

Heavy Ion Fusion– Using Heavy Ions to Make Electricity

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Speaking for the

U.S. Heavy Ion Fusion Virtual National Laboratory

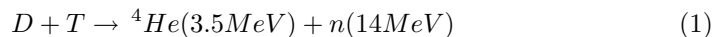
Abstract. The idea of using nuclear fusion as a source of commercial electrical power has been pursued worldwide since the 1950s. Two approaches, using magnetic and inertial confinement of the reactants, are under study. This paper describes the difference between the two approaches, and discusses in more detail the heavy-ion-driven inertial fusion concept. A multibeam induction linear accelerator would be used to bring ~ 100 heavy ion beams to a few GeV. The beams would then heat and compress a target of solid D-T. This approach is unique among fusion concepts in its ability to protect the reaction chamber wall from neutrons and debris.

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1. Introduction

The idea of using nuclear fusion to produce commercial electrical power has been an international pursuit since the 1950s. The easiest reaction to use, because it has the highest cross section, is shown in equation (1):



The tritium portion of the fuel would be generated in the reactor itself, by bombarding a lithium-containing compound with neutrons from the fusion reaction. The deuterium would be extracted from water. The attraction of fusion as an energy source is apparent from examination of the equation. Both deuterium and lithium are abundant. Deuterium constitutes 0.015% of water, and the small amount of deuterium in just 1 teaspoon of water produces as much energy as a gallon of gasoline. The reaction products are not radioactive, and though the reactor vessel would become activated by the neutrons, it would constitute low-level radioactive waste that could be disposed of at the end of its 30-year life by shallow land burial. There

is no possibility of a runaway chain reaction. No carbon dioxide is produced (so there is no resultant global warming), and none of the reaction products are air pollutants. The process is thus environmentally friendly and safe, and the fuel is plentiful.

The challenge is to give the deuterium and tritium enough energy to overcome the coulomb repulsion of the nuclei. To do this requires the D-T to be heated to a temperature, T , of approximately 100,000,000 °C. Further, the material must be maintained at this temperature for long enough that the energy produced by fusion exceed the energy used to heat the material and that lost through radiation and particle flow. Since the D-T cross section scales as approximately T^2 in this regime, the reaction rate scales as n^2T^2 , where n is the density. The power lost is proportional to nT/τ , where τ is the timescale for energy confinement in the material. Thus the product $n\tau$ must exceed a certain value (about 10^{20} s/m³– this is known as the Lawson Criterion, or "breakeven") for the fusion reaction to be used as a power source.

There are two approaches to producing this challenging set of conditions. In the magnetic confinement approach, a deuterium and tritium gas mixture is ionized, heated, and confined by magnetic fields so that as it heats its energy is not lost to the vacuum wall. Resistive heating is accomplished by inducing a current in the plasma, and this is supplemented with resonant deposition of RF waves, and possibly injected beams of energetic neutral particles. The scalelength of the plasma is several meters, and the energy must be confined for several seconds in order to reach breakeven. The main challenge in this approach is creating the right magnetic topology such that plasma waves, instabilities, impurities, and turbulence do not produce an energy confinement time that is too low. One magnetic confinement geometry has both met the Lawson criterion and reached the temperatures required for fusion (though not simultaneously), and produced fusion neutrons– the tokamak, which is a toroidal device. In a further step, an international experiment called ITER [1] is being planned to study the energy confinement of a tokamak burning plasma– i.e., one producing fusion reactions, so that alpha particles produced by fusion contribute significantly to the energy content. ITER would be a significant step toward a tokamak reactor, and would simultaneously test the plasma physics and some of the technology needed for energy production.

The second approach is called inertial confinement. In this case, the D-T mixture begins in the solid state– the density is very high, so the energy confinement time can be much less than in the magnetic confinement case. The few-millimeter-diameter cryogenic D-T capsule is symmetrically heated, using laser or ion beam,s so that the outer layer ablates and by conservation of momentum causes the capsule to compress by a radial factor of 25-30. The compression heats the D-T and raises the density, so that only their own inertia is needed for the particles to stay together long enough to reach and exceed breakeven. For commercial use, target designs plan for a gain of a factor of 50 or more over the input energy– this would give a reasonable efficiency for the entire power plant system. The challenge for this approach is not energy confinement, but rather maintaining a symmetrical implosion so that the

density increase is large enough, and being able to focus beams onto such a small target.

