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2. Inertial Fusion Driver Development and Future Prospects in the United States

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Abstract

A brief review is given of the requirements of inertial fusion energy drivers and their status and prospects in the U.S. Drivers based on lasers (diode-pumped solid-state and KrF) and heavy ions are discussed.

Keywords:

inertial fusion energy (IFE), direct drive, indirect drive, diode-pumped solid-state lasers, KrF lasers, heavy ion beams

2.1 Introduction and driver requirements

The outlook for future electric power plants based on inertial fusion energy (IFE) is quite positive because of recent results in target physics as well as advances in driver technology [1]. Drivers based on solid-state lasers, KrF lasers, and heavy ions are being evaluated for IFE. Each driver has special advantages in meeting the energy, efficiency, drive uniformity, lifetime, and cost goals for IFE. However since no driver can clearly meet all the requirements without significant advances, a multi-faceted development plan is proposed.

The baseline approach to laser-driven IFE is direct drive. As shown in Fig. 1(a), the laser driver shines directly on the spherical pellet with an energy absorption efficiency of approximately 90% and is predicted to produce an energy gain of approximately 100 [2]. The target is a spherical shell, approximately 5 mm in diameter, consisting of frozen DT surrounded by an ablator. The target ablator is symmetrically heated by about 60 laser beams, generating pressures of 50–100 Mbar that then implodes the cold DT fuel to densities of $\sim 400 \text{ g/cm}^3$, with a central hot spot at 5–10 keV for fuel ignition. Specific ablator materials are chosen to

avoid, or minimize, laser-plasma and hydrodynamic instabilities — for example, low-density foam or DT-wetted foam and may incorporate high-Z overlayers. The laser must deliver $\sim 2 \text{ MJ}$ pulses at a repetition frequency of 5–10 Hz and at a short wavelength ($\leq 0.5 \mu\text{m}$) with an overall efficiency of $> 5\%$ to minimize the electrical power which is recirculated back to drive the laser. The laser pulse must be temporally-shaped with a $\sim 5\text{-ns}$ “drive” pulse preceded by a $\sim 20\text{-ns}$ “foot” pulse which is tailored in time to minimize shocks which preheat the DT fuel. To produce the desired fuel compression and minimize hydrodynamic instabilities, the laser must illuminate the capsule with a uniformity of 1% or better when averaged over a timescale of $\sim 0.2\text{--}1 \text{ ns}$. This requires that the laser beams be precisely pointed and balanced in power to each other and that they incorporate temporal beam smoothing to produce a rapidly varying speckle pattern on target. It is currently believed that at least the foot pulse must have a bandwidth $> 1 \text{ THz}$ to produce adequate beam smoothing.

Experiments to establish the requirement for direct drive have been ongoing with the 3 kJ Nike laser at the

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Naval Research Laboratory. Nike affords excellent beam smoothness by the use of KrF technology in which 36 spatially incoherent beams are overlapped on target each having a bandwidth up to 2 THz. The Nike experiments on planar foils have yielded laser smoothing requirements adequate to control hydrodynamic stability. The 30-kJ Omega laser based on Nd:glass technology is being used to investigate direct drive requirements in a spherical geometry and will begin cryogenic target experiments in 2000. Omega is also testing the beam smoothing capability of solid-state lasers for direct drive.

The baseline approach for heavy-ion driven IFE is indirect drive, in which the ion energy is converted into thermal x-rays ($T \sim 200\text{--}300\text{ eV}$) which then are used to implode the fuel pellet. The energy gains [3] of these target designs are in the range of 60–140 and driver energies are in the range of 2–6 MJ; specific values depend upon the size of the radiation case and the potential brightness of the ion beams. However even with the lower energy gains, the high efficiency of an accelerator, $\sim 30\%$ is sufficient for economic electric power production. A schematic diagram of a heavy-ion-driven IFE target [3] which is predicted to produce a gain of 130 is shown in Fig. 1.

Because high-energy/pulse heavy-ion drivers are not currently available, x-ray-driven pellet physics is now being investigated in the U.S. at the 30-kJ level with the Nova laser at Lawrence Livermore National

Laboratory and with the 30-kJ Omega laser at the Laboratory of Laser Energetics, University of Rochester. Results in x-ray drive and capsule implosion are consistent with detailed models of target performance [4].

