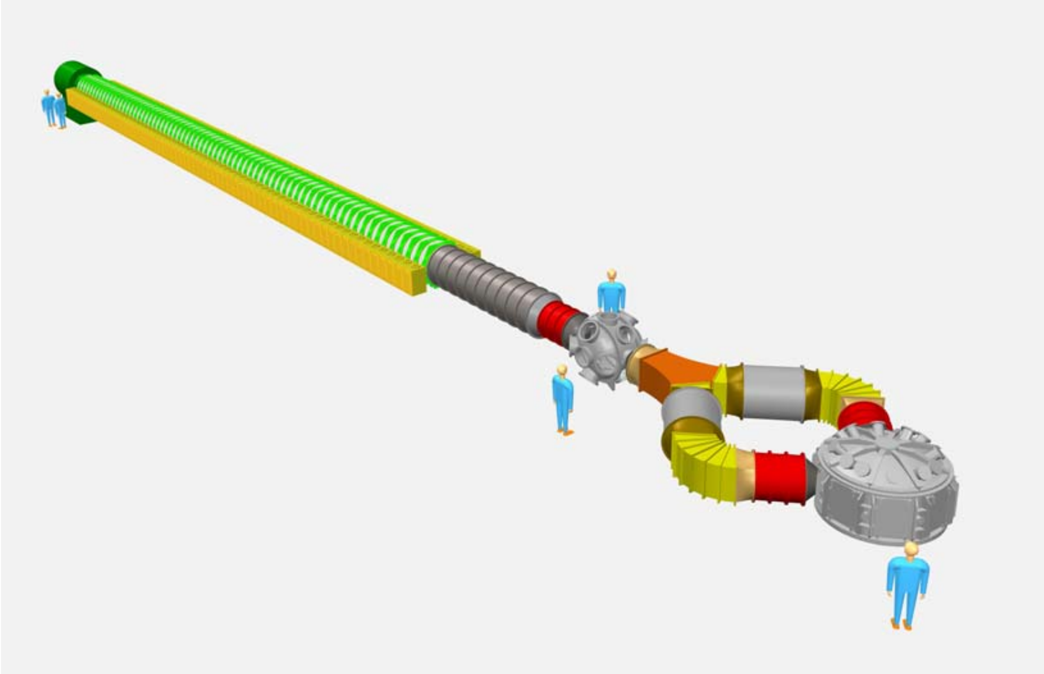
Integrated Beam-High Energy Density Physics Facility (IB-HEDPF)



I. The ability of the facility to contribute to world-leading science in the next decade

One of the four broad goals for Fusion Energy Sciences is to "pursue scientific opportunities and grand challenges in high energy density plasma science to explore the feasibility of the inertial confinement approach as a fusion energy source, to better understand our universe, and to enhance national security and economic competitiveness." In support of this goal, a facility for using intense, short-pulse heavy ion beams to study High Energy Density Laboratory Plasma (HEDLP) and materials science, and to explore the Heavy Ion Fusion (HIF) approach to inertial fusion energy, is proposed.

Over the past ten years, the Office of Science has consistently deemed a facility to experimentally advance HEDLP science related to heavy ion inertial fusion energy to be an important element of its portfolio of facilities. This new proposed Integrated Beam-High Energy Density Physics Facility (IB-HEDPF) is an up-to-date version of similar ion-beam based facilities already listed in past DOE-planned facilities lists. In the 2003 and 2007 Office of Science Strategic Plans for *Facilities for the Future of Science: A Twenty-Year Outlook*, an Integrated Beam Experiment (IBX) was proposed. The IBX facility would "generate very stable and intense ion beams, accelerate and compress them, guide them to travel in parallel without interacting, and yet be able to focus them on a very small fuel target." In the 2007 report, *Four Years Later: An Interim Report on Facilities for the Future of Science: A Twenty-Year Outlook*, the facility description was updated to emphasize its mission of Warm Dense Matter (WDM) target studies and IBX was renamed the Integrated Beam—High Energy Density Physics Experiment (IB-HEDPX). Mission Need (CD-0) for IB-HEDPX was approved by DOE in December, 2005. In 2012, the heavy ion beam program at LBNL, in collaboration with LLNL and PPPL, began commissioning the Neutralized Drift Compression Experiment II (NDCX-II). NDCX-II is an $11M user facility funded by the American Recovery and Reinvestment Act. It is

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designed to achieve unprecedented compression of intense ion beams to meet the needs of HEDLP and HIF applications. NDCX-II will support a broad range of target physics experiments related to WDM and inertial fusion energy, as well as explorations of the beam physics of HIF drivers.

