A Tutorial on Heavy-Ion Fusion Energy

This tutorial should provide some basic information about fusion energy research and development and more detailed information on inertial confinement fusion (ICF), inertial fusion energy (IFE) and heavy-ion fusion (HIF).

This tutorial contains:

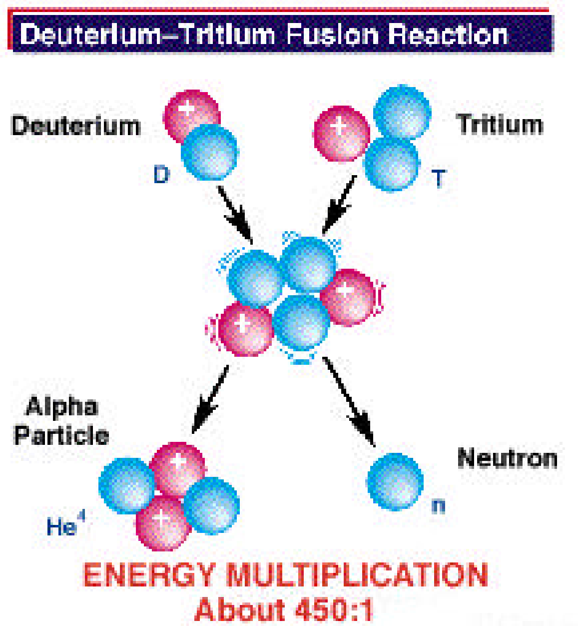
- An overview of fusion
- The principal approaches to controlled fusion energy
- Inertial fusion drivers - A few words about types of inertial fusion drivers
- Heavy ion accelerator requirements for IFE
- Why heavy ions - Advantages of heavy ion over light ion beams
- Types of heavy ion accelerators - A brief overview of RF and induction accelerators
- Considerations for the inertial fusion reactor chamber
- The projected cost of fusion energy
- Glossary of common HIF terms and acronyms

A General Overview of Fusion

The energy that powers the sun and most everything in the universe comes from nuclear fusion--the combining of lighter atomic nuclei to form heavier nuclei. In the process mass is converted to energy. The fossil fuels we use today can be traced through photosynthesis to the energy generated by the sun. One component of fusion fuel (deuterium) occurs naturally in water--in our oceans, lakes, rivers, even in the water we drink. The second component (tritium) must be generated artificially. Harnessing fusion on earth as an inexhaustible energy source is one of mankind's most significant scientific challenges.

What is Fusion?

Fusion is the combining of atoms to form other atoms, which occurs when their nuclei get close enough to each other. When nuclei are fused together, the total mass of the new nuclei is less than the original total. This mass is converted into energy in accordance with Einstein's famous equation $E=mc^2$. The most easily attained fusion combines two isotopes of hydrogen (deuterium and tritium) to make helium.



The complete fusion of a single milligram of deuterium and tritium produces as much energy as 175 pounds of TNT. Since nuclei carry positive electrical charge, they repel one another and intense heat and pressure are required to force the nuclei close enough to fuse. These conditions are achieved in the sun and stars by their size and large gravitational forces. On earth, other methods of confining a fusion plasma must be used.

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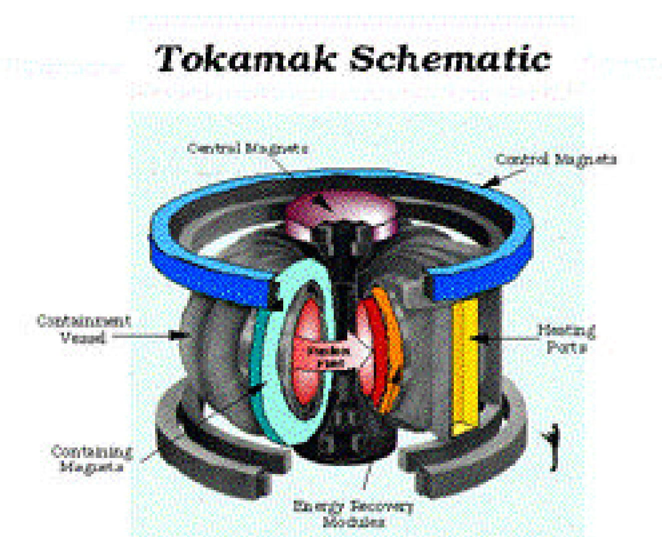
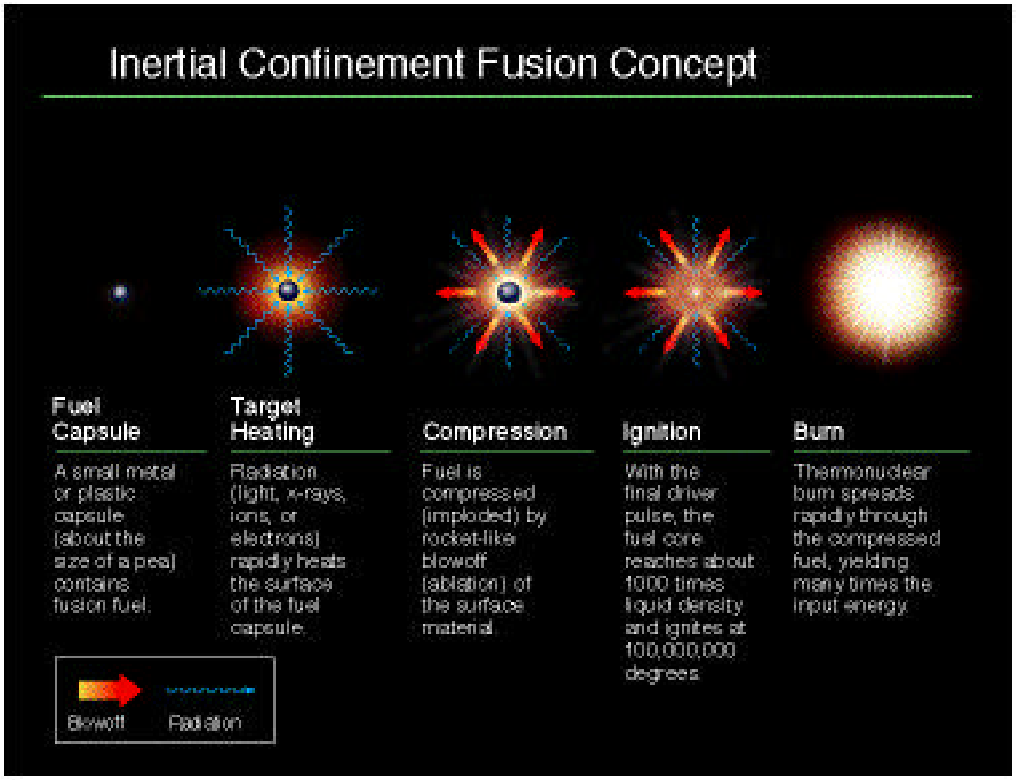
The principal approaches to controlled fusion energy.

