INERTIAL FUSION DRIVEN BY INTENSE HEAVY-ION BEAMS*

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Abstract

Intense heavy-ion beams have long been considered a promising driver option for inertial-fusion energy production. This paper briefly compares inertial confinement fusion (ICF) to the more-familiar magnetic-confinement approach and presents some advantages of using beams of heavy ions to drive ICF instead of lasers. Key design choices in heavy-ion fusion (HIF) facilities are discussed, particularly the type of accelerator. We then review experiments carried out at Lawrence Berkeley National Laboratory (LBNL) over the past thirty years to understand various aspects of HIF driver physics. A brief review follows of present HIF research in the US and abroad, focusing on a new facility, NDCX-II, being built at LBNL to study the physics of warm dense matter heated by ions, as well as aspects of HIF target physics. Future research directions are briefly summarized.

INTRODUCTION

Global energy demand is growing sharply in the world generally and in developing countries in particular. Projections for a tripling of demand by 2100 point to an energy market approaching $70-trillion for new electrical power plants in the present century.

Carbon-based sources currently account for 85% of energy use, but if we intend to curtail the growth of atmospheric CO_2, a preponderance of the new plants will have to be carbon-free [1]. While renewable sources, such as solar, wind, wave, and biomass, will no doubt play important roles in the expanding energy market, they probably will be unable to provide for the needed baseload demand [2]. Fission contributes significant electrical power today in several countries, but conventional, once-through reactors are not sustainable. Without reprocessing or a more efficient fuel cycle, such reactors would exhaust known uranium reserves in less than 100 years.

Controlled fusion offers the possibility of effectively limitless, carbon-free energy. Fusion occurs when light nuclei collide with sufficient energy. The nuclei repel each other due to their positive charge, but quantum-mechanical tunneling through this Coulomb barrier becomes more likely as the collision energy increases. If tunneling occurs, the nuclei fuse, forming a heavier nucleus and converting a small amount of mass into energy, released as kinetic energy of the resulting particles and, for some fusion reactions, as radiation. The reaction with the highest cross-section is deuterium (^{2}H, conventionally denoted D) plus tritium (^{3}H, written as T), yielding a 3.5-MeV helium nucleus (^{4}He) and a 14.1-MeV neutron. The fuel for this "D-T" fusion is abundant, since about one in 6500 hydrogen atoms in seawater is deuterium. While this proportion may seem low, the high energy yielded by fusion reactions makes extraction feasible. Tritium can be bred in a fusion reactor by capturing fusion neutrons in a material containing lithium.

According to the Lawson criterion [3], a D-T fusion plasma will reach "ignition" - that is, produce enough fusion energy to maintain the plasma temperature without external power input - when the product of the particle number density n, the plasma temperature T in keV, and the confinement time τ equals or exceeds about 3.3 x 10^{15} keV-s/cm^3.

The two principal approaches to controlled fusion have opposite strategies for meeting this criterion. Magnetic confinement attempts to constrain a hot ($T \approx 10$ keV), low-density ($n \approx 10^{14}$ cm^{-3}) D-T plasma for several seconds or longer ($\tau \geq 3$ s) using carefully designed magnetic fields [4]. A succession of experiments using this approach has been edging toward ignition during the past half century and may reach that goal in the 2020s with ITER (formerly called the International Thermonuclear Experimental Reactor), now being constructed in Caderache, France [5]. In contrast, inertial fusion seeks to quickly compress a D-T mixture isentropically to an average density 500 times solid density ($n \approx 1.5$ x 10^{25} cm^{-3}), thereby heating a portion of the fuel to 10 keV and initiating fusion before thermal pressure can disperse the compressed target, on the order of 20 ps. The fuel is, in effect, confined by its own inertia. Stated another way, the Lawson criterion requires that the product of the compressed fuel mass density ρ and radius R be about 1 g/cm^2 or higher. Laser-heated inertial confinement was proposed by Nuckolls in 1972 [6], decades before sufficiently intense lasers were developed, and in 1976, Maschke [7] and others advanced the idea of

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heating inertial-fusion targets with heavy ions. The recently completed National Ignition Facility (NIF) is beginning to test inertial fusion using 192 laser beams with a total energy up to 1.8 MJ [8].