IB-HEDPF is the logical next step for investigation of ion-beam-driven high energy density science and materials science, and experimental exploration of the scientific basis for HIF. The name has been changed from IB-HEDPX (an experiment) to IB-HEDPF (a facility), to reflect the user-facility emphasis of the reformulated project. This new facility will produce target temperatures up to 20 eV and target pressures of multiple Megabars, comparable to or exceeding those achievable on planned ion beam facilities in Germany (FAIR) and China (HIAF). Both FAIR and HIAF are nuclear physics facilities with a secondary interest in studying HEDLP. They are based on the storage ring approach as opposed to the linac approach of NDCX-II and IB-HEDPF, and have very different beam parameters and target designs than IB-HEDPF. IB-HEDPF will enable isochoric warm dense matter studies that are beyond the capabilities of any existing driver. In addition, since the beam intensity at IB-HEDPF will be two to three orders-of-magnitude higher than in NDCX-II, the facility will be used to further explore and validate the science of compressing ion beams in both time and space, in regimes related to those of an HIF driver. The multiple-beam accelerator at IB-HEDPF will employ simultaneous acceleration of multiple beams through a single row of induction cores to achieve cost savings. Other beam and plasma physics issues, such as the bending of space-charge-dominated beams and the merging of intense ion beams in plasma, will also be studied.

The unique ability to produce intense and tunable ion beam pulses with pulse lengths in the ns range enables, for the first time, direct access to the dynamics of radiation induced defects. Ions impinging on solids produce point defects such as interstitials and vacancies. Understanding recombination, diffusion and accumulation of defects is critical for the design of fusion and fission reactor materials, and many other applications. Short ion beam pulses from NDCX-II and IB-HEDPF, together with in situ diagnostics, will allow users to track defect dynamics on time scales from ns to hours. IB-HEDPF will greatly expand on the capabilities of NDCX-II by offering more flexible, shorter, more energetic pulses and pulse pairs, and a vastly greater suite of diagnostics. The resulting accelerated testing will critically advance multi-scale simulation efforts through benchmarking of models and promises to enable rapid and effective optimization of materials for intense radiation environments.

The IB-HEDPF facility will include short pulse lasers for x-ray backlighting diagnostics and plasma sources for beam neutralization. The four-beam induction linac will accelerate ~200 nC of Na^+ ions to roughly 30 MeV with pulse durations in the 1.0 ns range or shorter (pump-probe pairs are also possible). These parameters will permit uniform heating of initially solid material up to 10 microns thick. Multiple end-stations are envisioned for target studies in materials science, HEDLP, and HIF science, offering simultaneous operation of multiple experiments. Other HEDLP drivers, such as long pulse lasers, diamond anvils, piston-driven gas cells, etc. may be incorporated within the end stations, and may utilize the ion beam in a probe as well as a pump mode. A broad range of research projects at IB-HEDPF will be fielded by U.S. scientists (and international users, notably from FAIR and HIAF), and will focus on critical issues for materials science, HEDLP, and HIF science, including equation-of-state studies, material defect dynamics, detailed measurements of thermal and electrical conductivities in the WDM regime, and physics related to inertial fusion energy targets, such as energy coupling and fluid instabilities.

The long-term objective of the IB-HEDPF project is to create a dedicated user facility for experimental research in ion-beam-driven HEDLP and heavy ion fusion science in the US. Development of the facility will require the integration of sources, injection, acceleration, transport, compression, and focusing of four ion beams of high intensity for creating high energy density matter. The space-charge intensity of the heavy ion beams is sufficiently high that the beam particles act as non-neutral plasmas. The beam transport in the accelerator is collisionless, so that the ion beam distribution in phase space may retain a long memory of each accelerator section that the beam passes through. An integrated beam facility of this scale is essential for validating computational models of intense beams, plasmas, and beam-target interactions.

Heavy ion beams have a number of advantages as drivers of targets for high energy density physics and fusion energy applications. First, heavy ions can penetrate and deposit most of their energy deep inside the targets (in contrast with lasers). Second, the beam energy deposition has a pronounced peak at the end of the penetration range, allowing for very localized energy deposition. This property is enhanced for heavy ions with high Z and this makes heavy ions well suited for high energy density physics studies, because thin targets can be uniformly heated by locating the deposition peak near the target center. The primary scientific challenge in exploiting these desirable properties in the creation of high energy density matter and fusion ignition conditions in the laboratory is to compress the beam in time and focus the beam in space simultaneously. A pulse duration that is short compared to the target disassembly time can be produced. NDCX-I has already demonstrated the physics for transverse and longitudinal beam compression. Studies on NDCX-II are already advancing the understanding of transverse and longitudinal beam compression for intense beam pulses. IB-HEDPF will compress even more intense ion beams at sufficient energy and intensity to support a broad range of experiments with target temperatures in the much higher range of 20 eV. That will allow detailed studies in the regime of strongly coupled plasmas – an elusive goal for many experiments. Furthermore, though NDCX-II will launch shocks in sub-solid density matter and plow new ground in WDM research, strong ion driven shock interactions in solids and in WDM, and other aspects of ion coupling to matter at intermediate ion energies, will be studied for the first time on IB-HEDPF. By employing multiple beams that overlap at the target, higher target temperatures can be achieved, flexible illumination geometries are possible, and diagnostic flexibility is enhanced.

