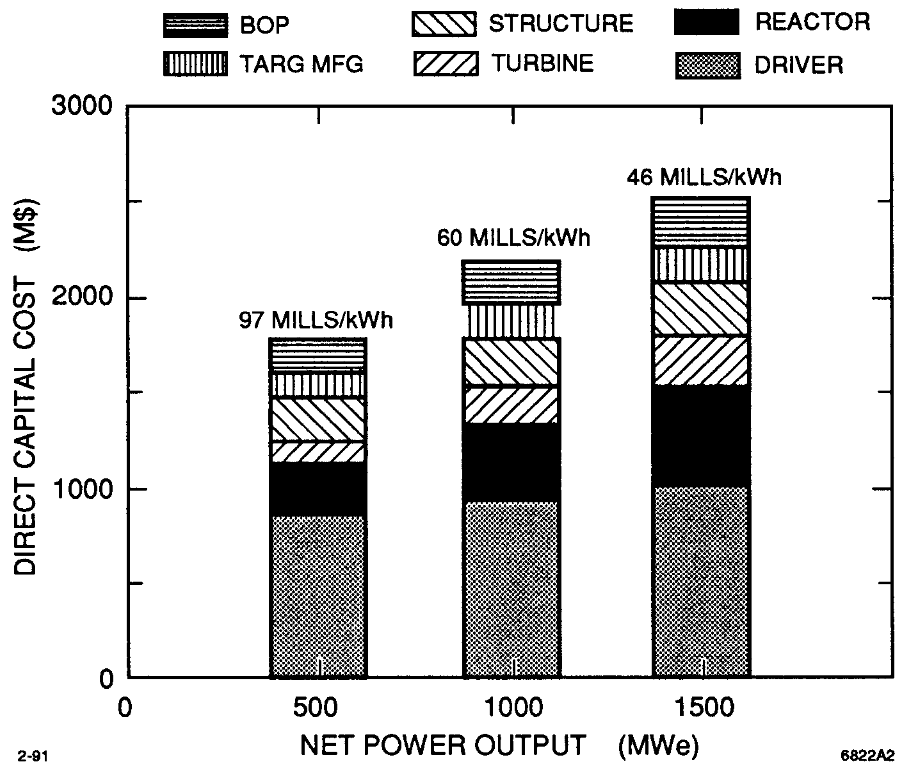


**Figure 3.** Results from the HIFSA[6] study showing the contributions of different components to capital cost and cost of electricity.

**Figure 3.** Résultats de l'étude HIFSA [6] démontrant les contributions de différents éléments sur le coût en capital et sur le coût de l'électricité.

**Figura 3.** Resultados del estudio HIFSA [6] en que se muestran las contribuciones de los diferentes componentes en relación al costo del capital y al costo de la electricidad.

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 Economic 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[4] by Germany and the University of Wisconsin, and the HIBLIC[5] study in Japan. A systematic evaluation of a variety of reactor and target systems was made for the Heavy Ion Fusion Systems Assessment[6] (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.

## 3. TARGET ISSUES
## QUESTIONS DE CIBLES
## ASUNTOS SOBRE LOS BLANCOS

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. As a result of this work, the report of the National Academy of Sciences Review of ICF[7] recommended proceeding with an ignition facility for ICF, following successful completion of a series of physics experiments on the Nova Laser at LLNL.