Most inertial-fusion energy (IFE) approaches assume a relatively modest yield per target, typically in the range 100-500 MJ. For a power plant to generate, say, 1 $GW_{electric}$, the reactor thermal output must be at least 2 $GW_{thermal}$, so the repetition rate must be 4-20 Hz. The performance and economic trade-offs entailed in designing an IFE power plant are discussed elsewhere [9].

Any inertial-fusion power plant has four principal subsystems. A "driver" is needed to concentrate sufficient energy to compress a target in 10 ns while heating the core of it to 10 keV. For laser IFE, this system is an array of short-pulse lasers, while for heavy-ion fusion (HIF), it consists of a particle-accelerator complex with whatever equipment is needed to aim and focus the beams. A "chamber" is needed to recover energy from fusion targets and to contain the products of the fusion reaction. A "target factory" must produce low-cost targets at the reactor repetition rate, and the balance of the plant converts energy from the reactor into electricity and possibly other marketable forms such as hydrogen.

While the preponderance of fusion research to date has been focused on magnetic fusion energy (MFE), IFE offers several distinct advantages. Projected MFE reactors have a toroidal fusion-power core that is integrated and interlinked with hard-to-maintain components, particularly the superconducting magnets threading the core. In contrast, IFE reactors use a comparatively simple chamber that is largely decoupled from the other major subsystems, potentially making the power plant more reliable and easier to maintain. The separability of IFE subsystems also simplifies the introduction of improved technologies as they become available, benefiting the development path. Another potential advantage is the option for using curtains of molten Li_2BeF_4 ("FLiBe") or other lithium salt to absorb the fusion neutrons, providing a long lifetime for structural components and a small inventory of activated material. Finally, decoupling the driver from the fusion chamber opens the possibility for multiple chambers with a single driver. Since the driver is the costliest subsystem, multiplexing chambers could substantially improve power plant economics and provide some operational redundancy.

The essential problem for inertial fusion is depositing enough energy in a target in a sufficiently short time. If this can be done, then questions of repetition rate, efficiency, reliability, cost, and safety become important in choosing the optimum driver, target, and chamber for power production. For a proof-of-principle test of inertial fusion, a laser-based driver, like that used in NIF, is well-suited. However, lasers have several characteristics that complicate their use in power plants. The NIF neodymium-glass lasers are less than 1% efficient. Krypton-fluoride lasers presently have efficiencies around 7%, while diode-pumped solid-state lasers (DPSSLs) are projected to be 16% efficient at best. Such low efficiencies would necessitate recycling a large portion of the power output to operate the lasers. The final optics for laser drivers necessarily intercept the beam, and any defects are expected to produce local hot spots that may fracture the lenses. Shrapnel and radiation from the target may also damage the final optics. Also, conceptual designs for laser IFE plants plan for a replaceable inner wall instead of molten-salt walls [10], necessitating periodic plant shut-downs for wall replacement.

APPROACHES TO HEAVY-ION FUSION

Heavy-ion accelerators are well matched to IFE driver requirements. Accelerators routinely demonstrate repetition rates in the required 4-20-Hz range or above, and efficiencies up to 40% are projected. Final optics are robust because the focusing magnets do not intercept the beam. Heavy ions are found to strip minimally in vapor of molten FLiBe, enabling the use of liquid protection of the inner chamber wall. With such protection, chamber materials would receive low enough activation over a thirty-year plant lifetime to qualify for shallow burial when the power plant is decommissioned.

An important concern about ion drivers, however, is the scaling of target gain, which is usually defined as the ratio of fusion energy generated to the input kinetic energy. Gain typically increases with increasing energy on target, decreasing focal-spot size, and decreasing range, which corresponds to a lower energy per ion. In contrast, ion accelerators are conventionally designed to deliver low current and high energy/ion, while at higher currents, the beam space charge and transverse temperature tend to give a large spot size. The physics challenge for heavy-ion drivers is to obtain sufficiently concentrated energy while still steering, aiming, and finally focusing the beam. The economic challenge is doing this at a cost that is competitive with other energy sources.

For the remainder of this paper, we examine design requirements for HIF drivers and review past and present research on these systems.

Target Concepts

A number of target concepts are being explored for HIF reactors. They range from targets similar to the conservative "indirect-drive" targets being used on NIF [11-12] to designs that have much higher gain but, at present, significantly higher known physics risks.