The U.S. DOE Office of Fusion Energy Sciences provides \sim \\$250 M/yr for magnetic confinement concepts, dominated by the tokamak. About \\$10 M/yr funds heavy-ion-beam-driven inertial fusion (HIF), with which the rest of this paper will be concerned. \\$25 M/yr from NNSA/DOE supports other inertial fusion concepts which use lasers and z-pinchs to provide the beams. Both a 1985 National Academy of Sciences review and a 1996 review by the DOE Fusion Energy Sciences Advisory Committee concluded that heavy ions were the most promising inertial fusion driver for energy applications.

2. Heavy-Ion-Driven Inertial Fusion

There are many reasons that ion accelerators were initially (mid-1970s) suggested as good drivers for inertial fusion. Worldwide investment over decades in the development and refinement of accelerators for HEP/NP had produced machines with long life; high pulse repetition rates (so that the average power plant output would be high— \sim 2 GW); high electrical efficiency; and complexity, cost, and final ion energy similar to what is needed for the fusion application. But both in beam physics and in technology the fusion driver is significantly different from a classical accelerator for HEP, NP, or photon production. The physics differences will be discussed first.

A target for HIF is shown in Fig. 1. In order to produce a symmetric implosion, the beams are not used to directly heat the D-T capsule. Instead, the beams strike an absorber ring, which heats, then radiates x-rays. The x-rays reflect around the cavity in which the capsule sits (called the hohlraum), and symmetrize. This symmetrized x-ray flux ablates the capsule coating, driving the implosion. Heavy ions are used because for a given total energy delivered by the beams, fewer ions are needed, thus reducing the total space charge and the attendant difficulties of focusing the beams. The implosion requires 3-8 MJ of beam energy, the exact figure depending on the target design. The energy must be deposited before the components of the target can move appreciably due to heating, destroying the symmetry. This implies deposition time \sim 10 ns. The ion range must be 0.02 - 0.2 g/cm² in order for the beams to stop in the absorber. Using heavy ions of about 200 amu, these specifications require accelerating about 10^{16} ions to a few GeV. This number of ions is a factor of about 10^3 higher than is found in a conventional accelerator pulse. It is impossible to economically focus this many ions in a single accelerator transport channel, so HIF designs show a multiple-beam (\sim 100 beams) accelerator, where each beam is focused by its own focusing magnets, but the beams are accelerated simultaneously in parallel. Even so, the current density per beam is extremely high, and unlike HEP/NP accelerators, where single-particle dynamics largely determine beam behavior, in HIF drivers the space-charge forces of the particles dominate dynamics. Beam focusing in this case balances the space charge force, while in HEP/NP accelerators the focusing balances beam thermal pressure.

In this space-charge-dominated scenario, the beams are nonneutral plasmas, exhibiting the waves, instabilities, and other phenomena found in plasmas. This area of plasma/beam physics has been pioneered by the HIF community. Ultimately the practical concern of this research is to keep the beams from heating, because the ultimate limit on focusability at the target is set by their thermal pressure (see below).

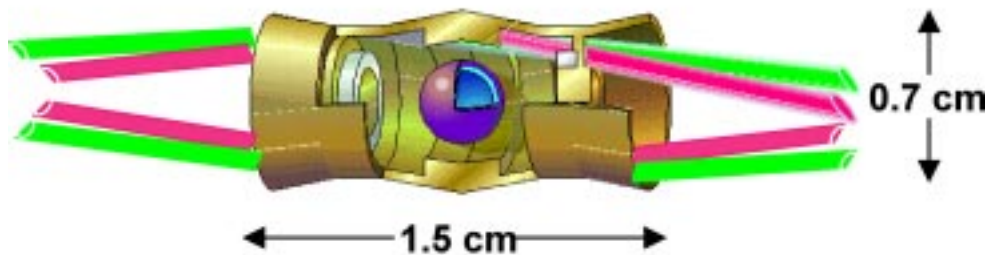


Fig. 1. A target designed for heavy-ion-driven fusion. Beams (not all shown) approach in a cone-shaped array from each end. The D-T capsule is in the center, held by low-density foam (not shown).