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 fuel, these layers serve as an ablator. Ion or laser beams heat the ablator to high temperature, producing high pressures (~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

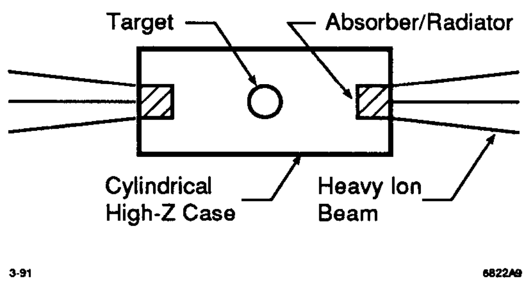


**Figure 4.** An indirect drive target configuration for heavy ion beams.

**Figure 4.** Configuration de cibles à entraînement indirect pour faisceaux d'ions lourds.

**Figura 4.** Una configuración de blancos con excitación indirecta para los haces de iones pesados.

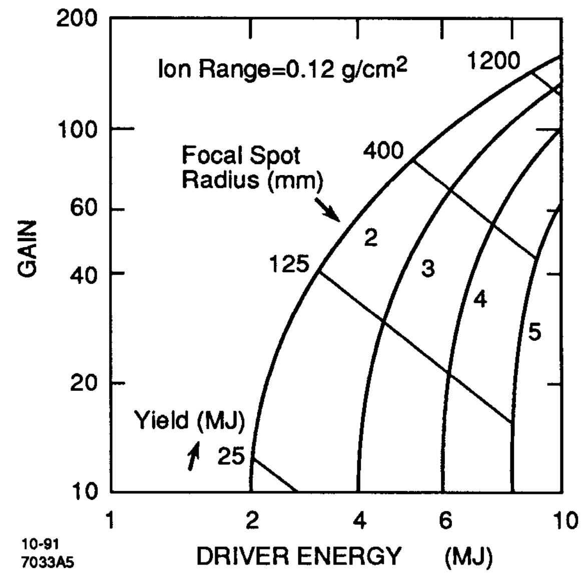


**Figure 5.** Gain predictions for targets with Range R=0.12g/cm$^2$ and spot radii from 2 to 5 mm.

**Figure 5.** Prédictions de gain pour les cibles avec un parcours $R = 0,12$ g/cm$^2$ et le rayon de spot entre 2 et 5 mm.

**Figura 5.** Las predicciones de ganancia para los blancos con un alcance $R = 0.12$ g/cm$^2$ y radios de enfocamiento del haz de 2 a 5 mm.

greatly aid reactor chamber design. Without a significant energy penalty, indirect drive by lasers cannot use the cluster method and still requires illumination by a large number of widely spaced beams.

Calculations of target gain for indirect drive 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 ion mass and 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.

## 4. POWER PLANT CONCEPTS
## CONCEPTION DE L'USINE GENERATRICE
## CONCEPTOS ACERCA DE LA PLANTA DE ENERGÍA

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, their maintenance will be unaffected by radiation from the thermonuclear environment 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.[8] 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 (~1 ns) of the x-ray pulse results in the requirement 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,[9,10] lead-lithium,[4] and FLiBe[11] (a molten salt consisting of flourine, lithium, and beryllium), or ceramic granules such as $Li_2O$ and $LiAlO_2$.[12] In the original HYLIFE[10] design, efficiency is improved by moving the heat transfer and tritium production "blankets" inside the reactor structural wall. HYLIFE–II,[13] shown in Fig. 6, 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

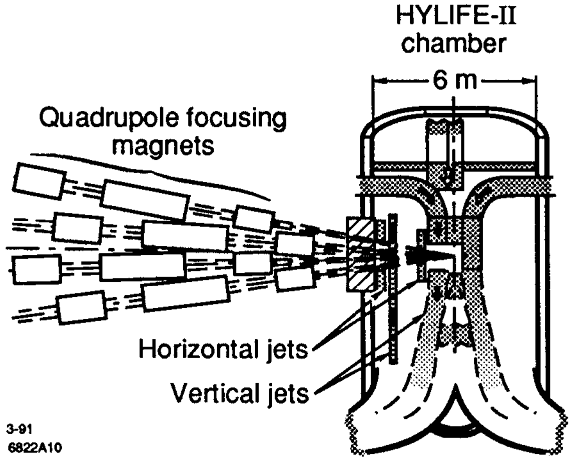


**Figure 6.** In the HYLIFE–II[13] structural components are protected from blast and neutron damage by thick jets of liquid FLiBe ($Li_2BeF_4$) in order to make the components last the lifetime of the plant. In the configuration shown, 12 beams (in a 2–4–4–2 pattern) are directed to the target from 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.