The fast ignitor [5] is an advanced approach to inertial fusion that separates the steps of target compression and ignition and potentially reducing driver requirements and increasing target gain. In the fast ignitor approach, a picosecond laser pulse from a solid-state laser is used to produce MeV electrons (or ions) which propagate onto a compressed pellet causing hot-spot ignition starting on the side. Depending on the electron production efficiency and angular divergence, picosecond pulse laser energies $\sim 100\text{--}kJ$ could be adequate. This approach and how it could be used in a power plant are subjects of current research and speculation.

The 1.8 MJ National Ignition Facility (NIF) is now under construction at LLNL. NIF was specified to produce ignition and gain (10–20) of indirect-drive targets. It is based on a 192-beam Nd:glass laser operating at its third harmonic with a 20-ns temporally-shaped pulse with its energy concentrated in the final 3 ns. Although NIF was designed and sized primarily for indirect drive, it has sufficient flexibility in target irradiation geometry to test direct drive after an upgrade to improve its temporal beam smoothing is installed. For planning purposes, NIF is expected to reach fusion ignition and gain by indirect drive in 2006 and by direct drive after 2008.

Fig. 1 Schematic diagram of (a) high-gain direct drive inertial fusion energy target and (b) high-gain indirect-drive target.

Presuming that NIF is successful in reaching its goals in target ignition and gain, a program to develop IFE drivers and chambers is now being proposed. A timeline for the necessary IFE developments adopted by consensus of leaders in the U.S. inertial fusion community is shown in Fig. 2. This timeline includes an initial four-year proof-of-principle phase I in which the technology of average-power laser drivers based on both solid-state and KrF laser technology and heavy ion technology are developed. Depending on the success of these rep-rated driver developments, one or more of the driver options would proceed to an Integrated Research Experiment (IRE) in which a several kilojoule driver is coupled with a fusion target at the required 5–10 Hz and at a driver efficiency of greater than 5%

as needed in a fusion power plant. A presumption in this scenario is that the IRE driver would incorporate all the necessary features of an IFE beamline to allow confidence in the construction of a full plant-scale driver in the next step. For both lasers and heavy ions, the size of the IRE will be large enough that the cost for the Phase II Engineering Test Facility (ETF) could be accurately projected. For lasers the plan is to develop and optimize one complete laser beam line, or fraction of a beam line, that could be used directly in a power plant. It could then be duplicated in parallel to produce the needed total driver energy. While one could also follow this parallel approach with ions, it does not lead to an optimal accelerator in terms of efficiency and cost. If the ion driver IRE is successful, it

Fig. 2 A cost effective IFE driver and power plant development plan developed by looking backward from the ultimate goal. Various decision points and development stages are noted.

would be more appropriate to add acceleration modules in series to produce the needed energy. A final step in this scenario is the construction of a full test reactor with the optimum driver incorporating all the features necessary for commercial electric power production.

For inertial fusion, it is possible to simultaneously evaluate the scientific, engineering, and economic feasibility at a relatively low cost. This is possible because the different components — driver, chamber, pellet factory — are physically separate and can be developed independently. In addition, a laser driver consists of ~100 parallel and identical beam lines. Only one beam line needs to be developed initially. And finally, the inertial fusion program can take advantage of the investments by the defense communities in large glass facilities, in target design capability, and in target interaction experiments.

2.2 Solid State Laser Drivers

Solid-state laser drivers operate in the energy storage mode in which a relatively long optical pump pulse (~0.1–1 ms) is used to accumulate energy in the upper laser level followed by a short energy extraction pulse (~1–10 ns) which, after beam conditioning, is used to drive the fusion target. Flashlamp-pumped Nd:glass lasers [6] are the classical form of such an energy storage system and provide the foundation for future designs. In large aperture (≤ 40 cm) Nd:glass systems, Brewster mounted slabs are excited by flashlamps over a period of order the storage lifetime. The aperture size and excitation period are limited by transverse amplified spontaneous emission in the laser slabs. The output energy of an amplifier chain is limited by

the beam size and optical damage limits of the output optics. The output power is limited by nonlinear self-focusing in the laser chain (causing growth of beam modulation) or possibly by Brillouin or Raman scattering in the optical components or propagation path. Finally the output is converted to the second or third harmonic in phase-matched frequency conversion crystals, (KDP and KD*P are most commonly used) and focused onto the target.