The main alternatives to the U. S. induction accelerator based approach for HEDLP and heavy-ion fusion are combinations of heavy-ion RF-linacs and storage rings being pursued in Germany, Russia, Japan, and China. Such RF linacs/storage rings have been developed primarily for nuclear physics research; HEDLP and heavy-ion fusion applications are secondary applications for these facilities, with only modest amounts of time currently allocated to their study. A billion dollar upgrade of the German GSI heavy-ion storage ring facility (FAIR), and a newly approved Chinese Institute of Modern Physics project (HIAF) of comparable scope, are expected to achieve 10 eV target temperatures when completed in about 5 - 10 years. These more extensive, multi-purpose facilities are far more costly than the induction-linac-based system proposed for IB-HEDPF. While RF-based accelerators are, and will continue to be, valuable tools for studying heavy-ion beam interactions with gas and dense plasma targets, the beam kinetic energies in such facilities lead to very long penetration ranges, and thus to relatively ineffective coupling into targets. Also, the ultra-short pulses needed for many studies of interest do not appear to be achievable on RF-based systems. Thus, in addition to being much less costly, the induction linac based IB-HEDPF, with its flexible short pulses and pulse pairs, will better support HEDLP research and attract an international user base.

Another facility for HEDLP studies is the Matter in Extreme Conditions (MEC) end station at the Linac Coherent Light Source (LCLS) at SLAC, which can isochorically heat targets with its X-ray free electron laser to temperatures up to the 100 eV range. This facility achieves very uniform temperatures and densities, but only in small volumes, approximately 1 micron^3. Its optical lasers can reach higher target temperatures, but that heating has thermal gradients. In comparison, IB-HEDPF will reach target temperatures up to 20 eV or more isochorically using ion beams instead of photon or X-ray beams, in spots with transverse scale sizes of 0.1-1 mm.

II The readiness of the facility for construction.

Subject to the availability of funds, the IB-HEDPF project can be accomplished over a period of 6-8 years, with the first two years dedicated to preparatory R&D. Previous experiments have laid the ground work: MBE-4 demonstrated the simultaneous acceleration of multiple, parallel ion beams in an induction accelerator; NDCX-I demonstrated the principle of neutralized drift compression and focusing; NDCX-II provides the vital engineering and physics data that, as outlined in DOE's previous plan for an IB-HEDPX, is a prerequisite for IB-HEDPF. The recent experience with NDCX-II and earlier detailed cost estimates of IBX give us confidence that we will be able to achieve our physics goals with an investment of approximately $150M and an operating cost of approximately $20 M/year including user support and a suite of diagnostics that will be continually upgraded.

III. Scientific community considerations

The Lawrence Berkeley National Laboratory will have the lead responsibility for execution and nominal hosting of the IB-HEDPF project. A project management organization will be formed within LBNL, reporting to the Department of Energy through the LBNL Director. LBNL will draw on other National Laboratories for major support, including technical leadership in specific areas of the project. LBNL has partnered with the Lawrence Livermore National Laboratory, Princeton Plasma Physics Laboratory, and SLAC National Accelerator Laboratory, on projects of this general nature. LBNL, LLNL, and PPPL have a strong record of collaboration under the auspices of the Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL), and worked closely together to construct the NDCX-II facility; LBNL and SLAC have also collaborated extensively. These four laboratories have recently joined together to create the Bay Area High Energy Density Science (BA-HEDS) Cooperative, offering technical leverage to individual scientists and groups and enhancing their ability to carry out high-impact research that spans multiple facilities. The capabilities of IB-HEDPF will be optimally exploited by its participation in such a scientific cooperative.

The Office of Fusion Energy Sciences (OFES) in the DOE's Office of Science has the responsibility for the programmatic and technical oversight of the project. The area manager of the DOE Berkeley Site Office will assign a DOE project manager having primary responsibility to ensure that the project is properly managed by LBNL and that its technical objectives are met within the baseline cost and schedule.

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