The two main methods for achieving fusion conditions on earth rely on magnetic or inertial confinement. As a result, two main approaches to controlled fusion are under study:



- The largest U.S. fusion energy research program uses strong magnetic fields to confine the fuel and is, therefore, called magnetic fusion energy (MFE). The thermonuclear fuel is in the form of a very hot, ionized gas ("plasma"). Most of the MFE effort is currently being spent on the tokamak approach, in which the reactor is doughnut-shaped and surrounded by strong magnets.



- Inertial fusion energy (IFE) relies upon the principles of inertial confinement. In IFE, a target about the size of a large pea containing frozen deuterium and tritium is placed in a reaction chamber and bombarded with either lasers or beams of ions. The target is heated very rapidly and the deuterium-tritium fuel is compressed by a factor of 1000 or more. The pellet's own resistance to movement, or inertia, confines it sufficiently for fusion ignition and burn, which occurs in much less than one nanosecond.

For more information on MFE, see the Princeton Plasma Physics Lab homepage.

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Inertial Fusion Drivers

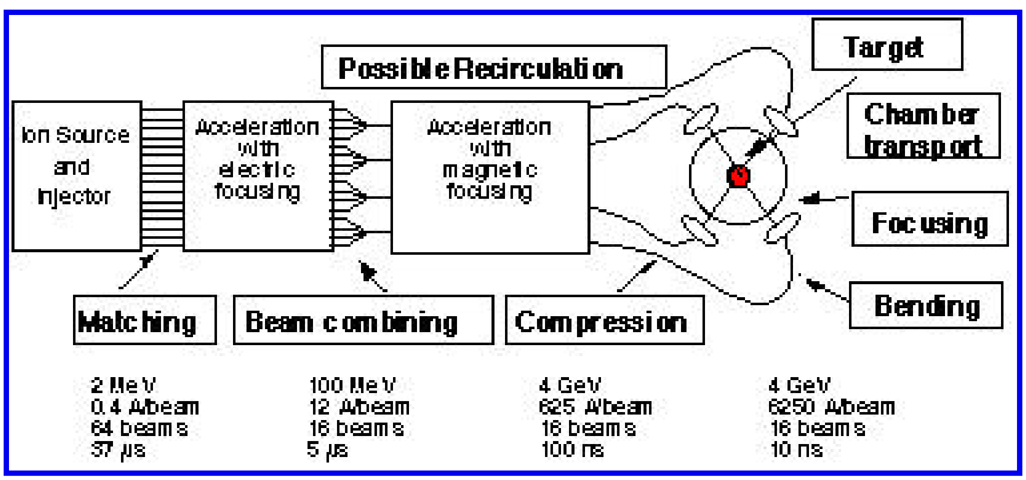
It takes about 100 watts of power to light up a room; by contrast, it takes 100 to 1000 trillion watts over a period approximately 10 billionths of a second (10 nanoseconds) to implode and ignite a target of thermonuclear fuel. These power levels imply that something near 5 million Joules (5 MJ) of energy must be supplied by the driver. Both high power lasers and powerful ion accelerators are being developed as inertial fusion drivers. To date, the most important physics issue for inertial fusion energy remains target ignition and burn and most of the effort has been spent developing lasers as the tool to study this physics. The driver for The National Ignition Facility will be a neodymium glass laser. For target physics research, high efficiency and repetition rate are not important advantages. However for commercial energy, the driver must be able to implode 5-10 targets each second with good energy efficiency. The low efficiency and slow repetition rate of existing laser drivers prohibits their use as a means of generating commercial fusion energy. Accelerators can achieve efficiencies well above 25% and, furthermore, can be operated dependably for dozens of years at repetition rates many times greater than needed for fusion energy. For these reasons, accelerators of heavy ions are currently viewed as the most promising approach to a practical driver for commercial inertial fusion energy.