Modern Nd:glass laser systems such as Beamlet, and now the National Ignition Facility employ considerable sophistication in this overall design. This sophistication is used to provide optimized target irradiation parameters, to minimize cost, and to maximize flexibility. A schematic diagram of a generic solid-state laser driver is shown in Fig. 3. The front-end injection system employs temporal pulseshaping to produce the desired temporally shaped drive pulse after energy extraction and frequency conversion. The front end provides temporal beam smoothing (temporarily changing speckle pattern on target) by phase modulation and spectrally dispersion in either a one or two dimensions (1D or 2D SSD) [7]. Smoothing by 2D SSD is used to provide the smooth beams needed for direct drive while 1D-SSD is adequate for indirect drive. The input beam is multi-passed through the large-scale amplifiers to minimize the number of components required to produce the necessary gain. A large aperture switch (plasma electrode Pockels cell and polarizer) is used to enable multipass operation while preventing parasitic oscillation during the pump pulse. A deformable mirror is used to correct the aberrations produced during amplification and produce a near-diffraction-limited output beam at the frequency conversion cell. Vacuum

Fig. 3 Generic Diagram of an energy storage solid-state laser system as used in NIF and proposed for an IFE driver.

spatial filters are used in the multipass cavity and in transport to the target chamber to “clean up” the beam profile and to relay image the beam without diffraction. After frequency conversion, a large-scale diffractive optic is used to control the spatial profile of the beam on target and possibly, as in NIF, to provide a small diagnostic sample of the output beam and to separate the desired third harmonic beam from the residual first and second harmonic beams. The National Ignition Facility, employing all these sophistications and producing 1.8 MJ at the third harmonic, has margin and flexibility to produce fusion ignition and gains of 10–20 according to a range of sophisticated laser and target models.

For a solid-state laser to reach the efficiency, repetition rate, cost, and lifetime required in a fusion power plant driver, major changes are required in this design while building on the overall concept. The flashlamps must be replaced by laser diodes which operate at greater than 50% efficiency into a narrow bandwidth. New optical designs are required to efficiently channel the light from the diodes into the laser material. The laser medium must be actively cooled in a geometry that still affords a large area beam as needed to maximize the energy per laser aperture, again consistent with the ASE limits of the amplification medium. LLNL has taken the approach of direct turbulent gas (He) cooling of the slab faces [8] still allowing for large area beams, while workers at the Institute for Laser Engineering at Osaka University [9] are currently investigating zig-zag slab designs in which water cooling can be directly applied to the slab faces. The laser medium and thickness are chosen to allow the necessary repetition rate while producing manageable thermal aberrations.

After an intensive evaluation of alternative gain modes, LLNL has selected a Yb-doped crystal gain medium which provides a longer storage time (1.0 ms versus 0.3 ms) than Nd, thereby minimizing the investment in laser diodes necessary to produce the required stored energy. A detailed system study [10] has shown that a large fraction of the driver cost is for laser diodes even at presumed cost of \$0.07/peak watt compared to current cost of \$3/peak watt. Such crystals also provides good thermal conductivity to easily enable the required repetition rate. However, the Yb-doped crystal (S-FAP, strontium fluorapatite) which produces high gain also has a relatively limited spectral bandwidth allowing only a tripled bandwidth of ~ 0.3 THz which may be inadequate for direct drive targets. Alternative Yb-doped crystals which provide broader bandwidth as well as Nd:glass itself are being considered to meet the

requirements of direct drive. Such gain media require operating at higher output fluence and if Nd:glass, higher diode costs. Because such a DPSSL driver would have 3000 subaperture beams, considerable flexibility is also possible in the laser design. For example, “foot” beams might be based on Nd:glass and converted to the second rather than the third harmonic for greater bandwidth (~ 2 THz) while the main drive beams might be based on Yb-doped crystals.