Many requirements for heavy-ion drivers are set by target physics. In typical indirect-drive HIF targets [13,14], a fuel "capsule" is centered in a shell or "hohlraum" made of a material with high atomic number Z. The capsule is a hollow shell of solid D-T mixture, filled with gaseous D-T and surrounded by a layer of medium-Z material called the "pusher" or "ablator." The beams deposit their energy in the hohlraum, which then heats and radiates soft x-rays that fill the interior. The x-rays heat and then gradually vaporize the pusher, and the reaction force from the ablating material isobarically pushes the D-T toward the center. If the compression maintains adequate symmetry, a "hot spot" develops inside the compressing capsule, finally reaching

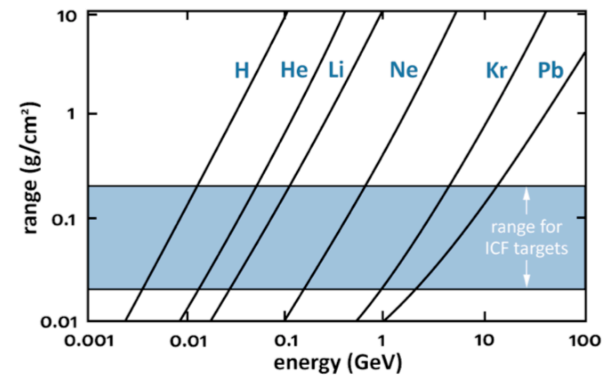

Figure 1: Ranges of selected singly charged ions as a function of kinetic energy. The blue band indicates ranges that are appropriate for inertial-fusion targets.

10 keV and igniting the rest of the fuel. Other types of target are being developed, including direct-drive [15], fast-ignition [16], and shock-heated [17] varieties. However, this paper focuses on the comparatively low-gain indirect-drive concept because it has received the preponderance of target-modeling effort.

The behavior of indirect-drive targets depends on details of the hohlraum geometry and materials, the capsule design, and the beam energy and pulse shape [11-12]. Nonetheless, basic beam parameters can be inferred from relatively simple considerations. For a given ion, the absorber thickness and material determine the required kinetic energy per ion, and the absorber surface area directly sets the beam spot size. The pulse duration and required energy deposition can be estimated from the capsule size and the implosion velocity. Simple hydrodynamics arguments suggest that isobaric compression can be achieved with an implosion velocity V_{imp} of about 3 x 10^7 cm/s, so if the inner radius of the fuel capsule is $R \approx 3$ mm, the pulse duration is $\tau_b \approx 10$ ns. Likewise, for a fuel mass M_f of 7 mg, the implosion energy $\frac{1}{2}M_f V_{imp}^2$ is roughly 2 x 10^5 J. Energy is lost in converting beam energy into x-rays, in ablating the outer layer of the fuel capsule, and in electron thermal conduction. The implosion efficiency is the fraction of the input beam energy that remains as kinetic and internal energy of the fully compressed fuel. If this efficiency is estimated to be 5%, the required beam energy on target is 1-10 MJ, and the corresponding average power on target is 10^{14} - 10^{15} W.

The choice of ion mass is somewhat arbitrary. Typical indirect-drive targets produce highest gain for incident ion ranges between 0.02 and 0.2 g/cm^2 [18]. As Fig. 1 illustrates, ions with a wide range of masses might be used, but because stopping power in an absorber is proportional to the inverse square of the ion velocity, the energy per ion must be lower with lighter ions, necessitating a higher total particle current, summed over all beams, to obtain the needed power. The required current increases inversely with decreasing ion mass, and for ions lighter than about 120 u, ballistic transport to a target becomes challenging due to the large total current needed. For example, a driver using 5-GeV $^{207}Pb^+$ ions requires 200 kA total current, but the requirement becomes 2 MA for 0.5-GeV $^{20}Ne^+$ ions. Most conceptual designs for HIF drivers, therefore, assume ions with a mass around 200 u.