Heavy Ion Accelerator/Drivers

The emphasis on heavy-ion drivers is readily understandable. For engineering and economic feasibility, drivers must be both reliable and efficient. They must also have a high pulse repetition rate (several pulses per second) and long life (about 30 years). Existing drivers-lasers and light-ion accelerators-are excellent for near-term research, but they have been designed for a low repetition rate, typically a few shots per day. Therefore, development of new drivers is needed for power production. During the last decade, nearly all high-level DOE and congressionally mandated committees have identified heavy-ion accelerators as the most promising drivers for power production.

These accelerators, designed to use the heavier ions such as xenon, cesium, or bismuth, are similar in many respects to the large accelerators that are used worldwide for basic research in high-energy physics. They have demonstrated many of the requirements for IFE usually with excellent reliability and long life. The new, additional requirement for fusion is the production of very high instantaneous beam power (greater than 10^{14} watts) in a beam that can be focused to hit a small target. There are two main methods of accelerating a heavy-ion beam in accordance with these requirements: induction and radio-frequency (rf) acceleration. Researchers in the US have chosen the induction accelerator because its relative simplicity and lower estimated cost appear to make it a more-promising driver candidate. (In Europe and elsewhere, the more converntional rf approach continues to be studied, so the aggregate effect worldwide is a greater chance that at least one of the methods will succeed.)

A schematic diagram of a generic induction accelerator designed to produce 100 kA of cesium ions at 4 GeV is shown in below. To achieve 100 kA, it uses several methods: multiple beams, beam combining, acceleration, and longitudinal bunching. Typical values of ion kinetic energy, beam current, and pulse length at various points in the accelerator are shown in the figure.



The accelerator systems and beam manipulations found in typical heavy-ion driver designs are represented by boxes. The shaded boxes represent systems that have been tested in past experiments.

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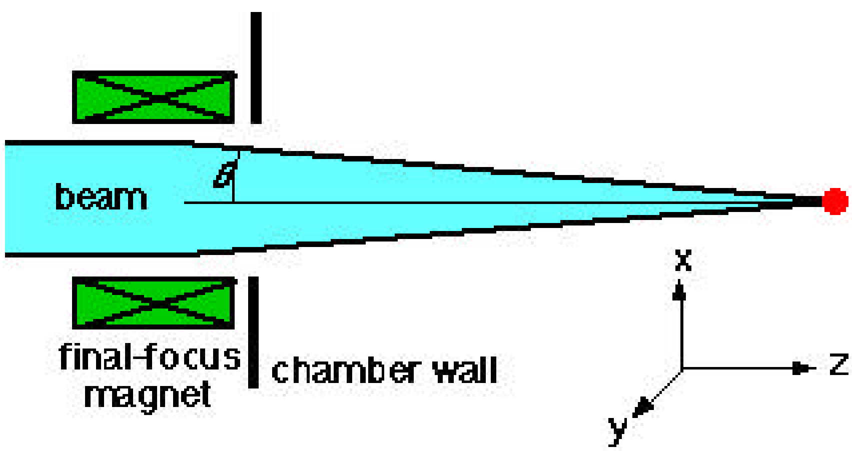
Accelerator Requirements

Accelerators have been developed extensively over the last 65 years. HIF requires accelerators to have certain features specific to the concept of inertial confinement fusion. This section describes some of the requirements for HIF drivers.