**Figure 6.** Dans le HYLIFE–II[13], les éléments structurels sont protégés des dégâts causés par les ondes de choc et les neutrons par des jets épais de FLiBe ($Li_2BeF_4$) liquide : ainsi, les éléments devraient durer aussi longtemps que l'installation. Dans la configuration illustrée, 12 faisceaux (disposés en configuration 2–4–4–2) sont dirigés sur la cible d'un ou de deux côtés. Des jets liquides horizontaux ou verticaux sont entremêlés aux 12 faisceaux afin de protéger les parois autour des ouvertures des faisceaux.

**Figura 6.** En el HYLIFE–II[13], los componentes estructurales están protegidos contra daños causados por ondas de choque y por neutrones mediante gruesos chorros de FLiBe ($Li_2BeF_4$) líquido con el fin de lograr que los componentes duren la vida Útil de la planta. En la configuración que se muestra, 12 haces (en un diseño de 2–4–4–2) se dirigen hacia el blanco desde uno o dos lados. Los chorros líquidos horizontal y vertical están entrelazados con los 12 haces con el fin de proteger los muros alrededor de las aperturas de los haces.

have shown that neutronically thick 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. It has also been shown[14] that for these designs, the neutron spectrum at the first structural wall is softened so that it resembles a fast-flux reactor spectrum. Therefore materials damage studies done for these reactors may be adequate for development of ICF reactors without the need for special 14 MeV neutron sources. 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 ($10^{-4}$–1.0 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.

## 5. FINAL FOCUS AND TRANSPORT<br>CONCENTRATION ET TRANSPORT FINALS<br>ENFOQUE Y TRANSPORTE FINALES

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.

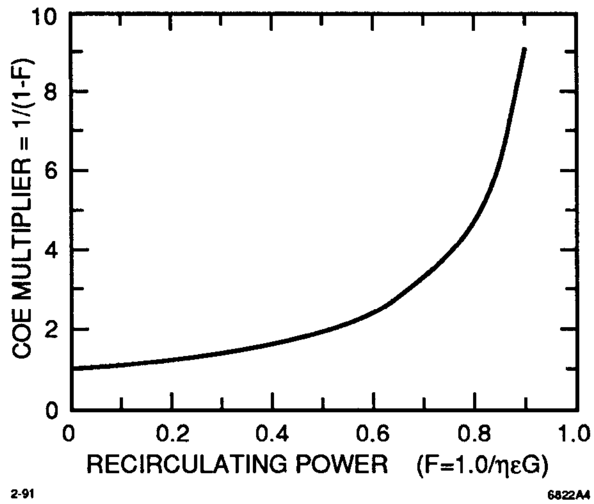


**Figure 7.** Effective cost of electricity as a function of the fraction of recirculating power $1/\eta G\epsilon$.

**Figure 7.** Coût effectif de l'électricité en fonction de la fraction de puissance recirculée $1/\eta G\epsilon$.

**Figura 7.** El costo efectivo de la electricidad en función de la fracción de la potencia recirculante $1/\eta G\epsilon$.

## 6. ECONOMIC ISSUES
## QUESTIONS ECONOMIQUES
## ASUNTOS ECONÓMICOS

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 $\eta$ is the driver energy efficiency given by the ratio power-to-target/input power, G is the target gain (including blanket gains), and $\epsilon$ is the thermal-to-electric conversion efficiency (usually $0.3 \leq \epsilon \leq 0.5$). 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 values of $\epsilon$, this means we require $\eta G \geq 6$–10. Note that if we do much better, for example if $\eta G\epsilon = 6$, the recirculating power drops to 16% and the cost penalty to consumers is only 20% of their power bill. Below this there is very little gain, so that most studies require $3 \leq \eta G\epsilon \leq 6$. Choosing a midrange value of $\eta G\epsilon = 5$, with $\epsilon = 0.4$, and an overall efficiency of 25% for an accelerator driver, results in a need for a target gain of 50.