Driver Concepts

Two fundamentally different HIF driver approaches have been advanced. European and most Japanese work has focused on radio-frequency (rf) accelerators, in which the oscillating electric field of microwaves in a series of tuned cavities accelerate beam bunches [19-22]. RF accelerator technology is widely used and offers acceleration gradients as high as 100 MeV/m. Another useful feature is automatic longitudinal confinement. When a bunch is timed to coincide with the rising portion of the sinusoidal rf electric field, ions in the front of the pulse accelerate less than ions near the tail. The rf field, in effect, forms a ponderomotive potential well a quarter wavelength long, and a properly timed bunch gains energy while trapped in this well.

Nonetheless, two aspects of rf accelerators make the approach challenging. First, due mainly to the cost of microwave power sources, rf accelerators rarely have currents exceeding 200 mA. Since a total current of order 200 kA is needed for indirect-drive targets, the output from one or several rf accelerators must be stored and then compressed into a suitable format. A second limitation is the difficulty of compressing an rf beam longitudinally during acceleration. The pulse duration is determined by the microwave frequency, and bunches have a fixed amount of charge, so rf accelerators are constant-current devices in the absence of multiple frequencies or non-Liouvillian beam stacking [23]. Researchers have proposed various methods for storing, stacking, and bunching rf pulses so they deliver their energy in the format needed by HIF targets [24-26], but such solutions tend to be complicated and expensive.

Induction accelerators [18,22,27-29], the second driver approach, are being developed in the US. Such accelerators can be thought of as a series of single-turn transformers, with the beam receiving the induced EMF from each as if it were the secondary winding. In each induction cell, voltage from a high-power pulse modulator builds up magnetic field B_θ around a ferri- or ferromagnetic torus or “core,” and the changing flux through the core induces an axial electric field E_z. The E_z pulse in each cell is timed to coincide with the beam arrival and accelerates the beam. Refs [22] and [29] provide a fuller discussion of induction-cell physics. The product of acceleration voltage and the voltage duration, the so-called “volt-seconds” of a cell is the cross-sectional area of the core times the flux swing of the core material, which is 0.7 T for ferrite and 2.7 T for certain amorphous metals like Metglas®[30].

Induction accelerators have several features that make them attractive HIF drivers. The accelerating structure is very low impedance, so currents as high as 100 kA can be accelerated. In addition, particles are accelerated independent of their energy, so beams can have a head-to-tail velocity increase or "tilt", allowing lengthwise compression of pulses during acceleration. These two features eliminate the need for beam accumulation and bunching found with rf accelerators. Core losses, due mainly to eddy currents, are quite small with modern amorphous or nanocrystalline ferromagnetic materials [31], so induction accelerators can be designed with wallplug-to-beam efficiencies of 40% and perhaps higher. Other useful features of induction drivers are the possibility of repetition rates exceeding 1 kHz, far more than HIF drivers require, and the ability to accelerate several beams through a single magnetic core, so that core cost scales as the square root of the number of beams rather than linearly.

In contrast with rf accelerators, the acceleration field in an induction cell does not intrinsically provide longitudinal focusing. This feature gives physicists great flexibility in designing acceleration schedules, since any waveform can be used that does not exceed the volt-seconds limit of the core or frequency limits of the drive circuitry. However, without confinement of the ends, a "space-charge-dominated" beam, in which space-charge forces predominate over thermal pressure, lengthens unacceptably during acceleration. This lengthening can be controlled by adding tailored acceleration fields, called "ears," that appropriately accelerate the beam tail and slow the head [32].

The main drawback of induction drivers is their limited acceleration gradient. In experimental devices, electrodes concentrate the acceleration field to gaps between cells, and the average gradient is constrained to the order of 1 MeV/m by the 10 MeV/m threshold for vacuum surface breakdown.

The US HIF experimental program has focused primarily on induction drivers due to he ease of matching the final beam to HIF target requirements [33]. In the rest of this paper, we therefore concentrate on this approach.

Transverse-Focusing Concepts

During acceleration, a driver beam requires transverse focusing to balance the outward forces resulting from the beam space charge and transverse "emittance," a measure of thermal pressure. Three common methods are solenoids, electrostatic quadrupoles, and magnetic quadrupoles. Solenoids, in their simplest form, are current-carrying coils around the beam axis that produce a magnetic field that is largely parallel to the axis within the coil and fans out at the ends, looping around the outside of the coil to close the field lines [34]. Beams begin rotating around the axis as they enter a solenoid in order to conserve canonical angular momentum, and the beam is then focused by the radial component of the **v** x **B** force. Electrostatic and magnetic quadrupoles both use the principle of alternating-gradient (AG) focusing [35]. Each quadrupole focusing element squeezes the beam in one of two orthogonal directions in the transverse plane, while defocusing the beam in the other direction. Quadrupole forces increase with distance from the accelerator axis, so a periodic series of quadrupoles, focusing alternately in the two directions, gives a strong net focusing force because the beam is larger in the focusing plane than the defocusing plane.