The acceleration technology of HIF drivers is also different from that of HEP or NP accelerators or light sources. Because of its high electrical efficiency for high-current beams and capability for long pulses, induction acceleration will be used. In this approach, a toroid, or induction core, of ferromagnetic glass encircles the array of accelerated beams. Cables encircling the cores provide a rising current, which produces an increasing magnetic field in the core. This induces an electric accelerating field parallel to the beam direction of motion. Unlike RF acceleration, the coupling impedance is low, and the losses in the system (which are dominated by resistive losses in the core material essentially unrelated to beam current) can be much less than the energy given to the beam, which scales as the beam current. While it has been used in research accelerators, induction is not as highly developed as RF cavity technology, and also requires an increased commercial market to bring costs down to what would make future experiments, and the fusion power plant, affordable.

From the discussion above, a picture of an HIF driver emerges. Multiple (~ 100) heavy-ion sources produce beams, each focused in its own transport channel (by quadrupole magnets, as in conventional accelerators), are accelerated together in an induction linac of length a few kilometers to about 3 GeV. At the end of the accelerator each beam has attained its full energy, but the beam pulses are too long—the pulse length is about 200 ns, the minimum length for good efficiency from the induction cores. Acceleration cores are then used to longitudinally compress each beam in a drift compression section. They then pass through a final focus system consisting of 4 or more quadrupoles per beam, enter the reactor chamber, and focus

onto the target. Targets are injected at 5 Hz, with the target chamber cleared of debris between shots. The space charge of the beams presents a significant difficulty in focusing them onto the target. A long focal length (~ 6 m) is required, so that final focus magnets can be protected from the fusion blast. If left unneutralized, the beam focus will blow up due to space charge before the beams reach the target. So neutralization is provided by a plasma introduced into the transport channels just after the final focus magnets, and also by ionization of gas in the target chamber, both by the beam and later by x-rays from the heated target.

Survival of the fusion chamber is a significant problem for both inertial and magnetic confinement. At this time, there is no solution for magnetic confinement which guarantees survivability of the first wall (i.e, the wall first impacted by the neutrons) for longer than a few (~ 2) years. Likewise, laser-driver inertial confinement approaches suffer from the fact that the final focusing lenses and chamber wall will be exposed to the fusion neutron flux. In the heavy-ion driver case, however, it is possible to interpose a neutron-absorbing fluid (e.g., the molten salt FLiBe, consisting of fluorine, lithium, and beryllium) between the target and the walls. The lithium in the FLiBe would also be used to breed the tritium fuel for targets. Protecting the wall with this fluid is possible because the heavy ions spend only ~ 100 nanoseconds in the chamber— acceleration and bunching are done in the good vacuum of the accelerator. Moreover, it appears from self-consistent, many-species 3-D simulations of the propagation of the beams through the chamber that the FLiBe vapor pressure in the chamber improves focusing of the beams through neutralization, which favorably competes with beam stripping. A description of the complicated geometry of the FLiBe jets and showers which protect the chamber walls, and results from experiments in making such flows, can be found in [2]. The life of the chamber and final focus magnets is projected by simulations of neutron and radiation transport to be ~ 30 years. This solution of the first wall problem is extremely important since it is required for a practical fusion power reactor. HIF is the only fusion concept at this point with a first-wall solution.

3. Status of Heavy-Ion Fusion Physics

In the 1980s and '90s, much of the fundamental physics of space-charge-dominated beams, as well as many of the needed beam manipulations, were explored in analytical theory, experiments, and computer simulations. But because of expense, most experiments were scaled, keeping dimensionless physics parameters equal to those of a power plant driver, but with absolute current and kinetic energy low.