Current concepts for high-power lasers for ICF fusion energy have projected efficiencies of 5–10%. Such a driver would require a target gain of 125–250 for a commercially viable power plant. Target gains near the lower end of this range appear feasible based on current results from the target physics program. Prospects for gains nearer the upper end of this range require success of much more speculative ideas. One cannot rule out inventions; a much more efficient laser or much higher gain targets. However, without assuming such an invention, a significant argument for heavy ions is the relaxed target-gain requirement. 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. Natural 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.[19]

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.[20] 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.[21] 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 a large amount of reactor waste *does* exist, and concern about waste *is* one of the principal impediments to wider development of nuclear power.[22] 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 than for pure fusion.

## 7. THE WORLD SCENE IN HEAVY ION INERTIAL FUSION LA SCENE MONDIALE EN MATIERE DE FUSION INERTIELLE A IONS LOURDS EL ESCENARIO MUNDIAL EN CUANTO A LA FUSIÓN INERCIAL MEDIANTE IONES PESADOS

### 7.1 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 (~ $50 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 was in the DOE Office of Basic Energy Sciences, has been moved to the Office of Fusion Energy (OFE). The HIFAR program had 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 has ended although not all of the experiments that were proposed have been completed.

The main IFE program element is at the Lawrence Berkeley Laboratory (LBL), with a strong collaborative effort at the Lawrence Livermore National Laboratory. Smaller program elements are at the Naval Research Laboratory, Stanford Linear Accelerator Center, Sandia National Laboratory, University of New Mexico, and University of Maryland.

The LBL program of driver research is based on the use of induction linacs. With induction linacs, the basic idea[23] is to inject a long bunch of high intensity ions and to achieve current amplification by ramping the inductive acceleration fields as the bunch passes. By this procedure the pulses have to be compressed from ~20 $\mu$s at injection down to ~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 better beam quality and has shown[6] to be cost effective if the number of beamlets is in the

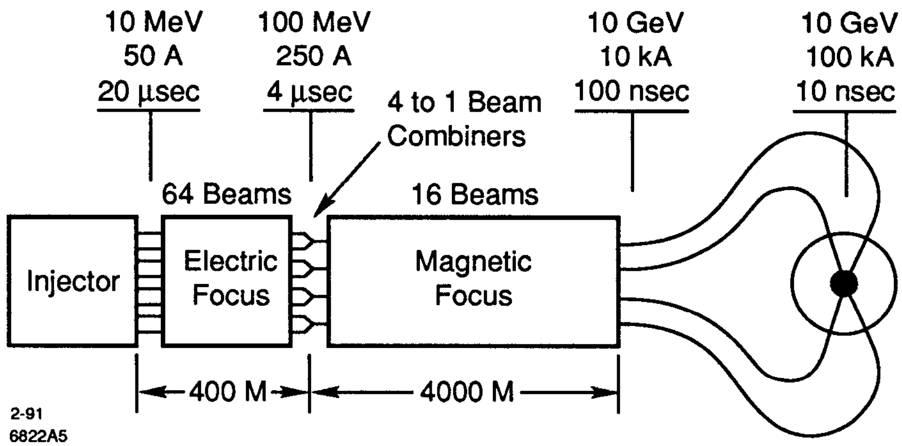


**Figure 8.** Linear Induction Accelerator Driver with typical parameters.

**Figure 8.** Entraînement par accélérateur linéaire à induction utilisant des paramètres typiques.

**Figura 8.** Excitador basado en un Acelerador de Inducción Lineal con parámetros típicos.

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 km, 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[24] which is intended to address all of the 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 after ILSE before a full-scale driver can be designed and constructed. In addition, a new concept is being considered; the recirculating induction accelerator[25] in order to reduce the cost for such a driver.

