Heavy Ion Fusion

by George Sawyer

Heavy ions provide the newest approach to inertial confinement fusion. This scheme uses high-current beams of heavy ions instead of laser beams to heat a fusion target. The targets are similar to those used for laser fusion. The beams of heavy ions (for example, xenon or uranium) are accelerated to energies of 5-20 GeV by nuclear particle accelerators.

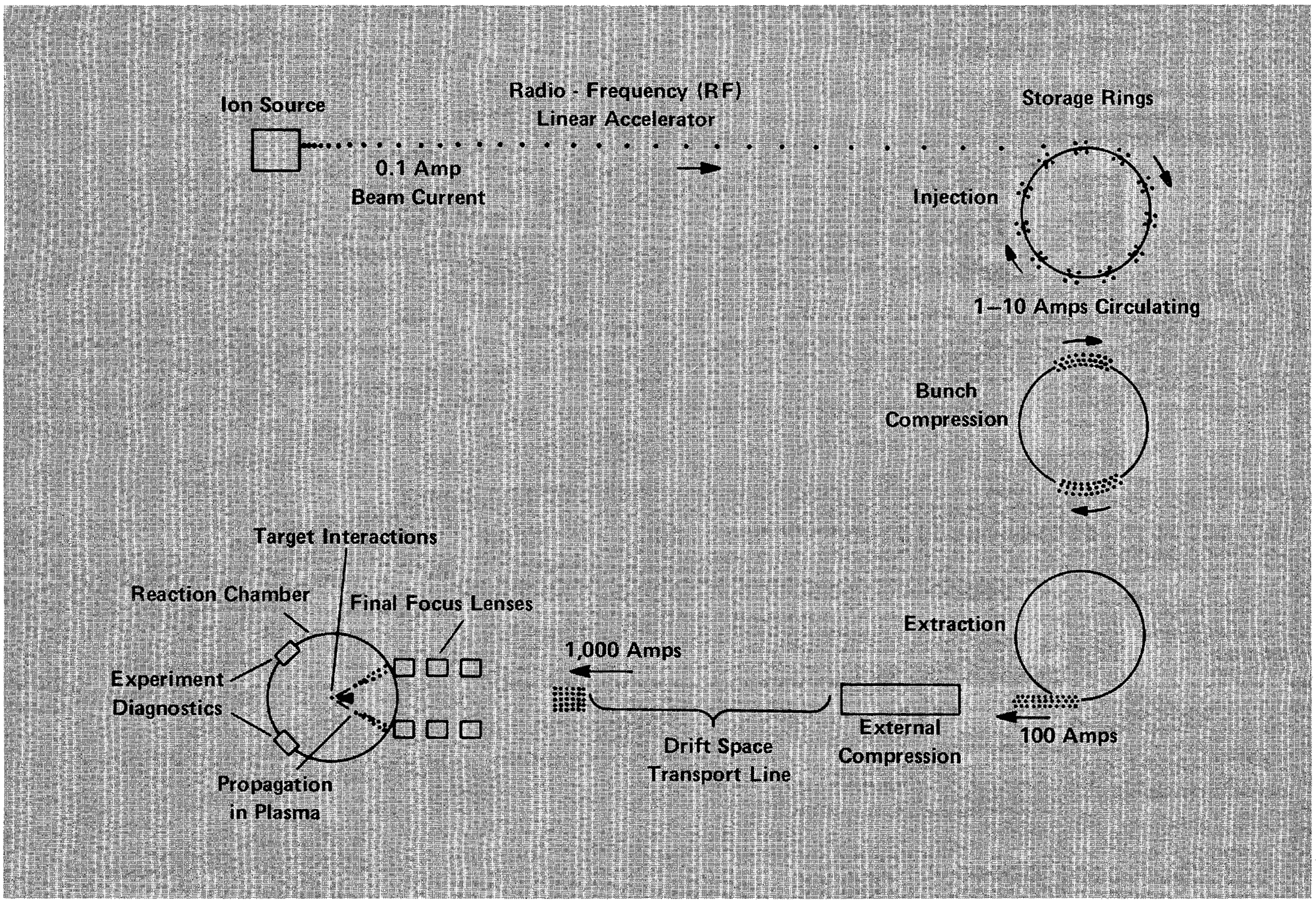
Recently, Donald M. Kerr, LASL's Director, formed a task force to make a complete assessment of heavy ion fusion (HIF). From our studies, we concluded that, although HIF is relatively untested, it has definite promise.

Subsequently, Duane C. Sewell, Assistant Secretary for Defense Programs in the Department of Energy (DOE), designated LASL to take a lead role in the management and technical direction of the DOE's HIF program. We will have the responsibility for directing the heavy ion efforts at Argonne National Laboratory (ANL), Lawrence Berkeley Laboratory (LBL), Lawrence Livermore Laboratory (LLL), Brookhaven National Laboratory (BNL), Sandia Laboratories (SLA), and other laboratories and universities contributing to the program.

Our studies indicate that heavy ions may have an advantage in efficiency and cost over lasers as drivers for inertial confinement fusion. The efficiency of accelerators for converting electric power into kinetic energy of heavy ions can be as high as 20-30%. In contrast, the most efficient lasers, the CO_2 lasers being developed at LASL, now have about 2% efficiency. A new technique for beam multiplexing may bring this up to 10%.