Aluminosilicate-based ion sources were made which produced the current, current density, and low emittance (phase space area) required for a driver, and recently experiments have shown that plasma ion sources might also have the required parameters in certain cases. A 2-MV injector, the low energy acceleration system after the ion source, was made which successfully accelerated a beam of driver-scale current (0.6 A at 1.8 MeV).

Transport experiments were particularly noteworthy for their groundbreaking physics. While analytical theory [3,4] indicated that space-charge-dominated beams were unstable to collective modes, particle-in-cell computer simulations showed all but one of these modes stabilizing nonlinearly and quickly, with negligible heating of the beam. The Single Beam Transport experiment [5] showed that the simulations were correct, and delineated the stable regime for propagation. The Multiple Beam Experiment [6] accelerated four beams simultaneously from 200 keV to 0.9 MeV, and compressed them by a factor of 7. Experiments were also done to combine beams transversely [7], and focus them to a spot (in a 1/10 scale model in linear dimension of a driver focusing system) [8]. Finally, a target tracking experiment showed that targets could be injected and tracked into the target chamber accurately enough for the beams to properly hit the target [9].

Except for the 2-MV injector, the beams in these experiments had currents of microamps to tens of milliamps, and final energies of less than 1 MeV. But the ratio of space charge potential energy to kinetic energy, the ratios of important frequencies, and other dimensionless physics parameters placed the experiments in the driver parameter regime. However there are some phenomena which must be studied at scale. Many of these involve the effect of stray electrons on the beam, where the absolute magnitude of the beam potential is obviously important to the dynamics. Two experiments running now at LBNL, the High Current Experiment (HCX) and the Neutralized Transport Experiment (NTX) are exploring these (and other) effects.

The HCX uses the 2-MV injector to produce a single K^+ beam (up to 0.6 A at 1.8 MeV), matches the beam shape into a quadrupole transport system, then transports it through 10 electrostatic, followed by 4 magnetic, quadrupoles. The short electrostatic-focused section has been used to study the extent to which the beam pipe can be filled with beam (i.e., the size of the clearance needed) before nonlinear focusing error fields, quadrupole fringe fields, steering errors, or the effects of electrons (produced by halo scraping and ionization of background gas) or gas degrade beam quality. The physics of these processes is nonlinear and complicated—especially the accumulation of electrons in the beam potential—but the answers have a strong impact on the cost of a HIF driver, because extra clearance in each of the ~ 100 beam transport channels will greatly increase the radius of the whole beam array, requiring much larger induction cores, and increasing the size of all hardware. A change from 60% radial fill to 80% is projected to raise the cost of the driver by perhaps \$1B. Simulations predict, for electrostatic quadrupoles, that 80% radial fill is the boundary of the dynamic aperture (i.e., the limit of the usable aperture set by dynamics), and, at least in the short focusing system available in the HCX, experiments agree.

Though the low-energy end of the driver may use electrostatic quadrupoles, magnetic quadrupoles will be used to focus through most of the system. Unlike electrostatic focusing, the magnetic quadrupoles do not sweep from the system electrons created if the beam halo scrapes the quadrupole. These electrons, and electrons created by ionization of background gas, will execute complicated orbits,

gyrating around field lines while subject to $\mathbf{E} \times \mathbf{B}$ drifts caused by the electrostatic beam potential and the quadrupole field. Experiments have begun on the HCX to measure the production of electrons, and their accumulation and orbit dynamics in a magnetic quadrupole system. This work has overlap with electron cloud studies in HEP colliders, where the electrons are produced by synchrotron radiation from the beam. New computational algorithms developed by HIF researchers are expected to be useful in both areas.

The NTX is studying the final focus and neutralization of the beams, using a 25 mA K^+ beam. Four magnetic quadrupoles focus the beam just before it transports through an Ar^+ plasma of density $3 \times 10^{11} \text{ cm}^{-3}$ and temperature of 3 eV. Figure 2 shows the beam with and without neutralization. Simulations are able to accurately predict the density profile of the beam exiting the focusing system, except for a slight halo which is under study. Simulation of the neutralization is presently underway. As can be seen from the figure, experiments show that this important process for the HIF driver clearly can be used to improve focusing if, as predicted by simulation, the neutralization is robust to small changes in conditions.