## 7.2 European IFE Potential and National Activities

### *7.2.A General Situation*

*Fusion Energy Research* in Western Europe is primarily 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, 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. There are research efforts along these lines in France, Israel, and the United Kingdom.

### *7.2.B 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.

<u>Germany</u>

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 plasma lenses and aberration-corrected focussing systems.

- IFE-relevant atomic physics experiments on beam-plasma interactions and intra-beam scattering providing data for stopping power and beam loss in storage rings.

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.[26] The driver power requirements that resulted from this work have been shown to be achievable by introducing the non-Liouvillian stacking technique into the acclerator design.

- extensive accelerator experiments are continuing at the GSI synchrotron (SIS) and experimental storage ring (ESR).[27]

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 have made substantial contributions. Z-Pinch experiments for plasma interaction studies have been made at the Fraunhofer Institute in Aachen.

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 experiments. The ESR cooling device allows the generation of beams with high phase space density and, therefore, provides opportunities for investigations on beam instabilities.

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. A post-graduate program in target and accelerator physics for heavy ion inertial fusion has been established.

Legnaro is the central nuclear physics laboratory with experience in accelerator physics and development. 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.

Spain

The Institute of Nuclear Fusion in Madrid is concentrating on the theory of target design and target dynamics and also on reactor neutronics. During the last decade the group has developed a number of hydrodynamic codes including all kinds of atomic and plasma physics issues, primarily concentrated on conditions for direct drive targets.[28] This group has also developed the capability of doing neutron transport calculations to estimate effects of neutron interactions on reactor structures.

Soviet Union

Activities on ICF relevant research in the Soviet Union are widespread 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). This group has heavy ion accelerators in operation but not dedicated facilities for ICF. 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. Laser-driven target implosion experiments have been done at the Lebedev Insitute in Moscow and at the State Optical Institute near St. Petersburg.