Solenoids and quadrupoles differ in the amount of current they can focus. The maximum transportable current for solenoids is given in SI units by $I_{max} \approx 0.5\ \pi\varepsilon_0\ q r_b^2 v_z B_z^2/m$, where q and m are the ion charge state and mass, v_z is the ion longitudinal velocity, r_b is the beam radius, and B_z is the longitudinal component of the solenoid field. The linear scaling with velocity and quadratic scaling with B_z make solenoids advantageous for high-current beams at low energy. For electrostatic quadrupoles with a pole-tip field of E_q and an aperture R, the maximum transportable current is approximately $I_{max} \approx 0.25\ \pi\varepsilon_0\ r_b^2 v_z E_q/R$. The analogous expression for magnetic quadrupoles with a pole-tip field strength of B_q is obtained by substituting $v_z B_q$ for E_q. The v_z^2 scaling of I_{max} gives magnetic quadrupoles a clear advantage at higher energies, but at lower energies, solenoids or electrostatic quadrupoles may prove superior.

Chamber Concepts

One virtue shared by all approaches to inertial fusion is the separation of the driver from the comparatively simple reaction chamber. Whereas magnetic-fusion reactors typically combine a vacuum vessel with intricate magnets to confine the plasma and other subsystems to heat it and remove impurities, an inertial-fusion chamber is little more than a vacuum vessel with some means to protect the inner wall from the damage.

The most thoroughly developed HIF chamber concept is the HILIFE-II design, published by Moir in several papers [36-38] and featuring liquid protection of the inner chamber walls. About 1 m of FLiBe is needed to absorb fusion neutrons and to breed sufficient tritium for continued operation. The HYLIFE-II design meets this requirement with a combination of FliBe curtains and jets. Oscillating nozzles produce rippled FliBe curtains that overlap to provide a series of falling horizontal tube-like cavities. A HIF target is injected along the axis of each of these cavities, and a cone of ion beams converges on the target from each end to heat the hohlraum. The space between the beams is protected by a lattice of crisscrossed FLiBe jets. Liquid curtains and jets of the sort prescribed by the HYLIFE work have been developed at UC Berkeley in a series of experiments using hydrodynamically equivalent water jets, with care taken to match the Reynolds and Weber numbers of molten FLiBe [39]. This wall protection is found to be adequate for chamber survival over the projected lifetime of a HIF power plant [40].

Obtaining the final longitudinal and transverse compression required of HIF beams is a key requirement of any chamber design. Increasing the number of beams allows adequate compression but directing and focusing a thousand or more beams makes the final transport system quite complicated, as seen in Refs. 24-26. However, numerical simulations in the early 2000s suggested that passing the beam through a plasma as it enters the chamber neutralizes the beam space charge sufficiently to

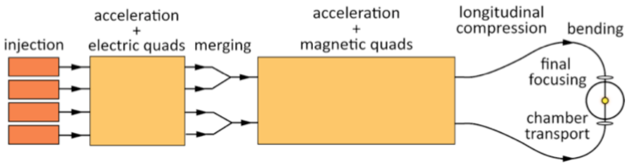

Figure 2: Schematic layout of a generic HIF driver using induction acceleration. An optional section for beam merging is included for completeness.

achieve sub-millimeter focal spot radii for driver-like beams [41-42]. With the experimental demonstration of this technique, described in the next section, neutralized chamber transport of high-current ion beams has become the preferred approach to managing the space-charge problem. The number of beams needed in a HIF driver, typically around one hundred, is now set more by symmetry and pulse-shape requirements of the target than by space charge [43].