In addition to producing driver energy efficiently, we must be able to deposit a fair fraction of this energy into the fusion target. Our estimates based on well-established theory for the electromagnetic scattering of ions in a medium suggest that heavy ion beams have a high absorption efficiency compared to glass or CO_2 laser beams. We must, however, add a note of caution. As yet we have no experience in stopping beams of heavy ions with (1) the high beam intensities, (2) the high energies (MeV's) per nucleon, and (3) the high temperatures in the stopping medium that will be involved in heavy ion fusion.

The interest in heavy ion fusion comes at a time of increased concern about the efficiency of laser interactions with fusion pellets. Calculations and experiments indicate that the amount of laser energy required to reach fusion breakeven is much larger than it was believed to be a few years ago. At least 20 MJ/g must be deposited in the pellet in about 10 ns. Pellets must have a radius of a few millimeters determined by compromises between the pellet gain, the pellet mass, the driver energy, and the practical limits on beam focus. These requirements lead to the conclusion that the driver energy must be 1-10 MJ with a peak power of about 10 TW. Achieving such a large driver energy with lasers will be difficult and expensive. In contrast, the cost scaling with size for large



Inertial confinement fusion driven by heavy ions. The drawing shows the production of peak beam currents in the kiloampere range. This method of driving fusion reactions will require many storage rings operating in parallel.

particle accelerators is favorable. Consequently, large heavy ion drivers should be considerably cheaper than lasers if, as expected, they are more efficient in producing and depositing beam energy.

However, formidable technical problems must be solved in HIF accelerators. Although the accelerators use well-established accelerator technology, they must operate at beam currents much larger than have ever been achieved. Typical design parameters for HIF include a beam of uranium ions with a 10-GeV particle energy, a 30-kA peak beam current, a 300-TW beam power, a 3-MJ beam, and a 5-mm focal spot size.

There are two quite different approaches to heavy ion acceleration, the rf linac approach being developed at ANL and BNL and the induction linac being developed at LBL. An rf linac, similar to the one used at the Clinton P. Anderson Meson Physics Facility (LAMPF), would accelerate a 100-mA current of heavy ions to 10 GeV (~50 MeV per nucleon). In this approach, continuous rf energy is applied to a series of drift tubes. The rf energy is phased so that a bunch of ions is accelerated across each gap between adjacent tubes. We believe that the necessary accelerator structure can be developed.

However, the 100-mA beam current from the accelerator is much too small for reactor requirements, so the beam must be accumulated in a storage ring until the current is built up to about 20 A; space-charge considerations limit the amount of current that can be stored in the ring. After the ring is filled, the circulating current is extracted and transmitted through a final beam line to the target chamber. In the final beam line, the pulse of ion current must be bunched or compressed by a factor of 20 to a length of about 10 ns before it hits the pellet. The compression is accomplished by passing the beam through a series of accelerating gaps having a voltage pulse profile that slows down the head and speeds up the tail of the beam bunch. After compression, the final beam current will be about 1000 A.

Thirty such beams must be stored to meet the typical reactor requirements of 30 kA. Multiple storage rings and final beam transport lines fed from the single main accelerator are needed to accumulate and transport this enormous current. Complex beam manipulation is required in the storage ring to stack many turns of current. In addition, large current and long storage times lead to the possibility of beam instabilities. However, the rf linac is based on proven technology and has an inherent high repetition rate required for commercial application.

The induction-linac approach being developed at LBL is based on a pulsed high-voltage technology originally developed at LLL for accelerating electrons in the Astron magnetic fusion device. A single, large pulse of ions is accelerated through a long series of gaps that are momentarily pulsed to high-voltage as the beam passes by. The ions gain only a few hundred kilovolts of energy in each gap, so thousands of gaps are required in a structure several kilometers long. The pulse of current must be bunched, as well as accelerated, as it passes through the gaps.

The voltage profiles across all the gaps must be carefully controlled, and the timing of voltage application across successive gaps must be precise. The high-voltage pulse technology is similar to that used in magnetic fusion and laser fusion. Although the configuration is simple, because no storage ring is required, it has not yet been demonstrated for ion acceleration. Instabilities in the beam associated with the very large currents may make maintaining the required beam quality difficult. These problems are shared by the rf-linac approach because its final beam transport section is an induction linac, required because of the very high current, short-duration pulse that must be accelerated onto the target.

The real issue for HIF is whether heavy ion accelerators can be developed that are capable of accelerating large currents while maintaining very good collimation of the beam so it can be focused on a small target. Over the next 3 to 5 years, the DOE-funded program will concentrate on development of small test bed accelerators at ANL and LBL to explore the two main accelerator approaches. The test bed accelerators, each costing about $25 million, will be used to explore critical accelerator issues. As with all inertial-fusion approaches, it is also important to determine the target-interaction physics for heavy ions. The test bed accelerators will not have enough beam energy for significant target experiments.

By fiscal year 1984, the more promising approach will be selected and a several hundred-million dollar test facility will be proposed at a site to be determined. The test facility will be capable of doing target-physics experiments and testing accelerator performance at large beam currents. The facility, which will be larger than LAMPF, will require a site with considerable space and electrical power.

As part of its lead role in the management and technical direction of the HIF program, LASL has begun a very small effort in accelerator design, target-design physics, beam-transport studies, and reactor-system studies. Given the present funding pressures, it is likely that the entire HIF program will need to be restructured in the near future with emphasis shifted from construction of expensive facilities to the design and execution of less expensive experiments to address the crucial issues of target interaction and beam transport.