General Requirements

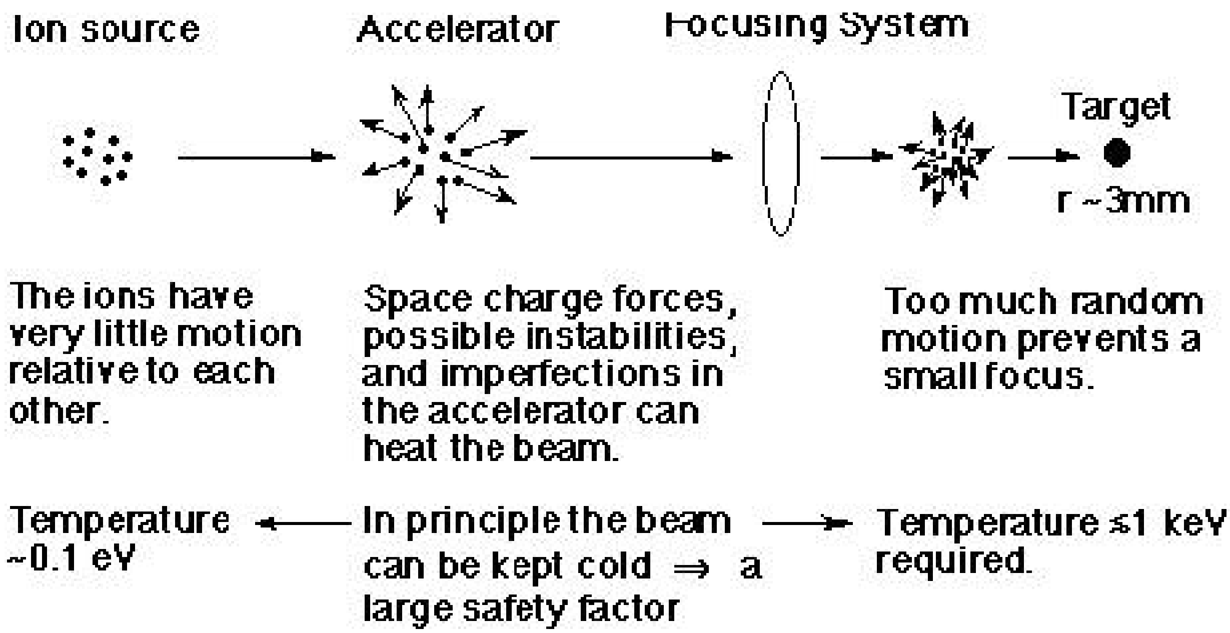
Total Beam Energy--5 MJ
Focal spot radius--3 mm
Ion range--.1 g/cm^2 (1 mm in typical materials)
Pulse duration--10 ns
Peak power--400 TW
Ion Energy--10 GeV
Current on target--40 kA (total)
Ion mass--200 amu

Additional Constraints



The target chamber and final focus requirements add more constraints:

- Target yield requires the repetition rate to be about 5 Hz for an attractive power plant of ~ 1 GWe.
- Thermal and mechanical stresses require the standoff from the target to the wall to be about 5 m.
- Chromatic aberration of optical system requires the energy variation to be less than 0.3%.
- Standoff and spot size require the transverse beam temperature to be less than 1 keV.



The main scientific and engineering challenge is to develop a working driver at a reasonable cost. A beam must be accelerated, directed, and focused to a small spot. This requires that the quality of the beam be maintained as summarized above. This must all be accomplished with the goal of producing an economically efficient driver.

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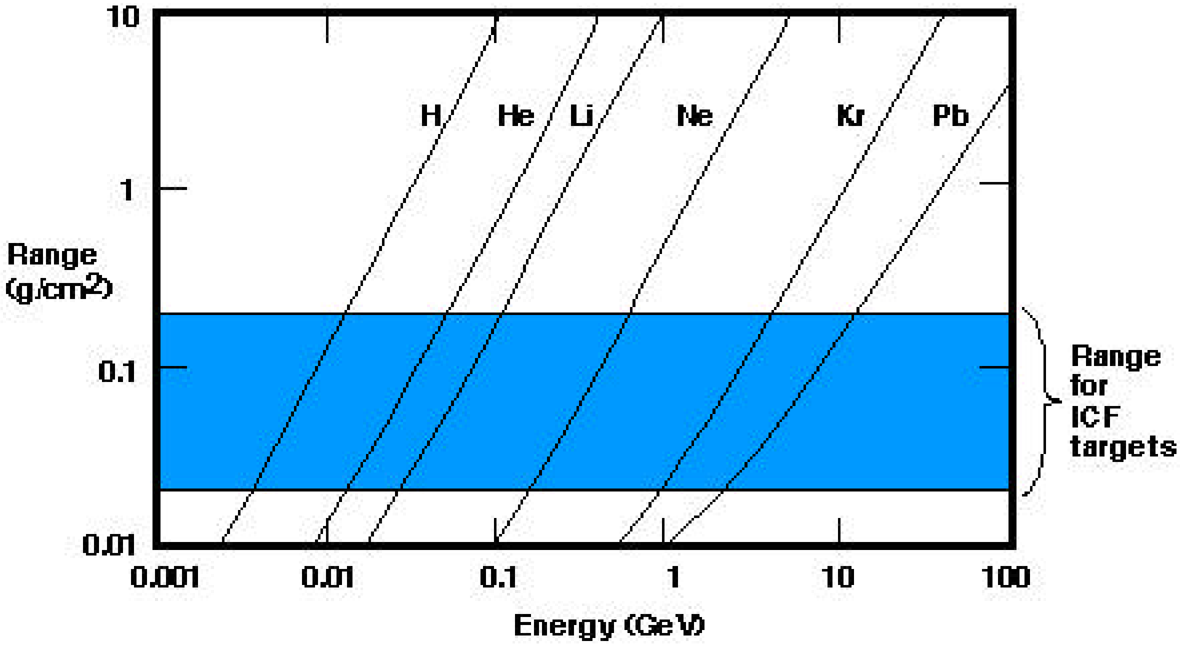
Why HEAVY Ions

Several methods for driving an ICF target are currently being researched. The main methods are lasers, light ions, and heavy ions. Here are a few advantages of using heavy ions:

- Target gain increases with total incident energy, and decreases with beam radius and ion stopping range. Using heavy ions allows the possibility of high energy at a low current.
- With a lower current it is in general easier to achieve a small focal spot.
- Heavy ions are attractive because ions of mass around 200 with energies as high as 10 GeV will still stop in a small amount of matter--between .03 and .3 g/cm^2--so relatively few ions are needed.
- 4 MJ can be achieved with ten 400 Amp, 100ns beams.
- Pulse compression after acceleration gives 4 kAmp, 10 ns beams.