A demonstration diode-pumped solid-state laser driver called Mercury is now under construction at LLNL. The goals of Mercury are to produce a 100-J first harmonic beam operating at 10 Hz with an overall efficiency of 10% in the year 2000. A Phase I development plan for DPSSL's as indicated in Fig. 2 includes demonstrating efficient frequency conversion and the required temporal beam smoothing on Mercury, developing laser diode pump arrays and laser crystals at a cost and size acceptable for the IRE, and investigating system design issues on Mercury. In parallel, final optics and chamber developments are required to prove the viability of DPSSL's as IFE drivers. An IRE based on a DPSSL driver would test the bundling of several fundamental apertures at the ASE-limited building-block size (≥ 1 kJ/aperture). The possibility of using the kJ-class DPSSL envisioned for an IRE as a chamber development facility which provides x-rays, neutrons, and debris studies is also under investigation [11].

2.3 KrF Laser Drivers

The 1992 Sombrero [12] reactor design study showed that a few-megajoule KrF (krypton-fluoride) gas laser with a directly-illuminated inertial fusion pellet has the potential of providing electricity at 5.5 to 6.5 cents/kW-hr — close to future coal and fission plants. Because the high-technology laser is physically separated from the reactor chamber, most maintenance procedures would not require access to the chamber.

This reactor study required that the pellet have an energy gain (thermonuclear yield divided by laser energy input) of approximately 100. There are new target designs proposed by NRL [2] that have the potential of this energy gain, and that may be consistent with all of the target physics constraints in laser-plasma instabilities and hydrodynamic instabilities. The computer model used for these target designs has been successfully compared with a variety of laser-target experiments using the few-kilojoule KrF laser at NRL called Nike.

The Sombrero reactor study also required that the

KrF laser driver have a repetition rate of 5–10 Hz, an efficiency of 7.5%, a cost of \$170/J, a durability of 10^8 shots, and a 90% availability. NRL has demonstrated significant progress by showing that a few-kilojoule KrF laser can be made sufficiently reliable for laser-target experiments. However Nike has only 5–10 shots per day and 200 shots between routine maintenance, with $\sim 1\%$ efficiency and relatively high cost. Nonetheless most of the areas that require laser development for a fusion reactor have been partially demonstrated elsewhere, and there appears to be technical paths to build the necessary laser driver.

To directly implode a pellet to high density requires highly uniform laser beams. The pellet shell has to converge about a factor of 25 in radius, and the acceleration is susceptible to the Rayleigh-Taylor instability. A major breakthrough was the invention of optical beam smoothing, and in particular a technique called ISI [13] (Induced Spatial Incoherence). The Nike KrF laser [14] with ISI has a flux nonuniformity at focus of only 1% rms in a 4 ns pulse. When we overlap 40 of these beams, the nonuniformity drops to about 0.15%, excluding the short-wavelength beam-beam interference. The ISI optical smoothing technique can only be used effectively with a gas laser such as KrF, in which there are negligible nonlinear optical effects in the amplifiers. Solid state lasers have used another optical smoothing technique, called 2D-SSD, and have achieved single-beam flux nonuniformities [15] of 8–10%. Efforts are underway to improve the uniformity of solid state lasers.

To develop KrF for a fusion reactor, we propose first a concept validation step. We would build a 400

J/pulse amplifier, with 5 Hz operation. Such a facility (named Electra) would be large enough to be technically convincing, yet small enough to be manageable. The six components of the 400 J laser that will require development are: the pulsed power driver, the electron beam source, the pressure foil support structure, the laser gas conditioning system, the laser front end, and the laser optics. We have preliminary and partial solutions to the various technical problems.

In addition there would be parallel laser development efforts in deformable mirrors, improved large aperture transmissive optics, optical high-reflectivity coatings with a higher damage threshold, improved laser pulse shaping capabilities, advanced laser kinetic modeling, along with complete architectural studies to guide all of the above. This initial effort could take as little as 4–5 years.

If this Phase I concept-validation activity is successful, the next step would be a scaling validation (shown as the IRE in Fig. 2), in which one KrF laser beam line would be scaled up to 30–50 kJ/pulse. In parallel, the NIF would be used for an integrated demonstration of direct drive implosions. The pellet performance with this glass lasers likely will be inferior to that of a KrF, because of inferior beam smoothing. Nonetheless, it would provide a useful integrated test of the pellet concept. If this scaling validation is successful, the next step would be a few-megajoule Engineering Test Facility, in which one would duplicate the laser beam line developed in the previous step, along with a reactor chamber and small scale pellet factory.