PAST HIF RESEARCH

The sketch in Fig. 2 shows the functions needed in a generic HIF driver. Over the past thirty years, almost all of these functions have been tested in reduced-scale experiments. In these experiments, dimensions and currents were orders of magnitude smaller than those for HIF drivers in order to reduce cost, but careful scaling kept key physics parameters - betatron phase advance per lattice period σ, tune depression due to space charge σ/σ_0, perveance, and the fraction of the cross-section filled by beam - close to driver values.

From 1980 to 1986, the Single-Beam Transport Experiment (SBTE) at LBNL investigated the limits of transportable current in a long AG lattice, consisting of 87 electrostatic quadrupoles [44-45]. Using a 200-keV Cs^+ beam, SBTE demonstrated that beams having a tune deprssion σ/σ_0 as low as 10% can be transported with little loss of beam quality. Above this value, both current and emittance are unaffected, provided the undepressed betatron phase advance per lattice period σ_0 remains below approximately 85 degrees. These studies opened up the field of space-charge-dominated beams, which has proven a fruitful field for theoretical as well as experimental research [46-47].

Longitudinal compression of ion beams during acceleration, sometimes called "current amplification," was first demonstrated in the four-beam MBE-4 experiment, operated at LBNL from 1985 to 1991 [44,48-49]. The experiment showed that properly shaped acceleration waveforms could impose a head-to-tail velocity tilt on the beam, leading to lengthwise compression. The MBE-4 beams showed negligible increase in normalized emittance while being accelerated along the 14-m lattice, and in a separate study, they were successfully compressed lengthwise by a factor of three, giving threefold current amplification. In addition, applying ear voltages to counter the beam space-charge force was shown to be effective.

In 1994, LBNL built and successfully tested an injector that provided K^+ ions at the energy, current, and emittance of a full-scale driver [44,50-51]. The beam is produced in a conventional 0.75 MV diode and further accelerated to 2 MV by an electrostatic-quadrupole-focused high-voltage column. The injector successfully met the design goals for beam emittance (normalized edge emittance less than 1 pi mm-mr), energy (greater than 2 MeV), and current (800 mA). Detailed measurements of transverse phase space over a broad range of energy and current have shown excellent agreement with computer simulations done with the 3-D particle-in-cell code Warp [52-53]. Experimenters achieved an energy variation of less than ±0.15% over the 1-μs duration of the beam pulse.

The MBE-4 injector was reused in 1996 in an experiment that, for the first time, merged four space-charge-dominated beams [54]. The four 4.8-mA Cs^+ beams were first brought close together transversely in a four-lattice series of converging electrostatic quadrupoles and then were combined into a single beam and transported through 30 more lattice periods. The transverse emittance of the merged beam exceeded the sum of the four initial emittances due to entrainment of empty phase space between the pulses, but the increase was near the geometrical minimum. Beam combining may be used in a driver to exploit the higher limits on transportable charge found at higher energies.

Around 2000, a scaled experiment was carried out to test the design for un-neutralized final focus proposed in 1985 in the HIBALL-II study [24]. The experiment used a 160-keV Cs^+ beam to model the 10 GeV Bi^+ HIBALL-II beams and chose beam and lattice parameters to replicate the physics at one-tenth scale [55]. The experimental beam succeeded in reproducing the calculated emittance-dominated spot size on target. It was further shown that, by neutralizing 80% of the beam space charge with electrons from a nearby hot filament, a beam with four times the current could be focused to the same spot size, demonstrating for the first time partially neutralized radial compression of an ion beam.

Operated during 2002-2005, the High Current Experiment HCX was the first experiment to transport a driver-scale heavy-ion beam [56]. The project, which employed the 2-MeV K^+ injector at reduced voltage, was designed to address important science questions involving the optimum beam size and the preservation of good beam quality during transport. Five principal issues were addressed: (a) measuring the allowable "fill factor" (the ratio of maximum beam radial extent to aperture radius) and understanding what physical phenomena limit it; (b) investigating how the maximum transportable current is affected by misalignments, beam manipulations, and field nonlinearities; (c) determining the radial extent of beam halo resulting from mismatch and other errors; (d) studying the effects of stray electrons generated by halo scrape-off and by ionization of the residual gas; and (e) improving techniques for measuring the phase-space distribution of a beam. The experiment indicated that transport with an 80% beam fill factor at the low-energy end of a HIF driver should be possible with acceptable values of emittance growth and beam loss.