This diagram shows the energy versus stopping range for various elements. For ICF, a certain amount of power needs to be delivered to the target from the beam. The beam power is proportional to both the beam energy and the beam current. Since a high-current beam can be difficult to accelerate and focus, the HIF approach maximizes the beam energy and minimizes the current. Within the "range for ICF targets," heavy ions carry more energy which means they require less current.

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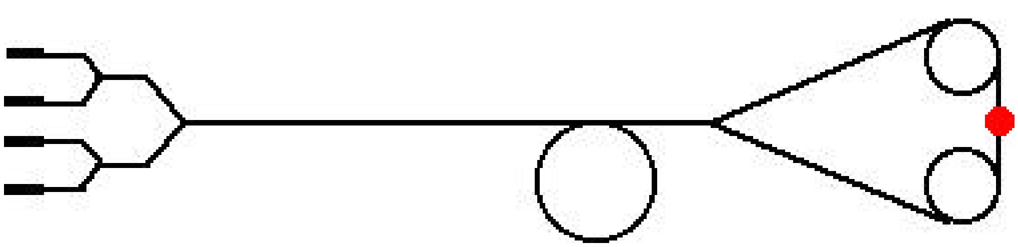
Types of heavy ion accelerators

Accelerator development over the past 65 years has laid the groundwork for HIF accelerator research. The task now is to develop and build accelerators specifically for HIF. Two main types of accelerators have been researched: Radio-Frequency (rf) and Induction Accelerators. This page describes these two types of accelerators and explains why HIF research in the U.S. concentrates on Induction Accelerators.

Driver Strategies

The following schematics show a representation of an IFE driver using rf and induction accelerators.

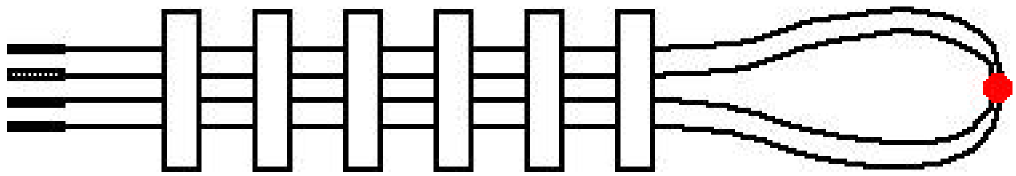
Radio-Frequency

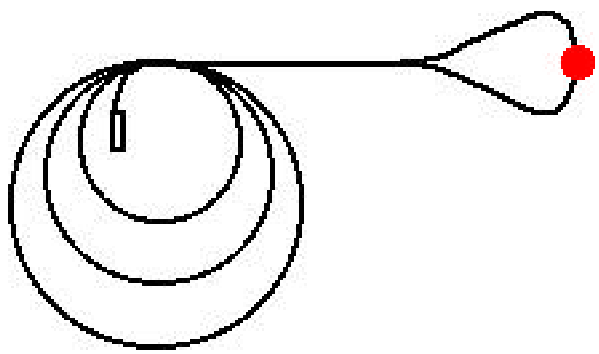


RF acceleration of low current beams followed by accumulation in storage rings and final compression. This type of driver is being studied in Europe and Japan.

Induction

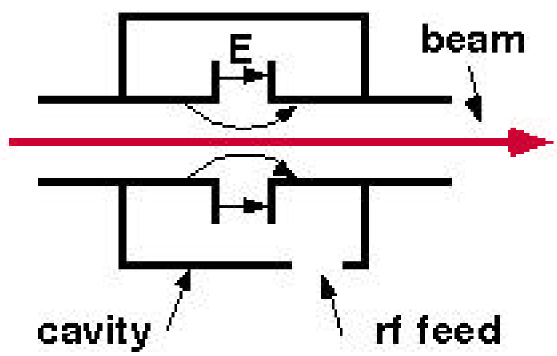
Induction cells simultaneously accelerate and compress multiple high-current beams. Two configurations are possible: linear (top) and recirculating (bottom) Induction accelerators are being studied in the U.S.





Radio-Frequency Accelerators

How do rf accelerators work?



An rf accelerator works by creating an electric field that interacts with and accelerates charged particles. Rf power is pulsed into a resonant cavity. This sets up standing wave electric fields in the gaps; the fields oscillate back and forth at the frequency of the rf source. Charged particles pulse through the gap. The pulsers are timed so that the beam reaches the gap when the E-field points in the correct direction to accelerate the particles through the accelerator. The electric field accelerates the particles as they pass by the gap.

Advantages and disadvantages of rf accelerators

Advantages:

- Technology is well established.
- Transverse beam dynamics is dominated by the transverse beam temperature instead of space charge during acceleration and storage.