2.4 Heavy Ion Drivers

Heavy ion accelerators are the third class of drivers. The goal of the heavy ion fusion program is to apply high energy and induction accelerator technology to IFE power production. Heavy ions ($A > 80$) at ion kinetic energies of 1–10 GeV have an ion penetration depth appropriate for inertial fusion targets. Multi-stage accelerators can readily produce such energies. Several types of accelerators are being developed. Radio frequency (RF) linacs (followed by storage rings) and induction linacs (without storage rings) are currently the favored approaches. The differences between these two approaches are comparable to the differences between diode pumped solid state lasers and KrF lasers. In the mid 1980's, the U.S. Department of Energy made a decision to focus its research on induction accelerators. Europe and Japan have favored the RF approach. Consequently, the worldwide program rather than the U.S. program would show four drivers rather than three.

Fig. 4 The measured focal spot laser intensity with the NRL KrF laser is only 1% rms (4 ns pulse; excluding tilt and curvature).

There are a number of reasons to consider accelerators for inertial fusion applications. An IFE driver must deliver 1 to 10 MJ of beam energy. The beams must be focused to a radius of a few millimeters and accurately aimed from a distance of several meters. The focusing system must survive in a fusion environment. The driver must be efficient, reliable, and durable. It must have a high-pulse repetition rate and good environmental characteristics. Based on accelerator experience, it should be relatively straightforward to achieve most of these requirements. Existing proton and electron accelerators are comparable to power plant drivers in terms of size, cost, total beam energy, focusing, average beam power, reliability, and durability. They can be efficient and they can easily produce the needed pulse repetition rates. Existing accelerators are good neighbors, operating in or under cities, villages, and farms. Since the beams are focused by magnetic fields, the conductors that produce these fields can be shielded from neutrons, gamma rays, and other fusion products. This provides a plausible solution to the problem of developing focusing elements that can survive in the fusion environment. However existing accelerators do not produce the beam current required for fusion. Since fusion targets require beam powers of 100–1,000 TW, the accelerators must deliver 10 kA – 1 MA of beam current. The primary scientific issue in adapting accelerator technology to inertial fusion is to produce these high beam currents while retaining the well established ability of accelerators to deliver beams that can be extremely well focus. In addition, accelerator cost, as in all three driver options, is an important issue.

As noted above, induction accelerators are the U.S. approach to heavy ion fusion. A simple linear induction accelerator consists of a number of magnetic cores surrounding the beam which are pulsed sequentially as the beam passes through them. These cores act as transformers in which the beam serves as the secondary winding. By using a sufficient number of cores, it is possible to accelerate ions to high kinetic energy. For fusion applications, it is not reasonable to accelerate the required current in a single beam. Consequently, most designs of fusion accelerators have 10 to 1,000 beams threading common induction cores. Each beam has its own focusing channel — usually an alternating gradient (quadruple) channel similar to the channels used in accelerators for high energy physics.

Induction accelerators also have a number of other components: an array of ion sources, an electrostatic injector (pre-accelerator) to accelerate the ions to a kinetic energy of the order of 1 MeV before they enter

the main induction accelerator, beam compression channels, and a focusing system to direct and focus the beams onto the fusion target. Typical accelerator designs carry a current that is approximately an order of magnitude smaller than the current required by the target. Thus compression channels are required to amplify the current to the desired value. This amplification is accomplished by accelerating the tail of the beams to a slightly higher velocity than the head of the beams. As the beams pass through the compression channels, the beams become shorter leading to current amplification. There is also current amplification in the accelerator itself. The current produced by a single ion source is of the order of 1 A. As the ion kinetic energy increases from approximately 1 MeV at the injector to perhaps 4 GeV at the end of the accelerator, the ion velocity increases by more than a factor of 60 leading to a corresponding current amplification as the physical beam length remains constant. One can also increase the current amplification factor in the accelerator by compressing the beam longitudinally as described above. Some accelerator designs employ one additional method of current amplification. In this method several (usually four) beams are combined transversely to produce a single beam having higher current. At the end of the accelerator each beam typically carries more than 100 A of current.