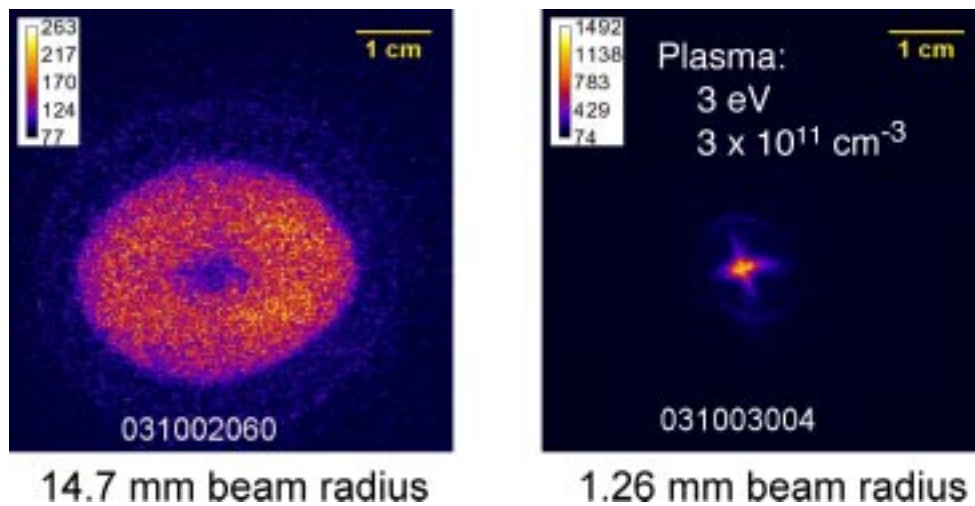


Fig. 2. NTX beam (25 mA at 255 keV) at the focus with (left) and without (right) plasma neutralization.

Along with the HCX and NTX, a major experiment on a novel injector approach is being fabricated and is expected to see first beam in a few months. If present experiments reach favorable conclusions, the results of these past and present experiments will have shown the feasibility of most of the beam manipulations of a HIF driver. What has not been tested is drift compression by the large factor (20) needed, multiple beam interactions, transport and acceleration over long distances, bending of beams during compression (as is done to direct half the beams to each end of the target after the linac), and target implosion. Some target experiments

have been done in classified underground tests, D-T capsule experiments are being done using the Z facility at SNL to provide the x-rays for heating, while other target physics will be done on the National Ignition Facility. But the non-target physics must await future larger accelerator experiments, and thus higher program funding.

4. Heavy-Ion-Driven Fusion: The Future

The next step for the HIF program would be an Integrated Beam Experiment (IBX). It would accelerate a single driver-scale beam from the source, through an ~ 10 MeV induction linac, then drift compress it by a factor of approximately 10, bend its orbit, focus it, neutralize, and measure the spot size at the focus. This would integrate the effects on the beam of all of the beam manipulations needed for a driver, with the exception of multiple-beam physics. The cost of the ~ 60 -meter long facility is about \$60 M, though because it is a linac, the experiment lends itself to being built in many much-less-expensive stages, with interesting experiments at each stage. This experiment would take the program forward to a facility of length sufficient to extend the dynamic aperture results of the HCX, look at the effects of electrons and many other phenomena on the beam during longer transport, and for the first time look at the complicated dynamics of the drift compression.

After the IBX, an Integrated Research Experiment (IRE) could be the last step before an engineering demonstration of a driver. The IRE would be a multiple beam (perhaps 30-100 beams) accelerator, with parameters which are an appreciable fraction of those of a driver: 400-800 MeV final kinetic energy, producing 30-200 kJ on target. The experiment could study multiple beam physics, long transport and higher energy intense beam physics, and some target physics particular to heavy ions. This few-hundred \$M facility would be a proof-of-principle experiment that might be extendible to an engineering test reactor.

The promise of fusion as a power source gives these experiments importance for the future of the planet. And survivability of the "first wall" of the target chamber in the heavy-ion fusion concept makes it particularly interesting to explore this concept. But the needed experiments are awaiting funding that will probably only come when energy again becomes a focus of U.S. attention.

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