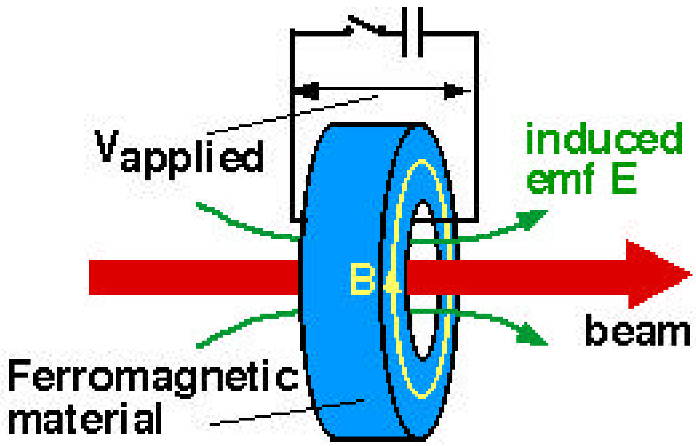
- Easy to obtain required energy per ion.

Disadvantages

- The rf power is relatively expensive.
- Low linac current of around 200 mA implies long acceleration times; beams must be accumulated in storage rings.
- Liouville theorem asserts that phase-space density cannot be increased so stacking without dilution is difficult.
- Long residence time in ring necessitates a high vacuum.

Induction Accelerators

How do induction accelerators work?



Just like an rf accelerator, an induction accelerator uses an electric field pulse to accelerate the beam. Instead of a radio frequency source, a changing magnetic field is used to induce an electric field which accelerates the particles. A pulsed voltage causes a magnetic field to build in the ferromagnetic core. The B-field change induces an electric field along the beamline according to Faraday's law. The voltage pulse is timed to accelerate the particles. One induction core can accelerate more than one beam.

Why the U.S. is developing induction accelerators

HIF research in the U.S. is dominated by induction accelerators. Here are a few reasons why:

- A pulser provides an almost flat pulse.
- There is no requirement of constant frequency, so longitudinal compression and increasing velocity can produce an increasing current, up to the limits of the transverse confining fields.
- Larger safety factor in beam quality or brightness than "conventional" rf.
- Lower cost due to the relative simplicity of the total system.
- Lower cost to test because the critical issues occur at low energies, as opposed to rf where critical issues related to the storage rings occur at high energies.

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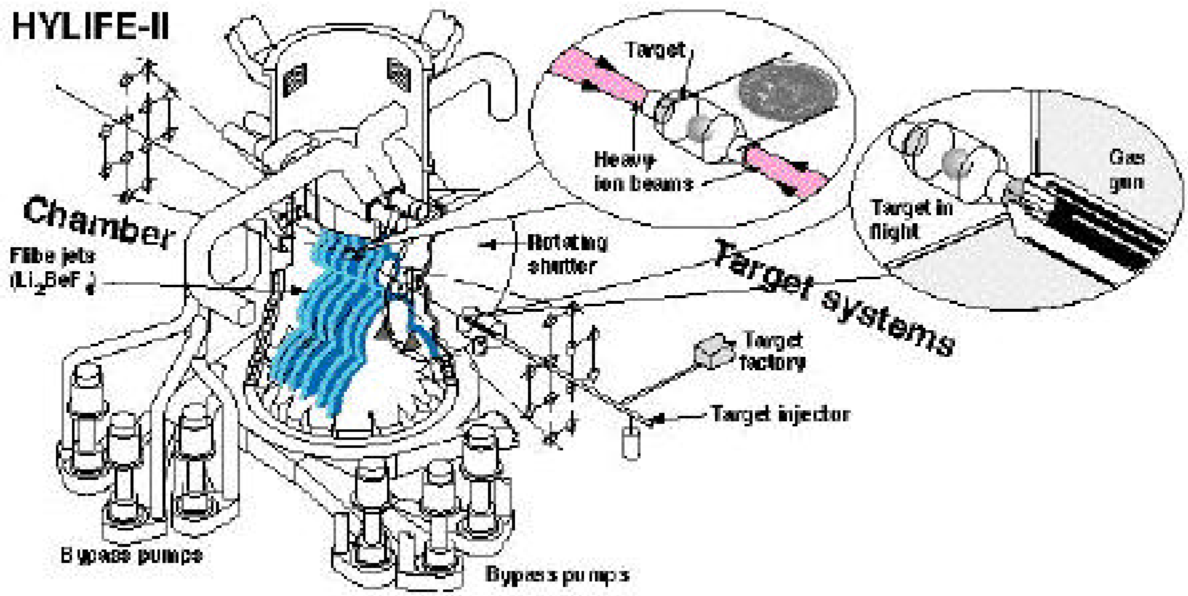
The inertial fusion reactor chamber



At present, we believe that an IFE reactor chamber will be about 5 m in radius. As shown above in a schematic of the HYLIFE-II reactor concept, fuel pellets will be "shot" into the chamber at a rate 5-10 per second with each one being irradiated by intense energy pulses produced by heavy ion beams (or possible future laser or light ion beams). The energy released by the fuel (mainly in the form of high energy neutrons and x-rays) will be absorbed by a special fluid blanket whose heat is eventually transferred to a relatively conventional steam generator where it is converted into electricity. The fluid is continually recirculated back through the reactor chamber. In most IFE reactor designs, the fluid contains the element lithium which will "breed" tritium when struck by neutrons from the D-T fusion reactions. The fluid blanket also serves the function of protecting the reactor walls from irradiation and resultant nuclear activation.