Concurrent with HCX, a 500-kV beam-source test stand STS-500 was built at Lawrence Livermore National Laboratory (LLNL) to test the concept of merging many small beamlets into a larger beam [57]. Compared with single-beam sources, this approach offers a smaller transverse footprint, more control over the shaping and aiming of the beam, and more flexibility in the choice of ion. Using an rf plasma source, beamlets with up to 5 mA of Ar^+ were extracted through an aperture plate, each with current density of 100 mA/cm^2. An elliptical array of 119 such beamlets was then focused and accelerated through Einzel lenses, and finally merged, demonstrating the feasibility of this concept.

Since 2005, the Neutralized Drift Compression Experiment (NDCX-I) has carried out a systematic study of plasma-neutralized ion-beam compression [58-60]. In addition to valuable experiments on solenoid transport and control of stray electrons, NDCX-I routinely achieves longitudinal beam compression factors of more than fifty, with simultaneous transverse focusing to radii of a few mm. After an induction cell imposes a controlled velocity tilt, the beam space charge is neutralized in a 1-m long column of $BaTiO_3$ rings, lined with a positively biased mesh of fine wires. Arcing between the wires and the barium titanate produces a plasma that fills the column. So long as the electron density inside this ferroelectric plasma source (FEPS) is a few times higher than the beam number density, the beam space charge is neutralized adequately to allow nearly ballistic longitudinal compression as the beam threads the column [61]. Final radial compression is achieved with a pulsed 8-T solenoid following the FEPS, and compression is further improved by surrounding the target with a second plasma from four cathodic-arc sources. Using an injected 30-mA K^+ ion beam with initial kinetic energy 0.3 MeV, the compression on NDCX-I has enabled a useful series of high-energy-density physics (HEDP) experiments.

PRESENT HIF RESEARCH

The focus of ongoing US HIF research is the construction of the second Neutralized Drift Compression Experiment (NDCX-II). Induction cells and pulsed-power hardware from the decommissioned Advanced Test Accelerator (ATA) at LLNL are being modified and reused. The baseline design calls for using 12 ATA cells to accelerate 30 nC or more of Li^+ ions to 1.2 MeV before neutralized drift-compression. To heat targets to useful temperatures, the beam must be compressed to a sub-millimeter radius and a duration of about 1 ns, a compression factor in time of more than 600 and a density compression of about 2 x 10^5. This facility, currently being constructed at LBNL, will enable studies of heavy-ion beam-heated matter in the poorly-understood "warm dense matter" (WDM) regime around 1 eV and near-solid density. Ion beams are particularly suited for such investigations because they deposit energy through the volume of a target, unlike laser beams, which deposit their energy near the surface. In addition, NDCX-II will enable studies of ion energy deposition into an ablating plasma, physics that is relevant to inertial fusion directly driven by ion beams.

The initial work to develop an NDCX-II physics model [62-63] used idealized analytic waveforms and focused on solving several design challenges: (a) use of ATA induction cells sets the lattice period, beam-pipe radius, and all properties of the ferrite cores; (b) the ATA Blumleins provide 70-ns FWHM acceleration pulses, and more-expensive custom pulsers are needed where the beam duration is longer; (c) budgetary considerations necessitate using passive circuit elements to shape waveforms; (d) in addition to accelerating the beam, the applied waveforms must compensate for the beam longitudinal space charge and impose a final velocity tilt prior to drift-compression; (e) limited floor space constrains the number of acceleration cells to fifty or fewer; and (f) the need for extreme longitudinal and transverse compression requires minimal emittance growth and halo formation during acceleration. These challenges were successfully met by a novel acceleration schedule. The 600-ns beam from the injector is first compressed by imposing a large (~30%) velocity tilt in order to shorten the beam as quickly as is feasible to 70 ns, so the ATA Blumleins can be used. The beam is then allowed to expand due to its own space charge as the pulse is quickly accelerated. A velocity tilt of about 10% is imposed in the final several acceleration cells, and the beam compresses as it drifts through a neutralizing plasma, reaching a longitudinal waist at the target. This physics design has been verified by 2-D and 3-D simulations with the particle-in-cell code Warp [52-53], and the solenoids strengths needed to maintain a nearly constant beam radius have been calculated. Many runs with ensembles of random errors in solenoid alignment and the timing of accelerator pulses have established error tolerances [64].