Although many of the components and beam manipulations just described are used in existing accelerators, the currents needed for fusion are unprecedented. Thus it is necessary to demonstrate what we define as high current operation. If beams are not confined in a focusing channel they expand because of their space charge forces and because of their internal temperature. In most conventional accelerators, temperature is the more important effect. In fusion accelerators, because of the high current, space charge dominates. From this point of view, the object of heavy-ion fusion driver research is to study and demonstrate the physics of space-charge-dominated beams.

Laser-driven fusion and heavy-ion research are strongly coupled. Lasers are well suited to near-term target physics experiments so there has been no need to develop large accelerators for these purposes. Consequently, the heavy ion fusion program has emphasized theory, numerical simulation, and small-scaled experiments to address the key issue of focusing high current heavy ion beams. Scaled experiments addressing all systems and beam manipulations in a full-scale driver have been completed or are nearing completion, e.g., injector experiments, a scaled focusing experiment that

produces millimeter focal spots, an experiment that combines four beams transversely while retaining good beam quality, compression experiments, and experiments on beam bending. The MBE-4 (Multiple Beam Experiment with Four Beams) at Lawrence Berkeley National Laboratory is typical of the machines built for the scaled experiments. These experiments explore the correct physics in the sense that dimensionless quantities such as the ratio of space charge effects to temperature effects have the correct values for fusion. For reasons of economy, the beam currents themselves are usually two orders of magnitude lower than those required for a fusion driver. The injector experiments are an exception. Present injectors produce one full-scale (approximately 1 A) beam. The scaled experiments are nearing completion. These experiments, in agreement with theory and simulation, suggest that it will be possible to achieve adequate focusing at the currents required for fusion.

Since the scaled experiments are nearing completion, we are now in a position to begin the Phase I heavy ion research illustrated in Fig. 5. The goal of the Phase I research is to enable the construction of an IRE, that, together with the results from the NIF, will lead to an ETF. The requirements on the IRE largely determine the Phase I research program. For heavy ion fusion, the IRE must complete our knowledge base relating to high current beams, it must demonstrate focusing onto a target, and it must validate expectations of good beam-target coupling. Beam-target coupling for

ions is the main target physics issue that will not be addressed on the NIF. Consider first the question of high beam current. The currents required for fusion are large enough to have a substantial effect on the acceleration cores and pulses. Specifically, high currents load the acceleration circuitry lowering the acceleration voltage. Under some circumstances, this beam loading can lead to instabilities. In order to show that these instabilities are sufficiently benign, it will be necessary for the IRE to accelerate more than 100 A. To demonstrate adequate focusing, the ions must be accelerated to more than 100 MeV. To validate the beam-target coupling, the beams must produce a high density plasma and the beam plasma frequency must be comparable to the beam plasma frequency in a full scale driver. These requirements dictate a total beam energy of several kilojoules focused to an intensity of 3 TW/cm² or more. We estimate that an IRE with the parameters given above will cost more than \$100 M. It is not prudent to build such a facility based on our current understanding of high current beams and it is highly desirable to minimize the cost of such a facility. To improve our understanding of high current beams and to minimize cost, we have developed a Phase I plan with the following tasks:

- 1) Complete the present scaled experiments.
- 2) Develop an end-to-end (ion source to target) numerical simulation capability.
- 3) Increase the current in our beam physics experiments from approximately 10 mA to 1 A.

Fig. 5 Schematic diagram of the elements of a heavy ion driver for IFE indicating where the critical questions are being addressed.

- 4) Develop a multi-beam injector capable of delivering of the order of 100 A.
- 5) Reduce the cost of all major accelerator components.

If these tasks are successfully completed, we will be in a position to build a highly capable IRE for heavy ion fusion experiments.

2.5 Conclusions

Inertial fusion energy developments have now reached a stage where they should be considered and funded in parallel with magnetic fusion energy developments. There are two well-developed and promising target approaches to IFE (direct and indirect drive) and one advanced but unproven approach (fast ignitor) as well as three candidate drivers (diode-pumped solid-state lasers, KrF lasers, and heavy ions). An orderly program of development and down-selection is proposed. To practically realize an IFE power source, considerable more effort is needed in chamber and power plant integration technologies as well as driver developments. The U.S. magnetic and inertial fusion energy communities are now working more closely together to solve the difficult problems that both communities face.

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