Reactor Lifetime and Activity

An attractive feature of fusion versus fission plants is the smaller amount of radioactive byproducts produced during the plant lifetime. Although the fusion reactions produce high energy neutrons which have the capability to contaminate parts of the reactor, there are a number of IFE reactor designs which prevent these neutrons from reaching and activating the reactor walls. The recirculating fluid inside the reactor both absorbs the neutrons and their energy AND breeds additional tritium fuel. The fluid will be pumped through small ports in the reactor walls and take the imparted energy to a generator.

Modularity

A power plant must be able to produce continual power for decades without unwanted long-term interruptions. The inherent modularity of a multiple laser driver or heavy ion accelerator driver for is attractive in terms of the ease of making repairs. Furthermore, it is also feasible for an IFE power plant to have multiple reactor chambers such that if one should have to be shut down, the driver would still ignite fuel pellets in the other chambers.

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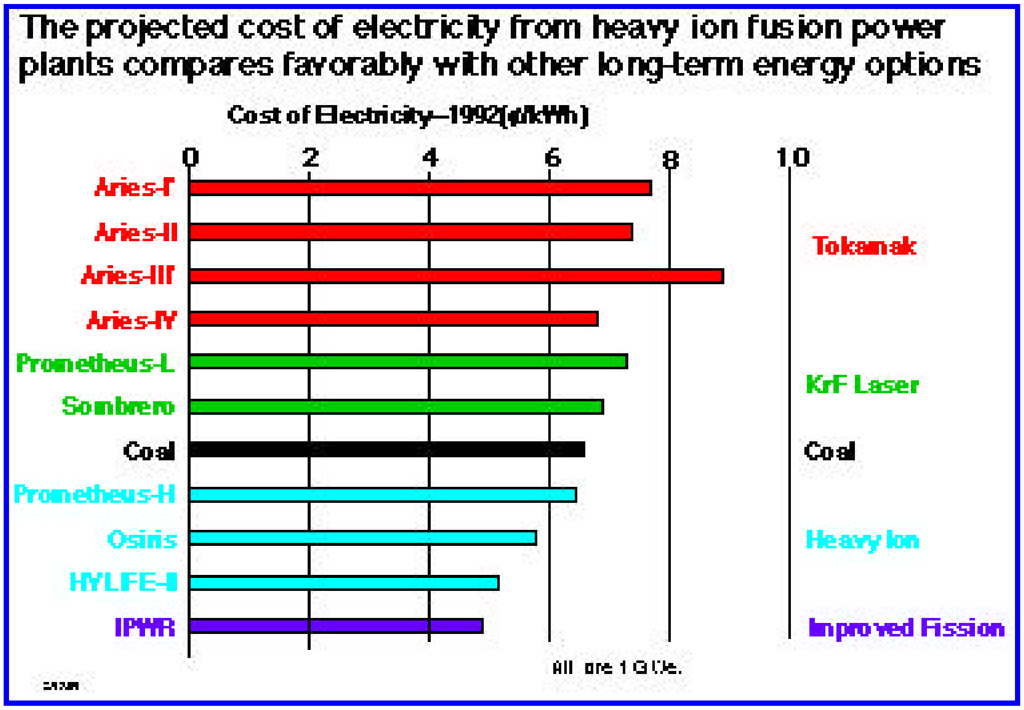
Cost of Fusion Energy



Another obvious concern with fusion energy is the cost of electric power. A fusion plant must be competitive with both conventional and fission plants in order to be economically viable. As the shown in the above figure which was assembled from several cost comparison studies, IFE plants driven by heavy ion accelerators may produce electricity at a 20-30% cost advantage to tokamaks and may also be competitive with fossil-fueled and advanced-designed fission plants,

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GLOSSARY of common HIF terms and acronyms

Ablator
: An **ablator** is the outer portion of a fuel pellet that is used to implode the fuel in the reaction chamber. The ablator is rapidly heated by the driver beams, and as it evaporates outwards, momentum conservation forces the contained fuel to implode (a "rocket" effect). This implosion increases the density of the fuel reactants by as much as a factor of 1000.

Confinement
: In order for significant thermonuclear energy production, the fuel must remained confined for a sufficiently long time (at both a high enough temperature and density) so that a large number of nuclear fusion reactions will occur. For **inertial confinement**, this time is less than a nanosecond. For the **magnetic confinement**, this time ranges from seconds to an eventual goal of hours.

Deuterium
: **Deuterium** is a naturally occurring isotope of hydrogen that contains one proton and one neutron. It and tritium, another hydrogen isotope with two neutrons, have a large fusion reaction cross-section which results in end products of one helium nucleus and one neutron with combined kinetic energies of 17.6 MeV.

Direct Drive
: The inertial fusion target is directly driven by energy from the fusion driver. That is the power from the driver couples directly to the surface of the fuel capsule. Although more efficient, this form of target coupling requires very precise beam aiming and uniform

target illumination.