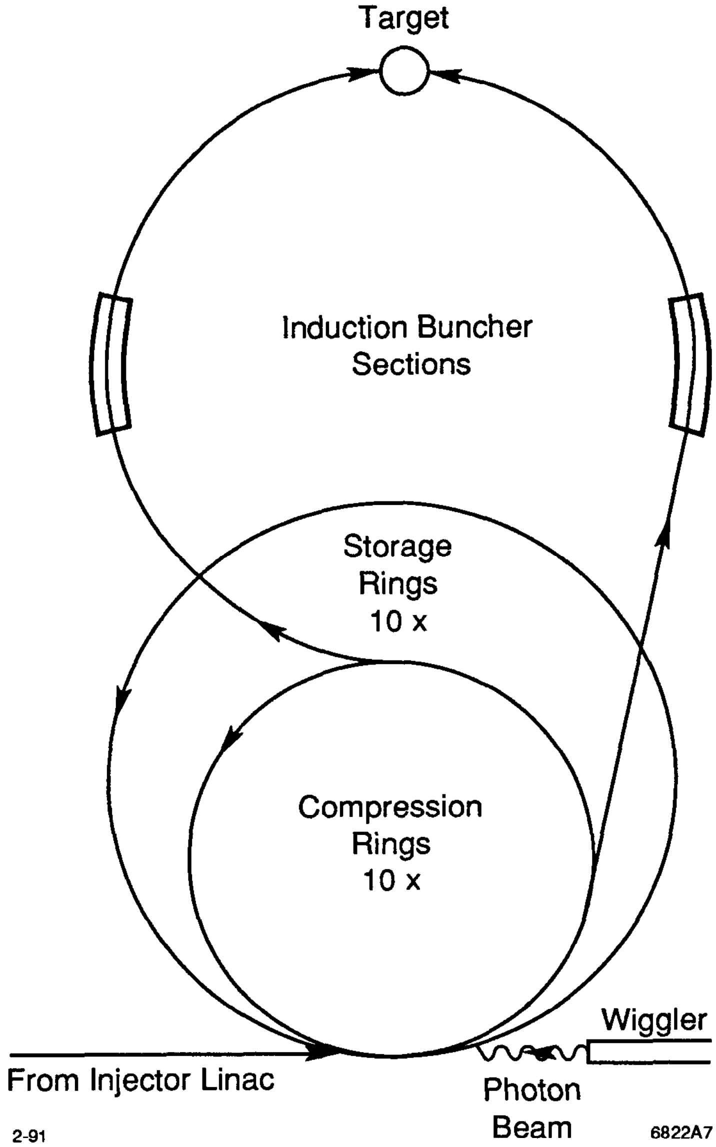


**Figure 9.** An accelerator/storage ring system using an FEL to cause charge changing at the point of injection into the Compression Ring.

**Figure 9.** Système accélérateur/anneaux de stockage utilisant un FEL pour provoquer le changement de charge au point d'injection dans l'Anneau de compression.

**Figura 9.** Un sistema de acelerador/anillo de almacenamiento que utiliza un FEL para causar un cambio de carga en el punto de inyección hacia el Anillo de Compresión.

*7.2.C 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. According to C. Rubbia, the expertise of

CERN in innovative development could lead to important spin-offs for heavy ion inertial fusion[29]. An ongoing working group involving CERN, GSI and Trieste was established in 1990 to work towards this goal. 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.

### 7.3 Japan

Even though Japan has a strong laser-based ICF program, including target implosions of both the direct and the indirect type, the activity in HIF is limited. The IAEA Topical Meeting on Drivers for Inertial Fusion was 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.

## 8. INTERNATIONAL COLLABORATION COLLABORATION INTERNATIONALE COLABORACIÓN INTERNACIONAL

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.

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,

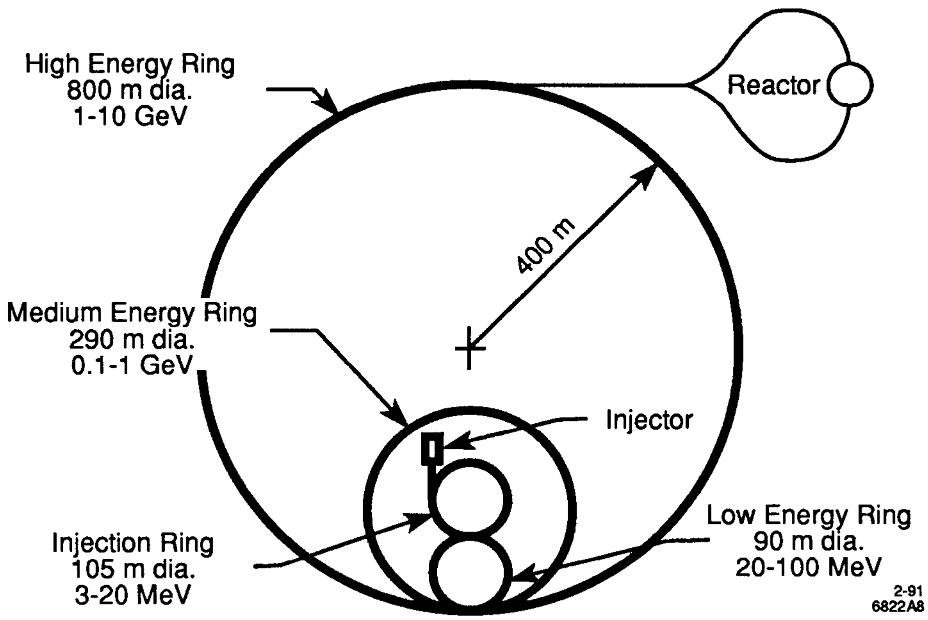


**Figure 10.** Recirculating induction accelerator.

**Figure 10.** Accélérateur à induction et à recirculation.

**Figura 10.** Acelerador de inducción recirculante.

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.