In addition to NDCX-II, other laboratories are investigating physics that is important to HIF. The University of Maryland and Princeton University both have long-running experiments that study the transport of space-charge-dominated beams over long distances. The University of Maryland Electron Ring (UMER) [65] uses a low-energy (~10 keV) 100-mA electron beam to model a space-charge-dominated ion beam. The experiment was built between 1997 and 2008, and beams have now been transported for distances exceeding 1 km, with and without applying ear fields to control beam lengthening due to space charge. The Princeton Paul Trap Simulator Experiment (PTSX) uses an alternate approach to modeling long path-lengths [66]. The beam remains stationary while quadrupolar electrodes produce oscillating electric fields that mimic the confining fields seen by a beam moving through a quadrupole lattice. PSTX is being used to study emittance growth, halo formation, beam mismatch, and related questions.

Two European laboratories have important programs on the physics of high-charge-state heavy-ion beams. In

Darmstadt, Germany, GSI is making a major addition to their rf accelerator complex [67]. The new project, FAIR for Facility for Antiproton and Ion Research, will boost 5 x 10^{11} ions per bunch to 150 MeV/u. The upgrade will provide ion beams of unprecedented intensity, enabling a wide range of experiments in exotic states of matter, nuclear forces, and laboratory astrophysics. The TeraWatt ACcumulator (TWAC) facility at the Institute for Theoretical and Experimental Physics (ITEP), Moscow, completed in 2008, uses multiple rf accelerator rings producing heavy ions up to 200 GeV/u [68]. Two valuable projects at TWAC are a laser ion source producing high-charge-state aluminum, iron, and silver ions, and an rf structure, called a "wobbler," that causes the beam focal spot to trace out a tiny circle on a target [69]. Since many HIF target concepts require that energy be deposited in a circular pattern, such a wobbler could reduce the number of beams needed to assure adequate symmetry. The concept will be tested at the GSI FAIR complex when that facility is operational.

Teams in Japan and China are likewise working on heavy-ion accelerators and deposition physics. The Japanese HEDP laboratory KEK is developing a programmable induction synchrotron that can accelerate ions with a wide range of masses [70]. Another Japanese laboratory, RIKEN, uses the heavy-ion cyclotron facility RIBF to study exotic, neutron-rich nuclei and HEDP questions such a solar neutrino production [71]. The Institute of Modern Physics in Lanzhou, China, is using their heavy-ion storage ring HIRFL-CSR for new isotope synthesis, HEDP experiments, and studies of the structure of relativistic ion beams [72]. Also, several Japanese and Chinese university groups are investigating HIF target design and approaches to achieving high gain [73].

PROSPECTS

Beam manipulations employed in NDCX-II are relevant to the physics of a HIF driver for power production. Driver beams will be space-charge dominated both transversely and longitudinally, in the sense that quiescent propagation is achieved primarily by balancing the space-charge forces with the applied transverse focusing, the thermal pressure (emittance) being a smaller contributor. The initial compression in NDCX-II, where velocity tilt is largely removed by space charge, resembles the method for energy equalization envisioned for use in a driver to enable final focusing with minimal chromatic aberration. NDCX-II will be the first experiment to demonstrate this process. The machine will also enable a wide variety of studies of beam dynamics, both non-neutralized and neutralized.

The modular design of NDCX-II allows straightforward and economical extension to as many as fifty active cells. A machine of that length, with an additional transport line, bend magnets, and a quadrupole final focus, could be used for scaled experiments on bending, non-neutral ion-beam compression, and final focusing with driver-like dimensionless parameters.

Recent advances in robust, high-gain targets [17,74] are leading us to reconsider HIF driver design. These targets use relatively low-energy beams to compress the fuel, followed by a short, intense pulse to ignite it. To meet these needs, we are looking at a new class of high-gradient core-less induction devices called dielectric-wall accelerators [75], as well as at the use of high-charge-state ions. Innovations of this sort may reduce the cost and complexity of HIF power plants.

International HIF workshops and symposia have been held on a nearly biennial schedule since 1976. Each begins with overviews of HIF programs worldwide and related work, and information on almost all aspects of HIF research is available in this series. Citations for the last several proceedings given in the References [76], along with a link to other HIF information [77].

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