Dipole

A device for deflecting the path of the beam. A magnetic dipole field bends the path charged particles (or beams of charged particles) with a force proportional to their velocity, the strength of the field, and the charge of the particles. An electric dipole field bends with a force proportional to the strength of the field and the charge of the particles.

Driver

The term **driver** is the name given to the apparatus that produces the required laser or ion beams and which directs them at the fuel pellet in an inertial confinement fusion reactor chamber.

Electrostatic Quadrupole

See Quadrupole

eV

Electron-volt -- a unit of energy used in particle and atomic physics representing the energy given to an electron accelerated though one volt potential difference. One **eV** is equivalent to $1.9x10^{-19}$ Joules. One keV is 1000 eV, one MeV is one-million eV, while one GeV is one-billion eV. The energy of one photon of visible light is about 1.7 eV. A typical power plant produces 1 GW of electrical power, which is 1 billion Joules per second.

Final Focus

The last focusing elements of a driver which reduce the beam size from several centimeters in radius to about 3 millimeters in radius at the fusion fuel target is referred to as the **final focusing** system.

ICF

Inertial Confinement Fusion (**ICF**) is the approach to controlled thermonuclear fusion which uses intense ion or laser beams to implode and ignite target pellets of deuterium-tritium fuel, whose inertia confines them for a sufficiently long time for a good "burn" to occur.

IFE

Inertial Fusion Energy (**IFE**) is the name for the research program in the U.S. Department of Energy whose goal is to use the ICF approach to controlled thermonuclear fusion energy to commercial power production.

ILSE

The Induction Linac Systems Experiments (**ILSE**) refers to a (now dormant) proposal by the LBNL HIF group to build a 10-MeV multiple beam accelerator that was to have modeled an ICF ion driver on a small scale but with several full-scale characteristics such as beam size and current.

Indirect Drive

The inertial fusion target is indirectly driven by energy from the fusion driver. That is the power from the driver is first converted to x-rays inside a type of oven called a "hohlraum". The fuel capsule placed inside the hohlraum is driven by the x-rays. Due to the inefficiency of the conversion to x-rays, three to four times more energy is required from the driver but the requirements on aiming precision and illumination uniformity are greatly eased.

Induction Linac

Induction Linac is the name given to a type of linear accelerator which accelerates charged particles by using the electric field produced by a rapidly-changing magnetic field strength in a ferrromagnetic core. Induction linacs are useful wherever relatively large (> 1 kiloamp) beam currents must be accelerated.

Injector

The ion source and first stage of acceleration up to 1-2 MeV is the **injector** of a driver.

Ion

An **ion** is an atom has lost (or occasionally gained) one or more electrons and thus has a net electrical charge. An plasma is said to be fully ionized if its atoms have completely loss their bound electrons.

MBE-4

The Multiple Beam Experiment (**MBE-4**) at LBNL refers to a accelerator which examined the physics of the acceleration and controlled transport of four parallel cesium ion beams at the same time. MBE-4, whose total energy (900 kEV) was much greater than SBTE, produced additional understanding of the beam dynamics of space-charge dominated beams.

MFE

Magnetic Fusion Energy (**MFE**) is the approach to controlled thermonuclear energy which uses magnetic fields to confine a hot, but rarefied thermonuclear fuel. A tokamak is an example of a device that operates upon the principles of magnetic confinement.

Magnetic Quadrupole

see Quadrupole

Plasma

The so-called fourth state of matter, a **plasma** is an ensemble of ionized particles which are not chemically bonded together. A plasma may be electrically neutral (as in the core of the Sun or ICF fuel pellet) or have a net charge (as is true of a beam in an accelerator). In general, the temperatures necessary for fusion imply that burning fuel is in a plasma state.

Quadrupole

A **quadrupole** is the name given to a force field produced by four individual poles, two positive and two negative. Quadrupoles may involve either electric or magnetic fields. Quadrupole fields are often used to focus and help transport charged particle beams in accelerators. For heavy-ion fusion accelerators, in general electrostatic quadrupoles are used at low energies and magnetostatic quadrupoles at higher energies.

SBTE

The Single Beam Transport Experiment (**SBTE**) at LBNL examined fundamental physics of transporting a low energy (200-keV) but space-charge dominated cesium ion beam. Results from SBTE showed that beams could be transported without significant degradation of beam quality even when the space-charge pressure exceeded the thermal pressure by factors of ten or more.

Space-charge dominated beams

A beam of charged particles is said to be **space-charge dominated** when the effective electrical force of repulsion of the like charges is stronger than the pressure associated with the internal temperature of the beam. Usually, this concept applies to non-relativistic ion beams since the repulsive space-charge force is normally nearly completely canceled by the attractive self-magnetic force in relativistic electron beams.

Tokamak

A **tokamak** is the Russian name given to a large, doughnut-shaped fusion device which is surrounded by electrical coils which produce intense magnetic fields to confine a hot, D-T fuel plasma.

Tritium

Tritium is an isotope of hydrogen that contains one proton and two neutrons. It and deuterium (see above) have a large thermonuclear fusion cross-section. It is also radioactive with a half-life of approximately 12.5 years.

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