A new feature of the U.S. program is interest in the recirculating induction accelerator. Although there are still many technical issues to be resolved, the recirculating induction accelerator 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.

Even without an approach like the recirculating induction accelerator, 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.

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 MJ in pulses about 10 ns 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 m away from the target.

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 worldwide. 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 accelerator 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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**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 twenty years. One approach, known as Heavy Ion Fusion, uses large, high energy accelerators based on concepts developed for basic research to deliver intense beams of ions to compress and ignite the targets.

The recently released Final Report of the Fusion Policy Advisory Committee (FPAC) 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. Accelerator technology has historically been an area for international sharing of knowledge, and at least in the case of CERN, has been at the heart of an entire institute based on international support.

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. The FPAC recommended the start of construction of this facility beginning in Fiscal Year 1994, following successful completion of the current Nova Physics Program. The progress leading to this recommendation and characteristics of the Nova Upgrade will be discussed.

The paper describes the schedule for resolving the remaining technical questions in both target and driver research. It includes discussions of appropriate research facilities

and the availability of scientists and engineers with the necessary experience to develop this new energy technology.

There are aspects of target design that are classified, which inhibits full international collaboration. However, the subject areas associated with the accelerator drivers and the designs of reactors are all unclassified and are historically fruitful areas for international collaboration.

The realization of commercial IFE power would provide a source of energy for which both the technology and the basic raw material, deuterium, are universally available.

## Resumé


L'objectif de la recherche en fusion thermonucléaire est de mettre au point une technologie qui nuise le moins possible à l'environnement pour produire de l'énergie électrique qui soit à la fois disponible sur le plan universel et concurrentielle sur le plan économique. La méthode qui consiste à contenir le plasma chaud et dense, connue sous le nom d'énergie de fusion à confinement inertiel (Inertially Confined Fusion Energy ou IFE) utilise de petites cibles qui renferment les isotopes de deutérium et de tritium de l'hydrogène et qui sont comprimées de façon implosive pour produire des conditions de fusion. La recherche en matière d'IFE se poursuit modestement dans plusieurs pays depuis une vingtaine d'années. Une approche, connue sous le nom de fusion à ions lourds, se sert d'accélérateurs haute énergie puissants et mis au point dans le cadre de recherches élémentaires, pour transmettre des faisceaux intenses d'ions qui provoquent la compression et l'ignition des cibles.

Dans son rapport final publié récemment, le comité consultatif sur les principes de fusion (Fusion Policy Advisory Committee ou FPAC) du département américain de l'énergie déclare : ≪Les accélérateurs d'ions lourds constituent actuellement les entraîneurs IFE les plus prometteurs.≫ Comme l'entraîneur représente l'élément le plus coûteux d'un système IFE, la recherche en matière d'entraîneurs d'ions lourds moins chers et plus efficaces promet d'être plus rentable dans la poursuite d'une approche pratique à l'énergie de fusion. L'histoire a montré que la technologie des accélérateurs est un domaine dans lequel le partage international des connaissances est accepté et, du moins dans le cas du CERN, qu'elle réside au centre d'un institut tout entier fondé sur la coopération internationale.

Le rapport FPAC recommande que la démonstration d'ignition constitue pour le programme IFE américain l'objectif à court terme de plus haute priorité. Des progrès suffisants ont été accomplis sur la physique des cibles pour que le FPAC recommande la modernisation du laser Nova par une option 1–2 MJ qui permettrait de démontrer l'ignition. Le FPAC recommande que la construction de cette unité commence au courant de l'année fiscale 1994, suite au succès du programme de physique Nova en cours. Le déroulement des opérations menant à cette recommandation et les caractéristiques de la modernisation Nova feront l'objet d'une discussion.

Cet article décrit le calendrier adopté pour résoudre les questions techniques subsistantes dans la recherche sur les cibles et sur les entraîneurs. Il comprend un débat sur les centres de recherche appropriés et sur la disponibilité des scientifiques et des ingénieurs dont l'expérience permettra la mise au point de cette nouvelle technologie de l'énergie.

Certains aspects de la conception des cibles étant classés secrets, une collaboration internationale totale n'est pas possible. Cependant, les sujets en rapport avec les accélérateurs et avec la conception des réacteurs sont tous classés non secrets et constituent historiquement des sujets propices à la collaboration internationale.

La réalisation d'une puissance IFE commerciale offrirait une source d'énergie pour laquelle la technologie et la matière première de base, c'est-à-dire le deutérium, sont universellement disponibles.

**Resumen**

El objetivo de las investigaciones en la fusión termonuclear es la de encontrar un tecnología, atractiva desde el punto de vista ambiental, para la producción de energía eléctrica que sea asequible universalmente y competitiva económicamente. El método de contención del denso plasma caliente conocido como Energía de Fusión Confinada Inercialmente (IFE) utiliza pequeños blancos que contienen los isótopos de hidrógeno, deuterio y tritio, los cuales se comprimen implosivamente para alcanzar las condiciones de fusión. Las investigaciones para desarrollar la IFE han sido llevadas a cabo a niveles reducidos en una serie de países a lo largo de los últimos veinte años. Un enfoque, conocido como la Fusión mediante Iones Pesados, utiliza grandes aceleradores de alta energía, basados en conceptos desarrollados para investigaciones básicas, que transmiten haces intensos de iones para comprimir y encender los blancos.

El recientemente publicado Informe Final del Comité Asesor de Política sobre Fusión (Fusion Policy Advisory Committee, FPAC) del Departamento de Energía de los Estados Unidos, dice que: "actualmente, se piensa que los Aceleradores de Iones Pesados son los (excitadores para la IFE) más prometedores." Dado que el excitador es el elemento más costoso de un sistema IFE, las investigaciones con el fin de desarrollar excitadores de iones pesados más eficientes y menos costosos presentan la recompensa potencial más grande en las investigaciones conducentes a un enfoque práctico a la energía de fusión. Históricamente, la tecnología de los aceleradores ha sido un área en que se comparte el conocimiento internacional, y por lo menos en el caso del CERN, ha estado en el centro propio de todo un instituto que está basado en el apoyo internacional.

El informe de la FPAC recomendó que la demostración de ignición fuese el objetivo a corto plazo de mayor prioridad en el Programa IFE de los EE.UU. Y como ya se ha alcanzado el suficiente progreso en la física de los blancos, la FPAC recomendó la construcción de una mejora de 1 a 2 MJ al láser Nova con el fin de demostrar la ignición. La FPAC recomendó que la construcción de dicha instalación diese comienzo en el Año Fiscal 1994, inmediatamente después de la terminación exitosa del actual Programa de Física Nova. Se discutirán, tanto el progreso que dio origen a esta recomendación, como las características de la Mejora Nova.

El documento describe el calendario para la resolución de las preguntas técnicas restantes acerca de las investigaciones de los blancos y acerca de los excitadores. Incluye exposiciones que versan sobre las instalaciones de investigación apropiadas y sobre la disponibilidad de científicos e ingenieros que tengan la experiencia necesaria para desarrollar esta nueva tecnología para la creación de energía.

Hay algunos aspectos del diseño de blancos que están clasificados, lo cual inhibe la colaboración internacional. No obstante, todas las áreas sobre la temática asociada con los aceleradores y los diseños de los reactores no están clasificadas e históricamente han sido áreas muy fructíferas para la colaboración internacional.

La realización de la potencia IFE, en forma comercial, suministraría una fuente de energía cuya tecnología y materia prima básica, el deuterio, están disponibles en forma universal.